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HERON

An Open Source Microbiology Experiment Platform In Low Earth Orbit

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REDEFINING LIMITS

HERON is a student-funded and built 3U Cubesat investigating ***the effects of microgravity on the human gut microbiome*** using a novel, open-source and cost-effective microfluidics platform with the goal of ***trailblazing the future of accessible space biology research***.

Overview

1. Mission Objectives & Impact on UN Sustainable Goals
2. The Biological Payload
3. The Microfluidic and Optical Sensor Experimental Platform
4. Key Performance Parameters
5. Mechanical Systems
6. Electrical Systems
7. Concept of Operations
8. Orbital Considerations
9. Implementation Plan
10. Who are we?
11. Conclusions

Mission Objectives & UN Sustainable Development Goals

Mission Objective	Impacted UN Sustainable Development Goal
1. **Biological Viability** demonstrating the validity of our novel experimental platform	
2. **Scientific Contribution** to our knowledge of the human microbiome in space	
3. **Open-Source Documentation** available around the world	
4. **Education** of the next generation of space talent	
5. **Budget** of the mission will be below $50,000 USD	

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The Biological Payload: Why **Immunocompromisation and Space Missions?**

1. What happens to the human body in long duration space missions?

- Evidence of adaptive and innate immune system compromisation/weakening
- Bone density decrease, increased cancer risk, social isolation etc.
- Vision problems, nutrition problems, microbiota – morphological and genetic changes

2. How can these issues be tackled if we continue to explore beyond Earth?

- Can our current Earth-based medicine and biomedical technologies still function?
- Medicine needs to “evolve” at a sufficient pace to keep up space exploration
- Our pharmacological interventions must adapt to meet the changes to our bodies in extreme microgravity and radiation environment over long periods of time
- This is even more crucial when considering a Mars mission

Reference: https://www.nasa.gov/hrp/bodyinspace

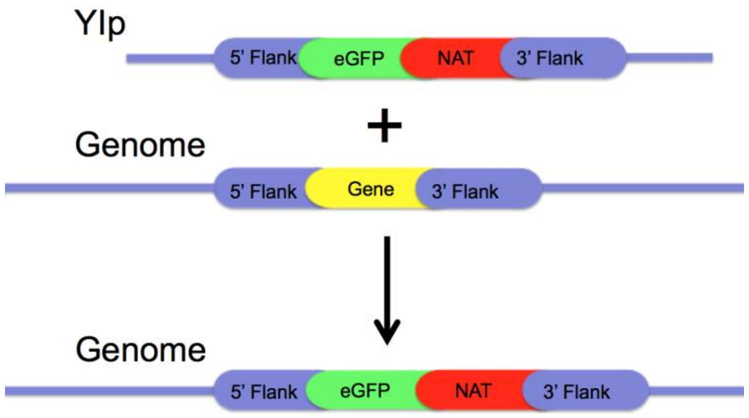
The Biological Payload: Organism of Interest

- *Candida albicans*
- Dimorphic opportunistic fungal pathogen
- Normal resident of the gut microbiota (BSL2)
- ***Why?*** Large eukaryotic genome that has useful natural properties that make it ideal for genetic manipulation

Enhanced Electron Microscopy, image credits

The Biological Payload: Purpose and Objectives

- Engineer *C. albicans* to express GFP with genes of interest to enable real-time gene expression quantification over a 48-hour period
- Assess the risk of auto-immune and immunosuppressive GI infections for long term space missions



Experiment 1: Track gene expression through fluorescence detection and optical density measurements

Experiment 2: FLC resistance via minimum inhibitory concentration, tracked through optical density measurements.

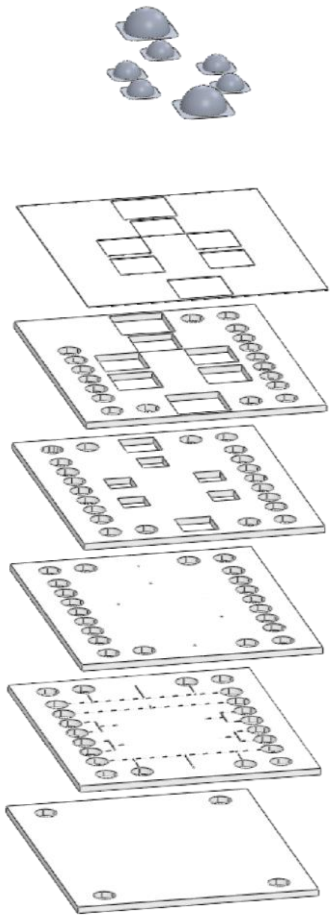
Payload Microfluidics: The How

1. Keep cells and growth media separate until experiment initiation
2. Load 9 dilutions of Fluconazole into 18 wells (2 MIC lanes) and growth media into 15 wells
3. Localize fluid actuation to chip

- Growth Media
  - 15 wells
- FLC Concentration 1
  - 2 wells
- FLC Concentration 2
  - 2 wells
- FLC Concentration 3
  - 2 wells
- FLC Concentration 4
  - 2 wells
- FLC Concentration 5
  - 2 wells
- FLC Concentration 6
  - 2 wells
- FLC Concentration 7
  - 2 wells
- FLC Concentration 8
  - 2 wells
- FLC Concentration 9
  - 2 wells
- Total
  - 33 wells

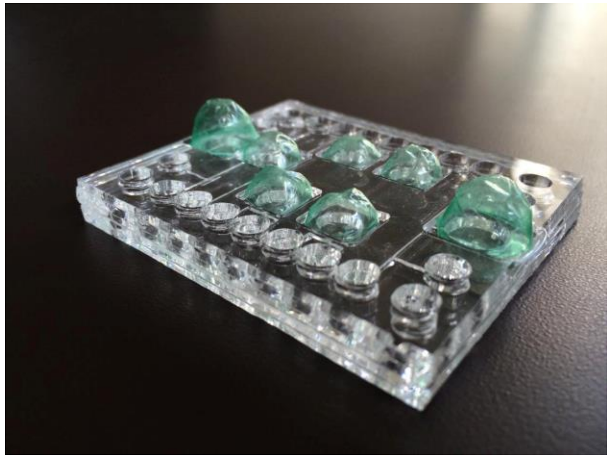
Payload Microfluidics

- 2 microfluidic chips: 64mm x 54mm x 7mm
- 36 total wells
- 5 layers of clear, extruded acrylic per chip, 1 layer PTFE membrane
- Blister packs adhered to the second layer of the chip
- 4X 350 uL blister packs each supplying 4 wells
- 10X 200 uL blister packs each supplying 2 wells



Manufacturing process:

- Laser cut each layer on 0.06” acrylic
- Remove edges & clean
- Use SVG Hot Embosser to thermally bond at 100℃



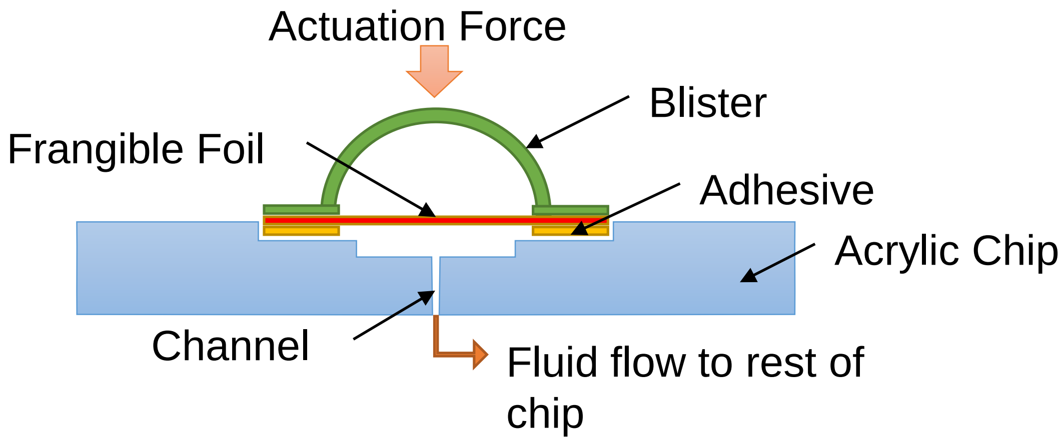
Payload Microfluidics

Blister Packs

Average Opening Force:

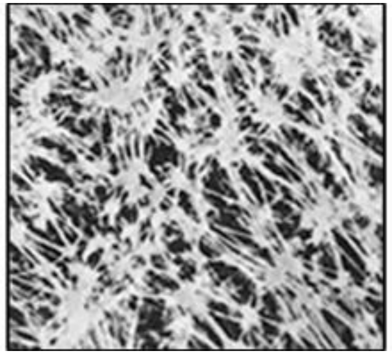
- 200uL blister pack: 30N, 350uL blister pack: 25N

