Thermal Correlation of Reduced Models Using an Adjoint-Based Solver

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Presented By

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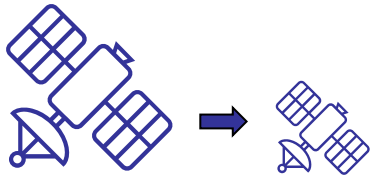
Agenda

- Introduction
- Overview of detailed and reduced models
- Thermal correlation of the reduced model
- Conclusion

Introduction: Why reduced-models?

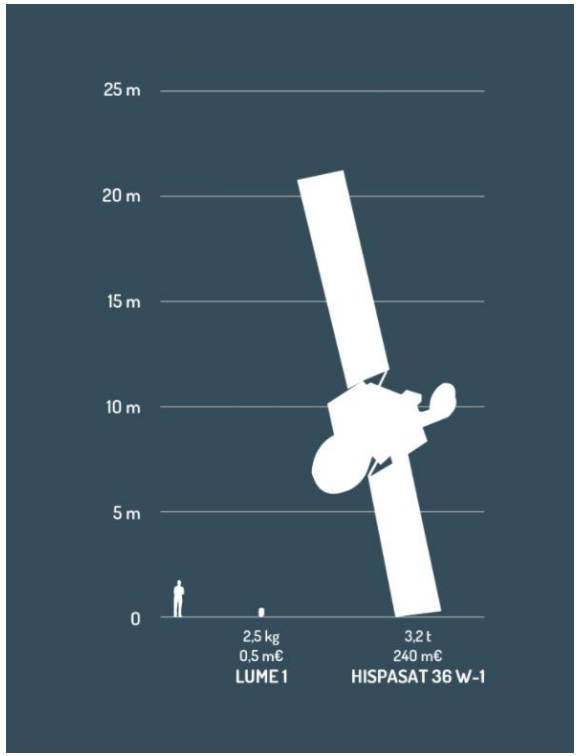
Less expensive satellites in shorter periods of time



Smaller

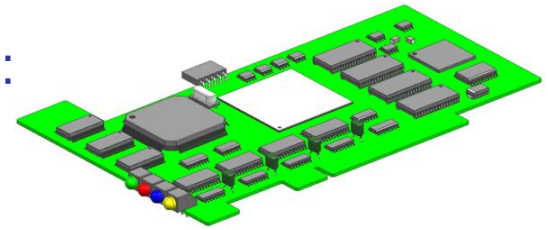
Faster

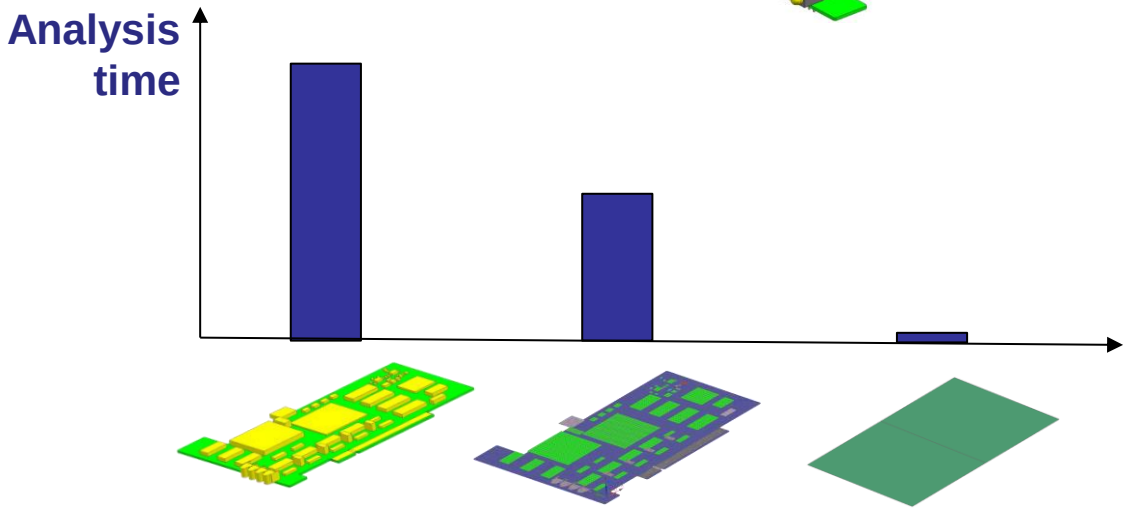
Cheaper



Reduced-models helpful to shorten analysis time

- PCB with components:

