Thermal Design, Analysis, and Thermal Vacuum Testing of a 3U CubeSat, CeREs

Thermal Engineering Branch
NASA GSFC, Code 545

Presented By
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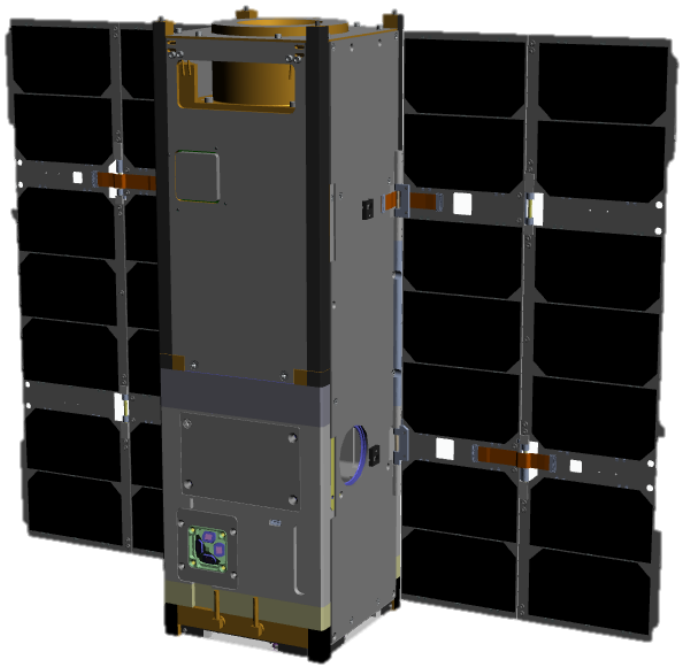
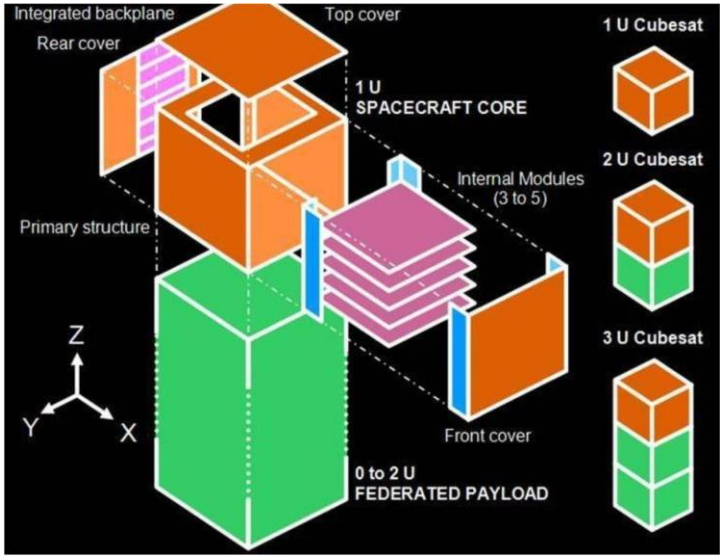
Houston, TX

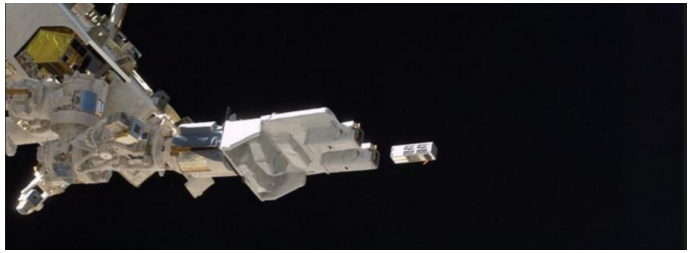
Outline

- Mission
  - CubeSats
  - CeREs Mission
  - CeREs CubeSat
- Objectives
- Thermal Design
  - Spacecraft Thermal Design
  - CeREs Thermal Design
- Thermal Vacuum Test
  - TVAC Model Design
  - Flight Vs TVAC Temperatures
  - Heat Flow Analysis
  - CeREs TVAC Test
- Model Correlation
- Conclusions & Lessons Learned



CubeSats



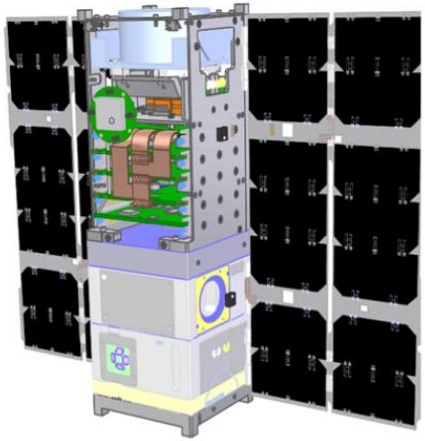


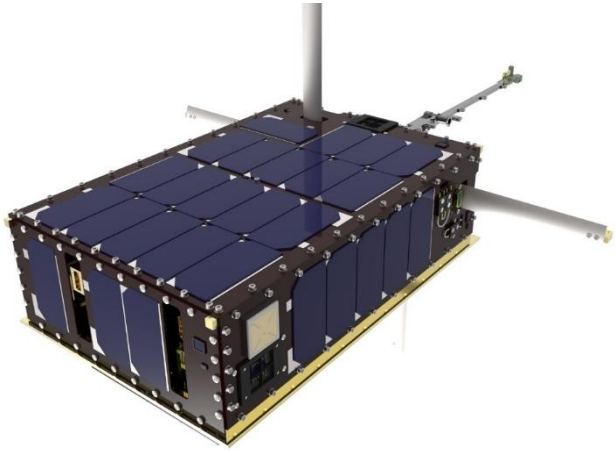
- A CubeSat is a small spacecraft with standardized geometry and dimensions
- They're classified as 1U, 2U, 3U, etc. Typically a 1U, is 10cm x 10cm x 10cm and approximately 1.3 Kg.
- This concept begun in 1999 as a relatively affordable and quick way for universities to gain access to space research
- Because of low cost and rapid turn-around university's CubeSats success rate was about 50%
- Taken into space as piggy-back payload

The CubeSat benefit to NASA

Offer an agile low-cost option for enabling scientific discovery, technology development, along with training and education

- Support larger missions
  - Augment their capabilities
- Push forward the development of compact and effective instruments and spacecraft components
- Allows for faster science return in missions
- Serve as great experience for newly hired engineers
  - Work mission from start to finish within 1-3 years
  - Allows for a direct interaction between scientist and engineer
- Opportunities for collaboration with universities/research centers





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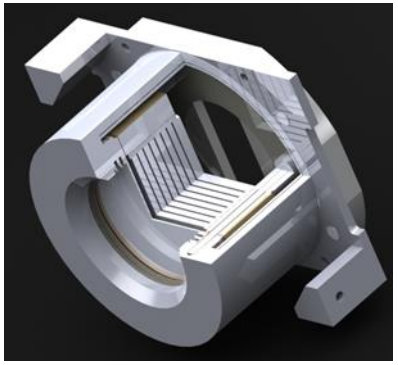
Mission Description

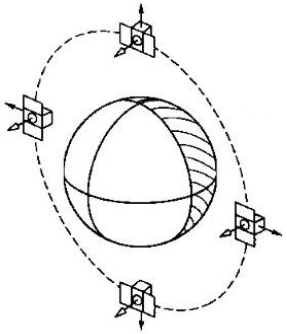
CeRES

RocketLab: **July 2018**
From Mahia Peninsula, New Zealand

- PI: **Shri Kanekal**
  - PI led mission with code 500 participation
- 3U CubeSat with BCT-XB1 S/C bus
- Southwest Research Institute (SwRI)
  - Keiichi Ogasawara
  - Avalanche Photodiode Detector (APD)
- High inclination, **LEO > 85°, 600 km,**
- Expected lifetime **~12 months**
  - Required lifetime: **3 months**
- Launch by **RocketLab**
  - Electron Rocket
- First Science and Mission Directorate (SMD) funded CubeSat



APD:
High time resolution up to 4 ms
Spectra covering energies from ~few keV to ~few MeV



CeREs Mission Science

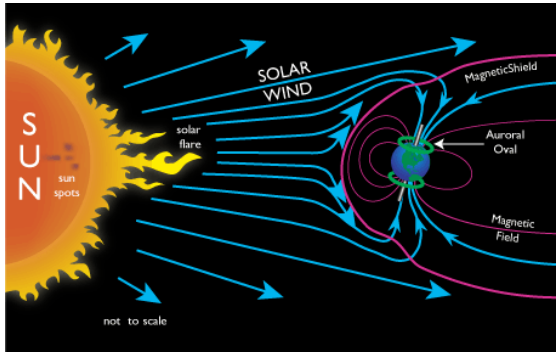
Energetic Electrons: Van Allen Belts

Primary Science

- Study of electron loss due to microbursts after geomagnetic storms
- Enhances science returns from Van Allen Probes

Secondary Science

- Characterizing solar electron spectra
- Furthering understanding of particle acceleration and transport



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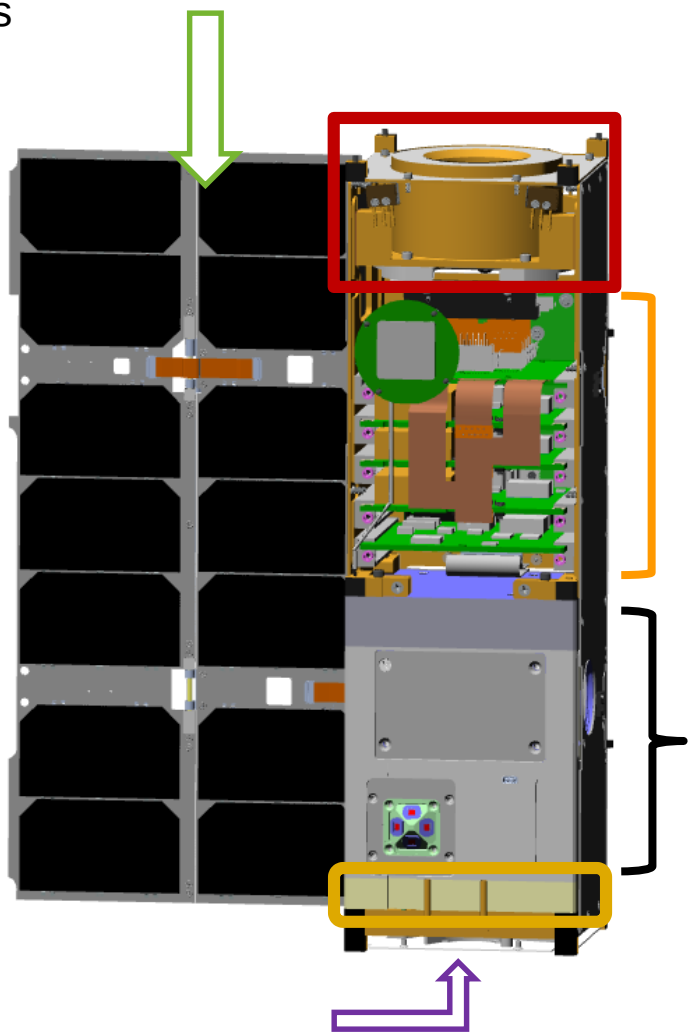
CeREs CubeSat

- Miniaturized Electron Proton Telescope Spectrometer (MERiT)
  - Avalanche Photodiode Detector (APD) & Solid State Detectors (SSD)
  - High time resolution
  - Broad energy spectrum
- Electronic Boards
  - 3 Front End Electronics (FEE)
  - CHEC Space Processor (CSP)
  - Backplane board
- Clyde Space SA
  - Deployable
  - 2 solar arrays
- BCT XB1 Spacecraft Bus
  - Power System
    - 3 li-on battery cells (2.6 A-h, 12.3 VDC)
  - Guidance & Navigation Control
    - 2 star trackers
    - 4 core Sun sensors
    - 3 reaction wheels
- L3 Cadet Radio
- ISIS UHF Antenna
  - Deployable



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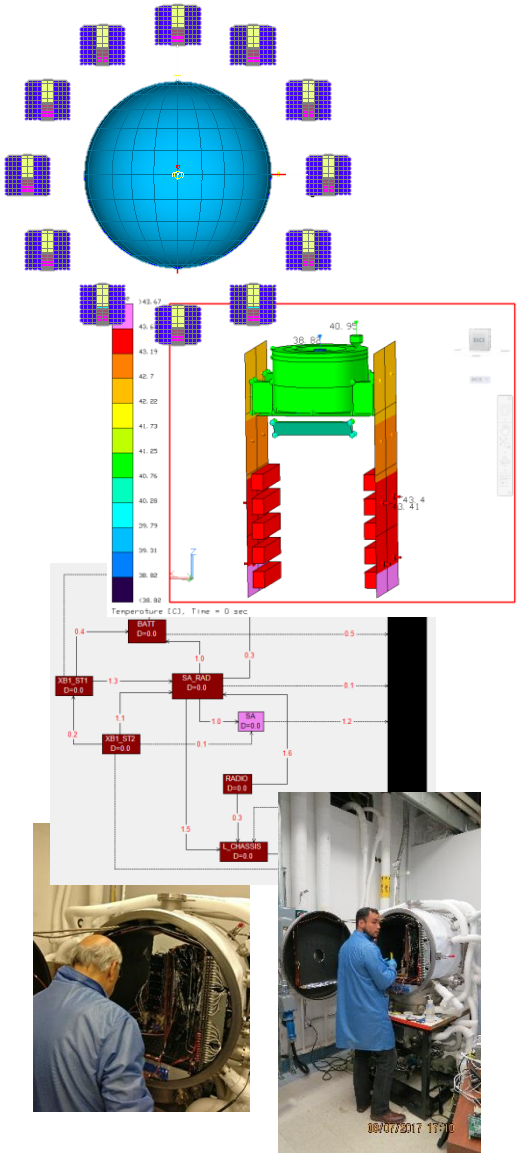
Objectives

Goals for CeREs Thermal

- Management of Thermal Model
  - Perform trade studies
  - Update & correlate model as needed
  - Provide flight predicts to systems team
- Design of TVAC Test Model
  - Determine location and temperature control for thermal environment
  - Provide predicts for qualification and thermal balance testing
- TVAC Test Campaign
  - Test Procedure
  - Hardware procurement
  - Test staffing
  - Chamber setup
- Thermal Model Correlation



