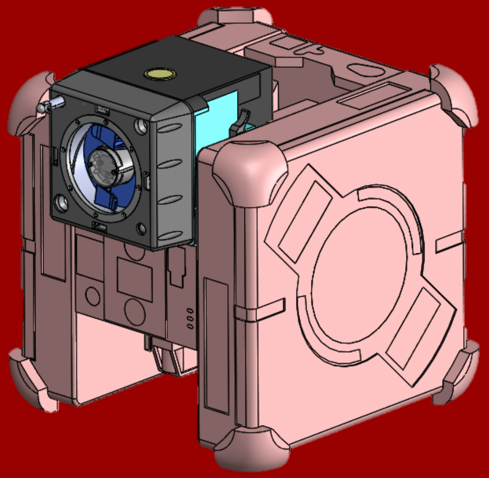
# ASTROBEE WORKING GROUP MEETING
# USC CLINGERS EXPERIMENT

***USC Space Engineering Research Center***
*Department of Astronautical Engineering*
*& Information Sciences Institute*

***June 1st 2023***

**Prof. Dave Barnhart, PD**
**&**
**CLINGERS TEAM**



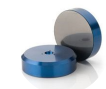
***"Cling-On"***

# TEAM

Haley Topper:
Lead I&T Engineer

David Barnhart – PI

Adarsh Rajguru – Lead Systems Engineer



Noah Gladden – Avionics Operations

Sami Haq – Lead RPO Test Engineer

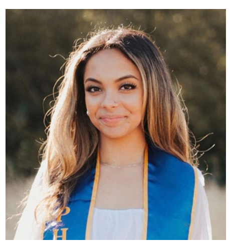
Kristina Andreyeva – I&T Engineer & Test Lead

Richard Henry Adam – Lead Communications Engineer (Astrobee)

Sam Feldman – Float Bot Test Bed Development Engineer

Griffin MacRae: Mechanical Support Engineer

Tristan Griffith: Mechanical Support Engineer



Camila Aristimuno Ots – RPO Test Engineer

Vidu Jayanetti Electronics Engineer

Melodie Ebrahimi – RPO Software Engineer

Pierson Lintala – Float Bot Test Bed Development Engineer

# ALUMNI

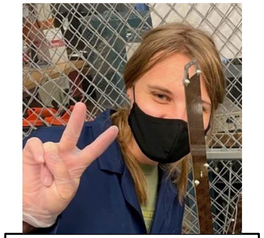
Ezra Eyre (Alumni) – RPO Algorithm Development Engineer

Jonathan Nguyen (Alumni) – Float Bot Test Bed Development Engineer

James Le(Alumni) – Float Bot GNC Engineer

Jet Propulsion Laboratory
California Institute of Technology

Miles (Astrobee Adapter Development)



Julia Schatz – Lead Electronics Engineer

Dr. Rahul Rughani – RPO Consultant

Enrique Cernas – Lead Mechanical Engineer

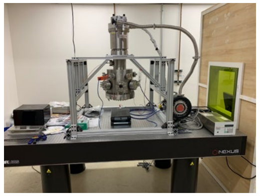
Shobhita Rajashekar – Electronics and I&T Engineer

# USC's Space Engineering Research Center: What is it

- **Space Engineering Research Center**
  - Formed in 2007 out of joint effort between Dept of Astronautical Eng. And ISI
  - ~230 undergrad/grad/PhD students involved in all aspects of hands-on space engineering to-date
  - >80 publications to-date
  - First satellites built/launched at USC
  - Operates as a "Space Engineering Teaching Hospital"

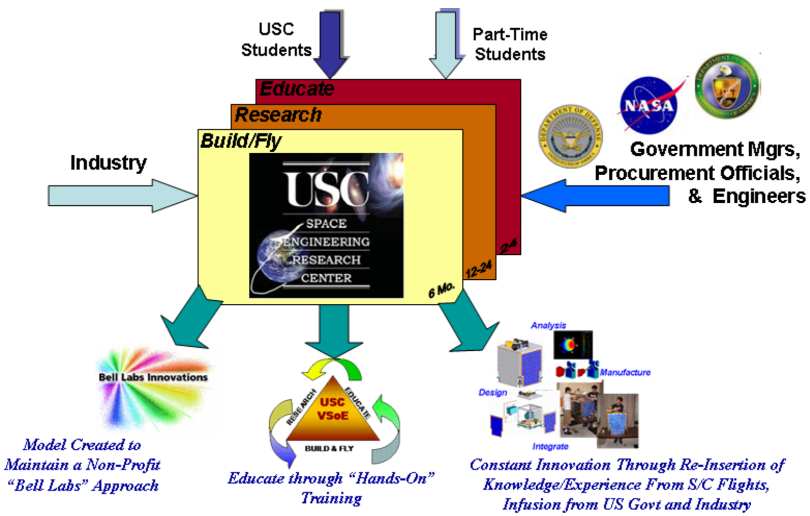
**SERC Engineering Offices, Clean Room and Labs (at ISI)**

**Satellite Ground Comm Station (on Campus)**

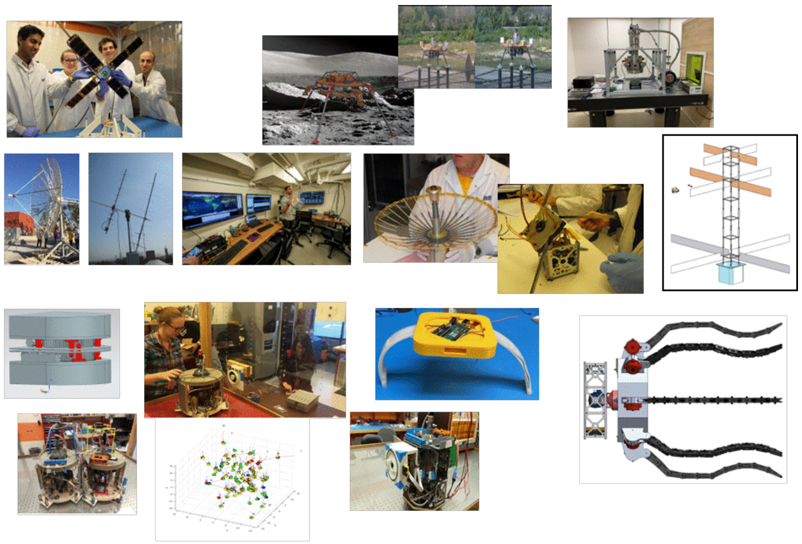


**SERC Laser Lab (On Campus)**

***SERC Research encompasses range of Spacecraft Engineering and Tech Innovation***




- Spacecraft Simulation, Coding, Build/Fly
- Ground and Flight Communication
- RPO Technologies and Techniques
- Swarm and Cellular Aggregation



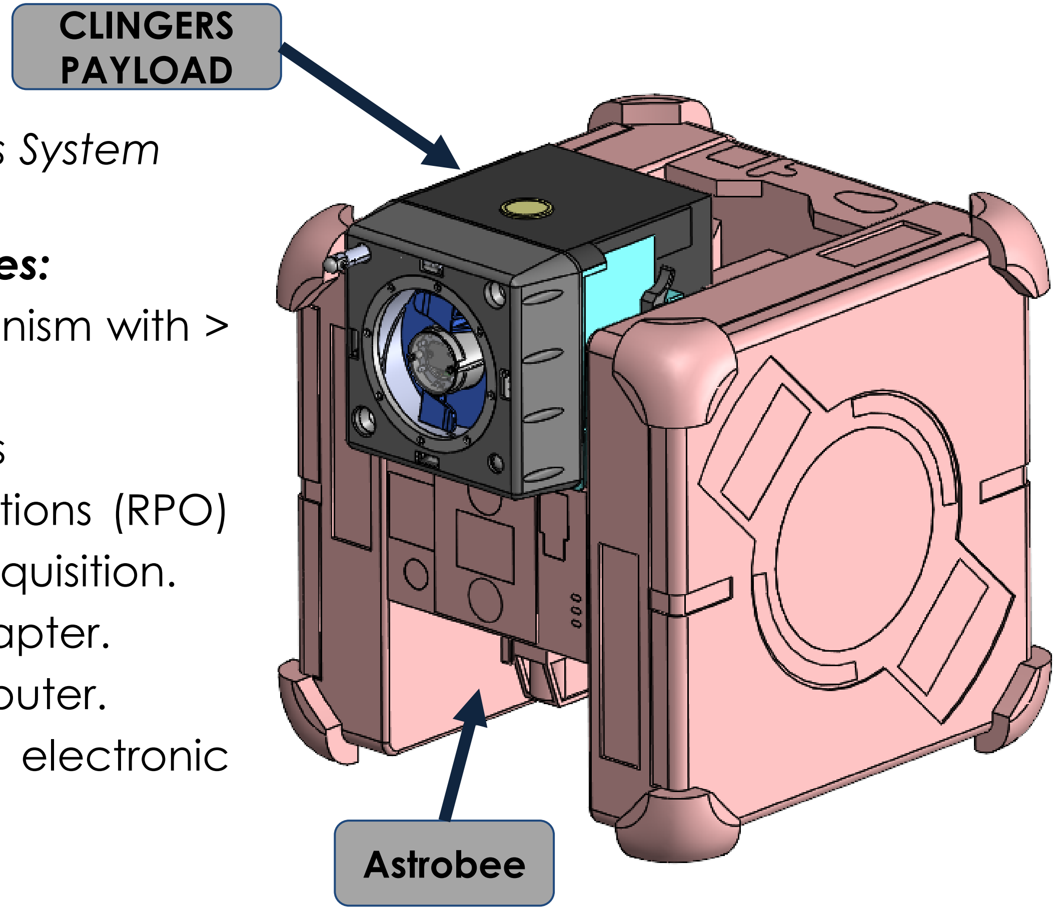
# CLINGERS FLIGHT DESIGN OVERVIEW

❑ ***CLINGERS stand for:***

- *C – Compliant*
- *L – Low Profile*
- *I – Independent*
- *N – Non-protruding*
- *G – Genderless*
- *ERS – Electronics Rendezvous System*

❑ ***CLINGERS flight design features:***

- Docking / undocking mechanism with > $8^0$ of nominal compliance.
- Standalone and autonomous
- Rendezvous Proximity Operations (RPO) sensor suite for target POS acquisition.
- Integrated with Astrobee Adapter.
- Raspberry Pi 4B as flight computer.
- Custom PCB for power and electronic components management.



