

CARIOQA-PMP: A Step Forward in Quantum Space Gravimetry

T. Lévêque^{*a}

^aCentre National d'Etudes Spatiales, 18 avenue Edouard Belin, 31400 Toulouse, France.

For the CARIOQA-PMP Consortium

ABSTRACT

Climate change represents one of the most pressing challenges of our time, making it crucial to comprehend its underlying mechanisms and causal relationships. Satellite-based monitoring of Earth's mass distribution changes provides an invaluable tool for acquiring this critical global knowledge. Quantum sensors based on atom interferometry stand out as a promising tool for improving the measurement of Earth's gravity field from space. By leveraging the quantum properties of cold atoms, used as test masses, this technology offers unparalleled accuracy. The extended free-fall times available in space further enhance the performance of atom interferometers, contributing to monitoring global phenomena with unprecedented sensitivity. However, adapting and qualifying these instruments for space applications presents significant challenges. To address these challenges, the CARIOQA-PMP project, funded under the European Commission's Horizon Europe program, aims to prepare the development of a Quantum Space Gravimetry Pathfinder Mission. This initiative seeks to unlock the key capabilities of space-based atom interferometry, paving the way for future high-precision gravimetry missions. A central objective of the project is the realization and testing of an Engineering Model of the quantum sensor, involving close collaboration between European industry and research institutions.

Keywords: cold atoms, atom interferometry, gravity, quantum sensors, space geodesy.

1. INTRODUCTION

Cold-atom interferometers constitute an inertial-sensing breakthrough, delivering enhanced sensitivity and long-term stability for measuring accelerations and gravitational fields. When operated in orbit, their extended free-fall times would contribute to the detection of gravity variations that are essential for space-geodesy applications such as monitoring glacier melt, groundwater loss, and sea-level rise. This article describes the development of a dedicated Quantum Pathfinder Mission, called CARIOQA (Cold Atom Rubidium Interferometer in Orbit for Quantum Accelerometry), that prepares these quantum sensors for routine space use. In this paper, we report on the Pathfinder mission's challenges and objectives, describes the organization and implementation of the associated project, and highlights the key technological elements employed. The focus is on the first implementation block, CARIOQA-PMP, whose objective is to advance the payload's technology through the design, assembly, and testing of an Engineering Model (EM).

2. SCIENTIFIC CONTEXT

2.1 Key challenges in space geodesy

The assessment of global mass-transport processes through satellite-borne gravity-field monitoring is a crucial method for confronting the environmental and societal challenges posed by climate change. Past and ongoing space missions (GRACE, GOCE, and GRACE-FO) have transformed our comprehension of Earth-system mass redistribution by delivering the first global, time-varying gravity fields. The observations from these missions have yielded uniquely valuable insights into climate-change drivers [1] [2], including glacier and ice-sheet melt, sea-level rise [3], regional droughts and floods, and they even offer the prospect of early-warning capabilities for such events [4]. The dominant source of error in current missions stems from aliasing, a consequence of incomplete observation geometry [6]. Future gravimetry missions will enhance the spatio-temporal sampling of the gravity signal with carefully designed satellite constellations, yet their accuracy and resolution will still be constrained. A breakthrough in technology, centred on a new generation of sensors, now promises a substantial leap in accuracy. This advancement would improve routine, global remote sensing of key climate variables across the ocean, cryosphere, atmosphere, and land hydrology, as well as monitoring geodynamic phenomena such as earthquakes and volcanic eruptions.