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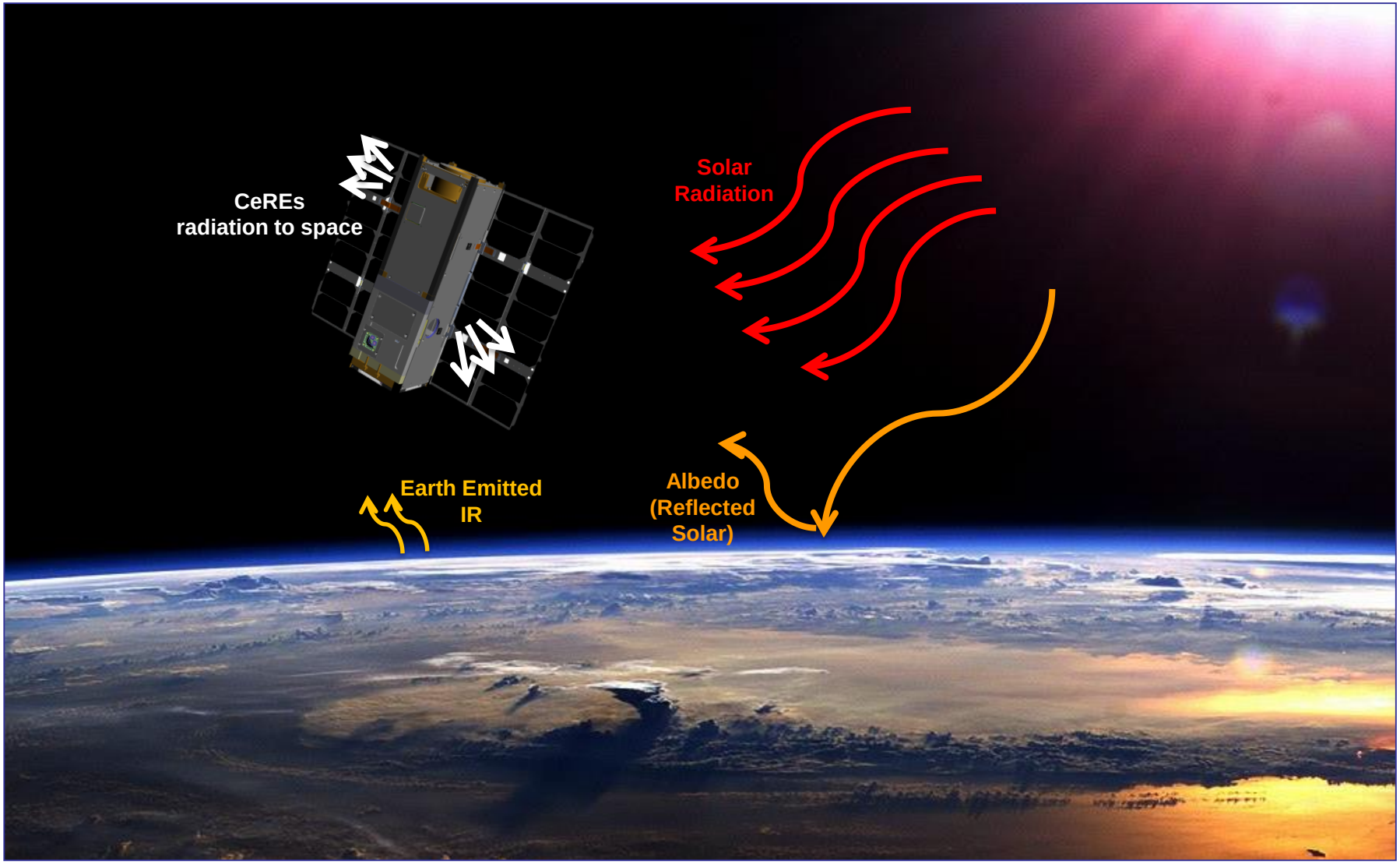
Spacecraft Thermal Design
CeREs On-Orbit Heat Loads



Essential to ensuring the spacecraft and payload survive and operate at their respective temperature limits for the mission

- Spacecraft thermal design encompasses the worst case environments experienced on a mission's orbit. These are known as the Hot Case and the Cold Case

Temperature Limits
Operational limits: Performance of hardware/components should be optimal

Qualification limits: Serve to determine thermal cycling goals of hardware to verify workmanship and performance

Survival limits: Exceeding these, could result in permanent hardware damage

	Hot case	Cold case
Solar Constant	High	Low
Albedo	Greater percentage of reflected sunlight	Lower percentage of reflected sunlight
Earth IR	High	Low
Radiator coating	End-of-life properties (higher α, lower ε)	Beginning-of-life properties (lower α, higher ε)
MLI Blanketing	Less effective emissivity on cold side	More effective emissivity on cold side
Power Dissipation	Maximum	Minimum

These parameters are **typical** of low Earth mission orbits

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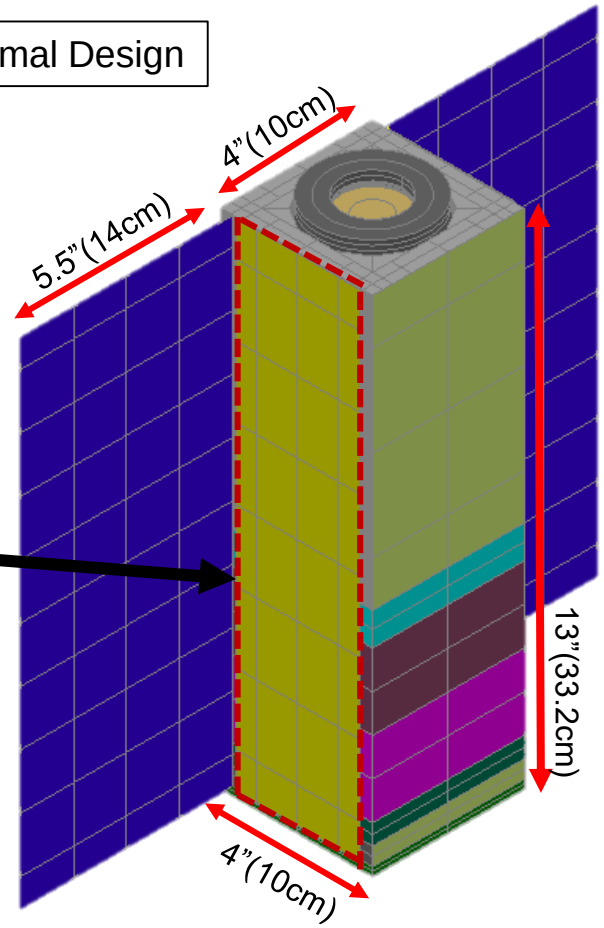
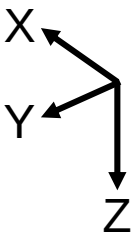
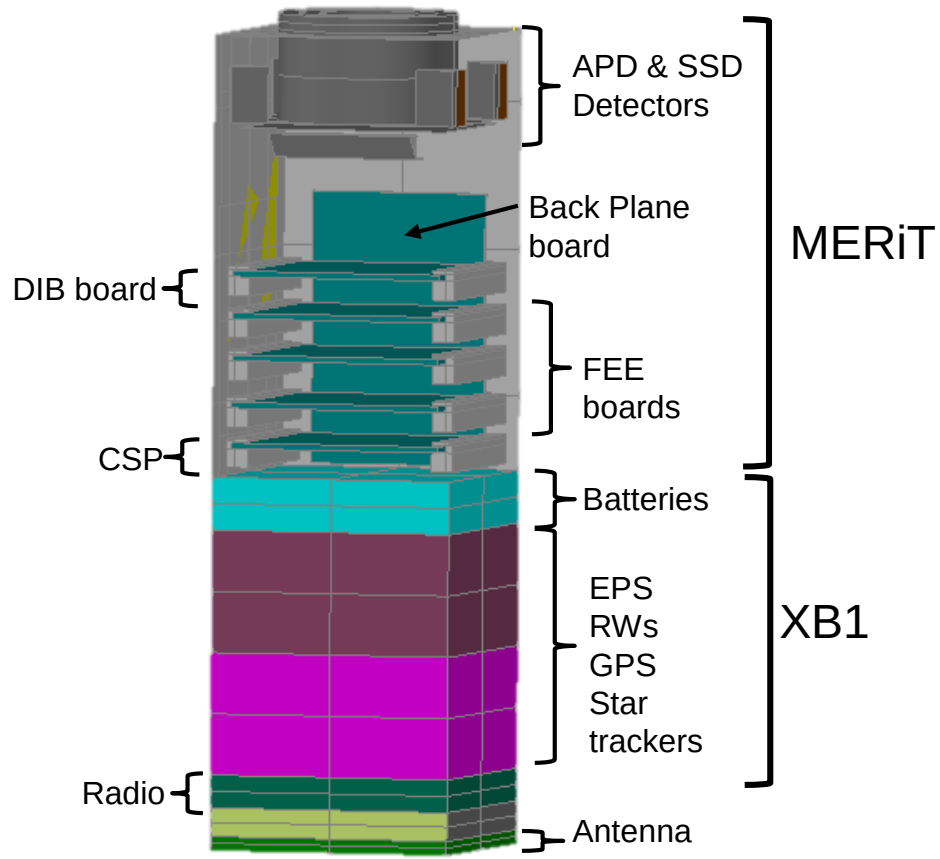
CeREs Thermal Design
Thermal Model Overview

Passive Thermal Design

ACS maintains Sun on the -X face at all times

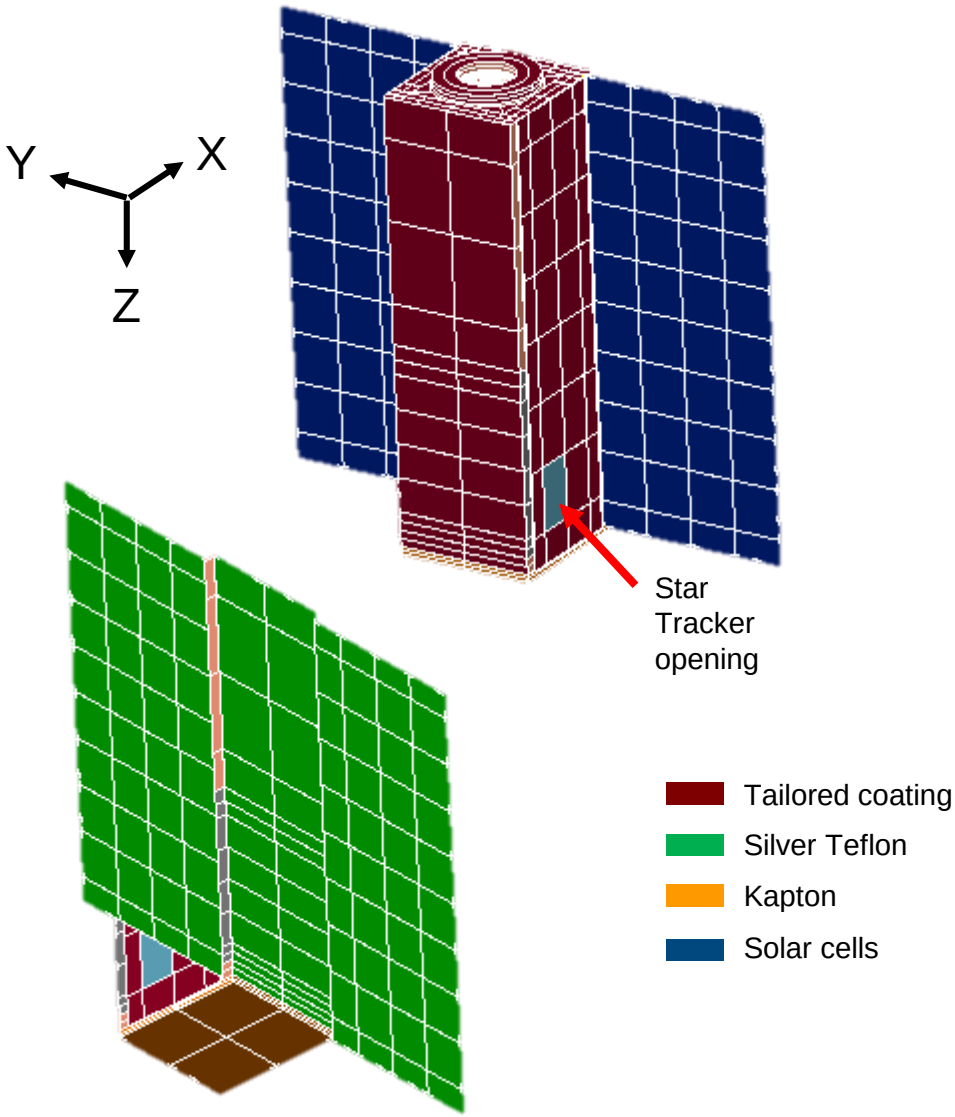




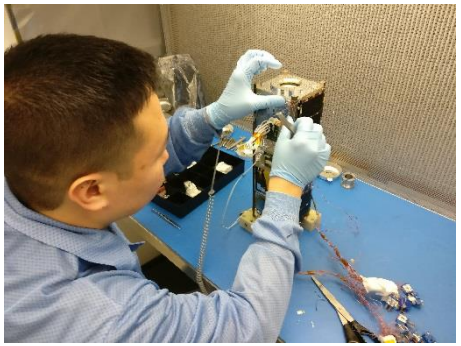


- All surfaces on CeREs are radiators. No blankets
- Thermal Interface material (eGraf)
  - CeREs to SA interface
  - Low sensitivity of thermal conductance at this interface
- Only in-flight heaters are on the batteries
  - 2 survival heaters
  - 1W each heater
  - Heaters: ON = 5° C, OFF = 18° C

CeREs Thermal Model
Coatings



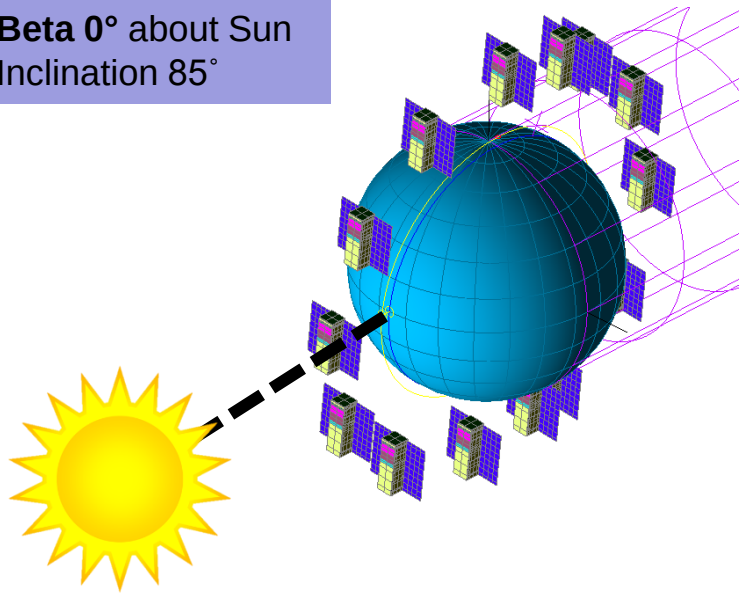
- Tailored coating, –X, -/+Y & -Z
  - ε = 0.22, α = 0.13
  - Al and SiO_2 (thickness of SiO_2 determines emittance)
  - Used on DELLINGR
- Silver Teflon, +X (back of solar panels as well)
  - ε = 0.85, α = 0.08
- Kapton tape, +Z
  - ε = 0.74, α = 0.42
- Mark Hasegawa and Code 546 provided support for the coatings and application



CeREs Thermal Model
Thermal Orbits

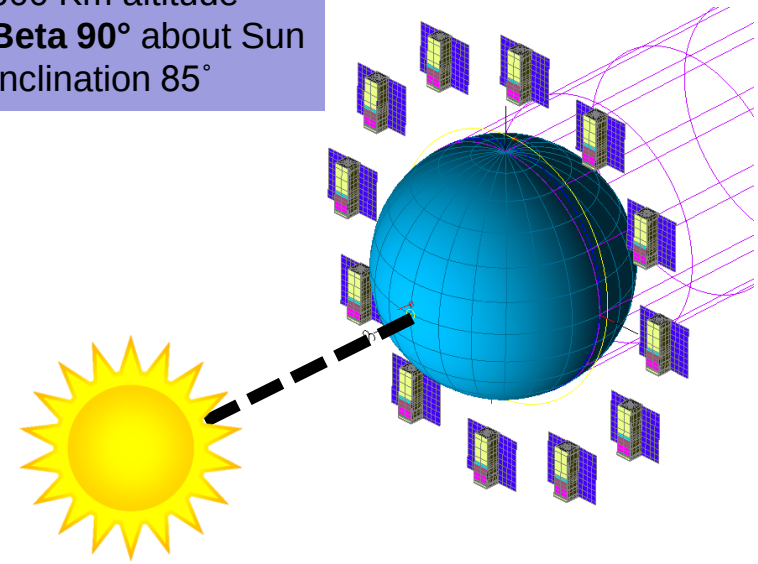
600 Km altitude
Beta 0° about Sun
Inclination 85˚

Cold Orbit



600 Km altitude
Beta 90° about Sun
Inclination 85˚

Hot Orbit



- Two orbit cases selected for analysis and thermal testing:
  - **Hot Case**: Beta 90˚
  - **Cold Case**: Beta 0˚

❖ The **Hot** and **Cold** cases are also define by the power configuration of the spacecraft

*Beta angle (β) is the angle between solar vector and orbit plane

CeREs Thermal Model
Power Dissipations

- CeREs has various power configurations for its mission. It was found that the Safe and Science modes provide for the worst cases.

