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Atom Interferometry as Stable Inertial References in Hybrid Sensing

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Motivation

Utilization of the matter-wave properties of atoms have lead to the creation of atom interferometers capable of performing absolute measurements of inertial effects, such as accelerations and rotations. Current commercially inertial measurement devices are susceptible to long term drifts, or are currently limited in the portability and sensitivity. Atom interferometry yields the possibility to develop compact drift-free inertial measurement devices. To build such a device requires hybrid sensing to address the dominant noise contribution in inertially sensitive atom interferometers; vibrational noise coupling to the inertial reference mirror. Utilization of novel compact opto-mechanical resonators for hybrid sensing eliminates limitations presented by commercially available motion sensors. This work was performed in collaboration with Quantum Sensing Group at the *Institute of Quantum Optics - Leibniz Universität Hannover*.

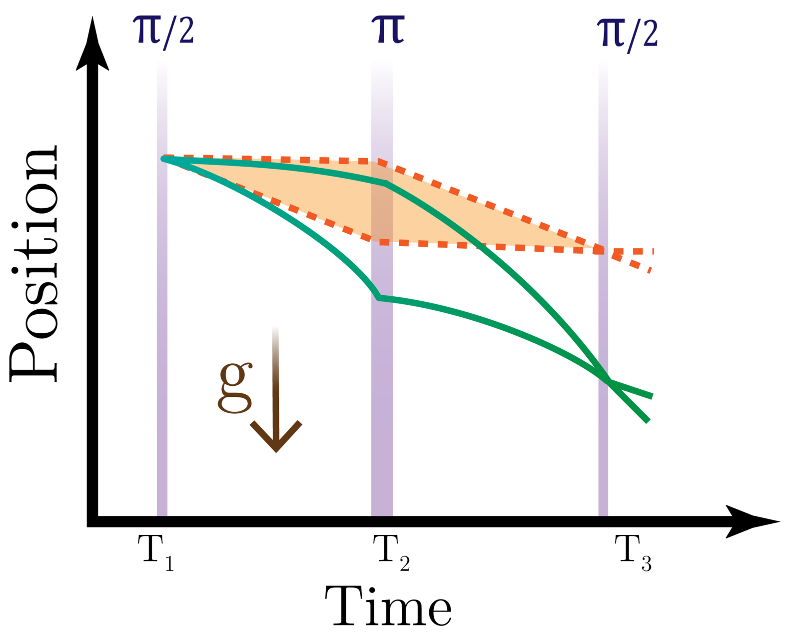


Fig 1: Mach-Zehnder Geometry for an atoms in free fall. Three optical pulses separated by a pulse separation time *T* coherently manipulate the state of an ensemble of cold atoms. In a gravimeter configuration, the output population is proportional to the gravitational acceleration of the atoms.

Atom Interferometers as Inertial Sensors

Using timed detuned pulses it is possible to coherently drive 2-photon transitions in an ensemble of cold atoms in a Mach-Zehnder geometry. Such an interferometer is sensitive to the phase difference between the two paths, which can be read out by the output population of the ensemble.