Total Force Required: 400 N



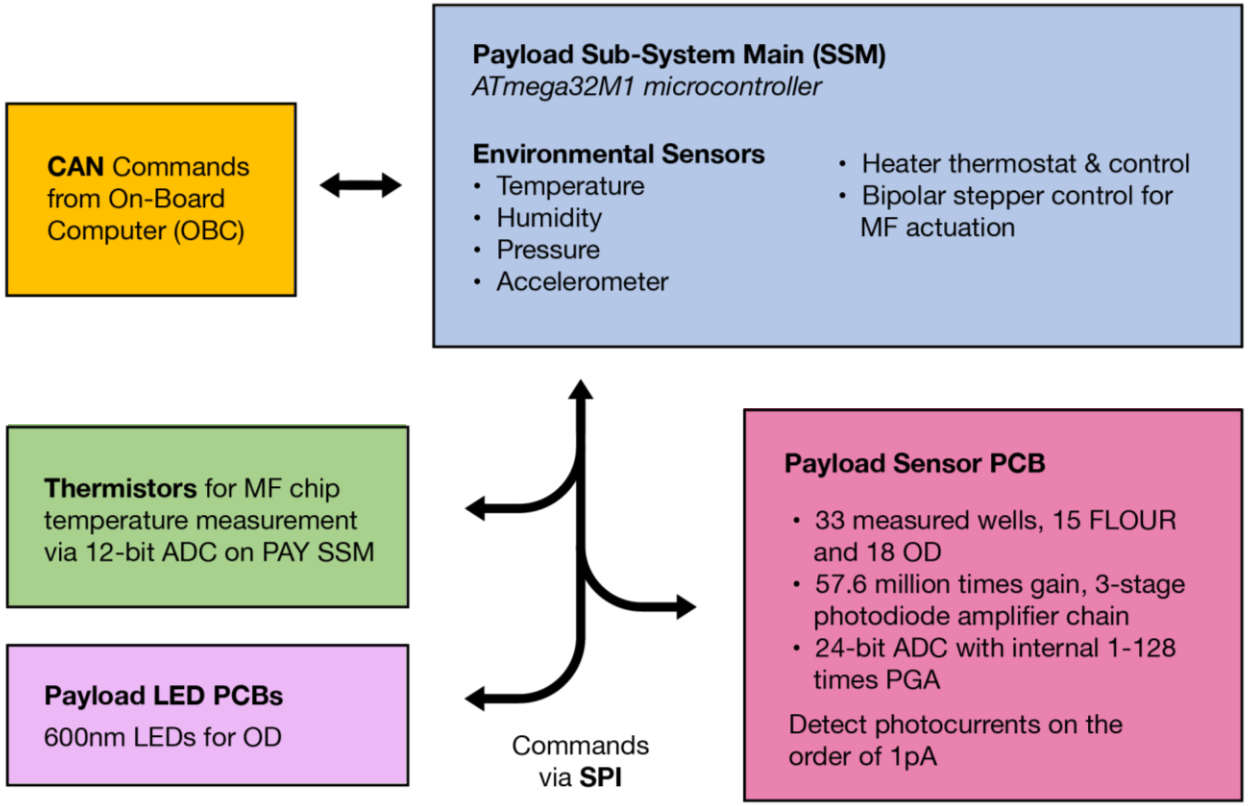
PTFE Membrane Filter

- Naturally hydrophobic & excellent chemical resistance
- Ideal for venting of gases - high to very high flow rate
- Very low protein binding
- Autoclave sterilization acceptable



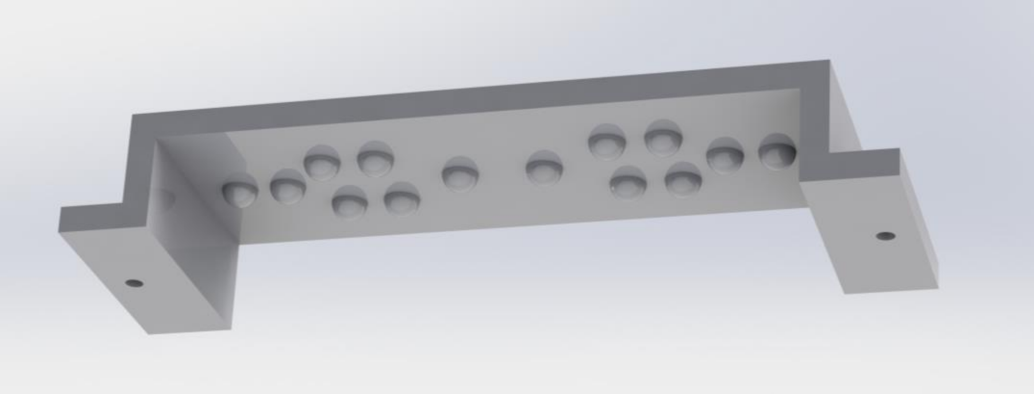
Payload Instrumentation: **Functional Overview**

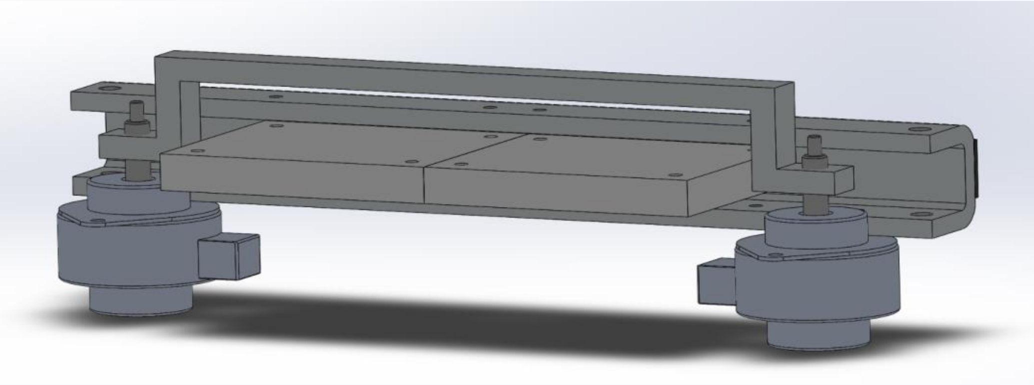
- **Light detection** sensitivity of ~3 nW/cm^2 for fluorescence measurements of ~1 pA photocurrents
- Amplifiers for performing **optical density** (OD) measurements
- Environmental **sensors**: pressure, temperature, humidity and acceleration sensors
- **Heater control** for payload bay and temperature measurement
- Stepper motor and special considerations in mechanical system to **control the fluid flow**

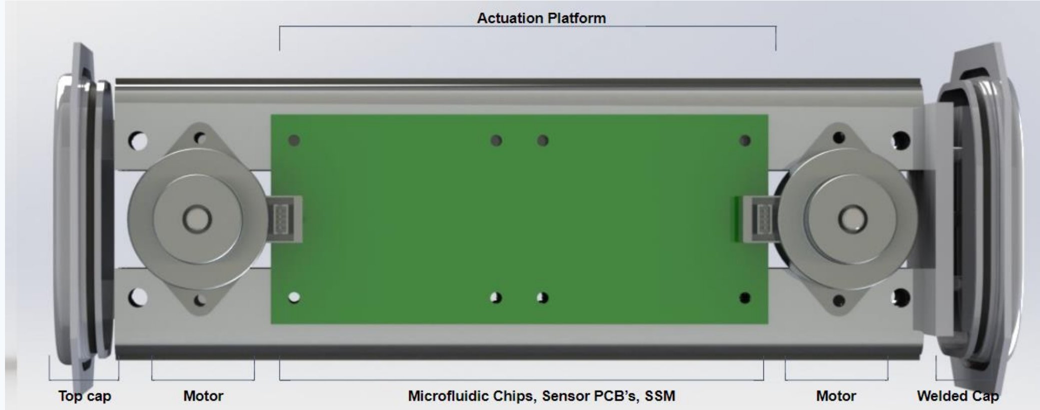


Payload:
Mechanical Burst Plate

- Lowers via 2 x 260N linear stepper motors to actuate the top plate
- Applies distributed force to the top of the blister packs, **bursting all at the same time**
- Remains depressed after bursting to **prevent reflowing** of liquid back to blister packs

