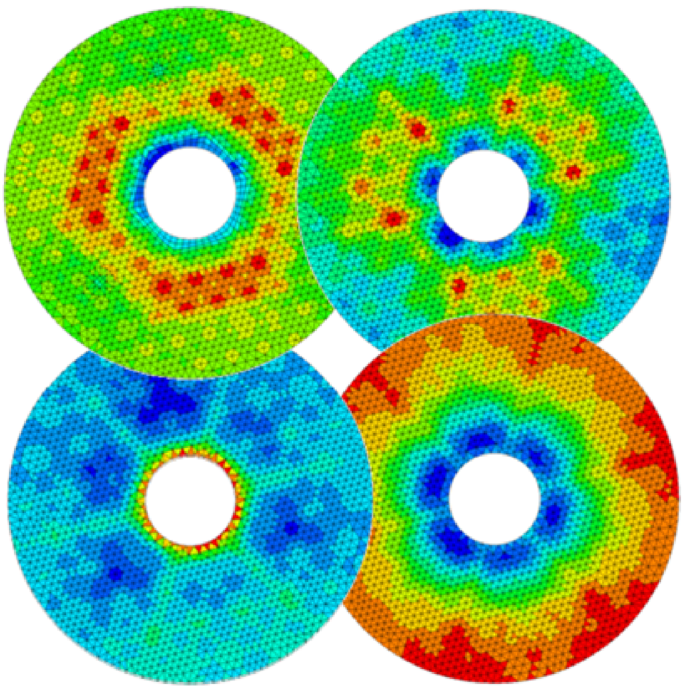
ESA-WPP-343
December 2014

Proceedings of the

28th European Space Thermal Analysis Workshop

ESA/ESTEC, Noordwijk, The Netherlands

14–15 October 2014



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European Space Agency
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Abstract

This document contains the presentations of the 28th European Space Thermal Analysis Workshop held at ESA/ESTEC, Noordwijk, The Netherlands on 14–15 October 2014. The final schedule for the Workshop can be found after the table of contents. The list of participants appears as the final appendix. The other appendices consist of copies of the viewgraphs used in each presentation and any related documents.
Proceedings of previous workshops can be found at http://www.esa.int/TEC/Thermal_control under 'Workshops'.

Please note that this document contains clickable hyperlinks which are shown as blue text.

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Appendices

Programme Day 1

9:00 Registration

9:45 **Welcome and introduction**
Harrie Rooijackers (ESA/ESTEC, The Netherlands)

10:00 **Definition of Experimental Based Thermal Parameters for a Standard Thermal Architecture of Electronic Boards and Units based on modular concept and relevant Thermal Mathematical Model Validation**
Andrea Zamboni (Selex ES, Italy)

10:25 **LISA pathfinder Inertial Sensor Head thermal analysis in frequency domain**
Paolo Ruzza (CGS S.p.A., Italy)

10:50 **Fluid-selection tool**
Henk Jan van Gerner (NLR, The Netherlands)

11:15 Coffee break in the Foyer

11:45 **Development of a thermal control system for South Africa's next generation Earth observation satellite**
Daniël van der Merwe (DENEL Spaceteq, South Africa)

12:10 **GENETIK** — Optimisation tool for thermal analyses performed with SYSTEMA
Hélène Pasquier & Guillaume Mas (CNES, France)

12:35 **An overview of CHEOPS Instrument thermal design and analysis**
Romain Peyrou-Lauga (ESA, The Netherlands)
Giordano Bruno (University of Bern, Switzerland)

13:00 Lunch in the ESTEC Restaurant

14:00 **PEASSS** — New horizons for cubesat missions
Luca Celotti & Riccardo Nadalini (Active Space Technologies GmbH, Germany)

14:25 **TMRT Module Software** — Use on an Industrial Application
Michèle Ferrier & David Valentini (Thales Alenia Space, France)

14:50 **Thermal issues related to ExoMars EDLS performance**
Emilie Boulier & Grégory Pinaud & Patrick Bugnon (Airbus Defence & Space, France)

15:15 **A personal look back on Thermal Software evolution within the past 36 years**
Harold Rathjen (HRC, Germany)

15:45 Coffee break in the Foyer

16:15 **General-purpose GPU Radiative Solver**
Andrea Tosetto & Marco Giardino & Matteo Gorlani (Blue Engineering & Design, Italy)

16:40 **Insight HP3** — Thermal Modelling with Thermal Desktop
Asli Gencosmanoglu & Luca Celotti & Riccardo Nadalini (Active Space Technologies GmbH, Germany)

17:05 **Analysis Strategies For Missions Involving Comprehensive Thermal Issues**
Nicolas Liquière (EPSILON, France)

17:30 Social Gathering in the Foyer

19:30 Dinner in *Iets Anders*

Programme Day 2

9:00 **Assessment of stochastic methods for the thermal design of a telecom satellite**
Nicolas Donadey (AKKA Technology, France)
Jean-Paul Dudon & Patrick Connil & Patrick Hugonnot (Thales, France)

9:25 **Development of an automated thermal model correlation tool**
Martin Trinoga (Airbus Defence and Space, Germany)

9:50 **On using quasi Newton algorithms of the Broyden class for model-to-test correlation**
Jan Klement (Tesat-Spacecom GmbH & Co. KG, Germany)

10:15 **SYSTEMA – THERMICA 4.7.0 & THERMICALC 4.7.0**
Timothée Soriano & Rose Nerriere (Astrium SAS, France)

11:00 Coffee break in the Foyer

11:25 **ESATAN Thermal Modelling Suite** — Product Developments and Demonstration
Chris Kirtley & Nicolas Bures (ITP Engines UK Ltd, United Kingdom)

12:10 **Tests of solids implementation in ESATAN TMS R6**
Olivier Frapsauce & Dominique Fraioli (Airbus DS Les Mureaux, France)

12:35 **Finite element model reduction for the determination of accurate conductive links and application to MTG IRS BTA**
Lionel Jacques
(Space Structures and Systems Laboratory, University of Liège & Centre Spatial de Liège, Belgium)
Luc Masset (Space Structures and Systems Laboratory, University of Liège, Belgium)
Tanguy Thibert & Pierre Jamotton & Coraline Dalibot (Centre Spatial de Liège, Belgium)
Gaetan Kerschen (Space Structures and Systems Laboratory, University of Liège, Belgium)

13:00 Closure

13:00 Lunch in the ESTEC Restaurant

Appendix A

Welcome and introduction

Harrie Rooijackers
(ESA/ESTEC, The Netherlands)

Workshop objectives

- To promote the exchange of views and experiences amongst the users of European thermal engineering analysis tools and related methodologies
- To provide a forum for contact between end users and software developers
- To present developments on thermal engineering analysis tools and to solicit feedback
- To present new methodologies, standardisation activities, etc.

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ESA Team

Benoit Laine Head of Section
James Etchells
Duncan Gibson
Harrie Rooijackers

Workshop organised by the Thermal Analysis and Verification Section TEC-MTV with help from the ESA Conference Bureau

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Programme

- Two-day programme
- Presentations of 25 min, including 5 minutes for questions and discussions
- Presenters:
  If not done already please leave your presentation (PowerPoint or Impress and PDF file) with Harrie before the end of Workshop.
- No copyrights, please!
- Workshop Proceedings will be supplied to participants afterwards, on the Web.

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Practical information

esa

- Lunch: 13:00 - 14:00
- Cocktail today around 17:30 in the Foyer
- Check your details on the list of participants and inform the Conference Bureau of any modifications.
  Leave your email address!
- Taxi service and Shuttle service to Schiphol Airport
  contact ESTEC Reception ☎ ext. 54000, ESTEC.Reception@esa.int
  or Taxi Brouwer ☎ +31(0)71 361 1000, info@brouwers-tours.nl
- Optional workshop dinner tonight!

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Workshop dinner

esa

- in “Iets Anders", Pickeplein 4,
  2202 CK Noordwijk, ☎ +31(0)71 8888 6111
- fixed menu with choice of main course (fish, meat or vegetarian) for €29,50 excl. 1 drink
  additional drinks are charged individually.
- Restaurant booked today for 19:30
- Please arrange your own transport
- "Dutch" dinner == to be paid by yourself
- If you would like to join, then fill in the form on the last page of your hand-outs and drop it at the registration desk today **before 13:00**, to let the restaurant know what to expect

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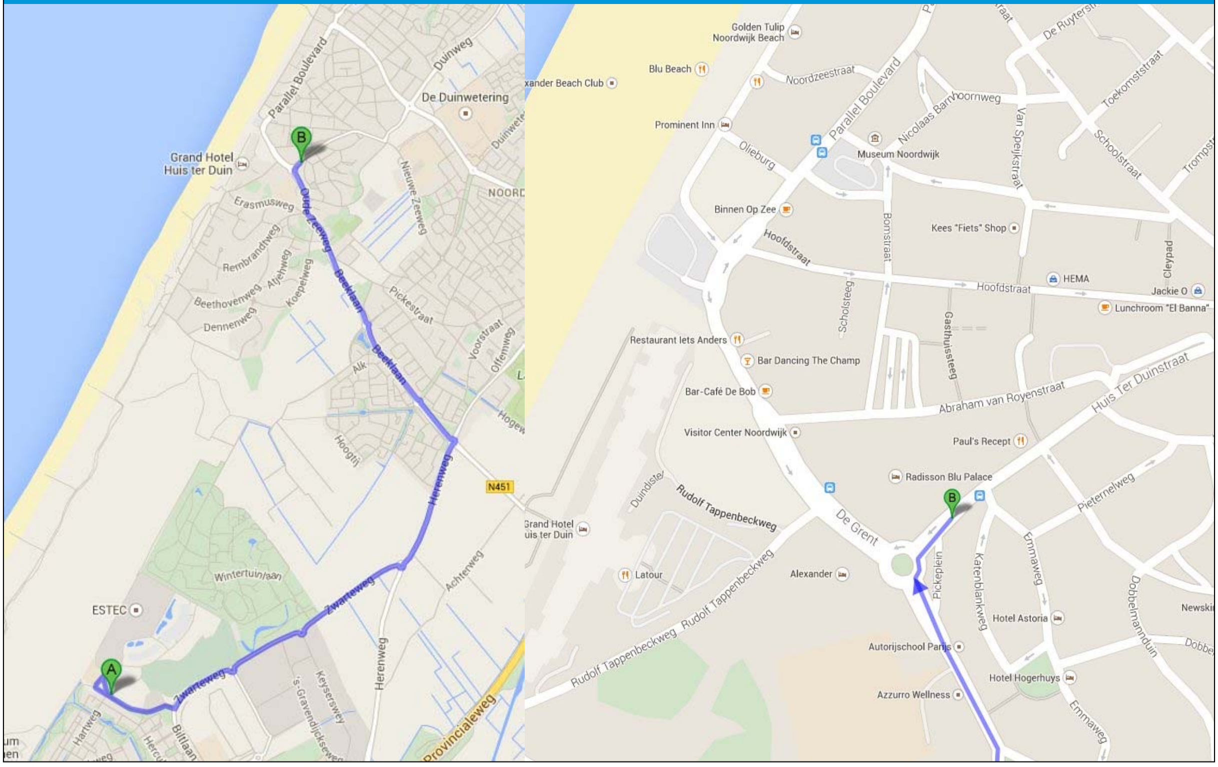
Restaurant “Iets Anders”



Menu (€ 29,50 p.p. excluding 1 drink)

Carpaccio with grated Parmesan, marinated tomatoes and rocket dressing
or
Goat cheese salad with sweet vinaigrette
or
Home-made lobster bisque with cognac and semi wipped cream
~~~~~~~~~~~~

Grilled salmon steak with remoulade sauce
or
Vegetarian pasta with grilled vegetables
or
Duo of beef tenderloin and slowly cooked brisket with Madeira sauce
~~~~~~~~~~~~

Crêpes Suzette, with orange sauce, Grand Marnier and vanilla ice cream
or
Dame Blance, Vanilla Ice Cream & Chocolate

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ICES

- The 45th International Conference on Environmental Systems (ICES) will be held 12-16 July, 2015, Bellevue, Washington, USA.
- Deadline for submitting abstracts: 3 November, 2014
- Abstracts must include paper title, author(s) name(s), mailing and e-mail addresses, phone and fax numbers
- Abstracts may be submitted online at www.depts.ttu.edu/ceweb/ices

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Workshop

Next year: 29th workshop, 3-4 November 2015

Current workshop:

20 very interesting presentations covering:

- Range of general applications
- New tools
- Existing thermal tools
  - Enhancements
  - Applications
  - User experiences

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Workshop
esa
Listen, Ask, Discuss
most of all: Enjoy
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28th European Space Thermal Analysis Workshop
11/11

Appendix B

Definition of Experimental Based Thermal Parameters for a Standard Thermal Architecture of Electronic Boards and Units based on modular concept and relevant Thermal Mathematical Model Validation

Andrea Zamboni
(Selex ES, Italy)

Abstract

The thermal design and development of Spacecraft, Sub-Systems or Equipments involve the establishment of a Thermal Mathematical Model (TMM), which shall be validated and calibrated by means of dedicated Thermal Survey test campaign; the thermal model calibration is then foreseen when the first representative hardware is available and typically this occurs in a project phase where the thermal design reached a certain maturity and some changes, if any, may have not negligible impact in term of schedule and cost. On the other hand, the space market is pushing for reducing schedule and typically the experimental activities verification is to be substituted with analysis whenever feasible. Defining standard thermal solution according to "re-use" and "modularity" philosophy will reduce the experimental activities and relevant risks and improve reliability of thermal prediction.
With the aid of Thermal Concept Design Tool (TCDT) and ESATAN, thermal analyses and relevant dedicated experimental test campaign have been carried out on a Standard PCB Assembly, designed for a modular concept Electronic Unit architecture
The main results obtained where

- Calibration of analysis parameter as contact resistance and PCB conductance with the aid of dedicated thermal vacuum test
- Definition of a standard PCB layout and architecture
- Issue of a (reduced) thermal model to be used for what-if analysis and for reference for future projects
- Definition of experimental based standard parameters for Thermal Mathematical Model at Board Assembly and Equipment level, reducing the effort of dedicated thermal survey and improving reliability

Selex ES

Introduction

The thermal design and development of Spacecraft, Sub-Systems or Equipments require the set-up of a **Thermal Mathematical Model (TMM),** which shall be **validated and calibrated** by means of dedicated Thermal Survey **test campaign**;

the thermal model calibration is then foreseen when the first **representative hardware is available**

- In that project phase **thermal design reached a certain maturity**: any **changes may have not negligible impact** in term of schedule and cost.
- the space market is pushing for reducing schedule & cost: the **experimental activities verification** is going to be substituted with **analysis whenever feasible**.
- Defining standard thermal solution according to “re-use” and “modularity” philosophy will reduce the experimental activities and relevant risks and improve reliability of thermal prediction.

Standard Thermal Architecture → «Standard» Thermal Mathematical Model

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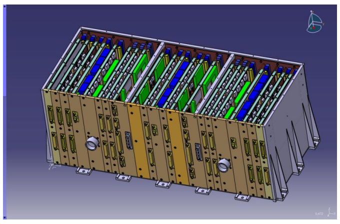
Modular Concept based Standard Unit Architecture-1

Brief overlook to the Selex ES Modularity Concept based Standard architecture for electronic equipment



Guideline

- *Modular based Architecture*
- *Standard layout of PCB modulus according to typical Program requirements*
- *Experience acquired on previous project*

Aim:

- *Standardisation*
- *PCB Modulus design re-use*
- *Modulus Assembling / disassembling optimisation*

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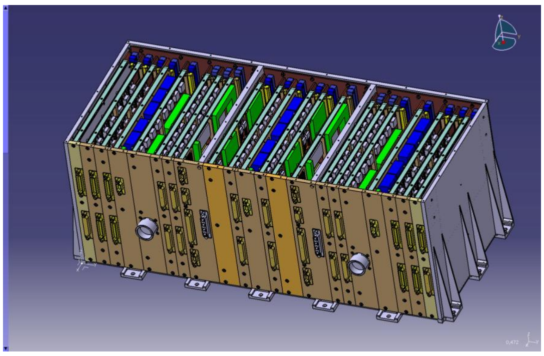
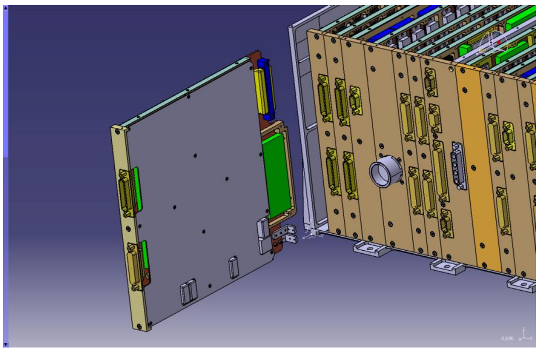
Modular Concept based Standard Unit Architecture-2

Brief overlook to the Selex ES Modularity Concept based Standard architecture for electronic equipment





Modular Architecture: The unit is assembled with Standard PCB Modulus design: the unit «connector wall» consist of the different PCB modulus front supports

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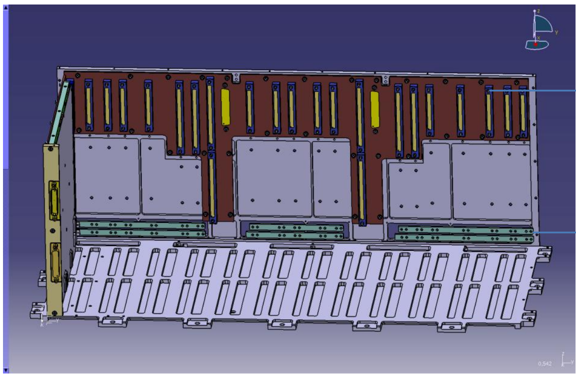
Modular Concept based Standard Unit Architecture-3

Brief overlook to the Selex ES Modularity Concept based Standard architecture for electronic equipment



Standard Mother Board Designs

Standard Power bars provision

Modular Architecture: Standard Mother Board Designs, with different configurations according to connectors layout

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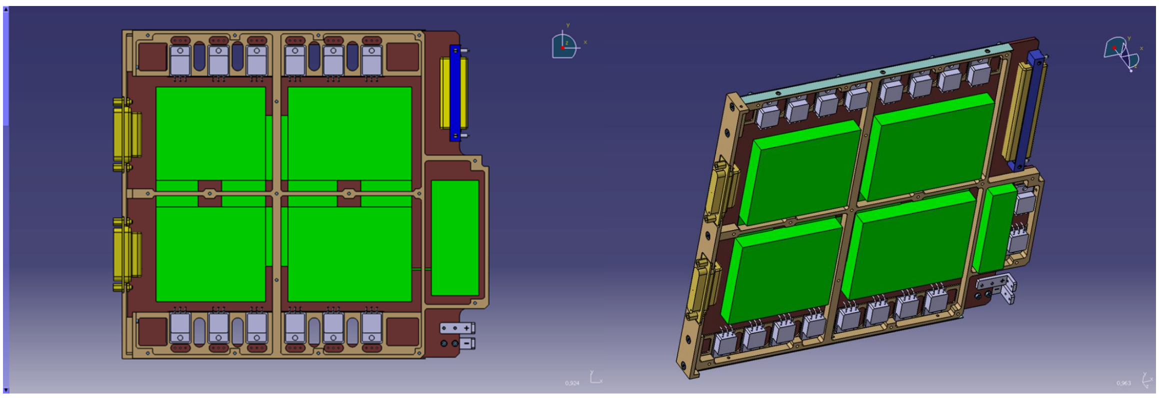
Standard Thermal Design of PCB Modulus

Standard PCB layout, according to the different Modulus functions : DC/DC converter is showed as example



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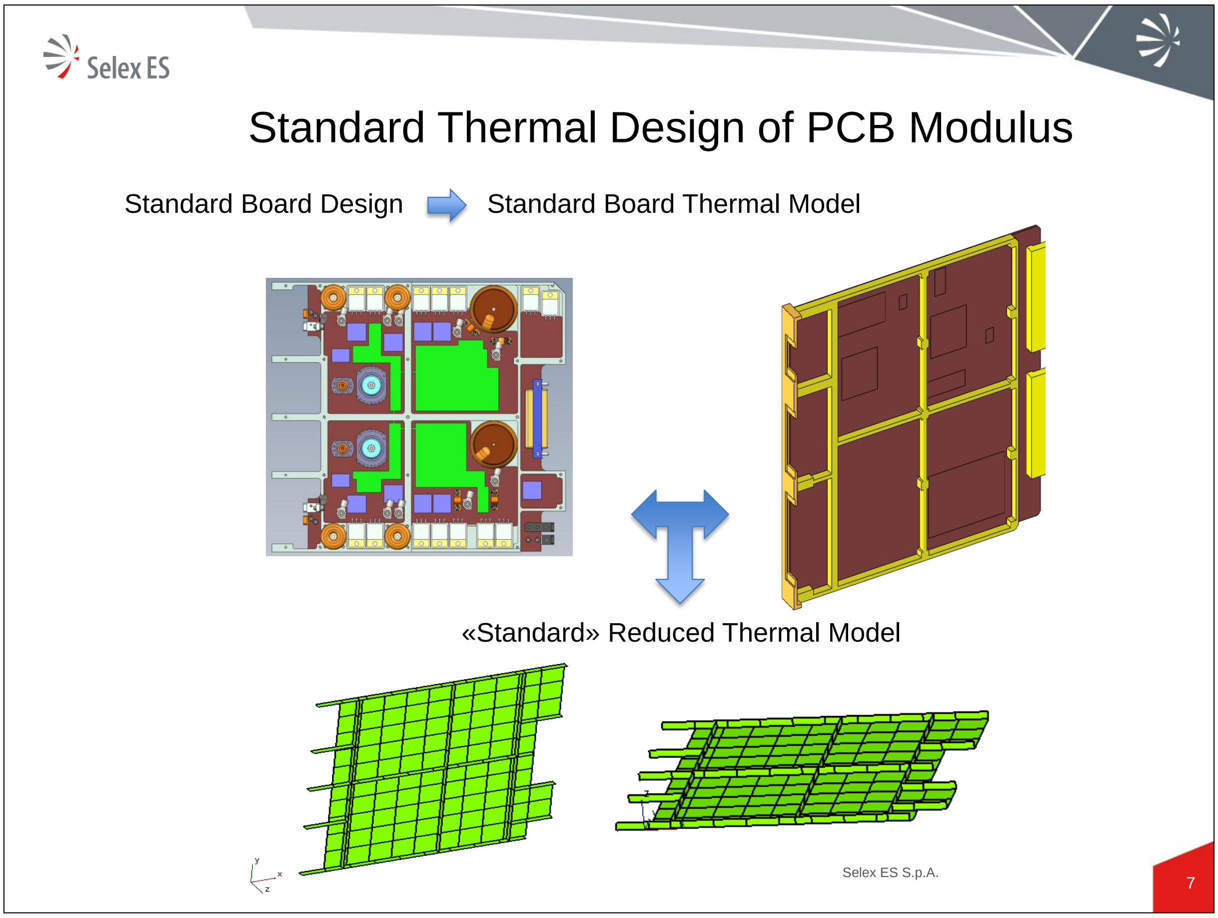
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Standard Thermal Design of PCB Modulus
Standard Board Design
Standard Board Thermal Model
«Standard» Reduced Thermal Model
Selex ES S.p.A.
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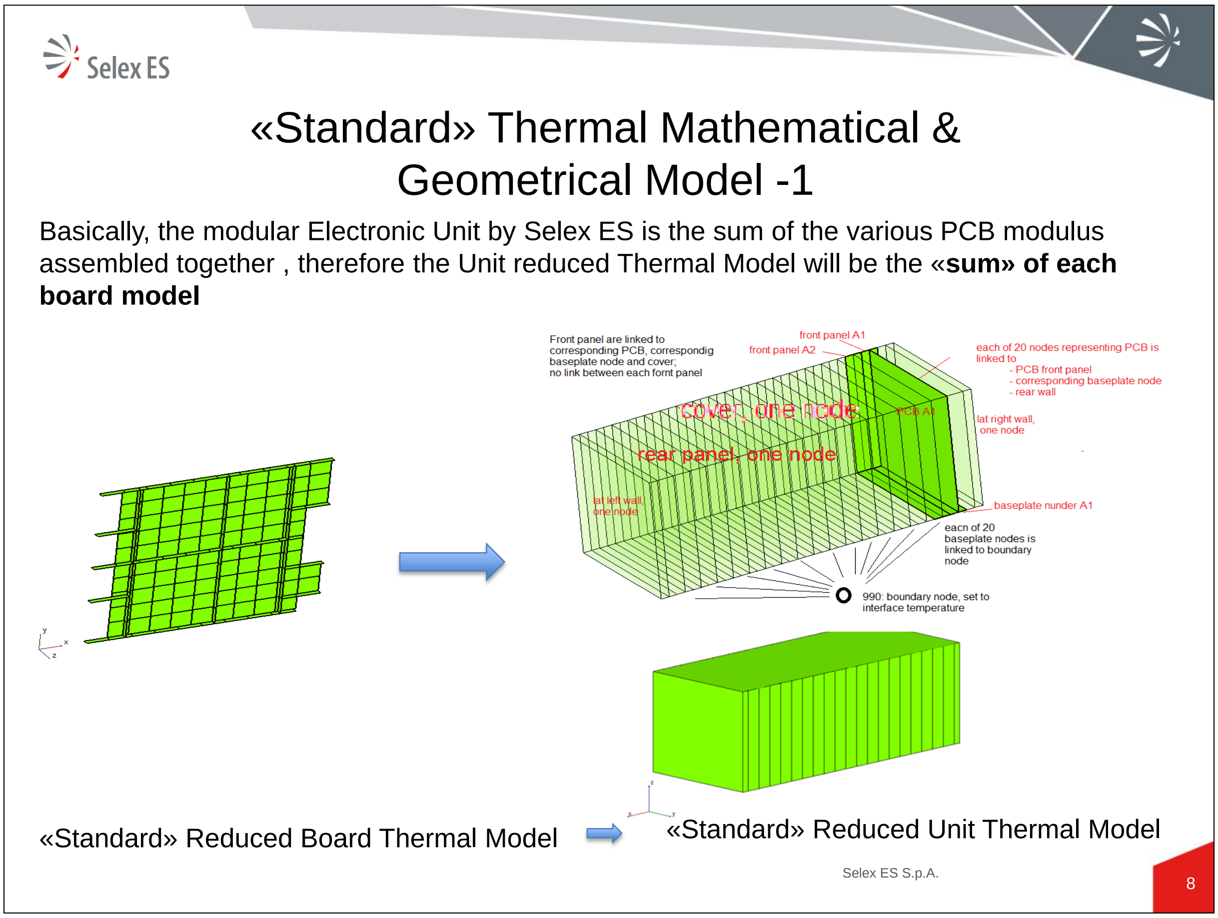
Selex ES
«Standard» Thermal Mathematical & Geometrical Model -1
Basically, the modular Electronic Unit by Selex ES is the sum of the various PCB modulus assembled together , therefore the Unit reduced Thermal Model will be the «sum» of each board model
Front panel are linked to corresponding PCB, correspondig baseplate node and cover; no link between each fornt panel
front panel A1
front panel A2
each of 20 nodes representing PCB is linked to
- PCB front panel
- corresponding baseplate node
- rear wall
cover, one node
PCB A1
lat right wall, one node
rear panel, one node
lat left wall, one node
baseplate nunder A1
eacn of 20 baseplate nodes is linked to boundary node
990: boundary node, set to interface temperature
«Standard» Reduced Board Thermal Model
«Standard» Reduced Unit Thermal Model
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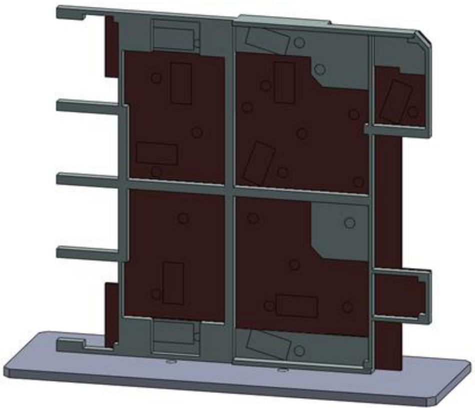
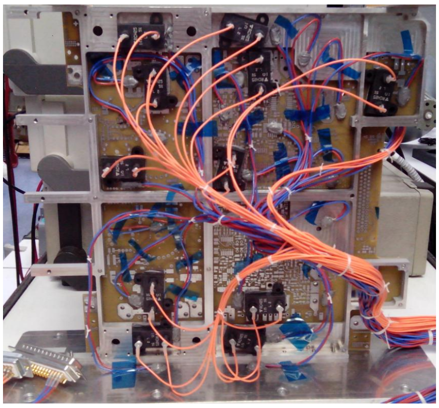
«Standard» Thermal Mathematical & Geometrical Model -2

To become «Standard» the «typical» Board Thermal Mathematical Model needs to be **experimetally calibarted**.

With the aid of **Thermal Concept Design Tool (TCDT)** and **ESATAN**, thermal analyses and relevant **dedicated experimental test campaign have been carried out on a Standard PCB Assemblies**, designed for a modular concept Electronic Unit architecture





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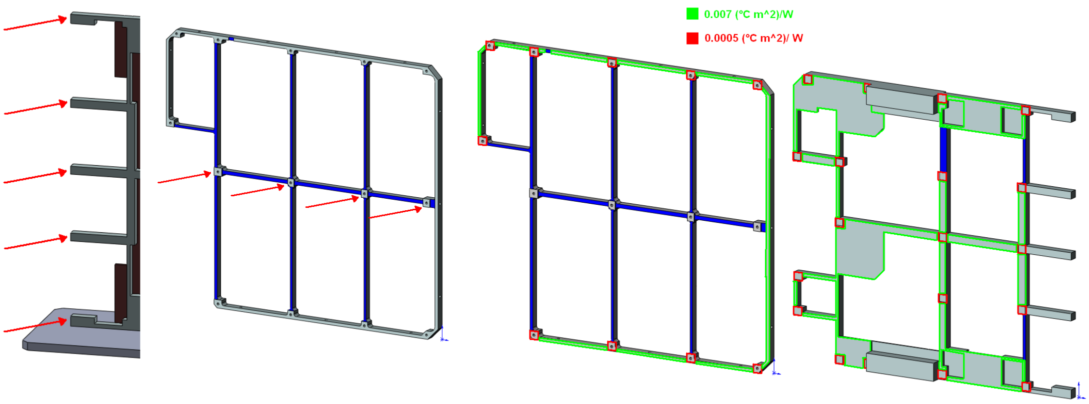
«Standard» Thermal Mathematical Model Calibration -3

The main results obtained, with the aid of dedicated thermal vacuum test, are

- ➢ Calibration of analysis parameter:
- • contact resistance for each bolted connection type, defined in terms of
  - - pitch between screws
  - - screws size



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«Standard» Thermal Mathematical Model Calibration -4

- Calibration of analysis parameter:

- PCBs conductivity (in discrete PCB region)
  - In plane : K = 15 to 60 W/mK depending on PCB type and region (*percentage of Cu and Cu layers thickness, vias, thermal layers*)
  - Out of plane: K= 6 to 18 W/mK depending on PCB type and region (*percentage of Cu and Cu layers thickness, vias, thermal layers*)

- Connectors between PCBs & Motherboard: Equivalent thermal conductance of about 13 W/(m x K) (for 62 pin connectors)

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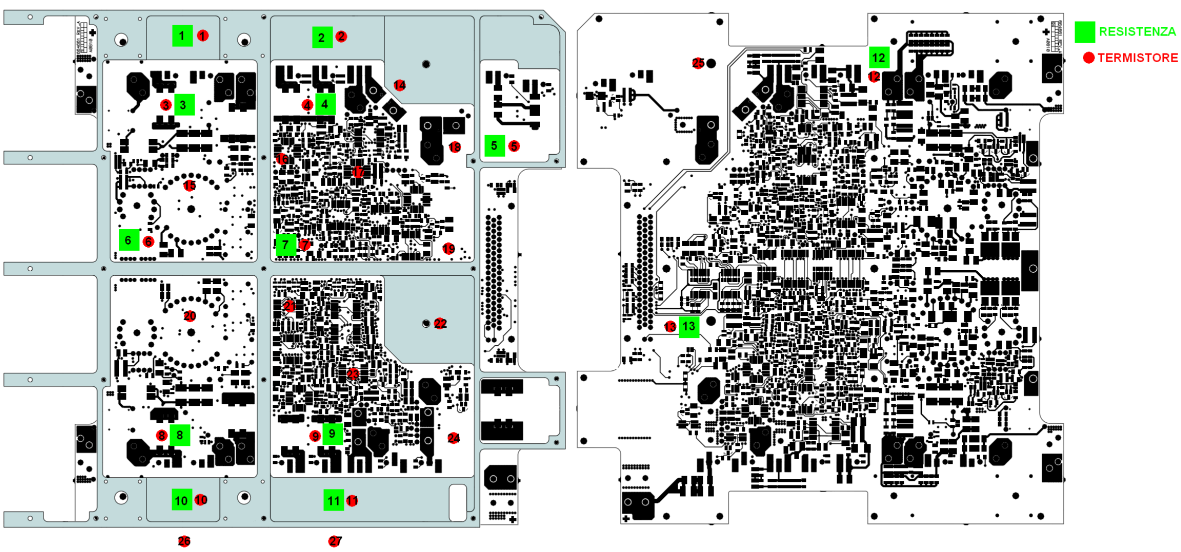
«Standard» Thermal Mathematical Model Calibration -5



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«Standard» Thermal Mathematical Model Calibration -6

R	P_d [W]	TC	T_0 [°C]	T_{TVT} [°C]	$T_{TVT-NORM}$ [°C]	$T_{analysis}$ [°C]	Δ [°C]
		$TC_{chamber}$			-1.0		
R1	0.884	TC1	1.6	20.2	17.6	20.2	3.7
R2	0.941	TC2	1.3	17.8	15.5	17.8	3.8
R3	0.970	TC3	1.2	24.7	22.5	24.7	-0.8
R4	0.865	TC4	1.1	26.5	24.4	26.5	-3.0
R5	0.792	TC5	1.0	20.0	18.0	20.0	1.8
R6	0.792	TC6	0.8	21.7	19.9	21.7	-2.3
R7	0.774	TC7	0.9	21.5	19.6	21.5	-2.6
R8	0.723	TC8	0.8	15.6	13.8	15.6	-3.1
R9	0.931	TC9	0.7	18.2	16.5	18.2	-3.9
R10	1.082	TC10	0.6	3.6	2.0	3.6	1.2
R11	1.082	TC11	1.1	3.1	1.0	3.1	0.9
R12	1.088	TC12	1.1	26.6	24.5	26.6	-3.4
R13	1.00	TC13	1.2	18.9	16.7	18.9	-2.7
		TC14	1.1	17.2	15.1	17.2	**4.2**
		TC15	1.0	22.9	20.9	22.9	-1.4
		TC16	1.2	24.7	22.5	24.7	-2.1
		TC17	1.3	22.0	19.7	22.0	-1.0
		TC18	1.2	19.3	17.1	19.3	1.9
		TC19	1.1	18.7	16.6	18.7	-0.9
		TC20	1.0	16.4	14.4	16.4	0.3
		TC21	1.1	17.8	15.7	17.8	-1.1
		TC22	1.0	13.3	11.3	13.3	1.2
		TC23	0.9	18.0	16.1	18.0	-2.4
		TC24	0.7	14.0	12.3	14.0	0.1
		TC25	0.8	19.3	17.5	19.3	2.2
		TC26	0.5	0.7	-0.8	0.7	0.1
		TC27	0.3	0.7	-0.6	0.7	-0.1

* $T_{TVT-NORM} = T_{TVT} - (T_0 - T_{chamber})$

Average: -0,35°C

Average on absolute values: 1,93°C

Standard Deviation: 2,3°C

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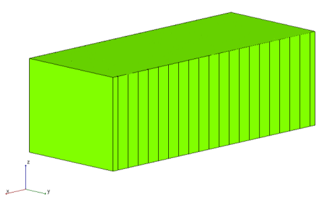
Conclusions

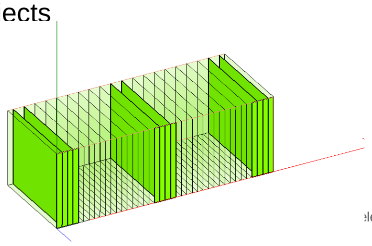
- The thermal design and development of Spacecraft, Sub-Systems or Equipments involve the establishment of a **Thermal Mathematical Model (TMM),** which shall be **validated and calibrated** by means of dedicated Thermal Survey **test campaign**: this is possible when dedicated thermal representative hardware is available

- Defining standard thermal solution according to “re-use” and “modularity” philosophy allows to **reduce the experimental activities** and relevant **risks** and improve reliability of thermal prediction.

- Definition of **experimental based standard parameters** for Thermal Mathematical Model at Board Assembly and Equipment level

- Issue of a (reduced) thermal models for different PCB board type (DC DC Converter, Control Board, Data Interface Board) to be used for what-if analysis and for reference for future projects





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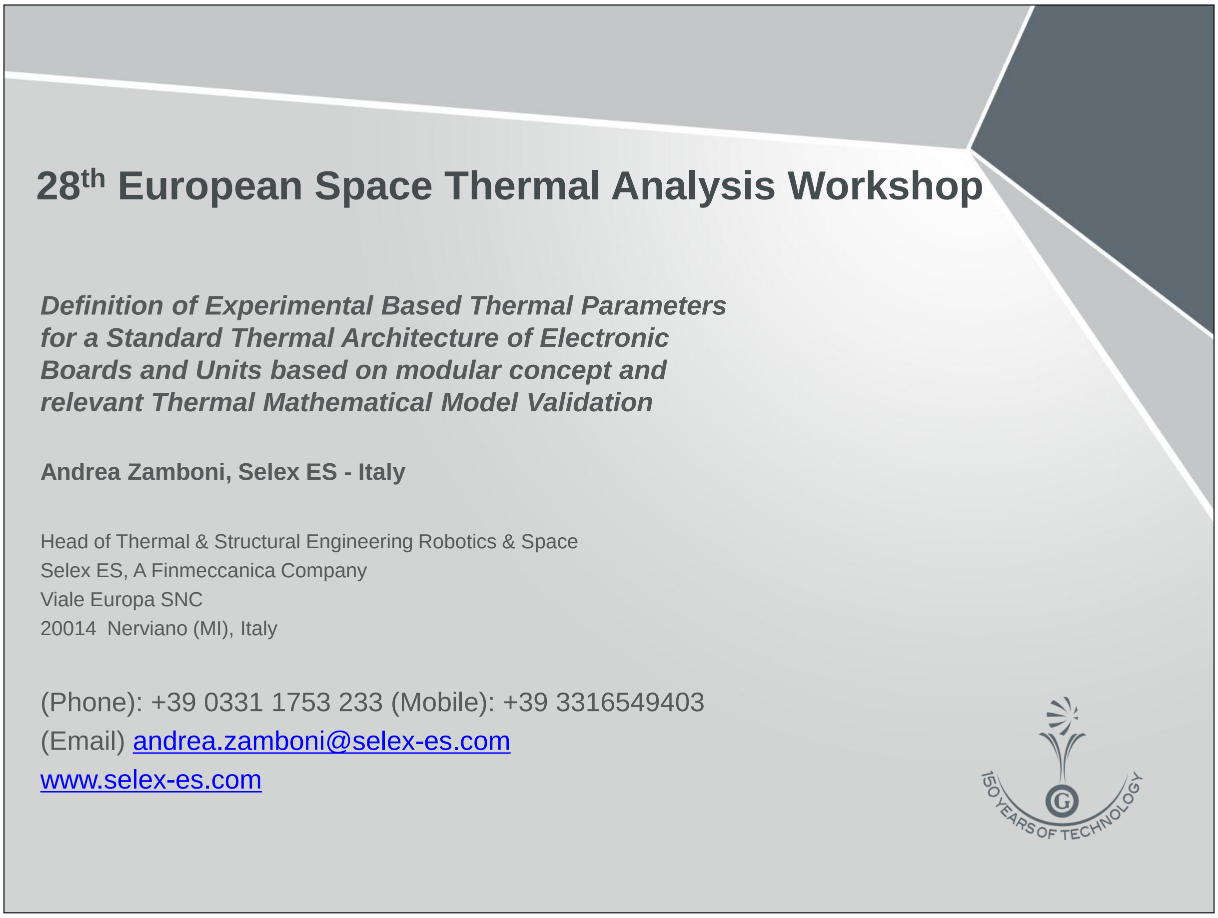
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Definition of Experimental Based Thermal Parameters for a Standard Thermal Architecture of Electronic Boards and Units based on modular concept and relevant Thermal Mathematical Model Validation
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www.selex-es.com
150 YEARS OF TECHNOLOGY

Appendix C

LISA pathfinder Inertial Sensor Head thermal analysis in frequency domain

Paolo Ruzza
(CGS S.p.A., Italy)

Abstract

LISA Pathfinder is the precursor of the ESA/NASA mission LISA (Laser Interferometer Space Antenna); it aims at demonstrating the feasibility of all the challenging key technologies needed by the operational mission.
CGS is responsible of the Thermal Design and Analysis of LISA Pathfinder ISH (Inertial Sensor Head). The main goal of the ISH TCS, as a part of the overall instrument TCS, is to damp the thermal disturbances coming from outside (i.e. external environment, rest of the satellite); the system performance requirements are expressed in terms of frequency-dependent allowable noise, inside the detector bandwidth (1 mHz - 30 mHz); for this reason most of the thermal analysis are not performed in the usual time domain, but in the frequency domain.
Main assumption of this approach shall be presented and the results compared with the standard time domain results and with test results, used to validate the thermal model. Finally the advantages of this method in terms of computational time and post-process capability shall also be presented.

Paolo Ruzza, 14 October 2014,
ESTEC

OHB CGS

SPACE SYSTEMS

LISA pathfinder Inertial Sensor Head thermal analysis in frequency domain

Table of contents

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SPACE SYSTEMS

LISA pathfinder Inertial Sensor Head thermal analysis in frequency domain

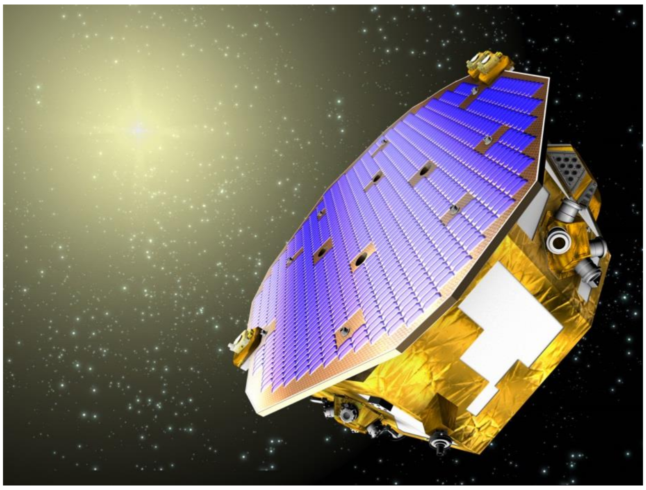
Introduction

Introduction to LISA Pathfinder (1)

LISA Pathfinder will test in flight the concept of low-frequency gravitational wave detection and all the technologies for future mission LISA (ESA/NASA)

Shall be orbiting in Earth-Sun L2

Launch foreseen in 2015



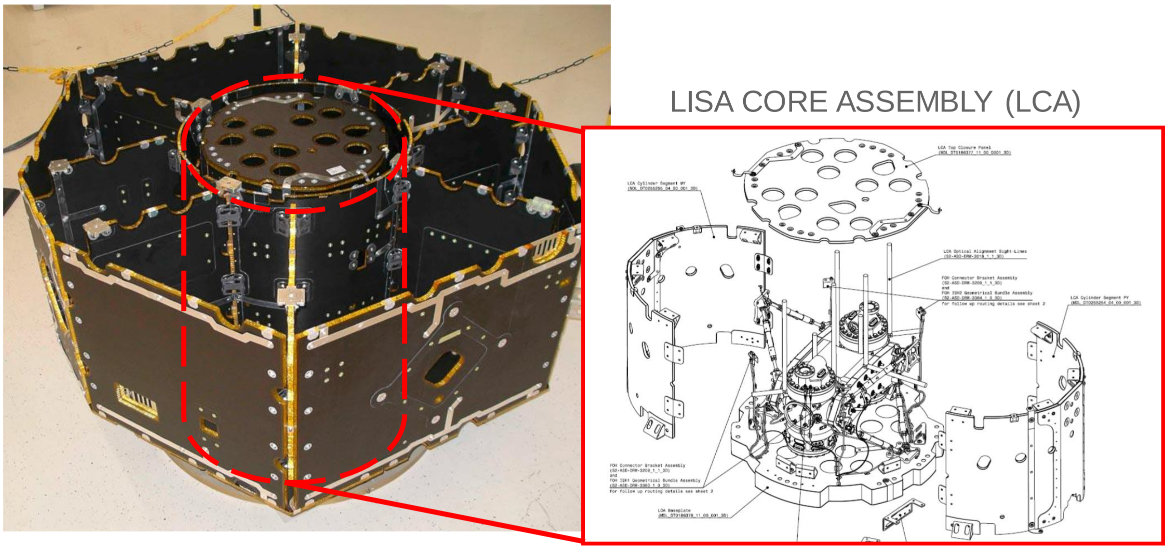
CGS S.p.A. / LISA pathfinder Inertial Sensor Head thermal analysis in frequency domain 14/10/2014 Seite 3

Introduction

Introduction to LISA Pathfinder (2)

LISA SATELLITE

LISA CORE ASSEMBLY (LCA)



CGS S.p.A. / LISA pathfinder Inertial Sensor Head thermal analysis in frequency domain 14/10/2014 Seite 4

Introduction

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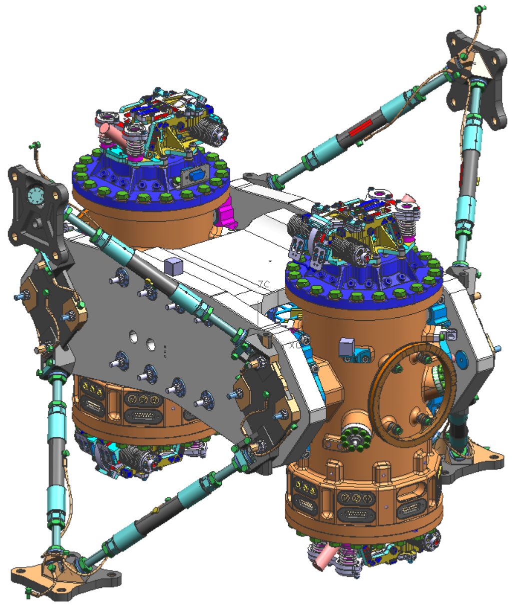
Introduction to LISA Pathfinder (3)



The LCA is composed by two Inertial Sensor Heads (ISH) separated by an optical bench. The whole assembly is connected to the LCA cage by means of 8 low conductance CFRP struts

The two ISH contain two test masses in a near-perfect gravitational free-fall, whose motion is controlled and measured with unprecedented accuracy

ISHs have been designed, manufactured integrated and tested at CGS

CGS S.p.A. / LISA pathfinder Inertial Sensor Head thermal analysis in frequency domain 14/10/2014 Seite 5

Analysis Approach

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LCA analysis (and testing) philosophy

- The LCA is a completely passive device;
- Thermal analyses have been performed at LCA level to predict the system damping capability with reference to external temperature oscillation;
- Performance requirements are expressed in terms of frequency-dependent allowable temperature noise, inside the bandwidth [1 mHz – 30 mHz];
- For this reason all analyses are performed in frequency domain (via transfer function);
- This approach also lead to design and perform a dedicated test for thermal model correlation

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Analysis Approach

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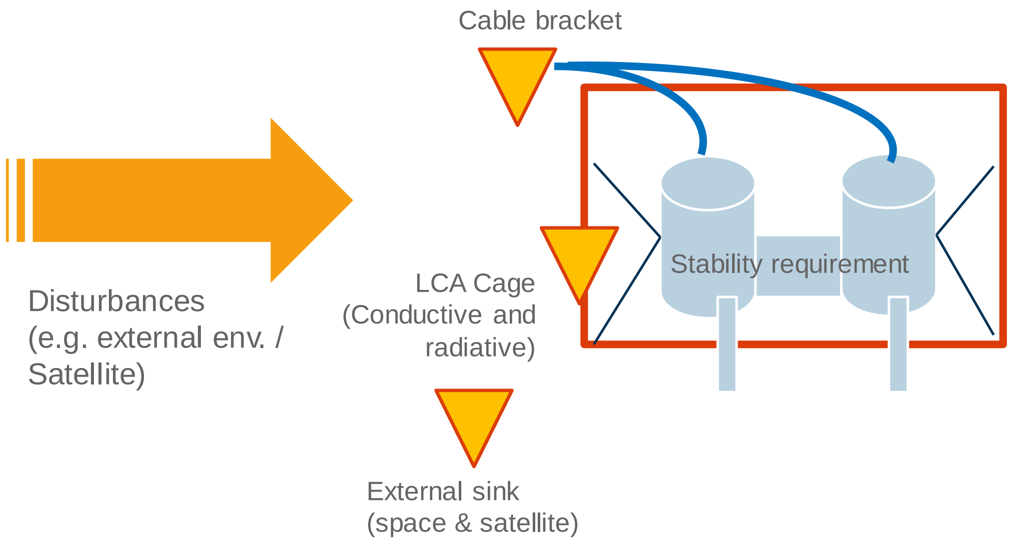
Set of boundary nodes



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Theory

OHB CGS

Frequency domain analysis* – brief theory (1)

$$
\begin{cases}
C_1\dot{T}_1 = -\sum_{i=1}^{N} GL_{1-i}\left(T_1 - T_i\right) - \sum_{i=1}^{N} GR_{1-i}\left(T_1^{\,4} - T_i^{\,4}\right) + Q_1 \\
C_2\dot{T}_2 = -\sum_{i=1}^{N} GL_{2-i}\left(T_2 - T_i\right) - \sum_{i=1}^{N} GR_{2-i}\left(T_2^{\,4} - T_i^{\,4}\right) + Q_2 \\
\vdots \\
C_j\dot{T}_j = -\sum_{i=1}^{N} GL_{j-i}\left(T_j - T_i\right) - \sum_{i=1}^{N} GR_{j-i}\left(T_j^{\,4} - T_i^{\,4}\right) + Q_j \\
\vdots \\
C_N\dot{T}_N = -\sum_{i=1}^{N} GL_{N-i}\left(T_N - T_i\right) - \sum_{i=1}^{N} GR_{N-i}\left(T_N^{\,4} - T_i^{\,4}\right) + Q_N
\end{cases}
$$

Linearization of radiative term

$$
C_i\delta\dot{T}_i = -\sum_{i=1}^{N} GL_{i-j}\left(\delta T_i - \delta T_j\right) + \\
-\sum_{i=1}^{N} GR_{i-j}\left(\delta T_i \cdot 4T_i^3 - \delta T_j \cdot 4T_j^3\right) + \delta Q_i
$$

* see [1],[2]

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Theory

OHB CGS

Frequency domain analysis – brief theory (2)

$$\{\delta\dot{T}\} = C^{-1}(K\{\delta T\}) + C^{-1}\{\delta Q\} \equiv A\{\delta T\} + B\{\delta Q\}$$

$$\begin{Bmatrix} \delta\dot{T}_V \\ \delta\dot{T}_B \end{Bmatrix} = \begin{bmatrix} A_{VV} & A_{VB} \\ A_{BV} & A_{BB} \end{bmatrix} \begin{Bmatrix} \delta T_V \\ \delta T_B \end{Bmatrix} \Rightarrow \delta\dot{T}_V = A_{VV}\,\delta T_V + A_{VB}\,\delta T_B$$

$$\frac{T_V(s)}{T_B(s)} \equiv F(s) = (sI - A_{VV})^{-1} A_{VB}$$

With s = *i*ω the frequency of interest

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Practice

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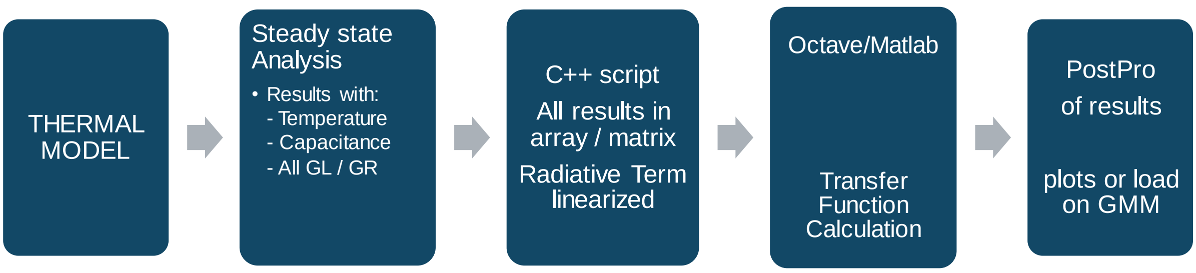
Practical application of the method



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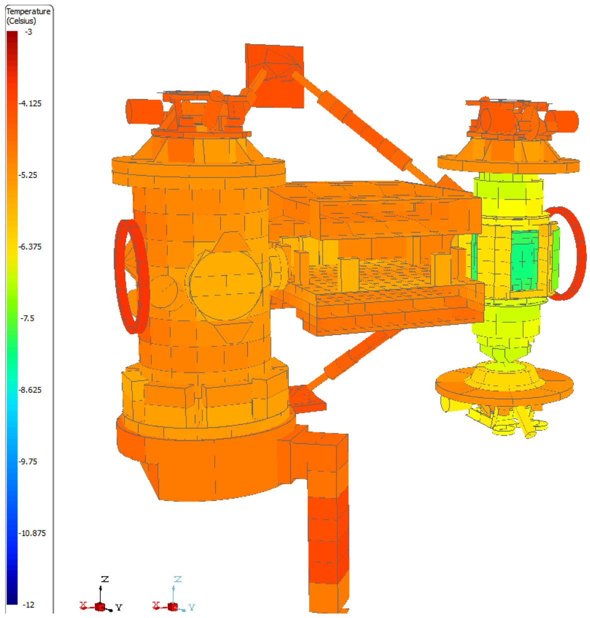
Post-processing

OHB CGS

Post Processing of data (1)



The temperature gain due to the boundary temperature oscillation (1mHz frequency) is calculated and plotted (in logarithmic scale) on the Geometrical Mathematical Model.