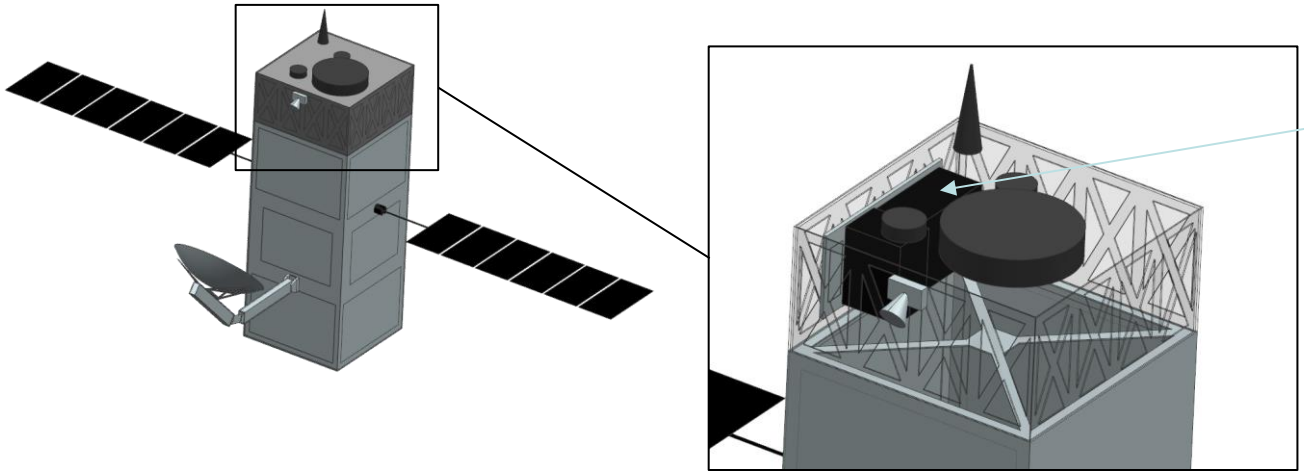


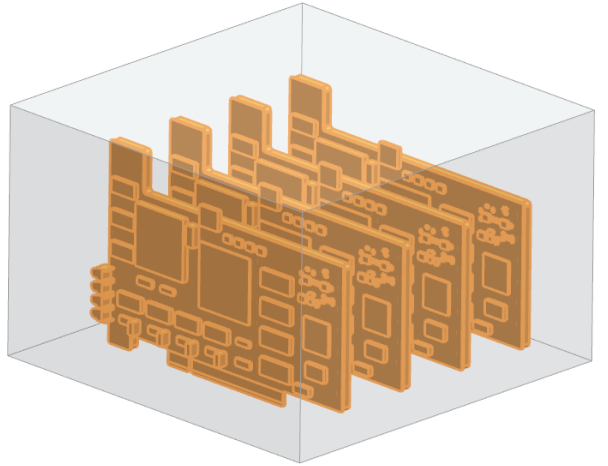


Introduction: Thermal models of electronics boxes

- **Challenges:**
  - Fidelity level of PCB and components thermal models affect the accuracy of temperature predictions for spacecraft electronics boxes
  - Development of reduced-models of electronics boxes require extensive correlation analyses with detailed models

- **In this presentation**: Development of an accurate reduced-model of an electronics box using an adjoint-based thermal correlation solver

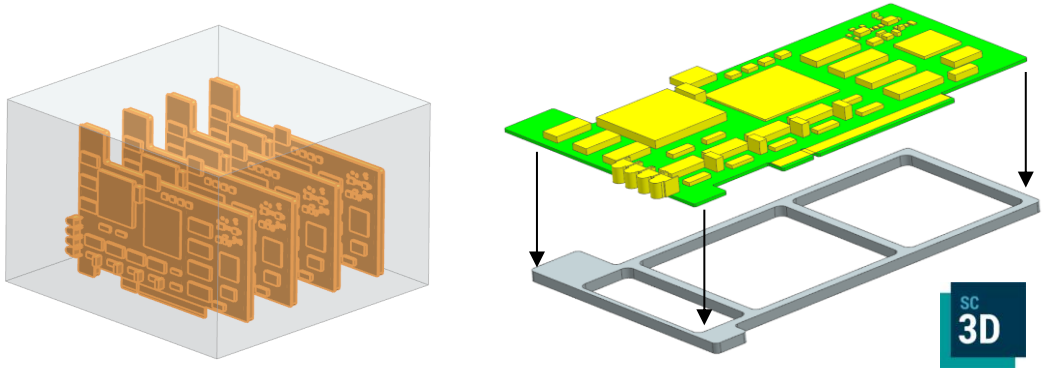




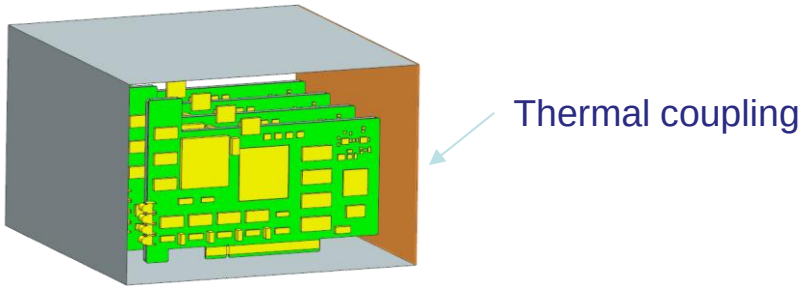
OVERVIEW OF DETAILED AND REDUCED MODELS OF THE ELECTRONICS BOX

Detailed model of the electronics box

- 3D thermal model contains:
  - Four PCBs and components (2 main + 2 backup) mounted on a frame

