Rotating atom interferometer for onboard quantum inertial sensing

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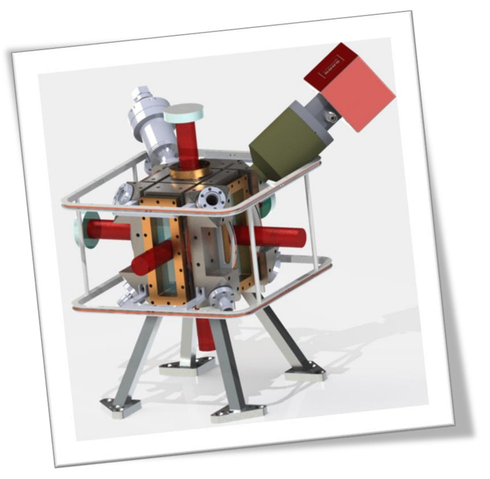
The Joint Laboratory **iXAtom** brings together the expertise of **Exail** and the **LP2N** to build a new generation of onboard, high-end inertial sensors for geophysics and navigation, through the hybridization of classical accelerometers and gyroscopes with quantum inertial sensors based on matter-wave interferometry.



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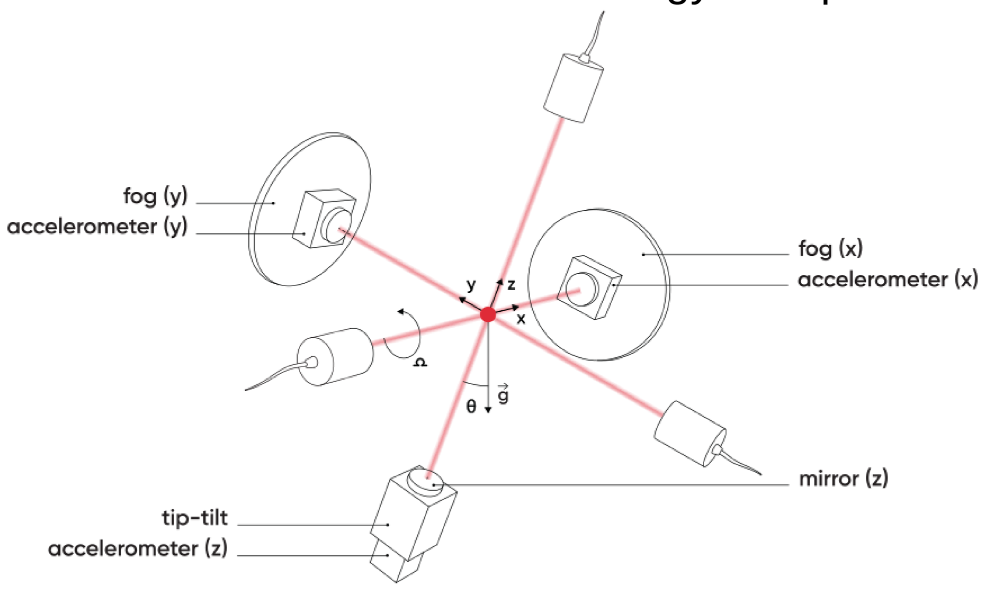
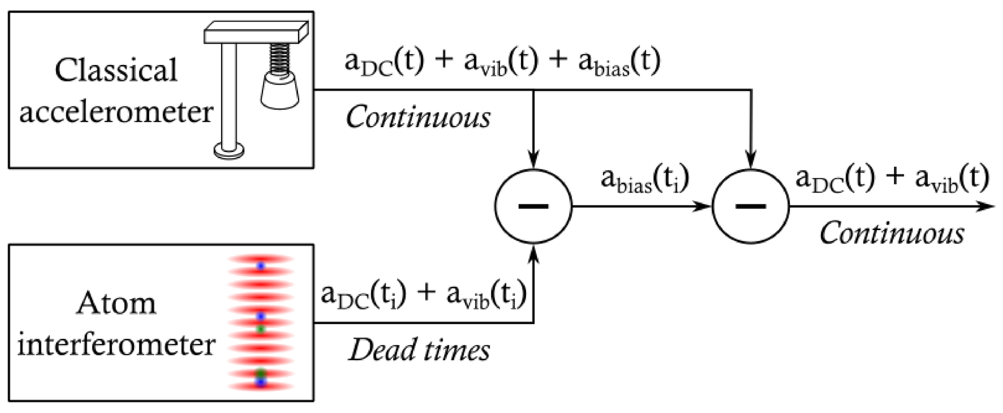
WHAT ARE THE REQUIREMENTS FOR AN ONBOARD INSTRUMENT WORKING IN NOISY ENVIRONMENTS?

