Speeding up Model Correlation with Breakout Models: The VIPER Integrated Thermal Model Correlation Story

Presented by: Lisa Erickson

Lisa Erickson, Veronica Pizor, Thomas Slusser	**NASA JSC**
Jodi Turk, Elijah Stewart	**NASA MSFC**
Chane Sladek, Cameron Moen, Blain Lancaster, Quoc Nguyen, Thomas Slusser, Thomas Paul, Glenn Waguespack, Rich Hogen	**Amentum**
Jose Dobarco-Otero	**HX5, LLC**

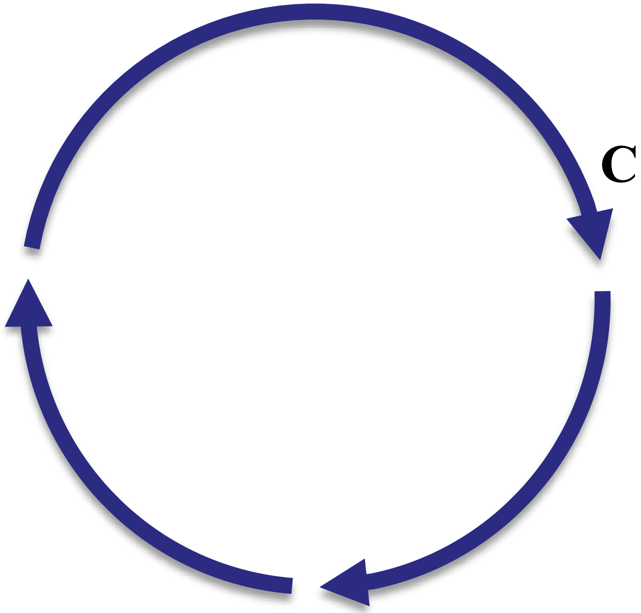
THERMAL & FLUIDS ANALYSIS WORKSHOP
Ames Research Center 2025

Thermal & Fluids Analysis Workshop 2025
NASA Ames Research Center

San Jose, CA
August 4-7, 2025

Background: Correlation Problem

- Correlating large models has a reputation for being slow.
- Parameters are methodically adjusted until model predictions match test data within an allowed error.



$$\Delta T_{rms} = \sqrt{\frac{\sum_{i=1}^{n}\left(T_{test(i)} - T_{model(i)}\right)^2}{n}}$$

Background: Correlation Problem

- How to Speed up Correlation?

Use software tools with optimization algorithms that automatically test parameters

Journal of Astronomical Telescopes, Instruments, and Systems 3(4), 044002 (Oct–Dec 2017)

Model-based thermal system design optimization for the James Webb Space Telescope

Giuseppe Cataldo,* Malcolm B. Niedner, Dale J. Fixsen, and Samuel H. Moseley
NASA Goddard Space Flight Center, Greenbelt, Maryland, United States

TFAWS Passive Thermal Session

Thermal Design and TVAC Test Correlation of a Lunar Rover Prototype

Jean-Frédéric Ruel, Jean-François Labrecque-P. (Maya HTT)
Josh Newman (Canadensys Aerospace Corp.)
Donatas Mishkinis (Allatherm SIA)
Guanghan Wang (CSA)

Presented By
Jean-François Labrecque-P.

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Thermal & Fluids Analysis Workshop
TFAWS 2020
August 18-20, 2020
Virtual Conference

JOURNAL OF SPACECRAFT AND ROCKETS
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Engineering Notes

Thermal Model Correlation of SNIPE Satellite Using Genetic-Algorithm-Based Multi-Objective Optimization Method

Ji-Seok Kim,* Seonho Lee,† and Hui-Kyung Kim‡
Korea Aerospace Research Institute, Daejeon 34133, Republic of Korea
and
Hae-Dong Kim§
Gyeongsang National University, Gyeongsangnam-do 52828, Republic of Korea

TFAWS Passive Thermal Paper Session

SWOT Thermal Model Correlation

Lina Maricic (ATA Engineering)

Presented By
Lina Maricic

Thermal & Fluids Analysis Workshop
TFAWS 2022
September 6th-9th, 2022
Virtual Conference

CORRELATION OF THERMAL FLUID CRYOGENIC MODEL THROUGH IMPLEMENTATION WITH OPTIMIZATION SOFTWARE

Ellen K. Smith and Nathan F. Andrews
Southwest Research Institute

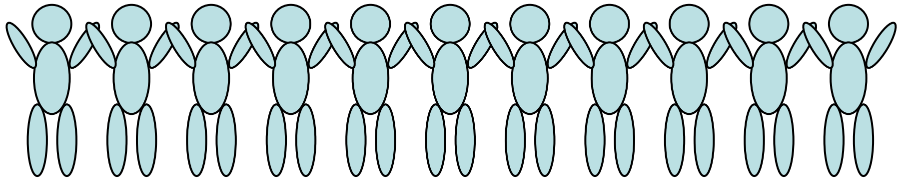
Use reduced order models

50th International Conference on Environmental Systems
12-15 July 2021
ICES-2021-424

Advanced Thermal Model Correlation Using Reduced-Order Models

Derek W. Hengeveld[1] and Jacob Moulton[2]
Redwire, Albuquerque, NM, 87106

Parallelize between multiple analysts



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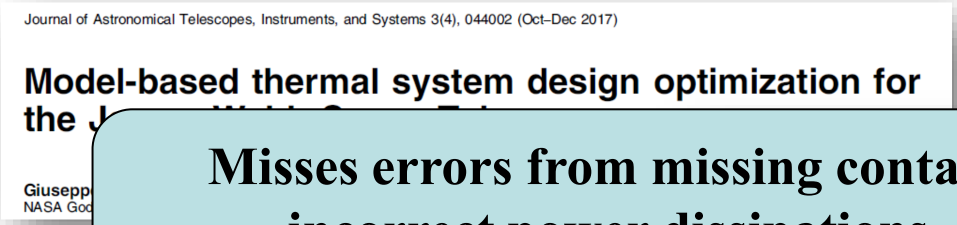
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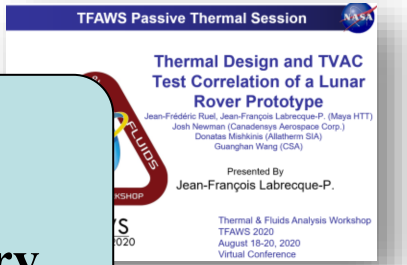
Model-based thermal system design optimization for the J

Giusepp
NASA God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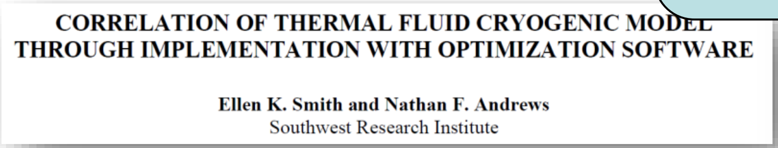
Use software tools with optimization algorithms that automatically test parameters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Misses errors from missing contacts, incorrect power dissipations, and incorrect or oversimplified geometry.

Use reduced order models

May not be available.

Parallelize between multiple analysts

How?

Background: Correlation Problem

- How to Speed up Correlation?

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Model-based thermal system design optimization for the J...

