

Progress towards the development of a cold-atom inertial measurement unit for onboard applications

Jeanne Bernard
DPHY, ONERA
Université Paris-Saclay
F-91123 Palaiseau, France
LCM-CNAM
61, rue du Landy
93120, La Plaine Saint-Denis, France
jeanne.bernard@onera.fr

Malo Cadoret
DPHY, ONERA
Université Paris-Saclay
F-91123 Palaiseau, France
LCM-CNAM
61, rue du Landy
93120, La Plaine Saint-Denis, France
malo.cadoret@lecnam.net

Yannick Bidel
DPHY, ONERA
Université Paris-Saclay
F-91123 Palaiseau, France
yannick.bidel@onera.fr

Clément Salducci
DPHY, ONERA
Université Paris-Saclay
F-91123 Palaiseau, France
clement.salducci@onera.fr

Nassim Zahzam
DPHY, ONERA
Université Paris-Saclay
F-91123 Palaiseau, France
nassim.zahzam@onera.fr

Sylvain Schwartz
DPHY, ONERA
Université Paris-Saclay
F-91123 Palaiseau, France
sylvain.schwartz@onera.fr

Alexis Bonnin
DPHY, ONERA
Université Paris-Saclay
F-91123 Palaiseau, France
alexis.bonnin@onera.fr

Cédric Blanchard
DPHY, ONERA
Université Paris-Saclay
F-91123 Palaiseau, France
cedric.blanchard@onera.fr

Alexandre Bresson
DPHY, ONERA
Université Paris-Saclay
F-91123 Palaiseau, France
alexandre.bresson@onera.fr

Abstract—In this paper we present our progress towards the development of a complete cold-atom Inertial Measurement Unit (IMU). Our goal is to have a single atomic sensor that will alternatively measure each inertial component (3 accelerations and 3 rotations). Every atomic measurement will be hybridized with a set of classical inertial sensors. Hybridization enables to combine the advantages of both technologies and to provide accurate continuous measurements with high dynamic range, in the scope of onboard inertial navigation compatibility.

Index Terms—inertial sensor, atom interferometry, cold atoms, hybridization

I. INTRODUCTION

Atom interferometer sensor is a promising technology for inertial measurement. It has the main advantage compared to classical technology to provide absolute measurements (no calibration needed) and high long term stability (no drift). An Inertial Measurement Unit (IMU) i.e 3 accelerometers and 3 gyroscopes using this technology could thus provide a breakthrough in navigation application in which the biases of the sensors lead to position errors. Vertical accelerometers i.e gravimeters based on atom interferometry have already demonstrated better performances than classical sensors for static [1] [2] and onboard measurements [3] and start to be commercialized [4]. Concerning other inertial sensors (horizontal accelerometer, gyroscope, gradiometer), the level of maturity is much lower with only few laboratory instruments

with performances at the level of the best classical inertial sensors [6]–[9]. There was only one demonstration of a complete atom interferometer IMU [10]. But it was a laboratory experiment which can work only in static condition and with rotation measurements not at the state of art level. There are still several blocking points to address in order to develop a compact atom IMU working in onboard environment.

Here, we will give our progress toward a cold atom inertial measurement unit. First, we will present the hybridization strategy that we choose for the IMU. Then, we will present our work on the development of an onboard horizontal accelerometer. Finally, we will conclude and present the remaining developments.

II. PRINCIPLE OF THE HYBRIDIZED ATOM INTERFEROMETER INERTIAL MEASUREMENT UNIT

The hybridized cold-atom inertial measurement unit relies on the periodic calibration of 3 classical accelerometers and 3 classical gyroscopes by a multi-axis atom interferometer sensor (see Fig. 1). This is an extension of the method developed for atom accelerometer [3], [11]. At each measurement cycle, the atom interferometer is configured to measure one of the six inertial components. This absolute measurement is then used to estimate the bias and the scale factor of the corresponding classical inertial sensor. On the other hand, the measurements

of the classical sensors are necessary to process the atom interferometer measurements in onboard environments.

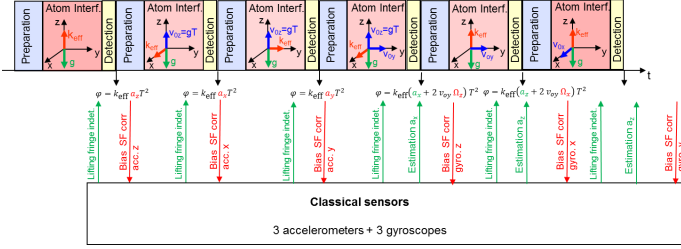


Fig. 1. Possible implementation of the hybridized cold atom IMU (SF: Scale Factor).