A compact, 3-axis sensor head…

- Robust and agile laser source (telecom-band fibered setup, IQ modulator) – *patented* **[1]**
- Classical accelerometers and gyroscopes



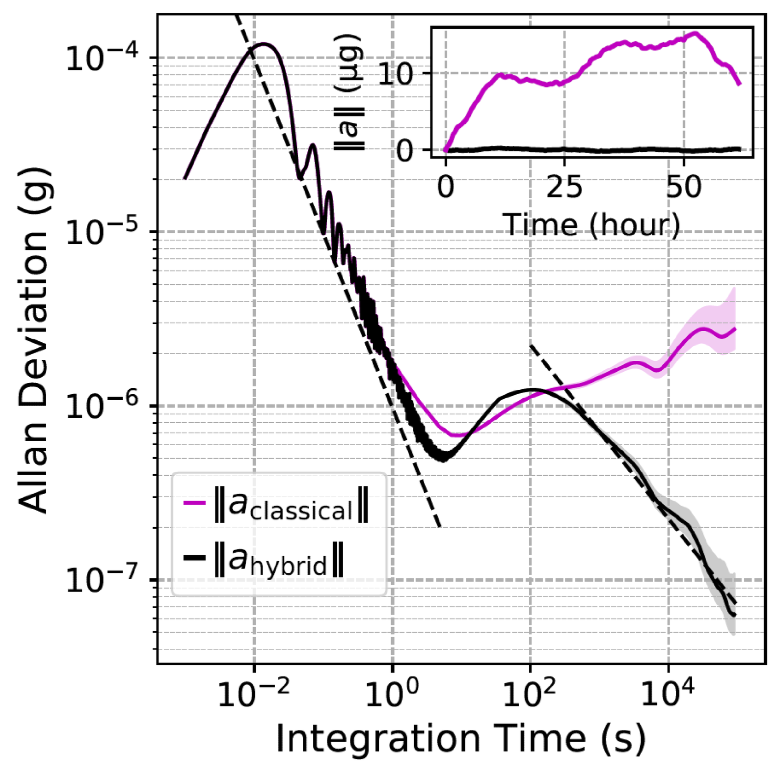
…Working under vibrations…



- Real-time correction of the Doppler frequency shift and vibrations phase noise – *patented* **[2]**
- Real-time cancellation of the classical bias
- ✓ High dynamic range, bias-free, continuous measurement of the acceleration components

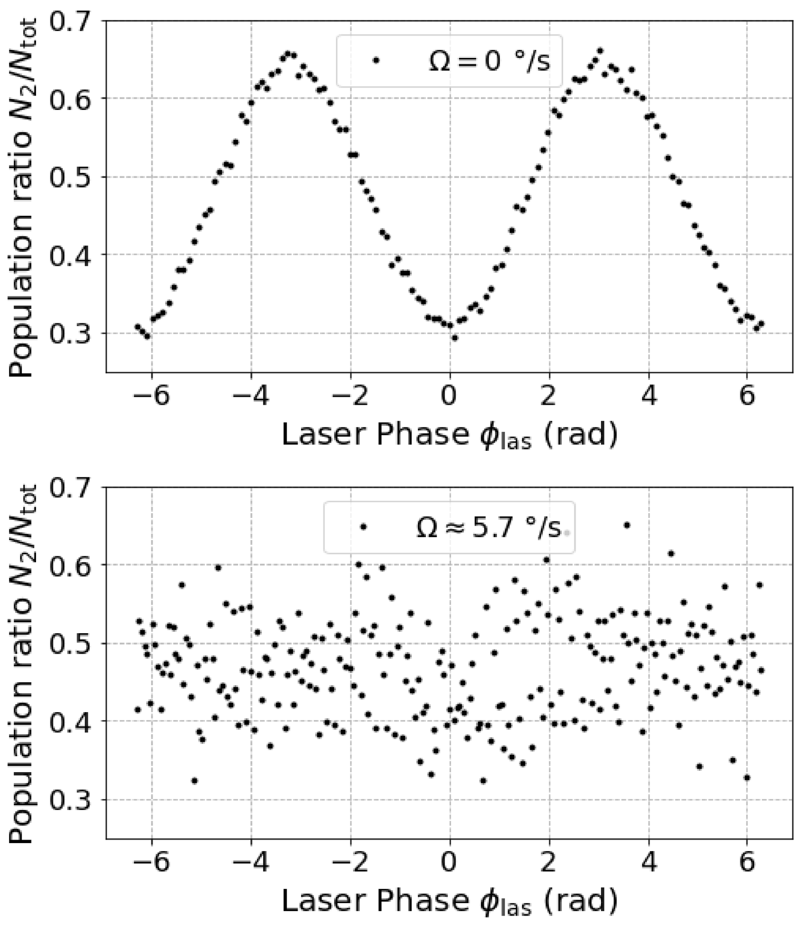
…For improved quasi-static performances [3]

