NASA Goddard Thermal Technology Roadmap 2026

Sergey Semenov - NASA Goddard Space Flight Center

2026 Spacecraft Thermal Control Workshop

The Aerospace Corporation

210 South Douglas Street, El Segundo, CA 90245, United States

March 31 – April 2, 2026

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Plankton, Aerosol, Cloud, ocean Ecosystem (PACE)

- Two years on orbit.
- All three instruments continue operating
  - Ocean Color Instrument (OCI)
    - Two LHPs (UVVIS and VISNIR) provide temperature control for the OCI instrument
  - Spectro-Polarimeter for Planetary Exploration (SPEXone)
  - Hyper-Angular Rainbow Polarimeter #2 (HARP2)
- Both LHPs operated flawlessly
- Over two year period PACE observatory was turned on/off 20 times
  - Each time both LHPs were shutdown and switched into survival mode.
  - Then LHPs were restarted using an autonomous scheme.
- No degradation of the LHP performance over two years.

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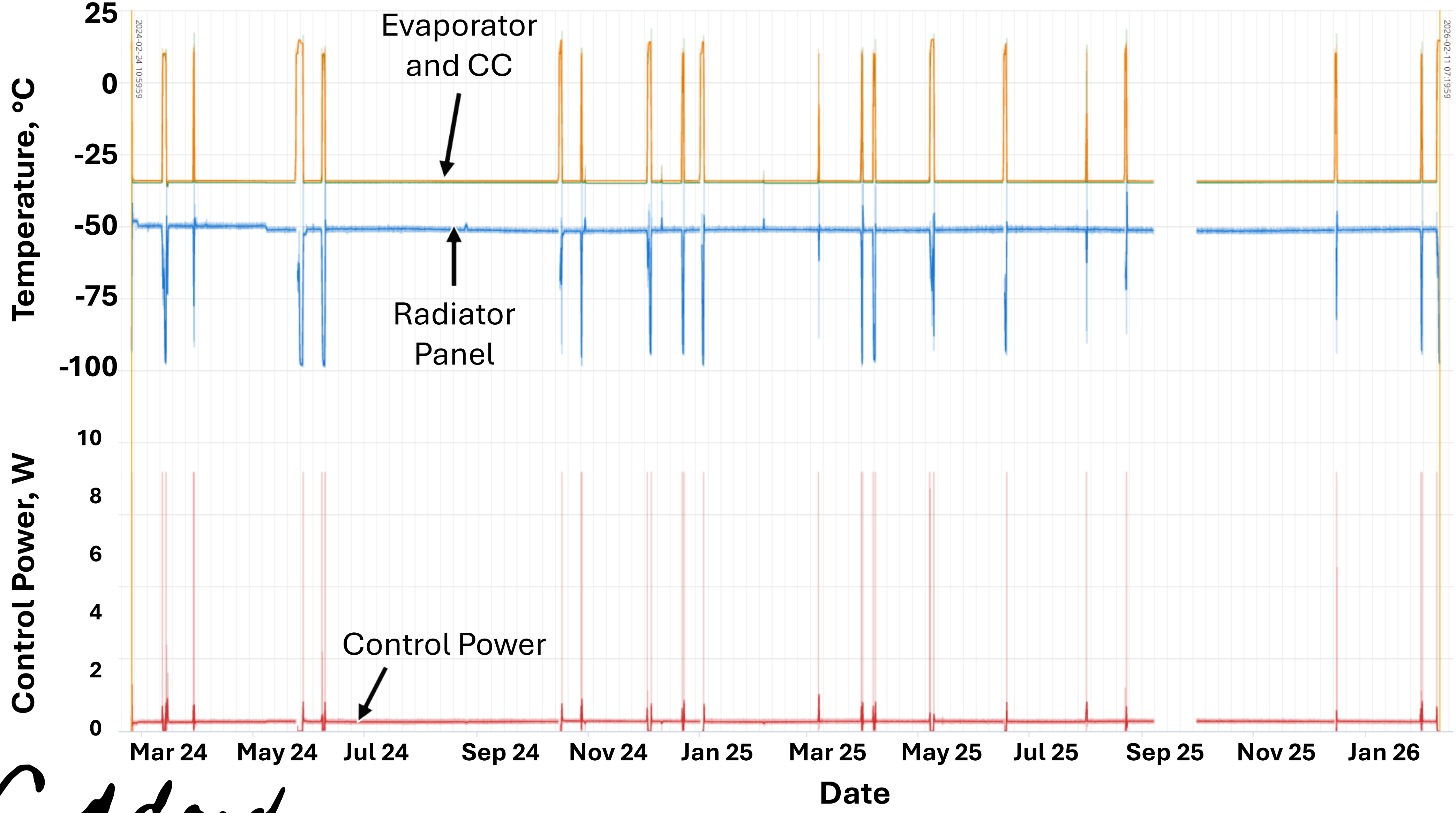
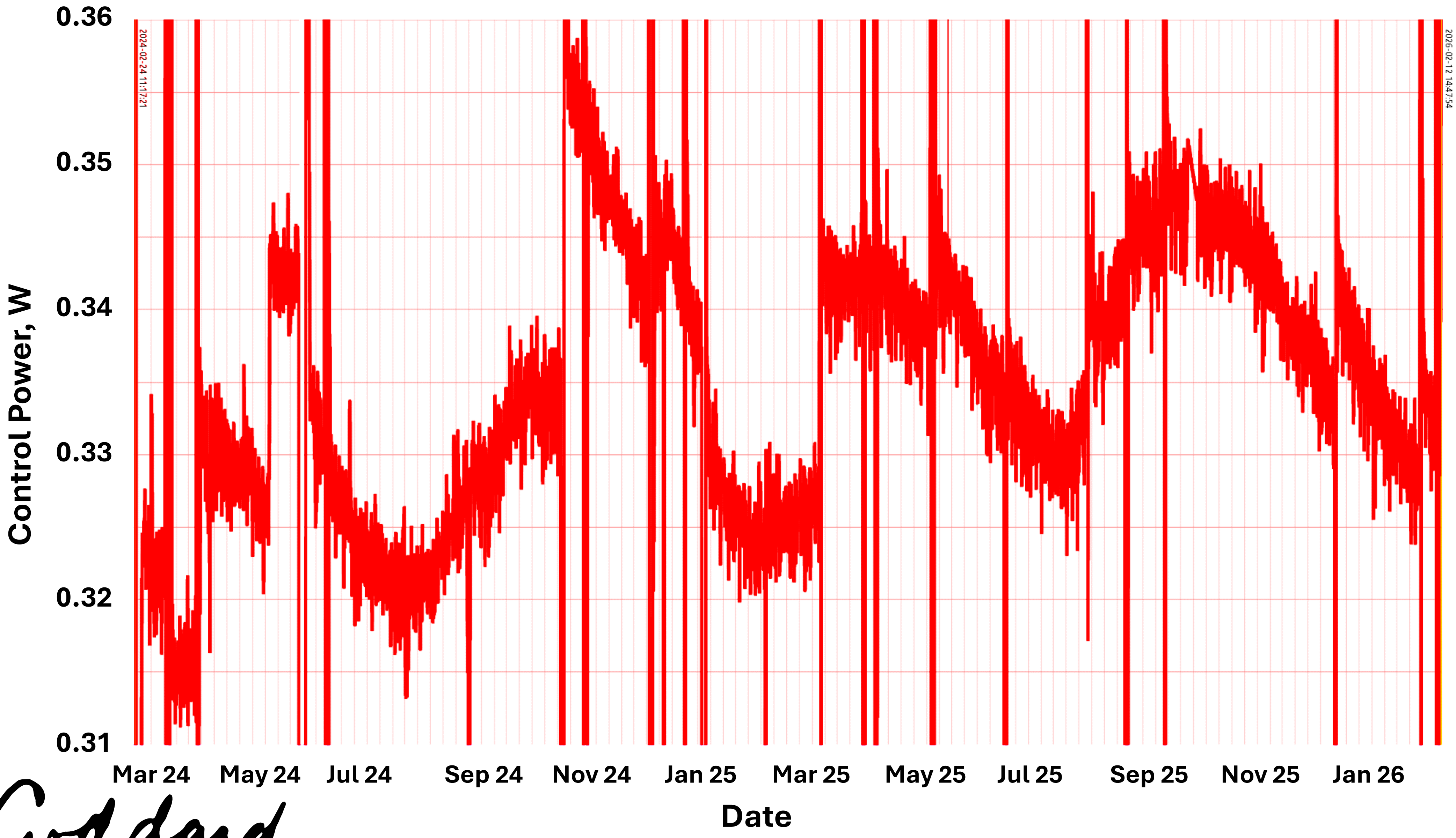
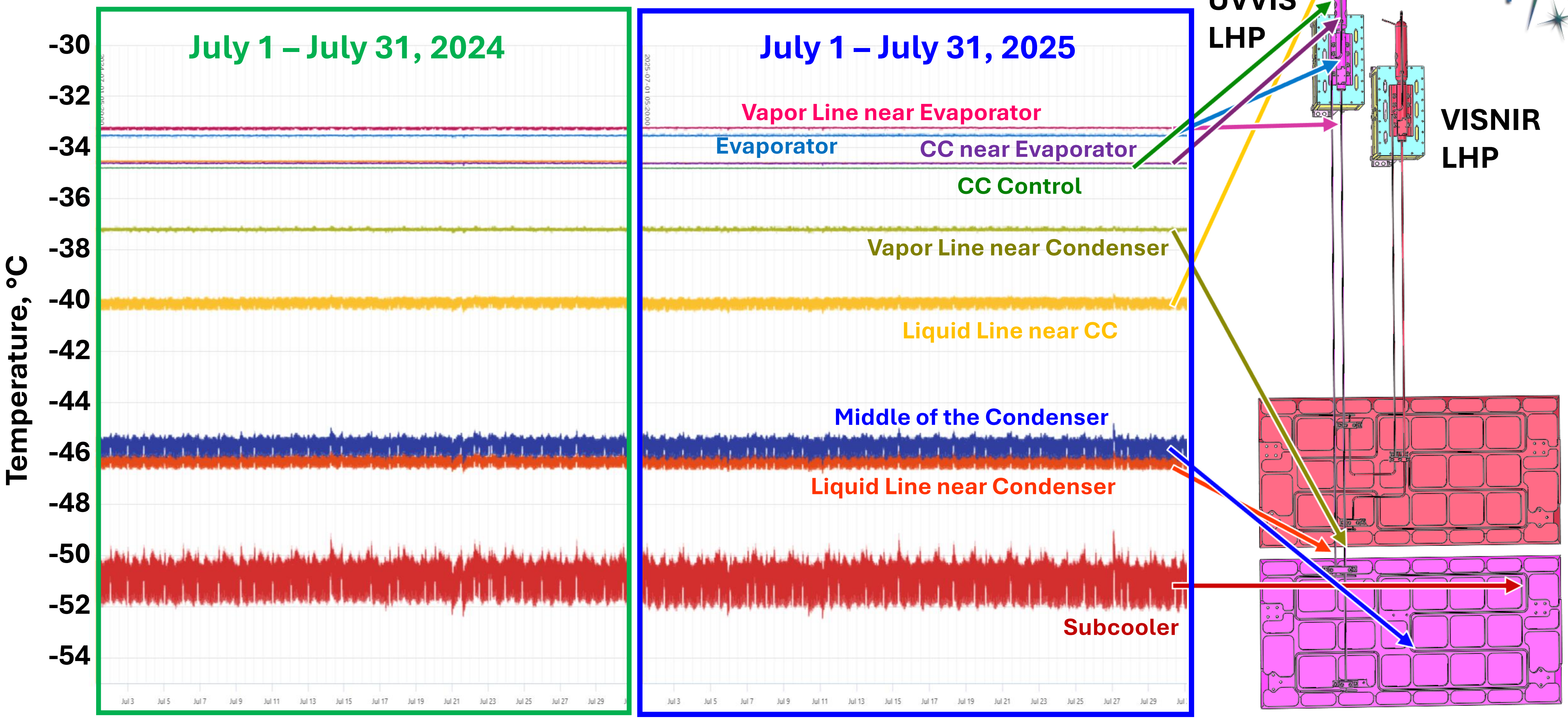
PACE UVVIS LHP Telemetry



UVVIS LHP Control Power (PACE OCI)



