Compact High Sensitivity Optomechanical Inertial Sensors

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Motivation

The Laboratory of Space Systems and Optomechanics (LASSO) at Texas A&M University is working to create novel, highly sensitive inertial sensors by combining our fused-silica optomechanical resonators with compact, high-precision interferometers. Our resonators have high mechanical quality factors and low thermal acceleration noise. Q's of 2.45 x 10^5 were previously achieved at mTorr pressures. This corresponds to an estimated thermal acceleration noise floor of 10^{-10} m $s^{-2}/\sqrt{Hz}$ at frequencies greater than 30 mHz. However, gas damping dominates losses at this pressure. We expect mechanical quality factors on the order of 10^6 and thermal acceleration noise levels of 10^{-11} m $s^{-2}/\sqrt{Hz}$ at lower pressures where gas damping is negligible. We are currently creating a vacuum set up to take Q measurements at these lower pressure ranges. These resonators will be incorporated with our compact high sensitivity displacement interferometer design, with the aim to read out test mass oscillations at picometer sensitivities. Current sensitivities at the sub-nm/√Hz level for sub-Hz frequencies are possible. By subtracting individual noise sources from our heterodyne interferometer benchtop prototype, sensitivities at the picometer level were reached for frequencies above 100 mHz. A compact mount that will hold the combined resonator and interferometer sensor system is being designed, and we hope to have a mount prototype to test with our fused-silica resonators by summer.

Combined Design

We plan to incorporate our 10 Hz fused-silica resonators with our compact quasi-monolithic heterodyne laser interferometer to form a compact sensor system (Figure 1). These components will be incorporated into a mount and housing (Figure 6) to form a compact sensor.

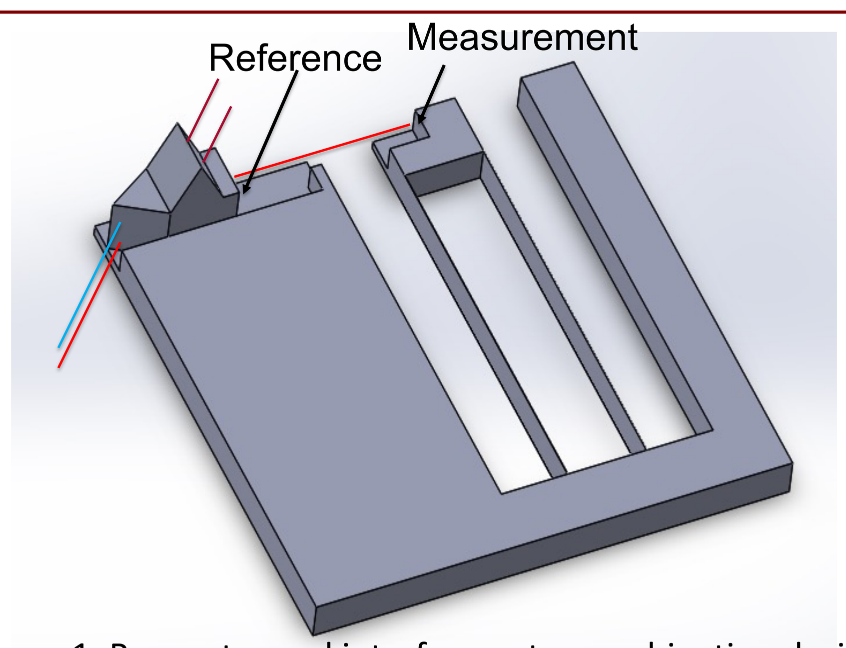

Figure 1: Resonator and interferometer combination design

Prototype Heterodyne Laser Interferometer

Figure 4 presents the design of our heterodyne laser interferometer breadboard prototype which was tested in air at 632.8 nm. Heterodyne interferometry uses two frequencies for inherent directional sensitivity and a large dynamic range. This results in periodic errors due to polarization and frequency mixing between the two frequencies. To overcome this, our design uses spatially separated beams with highly common optical paths. Frequencies are shifted with acousto-optic frequency shifters, one by 80 MHz and the other by 85 MHz, to produce a beat note frequency of 5 MHz.

