Proof-of-principle demonstration of vertical gravity gradient measurement using a single proof mass double-loop atom interferometer

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We demonstrate a proof-of-principle of direct Earth gravity gradient measurement with an atom interferometer-based gravity gradiometer using a single proof mass of cold $^{87}$Rb atoms. The atomic gradiometer is implemented in the so-called double-loop configuration, hence providing a direct gravity gradient dependent phase shift insensitive to DC acceleration and constant rotation rate. The atom interferometer (AI) can be either operated as a gravimeter or a gradiometer by simply adding an extra Raman $\pi$-pulse. We demonstrate gravity gradient measurements first using a vibration isolation platform and second without seismic isolation using the correlation between the AI signal and the vibration signal measured by an auxiliary classical accelerometer. The simplicity of the experimental setup (a single atomic source and unique detection) and the immunity of the AI to rotation-induced contrast loss, make it a good candidate for onboard gravity gradient measurements.

I. INTRODUCTION

Light-pulse Atom Interferometers (AIs) use short pulses of light to split, redirect, and then recombine cold atoms used as a matter-wave source. Since their advent in the 1990's [1, 2], they have demonstrated to be extremely sensitive and accurate sensors very useful in fundamental physics research where they have been used to measure fundamental constants [3-6], test the equivalence principle [7-11], put bounds on theories of dark energy [12], probe quantum superposition at the macroscopic level [13] as well as measuring gravito-inertial force such as gravity acceleration [14-18], rotations [19-21] and gravity gradient [22-24]. Most of these works consist in laboratory experiments but atom interferometer's inherent long term stability and accuracy have led to a global push towards performing experiments outside laboratory environment [17, 22-29]. Moreover, cold atom-based gravity sensors have started to be commercialized, hence targeting out of the lab applications. In this context, development of gravity gradiometers are also particularly attractive as they complement pure gravity measurements and find variety of applications including geodesy [27], geophysics [28] and inertial navigation [29]. Whereas an atomic gravimeter sensitivity is often limited by vertical vibration noise, it is not the case in a conventional atomic gradiometer where the gravity gradient is derived from the differential measurement of two simultaneous atom interferometers performed at two locations. However, this requires to use two clouds of cold atoms spatially separated. This can for example be achieved by using laser-cooled atomic sources originating from two separate 3-dimensional magneto-optical traps (3D-MOT) [22], or by launching the atoms from a single MOT using moving molasses [23] or Bloch oscillations as an atomic elevator [30-31] or using Large Momentum Transfer (LMT) beam splitters combining Bragg pulse and Bloch oscillations [32]. Although these techniques have proven to work in laboratory applications, their complexity could still be an issue regarding their implementation for onboard applications where simple and compact instruments are required.

In this paper, we perform a proof-of-principle experimental demonstration of an alternative method consisting in a direct measurement of the vertical gravity gradient with only one source of cold $^{87}$rubidium atoms in the presence of vibration noise. We use a double-loop four-pulse AI geometry as proposed initially in [33] for gravity gradient measurements which was investigated in [34] and now used in several experiments such as rotation rate measurements in atomic fountain configurations [35, 36] or for low frequency vibration noise rejection in the context of airborne tests of the Weak Equivalence Principle (WEP) using atom interferometry [23]. We perform vertical gravity gradient measurement with and without a passive isolation vibration platform and show that in the presence of parasitic ground vibrations the correlation of the vibration signal measured by a classical accelerometer [30, 37] allow to recover the interference fringes and extract the vertical gravity gradient. Moreover, we make a study of the systematics when using this double-loop AI geometry.

The paper is organized as follow: section [I] presents the double loop four-pulse AI used to measure the vertical gravity gradient. Section [II] presents the experimental setup. Section [IV] describes the vertical gravity gradient measurement performing the AI with a passive vibration isolation platform and Section [V] presents the measurement without seismic isolation, using the correlation technique. Section [VI] presents a study of the major systematic effects which affect the measurement. Finally in Section [VII] a discussion on scale factor comparisons