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Thermal & Fluids Analysis Workshop TFAWS 2020 August 18-20, 2020 Virtual Conference

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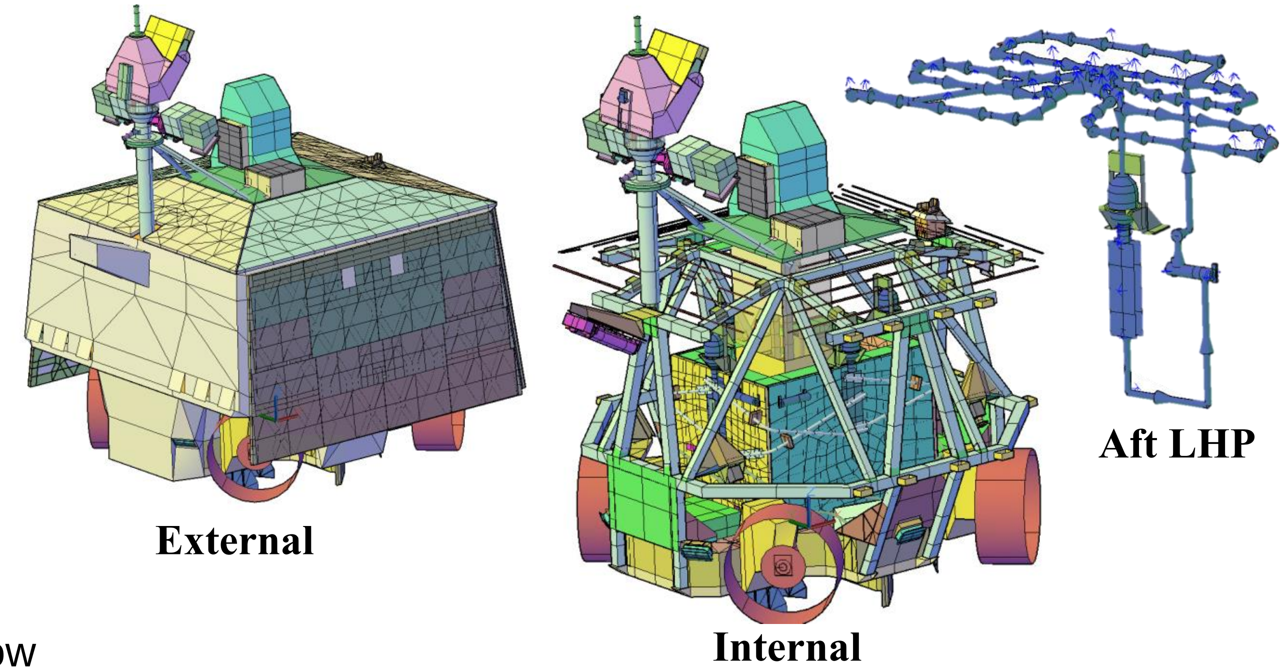
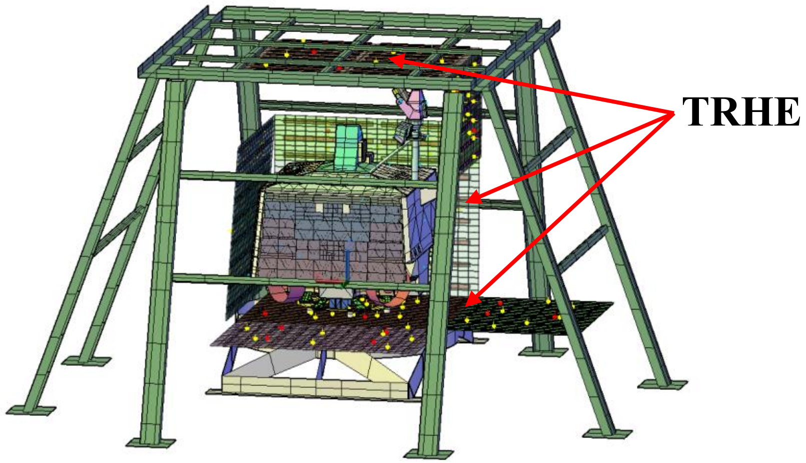
How?

Correlation Problem: VIPER ITM

- Volatiles Investigating Polar Exploration Rover (VIPER) TVAC in September - October 2024.
- VIPER Integrated Thermal Model (ITM) correlation needed to be parallelized to meet schedule.
  - Large model (no reduced order model)
  - Long run times 10-40 minutes (pre-test)
  - Model in work: updates to improve its fidelity overlapped with correlation timeline
  - Thermal Radiant Heat Enclosure (TRHE) correlation overlapped with ITM correlation window





VIPER in TVAC support structure and TRHE

VIPER ITM Thermal Desktop Model

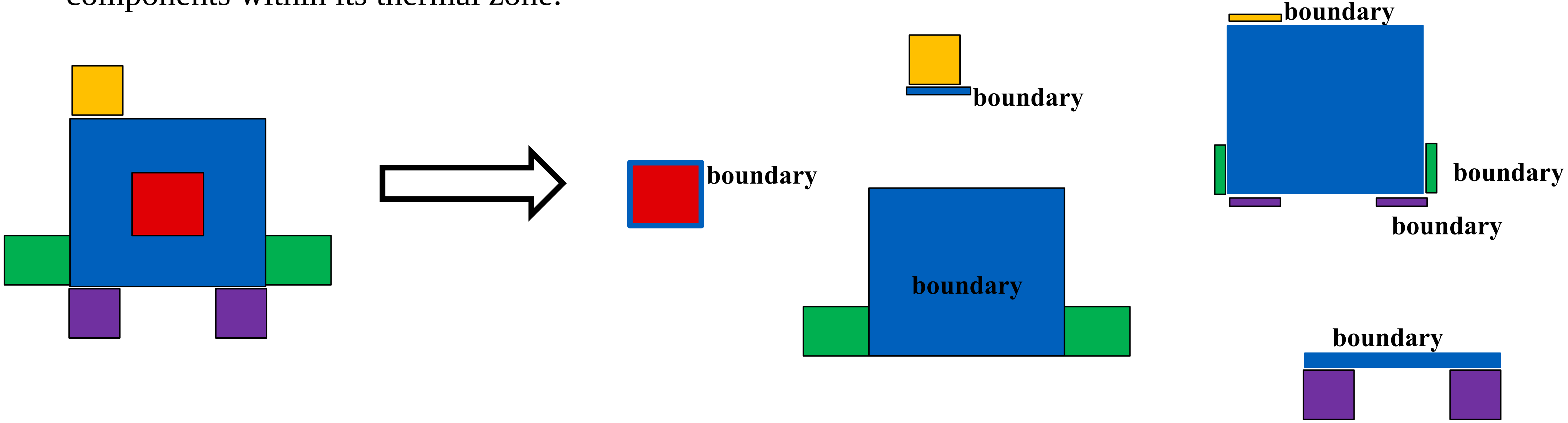
- Nodes: 20,019
- Submodels: 97
- Contacts: 1,327
- Heaters & Heat loads: 186
- Sensors to Correlate: 141
- People (full time): 14 (8)
- Points to Correlate: Hot & Cold Thermal Balance
- Time allotted: 22 weeks

Outline

- Correlation Problem
- **Solution Overview: *Veronica***
- Creating Breakout Models
- Results
- Correlation Time Survey

How to Parallelize ITM Correlation? Introducing *Veronica*

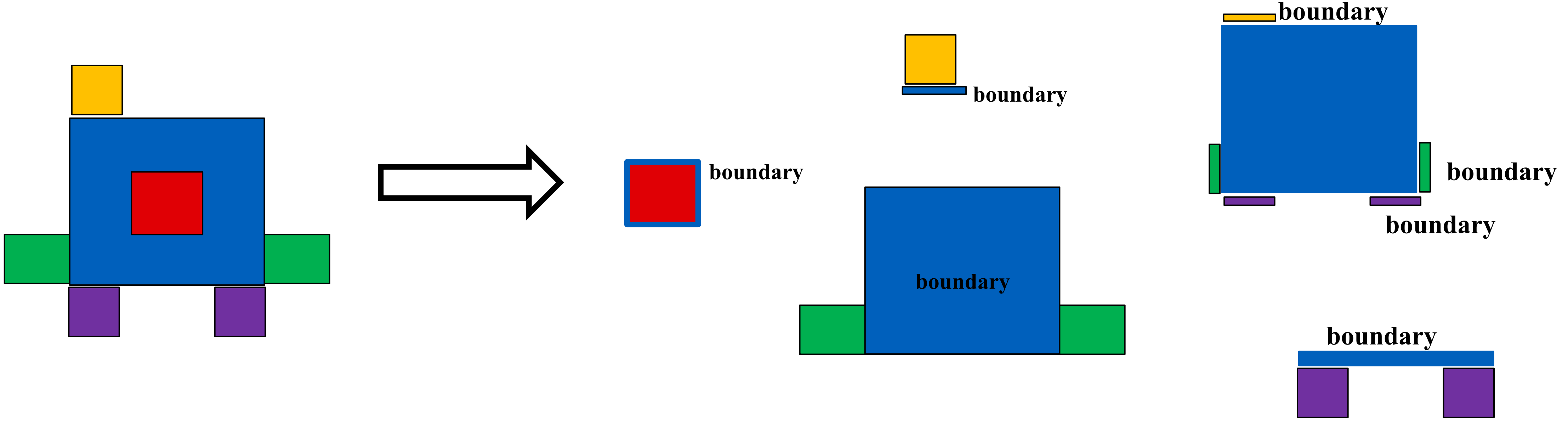
- New model correlation approach developed by VIPER thermal team.
- Specifies how multiple analysts can perform most correlation activities in parallel.
- *Veronica*'s Key idea:
  - It is possible to split an ITM into smaller *breakout models* – each corresponding to a particular thermal zone that is mostly independent of other thermal zones.
  - Each *breakout model* can match the ITM's predictions, within a small error, and be used for correlating components within its thermal zone.