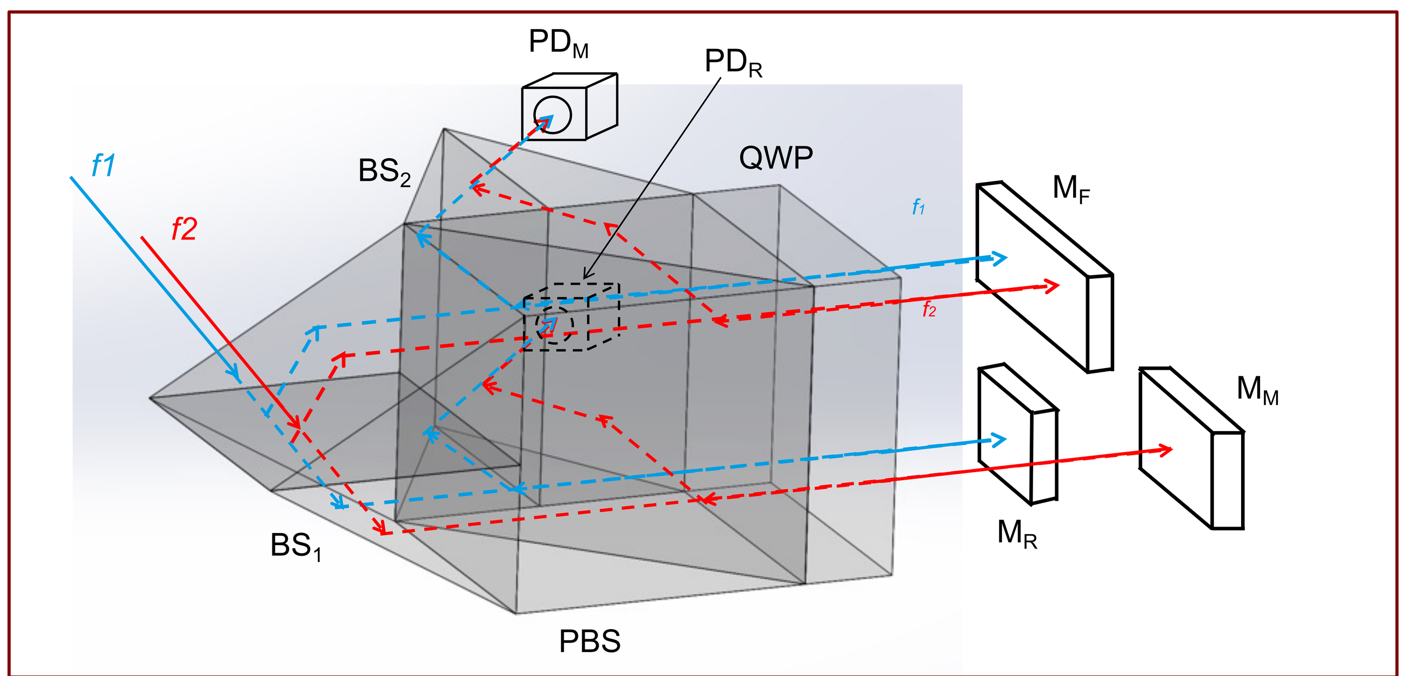

Figure 2: Compact quasi-monolithic heterodyne laser interferometer design

$$I_R = I_o(1+\cos(2\pi\delta f t + \phi_R + \Delta\phi_{ty}))$$
$$I_M = I_o(1+\cos(2\pi\delta f t + \phi_M + \Delta\phi_{ty}))$$

The intensity of the reference and measurement arms differ only by the difference in phase obtained from their optical path length, allowing displacement read out. Testing of an in air breadboard prototype indicated no detectable periodic errors and long-term stability:[2]

- Displacement Sensitivities: 3 nm/√Hz below 1 mHz and 10 pm/√Hz above 100 mHz
- Temperature Coupling Factor: 5 nm/K
- Stability: 3 pm over 1 s, 10 pm over 100 s, and 2 pm over 10,000 s