The output signal of a Mach Zehnder type atom interferometer consisting of three laser pulses is given by the following simplified expression:

$$P = P_m - \frac{C}{2} \cos \left(\vec{k}_{\text{eff}} \cdot (\vec{a} + 2\vec{v} \times \vec{\Omega}) T^2 \right) \quad (1)$$

where P_m and C are the offset and the contrast of the fringe, \vec{a} is the acceleration, \vec{v} is the atom velocity, $\vec{\Omega}$ is the rotation vector, \vec{k}_{eff} is the effective wave vector of the laser interrogating the atom and T is the time interval between the laser pulses.

The measured inertial component is selected with the direction of laser k_{eff} and the atom velocity. By imposing a zero velocity for the atom, we measure only the acceleration in the direction of the laser k_{eff} . By imposing a non-zero velocity, we measure a combination of a and Ω . To retrieve only the rotation, the acceleration is estimated by the calibrated classical accelerometer. Due to the periodic aspect of the signal of the atom interferometer, many values of the inertial quantities are possible for a given value of the atom signal. This ambiguity is lifted by using an estimated value of the atom phase provided by the classical inertial sensor. Finally by using this strategy, the six classical inertial sensors are regularly calibrated providing thus an absolute and continuous measurement of 3 accelerations and 3 rotations. A multi-axes atom interferometer sensor has thus to be developed. The vertical acceleration measurement is mature with the demonstration of airborne [12] and shipborne measurement [3]. The next steps of development are the horizontal accelerometer and the gyroscopes.

III. HORIZONTAL ACCELERATION MEASUREMENTS

A. Zero-velocity atom interferometry

In a light-pulse atom interferometer, laser pulses are used to coherently split, deflect, and recombine matter waves in order to create atom interference. Inertial sensors usually use stimulated two-photon (Raman or Bragg) transitions to create the beamsplitters and mirrors required for the interferometer. Stimulated two-photon transitions consist of an atom coherently absorbing and then emitting a photon

from a pair of counterpropagating laser beams with different frequencies. This process results in a transfer between two internal ground states of the atom, accompanied with a momentum change of $\pm \hbar k_{\text{eff}}$, where k_{eff} is the effective wave vector. For high precision measurements, the two counterpropagating Raman lasers are usually implemented in a retroreflected geometry, where a single laser beam with two laser frequencies is retroreflected off a mirror.

In an atom interferometer, the direction of the acceleration measurement is given by the Raman (or Bragg) lasers direction. Therefore, in order to measure horizontal accelerations, the Raman lasers must be horizontal. This configuration is more challenging than a vertical accelerometer where the Raman beams are vertical. First, the atoms fall under gravity perpendicular to the laser beam, therefore limiting the falling distance to the beam diameter for an instrument using a single laser beam. The use of several laser beams is possible, but complicates the setup. Second, the atoms are interrogated with zero velocity in the Raman beam direction. In a retroreflected configuration, two pairs of Raman beams with opposite effective wave vector $\pm k_{\text{eff}}$ can perform the two-photon transitions (see Fig. 2). When the atoms have a non zero velocity in the Raman beam direction, the Doppler effect naturally lifts the degeneracy between the two transitions $\pm \hbar k_{\text{eff}}$, and one can easily address a single transition. This is not the case in a horizontal accelerometer : lifting the degeneracy requires to give a velocity to the atoms thanks to a moving molasses technique for instance. The best horizontal accelerometers [6], [10] based on atom interferometry both use this technique. However, it leads to more complex and larger instruments. Another solution is to exploit the double diffraction scheme, but this only works if the two Raman transitions are perfectly degenerated. For onboard applications, where the atoms acquire an uncontrolled velocity under the effect of the vehicle accelerations, it is impossible to address the double diffraction scheme with high efficiency. This method is thus not appropriate to build an embedded horizontal accelerometer. Finally, a last method consists in selecting atoms with non-zero velocity within the atomic velocity distribution [13]. This technique leads to an important loss of atoms which is not satisfying. In this paper we present two new techniques using single-diffraction two-photon Raman transitions despite a zero Doppler shift in a retroreflected geometry.