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II. FOUR PULSE ATOM INTERFEROMETER-BASED GRAVITY GRADIOMETER

We consider a four pulse AI. The matter-wave beam splitters and mirrors are based on two-photon counterpropagating Raman transitions between the $F = 1$ and $F = 2$ hyperfine ground states of rubidium 87 atoms (see FIG. I(a)). An atom initially in state $|F = 1, p\rangle$ is coupled to state $|F = 2, p + h\vec{k}_{\text{eff}}\rangle$ where $h\vec{k}_{\text{eff}}$ is the two-photon momentum transfer. Here $\vec{k}_{\text{eff}} = \vec{k}_1 - \vec{k}_2$ is the effective wave vector (with $||\vec{k}_{\text{eff}}|| = ||\vec{k}_1|| + ||\vec{k}_2||$ for counterpropagating transitions). The AI consists of the light-pulse sequence $(\pi/2 - \pi - \pi - \pi/2)$ which differs from a usual Mach-Zehnder atomic gravimeter by the presence of an additional $\pi$-pulse and a different time sequence. Practically, a first $\pi/2$-pulse creates an equal superposition of ground ($F = 1$) and excited ($F = 2$) states. Then, two $\pi$-pulses redirect the two atomic paths letting the wave packets crossing each other in between, and a final $\pi/2$-pulse interferes the wavepackets. Thus, this sequence leads to a double-loop geometry. In our configuration, $\vec{k}_{\text{eff}}$ is aligned with the local gravity acceleration $\vec{g}$, for all Raman pulses. This sequence allows to measure the time derivative of the acceleration of the free-falling atoms.

Although a symmetric configuration is necessary to fully cancel the phase contribution due to constant acceleration $\vec{a}$, a time asymmetry $\Delta T$ is introduced to avoid interference of parasitic Ramsey-Bordé interferometers due to imperfect $\pi$ pulses [36], see FIG. II(b). In the absence of time asymmetry, these parasitic interferometers would close at the same time as the main interferometer and generate amplitude noise and a possible bias on the gravity gradient determination.

In the short, intense-pulse limit, the phase shift along the Raman laser direction of propagation, is expressed as [38]:

$$\Delta \Phi = 4(k_{\text{eff}}g - \alpha)T \Delta T - (2k_{\text{eff}}v_z T^3 + 4k_{\text{eff}}g T^4) \Gamma_{zz}$$

$$+ 4k_{\text{eff}} a_{vib} T \Delta T - 2k_{\text{eff}} a_{vib} T^3$$

$$\equiv \varphi_g + \varphi_{\text{grad}} + \varphi_{\text{vib}}$$

(1)

where $g$ is the Earth gravity acceleration along the Raman laser beams, $\alpha$ the radio frequency chirp rate applied to the effective Raman frequency to compensate the Doppler shift induced by the atom free-fall in order to keep resonance, $\Gamma_{zz}$ the vertical gravity gradient component, $v_z$ the initial atomic velocity along the vertical $z$ axis at the first Raman pulse, $a_{vib}$ the mirror acceleration, $a_{vib}$ its time derivative, and $T$ the time between the Raman $\pi/2$ and $\pi$ pulses in absence of timing asymmetry. In Eq. (1), the contribution to the phase shift contains three separate terms. The first term $\varphi_g$ is a remaining sensitivity to gravity acceleration induced by the timing asymmetry $\Delta T$. We have embedded the laser phase $\alpha T \Delta T$ in this term. The second term is the gravity gradient dependent phase shift $\varphi_{\text{grad}}$, and finally the third term is the phase shift induced by vibrations which we denote $\varphi_{\text{vib}}$. This vibrational phase noise may prevent from discriminating spatial acceleration variations from time varying acceleration variations, and remains an issue for gravity gradient measurements performed in this double-loop geometry. Nevertheless, to circumvent this problem the AI can be operated using a passive vibration isolation platform ($\varphi_{\text{vib}} \simeq 0$) or by estimating the $\varphi_{\text{vib}}$ phase term induced by the Raman mirror vibration using the acceleration noise recorded by an auxiliary classical accelerometer rigidly fixed to the Raman mirror. We have operated the AI using these two schemes. For both schemes the atomic gradiometer is operated in its most sensitive configuration with $T = 38.6 \text{ ms}$ limited by the falling distance (see [11]), a timing asymmetry $\Delta T = 300 \mu\text{s}$, an initial velocity at first Raman pulse $v_z = 0.38 \text{ m/s}$, leading to phase shift values reported in Table I. For our application we have neglected the effect.
of the recoil phase shift.

III. EXPERIMENTAL SETUP

In this section we describe the main parts of the apparatus as well as the time sequence of the experiment.