Component	Available Power (W)	SafeMode Power (W)	ScienceMode Power (W)
MERiT	1.641	0	1.641
Reaction Wheels	0.6	0.3	0.6
GPS	1.22	0	1.22
Star trackers	0.83	0.43	0.83
Radio RX	0.37	0	0.37
Radio TX	12.33	0	1
Antenna	0	0	0
CSP	1.48	1.48	1.48
EPS	1	1	1
XB1_ELEC	3.64	3.64	3.64
Total	23.11	6.85	11.78

- The combination of HOT and COLD orbits with power settings SCIENCE MODE and SAFE MODE, provide the worst HOT and COLD cases to study.

CeREs Thermal Model
Flight Predicts Temperatures

	Limits						Hot Case: B90_85_ScienceMode			Cold Case: B00_85_SafeMode			Margin from OP Limits	
Parameter:	Low Surv	Low Qual	Low Op	High_Op	High Qual	High Surv	Min	Avg	Max	Min	Avg	Max	B90 Science Mode	B00 Safe Mode
Component	[°C]						[°C]			[°C]			[°C]	
MERiT Instrument														
INST	-40	-30	-20	40	50	60	12	17	22	-1	2	5	+18	+19
INST_ELEC	-55	-40	-30	75	85	90	23	25	28	7	8	11	+47	+37
XB1														
XB1_ST1	-40	-30	-20	55	65	85	24	24	24	7	7	7	+29	+27
XB1_ST2	-40	-30	-20	55	65	85	24	24	24	7	7	7	+29	+27
BATT	-20	0	0	45	45	60	23	24	24	7	7	7	+19	+7
Comm														
RADIO	-40	-40	-20	75	85	85	24	24	24	6	6	6	+49	+26
ANT	-50	-40	-10	50	60	85	21	21	21	4	4	4	+29	+14
Structure														
SC_RAD	-100	-100	-90	90	100	105	23	24	24	6	7	7	+66	+84
SA	-110	-60	-50	116	121	125	57	59	63	29	30	33	+53	+79

Complies with GOLD (4.25) rules temperature margin requirements

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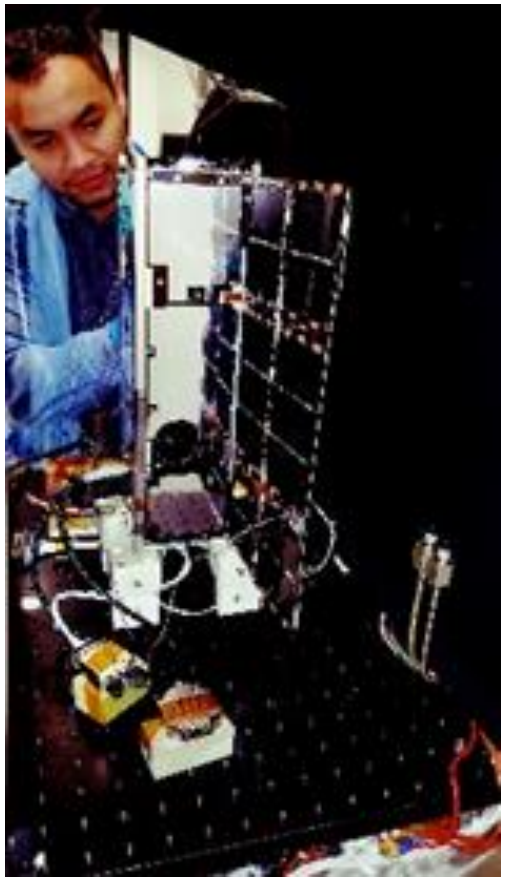
Thermal Vacuum Test

- The 2 major components of thermal testing are **Thermal Balance** and **Thermal Cycling** (Qualification)
  - Thermal Balance: Intended to validate the spacecraft's thermal design. Additionally, it provides data to correlate the thermal model
  - Thermal Cycling: Designed to take the flight hardware to its qualification goals, in order to verify workmanship and functionality
- Bakeout
  - For the spacecraft outgassing and for meeting launch vehicle requirements
- CeREs TVAC test was conducted from 09/11/2017 to 09/17/2017



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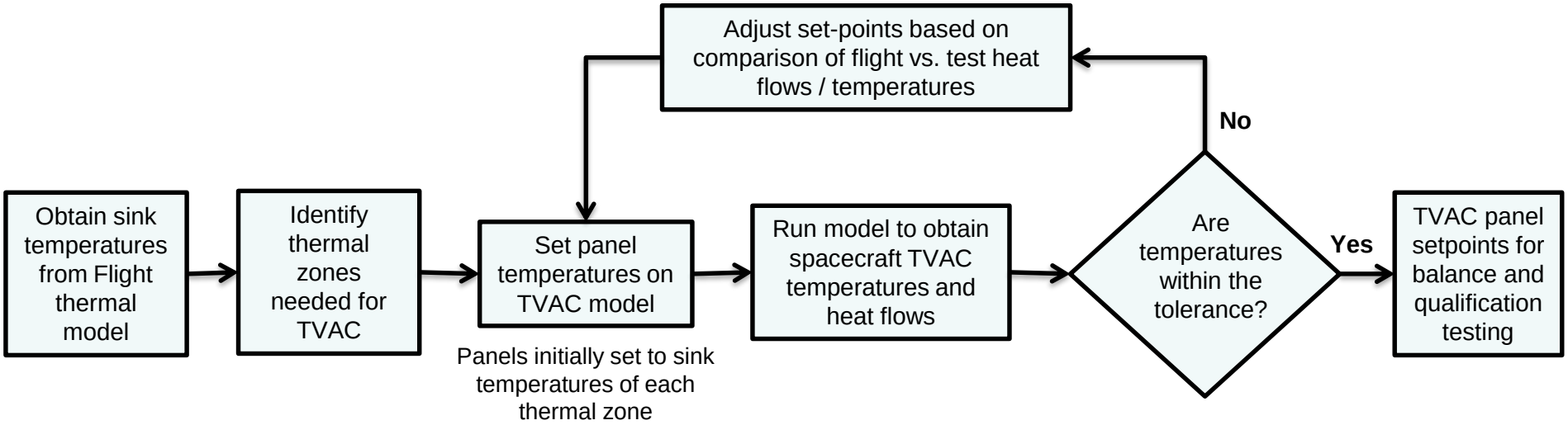
TVAC Model Design
Goals & Panel Setpoints Process

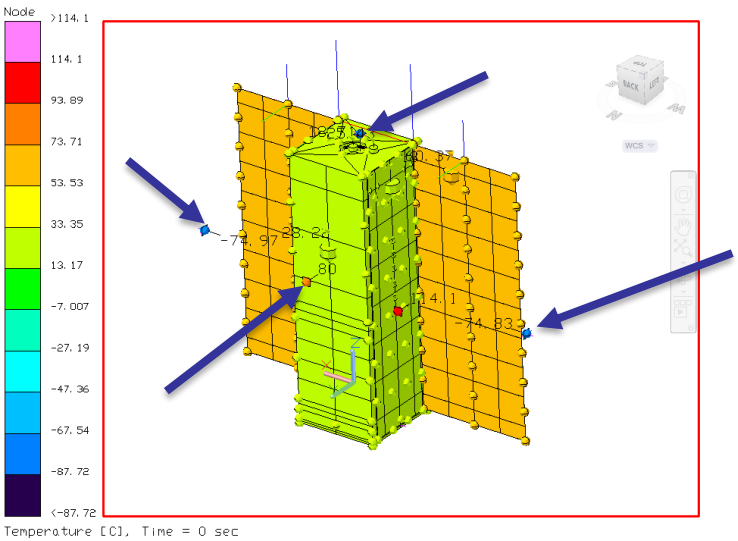
Goal: Simulating orbit environments inside a thermal vacuum chamber

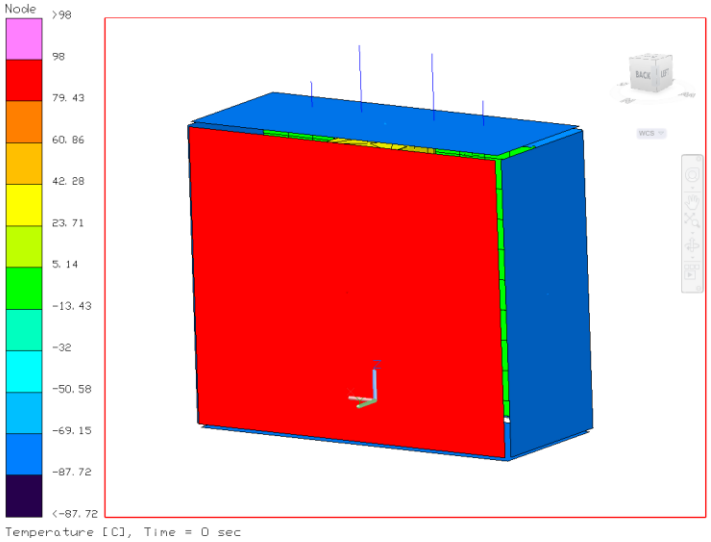
- Design a TVAC thermal model that accommodates for available test facilities. Provides sink temperatures necessary for achieving Flight-like spacecraft temperatures
- TVAC model should result in temperatures of CeRES within 3-5° C of flight predictions.



TVAC Model Design
TVAC Sink Temperatures & Thermal Zones

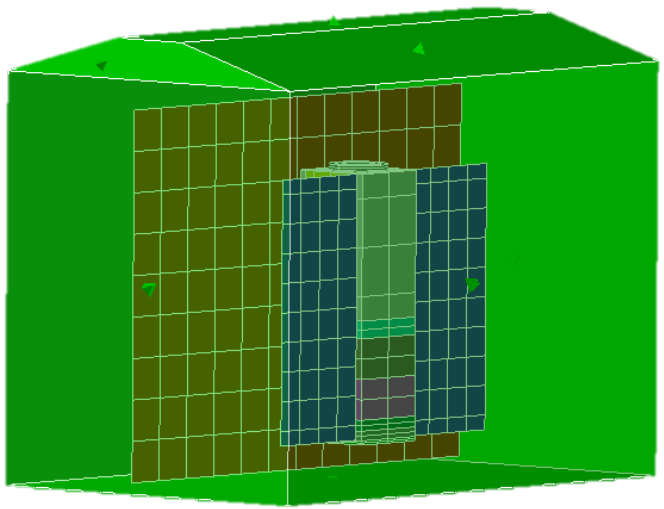
- Flight cases of interest are analyzed
  - Beta = 90°, Inc = 85°
  - Beta = 0°, Inc = 85°
- Small surfaces are placed surrounding spacecraft, obtaining <u>initial sink temperatures</u> for all zones
- Thermal panels are then created for all thermal zones
  - These are bounded to their respective sink temperatures
- Aim to reduce or combine thermal zones, minimizing the amount of panels needed

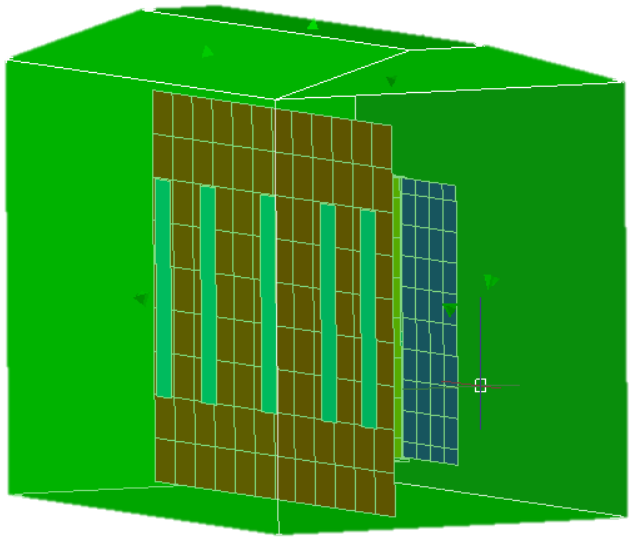




*Goal is to closely match the spacecraft temperatures experienced in the flight model

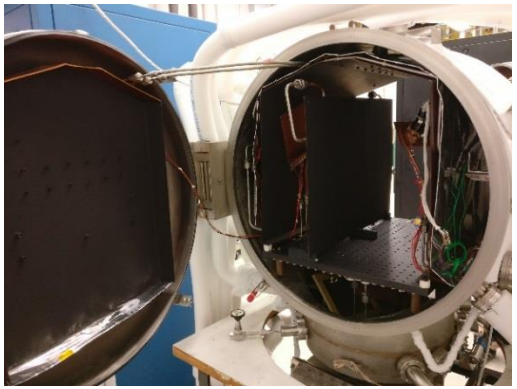
TVAC Model Design
TVAC GSE Setup





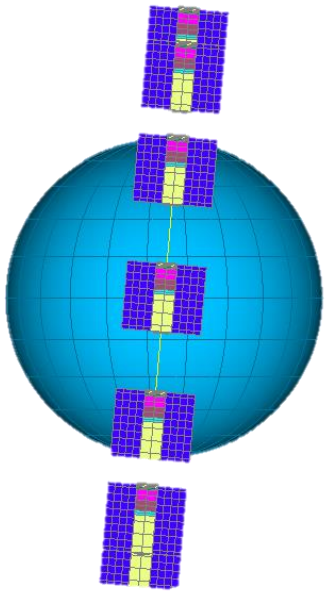
- Two independently controlled thermal zones are used to achieve thermal environment via radiation
  1. **Shroud** (Shown in green)
     - Views all sides of CeREs, but limited view to –X face
     - All sides of shroud controlled to one temperature
  2. **Heating Plate** (shown in red)
     - Solar arrays will not reach flight like temperature
     - Heaters modeled (as they're on plate) and temperature controlled (set-point)