B. Retroreflected frequency-chirped laser

The first technique demonstrated in 2019 [14] consists in applying a frequency chirp $\beta = \frac{1}{2\pi} \frac{d\omega_1}{dt} = \frac{d\omega_2}{dt}$ to the Raman laser frequencies ω_1 and ω_2 (see Fig. 3). Since the reflected beams are delayed with respect to the incoming ones by a time duration $t_d = \frac{2L}{c}$ (with L the distance between the atoms and the mirror), the incoming laser frequencies are shifted by $\delta\omega = 2\pi\beta t_d$ at the position of the atoms. Therefore, one transition is detuned from the other by $2\delta\omega$: such a frequency-chirped laser method lifts the degeneracy between the two transitions $\pm \hbar k_{\text{eff}}$, allowing one to selectively address

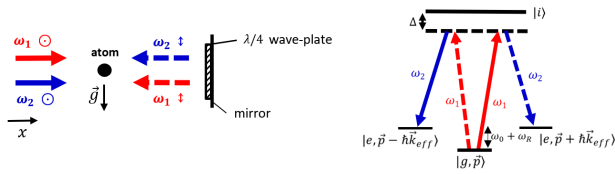


Fig. 2. Left : Schematic setup of two-photon Raman transitions in the commonly used retroreflecting geometry. Right: Scheme of the Raman transition between the two hyperfine ground states of an alkaline atom in the absence of Doppler shift. Both pairs $\pm \hbar \vec{k}_{\text{eff}}$ are simultaneously resonant.

one transition or the other. This effect can be interpreted as mimicking an effective atomic velocity in the reference frame of the lasers, resulting in an equivalent Doppler shift $\omega_D = 2\pi\beta t_d$.

Using this method, we demonstrated a Mach-Zehnder type atom interferometer hybridized with a force balanced accelerometer providing horizontal acceleration measurements with a short-term sensitivity of $3.2 \times 10^{-5} \text{ m}\cdot\text{s}^{-2}/\sqrt{\text{Hz}}$ (see Fig. 4). This is comparable to state of the art for horizontal configurations [5], despite shorter interrogation times (32 versus 226 ms). We cannot draw conclusions regarding the long-term stability of the hybridized accelerometer because of the fluctuations of the Raman mirror angle. Future improvements of the experimental setup could include the implementation of an auxiliary tilt sensor monitoring the angle between the Raman beam and the horizontal plane during the measurement.

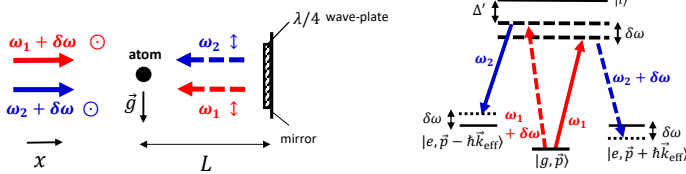


Fig. 3. Left : The frequency chirp β applied to the Raman lasers frequency shifts the incident laser frequency by $\delta\omega = 2\pi\beta t_d$ where $t_d = 2L/c$. Right : Energy diagram showing that the frequency chirp β allows to lift the degeneracy between the two resonant transitions by an amount $2\delta\omega$.

C. $\sigma^+ - \sigma^-$ Raman transitions between magnetically sensitive states

For the second technique, we implemented a horizontal accelerometer based on atom interferometry using counterpropagative Raman transitions between the hyperfine states $|F=1, m_F = \mp 1\rangle$ and $|F=2, m_F = \pm 1\rangle$ (see Fig. 5) [15]. Atom interferometry usually exploits the $|F=1, m_F=0\rangle \leftrightarrow |F=2, m_F=0\rangle$ transition, but our scheme presents several advantages. First, due to selection rules, only a single counterpropagating transition is allowed even if the Raman laser beams are retroreflected (see Fig. 5). Secondly, it uses Raman beams with the same polarization configuration as the magneto-optical trap. Finally, it allows

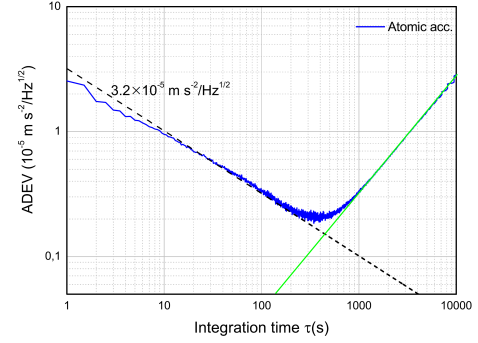


Fig. 4. The blue line represents the Allan standard deviation (ADEV) of the hybridized atomic accelerometer. $\tau^{-1/2}$ scaling is represented by the dashed line, whereas the τ scaling appears in the green line.

the control of the atom trajectory with magnetic forces.

