



U.S. AIR FORCE



AFRL

SPIRRAL: A Calorimetric Testbed for Characterizing Variable Emissivity Materials in Space

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AFRL/RV

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Agenda

- Variable Emissivity Materials (VEMs)
 - What are VEMs
- Space Power IR Regulation and Analysis of Lifetime (SPIRRAL) Flight Experiment
 - What is SPIRRAL
 - SPIRRAL Science Plan
- SPIRRAL Analysis Methods
 - SPIRRAL CONOPS
 - SPIRRAL Hardware and Analysis Methods
- First Order Results from On-Orbit Data
 - First order results for control samples from on-orbit data
 - First order results for VEM samples from on-orbit data

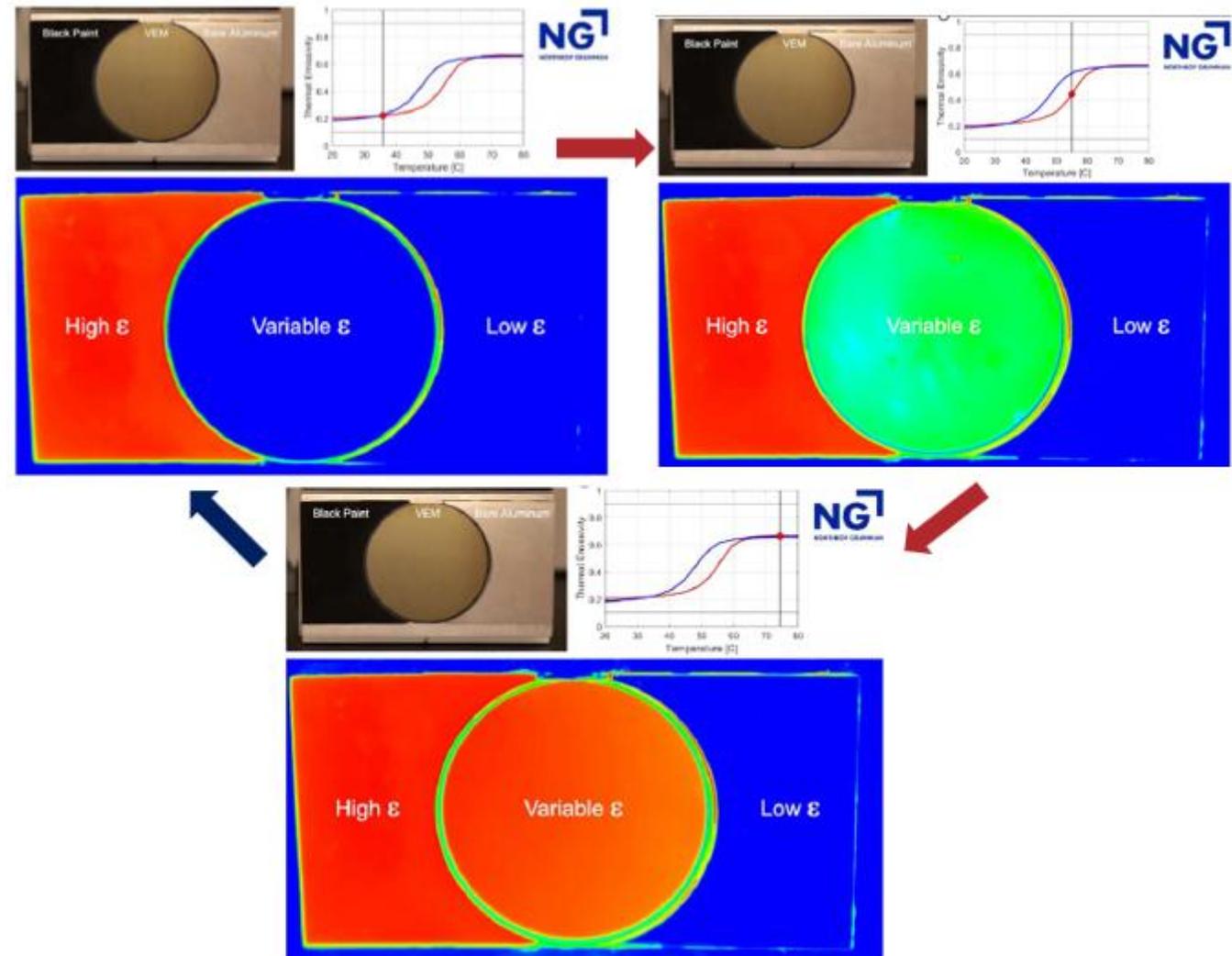
GOAL: Introduce you to VEMs and convince you that we have confirmation of their successful performance in the combined space effects thermal environment



Variable Emissivity Materials

What are VEMs?

- VEMs change thermal emissivity (ϵ) value in the infrared in response to a change in environment (i.e., temperature)
- VEMs defined by switching mechanism
 - Electrochromics
 - ϵ changes as a function of voltage
 - Active solution; requires support system
 - Comes with drawbacks
 - Thermochromics
 - ϵ changes as a function of temperature \rightarrow passive system
 - Focus of recent development efforts
- VEMs are useful to spacecraft thermal engineers for tricky heat regulation tasks
- VEMs enable novel satellite architectures (e.g., thinsats)

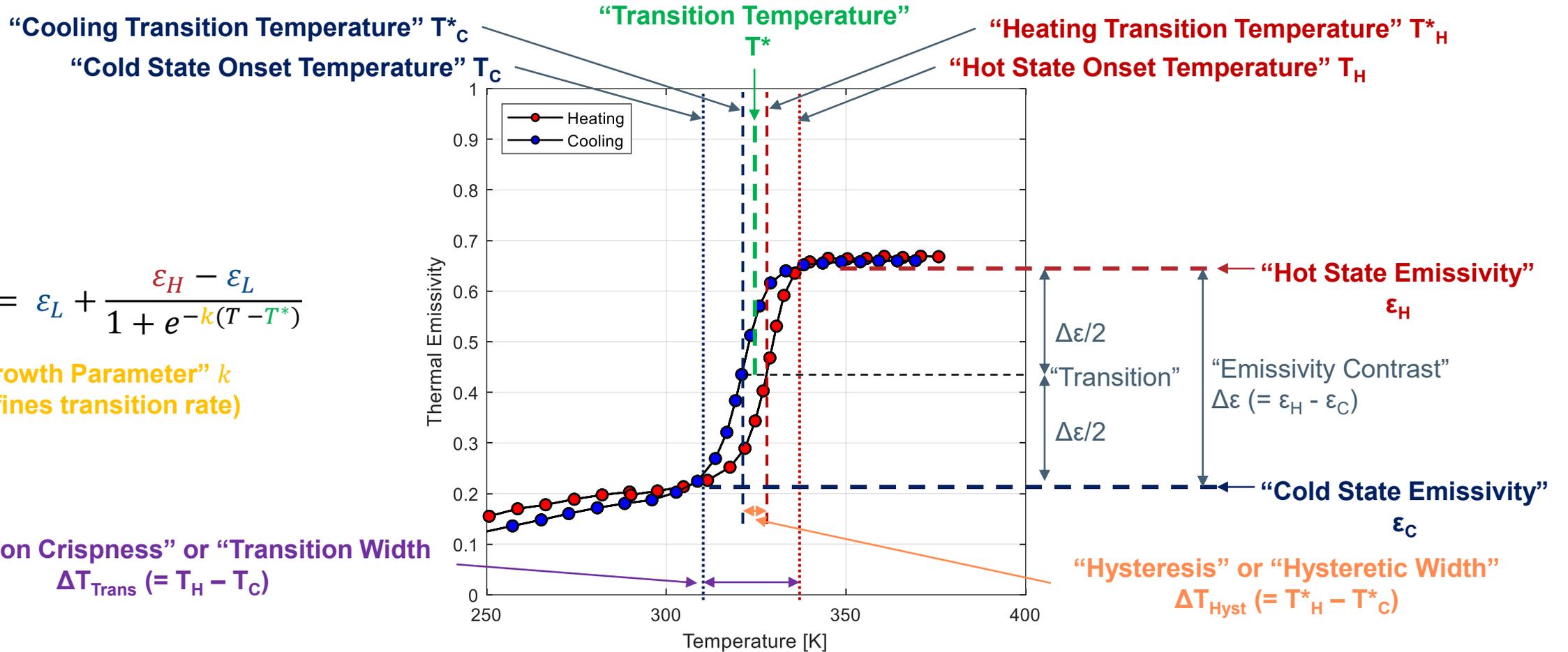


VEMs change thermo-optical properties in response to temperature change \rightarrow passive thermal control



Defining Thermochromic VEM Characteristics

Thermal Emissivity Vs. Temperature Curve for Thermochromic VEM



$$\epsilon(T) = \epsilon_L + \frac{\epsilon_H - \epsilon_L}{1 + e^{-k(T - T^*)}}$$

Clear definitions needed to aid communication about VEMs



Space Power IR Regulation and Analysis of Lifetime (SPIRRAL) Flight Experiment



What is SPIRRAL? Space Power IR Regulation and Analysis of Lifetime

- SPIRRAL is a spaceflight experiment designed to test variable emissivity materials (VEMs) and advance their TRL from 6 to 7

- SPIRRAL consists of 18 active 'sites' (13 VEMs + 5 control samples) from multiple VEM vendors

PLASMONICS INC

ISI Physical Sciences Inc.