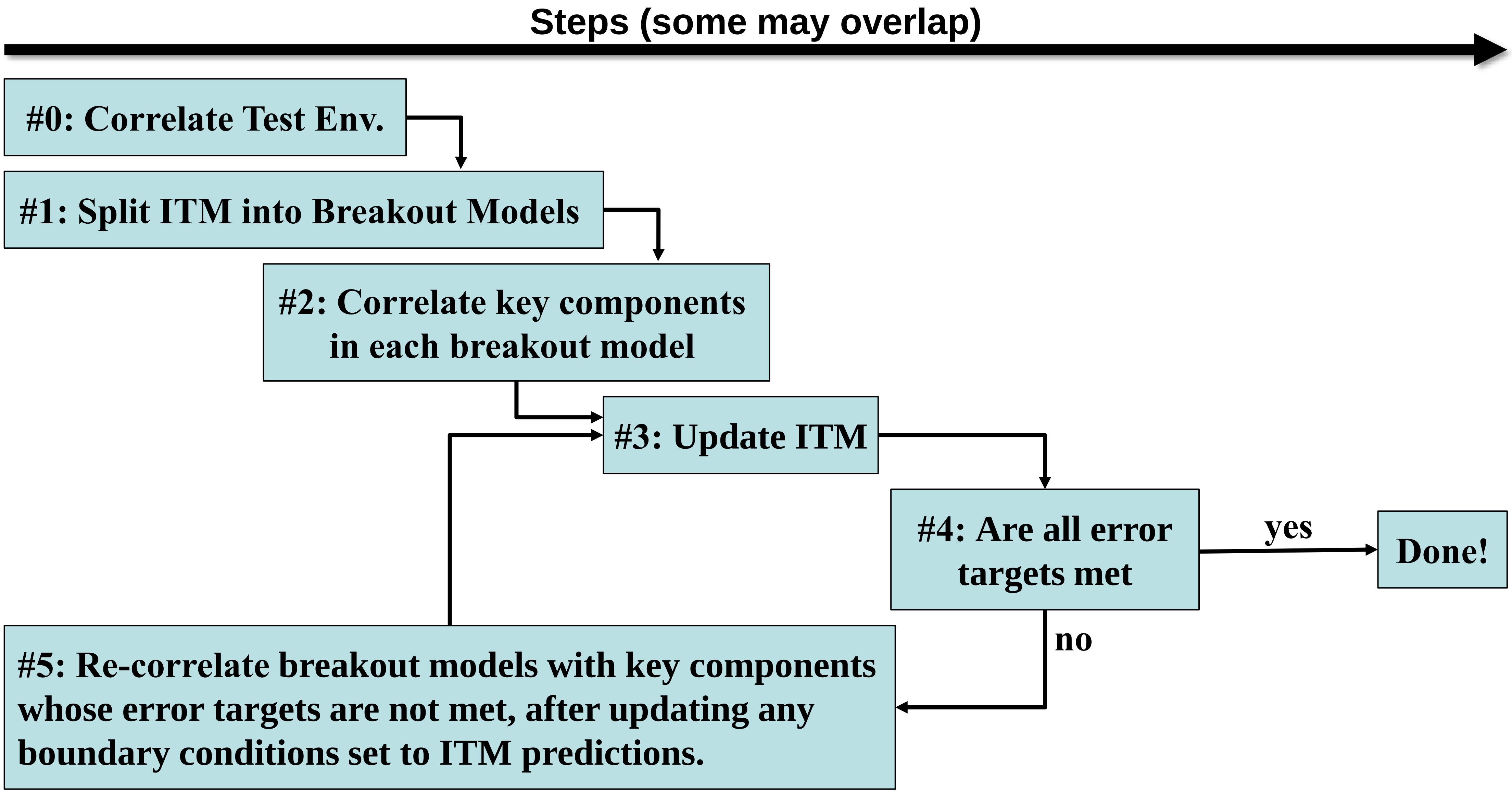
How to Parallelize ITM Correlation? Introducing *Veronica*

- Why can we use breakout models?
  - Observation #1: VIPER has several different 'thermal zones' that are mostly independent of each other.
  - Observation #2: If component A is not a significant contributor to component B's thermal balance, then the accuracy of A's temperature is not that important when predicting the temperature of B.

Example: 0.4% heat leaving MSOLO goes to its MLI. A 25-35C drop in MSOLO MLI → ~3C drop in MSOLO temperatures.



Veronica Overview



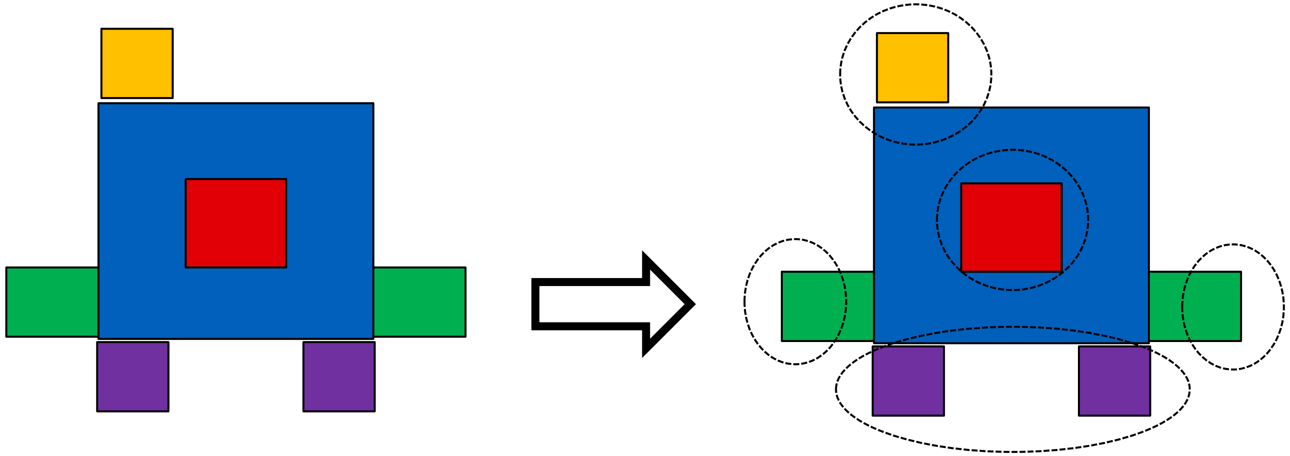
Outline

- Correlation Problem
- Solution Overview: *Veronica*
- **Creating Breakout Models**
- Results
- Correlation Time Survey

Veronica Overview: Creating Breakout Models

- Breakout models are cut-down ITM copies.

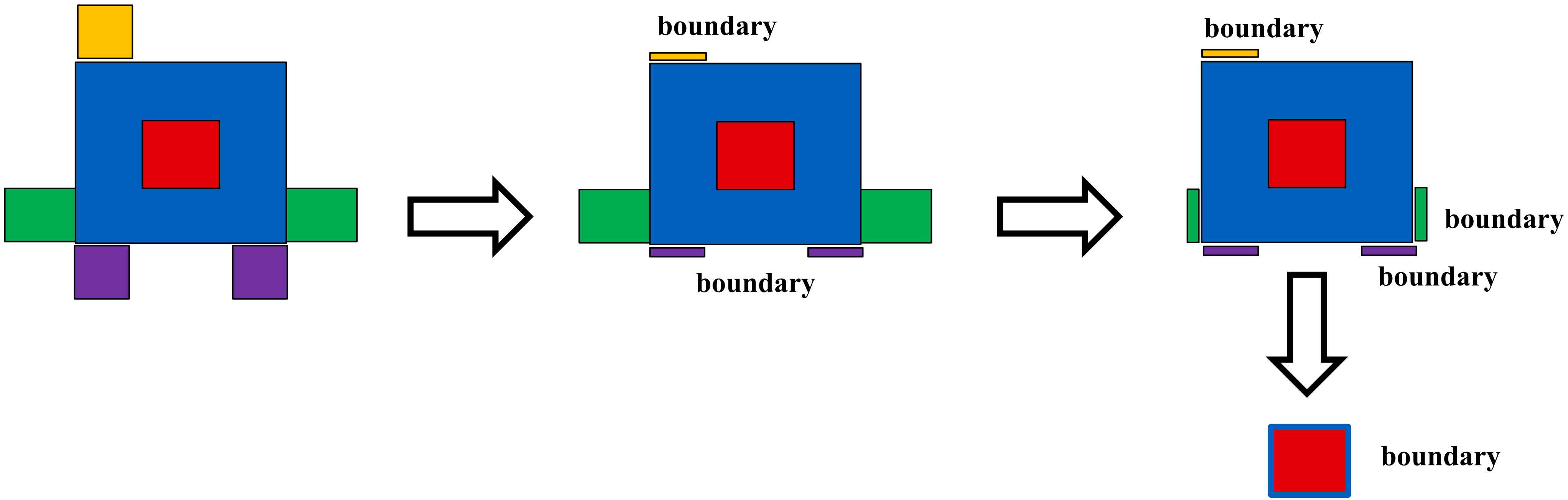
Step #1: Group components together into mostly independent thermal zones.