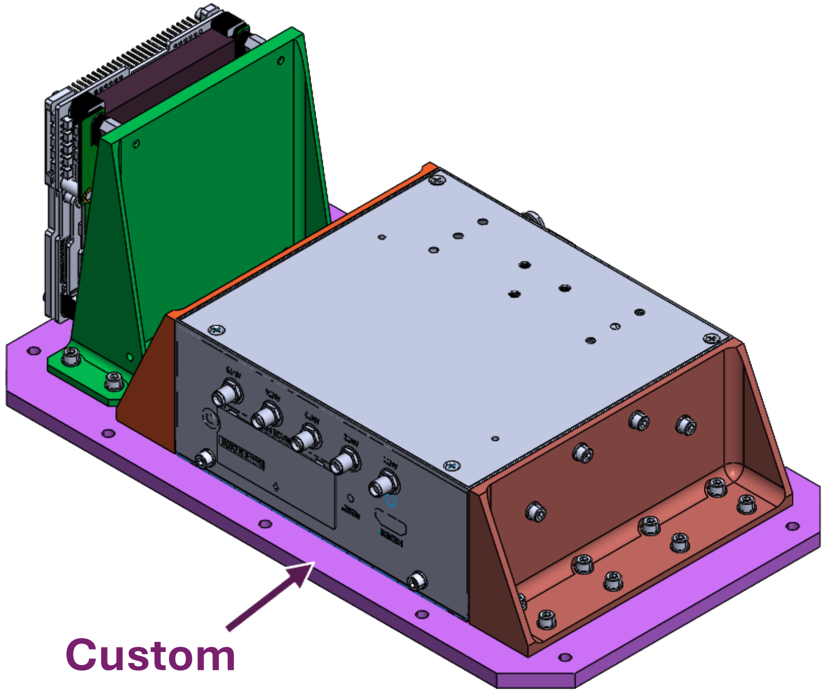
Comparison of UVVIS LHP Temperatures



Spaceflight - Compact Fire Imager (S-CFI)

- Fire Science & Applications
  - Observation of extreme fires to understand and anticipate rapid changes in fire risk.
  - Detection and tracking individual fire events.
  - Evaluation of fire impacts on ecosystems and communities.
- Goddard
  - Designing an onboard processing approach for near real-time data delivery from the airborne (ETU) and spaceflight CFI instruments
  - NASA's Wildland FireSense Project
  - Adaptation of NVIDIA's Jetson processor for space application
    - Thermal challenges
      - The convective cooling has to be replaced with conductive and radiative cooling mechanisms
      - The original high performance Thermal Interface Materials (TIM) shall be replaced with silicone free and low-outgassing TIMs.
    - Current status
      - Completed the design and fabrication of the custom heat sink
      - Investigating various TIMs
      - Addressing the contact pressure between the System-on-Chip (SoC) and the custom heat sink

<u>S-CFI processor</u>



Custom Heat Sink

Roman Space Telescope (RST)

NANCY GRACE ROMAN SPACE TELESCOPE

- Completed TVAC testing of the RST Observatory.
- All heat pipes (CGI and WFI) performed well.
- The RST will be moving to Kennedy Flight Center for launch preparation in September.

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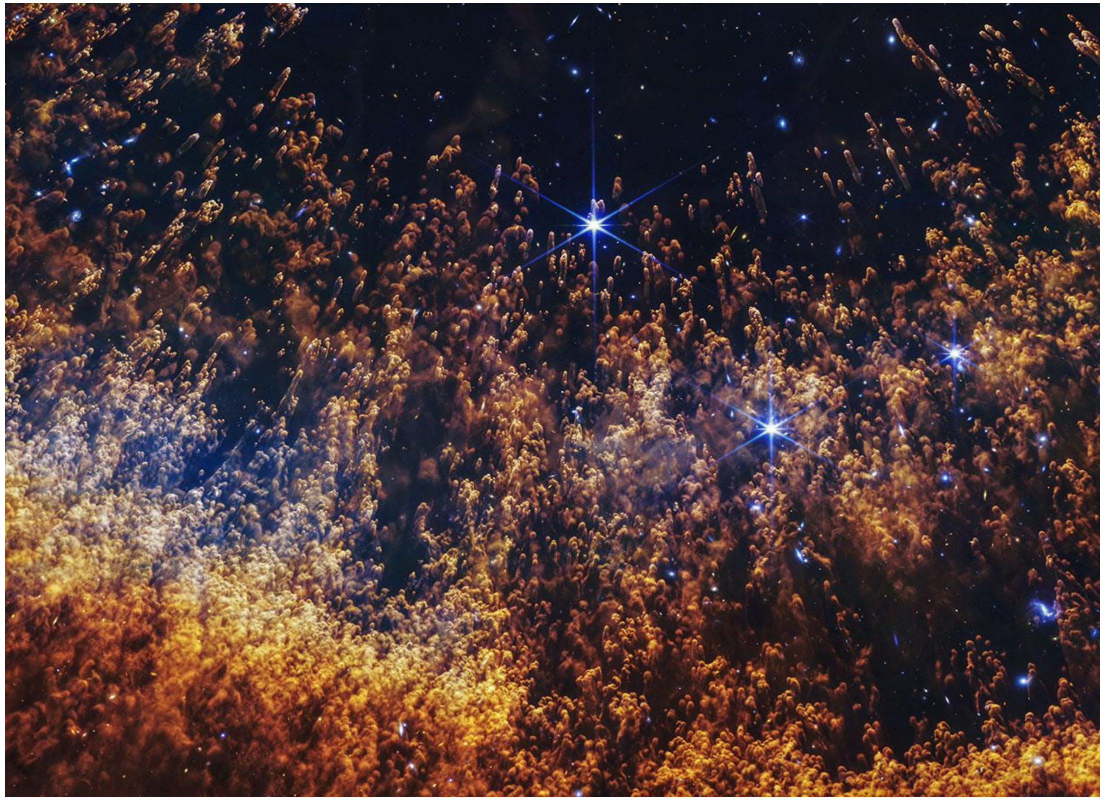
James Webb Space Telescope (JWST)

- JWST continues it’s journey.
- Scientists found that the thermal properties of 2024 YR4, in other words how quickly it heats up and cools down, and how hot it is at its current distance from the Sun, are not like what we see in larger asteroids. The hypothesis is that it is likely a combination of its very fast spin and a lack of fine-grained sand on its surface.

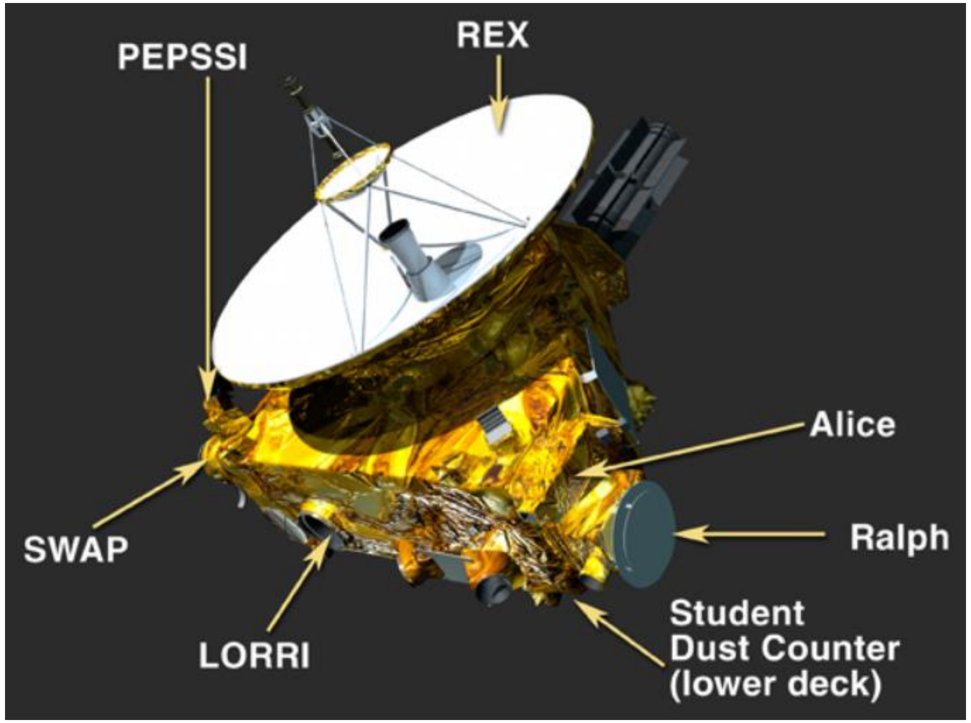


New Horizon

- New Horizons remains healthy while continuing its exploration of the Kuiper Belt and outer heliosphere.
- In April 2022 its mission was extended a second time to potentially conduct multi-disciplinary observations of relevance to the solar system and NASA's Heliophysics and Astrophysics Divisions.

Thermal Control

- The spacecraft is covered with MLI.
- Heat from the electronics has kept the spacecraft operating between +10 °C and +30°C.
- Active control with electrical heaters and louvers.



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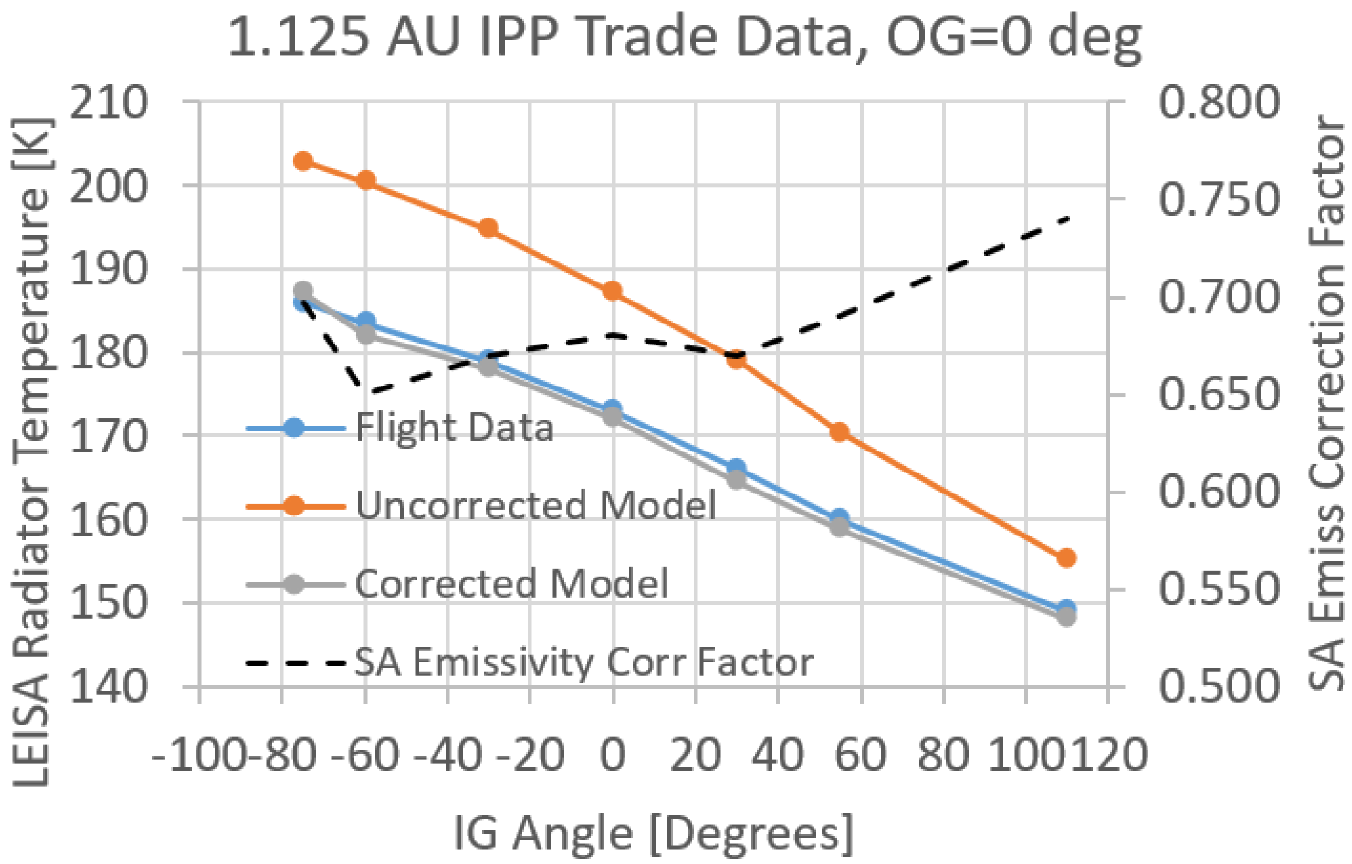
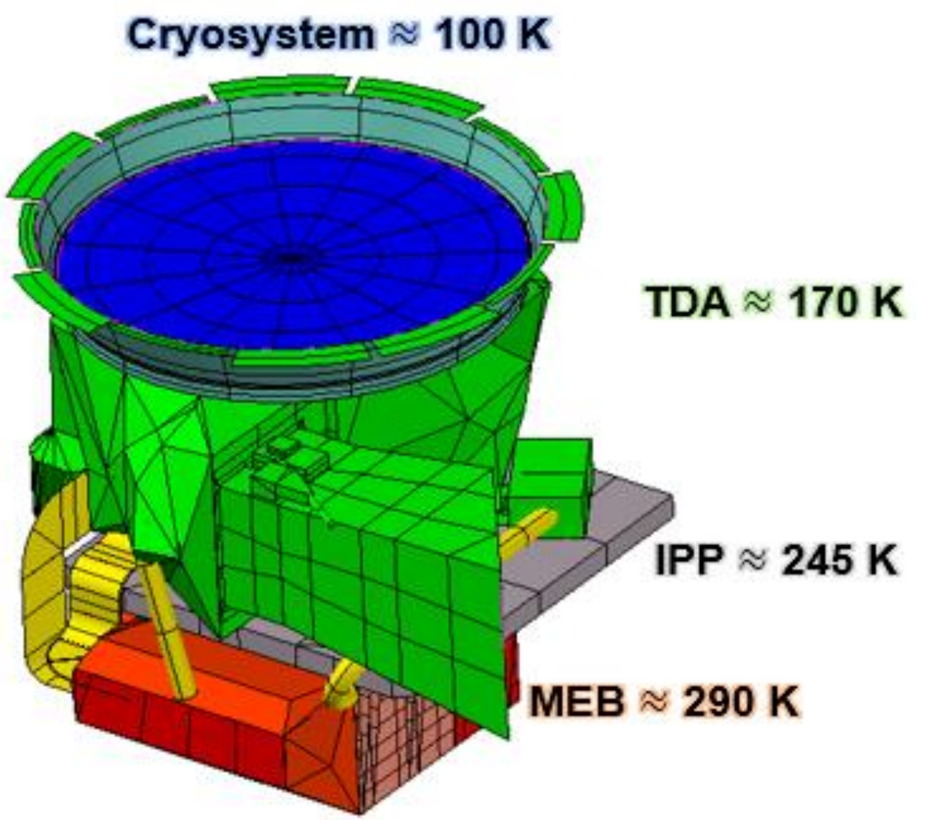
Lucy (L'Ralph)

