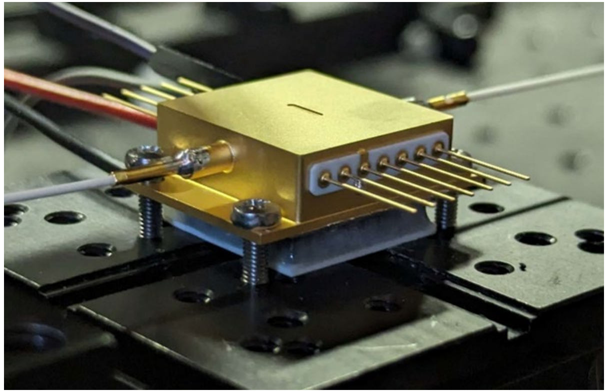
NASA Small Spacecraft Technology Program



Subsystems Design for a Suborbital Test of a Slot-Cavity Optomechanical Accelerometer

Wong group, Mesoscopic Optics and Quantum Electronics
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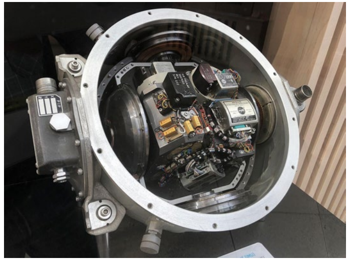
Why do accelerometers matter?

Highly accurate accelerometers are a key component of **inertial navigation systems**, which decrease a space system's reliance on GNSS systems for positioning and navigation.

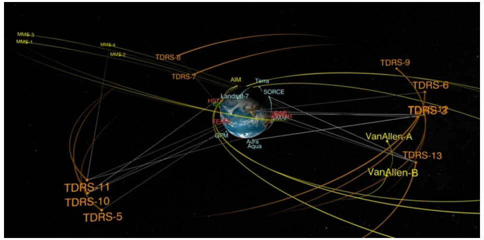
Two typical accelerometer designs: MEMS and piezoelectric. Can we do better?

- Our lab has developed accelerometers based on **cavity optomechanics** with several advantages (sensitivity, resolution, dynamic range) over traditional accelerometers.



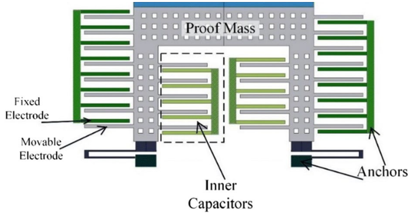
An Apollo inertial navigation system before the advent of GPS

Source: [a]



A modern example: communication with NASA's TDRS orbital fleet

Source: [b]



Part of a typical MEMS accelerometer design

Source: [c]

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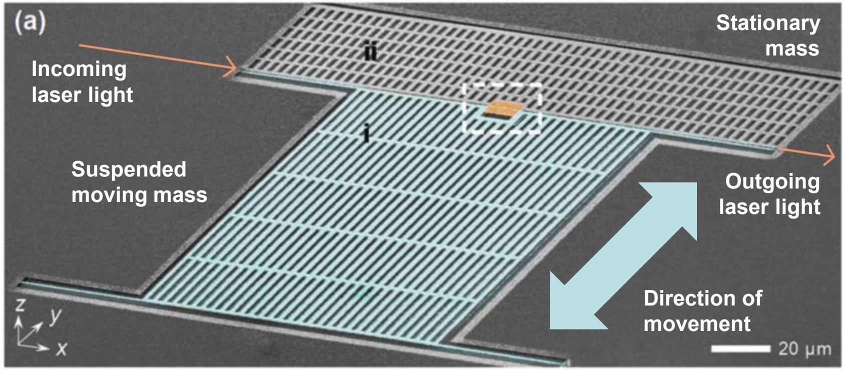
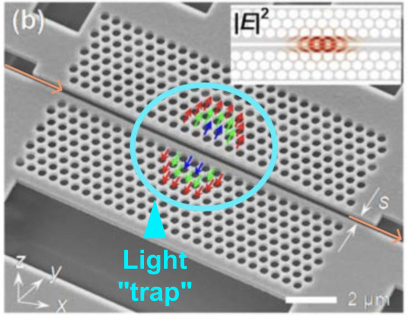
The cavity optomechanical accelerometer

At the core of our optomechanical accelerometer is a stationary mass (gray), a moving mass supported on cantilever beams (blue), and a photonic chiplet (yellow).