- Over a 1.5-year space exposed mission aboard the ISS, SPIRRAL will
 - Measure VEM IR emissivity (ϵ) and solar absorptivity (α) throughout mission, utilizing calorimetric methods
 - Determine space effects on VEM thermo-optical properties (TOPs); estimate degradation over mission life

13x VEM samples + 5x reference samples integrated into SPIRRAL

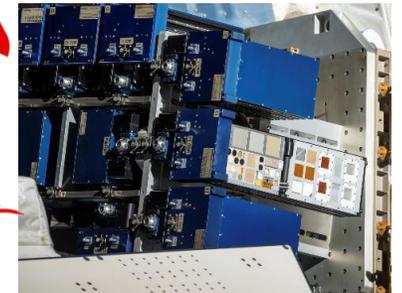


Nov 24', launched to ISS

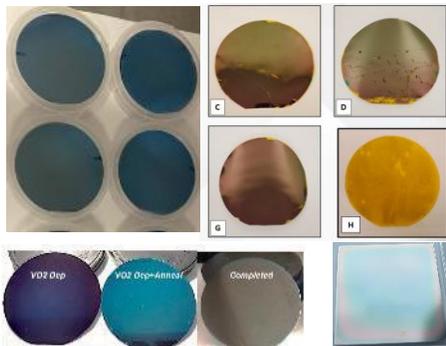


Photo Credit: SpaceX

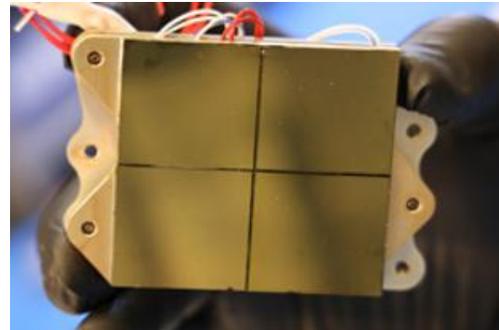
Integrated to MISSE-FF Zenith slot



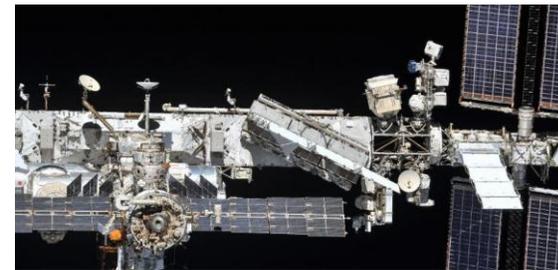
VEM sample coupons



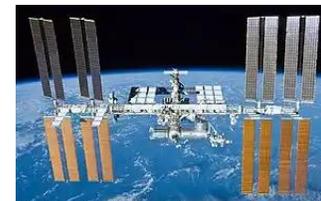
VEMs integrated onto test sites



Beginning of life
Late Nov 24'



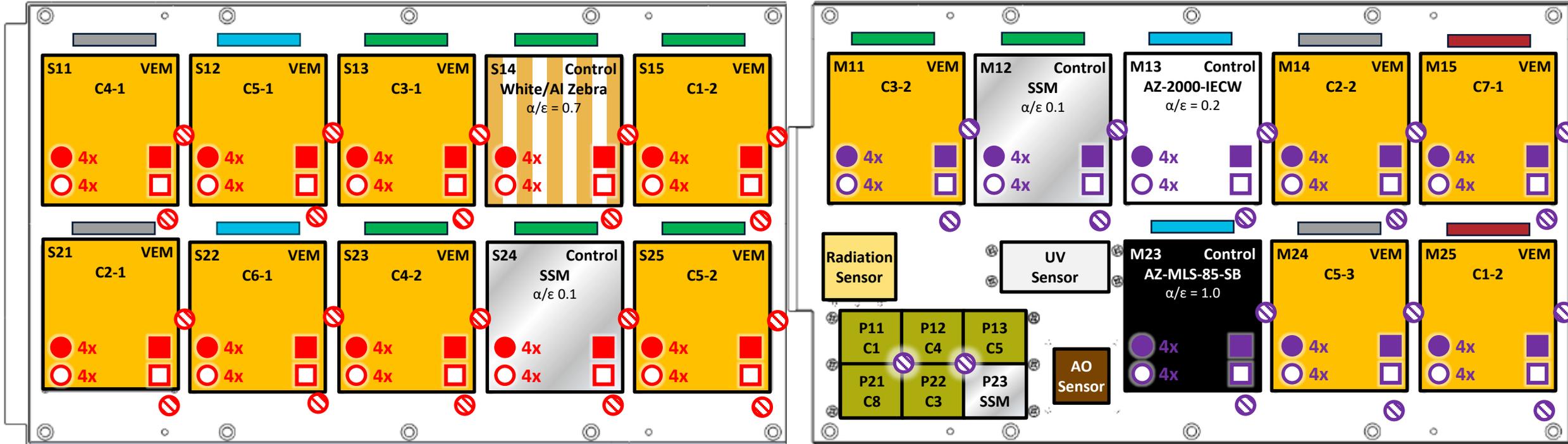
EOL Spring 26'



SPIRRAL flight experiment to take VEMs to TRL-7; operational since Nov 2024



Experiment Layout



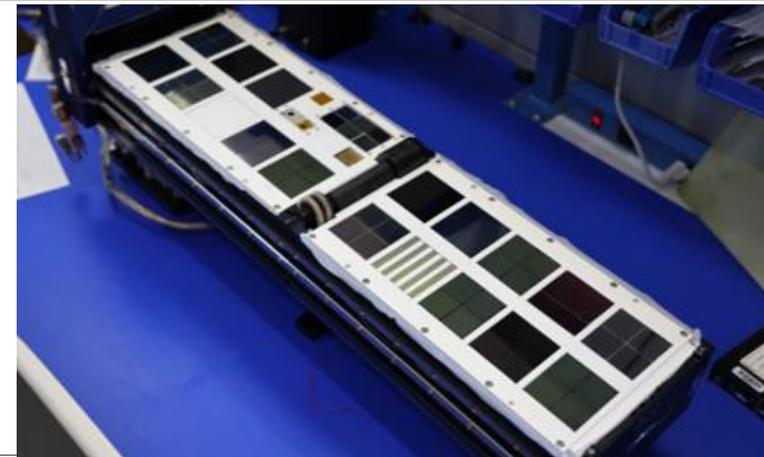
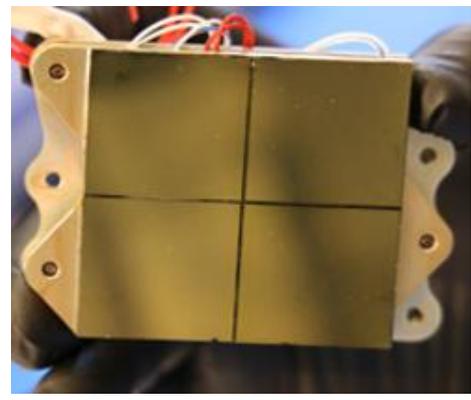
- ■ Swing/Mount electronics tile heater circuit (10 swing; 8 mount)
- □ Swing/Mount electronics guard heater circuit (10 swing; 8 mount)
- ● Swing/Mount electronics tile temperature TMP117 (40 swing; 32 mount)
- ○ Swing/Mount electronics guard temperature TMP117 (40 swing; 32 mount)
- ⊘ ⊘ Swing/Mount electronics deck temperature TMP117 (20 swing; 18 mount)

Site Desirability (Views to Space)

- Super-Prime
- Prime
- Near Prime
- Sub Prime

Controls	Details	BOL α (hot)	BOL ϵ (hot)	α/ϵ (hot)	BOL α (cold)	BOL ϵ (cold)	α/ϵ (cold)
		[--]	[--]	[--]	[--]	[--]	[--]
White/Al Zebra*	White/Al Zebra	0.27	0.41	0.7	0.27	0.41	0.7
AZ-2000-IECW*	White Control	0.19	0.92	0.2	0.19	0.92	0.2
MLS-85-SB*	Black Control	0.93	0.91	1.0	0.93	0.91	1.0
SSM**	Mirror Control	0.06	0.84	0.1	0.06	0.84	0.1

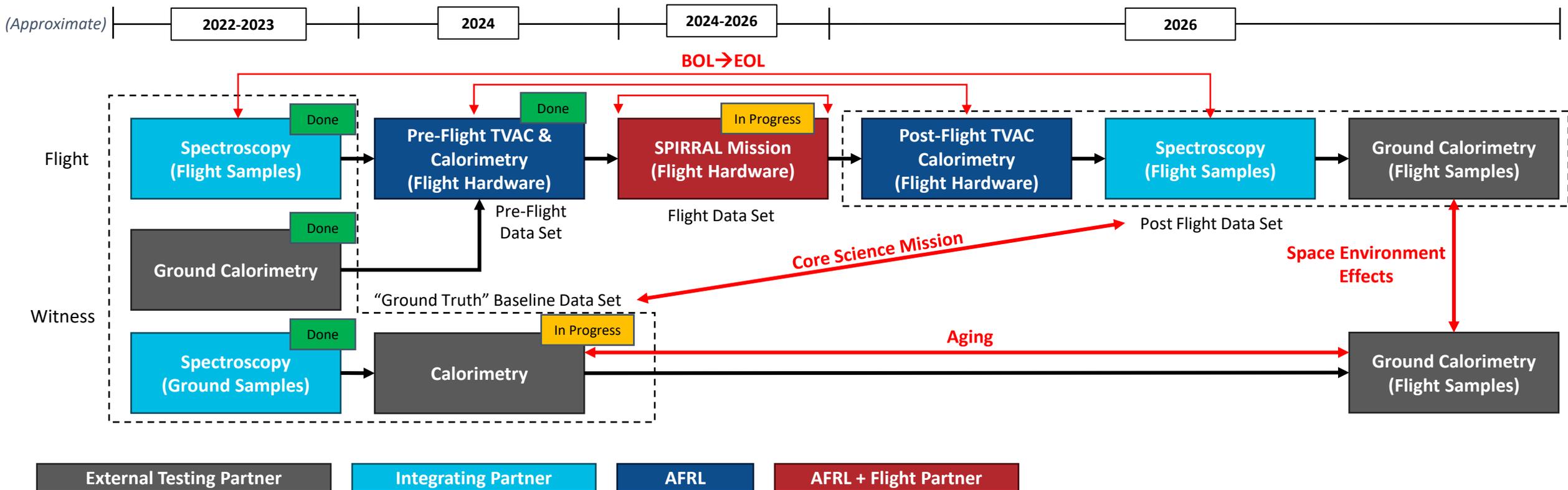
*Measurements from TESSA 2000 (total, hemispheric, emissivity and absorptivity)
 **Measurements from FTIR (17° off-normal, 2.5-25 μ m) (data package)