- Launched October 16th, 2021
- At low AU, radiative loading from solar array to the cryoradiator dominates the heat flow (>90% of heat input)
  - Cryoradiator has a good view to the backside of the solar array backside





Landsat 9 (Earth from Space)

- Science Instruments: OLI-2; TIRS-2
  - OLI-2 build: Ball Aerospace & Technology Corp.
  - TIRS-2 build: NASA Goddard Space Flight Center
- Design Life: 5 years
- Spacecraft Provider: Northrop Grumman Innovative Systems (NGIS)
- Image Data: > 700 scenes per day
- Launch Date: Sept. 27, 2021
- Launch Vehicle: United Launch Alliance Atlas V 401
- Orbit: near-polar, sun-synchronous at an altitude of 438 miles (705 km)
- Orbital Inclination: 98.2˚
- Spacecraft Speed: 16,760 mi/hr (26,972 km/hr)
- **All instruments and spacecraft operating normally.**

Laser Communications Relay Demonstration (LCRD)

- LCRD continues to operate successfully from its GEO orbit.
- No anomalies have been reported.

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Geostationary Operational Environmental Satellites (GOES)

- **GOES-T (GOES 18/GOES West)**
  - Launched and operational.
  - ABI LHPs were redesigned from propylene parallel condenser to ammonia serpentine condenser.

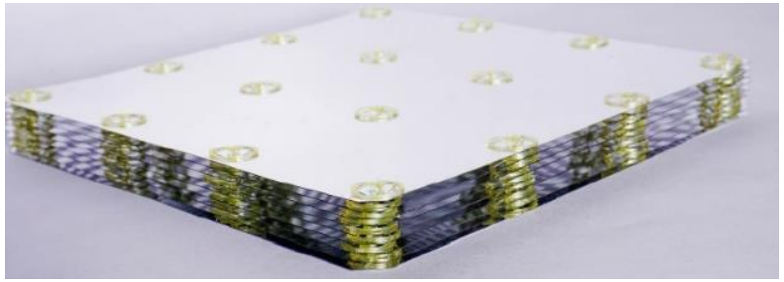
- **GOES-U (GOES 19/GOES East)**
  - Same LHP design as GOES-T (ABI LHP).
  - Launched in June 2024.
  - Operational from April 7, 2025.
  - The last satellite of the GOES-R series.

Lunar Environnent Monitoring Station (LEMS)

- LEMS is part of the Artemis III program
  - Surviving the Lunar Night
    - Minimizing heat leaks to the environment
      1. Integrated Multi-Layer Insulation (IMLI)
      2. Heat Switch
      3. Low thermal conductivity wire materials
      4. Low conductance supports

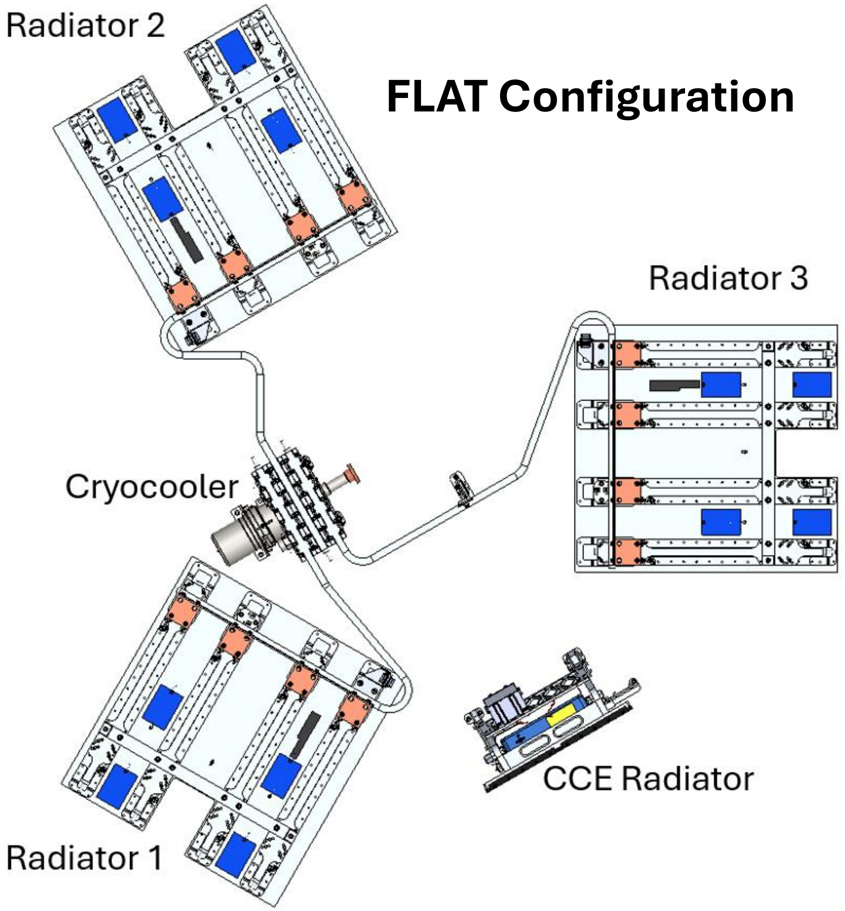
- Current Status
  - The flight IMLI has been installed on the LEMS bus assembly.
  - The IMLI is a high-performance insulation with low thermal conductivity polymer spacers to reduce heat leaks. This design allows LEMS to survive and operate during the cold lunar night.