Veronica Overview: Creating Breakout Models

Step #2: Cut-out 'unimportant components' the model until it runs fast enough.

- Replace cut components with boundary conditions set by uncorrelated ITM.
- Verify predictions agree with the ITM.



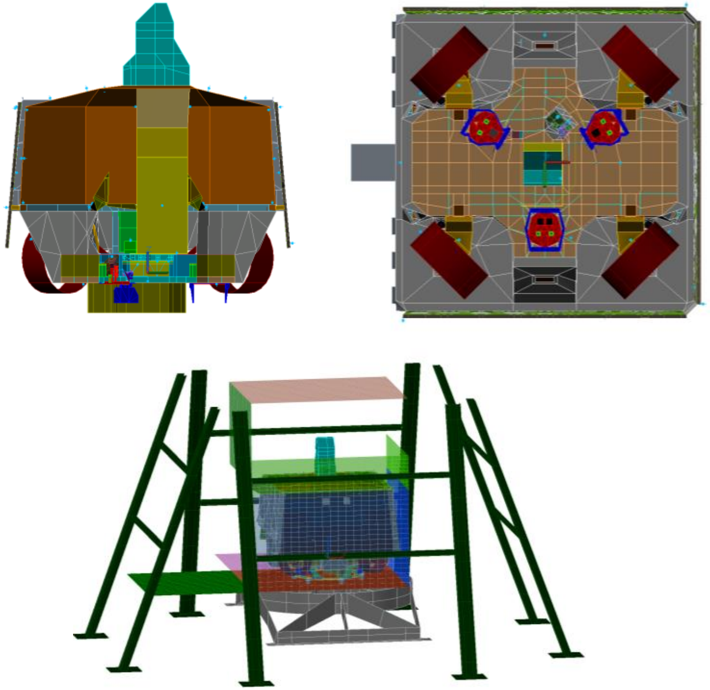
Step #3: Define boundary conditions using test data and/or uncorrelated ITM predictions.

Veronica Overview: Creating Breakout Models

Important Components:

1. Account for the top ~98% of the heat into or out of key components.
2. Act as reflectors/blockers of radiation between the key components and their radiation environment.

Example: Wheel Well Breakout Model & Sorted Output of SINDA Subroutine Submap



Hot Thermal Balance												
	A SUBMAP OF THERMAL SUBMODEL WHEEL_MODULE											
AVERAGE DIFF/ARIT TEMP.	=	51.529	(DEG)									
AVG. BDY/HTR NODE TEMP.	=	(NONE)	(DEG)									
TOTAL CAPACITANCE	=	17869	(ENERGY/DEG)									
TOTAL HEAT RATE IMPOSED	=	0	(ENERGY/TIME)							Sum	96.45	97.86
TOTAL HEAT TO INTL BDYS.	=	0	(ENERGY/TIME)							SUM	98.2	99.48
SUBMODEL	TYPE	AVG TEMP.	LIN/TIE COND	HEAT RATE TO	RAD. COND.	HEAT RATE TO	TOTAL COND.	TOTAL RATE	total rate out	total rate in	% Out	% In
SPACE	THERMAL	(NONE)	0	0	0.1423	88.827	0.35444	88.827	88.827	0	94.12	0
TV_RAD_ENCL_STBD	THERMAL	111.06	0	0	0.0441616	-37.51	0.4862	-37.51	0	37.51	0	39.75
TV_RAD_ENCL_BTTM	THERMAL	65.97	0	0	0.31964	-27.824	2.7761	-27.824	0	27.824	0	29.48
TV_RAD_ENCL_PORT	THERMAL	72.9	0	0	0.097658	-14.768	0.91143	-14.768	0	14.768	0	15.65
TV_RAD_ENCL_AFT	THERMAL	69.23	0	0	0.0781323	-6.2872	0.71682	-6.2872	0	6.2872	0	6.66
TV_RAD_ENCL_FRONT_BTTM	THERMAL	58.26	0	0	0.0254243	-5.9599	0.21842	-5.9599	0	5.9599	0	6.32
STRUCTURE_LOWER_CHASSIS	THERMAL	52.58	12.967	2.2323	0.058946	-0.0297921	13.448	2.2025	2.2025	0	2.33	0
WHEEL_MODULE_STEERING_MOTORS	THERMAL	54.52	98.248	-0.91587	0.000380693	-0.00363376	98.251	-0.91951	0	0.91951	0	0.97
SOLAR_PANEL_STRBD	THERMAL	-11.79	0	0	0.00476169	0.86518	0.0331745	0.86518	0.86518	0	0.92	0
MLI_LOWERSTRUCTURE	THERMAL	53.67	0	0	0.37664	-0.61341	3.1435	-0.61341	0	0.61341	0	0.65
TV_OVERHEAD_STRUCTURE_CROSS_BARS	THERMAL	-126.76	0	0	0.00059307	0.35209	0.00205152	0.35209	0.35209	0	0.37	0
HAZ_CAMERA	THERMAL	40.8	0	0	0.00193343	0.22056	0.0149249	0.22056	0.22056	0	0.23	0
MLI_FRONT_PANEL	THERMAL	-14.53	0	0	0.000544641	0.21565	0.00289431	0.21565	0.21565	0	0.23	0

$$\% \, Out_i = \frac{total \; rate \; out_i}{\sum total \; rate \; out_i} \qquad \% \, In_i = \frac{total \; rate \; in_i}{\sum total \; rate \; in_i + total \; heat \; rate \; imposed}$$

Veronica Overview: Creating Breakout Models

- VIPER ITM had 9 breakout models

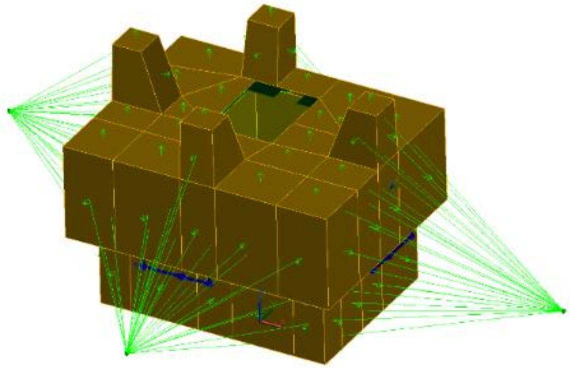
Breakout Model	Key Components	% of Heat Flow Captured	RMS Error ˚C to ITM*	Approx. SINDA Runtime
Warmbox	Forward Heat Spreader, Aft Heat Spreader, Port Heat Spreader, Starboard Heat Spreader, and their Avionics	>99%	0.5^{H}, 1.2^{C}	~1 minute
Mid-Upper Components	Solar Panels, Aft Cameras, Star Tracker	>99.2%	0.5, 0.06, 0.1	~4 minutes
Hazard Cameras and Lights	4 Hazard Cameras, 6 Hazard Lights	$>98\%^{H}$	0.1^{H}, 0.8^{H}	~6.5 minutes
MSOLO and NIRVSS	MSOLO and NIRVSS science instruments	$>99\%^{H}$	0.85^{H} 1.98^{C}	~10.5 seconds
Gimbal Mast	Gimbal Communication Motors, Navigation Motors, and Navigation Lights	>99%	0.85^{H}, 1.98^{C}	~2.5 minutes
NSS	NSS (enclosed in the Front Panel MLI)	100%, >99% Front Panel MLI ^{H}	0.4^{H}	~6.5 minutes
Batteries	Aft Battery, Forward Battery	>95%	0.8^{H} 4.8^{C}	~30 seconds
Wheel Well	Wheel Module, Mobility Module	>98%	0.12	~4.5 minutes
External Bottom	Rover kits, Rover release mechanisms	>97% of heat in, >99% of heat out	1.8^{H} 2.0^{C}	~2.2 minutes

$$\%\ of\ heat\ flow\ captured = \text{min of all key components in breakout model} \left[\frac{\sum Q_{key\ component's\ submodel \rightarrow submodels\ in\ breakout\ model}}{\sum Q_{key\ component's\ submodel \rightarrow submodels\ in\ ITM}}\right]$$

*Unless otherwise noted (1) the RMS error is the highest error out of the cold and hot thermal cases, and (2) the percent of heat flow captured is the lowest out of each key component for both the cold and hot thermal balance cases. ^{H} Designates hot and ^{C} cold thermal balance.

