Chip-scale Precision Optomechanical Inertial Sensors for GPS-free Navigation

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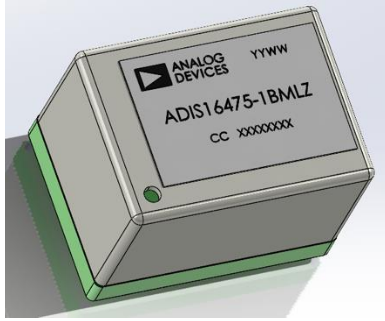
Limits of GPS & Potential of Precision Inertial Navigation

[1] Satellite in orbit

[2] Military Aircraft

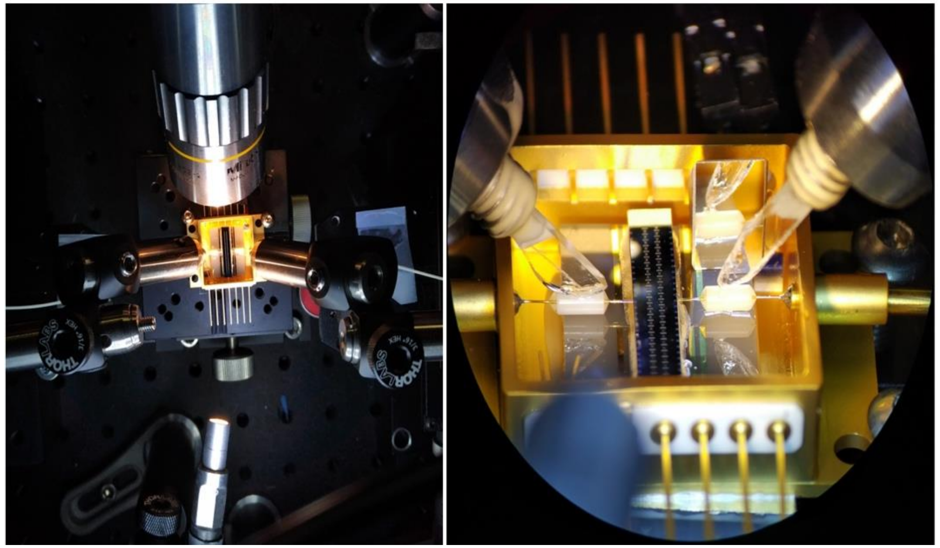
- Current ways to track location are not optimized for military use
  - GPS results in external signal transmission
    - INS – Inertial Navigation System
    - Uses both gyroscopes and accelerometers
- Propose an alternative method of measuring location:
  - Optomechanical Accelerometers (OMA)
    - High-sensitivity
    - No outside signals emitted

