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# Opto-Mechanical Inertial Sensors (OMIS) for High Temporal Resolution Gravimetry

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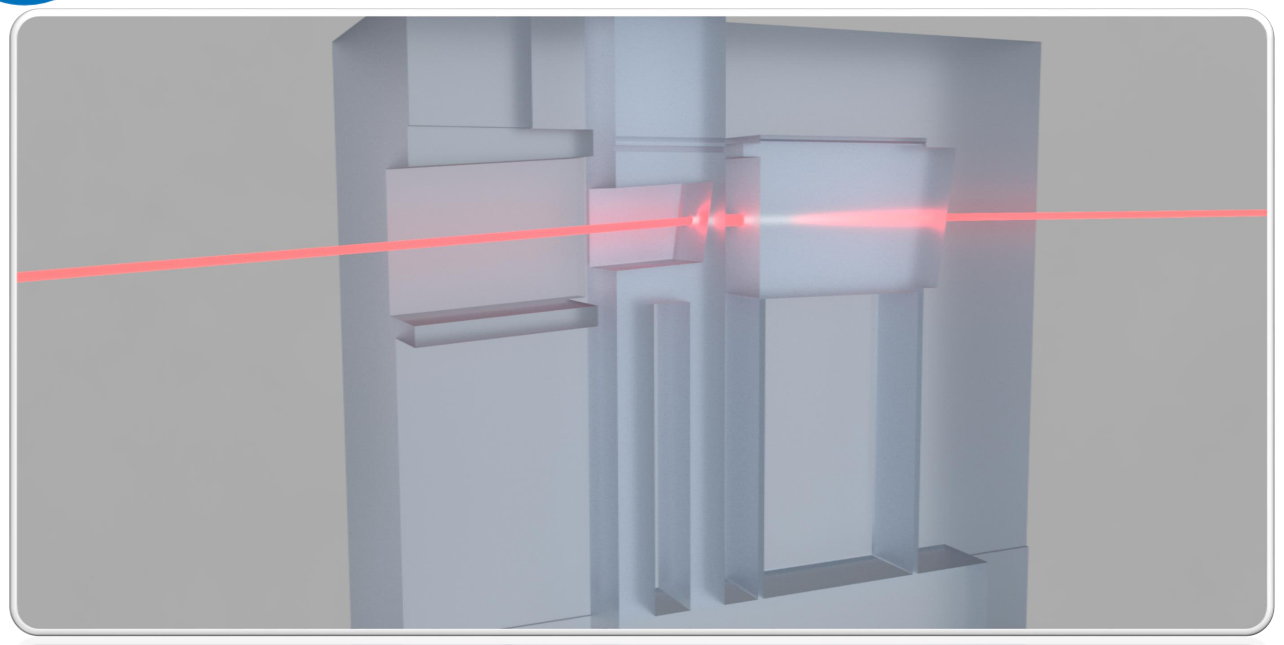
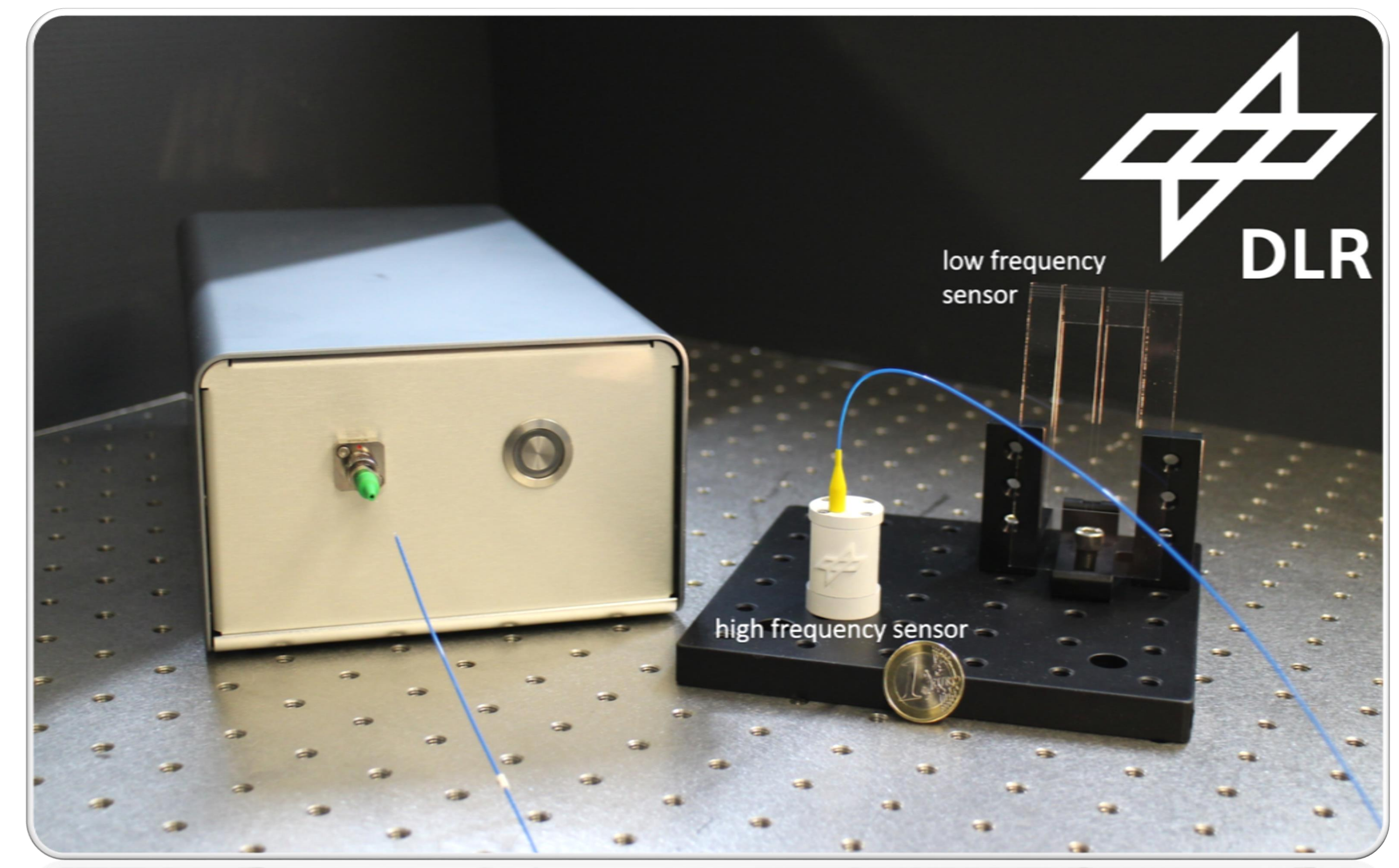
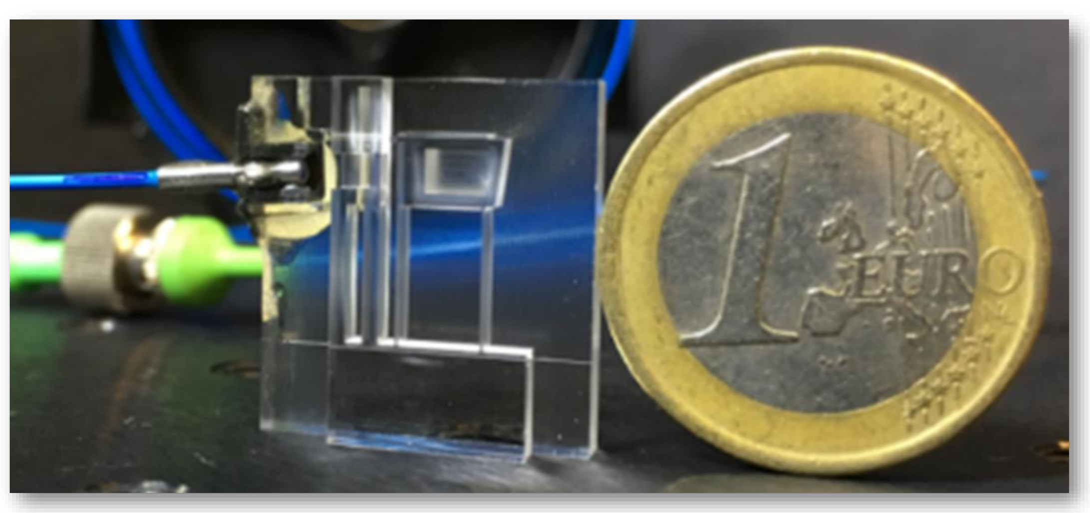