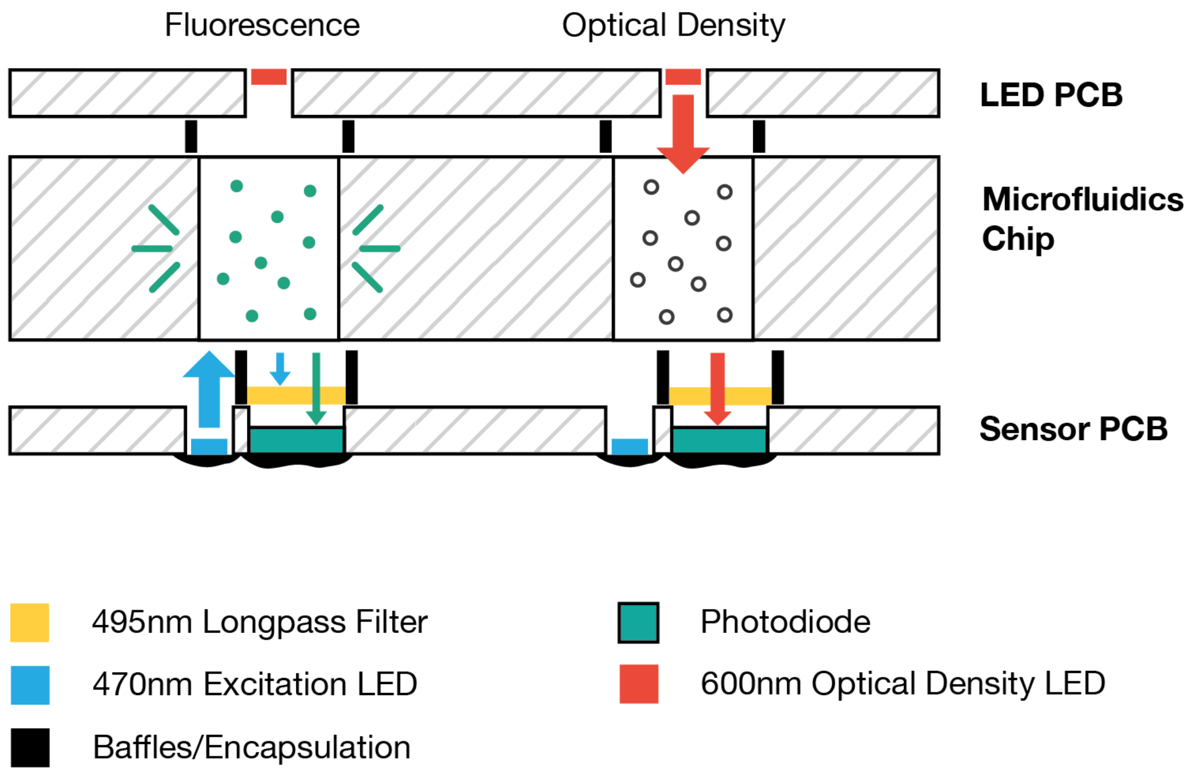






Payload Instrumentation: **Optical Sensor Layout**

- Separate **LED and Sensor PCBs** sandwich the microfluidics chips (modelled after GeneSat-1)
- LEDs illuminate through holes in the PCB for better **path linearity**
- **Photodiodes** are also mounted through holes in the PCB for easier filter mounting
- Black encapsulation on the back of the photodiodes and 3D printed baffles on the side of LEDs to **block stray light**



Optical sensor physical layout

Key Performance Parameters

Tagged genes of ***C. albicans*** must directly relate to measured characteristics, e.g. virulence	Scientific repeatability must be ensured by the microfluidics system accurately **isolating and actuating experimental fluids**	Payload bay must stay at **1 atm, 100% relative humidity** for the entire mission, **33±5°C** during 48h experiment, **4-40°C** before	Optical sensors must be **sensitive to fluorescence on the order of 3 pW/mm^2** from the GFP in cells

Concept of Operations

1

Gene tagging

(L-365 to L-120 days):

C. albicans strains are engineered to exhibit eGFP when select genes are expressed

2

Assembly and Handoff (L-120 to L):

Cells are put to *stasis* and loaded into the payload bay, satellite is then fully assembled and handed off to the launching party

3

Early Orbit

(L to L+14):

Detumbling and diagnostics while cells remain in *stasis* (4 – 40°C)

4

Experiment Preparation

(24h):

Payload bay heated to 33°C, optical sensor calibration

5

Experiment

(48h):

Motor actuated, blister packs popped open, and once-per-30-minute data collection

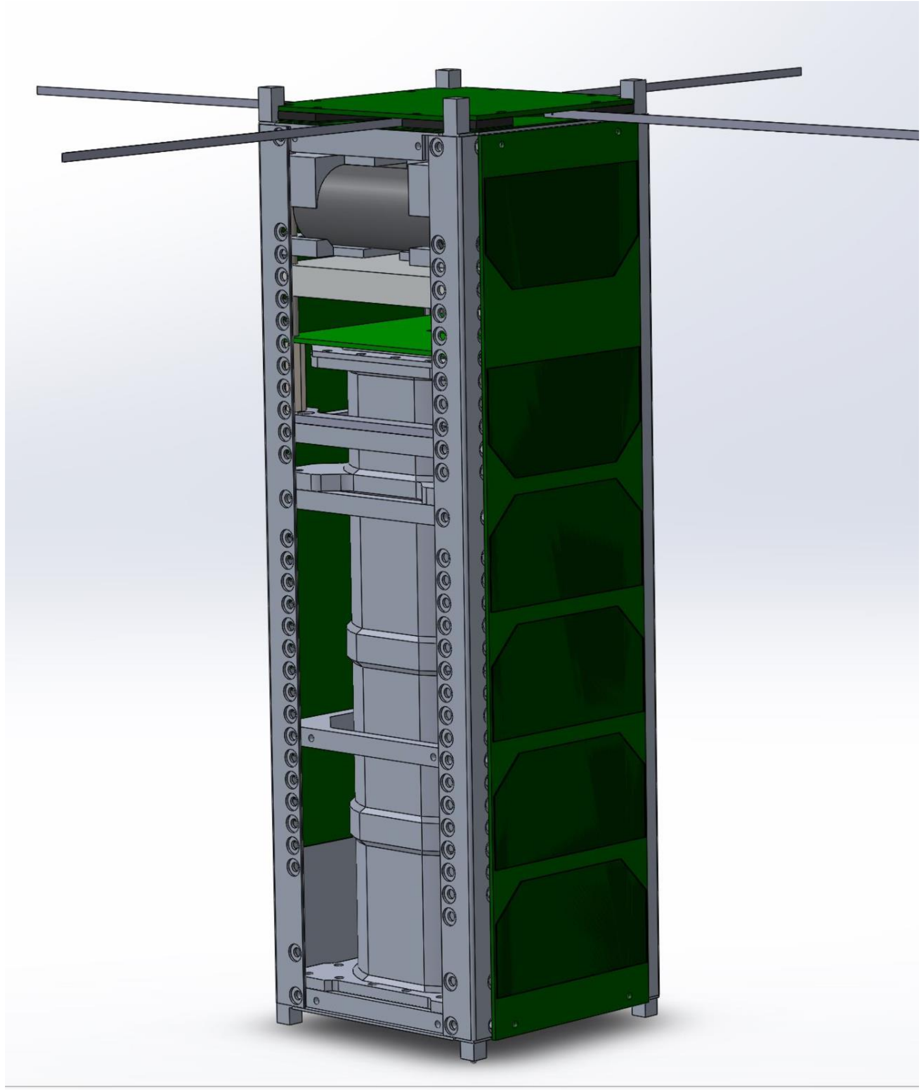
6

Diagnostics, End of Life:

After the experiment, HERON will be used for diagnostics & amateur radio outreach, its orbit will decay within 25 years.

Mechanical Systems

- **3U Cubesat** with 4 rails along the z-axis contacting the P-POD
- **α/ε ratio** of external faces controlled with **thermoptical tapes** at 1.17
- 23 cm high, 7.5 cm diameter octagonal **payload bay sealed at 1 atm**
- **Thermal decoupling between the payload bay and primary structure**; total conductance limited to 0.08 W/K based on cold-case steady-state thermal analysis
- **Passive attitude control system** with magnets & hysteresis rods for detumbling



Electrical Systems & Power

- Power requirements dominated by **payload heating**
  - **1.5W** before experiment (4-40°C)
  - **2.6W** during 48h experiment (33±5°C)
- Negative power margin for 48h during experiment, but **large batteries** (4x5000 mAh) compensate
- Battery longevity not a concern
- 6 solar cells for each long face for generation

Power Budget w/ Experiment OFF

Subsystem	Mode	Instant Consumption (mW)	Time Active (%)	Constant Power Subtotal (mW)
EPS	On	100	0	0
	On + heater	300	100	300
OBC	On	100	100	100
Comms	RX	200	95	190
	RX+TX	2100	0.05	105
Beacon	On	100	100	100
Payload	On	100	0	0
	On + heater	1500	100	1500
Deployment*	Antenna	2650	N/A	2650
	Payload	10000	N/A	10000

*Deployment occurs once, right after satellite is launched. It is therefore discounted from the power calculations.

Consumed Power	Generated Power	Efficiency	MARGIN (mWh)
Const. Pwr/orbit (mWh)	Const. Pwr/orbit (mWh)	85%	801.6
2295	3643	80%	619.4
		75%	437.3

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Consumed Power	Generated Power	Efficiency	MARGIN (mWh)
Const. Pwr/orbit (mWh)	Const. Pwr/orbit (mWh)	85%	−298.5
3395	3643	80%	−480.6
		75%	−662.8

Electrical: Data and Link Requirements

Low data size (<100kB), rate (1200bps) and completely autonomous experiment reduce the requirements and complexity of the communications & on-board computer modules.

