Appendix L

Quasi-autonomous spacecraft thermal model reduction

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Abstract

The lumped parameter method is widely used for thermal analysis of spacecraft. Often, the size of these thermal models needs to be reduced. A new method to reduce automatically the number of nodes has been developed. The reduction algorithm treats a processed conductive couplings matrix as a sparse graph adjacency matrix. Then, in order to identify the strongly connected components that define the condensed nodes, a depth-first search algorithm is used. The resulting restriction matrix serves to reduce the thermal entities, such as the conductive and radiative couplings matrices, thermal loads, etc. The method preserves the physical characteristics of the system (physical conductive paths, couplings matrices symmetry, etc.). The reduction process has been tested with a real thermal model (Solar Orbiter PHI instrument focal plane assembly). The results show a good correlation between the detailed and the reduced model, achieving a reduction in the number of nodes of about 75%. The limitations of the method and next steps are also shown.

QUASI-AUTONOMOUS SPACECRAFT THERMAL MODEL REDUCTION

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Thermal model reduction:

- Time consuming
- Error prone
- Lack of standardization

Goal:

- Develop a tool to reduce (almost) automatically the thermal mathematical models (LP models)

Guidelines:

- Preserve physical interpretation of the model
- Respect the physical characteristics of the model
- Inputs: TMD file from ESATAN

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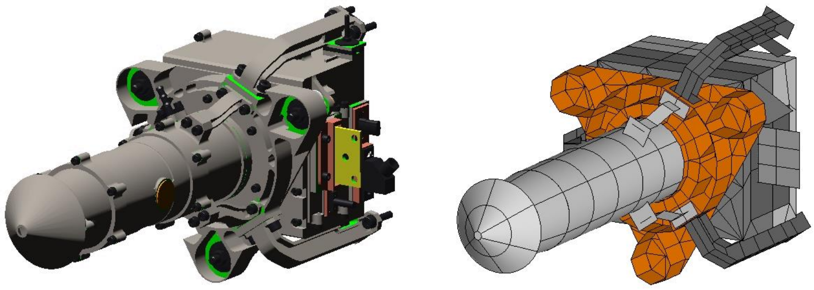
Basics

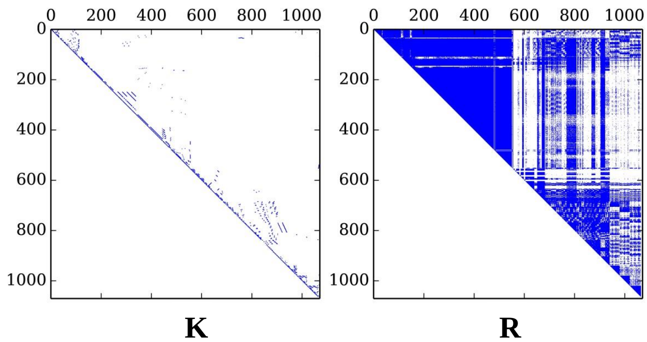
- GMM: reduced manually, although with input from RTMM
- Results correlation: nodal temperatures and heat fluxes through the model boundaries

How?

- Grouping the nodes, using a search algorithm on a processed conductive coupling matrix, which is treated as a sparse graph adjacency matrix
- The adjacency matrix is obtained according to the way in which they are connected to each other:
  - Strong vs. weak conductive couplings
  - Temperature similarity
  - Model boundaries preserved

Case study – Solar Orbiter PHI FPA





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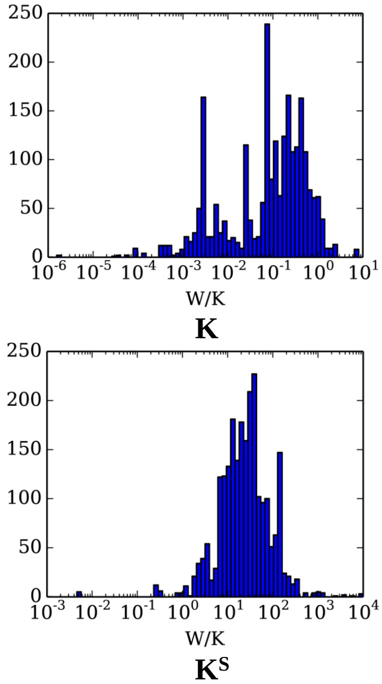
Conductive couplings

- Detailed TMM conductive couplings values can cover a wide range
- Make $\mathbf{K}$ dimensionless with $\mathbf{K}^S$
- Filter dimensionless $\tilde{\mathbf{K}}$ by a threshold (p_f)

$$\tilde{K}_{ij} = \begin{cases} 1 & \tilde{K}_{ij} > p_f \\ 0 & \tilde{K}_{ij} \leq p_f \end{cases}$$