Example: Breakout Model Boundary Conditions

- Boundary surface temperature = TVAC sensor's value:
  - Change node directly
  - Connect surface to a boundary node with a high conductor

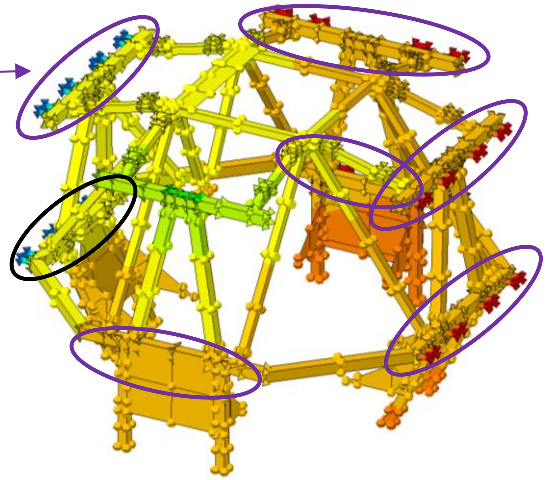


Warmbox MLI Boundary

- Boundary surface temperature = offset + TVAC sensor's value:

$$\underbrace{T_{Node} = T_{Node\ ITM\ run} - SENSOR\_TC.\#_{ITM\ run}}_{offset} + TC\#_{TVAC}$$

- Boundary set to uncorrelated ITM predictions
  - No TVAC data available



Structure Frame: Boundary

Outline

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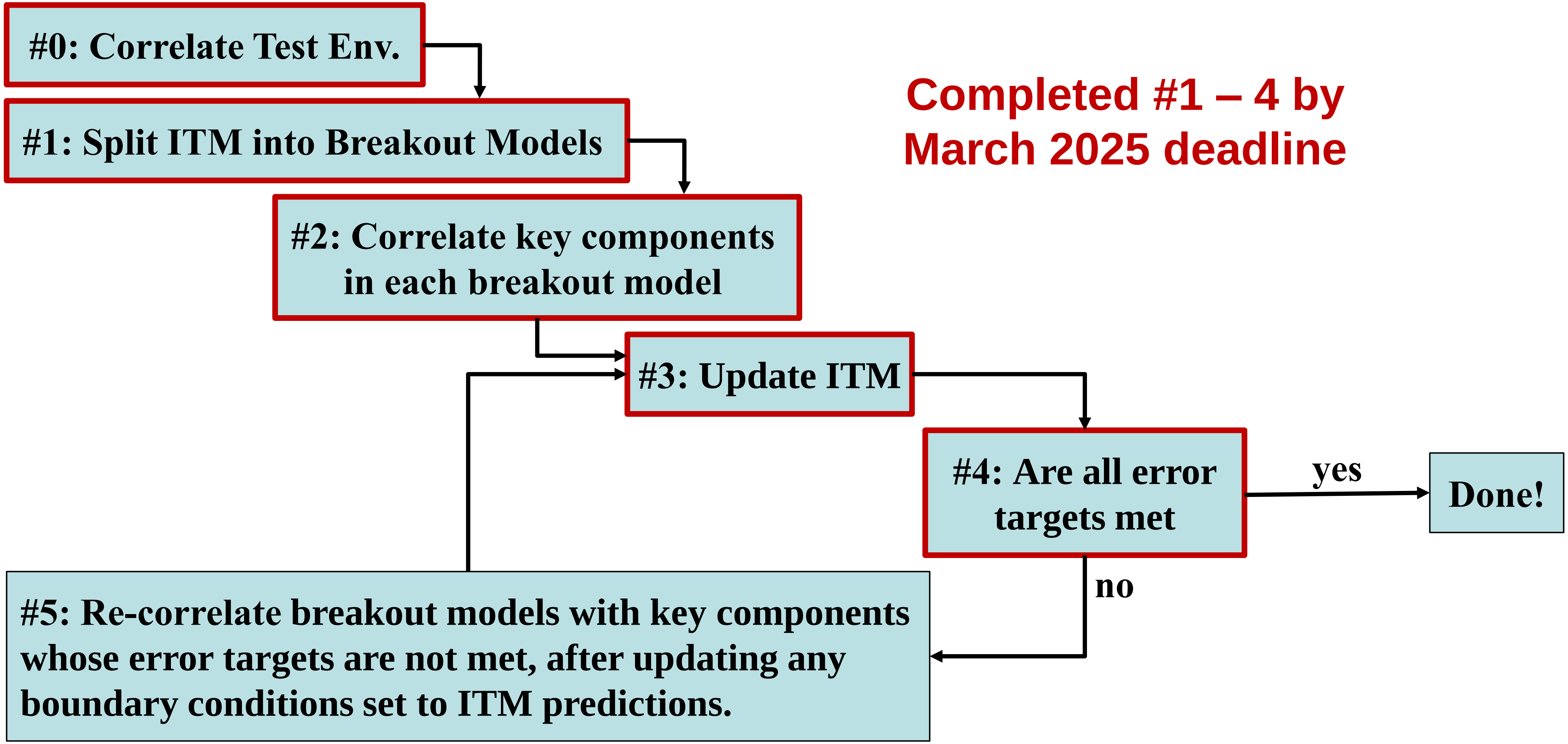
- **Results**
- Correlation Time Survey

Results:

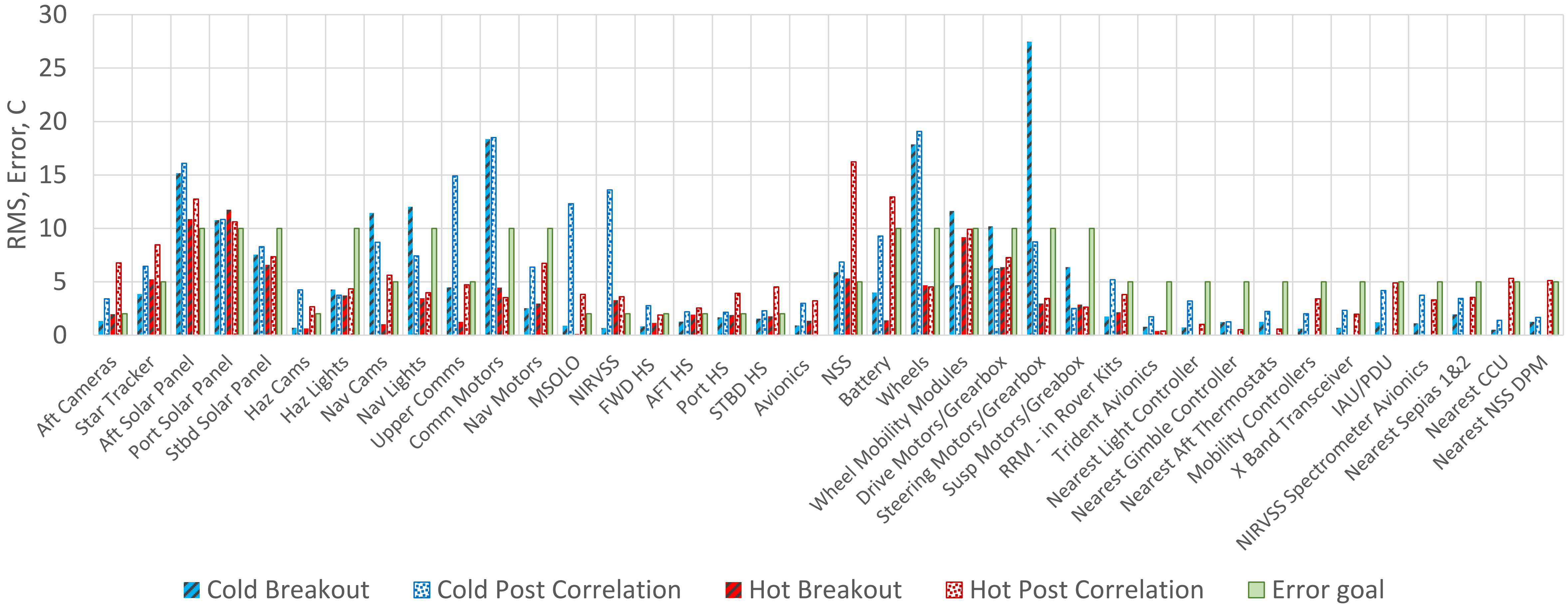
Steps (some may overlap)



