M2 internship : Large momentum transfer for differential quantum gravimetry

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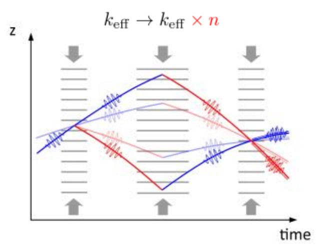
Key words: atom interferometry, inertial sensor, cold atoms, gradiometry, large momentum transfer (LMT)

Summary: The Atom Interferometry and Inertial Sensors Group (IACI) of LTE offers an M2 internship dedicated to the development of enabling technologies for quantum inertial sensors. The intern will implement and validate a high-power laser system for large momentum transfer (LMT) atomic beam splitters, aimed at enhancing the sensitivity of an atomic gravi-gradiometer.

Context:

A significant improvement in the sensitivity of ***atomic inertial sensors*** is linked to the deployment of architectures based on differential measurements, such as atomic ***gradiometers*** sensing the gradient of the Earth's gravitational acceleration, that allow rejection the *common-mode vibrational and laser phase noise*. This feature enables the measurements at the quantum projection noise limit and provides an ideal testbed for exploring cutting-edge techniques (advanced atom sources, LMT beam splitting, hybridization with other sensors, etc.) to boost sensitivity and accuracy. Moreover, the ***simultaneous access to*** $\boldsymbol{g}$ ***and*** $\boldsymbol{\nabla g}$ values discriminates the position and the mass of the gravitational source, opening intriguing perspectives in geoscience (natural resource exploration, civil engineering) and navigation [1].

The gravi-gradiometer of LTE ([2], see Figure, right) employs dual cold-atom source and a sensitive three-pulse (Mach-Zehnder like) interferometric sequence. The atom-optics elements (beam-splitters and mirrors) are implemented using short pulses of counter-propagating laser beams that Bragg-diffract the atomic wave packets. Ongoing work explores methods of quantum optimal control to enhance the efficiency of low-order ($n \leq 3$, $2n\hbar k$ photon transfer) ***multi-photon Bragg diffraction*** (see Figure, left), in combination with advanced optical beam shaping.



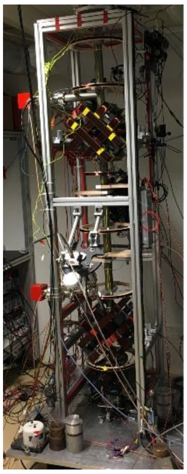


Figure: Scheme of the n-fold enhancement of interferometric area via LMT atomic beam splitter (left) and photo of laboratory atomic gravi-gradiometer of SYRTE (right)

Internship project:

To increase the separation of atomic wave packets - and thus interferometric area and sensitivity - we have recently developed a new higher-power laser system (fiber lasers and amplifiers, frequency-doubling stages, optical components and electronics for laser frequency, phase and power control) that should allow addressing $n > 3$ LMT transitions. The specific tasks of the internship will include:

- Improving the long-term stability of the new laser system and validating its performance via gravity gradient measurements in a conventional Bragg interferometer ($2\hbar k$ atom optics)
- Demonstrating LMT atom optics of $n > 3$ diffraction orders

The intern will perform experimental work requiring a good understanding of optics, laser physics, atom-light interaction and atomic physics, as well as scientific rigor and methodology. The skills in basic lab instrumentation, electronics, data analysis and physical modelling are a plus. The intern will join a team of three permanent researchers, postdoc and two PhD students, starting in spring 2026 for a period of up to 6 months, potentially followed by the PhD-thesis. The presentation of results at an internal group meeting is expected at the end of the internship.