This approach gives a direct and immediate view of the coupling strength at a given frequency inside the model for all the nodes in the model

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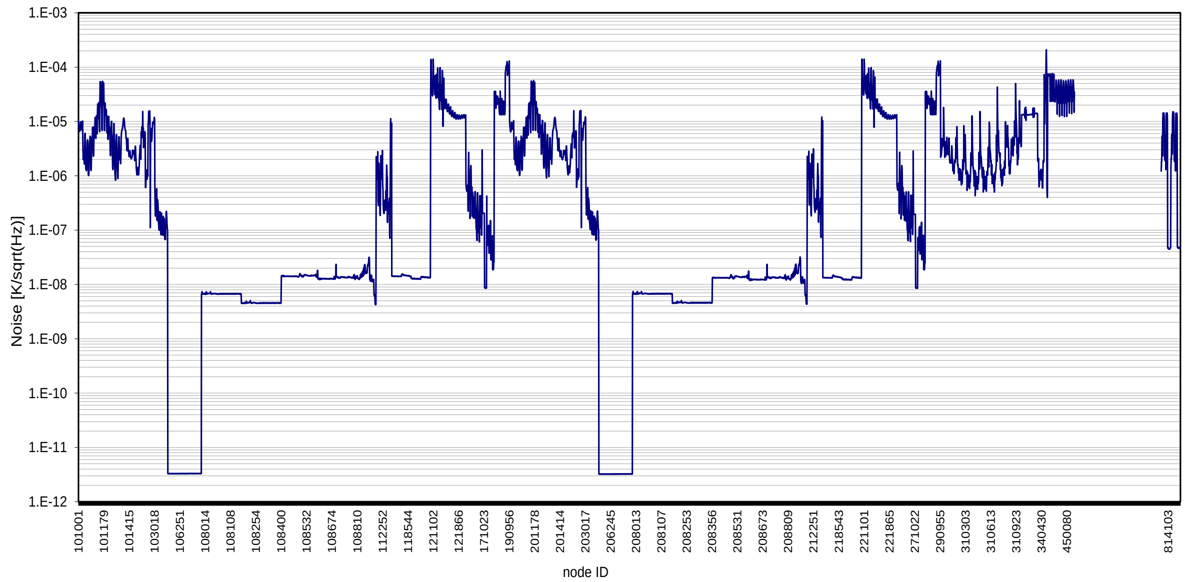
Post-processing

OHB CGS

Post Processing of data (2)



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Thermal model correlation

Thermal model correlation (on ISH)

- A dedicated test during qualification campaign has been designed and performed to correlate the thermal model in the frequency domain
- A standard balance test was not feasible since a too long stabilization time was needed (mass, high decoupling)
- A pulse input has been given to the system and the resulting oscillations have been considered for correlation:
  - ADVANTAGE: not needed to wait temperature stabilization, but the oscillation to be relatively stable
  - Two sets of heaters have been independently actuated with 1mHz profile (i.e. 500s ON / 500s OFF) to have two different correlation case

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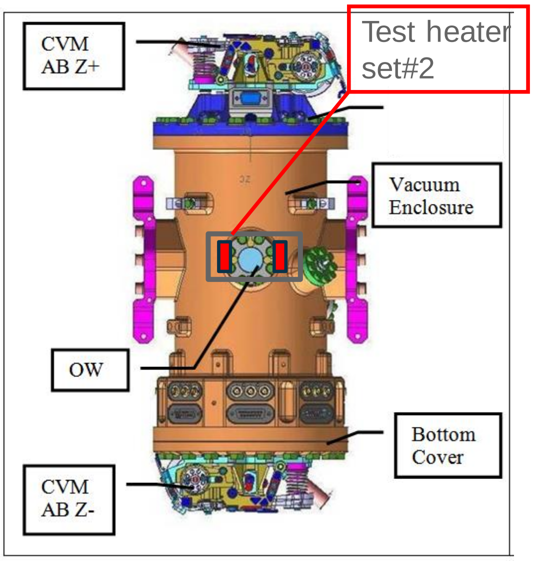
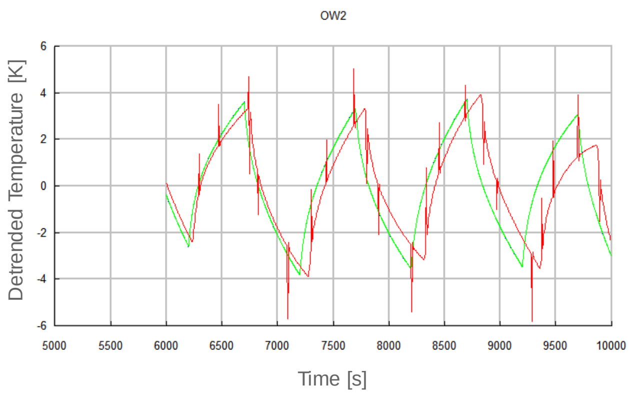
Thermal model correlation

Test description





Heater applied on Optical window
Red – test data / green model data

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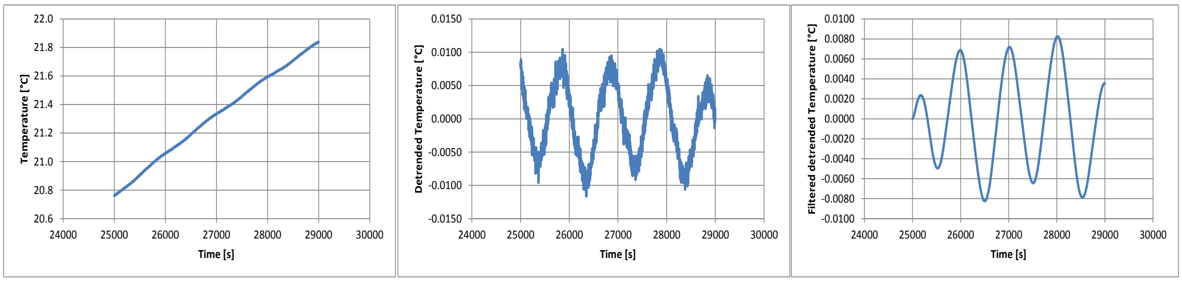
Thermal model correlation

OHB CGS

Test data post-processing



Raw data → **Detrended data** → **Filtered data**

Detrending with 3rd grade polynome

Low pass Butterworth filter with a 2mHz cut off frequency

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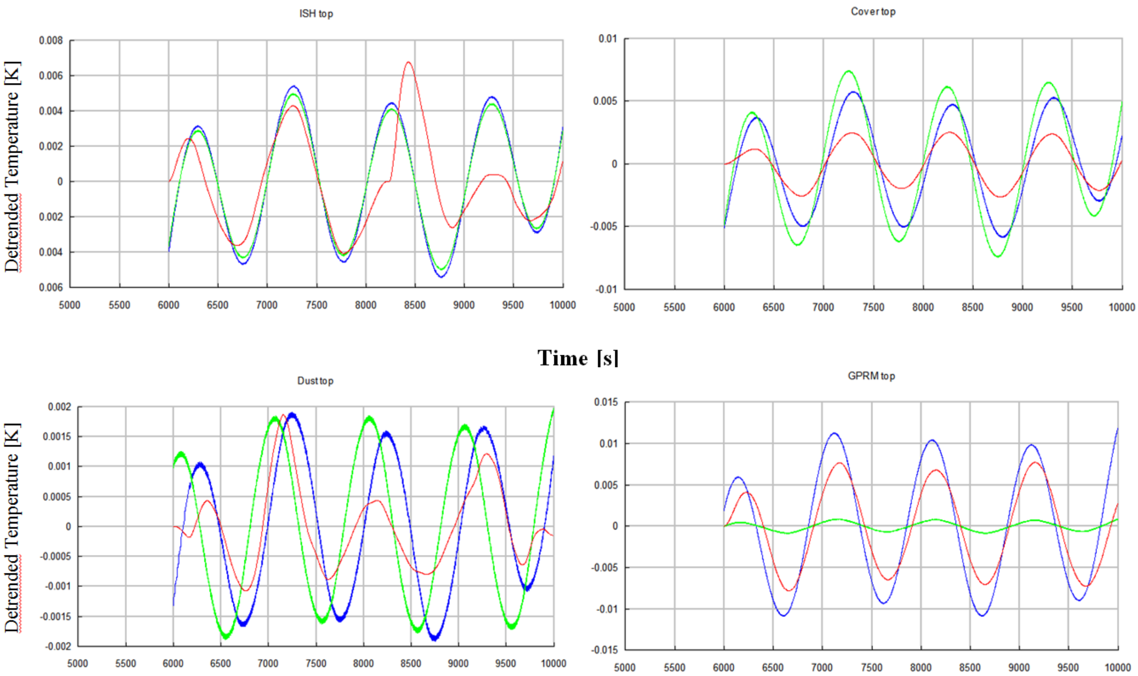
Thermal model correlation

OHB CGS

Correlation results (1)

Test data
Model data before correlation
Model data after correlation



Thermal model correlation

Correlation results (2)

Analyses in time domain are very time-consuming (several hours each analysis)

Frequency domain approach permits fast Steady State analysis (few minutes each). This approach has been used for all the intermediate analyses (with correlation parameters variation)

The two approaches show very similar results, especially with small oscillation.

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Thermal model correlation

Correlation results (3)

The time domain analysis (i.e. standard transient analysis with oscillating input) and the frequency domain analysis are showing comparable results

Peak to peak amplitude with given input power (1mHz)

	TEST [°C]	MODEL wt Time Domain Approach [°C]	MODEL wt Frequency domain Approach [°C]
ISH TOP	0.008	0.01	0.0103
COVER TOP	0.005	0.01	0.0106
DUST TOP	0.002	0.0036	0.0035
GPRM FLNG TOP	0.014	0.02	0.0215
TRP	0.0011	0.00052	0.0005
OW2	8	8	6.9

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Conclusions

Conclusions

The presented approach has been extensively used in LISA TCS analyses:

- Calculation of transfer function between a set of boundary nodes (which are assumed the source of the perturbations) and all the other nodes in the model
- The approach is valid for small oscillation / superimposition of effects (need to linearize the radiative coupling)
- The method has been validated with analytical and experimental results
- The strength of this alternative approach is that, with a unique analysis run in the frequency domain, one is able to calculate the response of the system to a set of oscillatory sources (Temperature or power sources)
- Great advantages for computational time (one steady state analysis only is needed)

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P. Ruzza, A. Franzoso, C. Vettore, P. Sarra, F. Venditti, F. Zanetti

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Appendix D

Fluid-selection tool

Henk Jan van Gerner
(NLR, The Netherlands)

Abstract

Fluid selection is one of the first and most important steps for the design of a thermal control system. The usual approach to fluid selection is to manually evaluate many different fluids. However, this is a very time-consuming process, since the number of fluids to choose from is very large, and the best fluid strongly depends on the application and temperature range. Furthermore, a potentially suitable fluid can be overlooked when fluids are manually selected. For these reasons, NLR developed a systematic, automated, fluid-selection tool. This fluid selection tool is implemented in Matlab, and it uses a figure of Merit to select the most suitable fluids from the REFPROP database. In this presentation, the use of the fluid selection tool is demonstrated for 4 different applications: Heat Pipe, Loop Heat Pipe, Two-phase mechanically pumped loop, and a heat pump. For example, it is explained why CO_2 is used in the thermal control system of AMS02 (which was launched with the space shuttle in May 2011 and subsequently mounted on the International Space Station) and why isopentane is selected for an ESA Heat Pump application.

With the fluid selection tool, fluids can be selected which would have been overlooked without the use of the figure of Merit. Furthermore, the tool offers a large saving in ccosts and time since the tedious process of finding and analyzing possibly suitable fluids can now be carried out with a single push on a button.


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Fluid selection tool
Johannes van Es (presenter), Henk Jan van Gerner
28th European Space Thermal Analysis Workshop, 14-15 October 2014, ESTEC
Nationaal Lucht- en Ruimtevaartlaboratorium – National Aerospace Laboratory NLR

Introduction

- Fluid selection is one of the first and most important steps for the design of a thermal control system
- The number of fluids to choose from is very large, and the best fluid strongly depends on application and temperature range
- Usually, the approach to fluid selection is to manually evaluate many different fluids

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Introduction

- This is a very time-consuming process
- Furthermore, very often the wrong fluids are analyzed and 'good' fluids are missed:
  - Standard fluids often have a poor performance in space applications, because the temperature range is usually very different than for terrestrial applications
  - Fluid flammability and/or toxicity are less an issue for space applications than for terrestrial applications
- Because of these reasons, NLR developed a systematic, automated, fluid-selection tool

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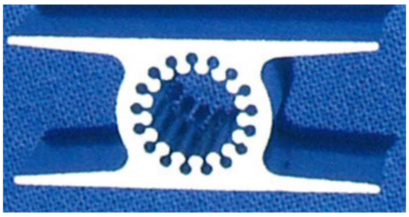
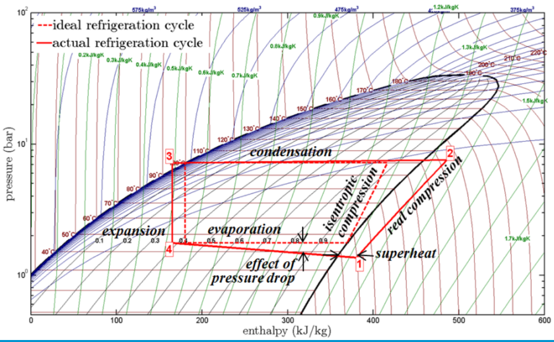
Introduction

- The fluid selection uses the 'figure of Merit'
- In this presentation, the use of the figure of Merit is demonstrated for 4 different applications
  - Heat pipe
  - Loop Heat Pipe/Capillary Pumped Loop
  - Two-phase mechanically pumped loop
  - Heat pump





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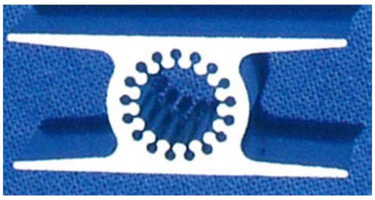
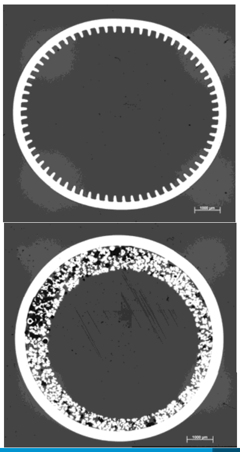
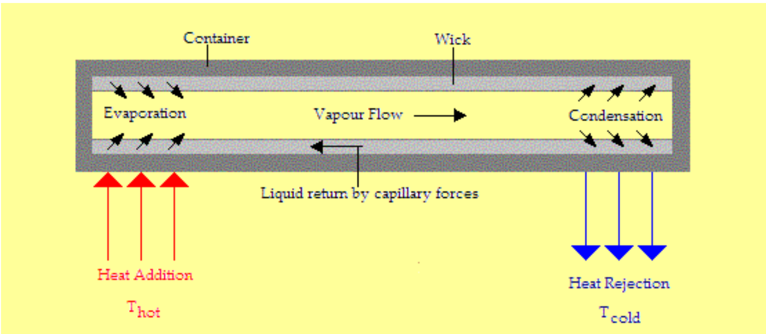
Heat Pipes

- Heat Pipes are capillary driven two-phase heat transfer devices
- Can transport large amounts of thermal energy with only a small ΔT (~10000 better than copper)
- Usually water or ammonia as working fluid







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Heat pipes

- There are several limits to the heat transport capacity of a heat pipe (capillary limit, entrainment limit, sonic limit etc.)
- The capillary limit is usually the most restrictive: $\Delta p_{\text{cap, max}} > \Delta p_{\text{friction}}$
- From this capillary limit, the maximum heat transport capacity P is derived:

$$P \propto \underbrace{\frac{d^3 N}{L}}_{\text{geometry dependent}} \underbrace{\frac{\rho_l h_{lv} \sigma}{\mu_l}}_{\text{fluid dependent}}$$

figure of Merit for heat pipes (well known from literature)

- The fluid selection tool plots the figure of Merit for all the fluids in the REFPROP fluid database

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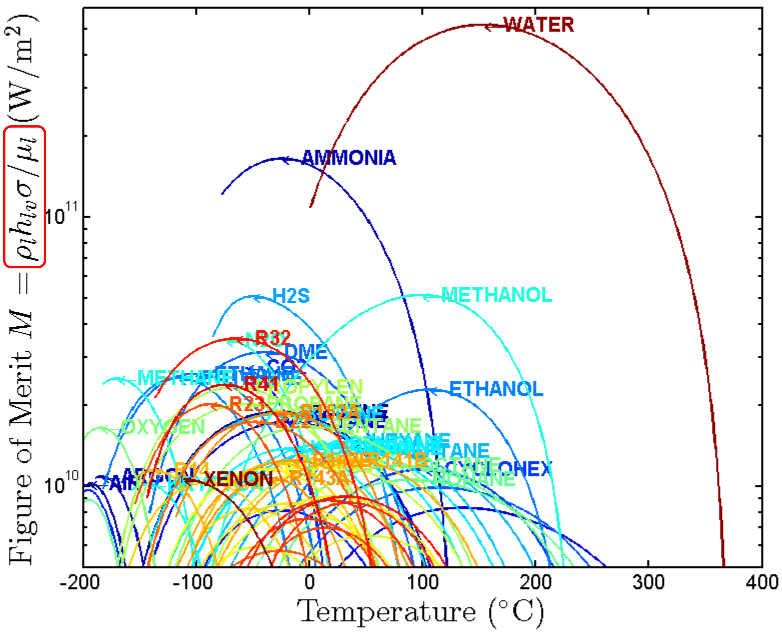
Heat pipes

- There are several lin (capillary limit, entr
- The capillary limit is
- From this capillary li

geometry dependent fluid c

$$P \propto \frac{d^3 N}{L} \frac{\rho_l h_{lv} \sigma}{\mu_l}$$

- The fluid selection tc REFPROP fluid datab



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Loop Heat Pipe

- For a Loop Heat Pipe, the figure of Merit is similar to that of a Heat Pipe
- The major difference with a Heat Pipe is that the vapour pressure drop is usually dominant over the liquid pressure drop
- The flow in the vapour line is generally turbulent
- The figure of Merit for LHP then becomes:

$$M = \frac{\rho_v {h_{lv}}^{7/4} \sigma}{{\mu_v}^{1/4}}$$

figure of Merit for Loop Heat Pipes [1]

[1] N. Dunbar, P. Cadell, *Working fluids and Figures of Merit for CPL/LHP applications*, CPL-98 Workshop (1998)

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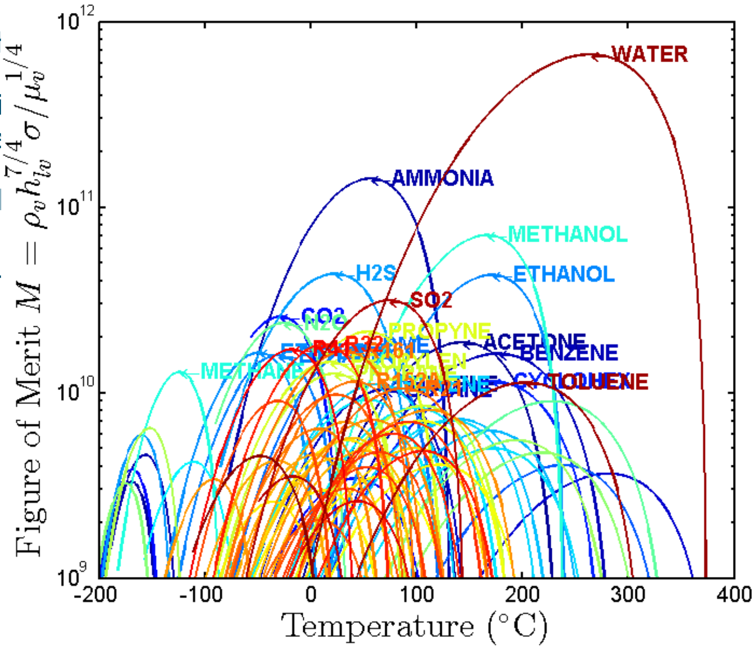
Loop Heat Pipe

- For a Loop Heat Pipe, tl
- The major difference wi is usually dominant ove
- The flow in the vapour
- The figure of Merit for L

$$M = \frac{\rho_v {h_{lv}}^{7/4} \sigma}{{\mu_v}^{1/4}}$$



[1] N. Dunbar, P. Cadell, *Working fluids and Figures of Merit for CPL/LHP applications*, CPL-98 Workshop (1998)

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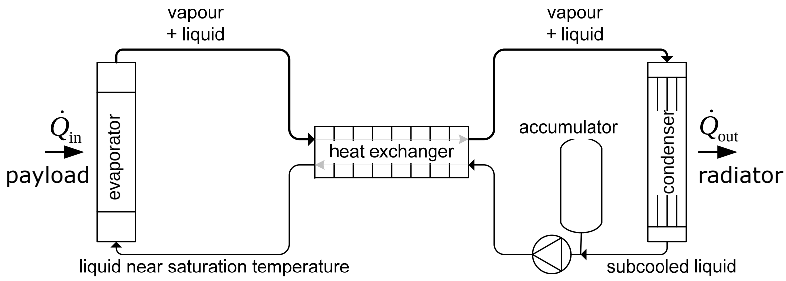
Two-phase Mechanically Pumped Fluid Loop

- In a 2Φ-MPFL, thermal energy is transported by circulating a fluid which evaporates and condenses at almost constant temperature
- Advantages compared to single-phase (e.g. water, glycol) cooling:
  - very uniform temperature
  - low mass flow (typically 10 to 100 times lower)
  - much smaller tubing diameter
  - much higher heat transfer coefficient



Schematic drawing of a 2Φ-MPFL (click drawing for video)

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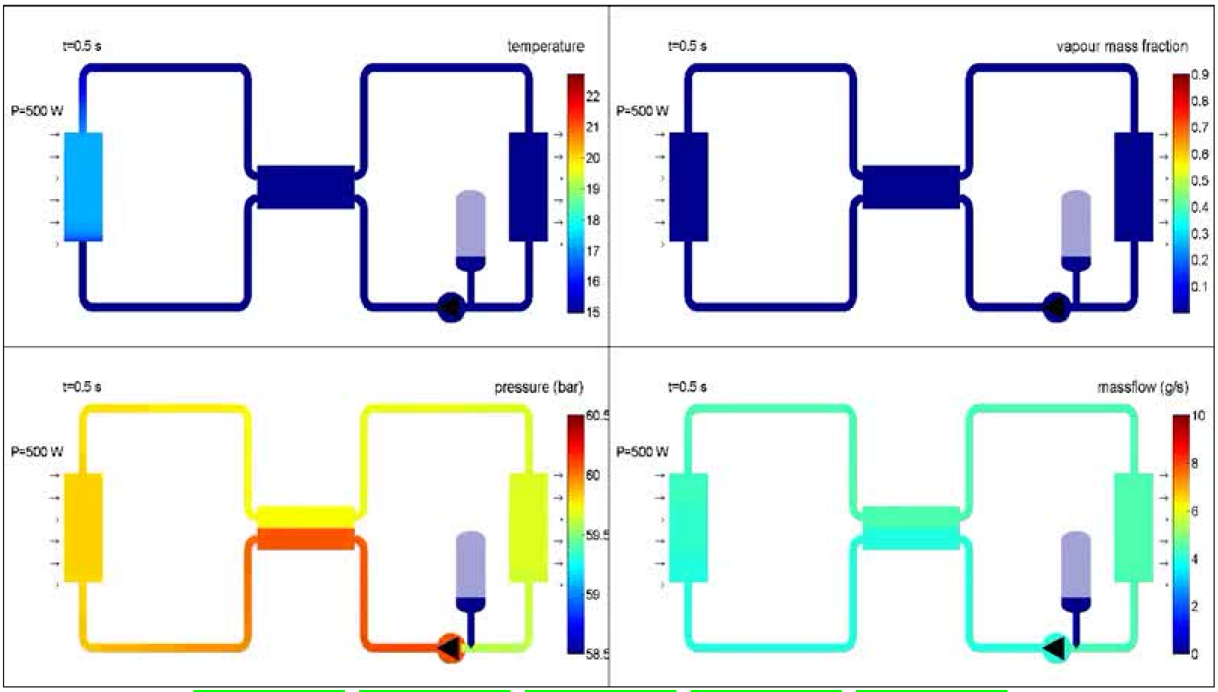
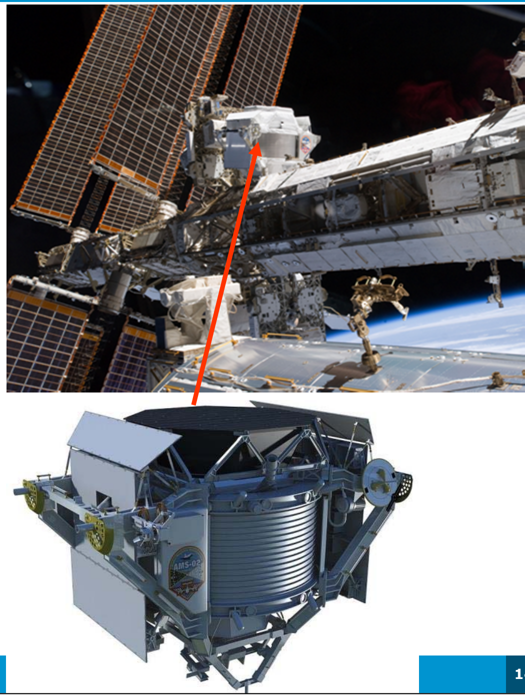


Slow Normal Fast Play/Pause Stop

2Φ-MPFL in space

2Φ-MPFL system for AMS02:

- Alpha Magnetic Spectrometer (AMS02) is a large detector (7000kg!) for cosmic particles that was mounted on the International Space Station in May 2011. CO_2 is the thermal control fluid
- NLR is leading the international team for the thermal control system for the AMS02 tracker
- **So why has CO_2 been chosen as the cooling fluid?**



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Two-phase Mechanically Pumped Fluid Loop

- The tubing inside the tracker must have a small diameter
- However, the available pump only has a small pressure head
  → minimize pressure drop in the system by choosing an optimal fluid
- $$\Delta p \propto \underbrace{\left(\frac{\mu_l^{1/4}}{\rho_l h_{lv}^{7/4}} + \frac{\mu_v^{1/4}}{\rho_v h_{lv}^{7/4}}\right)}_{\text{fluid dependent}} \underbrace{\frac{L}{d^{19/4}}}_{\text{geometry dependent}} \underbrace{P^{7/4}}_{\text{heat input}}$$
- Figure of Merit based on low pressure drop is $M=1/\Delta p_{\text{fluid dependent part}}$

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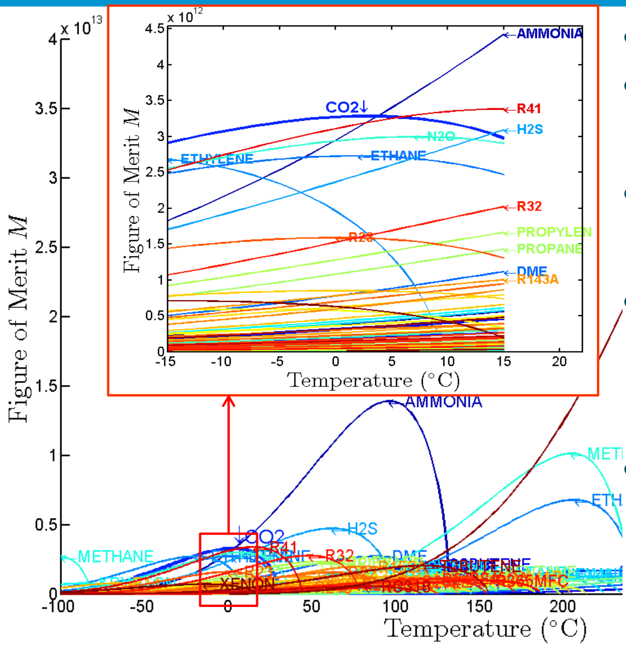
Two-phase Mechanically Pumped Fluid Loop



- CO_2 has the highest figure of Merit
- There are also other fluids with a similar *M*, such as ammonia, R41, N_2O, and ethane
- Some of these fluids would not have been found without the use of the figure of Merit
- After a detailed fluid trade-off, CO_2 was chosen because of low toxicity, inflammability, excellent radiation hardness and good material compatibility
- Other criteria for *M*, such as low pump power, are also possible

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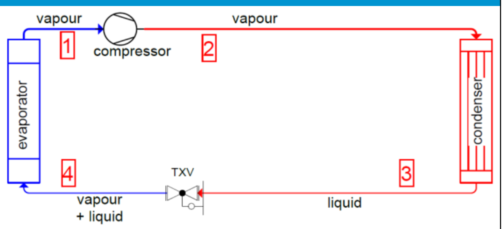
Heat pump



- A heat pump uses a compressor to raise the radiator temperature above the payload temperature
- This significantly increases the heat rejection capacity of the radiators
- Traditional compressors are too heavy and cause too much vibrations
- For this reason, a heat pump with a lightweight, low-vibration, high-speed (200,000 RPM) compressor has been developed in an ESA project
- The efficiency of a heat pump can be expressed with the Coefficient of Performance: COP=$P/w_{compressor}$
- So for a heat pump, the figure of Merit can be based on the COP → $M \propto$ COP

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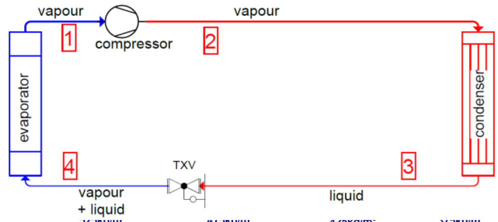
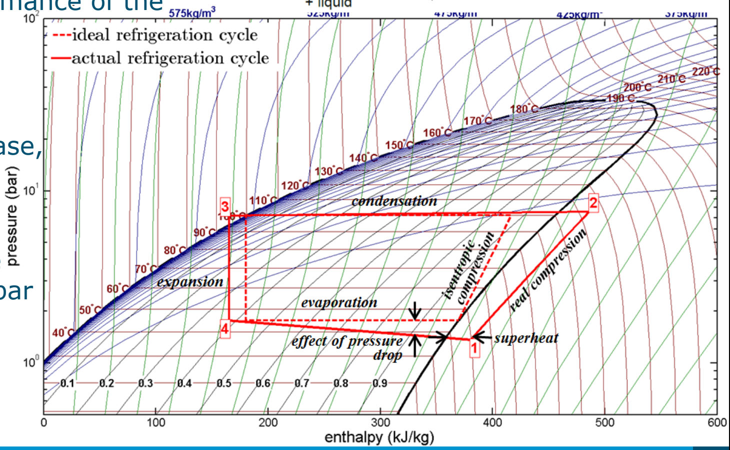
Heat pump

- The COP can be calculated from the enthalpies:
  $COP = P/W_{compressor} = \frac{h_1 - h_4}{h_2 - h_1}$
- The pressure drop in the system has a large influence on the performance of the system and must be taken into account
- The COP is calculated for all fluids in the REFPROP database, assuming $\Delta p = 0.4$ bar and 60% compressor efficiency
- For compressor reasons, the pressure must be below 14 bar





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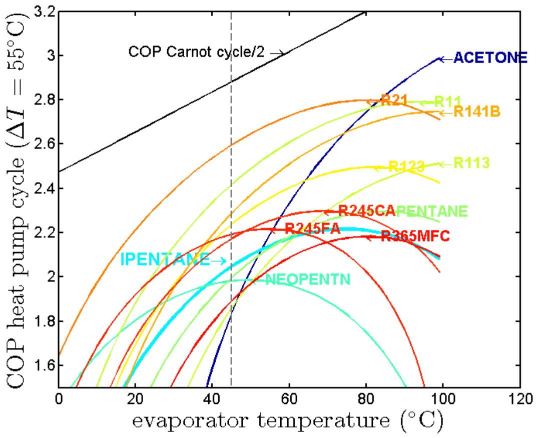
Heat pump

- The fluid selection tool shows that R21, R11, R141b, and R123 have the highest COP
- However, these fluids are banned or being phased-out according to the Montreal protocol
- The next best fluids are R245fa, R245ca, and isopentane (R601a)
- A detailed compressor analysis showed that the highest efficiency is obtained with isopentane, so this refrigerant is chosen for the heat pump application



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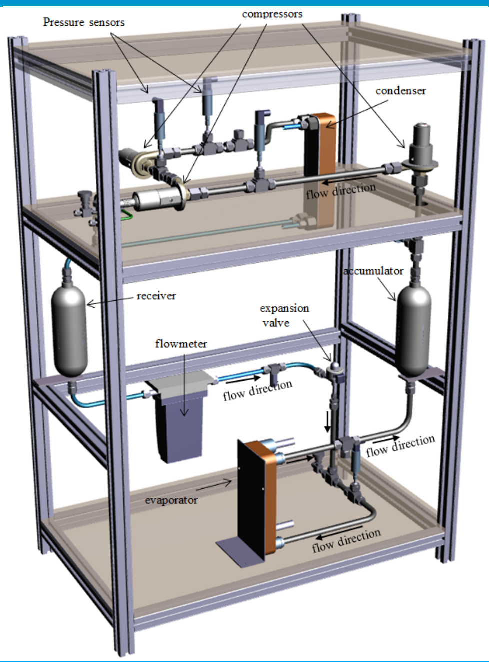
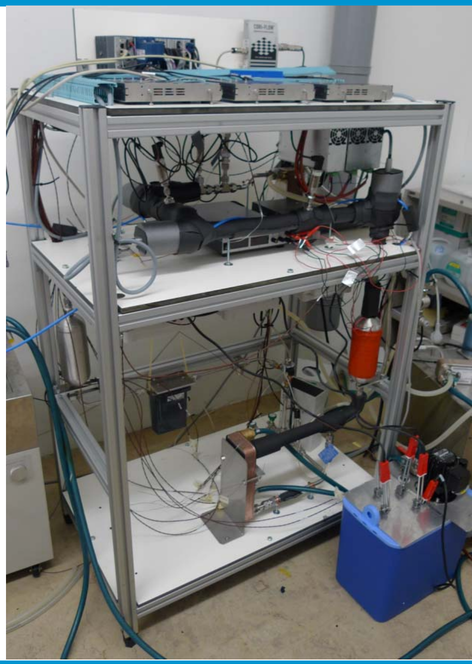
Heat pump measurements with isopentane





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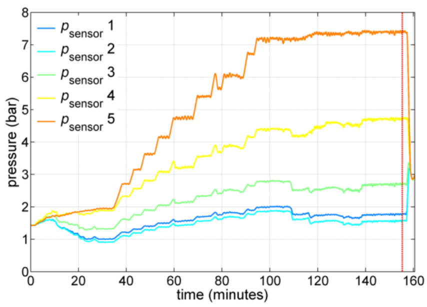
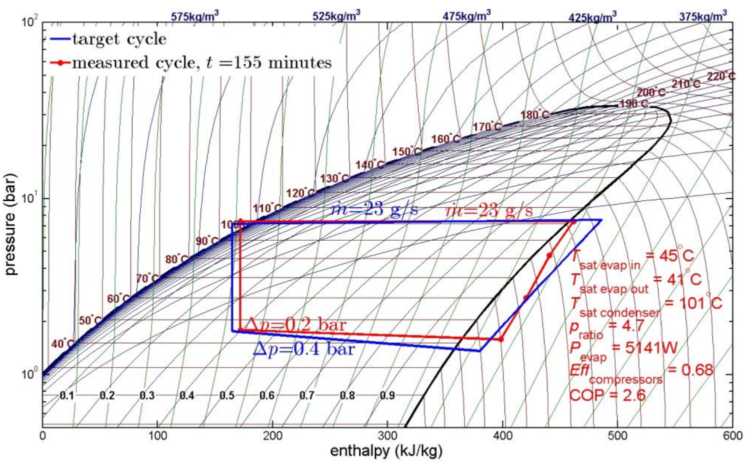
Heat pump measurements with isopentane

- Measurements have been carried out with isopentane as refrigerant
- The measured COP is 2.6, which is considerable higher than the ESA requirement of 2





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Conclusions

- With the figure of Merit, the most suitable fluids are selected from the REFPROP database for a wide range of applications
- With this systematic approach, fluids can be selected which otherwise would have been overlooked
- The use of the figure of Merit is implemented in a fluid selection tool
- With this fluid selection tool, the tedious process of finding and analyzing possibly suitable fluids can now be carried out with a single push on a button

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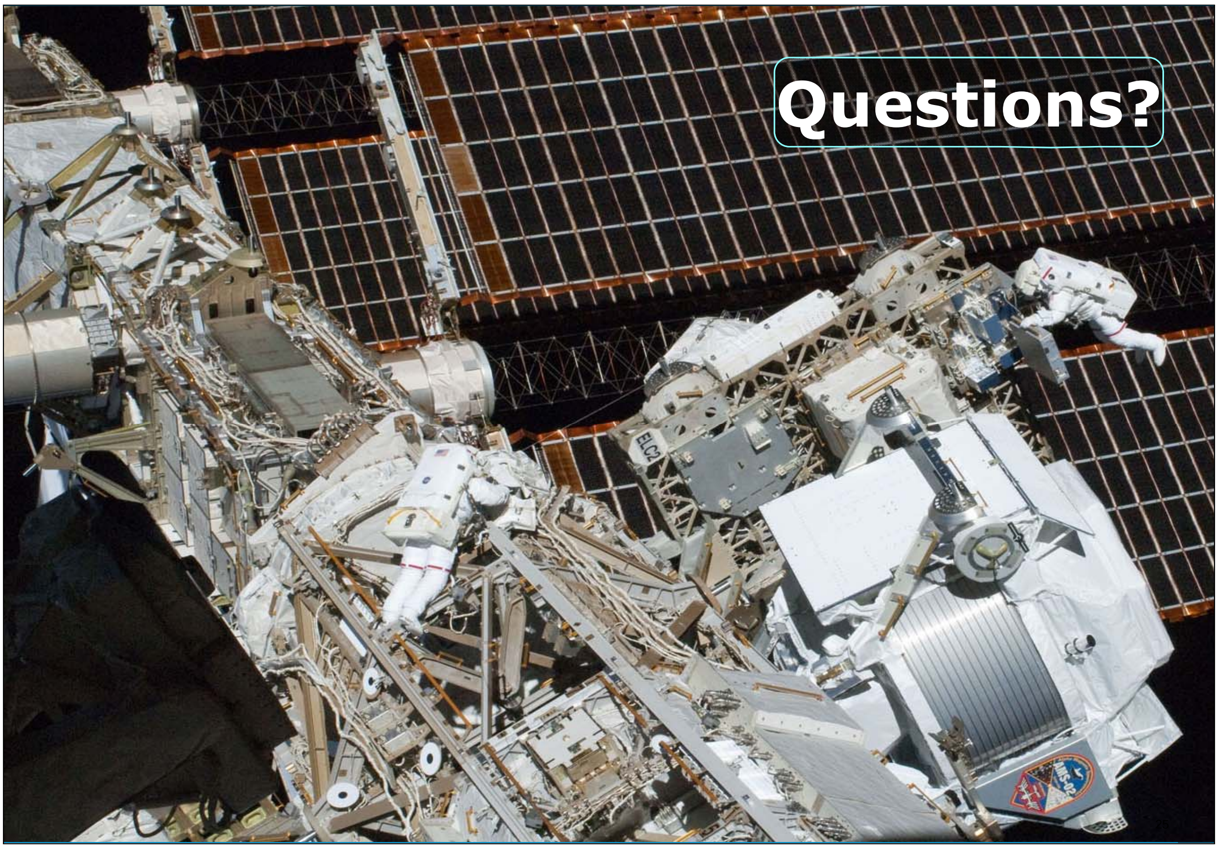


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Appendix E

Development of a thermal control system for South Africa's next generation Earth observation satellite

Daniël van der Merwe
(DENEL Spaceteq, South Africa)

Abstract

This presentation gives an overview of the work done so far in developing a thermal control system for South Africa's next generation Earth observation satellite. Correlated thermal models of critical major components were developed based on lessons learned from SumbandilaSAT (South Africa's first national satellite). These include amongst others an electronic housing unit and a typical solar panel. In addition, the thermo-optical properties of commonly used coatings and tapes were also measured. The performance of the proposed thermal control system was evaluated using the NX^{TM} Space Systems software. During the evaluation different satellite orientation modes were considered, as well as different mission scenarios. The results show that the suggested thermal control system creates a relatively low, uniform temperature inside the satellite.

Development of a thermal control system for South Africa's next generation EO satellite

Niël van der Merwe, M.Sc. Eng., Pr. Eng.
Chief Thermal Engineer
28th European Space Thermal Analysis Workshop

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1. INTRODUCTION

Scope

- Concept development
- Lessons-learned SumbandilaSAT, van der Merwe[1]

Thermal design challenges

- Batteries: 15-30 °C, uniform temperature field
- Data transmitters: 110 W heat dissipation per transmitter
- CCDs: low operating temperature
- Optical bench: uniform temperature field
- Solar panels: 0-80 °C
- EHU: 0-40 °C

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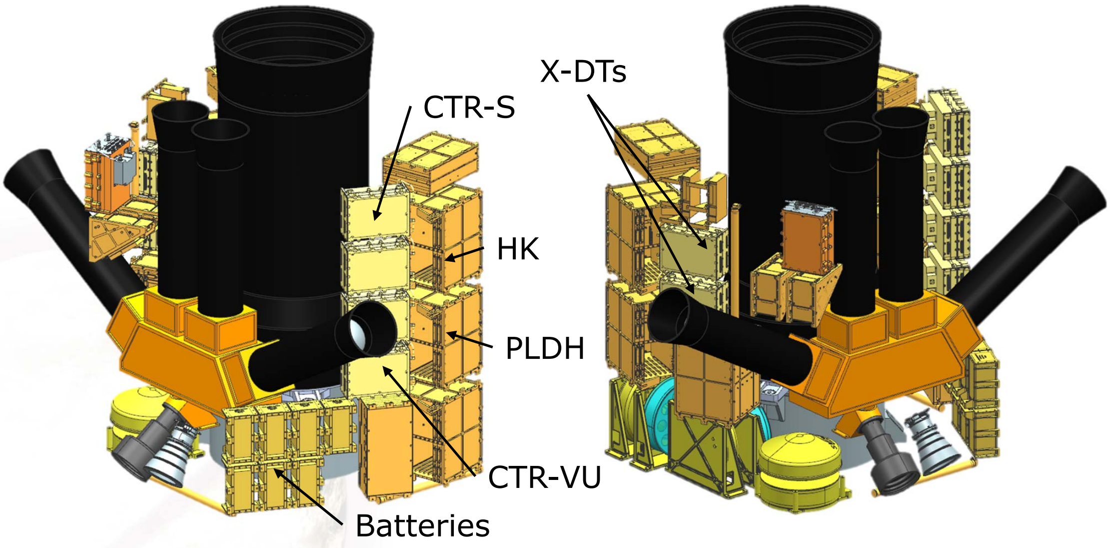
1. INTRODUCTION

Concept layout



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2. ORBITAL HEAT LOAD

Orbit

- Circular Sun-synchronous orbit, 700 km, LTAN 22:30
- Orbit inclination 98.15 °, period 98.6 min

Orbital radiation, Gilmore[2]

- Solar constant: 1367 W/m^2
- Earth IR emission: -18 ° C, 240 W/m^2
- Albedo: 30% of incident solar radiative energy, diffuse reflection
- Deep space: 3 K

Beta angle, Chobotov[3]

- Minimum angle between orbit plane and solar vector
- $\beta = \sin^{-1}(\hat{s} \cdot \hat{n}) = \sin^{-1}[\cos(\delta)\sin(i)\sin(\Omega_{AN} - \Omega_{TS}) + \sin(\delta)\cos(i)]$

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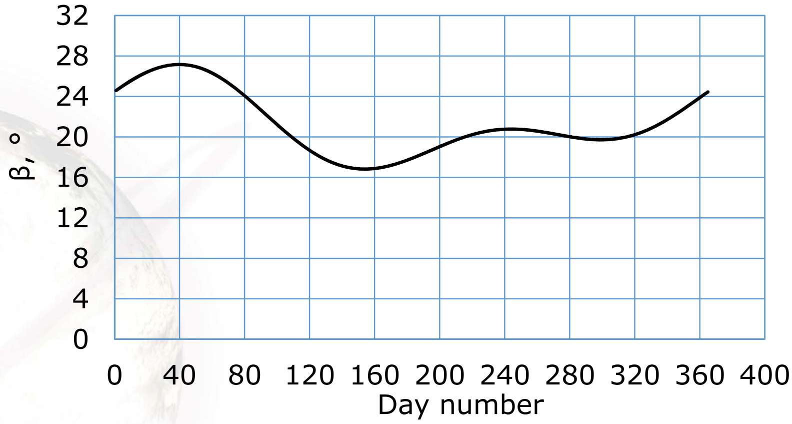
2. ORBITAL HEAT LOAD

Beta angle

- $\beta = \sin^{-1}(\hat{s} \bullet \hat{n}) = \sin^{-1}[\cos(\delta)\sin(i)\sin(\Omega_{AN} - \Omega_{TS}) + \sin(\delta)\cos(i)]$
- Meeus[4] algorithm for sun position vector
- $16.8° < \beta < 27.2°$



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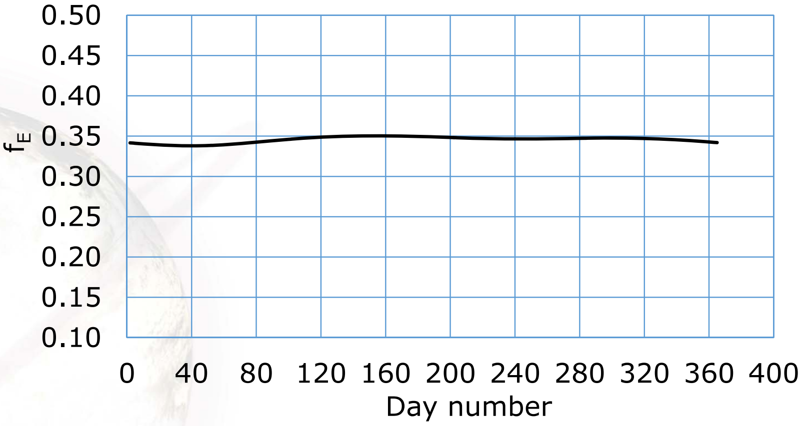
2. ORBITAL HEAT LOAD

Eclipse fraction

- $\beta^* = \sin^{-1}[\frac{R}{(R+h)}], \quad 0° \leq \beta \leq 90°$
- $f_E = \frac{1}{180°}\cos^{-1}[\frac{(h^2+2Rh)^{1/2}}{(R+h)\cos\beta}], \quad \text{if} \ |\beta| < \beta^* \ ; \qquad f_E = 0, \quad \text{if} \ |\beta| \geq \beta^*$



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3. INTERNAL HEAT LOAD

MC	Coasting, W	Imaging, W
HR CCD		6.6
HR EHU		5.0
MR CCD		8.4
MR EHU		5.0
ASF CCD		8.4
ASF EHU		5.0
ASA CCD		8.4
ASA EHU		5.0
SWIR CCD		8.4
SWIR EHU		5.0
X-DT EHU		110 each
CTR-VU EHU	4.0 cont.	4.0 cont. & 20.0
CTR-S EHU	4.0 cont.	4.0 cont. & 20.0
RW (each)	5.0 cont.	5.0 cont.
HK EHU	15.0 cont.	15.0 cont.
DRS out		5.0 transmitting
DRS in		7.0 imaging

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4. MISSION SCENARIOS

Mission phases

- Orbit: 14.6 revolution per day
- Coasting: Orbit 1 – 10
- Imaging: Orbit 11 – 12
- Cyclic stability: 10 orbits

Satellite orientation modes

- Least drag (LD)
- Sun-following (SF)
- Imaging (IM)

Coasting phase

- Sun-following (SF)

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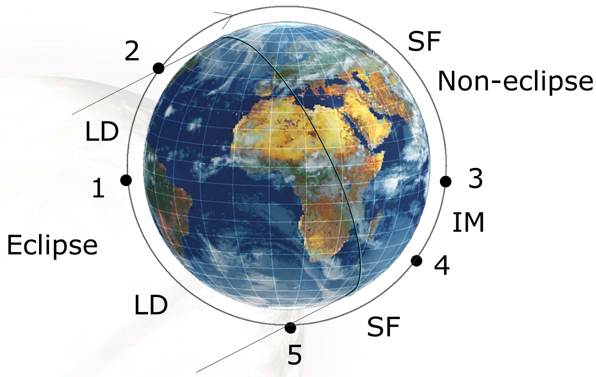
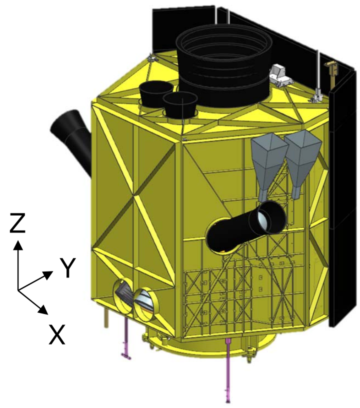
4. MISSION SCENARIOS

Imaging phase

Mode	X-axis	Y-axis	Z-axis
LD		Align orbit normal	Nadir pointing
SF	Align orbit normal	Sun pointing	
IM		Align orbit normal	Nadir pointing





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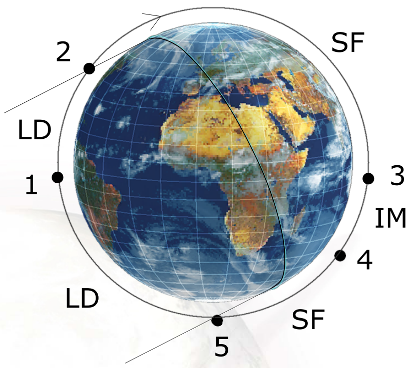
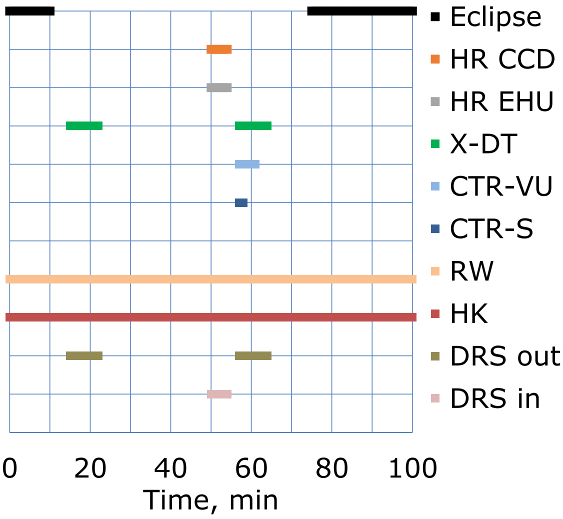
4. MISSION SCENARIOS

Imaging phase: MCs switching sequence





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5. PROPOSED TCS

High heat dissipating MCs

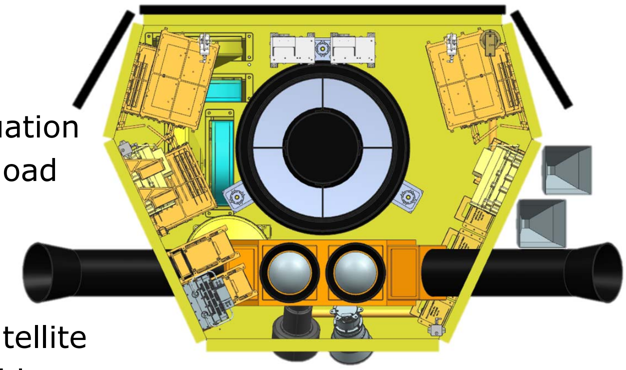
- Use primary structure as radiator, good thermal contact
- Strategic placing: external area with low solar irradiation and high IR emission

Batteries

- Batteries: area of low fluctuation in orbital and internal heat load

Thermal isolation

- Solar panels: prevent temperature gradients inside satellite
- Optical payload: ensure stable, uniform temperature



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5. PROPOSED TCS

Materials

Component	Coating	Material
Solar panels	Graphite epoxy, $\varepsilon = 0.85$, $\alpha = 0.93$	Al honeycomb, bare CF skins
Optical baffles	Black Z306, $\varepsilon = 0.87$, $\alpha = 0.95$	CF epoxy (25% vol.)
Rest of satellite	Alodine®, $\varepsilon = 0.15$, $\alpha = 0.08$	Al 6082 - T6

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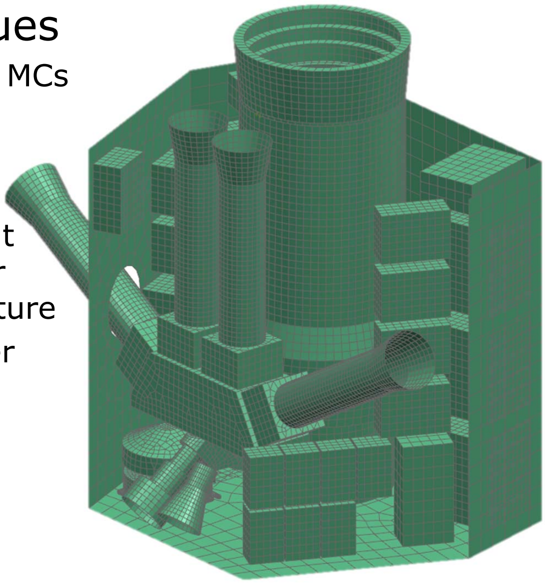
6. THERMAL MODEL

Assumptions and techniques

- Perfect thermal contact between MCs and primary structure
- Grey-body radiation, $\alpha=\varepsilon$
- All EHUs modelled as thin-walled boxes (zero temperature gradient over wall thickness), similarly for optical baffles and primary structure
- Heat loads applied uniformly over EHU



Performance evaluation

- Two mission phases
- Two beta angles: 16.8 °, 27.2 °

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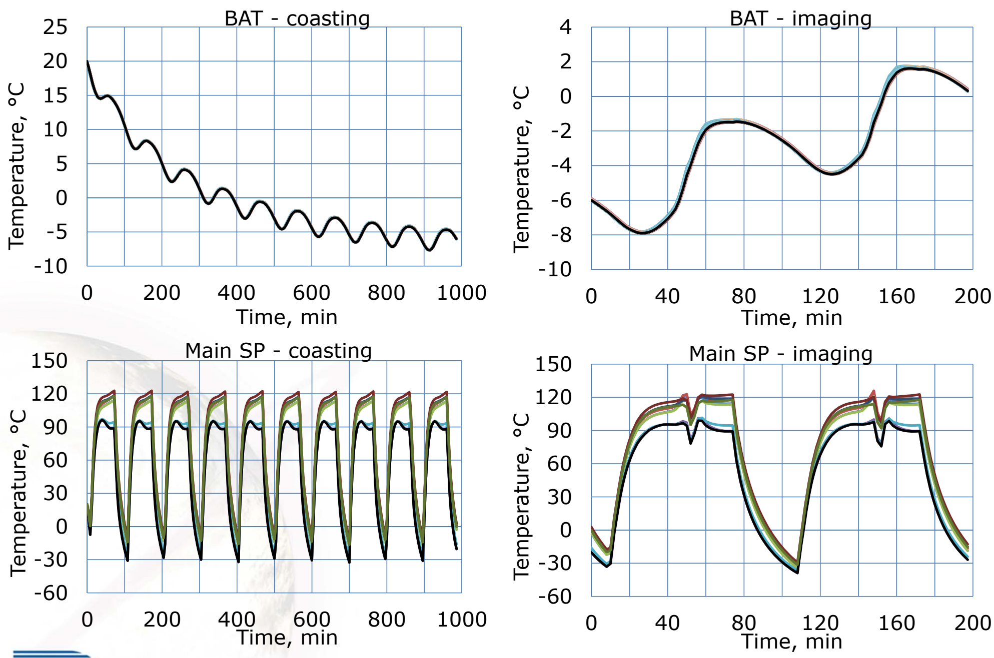
7. PERFORMANCE OF TCS