^{*}thomas.leveque@cnes.fr

2.2 Quantum technologies as essential building blocks for future space geodesy missions

Classical electrostatic accelerometers, which have been the keystone of previous gravimetry missions, deliver reliable performance across a broad frequency range and have enabled the first global maps of Earth’s gravity field. Their proven heritage, however, includes an increase in low-frequency noise and long-term drifts that can limit the reconstruction of long-wavelength gravity signals and the precise tracking of associated temporal variations [7]. These constraints have motivated growing interest in emerging technologies based on Cold-Atom Interferometry (CAI), which determine acceleration by manipulating freely falling atoms with laser light. These quantum-sensors are largely free from many of the systematic errors that affect classical devices, offering higher sensitivity at long wavelengths [8] [9], drift-free operation, and improved absolute accuracy for long-term measurements and intercomparisons. On the ground, state-of-the-art CAI gravimeters now reach low-nano-g absolute accuracy [10] [11], and gravity-gradiometer prototypes achieve differential-acceleration sensitivities on the order of nano-g/m [12] [13]. In space, where quantum superposition can be maintained for seconds, far beyond terrestrial limits, the long-wavelength sensitivity is projected to improve by several orders of magnitude, surpassing even the best classical instruments and enhancing observations of mass-transport processes linked to climate change.

2.3 Rationale for a Quantum Pathfinder Mission

Over the last 15 years, massive efforts have been invested in Research & Development (R&D) activities in order to prepare the spatialisation of quantum sensors [14] [15]. These technological developments were accompanied by broader reflections on their use in the frame of scientific space missions. Nevertheless, the technological maturity still remained insufficient in view of these ambitious objectives and deploying a quantum sensor in orbit presents significant scientific and engineering challenges. Indeed, to meet the stringent sensitivity required for a space geodesy mission (i.e. $\leq 10^{-10} \text{ m}\cdot\text{s}^{-2}\cdot\text{Hz}^{-1/2}$) the atom interferometer must operate, in free fall, with interaction times on the order of five seconds. Recent studies and experiments have shown that reaching these long interaction times in orbit requires the implementation of innovative technological elements (e.g. ultra-cold atoms, rotation compensation, dedicated design of the satellite platform) that can only be fully tested in space. Therefore, such large scale factor makes a full performance verification, including the characterization of ultra-low level disturbance sources, impossible in ground based facilities. Besides, the instrument’s architecture is intrinsically complex, involving high precision laser systems, ultra-high vacuum hardware, and sophisticated control algorithms. Launching directly into an operational space geodesy mission would therefore entail high technical risk, inflated cost, and extended development timelines.

In this context, we are developing a Quantum Pathfinder Mission called CARIOQA. This technology-focused mission is essential to validate the quantum technology in orbit, derisk the system, and pave the way for a reliable, cost-effective operational payload. It will provide a controlled platform to validate the instrument’s performance, quantify low level environmental effects, and refine operational procedures before committing to a full-scale post-pathfinder deployment. The Pathfinder thus serves as a risk mitigation step, ensuring that the scientific objectives of the final use are achievable. This approach is aligned with the roadmap for cold atoms in space recently developed and approved by a broad scientific community [16].

3. THE CARIOQA MISSION OVERVIEW

3.1 Mission objectives

The main ambition of the CARIOQA Quantum Pathfinder Mission is to demonstrate the operation of a quantum accelerometer in space using a simplified payload. It is therefore a crucial step that will enable the collection of data necessary for the design of a fully operational instrument capable of meeting all the requirements of a subsequent scientific mission. By validating key technologies in orbit, this Pathfinder mission will significantly reduce the technical and programmatic risks that typically accompany the transition from laboratory prototypes to a flight-ready system, thus ensuring that the final operational mission can be completed on time, within budget, ensuring a significant scientific return.

Recognizing space geodesy as a key application, the CARIOQA mission is organized around five primary objectives, which are outlined in Table 1. Each objective corresponds to the demonstration of a specific metrological capability of the quantum accelerometer. These goals were defined in close consultation with the broader scientific community to ensure that the mission delivers maximal data value. Consequently, both the instrument architecture and the satellite platform are engineered expressly to meet every listed objective.