## Introduction

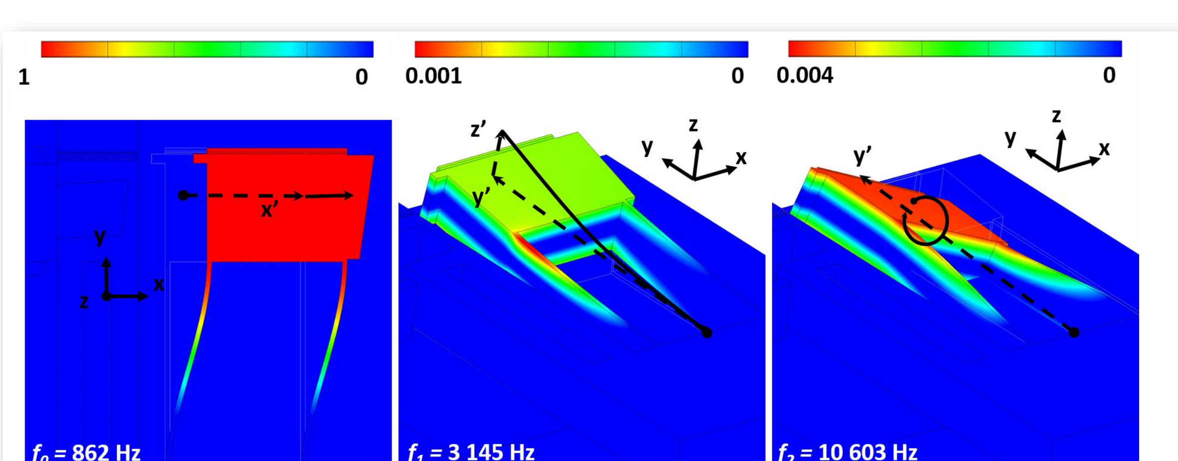
Free-falling atom interferometers offer the prospect of fundamental metrology for inertial measurement with ultra-high precision and long term stability (Bongs et al. 2019). But these devices currently suffer from low sampling rates (~1 Hz) which can be significantly improved by hybridizing with a classical inertial sensor. Classical sensors have challenges with long term stability due to their sensitivity to the environment. However, as long as the stable portion of the classical sensor bandwidth overlaps the atom sensor, the combined signal gains the benefit of both sensors. This means increased long term stability and bandwidth. Here we present work on a classical sensor design with a stable bandwidth (0.1-700 Hz) that overlaps with the specifications of current generation atom sensors (DC-1 Hz). We achieve this using a monolithic fused silica resonator with an integrated optical cavity that is injected with light stabilized to the P10 resonance of a hydrogen cyanide gas cell (standard reference material, NIST SRM 2519a). We demonstrate displacement imprecision of $10^{-13}$ m/√Hz and a acceleration imprecision of $10^{-7}$ *g*/√Hz.