# RESEARCH GOALS

*CLINGERS is an experiment on board the ISS to help raise TRL from 3 to 5 on an Applied docking concept*

1. **Investigate the mergence of traditional docking / undocking mechanisms with RPO sensors to increase overall safety through "co-operation".**

2. **Study the effectiveness of implementing a RPO solution independent of the host's navigational capabilities.**

3. **Investigate nominal and off-nominal contact dynamics in 6 DOF.**

4. **Investigate the performance of a Perspective aNd Point (P-N-P) algorithm to acquire accurate and reliable bearing and range knowledge from client.**

5. **Investigate the resiliency between co-operating devices as part of a limited networked distributed system to conduct in-orbit assembly**

# ENGINEERING SUCCESS CRITERIA

***CLINGERS will have to dock and undock autonomously in 3D dimensional space***

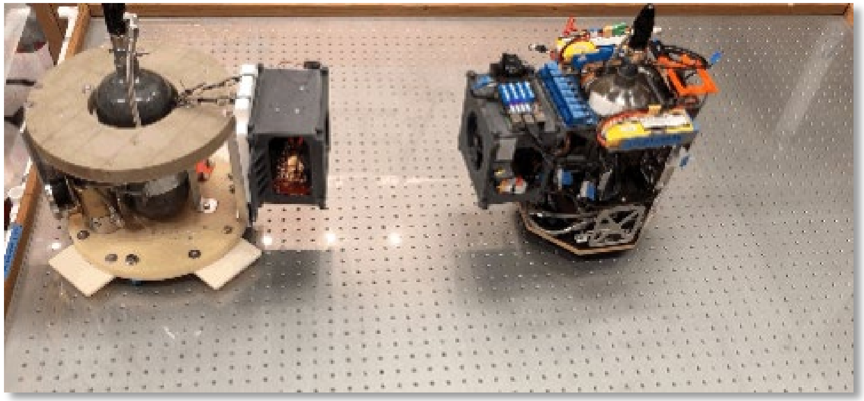
- ***Achieve hard dock from 1, 2 and 3 meters of initial separation from host autonomously under the following parameters:***
  - *Nominal angles (near-straight view during start) with an initial induced velocity of approach.*
  - *Off-nominal angles (inclined view during start) with an initial induced velocity of approach.*
  - *No initial visual of the target and starting from a stationary state (relative to target).*

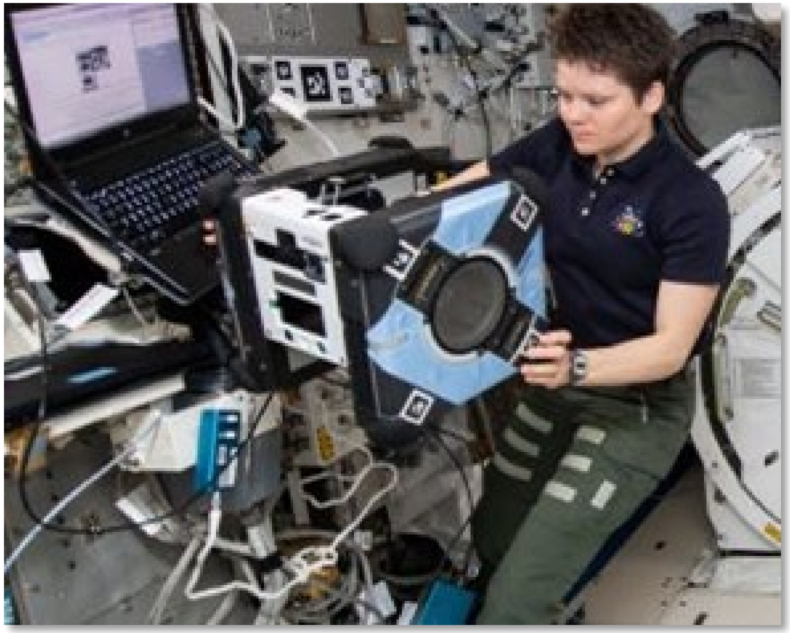
- ***Achieve docking and undocking with a "dead" CLINGERS (Except IR LED lights nothing else is operational in a dead CLINGERS)***
  - *Dead CLINGERS' Astrobee is rigidly mounted to the wall or held by a crew member.*
  - *Dead CLINGERS' Astrobee is free floating in space.*

- ***Achieve an acceptable level of accuracy of P-N-P's range and bearing POS output with respect to (w.r.t.) true range and bearing POS between chaser and target.***

# WHY ISS?

*CLINGERS flight design builds from 2D static and dynamic testing, to full 6DOF*





1g ground dynamic test on air bearing platform. 1 Plane and 3DOF (Limited Contact Dynamics)

***This test campaign is still insufficient since it does not validate CLINGERS performance in the z direction and pitch & roll rotations***

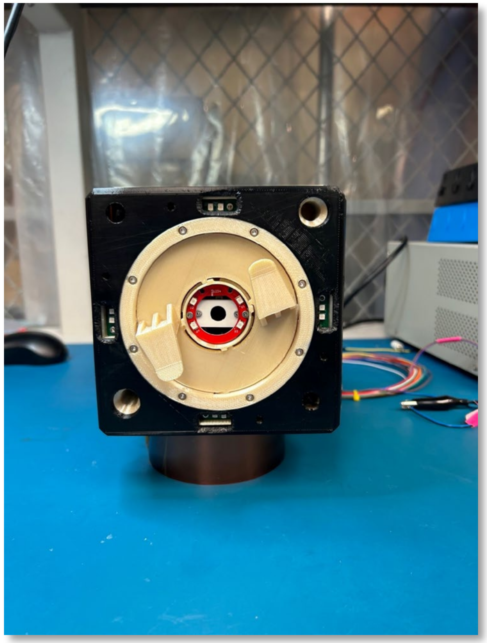
# WHERE ARE WE AS OF 1 JUNE 2023?

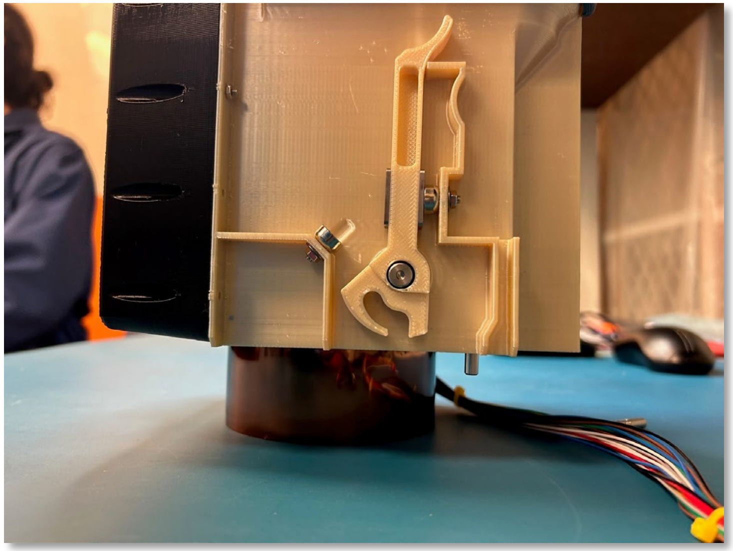
**Two flight units are in soft bag slung over shoulder of SpaceX integration engineer ready to toss into SpaceX-28 for launch 3 June…**

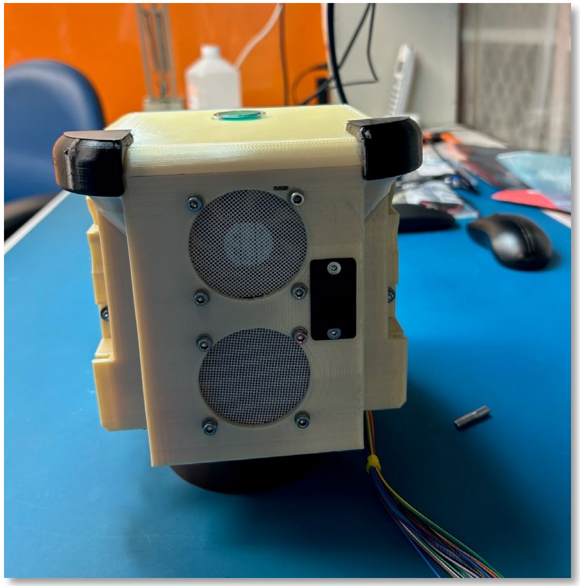

**The team is…**

- Excited
- Terrified
- Ready
- Panic'd
- Behind the curve on Crew procedures
- Scrambling to get USC IT and MSFC IT to talk to each other
- Very thankful Astrobee Team is patient, competent and used to excited, terrified, panic'd experimenters…