Data Source	Size Per Measurement
ADC (Optical Sensors) 48 x 24b	1152b
Thermistors (MF Chips) ~8 x 12b	150b
Pressure Sensor 24b	24b
Temp Sensor (PCB) 14b	14b
Humidity Sensor 14b	14b
IMU 48b	96b

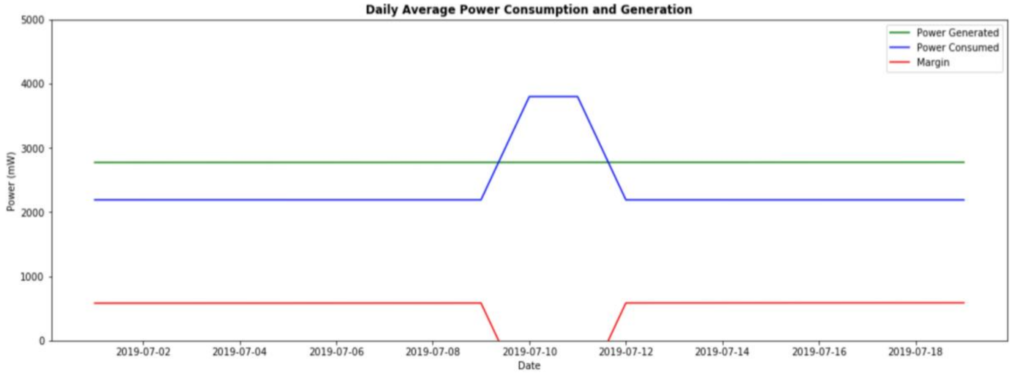
Link Budget			8	
Item	Symbol	Units	Uplink	Downlink
Transmit Antenna Gain (net)	G_t	dBi	19	0
Equivalent Isotropic Radiated Power (EIRP)	EIRP	dBW	29.5	1.26
Space Loss (FSPL)	L_s	dB	140.07	140.07
Propagation & Polarization Loss	L_a	dB	0	0
Peak Receive Antenna Gain	G_rp	dBi	1	20
Receive Antenna Pointing Loss	L_pr	dB	1	1
Receive Antenna Gain (net)	G_r	dBi	0	19
System Noise Temperature	T_s	K	615	220
System Noise	T_sn	dB-K	28.00	23.00
Receiver Noise Figure	R_nf	dB	3.00	0.50
Receiver Noise	R_n	K	289.00	36
Recieved Power	P_r	dBm	-81.1	-89.3
	P_r	dBW	-111	-119
	P_r	W	7.84E-12	1.18E-12
Data Rate	R	bps	1,200	1,200
Eb/N0	Eb/N0	dB	57.35	34.58
Carrier-to-Noise Density Ratio	C/N0	dB-Hz	88.14	65.37
Bit Error Rate	BER	-	1.00E-06	1.00E-06
Required Eb/N0	Req(Eb/N0)	dB	15	15
Implementation Loss	ImL	dB	2	2
Margin	-	dB	40.35	17.58

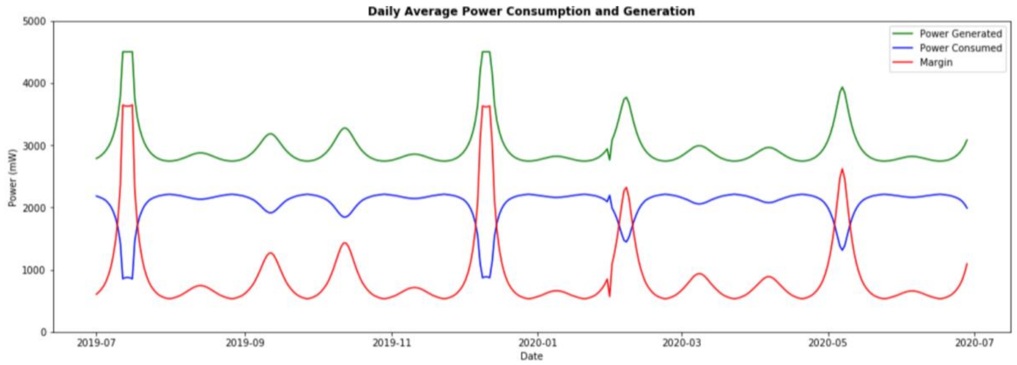
Orbit Selection

- Sun-Synchronous orbit with 550 km altitude, 98.6 inclination is the optimal orbit for HERON given thermal & power constraints.
- SSO is accessible, but has much more favorable conditionals than an ISS orbit:
  - Extremes of the ISS orbit are much harsher
  - SSO affords much more predictable thermal & power generation properties

Steady-State Orbit Average Temperature using 1-Node Analysis

	SSO	ISSO
Optimal a/e	1.17	1.09
Hot Case Temperatures	Avg = 33.0℃, Max = 33.3℃	Avg = 29.2℃, Max = 50.1℃
Cold Case Temperatures	Avg = -16.6℃. Min = -16.8℃	Avg = -19.7℃, Min = -21.9℃





Power Generation & Consumption of HERON in SSO (above) and ISSO (below)

Implementation Plan

- Our team is pioneering Canada's first fully student-funded satellite launch.
- Several-month long campaign mobilizing the UofT student body to raise a $400,000 levy fund
  - Charging 40,000 undergrads $2.77/semester for 2 years, up for renewal in early 2019
- The entirety of the fund is dedicated to development & launch of HERON
- A team of 50+ enthusiastic, talented students in our team working on HERON

Conclusions

- **HERON**'s contribution to space biology research is beyond the experiment on-board – our open-source experimental platform will make a genuine impact in the way such research is undertaken in the future
- The first mission of its kind designed with the goal of **equitable access to space**, highlighted by its low cost, open-source documentation and accompanying educational materials

ADDITIONAL INFORMATION

Who are we?

- Space-enthusiastic undergraduate or graduate students from various University of Toronto disciplines: Engineering, Math, Physics, Biology
- We are a united, welcoming and diligent team
- Team Culture: everyone can build a satellite!
- *To the stars, with friends!*

Payload Biology

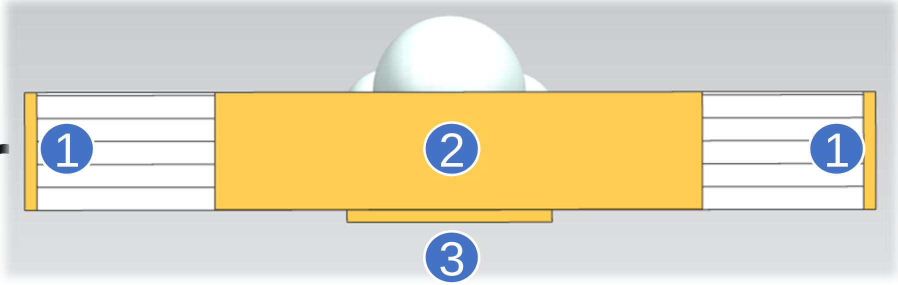
Summary "Equations"

- Microgravity (M) + *Candida albicans* (CA) = CA_M
  - (physically, genetically & pathogenically altered CA as a result of M)
- M + human immune system = low levels of immune cells
- Low levels of immune cells + CA_M = infection and disease!
- *An awful combination: weak humans & strong pathogens!*

Biological Payload - **Background Work by ISS & NASA**

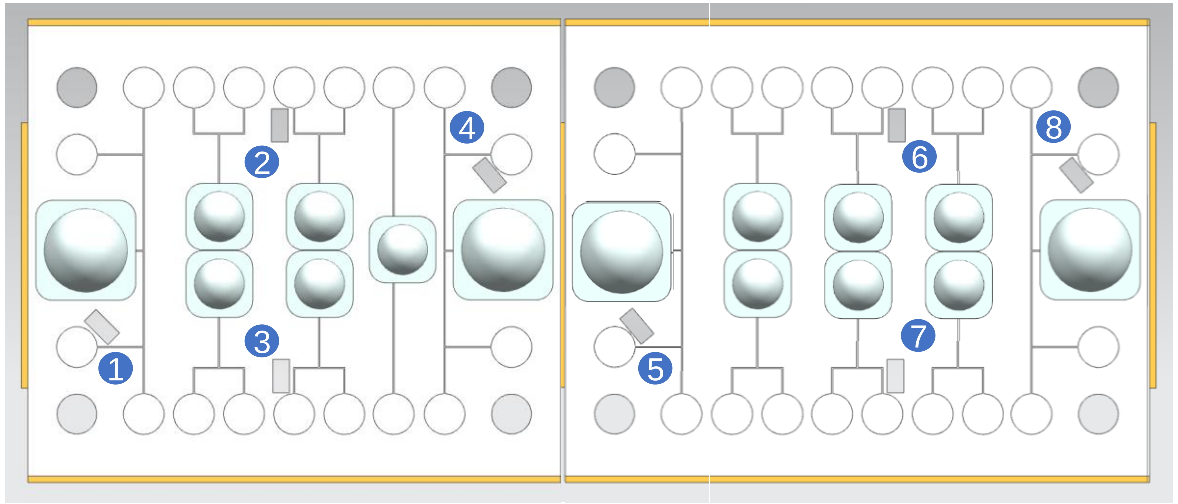
- GeneSat-1 demonstrated *in situ* microsatellite instrumentation
  - (Kitts et al. 2007)
- Microarray analysis of *C. albicans* grown in space
  - (Crabbe et al., 2013)
  - Experiment performed on the International Space Station (ISS)
  - Analyzed gene expression by microarray analysis on Earth
- EcAMSat: Investigating Space Microgravity Effects on Antibiotic Resistance of *E. coli*
- Pharmasat: yeast and drug resistance
- BioSentinel: deep-space 6U satellite to measure long term radiation on double strand breaks in DNA and repair processes
- No real-time studies exist
  - Our goal is to develop a (near) real-time platform