A. Apparatus overview

Our experimental setup is schematically shown in FIG. It consists of a titanium vacuum chamber where the atoms are produced and interrogated and to which are connected ion pumps, getters and rubidium dispensers. The vacuum chamber is magnetically shielded with two cylindrical layers of μ-metal. The cold atom source is produced at the top of the chamber using a 3D MOT configuration. The falling distance available for interferometry is 20 cm from the MOT. The two counterpropagating Raman beams are obtained with a phase-modulated laser at 6.8 GHz retro-reflected on a mirror (Raman mirror). The Raman laser beams enter the vacuum chamber through the top window. After passing through a quarter wave plate they are retroreflected by the Raman mirror at the bottom of the setup, outside the vacuum, in order to realize the counterpropagating configuration, thus obtaining a lin ⊥ lin configuration in the AI region. In this configuration, two pairs of counterpropagating Raman beams (↑ k1, ↓ k2 and ↓ k1, ↑ k2 ) in the vertical direction are present. Degeneracy between the two pairs of Raman beams is lifted through Doppler shift induced by gravity during free fall of the atoms. In this configuration, only the Raman mirror needs to be isolated from ground vibrations. In our setup the mirror is rigidly linked to a classical accelerometer (Titan Nanometrics) the whole being fixed to a passive vibration isolation platform (Minus-K).

B. Optical setup

The laser system used for cooling, detecting and driving the interferometer pulses is similar to the one described in [39]. Basically, it consists of a compact and robust laser system based on a single narrow linewidth Erbium doped fiber laser at 1.5 μm, amplified in a 5 W Erbium doped fiber amplifier (EDFA) and then frequency doubled in a periodically poled lithium niobate (PPLN) crystal. A power of 450 mW is available at 780 nm. The Raman laser and the repumper are generated thanks to a fiber phase modulator at 1.5 μm allowing to be free from any phase lock loop between the two Raman lines.

C. Experimental sequence

The experimental sequence of the atomic gravimeter is the following: first, a cold 87Rb sample is produced in a 3-dimensional MOT, loaded from a background vapor pressure of ~10^-9 mbar. After 700 ms of trap loading, a stage of optical molasses and a microwave selection, we assemble Na~t~ ~ 5 x 10^7 atoms in the magnetic insensitive groundstate |F = 1, mF = 0⟩ at a temperature Θ = 3 μK. A push beam gets rid of the atoms left in state F = 2. Then, after 38.6 ms of free-fall we apply the AI sequence consisting in four Raman laser pulses of 8,16,16 and 8 μs. This time delay before the first Raman pulse is necessary to first lift degeneracy between the two pairs of Raman beams and second to minimize the impact of parasitic Raman lines (see section VI). During the AI operation a bias magnetic field of 100 mG is applied. We set T = 38.6 ms corresponding to total interrogation time 4T = 154.4 ms. Following the interferometer sequence we measure the proportion of atoms in the two output ports F = 2 and F = 1 of the interferometer using state selective vertical light-induced fluorescence detection. The fluorescence is collected thanks to collimation lenses and photodiodes in the perpendicular direction. The measurement of the proportion of atoms P in the state F = 2 at the exit of the interferometer is a sinusoidal function of the interferometric phase shift:

\[ P = P_m + \frac{C}{2} \cos(\Delta \Phi) \]  

(2)

where P_m is the fringe offset, and C the fringe contrast which is in our case C = 0.1. Interferometric fringes are thus obtained through scanning the interferometric phase. In our experiment we operate the interferometer with and without vibration isolation platform. Therefore, a scanning of the phase is obtained first by varying the frequency chirp rate of the Raman laser and second by letting vibration noise operate a random sampling of the interferometric phase.

The repetition rate of the experimental sequence is 1 Hz, including atom loading, state preparation, atom interferometry, and state detection. The whole experimental sequence timing and data acquisition is computer controlled.
IV. GRAVITY GRADIENT MEASUREMENT WITH VIBRATION ISOLATION

In this section we present the vertical gravity gradient measurement when operating the AI with a vibration isolation platform.

A. Measurement method

To measure the vertical gravity gradient we take advantage of the acceleration sensitivity induced by the timing asymmetry $\Delta T$ of the interferometer. In presence of a vibration isolation platform ($\varphi_{vib} \approx 0$), interferometer fringes can be obtained by scanning the frequency chirp $\alpha$. The interference phase is obtained using the Fringe-Locking Method (FLM) similar to the one described in [17], which determines the frequency chirp nulling the phase. The sign of the radio-frequency chirp is changed every two drops, hence reversing the sign of $\Gamma_{zz}$ to cancel some systematic effects. Nevertheless, in our protocol, we suppress sensitivity to gravity acceleration by periodically reversing the sign of $\Delta T$ (every 5 minutes), hence reversing the sign of the acceleration phase shift in Eq. 1. Nulling the phase shift in both configuration and taking the mean value leads to:

$$\Gamma_{zz} = \frac{2T\Delta T(\alpha_+^0 - \alpha_-^0)}{2k_{eff} v_z T^3 + 4k_{eff} g T^4}$$  \hspace{1cm} (3)

where $\alpha_+^0, \alpha_-^0$ is the frequency chirp which nulls the phase for $\Delta T$ ($-\Delta T$) respectively.