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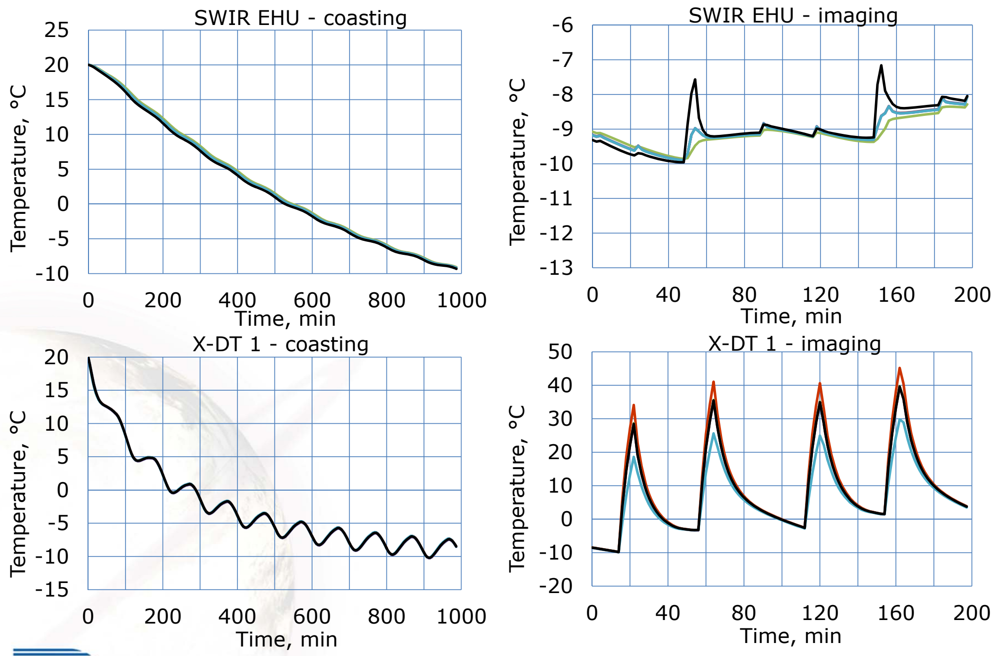
7. PERFORMANCE OF TCS



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7. PERFORMANCE OF TCS

X-DTs

- Coasting: low nominal temperature mainly due to absence of internal heat loads; -10.3 °C to -7.3 °C
- Imaging: Temperature jump 40 °C due to 110 W internal heat load; -9.9 °C to 45.2 °C

Optics

- CCDs not modelled hence EHU response is used
- Coasting: Don't reached cyclic stability
- Imaging: Temperature jump less than 7.5 °C

Solar panels

- Coasting: side -45 °C to 68 °C; main -30 °C to 121 °C
- Imaging: side -50°C to 78°C; main -38 °C to 133 °C

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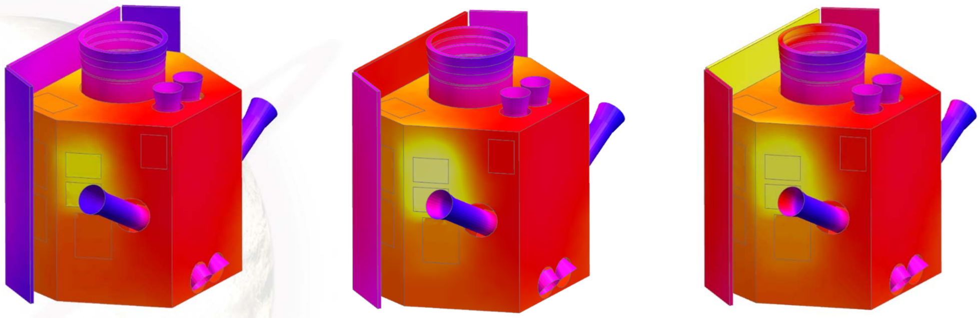
7. PERFORMANCE OF TCS

General

- Satellite experiences uniform orbital heat load
- Hot and cold condition mainly due to mission scenarios
- The suggested TCS seems to create a relatively low uniform temperature inside satellite
- More internal heat loads will be incorporated in the future which will probably increase the temperature



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8. EXPERIMENTAL WORK

EHU

- EHUs modelled as thin-walled boxes
- Thermal model comparison: thermal vacuum test

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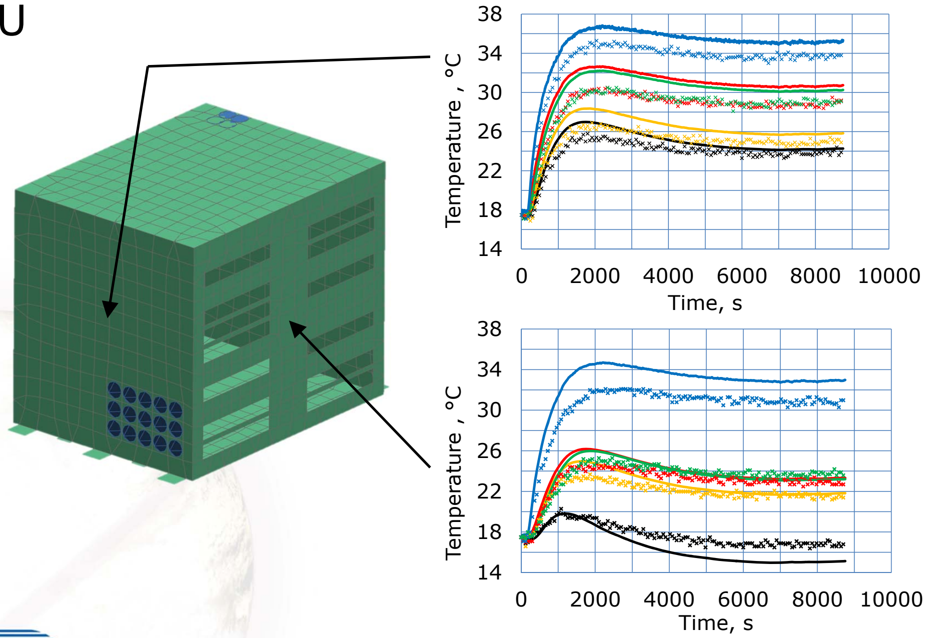
8. EXPERIMENTAL WORK

EHU



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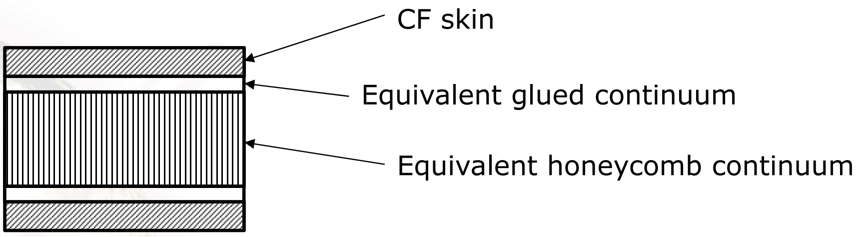
8. EXPERIMENTAL WORK

Solar panels

- Effective thermal conductivity models: Swann and Pittman[5], Gilmore, Daryabeigi[6] (modified Swann and Pittman model: glued interfaces and CF sheets)
- Expanding effective model to an equivalent continuum (k, ρ, c_p) similar to Liu[7]: 3D, orthotropic, transient conduction
- Thermal model still under investigation results look promising



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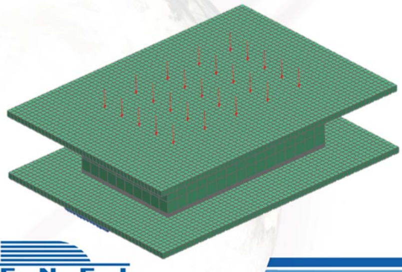
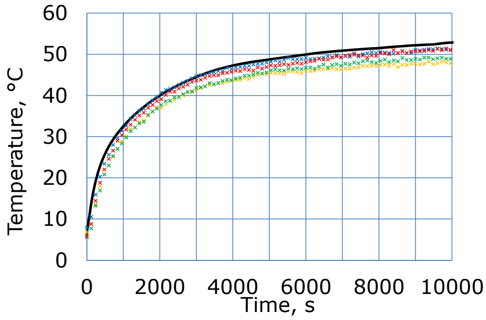
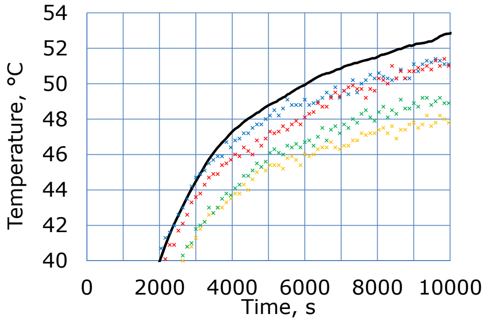
8. EXPERIMENTAL WORK

Solar panels







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8. EXPERIMENTAL WORK

Thermo-optical measurements

- Physics Department of the University of the Western cape using a Varian Cary 1/3 spectrophotometer
- Spectral values: hemispherical averaged and specular reflectivity (measured), hemispherical averaged absorptivity (indirect)

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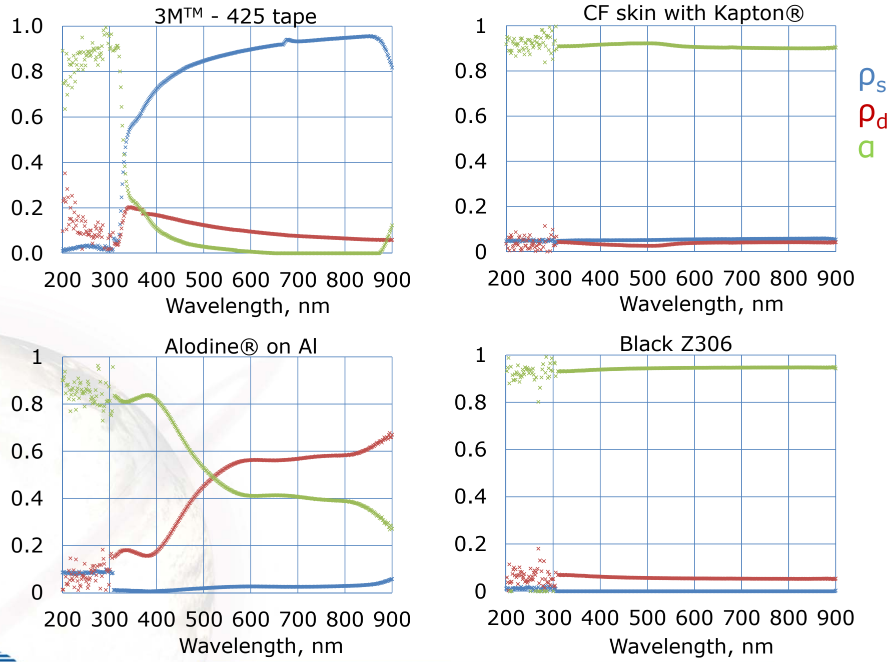
8. EXPERIMENTAL WORK



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9. Conclusion

TCS

- Relatively low uniform temperature inside the satellite
- Future work: update thermal model and adjust TCS where needed

Experimental work

- EHU thermal model shows good comparisons with measured data
- Similarly for the SP thermal model
- Thermo-optical test results shows good comparison with published data
- Future work: Complete SP thermal model, expand and refine thermo-optical databases

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- [2]D. Gilmore, *Satellite Thermal Control Handbook 2nd ed.*, The Aerospace Corporation, California, (2002).
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- [4]Meeus, *Astronomical Algorithms 2nd ed.*, Willmann-Bell, Inc., Virginia, (2000).
- [5]R.T. Swann, C.M. Pitmann, *Analysis of effective thermal conductivities of honeycomb-core and corrugated-core sandwich panels*, NASA, Washington, (1961).
- [6]K. Daryabeigi, *Heat transfer in adhesively bonded honeycomb core panels*, AIAA, Virginia, (2001).
- [7]D. Liu, L. Jin, X. Shang, *Comparison of equivalent and detailed models of metallic honeycomb core structures with in-plane thermal conductivities*, Elsevier ltd., ScienceDirect, (2011).

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Appendix F

GENETIK

Optimisation tool for thermal analyses performed with SYSTEMA

Hélène Pasquier Guillaume Mas
(CNES, France)

Abstract

GENETIK is a software developed by CNES to facilitate the detection of thermal sizing cases. It is based on genetic algorithm to explorate solution space and to determine the worst environmental conditions (solar, albedo and earth fluxes).

With some improvements on thermal study management in SYSTEMA V4, and particularly the possibility to perform parametric analyses, the coupling of optimization tool to SYSTEMA is made possible.

The objectives of the presentation are to:

- Present GENETIK functionalities
- Develop the possibilities of this optimisation tool

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GENETIK+

OPTIMIZATION TOOL FOR THERMAL ANALYSES (PERFORMED WITH SYSTEMA)

Guillaume MAS (CNES)
Hélène Pasquier (CNES)
Francesco Bilotta (Trainee)

14 – 15 October 2014

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AGENDA

- CONTEXT OF THE STUDY
- 2013 DEVELOPMENTS – GAETAN FUNCTIONNALITIES IMPLEMENTED INTO SYSTEMA
- GENETIK+ OVERVIEW
- APPLICATION CASES
- PERSPECTIVES AND CONCLUSION

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CONTEXT OF THE STUDY

Missions become more complex:

Drifting orbits, complex spacecraft attitudes, challenging thermal control designs…Limitation of classical thermal analyses for:

- Sizing thermal case definition
- Thermal design optimisation (radiator size / coating vs. Heating power budget)
- Calculation margins management

→ Development of GENETIK tool (2005 – 2009)

- GENETIK coupled with THERMICA V3
- Limited to analyses on external fluxes
- Not user friendly…

CONTEXT OF THE STUDY

Evolution of SYSTEMA :

New functionnalities of SYSTEMA V4:

- SYSTEMA easily controlled by Python scripts
- 2013 developments – Introduction of GAETAN main functionalities into SYSTEMA (Python script)

→ Possibility to interface GENETIK with SYSTEMA

- 2014 : Extension of GENETIK possibilities → Development of GENETIK+

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2013 DEVELOPMENTS

2013 – GAETAN main fonctionnalities implemented into SYSTEMA:

Development in collaboration with SYSTEMA team.

- GAETAN main functionnalities implemented:
  - Stabilized cycling computation
  - Temperature initialization (file / group /…)
  - …
- Formalism for management of complete thermal analysis with SYSTEMA
  - Calculation case definition = « SYSTEMA skeleton »
  - Global thermal Study definition

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2013 DEVELOPMENTS

Calculation case definition:

One file to describe a calculation case:

```
# This is an example of a Computation Case file
#--------------------------------------------------------

# Case Name
CASE = calcul_case_1

# Model Definition
#----------------------------
$MODEL
$GMM
  MATERIAL  = material.sysmtr
  MODEL = model\Test.sysmdl
  MESHING   = model\Test.sysmsh
$TMM
  model\user_file.dat

# Load Case Definition
#--------------------------------
$LOADCASE
$GMM
  TRAJECTORY   =      { Type=SunSynchronuous,
                        Alt=830, AscNode=22.5,
                        Date="22/10/2013  00:00:00.000",  End=1 }
  KINEMATICS   = { V1=-Z, D1=Sun, V2=-Y, D2=Velocity }
  MISSION  = { Comput=15.0 }
$TMM
        model\inits.nwk
        model\heaters.nwk

# Calculation Process Definition
#------------------------------------------
$PROCESS
# This is where to set a process file (Thermica+Thermisol)  with the command:
# PROCESS = comput.sysprc
# Or to indicate the process by specs
$THERMICA
        SUNCST  = 1400.0
        ALB_EARTH  = 0.31
        T_EARTH    = -25.0
        NB_RAYS_GR  = 10000
        NB_RAYS_SF =  5000
        GL_THRESH  = 1.0e-4

        SEQUENCE  = NOD + GR + GL + SF + PF

$THERMISOL
   Transient  = SCRANK
```

Nodal Network definition:
- Nodes definition
- Couplings (user files)

Load case definition:
- GMM : External fluxes → Systema mission
- TMM : Heating power, thermal dissipation …(user files)

Computation process definition:
- THERMICA process
- THERMISOL process

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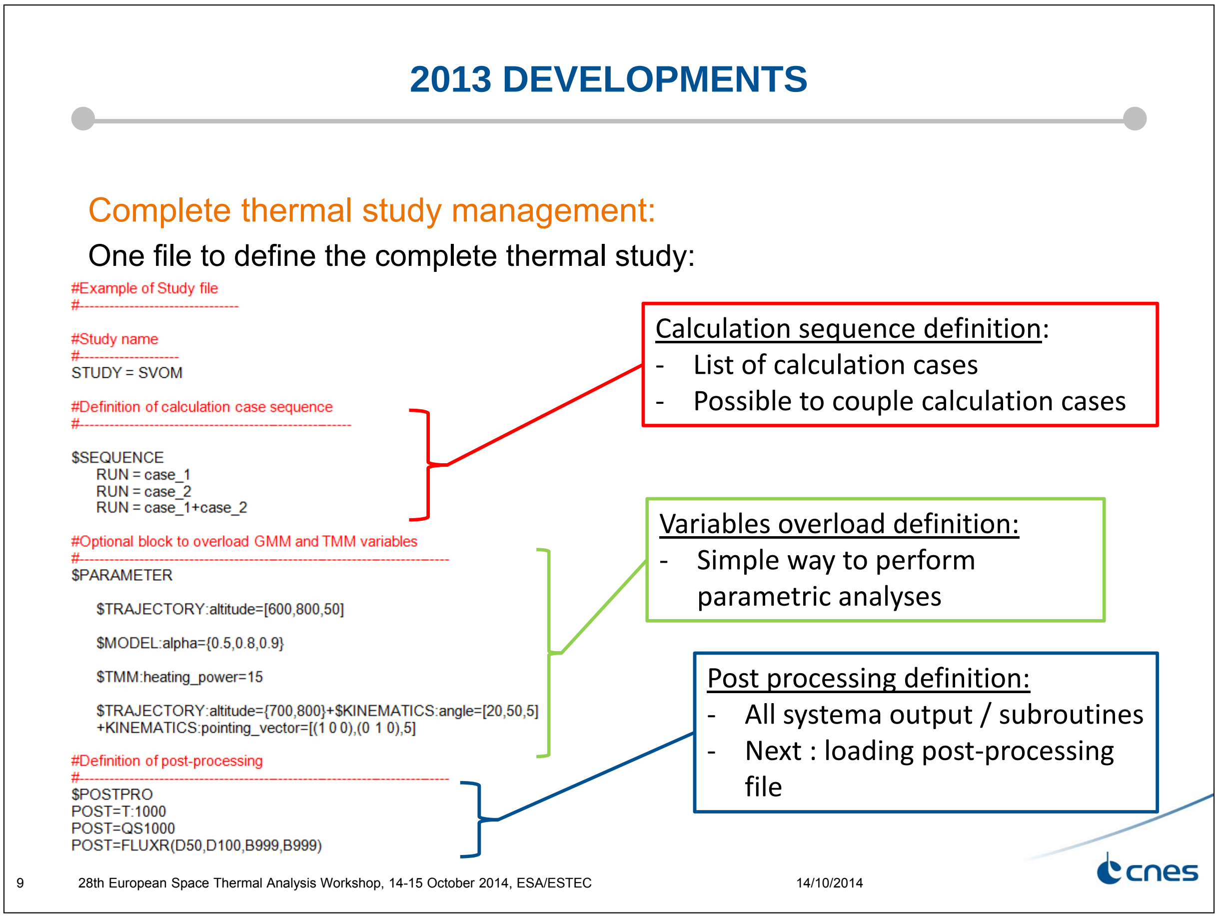
2013 DEVELOPMENTS
Complete thermal study management:
One file to define the complete thermal study:
#Example of Study file
#--------------------------------
#Study name
#---------------------
STUDY = SVOM
#Definition of calculation case sequence
#--
$SEQUENCE
RUN = case_1
RUN = case_2
RUN = case_1+case_2
#Optional block to overload GMM and TMM variables
#--
$PARAMETER
$TRAJECTORY:altitude=[600,800,50]
$MODEL:alpha={0.5,0.8,0.9}
$TMM:heating_power=15
$TRAJECTORY:altitude={700,800}+$KINEMATICS:angle=[20,50,5]
+KINEMATICS:pointing_vector=[(1 0 0),(0 1 0),5]
#Definition of post-processing
#--
$POSTPRO
POST=T:1000
POST=QS1000
POST=FLUXR(D50,D100,B999,B999)
Calculation sequence definition:
- List of calculation cases
- Possible to couple calculation cases
Variables overload definition:
- Simple way to perform parametric analyses
Post processing definition:
- All systema output / subroutines
- Next : loading post-processing file
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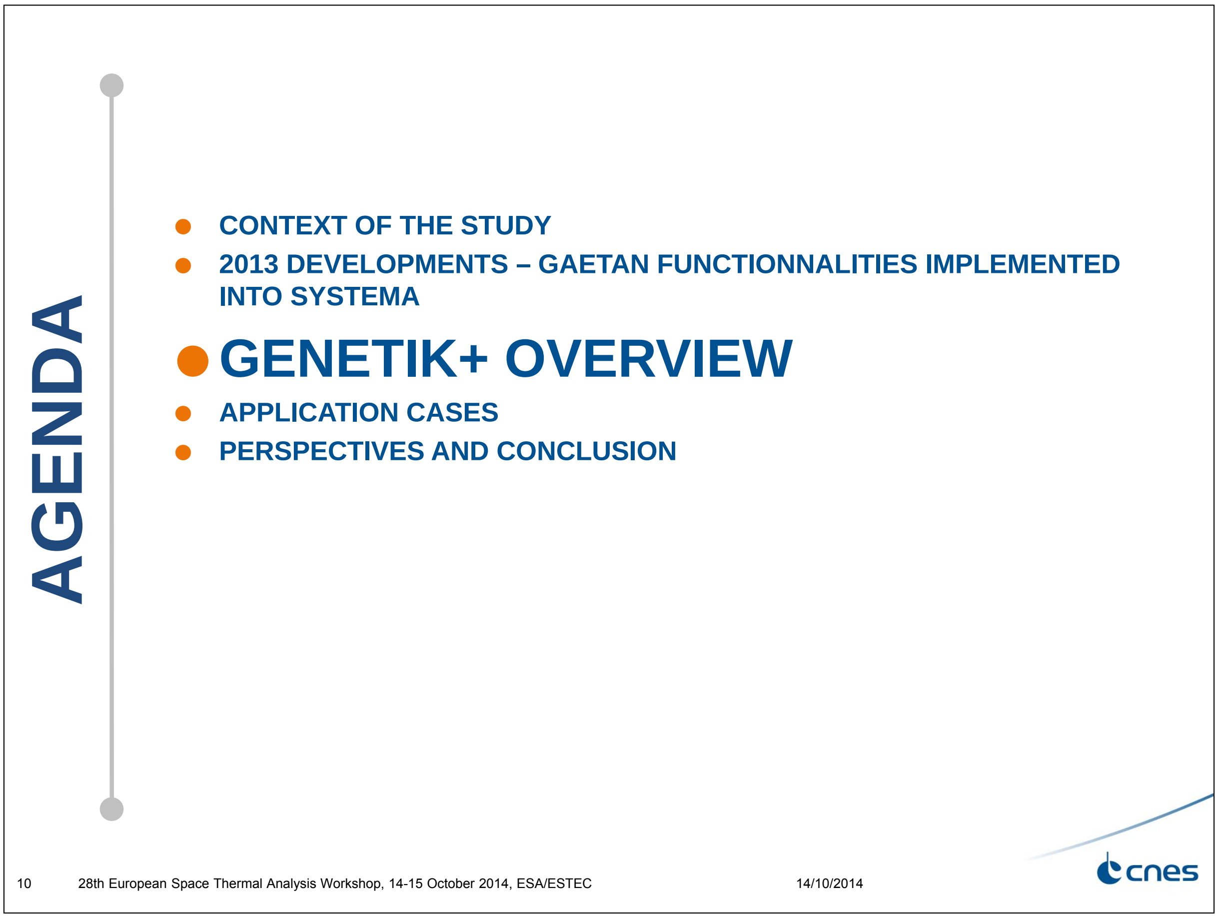
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GENETIK+ OVERVIEW

GENETIK+ presentation:

Tool based on genetic algorithm :

- GENETIK tool developed in CNES between 2005-2009
- Search technics used to find solutions to optimization problems
- Intelligent exploration of space solutions
- Technics inspired by evolutionary biology such as inheritance, mutation, selection, and crossover.

Some vocabulary…

- Gene : parameter of the problem (ex. : spacecraft altitude)
- Individual : combination of genes
- Population : set of individual
- Generation : selection of some individual in the population
- Fitness : evaluation function to optimize

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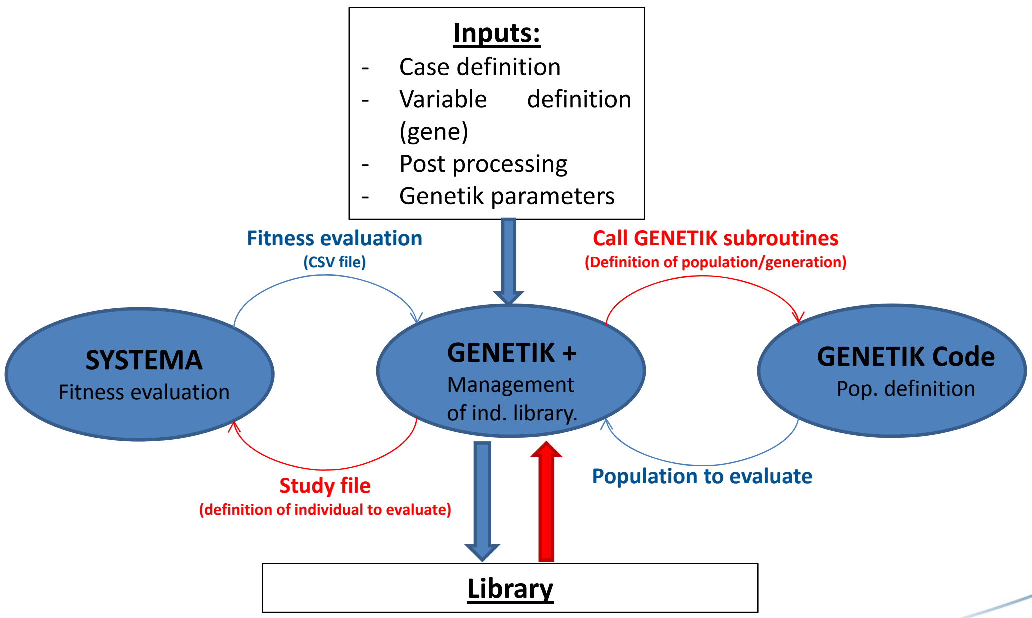
GENETIK+ OVERVIEW

GENETIK+ interfaces GENETIK code with SYSTEMA:



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- PERSPECTIVES AND CONCLUSION

APPLICATION CASES

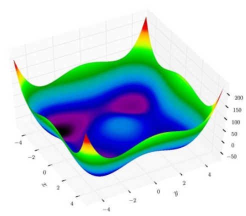
GENETIK + / GENETIK / SYSTEMA Gateways validation:

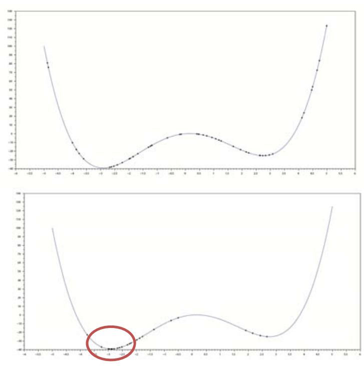
GENETIK+ / GENETIK:

- Use of well known function (Styblinski-Tang function) to evaluate population fitness :
  - Evaluation possible for n parameters
  - Locals and global extrema

$$f(\mathbf{x}) = \frac{\sum_{i=1}^{n} x_i^4 - 16x_i^2 + 5x_i}{2}, \quad \text{with } -5 \le x_i \le 5, \quad 1 \le i \le n.$$

$$f(\underbrace{-2.903534, \ldots, -2.903534}_{\text{n times}}) = -39.16599n$$





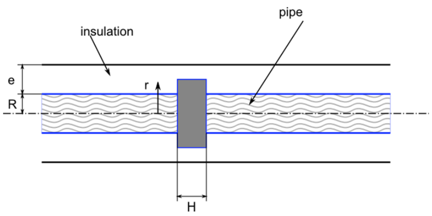
- Validation of GENETIK+ / GENETIK gateway : ***OK***
- Validation of GENETIK algorithm : ***OK***

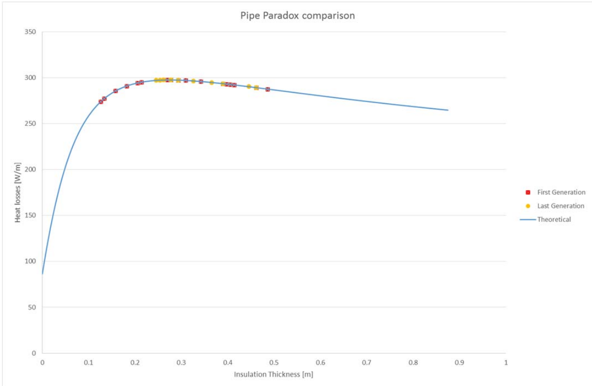
APPLICATION CASES

GENETIK + / GENETIK / SYSTEMA Gateways validation:

GENETIK+ / SYSTEMA

- Simple model with analytic solution - Pipe insulation paradox:
  - In particular configuration → Increase thickness = Increase heat exchange area = Increase losses
  - Find minimum thickness of insulation material to minimize losses





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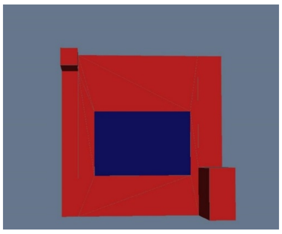
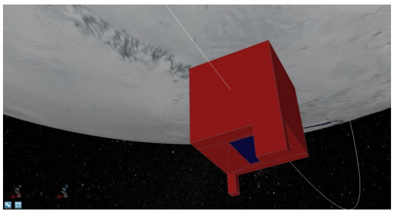
APPLICATION CASES

Application cases for demonstration of GENETIK+ performances:

Thermal control design optimization:

- Radiator size vs. heating power budget for instrument thermal control:
  - Definition of instrument temperature range in OP and NOP mode
  - Optimum temperature for OP mode
  - Definition of maximum OP and NOP heating budget
  - Parametric Radiator shape : 4 parametric points + variable thermo-optical properties (α,ε)
  - Search of radiator size and location → Best compromise to optimize instrument temperature, minimize its variation, minimize the use of heating power
- More than 120 000 possible configurations → 8 hours to reach stagnation criteria
- GENETIK+ gives a solution to analyse for understanding → help for design definition





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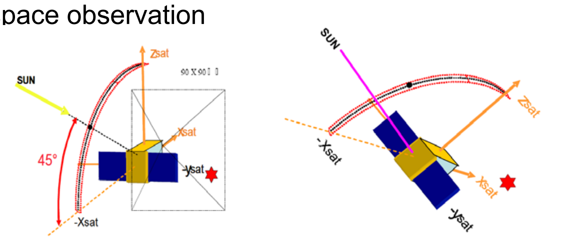
APPLICATION CASES

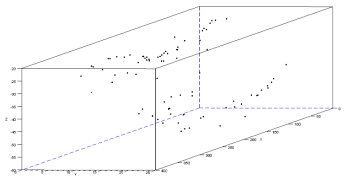
Application cases for demonstration of GENETIK+ performances:

Detection of sizing thermal case:

- Analysis of a complex mission for space observation
  - Drifting orbit
  - Complex spacecraft attitude



- No simple way to determine sizing thermal case
  - Thousands of computation cases and data to analyse
- GENETIK+ performances:
  - Full analysis led in 2011 (by hands) → 1 week
  - GENETIK+ → 1 hour to reach stagnation criteria
  - same results



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AGENDA

- CONTEXT OF THE STUDY
- 2013 DEVELOPMENTS – GAETAN FUNCTIONNALITIES IMPLEMENTED INTO SYSTEMA
- GENETIK+ OVERVIEW
- APPLICATION CASES
- **PERSPECTIVES AND CONCLUSION**

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PERSPECTIVES AND CONCLUSION

GENETIK+ shows real potential:

- Improvement of the optimization tool GENETIK:
  - More possibilities for optimization studies
  - Easy to use
  - Validated
- Potentiality shown on real cases
- Full potential to investigate
  - Exploitation of all data
  - Application cases: thermal model correlation, model reduction, management of calculation uncertainties
- Internship in 2015 to explore capabilities of GENETIK+:
  - Model correlation
  - Management of calculation uncertainties
  - Process to use optimization tool for thermal analyses
  - …

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Appendix G

An overview of CHEOPS Instrument thermal design and analysis

Romain Peyrou-Lauga
(ESA, The Netherlands)

Giordano Bruno
(University of Bern, Switzerland)

Abstract

CHEOPS (CHaracterizing ExoPlanet Satellite) is the first ESA S-class mission and is dedicated to search for planet transits by means of ultrahigh precision photometry on bright stars already known to host planets. The University of Bern is in charge of the CHEOPS instrument, which is a single aperture, high accuracy photometer operating between 0.4 and 1.1 micron. The focal plane detector consists of a single CCD operated at -40 °C and requires a thermal stability better than 10 mK. The presentation will provide an overview of the thermal design and of the thermal analysis of the instrument.

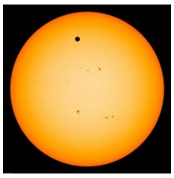
An overview of CHEOPS Instrument thermal design and thermal analysis

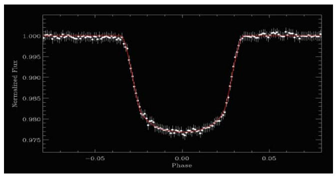
Giordano Bruno (University of Bern)
Romain Peyrou-Lauga (ESA)

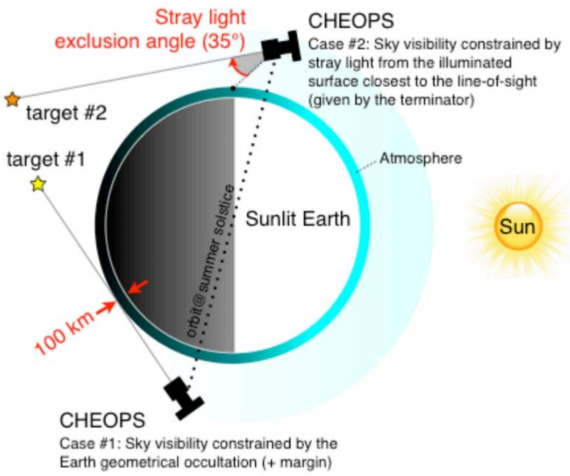
Thermal analysis workshop – ESTEC – 14-15 Oct. 2014

CHEOPS MISSION

- CHEOPS is the first ESA's Science Programme of class S (Small mission).
- The purpose of the mission is to characterise already known exoplanets: it will measure the bulk density of «super-Earth»- and «Neptune»-mass planets, for future in-depth characterisation studies of exoplanets in these mass ranges.
- A sun synchronous LEO orbit has been chosen with LTAN 6:00 am and altitude from 620 to 800 km.
- The Satellite Attitudes/pointings have been defined on the basis of the allowed observation field, which in turn, must respect the Earth stray light exclusion angles.







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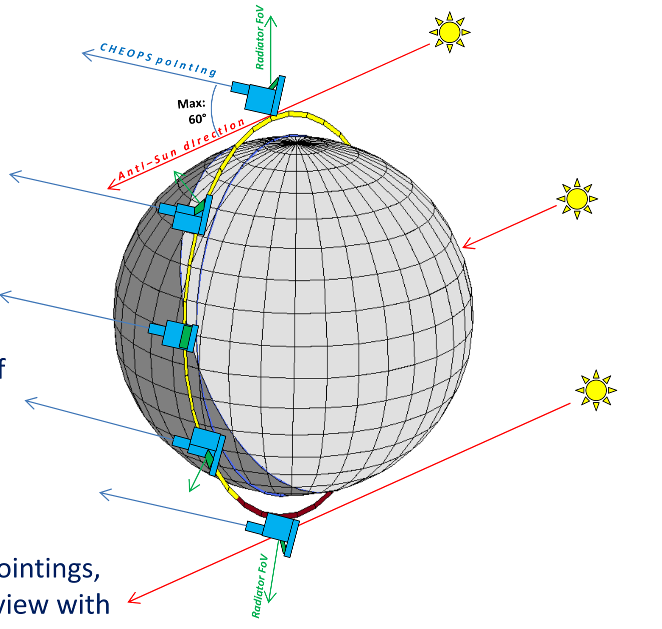
OVERVIEW OF CHEOPS ORBIT (1/2)

CHEOPS esa

- CHEOPS instrument must be able to point any star up to 60° away from the anti-Sun direction (combined azimuth / elevation angle)
- A rotation around the Telescope axis is possible (and used) to avoid (or minimize) the radiators field of view with the Earth.
- As a result, the Instrument is most of the time in the shade of the Sunshield and a constant spin allows the radiators never to face the Earth (for low off-axis pointings)
- BUT… for Instrument large off-axis pointings, radiators have an inevitable field of view with the Earth once per orbit – always above one of the Polar regions. Besides, the Telescope has also a large view factor with the Earth once per orbit.



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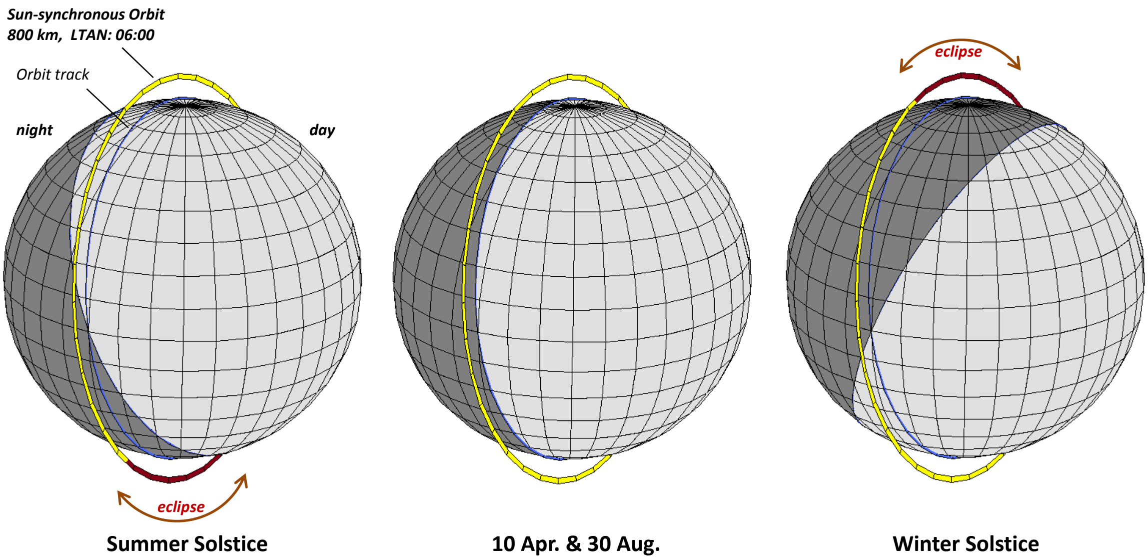
OVERVIEW OF CHEOPS ORBIT (2/2)

CHEOPS esa

- CHEOPS orbits is shown here at different periods of the year
- Eclipse occurs twice a year, around solstices.



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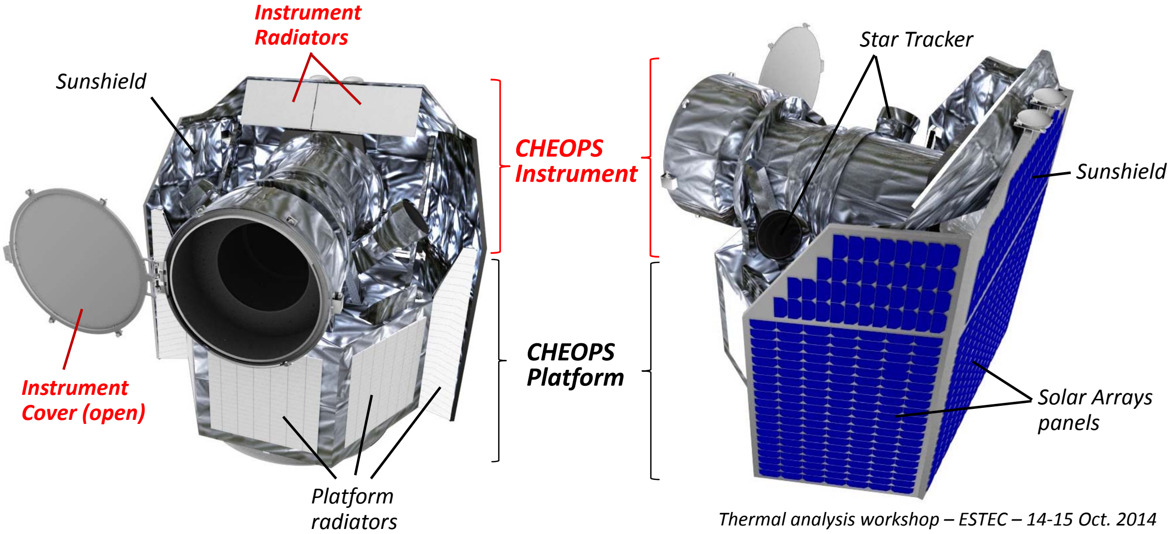
CHEOPS SPACECRAFT

- Enveloping dimensions: 1.5 m × 1.4 m × 1.5 m
- Spacecraft overall mass < 250 kg
- 60 W of continuous power provided to the Instrument by the Spacecraft
- Instrument radiators dimension is limited by the max allowed volume for the Spacecraft accomodation in the launcher



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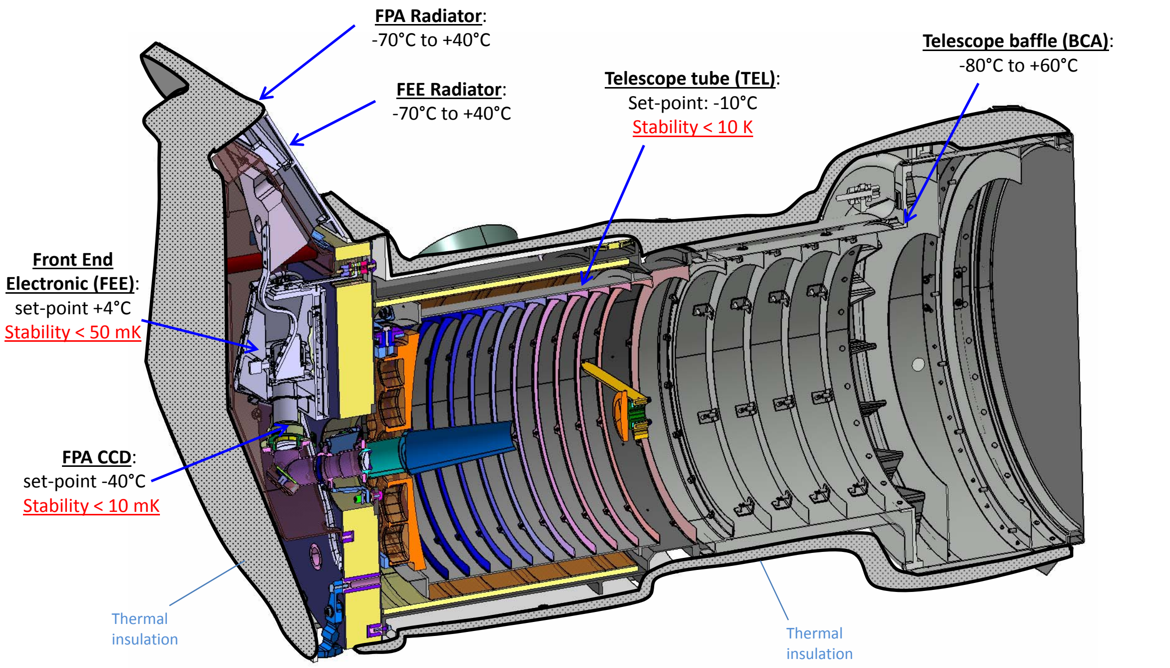
CHEOPS INSTRUMENT THERMAL REQUIREMENTS



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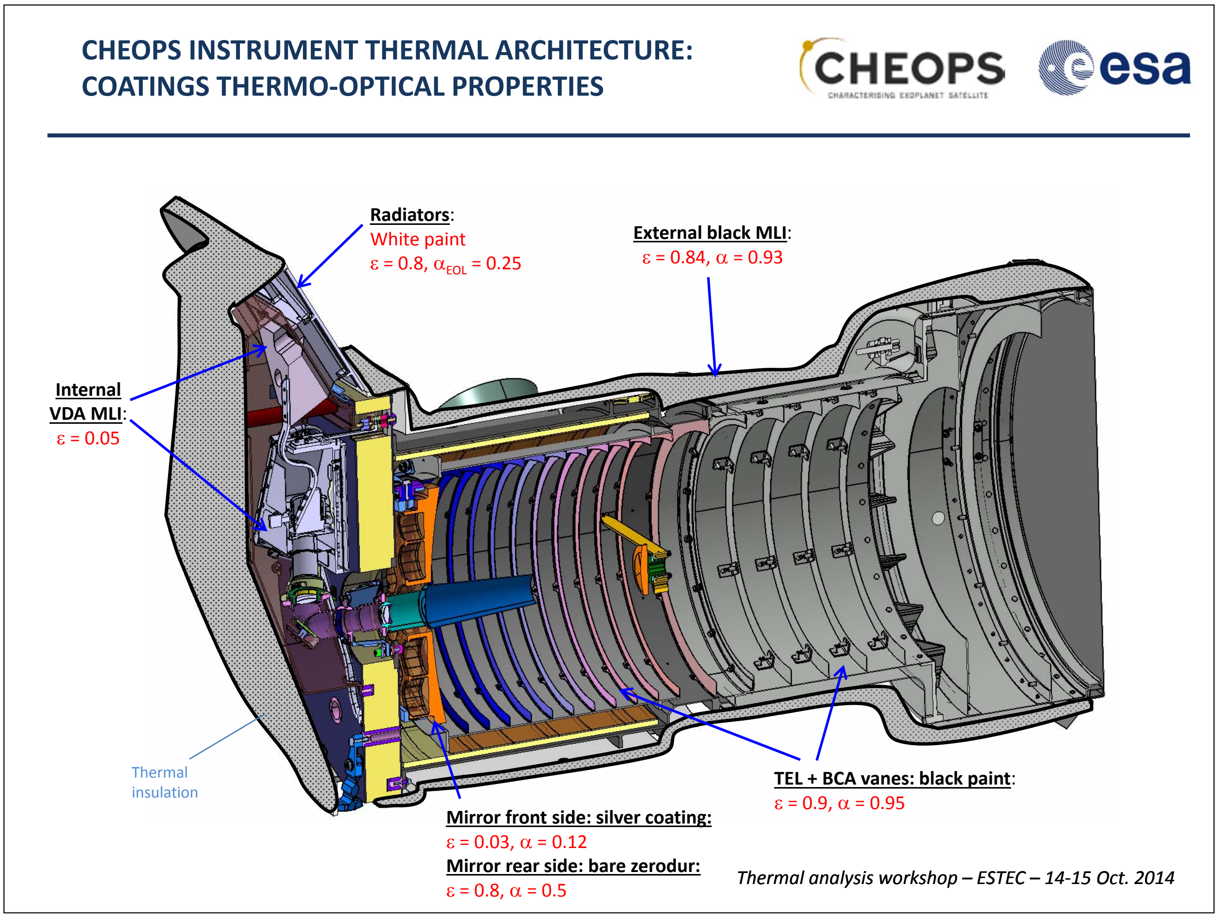
CHEOPS INSTRUMENT THERMAL ARCHITECTURE:
COATINGS THERMO-OPTICAL PROPERTIES
CHEOPS
CHARACTERISING EXOPLANET SATELLITE
esa
Radiators:
White paint
ε = 0.8, α_EOL = 0.25
External black MLI:
ε = 0.84, α = 0.93
Internal
VDA MLI:
ε = 0.05
Thermal
insulation
TEL + BCA vanes: black paint:
ε = 0.9, α = 0.95
Mirror front side: silver coating:
ε = 0.03, α = 0.12
Mirror rear side: bare zerodur:
ε = 0.8, α = 0.5
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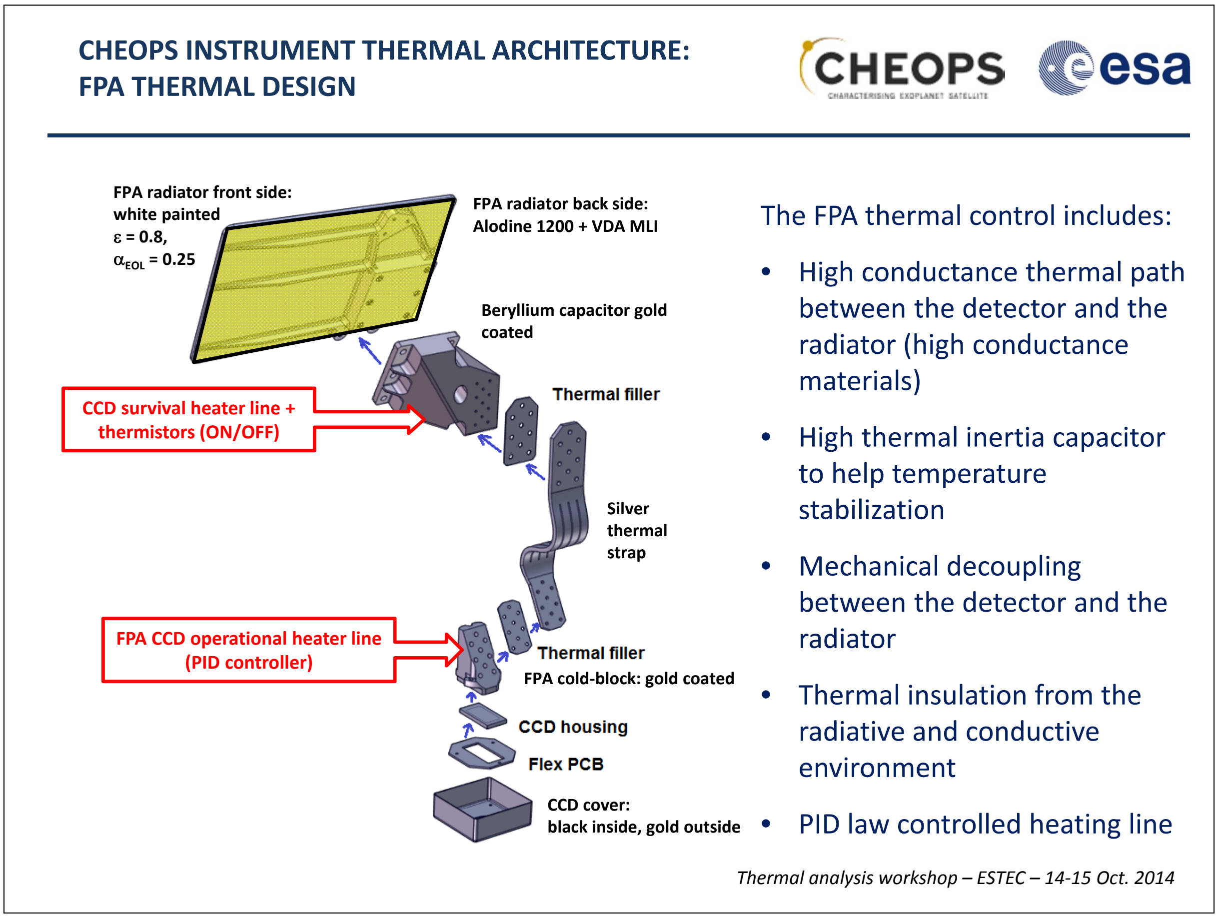
CHEOPS INSTRUMENT THERMAL ARCHITECTURE:
FPA THERMAL DESIGN
CHEOPS
CHARACTERISING EXOPLANET SATELLITE
esa
FPA radiator front side:
white painted
ε = 0.8,
α_EOL = 0.25
FPA radiator back side:
Alodine 1200 + VDA MLI
Beryllium capacitor gold
coated
CCD survival heater line +
thermistors (ON/OFF)
Thermal filler
Silver
thermal
strap
FPA CCD operational heater line
(PID controller)
Thermal filler
FPA cold-block: gold coated
CCD housing
Flex PCB
CCD cover:
black inside, gold outside
The FPA thermal control includes:
• High conductance thermal path between the detector and the radiator (high conductance materials)
• High thermal inertia capacitor to help temperature stabilization
• Mechanical decoupling between the detector and the radiator
• Thermal insulation from the radiative and conductive environment
• PID law controlled heating line
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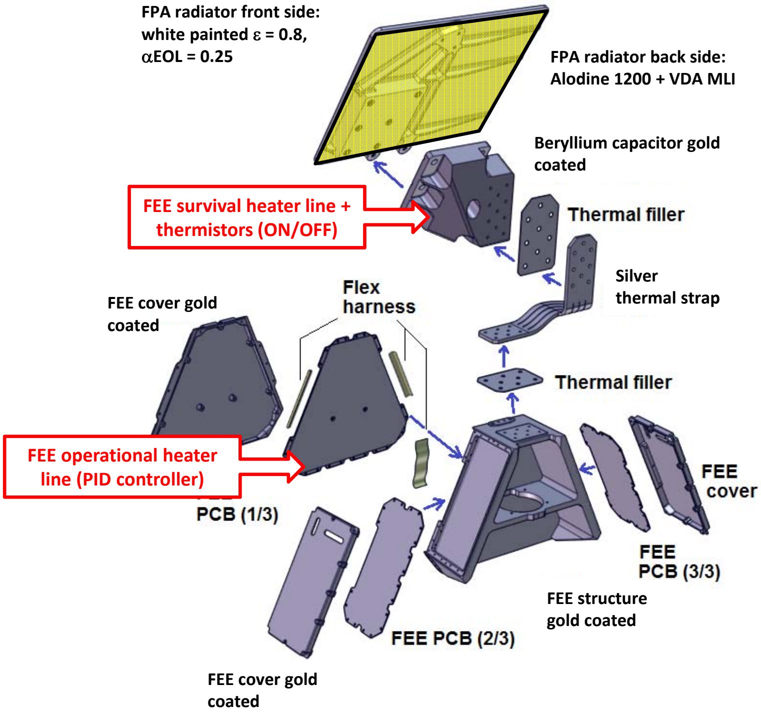
CHEOPS INSTRUMENT THERMAL ARCHITECTURE: FEE THERMAL DESIGN



The FEE thermal control presents similar features than the FPA (as seen previously):

- High conductance
- High thermal inertia
- Mechanical decoupling
- Thermal insulation
- PID law

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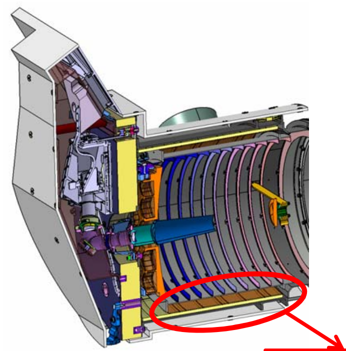
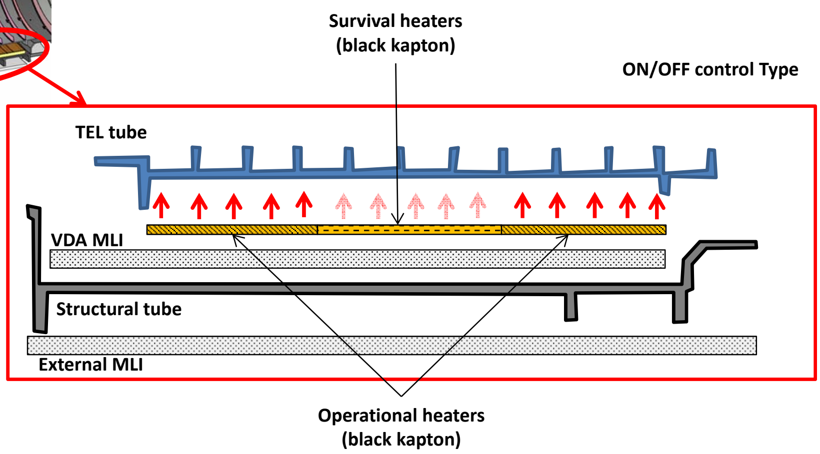
CHEOPS INSTRUMENT THERMAL ARCHITECTURE: TELESCOPE THERMAL CONTROL



The Telescope thermal control includes:

- 2 sets of MLI (one for each tube)
- Several local heating lines to counter gradients



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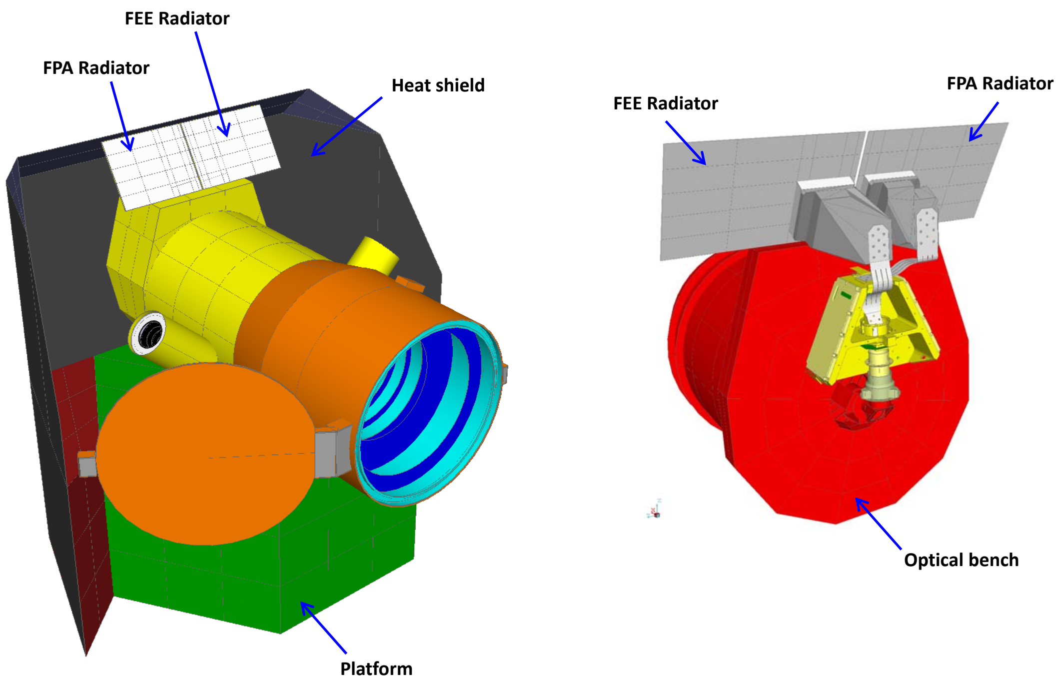
UP-TO-DATE CHEOPS GEOMETRICAL MODEL



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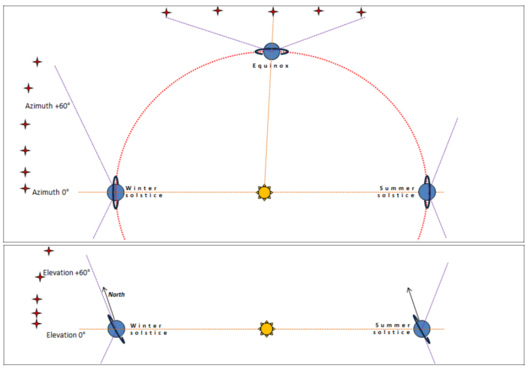
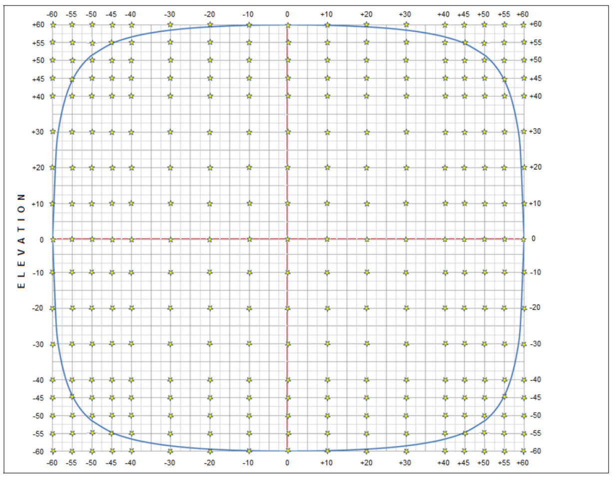
THERMAL ANALYSIS AT SRR





- An extensive survey has been performed by ESA at SRR, of all the possible attitudes, with Azimuth and Elevation steps of 5°/10° inside the required range (blue line in the picture)
- Azimut has been defined wrt the ecliptic plane, while the Elevation wrt to ortogonal plane to the ecliptic plane, containing the Sun and the Satellite

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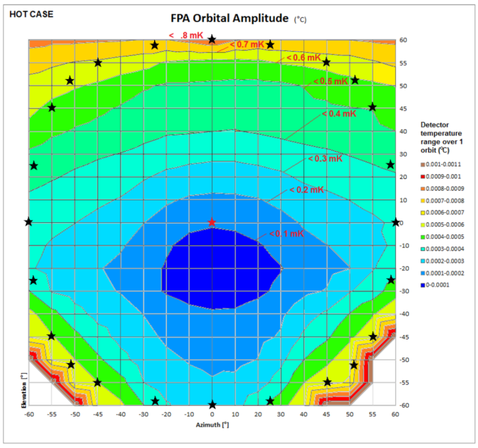
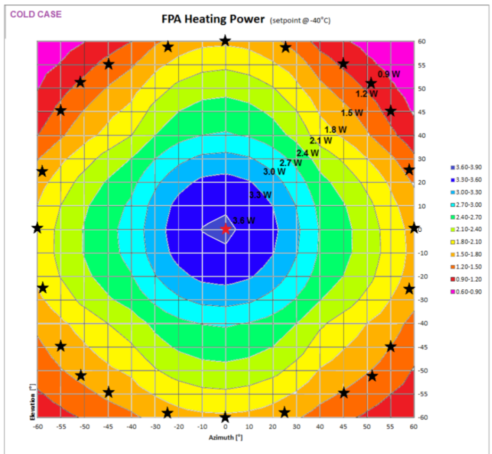
THERMAL ANALYSIS AT SRR



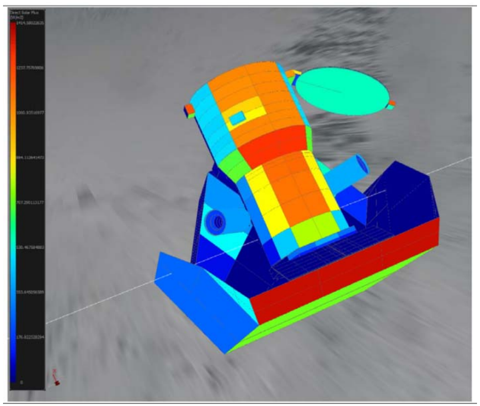
- The stability/gradients maps of the TEL tube, Mirrors, FPA CCD and FEE have been worked out, allowing to identify the attitude worst condition.



