Passively Deployed Radiators for Transfer and Rejection of CubeSat Waste Heat

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Presented By
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Cleveland, OH

Biography

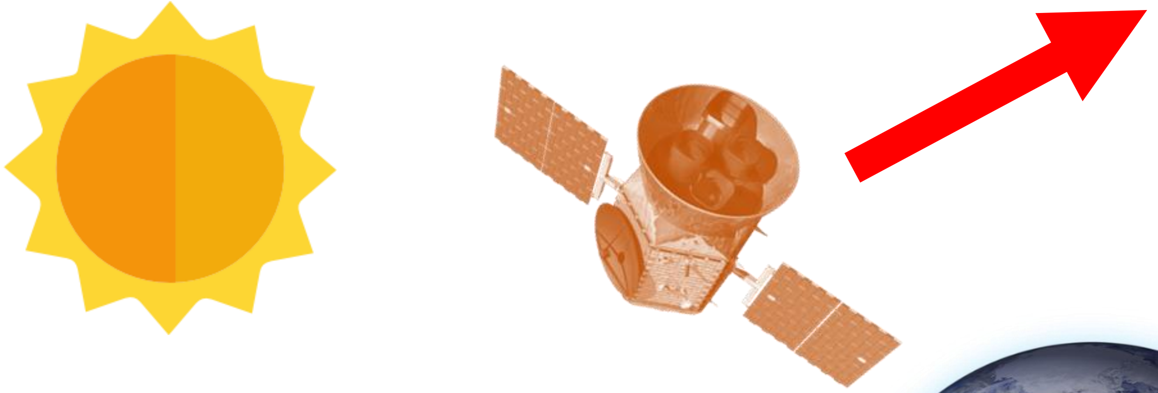
- PhD from Brigham Young University in 2019
- Assistant Professor at the University of Dayton Department of Mechanical Engineering since 2019
- Published areas of interest include: **Spacecraft thermal control**, High-speed vehicle power production (coordinating with JHAPL), PV panel orientation optimization and Greenhouse production optimization.

Introduction

Introduction – Motivation

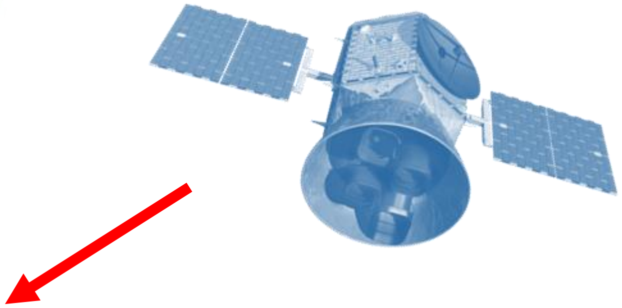
Spacecraft experience temperature variation while orbiting the Earth

CubeSats, with low thermal mass and no thermal control, experience the largest temperature swings



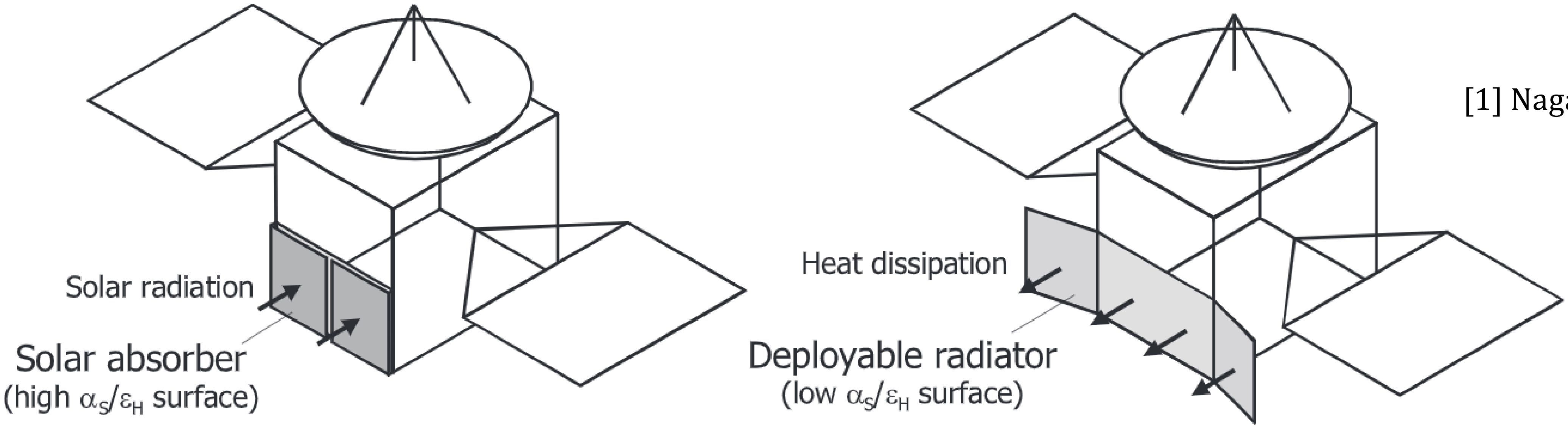
High Heating Loads:
Encourage Radiator Heat Rejection
- Increase emissivity
- Increase surface area

Low Heating Loads:
Discourage Radiator Heat Rejection
- Decrease emissivity
- Decrease surface area



Introduction – Innovation

- Increase radiative surface area and effective emissivity
- 200% more radiative heat loss than body mounted radiators
- NASA Technology Roadmap target turndown ratio: 6
  - Turndown ratio: maximum / minimum radiative heat loss



[1] Nagano, et al

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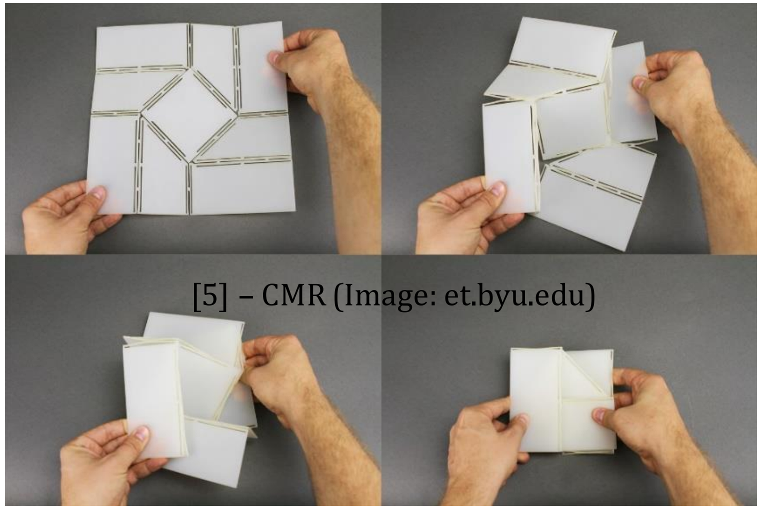
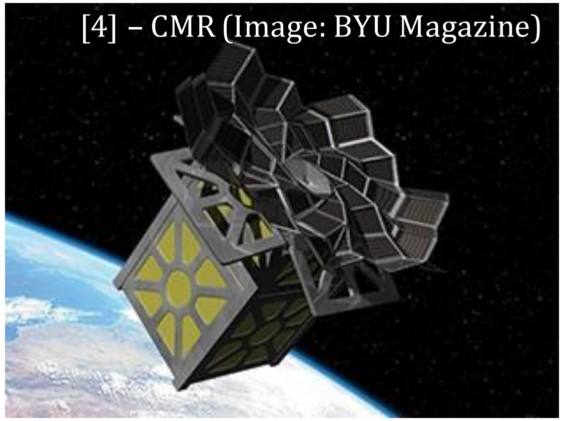
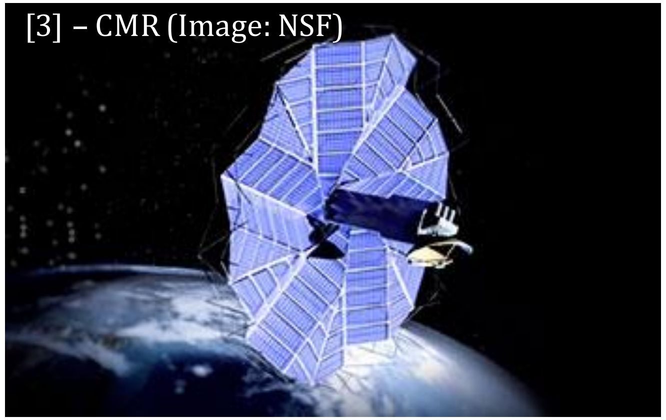
Introduction – Innovation

- Origami controls both emitting area and surface properties
- Large variations in emitting area
- Passive actuation possible







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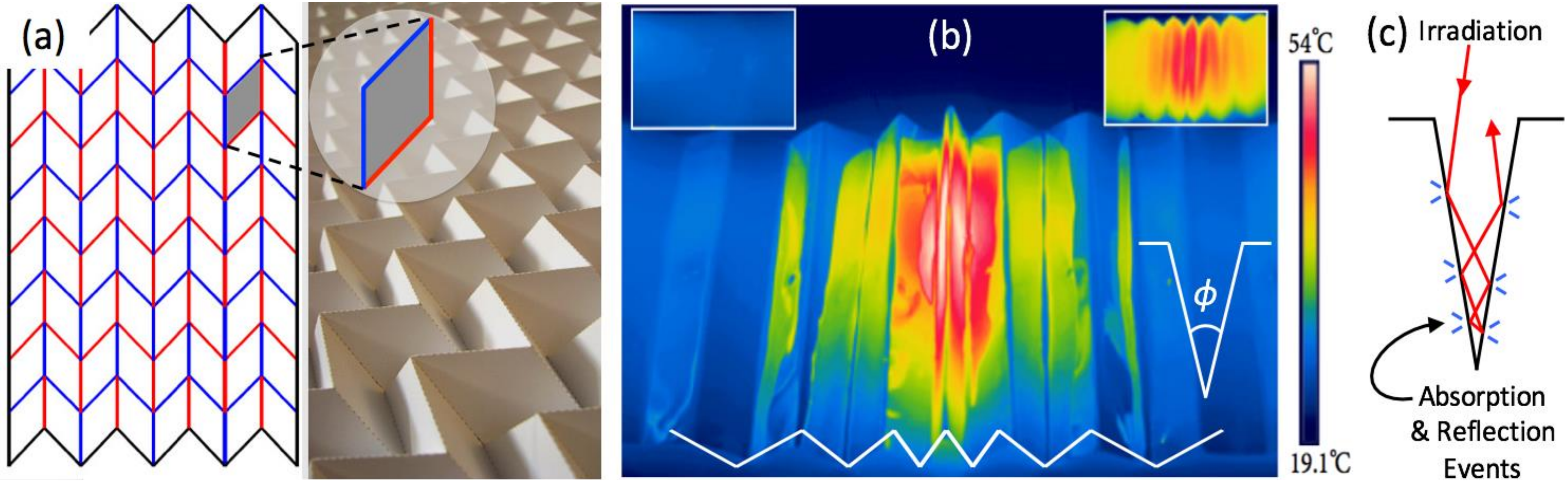
Introduction – Objectives

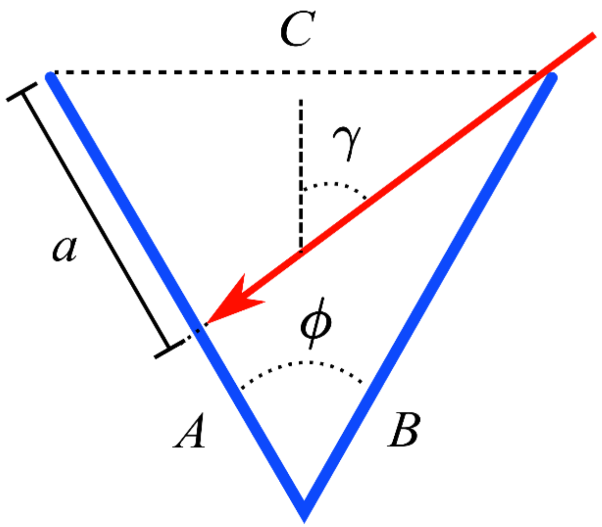
- **Concept -** Explore the fundamental behavior of heat transfer in geometrically-dynamic radiator systems (TRL 1 – 2)
- **Develop -** Develop technologies based on geometric manipulation for control of radiative heat transfer (TRL 3 – 5)
- **Demonstrate -** Implement and demonstrate dynamic technologies implemented into spacecraft systems (TRL >= 6)