B. Gradiometer sensitivity

We have operated the gravity gradiometer continuously during 2 days using the experimental sequence described in [16][17]. The time asymmetry $\Delta T$ is changed every 5 minutes. We obtained from equation 3 the uncorrected vertical gravity gradient mean value $\Gamma_{zz} = 7600$ E. The Allan Standard Deviation (ADEV) on the gravity gradient measurements is shown on FIG. 2. Each point corresponds to the measurements averaged over 10 minutes corresponding to the time necessary to operate the AI in two configurations ($+\Delta T$ and $-\Delta T$). A short term sensitivity of 65000 E/$\sqrt{Hz}$ is obtained during the two days of measurements. The stability of the gravity gradient measurement improves as $t^{-1/2}$ (where $t$ is the measurement time) and reaches 766 E after 2 hours. The sensitivity of our measurement is not limited by the contribution of residual vibration noise which has been measured with our low noise accelerometer at the level of 10000 E/$\sqrt{Hz}$, but more by technical noise which we did not investigate further for this experimental demonstration. We have investigated the main systematic effects which induce a bias on the gravity gradient measured value using this method. These systematics are presented in section VI.

![FIG. 2. Allan standard deviation of the gravity gradient measurements. The dash line illustrates the $t^{-1/2}$ scaling.](image)

V. GRAVITY GRADIENT MEASUREMENT USING THE CORRELATION TECHNIQUE

In this section we present gravity gradient measurement in the presence of vertical vibration noise.

A. Measurement method

First the vibration isolation platform on which is fixed the Raman mirror is made non-floating. In the absence of vibration isolation $\varphi_{vib} \neq 0$ in Eq. 1 thus the conventional FLM used in [15][16] is not applicable anymore as it requires phase fluctuations to be smaller than $\pi$. To circumvent the presence of vibration excess noise which washes out fringe visibility, we perform a correlation-based-technique [40][41] combining the simultaneous measurements of the output signal $P$ of our interferometer and the one from a classical accelerometer fixed to the Raman mirror (see FIG. 1). The method is the following:

First we held the laser phase fixed by setting the radio-frequency chirp $\alpha_0$ to its value compensating for gravity acceleration leading to $\varphi_{g} = 0$. This value of $\alpha_0$ is determined by operating the interferometer as a conventional 3-pulse Mach-Zehnder interferometer using $T = 81.9$ ms (Where $T$ is the time between two-consecutive Raman pulses). Second, the AI is operated with the same experimental sequence except that the radiofrequency chirp sign is changed every measurement cycle. The atomic fringes are scanned due to random vibration noise. The probability $P$ of the interferometer is plotted versus the estimated induced vibration-phase $\varphi_{vib}^E$, which is numerically calculated at each cycle by convoluting the mirror acceleration $a_M(t)$ measured by the classical accelerometer, with the time response function $h_{at}(t)$ of the AI:

$$\varphi_{vib}^E = k_{eff} \int a_M(t) h_{at}(t) dt$$  \hspace{1cm} (4)
where $h_{\text{at}}$ is a double triangle-like function represented on FIG. 3 defined as:

$$h_{\text{at}}(t) = \begin{cases} \frac{t}{2(T + \Delta T) - t} & \text{if } 0 < t < T + \Delta T \\ \frac{t - 4T}{4T} & \text{if } 3T + \Delta T < t < 4T \\ 0 & \text{Otherwise.} \end{cases}$$

Finally, we perform a sinusoidal least-square fit of the data using the function:

$$P = A + \frac{B}{2} \cos(\phi_{\text{eib}} + \delta \phi)$$

where $A$, $B$ and $\delta \phi$ are free-parameters. Performing a measurement of the transition probability in four configurations ($\vec{k}_{\text{eff}} \uparrow, \vec{k}_{\text{eff}} \downarrow, \pm \Delta T$) where reversing the sign of $\vec{k}_{\text{eff}}$ (e.g. changing the sign of $\alpha$) allows to reject some systematics, and reversing the sign of $\Delta T$ suppresses residual dependence to constant acceleration, one can obtain the gravity gradient.