Incoming laser light enters the slot cavity and excites the chiplet, sending the moving mass into an oscillation with a known frequency (an **optical spring**). We say the laser light inside the cavity is **optomechanically coupled** to the moving mass.

Any acceleration in the direction of movement changes the frequency of oscillation, creating a highly sensitive accelerometer!





Electric field strength shows diffraction of light within cavity

A close-up view of our optomechanical accelerometer

Source: [1] (annotated)

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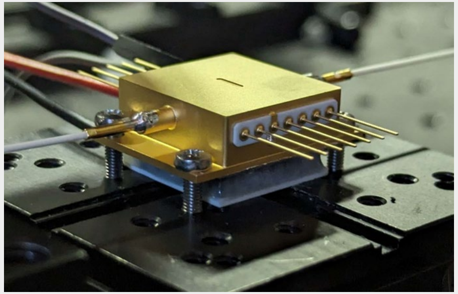
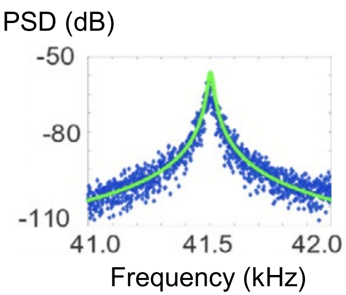
The cavity optomechanical accelerometer

We can indirectly measure changes in the device's oscillation – and thus **transduce** acceleration measurements – by measuring the power spectral density of the modulated outgoing laser light.

The device itself, not including the lasers, can be hermetically packaged into a small form factor (around 3 cm^3).

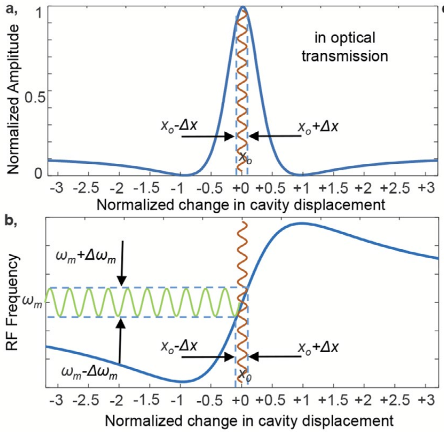


So what's the catch?



Peak in the power spectral density of the modulated light from one device's oscillation

Source: [2]



Any displacement of the cavity from acceleration alters this peak in consistent ways ("RF shift")

Source: [2]

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The real world

So far, our accelerometers have only been tested inside a controlled lab environment!

- Constant temperature, fine-tuned laser wavelength and polarization, easy data collection, etc.
- Not representative of real-world conditions: how can we make sure our accelerometers can function on an actual spacecraft?

Our group has planned a suborbital balloon test of three of these accelerometers on a suborbital Aerostar balloon flight in Q3 2025.

Goals:

- **Demonstrate the independent function of our accelerometers at altitudes up to 30 km (100,000 ft)**
- Compare the strapdown inertial navigation performance of our optomechanical accelerometers to that of reference MEMS accelerometers

Source: [d]

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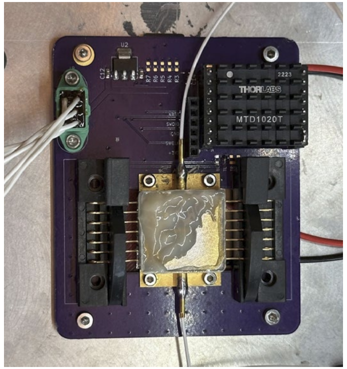
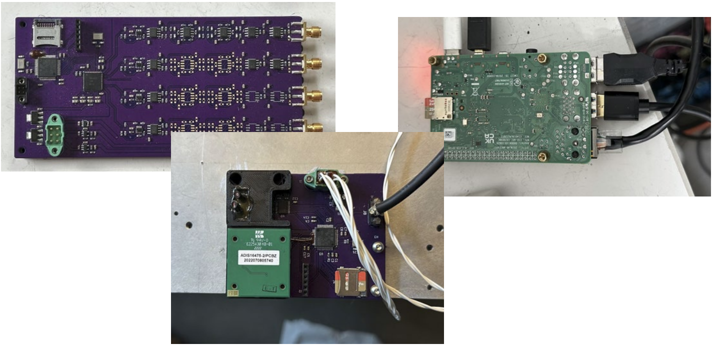
Subsystems