Payload Temperature Contr



Delivering Heat to Experiment:

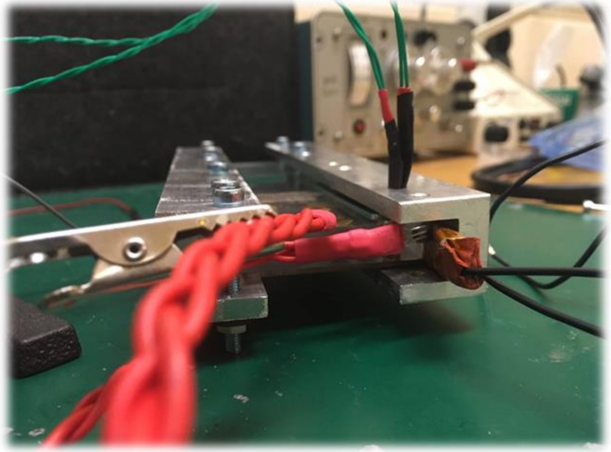
- Positioning of wells and heaters on microfluidic chips
  1. 2 Long side heaters for 28 wells
  2. 3 Small side heaters for 6 wells
  3. 1 Bottom heater for blister packs
- Temperature acquisition



Additional means of insulation:

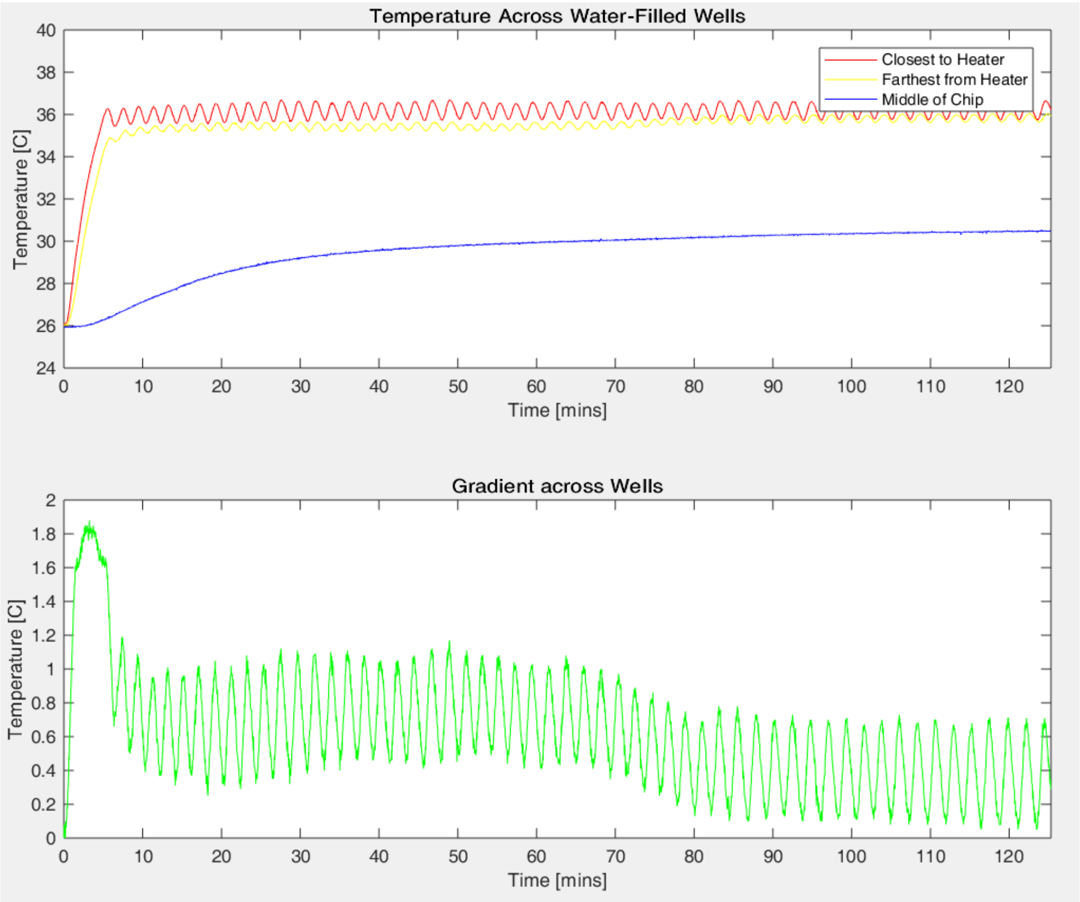
- Reflective gold adhesive tape for interior of payload (ε = 0.2)

Payload Temperature Control



- Thermostatic heater programming
- 4.86W at room temperature and limited convection

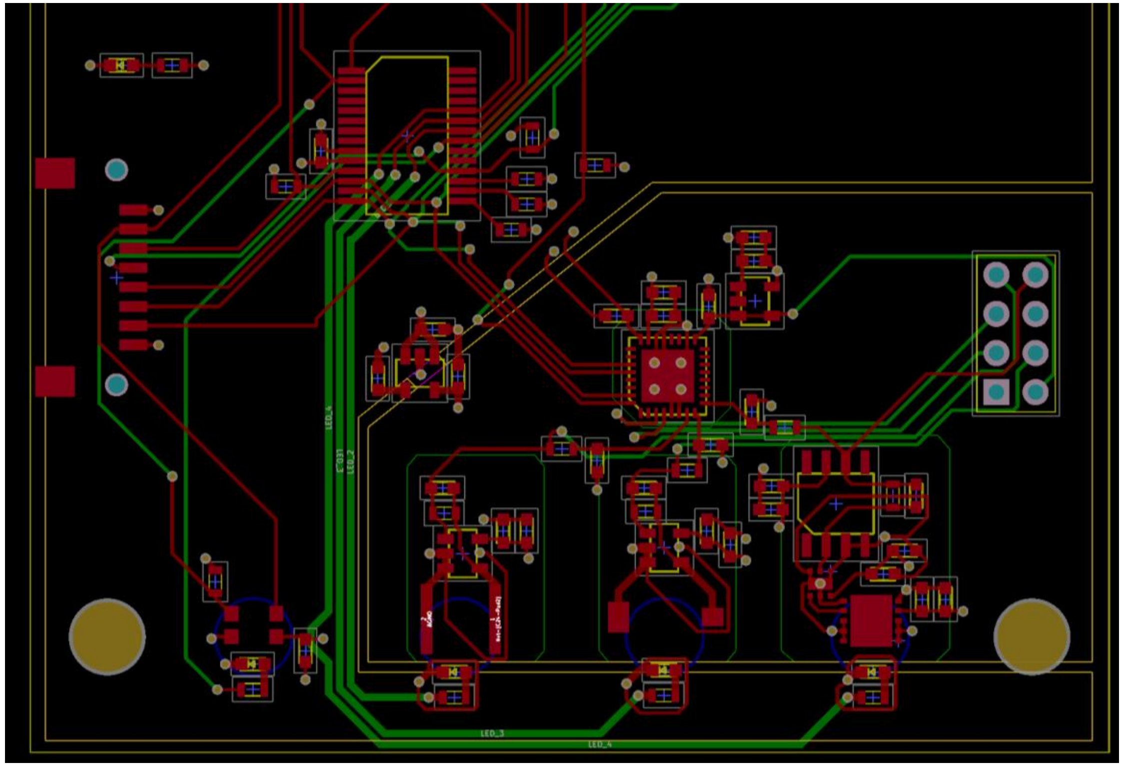
Offset max temp by 1°C	
Time ↑ 30°C [min]	16
Stabilization [±°C]	0.5
Gradient across wells	$< 1°C, \frac{dT}{dt} < 0$



Payload Instrumentation

PCB Layout

- 3V LDO supplies power for analog side
- Separate analog and digital GND planes connect at a choke point under the LDO
- Guard traces protect amplifier inputs
- No traces or current return paths pass under sensitive amplifiers
- All analog ICs outfitted with 10uF bulk and 0.1uF bypass capacitors
- Capacitor values have been calculated to stabilize transimpedance output