Introduction to Accelerometers & Optomechanical Accelerometers



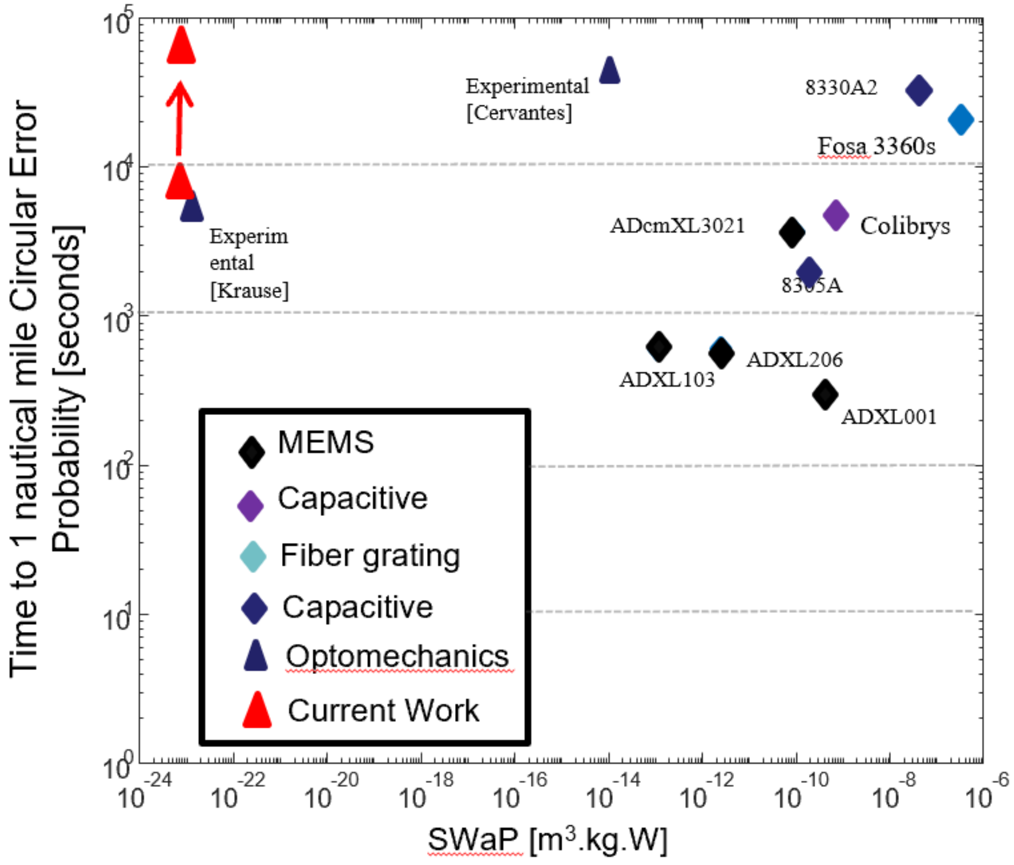
ADIS16475 - Precision Miniature MEMs IMU

Piezoelectric based accelerometer


Microscope image of nanofabricated optomechanical inertial sensor packaged at UCLA

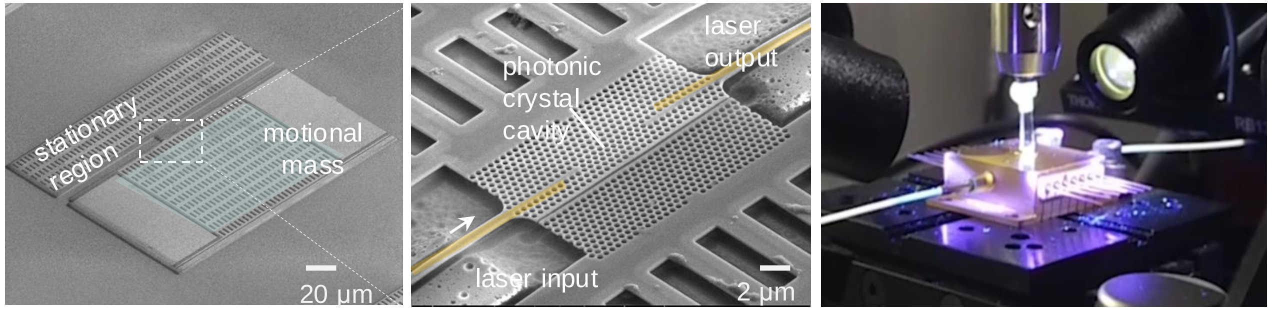
- Common accelerometers sensing method using Hooke's Law
  - Commercial accelerometers – MEMS, capacitive, and piezoelectric accelerometers
- Optomechanical Accelerometers (OMA)
  - Displacement - measured in mechanical domain
  - Resonant cavity frequency shift - measured in the optical domain
  - Measurement of acceleration found by detecting changes in resonant frequency of the oscillations