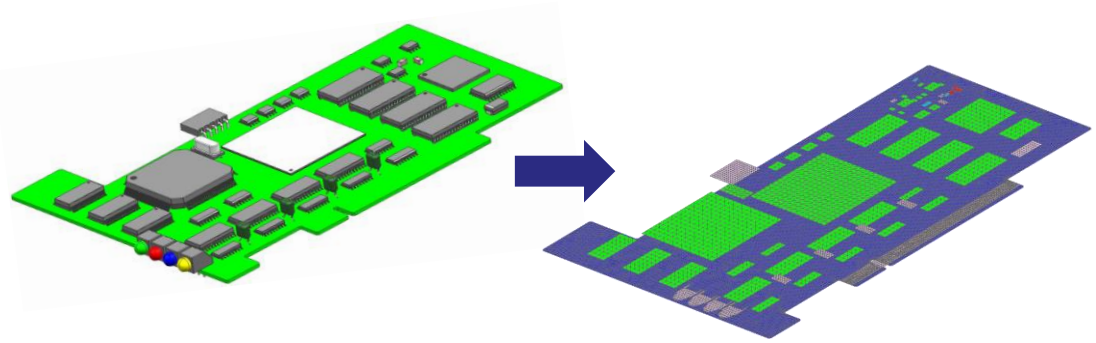


  - The frames are thermally connected to one side of an enclosure

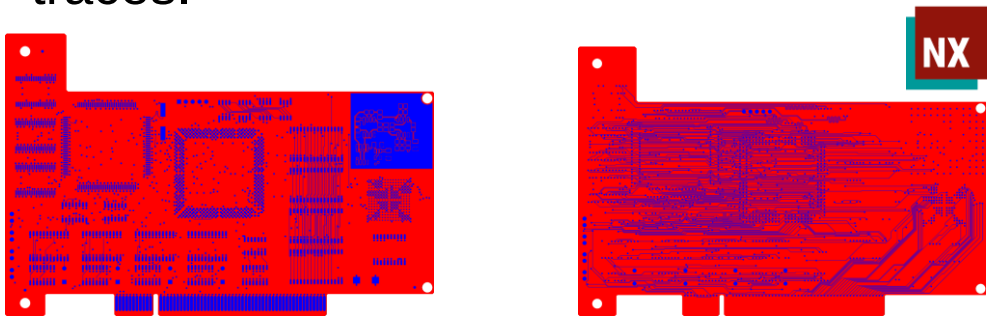


  - 220,000 elements (3D & 2D) in total

- Each PCB involves:
  - 121 components with associated dissipation models and 2D meshes

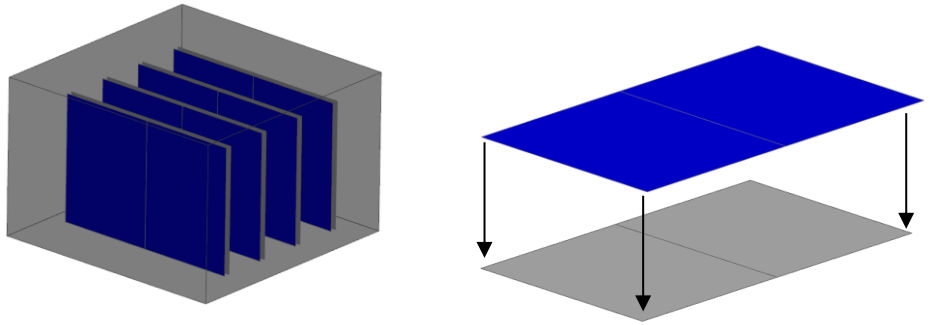


  - 2D fields material properties for each PCB layer to model vias and copper traces.

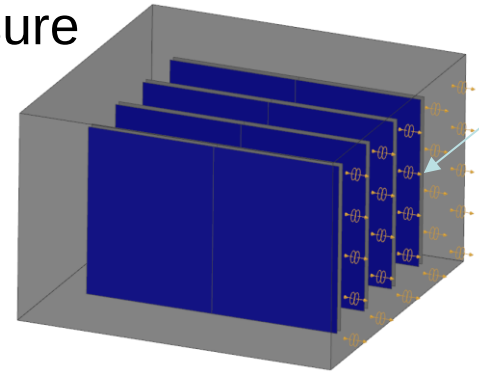


Reduced model of the electronics box

- Electronics box contains:
  - 2 x 2D null shell elements for each PCB and frame

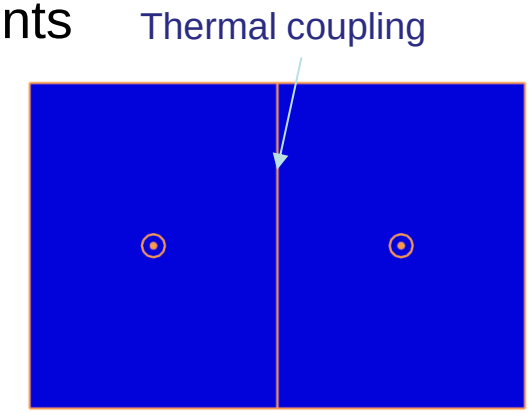


  - The edges of the frame elements are thermally connected to one side of the enclosure