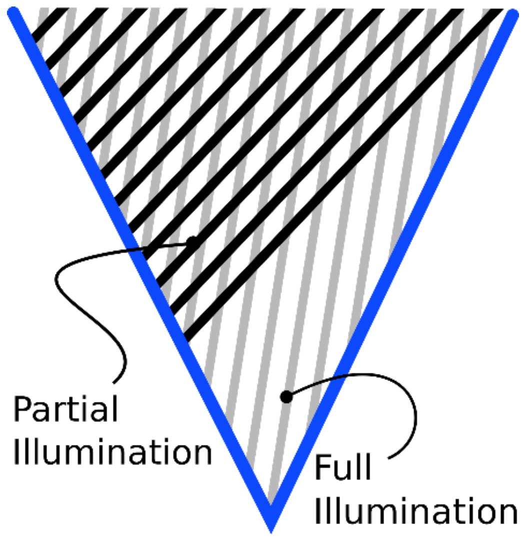
Concept

Concept – Cavity Effect



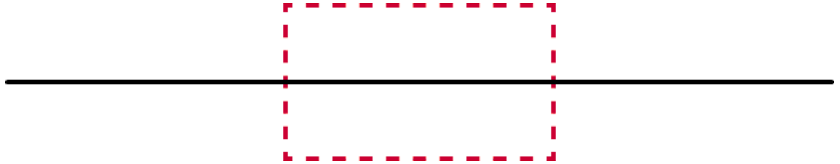
Concept – Cavity Effect

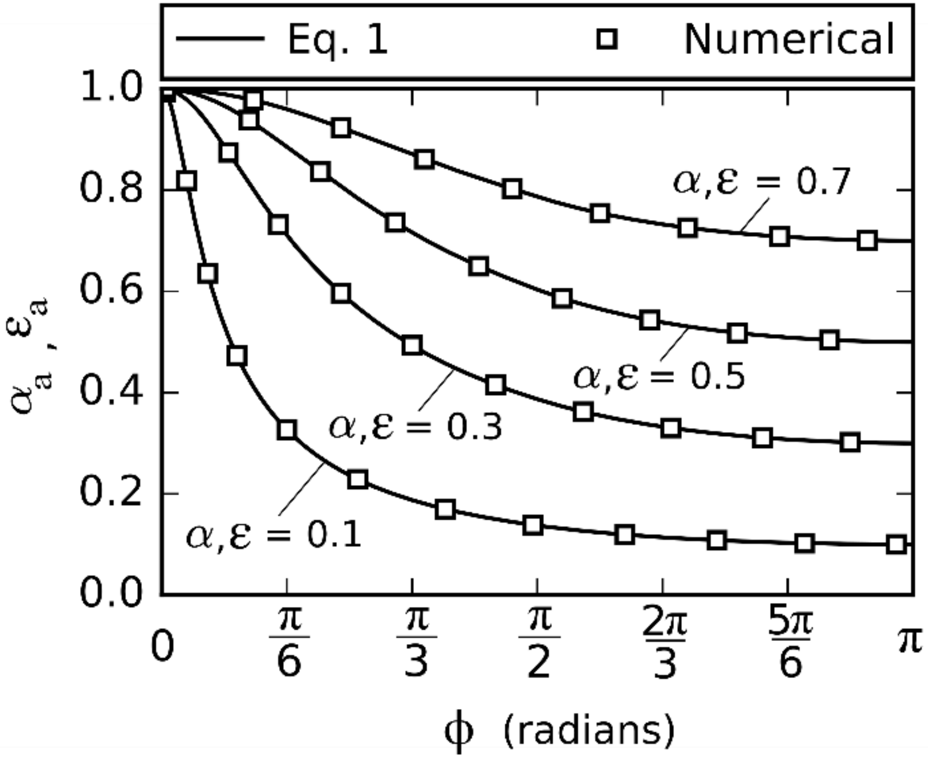




Conditions

- Diffuse/specular surfaces
- Geometry
- Full/partial illumination
- Normal/off-normal irradiation





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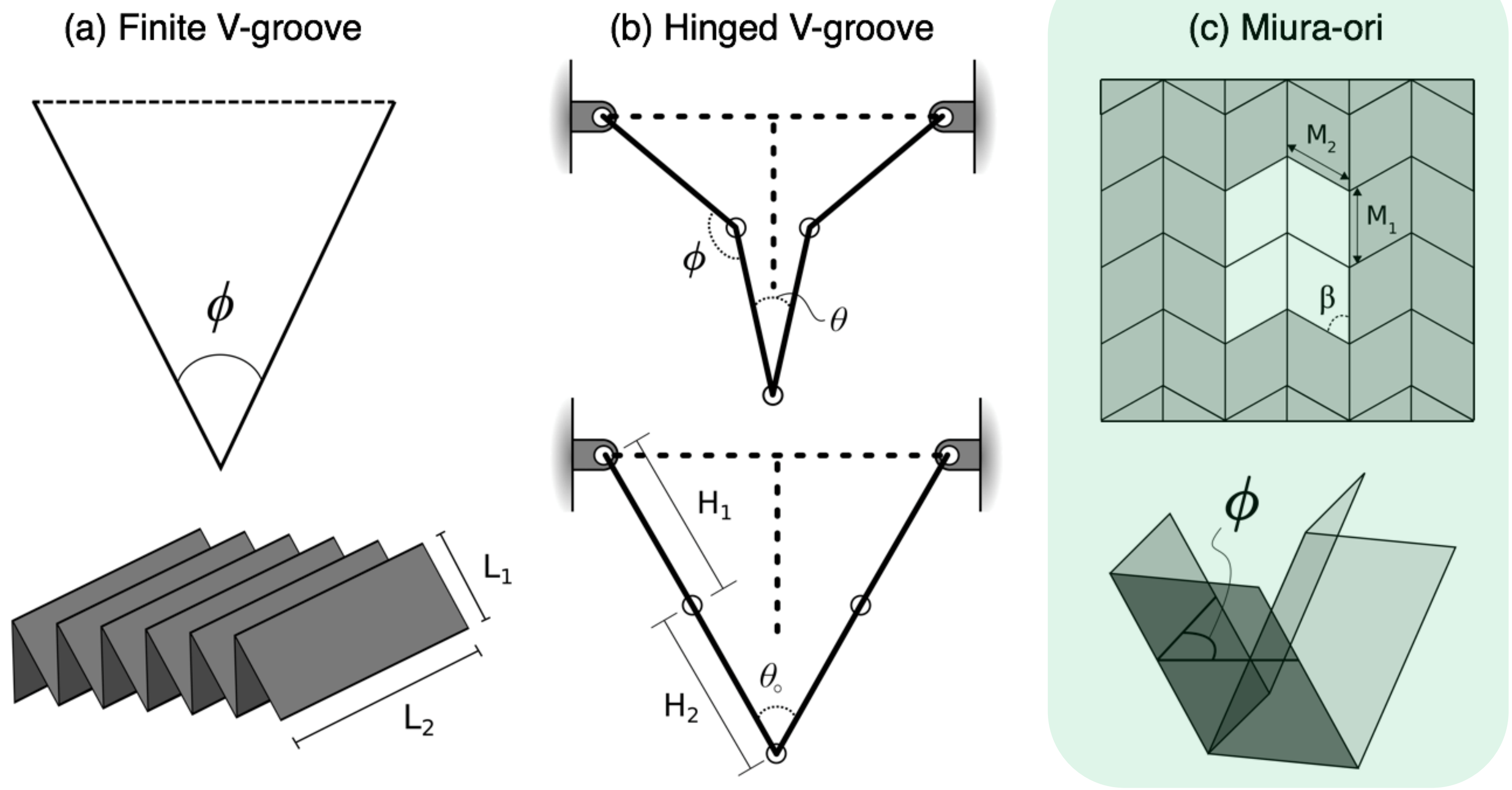
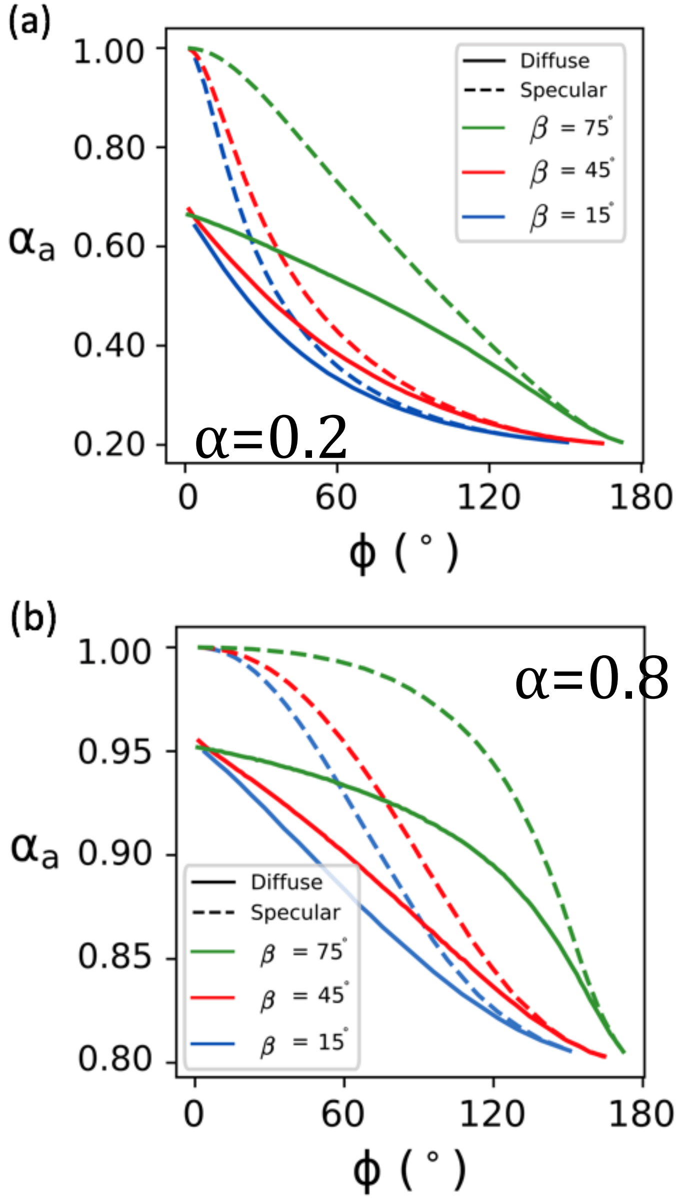
Concept – Cavity Effect





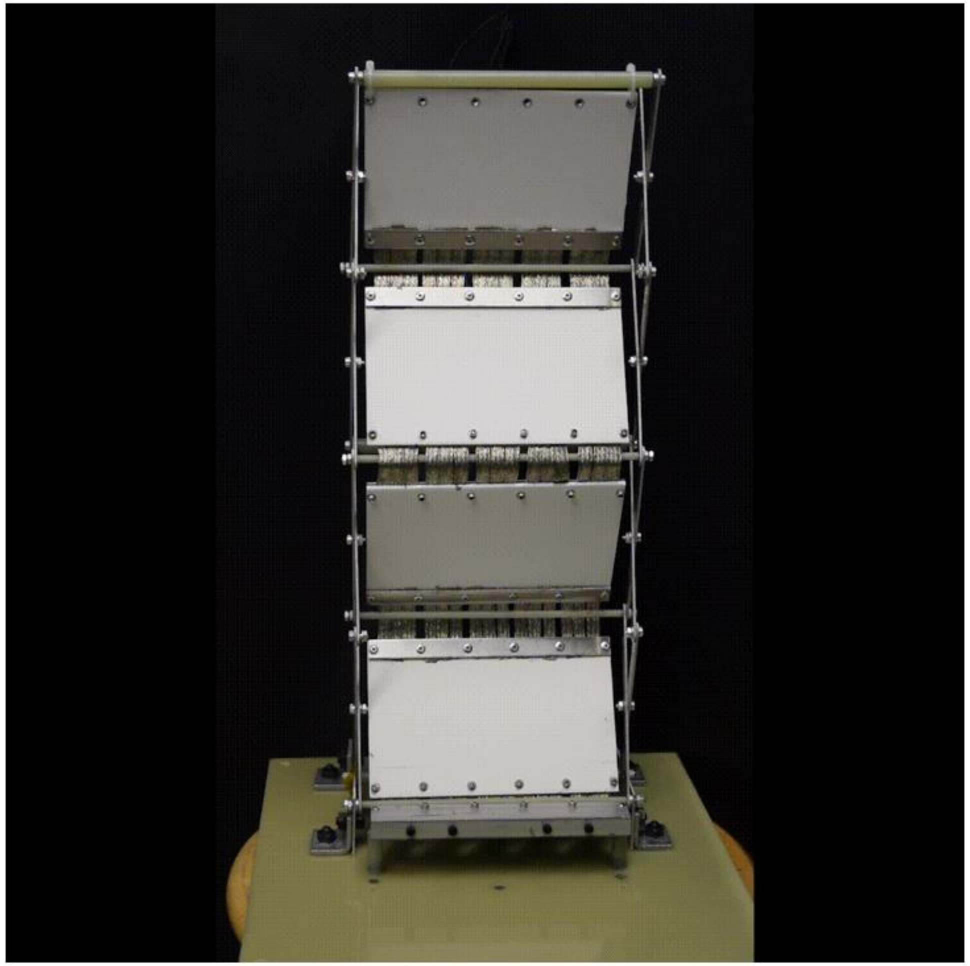
Concept - Takeaways

- Radiative surface properties can be controlled through actuation
- Surface property variations behave opposite the behavior of the surface area, reducing overall heat transfer effectiveness
- Various tessellations generally feature similar behavior
- "Conceal and Reveal" systems provide a means of increasing the emissivity and the area at the same time

Develop

Initial Development – Accordion Radiator

- An active dynamic radiator uses motorized methods to actuate and retract radiator panels.
- Theoretical Turn Down Ratio: 8
- Issues identified from beginning
  - Panels in series results in significant conduction losses
  - Active actuation is not ideal