- Two worst cases have been identified:
  - cold case: 10th of April in anti-sun pointing
  - hot case: winter solstice, pointing at the boundary of the observed field

THERMAL ANALYSIS AT PDR

- The insights of the SRR have been developed by Unibe in Systema / Thermica
- The margin policy has been consolidated:
  - an uncertainty of -10°C on the FPA and FEE set-points in hot condition, for the FPA and FEE radiators design
  - An uncertainty of +10°C on the FPA and FEE set-points in cold condition, for the TC power sizing



CHEOPS ABOVE SOUTH POLE: A=0°, E= 60°, Direct solar flux (Systema/Thermica)

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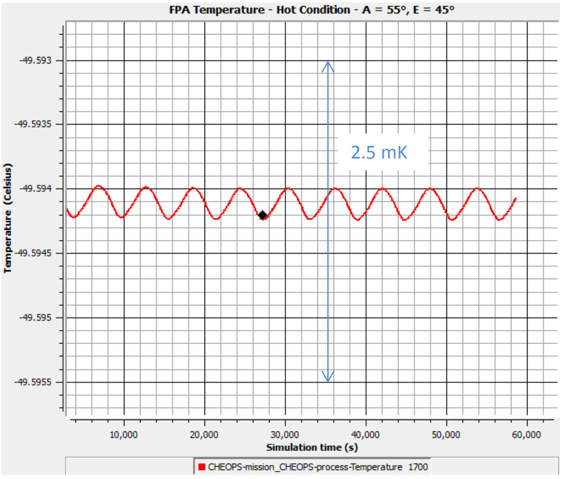
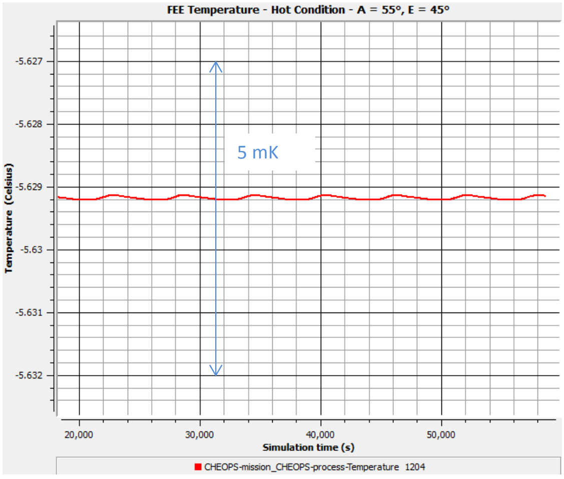
THERMAL ANALYSIS AT PDR

- The analysis results show that the demanding stability requirements for the FPA CCD and FEE (< 10 mK and < 50 mK respectively) are achievable, with a proper tuning of the PID controllers gains





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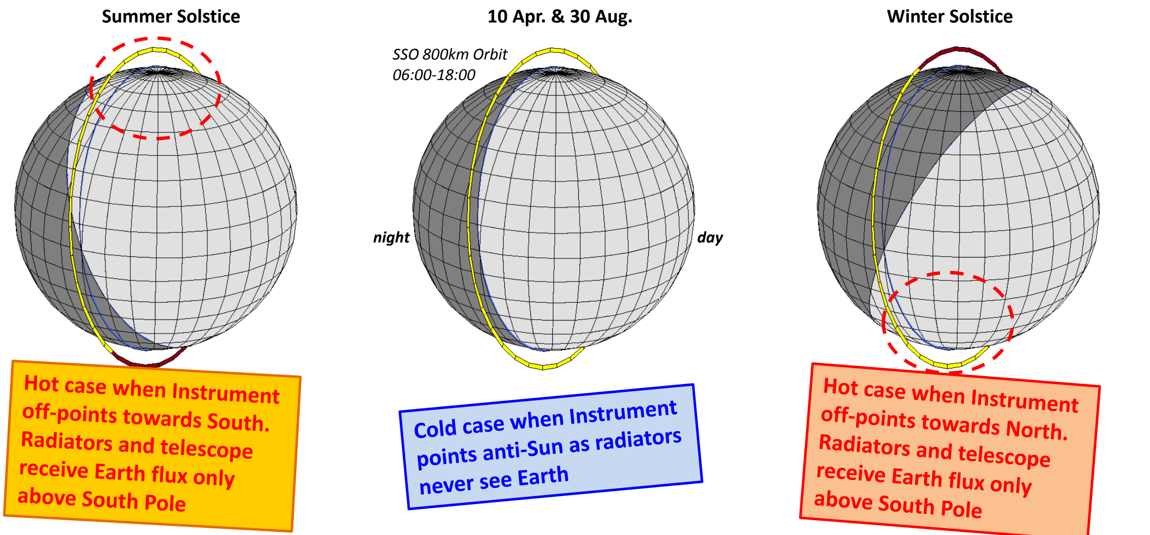
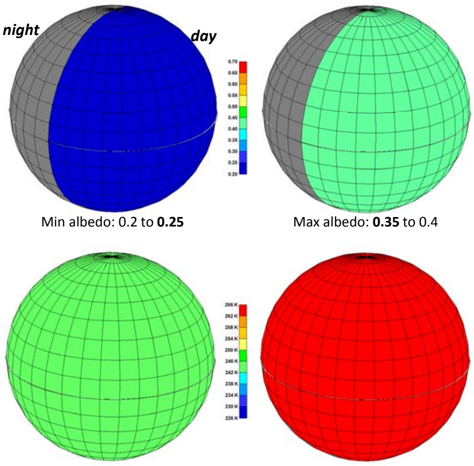
EARTH ENVIRONMENT HYPOTHESES (Albedo, IR flux) (1) Discussion for CHEOPS case…

- The recent thermal analysis activities led a specific reflection about the environment hypothesis in the pecular case of CHEOPS combined orbit/ pointings.
- For Instrument large off-axis pointings, radiators and telescope have an inevitable field of view with the Earth once per orbit – always above one of the Polar regions.



- So the legitimate question is whether albedo/ Earth IR are adequately modeled for those specific cases.

EARTH ENVIRONMENT HYPOTHESES (Albedo, IR flux) (2)
Common hypotheses…



Min albedo: 0.2 to **0.25**

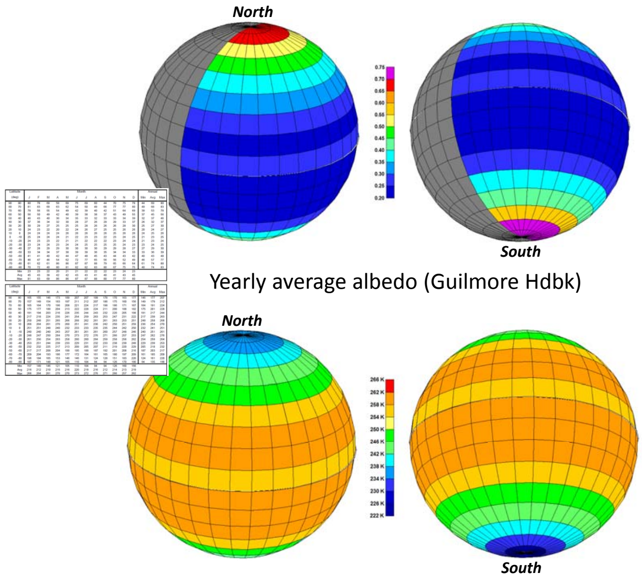
Max albedo: **0.35** to 0.4

Min Earth IR temp: 240 K to **244 K** (201 W/m² to

Max Earth IR temp: 260 K to **264 K**

For the SRR and PDR, usual values of albedo and IR flux were used. Min albedo + min IR flux were cumulated with min Sun flux (winter), which is conservative. As the radiators can receive Earth flux only above the Polar regions, we legitimately wonder if our hypothesis were not too conservative, leading to oversize the FPA and FEE radiators

Gilmore Handbook proposes a set of albedo / IR flux hypotheses depending on the latitude and the season:



Yearly average albedo (Guilmore Hdbk)

Yearly average Earth IR temp. (Gilmore Hdbk)

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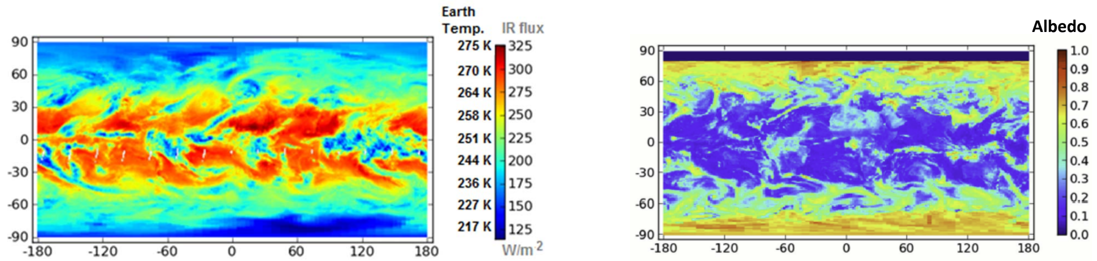
EARTH ENVIRONMENT HYPOTHESES (Albedo, IR flux) (3)
Using measured values of albedo/IR flux

- The idea is then to use real data of albedo / IR flux to get a realistic environment for the thermal simulation. NASA's CERES experiment provide daily geolocalised data for both albedo and IR flux (http://ceres.larc.nasa.gov/)

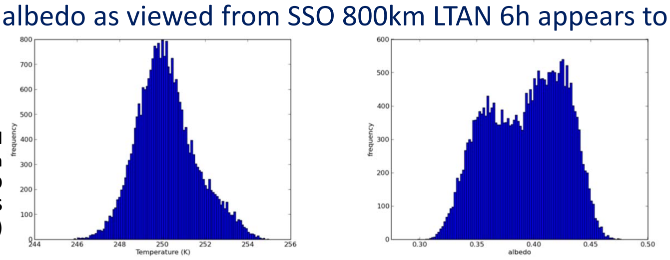


- Alex Green (PhD UCL/ESA) has computed 5 years of CERES data (2007-2011) to obtain averaged albedo /IR flux depending on the latitude, the season but also the orbit.

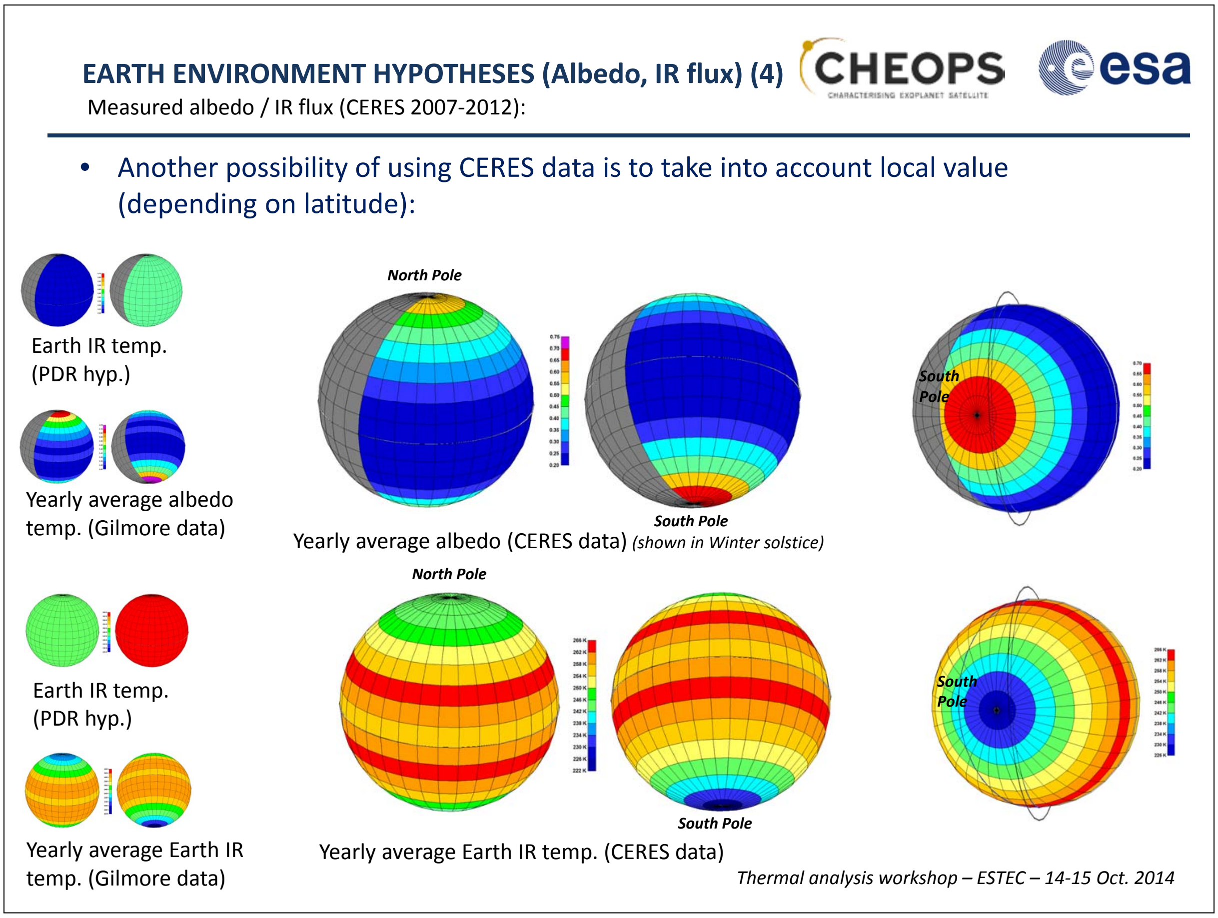
☞Average yearly IR Earth temp. as viewed from SSO 800km LTAN 6h appears to **250 ±4K**.

☞Average yearly albedo as viewed from SSO 800km LTAN 6h appears to **0.38 ± 0.07**.

Statistic orbital averaged value of Earth IR temperature for SSO 800km LTAN:6h (CERES data 2007-2011)



Statistic orbital averaged value of Albedo for SSO 800km LTAN:6h (CERES data 2007-2011)


EARTH ENVIRONMENT HYPOTHESES (Albedo, IR flux) (4)
Measured albedo / IR flux (CERES 2007-2012):
CHEOPS
CHARACTERISING EXOPLANET SATELLITE
esa
• Another possibility of using CERES data is to take into account local value (depending on latitude):
Earth IR temp.
(PDR hyp.)
Yearly average albedo
temp. (Gilmore data)
North Pole
South Pole
South Pole
Yearly average albedo (CERES data) (shown in Winter solstice)
Earth IR temp.
(PDR hyp.)
Yearly average Earth IR
temp. (Gilmore data)
North Pole
South Pole
South Pole
Yearly average Earth IR temp. (CERES data)
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THANK YOU !
Any questions…?
CHEOPS
CHARACTERISING EXOPLANET SATELLITE
esa

Appendix H

PEASSS
New horizons for cubesat missions

Luca Celotti Riccardo Nadalini
(Active Space Technologies GmbH, Germany)

Abstract

A cubesat is a type of miniaturized satellite for space research with external volume starting from 10x10x10cm3 (1U) and multiples of it (2U, 3U...). The cubesat platform is well-known to the academic researchers, small space companies and space amateurs, because of:

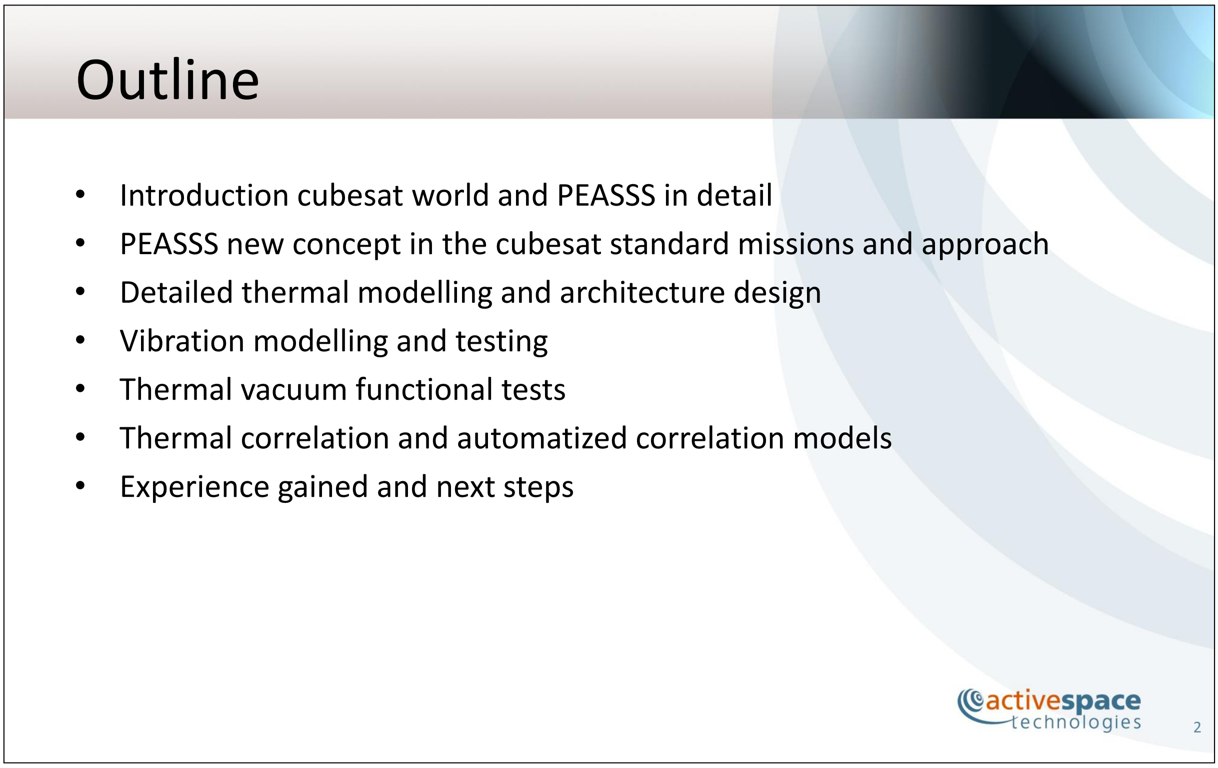
- standardized parts and interfaces;
- off-The-Shelf Components usage;
- "group" launches.

For these reasons, universities, small companies and space-enthusiasts have been the main users of this platform in the recent years. On the other hand, cubesat losses because of internal failures, not detailed design and analysis have been common.
PEASSS is a 3U cubsat under development as part of a FP7 European Commission project involving Active Space Technologies GmbH, TNO and ISIS (Netherlands), SONACA (Belgium), Technion and NSL (Israel). The main objective of the project is to develop, manufacture, test and qualify "smart structures" which combine composite panels, piezoelectric materials, and next generation sensors, for autonomously improved pointing accuracy and power generation in space. The system components include new nano satellite electronics, a piezo power generation system, a piezo actuated smart structure and a fiber-optic sensor and interrogator system.
The approach chosen for the design of PEASSS allows to combine the advantages of the cubesat platform to the complexity of the mission (technological demonstrator), achieving the mission success, technologies TRL step-up, while reducing the risk of the mission. This objective is achieved by increasing the level of analysis/verification of the whole satellite and the payloads/subsystems "like a non-cubesat mission", including:

- detailed thermal modelling with orbital and satellite life-time cases analysis;
- design of heaters and other active/passive thermal control solution;
- acceptance on breadboard and qualification on flight model for vibration tests;
- thermal vacuum functional tests;
- correlation and automatized correlation models;
- qualification thermal vacuum tests at payload level;
- acceptance thermal vacuum tests at satellite level.

The whole satellite thermal design and analysis are performed in Esatan-TMS and using AST's internally developed "model runner" and results "post-process" module.


PEASSS
New horizons for cubesat missions
European Space Thermal Analysis Workshop 2014
Luca Celotti
14-15 October 2014
Estec, Nordwijk - The Netherlands
making space a global endeavour
Luca Celotti, Riccardo Nadalini,
Małgorzata Sołyga, Israel Pons Mora
Active Space Technologies GmbH


Outline
• Introduction cubesat world and PEASSS in detail
• PEASSS new concept in the cubesat standard missions and approach
• Detailed thermal modelling and architecture design
• Vibration modelling and testing
• Thermal vacuum functional tests
• Thermal correlation and automatized correlation models
• Experience gained and next steps
2

Introduction - Cubesats

A cubesat is a type of miniaturized satellite for space research with external volume starting from 10x10x10cm^3 (1U) and multiples of it (2U, 3U…).

The cubesat platform is well-known to the academic researchers, small space companies and space amateurs, because of:

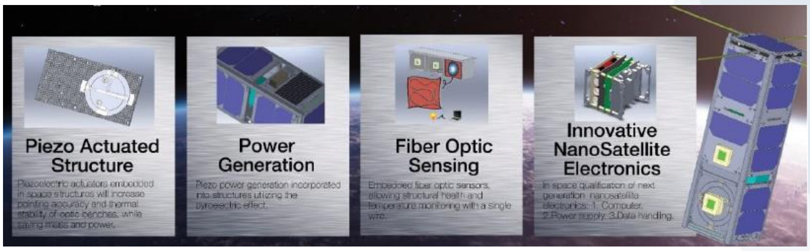
- standardized parts and interfaces;
- off-The-Shelf Components usage;
- “group” launches.

For these reasons, universities, small companies and space-enthusiasts have been the main users of this platform in the recent years. On the other hand, cubesat losses because of internal failures, not detailed design and analysis have been common.

activespace technologies 3

Introduction - PEASSS

PEASSS is a 3U cubsat under development as part of a FP7 European Commission project involving Active Space Technologies GmbH, TNO and ISIS (Netherlands), SONACA (Belgium), Technion and NSL (Israel).



SEVENTH FRAMEWORK PROGRAMME

The main objective of the project is to develop, manufacture, test and qualify “smart structures” which combine composite panels, piezoelectric materials, and next generation sensors, for autonomously improved pointing accuracy and power generation in space. The system components include new nano satellite electronics, a piezo power generation system, a piezo actuated smart structure and a fiber-optic sensor and interrogator system.

activespace technologies 4

Introduction - PEASSS "new" approach

The approach chosen for the design of PEASSS allows to combine the advantages of the cubesat platform to the complexity of the mission (technological demonstrator), achieving the mission success, technologies TRL step-up, while reducing the risk of the mission.

This objective is achieved by increasing the level of analysis/verification of the whole satellite and the payloads/subsystems "like a non-cubesat mission":

- Orbit modelling and trade-off
- Satellite attitude study
- Thermal cases evaluation
- Detailed thermal modelling and analysis (ESATAN-TMS) with worst-cases approach
- Detailed thermal design (taking into account the constraints of the mission)
- Structural analysis, vibration test for EM before acceptance for launch
- Thermal vacuum functional tests of payloads
- Thermal vacuum tests of payloads and system

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Detailed thermal modelling

Orbit and cases trade-off:

- Hot and cold cases evaluation taking into account the possible orbits PEASSS can have (depending on the launch).
- Two orbits have been considered:
  - 51° inclination, year period with the longest and the shortest eclipse duration (right ascension 0° and 90°)
  - SSO with 97.8° inclination, also with two sub-cases (longest and the shortest eclipse duration)
- Both orbits have altitude of 600km.

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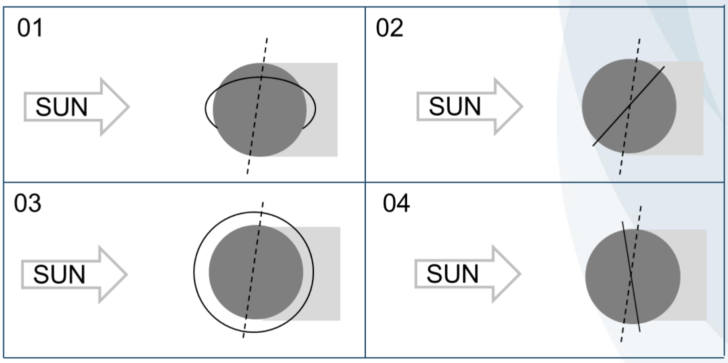
Detailed thermal modelling



Orbit no.	Inclination [°]	Right ascension [°]	Eclipse duration [min]	Case no.
01	51	0	35.5	CC01
02		90	26.8	CH01
03	97.8	0	35.5	CC02
04		90	0	CH02

Cold case chosen

Hot case chosen

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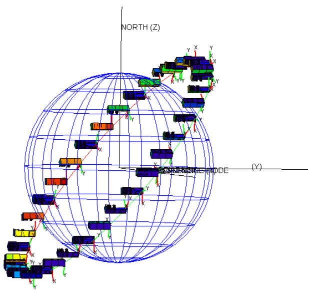
Detailed thermal modelling

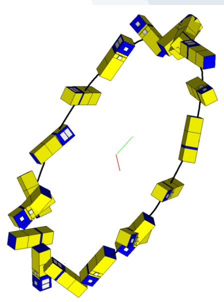
Spacecraft attitude: two attitudes evaluated during the development of the project

Spinned satellite

- Rotation around „Z“ axis

Tumbling satellite





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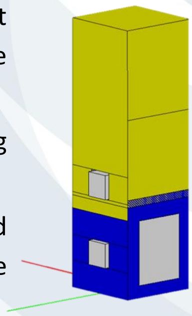
Detailed thermal modelling

Thermal cases definition in order to cover all possible operative modes of the satellite:

- **Hot case (C01)** - case with the hottest environmental conditions (orbit without eclipse). During the whole orbit payload instruments could operate with a pre-defined duty cycle.
- **Cold case (C02)** - case with the longest eclipse duration. Only during sunlight the payload components can operate.
- **Safe Mode (C03)** - the case with the longest eclipse (as C02) when payload components are not operating and the power dissipation within the spacecraft is as low as possible -surviving mode-.
- **Launch (C04)** - it covers the initial part of the mission, in the worst case scenario (ejecting form launcher in eclipse). Initial temperatures of all components are 15°C and the spacecraft is completely OFF during the maximum duration eclipse (35min).



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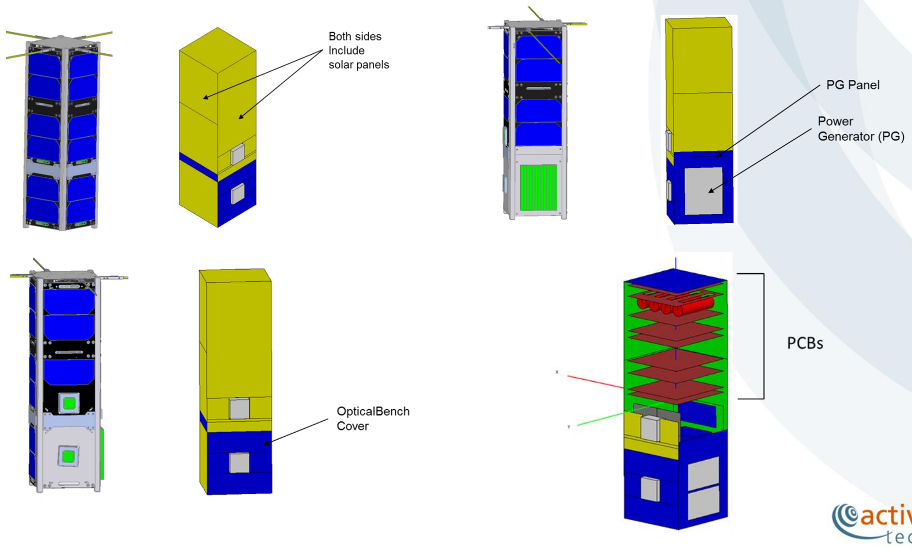
Detailed thermal modelling

→ From CAD to ESATAN model



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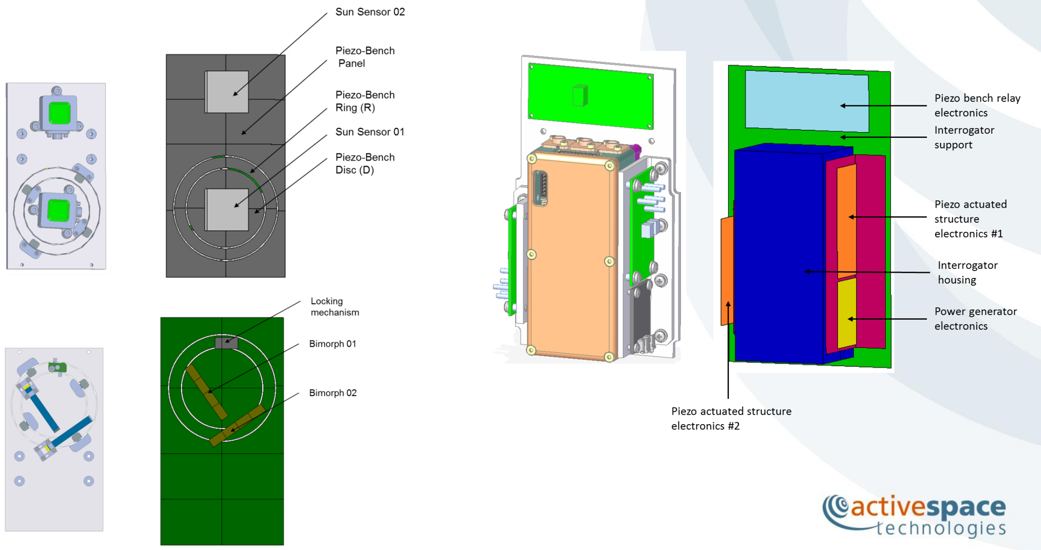
Detailed thermal modelling

→ From CAD to ESATAN model – payload components



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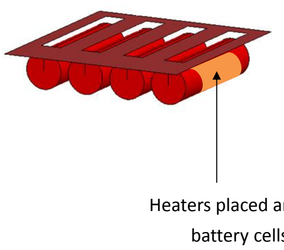
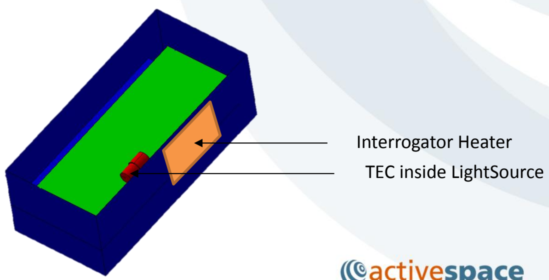
Architecture design - initial approach

- Passive thermal control preferred:
  - Internal and external coatings
  - Mechanical interfaces through the structure and the external panels modelled (insulators if needed)
  - Contrasting requirements form system (components within the temperature limits) and some of the payloads (power generator: maximize the deltaT on the payload panel -also satellite panel and so impacting on it-)
- Active thermal control elements:
  - Heaters on the battery cells (4 heaters, each placed on different cell)
  - Heater on the Interrogator housing – in order to increase the temperature of the payload during operations
  - TEC component inside the LightSource component – to provide stable temperatures during the component's operations





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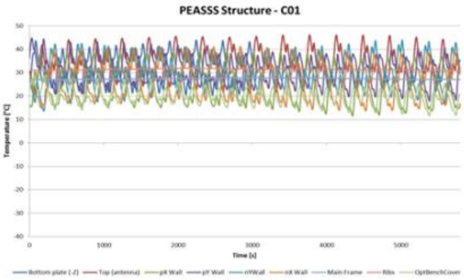
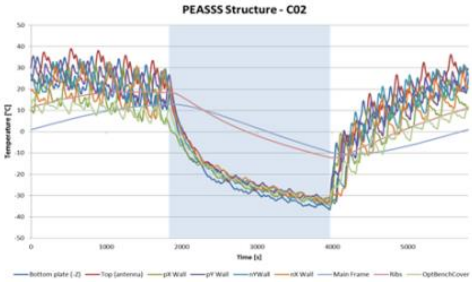
Thermal Results





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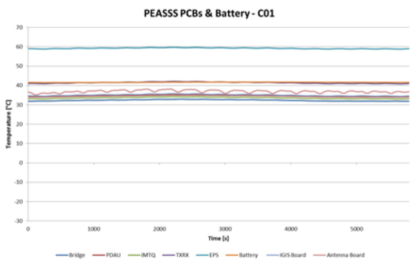
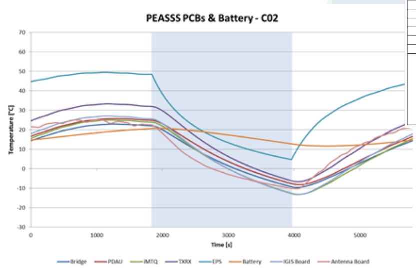
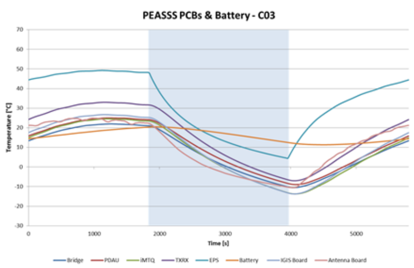
Thermal Results

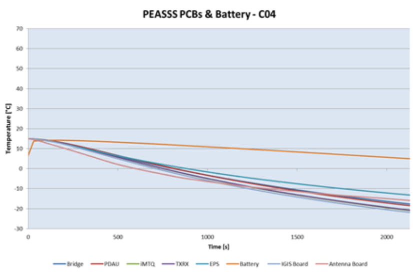
Results of the simulation show that the components are within their thermal limits.

Component		Temperatures [°C]					
		Non-operational min	Operational min	Operational max	Non-operational max	Maximum calculated	Margin to max
Battery		Always on	-5	45	Always on	41.8	3.2
EPS		Always on	-20	60	Always on	59.7	0.3
On Board Computer (OBC)		-30	-20	60	70	49.6	10.4
PDAU		-30	-20	60	70	35.2	24.8
ISIS TXRX		-30	-10	60	70	42.1	17.9
Antenna module		-50	-30	70	85	38.1	31.9
Bridge Board		-30	-20	60	70	32.9	27.1
IGIS board		-50	-30	70	85	35.8	34.2
iMTQ Board		-50	-40	70	85	34.3	35.7
Structure	Ribs	-50	-40	80	90	32.0	48.0
	Frames					27.8	52.2
	pX panels					39.5	40.5
	pY panels					44.8	35.2
	nX panels					41.2	38.8
	nY panels					44.0	36.0
	Top					44.0	36.0
	Bottom					46.2	33.8









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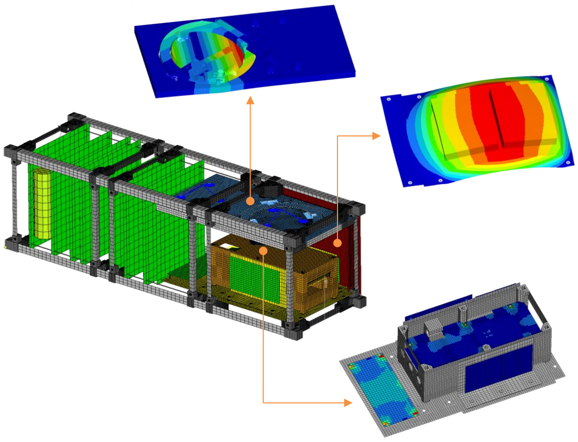
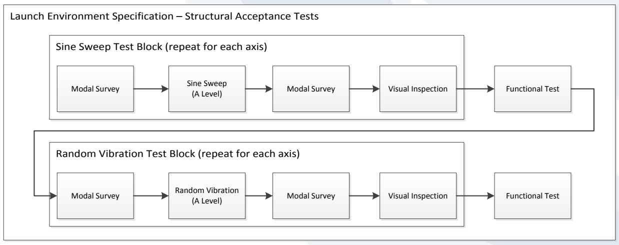
Vibration modelling and testing

FE Simulation
- Dynamic characterization
- Strength analysis

Testing
- SQM+FM Philosophy
- Test-Analysis correlation





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Thermal vacuum functional tests

In order to investigate the thermal behaviour of the interrogator, a thermal vacuum test has been performed in AST facilities.

The objectives of the test were:
- to collect data for thermal model correlation and reduce the thermal modelling uncertainties
- to verify whether the provisions for cooling and heating are sufficient and in correspondence with the simulations
- to check whether the interrogator perform within specifications over the specified temperature range.

Testing took place in AST facilities in Berlin, Germany.

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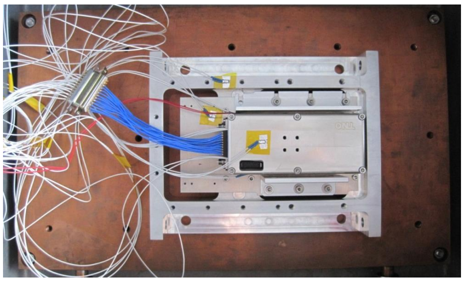
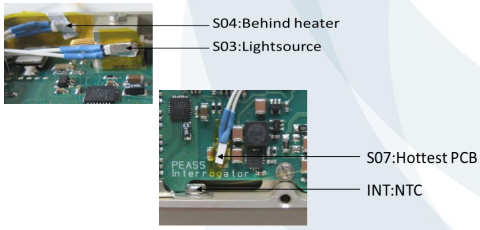
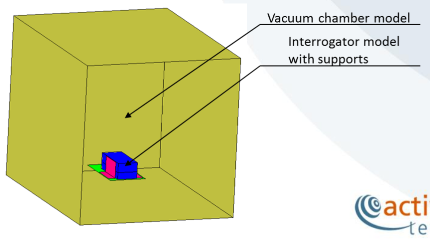
Thermal vacuum functional tests

Sensors installation and thermal modelling of the test assembly and cases tested.







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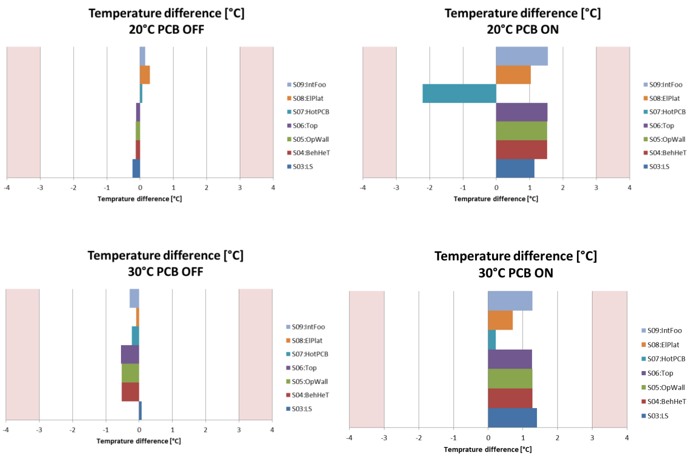
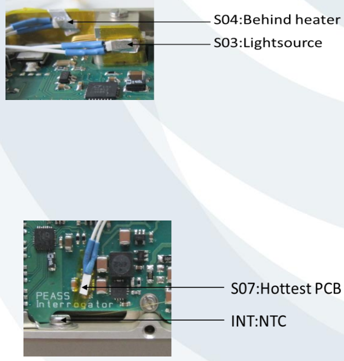
Thermal test correlation

The results of the thermal vacuum test of the interrogator have been correlated with the thermal model developed (manual correlation).





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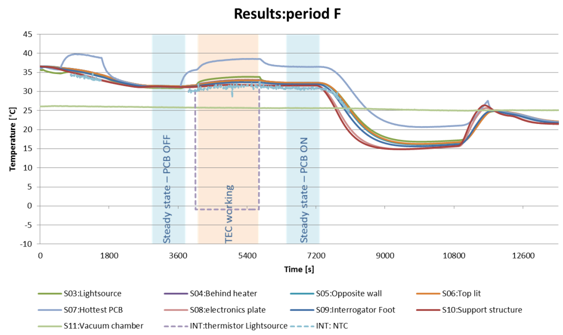
Thermal test correlation

Conclusions:

- the thermal model representing the test was correctly correlated
- the payload performed well in every vacuum conditions (“low” vacuum level, but COTS used, not space qualified components)
- unexpected thermal behaviour of the light-source:
  - COTS component (never used previously in space applications), but verified in vacuum via this test
  - internal thermal interfaces of the light-source unknown



Design (hardware) changes

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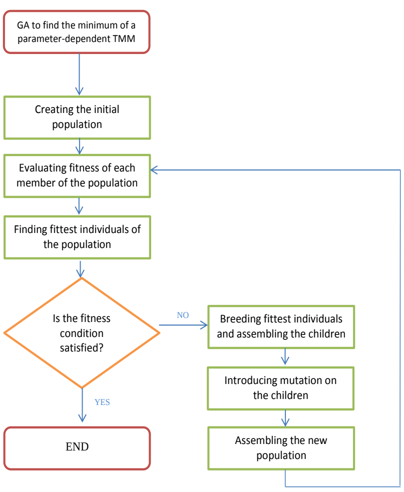
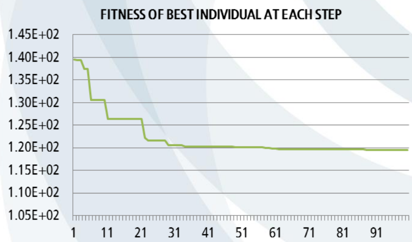
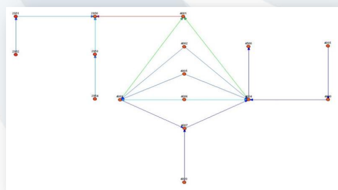
Automatized correlation models





P01	GL_PANEL_RIB
P02	GL_SUPP_INERR_01
P03	GL_SUPP_INERR_02
P04	GL_INTERR_PCB_01
P05	GL_INTERR_PCB_02
P06	GL_INTERR_PCB_03
P07	GL_INTERR_COVER_01
P08	GL_INTERR_COVER_02
P09	GL_INTERR_SUPP_01
P10	GL_INTERR_LS

GL



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Experience gained and next steps

Conclusions:

- the cubesat world is a promising one also in terms of detailed modelling and analysis
- cubesat missions are continuously growing in popularity and complexity
- “bigger” satellites thermal design approach can fit to cubesat missions increasing the mission success
- detailed analysis and tests performed for PEASSS allowed to implement changes in also in the design to assure better performances and mission success

Next steps:

- Implementing a qualification-acceptance path for the payloads and the whole satellite, both for thermal and structural aspects

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Thank you for the attention!

For further information, please visit our website

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Appendix I

TMRT Module Software
Use on an Industrial Application

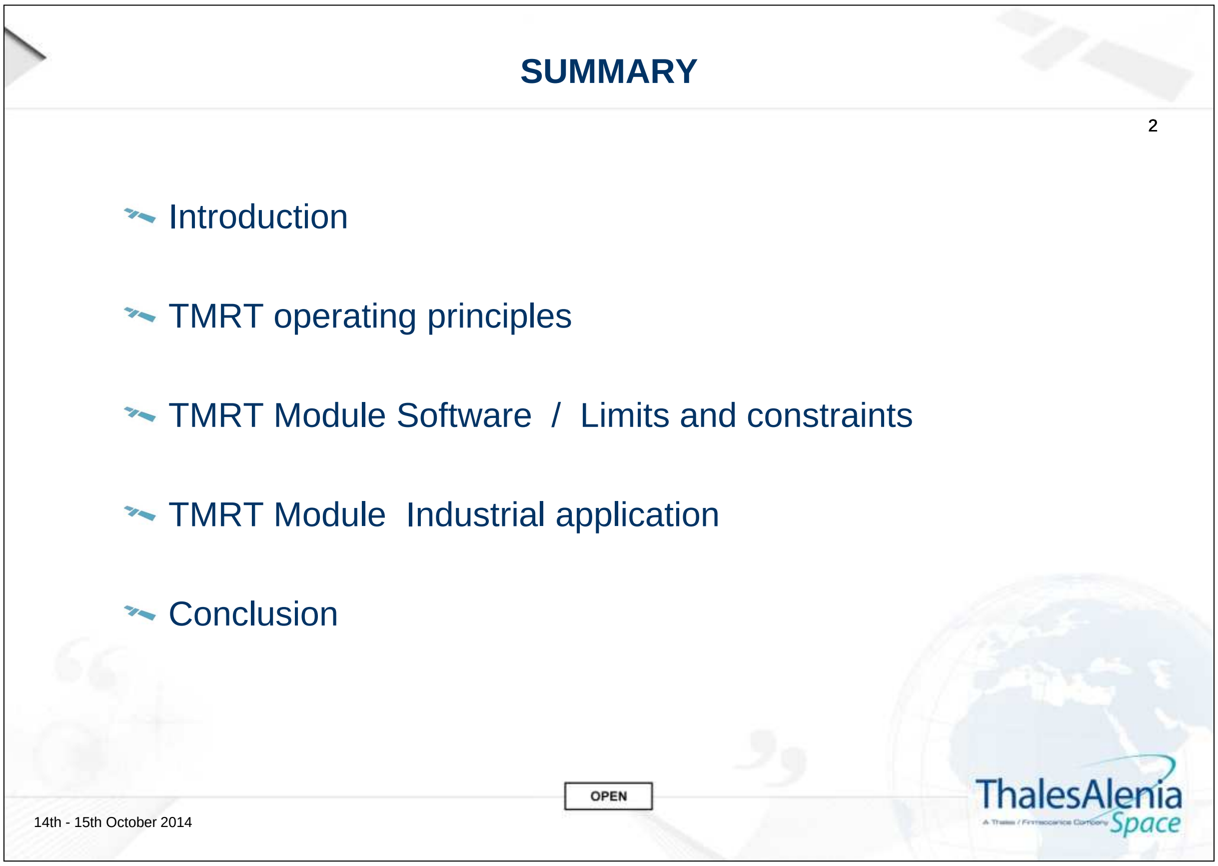
Michèle Ferrier David Valentini
(Thales Alenia Space, France)

Abstract

Reduction thermal model activity is a recurrent activity on a majority of space program. The reduction is usually done manually. This activity can also take a lot of time if the DTMM (Detailed Thermal Mathematical Model) to be reduced has a lot of nodes and thermal couplings. Moreover, the fact that the reduction is done manually increases the error risk on the RTMM (Reduced Thermal Mathematical Model) and so increases therefore the difficulty of the correlation activity between DTMM and RTMM. In order to optimize reduction activity, an initial module software (so called TMRT, Thermal Model Reduction Tool) has been developed by Airbus Defence & Space (ADS) and Thales Alenia Space (TAS) under ESA contract. This module has been afterward implemented in TAS Thermal Internal Software (E-THERM) and several evolutions have been done under TAS self-funding, in order to implement typical ESATAN-TMS parameters and functions and so to permit the reduction of an ESATAN-TMS DTMM. The objectives of the presentation are to :

- describe briefly the TMRT Module of E-THERM
- define limits and constraints of TMRT module for an ESATAN-TMS DTMM reduction
- present the reduction results obtained on an industrial application.


ESA 28th European Space Thermal Analysis Workshop
WE LOOK AFTER THE EARTH BEAT
TMRT (Thermal Model Reduction Tool)
APPLICATION ON ESATAN-TMS DETAILED THERMAL MATHEMATICAL MODEL
14th - 15th October 2014
michele.ferrier@thalesaleniaspace.com
david.valentini@thalesaleniaspace.com
ThalesAlenia Space
OPEN


SUMMARY
2
Introduction
TMRT operating principles
TMRT Module Software / Limits and constraints
TMRT Module Industrial application
Conclusion
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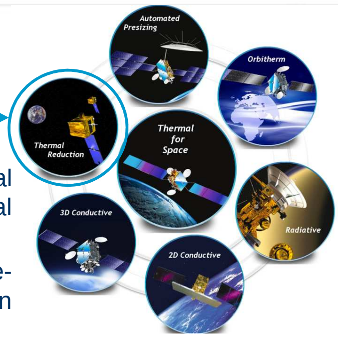
INTRODUCTION

- TMRT = Thermal Model Reduction Tool
  - Module of e-Therm Software
- TMRT permits :
  - to reduce the number of nodes of an initial Detailed Thermal Mathematical Model (DTMM) (nodal model) by generating a final Reduced Thermal Mathematical Model (RTMM).
  - to handle with two thermal model formats : ESATAN-TMS and e-Therm, for both input (DTMM) and output (RTMM). Crossing between formats is possible.