VEM Science Plan

- Testing plan utilizes pre-flight spectroscopic and calorimetric measurement of witness samples; in-flight calorimetric measurements of flight samples, and post-flight spectroscopic and calorimetric measurement of flight samples



VEM Testing plan enables accurate assessment of space thermal environment effects on VEMs



SPIRRAL Analysis Methods

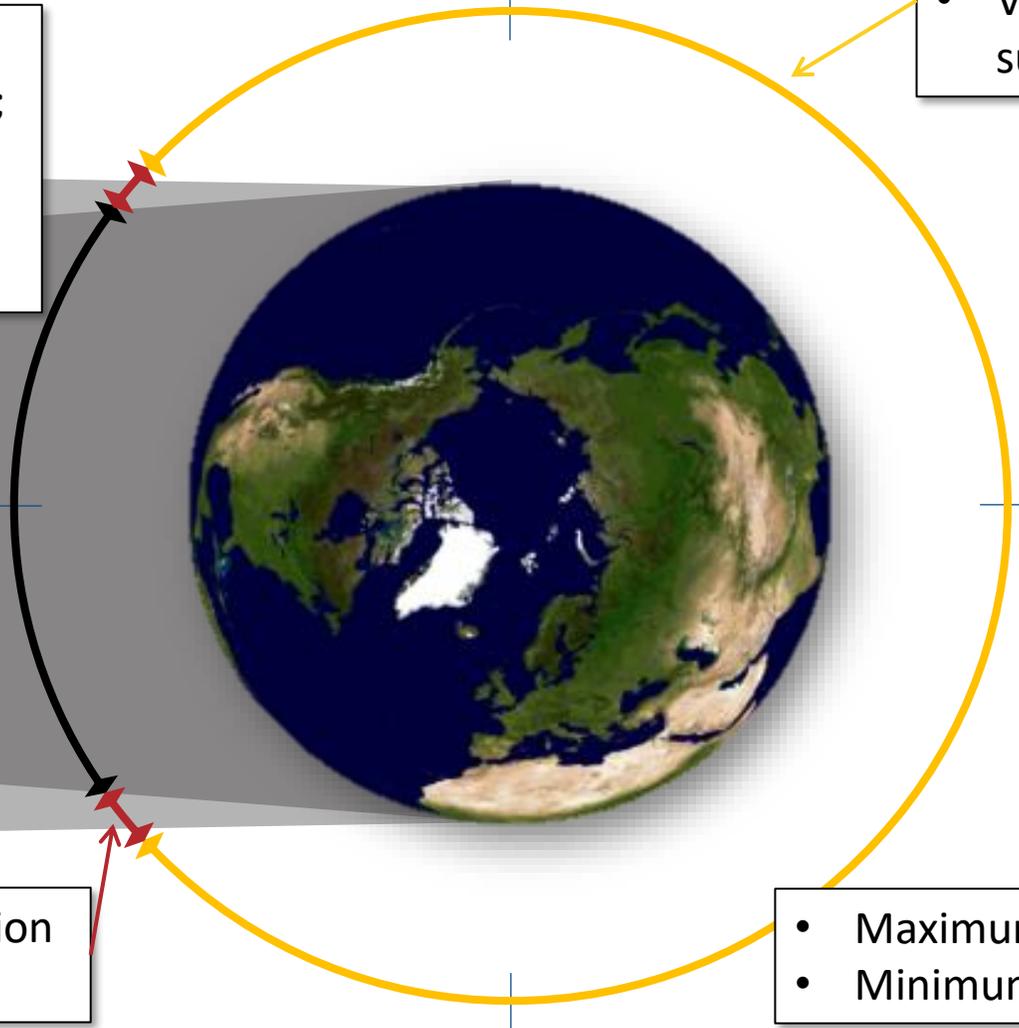


Testing Environment

ISS Orbit (~400 km)
Not to Scale

- Sunlit (~55 min)
- VEM absorptivity calculation while sunlit; numerical methods needed

- Umbral Eclipse Window (~30 min)
- VEM emissivity calc when eclipsed; analytical & numerical methods
- No VEM absorptivity calculation (no sunlight)



Umbral Eclipse Region

Penumbral Eclipse Region

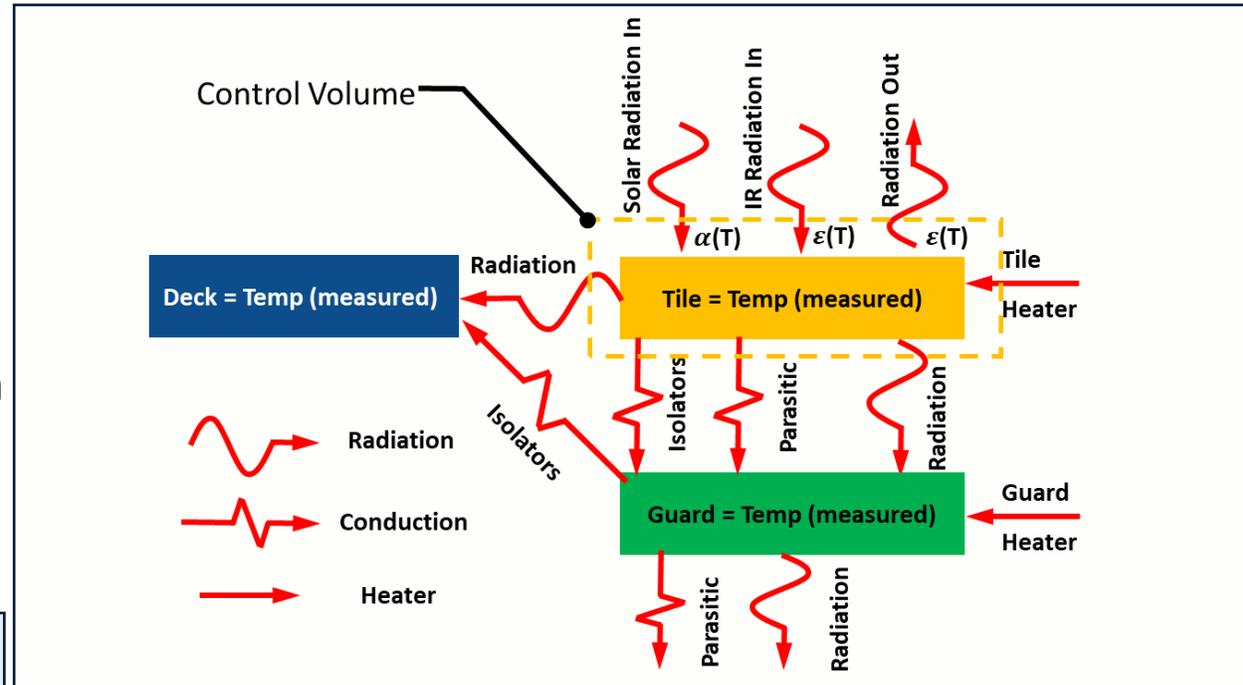
Umbral/Penumbral eclipse transition
"keep out" region for analysis

- Maximum eclipse duration, 35 minutes
- Minimum eclipse duration, 0 minutes

1.5 Year Mission: ~5256 hrs of data for VEM emissivity calculation, ~7884 hrs of data for VEM absorptivity calculation

Measuring VEM Parameters Using Radiative Calorimetry (1/2)

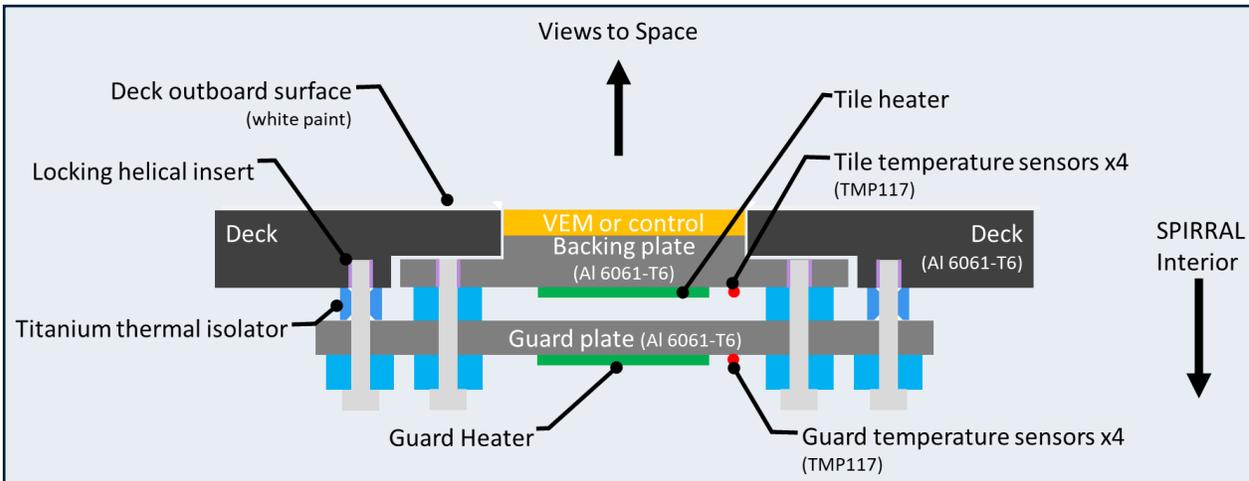
- Energy balance model quantifies heat entering and leaving a site; includes capacitive effects
- Leverage inverse heat transfer methods to determine a VEM emissivity vs. temperature curves from on-orbit data
- Account for thermal environment using control samples
 - IR flux from ISS; solar flux from direct and reflected sunlight