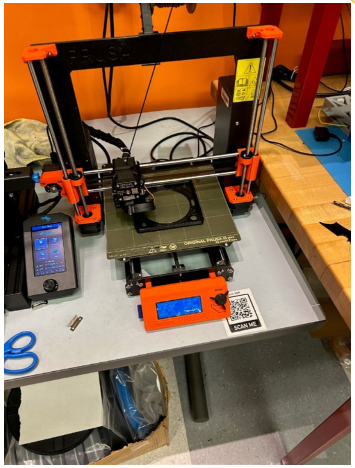
# As Built Photos

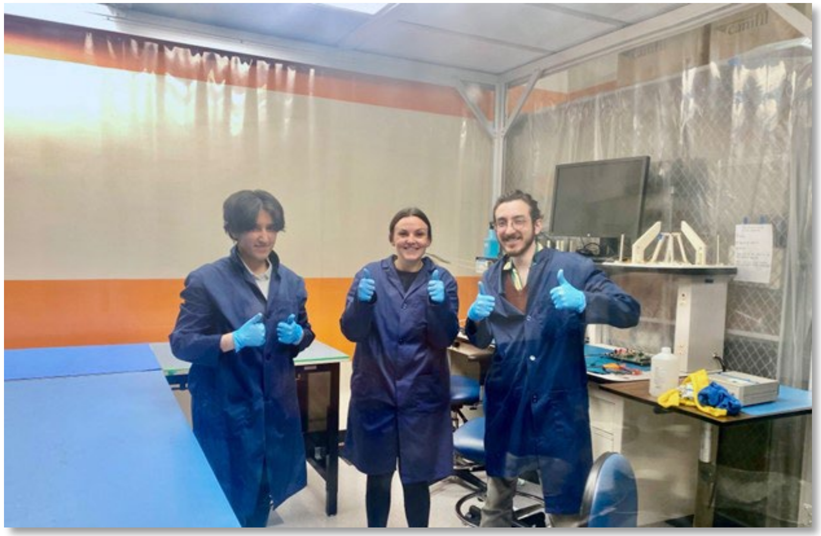






# The I&T Crew were somehow calm…





USC UNIVERSITY OF SOUTHERN CALIFORNIA

ISI Information Sciences Institute USC School of Engineering

**CLINGERS**

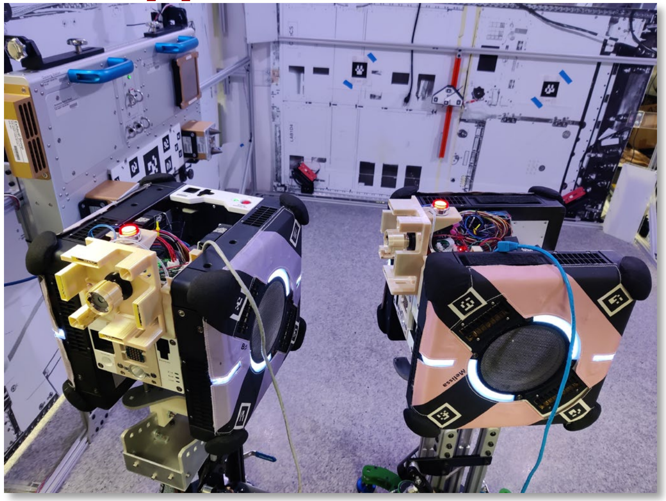
Flight Unit
Assembly and Integration Procedure
AIP-001

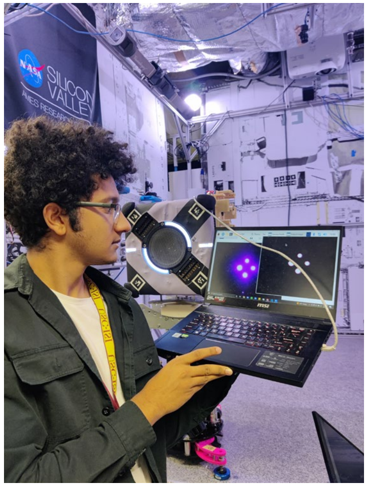
University of Southern California
Information Sciences Institute

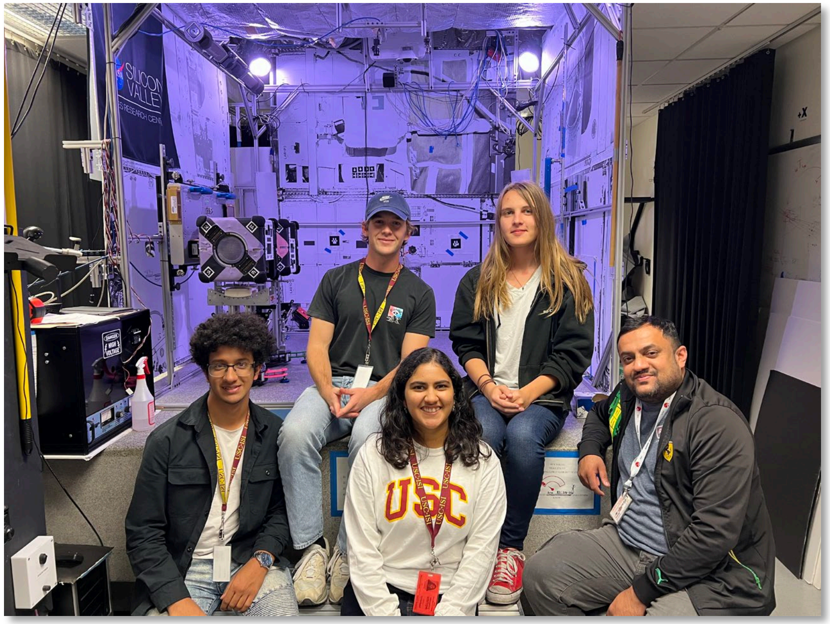
Space Engineering Research Center
4676 Admiralty Way,
Marina Del Rey, CA 90292