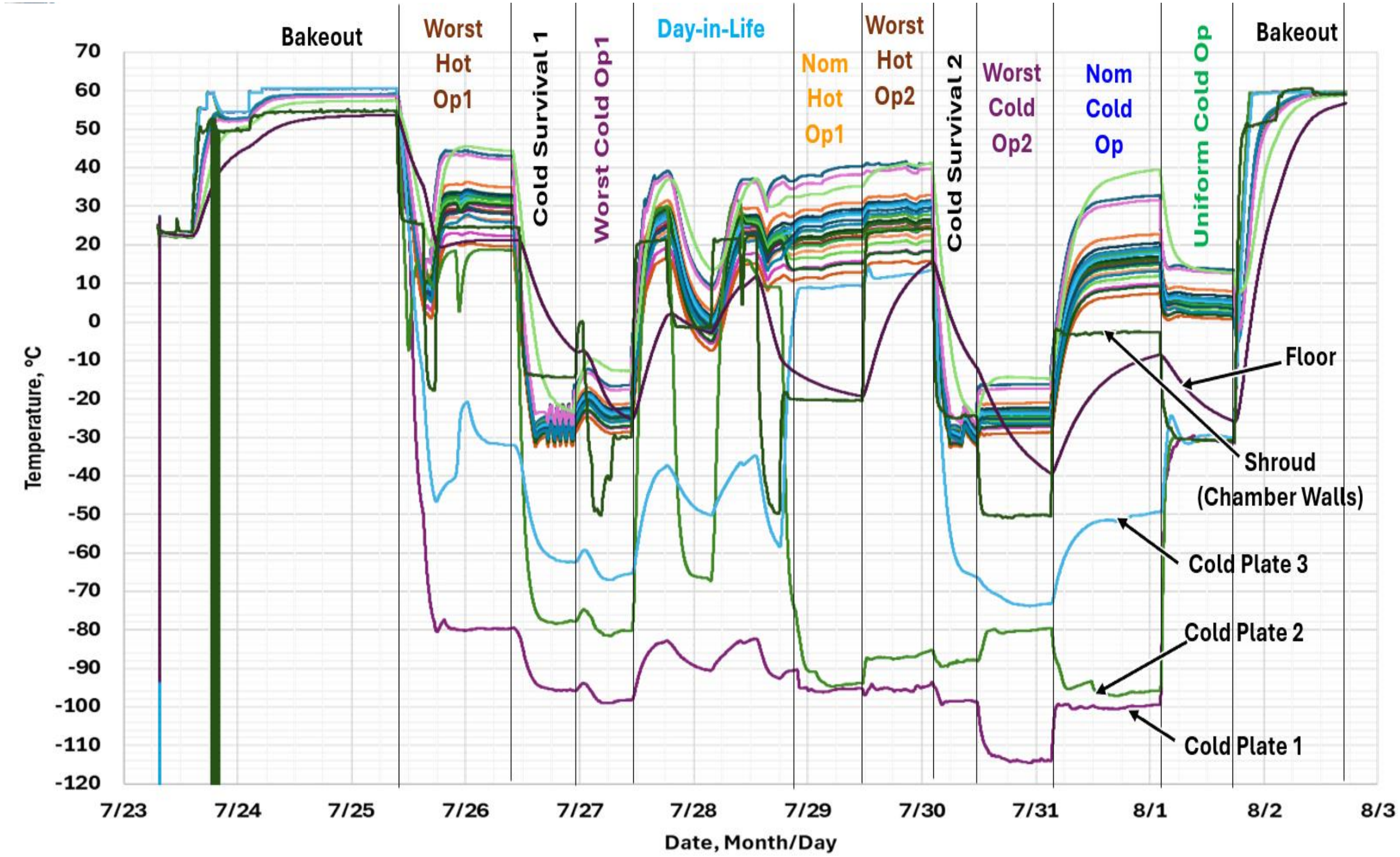
IMLI



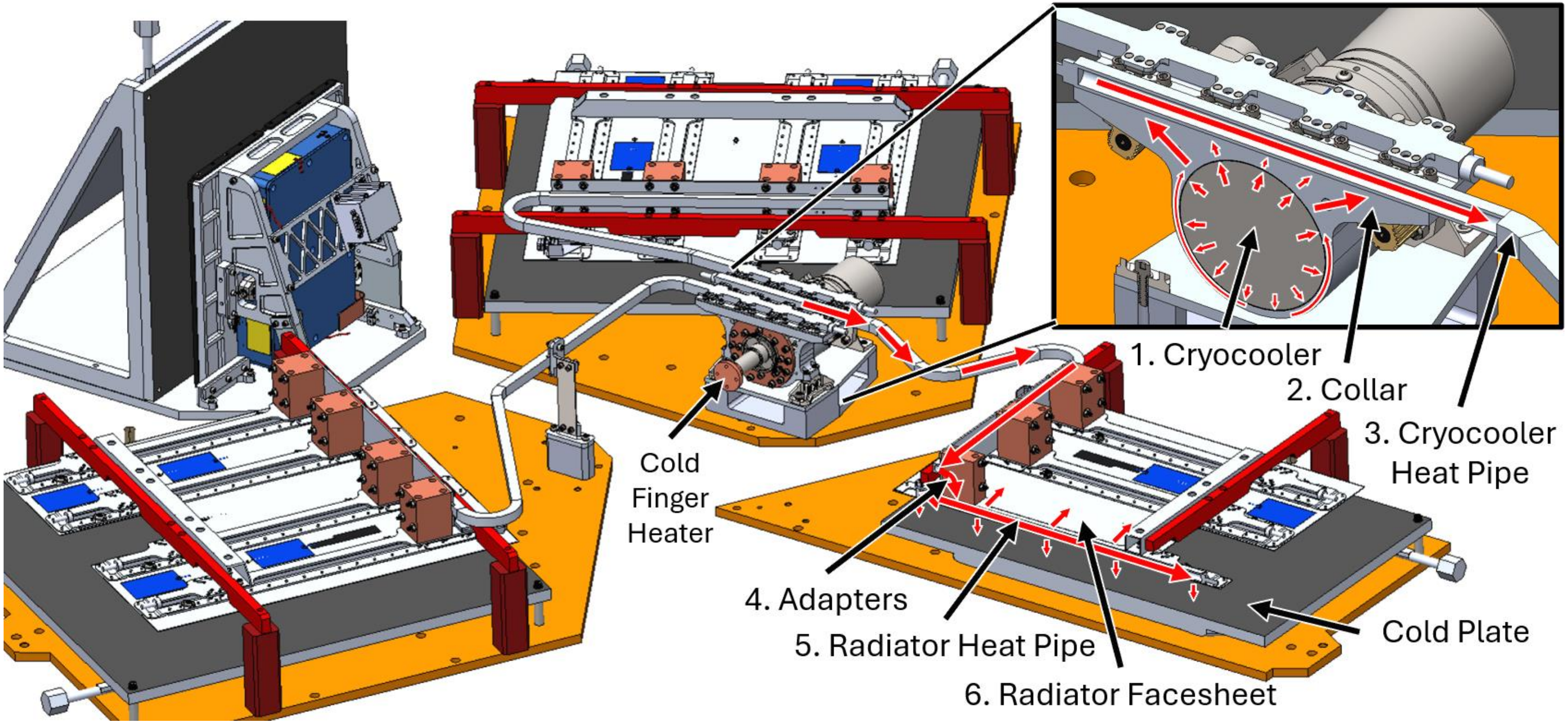
Compton Spectrometer and Imager (COSI)

Cryostat Heat Removal Subsystem (CHRS)

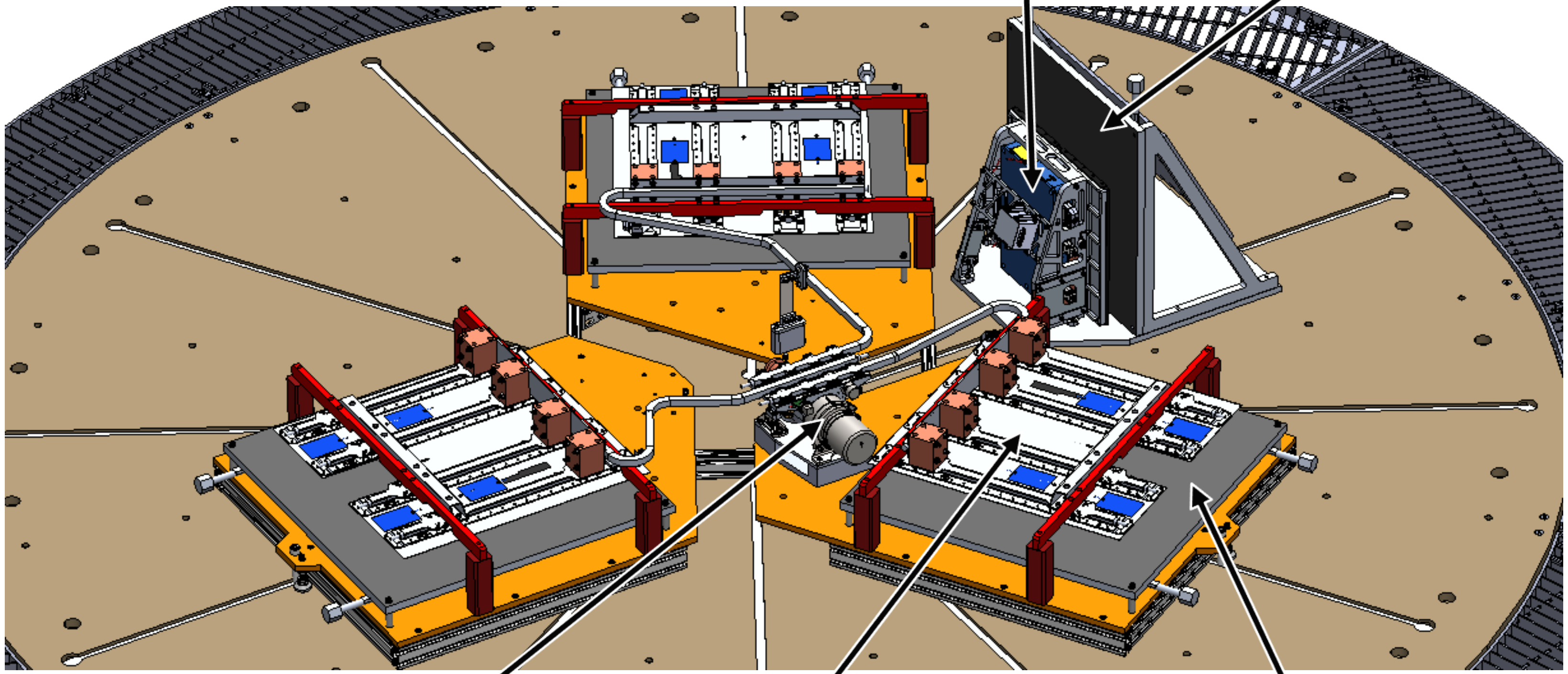




COSI CHRS Major Components and Heat Flow

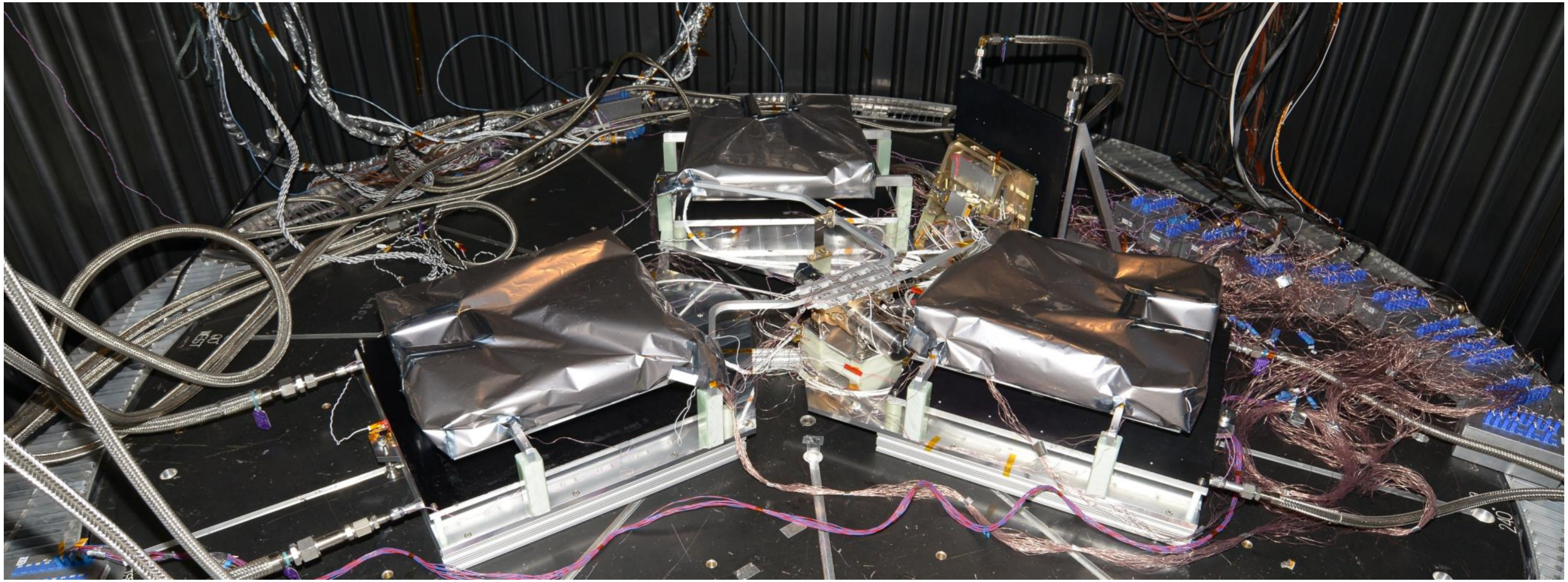


COSI CHRS TVAC Setup



COSI CHRS TVAC Setup

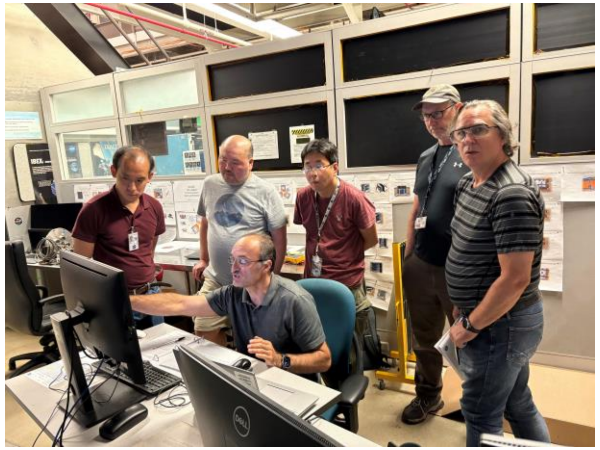
- The Radiators were covered with MLI.
- Cold plate temperatures were controlled individually.
- Almost 200 thermocouples in addition to flight temperatures sensors.
- All heat pipes were horizontal (FLAT configuration).



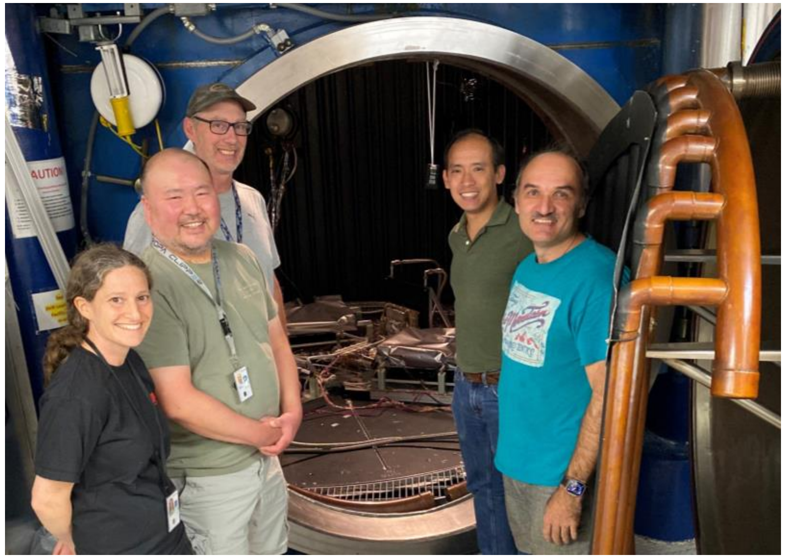
Lessons Learned from COSI CHRS TVAC

- **Not all Temperature Controlled Units (TCU) are the same.**
  a) One TCU was not capable reaching cold temperatures.
  b) Swathed the test conditions between radiators. One radiator exposed to Sun.
- **Thermocouple (TC) mislabeling can happen when it is done in phases.**
  a) The first round of TC labeling was performed on one radiator that went back to vendor for TVAC testing, while the other two radiators were instrumented later.
- **Ground Support Equipment (GSE) can impact cryocooler operation.**
  a) The cooler could not be operated in vibration control mode due to vibration from TCUs and GSE other equipment.
  b) The cryocooler was operated in the manual vibration control mode. <u>The heat removal was not affected.</u>
  c) The primary causes were:
     i. noise on the accelerometer signal (resulting from the grounding scheme implemented),
     ii. a loosened and possibly damaged accelerometer cable
     iii. and possibly background noise corrupting the accelerometer reading (due to frequency bleed or spectral leakage).

During Testing



COSI TVAC Team



ELO2
EPE + LUNAR OUTPOST
OCEANIA CONSORTIUM

Australian Moon ROO-VER

Australian Space Agency

- **ROO-VER** is the name of Australia’s history making rover.
- **ROO-VER** is likely to land in the South Pole region of the Moon and is expected to operate for 14 Earth days.
- To learn more about the Australian ROO-VER: https://www.roovermission.com.au/about-roo-ver

Power and Sense Card Assembly

- The Mechanical Engineering and the Integration and Test teams completed thermal testing of the Power and Sense Card electronics assembly and achieved Technology Readiness Level 6.
- The electronics assembly is part of the Multi-functional Nanosensor Platform (MNP) Instrument that will be delivered to Australia for their Lunar Rover Mission.