- Initial development made by Thales Alenia Space (TAS) & Airbus Defence&Space (ADS) under ESA contract.
- TMRT Module Software (included in e-Therm v1.4 software) for DTMM reduction *ESATAN-TMS* → *ESATAN-TMS* firstly used on TAS HR Satellite Export program and on sub-systems of CSO program

TMRT Module Software developed for use at System Level

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ESATAN-TMS DTMM REDUCTION : TMRT PRINCIPLE

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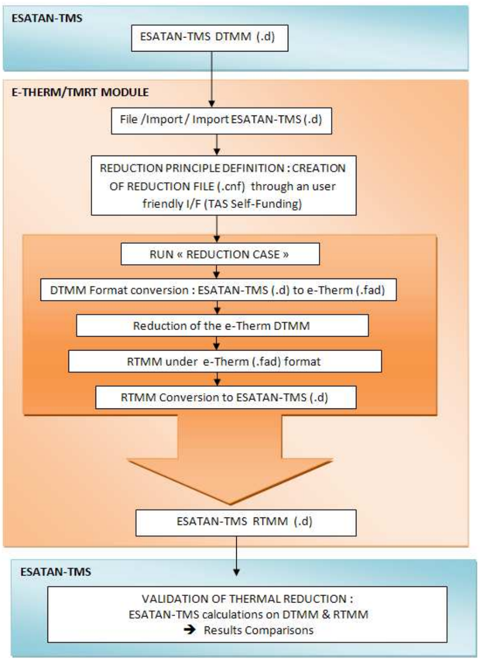

- Reduction limited to DTMM (Mathematical)
- "Physical" reduction taking into account non-linear radiative couplings, source terms and capacitances
- No reduction of DTGM (Geometrical) for ESATAN-TMS DTMM Reduction
  - Manual activity on the base of DTGM in order to create RTGM if needed.
  - *Nota: In the case of an e-Therm DTMM reduction, reduction of DTGM is possible (but reduction is limited to nodes – no reduction of number of faces)*

Thermal Reduction on e-Therm model format

Conversion ESATAN-TMS <-> e-Therm

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TMRT Constraints on ESATAN-TMS DTMM (TMRT Input) (1/2)

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TMRT ESATAN-TMS DTMM RECOGNIZED PARAMETERS & FUNCTIONS		
PARAMETERS & FONCTION	INITIAL VERSION OF TMRT	DEVELOPED VERSION (TAS SELF-FUNDING)
Node Label	YES	YES
Node Initial Temperature (T)	YES	YES
Node Area (A)	YES	YES
Node Capacitance (C)	YES (limited to numerical value)	YES (numerical value and calculated value with Esatan « variables »)
Node type (D, B, X)	YES (except X type)	YES
Internal dissipation (QI)	NO	YES (numerical value and time dependency value)
Radiative Couplings (GR)	YES (limited to numerical value)	YES (numerical value and calculated value with Esatan « variables »)
Conductive Couplings (GL)	YES (limited to numerical value)	YES (numerical value and calculated value with Esatan « variables »)
T(℃) dependency variable	NO	YES (for instance : tempe rature dependency of thermal conductivity)
Constant External fluxes QE Earth / QA Albedo /QS Solar	NO	YES
Time Dependency External fluxes QE Earth / QA Albedo /QS Solar	NO	YES (under conditions : a specific ESATAN-TMS format shall be apply)
Thermostatic Regulation Lines (THRMST function / QR)	NO	YES (under conditions : a specific ESATAN-TMS format shall be apply)
Fortran boucle "FOR" for nodes & conductors definition	NO	YES
§INCLUDE Function	NO	YES

TAS TMRT Developed version able to recognize & treat the main parameters of an ESATAN-TMS DTMM

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TMRT Constraints on ESATAN-TMS DTMM (TMRT Input) (2/2)

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- TMRT ESATAN-TMS DTMM unrecognized parameters & functions :
  - Nodes label with accent
  - Nodes coordinates (= ESATAN-TMS r5 outputs) : *FX = -0.887000, FY = -0.329500, FZ = 0.244750*
  - Convective conductors
  - Function LOG
  - All ESATAN-TMS functions and fortran subroutines not listed in the previous slide
- ESATAN-TMS DTMM Size :
  - TMRT can't import the ESATAN-TMS DTMM when this latter is too big (typically for a thermal model with conductors number > 400 000).
  - *Actual by-passing solution* = Conductive and radiative couplings reduction is done step by step (= creation of several DTMM as inputs for TMRT: one for instance with only conductive couplings and the other with only radiative couplings). A fusion activity shall also be done on the base of RTMM models issued from TMRT.

Some restrictions exist on ESATAN-TMS DTMM input format

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TMRT Reduction Methodology

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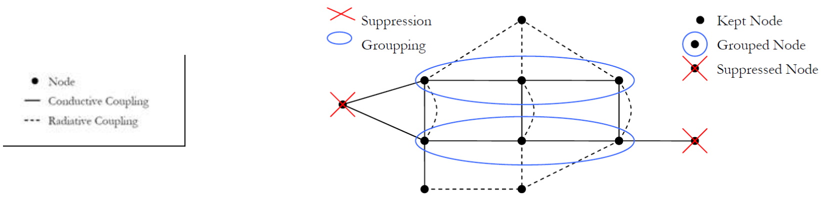
- STEP 1 : Generating RTMM node list starting from the RTMM one and performing combinations of DTMM nodes :
  - Kept nodes = Nodes present in DTMM and in RTMM with the same characteristics.
  - Average nodes = Grouping of nodes where the weights of all grouped nodes are either proportional to their areas or their thermal capacitances (depending on users will).
  - Suppressed nodes = Nodes removed from RTMM nodes list. Theirs characteristics are also reallocated on « kept nodes »



- STEP 2 : Run reduction case

TMRT Reduction philosophy based on combination of DTMM nodes

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TMRT Reduction Constraints

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- On combinations of DTMM nodes:
  - A DTMM node which has a radiative coupling with another node can't be suppressed in the reduction (= can't be a "SUPRESSED" node).
  - DTMM "KEPT " nodes can't be renumbered in RTMM through TMRT
  - The capacitance of a DTMM node which has the "SUPRESSED" status can't be attributed to an "AVERAGE" node of the RTMM. It can be attributed only to a " KEPT " node.
- On generated RTMM ESATAN-TMS:
  - Some renumbering shall be done manually (due to restriction listed hereafter)
  - Outputs definition shall be redefined manually with RTMM nodes list.
  - Comparison between DTMM & RTMM results shall be done through ESATAN-TMS calculation in order to validate the RTMM.

Some restrictions exist on TMRT reduction under ESATAN-TMS format

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TMRT Industrial Application (1/8)

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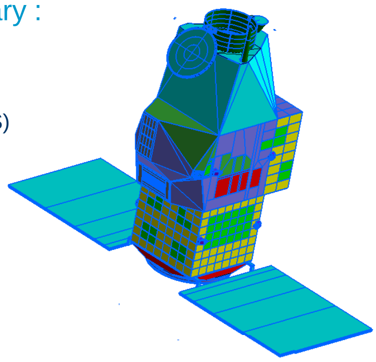
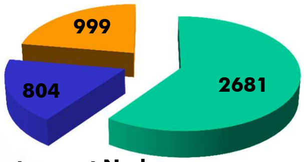
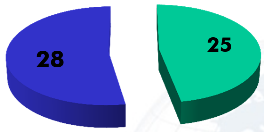
- HR Export Satellite Detailed Thermal Model Summary :
  - Software : ESATAN-TMS r4
  - Global Satellite Thermal Model is composed by :
    - **1** External Radiative Model (External DTGM – ESATAN-TMS)
    - **13** Internal Radiative Models (Internal DTGM)
    - **3** Conductive Models (e-Therm & ESATAN-TMS)
    - **1** Mathematical Thermal Model (DTMM – ESATAN-TMS)
  - Satellite DTMM nodes number = **4484** nodes
  - Satellite Thermal Regulation lines number = **53**





Instrument Nodes
MMS Nodes
PF Nodes

MMS = Mission Module Service
PF = Platform



Instrument Regulation Lines
MMS & PF Regulation Lines

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TMRT Industrial Application (2/8)

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- Satellite Reduction objectives :
  - RTMM nodes number < **400**
  - Temperature objectives (Difference between reduced & detailed Models):
    - for structural nodes : **ΔT(℃) < 3℃**
    - for MLI nodes : **ΔT(℃) < 10℃**
  - Consumption objectives(Difference between reduced & detailed Models):
    - **ΔP(W) < 5%** for :
      - Global heating power consumption of Satellite
      - Global heating power consumption of EOPL subsystem
      - Global heating power consumption of PF+MMS subsystem
    - **ΔP(W) < 15%** for line with an heating power consumption > 5W
    - **ΔP(W) < 0.5W** for line with an heating power consumption > 5W
  - Thermal cases validation number : **2**
    - Hot nominal Case
    - Safe Case

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TMRT Industrial Application (3/8)

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- Software version used : e-Therm 1.4b / TMRT Module
- Node Reduction Synthesis :
  - RTMM nodes number = **340** → Reduction **factor** is closed to **13 :**
    - 249 structural nodes (140 for EOPL / 109 for PF+MMS)
    - 89 MLI nodes
    - 1 Boundary node (Space node) / 1 Inactive node (X)
- Reduction Synthesis (Temperature) :
  - Hot Nominal Case **:**
    - **98%** of SATELLITE RTMM structural nodes have $\Delta T_{(DTMM/RTMM)} < 3$℃
    - **98%** of SATELLITE RTMM MLI nodes have $\Delta T_{(DTMM/RTMM)} < 10$℃
  - Cold Safe Case **:**
    - **93%** of SATELLITE RTMM structural nodes have $\Delta T_{(DTMM/RTMM)} < 3$℃
    - **97%** of SATELLITE RTMM MLI nodes have $\Delta T_{(DTMM/RTMM)} < 10$℃
  - *Note 1: Calculation of average temperature is made classically and not in proportion of MCP for structure or area for MLI. For the few nodes not in tolerance criteria, the calculus in proportion of area or mCp gives better results.*
  - *Note 2: At Instrument Level, 100% (resp. 99%) of RTMM structural nodes have $\Delta T_{(DTMM/RTMM)} < 3$℃ in hot nominal case (resp. in cold safe case).*

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TMRT Industrial Application (4/8)

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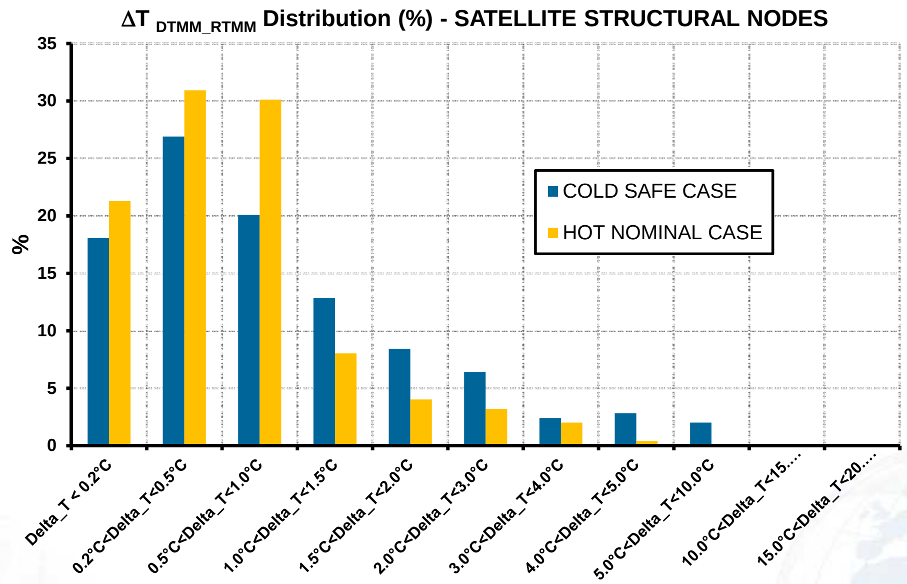

Good Representativeness of Structural Nodes Temperature

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TMRT Industrial Application (5/8)

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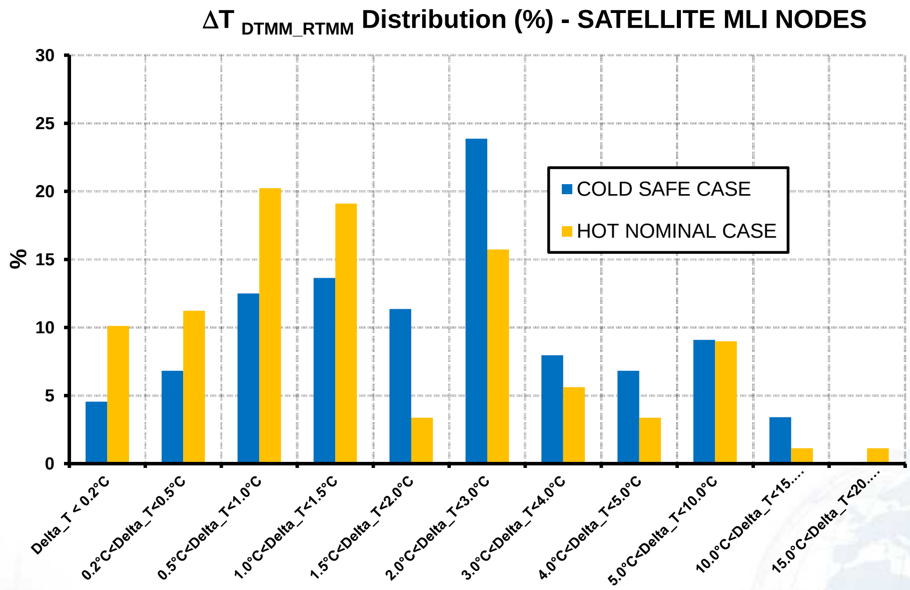

Good Representativeness of MLI Nodes Temperature

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TMRT Industrial Application (6/8)

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- Reduction Synthesis (Heating Power Consumption) :
  - Hot Nominal Case :
    - $\Delta P_{(DTMM/RTMM)}$ **= -0.9 %** on Satellite Global heating power consumption
    - $\Delta P_{(DTMM/RTMM)}$ **= -0.6 %** on EOPL Global heating power consumption
    - No heating power consumption on PF/MMS in hot case.
  - Cold Safe Case :
    - $\Delta P_{(DTMM/RTMM)}$ **= 0.9 %** on Satellite Global heating power consumption
    - $\Delta P_{(DTMM/RTMM)}$ **= 1.1 %** on EOPL Global heating power consumption
    - $\Delta P_{(DTMM/RTMM)}$ **= 2.8 %** on PF/MMS Global heating power consumption

$\Delta P_{(DTMM/RTMM)} < 5\,\%$ → Good representativeness of heating power consumption

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TMRT Industrial Application (7/8)

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GLOBAL SATELLITE ATC CONSUMPTION HOT NOMINAL CASE	DTMM	RTMM	ΔP (W)	Δ (%)	REDUCTION STATUS VS OBJECTIVES
GLOBAL SATELLITE ATC CONSUMPTION (W)	63.2	62.6	-0.6	-0.9	OK

CTA EOPL CONSUMPTION	DTMM	RTMM	ΔP (W)	Δ (%)	
DETECTION UNIT AREA	19.0	18.6	-0.4	-2.2	OK
BACK CAVITY AREA	18.6	18.7	0.1	0.5	OK
FONT CAVITY AREA	9.7	9.0	-0.7	-6.9	OK
M2 AREA	10.0	9.9	-0.1	-0.7	OK
M1 AREA	5.7	6.4	0.7	11.9	OK
TOTAL	63.0	62.6	-0.4	-0.6	OK

CTA PF+MMS CONSUMPTION	DTMM	RTMM	ΔP (W)	Δ (%)	
PCU	0.0	0.0	0.0	/	NO ATC CONSUMPTION
VPU	0.0	0.0	0.0	/	
CSFU	0.0	0.0	0.0	/	
ZONE PDHT (*)	0.2	0.0	-0.2	/	
CRYPTO TURK	0.0	0.0	0.0	/	
TANK	0.0	0.0	0.0	/	
PF -X PANEL	0.0	0.0	0.0	/	
BATTERY	0.0	0.0	0.0	/	
-Zinf RWs	0.0	0.0	0.0	/	
+Zinf RWs	0.0	0.0	0.0	/	
+Zsup TTC	0.0	0.0	0.0	/	
Pan -Y PCDU	0.0	0.0	0.0	/	
Pan +Y SMU	0.0	0.0	0.0	/	
CSS	0.0	0.0	0.0	/	
TOTAL	0.2	0.0	-0.2	/	OK

(*) Incluant OMUX/ Crypto TMI / MOD et EPC

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TMRT Industrial Application (8/8)

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GLOBAL SATELLITE ATC CONSUMPTION COLD SAFE CASE	DTMM	RTMM	ΔP (W)	Δ (%)	REDUCTION STATUS VS OBJECTIVES
GLOBAL SATELLITE ATC CONSUMPTION (W)	316.8	319.8	3.0	0.9	OK

CTA EOPL CONSUMPTION	DTMM	RTMM	ΔP (W)	Δ (%)	
DETECTION UNIT AREA	70.8	70.8	0.0	0	OK
BACK CAVITY AREA	35.8	34.8	-1.1	-3	OK
FONT CAVITY AREA	17.4	16.0	-1.3	-8	OK
M2 AREA	14.9	15.1	0.2	1	OK
M1 AREA	10.4	11.0	0.6	6	OK
TOTAL	149.3	147.6	-1.6	-1.1	OK

CTA PF+MMS CONSUMPTION	DTMM	RTMM	ΔP (W)	Δ (%)	
PCU	1.9	4.1	2.2	/	OK
VPU	0.0	0.0	0.0	/	OK
CSFU	0.0	0.0	0.0	/	OK
ZONE PDHT (*)	84.6	80.5	-4.1	-5	OK
CRYPTO TURK	0.0	0.1	0.1	/	OK
TANK	2.2	2.6	0.3	/	OK
PF -X PANEL	43.3	49.3	6.0	14	OK
BATTERY	23.8	22.1	-1.7	-7	OK
-Zinf RWs	0.0	0.0	0.0	/	OK
+Zinf RWs	0.0	0.0	0.0	/	OK
+Zsup TTC	0.0	0.0	0.0	/	OK
Pan -Y PCDU	0.0	0.0	0.0	/	OK
Pan +Y SMU	0.0	0.0	0.0	/	OK
CSS	11.7	13.5	1.8	15	OK
TOTAL	167.5	172.2	4.7	2.8	OK

(*) Incluant OMUX/ Crypto TMI / MOD et EPC

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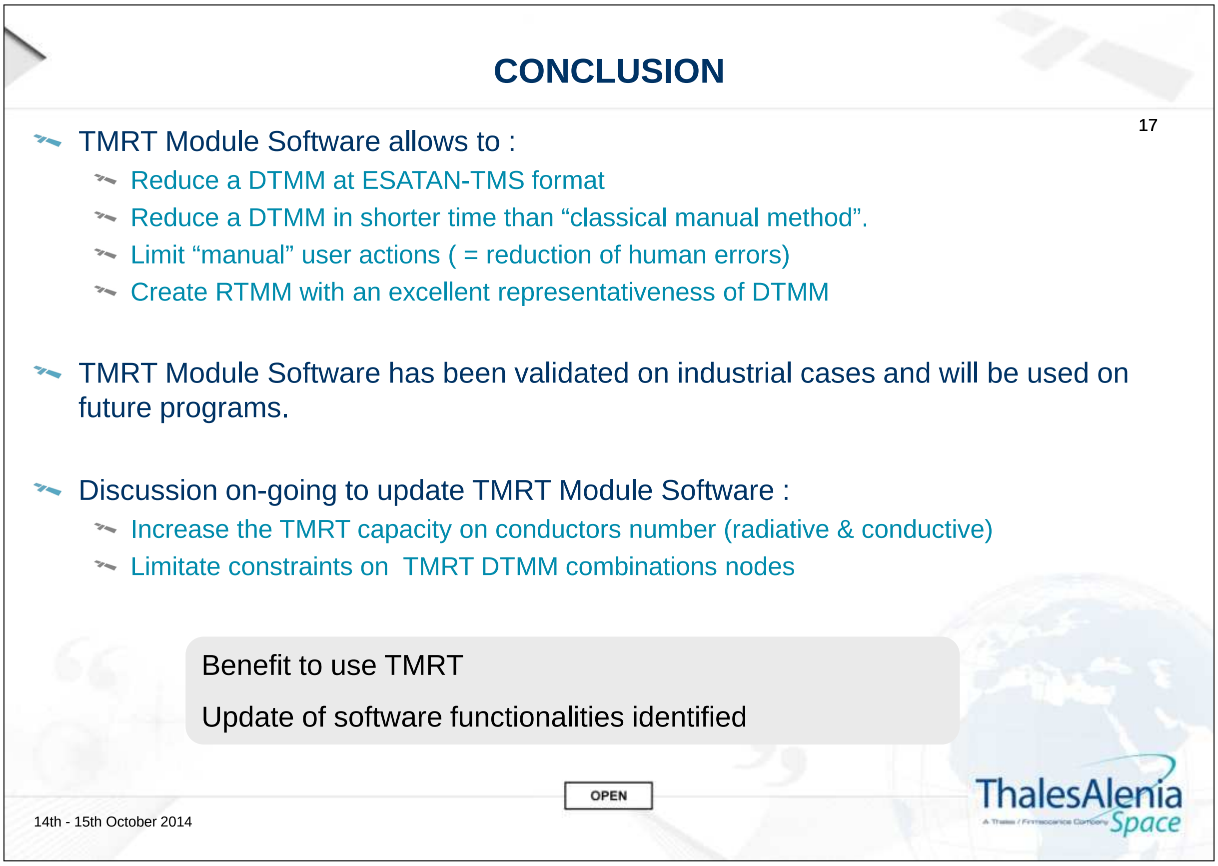
CONCLUSION
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TMRT Module Software allows to :
Reduce a DTMM at ESATAN-TMS format
Reduce a DTMM in shorter time than “classical manual method”.
Limit “manual” user actions (= reduction of human errors)
Create RTMM with an excellent representativeness of DTMM
TMRT Module Software has been validated on industrial cases and will be used on future programs.
Discussion on-going to update TMRT Module Software :
Increase the TMRT capacity on conductors number (radiative & conductive)
Limitate constraints on TMRT DTMM combinations nodes
Benefit to use TMRT
Update of software functionalities identified
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Thank you for your attention
Any questions?
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Appendix J

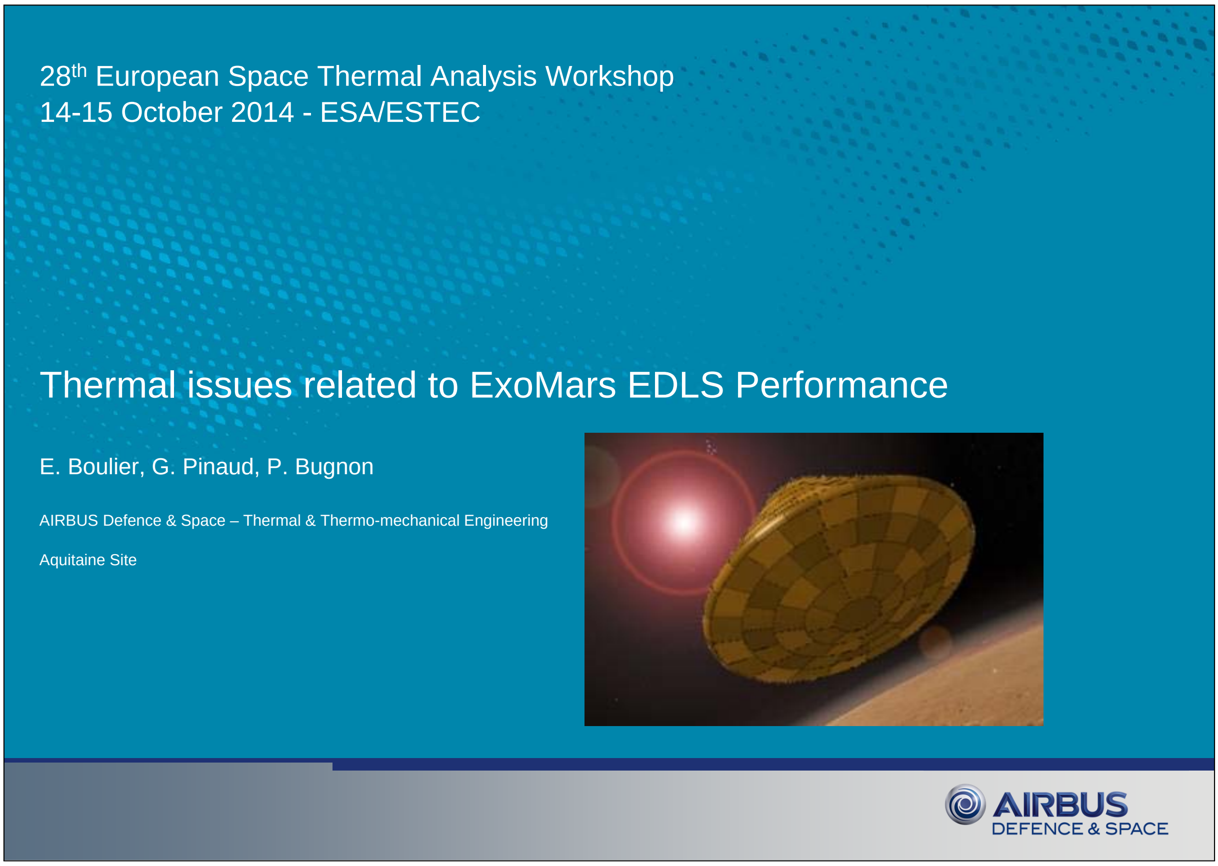
Thermal issues related to ExoMars EDLS performance

Emilie Boulier Grégory Pinaud Patrick Bugnon
(Airbus Defence & Space, France)

Abstract

During its planetary entry, EXoMars heatshield encounters specific hypersonic environments, in terms of aerothermochemistry, radiation, particule flows... and therefore requests a specific effort, in relation to aerodynamic characterisation and quantification of thermal / thermomechanical loads, as well as demonstration of thermostructural integrity and thermal efficiency.
Airbus Defense & Space is a major contributor to both issues.
The present communication aims at emphasizing two important axes of progress :

- Performance of the vehicle & application thanks to TPS optimisation
  - Updated material data sets could be derived from dedicated tests
  - Material data sets were integrated to thermophysical modelisations
  - Improved thermophysical modelisations allowed TPS thickness reduction
- Quality of planned postflight analysis, thanks to advanced modelisation including parametric and statistic analyses, inverse methodologies, cosimulation.


28th European Space Thermal Analysis Workshop
14-15 October 2014 - ESA/ESTEC
Thermal issues related to ExoMars EDLS Performance
E. Boulier, G. Pinaud, P. Bugnon
AIRBUS Defence & Space – Thermal & Thermo-mechanical Engineering
Aquitaine Site
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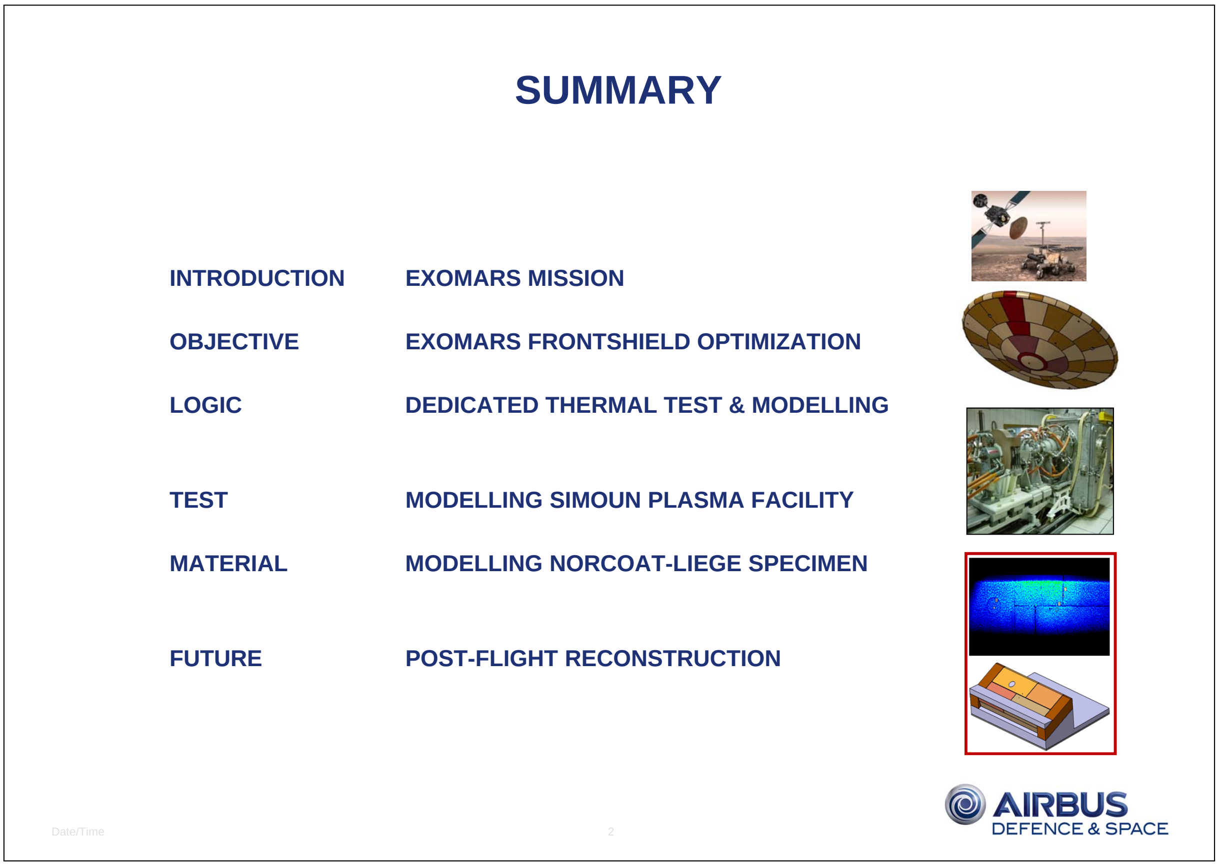
SUMMARY
INTRODUCTION
EXOMARS MISSION
OBJECTIVE
EXOMARS FRONTSHIELD OPTIMIZATION
LOGIC
DEDICATED THERMAL TEST & MODELLING
TEST
MODELLING SIMOUN PLASMA FACILITY
MATERIAL
MODELLING NORCOAT-LIEGE SPECIMEN
FUTURE
POST-FLIGHT RECONSTRUCTION
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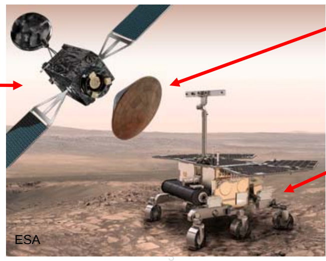
EXOMARS MISSION

14/03/2013 : ESA & ROSCOSMOS sign a cooperation agreement

- 2016 mission under ESA leadership
  - Satellite TGO (Trace Gaz Orbitor)
  - Demonstrator EDM (Entry & Descent Demonstrator Module)
- 2018 mission under ROSCOSMOS leadership
  - Russian EDM, ESA Rover on board

Both missions involve russian launcher PROTON



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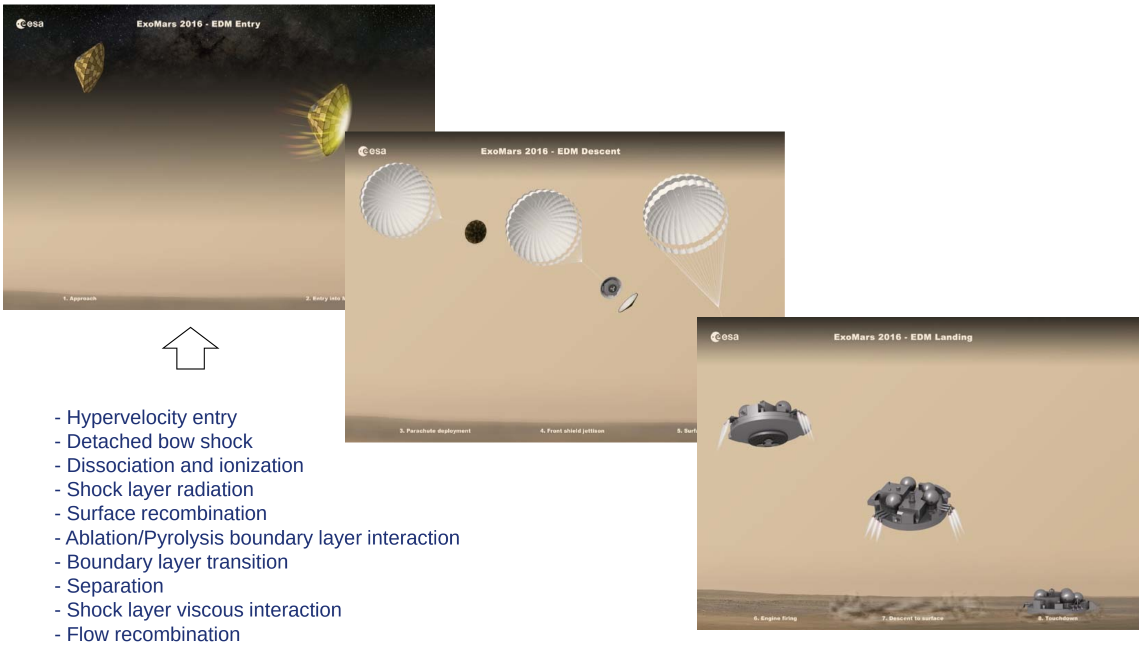
EXOMARS MISSION



- Hypervelocity entry
- Detached bow shock
- Dissociation and ionization
- Shock layer radiation
- Surface recombination
- Ablation/Pyrolysis boundary layer interaction
- Boundary layer transition
- Separation
- Shock layer viscous interaction
- Flow recombination

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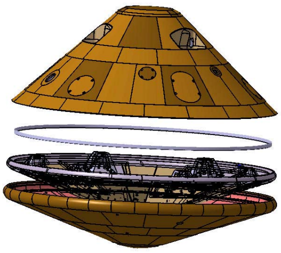
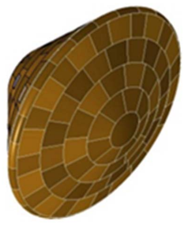
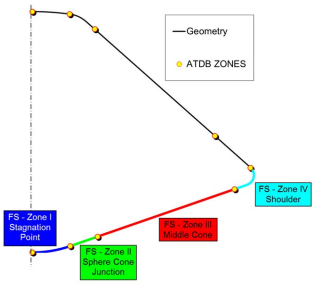
EXOMARS FRONTSHIELD OPTIMIZATION







Mars planetary entry includes environment specificities such as dust, CO_2 atmosphere, significant radiation.

Hypersonic kinetic energy → thermal energy (98%) → aerothermal flux (10%) → conduction inside heatshield (10%)

Peak load values during entry are 1,8 MW/m² for aerothermal flux, 7800 kg for integrated pressure on frontshield.
Expected frontshield temperature variations are [-110°C;+1750°C] for TPS , [-110°C;+180°C] for structure.

Frontshield diameter and mass are 2,4 m and 80 kg (~ 40 kg structure, ~ 40 kg TPS).
TPS consists of 90 tiles of outgassed NORCOAT-LIEGE fixed with ESP495, ACC Silicone glue.
Instrumentation includes 7 thermoplugs (each embedding several thermocouples), 7 thermistors, 4 pressure sensors.

Presently discussed issue : determination of optimal NORCOAT-LIEGE thickness per zone.
Application results in reducing TPS mass by ~ 8 kg (Payload mass ~ 10 kg)

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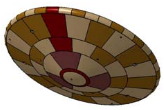
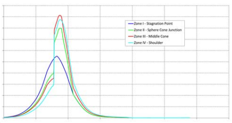
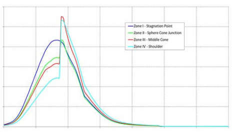
EXM EDLS Logic



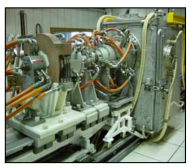
FS Sizing and Optimization



EXM Mission Requirements / Environments



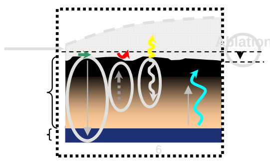
Ground Test (Plasma, IR,…)



FEM Tool

SAMTECH Amaryllis

Material Model



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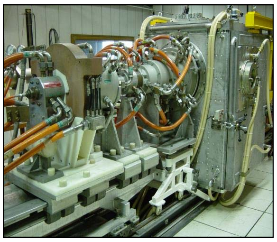
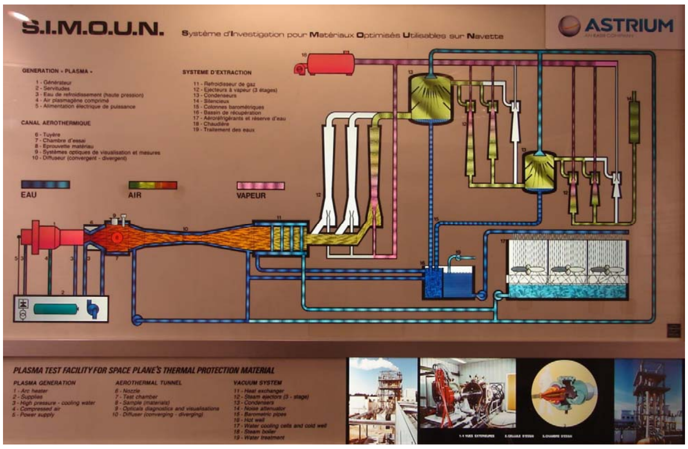
SIMOUN PLASMA FACILITY





SIMOUN delivers a Mach 4, high enthalpy (H_i/RT_0 ~ 100), low pressure (P_e ~ 0,1 bar), air / CO_2 flow.
Uniform conditions can be obtained on Flat Plate 30 cm wide samples, possibly using a wedge.
A Stagnation Point configuration is as well available.

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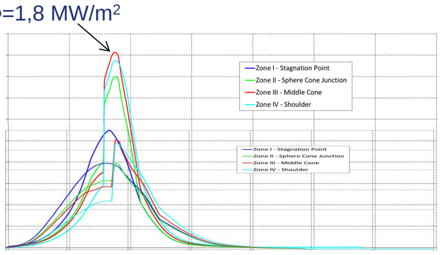
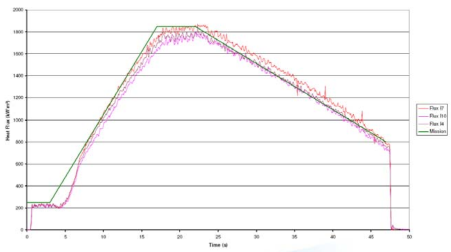
SIMOUN AEROTHERMAL MODEL

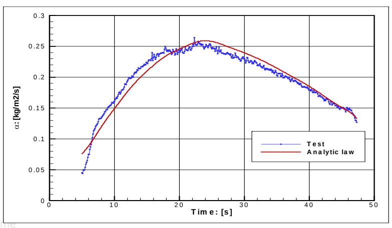
Φ=1,8 MW/m²

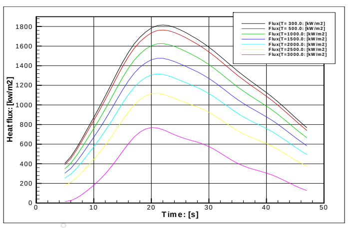




SIMOUN CO_2 test conditions deliver conservative, flight-representative aerothermal conditions on a Flat Plate sample, in terms of cold wall heat flux, shear stress, local pressure evolutions.

Calibration data (H_i/RT_0, P_i, T_{cw}, Φ_{cw}, P_e, Q), design data (nozzle expansion, wedge angle…), flow physical assumptions (frozen flow, heat flux formulas…) make possible an estimation of recovery enthalpy & convection coefficient. Estimated & experimental convection coefficients present similar evolutions, therefore a dependency of heat flux versus wall temperature can be derived from calibration data.





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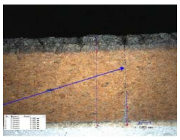
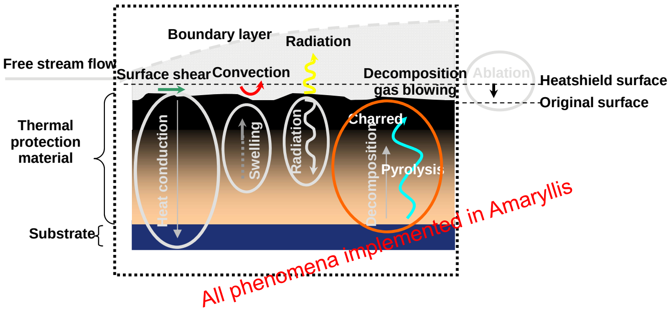
NORCOAT-LIEGE MATERIAL & SAMPLE

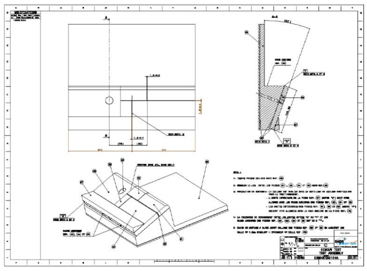
NORCOAT-LIEGE is a medium range insulator & ablator, in terms of admissible heat fluxes (Φ_{cw} < 2 MW/m²).



NORCOAT-LIEGE composition mainly includes phenolic resin & cork particles.

NORCOAT-LIEGE behaviour under aerothermal loads classically includes :
- a high temperature increase of the material at the wall,
- a pyrolysis layer underneath the surface : the virgin material decomposes into gasses and a charred phase,
- a percolation of the pyrolysis gasses through the charred zone and a swelling of the pyrolysing material.





SIMOUN sample presents a wedge configuration for local pressure and heat flux flight-representativity purpose.

Sample includes joints, steps and gaps. Instrumentation includes thermoplugs (each embedding several thermocouples), pressure & ablation sensors.

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MATERIAL THERMO-PHYSICAL MODEL

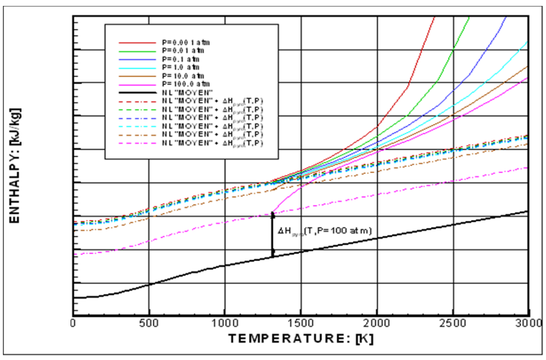
Conductivity & specific heat

Virgin properties are obtained from characterization ; charred properties are theoretical or extrapolated from virgin state.

Pyrolysis

Mass loss kinetic is described as a multi-Arrhenius law from a series of TGA at several heating rates.

Reference enthalpies of virgin & charred material can be determined from molecular composition analysis.
Pyrolysis heat of material is evaluated on the basis of an "average" solid enthalpy and continuity considerations, from finite rate to equilibrium heterogeneous chemistry.
Enthalpy of pyrolysis gas (as a function of pressure & temperature) is derived from homogeneous chemical equilibrium conditions.



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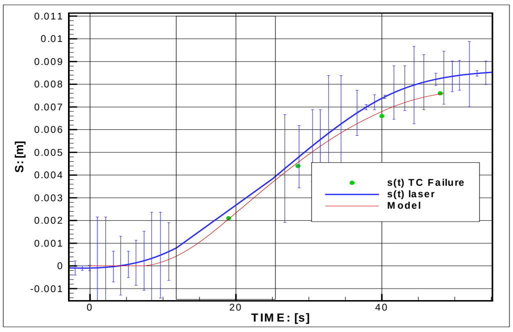
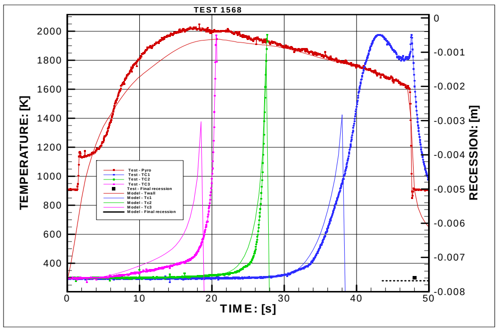
MATERIAL ABLATIVE MODEL

Experimental ablation evolution is obtained from laser recession sensor, location & failure time of thermocouples, post test micrographic cuts.

Model considers contributions of chemical and mechanical ablations, respectively depending on wall temperature and shear stress. Parameters are finally fitted from optimal matching of measured and calculated thermocouple temperature evolutions, under numerous aerothermal conditions.





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$$\alpha(H_a - H_w) + \varepsilon\sigma(T_r^4 - T_w^4) + \dot{m}_g[H_g] + \dot{m}_c[H_c] = -\lambda \frac{\partial T}{\partial x}$$

convection + radiation + pyrolysis + ablation = conduction

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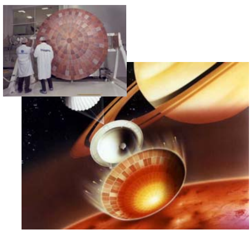
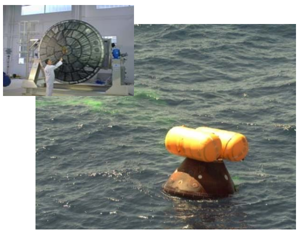
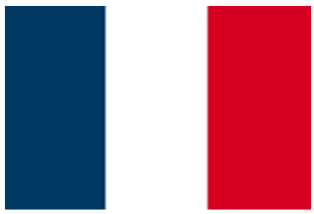
POST-FLIGHT RECONSTRUCTION



Huygens (1997-2005)



Atmospheric Reentry Demonstrator (1998)



French Deterrence Programs (since 1970s)

AIRBUS Defence & Space experience related to Post-flight analysis relays on a four decades continuous activity connected with miscellaneous Programs (ARD, military reentry vehicles & decoy systems).

Reconstruction of real flight conditions requires :

- multidisciplinary approaches,
- experience of inverse methods dedicated to loads rebuilding from structural responses,
- in-depth knowledge of “ground” justification models, in order to :
  - evaluate them with respect to flight restitution,
  - propose margin policies related to ground-flight extrapolation.

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POST FLIGHT EDLS RECONSTRUCTION

TGO capabilities and EDLS sensors shall provide numerous parameters for post-flight reconstruction :

(1) EDLS trajectory,
(2) Atmospheric data,
(3) Pressure evolutions on frontshield,
(4) Temperature evolutions inside frontshield.

From (1), (2), (3), aerodynamic database shall be possibly updated and applied to the real trajectory.

Updated heat flux evolution shall be applied to « ground » model and shall result into thermoablative data (4') which shall be compared to flight data (4).

In-depth analysis of divergences shall allow identification of high priority modelling efforts to be achieved, for an improvement of performance on future missions.

Key tools are ready :

- Automatic parametric optimization of direct problem,
- Full numerical implementation of inverse problem coupled with optimization algorithm.

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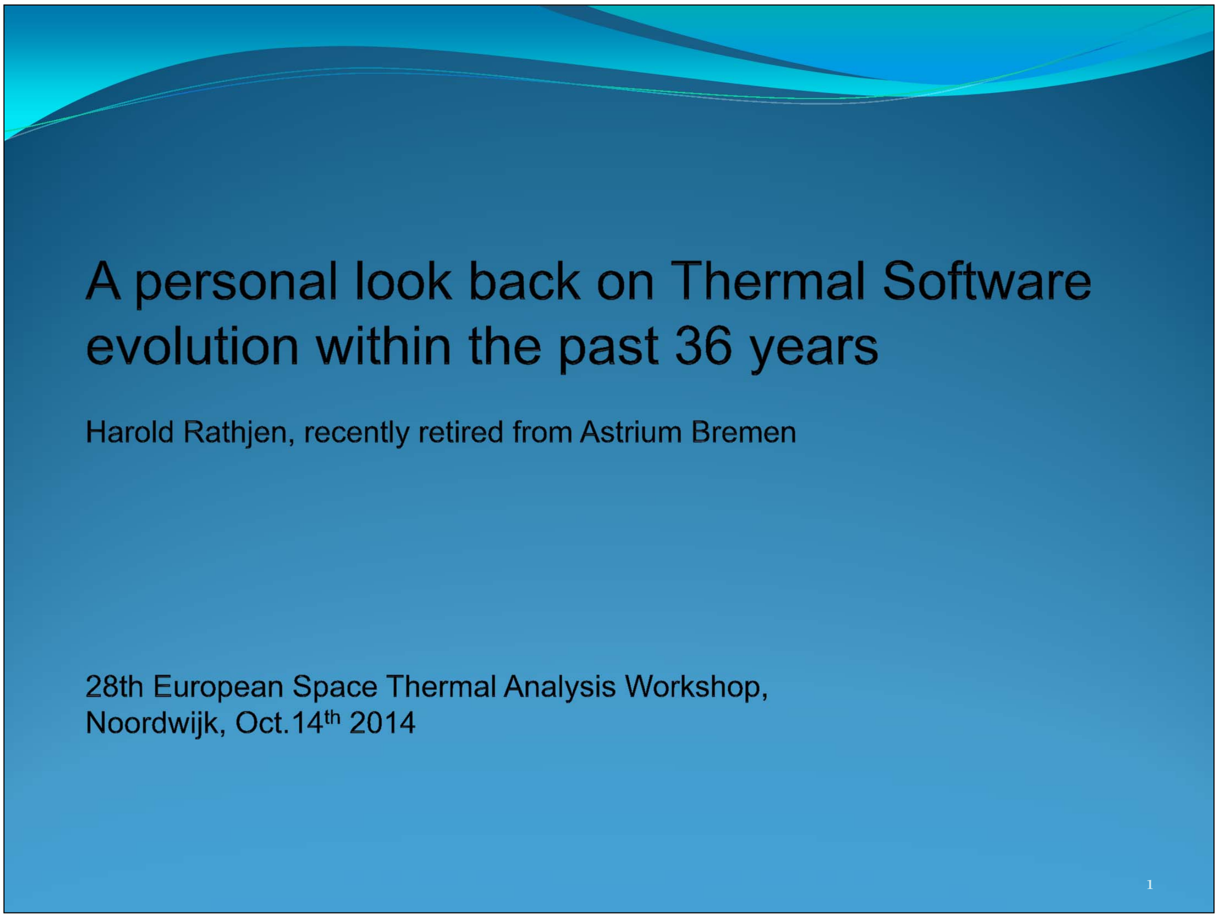
Appendix K

A personal look back on Thermal Software evolution within the past 36 years

Harold Rathjen
(HRC, Germany)

Abstract

The evolution of thermal software used in European space industries from the beginning until today marks a long way from some in-house written software to the current status of today's most important packages. During almost 30 years this way was accompanied by the ESTEC annual workshop on ECLS software that started in 1986 as the Esatan workshop, but soon had to be opened for other software developments, among which Thermica has to be mentioned in first place. This presentation gives a historical look back from a personal point of view of a young thermal engineer who started working in the thermal department of ERNO in Bremen right at the time when the Spacelab project was won and the first family of commercial communication satellites (ECS/MARECS) was started. Some highlights are the decision for the cooperation between ESTEC and a little company in England to develop Esatan, and a few years later the search for an appropriate radiation software for the Columbus project. Not to forget the Esabase framework, that was used during many years as an intermediate software. Finally the problems of establishing a common thermal analysis method within the Ariane project in front of the merging of the participating companies are mentioned.