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Temperature similarity

- A matrix $\mathbf{\Theta}$ is set up with the temperature difference between every pair of nodes (nodal temperatures are an input for the given thermal case)
- Filter matrix $\mathbf{\Theta}$ by temperature difference threshold ΔT_{max}

$$\Theta_{ij} = \begin{cases} 0 & \Theta_{ij} > \Delta T_{max} \\ 1 & \Theta_{ij} \leq \Delta T_{max} \end{cases}$$

Model boundaries

- To improve the correlation of the results, the boundary nodes are preserved (isolated) in the reduced thermal model
- Also the nodes to which are coupled the boundary nodes are kept independent from the rest of the model

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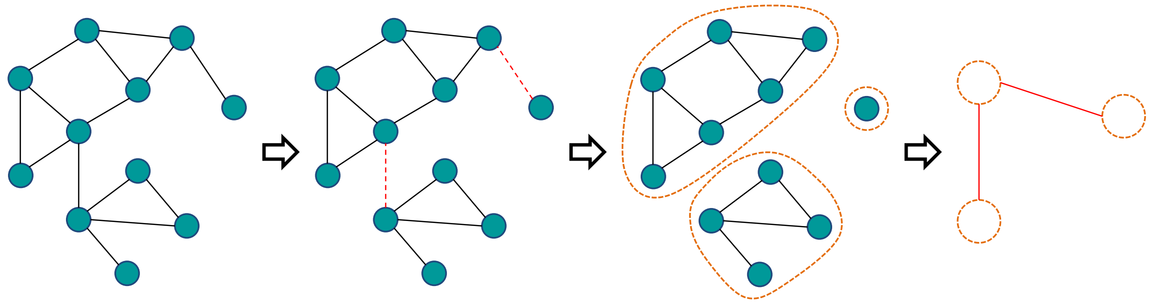
Connected components algorithm

- The algorithm finds the nodes that are connected to each other, and put them into groups
- The relation between the detailed and the reduced thermal model total number of nodes is called reduction ratio, r_r $\left(r_r = 1 - \frac{n_c - n_b}{n_d - n_b}\right)$



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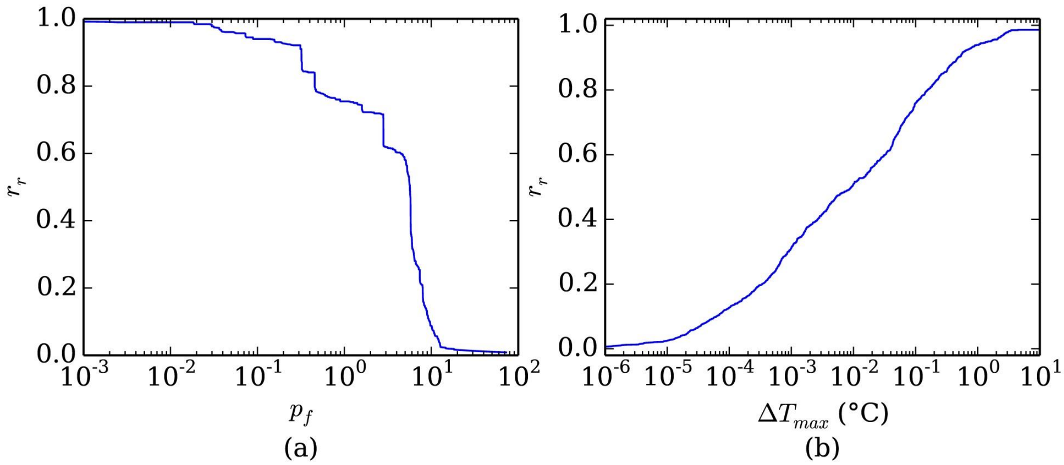
Variation of r_r with p_f and ΔT_{max}