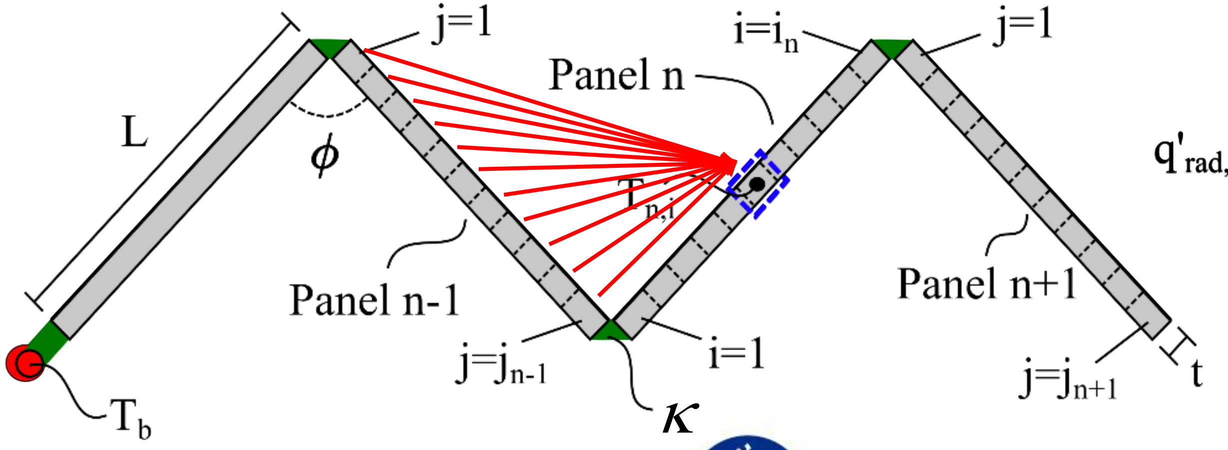


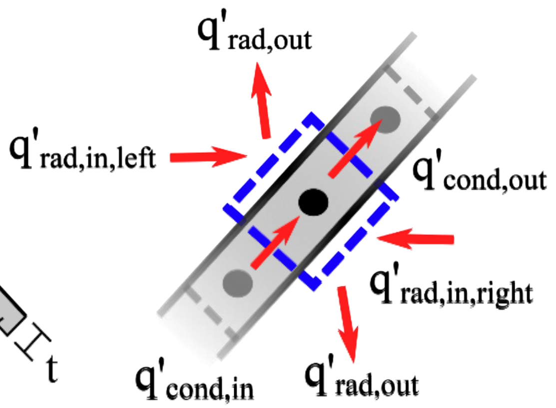
Initial Development – Accordion Radiator Model

$$q'_{cond,in} - q'_{cond,out} + q'_{rad,in,left} + q'_{rad,in,right} - q'_{rad,out} = 0$$

$$-kt\frac{T_{n,i}-T_{n,i-1}}{\Delta x} + kt\frac{T_{n,i+1}-T_{n,i}}{\Delta x} + \alpha\sum_{j=1}^{j=j_{n-1}} J_{n-1,j}F_{j-i}\Delta x + \alpha\sum_{j=1}^{j=j_{n+1}} J_{n+1,j}F_{j-i}\Delta x - 2\Delta\varepsilon x\sigma T_{n,i}^{4} = 0$$

$$J_{n,i} = \varepsilon\sigma T_{n,i}^{4} + (1-\varepsilon)\sum_{j=1}^{j=j_{n+1}} J_{n+1,j}F_{j-i}$$





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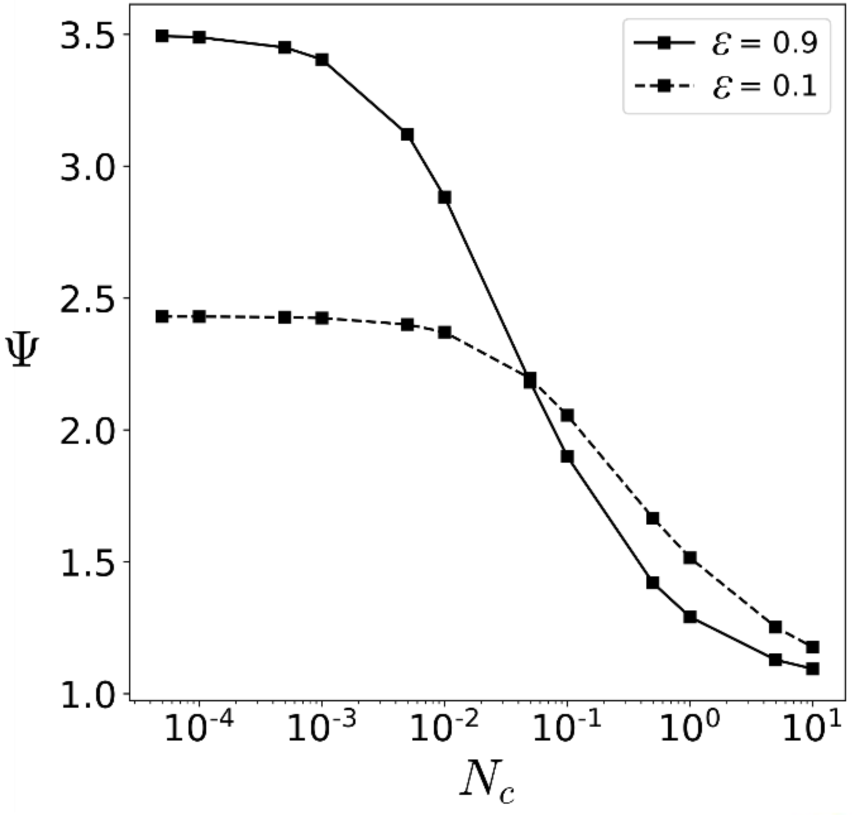
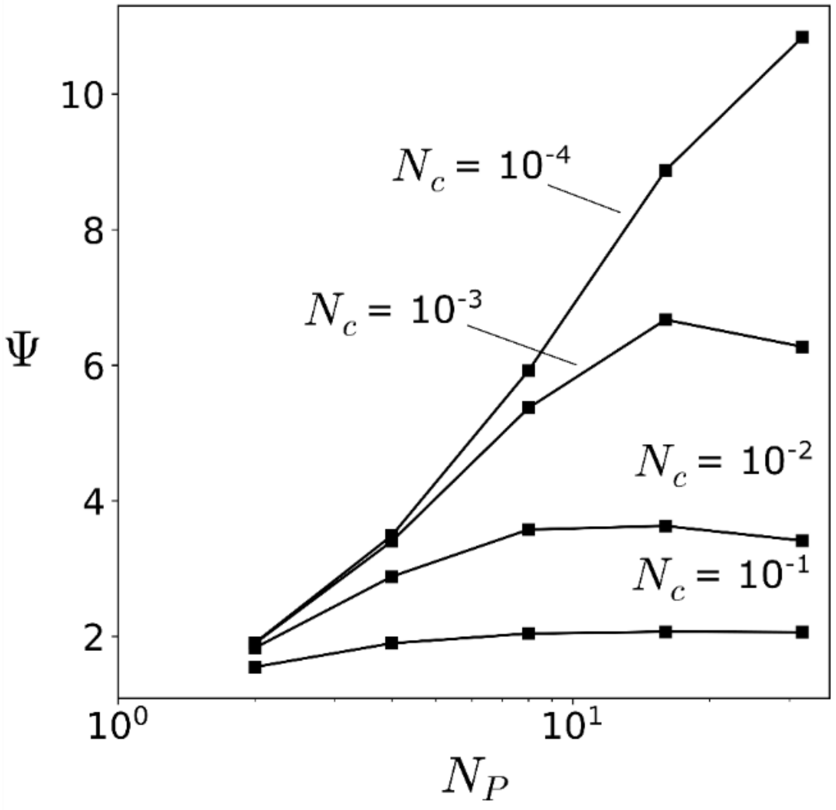
Initial Development – Model Results

$$\Psi = \frac{q_{max}}{q_{min}} \qquad N_c = \frac{R_{conduction}}{R_{radiation}}$$

↑ Ψ Improved Heat Transfer Control
↓ Ψ Poor Heat Transfer Control





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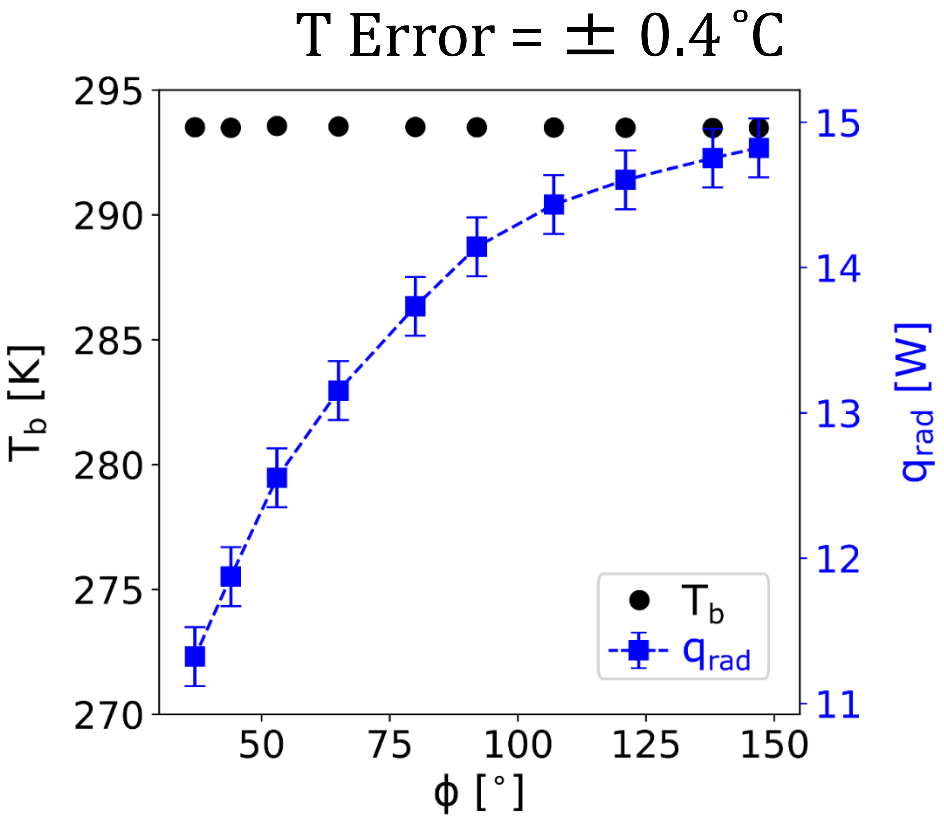
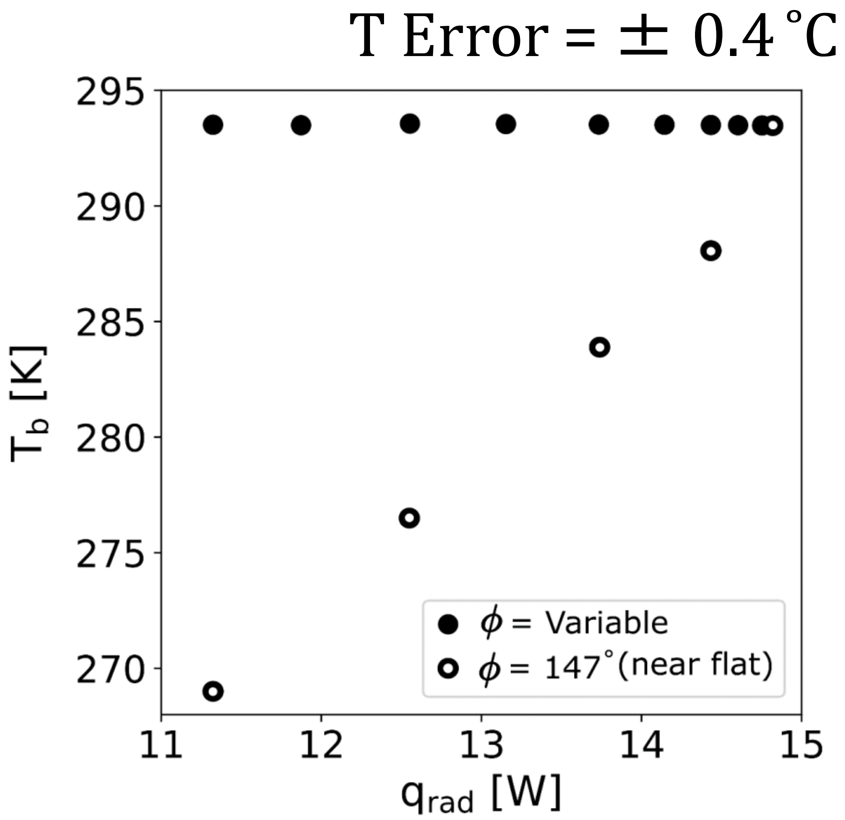
Initial Development – Model Results

	κ [W K^{-1}]	0.6			6			60			∞		
	Panels	2	4	8	2	4	8	2	4	8	2	4	8
k_p [W m^{-1} K^{-1}]	**237**	1.81	2.27	2.46	1.95	2.82	3.34	1.97	2.93	3.55	1.97	2.95	3.58
	401	1.82	2.32	2.55	1.96	3.02	3.77	1.98	3.19	4.14	1.99	3.21	4.19
	1950	1.82	2.39	2.67	1.97	3.38	4.82	1.99	3.70	6.01	1.99	3.74	6.22
	∞	1.82	2.41	2.71	1.97	3.52	5.37	1.99	3.92	7.46	2.00	3.98	7.92

Highest Turn-Down Ratio (Achievable): 6.01
Highest Turn-Down Ratio (Theoretical): 7.92