[1] R. Caldani, et al., PRA **99**, 033601 (2019), R. Piccon, et al., PRA **106**, 013303 (2022)
[2] R. Geiger et al., AVS Quantum Sci. **2**, 024702 (2020)

PhD thesis : Enabling technologies for differential quantum gravimetry

Laboratory: Laboratoire Temps Espace – Observatoire de Paris, 77 avenue Denfert-Rochereau, 75014 Paris, France

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Key words: atom interferometry, inertial sensor, cold atoms, gradiometry, large momentum transfer (LMT)

Requirements: solid background in atomic and laser physics, optics, atom-light interaction

Context: A significant improvement in the sensitivity of ***atomic inertial sensors*** is linked to the deployment of architectures based on differential measurements, such as atomic ***gradiometers*** sensing the gradient of the Earth's gravitational acceleration, which allow rejection the *common-mode vibrational and laser phase noise*. This feature enables the measurements at the quantum projection noise limit [1] and provides an ideal testbed for exploring cutting-edge techniques (advanced atom sources, large momentum transfer (LMT) beam splitting, hybridization with other sensors, etc.) to boost sensitivity and accuracy. Moreover, the ***simultaneous access to g and ∇g*** values discriminates the position and the mass of the gravitational source, opening intriguing perspectives in geoscience (natural resource exploration, civil engineering) and navigation [2].

Thesis project: The PhD thesis work will aim at development of enabling technologies and metrological characterization of the gravi-gradiometer of LTE ([3], see Figure, right). It employs a dual cold-atom source and a sensitive three-pulse (Mach-Zehnder like) interferometric sequence. The atom-optics elements (beam-splitters and mirrors) are implemented using short pulses of counter-propagating laser beams that Bragg-diffract the atomic wave packets. Our gradiometer has recently reached differential sensitivity of about 100 nm/s^2 at 1-second measurement time, close to the state-of-the-art [1]. Ongoing work explores methods of ***quantum optimal control*** to enhance the efficiency of low-order (n ≤ 3, $2n\hbar k$ photon transfer) ***multi-photon Bragg diffraction*** (see Figure, left), in combination with ***advanced optical beam shaping***. The PhD student will explore the possibilities to enhance the sensitivity of the gradiometer via:

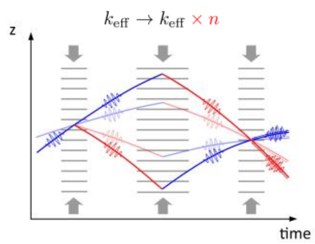
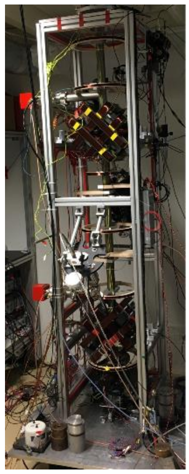


Figure: Scheme of the n-fold enhancement of interferometric area via LMT atomic beam splitters (left) and photo of laboratory atomic gravi-gradiometer of LTE (right)



- Developing atom-optics to address $n > 3$ LMT transitions, which will further increase the separation of atomic wave packets and thus interferometric area

Such atom optics will employ the elements of quantum optimal control to suppress the parasitic momentum states, that was developed for $6\hbar k$ (n=3) LMT. It will rely on the new higher-power laser system (that should be validated during M2 internship), and recently implemented top-hat collimators [4] for a versatile and controlled atom-light coupling.

- Implementing and validating atom traps that allow for rapid production of ultracold atoms or BECs in the gravi-gradiometer apparatus

The atom traps' architecture will be based on either atom chip technology or painted–potential off-resonant optical dipole traps. As ultracold atom samples feature reduced velocity and position dispersion, the envisioned gradiometer sequences will benefit from homogeneous atom-light coupling and extremely efficient LMT atom optics. The deployment of BECs, in addition, will pave the way to quantum metrology protocols [5] that involve spin squeezing and promise differential sensitivities below the standard quantum limit of precision.

[1] C. Janvier *et al*, Phys. Rev. A **105**, 022801 (2022)

[2] R. Geiger *et al*, AVS Quantum Sci. **2**, 024702 (2020)

[3] R. Caldani, *et al*, PRA **99**, 033601 (2019), R. Piccon, *et al*, PRA **106**, 013303 (2022)

[4] J. Gomes *et al*, in preparation (2026)

[5] R. Corgier *et al*, Quantum Sci. Technol. **10,** 045016 (2025)