Note: Each thermal zone includes multiple components within CeREs. One component will often limit the others from achieving qualification conditions.
E.g. the Battery has the hottest cold qualification limit when charging (0°C)

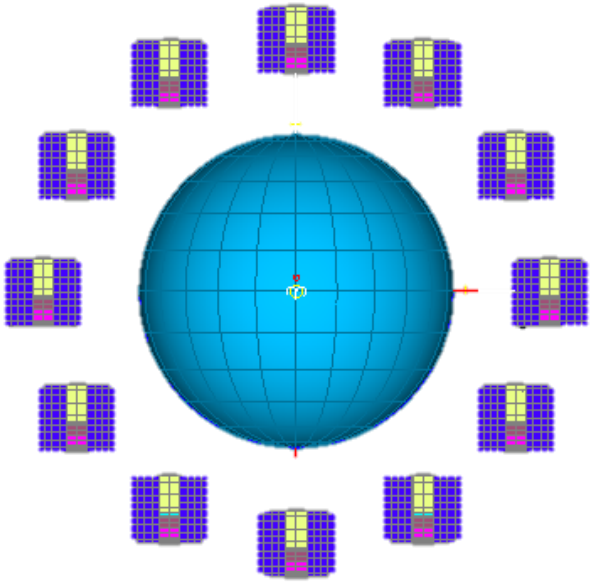


GSFC Chamber 28DD – Building 4

TVAC Model Design
Thermal Panels Set-points



B00_Inc85



B90_Inc85

	Hot Qual (˚C)	Cold Qual (˚C)	CB (˚C)	HB (˚C)	CSB (˚C)
Shroud	-30	-120	-90	-90	-90
Heating Plate	100	25	70	96	70

- **Cold Balance (CB)** set points are obtained from a **B00**, inclination 85˚ orbit in **Science Mode**
- **Hot Balance (HB)** set points are obtained from a **B90**, inclination 85˚ orbit in **Science Mode**
- **Cold Survival Balance (CSB)** is determined by the observatory being in **Safe Mode** at **B00**, inclination 85˚
- **Hot** & **Cold Qual** pacing component was the battery (charging mode)

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Flight Vs TVAC Temperatures
TVAC Balance Predictions

							Hot Balance	Cold Balance	Cold Survival Balance
	Limits						B90_85_ScienceMode	B00_85_ScienceMode	B00_85_SafeMode
Parameter:	Low_Surv	Low Qual	Low Op	High_Op	High Qual	High Surv	Avg		
Components	[°C]						*[°C]*	*[°C]*	*[°C]*
MERiT Instrument									
INST	-40	-30	-20	40	50	60	19	9	2
INST_ELEC	-55	-40	-30	75	85	90	26	16	8
XB1									
XB1_ST1	-40	-30	-20	55	65	85	25	14	7
XB1_ST2	-40	-30	-20	55	65	85	24	14	7
BATT	-20	0	0	45	45	60	24	14	7
Comm									
RADIO	-40	-40	-20	75	85	85	24	14	6
ANT	-50	-40	-10	50	60	85	21	11	4
Structure									
SC_RAD	-100	-100	-90	90	100	105	24	14	7
SA	-110	-60	-50	116	121	125	10	-6	-7

- TVAC balance temperature predicts obtained using previously defined temperature set-points for **Heater Plate** and **Shroud** (2 Thermal control zones)

NOTE: In TVAC, component power settings were modified from nominal in-flight settings to simplify thermal balance testing

Flight Vs TVAC Temperatures
Hot Balance Temperatures

TVAC	
B90	ScieceMode Avg
Component	[°C]
INST	19.07
INST_ELEC	26.25
BATT	24.45
XB1_ST1	24.62
XB1_ST2	24.22
RADIO	23.57
ANT	20.78
SC_RAD	24.23
SA	9.59

Flight	
B90	ScienceMode Avg
Component	[°C]
INST	18.80
INST_ELEC	26.77
BATT	24.91
XB1_ST1	25.12
XB1_ST2	24.84
RADIO	24.12
ANT	20.94
SC_RAD	24.78
SA	59.53

Comparison	
B90	**Flight vs TVAC**
Component	Δ[°C]
INST	-0.27
INST_ELEC	0.52
BATT	0.46
XB1_ST1	0.5
XB1_ST2	0.62
RADIO	0.55
ANT	0.16
SC_RAD	0.55
SA	49.94

- Most components are within 2°C of flight predictions

- Due to the setup limitation, it is noticeable that the Solar Array's TVAC temperature is significantly colder than flight temperatures.
  - This is acceptable due to the thermal isolation between the arrays and the adjacent chassis. Analysis shows that CeRES is almost independent of the Solar Array temperatures.

Flight Vs TVAC Temperatures
Cold Balance Temperatures

TVAC	
B00	ScienceMode Avg
Component	[°C]
INST	9.3
INST_ELEC	16.0
BATT	14.3
XB1_ST1	14.4
XB1_ST2	14.1
RADIO	13.5
ANT	11.0
SC_RAD	14.0
SA	-6.0

Flight	
B00	ScienceMode Avg
Component	[°C]
INST	9.61
INST_ELEC	16.52
BATT	14.69
XB1_ST1	14.92
XB1_ST2	14.69
RADIO	14.10
ANT	11.55
SC_RAD	14.56
SA	30.72

Comparison	
B00	**Flight vs TVAC**
Component	Δ[°C]
INST	0.3
INST_ELEC	0.5
BATT	0.4
XB1_ST1	0.5
XB1_ST2	0.6
RADIO	0.6
ANT	0.5
SC_RAD	0.5
SA	36.7

- Most components are within 2°C of flight predictions

- Due to the setup limitation, it is noticeable that the Solar Array's TVAC temperature is significantly colder than flight temperatures.
  - This is acceptable due to the thermal isolation between the arrays and the adjacent chassis. Analysis shows that CeRES is almost independent of the Solar Array temperatures.

Flight Vs TVAC Temperatures
Cold Survival Balance Temperatures

TVAC	
B00	SafeMode Avg
Component	[°C]
INST	2.48
INST_ELEC	7.60
BATT	6.99
XB1_ST1	7.00
XB1_ST2	6.76
RADIO	6.29
ANT	4.17
SC_RAD	6.65
SA	-6.71

Flight	
B00	SafeMode Avg
Component	[°C]
INST	2.82
INST_ELEC	8.00
BATT	7.33
XB1_ST1	7.39
XB1_ST2	7.28
RADIO	6.81
ANT	4.65
SC_RAD	7.10
SA	30.29

Comparison	
B00	**Flight vs TVAC**
Component	Δ[°C]
INST	0.34
INST_ELEC	0.4
BATT	0.34
XB1_ST1	0.39
XB1_ST2	0.52
RADIO	0.52
ANT	0.48
SC_RAD	0.45
SA	37

- Most components are within 2°C of flight predictions

- Due to the setup limitation, it is noticeable that the Solar Array's TVAC temperature is significantly colder than flight temperatures.
  - This is acceptable due to the thermal isolation between the arrays and the adjacent chassis. Analysis shows that CeRES is almost independent of the Solar Array temperatures.

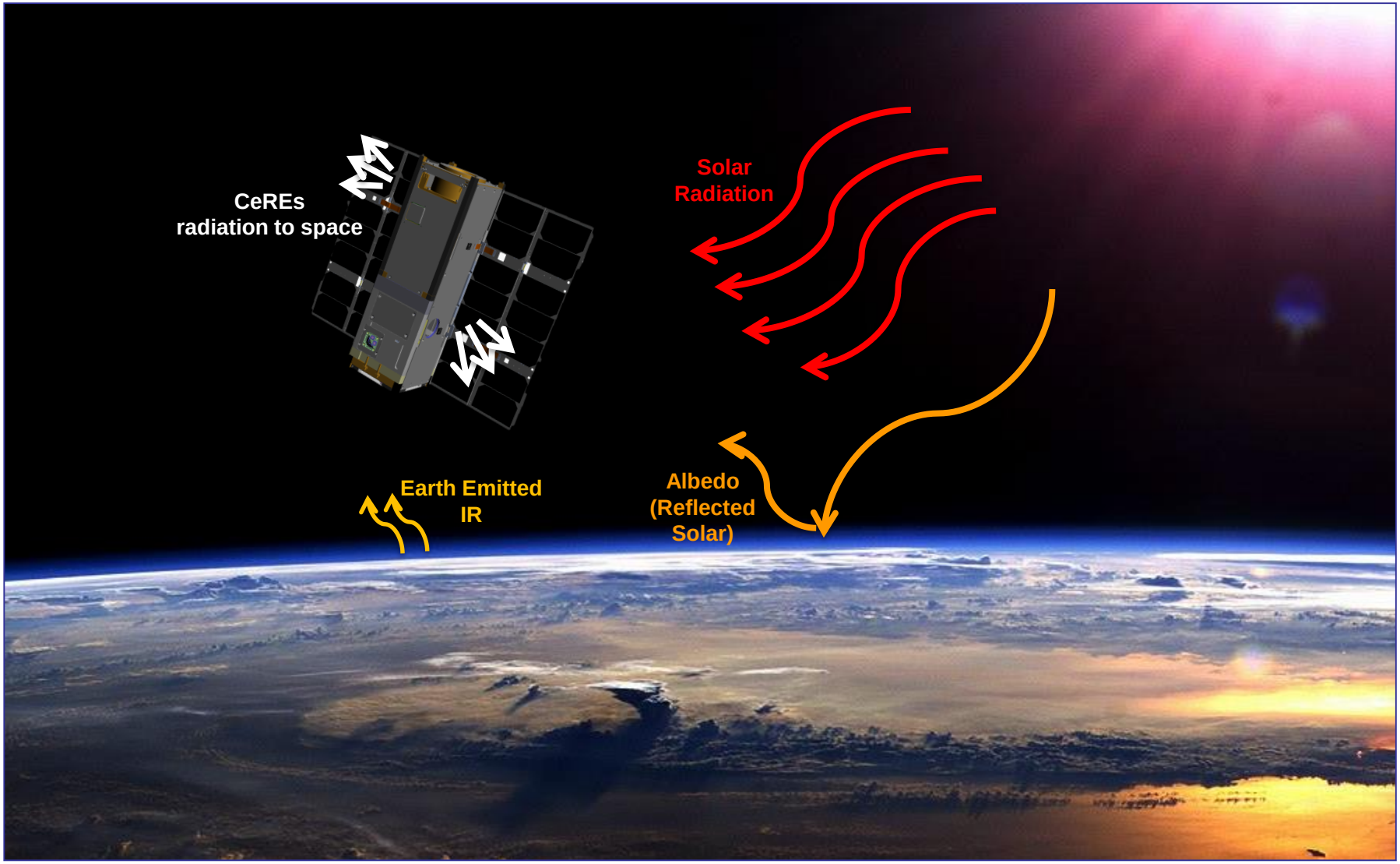
Outline

- **Mission**
  - CubeSats
  - CeREs Mission
  - CeREs CubeSat
- **Objectives**
- **Thermal Design**
  - Spacecraft Thermal Design
  - CeREs Thermal Model
- **Thermal Vacuum Test**
  - TVAC Model Design
  - Flight Vs TVAC Temperatures
  - Heat Flow Analysis
  - TVAC Test
- **Model Correlation**
- **Conclusions & Lessons Learned**

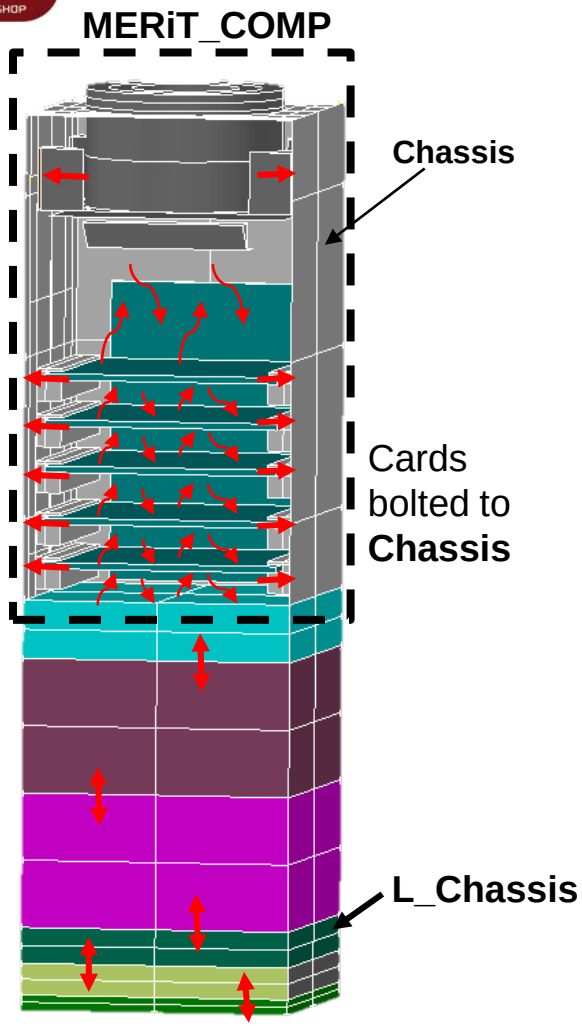
Things to Note:

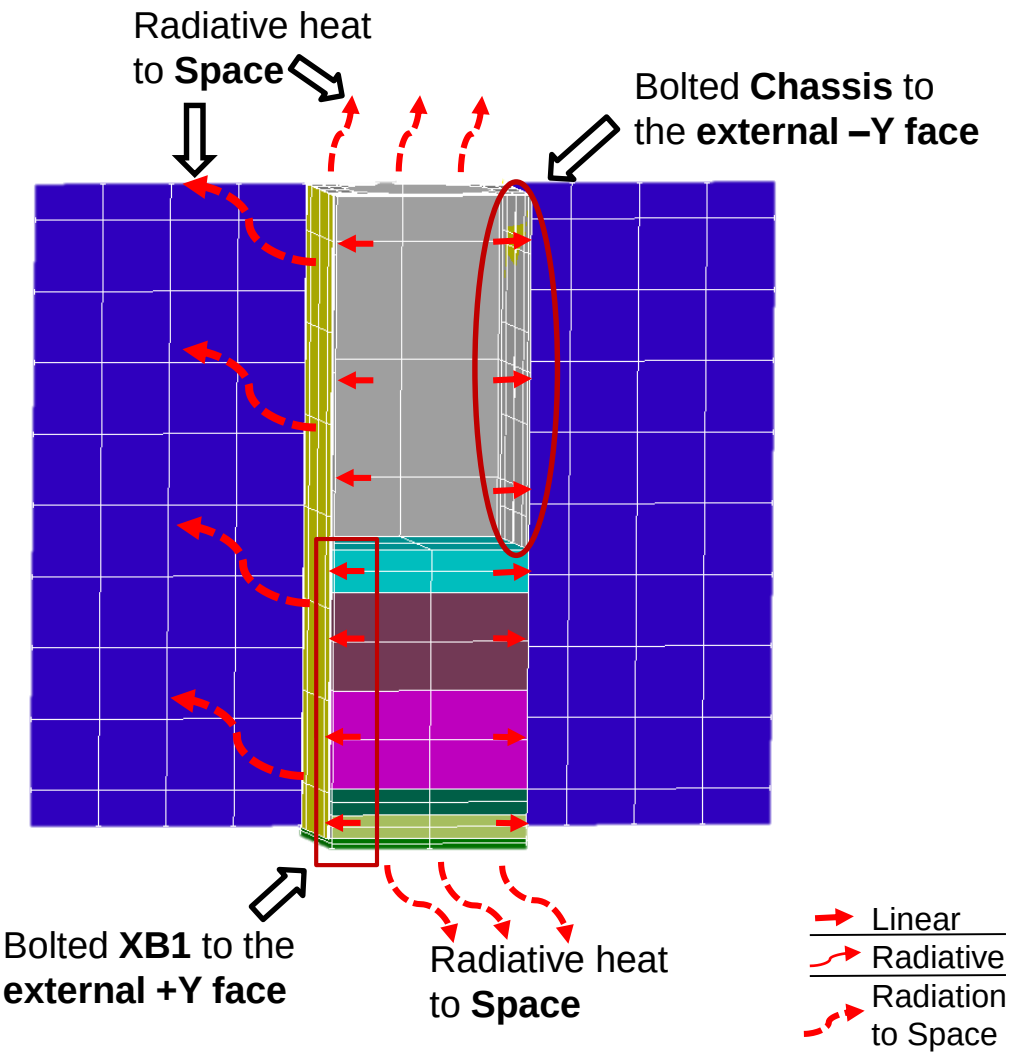
- Groupings were made to better represent heat flow between components
  - **MERIT_COMP** = Instrument/detectors, FEE boards, CSP & DIB boards, and payload chassis
  - **L_CHASSIS** = part of payload chassis at the bottom on CeREs
  - **SPACE** (for TVAC)= Shroud and heating plate
  - **XB1_ST1** = Star tracker 1, reaction wheels and GPS
  - **XB1_ST2** = Star tracker 2 and sun tracker
  - **SA_RAD** = -/+ Y faces of CeREs, acting as radiators (Solar arrays baseplate)
  - **BATT** = Batteries
  - **ANT** = Antenna
  - **Radio**
  - **SA** = Solar Arrays

Heat Flow Analysis
CeREs On-Orbit Heat Loads



Heat Flow Analysis
Component Heat Flow



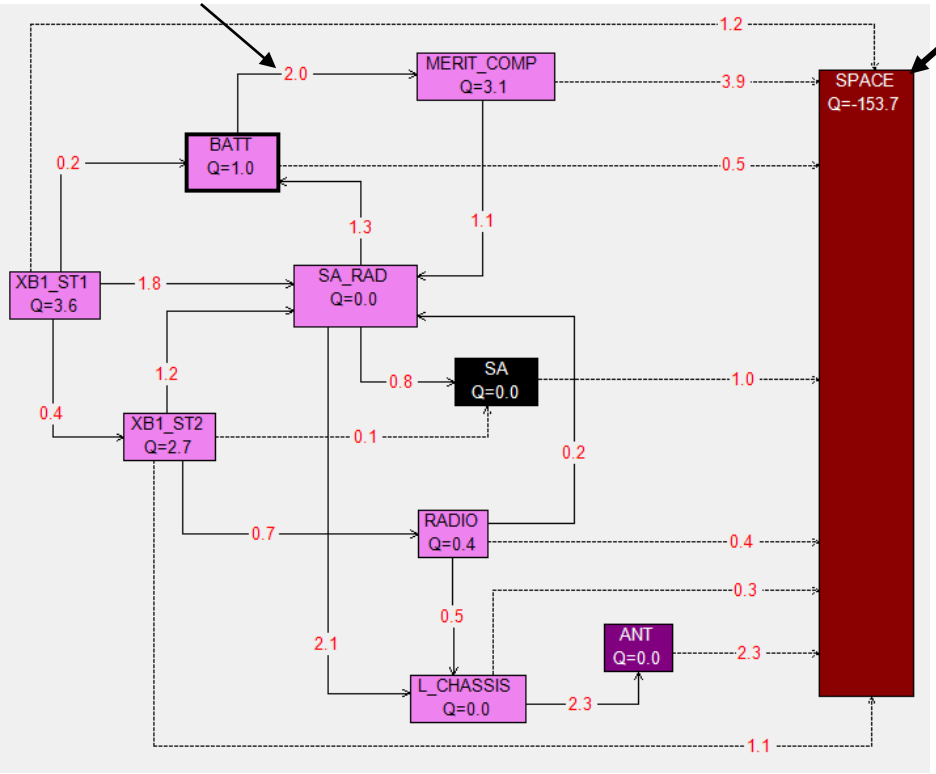


Internal Heat flow

External Heat flow

Heat Flow Analysis
Hot Balance Heat Map

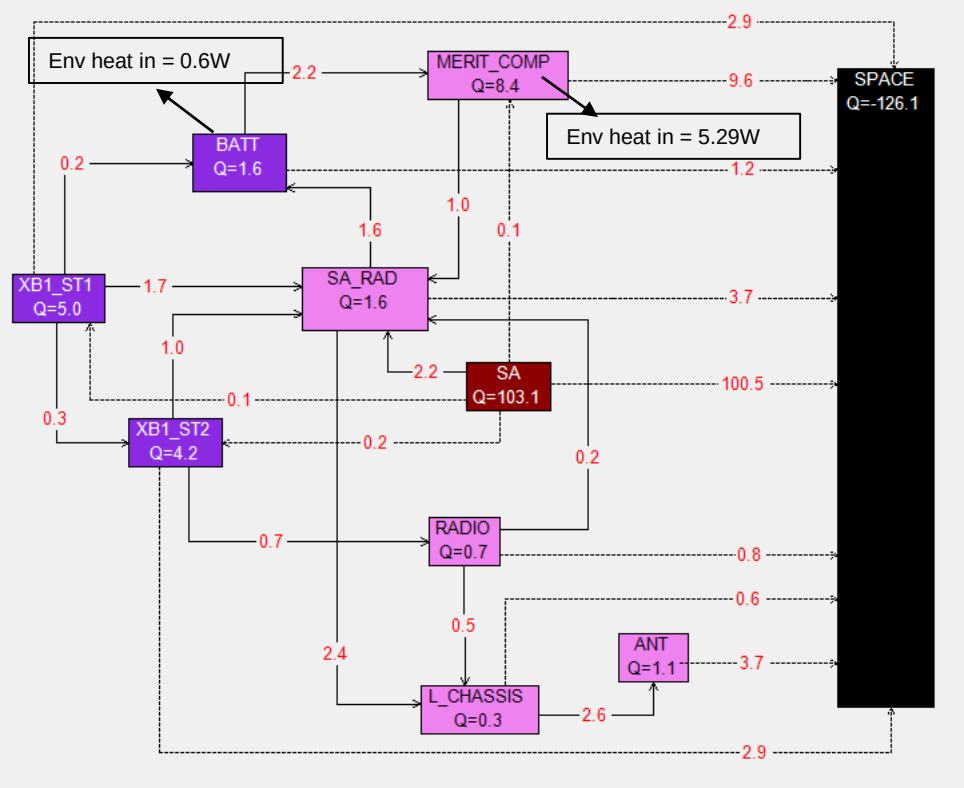
Q(W)



Space contains **Shroud** and **Heating plate** for TVAC heat map

FLIGHT

Note: General heat flow patterns are the same as **flight**



Dashed lines = radiative heat
Solid lines = linear heat

TVAC

Due to the setup limitation, it is noticeable that the Solar Array's **Flight** heat transfer is significantly different than **TVAC** heat transfer to Space

- **TVAC** linear heat flow between components closely matches **Flight**

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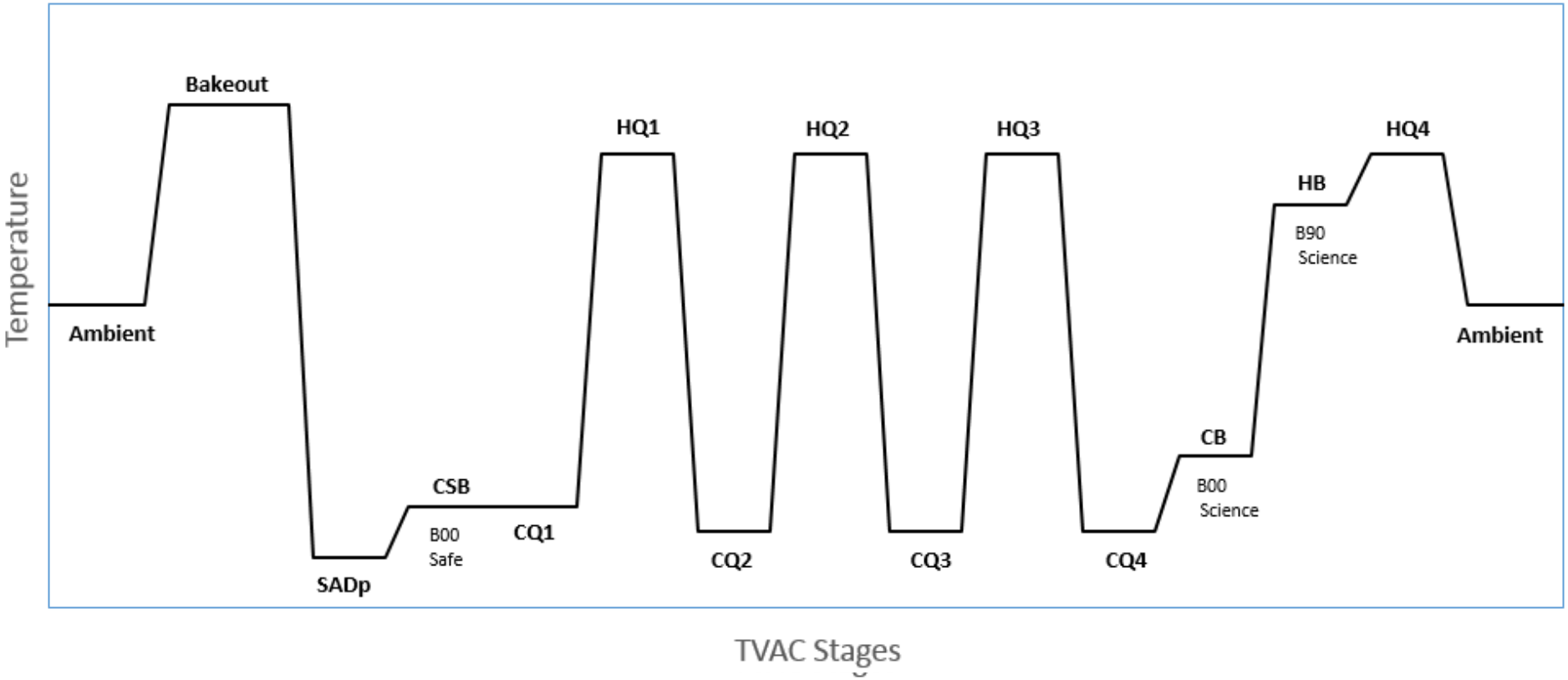
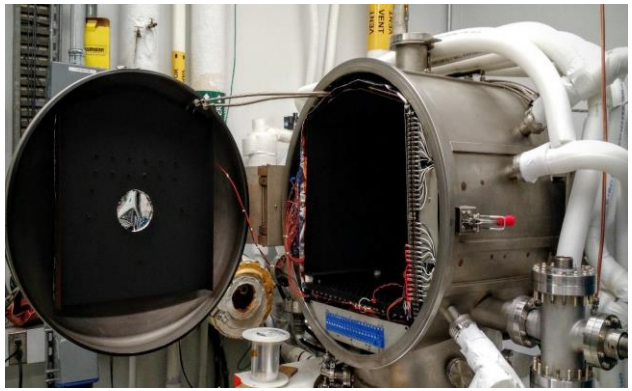
TVAC Test
Test Profile



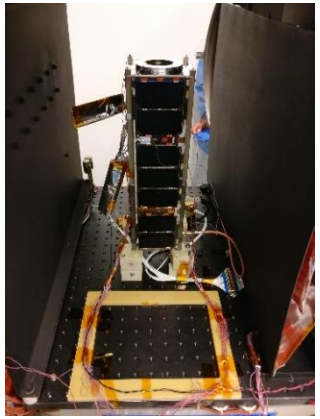
- Bakeout requirement provided from launch vehicle
  - Soak at 60˚C for 6 hours
- **Hot Turn ON** in transition from Bakeout to SA deployment (~+10˚C). Turned OFF at ~+0˚C (TCs 8,10)
- **Cold Turn ON** when SA are at -19˚C(-/+1˚C) for deployment. (TCs 12, 13)
- Heaters verification

- Cold Survival Balance (CSB)
  - Safe mode in a B00 orbit
- 4 Hot/Cold Qualification cycles
- Cold thermal balance (CB)
  - Science mode in a B00 orbit
- Hot thermal balance (HB)
  - Science Mode in a B90 orbit

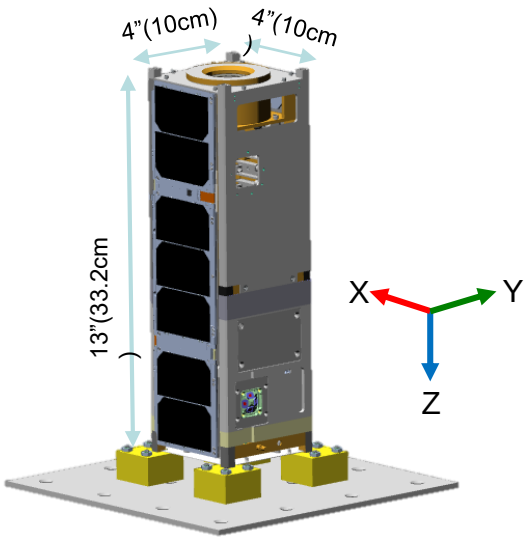
TVAC Test Chamber & GSE



- GSFC Chamber 28DD – Building 4
  - Size: 27” depth, 18” width, 18.5” min height (21” max height)
  - Thick black anodized aluminum platen (3/4” thick) with ¼-20 screw holes at 1” centers.
  - Other five sides are Z306 black paint coated copper (1/16” thick)