Initial Development – Model Results





$\Psi = 1.31 \qquad 35^\circ < \phi < 160^\circ$

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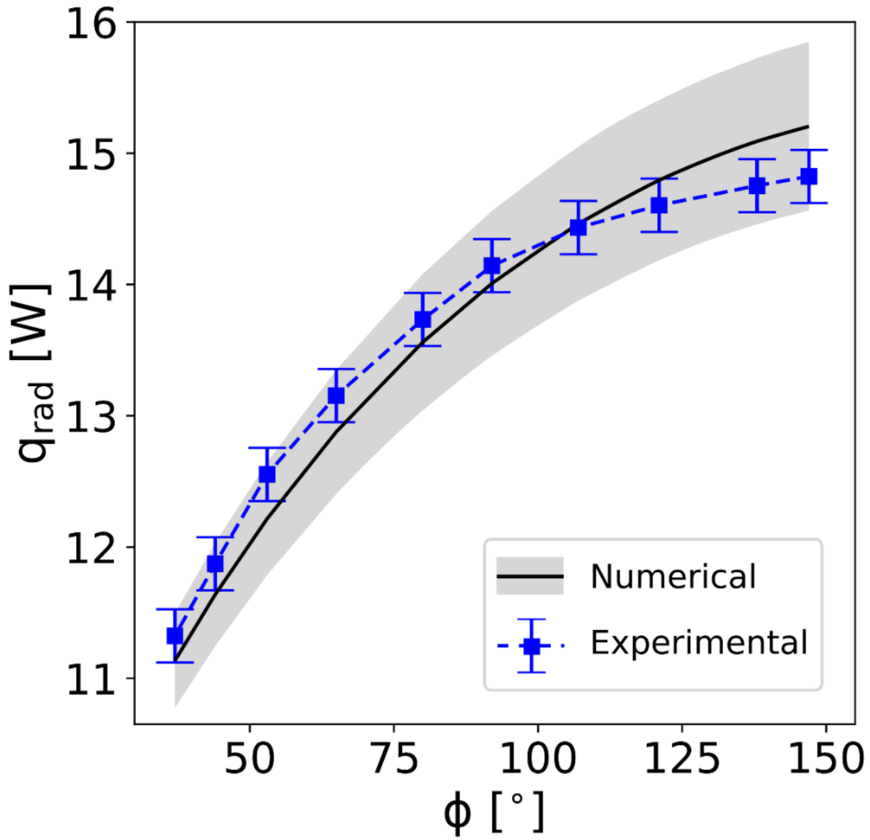
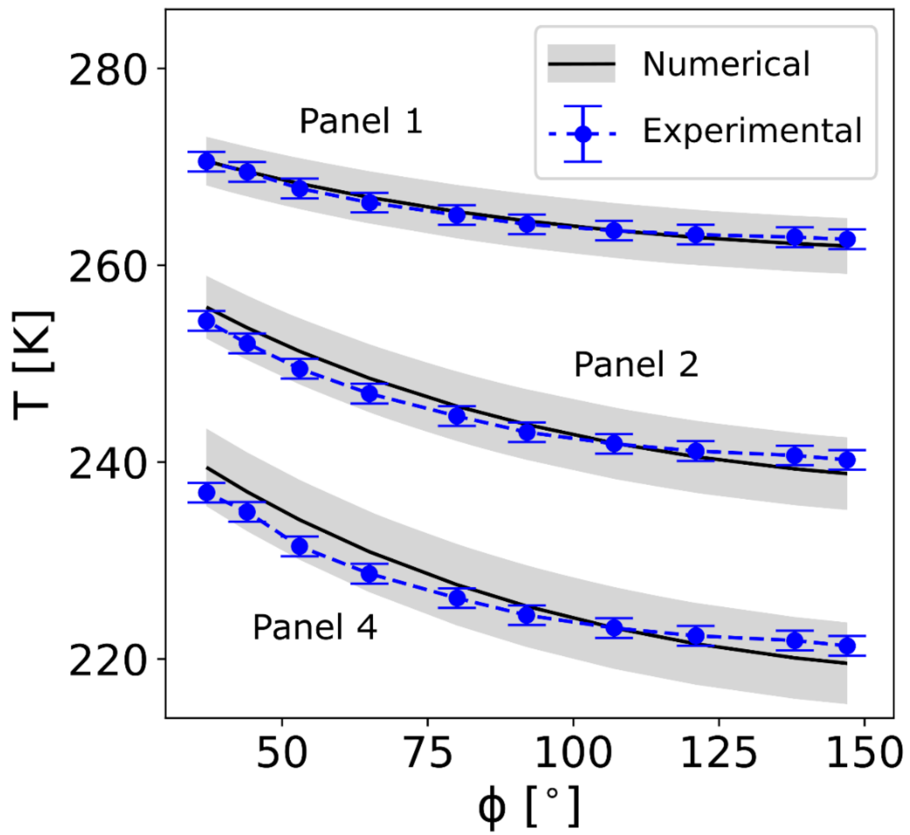
Initial Development – Model Results





Numerical Uncertainty = Uncertainty in hinge conductance, panel emissivity panel dimensions, and radiator angle

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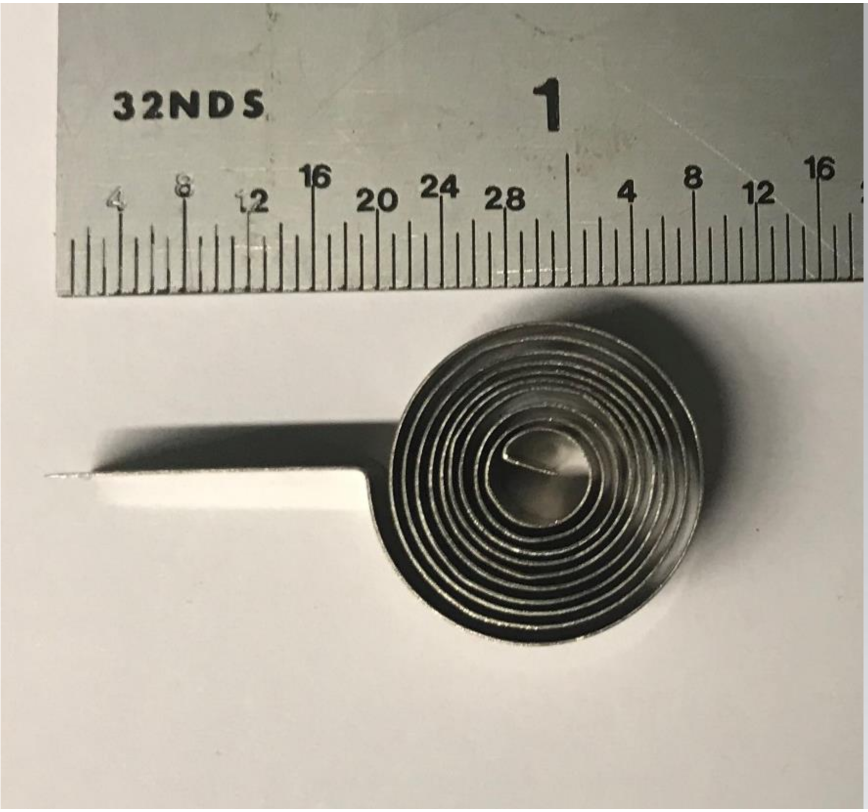
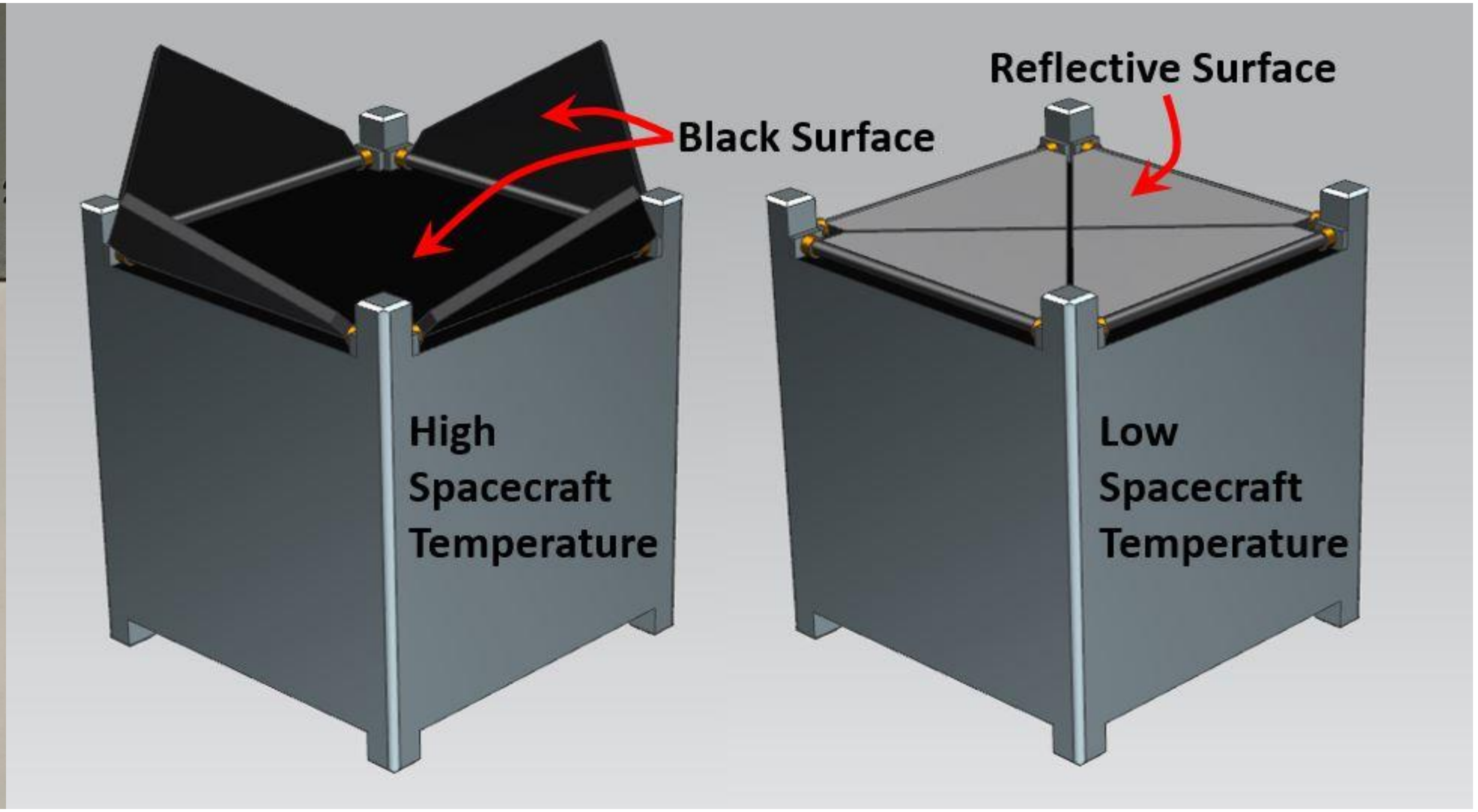
Initial Development - Takeaways

- Panels in series are not effective
- Passive actuation is preferred by the thermal control community
- Smaller form-factor spacecraft (CubeSats) require simplicity but need the most variation