- Bandwidth $BW > 100$ Hz
- Trueness (norm) $|\overline{a} - g| \approx 700$ ng
- Short-term sensitivity $\sigma_a \approx 22$ µg @ 1 s
- Long-term stability $\sigma_a \approx 60$ ng @ 24 h
- ✓ 50-fold improvement on the norm of the acceleration vector



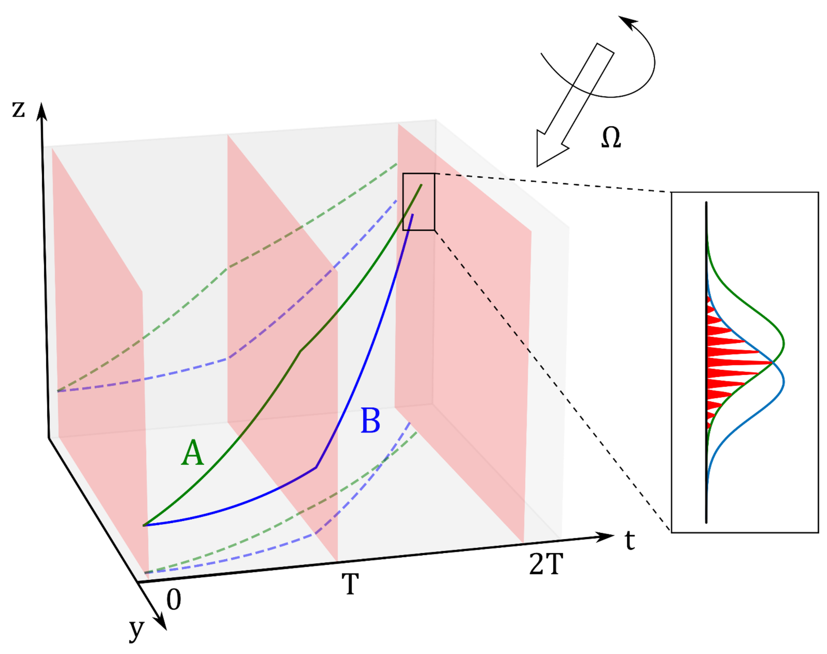
AND WHAT ABOUT ROTATIONS?

Two dramatic effects on the atomic interferences:

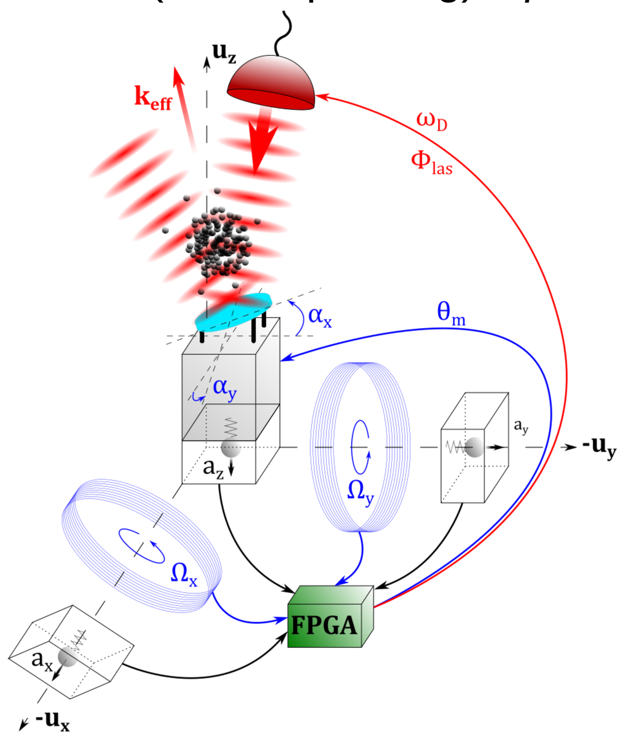


A relative displacement of the atomic wave packets in position and momentum

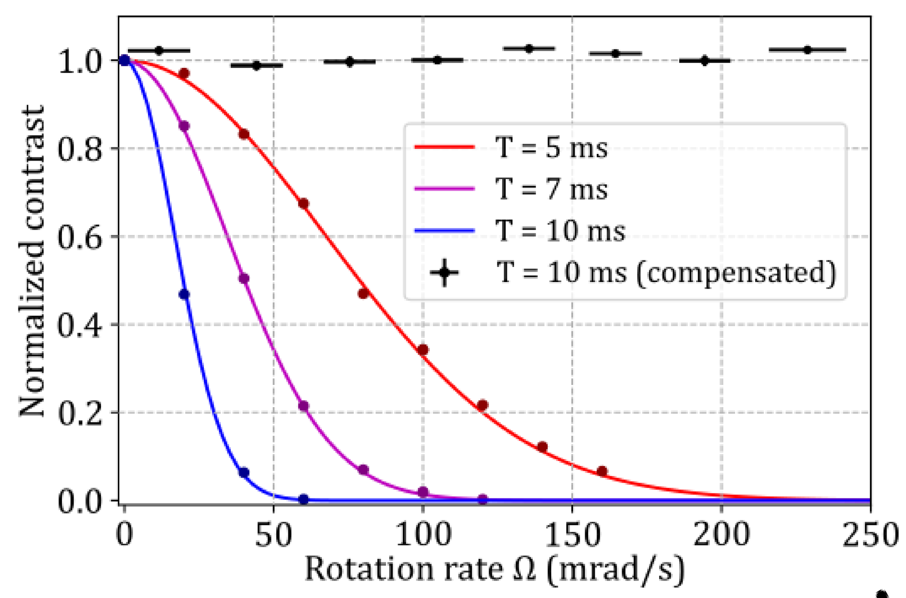
- **Problem:** fringe pattern in the density profile at each output port
  - ➢ For averaging detection systems (photodiodes): overall contrast loss $C(\Omega) \approx C_0 \exp\left[-\left(k_{eff}\sigma_v\right)^2 \Omega^2 T^4\right]$



- **Solution:** real-time stabilization of the effective wave vector's orientation
  - ➢ Mirror's rotation opposed to that of the chamber (inertial pointing) – *patented*