How do we ensure that our optomechanical accelerometers are ready to fly on a suborbital balloon – or, in the future, a CubeSat or cislunar satellite?



Temperature control

Polarization control



Readout systems and reference sensors

These subsystems lay the groundwork for future optomechanical devices to fly.

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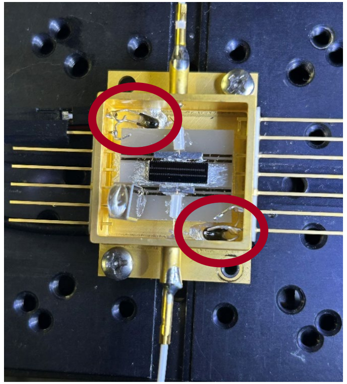
Temperature control

Though the device can operate within a range of temperature levels, any **changes** in temperature will affect the resonance frequency and will be indistinguishable from a change due to acceleration.

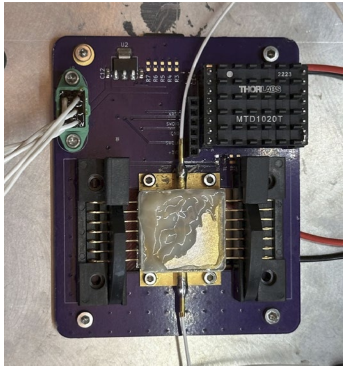
- Simply controlling the temperature of the payload as a whole is insufficient!

Our devices are individually temperature compensated through a Peltier-effect thermoelectric cooler (TEC) that sits underneath each accelerometer package.

- Each package contains two thermistors on the inside to measure temperature, allowing a TEC controller to maintain temperature control within 25 mK



Inside of device package, with thermistors circled in red



Package placed in supporting PCB with TEC, TEC controller, and microcontroller

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Polarization control

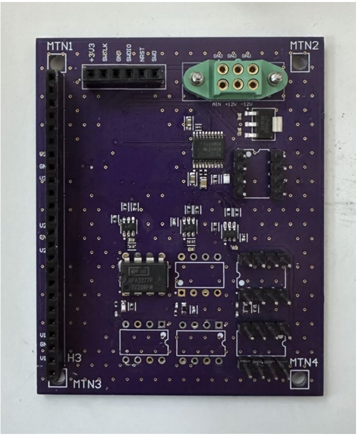
Our devices are also sensitive to the **polarization** of the input laser. Differences in polarization will cause losses in the power delivered to our accelerometer, which reduces its sensitivity.

A simple fiber polarization controller, and a strategy of taping down all optical fibers, is used in our current flight payload.

- We expect any possible drift in polarization to be negligible over a few hours of flight time
- For longer flights or missions, this cannot be assumed – an electric polarization controller must be used to maintain a consistent polarization state

A mechanical fiber polarization controller with three degrees of freedom

Source: [e]



Prototype of a PCB to support an electric polarization controller

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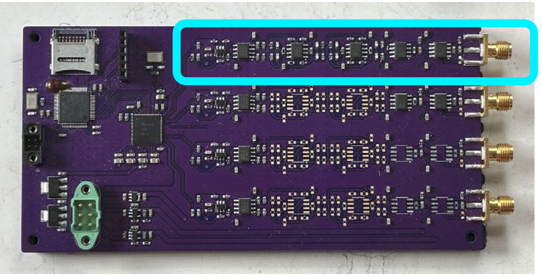
Readout systems and reference sensors