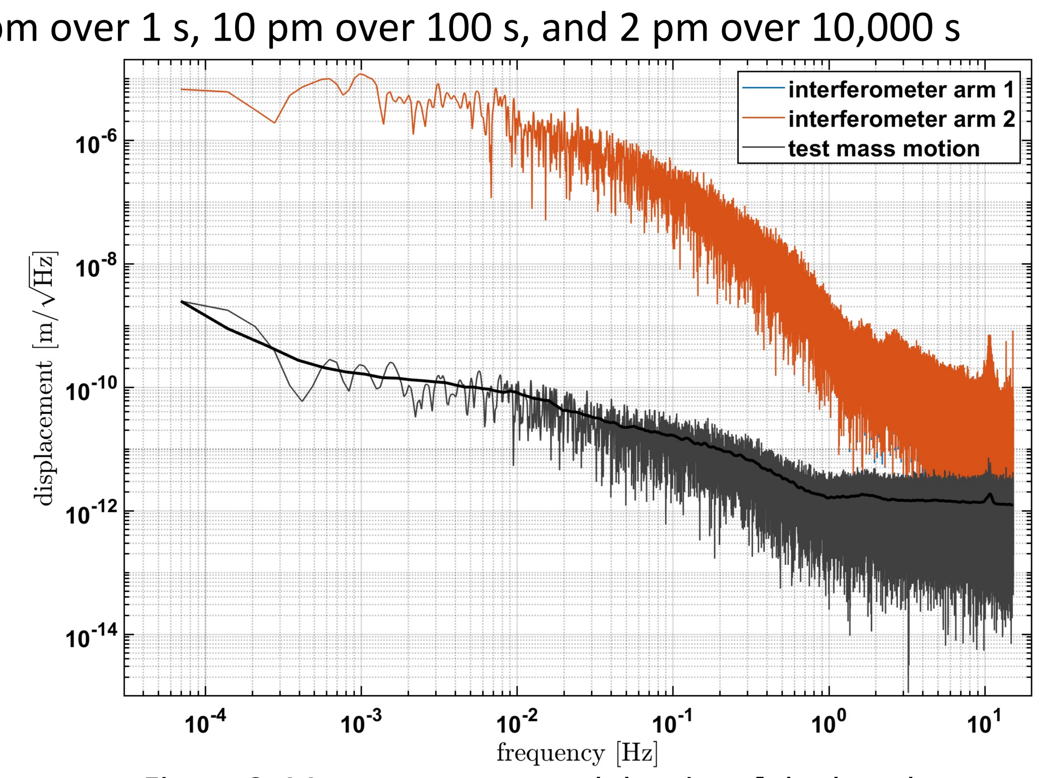

Figure 3: Most recent spectral density of the benchtop interferometer prototype at atmospheric pressure

Fused-Silica Optomechanical Resonator

Sensors with high displacement sensitivities can be implemented for use in acceleration measurements.

- We use low loss monolithic fused-silica 10 Hz resonators to test the displacement of a mirror test mass.
- Acceleration sensitivity $\Delta a_{ext}(\omega)$ is limited by displacement sensitivity $\Delta z(\omega)$:

$$\frac{\Delta z(\omega)}{\Delta a_{ext}(\omega)} = -\frac{1}{\omega_0^2-\omega^2+i\frac{\omega_0}{Q}\omega}$$

- To reach thermal acceleration noise estimates of 10^{-11} m $s^{-2}/\sqrt{Hz}$ requires interferometer displacement sensitivities on the order of 10^{-14} m/√Hz.[1]