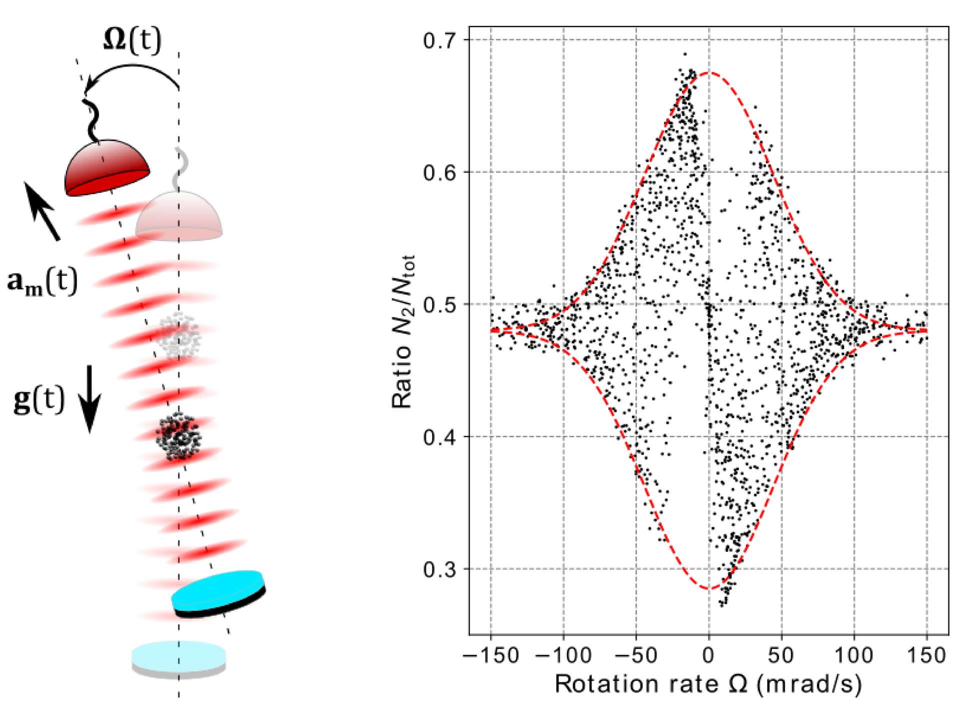


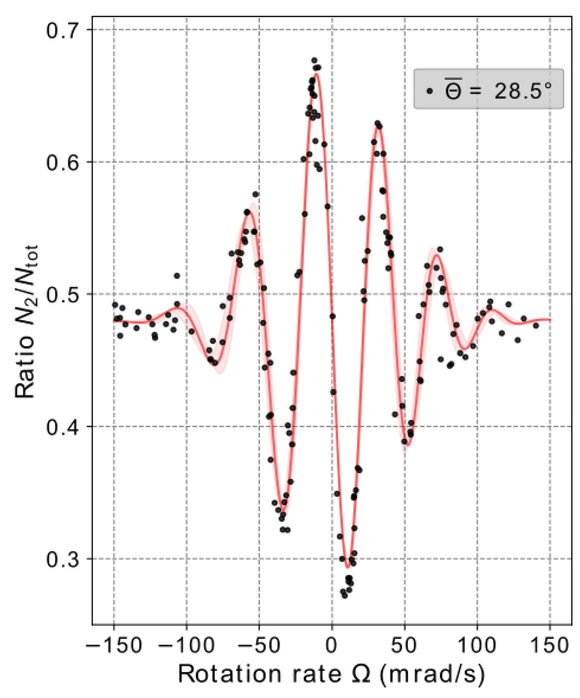
- **Outcome:** recovery of the atomic interference pattern's full amplitude
- ✓ Stable value over the measured range $|\Omega| \le 250$ mrad/s $\simeq 14$ °/s
- ✓ Compatible with navigation applications



A more complex atomic trajectory in the mirror's rotating frame

- **Problem:** rotation-induced acceleration terms scrambling the atomic phase
- No information can be retrieved at the output of the atom interferometer





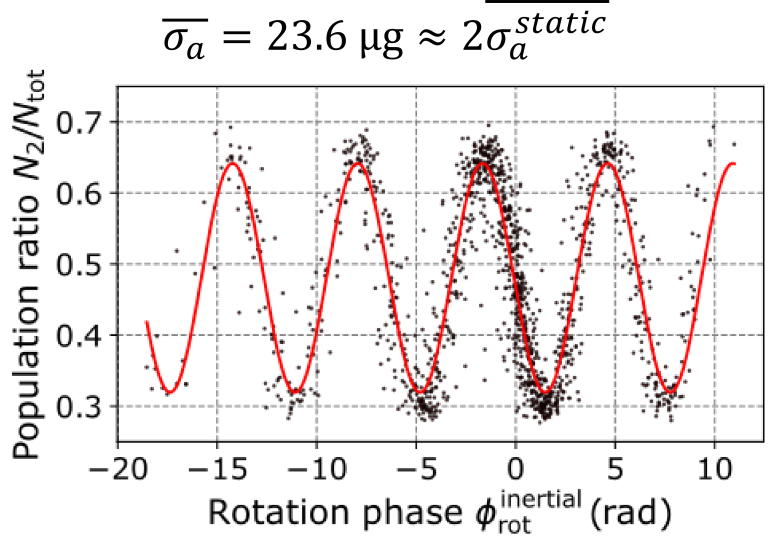
- **Solution:** determination of the new equation of motion

$$\boldsymbol{a}(t) = \ddot{\boldsymbol{r}}(t) + 2[\boldsymbol{\Omega}(t) \times \dot{\boldsymbol{r}}(t)] + \boldsymbol{\Omega}(t) \times [\boldsymbol{\Omega}(t) \times \boldsymbol{r}(t)] + \dot{\boldsymbol{\Omega}}(t) \times \boldsymbol{r}(t)$$