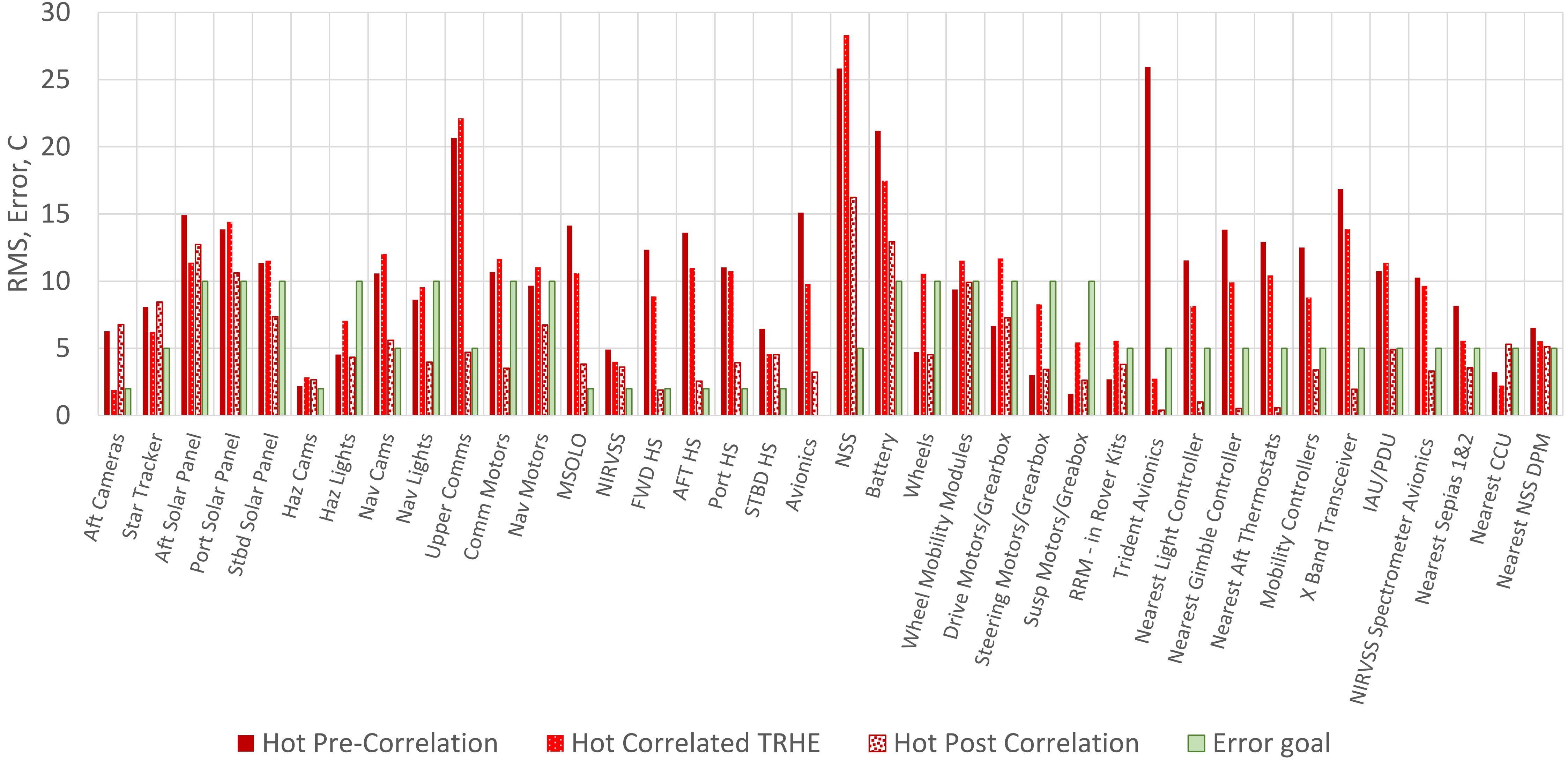
Completed #1 – 4 by March 2025 deadline

Results: Implemented Changes from Breakout Models

- Overall RMS errors 9.99C Cold & 7.44C Hot
- Small increases in error from breakout models to ITM