Precision Inertial Navigation: Performance Metrics



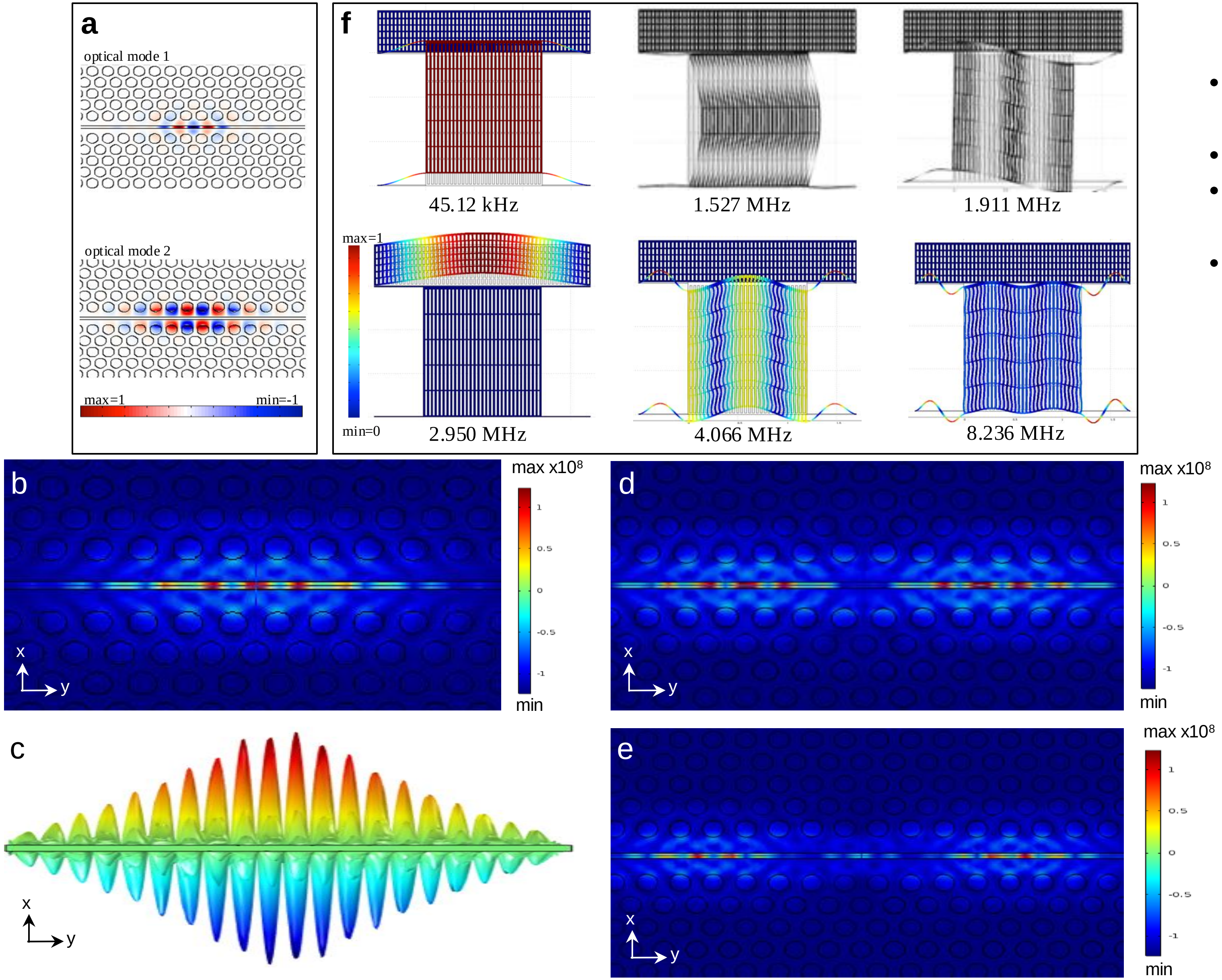
Inertial sensor metric	Performance
Volume/Weight	full package 2.8 cm^3 [chiplet is 0.034 cm^3] 31.5 grams [chiplet is 0.08 grams]
Power	58 mW [1-2 W cont. operation of TEC]
Dynamic range	≈30 dB
Velocity random walk	8.2 µg/Hz$^{1/2}$
Bias sensitivity	1.3 mg/Hz
Scale factor repeatability	optical resonance repeatability at ~0.7 ppm
Bias instability	52 µg

Above: Demonstrated metrics of the chip-scale inertial sensor
Below: Packaged inertial navigation unit with experience from JPL



- **Size Weight and Power (SWaP)** - SWaP vs. time to achieve a 1 nautical mile (nmi) error in seconds, for different accelerometers and technologies
- Commercial accelerometers are shown and labeled by model and technology they use
- Optomechanical accelerometers presented in red are our SSTP-STP device modules