## Opto-mechanical design

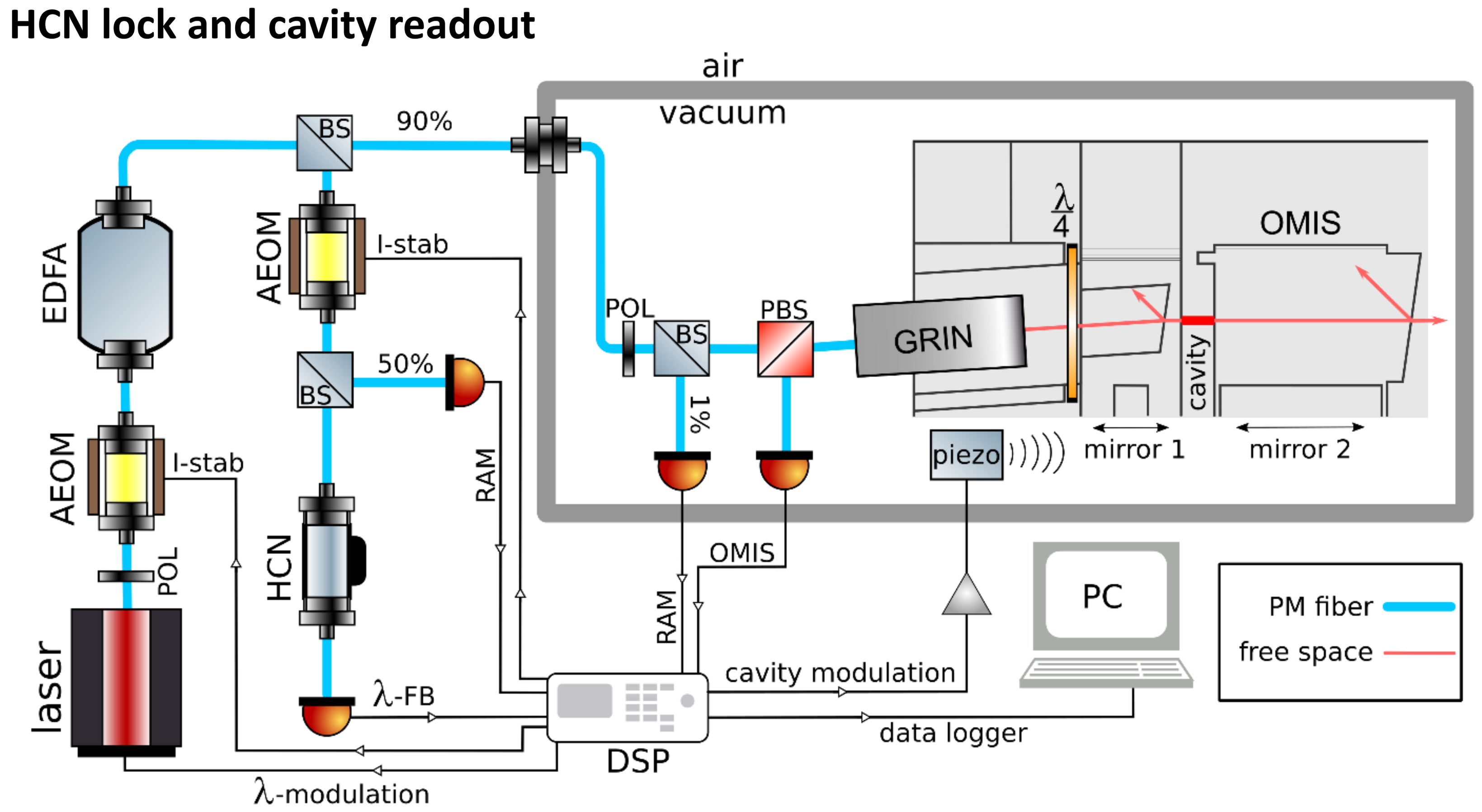


The OMIS is laser machined from a single fused silica wafer to create a completely monolithic part with integrated mirrors for the optical cavity (Guzman et al. 2018). These mirrors are merely the reflection from the air-glass interface (reflectivity ~4%). Since fused silica has a coefficient of thermal expansion of $5\times10^{-7}$ and the entire sensor is monolithic, it is extremely stable to the environment. The sensor operates in vacuum eliminating noise due to air currents and it is immune to EMI. The result is a highly stable resonator currently limited on long time scales by laser frequency noise. Machined into the sensor is also a socket providing the option to hold a fiber (depicted above) or light can be beamed from free-space (depicted very top).