Results: Improvement in Correlation

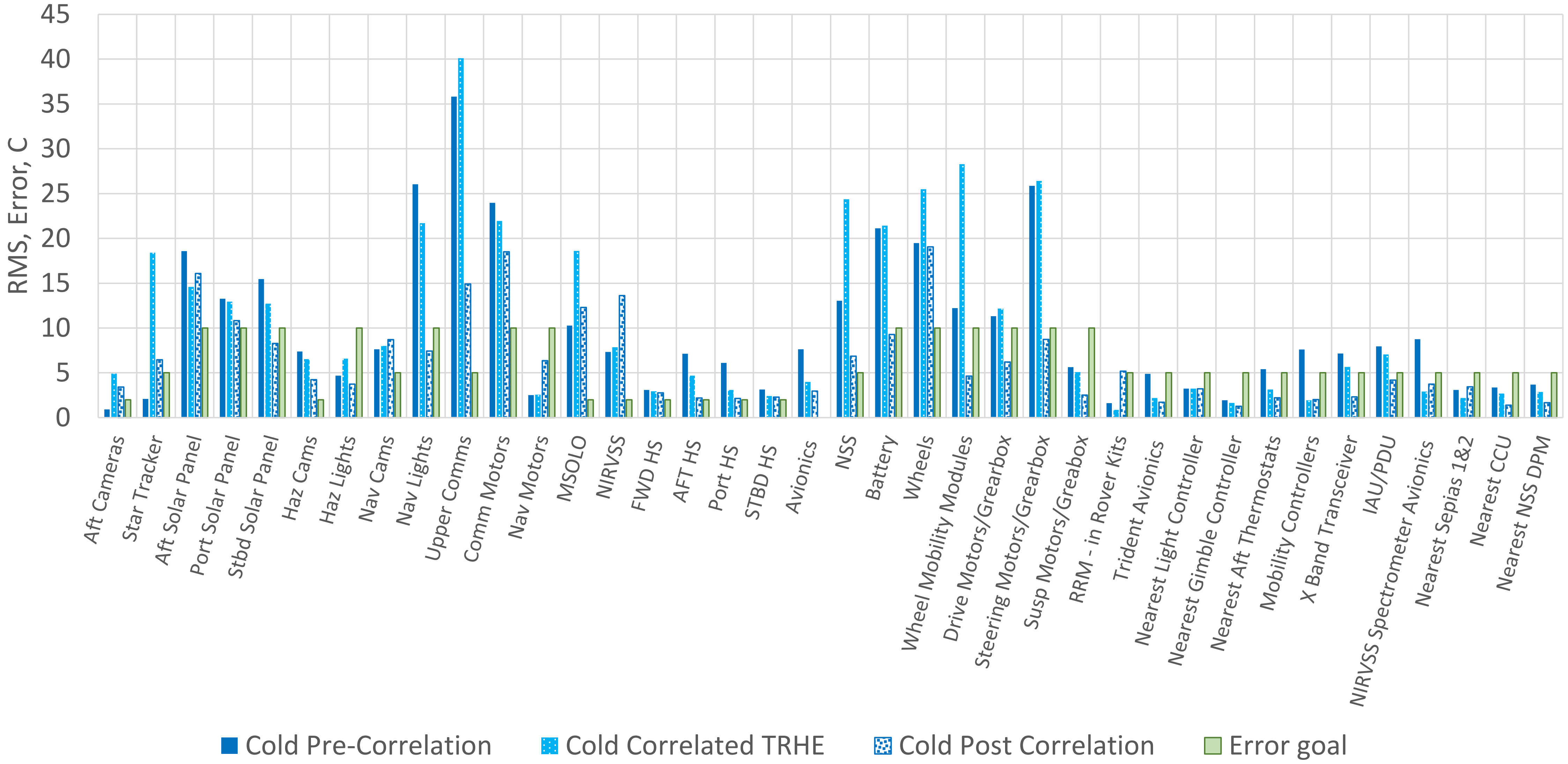


Overall RMS: 12.1C

Overall RMS: 11.7C

Overall RMS: 7.4C

Results: Improvement in Correlation



Overall RMS: 14.8C | Overall RMS: 17.7C | Overall RMS: 10.0C

Results: Improvement in Correlation

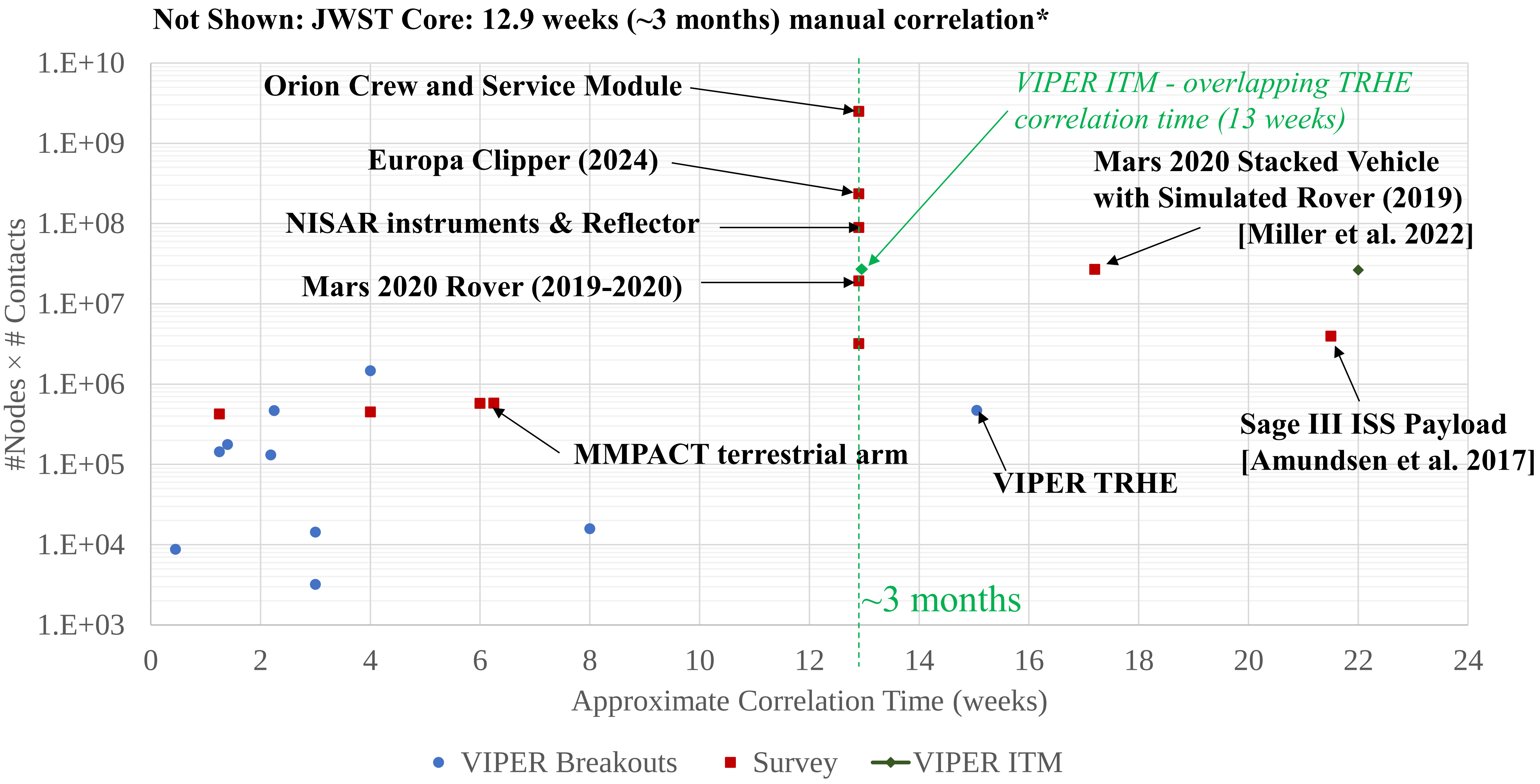
- Model correlation significantly improved after incorporating changes from breakout models correlation.
- Changes included:
  - Updated power dissipations
  - Added missing contactors
  - MLI ε* adjustments
  - Contact resistance adjustments
  - Sensor location adjustments
  - Updated LHP and CCHP condensing/evaporating constants
  - Node refinement of solar panels and FWD heat spreader
- “Sustainment Team” phase will look at further improving the correlation.

37 key components	Cold Thermal Balance			Hot Thermal Balance		
	% <5C	% <10C	% Within Error Goal	% <5C	% <10C	% Within Error Goal
Pre-Correlation	35%	65%	32%	22%	46%	27%
Correlated TRHE	43%	62%	35%	16%	51%	19%
Post Correlation	54%	81%	54%	65%	89%	59%

Correlation Time Survey

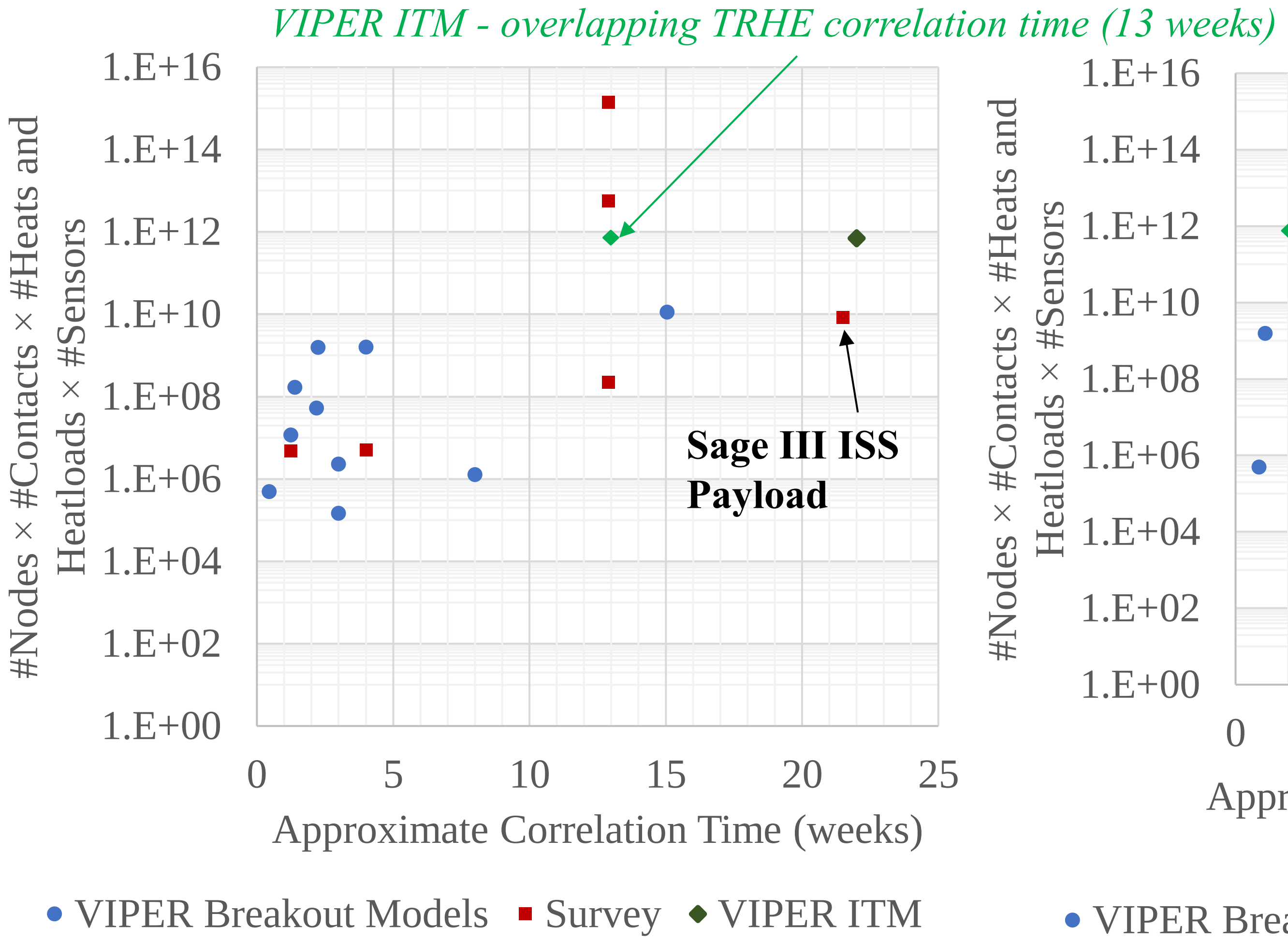
- Model correlation has a reputation for being slow, but how exactly slow is it?
- Polled thermal community for model correlate times and model parameters.
  - 16 responses + 11 VIPER models