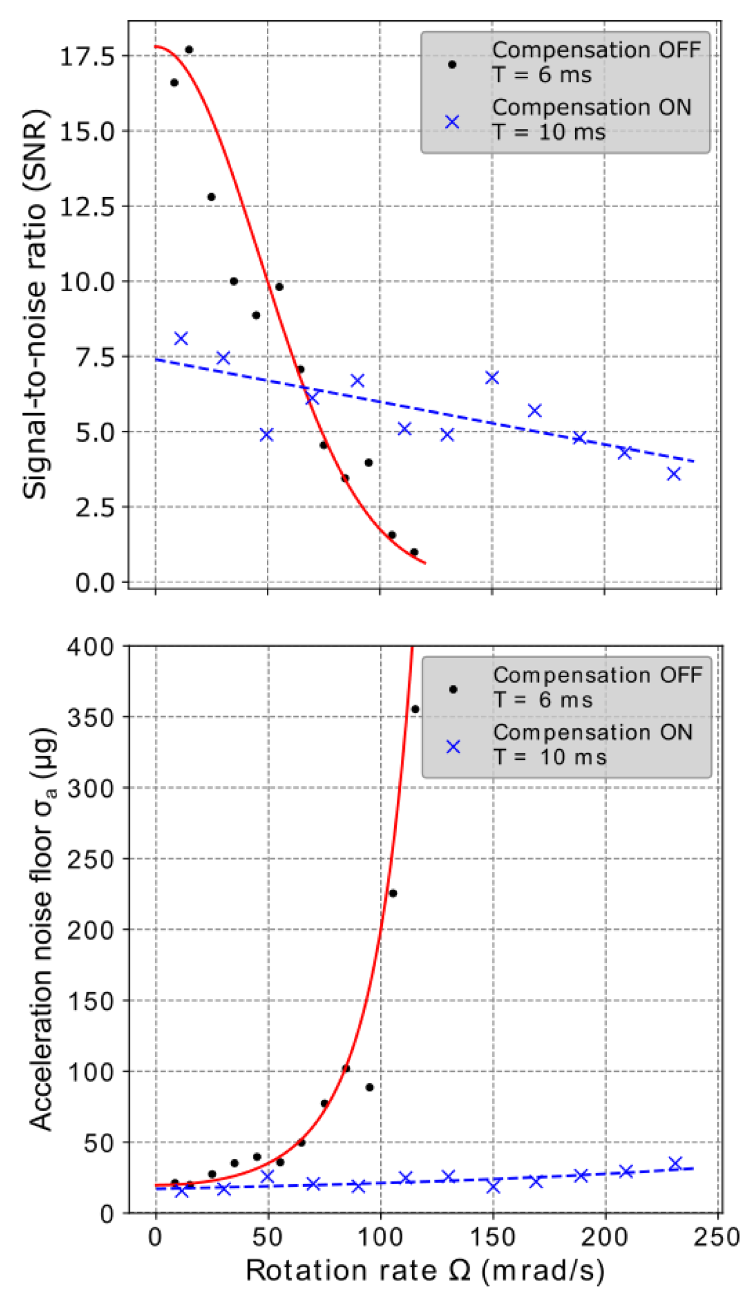
- ➢ Correction of the additional rotation-induced phase shift

Yielding a robust quantum inertial sensor operable at any arbitrary orientation and rotation rate [4]

- Wide operating range recovered $|\Omega| \le 14°/s \,;\, \theta \in [0,30]°$
- Signal-to-noise ratio at T = 10 ms $\mathrm{SNR} = C(\Omega)/\sigma_\phi = 5.4$
- Corresponding accel. sensitivity $\overline{\sigma_a} = 23.6$ µg $\approx 2\overline{\sigma_a^{static}}$



- ✓ **Improved dynamic, compatible with navigation requirements**
- ✓ **Uncompensated performances limited by the contrast decay**
- ✓ **Compensated performances limited by the vibrations regime**



References

[1] Templier, S. et al. "Carrier-Suppressed Multiple-Single-Sideband Laser Source for Atom Cooling and Interferometry", Phys. Rev. Applied **16**, 044018 (2021)

[2] Cheiney, P. et al. "Navigation-Compatible Hybrid Quantum Accelerometer Using a Kalman Filter", Phys. Rev. Applied **10**, 034030 (2018)

[3] Templier, S. et al. "Tracking the vector acceleration with a hybrid quantum accelerometer triad", Science Advances **8**.45, eadd3854 (2022)

[4] d'Armagnac de Castanet, Q. et al. "Atom interferometry at arbitrary orientations and rotation rates", arXiv:2402.18988 (2024)

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