### B. Experimental results

We performed gravity gradient measurement during two hours integration time. For the measurement, the sign of $\Delta T$ was changed after one hour integration time whereas the direction of the effective wavevector was reversed every measurement cycle. Atomic fringes in configuration $(\pm \Delta T)$ are displayed on FIG. 4 when operating the interferometer with total interrogation time $4T = 154.4$ ms. We obtained 4 spectra in total corresponding to approximately 1800 points per fringe pattern. $\delta \phi$ is estimated from the fit to the data points for each fringe pattern. The gravity gradient is extracted from the phase offset $\delta \phi$ considering the four configurations ($\vec{k}_{\text{eff}} \uparrow, \vec{k}_{\text{eff}} \downarrow, \pm \Delta T$) leading to 4 phases $(\delta \varphi_{\uparrow, +}, \delta \varphi_{\uparrow, -}, \delta \varphi_{\downarrow, +}, \delta \varphi_{\downarrow, -})$. Considering the experimental protocol one obtains:

$$\Gamma_{zz} = \frac{1}{4} \left( \frac{\delta \varphi_{\uparrow, +} + \delta \varphi_{\uparrow, -} + \delta \varphi_{\downarrow, +} + \delta \varphi_{\downarrow, -}}{2k_{\text{eff}} v_{z} T^3 + 4k_{\text{eff}} g T^4} \right)$$

corresponding to an uncorrected gravity gradient of $\Gamma_{zz} = 3691$ E. The sensitivity of the gradiometer is evaluated from the combined statistical uncertainty from the fitted fringes leading to $\Delta \Gamma_{zz} = 2355$ after 2 hours integration time. The sensitivity of the measurement using the correlation technique is degraded by a factor of 3 in comparison with the measurement performed in presence of vibration isolation. First, a decrease by a factor of $\sqrt{2}$ may originate from the use of a Fringe Scanning (FS) method instead of a more sensitive Fringe Locking Method [42]. Second, degradation of the sensitivity may
come from non-perfect correlations due to several factors that we did not have time to investigate such as: misalignment between the classical accelerometer and the AI, unprecise knowledge of the mechanical accelerometer scale factor, uncertainty in the accelerometer transfer function, bias drift, among others. We estimate the classical accelerometer self-noise to limit our sensitivity at the level of $2\ \text{E}/\sqrt{\text{Hz}}$. An improvement of the sensitivity on our measurement is therefore possible. We give in section VII some possible improvements of the method.

Systematic effects are studied in the next section.

VI. SYSTEMATIC EFFECTS

In this section we present a study of the main systematics limiting the measurement of the gravity gradient and their related uncertainties.

A. Effect of a slope on fringe offset

In our experiment, we noticed that the fringes obtained by scanning $\alpha$ have a slope on the offset. This slope is due to a change in the resonance condition which appears because of a relatively large fringe spacing ($\propto 1/4T\Delta T$) relative to the fringe envelope ($\propto 1/\tau_{\text{eff}}/2$). This slope is different for each of the four configurations and therefore when the FLM is used, it is responsible of a bias on the gravity gradient measurement equal to:

$$\Delta \Gamma = \frac{\pi}{24Ck_{\text{eff}}gT^5\Delta T} \times A$$

where $A$ is the slope of the fringe offset defined as:

$$P_m = P_{m0} + (\alpha - \alpha_0)A$$

$A$ has been measured for the four configurations of the experiment ($k_{\text{eff}}, \gamma, \pm \Delta T$). From these four measurements one can obtain the value of $A$ to estimate the bias:

$$A_{\uparrow,\downarrow,\pm} = \frac{(A_{\uparrow,-} - A_{\downarrow,-}) - (A_{\uparrow,+} - A_{\downarrow,+})}{2}$$

Using the value of $A$ from equation (10), one obtains an estimated bias equal to 4351 $\text{E} \pm 430 \text{E}$ in our configuration.

B. Raman detuning

In our experiment, the one photon light-shift is largely canceled by adjusting the intensity ratio between the Raman lasers and using the effective wave vector reversal protocol. Nevertheless, sensitivity to laser detuning remains through two-photon light-shift (TPLS) and initial velocity of the atoms.

FIG. 5. (a): Space-time diagram of the four pulse AI in absence of gravity considering the photon momentum exchange to be centered on the pulse (straight line) and taking into consideration the response function of the interferometer during the pulses (dash-line). The dissymmetry due to the presence of the extra $\pi$-pulse with respect to a Mach-Zehnder-type AI, leads to a phase shift at the exit of the AI ($z_0 \neq z_0'$. (b) Sensitivity function to displacement $f_p(t)$ considering finite Raman pulses. (c) Timing diagram of the four pulse AI defining time with respect to the center of the Raman light-pulse.