CubeSat Development – Ideation





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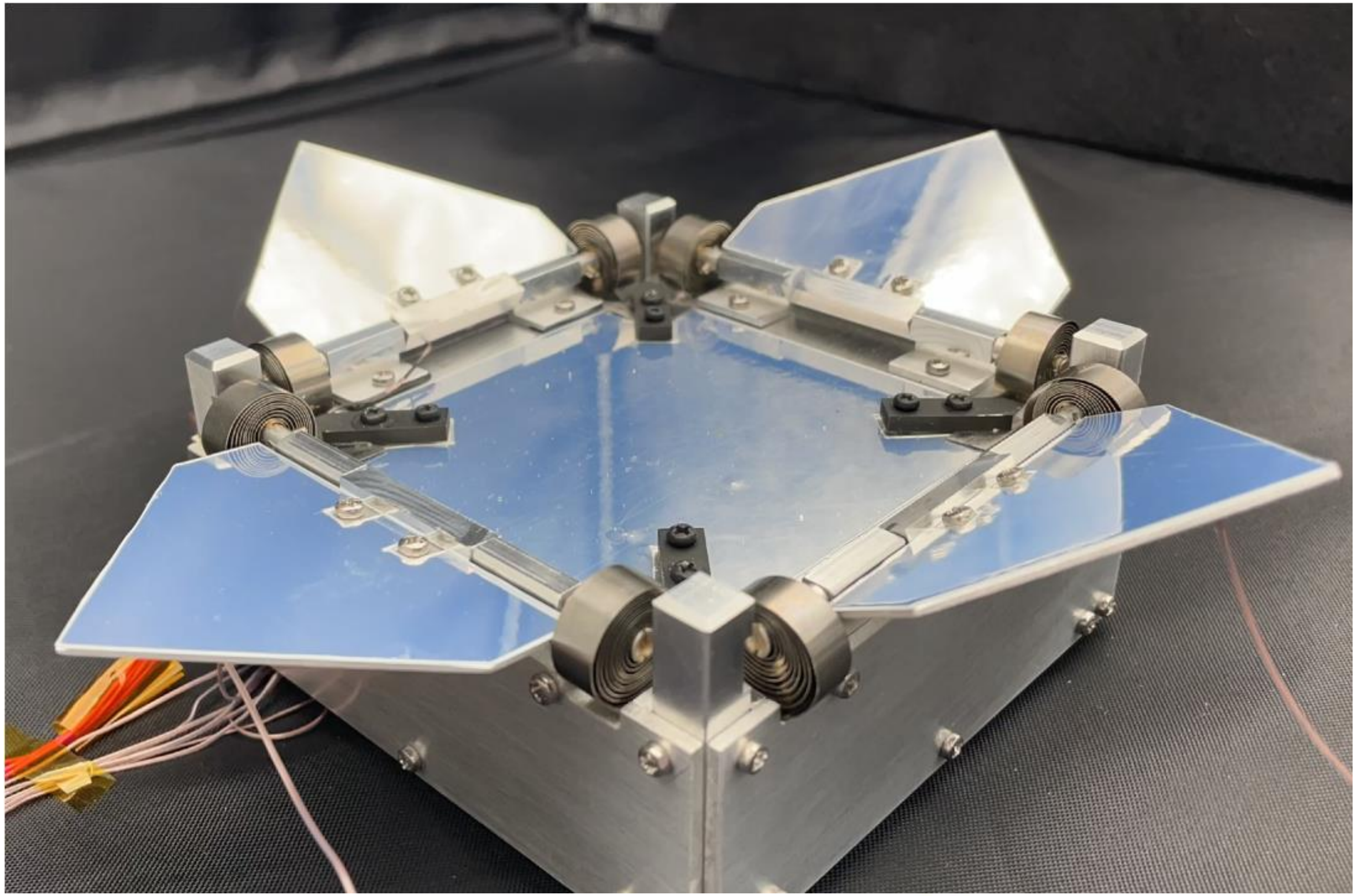
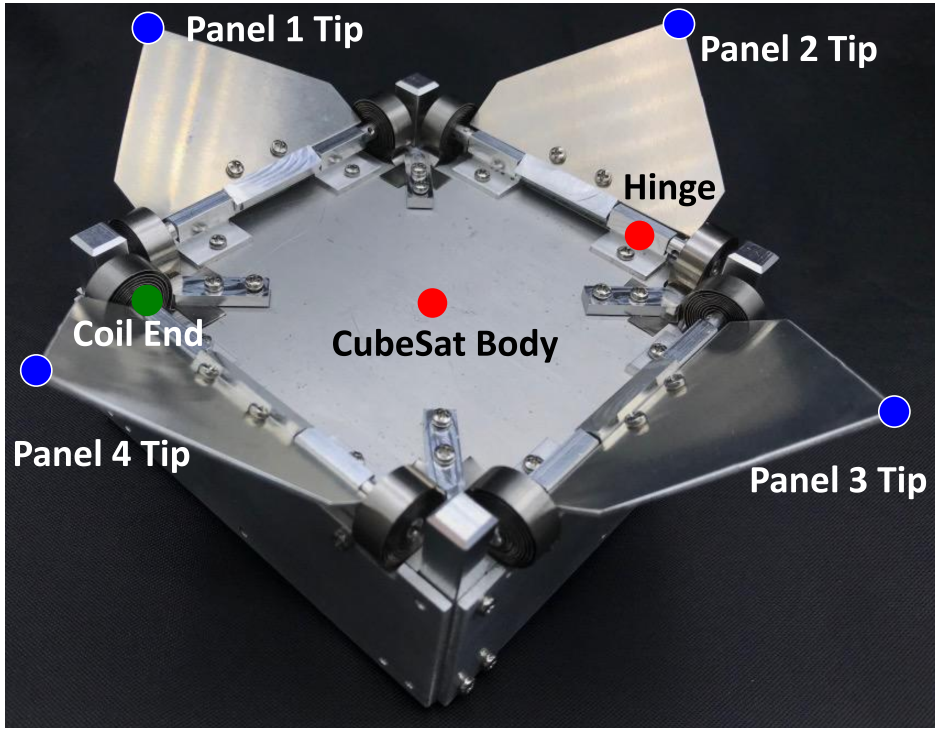
CubeSat Development - Prototype

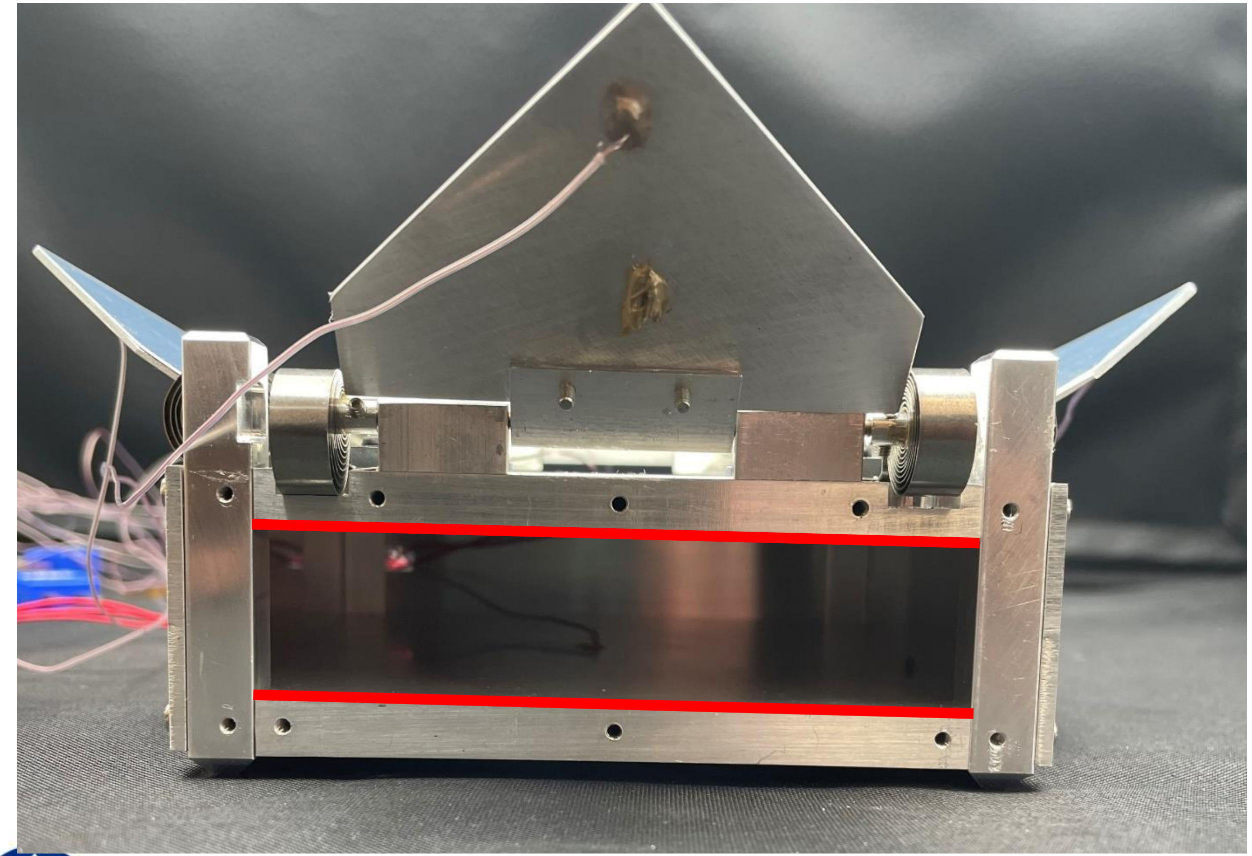


- Bimetallic coil actuation
  - Crest P675R
  - 4° of angular rotation per 1 °C (unloaded)
  - Temperature responsive
  - Intermediate positioning
  - Tunable actuation T
- CalPoly CubeSat design standard
- Sheldhal surface coating (149598)
- Contactless rotary magnetic encoders

CubeSat Development - Testing

- Truncated CubeSat body
- Chamfered base contact
- Kapton heaters (red)





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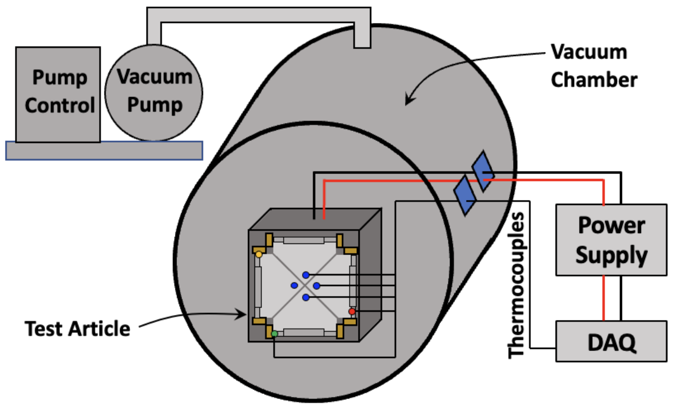
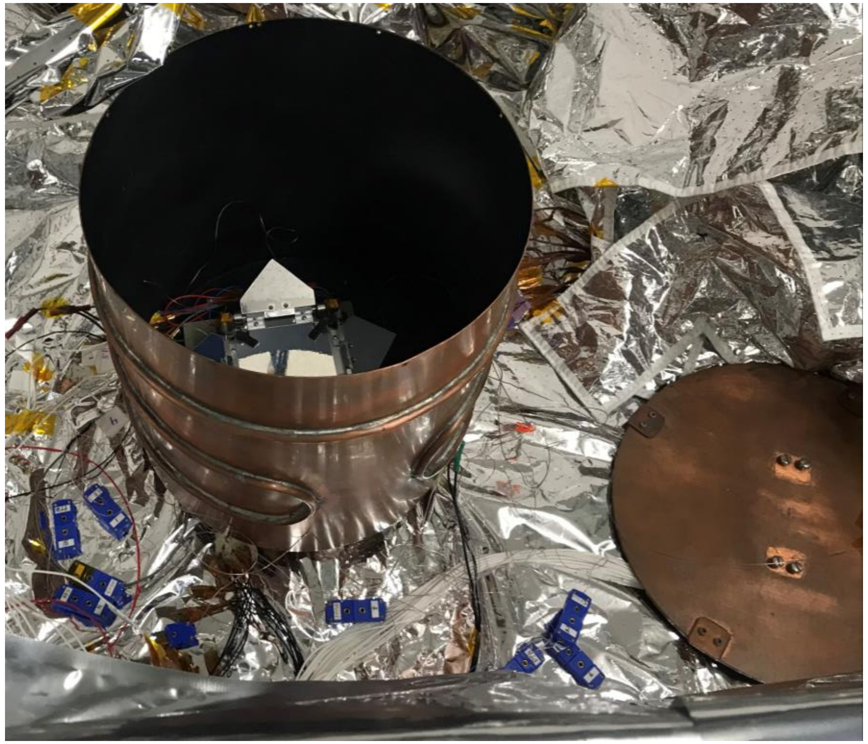
CubeSat Development - Testing

Vacuum chamber (JPL)

- Pressure: 10^{-6} Torr
- Temperature and power feedthroughs
- Test article on insulating G10
- Liquid N_2 shroud (83 K)