Inertial Accelerometer: Optical & Mechanical Design

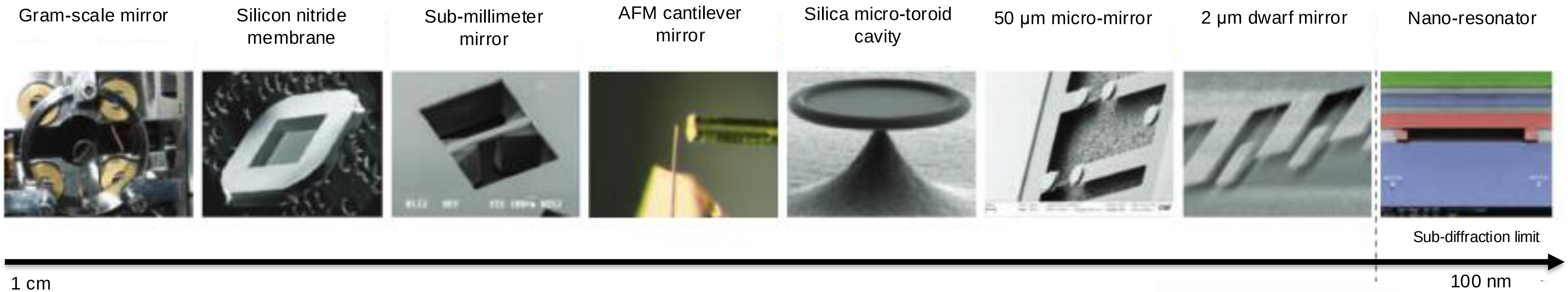


- **Mechanical modes** - designed for the oscillation-mode accelerometer
- Fundamental mode at 45.12 kHz
- Forbidden modes in grey (due to symmetry constraints)
- Finite-element modeling

- **Simulated optical modes** - Figures c-f represent the calculated electric field $(V/m)^2$ of the optical mode for the fully integrated photonic crystal
- **c.** Fundamental mode
- **d.** x-z view of the zoomed in z-component electric field (V/m)
- **e.** Second-order mode
- **f.** Third-order mode

Inertial Navigation: Fundamental Operating Architecture

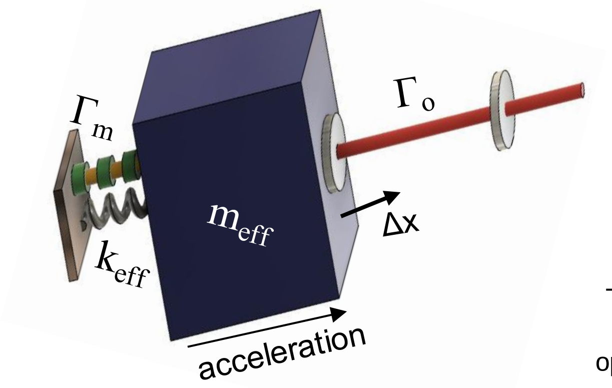
1. Light forces at the Nanoscale



2. Coupled mode and first-order perturbation theory

$$\frac{da}{dt} = i\Delta(x)a - \left(\frac{1}{2\tau_0} + \frac{1}{2\tau_{ex}}\right)a + i\sqrt{\frac{1}{2\tau_{ex}}}s \qquad \Delta(x) = \Delta + g_{OM}x = (\omega - \omega_o) + g_{OM}x$$

$$\frac{d^2x}{dt^2} + \frac{\Omega_m}{2Q_m}\frac{dx}{dt} + \Omega_m^2 x = \frac{F_o}{m_{eff}} + \frac{F_{th}}{m_{eff}} = -\frac{|a|^2 g_{OM}}{m_{eff}\,\omega_0} + \frac{F_{th}}{m_{eff}}$$



To learn more about cavity optomechanics:

Inertial Navigation: Fundamental Operating Architecture

3. Optomechanical coupling

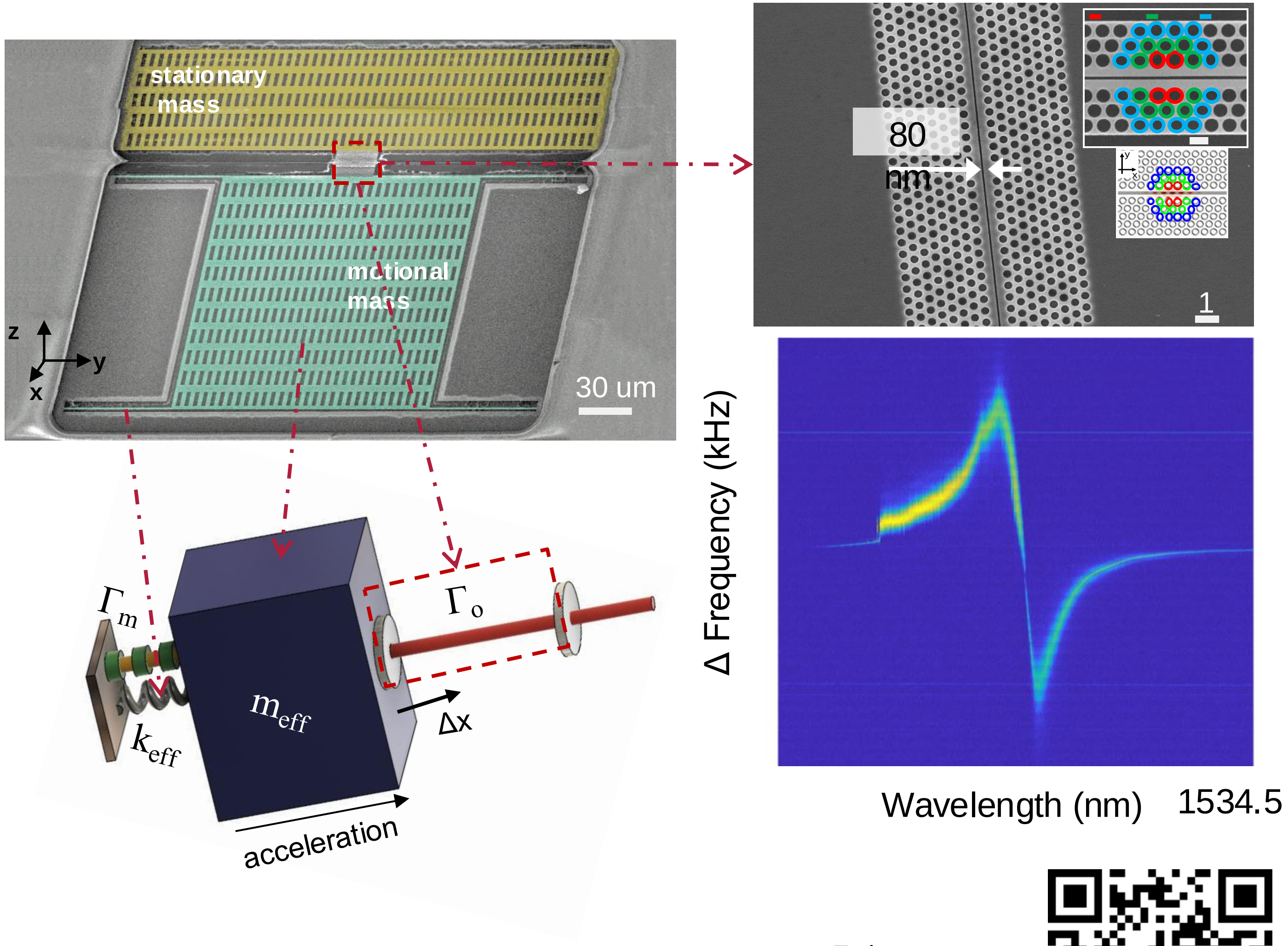
$$g_{om} = \frac{d\omega}{dx} \qquad L_{om}^{-1} = \frac{1}{\omega}\frac{d\omega}{dx}$$