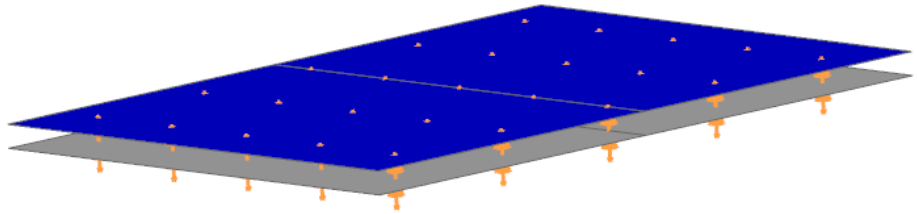


  - 500 elements (2D) in total

- Each PCB & frame involves:
  - One contact between the 2D null shell elements

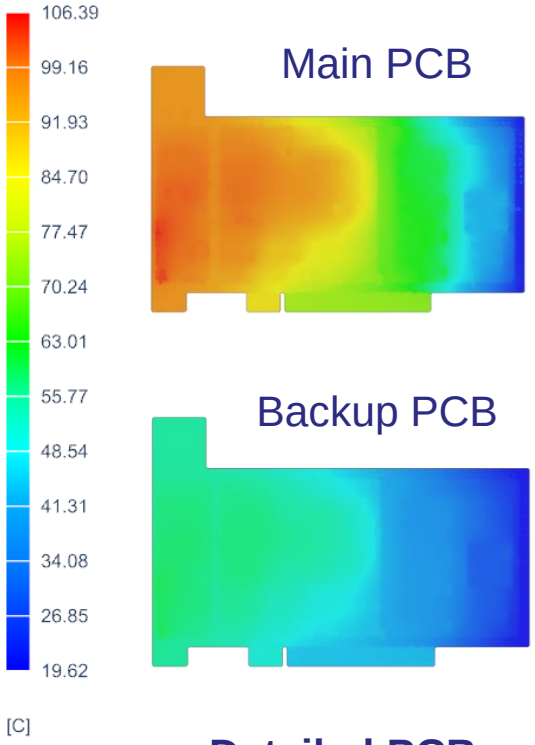


  - One thermal coupling for each PCB-Frame pair

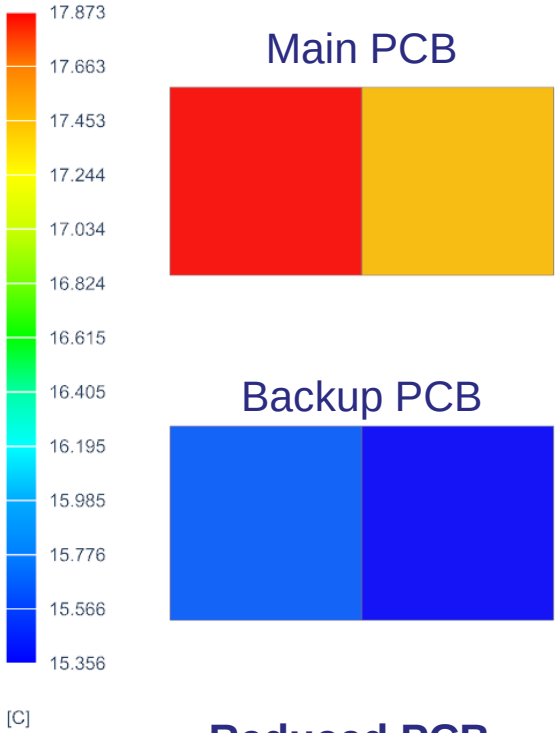


Detailed model vs. Reduced model

- Temperature contours for cold case scenario (Enclosure wall at 15 ℃)



Detailed PCB



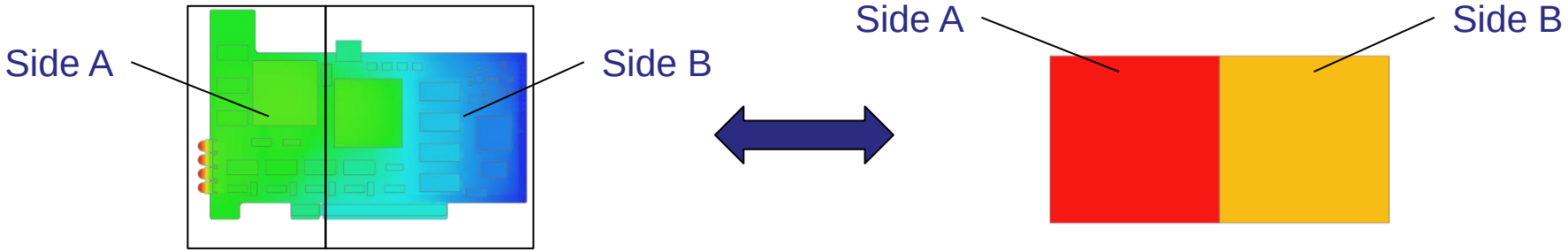
Reduced PCB

Simplification/Reduction requires updating all thermal contacts to match detailed model results

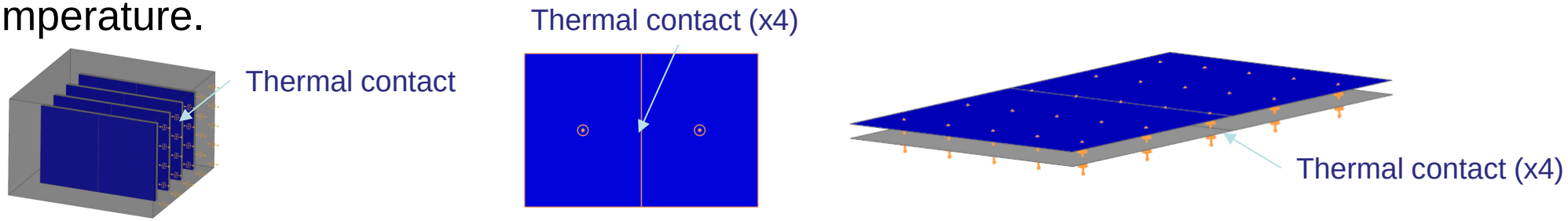
THERMAL CORRELATION

Thermal Correlation objectives

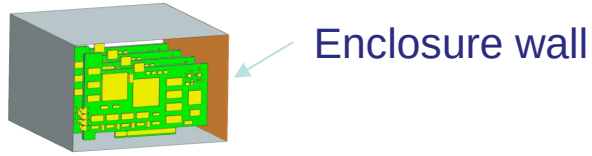
- Objectives:
  1. The temperature of the reduced PCB elements must match the respective averaged temperature on each side of the PCBs