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Dragonfly Mass Spectrometer (DraMS)

- A successful CDR was completed for the DraMS Instrument in February 2025.
- DraMS is fully in the I&T phase right now.
  - Thermal models have been created for all component.
  - All thermal hardware (thermostats, PRTs, heaters) have been purchased, and currently thermal hardware is being integrated on the Instrument.
- Thermal vacuum and Titan-like pressure thermal tests will happen in September 2026.
- Instrument delivery to the Dragonfly Lander is slated for November 2026

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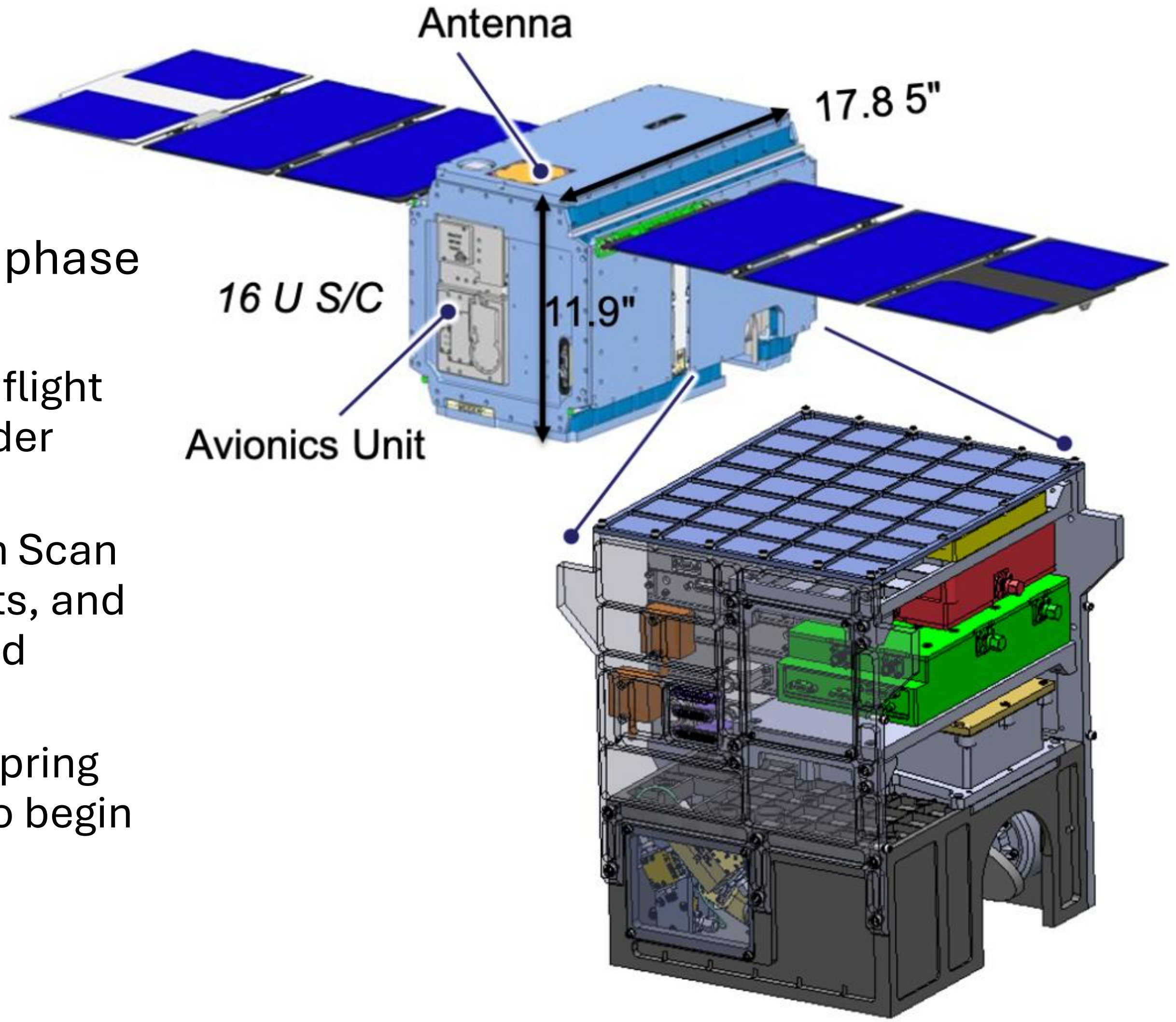
Polarized Submillimeter Ice-Cloud Radiometer (PolSIR)

- The PolSIR project is currently in the I&T phase
  - working on assembly of flight unit #1.
  - Intermediate Frequency Assembly (IFA) flight model 2 has been assembled and is under thermal characterization.
  - Thermal hardware has been installed on Scan Mechanism hardware for both flight units, and flight unit #1 has successfully completed characterization activities.
  - I&T activities will continue through the spring with thermal vacuum testing estimate to begin mid/late spring.

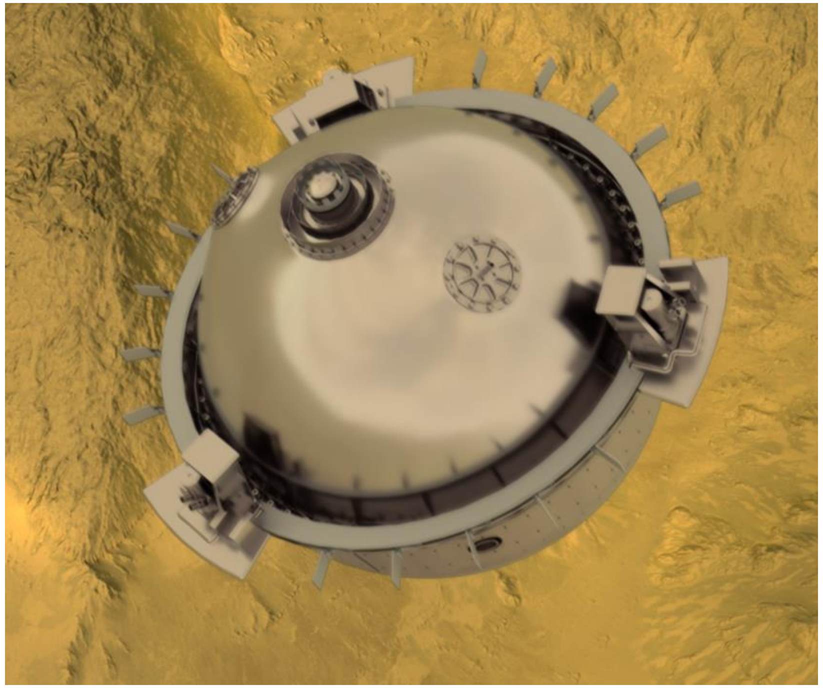


PolSIR Instrument

DaVinci – Extreme Temperature Technologies

- The DAVINCI (Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging) mission will explore whether the inhospitable surface of Venus could once have been a twin of Earth – a habitable world with liquid water oceans.

- The DAVINCI program has been doing trade studies between descent sphere fully at high vacuum pressure or elevated pressures.
- There is a concern that outgassing will prevent the descent sphere remaining at high vacuum conditions (lowest heater power).
- Contamination analysis and testing results show a 50torr pressure may be achievable, but this still requires a lot of CFD modeling to calculate convective coefficients correctly for adequate thermal modeling.



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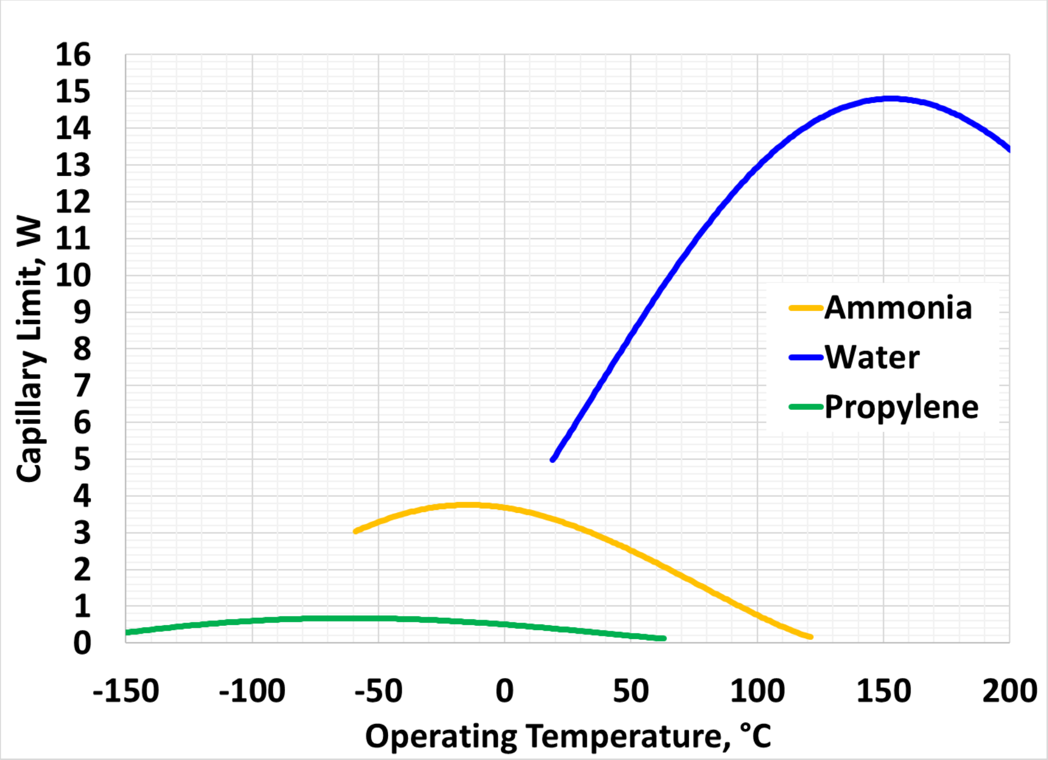
Game Changing Development (GCD) Program

- Two-Phase Active and Passive Thermal Control in Future Exploration Missions Study
- Joint effort between Goddard and JPL.
- Passive and active two-phase Thermal Control Systems (TCS).
  - Completed Heat Pipe module of the TCS sizing tool
  - LHP module of the TCS sizing tool is under development



GeoXO status

GEOSTATIONARY EXTENDED OBSERVATIONS

- NOAA's Geostationary Extended Observations (GeoXO) satellite system will expand observations of Earth that the GOES-R Series currently provides from geostationary orbit.
- The information GeoXO supplies will improve short-term forecasting and warning of severe weather and hazards that threaten the security and well-being of everyone in the Western Hemisphere.
- The first GeoXO launch is planned for 2032 to ensure continuity of observations from geostationary orbit as the GOES-R Series nears the end of its operational lifetime.
- GeoXO will maintain and advance U.S. observational capabilities through 2050
- Critical Milestone:
  - Last year NASA completed Preliminary Design Reviews (PDR) with L3Harris and Lockheed Martin.