With this method, we performed the measurement of the horizontal component of acceleration with a hybridized accelerometer and reached a short-term sensitivity of $25 \times 10^{-5} \text{ m}\cdot\text{s}^{-2}/\sqrt{\text{Hz}}$ (see Fig. 6). Specific features of our technique, in comparison with usual magnetically-insensitive Raman-based atom interferometers, are the following : higher spontaneous emission rate (as the Raman lasers require to be tuned closer to atomic transitions), additional sensitivity to magnetic field inhomogeneity and light shifts (the differential light shift can not be cancelled out by tuning the intensity ratio between the Raman pair). The bias due to the magnetic field gradient is the main limitation to this hybridized atom accelerometer accuracy ($2 \times 10^{-4} \text{ m}\cdot\text{s}^{-2}$).

Using the D_1 line (instead of the D_2 line) for the Raman excitation scheme could enhance the short-term sensitivity of this sensor, because it would drastically reduce spontaneous emission. In addition, the bias could be reduced by using a high-performance magnetic shielding. Moreover, that acceleration bias could be canceled out by implementing a fountain geometry.

IV. CONCLUSION AND PERSPECTIVES

We have demonstrated two new methods for measuring horizontal accelerations in a close-to-zero velocity regime. Both methods can be implemented in an embedded IMU. Next step of development are the gyroscopes. Here the challenge is to perform interferometric measurements of rotations in a compact device but with state-of-the-art performance. Large momentum transfer beamsplitters will be necessary since the sensitivity of the interferometric sensor is proportional to its enclosed space-time area.

REFERENCES

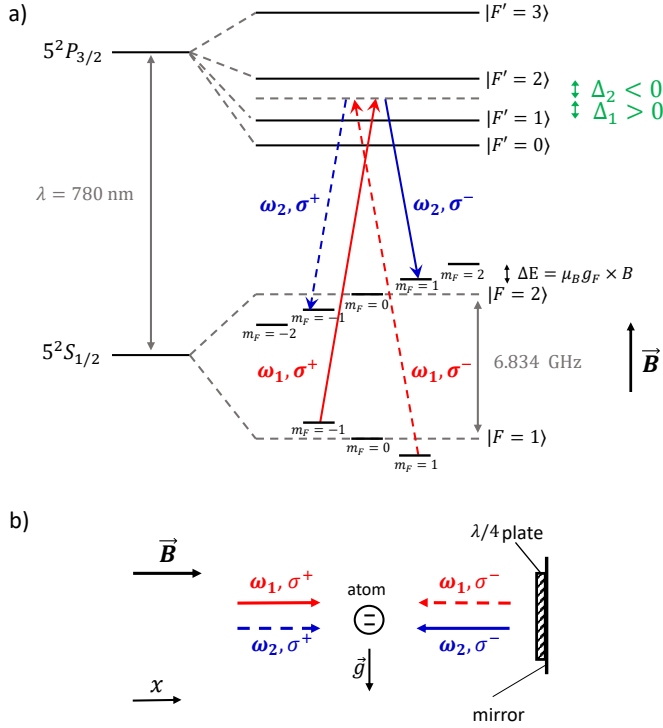


Fig. 5. (a) Energy diagram of the two hyperfine ground states of ^{87}Rb when a magnetic field is applied. The degeneracy between the Zeeman sublevels is lifted and one can perform $\sigma^+ - \sigma^-$ Raman transitions. The circularly polarized beams which perform the $|F=1, m_F=1\rangle \leftrightarrow |F=2, m_F=1\rangle$ transition appear in solid lines, whereas the beams performing the $|F=1, m_F=1\rangle \leftrightarrow |F=2, m_F=-1\rangle$ transition are represented in dashed lines. (b) Usual implementation of two-photon Raman transitions in a retroreflected configuration. The atom is a two-level system which interacts with two pairs of counterpropagating light fields with $\sigma^+ - \sigma^-$ polarizations. Such a polarization scheme allows only one pair of counterpropagating light beams to drive the Raman coupling. This results in a single diffraction process even if there is no Doppler shift.