Energy Balance Model Illustration

$$\underbrace{\dot{Q}_{h,t} + \epsilon_t \dot{Q}_{IR} + \alpha_t \dot{Q}_{solar}}_{\text{Energy Rate In [W]}} - \underbrace{A_t \sigma \epsilon_t T_{t,n}^4 - \dot{Q}_{loss}}_{\text{Energy Rate Out [W]}} = \underbrace{m_t C p_t \frac{T_{t,t_2} - T_{t,t_1}}{t_2 - t_1}}_{\text{Net Energy Rate [W]}}$$

Energy Balance Model



VEM/Control Experiment Site Design Illustration

VEM performance characteristics calculable using radiative calorimetry and custom flight hardware



Measuring VEM Parameters Using Radiative Calorimetry (2/2)

1. Start with simple energy balance
2. Account for parasitic heat flow vectors (e.g., wires, radiation)
 - All sites manufactured to be identical
 - \dot{Q}_{loss} term construction the same for ever site
- 3.A For controls, solve for thermal backloading
 - Can average results across all 5 control tiles
- 3.B For VEMs, solve for thermal emissivity
 - Use thermal backloading calculated from control tiles

$$\dot{Q}_{in} - \dot{Q}_{out} = \dot{Q}_{net}$$

$$\dot{Q}_{h,t} + \epsilon_t \dot{Q}_{IR} - \sigma A_t \epsilon_t T_{t,n}^4 - \dot{Q}_{loss} = \dot{Q}_{net}$$

$$\dot{Q}_{IR} = \frac{\dot{Q}_{C,net} + \dot{Q}_{C,loss} + \sigma A_{C,t} \epsilon_{C,t} T_{C,t,n}^4 - \dot{Q}_{C,h,t}}{\epsilon_{C,t}}$$

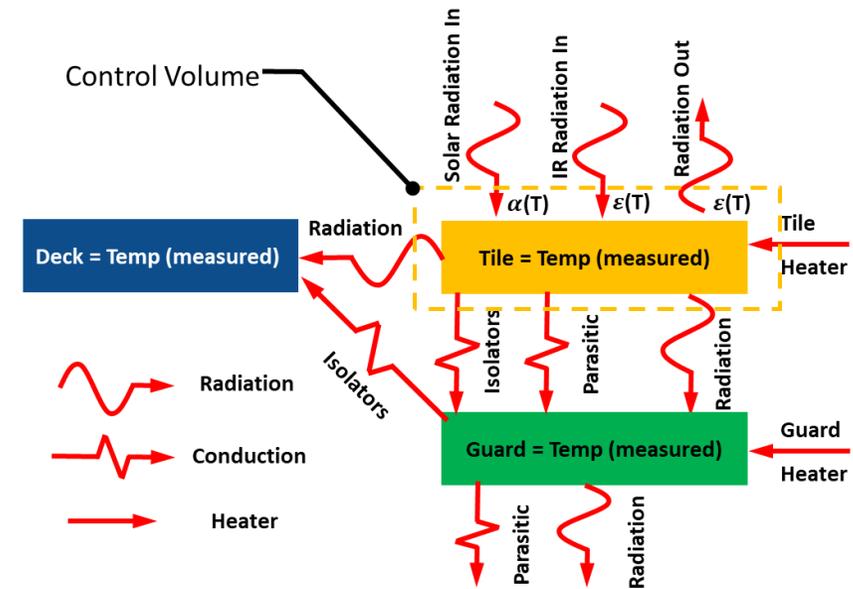
$$\epsilon_t = \frac{\dot{Q}_{net} + \dot{Q}_{loss} - \dot{Q}_{h,t}}{\dot{Q}_{IR} - \sigma A_t T_{t,n}^4}$$

Supporting Equations for Energy Balance Models

$$\dot{Q}_{net} = m_t C p_t \frac{T_{t,t_2} - T_{t,t_1}}{t_2 - t_1}$$

$$\dot{Q}_{loss} = \frac{(T_{t,t_2} - T_{g,t_2})}{R_{tg,wires}} + \frac{(T_{t,t_2} - T_{g,t_2})}{R_{tg,BI}} + \sigma A_{tg} f_{t \rightarrow g} \frac{(T_{t,t_2}^4 - T_{g,t_2}^4)}{\frac{1}{\epsilon_{tg}} + \frac{1}{\epsilon_{gt}} - 1} + \sigma A_{td} f_{t \rightarrow d} \frac{(T_{t,t_2}^4 - T_{d,t_2}^4)}{\frac{1}{\epsilon_{td}} + \frac{1}{\epsilon_{dt}} - 1}$$

Good hardware design enabled straightforward model construction
→ enables more efficient and accurate analysis





First Order Analysis Formulation

1. Using heater setpoint control, set guard and tile temperature to be equal (pseudo adiabatic boundary condition); assume radiation between deck and tile is negligible → \dot{Q}_{loss} zeroed

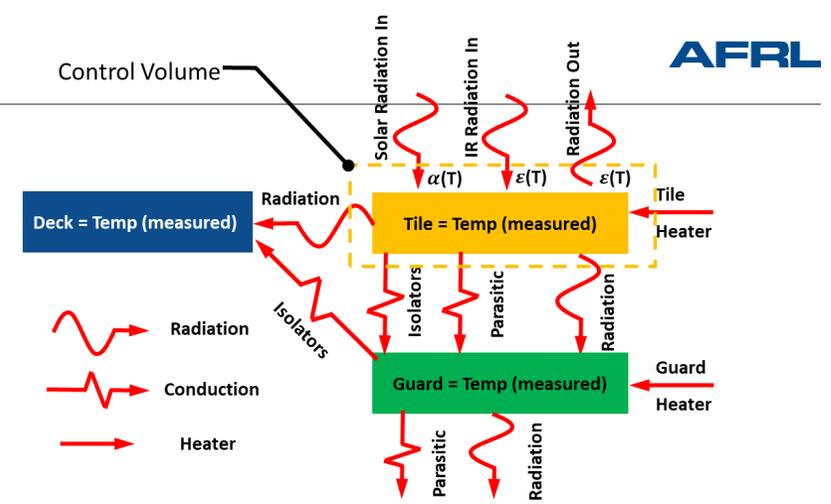
$$\dot{Q}_{loss} = \frac{(T_{t,t_2} - T_{g,t_2})}{\epsilon_{tg,wires}} + \frac{(T_{t,t_2} - T_{g,t_2})}{\epsilon_{tg,BI}} + \sigma A_{tg} f_{t \rightarrow g} \frac{(T_{t,t_2}^4 - T_{g,t_2}^4)}{\frac{1}{\epsilon_{tg}} + \frac{1}{\epsilon_{gt}} - 1} + \sigma A_{td} f_{t \rightarrow d} \frac{(T_{t,t_2} - T_{d,t_2})}{\frac{1}{\epsilon_{td}} + \frac{1}{\epsilon_{dt}} - 1}$$

2. Using heater setpoint control, hold guard and tile at a constant temperature (pseudo steady state condition). This is possible during eclipse → \dot{Q}_{net} term can be zeroed

$$\dot{Q}_{net} = m_t C p_t \frac{T_{t,t_2} - T_{t,t_1}}{t_2 - t_1}$$

3. Hold temperature setpoints during eclipse → no solar loading; minimal IR loading (zenith pointing, minimal views to ISS). Using previous simplifications, complete energy balance reduces to the following

$$\dot{Q}_{h,t} + \epsilon_t \dot{Q}_{IR} - \sigma A_t \epsilon_t T_{t,n}^4 \cong 0 \quad \frac{\dot{Q}_{h,t}}{\epsilon_t} + \dot{Q}_{IR} - \sigma A_t T_{t,n}^4 \cong 0 \quad \dot{Q}_{IR} \cong \sigma A_t T_{t,n}^4 - \frac{\dot{Q}_{h,t}}{\epsilon_t}$$



4. Assume VEM and control tile sites are thermo-mechanically identical; assume VEM and control tiles receive identical thermal backloading → set simplified VEM and control tile energy balances equal

$$\sigma A_{t,V} T_{t,n,V}^4 - \frac{\dot{Q}_{h,t,V}}{\epsilon_{t,V}} \cong \sigma A_{t,C} T_{t,n,C}^4 - \frac{\dot{Q}_{h,t,C}}{\epsilon_{t,C}}$$

5. Solve for VEM emissivity

$$T_{VEM} \neq T_{Control} \quad \epsilon_{t,V} \cong \frac{\dot{Q}_{h,t,V}}{\frac{\dot{Q}_{h,t,C}}{\epsilon_{t,C}} + \sigma A_{t,V} T_V^4 - \sigma A_{t,C} T_C^4}$$

$$T_{VEM} = T_{Control} \quad \epsilon_{t,V} \cong \epsilon_{t,C} \frac{\dot{Q}_{h,t,V}}{\dot{Q}_{h,t,C}}$$