December 2022

# Testing To-Date – NASA Ames Granite Table, Initial Prototype Units

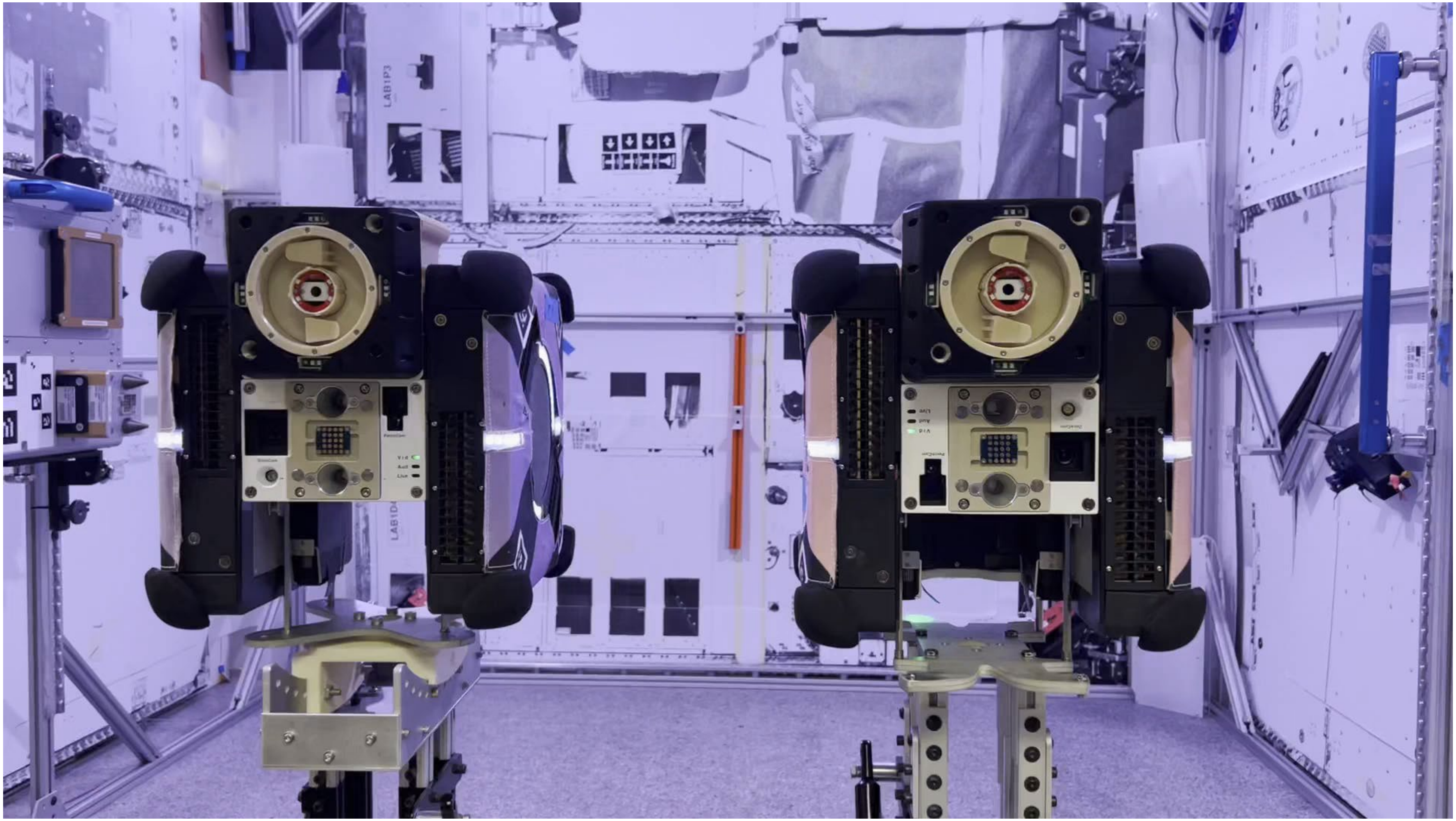






# TESTING TO DATE – NASA Ames, Flight EDU's

*Giving the Crew something to see when we start up…*

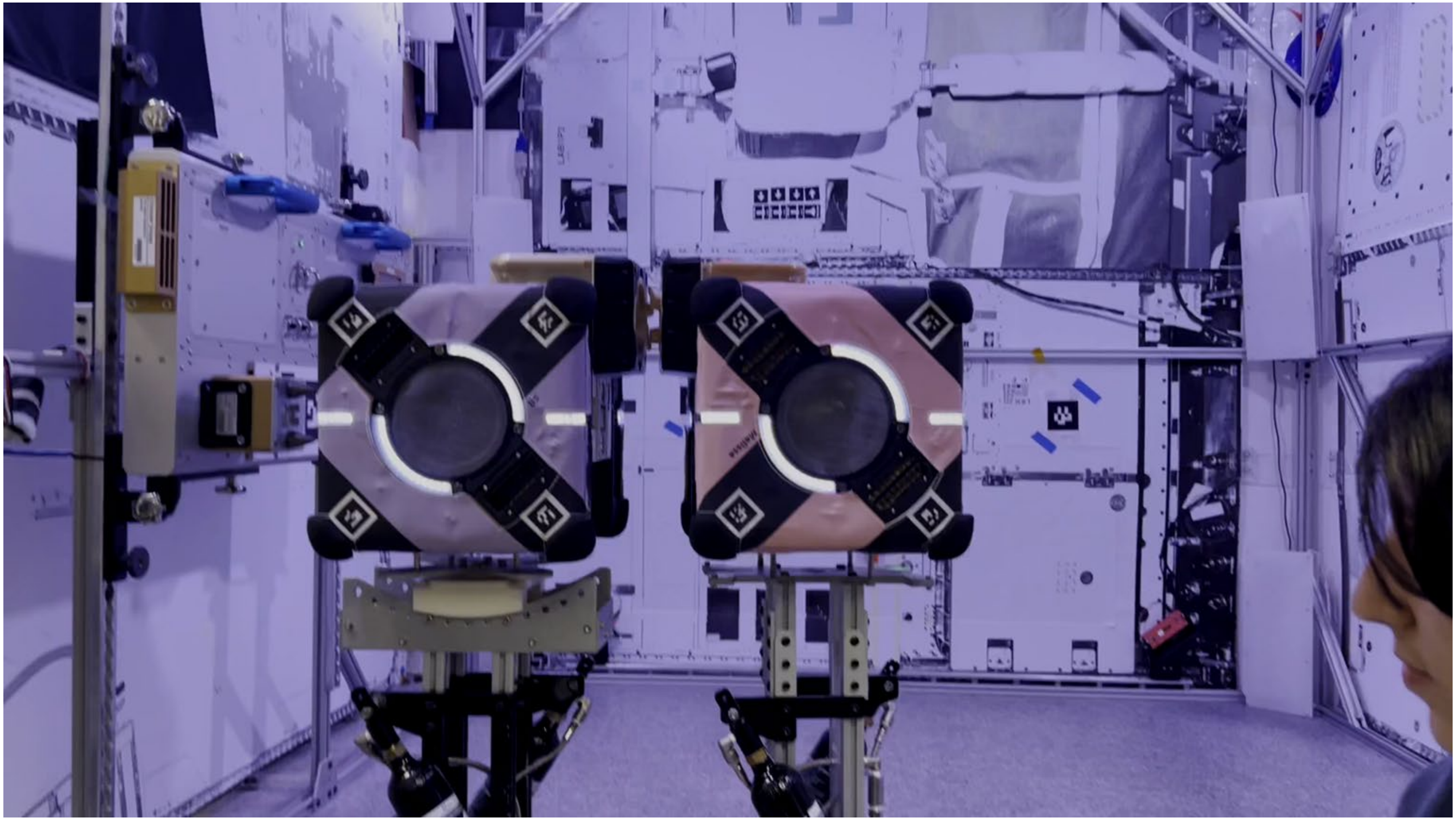


# TESTING TO DATE – NASA Ames, Flight EDU's (cont).

*Close by no cigar…*

# TESTING TO DATE – NASA Ames, Flight EDU's (cont.)

*The PhD gets surprised… and he wrote the code…*



# SOME POTENTIAL ASTROBEE TEAM PAYLOAD FIRSTS…

**Pioneering Firsts (yes, in some cases we wish we were second!):**

- Ability to upload software independent of Astrobee from an ISS Laptop
  - CLINGERS had an RJ45 ethernet connection installed in Integration for that purpose
  - Developed new procedures for S/W Upload
- First operation of Rasberry Pi4B on ISS
- Use of BlueTooth onboard ISS to talk to ourselves…
  - *(ixnay on Wifiay)*
- Approval to "stick out" from the Astrobee structural limits(not first…)
  - Approval for "bumper material" on CLINGERS