1. Residual sensitivity to atom velocity

Contrary to a three-pulse Mach-Zehnder-type AI, a four pulse AI exhibits a phase sensitivity to initial velocity due to a dissymmetry between the first and last $\pi/2$-pulses induced by the presence of the extra $\pi$-pulse. This dissymmetry appears when considering finite Raman pulses and is responsible of a phase shift separation at the exit of the interferometer. This effect is illustrated on (FIG. 5) which represents the atomic trajectories (FIG. 5a) as a function of the position response function of the AI (FIG. 5b)). To circumvent this effect, one has to precisely adjust the timing $\delta T$ between the two $\pi$-pulses and between the $\pi/2$ and $\pi$-pulses in order to have a closed interferometer and to have no dependency on the atom velocity on the phase shift.

Assuming perfect $\pi/2$-pulses, the time separation between the center of each pulses should be equal to:

$$T_{\frac{\pi}{2}-\pi} = T + \Delta T + \delta T$$

$$T_{\pi-\pi} = 2T$$

$$T_{\pi-\frac{\pi}{2}} = T - \Delta T + \delta T$$

where $\delta T = (\frac{\tau}{2} - \frac{\tau}{2}) \tau_{\text{eff}}$.

Thus, a time compensation $\delta T = 1\ \mu$s is added to the sequence to compensate for this effect. Nevertheless, experimental defaults such as non perfect $\frac{\pi}{2}$ pulse or pulse shape asymmetry could affect this timing. We thus measured experimentally the phase shift versus the atom velocity at the first Raman pulse (see FIG. 5). This was
FIG. 6. Gravity gradient measurement as a function of the time delay to switch on the radiofrequency chirp. The slope given by the linear fit is $\approx 3000$ E/µs.

done by varying the time delay at which the radiofrequency chirp $\alpha$ used to compensate the Doppler shift is switched on. One obtains a slope of $3000$ E/µs. The uncertainty on the atom velocity is estimated at 1 mm/s leading to an uncertainty on the gravity gradient equal to 300 E.

2. Two-photon light shift

In our setup there are two pairs of beams which can drive the counterpropagative Raman transition (see FIG. 1) with wavevector $\pm \vec{k}_{eff}$. Consequently, the pair which is out of resonance will induce a two-photon light shift (TPLS).

The TPLS is estimated by measuring the gravity gradient as a function of the $\pi/2$-pulse duration. For the measurements, the mirror pulses are kept constant to preserve the interferometer’s contrast. Moreover, as the contrast changes with the pulse duration, the measurements are corrected from the slope effect (see FIG. 7). From the linear fit of the measurements we obtained a bias of $\Delta \Gamma = -4351 \pm 2019$ E (uncertainty from the fit).

C. Additional Raman laser lines

Our method of generating the Raman laser by modulation leads to the presence of additional laser lines inducing a supplementary phase shift which if not corrected, induces an error on the gravity gradient measurement. We can numerically calculate this supplementary phase shift according to \[45\] and transposing to the case of a four-pulse AI. In the symmetric configuration of the interferometer ($\Delta T = 0$) it is possible to find an AI configuration where this phase shift is equal to zero. This corresponds to the case where the distance between the position of the atoms at the moment of the four Raman pulses are multiples of the microwave wavelength $\Lambda = c/2\omega_{HF S}$. According to \[45\] and transposing to the four pulse AI the conditions on interrogation time $T$ and initial velocity of the atoms are given by:

$$T = \sqrt{\frac{n\Lambda}{3g}} \text{ and } v_z = \frac{n'\Lambda - \frac{1}{2}gT^2}{T} \text{ with } n, n' \in \mathbb{N} \quad (12)$$

Considering the available free-fall height of 20 cm one finds $n = 2$ and $n' = 1$ leading to $T = 38.6$ ms and initial atomic velocity at first Raman pulse $v_z = gT = 0.38$ m/s. However, timing asymmetry $\Delta T = 300$ µs required to avoid the presence of extra RB interferometers, changes the atoms position and prevents from operating the interferometer in this optimal configuration. We have numerically calculated the error on the gravity gradient for time asymmetry $\Delta T = 300$ µs. This error is a periodic function of the atom-mirror position $z_M$ and is comprised between $-300$ E and 180 E.