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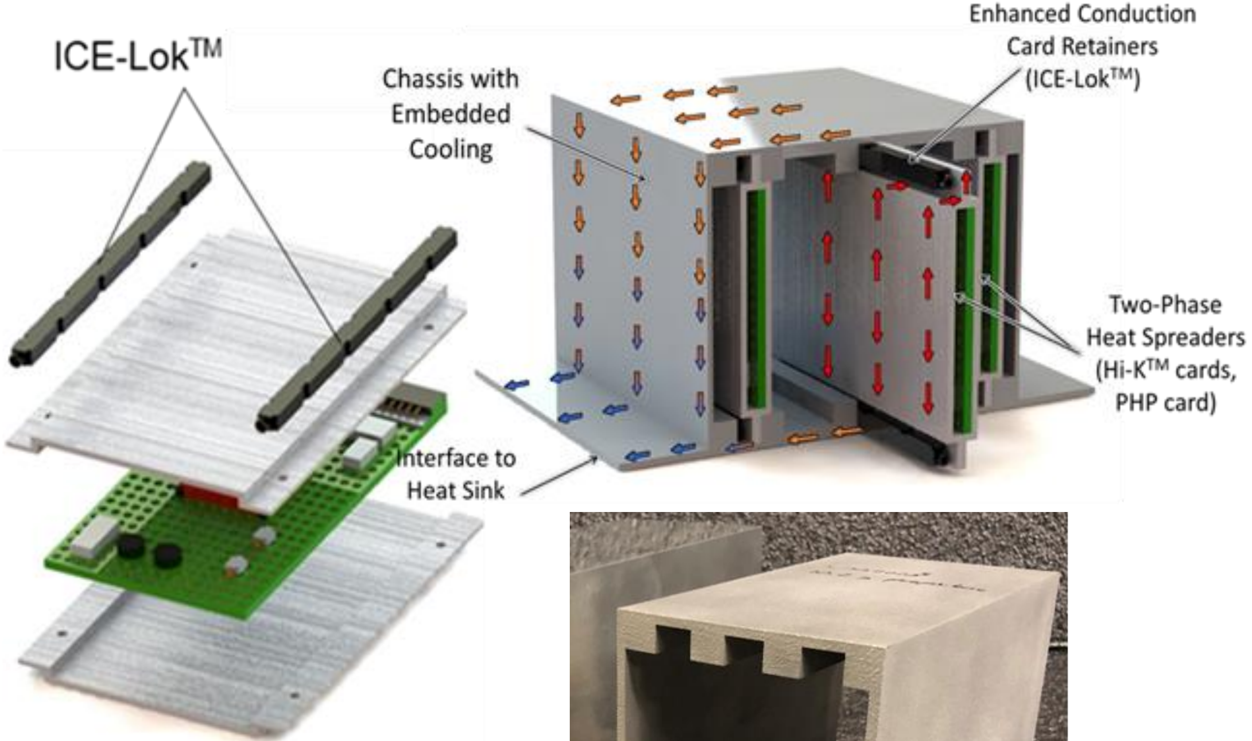
Nuclear Propulsion Technology Maturation (NP-TM)

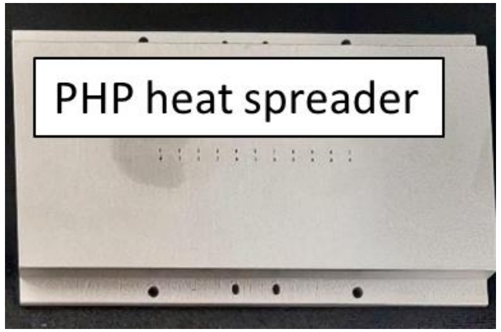
- The NP-TM program is a collaboration effort between several NASA centers, including MSFC, GRC, GSFC, JPL and LaRC.
- The Thermal Management team includes Subject Matter Experts from GRC, MSFC, LaRC and GSFC.
  - GRC – Greeta Thaikattil (greeta.j.thaikattil@nasa.gov)
  - MSFC – Michael Baldwin (michael.r.baldwin@nasa.gov
  - LaRC – Amanda Stark (amanda.stark@nasa.gov)
  - GSFC - Sergey Semenov (sergey.y.semenov@nasa.gov)
- The main focus is on development of high temperature active and passive heat transfer systems such as:
  - Pumped single-phase and two-phase systems.
  - High temperature heat pipes.
  - High temperature radiators.
- Related programs: RDU, MARVEL

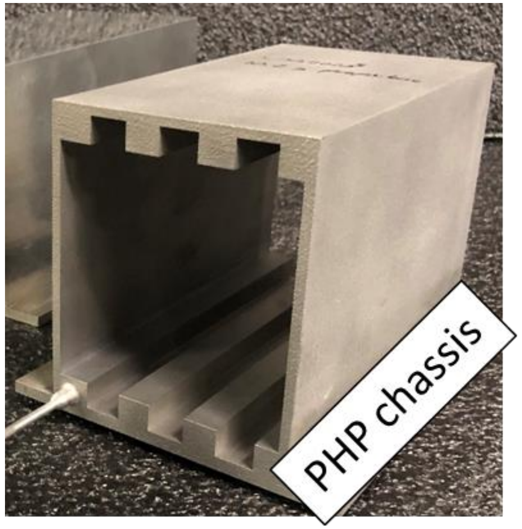
SBIR - Advanced Cooling System for Modular Power Electronics

NON-PROPRIETARY DATA

- SBIR Phase II E Z2.01-1280
- PI: Sai Kiran Hota, saikiran.hota@1-act.com;
- Pulsating heat pipe (PHP) embedded electronics cooling system developed in SBIR Phase II program
- Investigation conducted on modular 3U form factor heat spreader & enclosure chassis
- PHP devices additively manufactured using aluminum alloy
- Start TRL: 4
- End TRL: 6
- Current plans: Mature technology through Phase II-E efforts



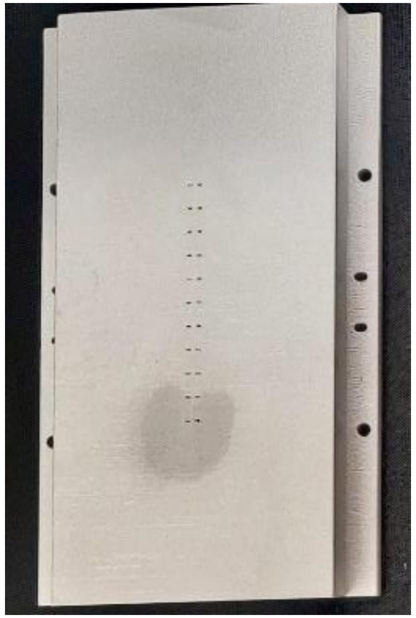




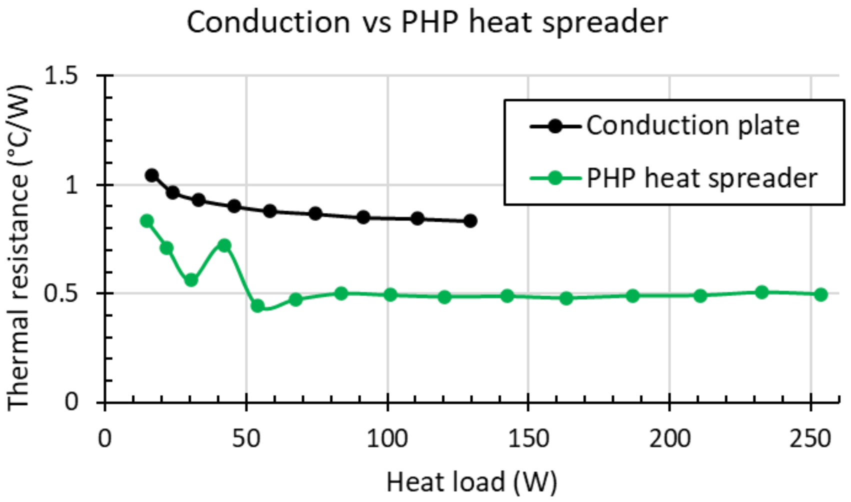
SBIR - Advanced Cooling System for Modular Power Electronics

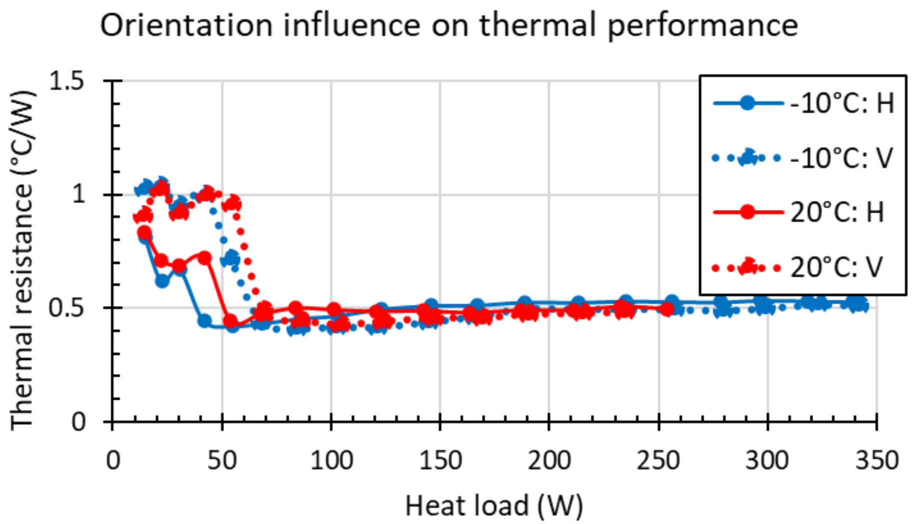
NON-PROPRIETARY DATA

PHP Heat spreader



H: Horizontal
V: Vertical



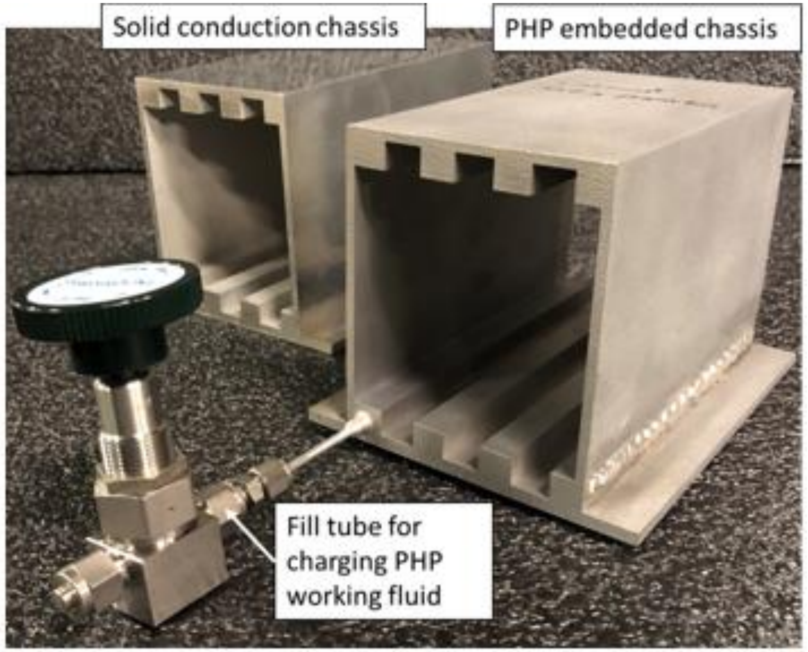


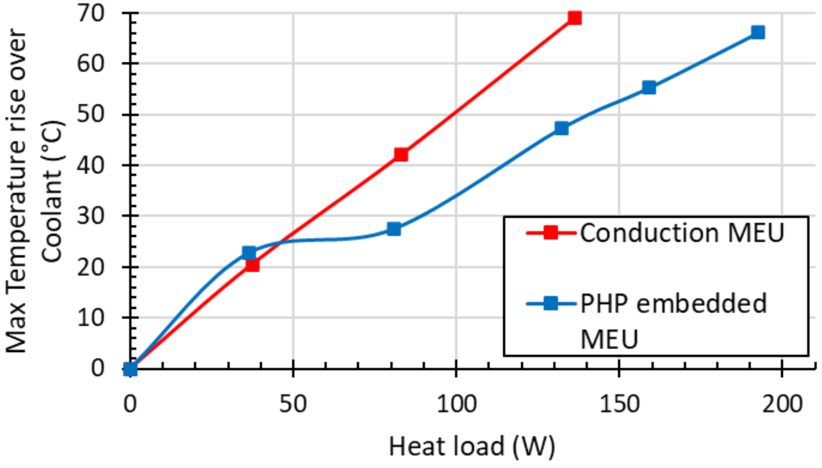
- Thermal resistance reduced by 45% over conduction – in both ambient & vacuum environments
- Gravity insensitive operation even at heat rejection below 0°C – repeatable performance
- Up to 5% mass reduction over conduction alternative
- Passed shock & vibration qualification

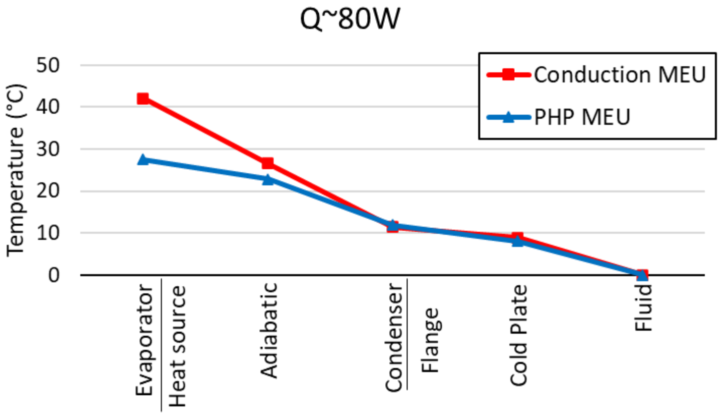
SBIR - Advanced Cooling System for Modular Power Electronics