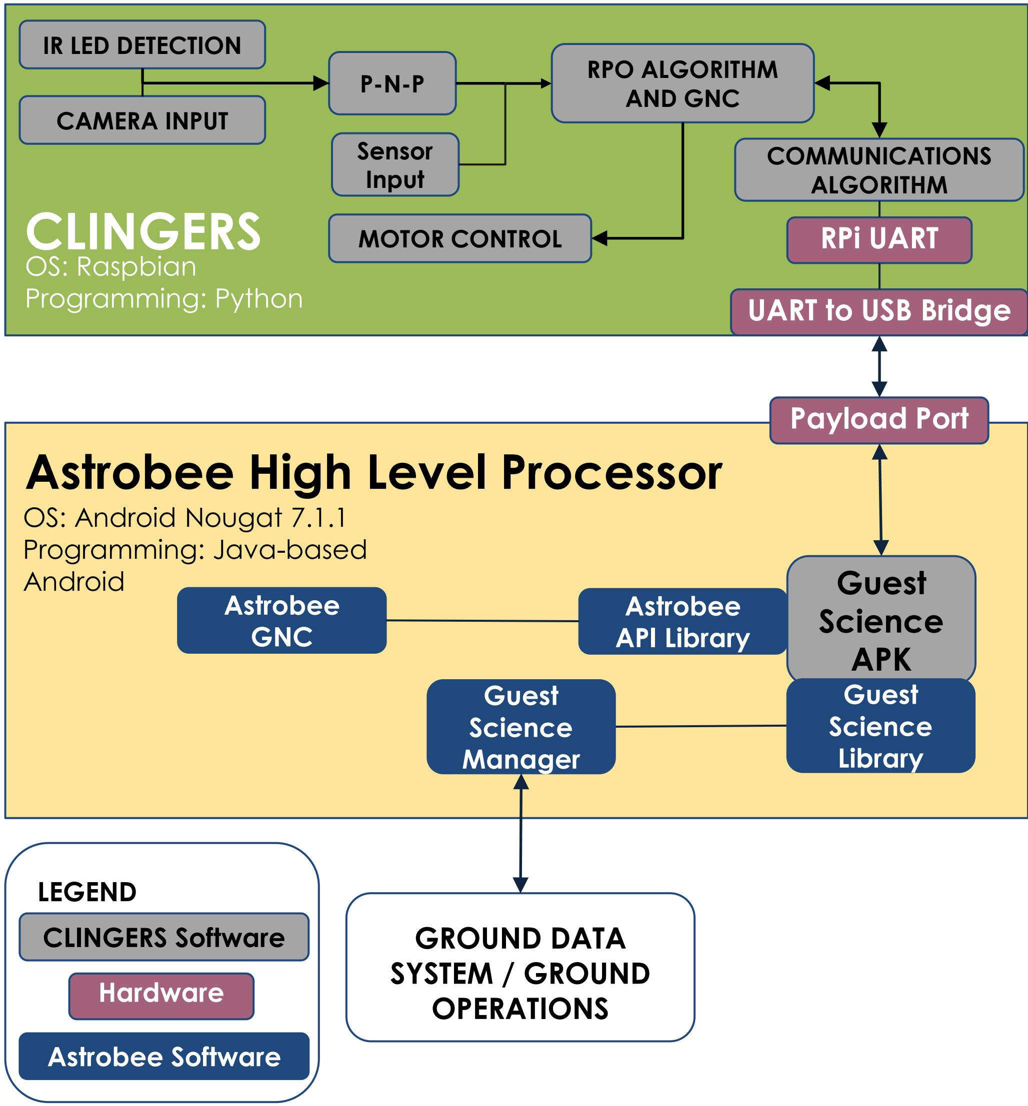
# THINGS WE WISH WE KNEW MORE ABOUT…

**Things like…**

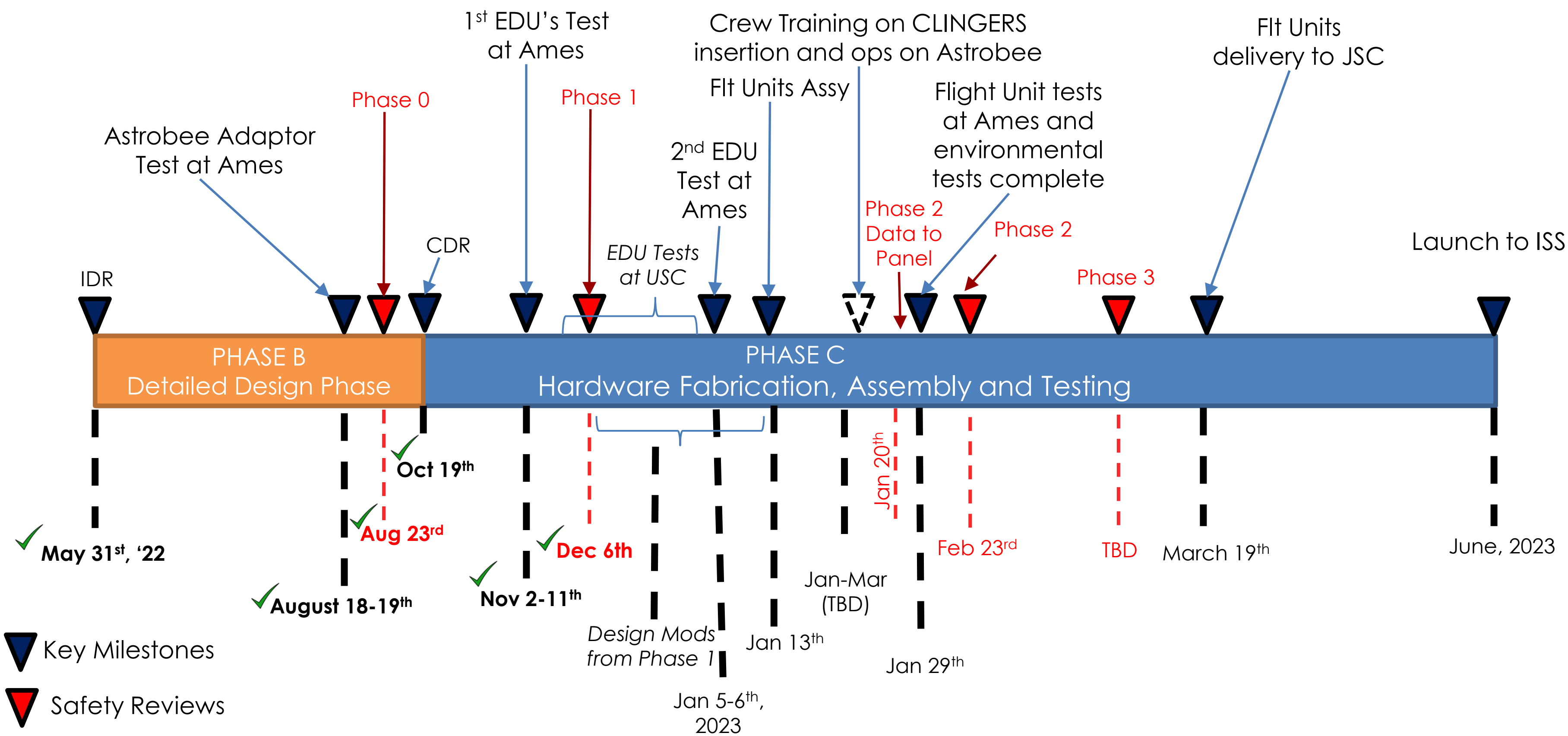
- That the Safety Review committee and verifications required for Safety ARE NOT THE SAME as Veritas…!
- FCC STE License required for Bluetooth, inside the ISS…
- That once you get a NASA account EVERYONE at NASA assumes you know every acronym, every process, and every minutia of beauracracy…
- TAKE whatever training NASA offers in ORBITS and VERITAS… 😉
- Take schedule snafus (like being de-manifested) with lots of grains of salt… 😉
- Green Buttons…Good, Red Buttons…Bad
- Get LOTS of extra Astrobee connectors, make up multiple pigtail connector leads… WRING IT OUT AND LABEL
- Can't put your own Stickers on your units… but there is a whole shop that will design your logo and labels at NASA! (the catalog is over 400 pages… no kidding… recommend letting them recommend the font…)
- USE THE APK Astrobee offers you!!!!! It works!!!!!

# DATA FLOW TO ASTROBEE: USE THE APK!!!

- **CLINGERS Communication Algorithm formats GNC suggestions as JSON strings, binarizes them, and sends them to the RPi UART port**
- **Data received in the Astrobee Payload Port is gathered by the CLINGERS APK, decoded, and parsed to execute Astrobee GNC**
  - *NASA's Astrobee API library allows Guest Science APKs to control Astrobee's movement*
- **If LEDs are not detected, CLINGERS queries Astrobee for orientation data to execute a rotation to face the client CLINGERS**
- **The Guest Science Manager is a critical application built into the HLP that allows our APK to receive commands from the Ground Data System at JSC**



# A year? Piece of cake….NOT SO FAST….




- We thought 12 months was a long time….;)
- Flight Manifest projected for June 2023, SpaceX 28
- But JSC needed it 90 days prior to projected launch
- So it wasn't 12 months, it was 10 months!

# SOME OBSERVATIONS-PRE FLIGHT…

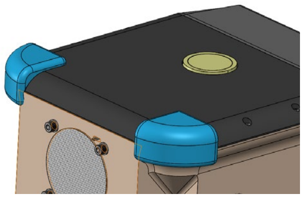
- **Safety Review Process was very Straight forward.**
  - The Safety Representative assigned to you IS YOUR FRIEND!
  - Take their "recommendations"….seriously
  - Our Safety process, while rigorous, was seamless.

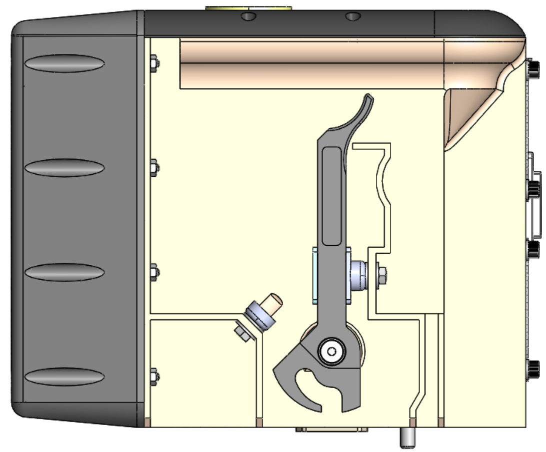
- **Expect to do Tests that you didn't anticipate!!!**
  - If you have Magnetics (and you will) do a Magnetic Field test
  - If you have anything that makes Noise, do Acoustic Test
  - If you have anything that heats up more then tepid warm water, and you will, you have to do a Thermal Touch temperature test
  - If you have anything that radiates EM, you have to do an EMI test (at MSFC)
  - If you have "soft" materials, you have to do toxicity analysis (if JSC hasn't done it already)
  - If you have rotating things, you have to protect them from stray fingers…
  - If you radiate, you have to do an RF Hazard Analysis

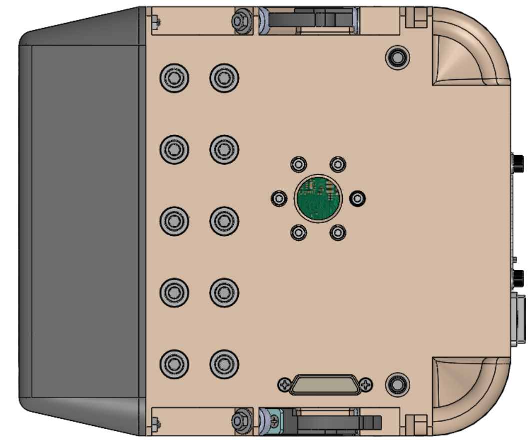
# DESIGN AND CONFIGURATION (FLIGHT) WAS ROUNDED AND PADDED

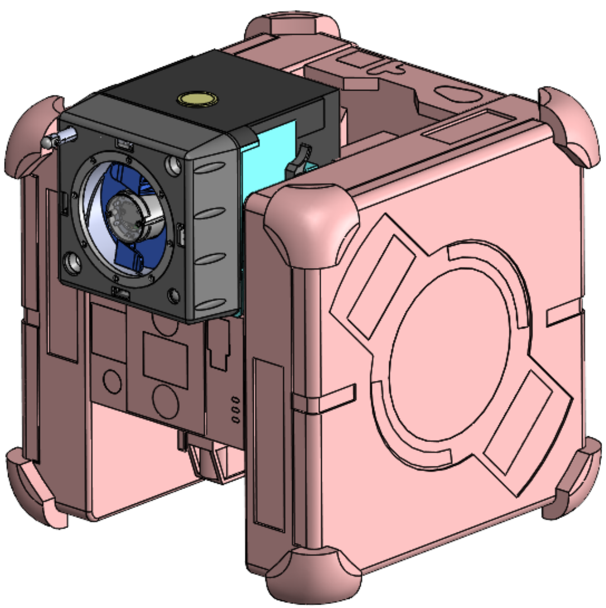
## Bumpers were Added

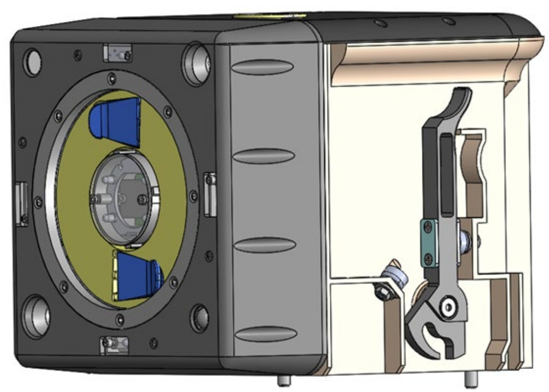
**We went through multiple design iterations before getting to the final Flight configuration**