D. Verticality

In our setup, verticality can be ensured with an error of about $\delta \theta = 80$ µrad. As a consequence, supplementary terms in the phase shift arise from the projection of gravity on the horizontal axis which leads to a transverse velocity of the atoms $\delta v = g\delta \theta T$ and a sensitivity to rotation rate with respect to horizontal axis $\Omega_y$. According to \[38\] this supplementary phase shift is expressed as $\phi = 4\kappa \Omega_y \delta v T^2 = 0.14$ mrad corresponding to an uncertainty of ±67 E on gravity gradient with $\Omega_y$ the Earth rotation rate.
E. Drift of classical accelerometer

The gravity gradient measurement using the correlation technique is sensitive to errors on the measurement of vibrations such as the bias $a_0$ of the classical accelerometer and its drift $\frac{da_0}{dt}$ during the measurement. We have estimated this drift by measuring the output signal of the accelerometer as a function of time during one day. The bias drift has been estimated from a linear fit to the data to $\frac{da_0}{dt} = -0.47 \times 10^{-9}$ g/s. From this measurement we have calculated the bias phase induced by the bias drift of our mechanical accelerometer:

$$\varphi_b = 4k_{\text{eff}} \frac{da_0}{dt} T \Delta T \times T_{\Delta T} + 2k_{\text{eff}} \frac{da_0}{dt} T^2 \quad (13)$$

The first contribution to the bias phase arises from the change in acceleration bias between 2 measurements performed at $\Delta T$ and $-\Delta T$ respectively. In our experimental protocol, the time asymmetry is changed after a time $T_{\Delta T} = 1$ hour leading to a bias phase $\simeq 1.26$ mrad corresponding to a bias $\Delta \Gamma = 900$ E.

The second effect arises from the contribution of the drift during the interferometer integration time. This term gives rise to a bias on the gravity gradient measurement of $\Delta \Gamma = \frac{da_0/\Delta t}{2gT} = 62$ E.

F. Effect of magnetic field

Our interferometer sequence is applied to atoms selected in the $m_F = 0$ state. Nevertheless, a quadratic Zeeman shift and an inhomogeneity in the bias magnetic field applied to the atoms during the interferometer induces an additional phase shift and a bias on the gravity gradient measurement that can be calculated using [47]. Thanks to our effective wave vector reversal protocol, this effect is mainly canceled and the associated bias is $\Delta \Gamma = 100$ E ± 100 E.

G. Self attraction effect

Because our experimental setup is not massless, one has to take into account the gravitational attraction of the upper part and lower part of the titanium vacuum chamber on the atomic sensor. The mass difference between the two parts is estimated to $\Delta m = 1.5$ kg. Thus, using a point mass calculation approximation, one can estimate this mass difference to induce an artificial gravity gradient effect of the form $\Delta \Gamma = \frac{2G \Delta m}{r}$ where $G = 6.67 \times 10^{-11}$ N·m²·kg⁻² is the gravitational constant and $r$ the distance between the masses. Assuming the distance from the atoms to be between 5 cm and 10 cm the effect is comprised between 1600 E and 200 E respectively.

TABLE II. Correction (Corr.) and uncertainties (u) in Eötvös [E] of the main systematic effects affecting the cold atom gradiometer using two different measurement methods: (1) vibration isolated (2) Without vibration isolation.

| Source Corr. u | Corr. u |
|---------------|--------|
| (1) (1) (2) (2) |
| Effect of slope -4351 430 - - |
| Two-photon light shift 3920 2019 3920 2019 |
| Sensitivity to initial velocity 0 300 0 300 |
| Additional laser line 0 [-310;180] 0 [-310;180] |
| Verticality 0 67 0 67 |
| Accelerometer drift - - -1.5 962 |
| Effect of magnetic field -100 100 -100 100 |
| Self attraction effect -1000 1000 -1000 1000 |
| Statistical u. 766 - 2355 |
| Total -1531 2459 2818 3428 |

H. Conclusion on systematic effects

The results of the main systematics are summarized in Table[11] We finally obtained the gravity gradient values $\Gamma^{(i)}_{zz} = (6069 \pm 2459)$E and $\Gamma^{(2)}_{zz} = (5173 \pm 3428)$E which are statistically in agreement. For both methods the dominant systematic uncertainty comes from TPLS effect. The correlation technique remains limited by statistical uncertainty, the dominant noise coming from the technical detection noise.