Simple first order methods enable fast V&V of flight hardware and flight data



First Order Results from On-Orbit Data



First Order Assessment of SPIRRAL's Capabilities

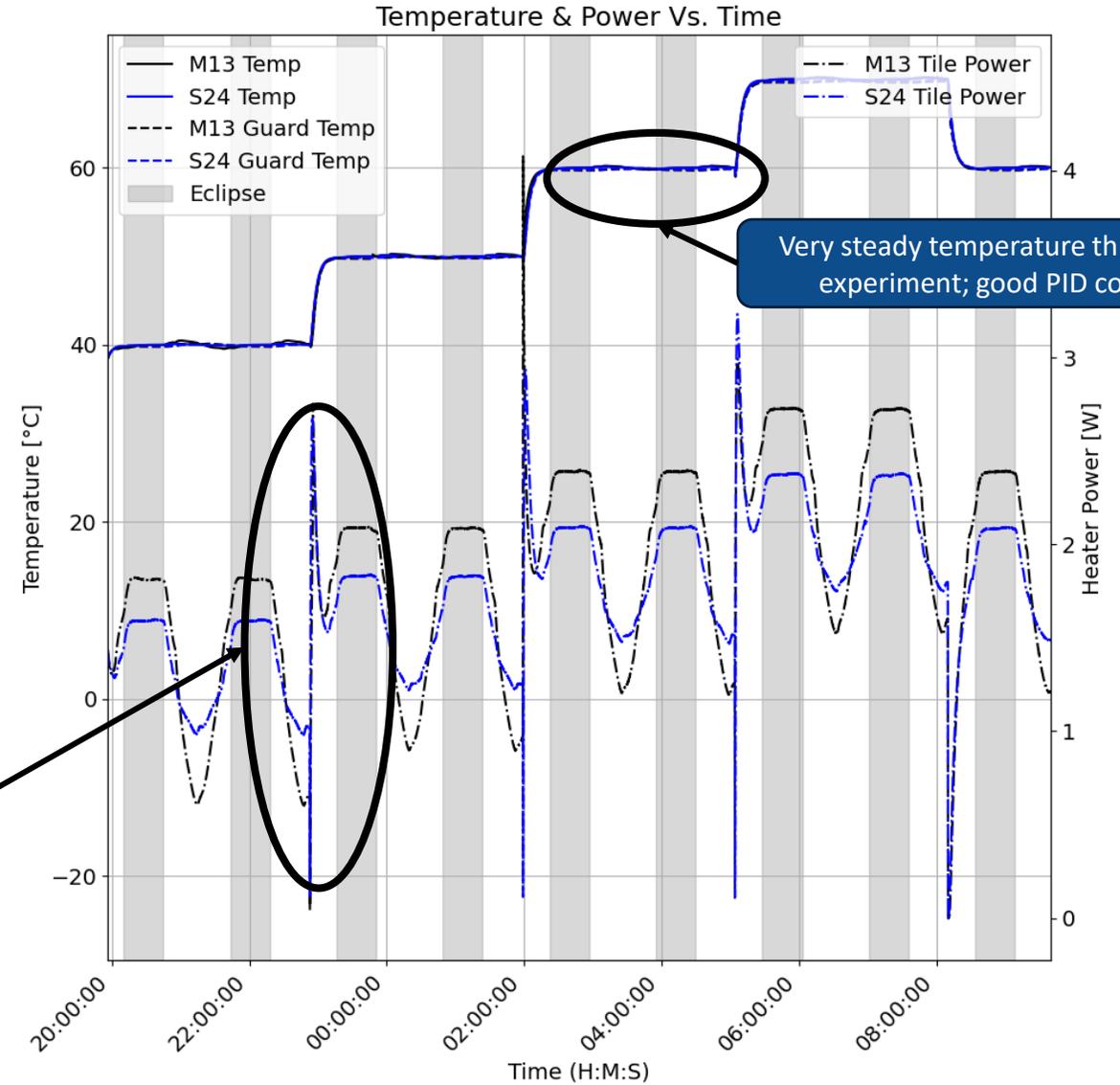
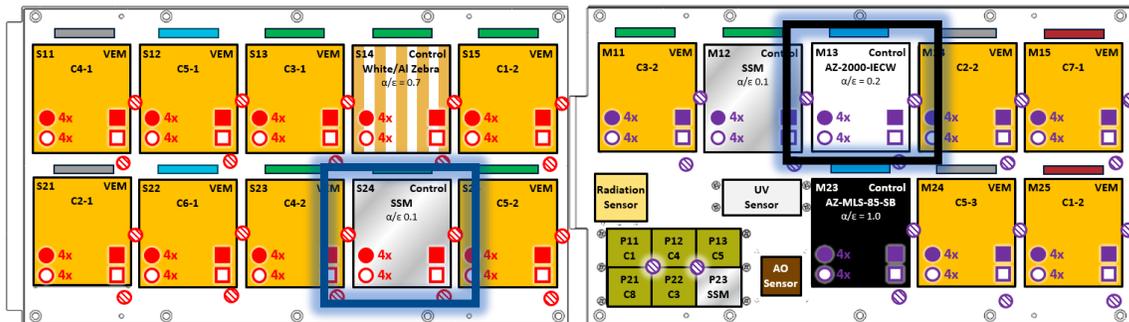
- Comparing first order flight results with ground baseline measurements will inform model correlation and future analysis decisions
- Ground baseline measurements gathered using multiple methods:
 - VEM Samples: On-ground calorimetry; measurement uncertainty +/- 0.04 1-sigma
 - Control Samples: AZ Technology TESA 2000 Portable Emissometer/Reflectometer and Solar Reflectometer; measurement uncertainty +/- 0.03 1-sigma
- On-orbit experiments performed during eclipse, tile and guard in a pseudo steady-state condition using temperature control mode
- On-orbit radiative calorimetry result uncertainty estimated to be +/- 0.05 1-sigma
- No input parameter adjustment or correlation attempts; all calculations are “out-of-the-box”

First order results will inform subsequent analysis decisions and assess SPIRRAL performance

First Order Flight Results: White (AZ-2000-IECW) Control Tile (1/4)

- Initial assessment of SPIRRAL's experiment capability; calculate AZ-2000-IECW emissivity from flight data
- Treated AZ-2000-IECW's thermal emissivity as an unknown; used SSM and MLS-85-SB as the control samples
- Utilized temperature control mode during eclipse to achieve pseudo steady-state; guard commanded to match the tile's temperature to achieve pseudo adiabatic boundary condition

Power dips due to entering/exiting eclipse or changes in setpoint



SPIRRAL Experiment CONOPS Successful

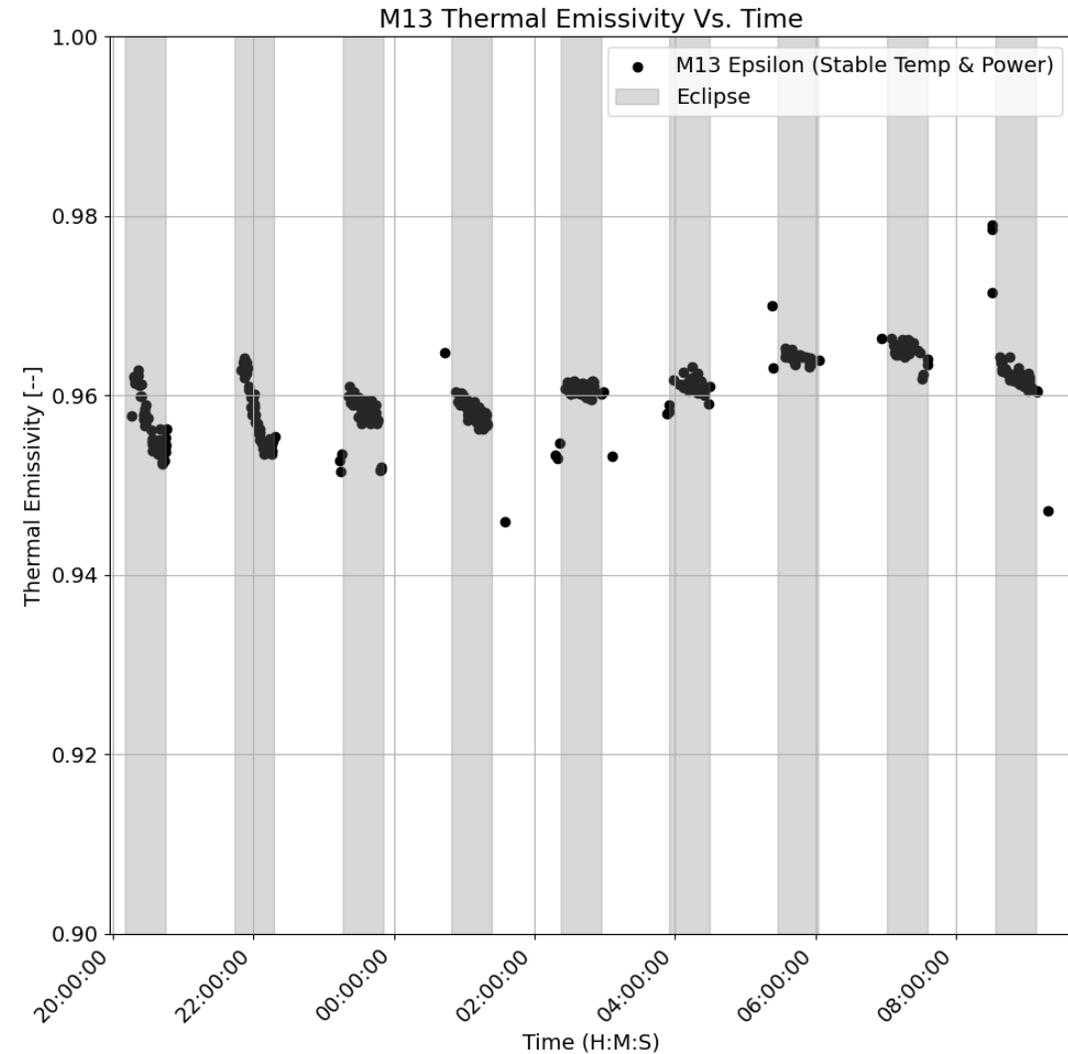
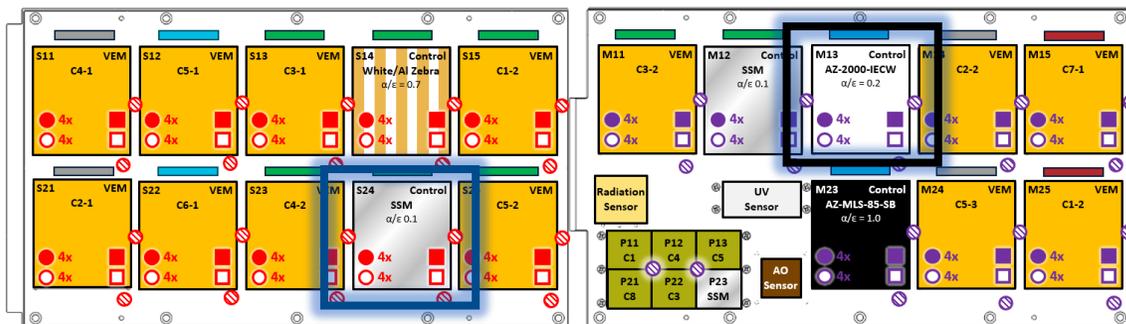