  2. Finding the right thermal contact values for matching the detailed PCB model averaged-temperature.



  3. Thermal contacts of the reduced model must be valid for hot and cold case scenarios
     - Cold case scenario: Enclosure wall @15˚C
     - Hot case scenario: Enclosure wall @55˚C



TMG Correlation: An adjoint-based solver for correlation

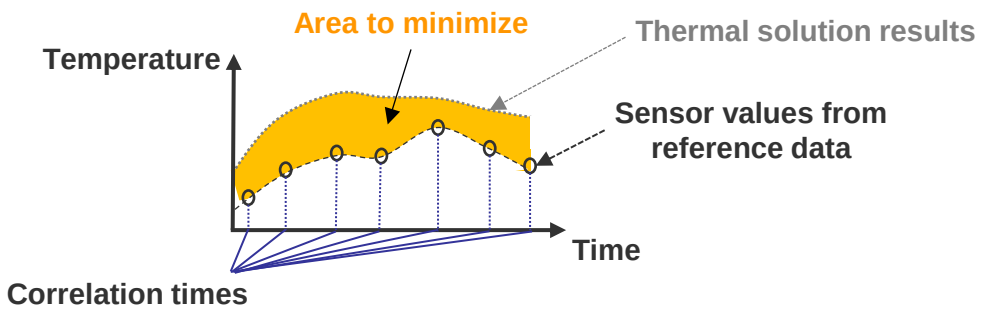
- TMG Correlation is an add-on to Simcenter 3D Space Systems Thermal.

- It combines the adjoint-method and gradient-based optimization algorithms to correlate models by minimizing the following objective function:

$$F = \sqrt{\frac{1}{N_{times} * \sum(W_{target})} \times \sum_{times} \left(\sum_{target} W_{target} \left(T - T_{target}\right)^2 \right)}$$

N_{times}: number of correlation times
$\sum(W_{target})$: Total weight factors defined on the targets
W_{target}: weight factor on the targets (sensors)

- For transient problems, the correlation times define the times at which the model calibration is performed



TMG Correlation: An adjoint-based solver for correlation

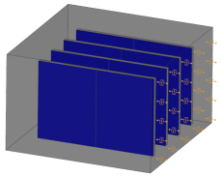
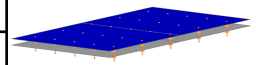
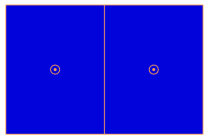
- The adjoint method [1,2] is used to compute the gradients $\vec{G}$ that are passed to an optimization algorithm, which updates the design variables $\vec{h}$ at each design cycle i.
  - Adjoint equation: $\left(\frac{\partial R}{\partial \vec{h}}\right)^T \vec{\psi} = -\frac{\partial F}{\partial T}$
  - Gradient: $\vec{G} = \frac{\partial F}{\partial \vec{h}} + \psi^T \frac{\partial R}{\partial \vec{h}}$
  - Update of the design variables by the optimization algorithm: $\vec{h}^{i+1} = \vec{h}^i - \alpha \vec{G}$

- Why use the adjoint method?
  - Classic gradient computation based on finite differences requires solving $\boldsymbol{N+1}$ times the system for N design variables.
  - Using the adjoint method, we only solve 2 systems: the original system (energy equation) + the adjoint system

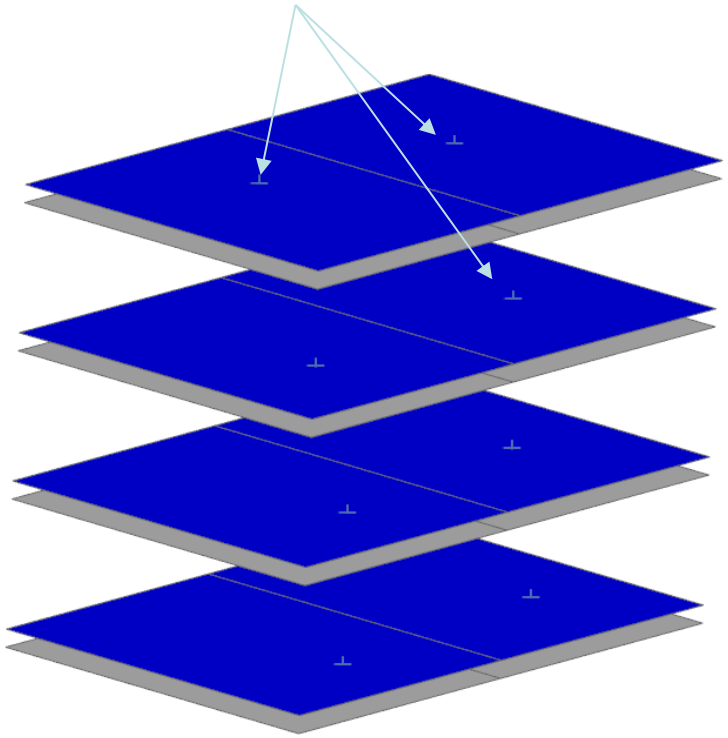
[1] Michaleris, P., Tortorelli, D. A., & Vidal, C. A. (1994). Tangent operators and design sensitivity formulations for transient non-linear coupled problems with applications to elastoplasticity. *International Journal for Numerical Methods in Engineering*, *37*(14), 2471-2499.
[2] Kast, S. M. (2017). An introduction to adjoints and output error estimation in computational fluid dynamics. *arXiv preprint arXiv:1712.00693*.