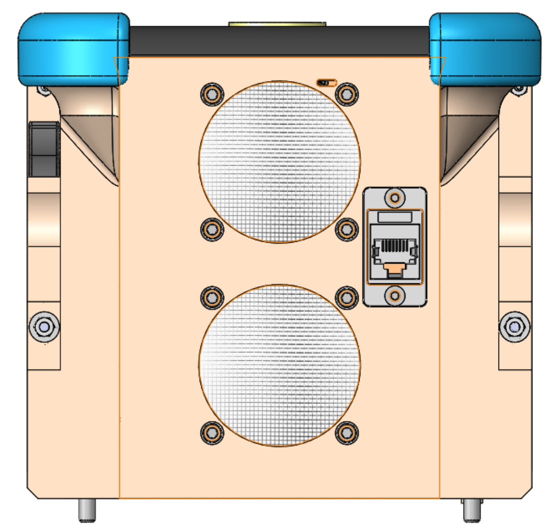










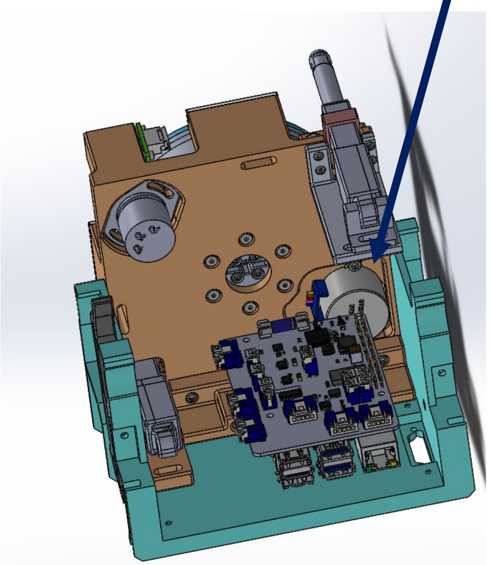


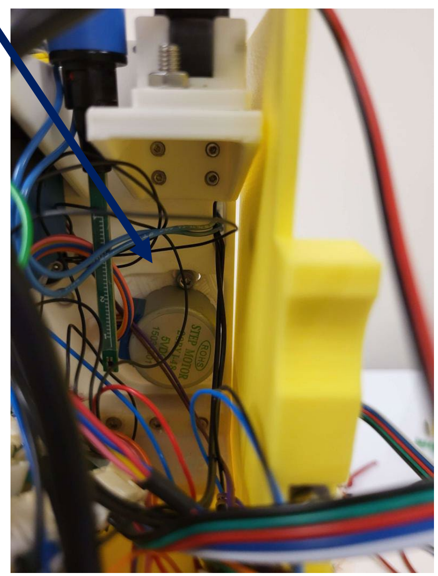
# MAGNETICS: You may have to actually measure them!

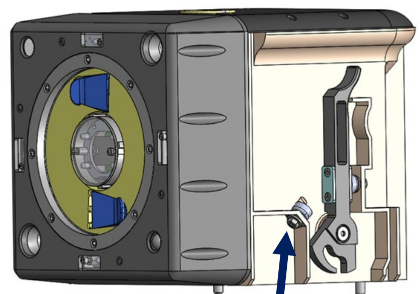
There are two sets of magnetic elements on CLINGERS:

1. The Stepper Motor has permanent magnets
2. The Astrobee adaptor chassis has two permanent magnets for each lever Arm, a total of 4 per Unit

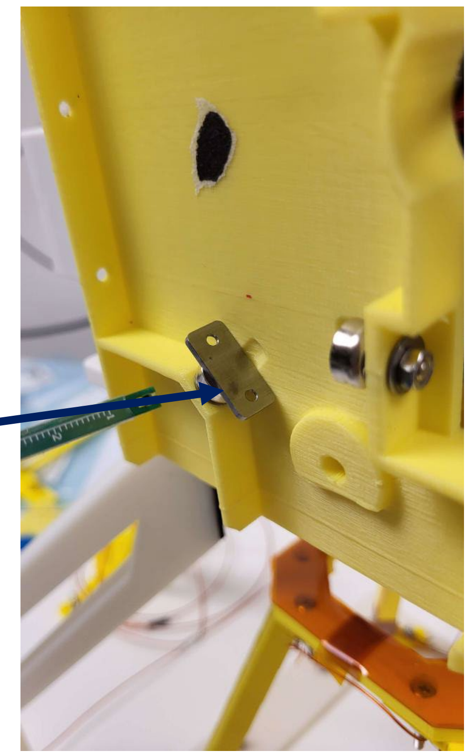
**Stepper Motor inside the structure**







**Permanent magnets to hold the astrobee docking lever in place, 2 on each side.**

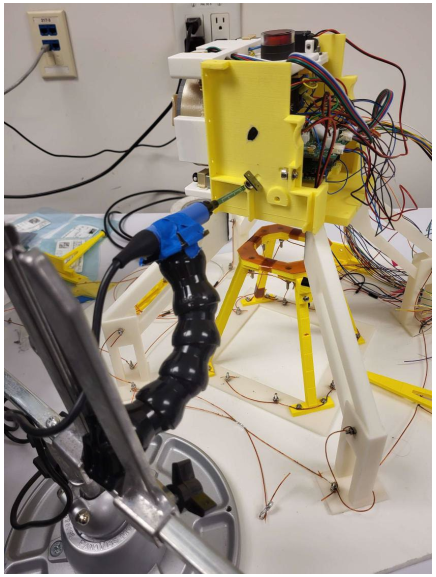


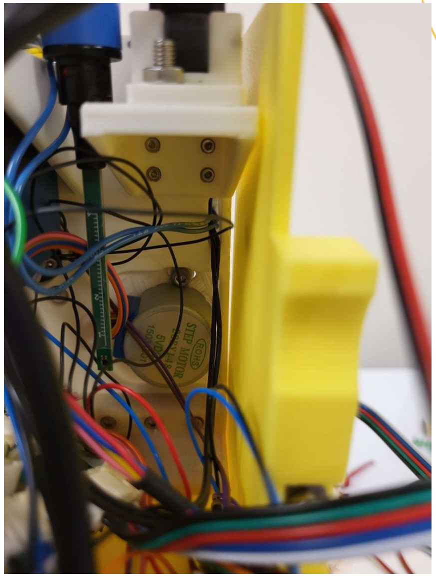
# MAGNETICS TESTING FOR ACCEPTANCE IN SSP 50835, paragraph 3.2.4.7.1

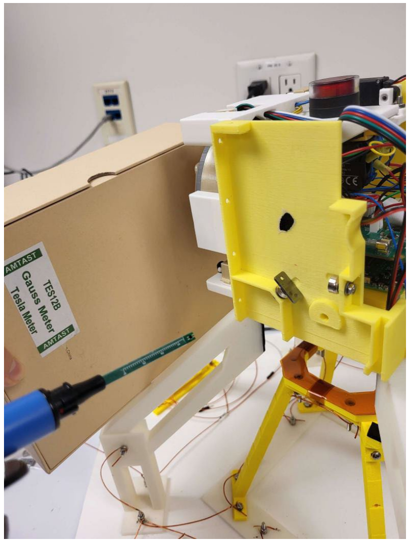
- Per SSP 50835, each magnetic element should be **< 3.16 Gauss at 7cm**
- Testing was done with a Gaussmeter at different distances to both magnetic elements.
- **Testing results show we Comply with DC magnetic field requirements.**

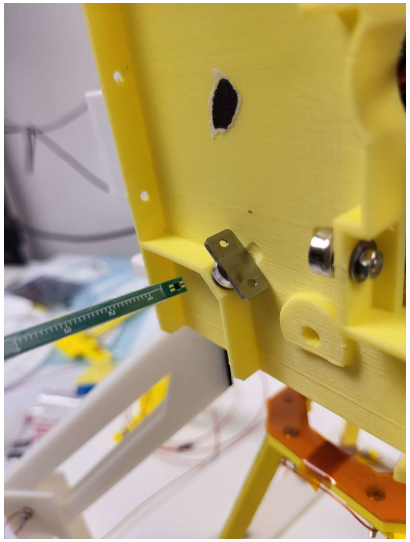
| Object | Distance | Gauss Reading |
|---|---|---|
| Side Magnet and Locking Lever Magnet | 1 cm | 6.3 |
| | 4 cm | 1 |
| | **7 cm** | **0.6** |
| Stepper Motor | 1 cm | 1.2 |
| | 4 cm | 1.3 |
| | **7 cm** | **0.4** |