Table 1: Primary mission objectives

Mission Objective	Description
Functionality	Demonstrate the functionality of the instrument on board the satellite. In particular, its ability to provide an acceleration measurement after a tuning and characterisation of the instrument in flight.
Sensitivity	Allow a metrological characterization of the sensitivity and stability of the accelerometric measurement on short time-scales (i.e. 10 – 100s) through a dedicated procedure.
Accuracy	Allow a characterization of the accuracy of the sensor by determining its bias and measuring their stability over long time-scales (> 1000s). This characterization will be achieved by comparison with precise orbit determination (GNSS and/or ground-to-satellite laser ranging).
Dynamic range	Demonstrate the ability to measure accelerations whose amplitude and typical variations correspond to the non-gravitational forces acting on a space geodesy satellite.
Compatibility	Demonstrate the ability to measure in nadir pointing mode in order to allow subsequent use of the sensor in the context of space geodesy.

In addition, even if the primary objective of this mission is the technical validation of quantum sensors in space, the CARIOQA mission secondary objectives focuses on scientific application to geoscience. First, the CARIOQA pathfinder mission shares some conceptual similarities with the CHAMP satellite gravimetry mission. Therefore, its data can be evaluated for gravimetric field recovery by using a similar High-Low Satellite-to-Satellite Tracking (HL-SST) approach. Second, the CARIOQA mission, as similar missions equipped with accelerometers, can be used to derive the density of the upper atmosphere at orbital altitude. Finally, the last secondary objective is to operate the instrument in a gradiometer mode in order to demonstrate the ability of the instrument to perform differential acceleration measurements. This would ease the definition of future atomic space gradiometer instruments.

3.2 Proposed mission scenario

The CARIOQA Pathfinder Mission shall enable to fully characterize the payload and its capabilities in a suitable environment. For this reason, the mission will be implemented on board a dedicated satellite platform. This will allow the satellite design and mission parameters to be optimized to best meet the payload requirements. In particular, the instrument will be accommodated at the center of mass (COM) of the satellite and the AOCS system will be chosen to optimize the rejection of rotations and the performance of the instrument. In addition, this dedicated mission will enable to choose an orbit allowing the best characterization of the instrument and to consider maneuvers dedicated to its calibration.

The CARIOQA mission scenario is precisely tailored to fulfill its primary mission objectives. The approach consists of mounting a single-axis atomic accelerometer on a dedicated satellite platform. In nominal operations the satellite will adopt a nadir-pointing attitude at an orbital altitude of roughly 500 km, thereby reproducing the environment of a true space-geodesy mission. The instrument's measurement axis will be aligned with the orbital velocity vector, so that the accelerometer is sensitive to the main non-gravitational forces (principally aerodynamic drag) that act on the platform. This configuration enables a direct, high-precision determination of the satellite's non-gravitational acceleration, which is essential for validating the quantum sensor's performance in a realistic geodetic context.

4. PROJECT IMPLEMENTATION STRATEGY

4.1 Overall approach and timeline

The CARIOQA programme is organized as a suite of modular building-blocks, each explicitly designed to tackle a distinct technical or scientific challenge of the overall effort (see Figure 1). Every building-block is constituted as an independent Horizon Europe project funded by the European Commission and executed by a dedicated consortium that brings together the requisite expertise and resources. Overseeing the entire effort, CNES and DLR jointly provide project-wide coordination to guarantee coherence, integration, and consistency across all activities. The overarching ambition is to prepare the CARIOQA Quantum Pathfinder Mission for launch within the coming decade.



Figure 1: CARIOQA programme implementation

The idea originated in a Phase-0 study carried out jointly by CNES and DLR between 2019 and 2022 [17]. That study materialised at the end of 2022 with the launch of the first European effort, CARIOQA-PMP. The primary objective of CARIOQA-PMP was to develop an initial Engineering Model (EM) of the instrument that will fly on the mission, concentrating on hardware development to accelerate the maturation of the quantum technology and raise its Technology Readiness Level (TRL). CARIOQA-PMP therefore focuses on the instrument payload development. The other building blocks of the CARIOQA programme are tasked with mission-concept development, system architecture, and early engineering to ready the flight. First, CARIOQA-PHA was charged with carrying out the full Phase-A mission study (feasibility study). Consequently, its scope was to examine every aspect required to realise the mission, putting particular emphasis on the challenging integration of the instrument onto a satellite platform and its on-orbit operation. A preliminary design of the satellite platform has been carried out, fulfilling the mission requirements. The CARIOQA-PHA project concluded in mid-2025. Mission-study activities now continue under the subsequent Horizon Europe project CARIOQA-PHB, which advances the work into Phase B (Preliminary Definition Study) of the CARIOQA mission. Together, the Horizon Europe projects CARIOQA-PMP, CARIOQA-PHA and CARIOQA-PHB involve 17 partners from six EU member states (Germany, Italy, France, Denmark, Spain and Greece) and bring together the EU leading academic and industrial experts in quantum and space technologies.