A personal look back on Thermal Software evolution within the past 36 years
Harold Rathjen, recently retired from Astrium Bremen
28th European Space Thermal Analysis Workshop,
Noordwijk, Oct.14th 2014
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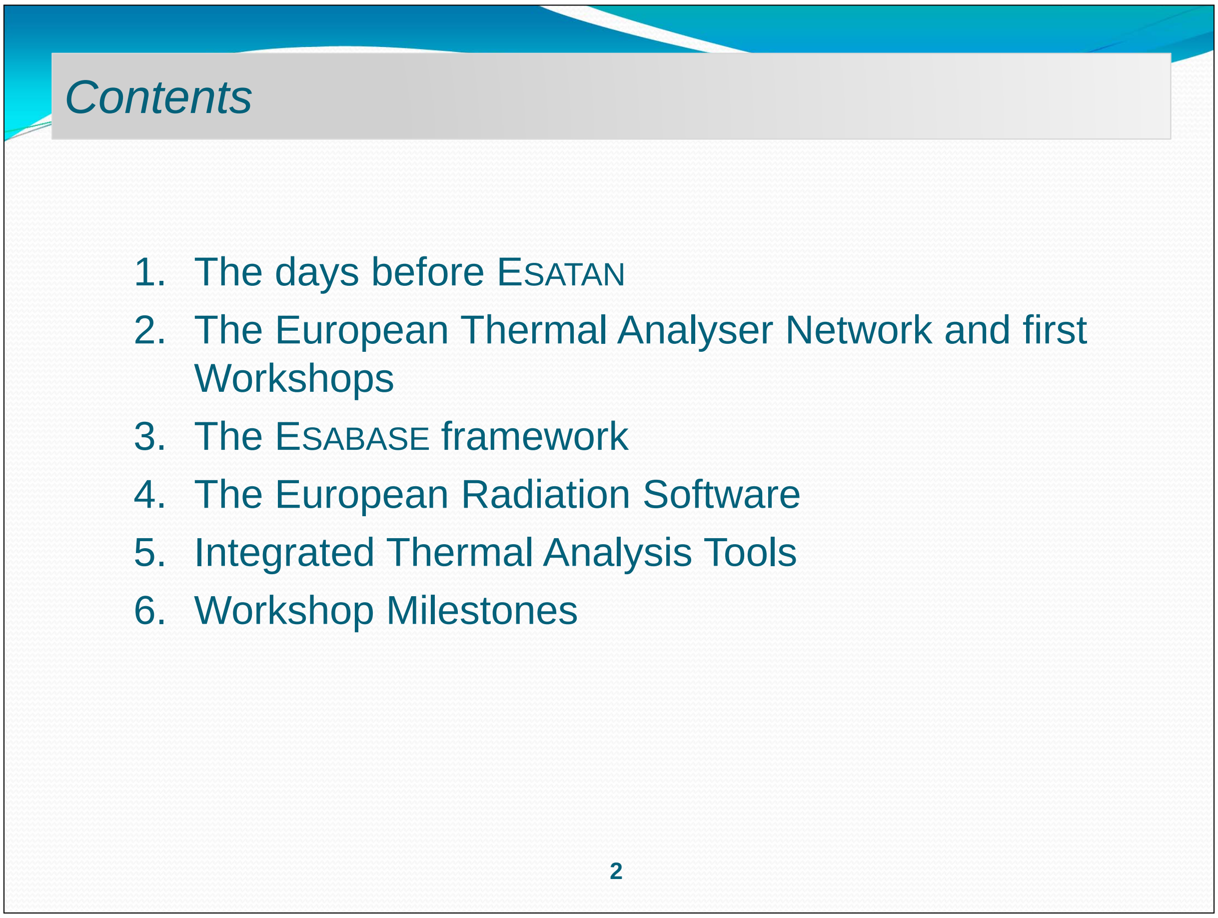

Contents
1. The days before ESATAN
2. The European Thermal Analyser Network and first Workshops
3. The ESABASE framework
4. The European Radiation Software
5. Integrated Thermal Analysis Tools
6. Workshop Milestones
2

1. The days before Esatan

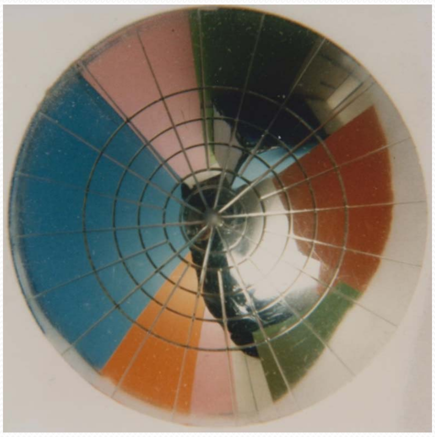
This period lasted from the first European space activities (in the early sixties) until the introduction of ESATAN in most of the European space companies. It was characterised by the following:

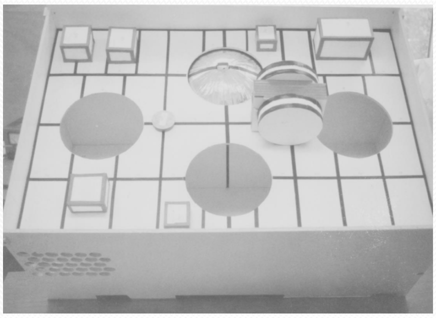
- In the early years no off-the-shelf thermal software was available and companies had to rely on their own in-house written software
- In ERNO these were GLEITEX for steady state and TRANSIT for transient analyses (developed for the Helios project)
- Models were defined in punch cards and output was given on endless computer paper, i.e. it could not be directly used for the report but had to be included via cut and paste
- Computations were performed in a remote computer center with partly tremendous costs leading to the strange situation that the engineers spent extra effort in order to save computer CPU time

3

1. The days before Esatan (cont'd)

- View factors were defined manually with the help of a view factor meter applied in a wooden scale model of a satellite
- A view factor meter was a small parabolic mirror with a grid on it that was placed on surface i in the model. The percentage of the grid that was covered by the mirror image of surface j gave then the view factor to that surface
- Each relevant internal radiative link had to be defined that way and the results had to be written into form sheets that were then processed by a software (SPIEGEL) considering multi reflection and outputting the relevant conductor format





4

1. The days before Esatan (cont'd)

Around 1977 when the Spacelab project started, the NASA Thermal Software SINDA was distributed by ESTEC to the European space industry, accompanied by further software:

- NASA radiative software called LOHARP with following 4 modules:
  - VUFAC View factor calculation using double integral method
  - RADCON Computation of multi reflection
  - ROHEAT Computation of natural radiation
  - PRTPCH Outputting the results in SINDA format
- Later ESTEC established a revised version of LOHARP and distributed it under the name VWHEAT with the same 4 modules
- For visualisation of the used geometries a simple plot program called PTD10 was also provided. It was only a wire frame display without hidden line feature but nevertheless was well appreciated
- All was provided with the source code

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1. The days before Esatan (cont'd)

In the period that followed, SINDA was established at ERNO, at least for the most important projects (Spacelab and the new European family of communication satellites OTS/ECS/MARECS)

- The old programs/methods were used in parallel for a long time
- The results of the radiative software and even of the form factor meter method, once established, were used during almost the complete life time of the model. The manual introduction of modifications (e.g. for taking into account new surface properties) was deemed easier than repeating the calculations due to the high CPU times
- During this time still a lot of little Fortran programs were written by the thermal engineers to handle and modify model data and to plot transient temperature results
- In the early eighties we made a test of the thermal module of Nastran in cooperation with our structural colleagues. The result was not very encouraging (at that time!) and we soon gave up

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2. The European Thermal Analyser Network and first Workshops

While industry was working with the a.m. NASA software, ESTEC was thinking about a completely new European thermal software, the driving power behind this being Mr. Charles Stroom of ESTEC/TST:

- First idea was to create a software corresponding to the state of the art combining thermal and radiative analysis in one tool
- Working title for this ambitious project was MANIP and a very first version was presented to space industry under the name of MINIP (around 1982 ?) which indeed looked very impressive but a long development time had to be envisaged
- While MANIP was internally further pursued it was then decided to proceed in small steps and to begin simply with a European version of SINDA. In fact, still today ESATAN consists of the same block structure as SINDA

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2. The European Thermal Analyser Network and first Workshops (cont'd)

- It was furthermore decided to assign the development of this sofware to an external company under ESTEC contract and finally the Mechanical Engineering Laboratory (MEL) of GEC in England was selected. Today known as ITP, this company is still responsible for ESATAN

The first version of the new software was presented by Mr. John Turner of MEL on the first (ESATAN-) workshop that took place in April 1985 and that was organized by Ch. Stroom

- Representatives of 25 companies participated out of 37 that were invited. They had first contact with the software during hands-on sessions on the ESTEC IBM mainframe
- As for the software provided by ESTEC before, distinction had to be made between the various computer platforms used, not only w.r.t. the software itself, but also to the run procedure

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2. The European Thermal Analyser Network and first Workshops (cont'd)

- Most companies had DEC-VAX and IBM mainframes, while PCs did not yet play a significant role

The next 3 workshops, at that time called ESATAN User Meeting, took place in 1987, 1989, and 1990

- These were characterised by user presentations about their companies experience with ESATAN and discussions about how to improve the software
- Major issues were the computation speed and stability, modelling problems and output options
- Also the flow software FHTS and its integration into ESATAN was a subject
- Different hardware platforms were still under discussion, e.g. to make ESATAN run on multi processor machines

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3. The ESABASE Framework

In the early eighties another software tool was available from ESTEC, called ESABASE, this time provided by the mathematical department WMA and probably resulting from the MANIP development

- It was a framework intended as a multi disciplinary tool where a common geometry model could be used for various analyses tools such as:
- Thermal, Radiation, Plume, Mass, Atomic Oxygene, Perturbation, Meteorite/Debris, Charging, Field of View and others
- It provided a modelling environment and its own language to define the geometry. Today this language (with some modifications) is still used in THERMICA
- An orbit generator ORHPL and a graphical interface for pre and post processing were also available
- The first presentation of ESABASE at the workshop was in 1993 after the software existed already some ten years

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3. The ESABASE Framework (cont'd)

- At ERNO we had installed ESABASE since the beginning with the following software attached:
  - VWHEAT with its 4 modules (see above)
  - SINDA – it was used at ERNO in parallel with ESATAN for a long time for projects with interfaces with NASA (e.g. the German SPACELAB missions D1 and D2)
  - ESATAN – included when it became operational at ERNO
  - THERMICA with its modules MATRAD and MATFLUX (see next chapter)
  - PATRAN – used for visualisation of the geometry and for post processing with coloured overlay
  - Mass – not used in thermal department
- Interfaces with Esarad and Ideas/TMG became available later
- With the exception of VWHEAT this software configuration was the main thermal modelling environment used at ERNO (meanwhile becoming DASA) until we switched to the stand-alone versions of THERMICA and ESATAN (around 1998 ?)

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4. The European Radiation Software

In the late eighties the European space industry was preparing the start of the COLUMBUS project. It was clear that ESATAN would be used as thermal analyser but a corresponding radiation software was still missing

As the COLUMBUS prime contractor, it was the task of ERNO to find an appropriate tool and in fact there were two candidate solutions available:

- At DORNIER in Germany they had meanwhile spent some effort to develop a new version of VWHEAT (STARDUST) and indeed they had achieved a considerable improvement. However, view factor calculation was still based on the double integral method
- At MATRA in France, who co-operated at that time with the ESTEC mathematical department WMA for the MANIP development, they proposed a new software based on the ray tracing technique (MATRAD and MATFLUX)

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4. The European Radiation Software (cont'd)

- Under the working title Columbus Bridging Thermal Software (CBTS) a comparative study between the two was started at Erno
- As a result it was found that Matrad/Matflux was approximately 10 times faster and provided a lot of additional advantages
- Hence it was decided that Matrad/Matflux should be used within the Columbus project
- Later on these two modules and an also existing visualisation tool called Matview were combined under the name Thermica
- Thermica soon became the most important radiation software long time before Esarad was available and was also successful on the American market

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4. The European Radiation Software (cont'd)

Nevertheless, it was the intention of the Estec thermal department YCV to develop their own radiation software. There was obviously an internal dissent between WMA with Matra on one side and YCV on the other about the software development policy

- This is probably the reason why today we have two concurrent European thermal software tools: Systema-Thermica and Esatan-TMS
- This is good for competition but on the other side, wouldn't it be more efficient to put all development effort into only one tool?
- It was then an evident decision that GEC was assigned to develop this software under the name Esarad
- Due to contractual reasons WMA had to provide the kernel of their tool to GEC who built Esarad around it, which hence is also based on the ray tracing technique

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4. The European Radiation Software (cont'd)

- The development of ESARAD was first announced on the 1990 workshop and the first version was presented on the next workshop in 1991
- The 1991 workshop was the only one so far that took not place in Noordwijk, but was scheduled together with the ICES conference which that year took place in Florence, Italy
- Therefore a lot of thermal people where present, among them the head of thermal department in Bremen, and I could convince him together with GEC people to allow the purchase of our first Sun/Solaris work stations that were needed to run ESARAD
- Thus we could early familiarise ourselves with the dominant hardware platform for the next couple of years
- A few month later we had our first ESARAD installation in Bremen and we became early (beta-) users of a new software

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4. The European Radiation Software (cont'd)

- Different from the first ESATAN version we had, I must say that working with this early ESARAD version was really hard and it was far away from being applied for a real project
- One reason for this was the concept of ESARAD to define the model on the screen and to store everything directly in a model data base without the use of an ASCII input file
- When the software crashed for whatever reason the data base could not be restored and all work was lost. It was said that all data were stored on the session log file, but before reloading the relevant model data from there, this log file had to be cleaned, which was not so easy
- Today this problem is solved by the option to automatically create a clean log file at any time during model creation which allows the user to reload or copy the model

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4. New European Radiation Software (cont'd)

- Another reason for the early problems was the ORACLE software used for the model data base. A reduced ORACLE version has been provided together with ESARAD that often was in conflict with our own Oracle installation in the ERNO network
- Meanwhile the use of ORACLE in ESARAD was given up

As a big advantage of ESARAD the new cutting tool was considered which allows to cut the existing set of primitive shapes to more complex shapes

- One example, reported on the 1995 workshop, was the Soho space craft space simulation test were a good correlation could only be obtained after remodelling the INTESPACE test chamber under extensive use of the cutting tool. Without cutting the cylindrical chamber walls, intruding each other and, moreover, being partly not covered by the cold shroud, could not be correctly modelled

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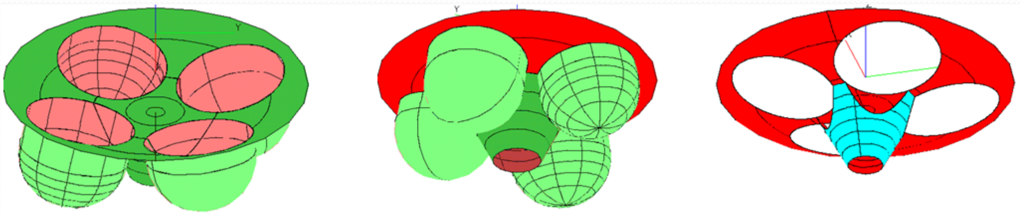
4. The European Radiation Software (cont'd)

- The other example is my own model of the upper stage EPS of the new Ariane 5 launcher as shown below:



- The lower side of the stage consisted of a large spherical structure with cylinders and cones intruding each other
- Radiation played a significant role in that area due to the very hot engine and nozzle (not shown in the figure)
- Therefore this feature would have been very helpful for this model but unfortunately ESARAD became operational too late and I had to work around without cutting

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4. The European Radiation Software (cont'd)

- The conventional method to model the above geometry was to approximate the cutting edges by small bits of non-cut primitives. However for curved shapes this was difficult and led to a unnecessary high number of nodes
- At DASA, ESARAD became operational around 1998 but still was not always robust. Only after switching from Solaris to Windows workstations ESARAD worked satisfactory

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5. Integrated Thermal Analysis Tools

Today each of the two European thermal analysis packages is available as fully integrated tool for radiation and thermal analysis including pre and post processing operated from a common graphical user interface. Furthermore both provide an automatic conductor generation based on the geometry

- ESATAN/ESARAD became ESATAN-TMS recently enhanced by the solid modelling feature as commonly required by AST-LMX and AST-BRE for the Ariane project
- THERMICA was enhanced by its own thermal solver THERMISOL and became SYSTEMA-THERMICA. V4 is not yet operational in Bremen, as the step from v3 is considered too big to be done in a running project
- Some other software packages providing similar features have also been considered or are used at Dasa (later Astrium) in Bremen

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5. Integrated Thermal Analysis Tools (cont'd)

- When we started the analyses of the new cryogenic upper stage for Ariane 5 ESC (ESC) we engaged a TMG expert to sit in my office and build a TMG model of ESC in parallel to my ESATAN modelling. The result after some months was, that TMG was not a suitable alternative, namely w.r.t. the radiative part (today the result might be different!)
- For the same project also some FEM tools (a.o. SAMSEF) were considered but were all deemed not suitable
- For projects with interfaces with NASA we are using the (US-) Thermal Desktop software that is also fully integrated with AUTOCAD as GUI, SINDA and a ray tracing radiation software (NEVADA)
- An extensive thermal software development was going on in the Ariane world (Astrium, Les Mureaux) but unfortunately was not present on the workshops before 2012

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6. Workshop Milestones

1985: Presentation of first ESATAN version - Followed by 3 ESATAN User Meetings in 1987, 1989 and 1990

1991: Presentation of first ESARAD version - Took place together with ICES conference in Florence, Italy – An Overview over Soviet Standard Software for thermal modelling of Spacecraft was give by Prof. Anfimov from Kaliningrad was given

1992: Increasing participation of other software, e.g. TMG, ECOSIM, and many others. Users present projects, for that the software was used

1993: First presentation of ESABASE on the workshop, workshop renamed to Workshop on Thermal and ECLS Software

1994: First presentation of STEP-TAS

2001: First presentation of THERMICA on the workshop

2012: Renamed to Space Thermal Analysis Workshop

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Appendix L

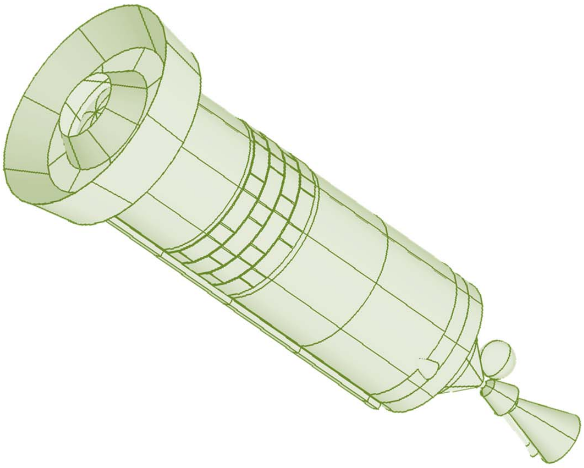
General-purpose GPU Radiative Solver

Andrea Tosetto Marco Giardino Matteo Gorlani
(Blue Engineering & Design, Italy)

Abstract

In the scope of the CADET project, a new radiative tool was developed in Blue Engineering. The tool can compute the extended view-factor and extended incident heat fluxes for solar, planetary and albedo contributions using the Monte Carlo Ray Tracing model. The software is implemented using the OpenCL framework, in order to take advantage of the computational capabilities of GPGPU hardware and dedicated computation hardware.
A comparison between tool results and ESATAN TMS results is performed in order to validate the tool.

GPGPU Radiative solver



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Sheet 1

Contents

- CADET Project
- Radiative heat exchange
- Why GPGPU?
- GPGPU Programming languages
- Software platform structure
- Acceleration structures
- Tool architecture
- Box test
- H10 test
- Tool performances
- Bibliography

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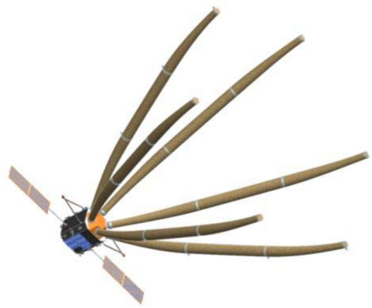
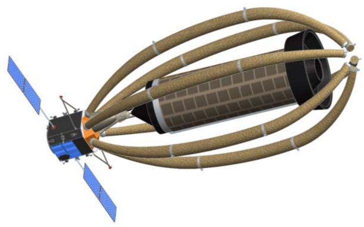
CADET Project

- CApture and DE-orbiting Technologies
- Develop enabling technologies required for Active Debris Removal from LEO orbits:
  - IR and Visible tracking of the target
  - Develop GNC for close rendez-vous, final approach and capture phases
  - technologies, strategies and concepts for target capture and solidarization
- BLUE contribution: onboard IR image processing to get target relative position and motion, with simplified thermal analysis (low power HW)





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Radiative heat exchange

Radiation exchange	Heat fluxes
View Factor F_{ij}: fraction of the radiant energy emitted by surface *i* directly intercepted by surface *j*;	**Direct incident heat fluxes**: radiative energy emitted by an external source directly intercepted by a surface;
Radiative exchange factors (REF, also Gebhart factors) B_{ij}: fraction of the radiant energy emitted by surface *i* finally absorbed by surface *j* (including surfaces diffuse reflections);	**Total absorbed heat fluxes**: radiative energy emitted by an external source finally absorbed by a surface (including diffuse reflection component);
Extended view factors F_{ij}: fraction of the radiant energy emitted by surface *i* finally absorbed by surface *j*, directly of through diffuse or specular reflections and through transmissions; → **GR (also REF)**	**Extended incident heat fluxes**: radiative energy emitted by an external source finally absorbed by a surface, directly of through diffuse or specular reflections and through transmissions;

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Why GPGPU?

- Rendering real life pictures is quite similar to evaluate heat fluxes and view factors
- GPU are made for rendering
- Modern GPU are programmable for general purpose calculations using CUDA or OpenCL programming languages (most mature and common)
- GPU are powerful: CPUs ~10GFLOPS, GPUs ~5TFLOPS
- GPU consume less power per GFLOPS (mobile GPUs ~4watts)

General-Purpose computing on Graphics Processing Units (GPGPU)
→ using GPU hardware to perform computations

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GPGPU - history

General-Purpose computing on Graphics Processing Units (GPGPU)
→ using GPU hardware to perform computations

- Dedicated graphic hardware evolved aiming to boost simple operation on huge data sets in order to render more detailed CG scenes
- From 2002 (NVIDIA GeForce 3, ATI Radeon 9700): introduction of programmable rendering pipeline (Direct3D 8.0, OpenGL 1.4)
- Dedicated languages enabled GPU processors to be used for computations:

CUDA, 2007	OpenACC, 2012
OpenCL, 2009	C++ AMP, 2012

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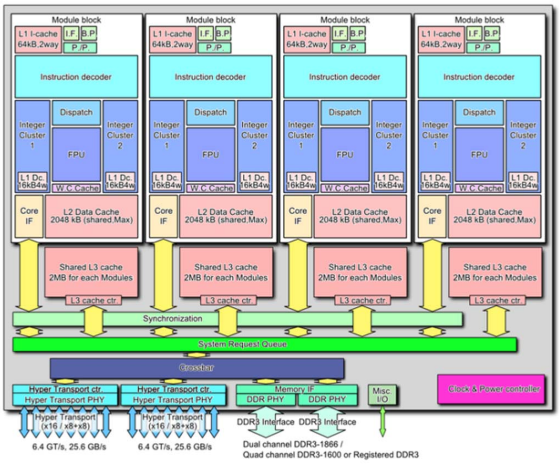
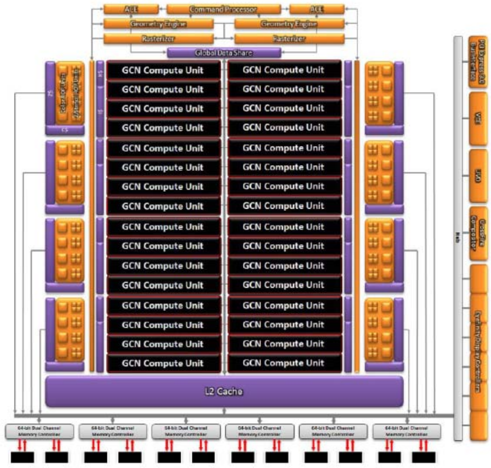
GPGPU – structure (1)

AMD Bulldozer CPU block diagram



AMD Radeon HD 7790 GPU block diagram



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GPGPU – structure (2)

	CPU	GPU
Architecture	MIMD (Multiple Instruction Multiple Data) → Multi purpose, independent processors/cores	SIMD (Single Instruction Multiple Data) → 1 control unit dispatch commands to multiple ALUs. Texture units
Execution	Branch execution flow, control structures	Optimized for branchless execution (maximize occupancy)
Memory structure	• Low latency, low bandwidth memory (RAM, up to 20 GB/s) • L1, L2, L3 levels cache memory • CPU registers	• High latency, high bandwidth memory (VRAM, up to 300 GB/s) • On chip, block shared memory • GPU registers
Memory management	Automatic (e.g. cache pre-fetch)	User controlled data flow between VRAM and shared memory, registers
Context switch	Software (thread management by OS)	HW (thread switch controlled by the control unit to hide memory latency)
Precision	Single, double, quad, with almost same performances	Preferred single, double available but with huge performance losses (at best, ¼ of single precision on latest hardware)

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GPGPU Programming languages

CUDA	OpenCL
GPGPU language by NVIDIA	Open standard by Khronos Group (OpenGL)
Specific and available only on NVIDIA GPUs	Designed for heterogeneous computing: available on NVIDIA and AMD GPUs, ARM processors, CPUs (Intel & AMD), FPGA vendors
Offline kernel compilation to intermediate language	Runtime kernel compilation of the provided kernel sources by the device specific driver
Mature framework, with libraries (CuFFT, CuBLAS, etc.) and tools (IDE, profiler, debugger, etc.)	Less advanced libraries and tools, generally from open source projects
Work only on NVIDIA hardware	The standard guarantee software portability among different HW (NB execution performances are not guaranteed: they can only be achieved tuning software on each specific hardware architecture)

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GPGPU Platform (OpenCL dialect)

Host (CPU)	Device (GPU, FPGA, etc)
Host code: C, C++, Fortran, C#, Java, Python, ecc.	Device code (kernels): OpenCL C, which is a modified C99 (add vector primitives and vector functions; some restrictions in use of pointers, some standard C99 headers are missing)
Manage the algorithm workflow	Perform computations on the provided data sets
Manage the data transfer between host memory (RAM) and device memory (VRAM); memory can be a shared area between host and device	Manage data flow among device mass memory, device shared memory and processor registers, through kernel's instructions
Manage global execution synchronization	Execution is divided in 1D, 2D or 3D workgroups; block synchronization can be obtained through device shared memory

Host code controls the parallel execution of dedicated kernels on one or more devices; kernels are compiled during initialization

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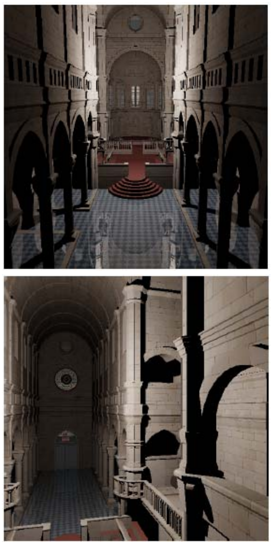
Computer Graphics Rendering Heritage

- Rasterisation → objects lightning obtained through artifacts (textures)
- Global illumination → direct evaluation of an objects appearance, due to objects and light sources positions, object properties, etc
- Ray Tracing Monte Carlo (RTMC) → Elegant solution to compute global illumination, under development from 1980s [Kay & Kajiya 1986]



[Fabianowski 2011]

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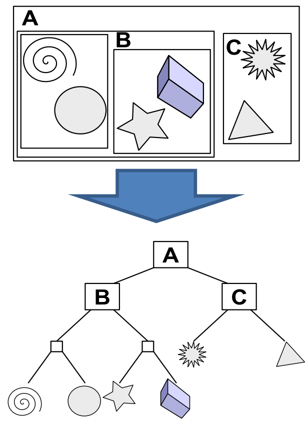
Acceleration Structures

Organize the geometry elements in order to compute ray-geometry intersection without testing **ALL** the model elements

- Voxels
- Octrees
- K-d trees
- Binary Volume Hierarchy (BVH):
  - Recursive binary tree partition
  - Each element belong to a single tree leaf



Courtesy Wikipedia

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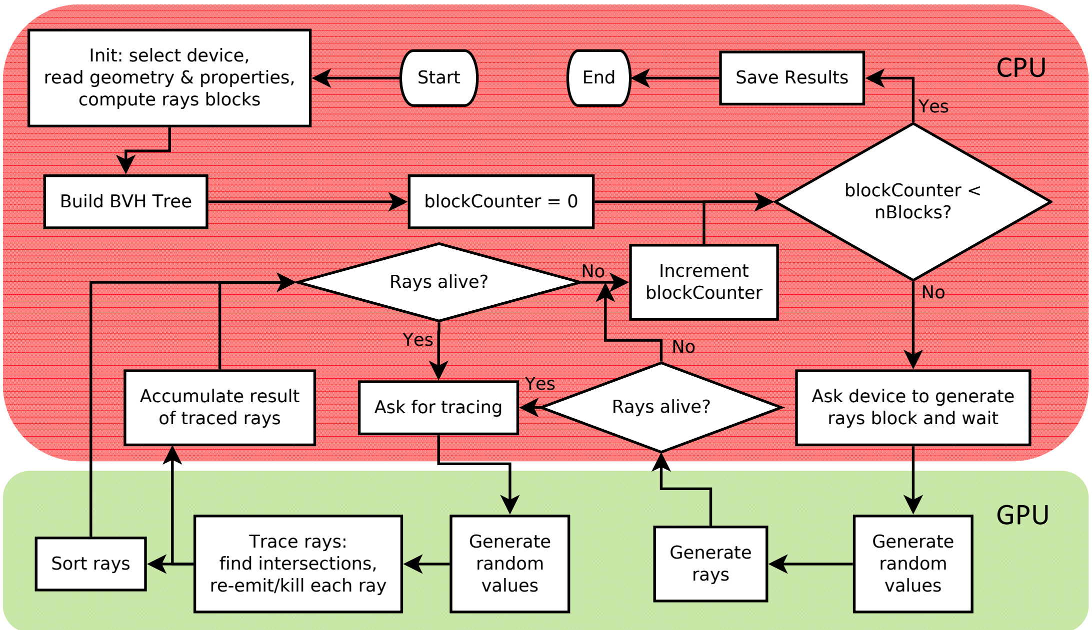
Tool architecture



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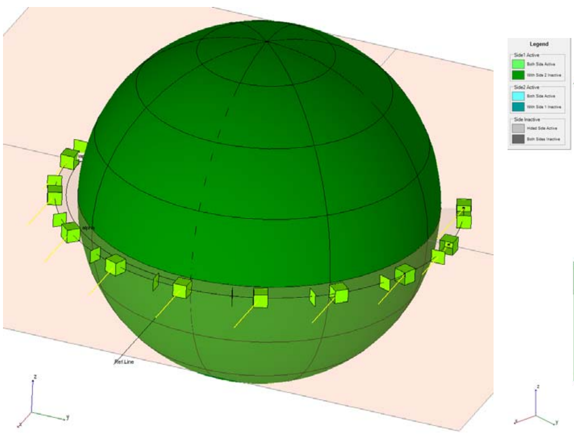
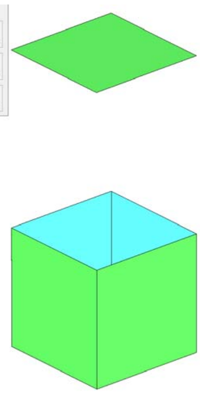
Open Box test





Node	Pos.	Node	Pos.
10	-X,1	11	-X,2
20	-Y,1	21	-Y,2
30	-Z,1	31	-Z,2
40	+X,1	41	+X,2
50	+Y,1	51	+Y,2
60	+Z,1	61	+Z,2

Orbit height	800 km over Earth surface
Sun constant	1000 W/m^2
Ray densities	10k rays/m^2 (Sun), 100k rays/m^2 (Earth, GR),

Side 1 optic	UV: $\alpha = 1$ IR: $\varepsilon = 0.5$, $\tau = 0$, $\rho_{ratio} = 0.5$
Side 2 optic	UV: $\alpha = 0$, $\tau = 0$, $\rho_{ratio} = 0$ IR: $\varepsilon = 0.5$, $\tau = 0$, $\rho_{ratio} = 0.5$

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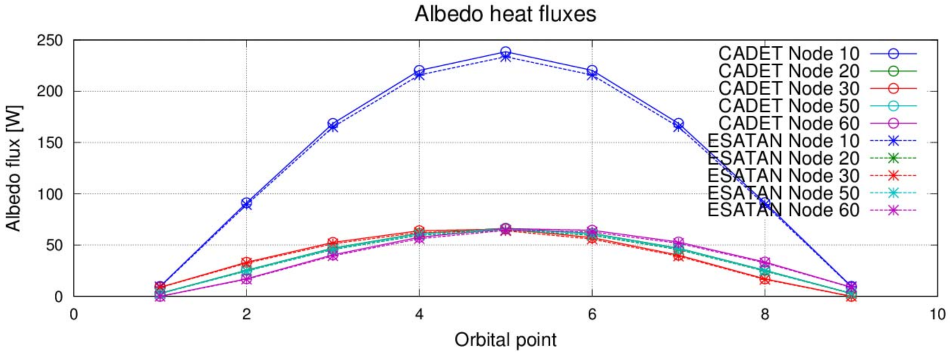
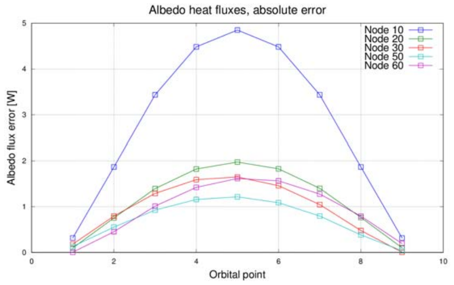
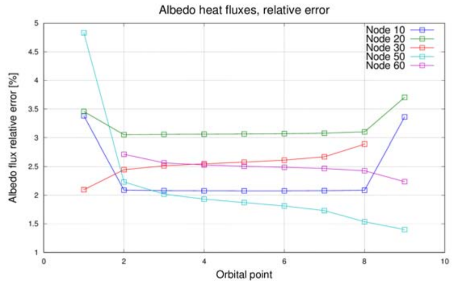
Open Box test - albedo results







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Open Box test – Earth flux results

Node	10	11	20	21	30	31
CADET	153.7860	6.7952	43.1359	11.6836	42.5930	10.3962
ESATAN	153.6489	6.9998	42.6820	11.4758	42.3568	10.1615
Abs. err.	0.137070	-0.204551	0.453887	0.207798	0.236169	0.234655
Rel. Err. %	0.089209	2.922240	1.063411	1.810749	0.557570	2.309245

Node	40	41	50	51	60	61
CADET	0	34.9459	42.9083	11.7025	42.9015	42.9358
ESATAN	0	35.0538	42.9592	11.4846	42.6880	42.7810
Abs. err.	0	-0.107996	-0.050915	0.217839	0.213462	0.154752
Rel. Err. %	0	0.308085	0.118519	1.896782	0.500051	0.361730

NB due to the selected attitude, Earth fluxes are the same on each point of the orbit

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Open Box test – Sun flux results

CADET Sun Fluxes [W]

	10	11	20	21	30	31	40	41	50	51	60	61	Tot
P1	0.00	0.00	0.00	0.00	1000.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1000.00
P2	0.00	0.00	0.00	0.18	923.88	0.00	382.68	0.00	0.00	0.09	0.00	0.00	1306.84
P3	0.00	0.00	0.00	0.00	707.11	0.07	707.11	0.14	0.00	0.00	0.00	0.00	1414.43
P4	0.00	0.00	0.00	0.00	382.68	0.04	923.88	0.08	0.00	0.00	0.00	0.00	1306.68
P5	0.00	0.00	0.00	0.00	0.00	0.00	1000.00	0.00	0.00	0.00	0.00	0.00	1000.00
P6	0.00	0.09	0.00	0.18	0.00	0.09	923.88	0.09	0.00	0.00	382.68	0.18	1307.21
P7	0.00	0.28	0.00	0.14	0.00	0.42	707.11	0.57	0.00	0.35	707.11	0.07	1416.05
P8	0.00	0.28	0.00	0.28	0.00	0.26	382.68	0.50	0.00	0.22	923.88	0.09	1308.19
P9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1000.00	0.00	1000.00

Absolute error, CADET – ESATAN [W]

	10	11	20	21	30	31	40	41	50	51	60	61	Tot
P1	-0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.05
P2	0.00	0.00	0.00	0.18	-0.02	0.00	0.00	0.00	0.00	0.09	0.00	0.00	0.26
P3	0.00	0.00	0.00	0.00	-0.02	0.07	0.00	0.14	0.00	0.00	0.00	0.00	0.19
P4	0.00	0.00	0.00	0.00	-0.02	0.04	0.00	0.08	0.00	0.00	0.00	0.00	0.10
P5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P6	0.00	0.09	0.00	0.18	0.00	0.09	0.00	0.09	0.00	0.00	-0.02	0.18	0.63
P7	0.00	0.28	0.00	0.14	0.00	0.42	0.00	0.57	0.00	0.35	-0.02	0.07	1.81
P8	0.00	0.28	0.00	0.28	0.00	0.26	0.00	0.50	0.00	0.22	-0.02	0.09	1.61
P9	-0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.05

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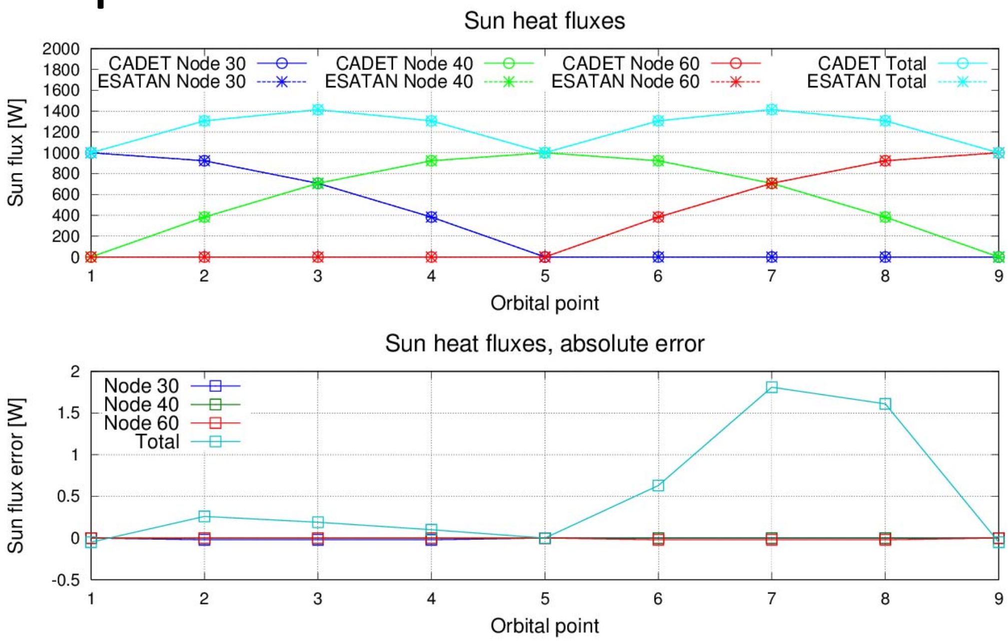
Open Box test – Sun flux results



All other nodes: null flux due to attitude and null alpha

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H10 test – Description (1)

- Ariane IV 3rd stage, standard CADET target
- Analyze target thermal behavior to allow IR tracking
- Test orbital parameters:

Radius *r*	7161 km
Eccentricity *e*	0
Inclination *i*	45°
Argument of periapsis *ω*	0°
Ascending node *Ω*	-90°

- Attitude: LOCS, Z body aligned with $-\vec{V}$, Y body aimed to Z Earth
- Optical properties: guess, obtained through aerospace materials data base ($\bar{\alpha}$=0.537, $\bar{\varepsilon}$=0.266)
- Ray density (rays/m^2): 10k (Sun), 100k (Earth, albedo)
- 41 orbital position computed (half orbit, no eclipse)

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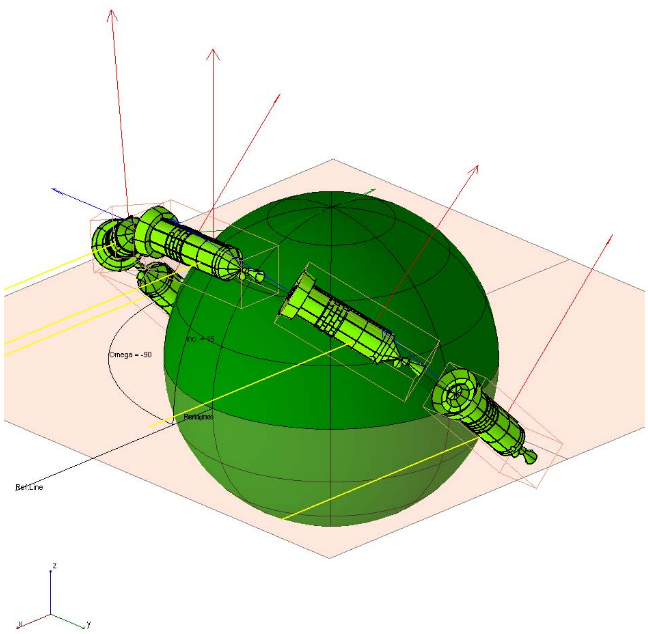
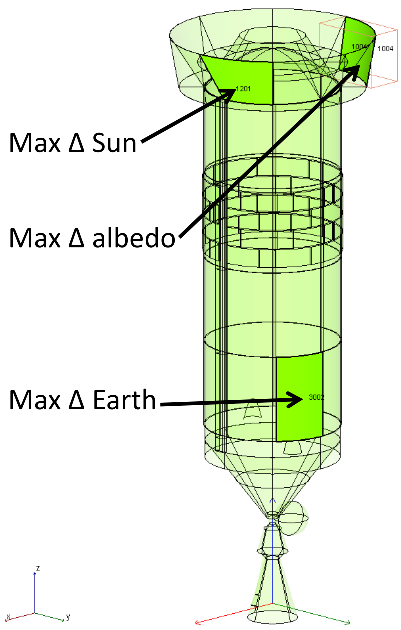
H10 test – Description (2)





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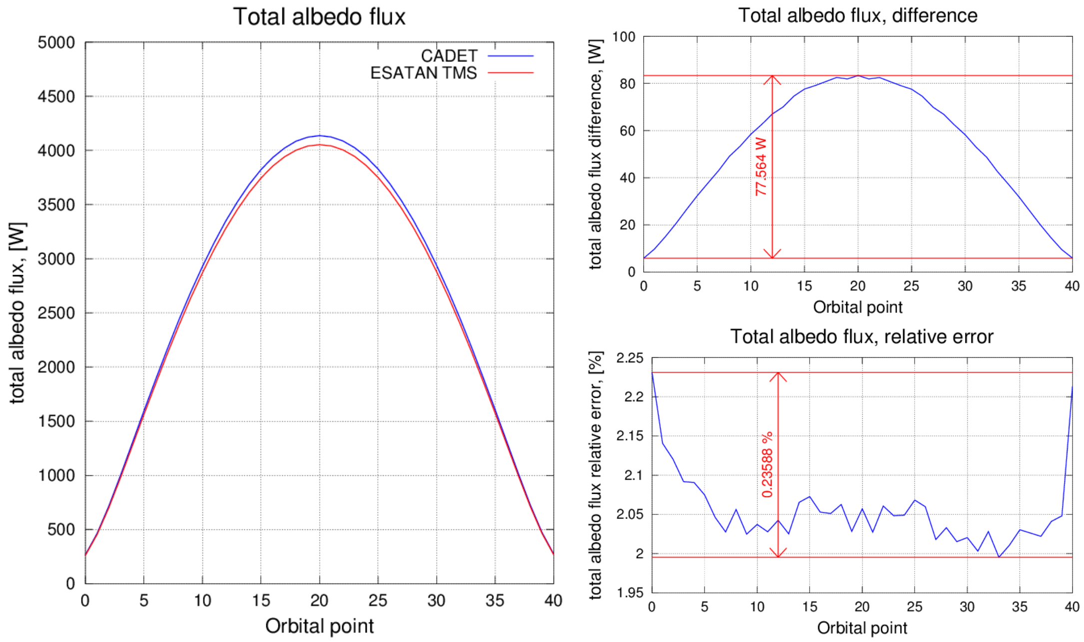
H10 test – total albedo flux



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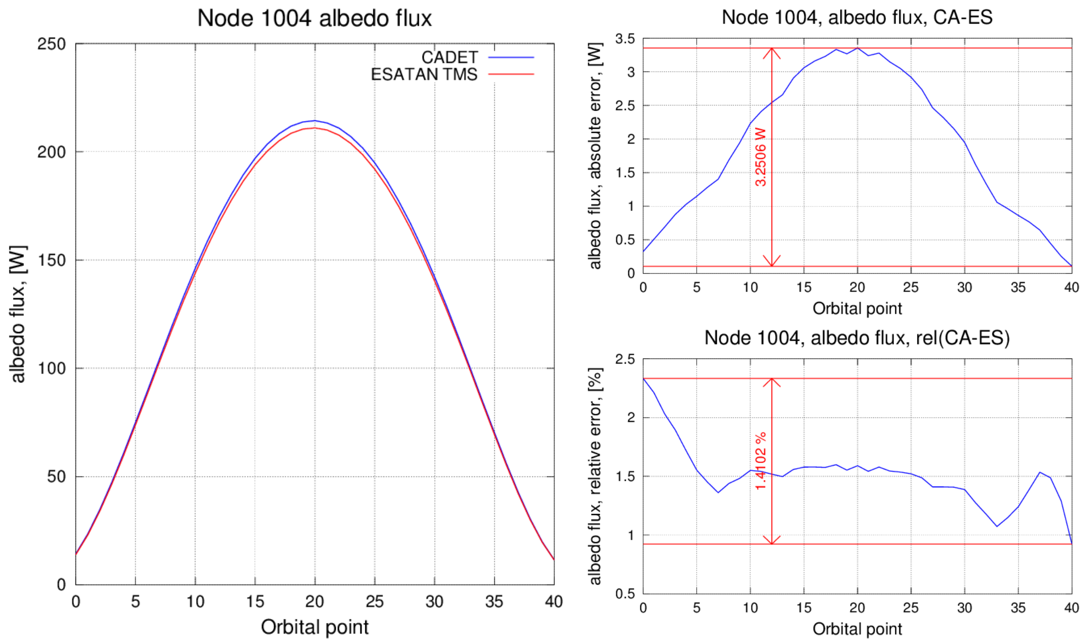
H10 test – max. albedo flux diff.



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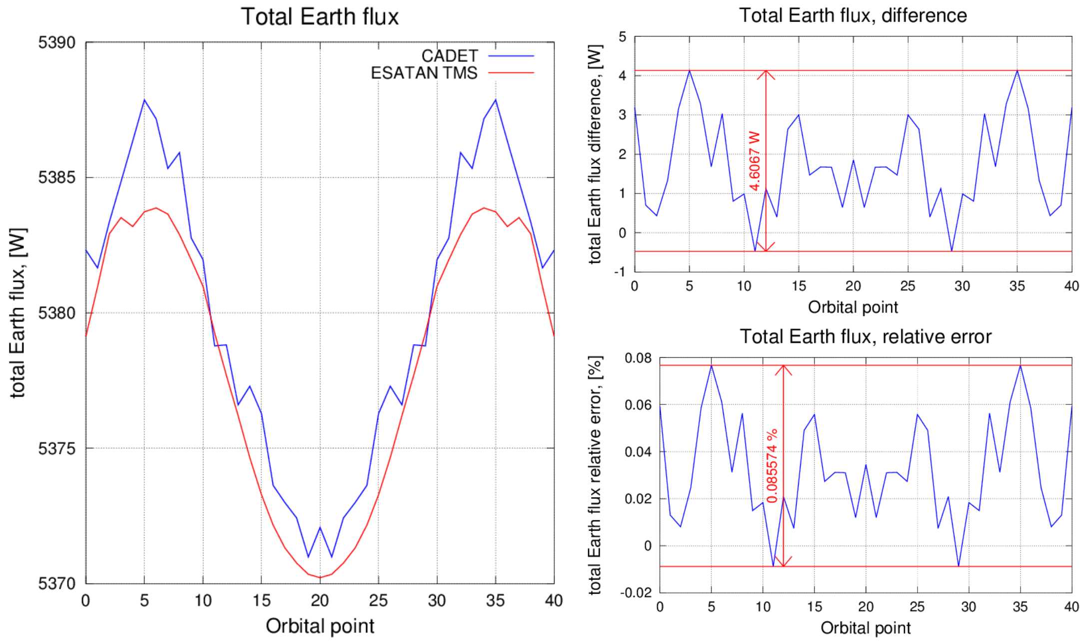
H10 test – total Earth flux



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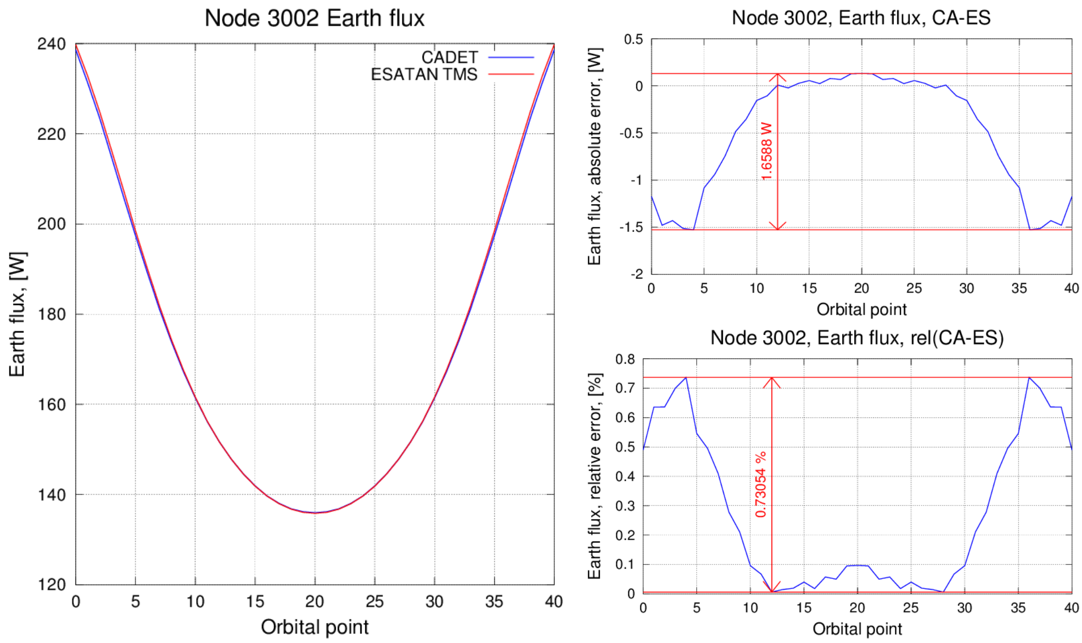
H10 test – max Earth flux diff.



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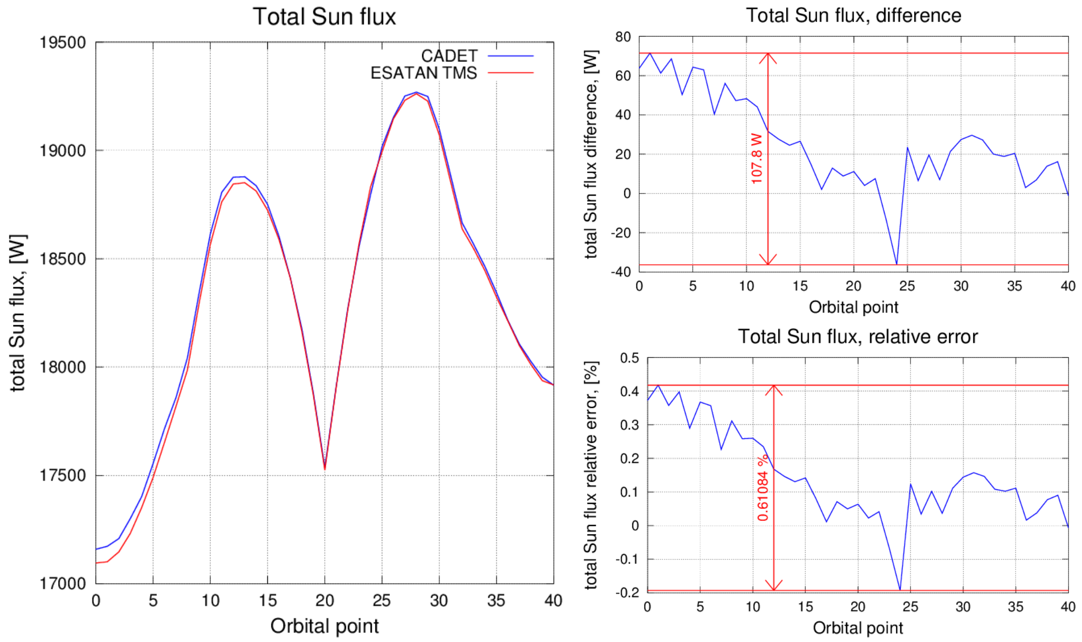
H10 test – total Sun flux



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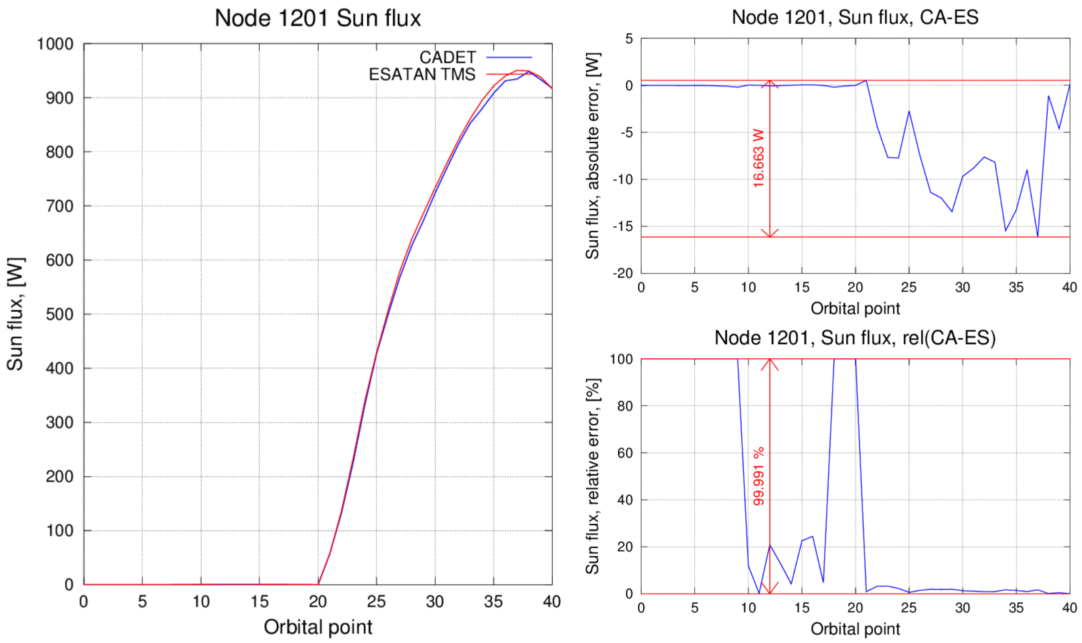
H10 test – max Sun flux diff.