Thermal Correlation Setup

- Convergence Criterion: 0.01 ℃
- Optimization algorithm: Sequential Least Square Programming

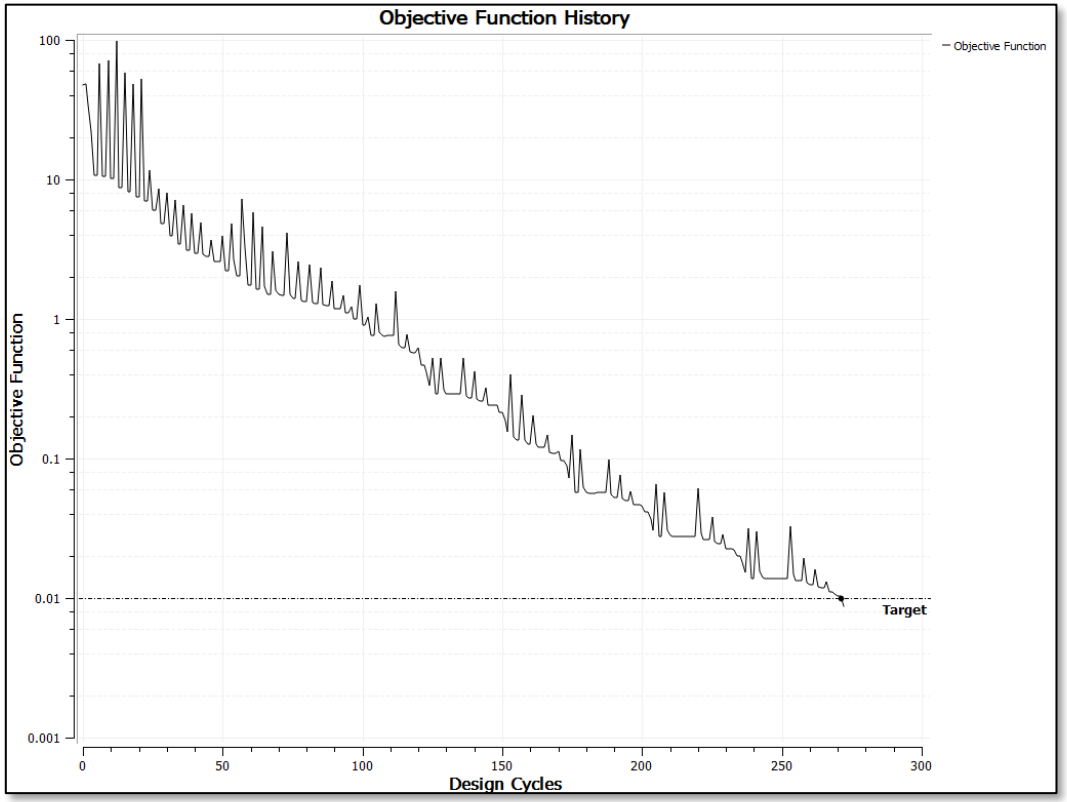
Design Variable	Initial value	Min - Max	Location
Frame_to_Heatsink_Total_Conductance	30 W/C	0.3 – 3000	
Frame_to_PCB_1_Total_Conductance	5 W/C	0.05 – 500	
Frame_to_PCB_2_Total_Conductance	5 W/C	0.05 – 500	
Frame_to_PCB_3_Total_Conductance	5 W/C	0.05 – 500	
Frame_to_PCB_4_Total_Conductance	5 W/C	0.05 – 500	
PCB_1_A_to_B_Total_Conductance	5 W/C	0.05 – 500	
PCB_2_A_to_B_Total_Conductance	5 W/C	0.05 – 500	
PCB_3_A_to_B_Total_Conductance	5 W/C	0.05 – 500	
PCB_4_A_to_B_Total_Conductance	5 W/C	0.05 – 500	