NON-PROPRIETARY DATA

PHP Embedded Modular Enclosure Unit (MEU) / Chassis





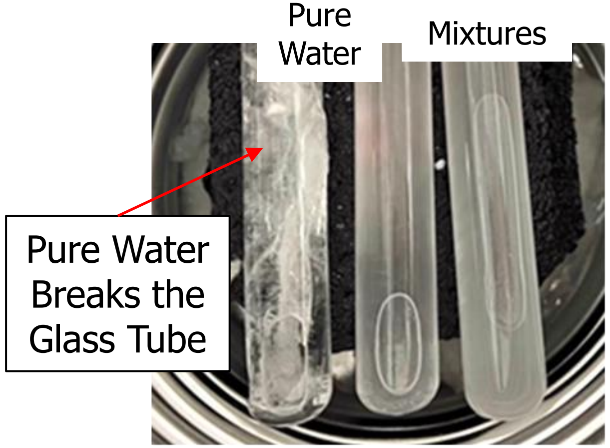


- Maximum temperature lowered by more than 10°C compared to pure conduction
- Up to 5% mass reduction over solid conduction alternative

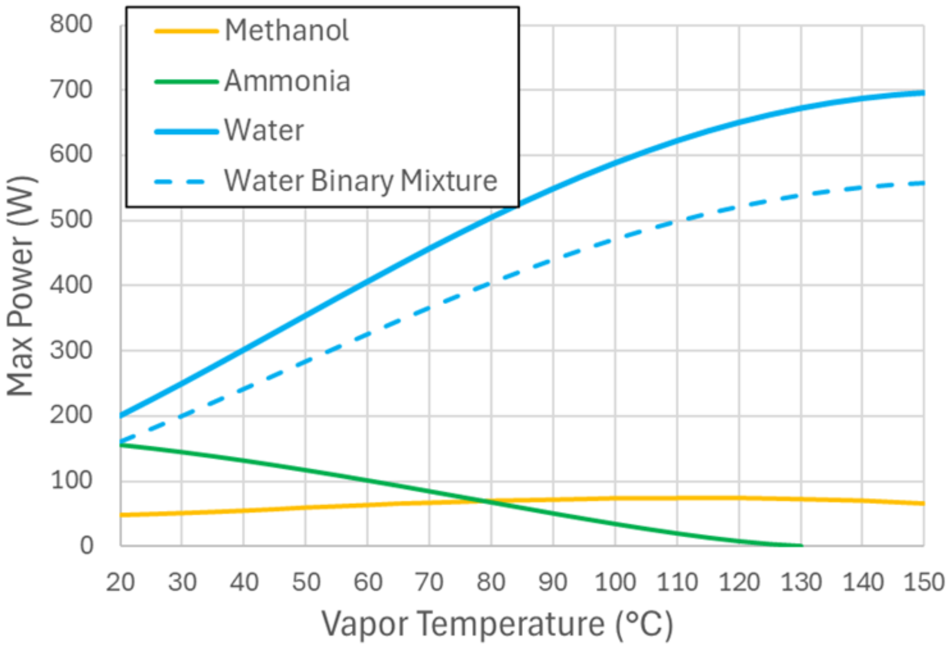
SBIR – Freeze Tolerant Water-Based Heat Pipes

NON-PROPRIETARY DATA

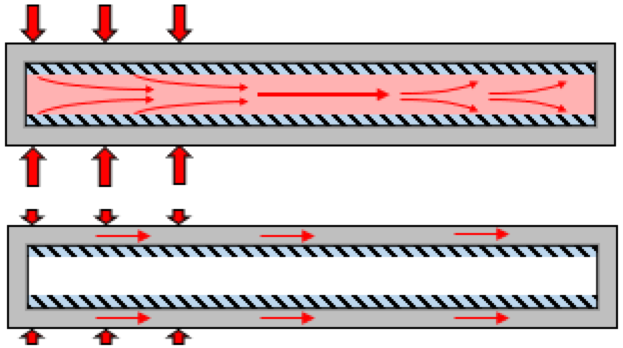
- SBIR Phase I: S16.05-1002
- Water is a strong working fluid over a temperature range relevant to many electronics but can be challenging to use due to expansion upon freezing
- ACT is developing unique water-based fluid mixtures to alter the freezing properties and provide burst protection to the heat pipe while maintaining the strong performance of water
- A freeze tolerant heat pipe that freezes at 0°C can be used as a temperature dependent thermal switch



a) Burst Protection Provided by Binary Mixture



b) Comparison of Water and Binary Mixture to other Working Fluids



Heat transfer only via conduction through envelope

c) Frozen Heat Pipe Acts as a Thermal Switch

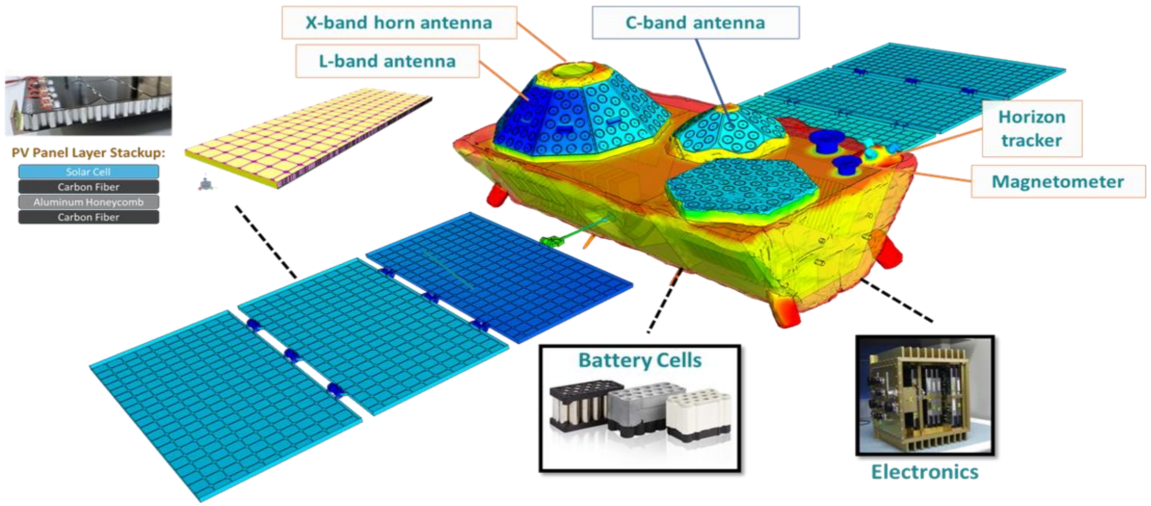
SBIR – Physics-Informed Machine Learning for Spacecraft Thermal Surrogate Modeling

NON-PROPRIETARY DATA

- SBIR Phase I: S16.05-1017
- PI: Timofey Golubev, ThermoAnalytics, Inc.;
- TM: Juan Rodriguez, Sergey Semenov

- Comprehensive design studies of thermal control systems over wide variety of operating conditions can be computationally expensive with traditional thermal analysis software
- ThermoAnalytics is developing software for generation of thermal surrogate models using physics-informed machine learning (PIML)
  - Unlike data-driven ML, the loss function directly encodes the physics equations of the problem, instead of an error between simulation/measured data and ML model predictions
    - No simulation data required for training

3D Satellite Thermal Model



Physics-Informed Surrogate Model

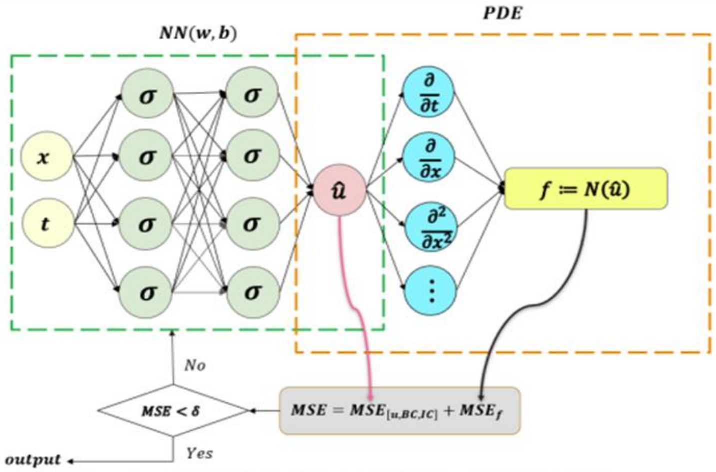


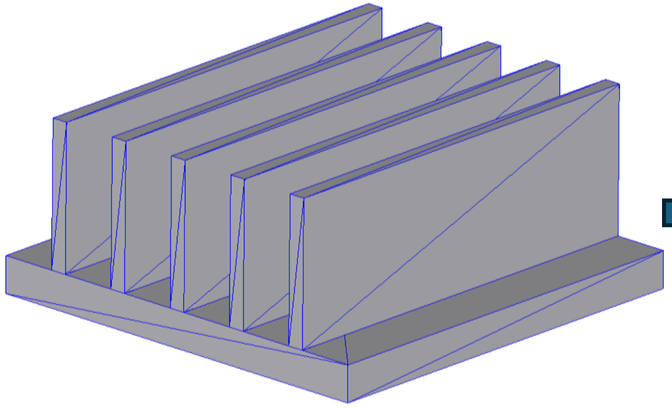
Image from: Appl. Sci. 2019, 10, 5917; doi:10.3390/app10175917. CC BY license.

SBIR – Physics-Informed Machine Learning for Spacecraft Thermal Surrogate Modeling

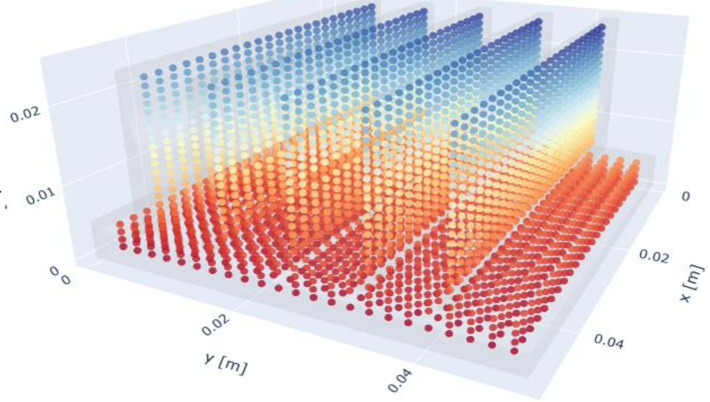
NON-PROPRIETARY DATA

- Physics-informed ML models are trained using CAD geometry as input
  - No meshing of geometry required
- Temperature predictions are performed on a set of interior and surface sampling points, which can then be interpolated to make continuous temperature visualizations
- Validation is being performed using our commercial heat transfer software TAITherm