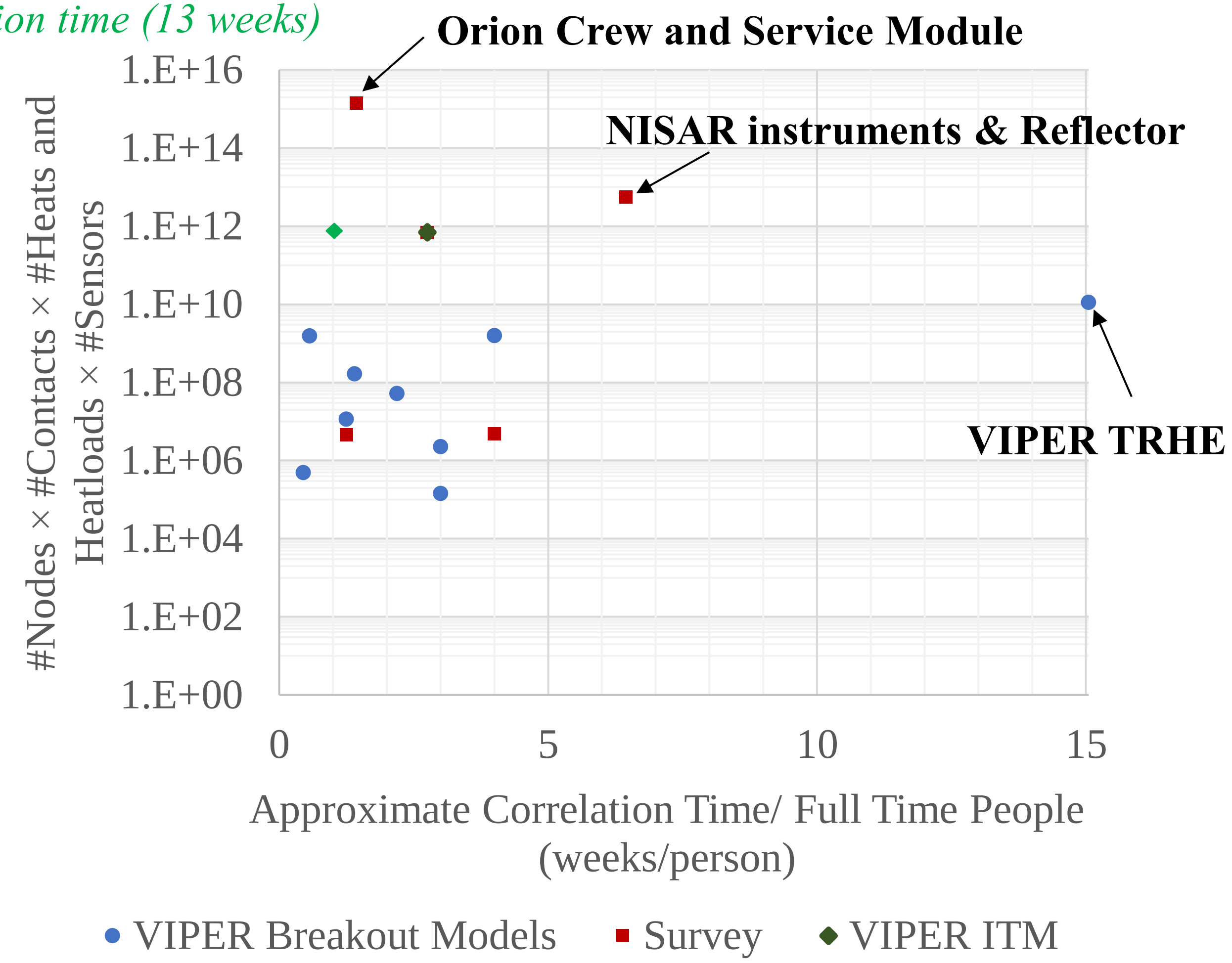
Correlation Time Survey



*JWST core semi-automatic correlation took 2 weeks [Cataldo et al. 2017]

Correlation Time Survey





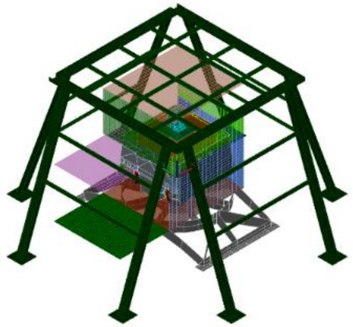
 # Sensors N/A: Europa Clipper, & Mars 2020 Models
 # Conductors N/A: JWST Core

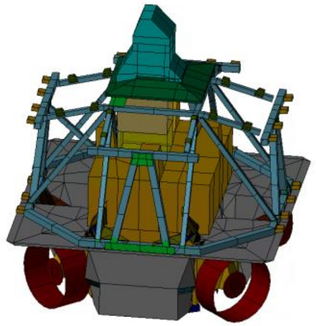
QUESTIONS?

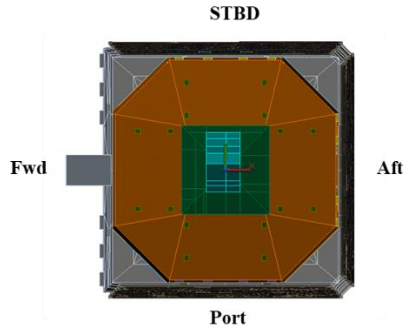
BACKUP

Example breakout models:

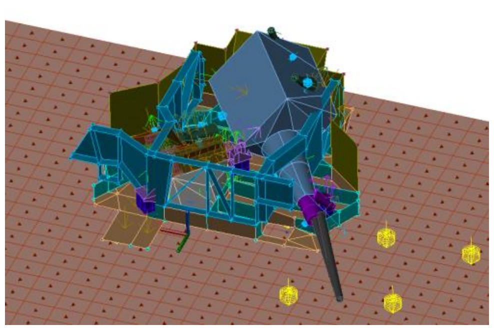
Hazard Cameras and Hazard Lights Breakout Model, inside view (center), top view (right).

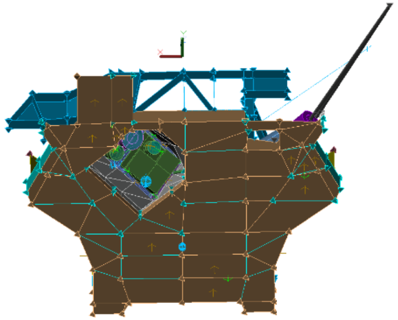




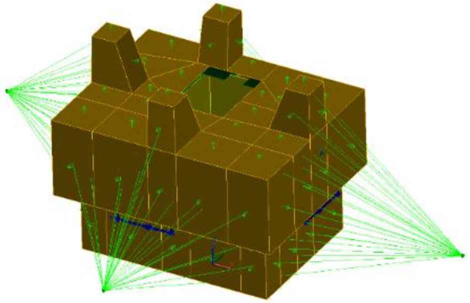


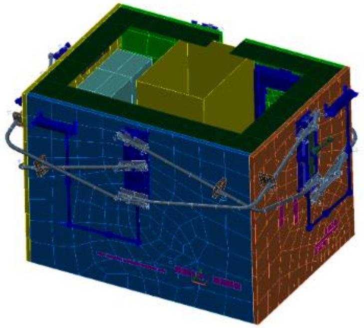
MSOLO and NIRVSS Breakout Model





Warmbox Breakout Model. MLI (left image) surrounds heat spreaders (right image) which are connected by CCHPs (in light blue) and cooled by LHPs (dark blue).





References:

- J. Turk, E. Stewart, T. Page, E. Medichi and J. Otero, "Volatiles Investigating Polar Exploration Rover (VIPER) System Integrated Thermal Vacuum Test," in TFAWS, 2025.
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