8 targets defined using points

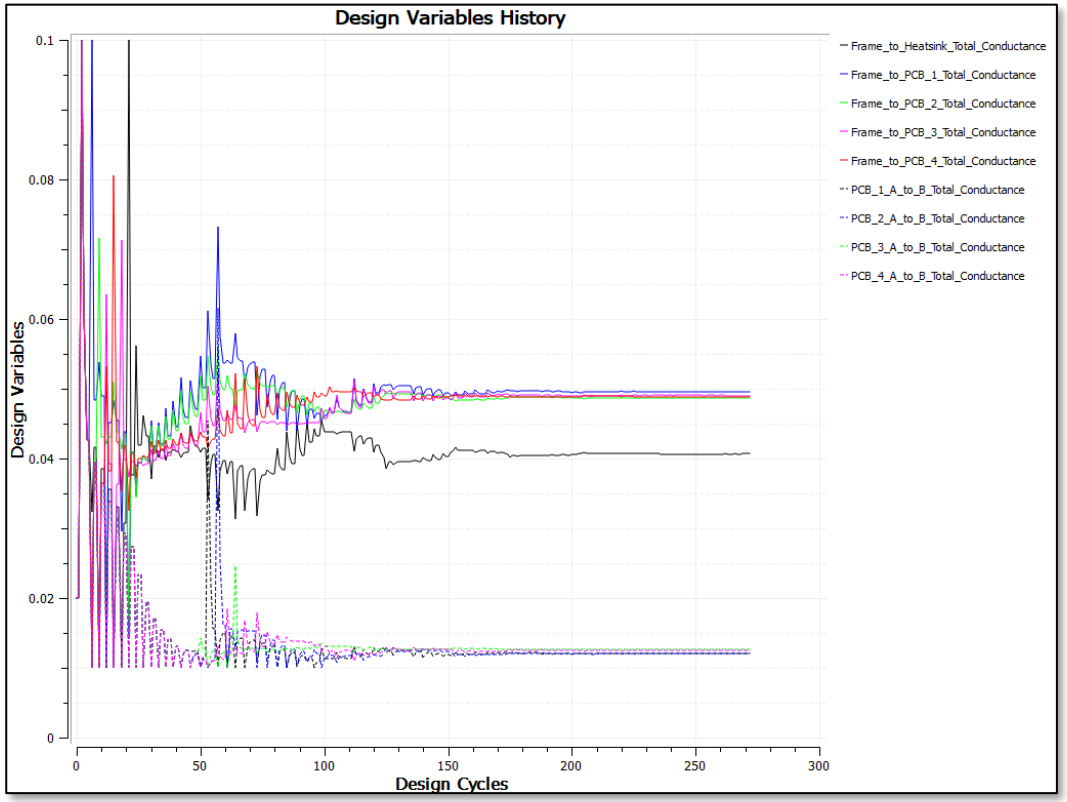


Thermal Correlation Results – Convergence

Correlation run took **11 seconds to converge** under **0.01 ℃** after **272 design cycles**

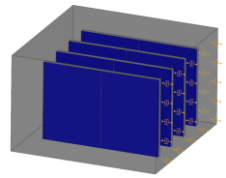
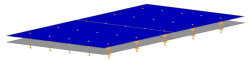
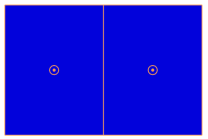


Design variables reached **stable** values



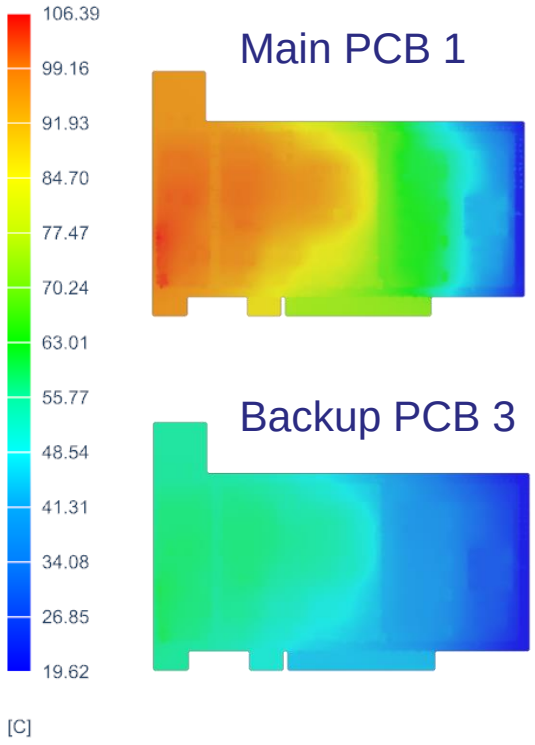
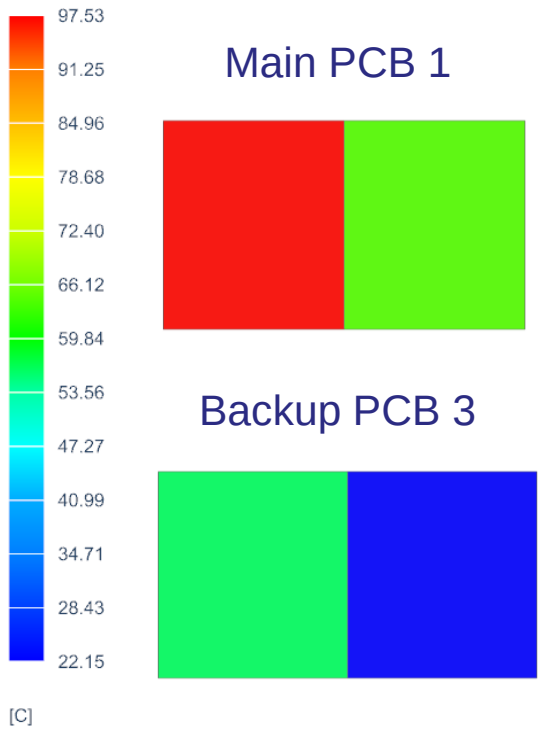
Thermal Correlation Results – Design Variables

- The tool reduced all conductance values to match detailed model results.
- Similar thermal contact implies similar conductance value.