Photodetectors and signal conditioner board

- Photodetectors measure output laser power transmitted through device and turn it into an electrical signal
- Signal conditioner uses analog bandpass filter to isolate only the power associated with each device's oscillation (in the tens of kHz, but varies per device)
- Frequency counter then outputs frequency of oscillation (the "peak"), which can later be converted into an acceleration



Signal conditioner board
(filters for one accelerometer axis highlighted)

Conventional sensor board

- Houses MEMS inertial measurement unit, a basis for reference with our optomechanical accelerometers
- Also provides a way to evaluate the strapdown inertial navigation performance of our accelerometers

Conventional sensor board
(MEMS IMU in bottom left)

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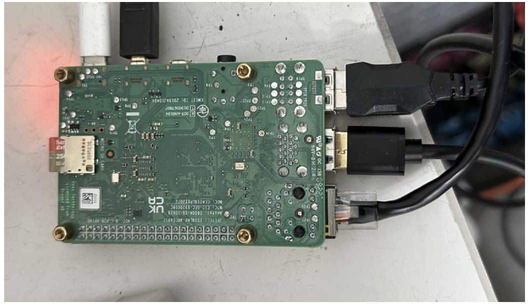
Readout systems and reference sensors

Raspberry Pi

- Streams in data in 1024-byte packets over USB from signal conditioner and conventional sensor boards
- Closely integrated with balloon flight: logs GPS readings and transmits mission data to the ground using balloon's Ethernet interface



Raspberry Pi with microSD card and USB connections

Key design paradigm: robust logging and backups

- In addition to transmitting data, all readout systems save data and timing information to microSD cards
- Additionally, to ensure that problems don't arise in writing to a single large file, these systems frequently rotate between smaller files

```
43386.232179 > 1503061265.932082 43.700367 -96.707753 430.825000
43387.223255 > 1503061266.921962 43.700367 -96.707752 430.893000
43388.212417 > 1503061267.911860 43.700367 -96.707751 430.930000
43389.203704 > 1503061268.901759 43.700368 -96.707751 430.957000
43390.191405 > 1503061269.881700 43.700368 -96.707750 431.007000
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43399.142387 > 1503061278.830680 43.700368 -96.707751 430.966000
43400.220595 > 1503061279.920563 43.700368 -96.707751 431.050000
43401.211281 > 1503061280.910443 43.700368 -96.707751 431.187000
43402.190701 > 1503061281.890389 43.700367 -96.707752 431.349000
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```

Sample of timing and telemetry data stored on the Raspberry Pi

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Next steps

- **Launching and evaluating the suborbital balloon flight** (scheduled for Q3 2025)
  - Includes comparing performance of our accelerometers vs. MEMS accelerometers
- **Adapting the payload to a smaller form factor, such as one that can fit in a CubeSat**
  - Main task: optimizing the electronics that support and read data from the accelerometer, including power supplies, lasers, and subsystems
- **Eventual deployment in CubeSats, small satellites, and cislunar satellites**
  - Position, navigation, and timing systems are often auxiliary to a spacecraft's mission, and mass/volume is a critical consideration for spaceflight
    - A CubeSat would be an especially attractive deployment environment to show that an optomechanical-accelerometer-based IMU can be supported without taking up too much volume or mass

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Acknowledgments and sources

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Sources

[1] Huang, Y. et al. "A chip-scale oscillation-mode optomechanical inertial sensor near the thermodynamical limits" (2020).

[2] Flor Flores, J. G. et al. "Parametrically Driven Inertial Sensing in Chip-Scale Optomechanical Cavities at the Thermodynamical Limits with Extended Dynamic Range" (2023).

Image sources

[a] Reinhold, A. "Apollo program Inertial Measurement Unit on display at the Draper Labs 2019 'Hack the Moon' exhibit" (2019).

[b] Elkins, K. "Tracking Data Relay Satellite (TDRS) Orbital Fleet Communicating with User Spacecraft 2017" (2017).

[c] Keshavarzi, M. "Design and optimization of fully differential capacitive MEMS accelerometer based on surface micromachining" (2019).

[d] Aerostar. "Thunderhead Balloon Systems".

[e] Thorlabs. "Manual Fiber Polarization Controllers".

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