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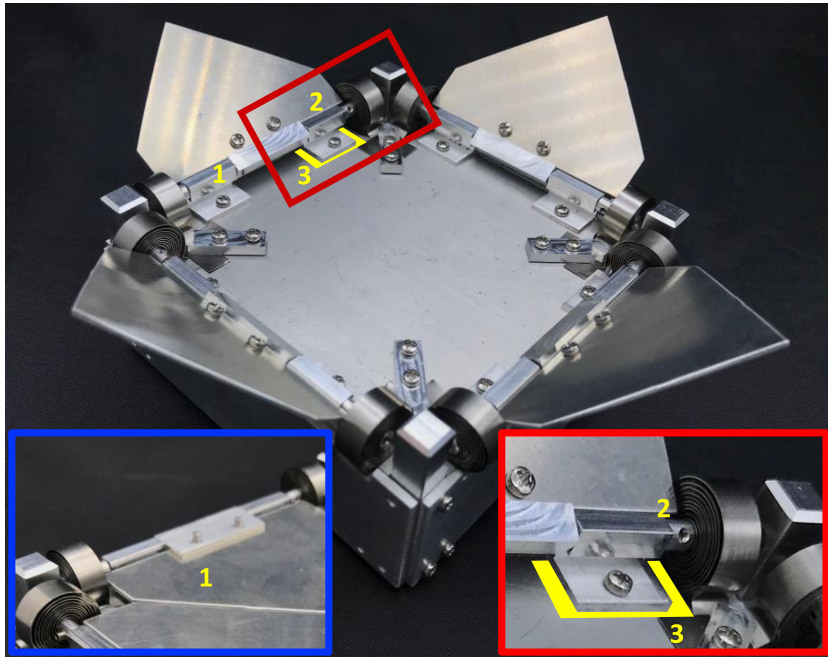
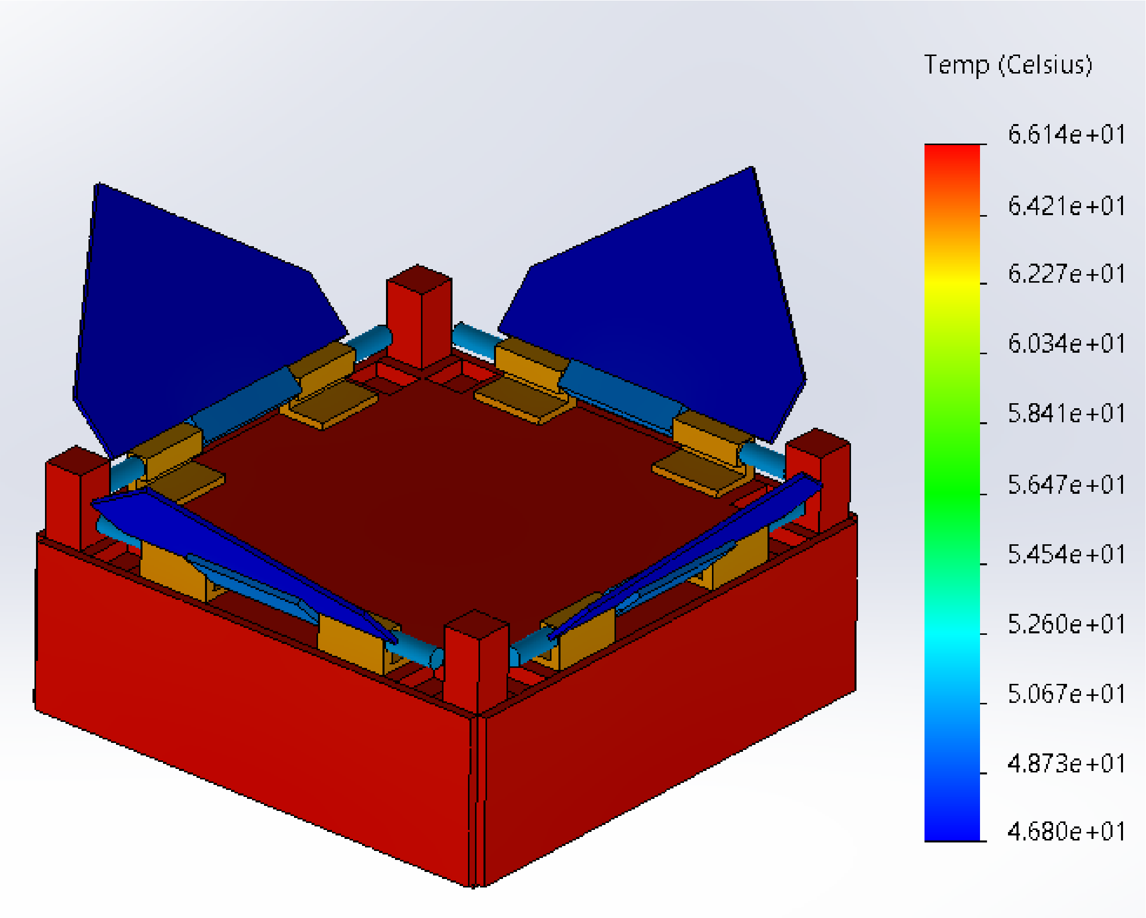
CubeSat Development - Model

- Fixed deployment angle (135°)
- Heating: 2.5 and 5 W (ambient T_{surr})
- Thermal resistance tuning
- Agreement < 1 °C





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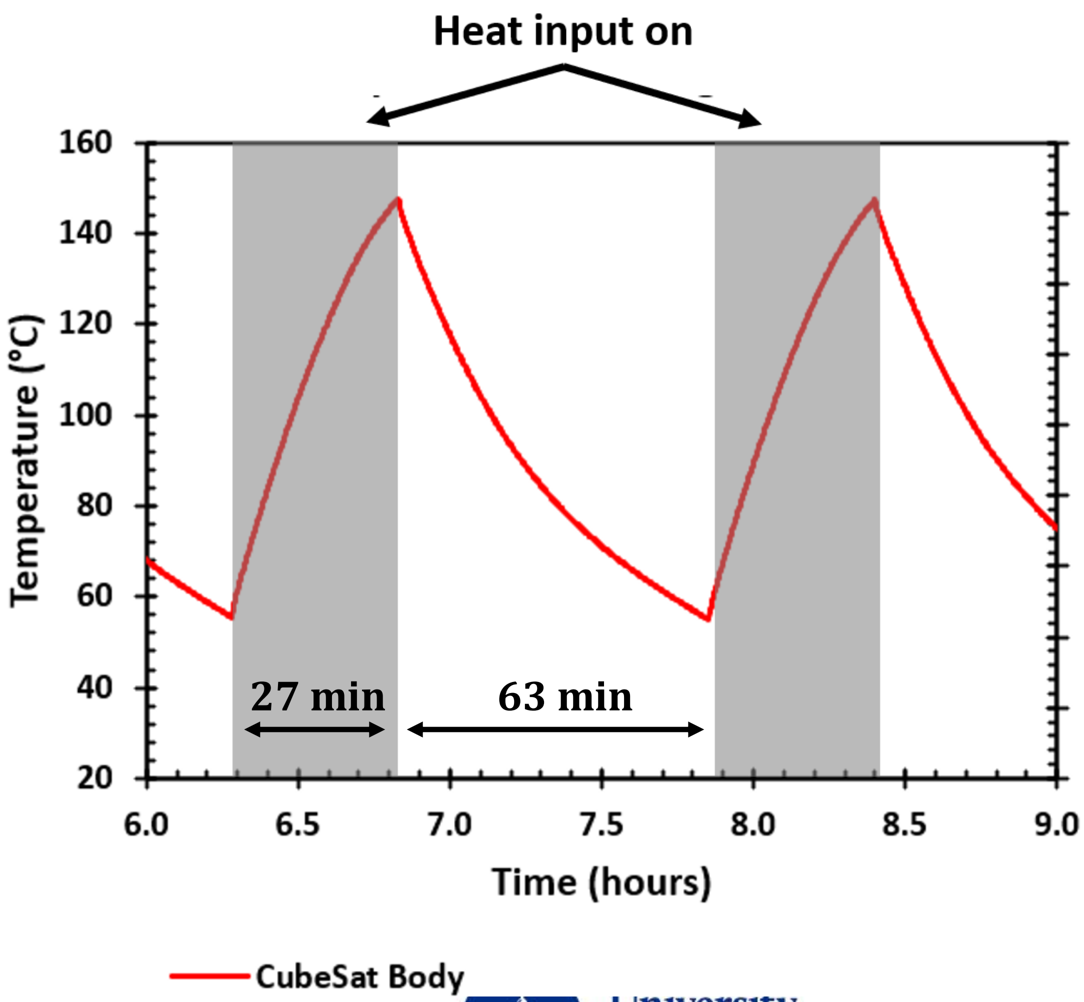
CubeSat Development - Results

- 90 min orbit
- 30% duty cycle
- 35 W



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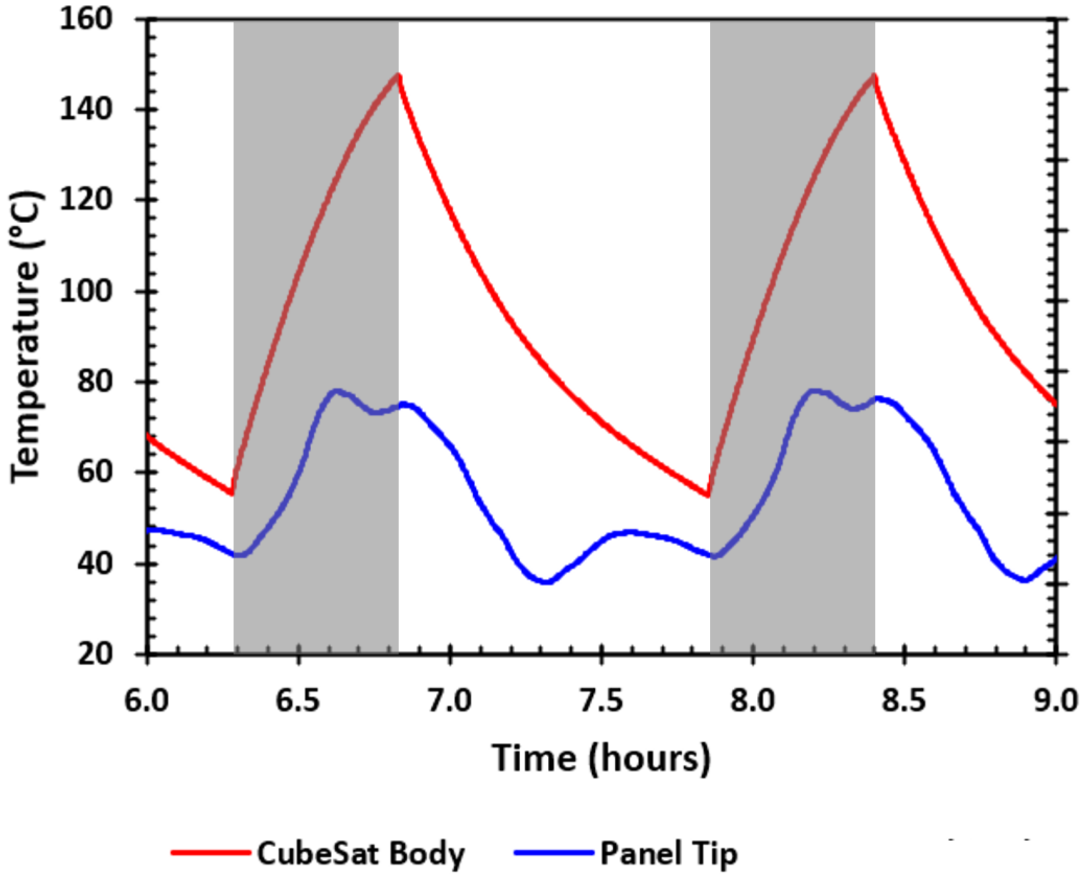
CubeSat Development - Results



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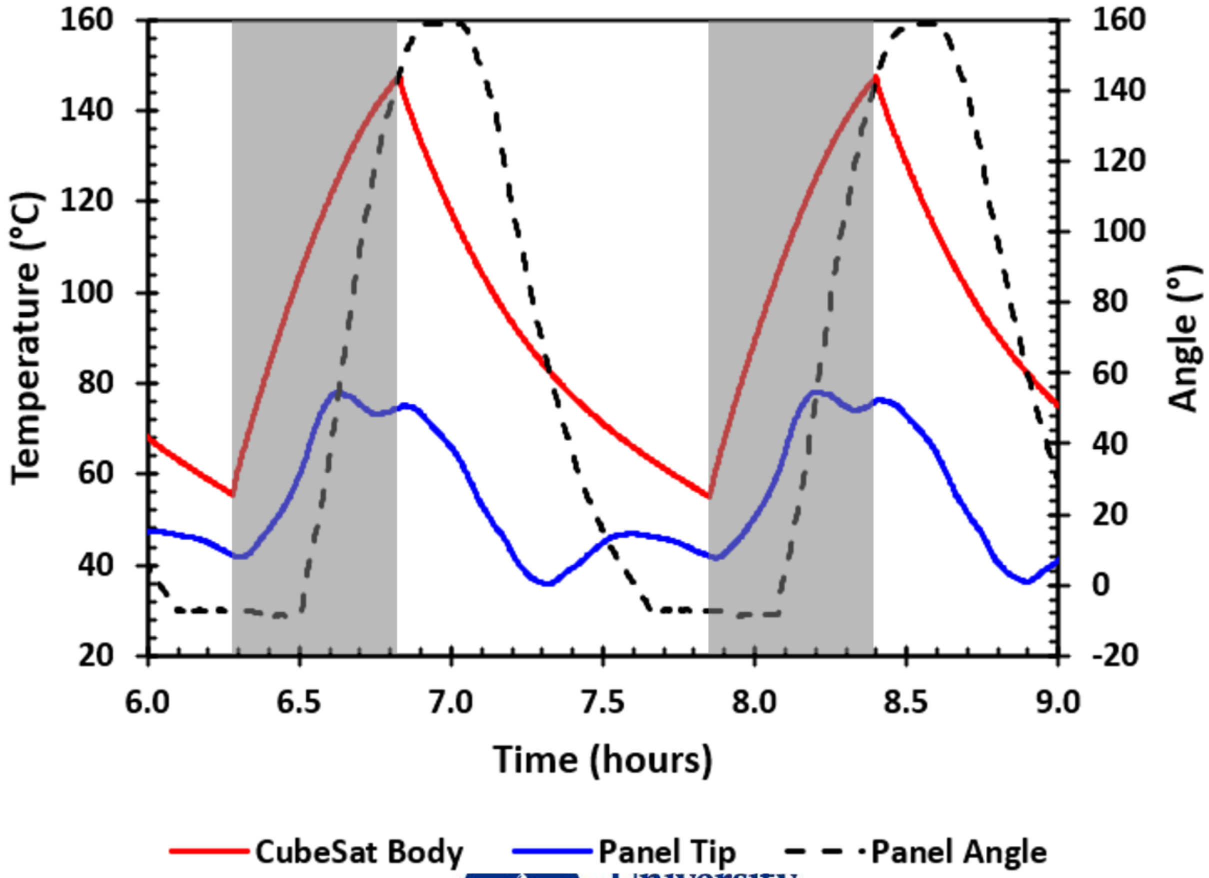
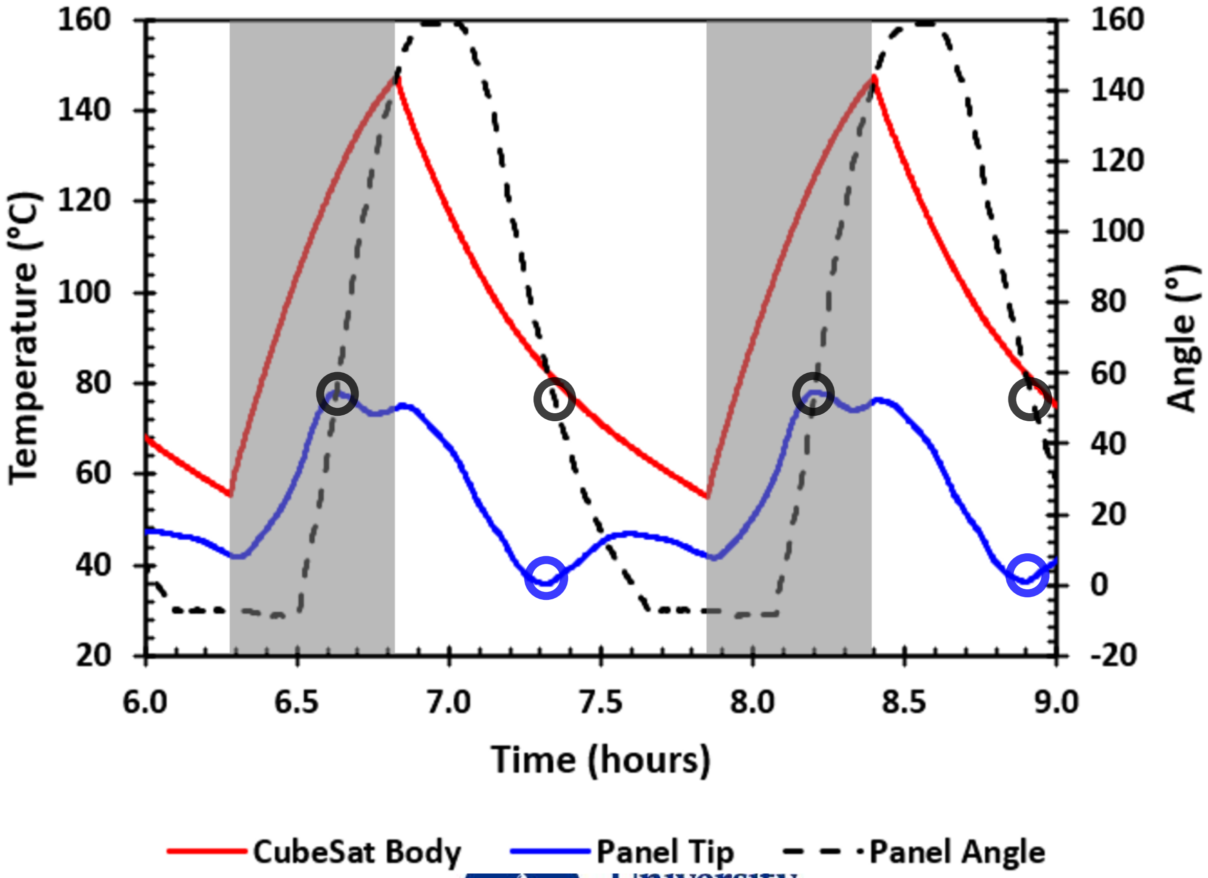
CubeSat Development - Results