First Order Flight Results: White (AZ-2000-IECW) Control Tile (2/4)

- Used simplified energy balance to calculate the thermal emissivity of the AZ-2000-IECW control sample

$$\epsilon_{t,AZ2000IECW} \cong \epsilon_{t,SSM} \frac{\dot{Q}_{h,t,AZ2000IECW}}{\dot{Q}_{h,t,SSM}}$$

- GROUND: SSM emissivity: 0.84 +/- 0.03
- GROUND: AZ-2000-IECW emissivity: 0.92 +/- 0.03
- FLIGHT: AZ-2000-IECW emissivity: ~0.96 +/- 0.05

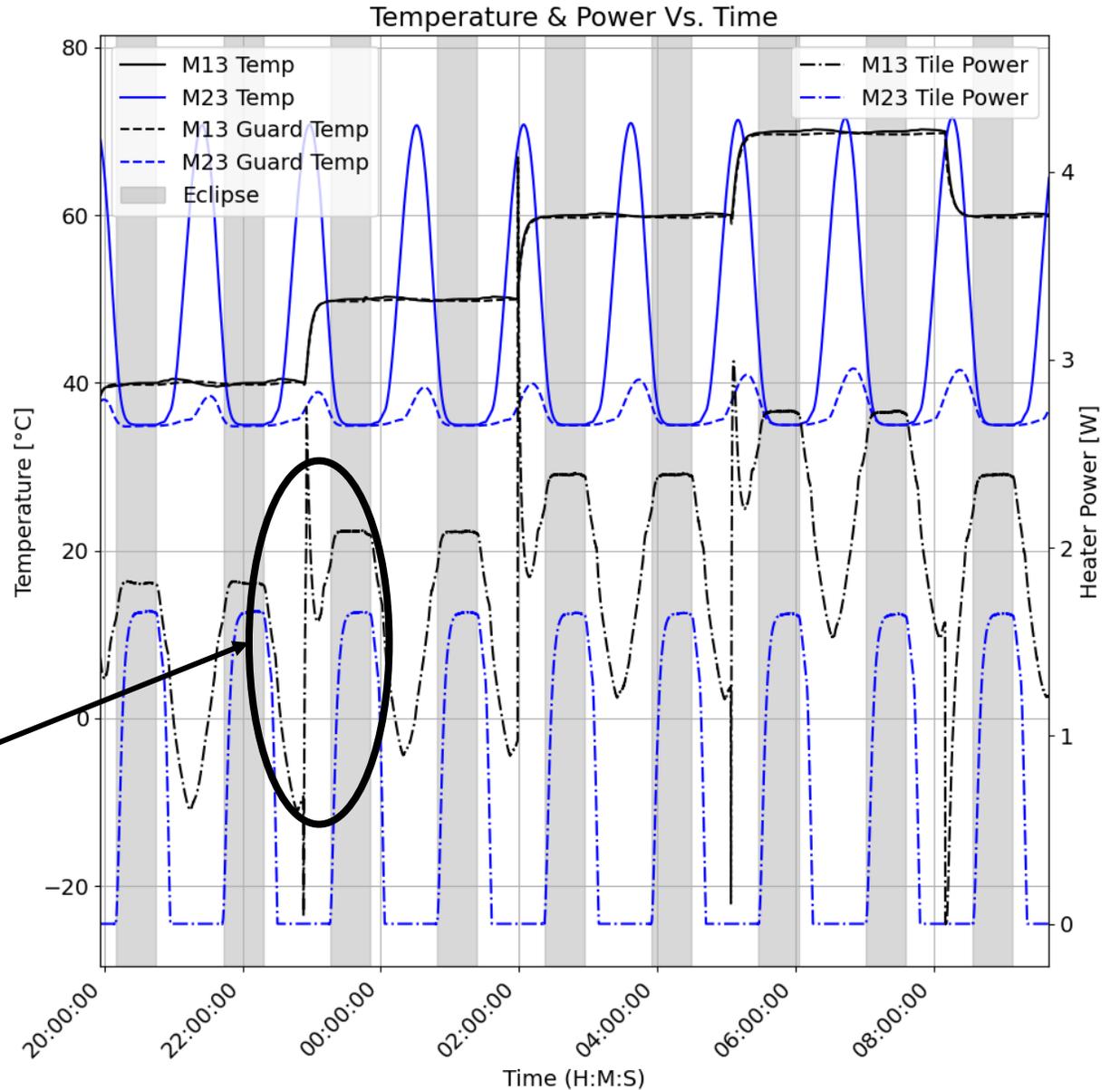


AZ-2000-IECW mean thermal emissivity calculated using radiative calorimetry to within +0.04 of ground measurement

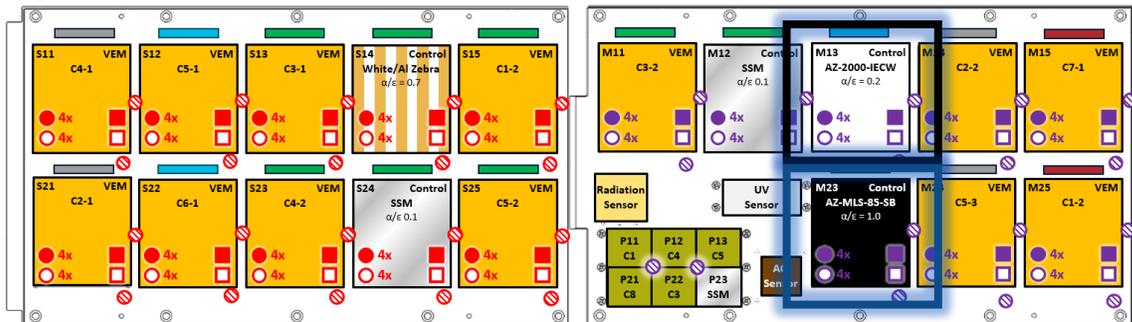


First Order Flight Results: White (AZ-2000-IECW) Control Tile (3/4)

- Compare calculated AZ-2000-IECW emissivity using SSM with that using MLS-85-SB
- Used simplified energy balance to calculate the thermal emissivity of the AZ-2000-IECW control
- MLS-85-SB had different temperature profile than AZ-2000-IECW control (not temperature matched)