PCB schematic of the current optical sensor PCB prototype

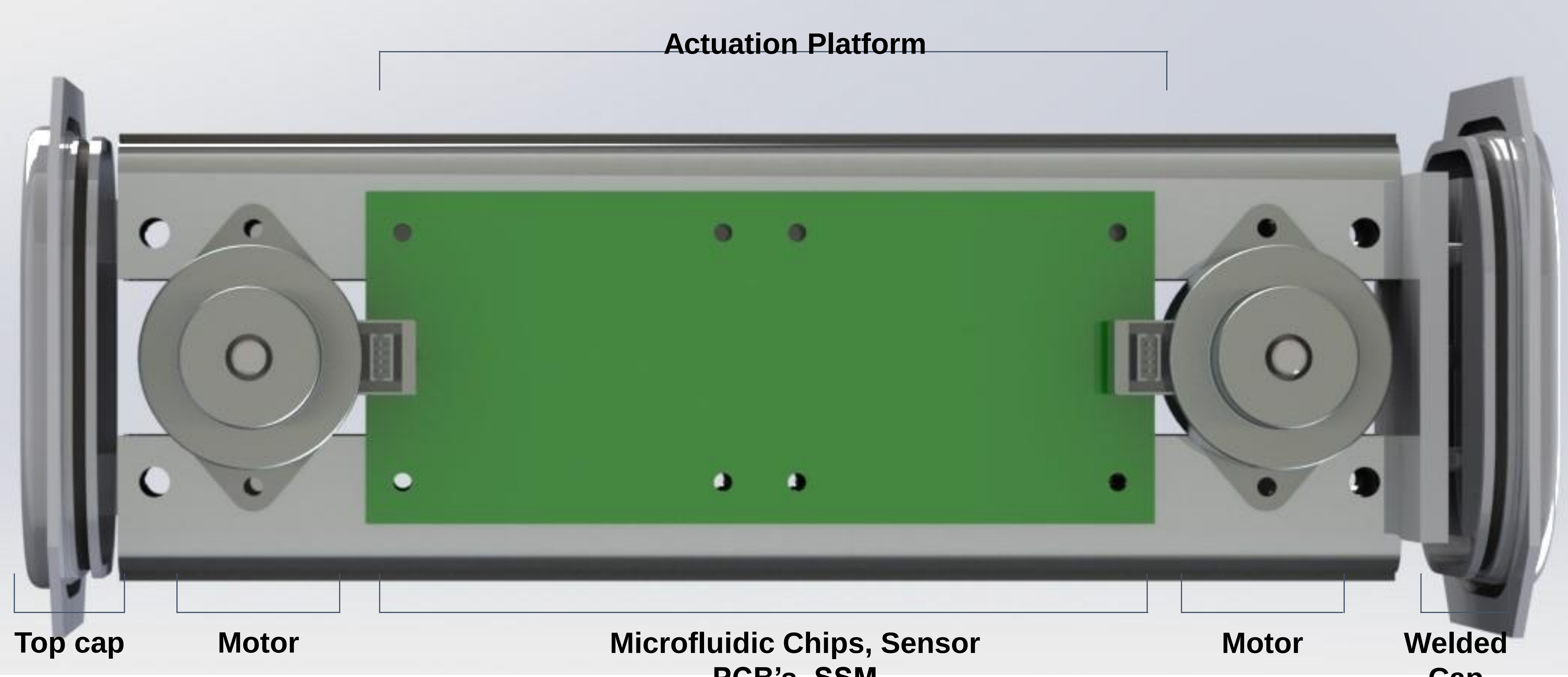
Payload Instrumentation

Amplifier Chain Design

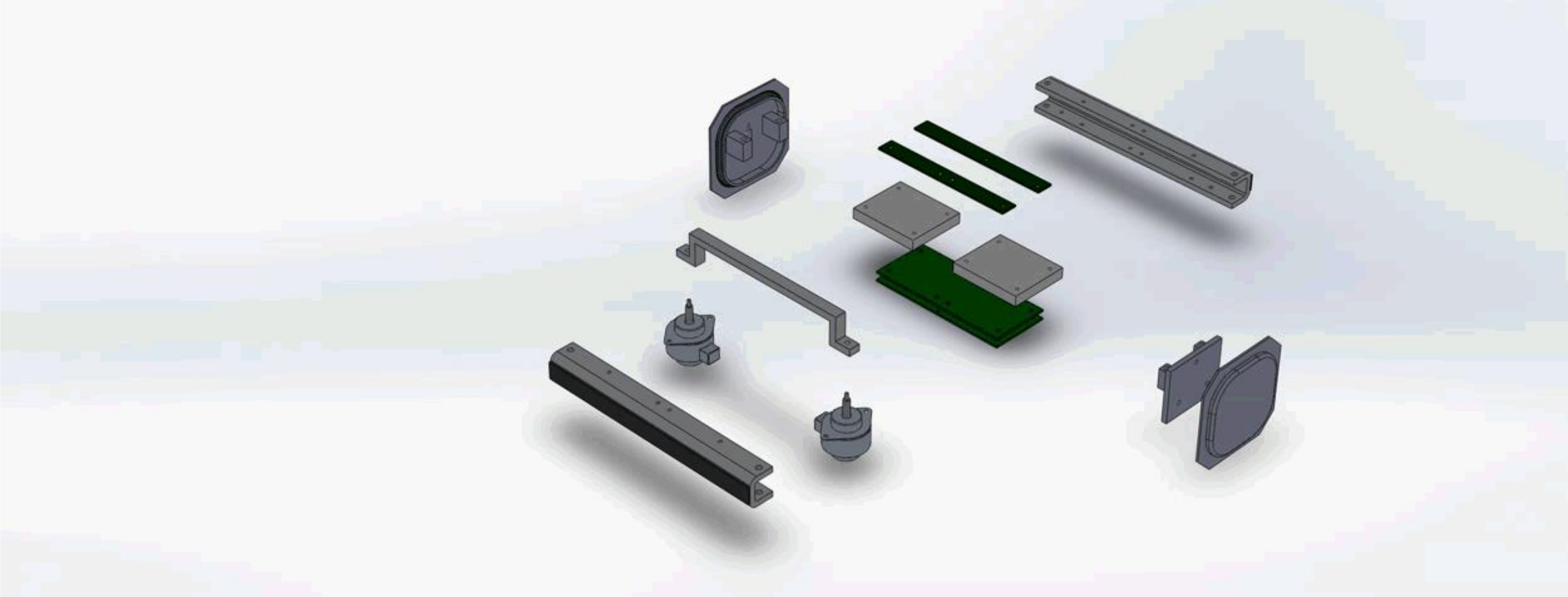
- Total gain ~7.4 billion times with 128x PGA (ideal)
- Practical gain achieved likely lower, although we're on track to return very usable values

- First two stages have a very low typical noise floor: 80 fA/√Hz
- Gain of the transimpedance amplifier has been lowered from 10 M to 100 K for stability and shifted partially to the second ADPD2210