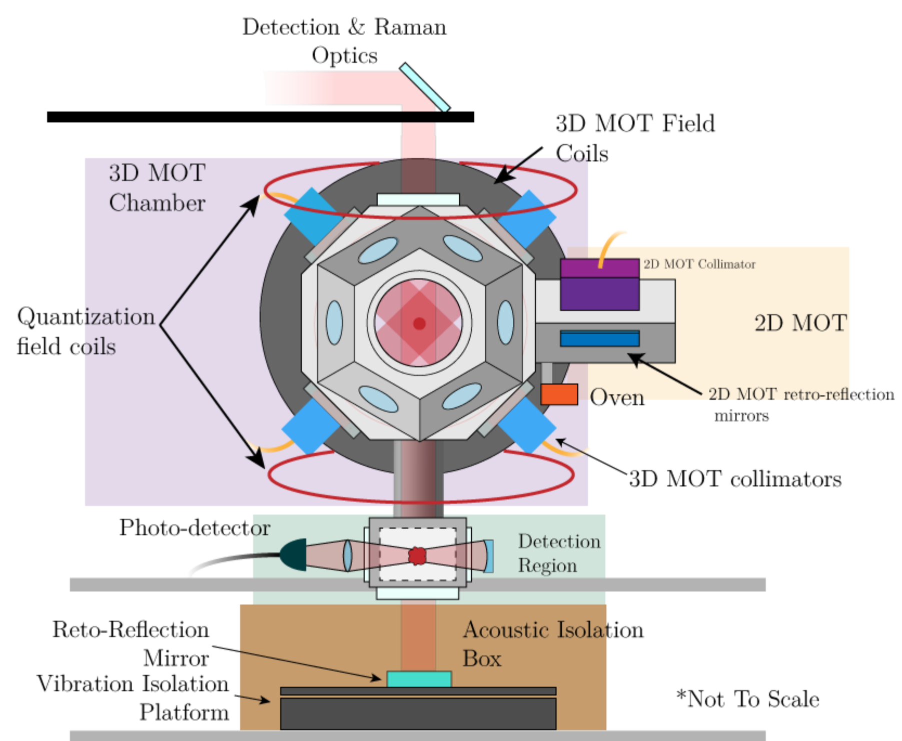
$$P_{|e\rangle} = \frac{C_0}{2}[1+\cos[\Delta\phi]]$$

For a ensemble of atoms in free fall the total phase difference between the paths is given by:

$$\Delta\phi = \underbrace{\vec{k}_{\text{eff}} \cdot aT^2}_{\text{Accelerations}} + \underbrace{2\,\vec{\Omega}_{\text{rot}}\,(v_0 \times \vec{k}_{\text{eff}} T^2)}_{\text{Rotations}} + \underbrace{\Delta\phi_{\text{HO}}}_{\text{Higher Order Terms}}$$

In this work we will focus on **gravimeter configuration** of atom interferometers, which is oriented in a manner to minimize phase contributions from rotations.

Fig 2: Experimental configuration of an atom interferometer



Inertial Noise on Atom Interferometers

Given by the equivalence principle, vibrations coupling into the inertial reference (retro-reflection mirror) cannot be discerned from acceleration of the atoms. This noise source is a major limitation to the sensitivity of current generation atom interferometers, and is especially limiting in portable devices measuring in the field, where ground motion is typically higher.

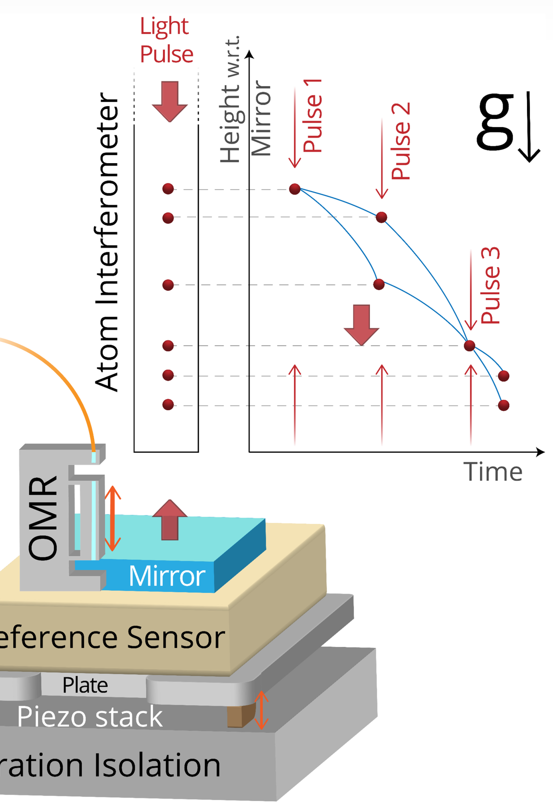


Fig 3: Hybrid sensor configuration. Motion of the retro-reflection mirror can be tracked by the opto-mechanical resonator and convolved with the time dependent atom interferometer sensitivity function to post-correct vibrationally induced phase shifts. Additional motion can be added via piezo-electric transducers.