CubeSat Development - Results

- Transition in heating behavior at 55°



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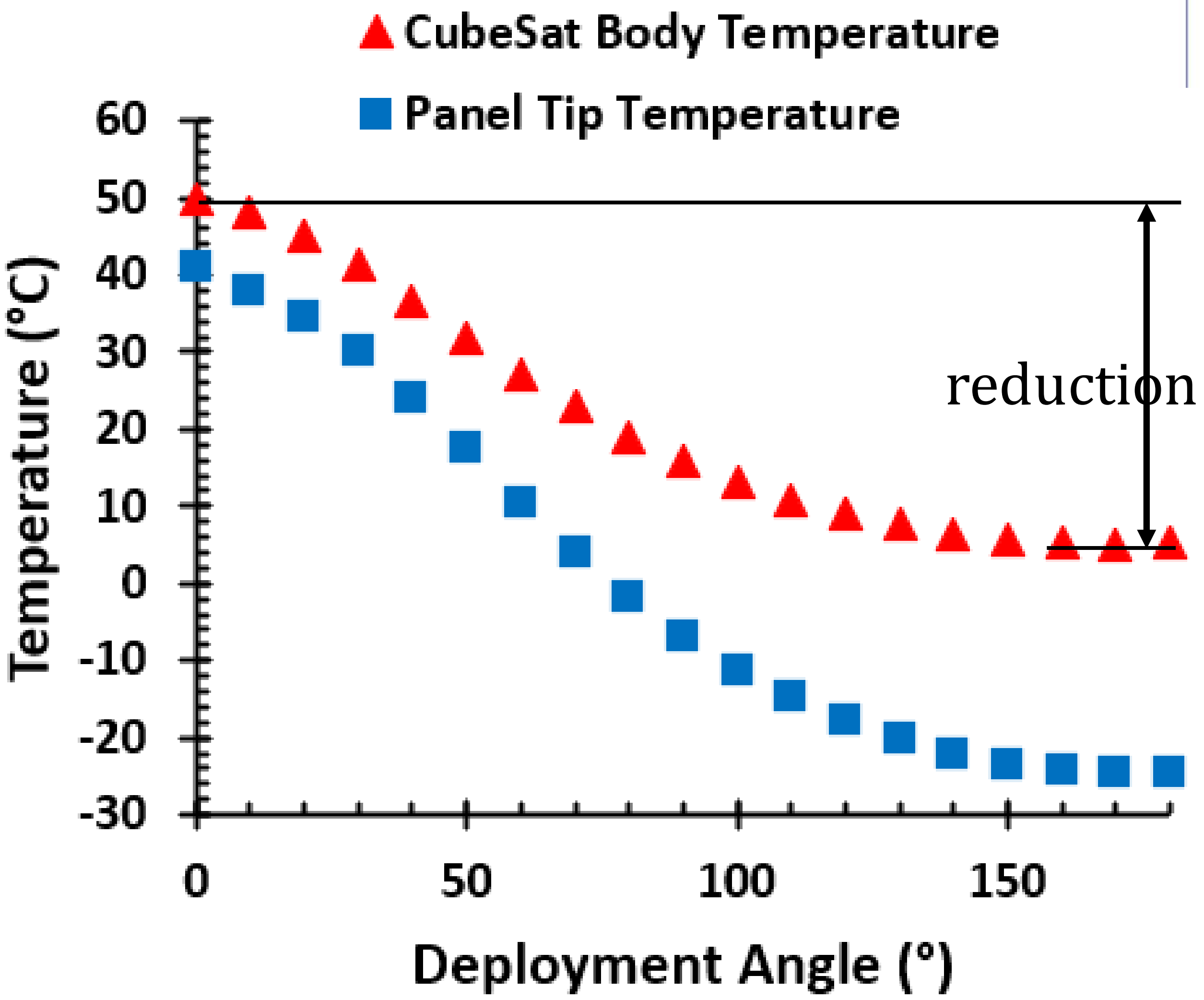
CubeSat Development - Results

- Turndown ratio = 5.4 (experimental)
  - Max heat loss 5.5 W at 180°
  - Min heat loss 1.0 W at 0°
- Temperature decrease (model)
  - Heat rate: 5 W
  - Evaluated over all deployment angles
  - 45 °C temperature reduction
  - 95% benefit by 135°



Effectiveness limited by heat transfer path to the radiator fins

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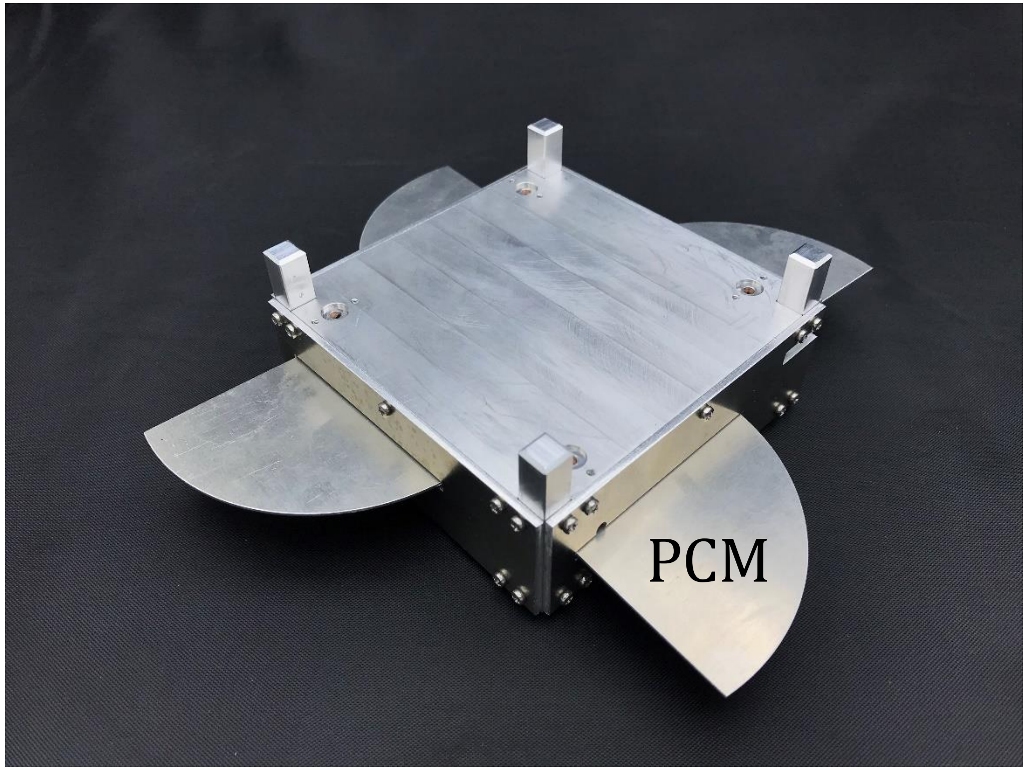
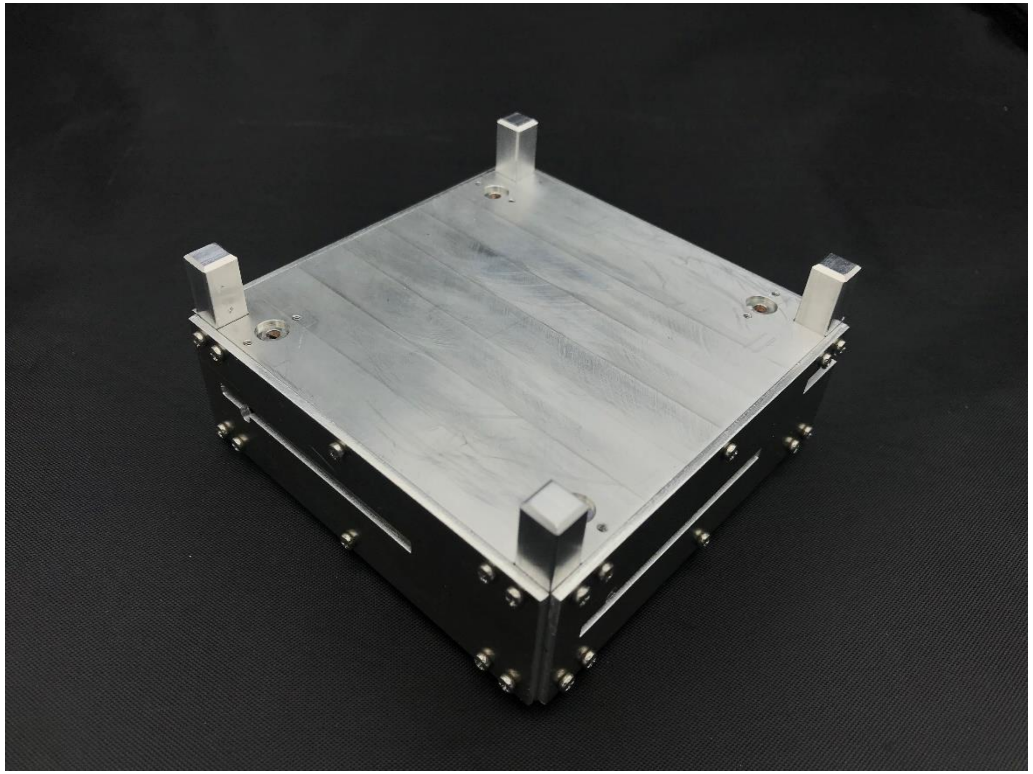
CubeSat Development - Prototype