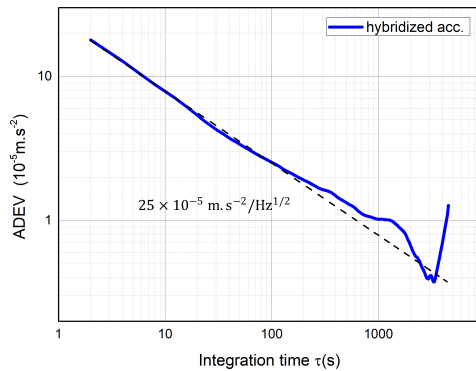


Fig. 6. The blue line represents the Allan standard deviation (ADEV) of the hybridized horizontal atom accelerometer. $\tau^{-1/2}$ scaling is represented by the dashed line.

- [1] R. Karcher, A. Imanaliev, S. Merlet, and F. P. D. Santos, "Improving the accuracy of atom interferometers with ultracold sources", *New J. Phys.*, vol. 20, no. 11, p. 113041, 2018.
- [2] Z.-K. Hu et al., "Demonstration of an ultrahigh-sensitivity atom-interferometry absolute gravimeter", *Phys. Rev. A*, vol. 88, p. 043610, 2013.
- [3] Y. Bidel et al., "Absolute marine gravimetry with matter-wave interferometry", *Nature Communications*, vol. 9, p. 627, 2018.
- [4] V. M  noret et al., "Gravity measurements below 10^{-9} g with a transportable absolute quantum gravimeter", *Scientific reports*, vol. 8, no. 1, p. 12300, 2018.
- [5] W. Xu, M. Zhou, M. Zhao, K. Zhang, et Z. Hu, "Quantum tiltmeter with atom interferometry", *Phys. Rev. A*, vol. 96, p. 063606, 2017.
- [6] J. Liu, W.-J. Xu, C. Zhang, Q. Luo, Z.-K. Hu and M.-K. Zhou, "Sensitive quantum tiltmeter with nanoradian resolution", *Phys. Rev. A*, vol. 105, p. 013316, 2022.
- [7] D. S. Durfee, Y. K. Shaham, and M. A. Kasevich, "Long-Term Stability of an Area-Reversible Atom-Interferometer Sagnac Gyroscope", *Physical Review Letters*, vol. 97, p. 240801, 2006.
- [8] D. Savoie, M. Altorio, B. Fang, L. A. Sidorenkov, R. Geiger, and A. Landragin, "Interleaved atom interferometry for high-sensitivity inertial measurements", *Science Advances*, vol. 4, 2018.
- [9] J. M. McGuirk, G. T. Foster, J. B. Fixler, M. J. Snadden, et M. A. Kasevich, "Sensitive absolute-gravity gradiometry using atom interferometry", *Phys. Rev. A*, vol. 65, p. 033608, 2002.
- [10] B. Canuel et al., "Six-Axis Inertial Sensor Using Cold-Atom Interferometry", *Phys. Rev. Lett.*, vol. 97, p. 010402, 2006.
- [11] J. Lautier et al., "Hybridizing matter-wave and classical accelerometers", *Appl. Phys. Lett.*, vol. 105, no. 14, p. 144102, 2014.
- [12] Y. Bidel et al., "Absolute airborne gravimetry with a cold atom sensor", *Journal of Geodesy*, vol. 94, no. 2, p. 20, 2020.
- [13] R. Geiger, V. M  noret, G. Stern, N. Zahzam, P. Cheinet, B. Battelier, A. Villing, F. Moron, M. Lours, Y. Bidel, A. Bresson, A. Landragin, and P. Bouyer, "Detecting inertial effects with airborne matter-wave interferometry," *Nat. Commun.*, vol. 2, p. 474, 2011.
- [14] I. Perrin, J. Bernard, Y. Bidel, A. Bonnin, N. Zahzam, C. Blanchard, A. Bresson, and M. Cadoret, "Zero-velocity atom interferometry using a retroreflected frequency-chirped laser," *Phys. Rev. A* 100, 053618, 2019.
- [15] J. Bernard, Y. Bidel, M. Cadoret, C. Salducci, N. Zahzam, S. Schwartz, A. Bonnin, C. Blanchard and A. Bresson, "Atom interferometry using $\sigma^+ - \sigma^-$ Raman transitions between $|F=1, m_F=\mp 1\rangle$ and $|F=2, m_F=\pm 1\rangle$ ", arXiv:2111.05642, 2021.