Quantum Sensing in Space for Fundamental Physics and Earth Observation

Gaaloul N. for the MAIUS, CUAS, STE-QUEST and CARIOQA consortia
Leibniz University of Hanover, Institute of Quantum Optics, Hanover, Germany
gaaloul@iqo.uni-hannover.de

Space-borne quantum technologies and more particularly atom-interferometry-based devices are announcing a new era of strategic, intense space exploitation. Indeed, space offers a unique environment characterized by low-noise and low-gravity necessary for a wide spectrum of applications ranging from time and frequency transfer to Earth observation and the exploration of fundamental laws of physics.
Efforts to operate atom physics experiments in these ideal conditions are however challenged by a number of technical limitations as the extreme miniaturization or power consumption requirements for example.
In this contribution, we report about recent advances of pioneering successful space implementations of atom optics experiments[1][2][3][4] as well as about recent mission concepts based on the use of quantum-gas sensors. Of particular interest for Fundamental Physics, is the satellite mission Space-Time Explorer and QUantum Equivalence Principle Space Test (STE-QUEST)[5][6] featuring a dual-species atom interferometer operating over tens of seconds, which will address some of the most fundamental and puzzling questions of physics by testing the universality of free fall with an accuracy better than one part in 10^{-17}, searching for different types of Ultra-Light Dark Matter (ULDM) and testing the foundations of quantum mechanics.
Moreover, atomic sensors could also map temporal variations in Earth's gravity field opening the era of Space Quantum Gravimetry. We will report on the CARIOQA satellite mission pathfinder[7], recently endorsed by the European Commission. It is set to lay the groundwork for a space Geodesy mission, utilizing atom accelerometers.

---

[1] D. Becker, *et al.,* "Space-borne Bose–Einstein condensation for precision interferometry", *Nature,* **562**, 391 (2018).
[2] M. D. Lachmann, et al., "Ultracold atom interferometry in space", *Nature Comm.* **12**, Article number: 1317 (2021).
[3] D. Aveline, et al., "Observation of Bose–Einstein condensates in an Earth-orbiting research lab" *Nature*, **582**,11 (2020).
[4] N. Gaaloul, et al., "A space-based quantum gas laboratory at picokelvin energy scales", *Nature Communications*, **13**:7889 (2022).
[5] H. Ahlers, et al., "STE-QUEST: Space Time Explorer and QUantum Equivalence principle Space Test", arXiv:2211.15412 (2022).
[6] C. Struckmann, et al., "Platform and environment requirements of a satellite quantum test of the Weak Equivalence Principle at the 10^{-17} level" Phys. Rev. D **109**, 064010 (2024).
[7] T. Lévèque, C. Fallet, J. Lefebve, et al., Proc. SPIE — ICSO 12777, (2023).