Sensor Hybridization

One method to address inertial noise is through the use of external sensors measuring the ground motion occurring during a measuring cycle. By tracking the motion of the inertial reference, we can use the atom interferometer's sensitivity function, $s_{AI}(t)$ to determine the vibrationally induced phase shift that occurred during measurement, given by:

$$\Delta\phi_{PC} = \int_0^{2T+4\tau} a(t) \cdot s_{AI}(t)\,dt$$

Joint measurements of matter wave interferometers with commercial accelerometers of large mass and volume have already been demonstrated, resulting in large systems not easily transportable. Our concept paves the way for miniaturization and enhanced portability, as well as increased robustness for operation under large vibrations affecting the inertial reference mirror in the system that is co-located with the opto-mechanical resonator.

Experimental Setup

The experiment consist of a Mach-Zehnder-type atom interferometer housed at the *Leibniz Universität Hannover* [1], and a prototype optomechanical resonator [2] that has been mounted on a 2 inch square retro-reflection mirror. This assembly is attached to the top of a commercial 3-axis accelerometer. The setup is resting on a piezoelectric transducer tripod and rests on a commercial vibration isolation platform under atmosphere. The light reflected back from the optomechanical resonator is read out by a photodetector. The effective post-correction of the atom interferometer's raw data is achieved by digitally convolving the optomechanical signal with the transfer function of the atom interferometer, thus computing the necessary phase corrections.

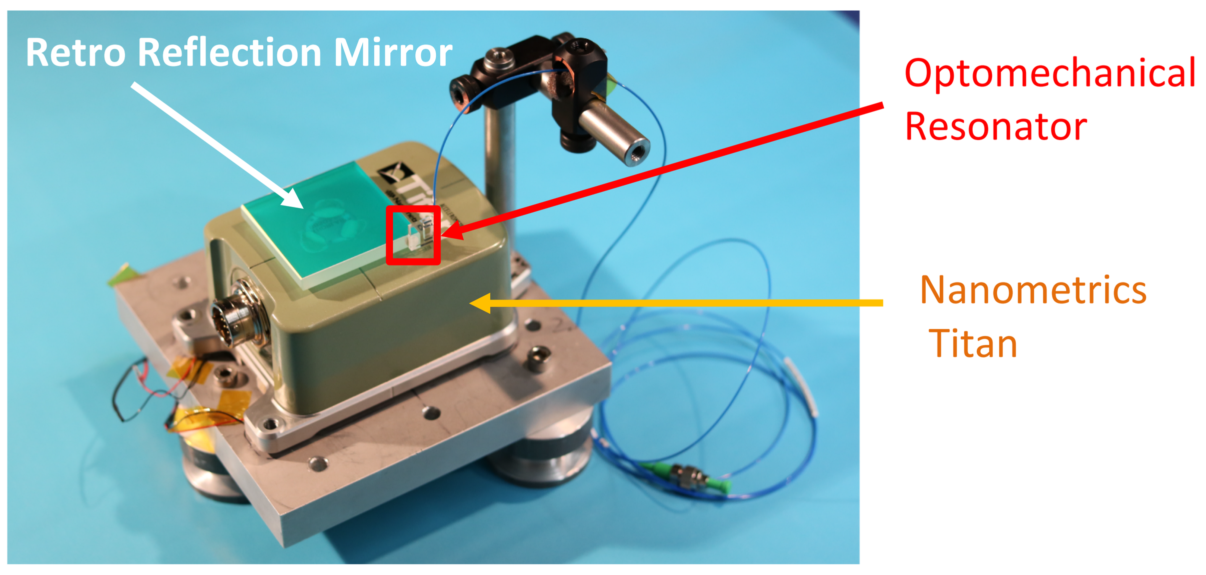


Fig 4: Sensor stack configuration used.