**Note:** Higher reading at 4cm for stepper motor due to sensor in proximity of the two external lever magnets



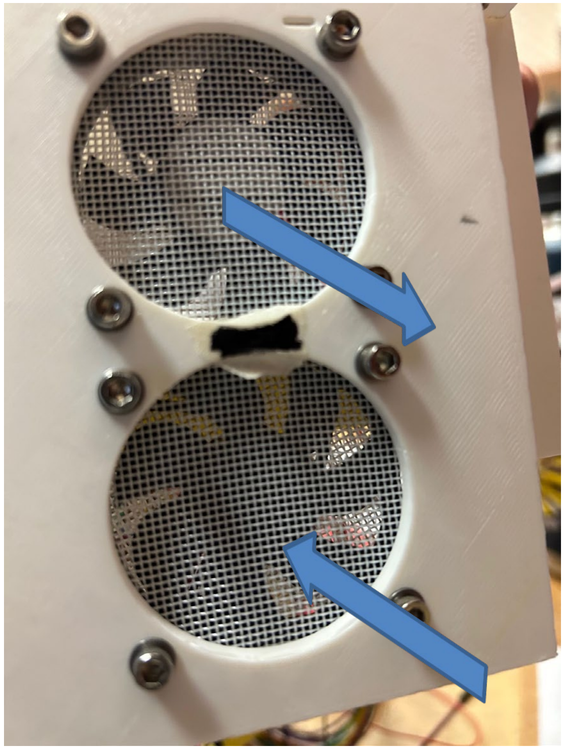




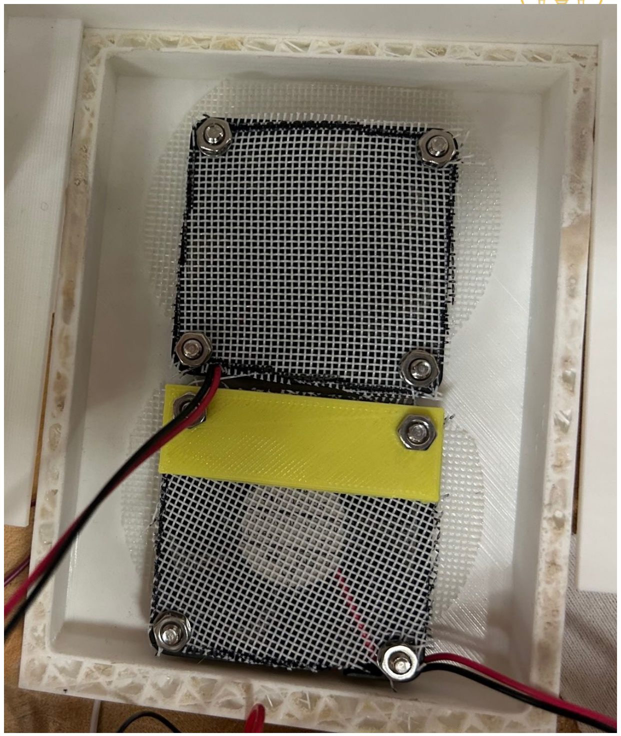



# Fan safety mesh installation was Required

- Each CLINGERS unit has two fans on the aft Face
  - The bottom fan brings air in, and the top fan draws air out.
- A nylon mesh material is used to cover the access of the fan from the outside, as well as to cover the entrance to the fan on the inside of the device
  - The external access is for safety of contact with a spinning fan
  - The internal access is to avoid potential to ingest FOD from any source.



One layer of mesh is located on the inside of the Aft Enclosure, securely fastened in between fan and structure.



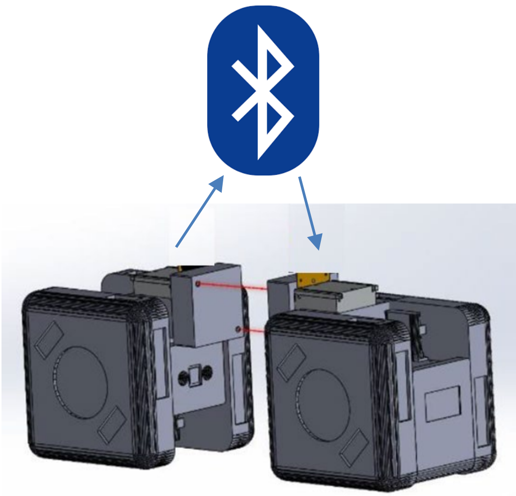
A second layer of mesh is located on the inside of the structure on the fan itself to preclude FOD.
Note, a small piece of PLA is used on the top of the bottom fan as further protection for a cable that could press against it.

The cooling fan is 50mm diameter and operates at 5800 rpm. It meets the low energy exemption (<200 mm, <8000 rpm).

**Containment meets reqmt per NASA-HBK-5010 Section 5.1.5**

# BlueTooth RF Operation: FCC approved at ISS Altitude!

***CLINGERS uses internal Bluetooth RF to communicate forensics back and forth for assessing operations***



## Per SRAG_RF_HA_v1.2 Analysis

*SRAG_RF_HA_v1.2(Version Approved April 7, 2020)*

**ISS System/Payload:**

**Hazard Analysis Verification**
**Space Radiation Analysis Group (SRAG)**

**SRP POC:** **Date:**

**POC:** **Ramona Gaza**

**System/Payload POC:** **D. Barnhart** 10/29/2022

**Alternate POC:** **Jeff Reilly**

### SSP 50005 Rev. G

| RF Emitter Name | Frequency (MHz) | Max Power (W) | Attenuator (Gain loss) (dB) | Max Gain (dBi) | Emitter Power Density ($W/m^2$) | Power Density Requirement ($W/m^2$) | Minimum Safe Distance (m) | Program Requirement Compliance | Payload Actions |
|---|---|---|---|---|---|---|---|---|---|
| CLINGERS Bluetooth (Lower) | 2402.00 | 0.00 | 0.00 | 3.50 | 0.01 | 16.01 | No Hazard | PASS | |
| CLINGERS Bluetooth (Upper) | 2480.00 | 0.00 | 0.00 | 3.50 | 0.01 | 16.53 | No Hazard | PASS | If Column P shows PASS, there is no Crew Hazard from the transmitter. Payload will submit Form SRAG_RF_HA_v1.2 to NIR SME for overall HA verification. |

## Per RF Hazard Calculator Analysis

| Transmit Power (W) | Antenna Gain (dBi) | Antenna Type | Upper Frequency (MHz) | Lower Frequency (MHz) | Antenna Dimension (m) | Transition Distance (m) | Power Density (W/m^2) | Electric Field (V/m) | Power Density Limit | Possible Hazard? |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.0045 | 3.5 | Bluetooth | 2480 | 2402 | 0.025 | 0.41333333 | 0.000802 | 0.549752084 | 0.955 | NO |

# Analysis of WiFi on RPi Chip for Hazards: Important for Safety AND ISS Operations

- WiFi on the Rasberry Pi4B will be SOFTWARE DISABLED.
- The Transmitter Chip on the RP4B is the same chip for both Wifi and BT
- The SRAG and RF Hazard Calculator Analysis was validated at the frequencies of **BOTH WIFI and BT**

**BT Frequencies:**
**2402 to 2480 MhZ**

**WiFi Frequencies (FCC Allows 11 channels):**
**2401 to 2473 Mhz**

**Per SRAG_RF_HA_v1.2 Analysis**

*SRAG_RF_HA_v1.2(Version Approved April 7, 2020)*

**ISS System/Payload:**

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**Space Radiation Analysis Group (SRAG)**

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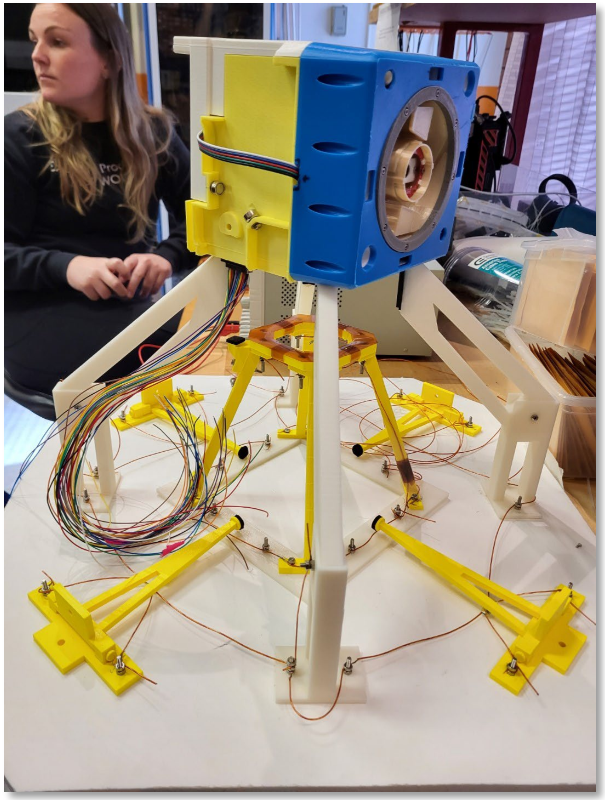
| RF Emitter Name | Frequency (MHz) | Max Power (W) | Attenuator (Gain loss) (dB) | Max Gain (dBi) | Emitter Power Density (W/m$^2$) | Power Density Requirement (W/m$^2$) | Minimum Safe Distance (m) | Program Requirement Compliance | Payload Actions |
|---|---|---|---|---|---|---|---|---|---|
| LINGERS Bluetooth (Lower) | 2402.00 | 0.00 | 0.00 | 3.50 | 0.01 | 16.01 | No Hazard | PASS | |
| LINGERS Bluetooth (Upper) | 2480.00 | 0.00 | 0.00 | 3.50 | 0.01 | 16.53 | No Hazard | PASS | If Column P shows PASS, there is no Crew Hazard from the transmitter. Payload will submit Form SRAG_RF_HA_v1.2 to NIR SME for overall HA verification. |

**Per RF Hazard Calculator Analysis**

| Transmit Power (W) | Antenna Gain (dBi) | Antenna Type | Upper Frequency (MHz) | Lower Frequency (MHz) | Antenna Dimension (m) | Transition Distance (m) | Power Density (W/m^2) | Electric Field (V/m) | Power Density Limit | Possible Hazard? |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.0045 | 3.5 | Bluetooth | 2480 | 2402 | 0.025 | 0.41333333 | 0.000802 | 0.549752084 | 0.955 | NO |

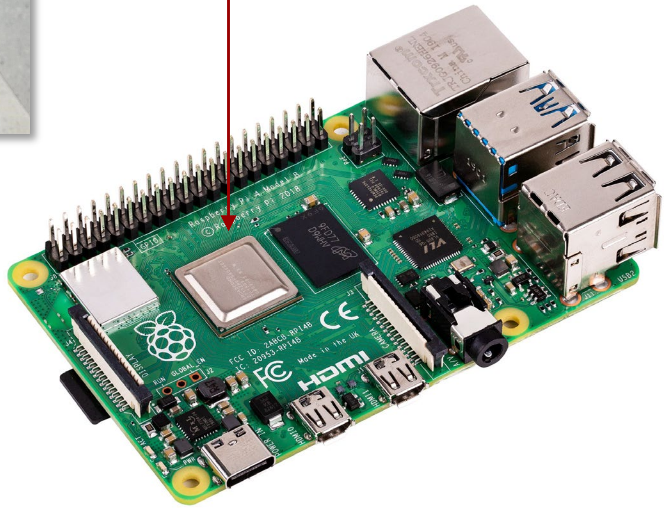
# Internal Rasberry Pi 4B Testing for heat load understanding only