The test mass deflects under acceleration with in-plane motion. The dual-flexure design insures reduced cross-axial sensitivity. Below is the FEA result of the first three modes excited by equal amplitude accelerations. The color indicates the level of in-plane motion normalized to the fundamental mode. To further reduce cross coupling, the laser is aimed at the blue strip of modes 1 and 2.



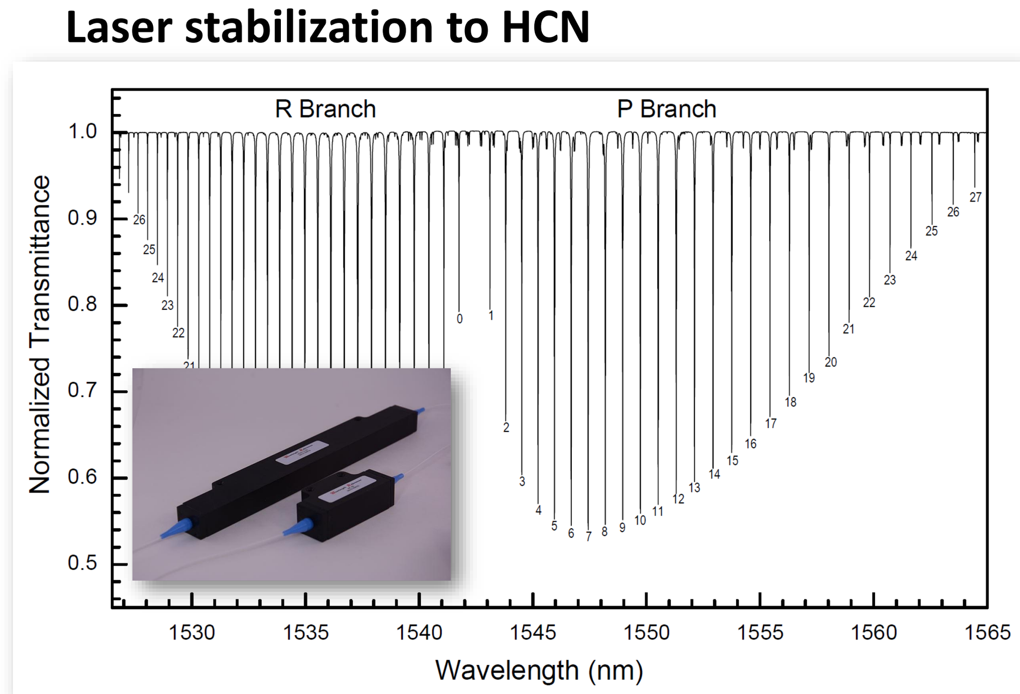

## HCN lock and cavity readout

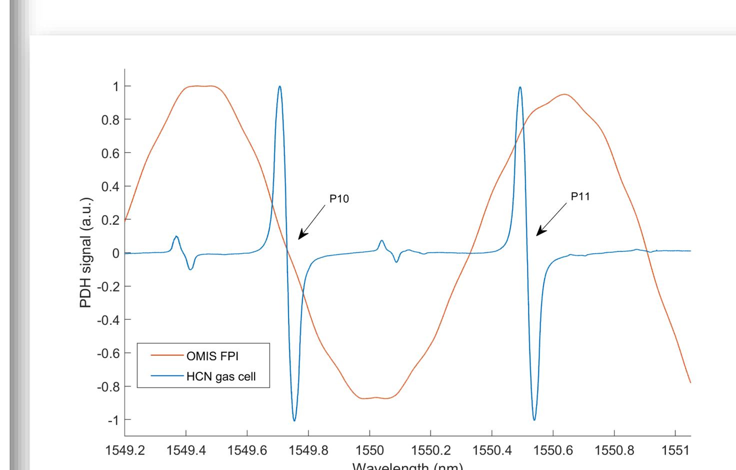



The HCN resonances have a linewidth of about 3 GHz. Modulation base locking is optimal when the sidebands fall outside the linewidth of the resonance. Direct phase modulation at 3 GHz poses challenges for the digital signal processor (DSP). Instead, the laser current was modulated to shift the laser frequency ~6 GHz at a 2 MHz repetition rate. The Pound-Drever-Hall (PDH) signal (below right, blue curve) was not significantly distorted leading to solid locks. However, the OMIS cavity linewidth was far broader (75 GHz) and only produced a very weak PDH signal. Adjusting the modulation depth to cover 75 GHz, while good for the cavity signal, severely distorted the HCN signal. Therefore, the OMIS cavity itself was modulated by a piezo.

Modulating the cavity length without compromising its stability meant the piezo could not act directly on the mirror position. Otherwise, stray electric fields, temperature, circuit noise, and material aging would affect the shape of the piezo crystal and thus move the mirror. Instead, the piezo was coupled in an AC fashion, transferring energy seismically from a remote location. One cavity mirror was designed as a high frequency resonators (mirror 1 ~80 kHz, depicted above). Simply exciting the mirror resonance with a nearby piezo was enough to modulate the cavity length, shifting the cavity resonance by ~75 GHz. This gave a good PDH signal for cavity readout (below right, red curve). The OMIS itself was unaffected by this tone because its resonance was two decades lower (~800 Hz) in effect filtering it out.