Power dips due to entering/exiting eclipse or changes in setpoint



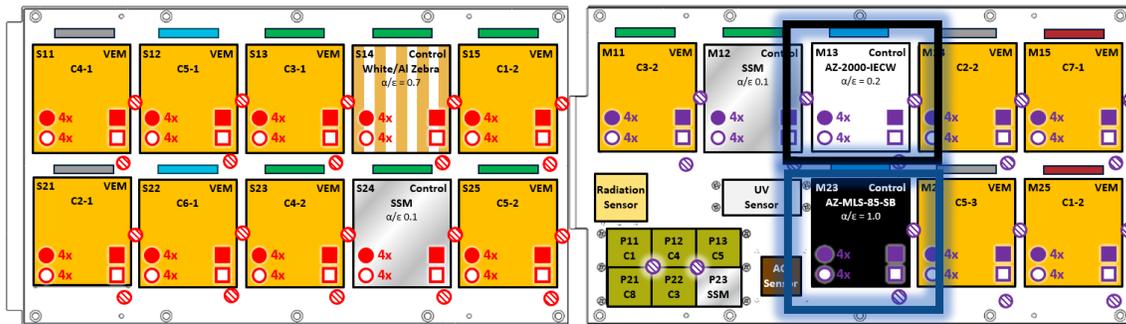
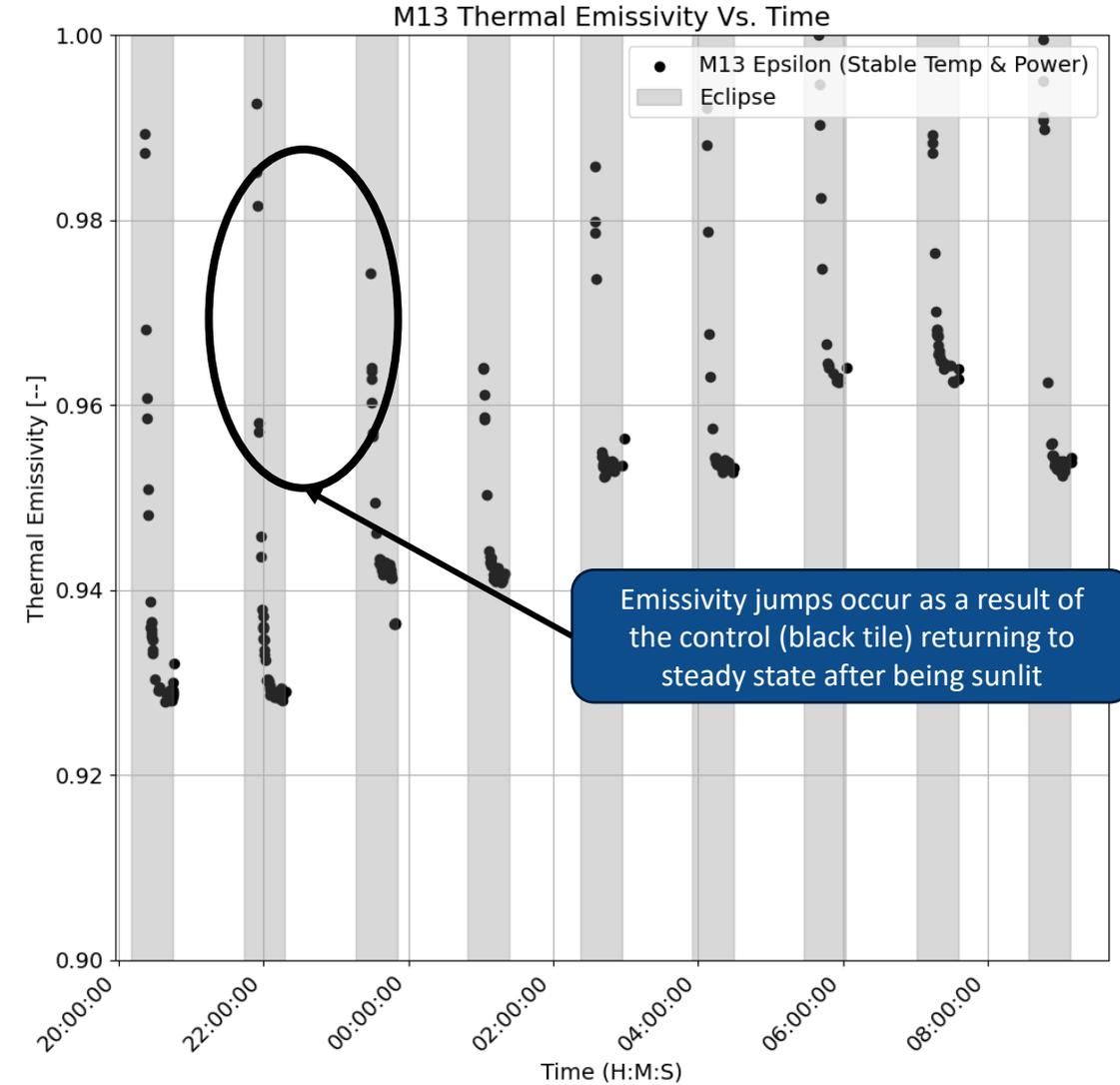


First Order Flight Results: White (AZ-2000-IECW) Control Tile (4/4)

- Used simplified energy balance to calculate the thermal emissivity of the AZ-2000-IECW control sample

$$\epsilon_{t,AZ2000IECW} \cong \frac{\dot{Q}_{h,t,AZ2000IECW}}{\frac{\dot{Q}_{h,t,MLS85SB}}{\epsilon_{t,MLS85SB}} + \sigma A_{t,AZ2000IECW} T_{AZ2000IECW}^4 - \sigma A_{t,MLS85SB} T_{MLS85SB}^4}$$

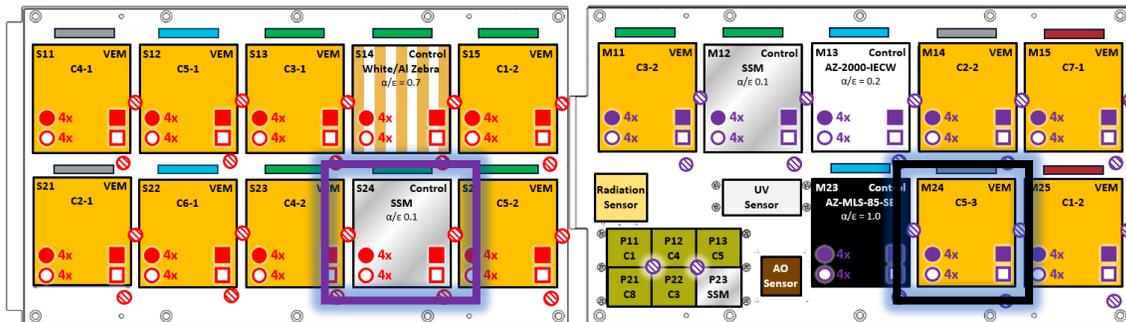
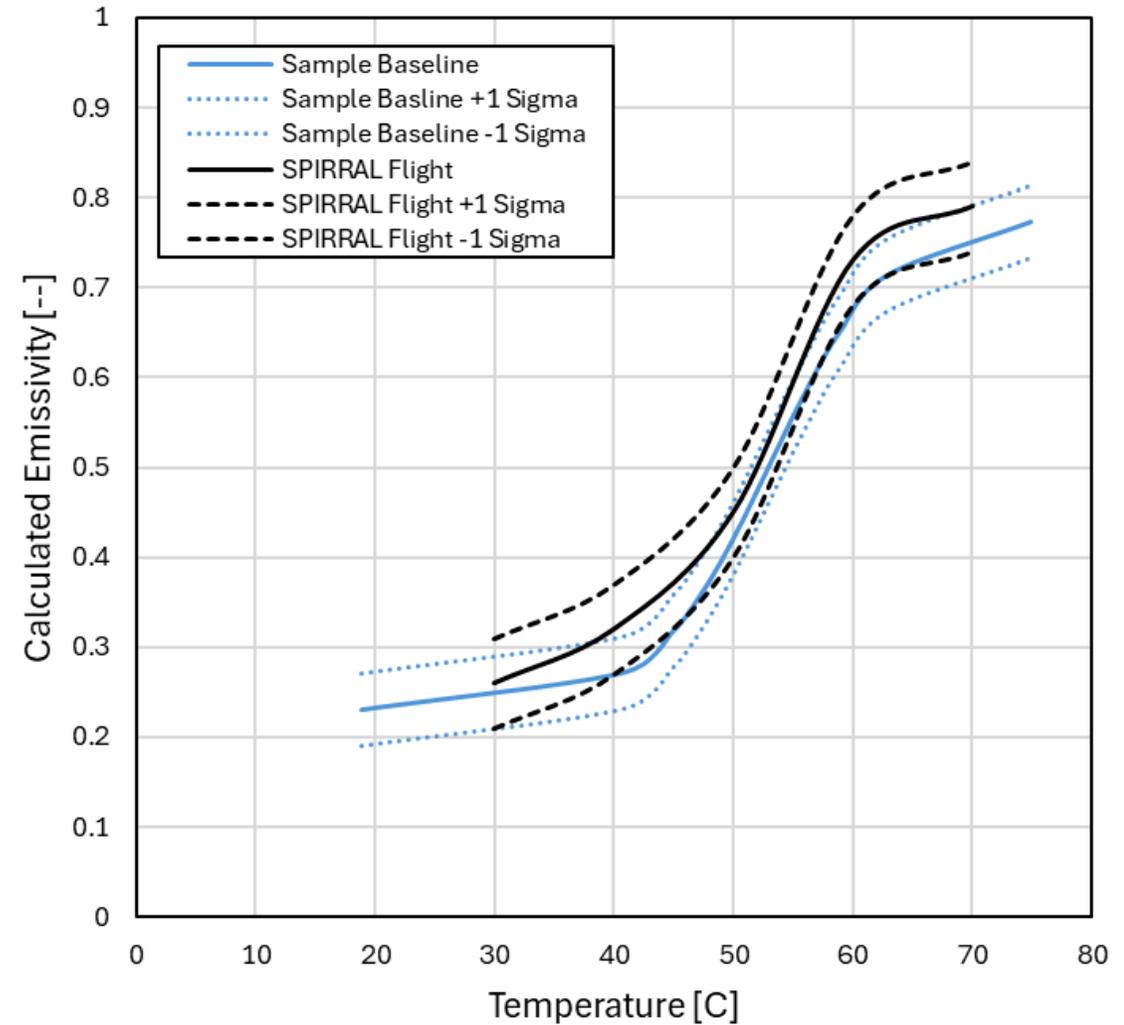
- GROUND: MLS-85-SB emissivity: 0.91 +/- 0.03
- GROUND: AZ-2000-IECW emissivity: 0.92 +/- 0.03
- FLIGHT: AZ-2000-IECW emissivity varies between 0.92 and 0.97 during “steady state” data periods
 - Variation likely due to temperature dependent effects
 - Model correlation expected to reduce this variation



AZ-2000-IECW emissivity accurately calculated out-of-the-box using two independent control tiles; SPIRRAL works!