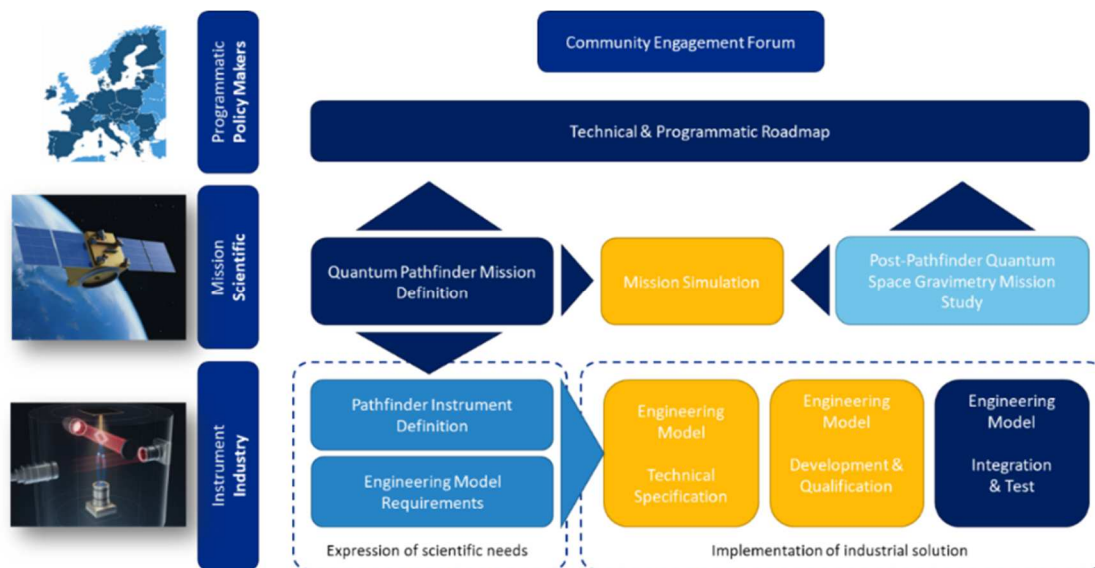


Figure 2: Scope of the CARIOQA-PMP study.

4.2 Scope of the CARIOQA-PMP study

The primary objective of the CARIOQA-PMP activities is to deliver an Engineering Model (EM) of the mission payload as depicted on Figure 2. To this end, the academic partners first produced a preliminary mission concept, which informed

an initial definition of the instrument and generated a set of specifications for the industrial consortia. An industrial-level EM of the sensor was subsequently designed, manufactured, and assembled so that it could be tested within the scope of the project. In parallel, a dedicated academic work-package carries out simulation studies to evaluate the contribution of quantum sensors to future space-geodesy missions, thereby ensuring that the Pathfinder-grade instrument will be compatible with the requirements of subsequent scientific missions. All outcomes are consolidated into a technical and programmatic roadmap that will be disseminated to stakeholders through dedicated community forums. The next section focuses on the development of a functional EM of the quantum accelerometer, which will serve as the prototype for the flight instrument.