4. First-order perturbation theory

$$g_{om} = \frac{1}{2\omega}\frac{\int dA\left(\vec{q}\cdot\vec{n}\right)\left[\Delta\varepsilon|E|^2 - \Delta\left(\varepsilon^{-1}\right)|D|^2\right]}{\int dV \varepsilon |E(r)|^2}$$

5. Optical spring effect

$$\Omega'_m = \sqrt{\Omega_m^2 + \left(\frac{2|a|^2 g_{om}^2}{\left((\omega_l - \omega_c + g_{om}x_s)^2 + \left(\frac{\Gamma}{2}\right)^2\right)\omega_c m_{eff}}\right)(\omega_l - \omega_c + g_{om}x_s)}$$



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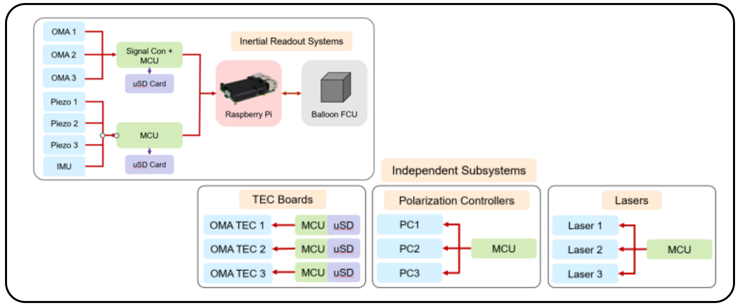
To learn more about cavity optomechanics:

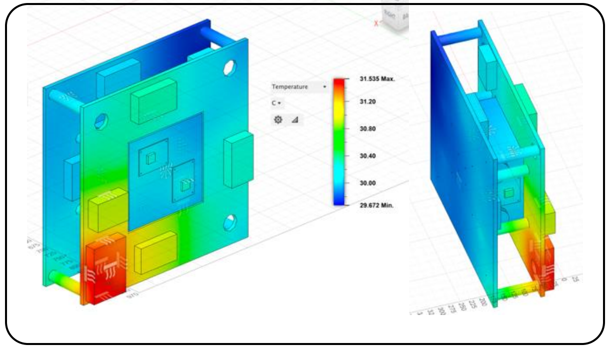
SSTP: Suborbital Flight Project

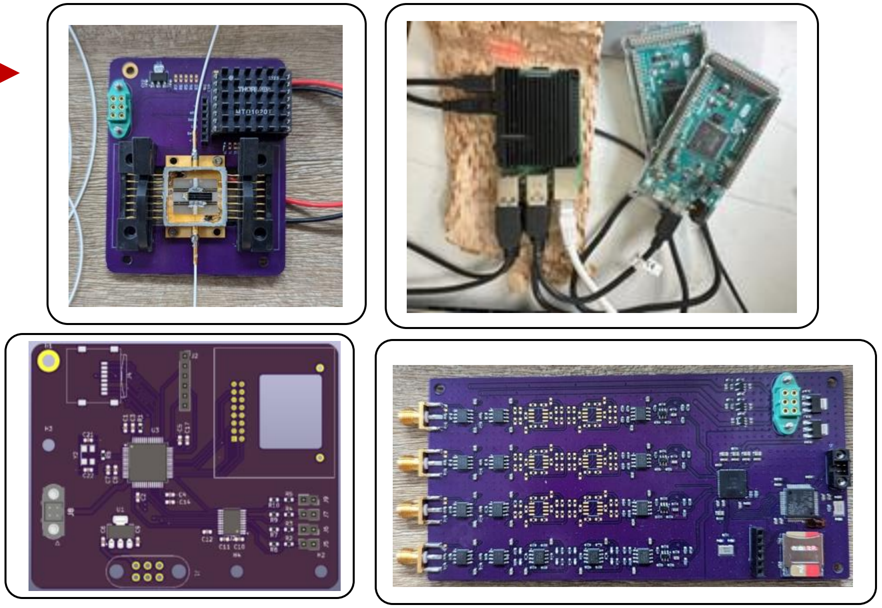
[3] Suborbital Balloon Flight



Electronics System Layout

Thermal Simulations





Electronics System Components & Data Collection

Device Packaging