VII. DISCUSSION AND POSSIBLE IMPROVEMENTS

We have compared the scale factor ($\Delta = \partial \Delta \Phi / \partial \Gamma$) of our four pulse AI with the one of a conventional atomic gradiometer using two pairs of Mach-Zehnder-like atom accelerometers in differential mode. For this comparison we have adressed both Earth-based, and space-based (e.g microgravity) issues. The calculation assumes a total interrogation time $T_{\text{int}}$ and apparatus length $L$. We have neglected the recoil effect term. The recoil term is responsible of a displacement of the atoms that we have assumed to be small compared to the length of the apparatus for our interrogation time. Nevertheless, this term should be considered for long interaction time where the atom displacement is larger. Results are presented in Table[11] From [11] in a microgravity environment, a dual Mach-Zehnder atom accelerometer geometry has a scale factor 8 times larger than the one of a four-pulse AI. However, using a single cloud atomic gradiometer for terrestrial applications could be of interest as the reduction in its scale factor is only a factor of 2. This scale factor reduction has to be put in balance with the ease of implementation of such an experimental setup which only requires (i) one
atomic source, (ii) an additional Raman π-pulse with respect to a conventional Mach-Zehnder atomic gravimeter. One can calculate the gravity gradient sensitivity $\delta \Gamma$ that can be obtained using our technique and considering an Earth based gravity gradient measurement with an interrogation time $T_{int} = 4T$ corresponding to a 1 meter length apparatus. We have taken the case where the atoms are not launched. Assuming that the ultimate phase resolution is quantum projection noise limited $\delta(\Delta \Phi) \approx 1/\sqrt{N_{at}}$ the single-shot gradiometer sensitivity is given by:

$$\delta \Gamma \approx \frac{2}{6C\sqrt{N_{at}}k_{eff}gT^4}$$  \hspace{1cm} (14)$$

Assuming $10^6$ detected atoms, a total interrogation time of $4T \approx 452$ ms, a contrast of $C = 0.5$ which can be obtained with a thermal atomic sample using adiabatic passage technique \cite{47} one obtains $\delta \Gamma \approx 13 E/\sqrt{Hz}$. The contribution of the mechanical accelerometer self-noise to the sensor’s sensitivity is estimated to be $\approx 1 E/\sqrt{Hz}$.

We can expect an improvement of our atomic gravimeter. When using the correlation technique, an increase in sensitivity could be obtained (i) by changing the sign of the timing asymmetry $\Delta T$ at the repetition rate of the experiment, hence reducing the effect of the classical accelerometer drift by a factor of 3600, (ii) replacing the fringe fitting procedure by a more sensitive FLM technique using the signal of the classical accelerometer to compensate in real time the phase shift of the AI as in \cite{37}. When measuring the gravity gradient using the vibration isolation platform, applying a phase step $\delta \varphi$ on the Raman laser phase rather than changing the chirp rate $\alpha$ when performing the FLM technique, would allow to cancel the slope effect as the same slope would appear for each of the four fringe patterns.

In the scope of field applications, using a single-cloud double-loop AI geometry allows to be insensitive to Coriolis force \cite{48} which is responsible of both a bias and mostly a severe loss of contrast when performing the AI on a boat \cite{26} or a plane \cite{25} if no rotation compensation is used such as a tip-tilt mirror \cite{49} or a gyrostabilized platform.

| Environment     | Mach-Zehnder 4-pulse AI | Scale factor ratio $S_{MZ}/S_{4P}$ |
|-----------------|-------------------------|-----------------------------------|
| Microgravity    | $\frac{1}{4}kLT_{int}^2$ | $\frac{1}{32}kLT_{int}^2$ | 8 |
| Earth-based     | $\frac{1}{8}kL^2$ | $\frac{1}{16}kL^2$ | 2 |
| Earth-based + atom launch | $\frac{1}{4}kL^2$ | $\frac{27}{256}kL^2$ | $\approx 2.37$ |

**TABLE III.** Comparison in scale factors $S$, of Earth-based dual cloud atomic gravimeter with respect to a single-cloud gradiometer. $L$:apparatus length; $g$:gravity acceleration; $T_{int}$:total interrogation time. $T_{int} = 2T$ ($4T$) for a Mach-Zehnder type geometry and Four-pulse geometry respectively.

### VIII. CONCLUSION

In conclusion, we have demonstrated an experimental proof-of-principle measurement of the vertical gravity gradient using a single proof mass of cold $^{87}$Rb atoms and a four-pulse double-loop AI. We performed the measurements first using a vibration isolator and then demonstrating the correlation technique in presence of vibration noise. The results obtained using both methods are in fair agreement despite a reduced sensitivity in comparison with state-of-the-art atomic gradiometer \cite{23}, due to a rather short interrogation time ($4T = 154.4$ ms). Better performances of the four-pulse gradiometer are expected with larger interrogation time and using efficient atom optics techniques such as adiabatic rapid passage optical pulses \cite{47} which does not require a colder atomic sample. Finally, the results obtained in a strap down configuration using the correlation technique, combined with the simplicity of our experimental setup, (single source and unique detection), the ability to switch easily from a gravimeter to a gradiometer sensor immune to constant rotation, could be of interest for the realization of instruments dedicated to gravity or gradiometry measurements in noisy environments.

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