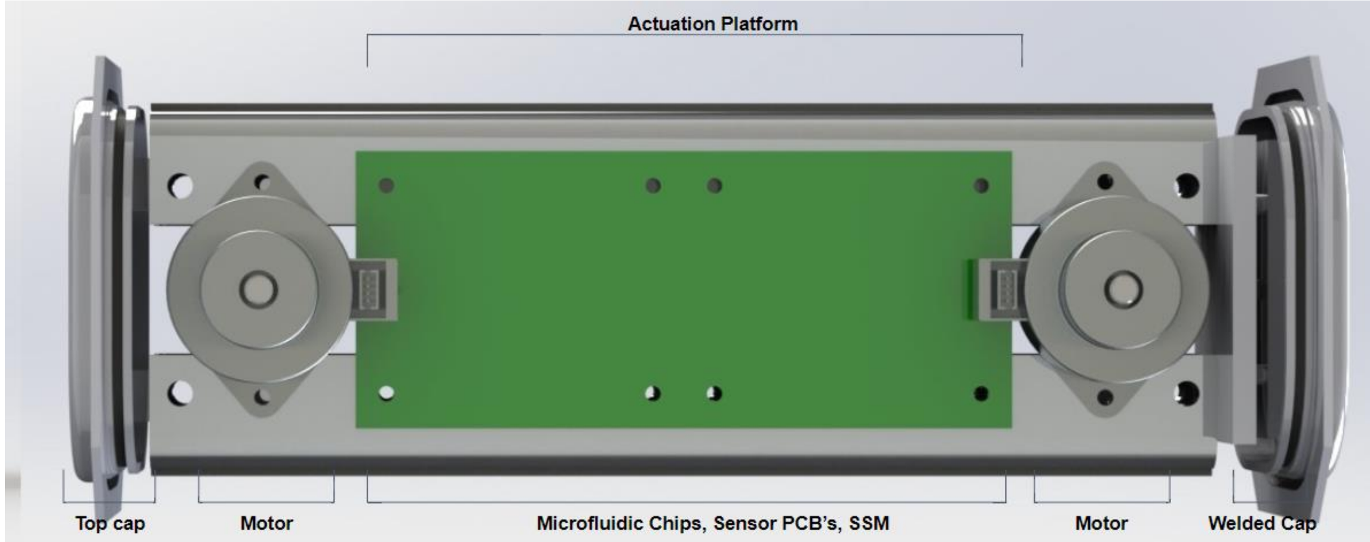
Overall Design

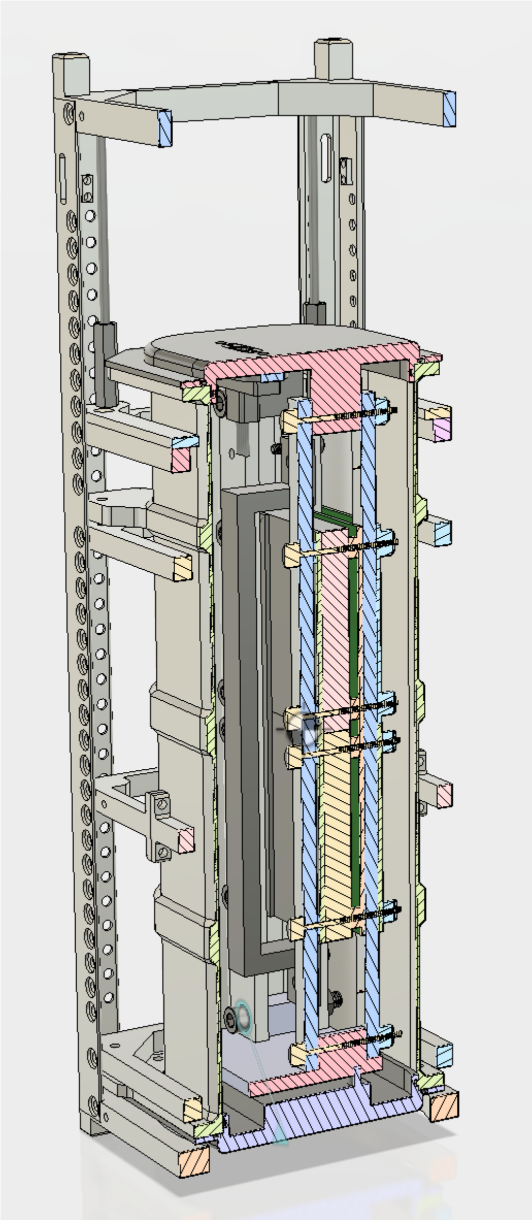


Overall Design - Assembly



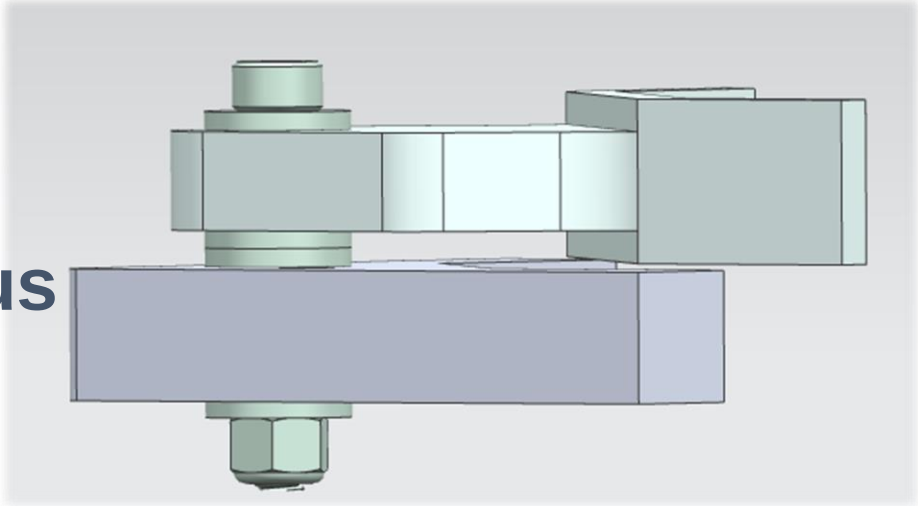
Cross-Section of Structure





Thermal Conductance

Limit heat flow between Payload and Bus



Material	Conductivity [$\frac{W}{m \cdot K}$]	Part
Al 6061-T6	167.00	Structures
PEEK Plastic	0.25	Washers
18-8 SS	16.20	Bolt and Nut

- Target K < 0.06 W/K

Calculated conductance = 0.04 W/K

Method of verification:

- Homogeneous material: effective thermal conductivity $\mathrm{k}_{eff} = 4.56 \frac{W}{m \cdot K}$
- Closed system: $\dot{Q}_{stack} = \dot{Q}_{water} \rightarrow k_{eff} = -c_w \frac{L}{A} \frac{m}{\Delta t} \frac{\Delta T_{water}}{\Delta T_{stack}}$

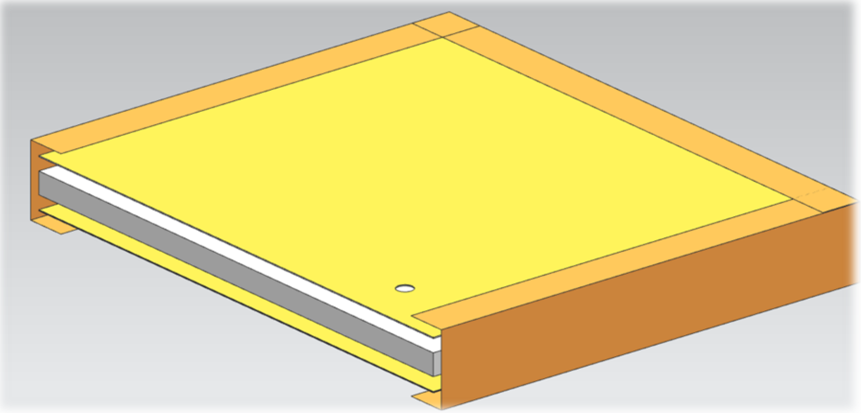
Aerogel Insulation Solution

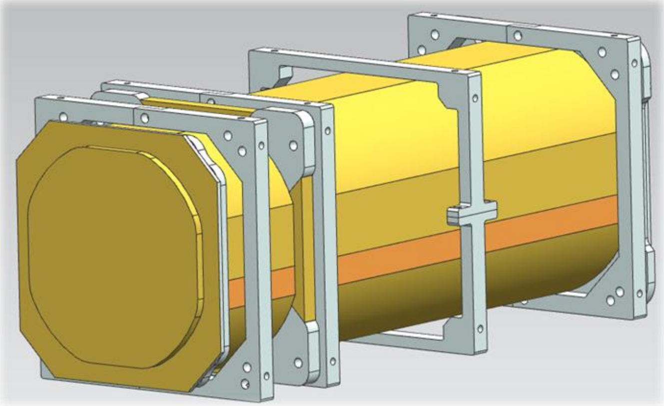
Minimize effects of radiative heat transfer

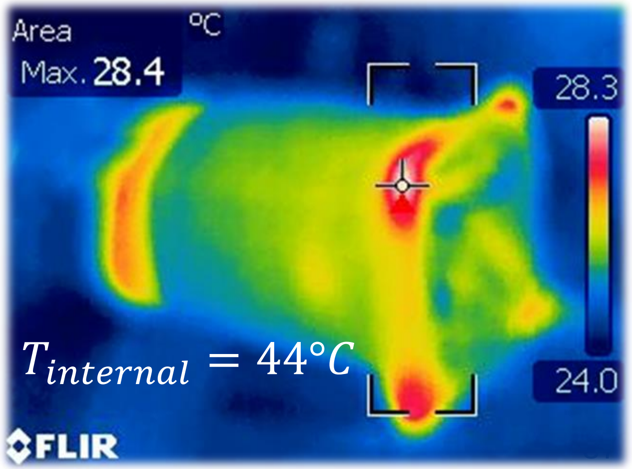
- Fully-breathable nanoporous material

Materials	Emissivity (ε)
Gold Mylar	$\varepsilon \sim 0.02 - 0.04$
Aerogel– Cryogel Z Blanket	$\varepsilon^* = 0.042 \quad k_{eff} = 0.016 \frac{W}{m \cdot K}$
Kapton Tape	Negligible
Filter	Negligible