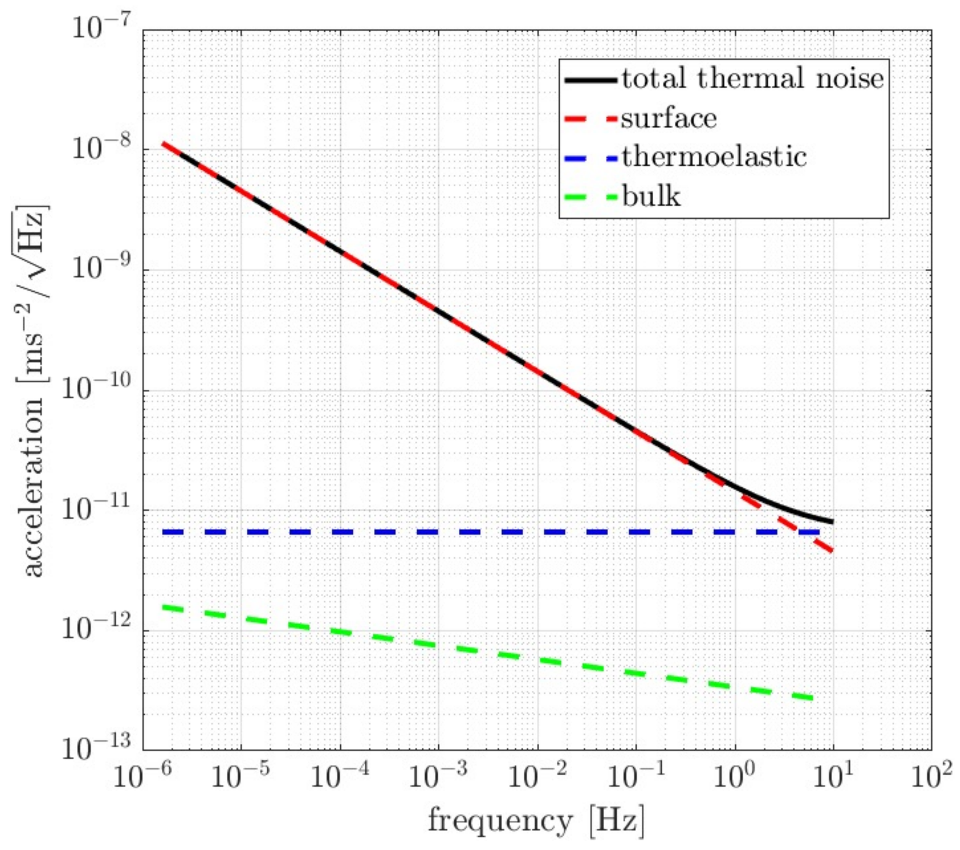

Figure 4: Estimated acceleration sensitivities for these resonators are on the order of 10^{-11} ms^{-2}/√Hz[1]

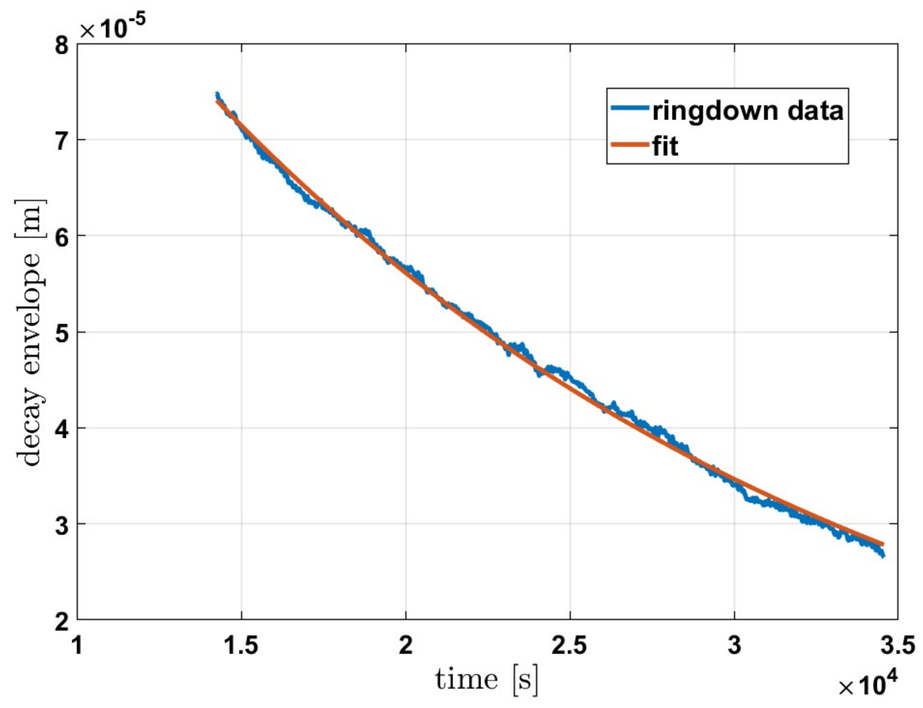

Figure 5: A 12-hour ringdown measurement at 1 mTorr. From the exponential fit, we find a mechanical quality factor of 2.45x10^5.

Compact Inertial Sensor Mount

Measurements using our prototype heterodyne displacement interferometer show a stable system with no detectable periodic errors. We are currently aligning the breadboard prototype in Vacuum to take Q measurements at reduced pressures. Significant improvement in displacement sensitivity measurements is expected. A mount is being designed to hold all components in a compact sensor system (Figure 6).