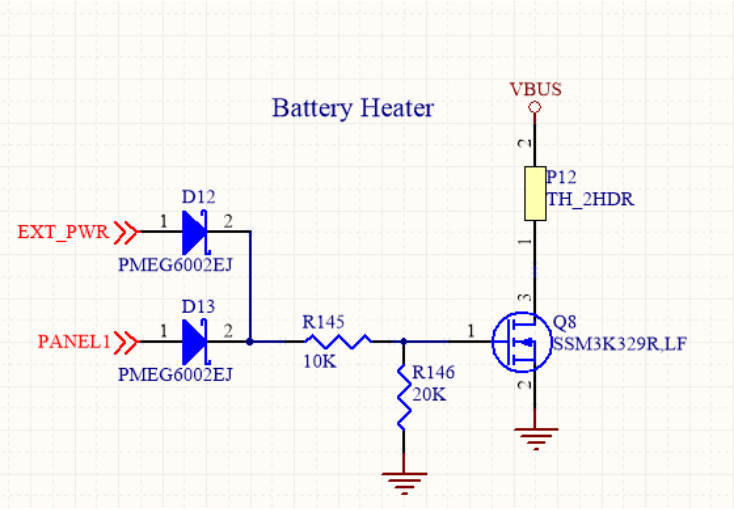


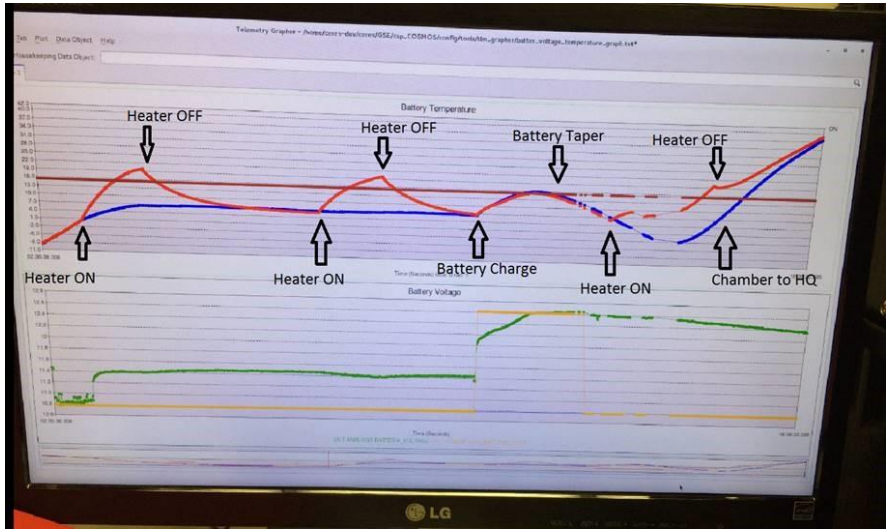
- Heater plate: 18” x 24” copper plate coated in Z306 black paint (1/16” thick), 5 heaters (1.5” x 10”) are attached on the back side of plate.
- Zero Q heater used for cables/wires coming of the back (+X) of CeREs



- Antennas remained stowed for TVAC
  - Deployment testing was done at -9C during component level testing
- G10 blocks support CeREs inside chamber
  - 4 - 2.6” x 2.6” x 1”
  - Provide stable mechanical support for CeREs
  - Provide thermal isolation from cold baseplate

TVAC Test
CeREs Battery





- It was discovered that for the survival heaters on the battery to function, power had to be supplied from the Solar Arrays or from the GSE power supply.
- Battery was pacing/limiting components for Qualification soaks
  - A heater could've been added to the battery to allow other components to reach Qual goals. Adding another thermal control zone

TVAC Test
Uncorrelated TVAC Balance Results

		NodeInfo						Hot Balance	Cold Survival	Cold Balance
		Low_ Surv	Low Qual	Low Op	High_Op	High Qual	High Surv	Avg	Avg	Avg
TC	**Component**							*[°C]*	*[°C]*	*[°C]*
TVAC_TCs										
1	Inst_pX_1	-40	-30	-20	40	50	60	19.4	-4.3	8.8
2	Inst_mX_2	-40	-30	-20	40	50	60	30.8	5	18.0
3	Inst_Elec_pX_3	-55	-40	-30	75	85	90	22.9	-1.8	12.4
4	Inst_Elec_mX_4	-55	-40	-30	75	85	90	33.1	7.3	19.9
5	GPS_mX_5	-40	-30	-20	55	85	85	37.8	10.4	25.2
6	Radio_pX_6	-40	-40	-20	75	85	85	21.6	-0.9	12.2
7	Radio_mX_7	-40	-40	-20	75	85	85	29.4	6.2	17.1
8	Batt_pX_8	-20	0	0	45	45	60	24.7	-0.3	14.3
9	Batt_mX_9	-20	0	0	45	45	60	29.4	8.1	20.9
10	RW_pX_10	-40	-40	-20	75	85	85	27.0	3.1	17.1
11	ANT_pZ_11	-50	-40	-10	50	60	85	10.3	-8.4	1.1
12	SA_pY_12	-110	-60	-50	116	120	125	12.8	-4.9	-4.6
13	SA_mY_13	-110	-60	-50	116	120	125	10.7	-7.7	-7.0
14	SA_mY_pZ_14	-110	-60	-50	116	120	125	23.7	-0.2	13.8
15	SA_pY_mZ_15	-110	-60	-50	116	120	125	22.2	-2.1	11.7
16	Inst_pZ_16	-40	-30	-20	40	50	60	22.5	-1.7	11.5

- For comparison between TVAC model predicts and TVAC real temperatures, the TCs used for monitoring were also created on the TVAC model, and used for comparison.

TVAC Test
Uncorrelated Hot Balance Temperatures

HOT Thermal Balance	TVAC Predictions		TVAC Data		Comparison
	B90	Science Mode Avg	B90	Science Mode Avg	Flight vs TVAC Δ(Pre-Real)
TC	Component	[°C]	Component	[°C]	[°C]
1	Inst_pX_1	16.5	Inst_pX_1	19.4	-2.9
2	Inst_mX_2	28.0	Inst_mX_2	30.8	-2.8
3	Inst_Elec_pX_3	15.9	Inst_Elec_pX_3	22.9	-7
4	Inst_Elec_mX_4	28.3	Inst_Elec_mX_4	33.1	-4.8
5	GPS_mX_5	24.7	GPS_mX_5	37.8	-13.1
6	Radio_pX_6	23.5	Radio_pX_6	21.6	1.9
7	Radio_mX_7	23.7	Radio_mX_7	29.4	-5.7
8	Batt_pX_8	24.2	Batt_pX_8	24.7	-0.5
9	Batt_mX_9	24.7	Batt_mX_9	29.4	-4.7
10	RW_pX_10	24.5	RW_pX_10	27.0	-2.5
11	ANT_pZ_11	20.8	ANT_pZ_11	10.3	10.5
12	SA_pY_12	9.8	SA_pY_12	12.8	-3
13	SA_mY_13	11.2	SA_mY_13	10.7	0.5
14	SA_mY_pZ_14	8.7	SA_mY_pZ_14	23.7	-15
15	SA_pY_mZ_15	24.2	SA_pY_mZ_15	22.2	2
16	Inst_pZ_16	22.3	Inst_pZ_16	22.5	-0.2

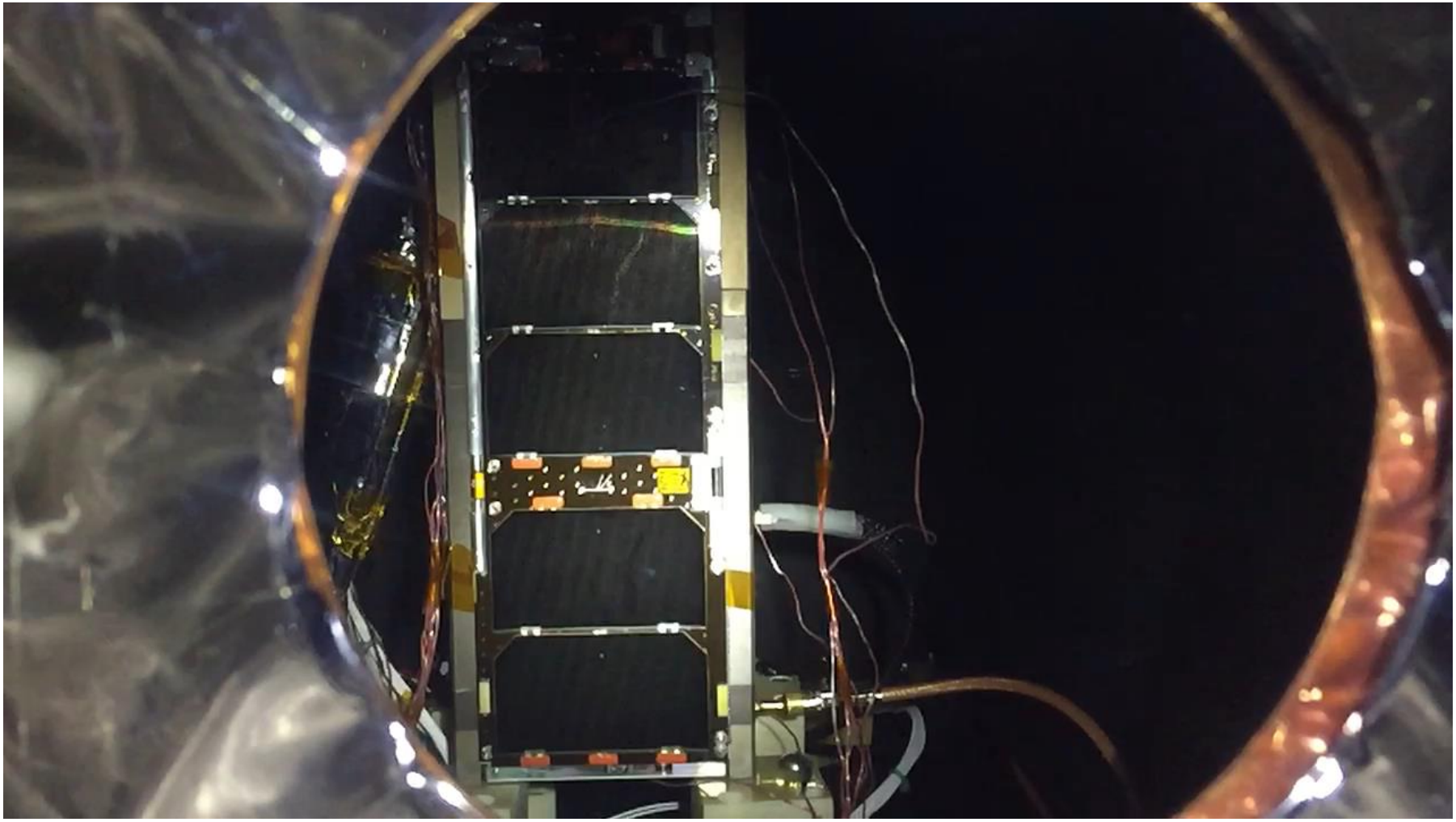
Hot Balance	
Max Cold err (°C)	-15
Max Hot err (°C)	10.5
Avg error (°C)	-2.58
%within +/-5C	69%
%within +/-3C	56%

TVAC Test
Uncorrelated Cold Balance Temperatures

COLD Thermal Balance	TVAC Predictions		TVAC Data		Comparison
	B00	Science Mode Avg	B00	Science Mode Avg	Flight vs TVAC Δ(Pre-Real)
TC	Component	[°C]	Component	[°C]	[°C]
1	Inst_pX_1	7.3	Inst_pX_1	8.8	-1.5
2	Inst_mX_2	16.4	Inst_mX_2	18.0	-1.6
3	Inst_Elec_pX_3	6.8	Inst_Elec_pX_3	12.4	-5.6
4	Inst_Elec_mX_4	16.7	Inst_Elec_mX_4	19.9	-3.2
5	GPS_mX_5	14.5	GPS_mX_5	25.2	-10.7
6	Radio_pX_6	13.4	Radio_pX_6	12.2	1.2
7	Radio_mX_7	13.6	Radio_mX_7	17.1	-3.5
8	Batt_pX_8	14.0	Batt_pX_8	14.3	-0.3
9	Batt_mX_9	14.5	Batt_mX_9	20.9	-6.4
10	RW_pX_10	14.4	RW_pX_10	17.1	-2.7
11	ANT_pZ_11	11.0	ANT_pZ_11	1.1	9.9
12	SA_pY_12	-6.5	SA_pY_12	-4.6	-1.9
13	SA_mY_13	-5.3	SA_mY_13	-7.0	1.7
14	SA_mY_pZ_14	-5.8	SA_mY_pZ_14	13.8	-19.6
15	SA_pY_mZ_15	13.9	SA_pY_mZ_15	11.7	2.2
16	Inst_pZ_16	12.2	Inst_pZ_16	11.5	0.7

Cold Balance	
Max Cold err (°C)	-19.6
Max Hot err (°C)	9.9
Avg error (°C)	-2.95
%within +/-5C	69%
%within +/-3C	56%

SA Deployment



Deployed at -19.2°C

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Model Correlation
Thermal Model Updates/Changes

Thermal Model Changes	Pre-TVAC Test	Post-Model Correlation	Notes
Vertical interface contactor: aluminum chassis walls	**Conductance** 4 #4-40 bolts (1.04 W/C)	**Conductance** 1.0 W/C	Conductance used (1 W/C) was found to help better the correlation results
Horizontal interface contactor: antenna/lower chassis	**Conductance** 2 #2-56 (1.04 W/C)	**Conductance** 0.13 W/C	Conductance used (.13 W/C) was found to help better the correlation results
Location of test thermocouple-14	On Solar Array	On CeREs Rail	TC was reading much colder SA temperatures
Thickness of the –X aluminum chassis plate	1.27 mm	2.25 mm	New thickness was obtained from Mechanical model
Thickness of the +X aluminum chassis plate	1.27 mm	2.07 mm	New thickness was obtained from Mechanical model
Nodalization of the wedgetainers / Interface contactors to the chassis	One node to Chassis	Wedgetainer surface to Chassis	Old model had improper modeling and nodalization of wedgetainer. Contactor also wrongly applied
Nodalization of the XB1, Battery, Antenna, Radio, and FEE boards, thermal blocks	**Nodes** XB1, Radio, Batt, Ant – 8 FEE boards – 1	**Nodes** XB1, Batt – 144 Radio – 72 Ant – 32 FEE boards – 16/board	Nodalization was increased arbitrarily to see proper heat/temperature contours and distribution
Conductivity multiplier for the XB1, Antenna, Radio, and FEE boards, thermal blocks (x-direction)	**Conductivity multiplier** 1	**Conductivity multiplier** 0.05	Conductivity multiplier used was found to help better the correlation results