5. QUANTUM ACCELEROMETER INSTRUMENT

5.1 Major design tradeoffs

A quantum sensor intended for a future space-geodesy mission must meet the following key capabilities: 1 – Ultra-sensitive atomic measurements achieved with long interaction times. 2 – Full three-axis acceleration sensing. 3 – Hybrid operation together with a conventional electro-static accelerometer. 4 – Gradiometric capability if the mission requires gravity-gradient observations. In the CARIOQA Pathfinder mission, the instrument's primary objective is to demonstrate the ability to deliver ultra-sensitive acceleration measurements by exploiting long interaction times. This capability is the most critical, and most innovative, technology milestone for a demonstrator mission. The performance data gathered during this phase will enable an optimal implementation of the remaining functions (gradiometry, three-axis operation, and hybridisation) in a subsequent, post-Pathfinder mission. Therefore, considering the CARIOQA mission objectives, several payload options have been investigated to cope with the main challenges presented in Table 1. Several sorts of atomic source technologies have been compared considering their potential performances with respect to space atom interferometry, their compatibility with space application, and their TRL. As a result, the utilisation of a Bose-Einstein Condensate (BEC) atomic source has been chosen as it enables a higher mitigation of rotation effects and then enables to demonstrate significantly higher instrument performances. For producing the BEC, the choice of atom chip technology has been realized as it presents the highest TRL for space application [18] [19].

5.2 Instrument operating principle and architecture

For CARIOQA, a one-axis quantum accelerometer based on ultra-cold Rubidium atoms manipulated by Raman transitions will be used. Rubidium atoms are first prepared from a vapor to form a BEC, using an atom-chip. The atomic cloud is then moved away from the surface of the chip and collimated via magnetic lensing. Then, the free-falling Rubidium cloud successively interacts three times with a unique pair of retro-reflected Raman beams, acting on matter waves as beam splitters or mirrors. This creates an interferometer of 2T total interaction time in a so-called double-diffraction configuration [20]. This interferometer scheme is particularly adapted to space instruments. Indeed, for inertial sensors in microgravity environments, the Doppler Effect cannot be used to select one or the other of the two effective Raman transitions possible in the most common retro-reflected configuration, which is needed for accuracy. The atomic phase shift is obtained from the measurement of populations in each output port of the interferometer, using a fluorescence or absorption imaging technique on cameras.

The complete instrument is made up of four subsystems each of which has been developed through a dedicated industrial effort under Airbus Defense and Space (France) coordination. It is made of the following elements:

- The Physics Package, developed by Airbus Defense and Space (Germany), forms the instrument's sensor head where atoms are cooled, interrogated and detected. It harnesses signals from the laser system and microwave source to generate the required magnetic, microwave and optical fields at the atomic level, and incorporates a vacuum system, magnetic shielding, collimators, coils, an atom chip, detectors and a movable reference mirror.
- The Laser System, developed by Exail SAS, provides the different laser beams needed to cool, diffract and detect the atoms. To achieve that, the lasers need to be stable both in frequency and power, with very accurate control of these parameters.
- The Microwave Source, developed by Leonardo, that produces the radio and microwaves frequencies needed to adjust the laser frequencies, to perform the microwave evaporation as well as the master clock of the instrument.
- The Instrument Control and Power Unit (ICPU), developed by Teletel, supplies energy and controls the instrument by commanding the different measurement sequences.