Moving forward:

- In vacuum measurements of prototype interferometer – significant improvement in sensitivity is expected in vacuum
- Compact quasi-monolithic heterodyne laser interferometer design (Figure 1) – we expect a prototype by the end of year
- Integration of interferometer and resonator units for compact sensors (Figure 1)
- Redesign sensors to work at near infrared wavelengths 1064 nm and 1550 nm where more stable and cost-effective laser units are available
- Complete mount design and prototype fabrication (Figure 6)

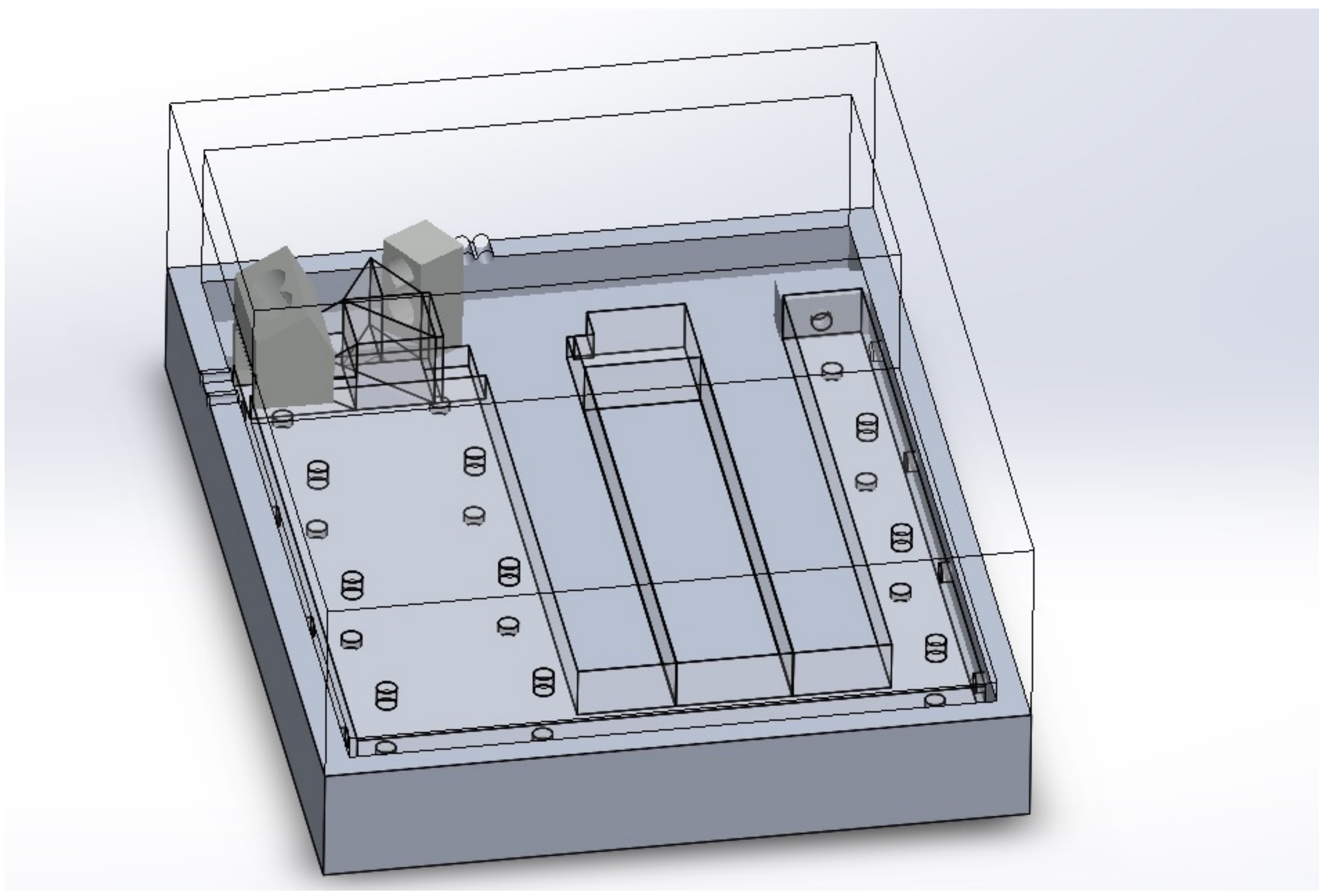

Figure 6: Preliminary mount design to hold the interferometer, resonator, fiber injectors, and photodetectors.

References

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We acknowledge Support from:
National Geospatial-Intelligence Agency (NGA) grant number: HM04762010016
National Science Foundation (NSF) grant number: PHY-2045579
National Aeronautics and Space Administration (NASA) grant number: 80NSSC20K1723