First Order VEM Result (1/2)

- M24/C5-3 VEM sample thermal emissivity calculated using simplified energy balance
- M24/C5-3 VEM sample flight emissivity vs. temperature curve (black) compared against ground emissivity vs. temperature curve (blue)
- Estimated flight 1-sigma uncertainty: +/- 0.05
- Sample baseline 1-sigma uncertainty: +/- 0.04
- Discrepancy between flight and ground test results likely due to lack of flight model correlation and sample-to-sample variability

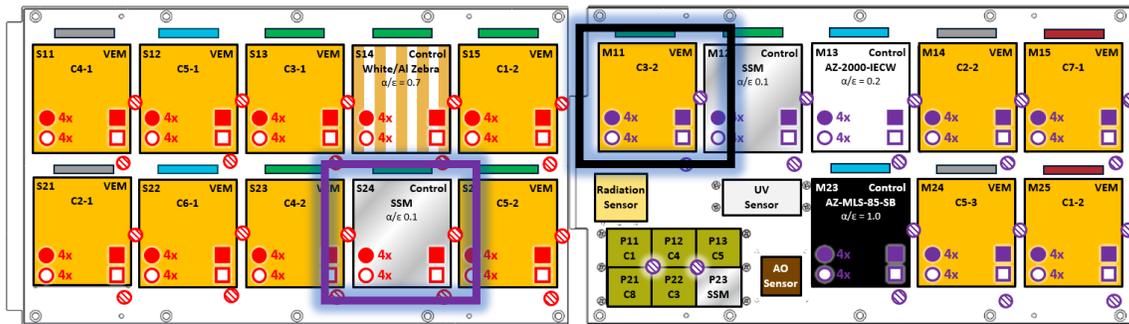
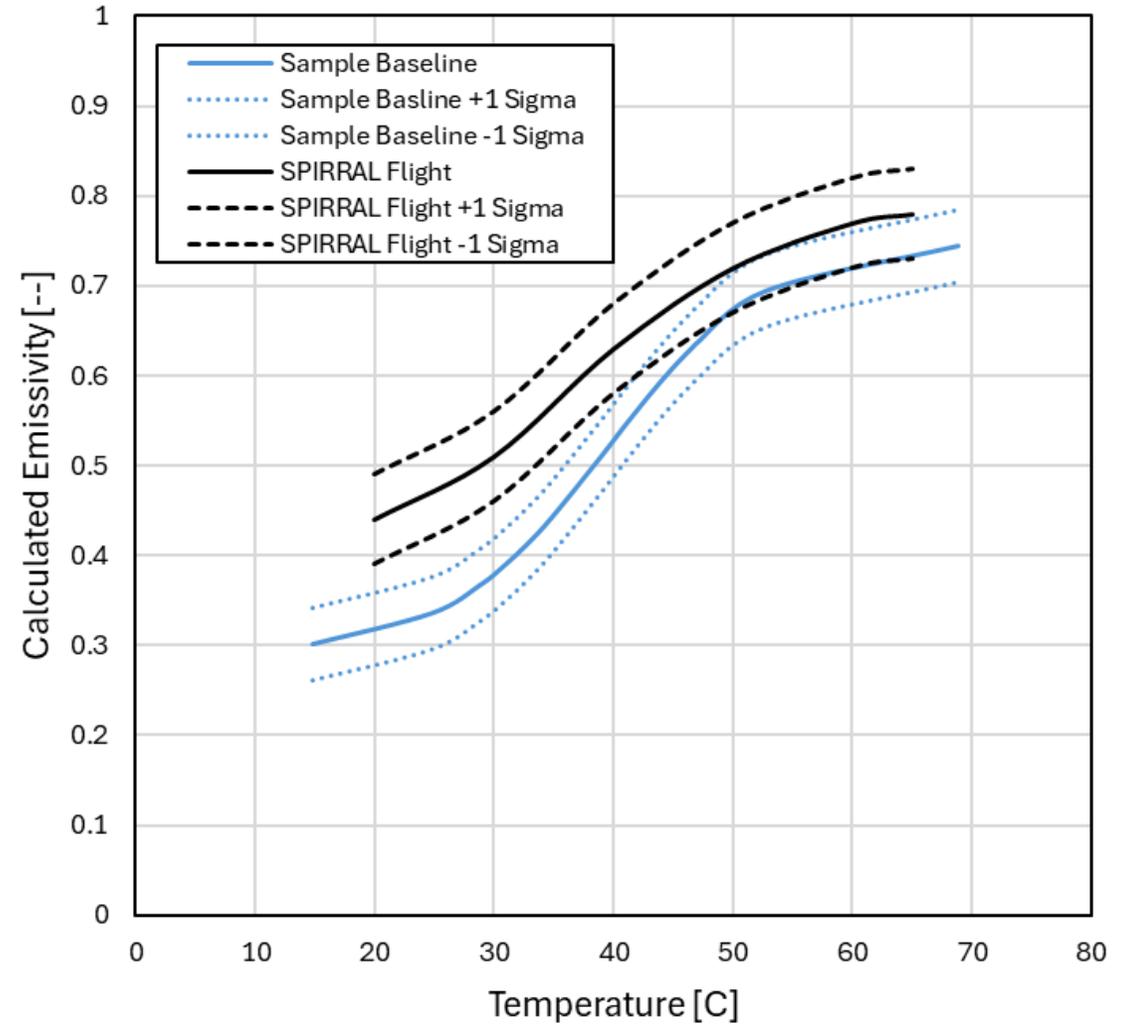


Excellent alignment between flight and sample baseline results; VEMs confirmed to have switched emissivity in space!



First Order VEM Result (2/2)

- M11/C3-2 VEM sample thermal emissivity calculated using simplified energy balance
- M11/C3-2 VEM sample flight emissivity vs. temperature curve (black) compared against ground emissivity vs. temperature curve (blue)
- Estimated flight 1-sigma uncertainty: +/- 0.05
- Sample baseline 1-sigma uncertainty: +/- 0.04
- Discrepancy between flight and ground test results likely due to lack of flight model correlation and sample-to-sample variability



Good alignment between flight and sample baseline results; VEMs confirmed to have switched emissivity in space!



Conclusion



Conclusion

- VEMs enable a new paradigm of thermal control and enable novel satellite architectures
- SPIRRAL is THE flight experiment designed to characterize thermochromic VEMs in space and enable VEMS to cross the TRL valley of death from 6 to 7
- First order results show that SPIRRAL functions as designed, and is capable of accurately calculating thermal emissivity from temperature, current, and voltage measurements
- This is the first known public work to successfully demonstrate thermochromic variable emissivity material performance in space using radiative calorimetric methods!
- Future work will investigate how VEMs might degrade during the mission, determine emissivity curves for all VEMs on SPIRRAL, compare beginning-of-mission results to end-of-mission results, and perform uncertainty propagation/quantification

- 1. SPIRRAL functions as designed!**
- 2. VEMs have been shown to operate in space!**
- 3. VEMs moving to TRL 7!**



QUESTIONS?



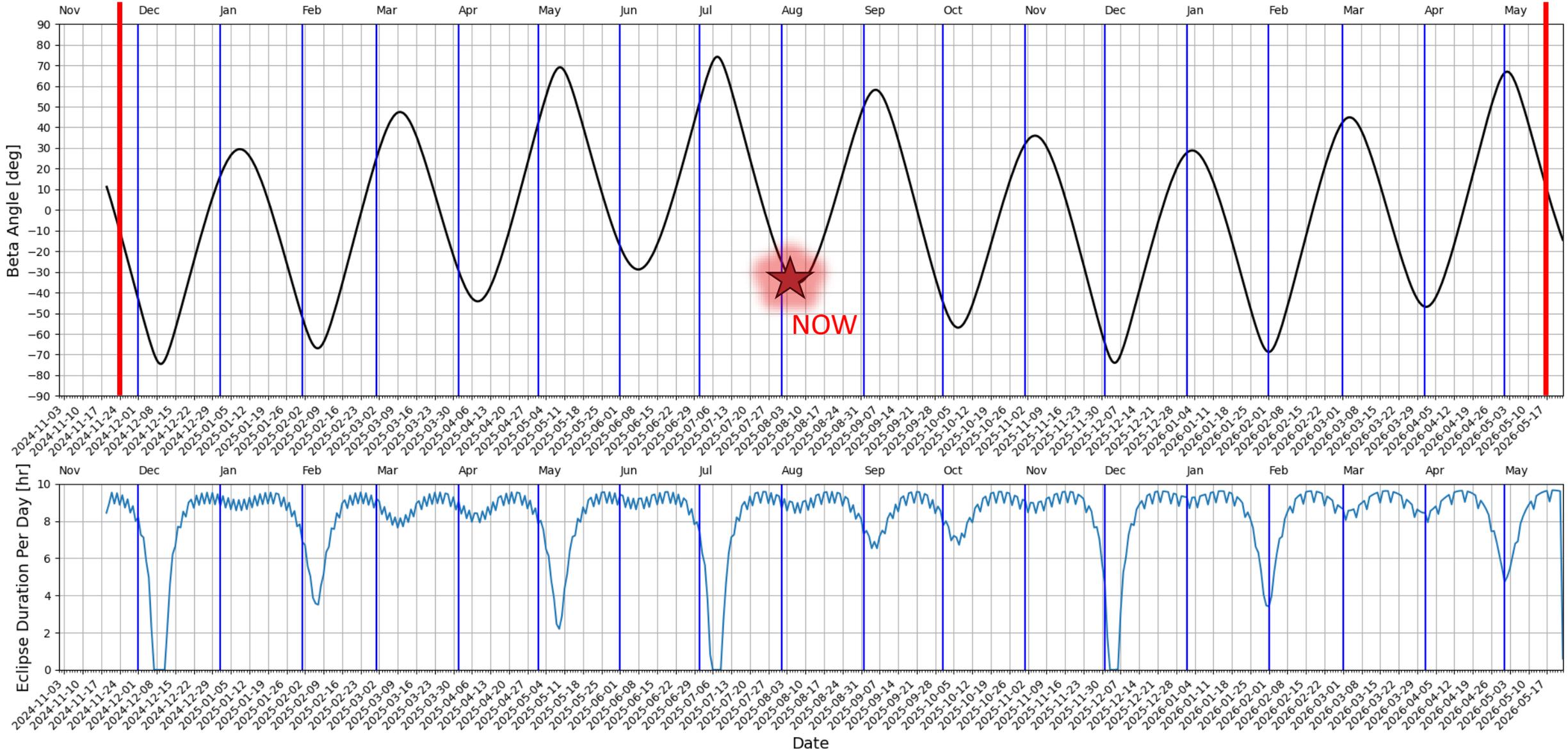
Reference



START

END

Beta Angle & Eclipse Duration per Day Vs. Date



VEMs will experience variety of typical spacecraft operating environments; beta -75 to beta +75, 400 km

Thermal & Fluids Analysis Workshop 2025. NASA Ames Research Center. San Jose, CA. August 4-7, 2025. Paper No. TC&P XII – 04.

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