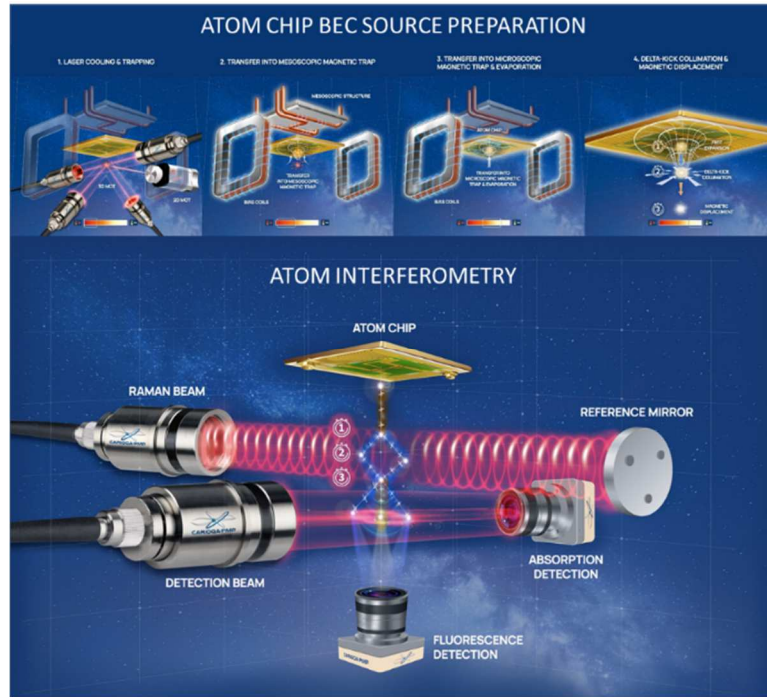


Figure 3: Up - Atomic source preparation at the surface of the atom chip; Bottom – Schematic view of principle of the atom accelerometer based on atom interferometry.

6. CONCLUSIONS AND OUTLOOK

The CARIOQA Quantum Pathfinder Mission is essential for maturing quantum inertial sensors for space-geodesy, contributing to high-precision monitoring of climate-related mass redistribution (ice melt, sea-level rise, groundwater loss). Demonstrating the technology in orbit will validate the performance, reliability and operational concepts required for accurate gravity measurements. The CARIOQA-PMP project will deliver a complete Engineering Model of a cold-atom accelerometer, proving that the laser, ultra-high-vacuum and control subsystems can be industrially built to meet mission specifications. Data and lessons learned from the EM are fed directly back into the early-stage mission design, strengthening the system architecture, requirement flow-down and markedly reducing overall risk of the project. To date, all of the instrument's subsystems have been designed and fabricated. The various elements are now being received and assembled at the CNES facilities. Following a verification phase, the first functional tests of the complete EM will be implemented. An extensive characterization of the instrument performance will follow, to ensure the compliance of the payload for the future development phases of the mission.

ACKNOWLEDGEMENTS

CARIOQA-PMP is a joint European project, including experts in satellite instrument development (Airbus Defense and Space, Exail SAS, TELETEL, LEONARDO), quantum sensing (LUH, LTE, LP2N, LCAR, ONERA, FORTH), space geodesy, Earth sciences and users of gravity field data (LUH, TUM, POLIMI, DTU), as well as in impact maximisation and assessment (PRAXI Network/FORTH, G.A.C. Group), coordinated by the French and German space agencies CNES and DLR under CNES lead. This project is supported by the European Union's Horizon Europe research and innovation programme under grant agreements No 101081775 (CARIOQA-PMP project).