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H10 test – GR

Case	ESATAN TMS	CADET
# GR	9453	9287
Common GR	6495	
Additional GR	2958	2792
$\sum GR_{Uncommon}$	1.2167e-3	57.818e-3
Max $Gr_{Uncommon}$	0.1372e-3	1.079e-3

Case	ESATAN TMS	CADET	Δ X1000	Δ%
$\sum GR$	83.070	83.154	84.240	0.101
$\sum GR_{Model\ to\ space}$	48.304	48.298	-6.476	-0.013
$\sum GR_{Model\ to\ inactive}$	6.595	6.595	0.834	0.012
$\sum GR_{Model\ to\ model}$	28.17	28.26	89.882	0.319
$\sum GR_{Common}$	83.068	83.096	27.859	0.033
Max Δ, GR(3105,3205)	0.31389	0.31152	2.372	0.755

ESATAN and CADET GR cut off value: 1e-6

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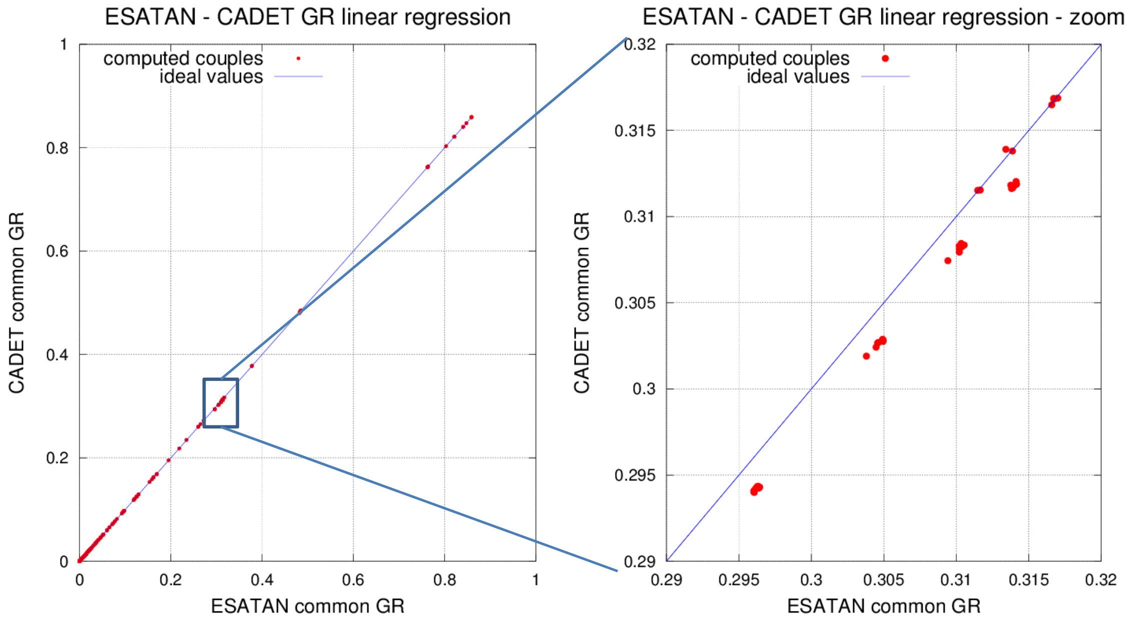
H10 test – GR



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Performance – Test Hardware

Device	Vendor	Type	CU	Clock GHz	Memory				Peak performances		
					Type	GB	Float4 GB/s	Float16 GB/s	Int4 GIOPS	Float4 GFLOPS	Float16 GFLOPS
Core i7 940	Intel	CPU	4+4	2.93	DDR3	18	12.29	12.29	8.90	27.77	25.69
Core i3 2370M	Intel	CPU	2+2	2.40	DDR3	4	9.56	9.06	/	19.12	19.12
Core i3 3220	Intel	CPU	2+2	3.30	DDR3	8	10.96	11.05	/	26.19	26.61
Core i7 4700HQ	Intel	CPU	2.4	2.40	DDR3	8	17.20	17.09	/	35.06	36.71
GT 630	NVIDIA	GPU	2	1.62	GDDR3	1	17.52	4.56	103.07	307.50	280.09
GTX 670M	NVIDIA	GPU	7	1.20	GDDR5	1.5	61.46	15.36	/	786.62	718.22
GT 750M	NVIDIA	GPU	2	1.10	DDR3	4	25.60	11.64	/	740.01	740.00
GTX Titan Black	NVIDIA	GPU	15	0.98	GDDR5	6	298.26	107.37	1010.58	4685.42	4685.42
Quadro 2000	NVIDIA	GPU	4	1.25	GDDR5	1	35.87	8.97	158.94	472.28	459.16
HD 5850	AMD	GPU	18	0.725	GDDR5	1	86.04	34.41	443.27	1738.85	1782.76
HD 7870 GE	AMD	GPU	20	1.00	GDDR5	2	130.31	35.51	505.76	2507.83	437.86
HD 7950 Boost	AMD	GPU	28	1.15	GDDR5	3	278.37	48.54	748.95	3725.15	3650.85
HD 8970M	AMD	APU*	5	0.825	DDR3	2	7.99	2.21	/	251.56	247.00

* Accelerated Processing Unit, AMD definition of a chip which contains a CPU section and a GPU section

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Performance – Results

Device	Tracing, Mr/s		Execution times, seconds						Gain
	Sun	REF Planet	41 Sun fluxes	Sun, mean	GR + UV REF	41 Earth + Albedo (CPU)	Earth + Albedo, mean	Total	
Core i7 940	2.25	1.61	57.21	1.40	224.28	8.94	0.22	302.66	3.24
Core i3 2370M	1.21	0.65	240.72	5.87	590.10	15.02	0.40	863.11	1.14
Core i3 3220	1.23	1.01	106.41	2.60	378.89	20.14	0.50	524.39	1.87
Core i7 4700HQ	2.25	1.56	57.14	1.39	231.73	5.17	0.13	303.27	3.24
GT 630	2.02	1.33	62.98	1.54	307.10	20.15	0.48	410.16	2.39
GTX 670M	4.29	3.39	29.61	0.72	119.21	12.70	0.31	167.00	5.88
GT 750M	2.73	1.99	46.61	1.14	158.05	5.53	0.19	218.61	4.49
GTX Titan Black	9.42	13.35	13.49	0.33	30.24	7.12	0.17	53.84	18.23
Quadro 2000	1.65	1.29	40.82	1.00	302.21	7.68	0.19	357.95	2.74
HD 5850	3.61	4.34	35.26	0.86	94.15	5.13	0.19	144.74	6.78
HD 7870 GE	6.21	8.52	20.71	0.51	47.60	5.07	0.12	81.58	12.03
HD 7950 Boost	8.18	13.85	15.54	0.38	29.48	6.03	0.15	58.93	16.66
HD 8970M	3.08	2.85	41.23	1.01	143.36	5.16	0.14	197.28	4.98
ESATAN TMS*	/	/	319.00	7.78	650.00	12.50	0.30	981.50	1.00

* Calculation on Intel i7 940 2.93 GHz; single core execution with Intel Turbo Boost, (clock set to 3.2 GHz)
All computations on Windows 7/8 64 machines; tools also works on Linux

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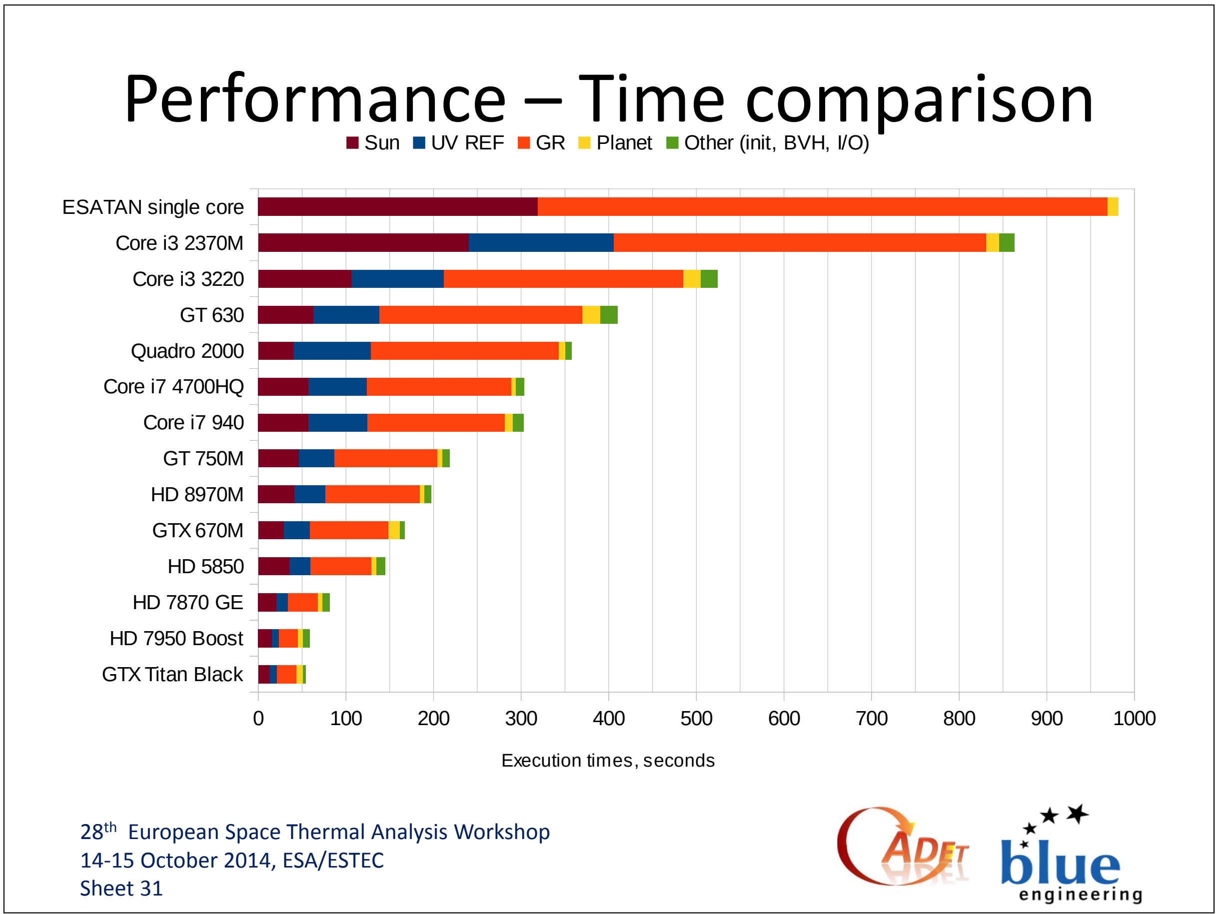

Performance – Time comparison
Sun
UV REF
GR
Planet
Other (init, BVH, I/O)
ESATAN single core
Core i3 2370M
Core i3 3220
GT 630
Quadro 2000
Core i7 4700HQ
Core i7 940
GT 750M
HD 8970M
GTX 670M
HD 5850
HD 7870 GE
HD 7950 Boost
GTX Titan Black
0
100
200
300
400
500
600
700
800
900
1000
Execution times, seconds
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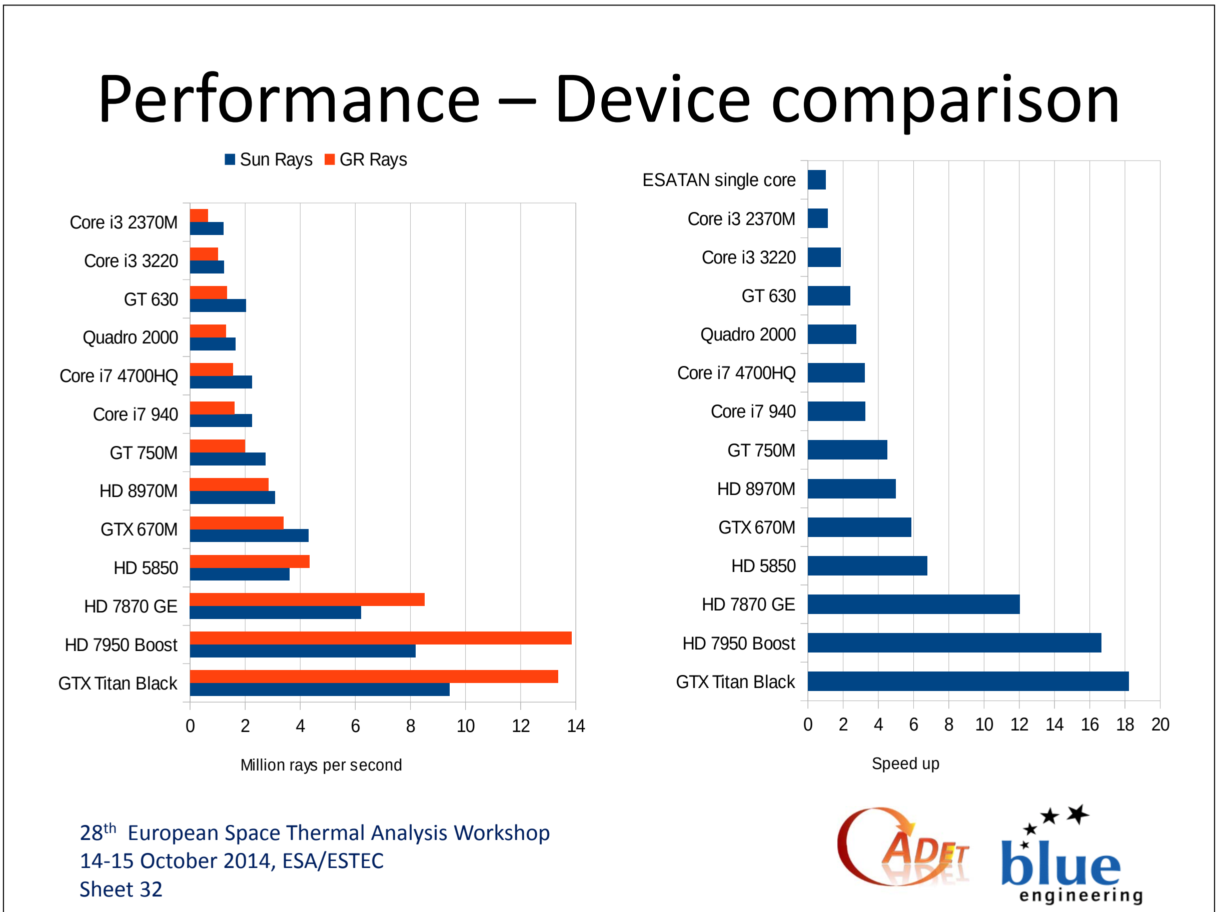
ADET
blue engineering



Performance – Device comparison
Sun Rays
GR Rays
Core i3 2370M
Core i3 3220
GT 630
Quadro 2000
Core i7 4700HQ
Core i7 940
GT 750M
HD 8970M
GTX 670M
HD 5850
HD 7870 GE
HD 7950 Boost
GTX Titan Black
0
2
4
6
8
10
12
14
Million rays per second
ESATAN single core
Core i3 2370M
Core i3 3220
GT 630
Quadro 2000
Core i7 4700HQ
Core i7 940
GT 750M
HD 8970M
GTX 670M
HD 5850
HD 7870 GE
HD 7950 Boost
GTX Titan Black
0
2
4
6
8
10
12
14
16
18
20
Speed up
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ADET
blue engineering

Performance – CG reference

Reference code [Aila&Laine, 2009]	CADET code
Language: **CUDA**	Language: **OpenCL**
Sibenik Cathedral model (80131 triangles)	Sibenik Cathedral model (80131 triangles)
NVIDIA GT 630	NVIDIA GT 630
Test on diffuse illumination rays	GR/UV REF computation

15M rays/s | **~1.17M rays/s**

Reference code is about 13 times quicker than the developed the code!

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Possible Improvements

- Data flow:
  - Float16 to float4 data items conversion
  - Data caching through constant memory blocks for initialization (BVH data etc.)
  - Data caching through texture units (simpler if OpenCL 1.2 is used)
- Improve BVH structure (Split BVH construction → SBVH)
- Stack-less tracing kernel (reduce register pressure and improve the number of concurrent threads)
- Take advantage of multiple devices (multi GPU, GPU+CPU configurations)
- Evaluate different ray tracing strategies:
  - Offloading part of the ray tracing procedure to the CPU when few rays need to be traced, and leave on device only mass evaluations
  - Use device fission (OpenCL 1.2) to parallelize ray spawning and ray tracing on device, in order to maximize device occupancy

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Conclusions

- CADET radiative solver is implemented and its results are consistent with the ESATAN TMS tool (considering RTMC fluctuations).
- On GPU devices, the tool use the huge computation power of GPU HW and get acceptable performances (up to 18x respect to ESATAN TMS on high end hardware).
- Additional speedup of 10x and more could be achieved improving the tool (compared to NVIDIA computer graphics rendering algorithm).
- New developers' skills are needed to maximize GPGPU performances.

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CADET blue engineering

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CADET blue engineering

Appendix M

Insight HP3

Thermal Modelling with Thermal Desktop

Asli Gencosmanoglu Luca Celotti Riccardo Nadalini
(Active Space Technologies GmbH, Germany)

Abstract

The Heat-Flow and Physical Properties Probe (HP3) is an instrument package built by Deutsches Zentrum für Luft- und Raumfahrt (DLR) as a part of NASA-JPL Insight Mission (The Interior Exploration Using Seismic Investigations, Geodesy, and Heat Transport) which will investigate the interior structure and processes of Mars. The mission will be launched on a Type I trajectory to Mars in March of 2016.
The main subsystems of HP3 includes:

- Hammering mechanism , the Mole that penetrates below the Martian surface
- Support structure that houses the Mole prior to ground penetration
- Radiometer mounted on the lander
- Back-end electronics in the lander thermal enclosure

The thermal analysis and design of the HP3 Instrument for the landed phase of the mission have been performed by Active Space Technologies GmbH using Thermal Desktop and Sinda/Fluint. In the scope of the thermal analysis and design activities, the detailed thermal and geometrical models of each subsystem as well as the integrated models are created. Being composed of subsystems which are permanently mounted on the lander, deployed on the Mars surface after landing and deployed into the Martian soil, different external thermal environments are defined for each subsystem for the different phases of the mission, including the mars heating environment modelling. The detailed models are integrated on the simplified lander model and the reduced models of the subsystems are also created to be integrated into the detailed lander model.
The features of Thermal Desktop used for the different stages of the HP3 instrument thermal modelling and analysis process are presented:

- General features;
- Generation of thermal models;
- Integration of geometrical and thermal models
- Planet heating environment modelling;
- Post-processing;
- Data exchange.

Insight HP3
Thermal Modelling with Thermal Desktop

European Space Thermal Analysis Workshop 2014

Asli Gencosmanoglu
14-15 October 2014
Estec, Nordwijk - The Netherlands

making space a global endeavour

Asli Gencosmanoglu, Riccardo Nadalini
ActiveSpace Technologies GmbH

Contents

- HP3 Mission and Instrument Description
- Thermal Models Created for HP3
- Thermal Desktop General Features
- Generation of Thermal Models
- Integration of Thermal Models
- Planet Heating Environment Modelling
- Post-Processing
- Data Exchange

2

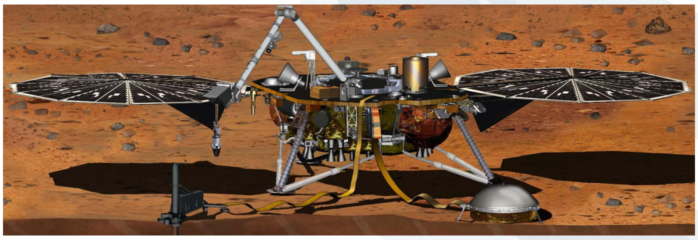
HP3

The Heat-Flow and Physical Properties Probe (HP3) :

- Instrument package built by DLR as a part of NASA-JPL Insight Mission
- Investigate the interior structure and processes of Mars
- Will be launched on a Type I trajectory to Mars in March of 2016

The main subsystems of HP3:

- Hammering mechanism , the Mole that penetrates below the Martian surface
- Support structure that houses the Mole prior to ground penetration
- Radiometer mounted on the lander
- Back-end electronics in the lander thermal enclosure



http://insight.jpl.nasa.gov/images.cfm?IM_ID=8301

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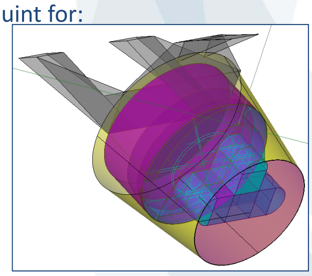
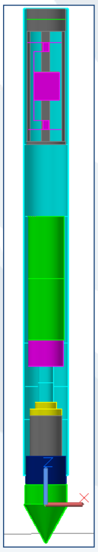
HP3 Thermal Models

Thermal Models are created using Thermal Desktop/Sinda Fluint for:

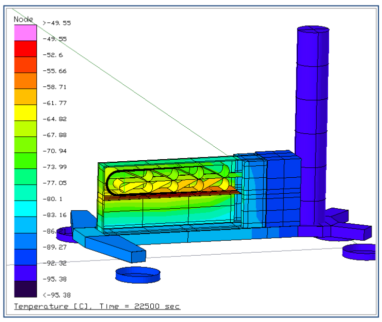
- Mole
- Support Structure
- Radiometer mounted on the lander
- Back-end electronics in the lander thermal enclosure



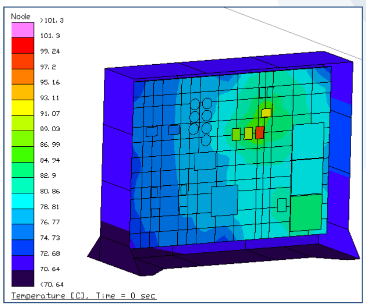
Radiometer



Mole



Support Structure



Back End Electronics

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Thermal Desktop Modelling

GENERAL FEATURES

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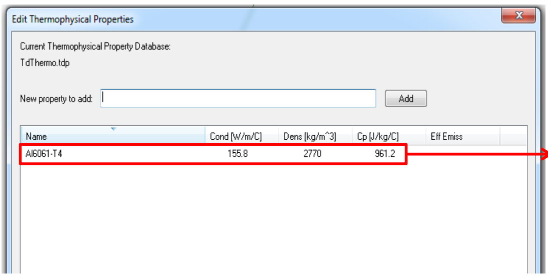
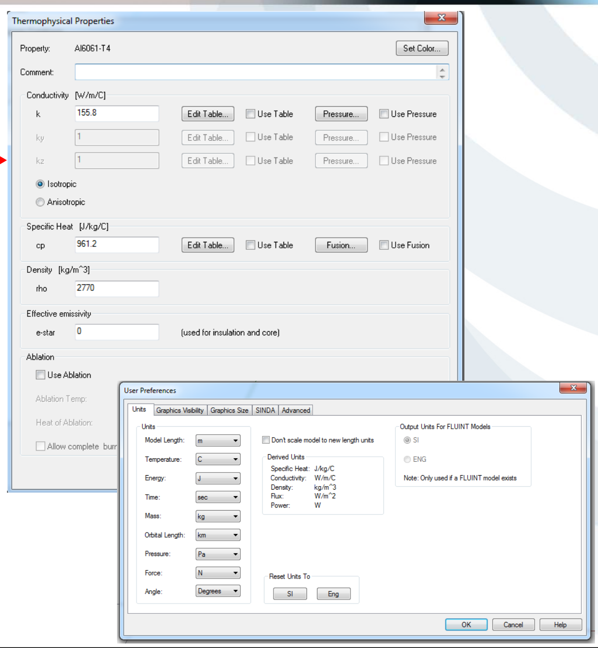
Thermophysical Property Database





- Temperature dependent properties
- Anisotropic material properties
- Thermo-physical Property Database (*.tdp) can also be imported from other models

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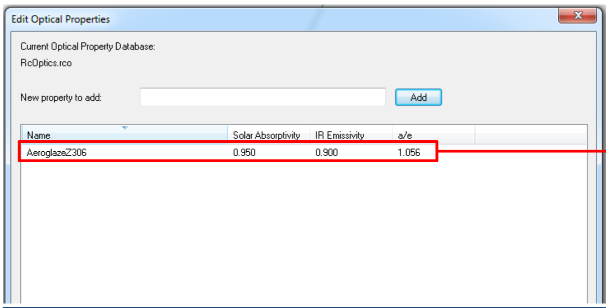
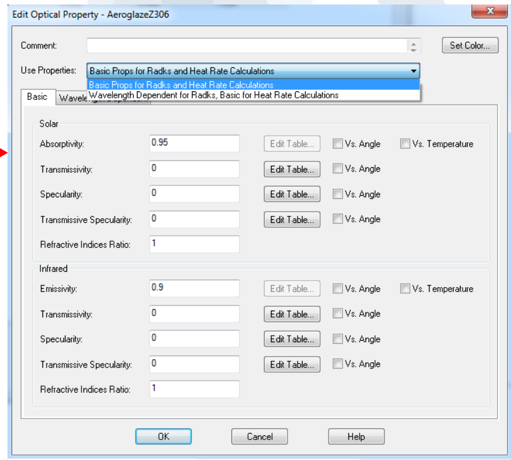
Optical Property Database



- Optical Property Database (*.tdp) can be imported from other models
- Wavelength, temperature and angle dependent properties can be defined



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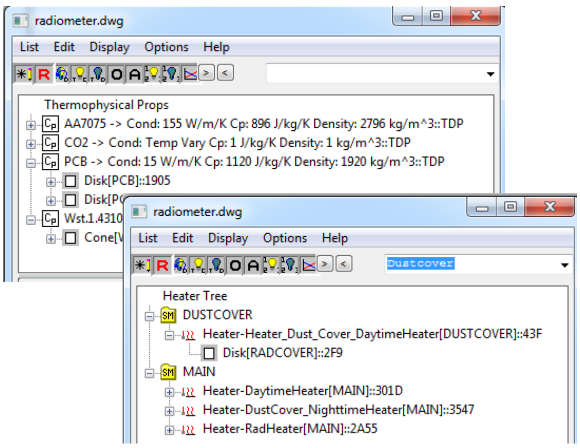
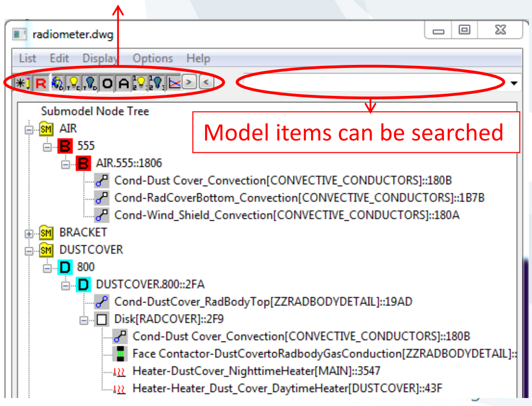
Model Browser

Several Listing Options:

- Optical Properties
- Thermo-physical Properties
- Heaters/Heat Loads
- Contactors
- Surfaces/solids etc.

- The thermal entities can be selected and edited from model browser menu
- The visibility of graphical objects can be adjusted
- The visibility of Node IDs can be turned ON/OFF
- Multiple edits can be performed
- All thermal entities (nodes, conductors, heat loads, user logic) are placed in a thermal submodel





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Thermal Desktop Modelling

GENERATION OF THERMAL MODELS

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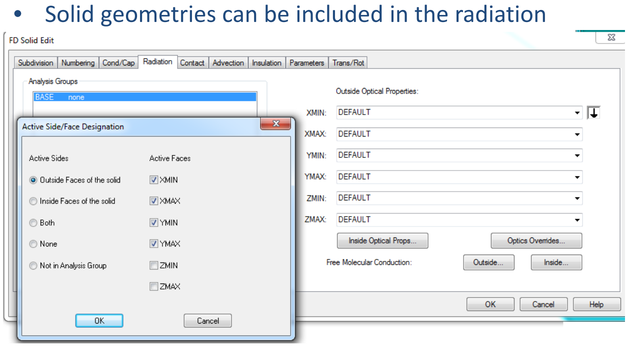
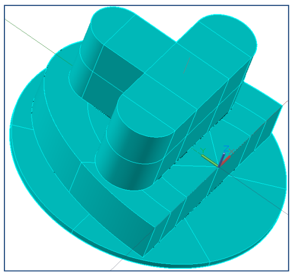
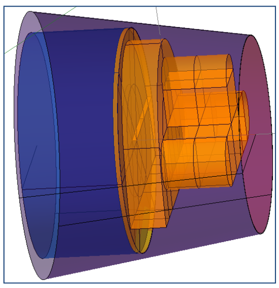
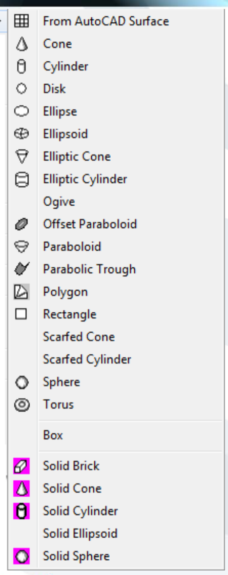
Radiometer-Finite Difference Solids

- ➢ Radiometer body temperature gradients are important
- ➢ Radiometer body radiative heat exchange
- Creating finite difference surfaces/solids using AutoCad interface
- Possibility to use AutoCad surfaces to create finite difference surfaces (drawback : irregular meshes)
- Solid geometries are useful when the through thickness gradients are important
- Solid geometries can be included in the radiation









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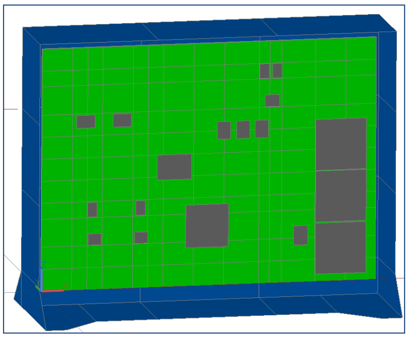
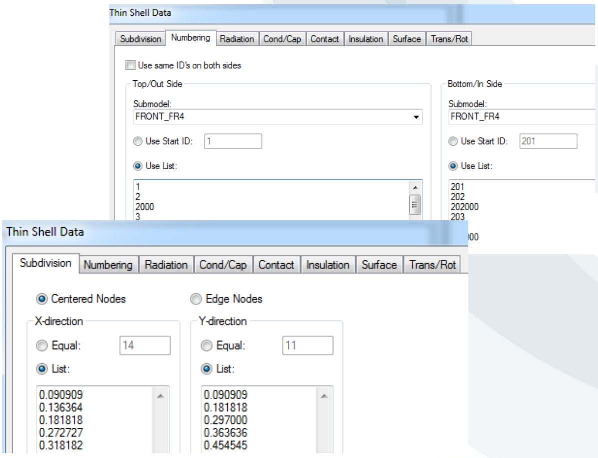
BEE-Thin Shell Data

- BEE PCB nodal break-down is adjusted to fit component dimensions
- It is important to have control on the node sizes
- It is important to have control on the node numbering, especially for the late stage modelling changes



- Possibility to create user defined sub-divisions
- Possibility to define node IDs manually
- Assigning different node IDs for different sides of the surface



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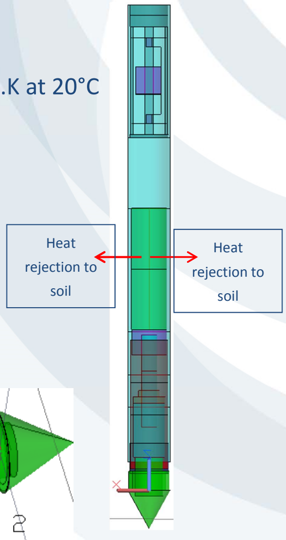
Mole-Mars CO_2 Gas Conduction

- Mars Atmosphere: 95.5% CO_2
- Surface Pressure : around 8 Torr
- Thermal conductivity of CO_2 varies from 0.010W/m.K at -60°C to ~0.016W/m.K at 20°C
- Gas conduction is dominant, clearances are small <0.3mm
- Pure gas conduction, no convection
- The Mole consists of many concentric cylinders

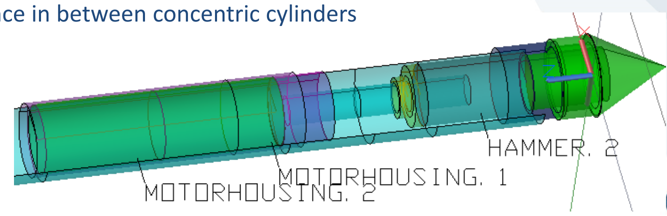
    Modelling of CO_2 conduction is important :
    - To estimate the required heater power for the motor
    - To estimate the maximum allowable operation time



- The gas conduction is modelled in radial direction: k(T)*(A/l)

    A: cylindrical area

    l : Clearance in between concentric cylinders



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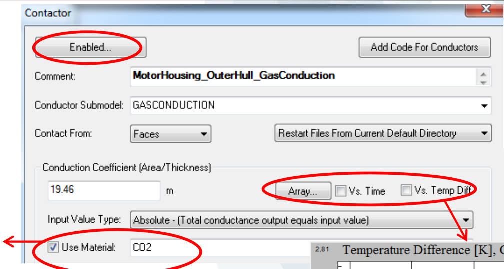
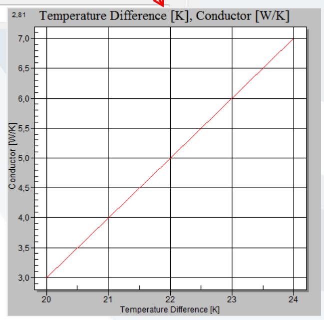
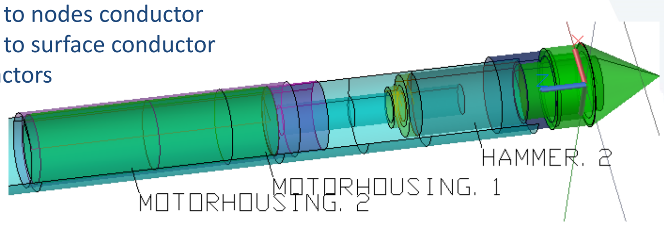
Mole-Conductance Calculations

- The modelling items can be enabled/disabled
- Possibility to introduce temperature or time dependent conductance values as arrays
- Temperature dependent conductance values can also be defined using temperature dependent thermo-physical data
- Conductors can be defined using GUI:
  - Node to node conductor
  - Node to nodes conductor
  - Node to surface conductor
  - Contactors







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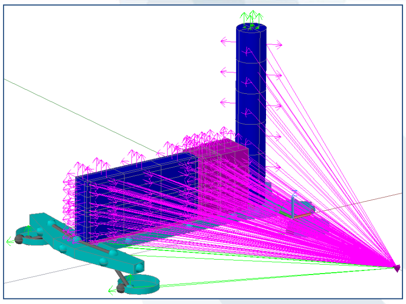
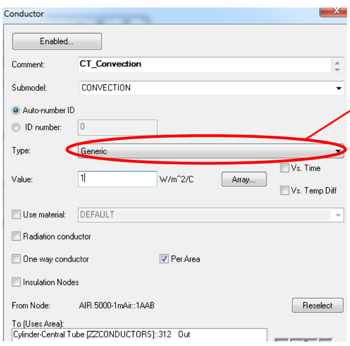
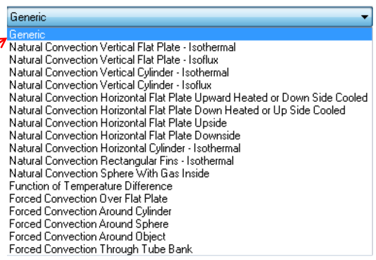
Support Structure- Mars CO_2 Convection

- Support Structure convective heat exchange with atmosphere is significant
- It is a function of Martian wind speeds
- Mars Pathfinder and Mars rover Sojourner tests in JPL:
  h = 1 to 2 W/m2.K for wind speeds = 0 to 5 m/sec
  (ref: The Mars Thermal Environment and Radiator Characterization (MTERC) Experiment Kenneth R. Johnson and David E. Brinza JPL)

- Convective and conductive heat transfer to air is modelled with a constant convective heat transfer coeff.







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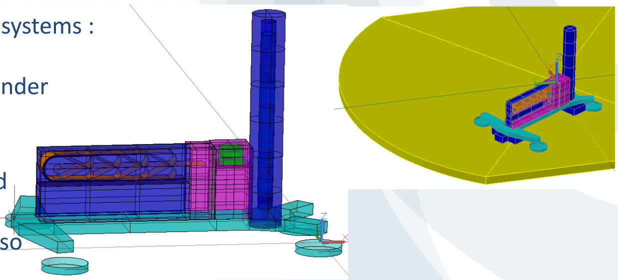
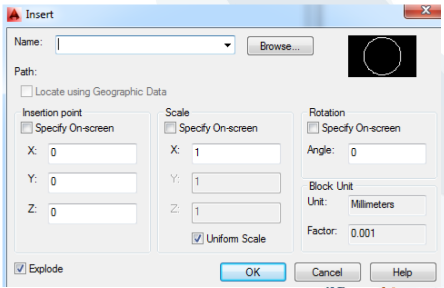
HP3-Integrating Thermal Models

- The Support Structure is housing the other subsystems : Mole, TLM, Tethers etc.
- The Support Structure itself mounted on the lander before deployment



- Entire thermal desktop models can be inserted to merge thermal models
- A subset of thermal desktop submodels can also be inserted (defined subset should be exported first)
- Thermo-optical and thermo-physical data bases should be imported separately

- Once the defined models are inserted as a `block` then it is exploded to convert the block into individual entities
- Sub-model names should be checked
- Boundaries should be checked



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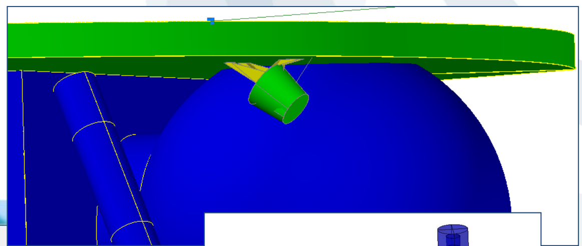
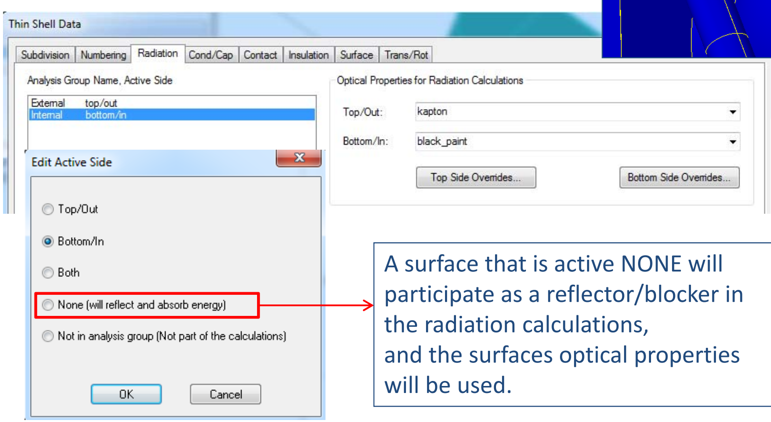
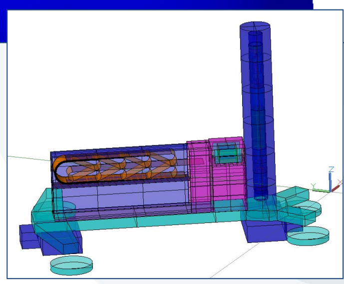
Radiation Analysis Groups

- Radiation analysis groups can be created for radiation and external heating calculations
- The radiation groups can be included/excluded from the analysis
- The active sides can be displayed by colors for the selected radiation group





A surface that is active NONE will participate as a reflector/blocker in the radiation calculations, and the surfaces optical properties will be used.



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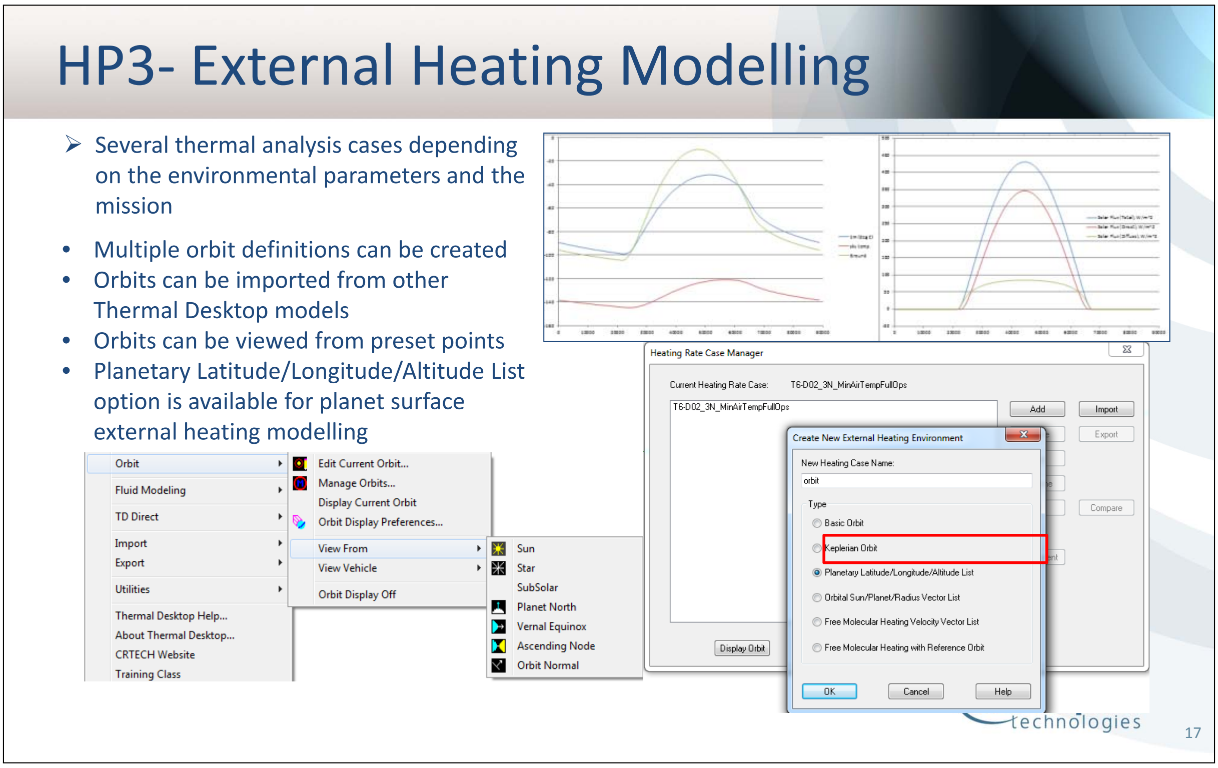
HP3- External Heating Modelling
Several thermal analysis cases depending on the environmental parameters and the mission
Multiple orbit definitions can be created
Orbits can be imported from other Thermal Desktop models
Orbits can be viewed from preset points
Planetary Latitude/Longitude/Altitude List option is available for planet surface external heating modelling
Orbit
Fluid Modeling
TD Direct
Import
Export
Utilities
Thermal Desktop Help...
About Thermal Desktop...
CRTECH Website
Training Class
Edit Current Orbit...
Manage Orbits...
Display Current Orbit
Orbit Display Preferences...
View From
View Vehicle
Orbit Display Off
Sun
Star
SubSolar
Planet North
Vernal Equinox
Ascending Node
Orbit Normal
Heating Rate Case Manager
Current Heating Rate Case: T6-D02_3N_MinAirTempFullOps
Add
Import
Export
Compare
Display Orbit
Create New External Heating Environment
New Heating Case Name:
orbit
Type
Basic Orbit
Keplerian Orbit
Planetary Latitude/Longitude/Altitude List
Orbital Sun/Planet/Radius Vector List
Free Molecular Heating Velocity Vector List
Free Molecular Heating with Reference Orbit
OK
Cancel
Help
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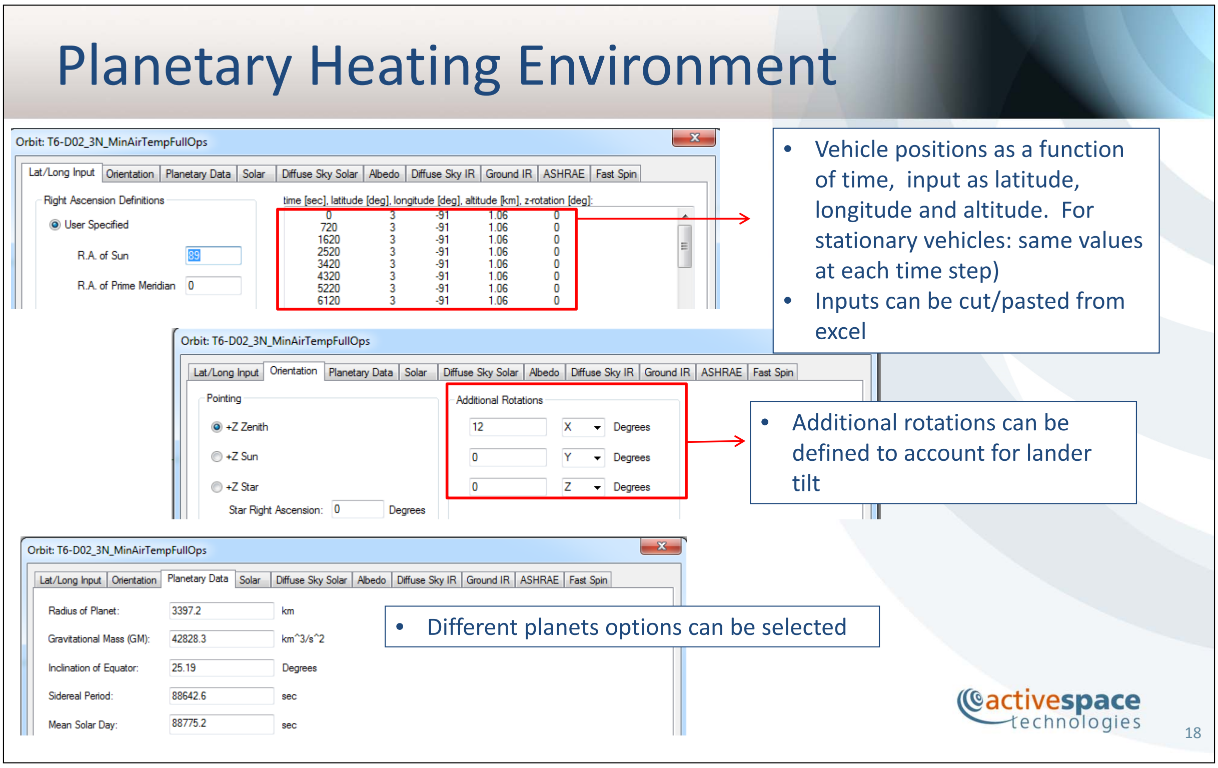
Planetary Heating Environment
Orbit: T6-D02_3N_MinAirTempFullOps
Lat/Long Input
Orientation
Planetary Data
Solar
Diffuse Sky Solar
Albedo
Diffuse Sky IR
Ground IR
ASHRAE
Fast Spin
Right Ascension Definitions
User Specified
R.A. of Sun
R.A. of Prime Meridian
time [sec], latitude [deg], longitude [deg], altitude [km], z-rotation [deg]:
Vehicle positions as a function of time, input as latitude, longitude and altitude. For stationary vehicles: same values at each time step)
Inputs can be cut/pasted from excel
Pointing
+Z Zenith
+Z Sun
+Z Star
Star Right Ascension:
Degrees
Additional Rotations
Additional rotations can be defined to account for lander tilt
Radius of Planet: 3397.2 km
Gravitational Mass (GM): 42828.3 km^3/s^2
Inclination of Equator: 25.19 Degrees
Sidereal Period: 88642.6 sec
Mean Solar Day: 88775.2 sec
Different planets options can be selected
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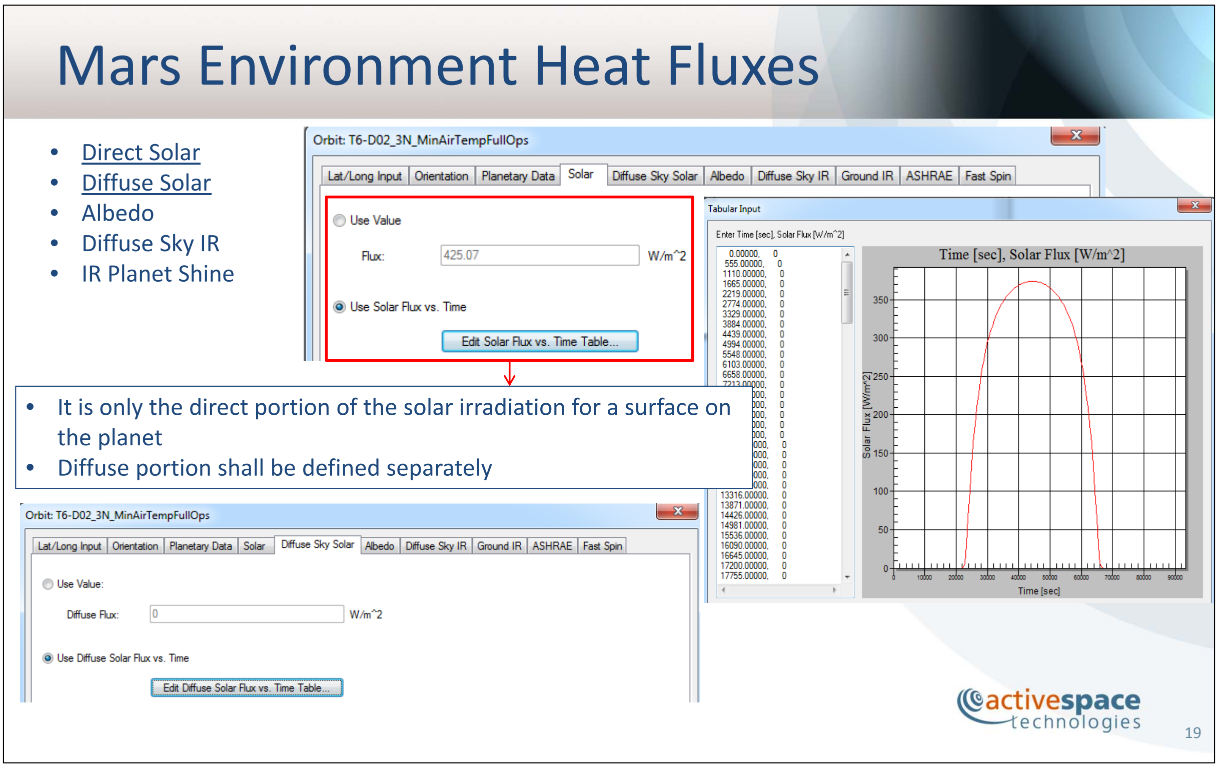
Mars Environment Heat Fluxes
Direct Solar
Diffuse Solar
Albedo
Diffuse Sky IR
IR Planet Shine
Orbit: T6-D02_3N_MinAirTempFullOps
Lat/Long Input
Orientation
Planetary Data
Solar
Diffuse Sky Solar
Albedo
Diffuse Sky IR
Ground IR
ASHRAE
Fast Spin
Use Value
Flux:
425.07
W/m^2
Use Solar Flux vs. Time
Edit Solar Flux vs. Time Table...
Tabular Input
Time [sec], Solar Flux [W/m^2]
Solar Flux [W/m^2]
Time [sec]
It is only the direct portion of the solar irradiation for a surface on the planet
Diffuse portion shall be defined separately
Diffuse Flux:
Use Diffuse Solar Flux vs. Time
Edit Diffuse Solar Flux vs. Time Table...
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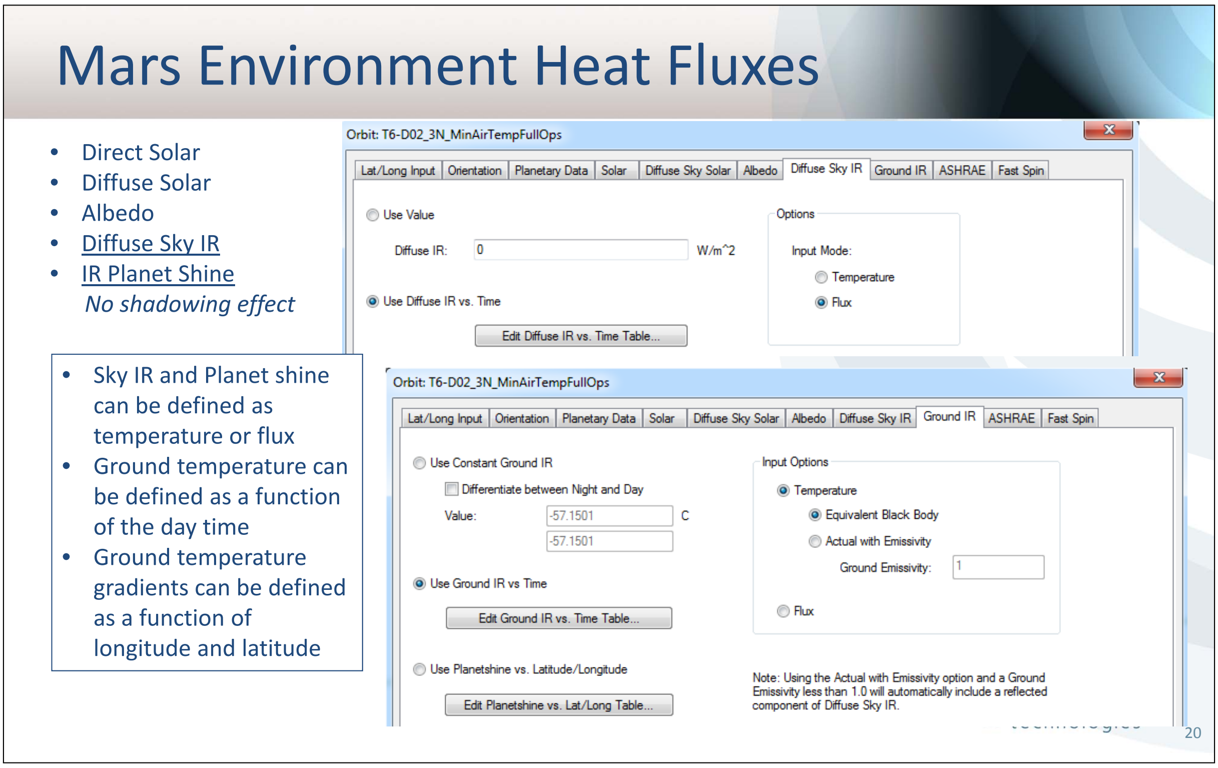
Mars Environment Heat Fluxes
Direct Solar
Diffuse Solar
Albedo
Diffuse Sky IR
IR Planet Shine
No shadowing effect
Sky IR and Planet shine can be defined as temperature or flux
Ground temperature can be defined as a function of the day time
Ground temperature gradients can be defined as a function of longitude and latitude
Orbit: T6-D02_3N_MinAirTempFullOps
Use Value
Diffuse IR:
W/m^2
Use Diffuse IR vs. Time
Edit Diffuse IR vs. Time Table...
Options
Input Mode:
Temperature
Flux
Use Constant Ground IR
Differentiate between Night and Day
Value:
-57.1501
Use Ground IR vs Time
Edit Ground IR vs. Time Table...
Use Planetshine vs. Latitude/Longitude
Edit Planetshine vs. Lat/Long Table...
Input Options
Equivalent Black Body
Actual with Emissivity
Ground Emissivity:
Note: Using the Actual with Emissivity option and a Ground Emissivity less than 1.0 will automatically include a reflected component of Diffuse Sky IR.
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Thermal Desktop Modelling

POST PROCESSING

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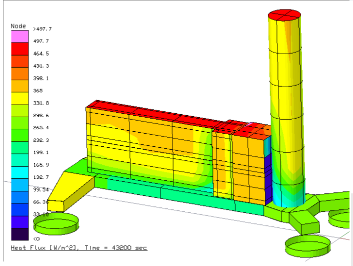
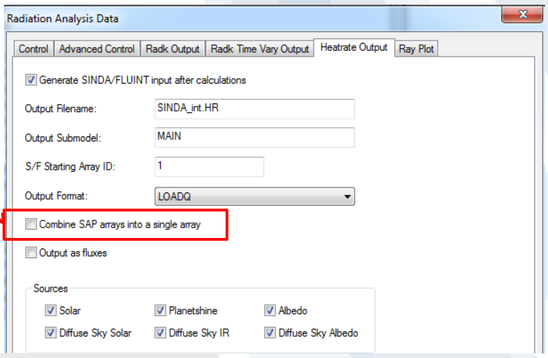
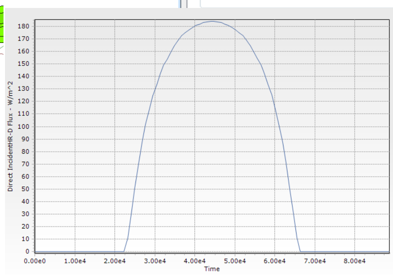
SS-Post Processing of Heat Fluxes

- All heat fluxes can be stored separately and post-processed when the radiation and heating calculations are completed







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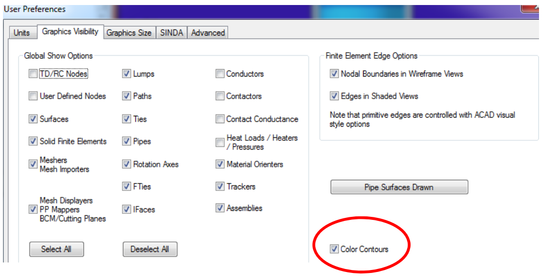
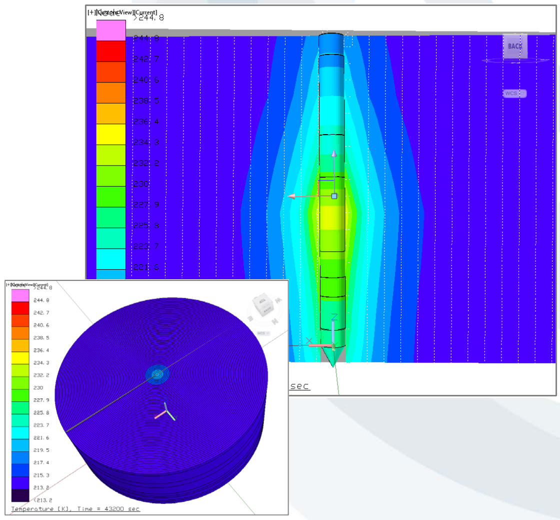
Soil- Post Processing Cutting Plane

- Visualization of results within a solid object
- Mapping the temperature results
- Domain Tag sets can be created to select the solids to be included in the cutting plane



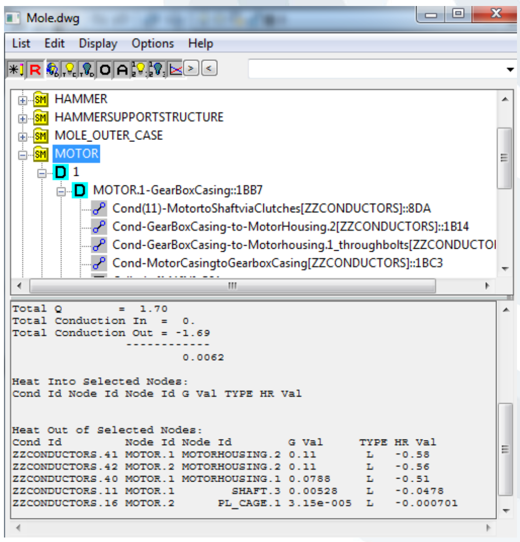


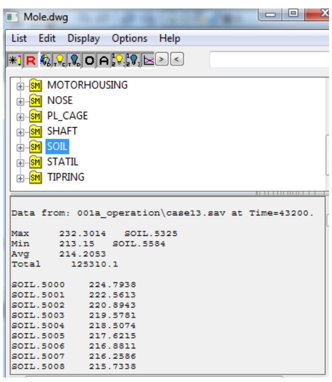
Post Processing – Model Browser

Heat Map:

- The heat flow in between nodes can be listed from Model Browser, selecting the individual nodes or submodels
- The radiative and conductive heat flows are listed separately
- No visual thermal map generation, each node or submodel is displayed separately

Temperature List:





Thermal Desktop Modelling

DATA EXCHANGE

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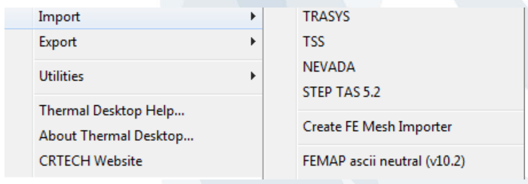
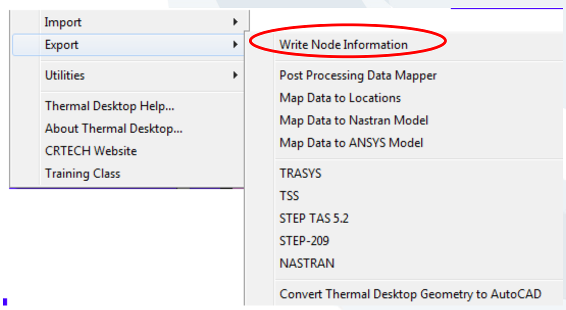
Importing/Exporting Models

- Geometric models can be imported from other radiation analysis codes
- Only the surface types supported by Thermal Desktop are imported
- The capacitance and conductance values can be assigned once the geometries are imported into Thermal Desktop
- Node locations , current post-processed values, surface areas can be exported into a text file





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Thank you for the attention!
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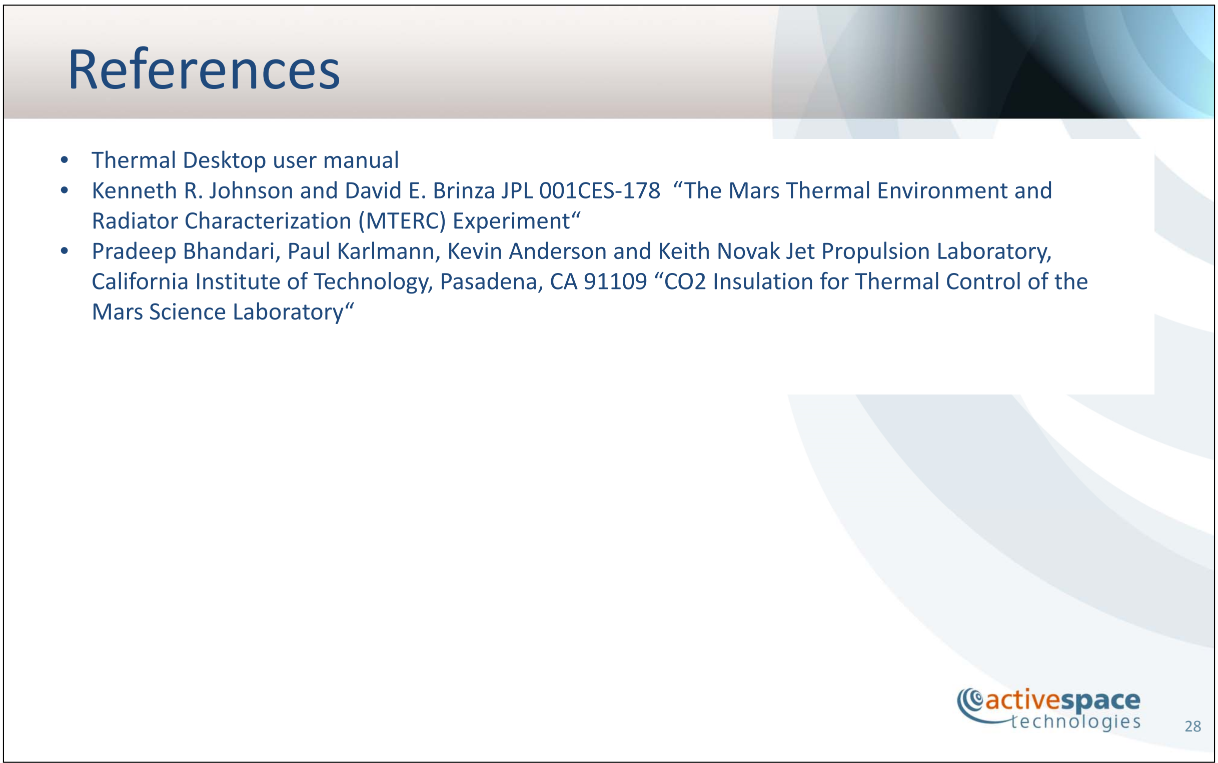
References
• Thermal Desktop user manual
• Kenneth R. Johnson and David E. Brinza JPL 001CES-178 “The Mars Thermal Environment and Radiator Characterization (MTERC) Experiment“
• Pradeep Bhandari, Paul Karlmann, Kevin Anderson and Keith Novak Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 “CO2 Insulation for Thermal Control of the Mars Science Laboratory“
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Appendix N

Analysis Strategies For Missions Involving Comprehensive Thermal Issues

Nicolas Liquière
(EPSILON, France)

Abstract

Epsilon works on projects whose complexity is expressed in different terms:

- The nature of the missions always looking for increasing performances. These induce the development of new mechanisms such as on the 3POD project, the high level of thermal stability such as on the INSIGHT mission, and high accuracy level on optical performances such as on the OTOS telescope program.
- Serious environmental constraints as for PAS instrument on the Solar Orbiter mission which directly braves the fierce Sun, and INSIGHT-SEIS instrument or Exomars-MOMA instruments which are subject to Martian environment.