Model Correlation
Correlated Hot Balance Temperatures

HOT Thermal Balance	TVAC Predictions		TVAC Data		Comparison
	B90	Science Mode Avg	B90	Science Mode Avg	Flight vs TVAC Δ(Pre-Real)
TC	Component	[°C]	Component	[°C]	[°C]
1	Inst_pX_1	19.3	Inst_pX_1	19.4	-0.1
2	Inst_mX_2	28.5	Inst_mX_2	30.8	-2.3
3	Inst_Elec_pX_3	19	Inst_Elec_pX_3	22.9	-3.9
4	Inst_Elec_mX_4	29	Inst_Elec_mX_4	33.1	-4.1
5	GPS_mX_5	27.7	GPS_mX_5	37.8	-10.1
6	Radio_pX_6	24.5	Radio_pX_6	21.6	2.9
7	Radio_mX_7	26.4	Radio_mX_7	29.4	-3
8	Batt_pX_8	23.8	Batt_pX_8	24.7	-0.9
9	Batt_mX_9	27.8	Batt_mX_9	33.1	-5.3
10	RW_pX_10	25.5	RW_pX_10	27.0	-1.5
11	ANT_pZ_11	8.3	ANT_pZ_11	10.3	-2
12	SA_pY_12	9.8	SA_pY_12	12.8	-3
13	SA_mY_13	11.4	SA_mY_13	10.7	0.7
14	SA_mY_pZ_14	25.5	SA_mY_pZ_14	23.7	1.8
15	SA_pY_mZ_15	25.5	SA_pY_mZ_15	22.2	3.3
16	Inst_pZ_16	23.9	Inst_pZ_16	22.5	1.4

Hot Balance	
Max Cold err (°C)	-10.1
Max Hot err (°C)	3.3
Avg error (°C)	-1.6
%within +/-5C	88%
%within +/-3C	69%

TVAC Test
Correlated Cold Balance Temperatures

COLD Thermal Balance	TVAC Predictions		TVAC Data		Comparison
	B00	Science Mode Avg	B00	Science Mode Avg	Flight vs TVAC Δ(Pre-Real)
TC	Component	[°C]	Component	[°C]	[°C]
1	Inst_pX_1	10	Inst_pX_1	8.8	1.2
2	Inst_mX_2	17.44	Inst_mX_2	18.0	-0.56
3	Inst_Elec_pX_3	9.9	Inst_Elec_pX_3	12.4	-2.5
4	Inst_Elec_mX_4	17.9	Inst_Elec_mX_4	19.9	-2
5	GPS_mX_5	17.3	GPS_mX_5	25.1	-7.8
6	Radio_pX_6	14.6	Radio_pX_6	12.2	2.4
7	Radio_mX_7	16.2	Radio_mX_7	17.1	-0.9
8	Batt_pX_8	14.1	Batt_pX_8	14.3	-0.2
9	Batt_mX_9	17.3	Batt_mX_9	20.9	-3.6
10	RW_pX_10	15.6	RW_pX_10	17.1	-1.5
11	ANT_pZ_11	-0.1	ANT_pZ_11	1.1	-1.2
12	SA_pY_12	-6.3	SA_pY_12	-4.6	-1.7
13	SA_mY_13	-5.4	SA_mY_13	-7.0	1.6
14	SA_mY_pZ_14	15.5	SA_mY_pZ_14	13.8	1.7
15	SA_pY_mZ_15	15.4	SA_pY_mZ_15	11.7	3.7
16	Inst_pZ_16	13.9	Inst_pZ_16	11.5	2.4

Cold Balance	
Max Cold err (°C)	-7.8
Max Hot err (°C)	3.7
Avg error (°C)	-0.5
%within +/-5C	94%
%within +/-3C	81%

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Conclusion

- CeREs Thermal Design/Model
  - Identified worst HOT and COLD cases/environments for CeREs Mission
  - Managed thermal model for CeREs and provided temperature predicts to systems as required
- Thermal Vacuum Model
  - Determined **temperature set-points** for thermal zones/panels
  - Provided **TVAC** temperature predictions and compared against flight predicts
  - Created heat maps of **TVAC** and **Flight** cases, and verified heat flows were similar and components were balanced
- Thermal Vacuum Test
  - Procured all hardware in preparation for TVAC test
  - Wrote/updated TVAC test plan/procedure
  - Completed TVAC testing for CeREs
    - Bake-out
    - Cold Solar Array Deployment
    - Heater Verification
    - 3 Thermal Balances
    - 4 Qualification Cycles
  - Compared TVAC model predictions to TVAC test results
- Model Correlation
  - Reduced number of temperature predicts outside of the +/-5˚C error range, 5 to 2 in the Hot balance case (88% in this range) and 5 to 1 on the Cold balance (94% in this range).

Lessons Learned

Procedure

1. Adaptability while testing, the procedure had to be adjusted couple of times while testing.
2. Work early with the flight software engineer to lay out the groundwork for monitoring flight temperature sensors.

Scheduling

1. Always send out the support request month + in advance (if schedule is available)

Setup (hardware)

1. Limit the amount of GSE that might be blocking the views between your hardware and the environment

Analysis

1. Perform trade studies to identify the sensitivity of either the amount of GSE panels, or interface conductance.
2. Account for as much detail as possible in modeling power dissipating components such as the spacecraft bus.
3. Reduce complexity of the test while maintaining similar temperature predictions

Testing

1. Add a test heater for components that will be the limiting factor during Qual testing (battery testing range of only 0˚C to 45˚C).
2. Identify/understand heater circuit operation. Battery heaters would only energize through either the solar arrays (during on-orbit) or through GSE power supply.
3. Always keep thermal in the loop when performing critical activities, for example:
   a. Deploying solar arrays
   b. Enabling a component that will dissipate high power
4. Not all personnel had read through the provided training slides
   a. Present to the test staff the training slides
5. Be more specific on what you would like the support staff to record/log. Re-iterate as many times as necessary.
6. Make an excel sheet to track all final goals for each phase of test.

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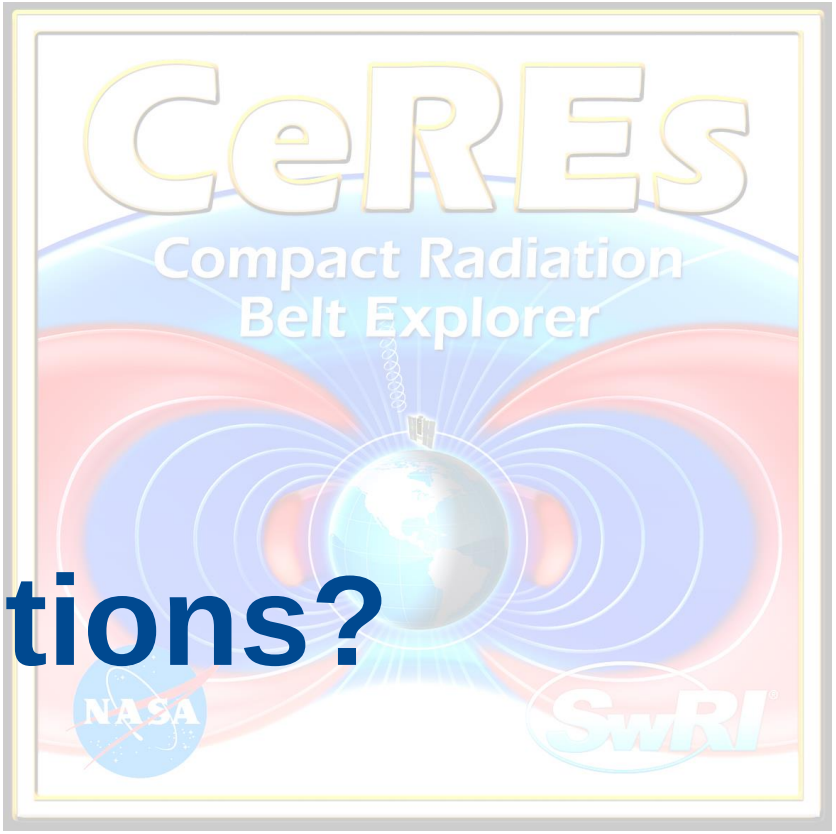
Glossary of Acronyms

APD	Avalanche Photodiode
CSP	CHREC Space Processor
FEE	Front End Electronics (electronics for the detectors)
DIB	Detector Interface Board
MERiT	Miniaturized Electron Proton Telescope Spectrometer
XB1	This is the name of the spacecraft bus, given by the manufacturer
BCT	Blue Canyon Technologies (Manufacturer of spacecraft bus)
RX	Receiving (for the radio mode)
TX	Transmitting (for the radio mode)
SA	Solar Arrays
SADp	Solar Array Deployment
CSB	Cold Survival Balance
CB	Cold Balance
HB	Hot Balance
CQ	Cold Qual
HQ	Hot Qual
GSE	Ground Support Equipment

Thank you for your attention!

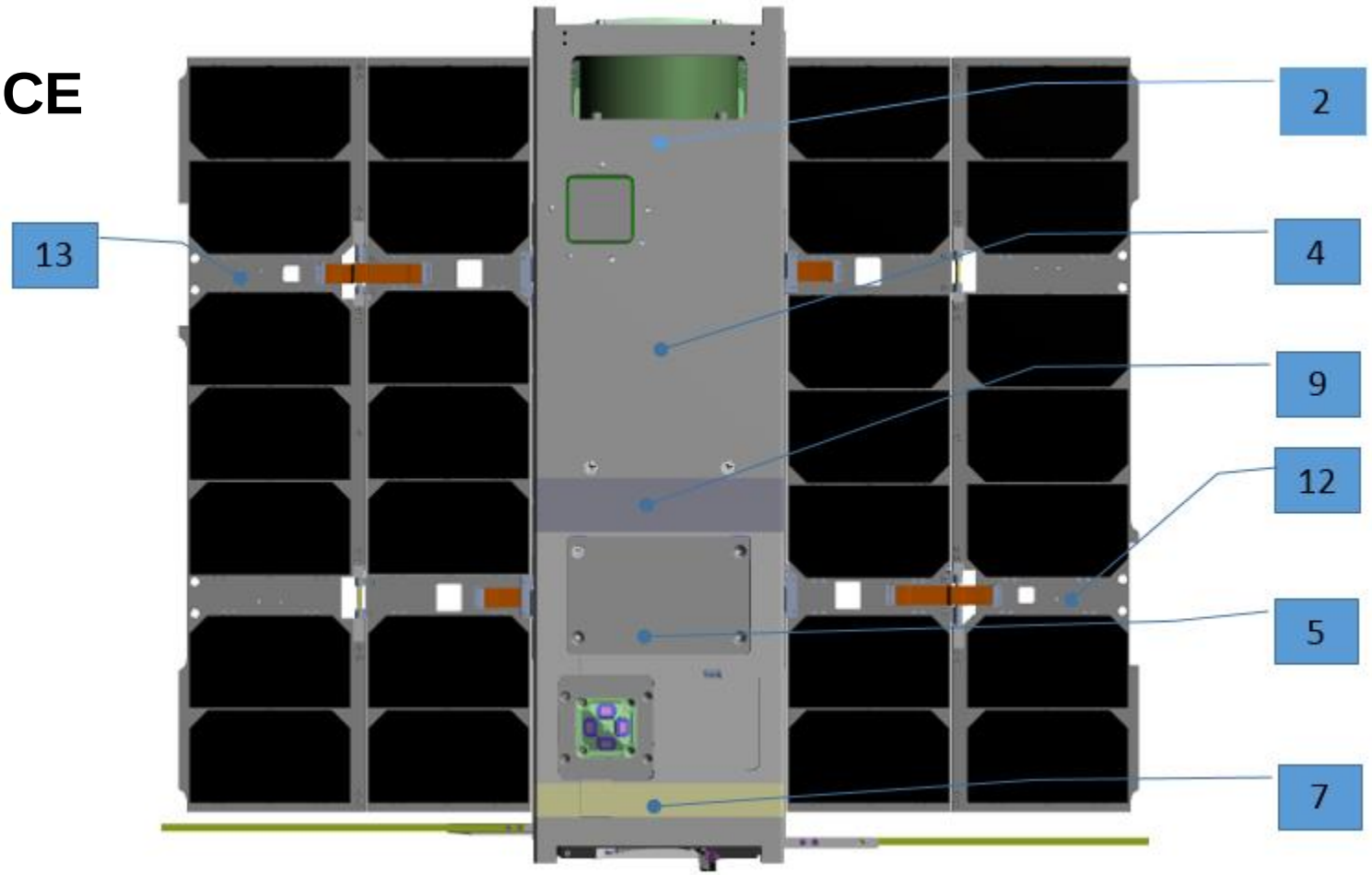


Questions?