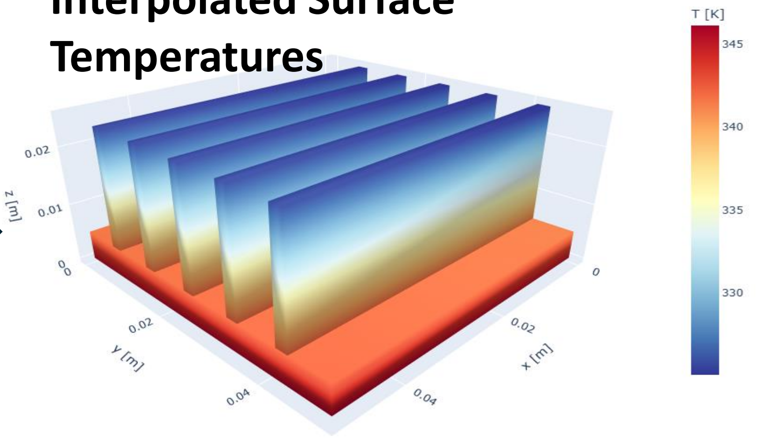
Input CAD Geometry



PIML Temperature Predictions on Point Cloud



Interpolated Surface Temperatures



THERMO ANALYTICS

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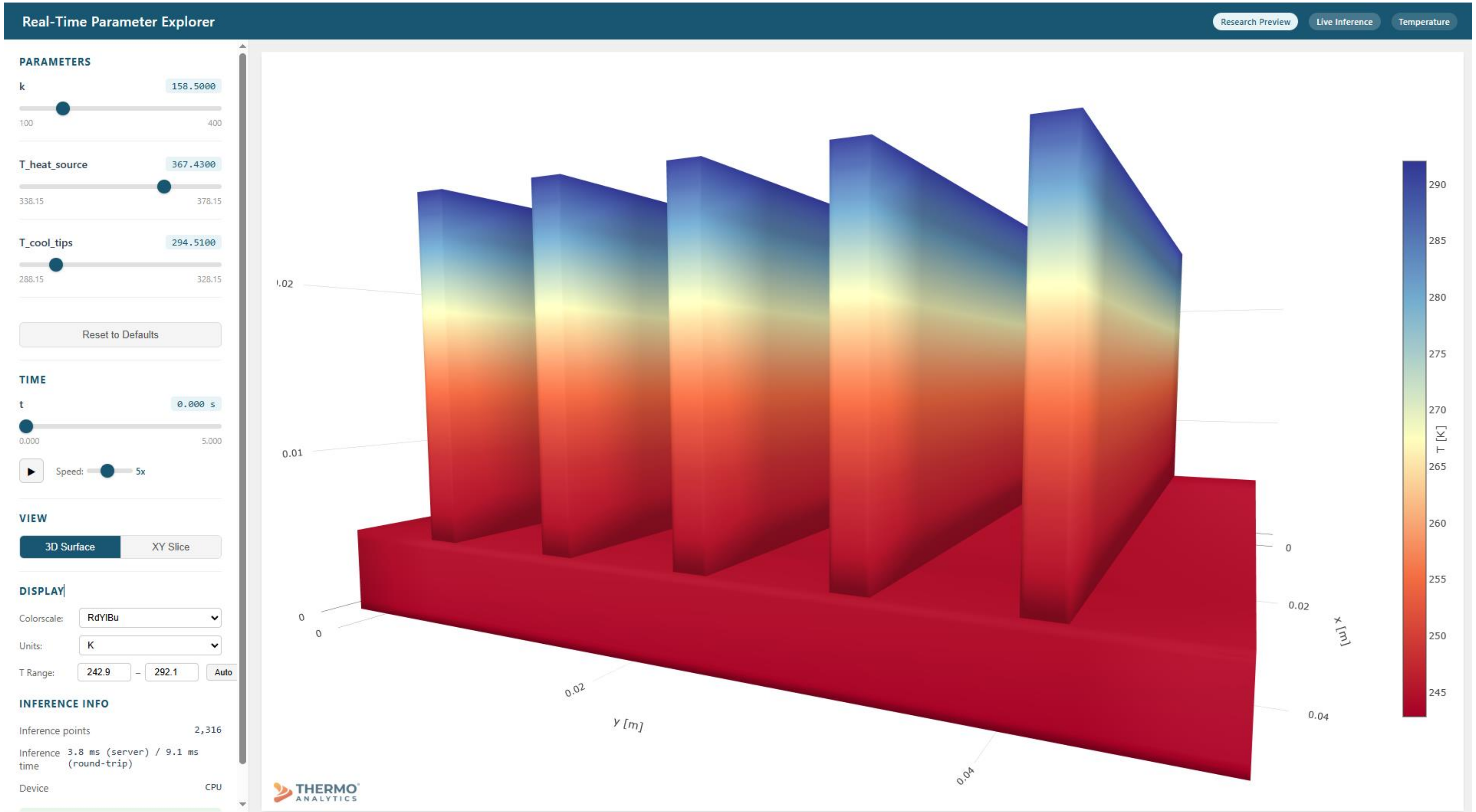
SBIR – Physics-Informed Machine Learning for Spacecraft Thermal Surrogate Modeling

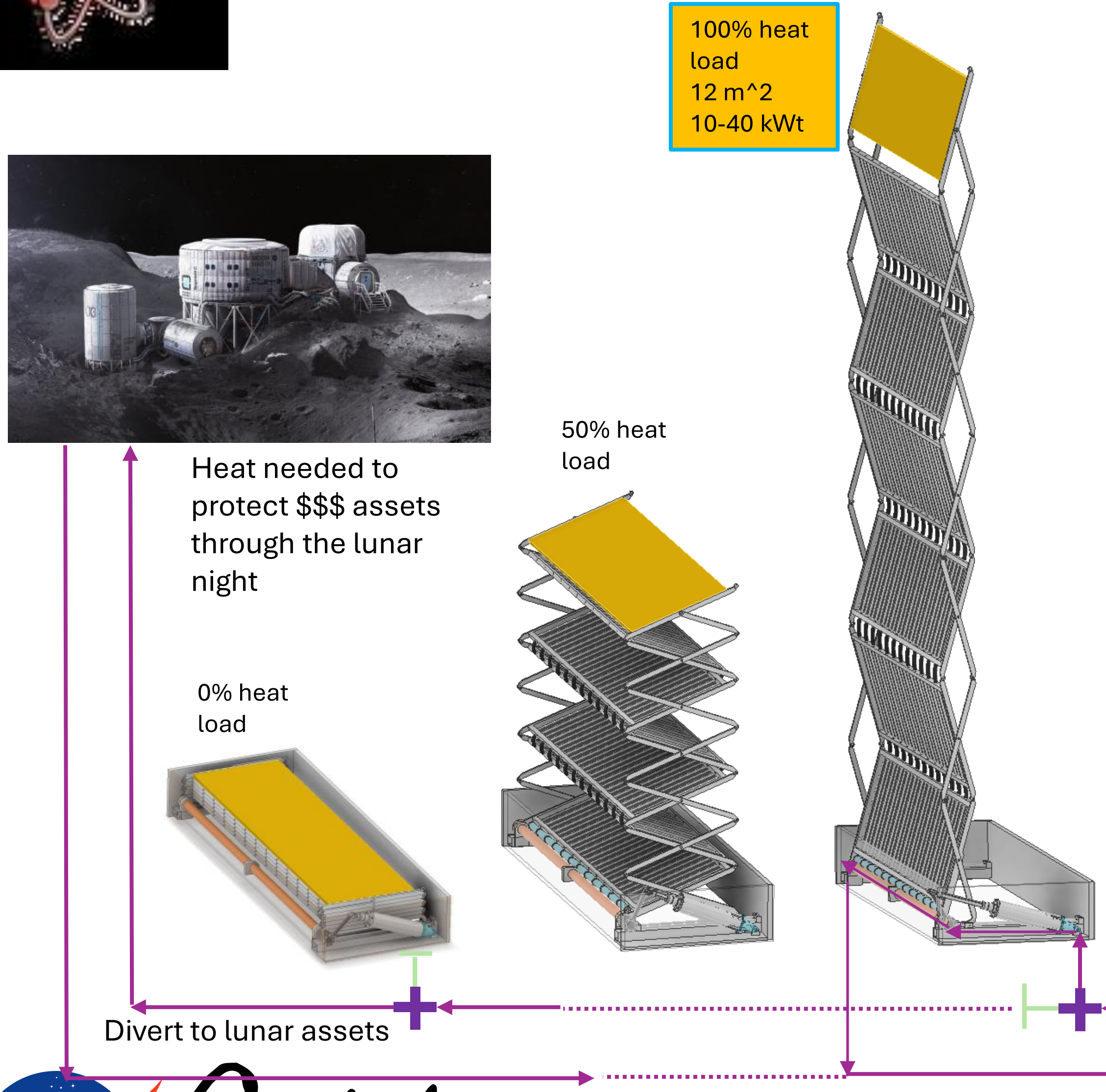
NON-PROPRIETARY DATA

- Once trained, PIML surrogate models can predict 3D temperature distributions due to varying boundary conditions, material properties, and geometry in 10 milliseconds per parameter combination



SBIR – Freeze Tolerant Water Azeotrope Radiators

NON-PROPRIETARY DATA



SBIR Phase I: Z-LIVE.02-1008

PI: Marc Gibson; TM: Sergey Semenov

Significance of Innovation

- A passive heat rejection system that stows and deploys based on temperature input from its heat source ranging from 350-500K
- Water azeotrope heat pipes provide freeze capability down to 100K to survive the lunar night
- Thermal actuator deploys radiator array based on heat source rejection temperature and power needs. 100% turn down ratio
- Designed to passively manage heat loads in the most extreme conditions

NASA Applications

- Heat rejection and diversion for large heat loads through the extreme lunar day/night temperatures
  - Reject heat loads during the lunar day and divert the heat load to human habitats and other $$$ assets during the lunar night
  - As heat is diverted from the radiator array to other assets during the lunar night it will stow/hibernate/survive until needed

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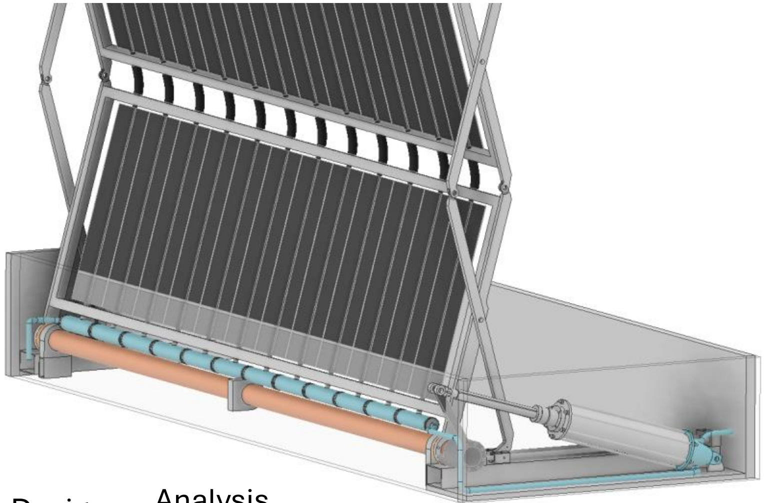
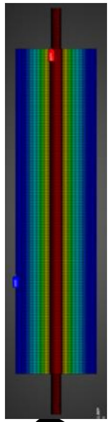
SBIR – Freeze Tolerant Water Azeotrope Radiators

NON-PROPRIETARY DATA



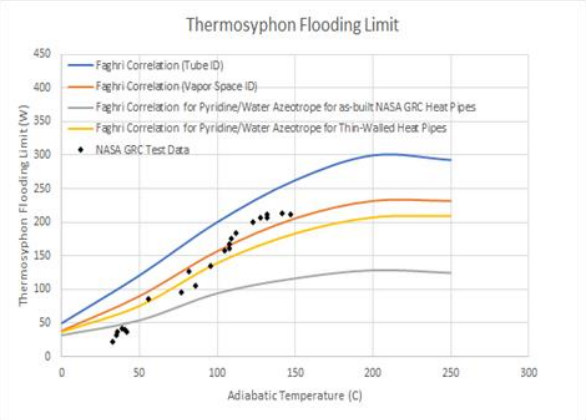
Design

Analysis



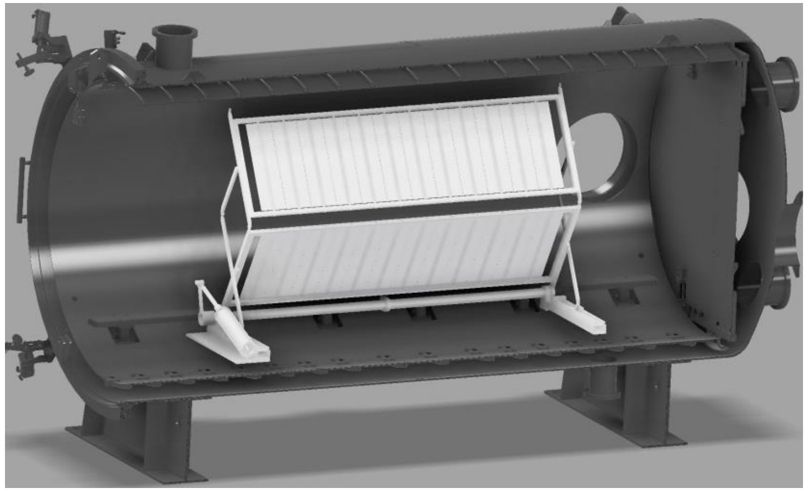
Fabrication

Test



- Phase I Objectives
  - Evaluate and down-select azeotropic mixtures using existing heat pipe hardware
  - Develop optimized heat pipe design for next-phase fabrication
  - Design passively deployable radiator system for construction in phase 2

- **Phase II Objectives**
  - Fabricate and test composite radiator array with embedded azeotropic heat pipes
  - Perform thermal vacuum testing of a 2 panel array (4 m^2) down to 100K and up to 500K to evaluate survivability and deployment cycling



NASA Goddard Thermal Technology Roadmap

What Thermal Branch at NASA Goddard is providing?

Make space exploration sustainable through existing and new technologies that allow surviving extreme environments in a cost-effective manner.

- Provide appropriate temperature conditions for various space components, such as:
  - Instruments,
  - Optics,
  - Electronics,
  - Cryocoolers
- Develop thermal control systems that allow instruments to survive and operate through the extreme space environments:
  - Moon: -200°C to +120°C
  - Mars: -130°C to +100°C
  - Venus: +460°C and 1,350PSI pressure

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NASA Goddard Focus Areas

Planetary Defense

- Decrease the cost and mass for cooling electronics, detectors and optics.
- Faster and more precise detection of space objects that could be a threat to the planet.

Moon to Mars

- More efficient thermal management will prolong operation during lunar nights and inter-planetary cruises.
- Expand applicability of human exploration beyond ISS.

National Security

- Improve forecasting for emerging environmental issues.
- Precision temperature control for sensors in specialized ranges [infrared to UV] helps US to see small changes in Earth surface or clouds/atmosphere.
- Develop unique technologies and commercialize once a certain TRL is reached.

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