REFERENCES

- [1] Tapley, B. D., Watkins, M. M., Flechtner, F., Reigber, C., Bettadpur, S., Rodell, M., et al., “Contributions of GRACE to understanding climate change,” *Nature climate change*, 9(5), 358-369 (2019).
- [2] Rodell, M., Famiglietti, J. S., Wiese, D. N., Reager, J. T., Beaulieu, H. K., Landerer, F. W., and Lo, M. H., “Emerging trends in global freshwater availability,” *Nature*, 557(7707), 651-659 (2018).
- [3] Chen, J., Tapley, B., Wilson, C., Cazenave, A., Seo, K. W. and Kim, J. S. “Global ocean mass change from GRACE and GRACE Follow-On and altimeter and Argo measurements,” *Geophysical Research Letters*, 47(22), e2020GL090656 (2020).
- [4] Jäggi, A., Weigelt, M., Flechtner, F., Güntner, A., Mayer-Gürr, T., Martinis, S., et al., “European gravity service for improved emergency management (EGSIEM)—from concept to implementation,” *Geophysical journal international*, 218(3), 1572-1590 (2019).
- [5] Abich, K., Abramovici, A., Amparan, B., Baatzsch, A., Okihiro, B. B., Barr, D. C., et al., “In-orbit performance of the GRACE follow-on laser ranging interferometer,” *Physical review letters*, 123(3), 031101 (2019).
- [6] Loomis, B. D., Rachlin, K. E., Wiese, D. N., Landerer, F. W. and Luthcke, S. B., “Replacing GRACE/GRACE-FO with satellite laser ranging: Impacts on Antarctic Ice Sheet mass change,” *Geophysical Research Letters*, 47(3), e2019GL085488 (2020).
- [7] Christophe, B., Foulon, B., Liorzou, F., Lebat, V., Boulanger, D., Huynh, P. A., et al., “Status of development of the future accelerometers for next generation gravity missions,” In *International Symposium on Advancing Geodesy in a Changing World* (pp. 85-89). Springer, Cham (2018).
- [8] Lévêque, T., Fallet, C., Manda, M., Biancale, R., Lemoine, J. M., Tardivel, S., et al., “Gravity field mapping using laser-coupled quantum accelerometers in space,” *Journal of Geodesy*, 95(1), 1-19 (2021).
- [9] Abrykosov, P., Pail, R., Gruber, T., Zahzam, N., Bresson, A., Hardy, E., et al., “Impact of a novel hybrid accelerometer on satellite gravimetry performance,” *Advances in Space Research*, 63(10), 3235-3248 (2019).
- [10] Ménoret, V., Vermeulen, P., Le Moigne, N., Bonvalot, S., Bouyer, P., Landragin, A. and Desruelle, B. “Gravity measurements below 10⁻⁹ g with a transportable absolute quantum gravimeter,” *Sci. Rep.*, 8, 1–11 (2018).
- [11] Hauth, M., Freier, C., Schkolnik, V., Senger, A., Schmidt, M. and Peters, A. “First gravity measurements using the mobile atom interferometer GAIN,” *Applied Physics B*, 113(1), 49-55 (2013).
- [12] Biedermann, G. W., Wu, X., Deslauriers, L., Roy, S., Mahadeswaraswamy, C. and Kasevich, M. A. “Testing gravity with cold-atom interferometers,” *Physical Review A*, 91(3), 033629 (2015).
- [13] Janvier, C., Ménoret, V., Desruelle, B., Merlet, S., Landragin, A. and Pereira dos Santos, F. “Compact differential gravimeter at the quantum projection-noise limit,” *Physical Review A*, 105(2), 022801 (2022).
- [14] Barrett, B., Antoni-Micollier, L., Chichet, L., Battelier, B., Lévêque, T., Landragin, A. and Bouyer, P. “Dual matter-wave inertial sensors in weightlessness,” *Nature communications*, 7(1), 1-9 (2016).
- [15] Trimeche, A., Battelier, B., Becker, D., Bertoldi, A., Bouyer, P., Braxmaier, C., et al., “Concept study and preliminary design of a cold atom interferometer for space gravity gradiometry,” *Classical and Quantum Gravity*, 36(21), 215004 (2019).
- [16] Alonso, I., et al., “Cold Atoms in Space: Community Workshop Summary and Proposed Road-Map,” *arXiv preprint arXiv:2201.07789* (2022).
- [17] Lévêque, T., Fallet, C., Lefebvre, J., Piquereau, A., Gauguier, A., Battelier, B., Bouyer, P., Gaaloul, N., Lachmann, M., Piest, B., Rasel, E., Müller, J., Schubert, C., Beaufils, Q., and Pereira Dos Santos, F. (2023, July). CARIOQA: definition of a Quantum Pathfinder Mission. In *International conference on space optics—ICSO 2022* (Vol. 12777, pp. 1536-1545). SPIE.
- [18] Becker, D., Lachmann, M. D., Seidel, S. T., Ahlers, H., Dinkelaker, A. N., Grosse, J., et al., “Space-borne Bose-Einstein condensation for precision interferometry,” *Nature*, 562(7727), 391-395 (2018).
- [19] Gaaloul, N., Meister, M., Corgier, R., Pichery, A., Boegel, P., Herr, W., et al., “A space-based quantum gas laboratory at picokelvin energy scales,” *arXiv preprint arXiv:2201.06919* (2022).
- [20] Lévêque, T., Gauguier, A., Michaud, F., Pereira Dos Santos, F. and Landragin, A., “Enhancing the area of a Raman atom interferometer using a versatile double-diffraction technique,” *Physical review letters*, 103(8), 080405 (2009).