Back up

TVAC Test
TCs Placement

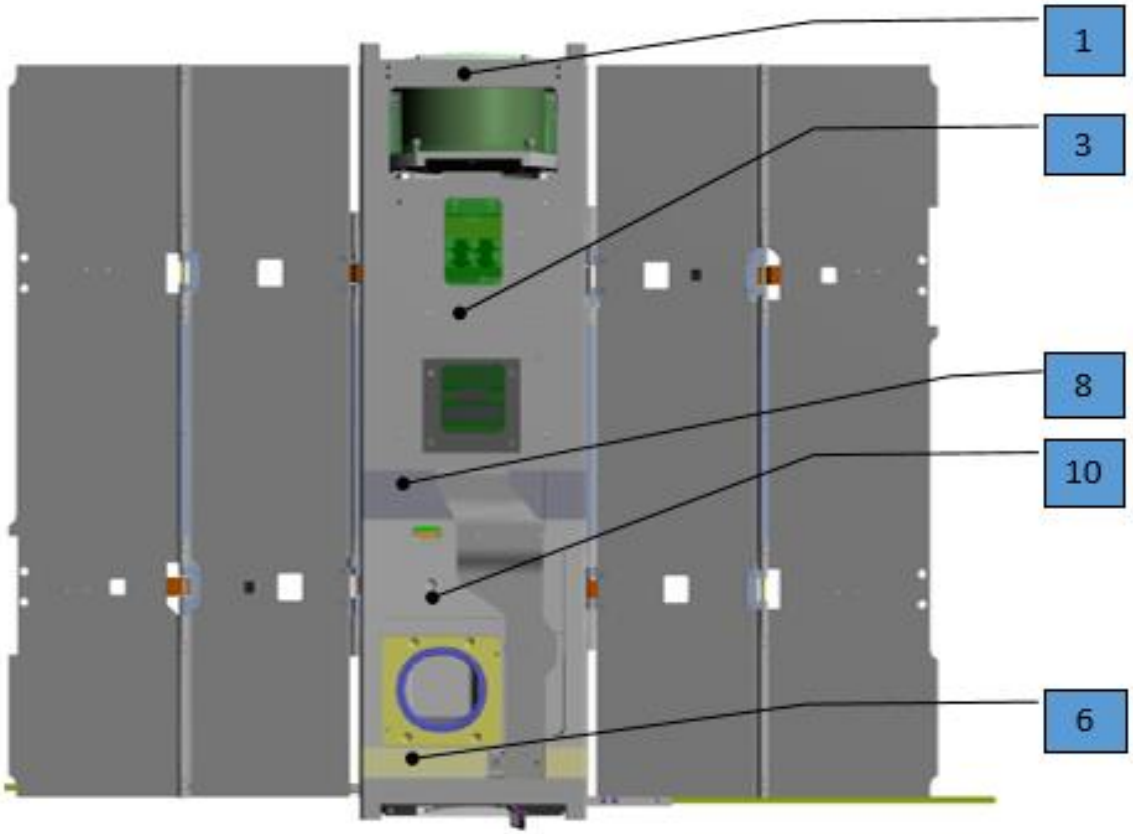
-X FACE



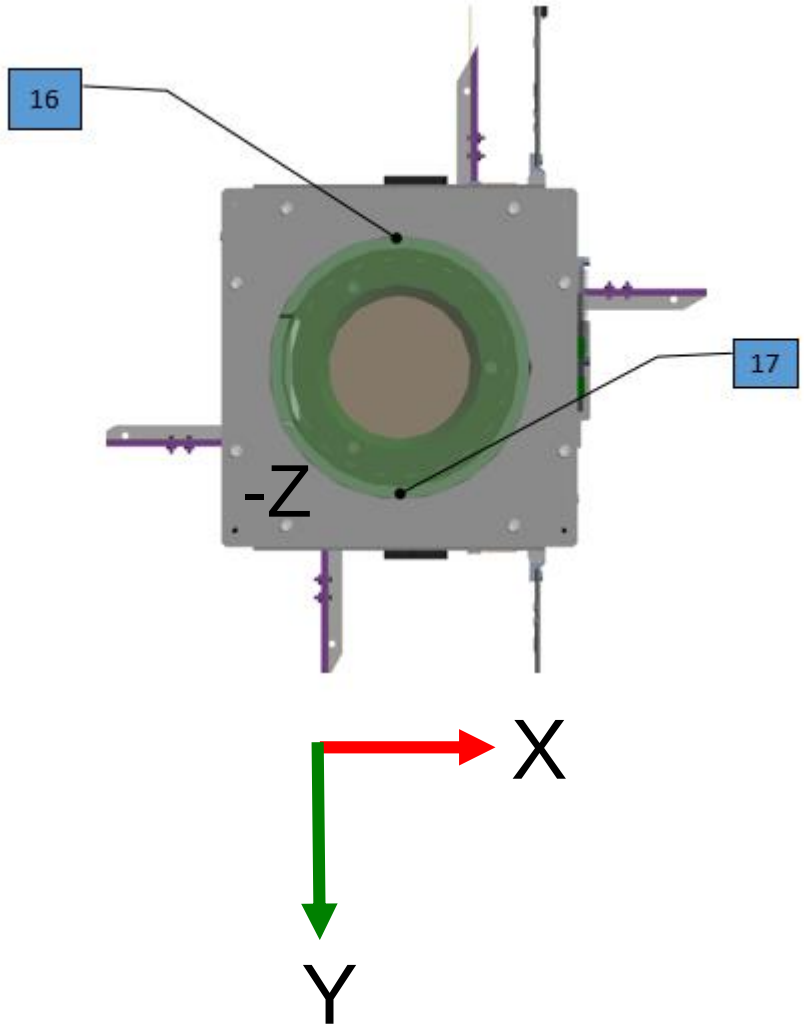
- TC locations were chosen to best read interface temperatures of XB1, MERiT, and thermal knife circuit of solar arrays (deployment)

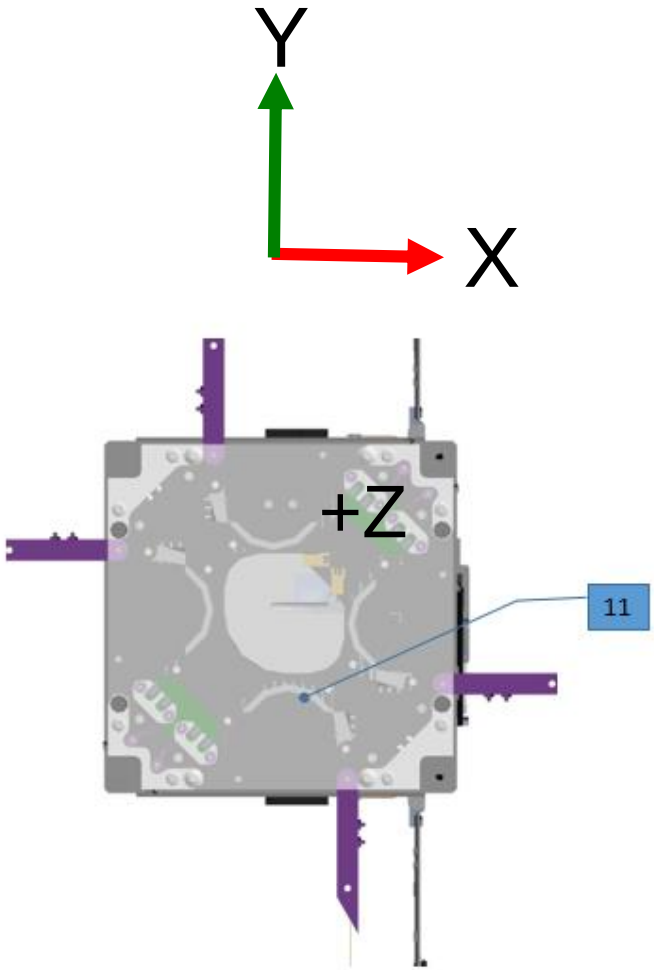
TVAC Test
TCs Placement

+X FACE

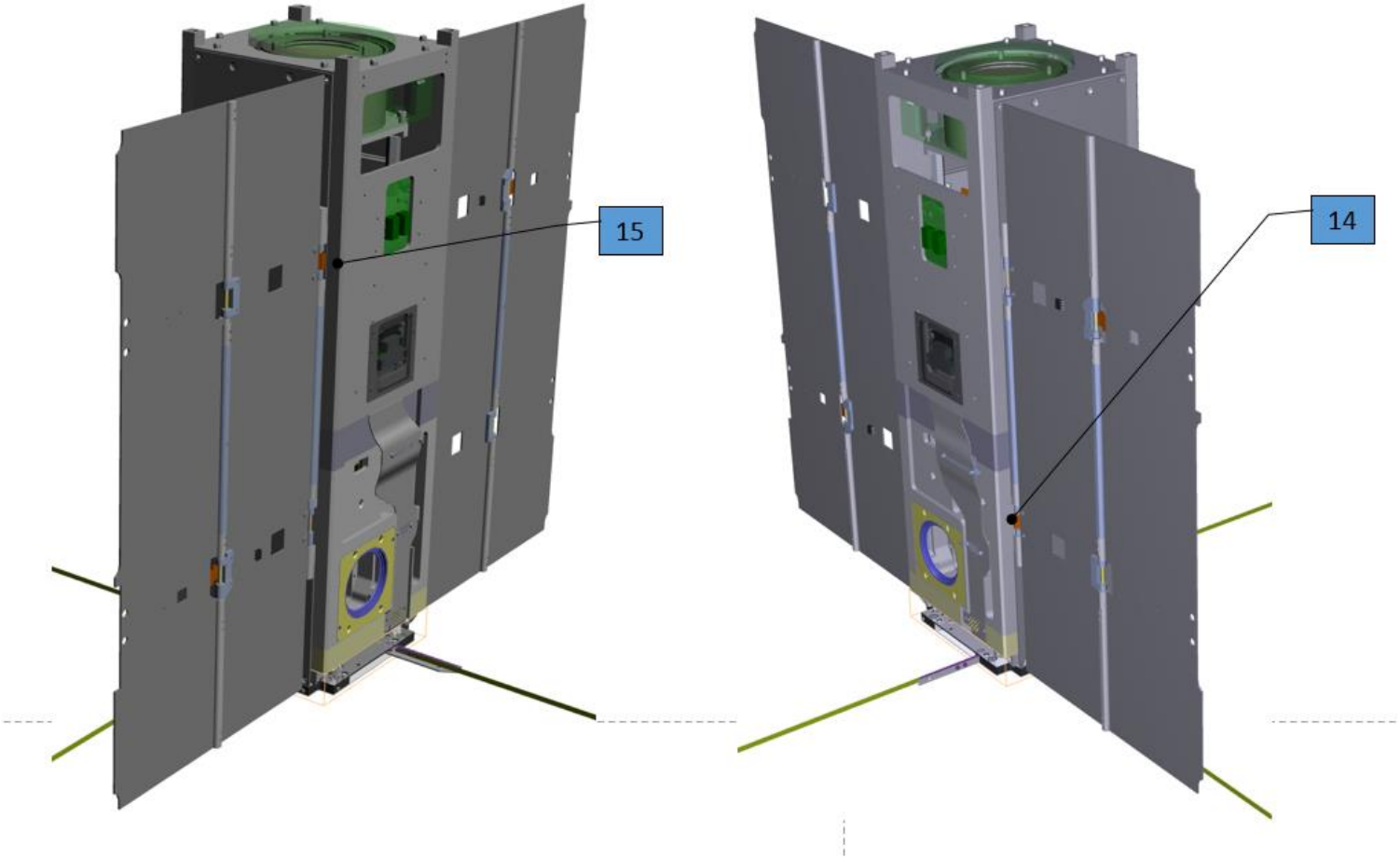


TVAC Test
TCs Placement





TVAC Test
TCs Placement



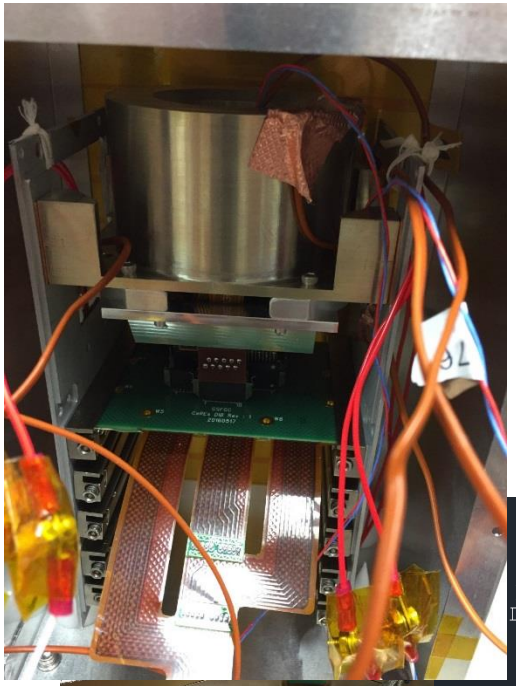
- There's limited access to -/+ Y faces of CeREs, TCs were placed on side rails

Instrument Level Thermal testing

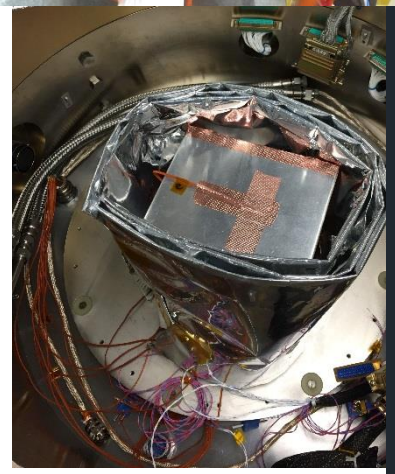
APD TVAC test

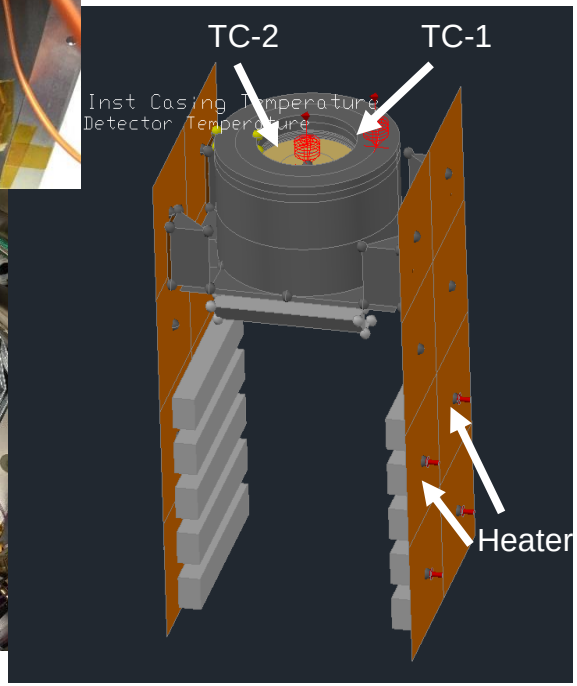
- Instrument thermal balance tests were performed. Test goals:
  - Obtain a better temperature relation between the APD detector and its Al housing
  - In order to correlate thermal model to provide better temperature predictions
- 3 balanced points were obtained:

Settings	Case 1	Case 2	Case 3
Heater (W)	0.94	0.46	2
Chamber Temp (°C)	-19.5	-1.8	17.6



- Kapton heaters were placed on each side (Al chassis)
- TCs were placed on APD detector and Al housing
- Cold-plate shroud also monitored with TCs





APD TVAC Results

Comparison error

TEST Vs MODEL	CASE 1	CASE 2	CASE3
	Ch -19.5˚C_0.94W	**Ch 0˚C_0.5W**	**Ch 20˚C_2W**
	Δ(data - model)	Δ(data - model)	Δ(data - model)
Components	**Δ (˚C)**	**Δ (˚C)**	**Δ (˚C)**
APD	-2.77	-1.69	-4.32
APD Housing	1.28	1.26	0.85
HP1	0.19	1.13	-0.61
HP2	0.57	0.56	-0.72
Cold Plate	0.00	0.00	0.00
Shroud Walls	0.00	0.00	0.00

Housing Vs APD

CASE 1	CASE 2	CASE 3
Ch -19.5˚C_0.94W	**Ch 0˚C_0.5W**	**Ch 20˚C_2W**
Δ(housing-APD)(˚C)	Δ(housing-APD)(˚C)	Δ(housing-APD)(˚C)
5.20	2.40	7.30

- Temperature gradient between **APD** and **Housing** does not exceed 8 degrees
- Test results led to an improvement in thermal model
- Small error between test and model predictions after model correlation

- Thermal balance criteria was set to a rate of change of 0.1 C/2hr (desired, 0.05 C/hr), as the readings could only read to the first decimal
- All 3 test cases reached thermal balance criteria, running test over night allowed for this to happen.
- Difference between test data and model prediction
  - APD less than +/- 5°C
  - APD housing and chassis (HP1&2) less than +/- 1°C
- Temperature gradient between APD and Housing
  - Under 6°C for Case 1
  - Under 3°C for Case 2
  - Under 8°C for Case 3

APD TVAC Model Correlation

- All test cases reach thermal balance criteria (rate of change= 0.05 C/hr), the ability to leave the test running over night helped achieve this.
  - Because of test setup limitations
- All components demonstrated an error (difference) lower than +/- 5° C between test data and model prediction.
- Temperature gradient between APD and Housing does not exceed 8 degrees
- Modifications made to thermal model:
  - An Enclosure was modelled around the test setup to best represent radiation from walls and temperatures zones on walls
  - The thermal contactor path was revised and adjusted
  - Optical properties for the APD sensor were adjusted