Results

Utilizing a Mach-Zehnder atom interferometer with pulse separation time T = 10 ms and with additional motion from a piezo-driven retro-reflection mirror we were able to post-correct the output population of the atom interferometer and generate a reconstructed fringe increasing the uncorrected atom interferometer short term stability of $\sigma_{upc} = 8\times10^{-3}\,{}^{m}/_{s^2}/\sqrt{Hz}$ to $\sigma_{pc} = 5\times10^{-4}\,{}^{m}/_{s^2}/\sqrt{Hz}$

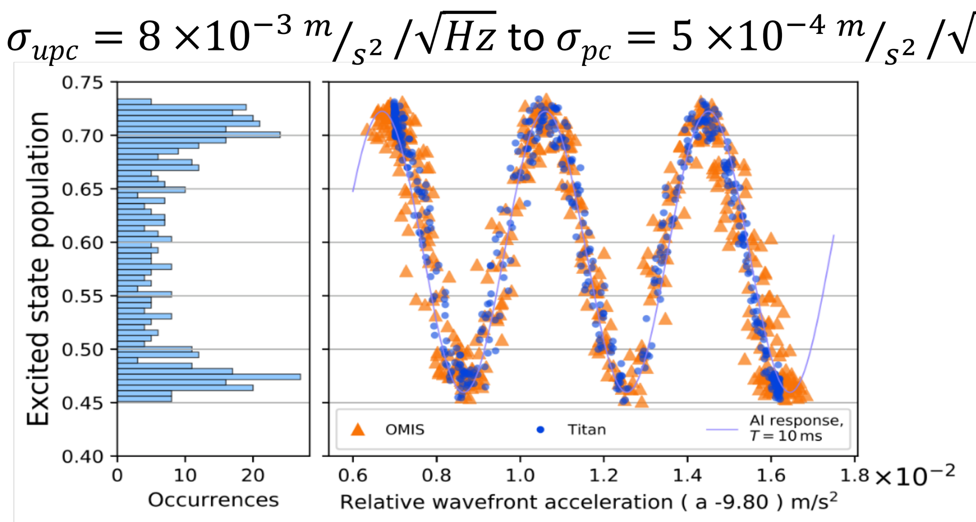
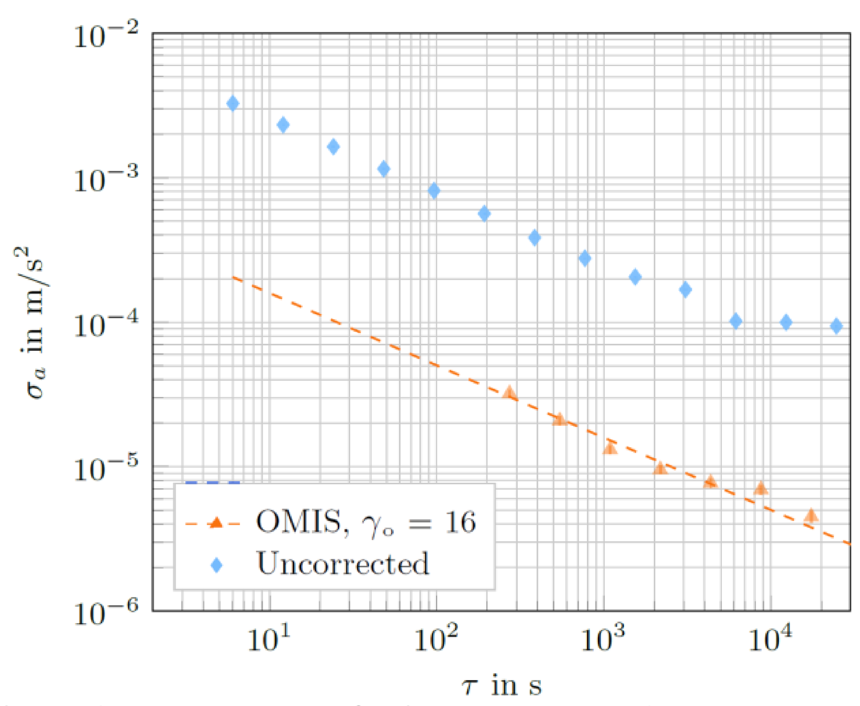
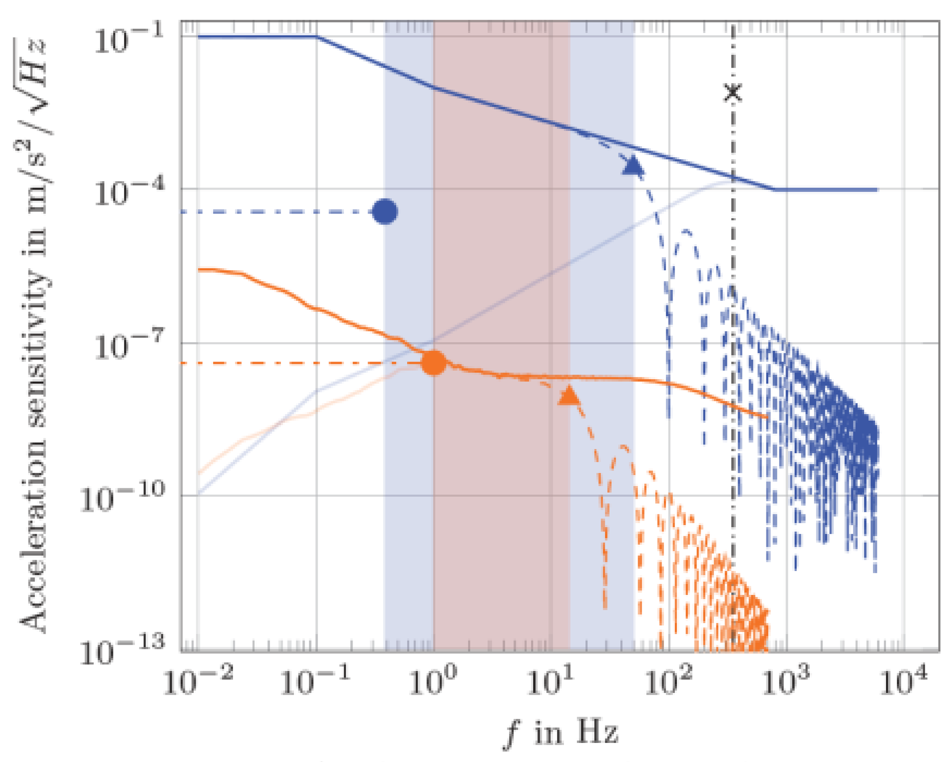


Fig 5: reconstructed fringe of driven atom interferometer. Post-correction performed with opto-mechanical sensor signal (orange triangles) compared to Nanometrics Titan (blue circles). Histogram of AI population is shown on the left



Allan deviation a of the measured gravitational acceleration as a function of averaging time for the uncorrected data (light blue diamonds) and the measurements corrected by utilizing the signal from optomechanical sensor (orange triangles). Integration down to $\sigma = 4.5\times10^{-6}\,{}^{m}/_{s^2}/\sqrt{Hz}$ after 10900 points (25,000 seconds)

Outlook



As the sensitivity of the optomechanical sensors depends quadratically on the resonance frequency and linearly on the finesse of the micro-optical cavity, there is large room for improvements by trading sensitivity against smaller dynamic range. For a resonance frequency of 700 Hz and a finesse $\mathcal{F}$ = 1600 [3], we project a compact gravimeter with a pulse separation time of T = 35 ms and repetition rate of 1 Hz to be vibration limited at a level of $2.7\times10^{-7}\,{}^{m}/_{s^2}/\sqrt{Hz}$ without seismic isolation. This would be less than an order of magnitude away from the lowest noise obtained in a quiet environment with an active vibration isolation [4].

References

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