## Laser stabilization to HCN



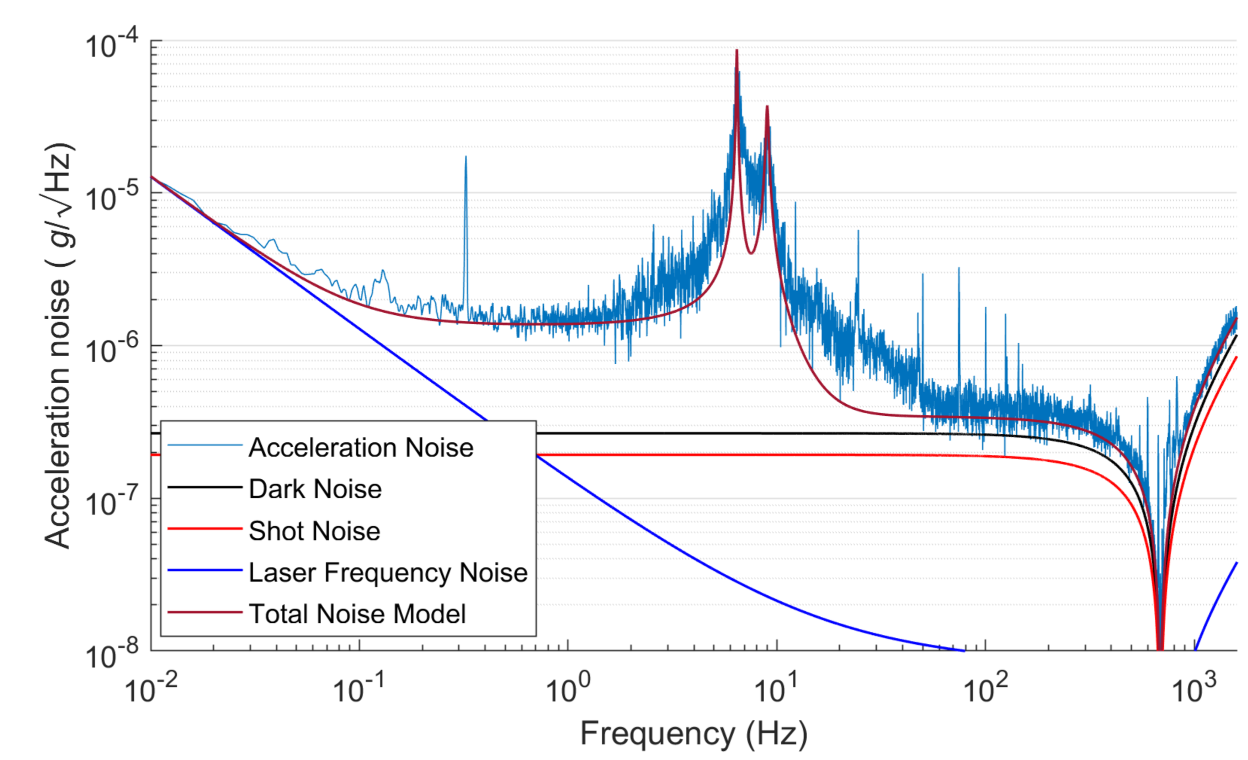



We chose to stabilize the laser against a molecular reference as a step toward realizing a working acceleration standard which requires knowing the precise frequency of the OMIS optical cavity resonance. One way to get this information is to lock the laser to a certified reference material (HCN, SRM 2519a) and then shift the frequency by a known amount to until resonant with the OMIS cavity. In this work, we only lock the laser to the reference material. We use a fiber coupled HCN gas cell at 25 Torr pressure (top left inset). HCN has a resonance about every 100 GHz (top left) which matches closely with the OMIS free spectral range (FSR) of 150 GHz (top right, HCN blue, OMIS red). The linewidth of these resonances are pressure broadened (at 25 Torr) up to ~3 GHz.

The OMIS readout linearity requires near-resonance with a cavity mode. The FSR was too large to shift the laser frequency (up to 150 GHz). And to preserve the stability of the OMIS cavity, we could not tune the cavity length directly with a piezo. Therefore, our method was to search the HCN spectrum for a resonance close to the OMIS cavity resonance (top right). In this case, the laser was locked to P10.

## Results and discussion

The readout of the test mass motion, converted to acceleration, is shown below. Above about 50 Hz, the OMIS shows near shot noise level performance. Below 50 Hz, the noise is dominated by the mechanics of the vibration isolation platform. The isolation platform has three piston modes and three rocking modes. Simplifying the mechanics as the sum of two first order systems fits the data quite well. Below 0.1 Hz, the noise is dominated by the laser frequency noise.




We considered many noise processes known to exist in opto-mechanical resonators such as substrate noise (Levin 1998) but these are well below the range of the plot. Also our model includes structural damping, i.e. complex spring stiffness, but this would only be evident in a thermally limited curve (Saulson 1990). The temperature spectrum of the room was measured and inserted into a thermal model of the vacuum enclosure. The result is outside the plot field on the timescales presented here.

Since the shot and dark noises scale down with increased finesse, the next step will be to increase finesse using higher reflectivity mirrors. Our measurement setup was designed exactly for this purpose, requiring no other changes in equipment or signal processing. And this study has already identified the laser frequency noise as a major hurdle to overcome in the next phase. The essential problem is that the HCN linewidth is too broad. It's possible to reduce the gas cell pressure to narrow the linewidth and further to perform a Doppler-free measurement. Simpler would be to incorporate a reference cavity into the OMIS. We will look into the tradeoffs for these options.

Another challenge will be seismic isolation. Any reductions to noise will be hidden under ~$10^{-6}$ *g*/√Hz of seismic activity. Likely, future measurements will be performed by comparing two sensors such that the seismic noise is common mode and can be suppressed.

## References

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