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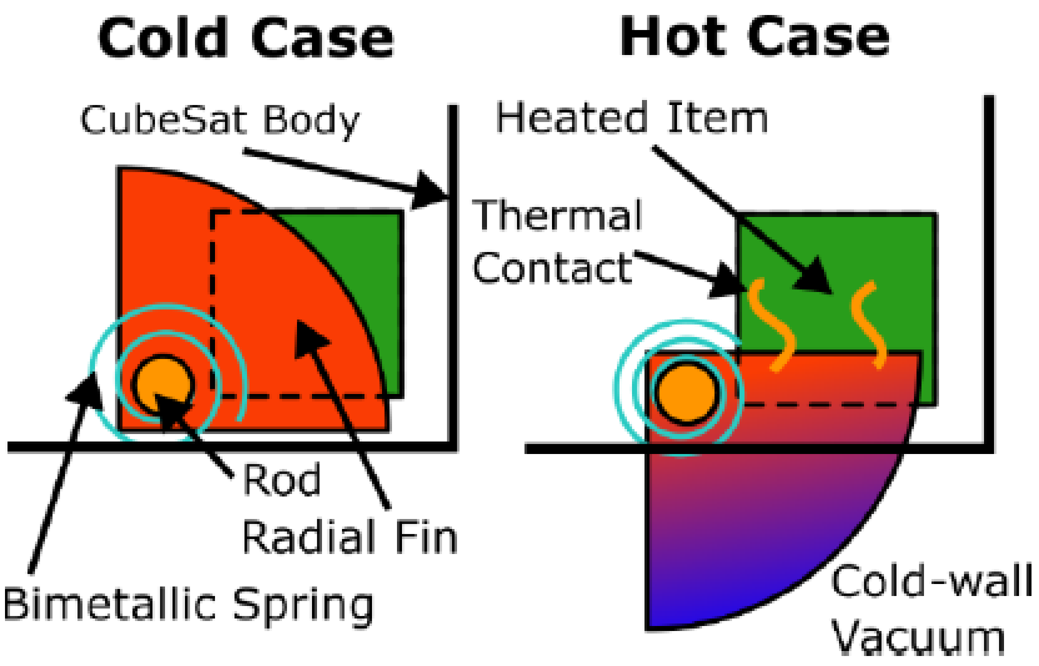
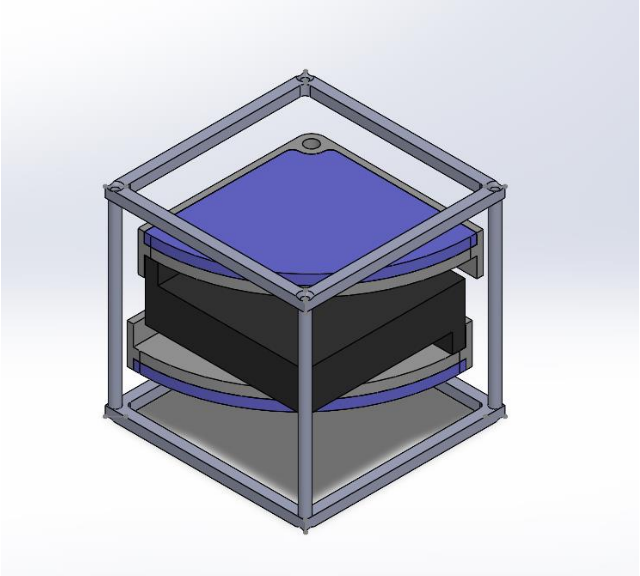
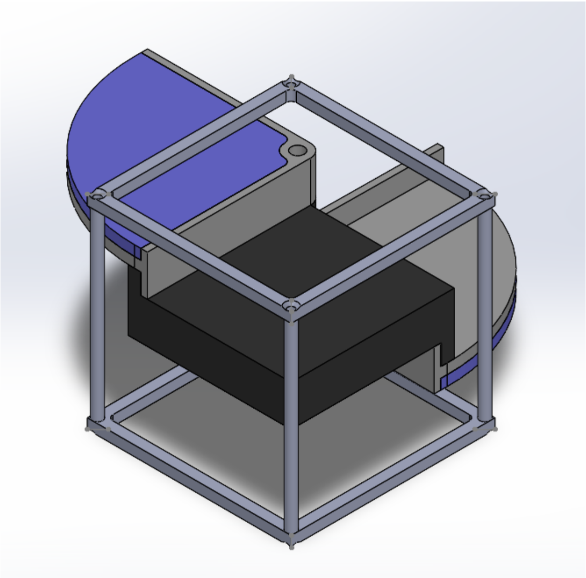
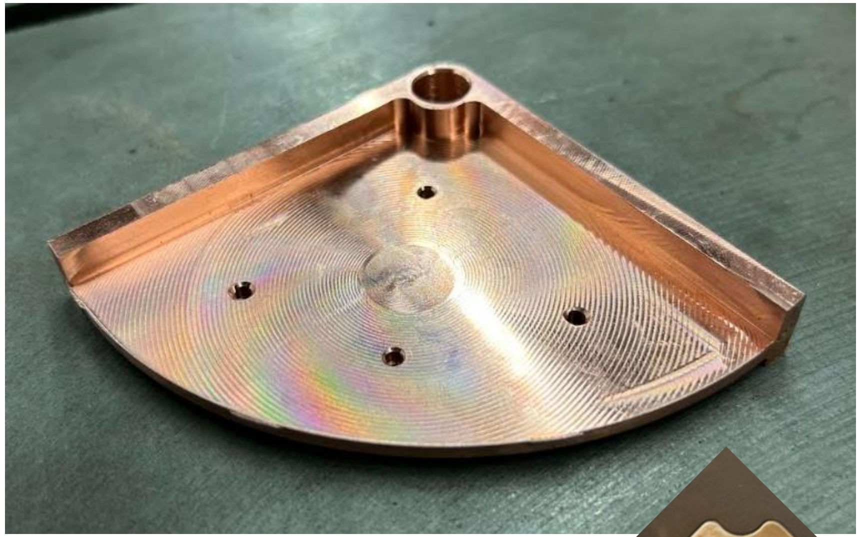
CubeSat Development - Prototype

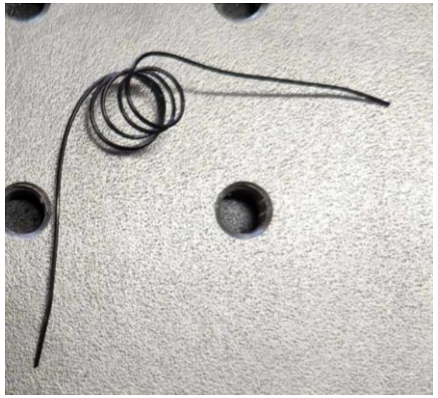


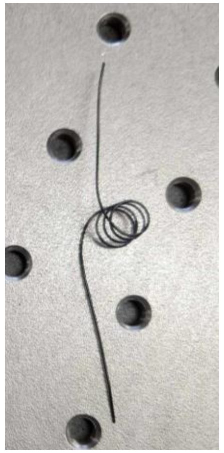


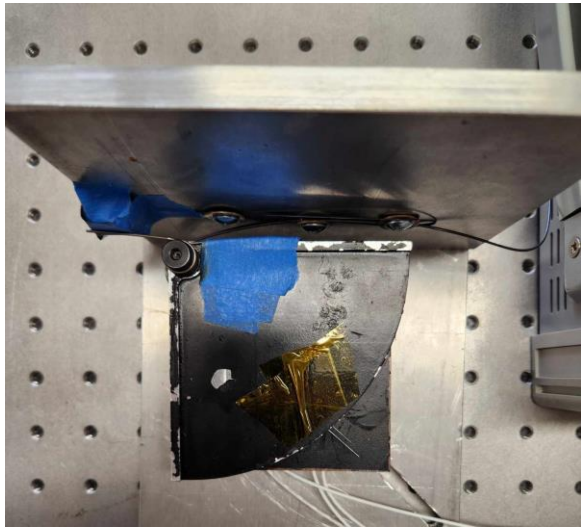


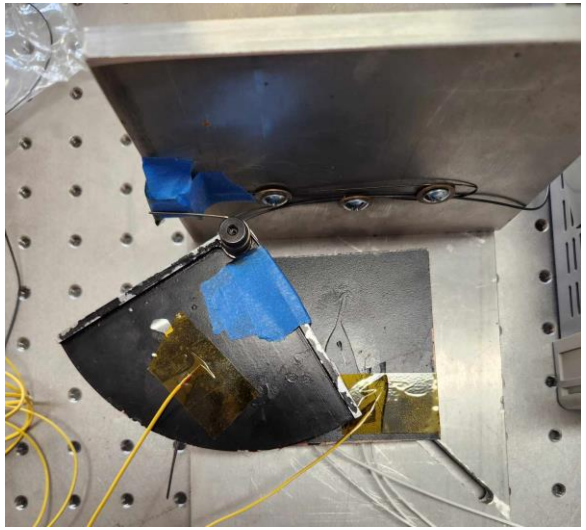
CubeSat Development - Prototype



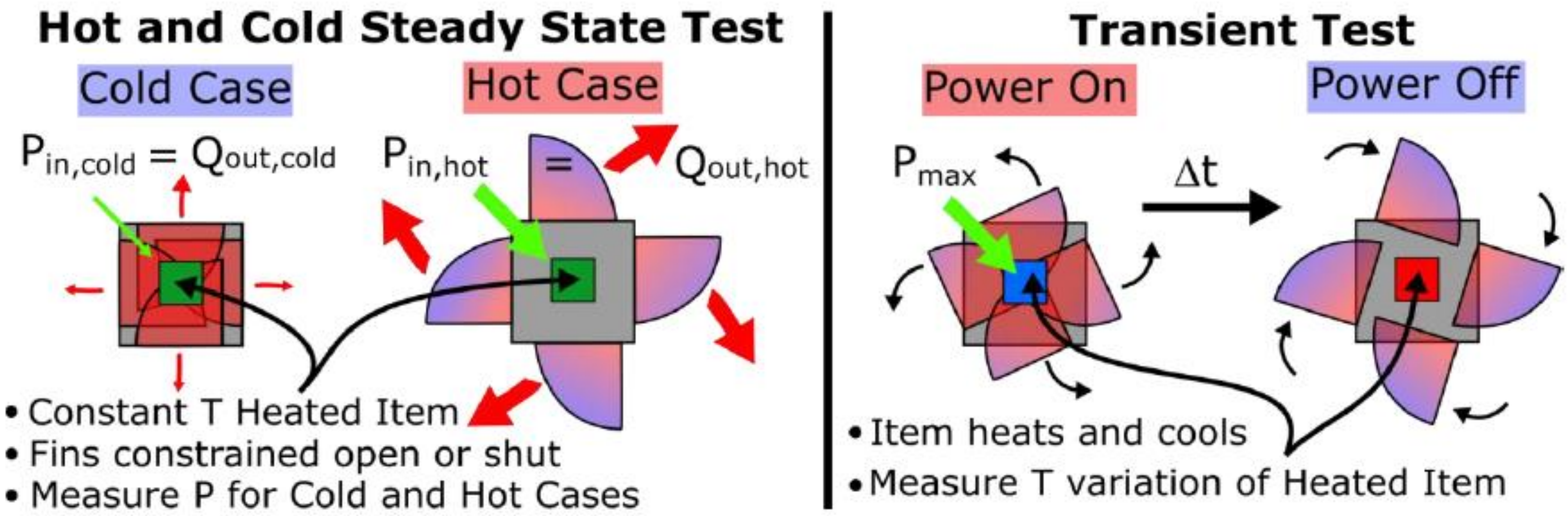








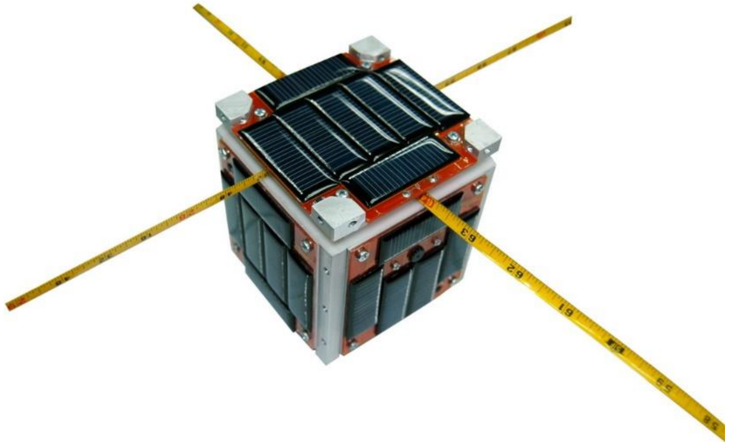
CubeSat Development - Test

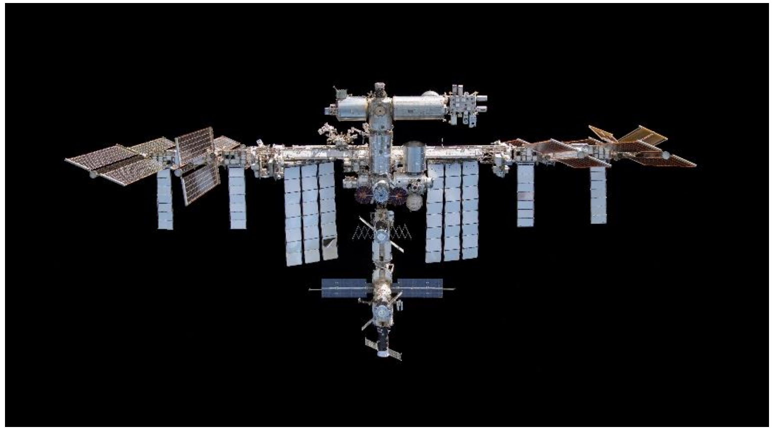


Demonstrate

Demonstrate – Flight Opportunity?

- Currently coordinating with Dr. Alex Rattner at Penn State to launch a demonstration platform hosting a variety of passive thermal control technologies.
- Possible platform – CubeSat, ISS, Varda Space Industries, etc.
- Targeting NASA Flight Opportunities and the CubeSat Launch Initiative for this work





Acknowledgements

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Questions?

FYI: Currently hiring PhD student to start in January 2025.
Please send me any interested applicants.

References and Image Credits

[1] Nagano, H., Ohnishi, A., & Nagasaka, Y. (2011). Development of a lightweight deployable/stowable radiator for interplanetary exploration. *Applied Thermal Engineering*, *31*(16), 3322–3331.

[2] NASA. https://www.nasa.gov/mission_pages/station/structure/elements/radiators.html#.W-HbzZNKi70

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