- **Even though the Rasberry Pi was inside CLINGERS and Encapsulated, we did a "touch test" to the entire structure**
- **Two different Configurations used to test the Pi thermal load**
  - Static Test Stand with Open Flow Configuration
  - CLINGERS encapsulated with single Fan (i.e. dual fault tolerant)

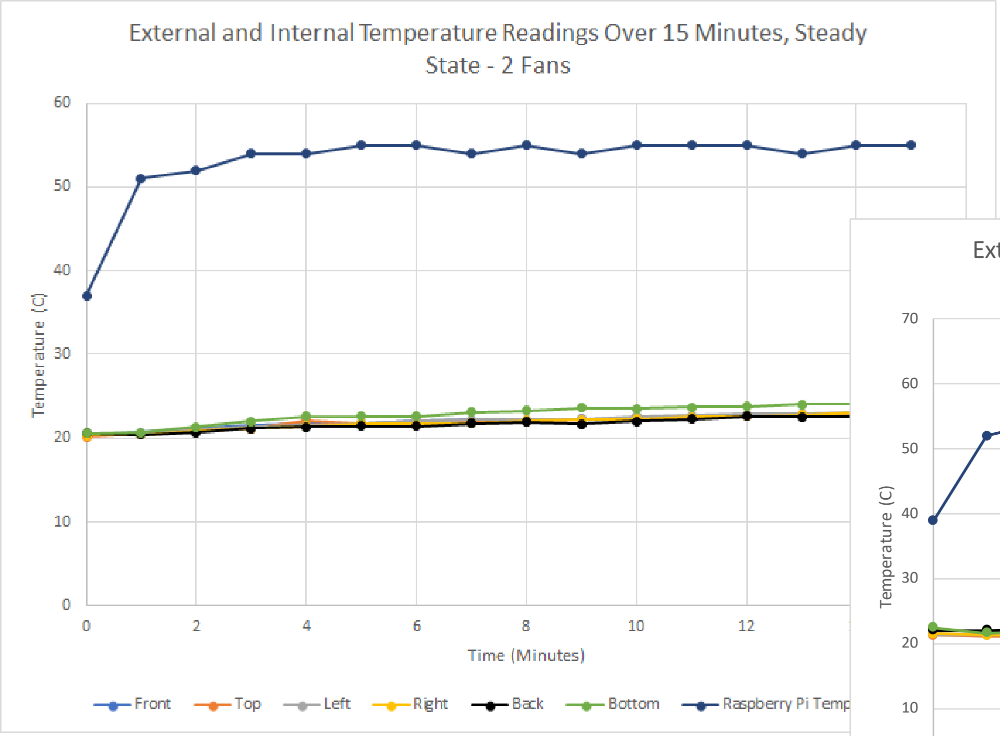


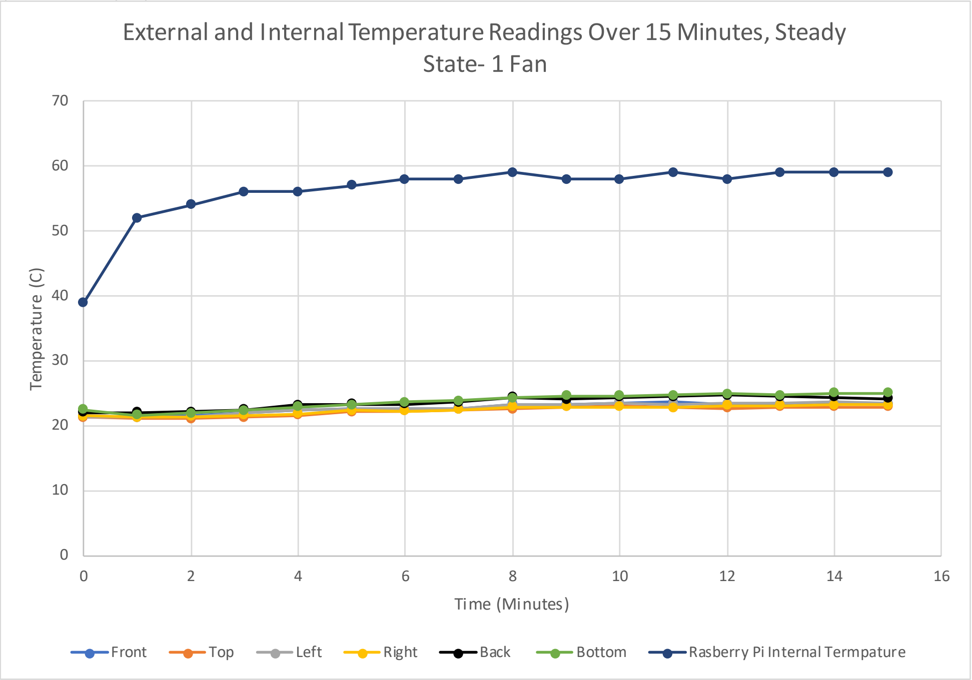
**Static Test Stand**

Processor



# Touch Temperature Thermal Test Results: Examples




Resultant Temperature readings from external surfaces on CLINGERS unit during steady state test, compared to the Rasberry Pi readings during same time frame, [left] both fans operating, and [right] one fan operating

# ELECTRICAL HARNESSING HAVE REQUIREMENTS FOR VOLTAGE AND CURRENT, HEED THEM

*All cables are well below heavily derated allowable current limits*

| Wire | Current capacity (A) (Rule of thumb) | Current capacity derated by 50% (A) (Rule of thumb) | Upstream Current Protection Limit for a Single Wire (Isw) (amps)* | Expected maximum sustained current per conductor (A) | Temperature Rating (°C) | Circuit |
|---|---|---|---|---|---|---|
| 24 AWG | 3.5 A | 1.75 A | 5.4A | 0.375A | -40 to 105 °C | Other (power harness, other boards) |
| 26 AWG | 2.2A | 1.1A | 3.8A | 0.5A | -40 to 105 °C | Linear Actuator Harnessing |
| 1061 UL<br>26 AWG | 2.2A | 1.1A | 3.8A | 0.5A | 80 °C | Stepper Motor |
| 1007 UL<br>26 AWG | 2.2A | 1.1A | 3.8A | 0.5A | 80 °C | Linear Actuator |
| 28 AWG<br>ASSHLSSHL28K305<br>(UL 1571 Style) | 1.4A | 0.7A | N/A, table does not prescribe wires >26awg | 0.01A | 80 °C | Inner LED board |
| Astrobee Harness<br><br>26 AWG | 2.2A | 1.1A | 3.8A | 0.5A | -55°C to +200°C | Astrobee Harness (Connects CLINGERS to Astrobee) |

# INITIAL ISS EXPERIMENT MATRIX (DRAFT)

***What we WISHED for MAY NOT be what WE GET….***
***Calculate your Science to Crew Time Ratio***

| Test Number | Test Description | Test Type | Data Products |
|---|---|---|---|
| **1** | Pre-test checks | N/A | Health data |
| **2** | Autonomous docking from a straight-line view from half a meter of separation | 2 Body Problem | Raw range and bearing data, Astrobee POS, ISS test video, Astrobee thrust vector profile |
| **3** | Autonomous undocking and from half a meter of separation in a straight line | 2 Body Problem | Raw range and bearing data, Astrobee POS, ISS test video, Astrobee thrust vector profile |
| **4** | Autonomous docking with a partial angular view from 2 meters of separation | 2 Body Problem | Raw range and bearing data, Astrobee POS, ISS test video, Astrobee thrust vector profile |
| **5** | Autonomous undocking and from 3 meters of separation | 2 Body Problem | Raw range and bearing data, Astrobee POS, ISS test video, Astrobee thrust vector profile |
| **6** | Autonomous docking with no initial view (both CLING-ERS' RPO cameras are pointed in the opposite direction) from 3 meters | 2 Body Problem | Raw range and bearing data, Astrobee POS, ISS test video, Astrobee thrust vector profile, motor current and health data |
| **7** | Autonomous undocking and return to initial state | 2 Body Problem | Raw range and bearing data, Astrobee POS, ISS test video, Astrobee thrust vector profile |
| **8** | Autonomous docking to a stationary floating CLING with no initial view (Chaser CLING initially pointed in the opposite direction) from 3 meters. | 2 Body Problem | Raw range and bearing data, Astrobee POS, ISS test video, Astrobee thrust vector profile, motor current and health data |
| **9** | Autonomous undocking from a stationary floating CLING and return to original position | 2 Body Problem | Raw range and bearing data, Astrobee POS, ISS test video, Astrobee thrust vector profile |
| **10** | Autonomous docking to a stationary CLING mounted on an Astrobee that is rigidly attached to the Space Station | 2 Body Problem | Raw range and bearing data, Astrobee POS, ISS test video, Astrobee thrust vector profile |

# Summary and Discussion

# SUMMARY

- **Honor to be first up to ISS from our University as experiment on Astrobee**
  - From time to signing the document with CASIS/ISS National Lab to delivery of Flight hardware was 12 months

- **Balancing the desires vs reality of an "Orbital Lab" is a learning process**
  - We are now in the process of optimizing the time in operation, vs crew time
  - The idea you can't just "call up the crew" was strange to some of the team…lol.

- **Using the APK was critical to success, START EARLY!**
  - Having a dedicated person focusing on the APK communications is truly essential and critical to early success when doing first checks with Astrobee
  - The documentation and the hardware they offer works well, use it!

- **Be VERY mindful of the Validation process on ISS: It requires both Safety AND ISS Verifications**
  - Veritas is a font of information on best practices for electrical wiring, grounding, signals and power transfer; print them all out AT THE SAME TIME as the Safety Requirements and follow both