Design Variable	Initial value [W/C]	Final Value [W/C]	Location
Frame_to_Heatsink_Total_Conductance	30	1.221	
Frame_to_PCB_1_Total_Conductance	5	0.247	
Frame_to_PCB_2_Total_Conductance	5	0.243	
Frame_to_PCB_3_Total_Conductance	5	0.245	
Frame_to_PCB_4_Total_Conductance	5	0.244	
PCB_1_A_to_B_Total_Conductance	5	0.060	
PCB_2_A_to_B_Total_Conductance	5	0.060	
PCB_3_A_to_B_Total_Conductance	5	0.063	
PCB_4_A_to_B_Total_Conductance	5	0.062	

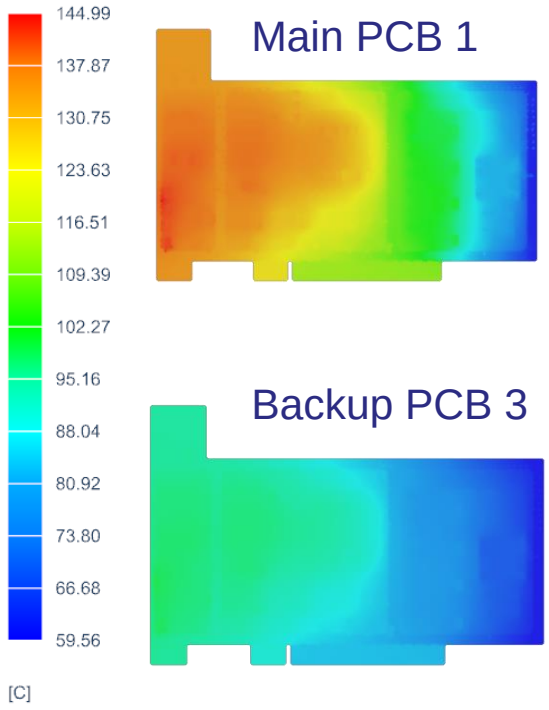
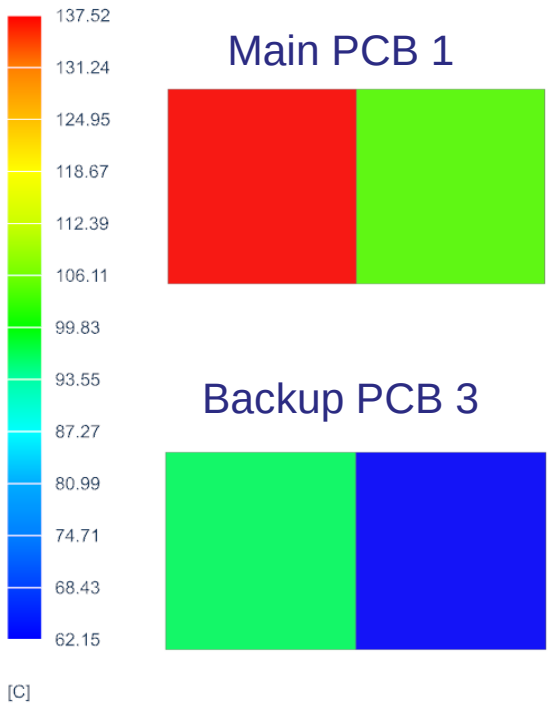
Thermal Correlation Results – Temperatures

- Reduced model results match detailed model averaged temperatures.

Target	Detailed model		Reduced model		Absolute Errors [C]
	Averaged Temperature [C]	Contours for PCB 1 & 3	Temperature [C]	Contours for PCB 1 & 3	
PCB_1_A	64.61		64.63		0.015
PCB_1_B	97.45		97.45		-0.003
PCB_2_A	65.26		65.26		0.001
PCB_2_B	97.53		97.53		-0.003
PCB_3_A	39.77		39.78		0.008
PCB_3_B	56.40		56.40		0.0007
PCB_4_A	39.83		39.83		-0.003
PCB_4_B	56.43		56.45		0.017

Thermal Correlation Results – Cross-validation

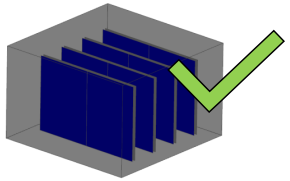
- Reduced model slightly overpredicts temperatures for the hot case scenario

Target	Detailed model		Reduced model		Absolute Errors [C]
	Averaged Temperature [C]	Contours for PCB 1 & 3	Temperature [C]	Contours for PCB 1 & 3	
PCB_1_A	101.91		104.62		2.712
PCB_1_B	136.03		137.45		1.418
PCB_2_A	102.07		105.26		3.188
PCB_2_B	136.27		137.52		1.247
PCB_3_A	78.49		79.78		1.289
PCB_3_B	95.79		96.40		0.614
PCB_4_A	78.53		79.83		1.296
PCB_4_B	95.83		96.45		0.621

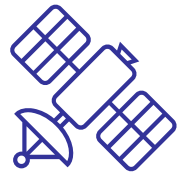
CONCLUSION

Conclusion and Perspectives

- Using **TMG Correlation**, an adjoint-based solver, we successfully correlated the reduced-model of an electronics box
  - Reduced model **predictions are accurate** even on a different operating case
  - The entire **correlation procedure took less than one hour** in total



- The **same approach** can be used for correlating **larger systems** or spacecraft for **steady-state and transient** operation cases.



- The procedure can be enhanced by **automating the generation** of the **reduced model** to **save engineering time**

Thermal Correlation of Reduced Models Using an Adjoint-Based Solver

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For details on TMG Correlation…

https://www.mayahtt.com/products/tmg-correlation/

For More Info about Maya HTT…

www.mayahtt.com

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