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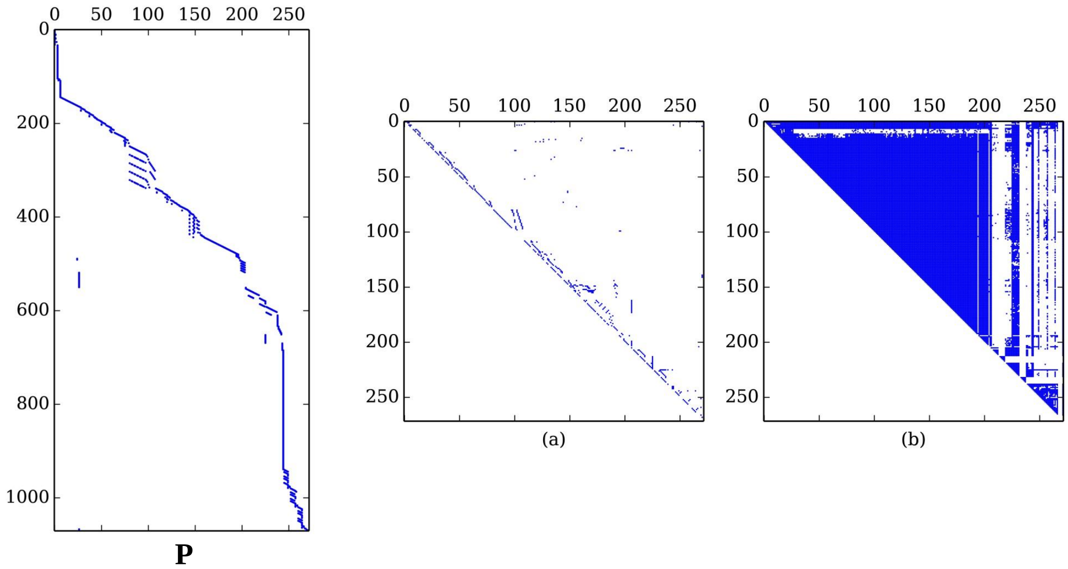
Model reduction

Reduction of matrices (**K, R**) and vectors (**Q, C, T**)



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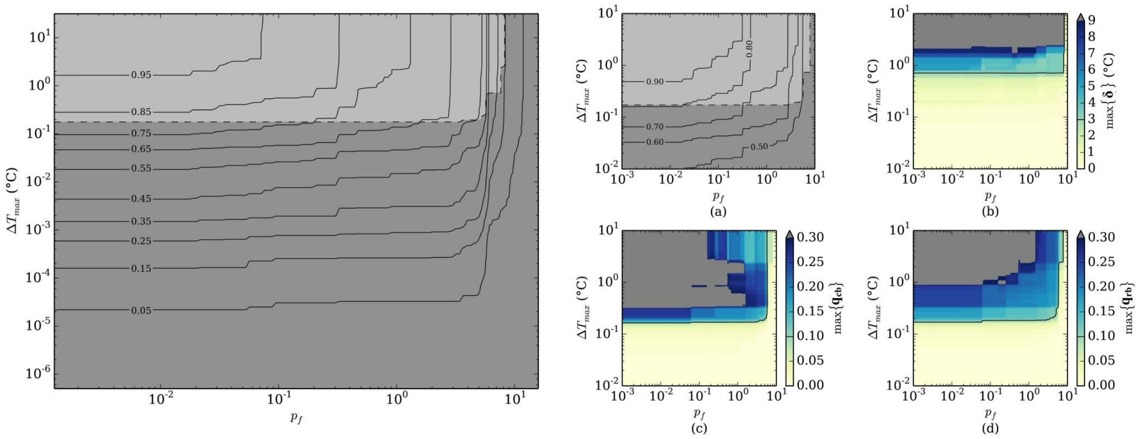
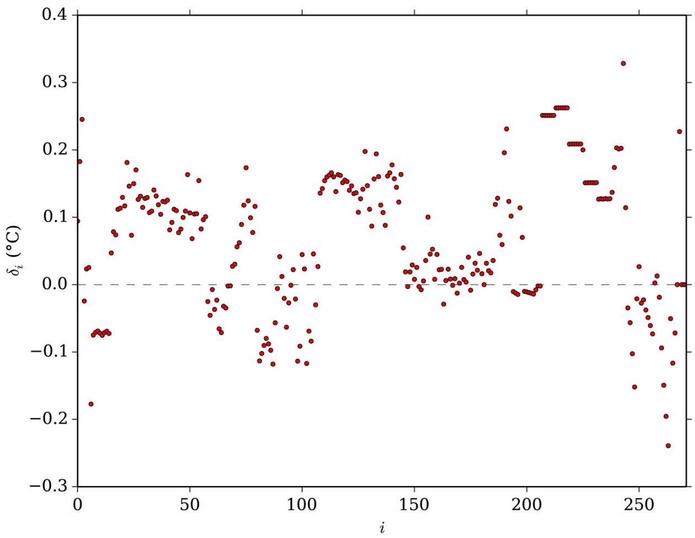
Contour plot of the function $r_r = f(p_f, \Delta T_{max})$



Results

Maximum heat flux difference around 5%



Final remarks

- Focus on internally mounted space scientific instrument thermal models
- Preservation of all the physical characteristics of the detailed model
- Maximum reduction ratio (r_r) ~ 90%
- Only for steady-state conditions
- Correlation only with one thermal case
- GMM reduction

Thanks!

Any questions?

More info: G. Fernández-Rico et al., Quasi-autonomous thermal model reduction for steady-state problems in space systems, Appl. Therm. Eng. (2016), http://dx.doi.org/10.1016/j.applthermaleng.2016.03.017

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