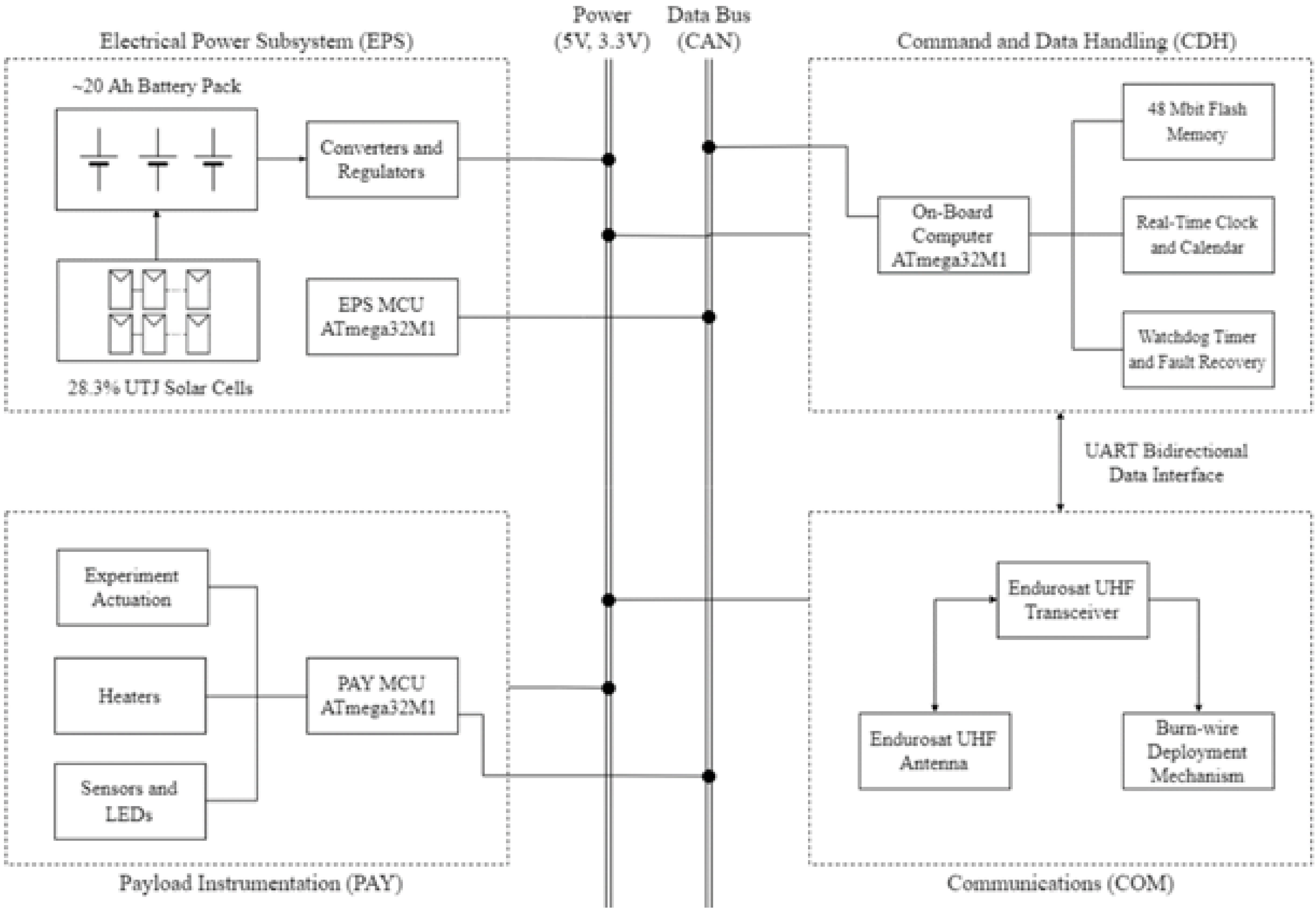
- Easy custom fabrication:
  - Conventional hand tools – sleeve to minimize seams
  - Controlled Volatility RTV Silicone adhesive ($0.27 \frac{W}{m \cdot K}$)
- Attention to corners and solution for caps



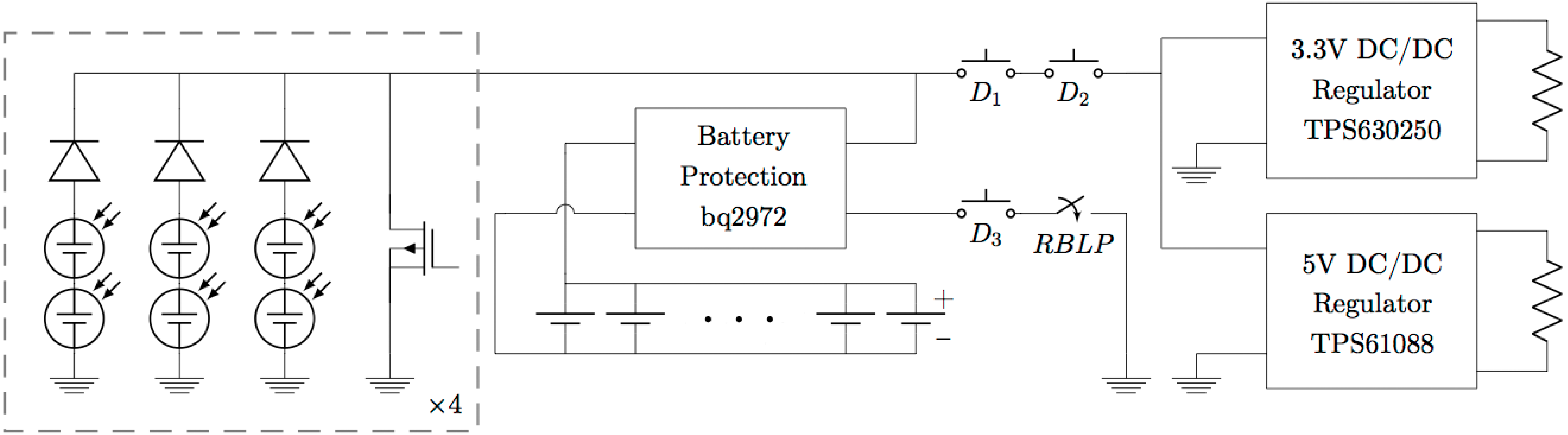




Electrical System Overview

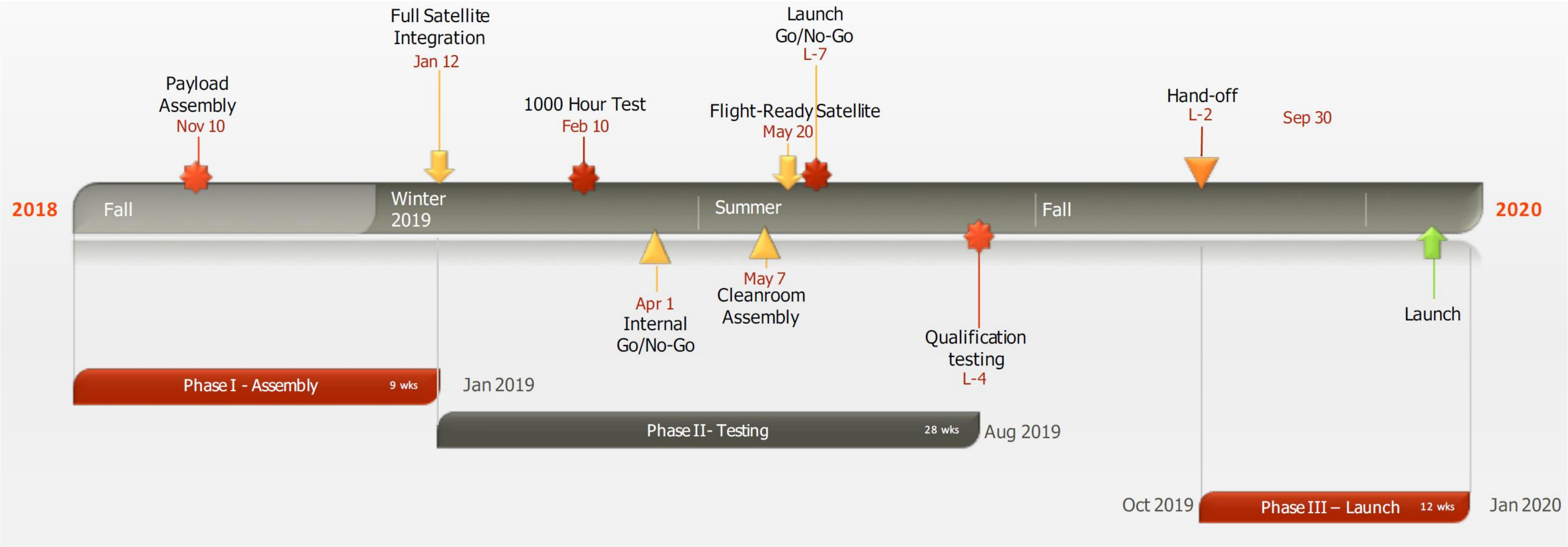


System Architecture



Implementation: Scheduling

- UTAT’s development cycle for HERON Mk II, which started in Fall 2016, is leading up to a January 2020 launch. Many iterations of design, manufacturing testing and have brought us to the final manufacturing & testing phase this winter.



Design Risk and Mitigation Table

Risk	Alternative A	Alternative B
Pressure Leak	Update O-ring positioning	Weld both caps
Blister Packs not fitting	Mechanical fixture for alignment	Other methods to bond, apart form heat, for less warping
Detection of Fluorescence	Continue higher fidelity prototypes	Go back to Genesat sensors, with high dynamic range and low saturation
Chip manufacturing (alignment/collapsing/ distortion)	Mechanical fixture for alignment	Other methods to bond, apart form heat, for less warping
Payload Tolerance	Develop hierarchy of assembly components	Develop mechanical fixtures