All studies conducted by EPSILON on such projects require specific thermal architecture works and major modeling and simulation efforts. For each aspect, software (Systema, NX / TMG, STAR CCM + ...) is selected due to its advantages and its fit with needs.
It is proposed to walk you through some thermal problems on INSIGHT and OTOS projects, to expose how the thermal modeling and simulation problems have been managed.


EPSILON
ALCEN
bridge the thermal gap
Analysis Strategies For Missions Involving Comprehensive Thermal Issues
Nicolas Liquière / EPSILON
28th European Space Thermal Analysis Workshop – 14-15 Oct 2014


Context
EPSILON
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Page 2

CONTEXT INSIGHT OTOS

Activities with complex background

- **Projects and objectives** are more and more challenging:
  - Nature of the mission
  - Serious environmental constraints
- **Architecture works, major modeling and simulation efforts** are required
- **Software** must be selected due to their advantages to fit with needs

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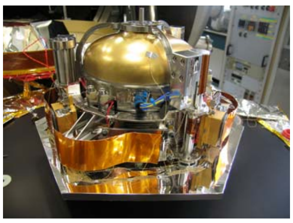
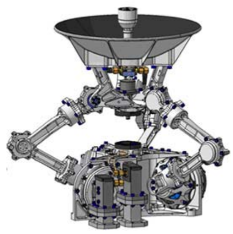
CONTEXT INSIGHT OTOS

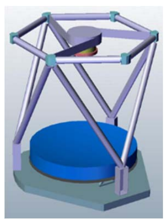
Some projects in which EPSILON is involved



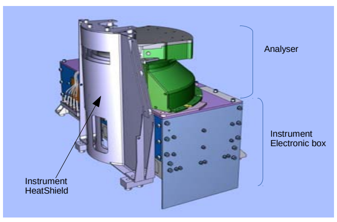
INSIGHT-SEIS (CNES)



APM 3POD (COMAT)



OTOS – Technology demonstrator (CNES)



SOLAR ORBITER – PAS (IRAP)

EXOMARS – MOMA (LATMOS)

Balloon – BSO-BPS (CNES)

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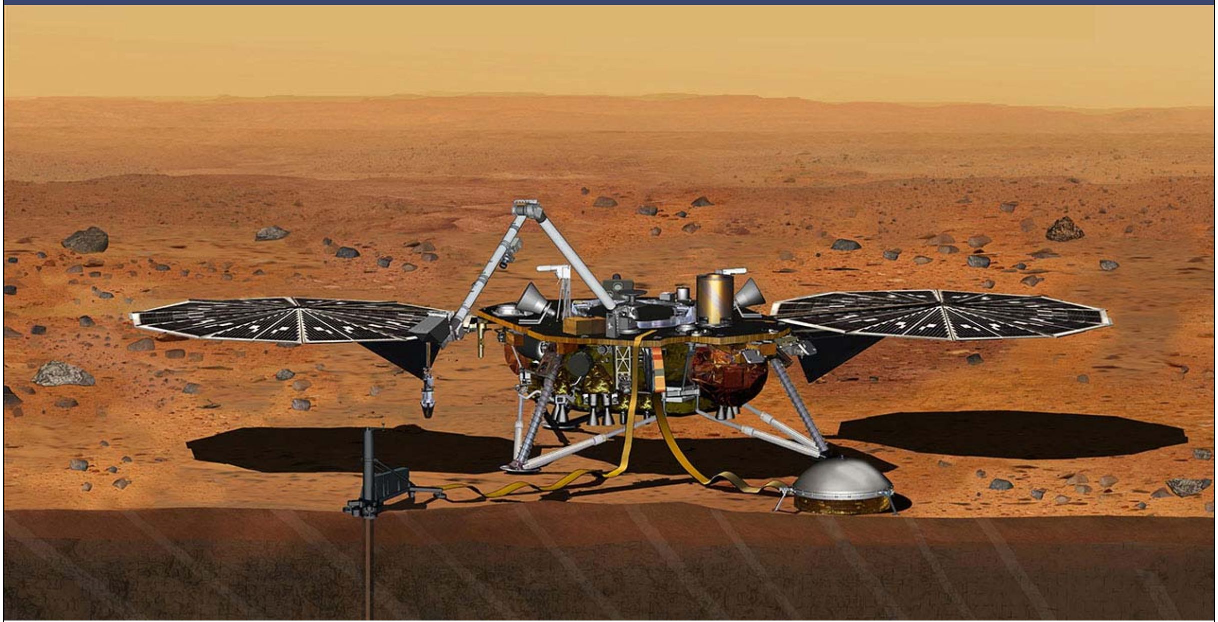
INSIGHT



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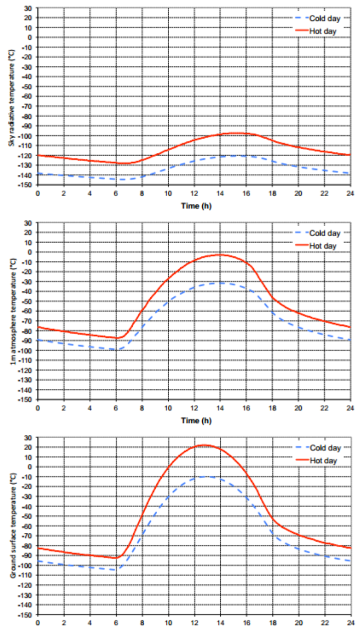
CONTEXT INSIGHT OTOS

Main context

→ **A single geophysical lander** on Mars to study its deep interior

→ **A SEIS seismometer sensitive** to very low vibration levels.

→ **A harsh Martian environment conditions**
ex: large daily variations
(-100°C @nighttime to +20°C @daytime)



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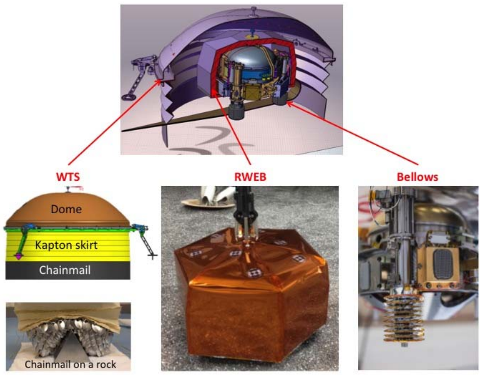
CONTEXT INSIGHT OTOS

Thermal control design

→ **Objective:** a thermal design providing a stable thermal environment

Protect from wind / external fluctuation	**WTS + skirt**
Reduce radiative exchanges	**Coatings with low εIR**
Reduce gas effect	**RWEB + bellows**
Reduce conductive effects	**Titanium + washers**
Heating power during winter	**1.5W**



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CONTEXT INSIGHT OTOS

TCS performances validation

→ **Through analyses:**

- SEIS instrument modeling
- SEIS thermal behavior driven by environment… So accurate modeling needed!
  - Identification of the environment mains contributors: Sun, wind, dust, ground…
  - Acceptable representation of contributors → predictions validated thanks to measurements

→ **Through thermal test** (Not addressed here)

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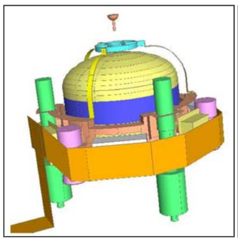
CONTEXT INSIGHT OTOS

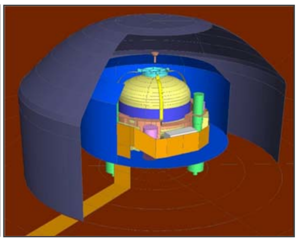
Thermal modeling

→ The instrument

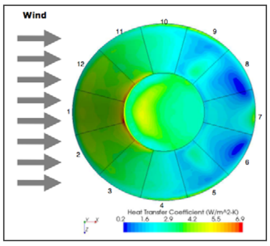
- Conduction + radiation + CO_2 effects modeling (convection & gas conduction)
- Nodal model composed of 332 nodes
- Helped by CFD refined modeling



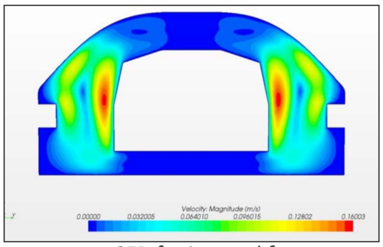
SEIS « naked » model



SEIS + thermal protection



CFD for external forced convection



CFD for internal free convection

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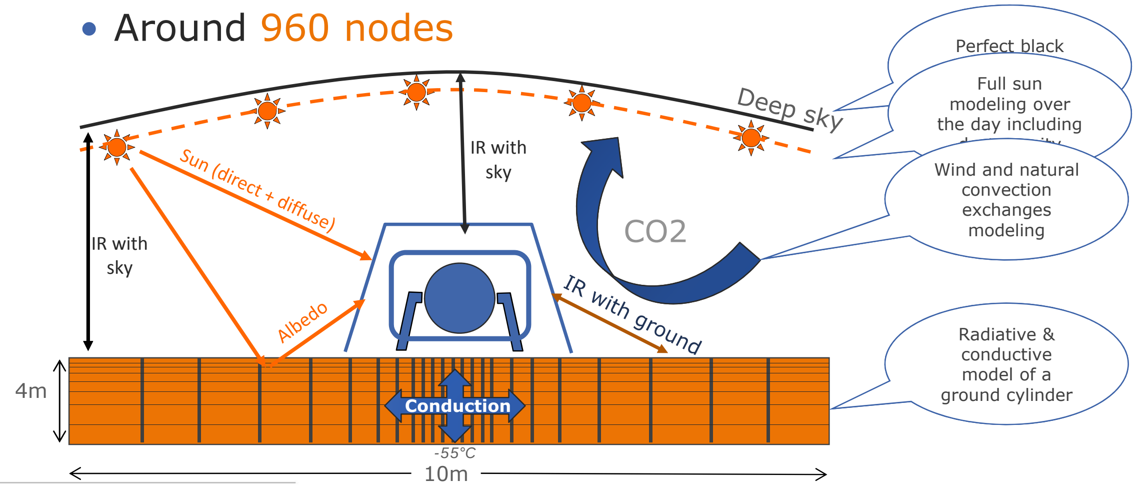
CONTEXT INSIGHT OTOS

Thermal modeling

→ The environment

- SEIS thermal behavior driven by environment … so accurate modeling needed!
- Around 960 nodes



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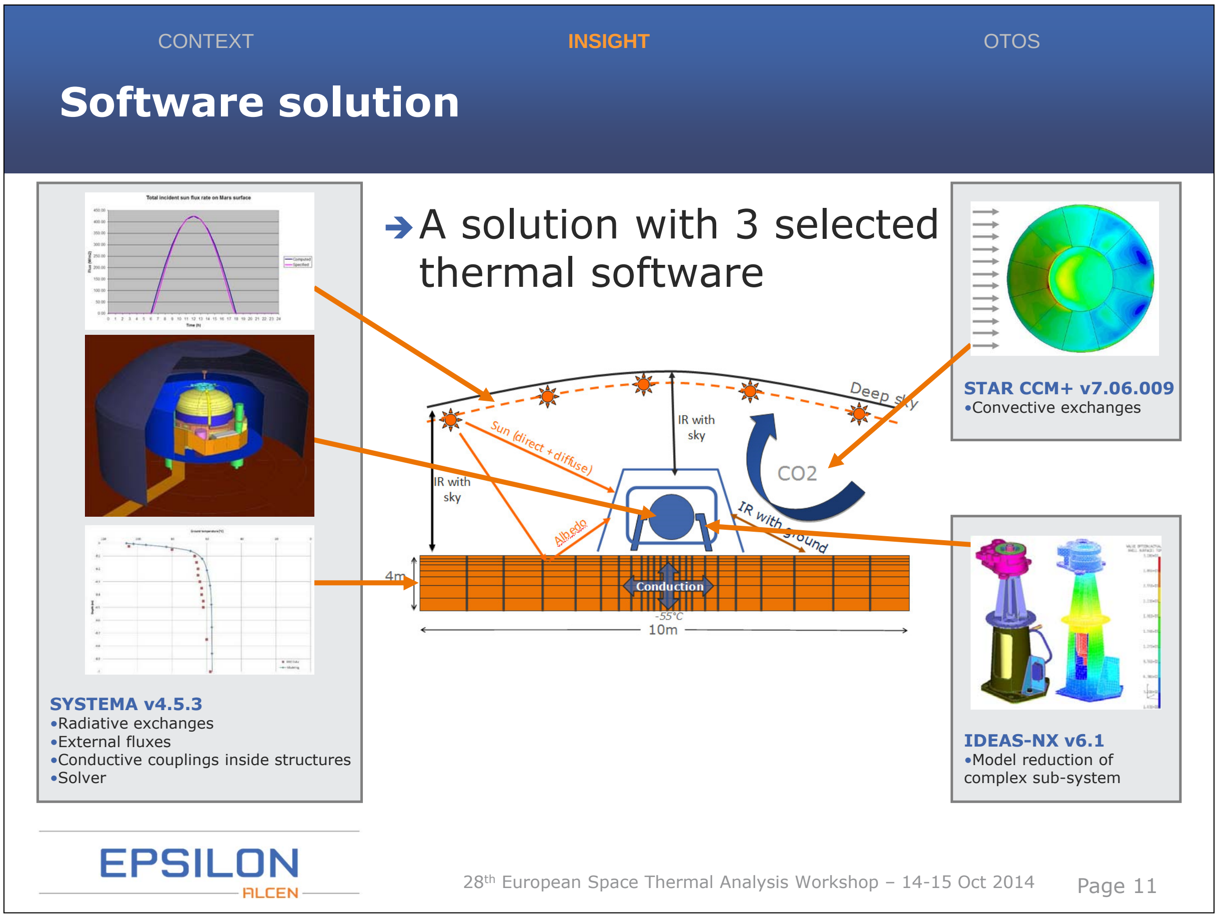
CONTEXT
INSIGHT
OTOS
Software solution
➔ A solution with 3 selected thermal software
Deep sky
Sun (direct + diffuse)
IR with sky
IR with sky
Albedo
CO2
IR with ground
4m
Conduction
-55°C
10m
SYSTEMA v4.5.3
•Radiative exchanges
•External fluxes
•Conductive couplings inside structures
•Solver
STAR CCM+ v7.06.009
•Convective exchanges
IDEAS-NX v6.1
•Model reduction of complex sub-system
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OTOS
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CONTEXT INSIGHT **OTOS**

Main context

- Telescope with a large mirror
- Thermal stability required for optic performances purpose → PI controller
- High degree of accuracy desired for thermo-elastic study purpose
- Telescope thermal behavior driven by environment … so accurate modeling needed!

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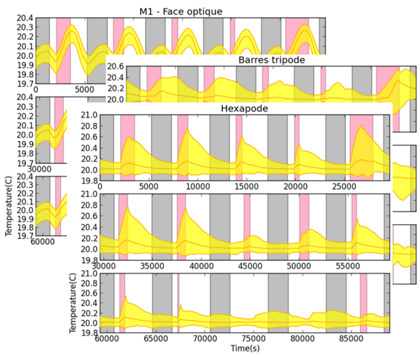
CONTEXT INSIGHT **OTOS**

Consequences

- Realistic missions taken into account:
  - 2 typical days (15 orbits) scenarios performed
  - Realistic telescope attitude (tabulated data)
  - A PI controller operating according to real flight conditions (algorithm, 18 second of time resolution)



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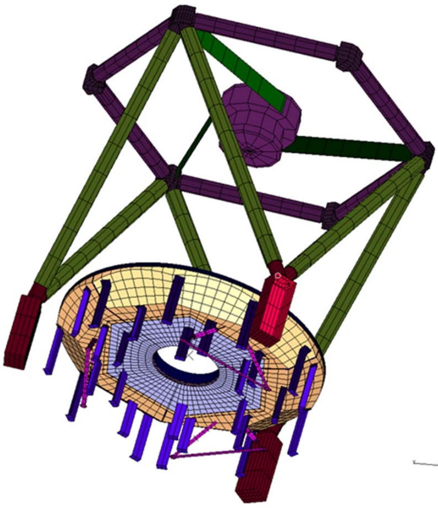
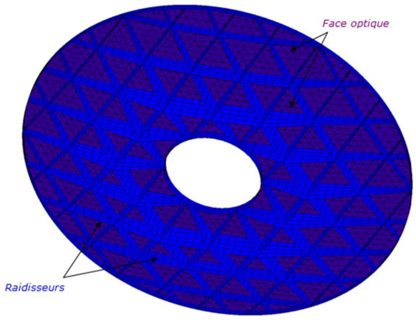
CONTEXT INSIGHT **OTOS**

Consequences

➔ Observe the complex geometries and assemblies representation





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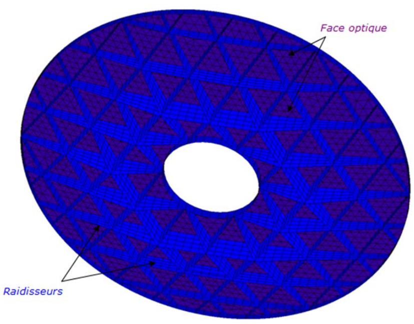
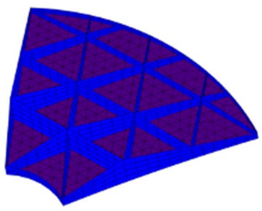
CONTEXT INSIGHT **OTOS**

Consequences

➔ An meshing definition adapted to detect low levels of temperature gradients (M1)





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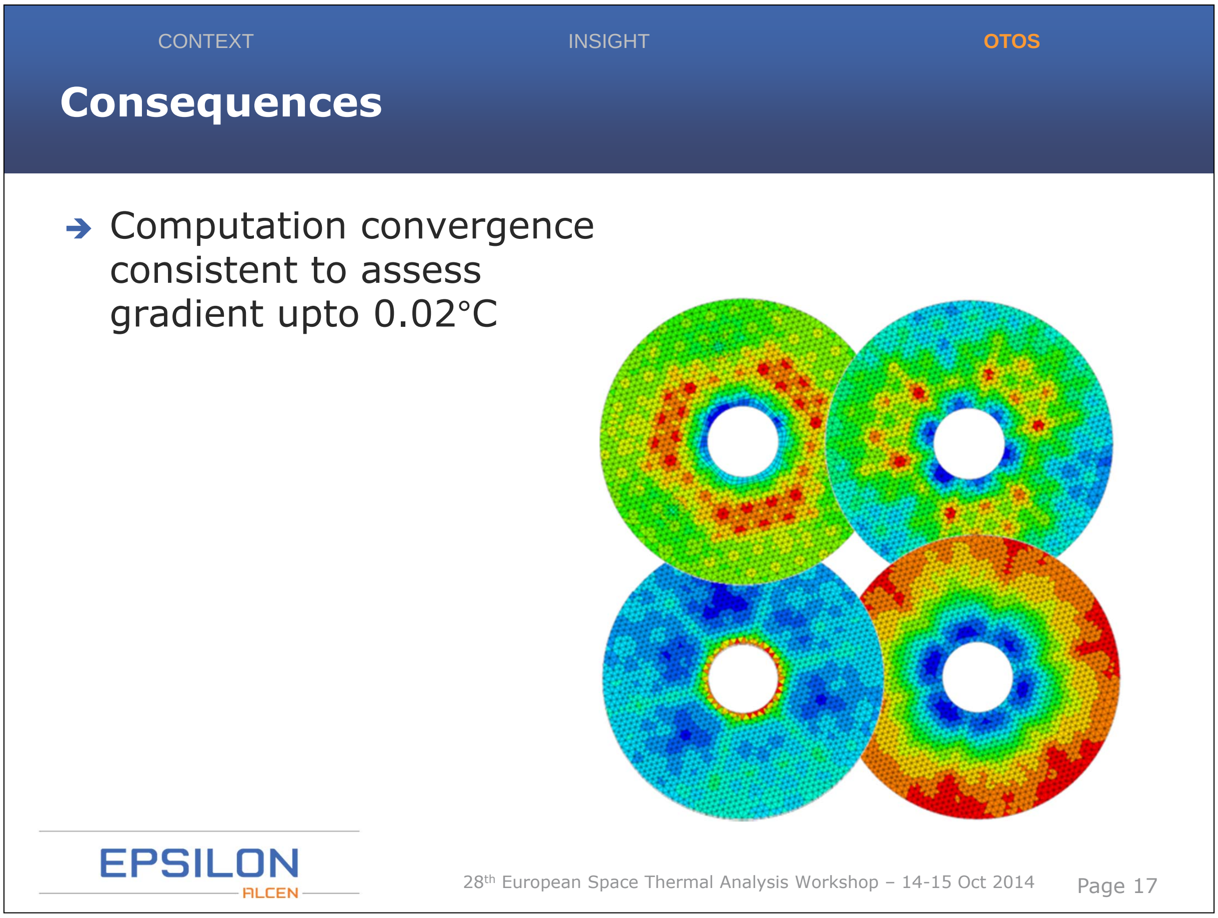
CONTEXT
INSIGHT
OTOS
Consequences
Computation convergence consistent to assess gradient upto 0.02°C
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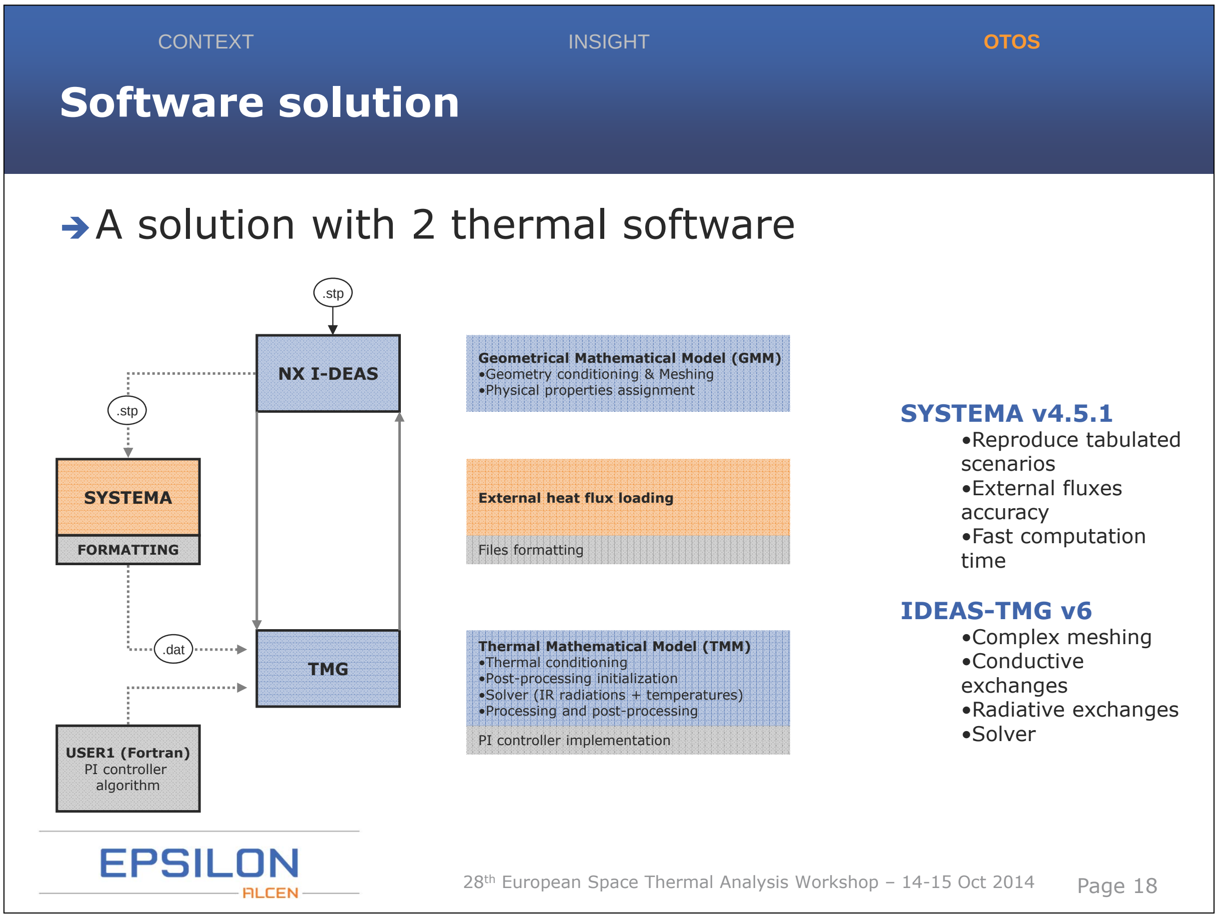
CONTEXT
INSIGHT
OTOS
Software solution
A solution with 2 thermal software
.stp
NX I-DEAS
.stp
SYSTEMA
FORMATTING
.dat
TMG
USER1 (Fortran)
PI controller algorithm
Geometrical Mathematical Model (GMM)
•Geometry conditioning & Meshing
•Physical properties assignment
External heat flux loading
Files formatting
Thermal Mathematical Model (TMM)
•Thermal conditioning
•Post-processing initialization
•Solver (IR radiations + temperatures)
•Processing and post-processing
PI controller implementation
SYSTEMA v4.5.1
•Reproduce tabulated scenarios
•External fluxes accuracy
•Fast computation time
IDEAS-TMG v6
•Complex meshing
•Conductive exchanges
•Radiative exchanges
•Solver
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Conclusion

➔ EPSILON experience show that:
- Software should be combined in order to
  - Benefit of fitted and accurate functionality
  - Develop specific thermal models integrating the 3 thermal transfer modes
  - Reconcile model accuracy, completeness, computation time and computer means
- Major efforts are required to validate the accuracy level of models
  - INSIGHT: ground modeling, convection…
  - OTOS: fluxes absorbed at mirror level…

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Thank you for your attention

For further information, please

read our newsletter
marketing.epsilon-alcen.com/Divers/newsletters/spatial0914/en

and visit our website www.epsilon-alcen.com

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Appendix O

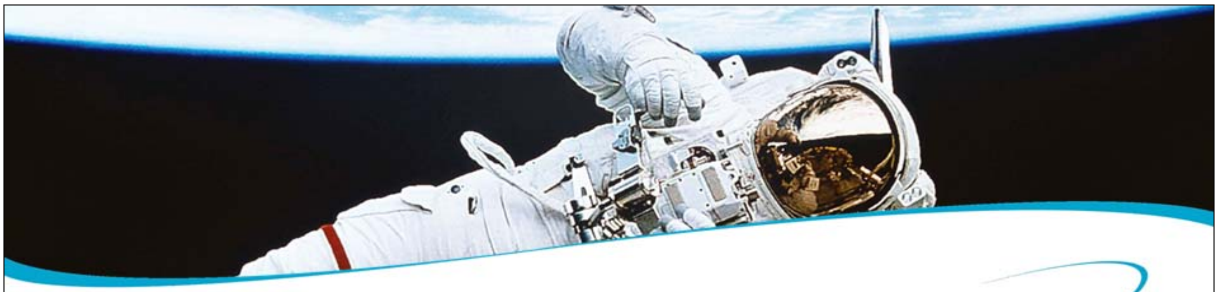
Assessment of stochastic methods for the thermal design of a telecom satellite

Nicolas Donadey
(AKKA Technology, France)

Jean-Paul Dudon Patrick Connil Patrick Hugonnot
(Thales, France)

Abstract

The aim of the study is to assess the interest of using probabilistic methods and tools for the thermal design of a telecom satellite. This work has been done in the frame of system development for new satellites.
In the past the interest of such methods compared to deterministic approach leading to use of margin has been pointed locally in the system. It was concluded that these methods are useful to have a more clear and complete exploration of the design and system performances, and thus to identify easily sizing parameters among many inputs. Moreover by associating an occurrence probability to system temperatures related to the dispersion law of relevant input parameters, stochastic approach is expected to avoid a final risky or oversized design.
Here we assess the feasibility of such approach at system level on a telecom satellite by benchmarking probabilistic versus margin method for a S/C communication module. The tools used for this study is OPTIMUS (stochastic methods and computation workfow) and ETHERM (TAS thermal solver)
In this purpose the classical margin approach is compared to a deterministic uncertainty analysis (RMS of cumulative incertainties on relevant parameters of the thermal design) and to a probabilistic approach (consideration of probabilistic distribution for relevant input parameters).
Methods, tools, and results are presented and current conclusions and perspectives are given considering technical and industrial objectives.



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Assessment of Stochastic Approach for Thermal Design of a Telecom Spacecraft

by Nicolas DONADEY (AKKA technology)
and Jean-paul DUDON, P CONNIL and P HUGONNOT (TAS)

28th ESA Space Thermal Analysis Workshop
14-15 oct 2015

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SUMMARY

1- INTRODUCTION TO STOCHASTIC APPROACH FOR UNCERTAINTY ANALYSIS

2- OBJECTIVES OF THE STUDY

3- METHODOLOGY FOR TELECOM S/C

4- RESULTS

5- CONCLUSION & PERSPECTIVES

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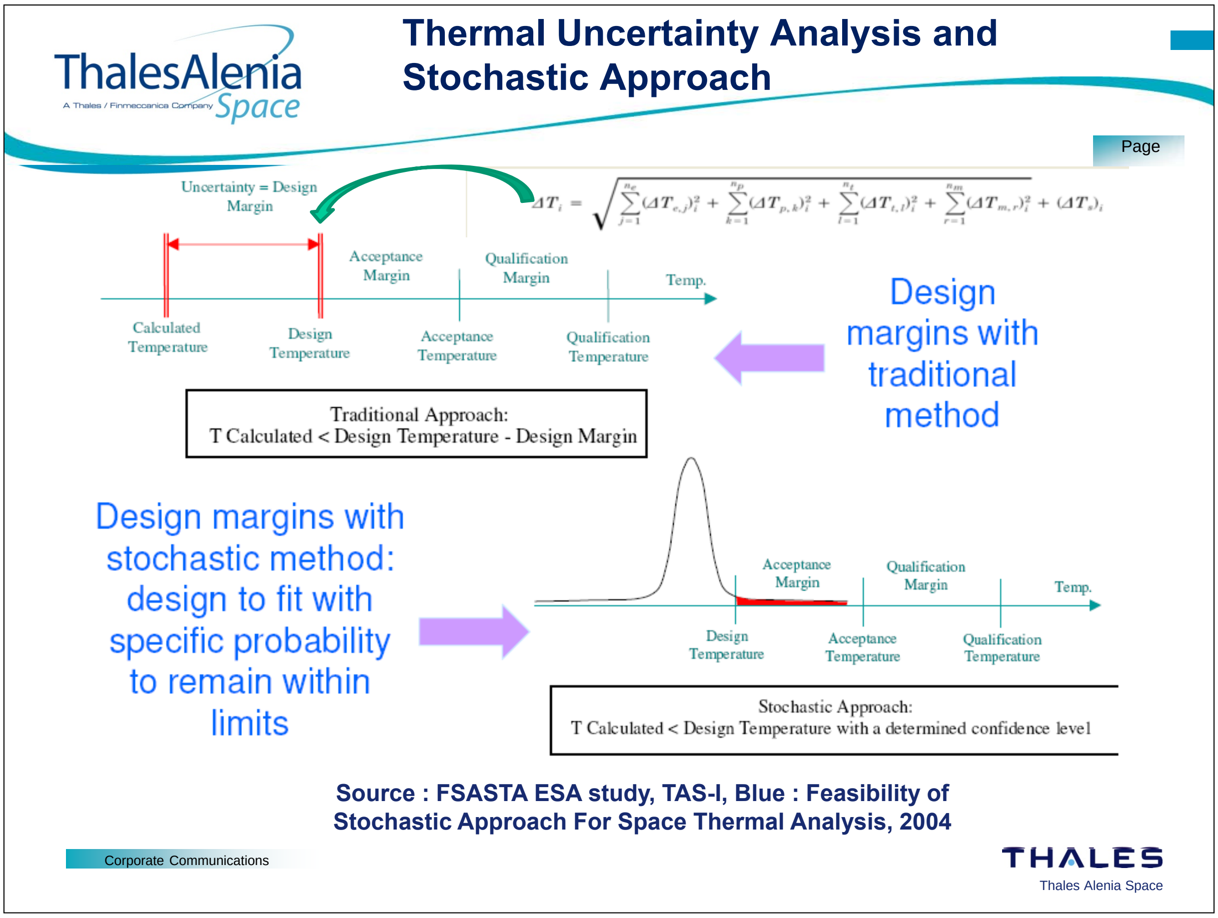
Thermal Uncertainty Analysis and Stochastic Approach
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Uncertainty = Design Margin
$\Delta T_i = \sqrt{\sum_{j=1}^{n_e}(\Delta T_{e,j})_i^2 + \sum_{k=1}^{n_p}(\Delta T_{p,k})_i^2 + \sum_{l=1}^{n_t}(\Delta T_{t,l})_i^2 + \sum_{r=1}^{n_m}(\Delta T_{m,r})_i^2 + (\Delta T_s)_i}$
Acceptance Margin
Qualification Margin
Temp.
Calculated Temperature
Design Temperature
Acceptance Temperature
Qualification Temperature
Design margins with traditional method
Traditional Approach:
T Calculated < Design Temperature - Design Margin
Design margins with stochastic method: design to fit with specific probability to remain within limits
Acceptance Margin
Qualification Margin
Temp.
Design Temperature
Acceptance Temperature
Qualification Temperature
Stochastic Approach:
T Calculated < Design Temperature with a determined confidence level
Source : FSASTA ESA study, TAS-I, Blue : Feasibility of Stochastic Approach For Space Thermal Analysis, 2004
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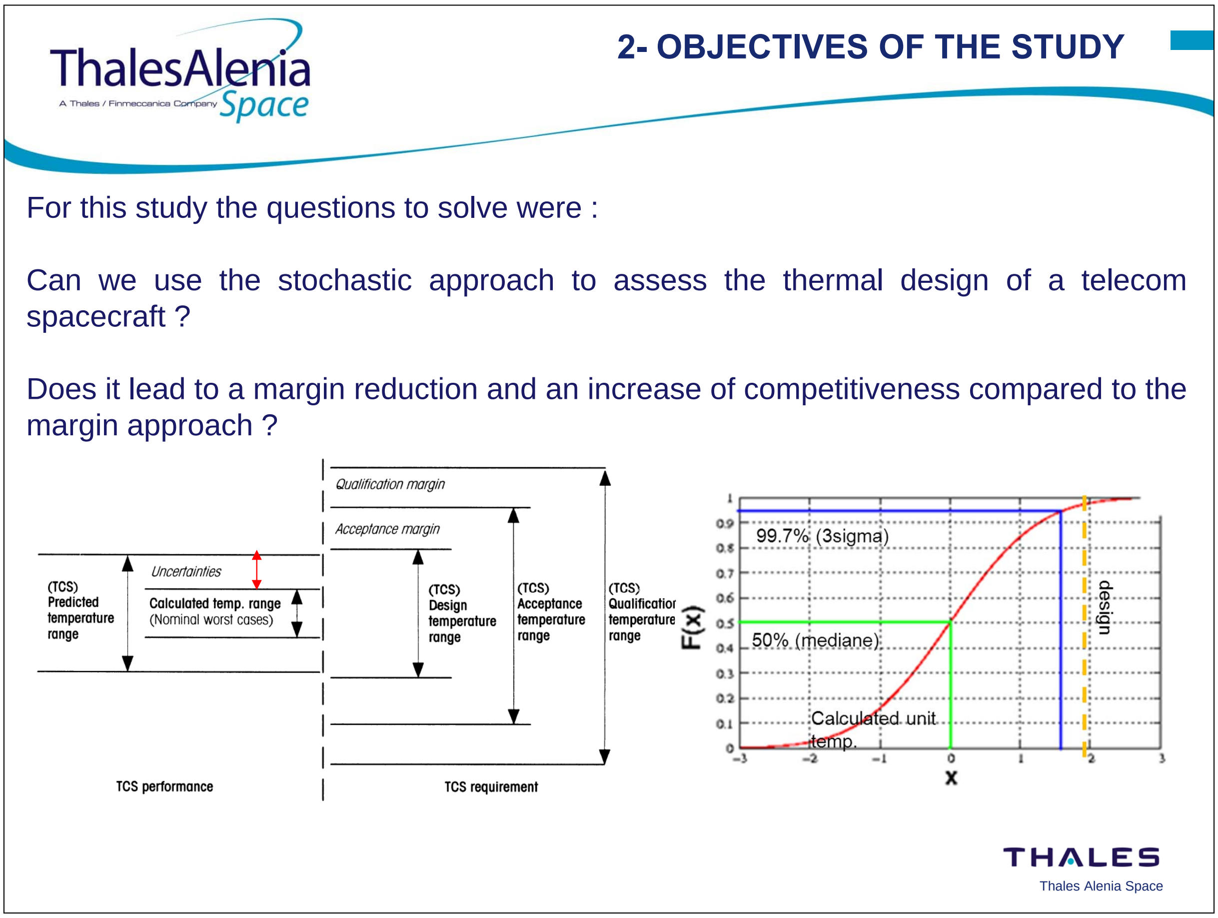
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2- OBJECTIVES OF THE STUDY
For this study the questions to solve were :
Can we use the stochastic approach to assess the thermal design of a telecom spacecraft ?
Does it lead to a margin reduction and an increase of competitiveness compared to the margin approach ?
Qualification margin
Acceptance margin
Uncertainties
(TCS) Predicted temperature range
Calculated temp. range (Nominal worst cases)
(TCS) Design temperature range
(TCS) Acceptance temperature range
(TCS) Qualification temperature range
TCS performance
TCS requirement
F(x)
99.7% (3sigma)
50% (mediane)
Calculated unit temp.
design
x
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3- METHODOLOGY

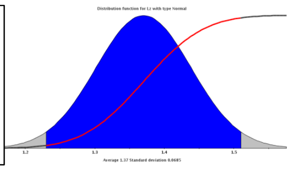
GENERAL APPROACH

THERMAL MODEL
OUTPUT PARAMETERS
THERMAL COMPUTATION CASE

→ TELCOM SAT
EPC LDLA RECEIVER DOCON BEACON TWT OMUX
WS EOL CONF1-3

THERMAL INPUTS AND VARIATION LAW

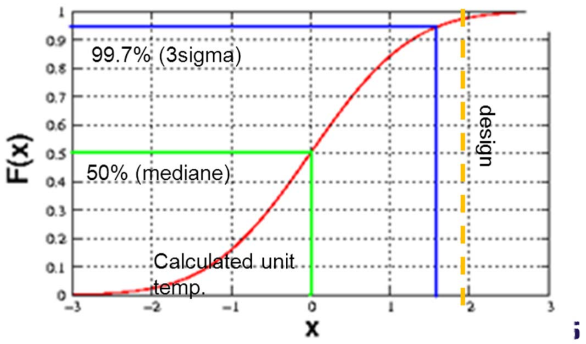
→ SOLAR CONSTANT
OPTICAL PROPERTIES
CONDUCTIVITY PROPERTIES
INTERNAL DISSIPATION
CAPACITANCE



WORKLOW OPTIMUS
INTERFACE OPTIMUS/ETHERM

RMS METHOD | MARGED APPROACH | STOCHASTIC METHOD

COMPARATIVE ANALYSIS



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3- METHODOLOGY

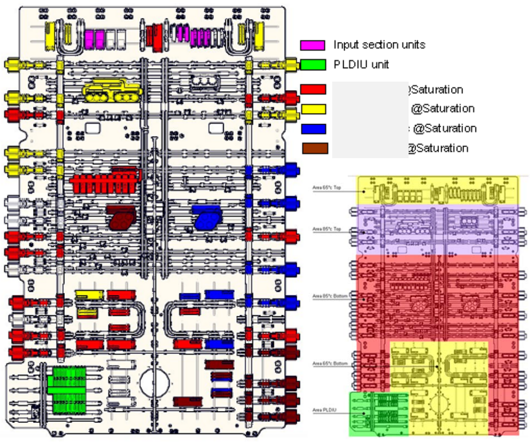
MODEL DESCRIPTION

For the study we selected the thermal model TELCOM SAT that was correlated with thermal vacuum test results.
Configuration case chosen : WS EOL CONF 1-3 (worst case with regard to our goal) .

In order to minimize the data volume, we focused on one of both CM N/S panels. But results shall be similar for the other one.

			Nomenclature	Trp
PAYLOAD South CM	Top 65°C	EPC	1EP403 (middle)	4766
		LDLA	1CL2-08 (+x)	4786
		RECEIVER	1RE3-05	4707
		DOCON	1DC1-03	4704
		BEACON	1BE2-01	4844
	Top 85°C	TWT	1TE403A (+x)	4694
		OMUX	1MS502(Northern)	4140
	Bottom 85°C	TWT	1TE309B (-x)	4574
		OMUX	1MS401 (Russian)	4145
	Bottom 65°C	EPC	1EP307 (-x)	4762
		LDLA	1CL2-09 (--x)	4796

TELCOM SAT CM SELECTED OUTPUT DATA



TELCOM CM Configuration 1-3

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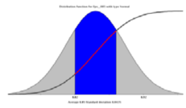
3- METHODOLOGY

COMPUTATION HYPOTHESIS

Dispersion law for inputs (range and form) taken from :

- ECSS-E-30-PART 1A : min/max range
- Doc 02,07,035/TN5 p226 (FSASTA study for ESA 2004) : law type
- Internal TAS applicable documents for thermal control (modeling error=2°C)



Variable inputs are grouped by type of coating, by material, by type of contact, …

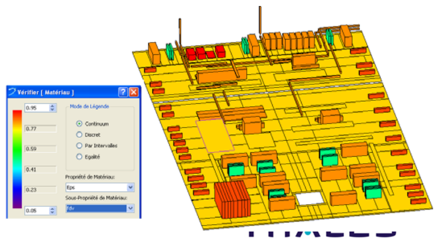
The attached variation law is operated in the same way to all inputs of each group

- Ex: All the EPC surfaces have an emissivity equal to 0.85. If this value change from 0.85 to 0.86, each EPC will have an emissivity of 0,86
- Ex2 : All dissipations of the CM module are also varied in the same rate

			WS EOL 100% Drive CONF 1-3		
			Tmax	Nomenclature	Trp
PAYLOAD South CM	Top 65°C	EPC	44.7	1EP403 (middle)	4766
		LDLA	44.3	1CL2-08 (+x)	4786
		RECEIVER	45.2	1RE3-05	4707
		DOCON	44.9	1DC1-03	4704
		BEACON	42.4	1BE2-01	4844
	Top 85°C	TWT	60.7	1TE403A (+x)	4694
		OMUX Northern (6ch)	54.4	1MS502(Northern)	4140
	Bottom 85°C	TWT	59.4	1TE309B (-x)	4574
		OMUX Russia (9ch)	56	1MS401 (Russian)	4145
	Bottom 65°C	EPC	32.5	1EP307 (-x)	4762
		LDLA	29.97	1CL2-09 (--x)	4796

TELCOM SAT CM NOMINAL TEMPERATURE FOR CONSIDERED UNITS

VIEW OF ETHERM RADIATIVE MODEL OF THE PANEL WITH UNITS



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3- METHODOLOGY

THERMAL INPUT PARAMETERS

			Valeur nominal	Loi de variation	SIGMA (Loi gaussienne) Doc 02,07,035/TN5 p226 (%)	Sigma	INCERTITUDE ECSS-E-30-PART 1A %	Fixe	Borne min	Borne max	Affectation
CONDUCTIF	PANNEAU CM	Lx Ly	3,81	Normal	5	0,1905	10		**3,43**	**4,19**	**Fichier cas de calcul plateau**
		Lz	1,37	Normal	5	0,0685	10		**1,23**	**1,51**	
	CONDUCTANCE CONTACT	Heat-pipe/Stucture1	933,00	Normal	25	233,2500	25		**700**	**1166**	**Table gopl 41**
		Heat-pipe/Stucture2	2400,00	Normal	25	600,0000	25		**1800**	**3000**	
		Unit/Aluminium	1200,00	Normal	25	300,0000	25		**900**	**1500**	
		Heat-pipe/Xing	5000,00	Normal	25	1250,0000	25		**3750**	**6250**	**Table CONDHP 241**
		Unit/Heat-pipe	5000,00	Normal	25	1250,0000	25		**3750**	**6250**	
		coeff*	1,00	Normal	25	0,2500	25		**0,75**	**1,25**	
RADIATIF	INTERNE	Eps CAMP	0,50	Normal	5	0,0250		0,03	**0,47**	**0,53**	**Table alvéole interne 628**
		Eps E_D_R_O **(Eps__085)**	0,85	Normal	5	0,0425		0,03	**0,82**	**0,88**	
		Eps Z307_BEACON **(Eps_Z307)**	0,95	Normal	5	0,0475		0,03	**0,92**	**0,98**	
		Eps Z306_TWT **(Eps_Z306)**	0,90	Normal	5	0,0450		0,03	**0,87**	**0,93**	
		Eps NIDA	0,80	Normal	5	0,0400		0,03	**0,77**	**0,83**	
		Eps MLI **(Epsl_MLI)**	0,05	Normal	5	0,0025		0,02	**0,03**	**0,07**	
		Beq MLI (W/°C,mm²)	1,0000E-07	Normal	15	0,000000015	50		**5,00E-08**	**1,50E-07**	**Table appel 2624**
		Eps_eq MLI	0,0050	Normal	15	0,0008	50		**2,50E-03**	**7,50E-03**	
	EXTERNE	Alp OSR	0,255	Normal	5	0,0128		0,03	**0,23**	**0,29**	**Table alvéole externe 1062**
		Eps OSR	0,84	Normal	5	0,0420		0,03	**0,81**	**0,87**	
		Eps TWT	0,80	Normal	5	0,0400		0,03	**0,77**	**0,83**	
		Alp TWT	0,70	Normal	5	0,0350		0,03	**0,67**	**0,73**	
		Eps MLI	0,84	Normal	5	0,0420		0,03	**0,81**	**0,87**	
		Alp MLI	0,93	Normal	5	0,0465		0,03	**0,90**	**0,96**	
		Beq MLI (W/°C,mm²)	2,0000E-08	Normal	15	0,000000003	50		**1,000E-08**	**3,000E-08**	**Table appel 2624**
		Eps_eq MLI	0,0109	Normal	15	0,0016	50		**5,430E-03**	**1,629E-02**	
EXTERNE		Constante solaire	1418,00	Normal	10	141,8000		21,00	**1397**	**1439**	**Cas de calcul solaire**
CAPACITANCE	Cp	Equipement	1,00	Normal	5	0,0500	25		**0,75**	**1,25**	**Table 2174***
		Structure	1,00	Normal	5	0,0500	15		**0,85**	**1,15**	
PUISSANCE	CM	Table Puissance	1,00	Uniforme		0,0000	5		**0,95**	**1,05**	**Table 1893 ***
		Table Harness	1,00	Uniforme		0,0000	5		**0,95**	**1,05**	**Table 1888 ***
	TOTAL	**25**									

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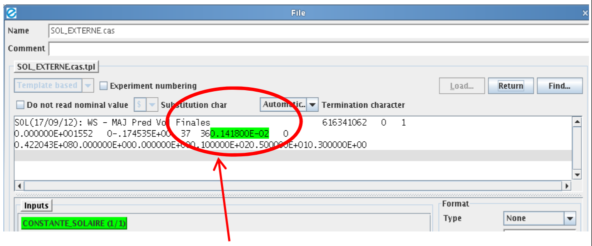
3- METHODOLOGY

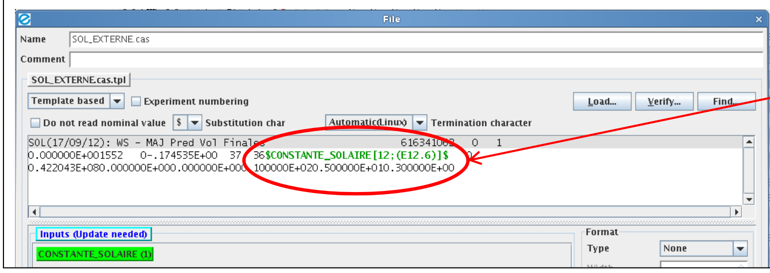
Brief presentation of OPTIMUS tool (by NOESIS)

For this study, OPTIMUS tool was used to manage and automatize all the computation process & to perform the stochastic analysis

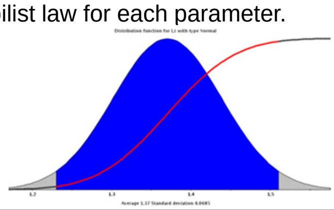
Typically OPTIMUS allows to :

- Attach probabilistic distributions to inputs
- Launch all required calculation cases (including parallel run capability) on any thermal tools (ETHERM here)
- Use many powerful stochastic & deterministic methods for model exploration, uncertainty & sensitivity and for optimisation (DOE, RSM, MCS, global optimisation,…)
- Post-process all results in an ergonomic and rapid way (table, graphics, …)





Via Optimus, the input parameters are changed as a variable.
The user can choose a different probabilist law for each parameter.



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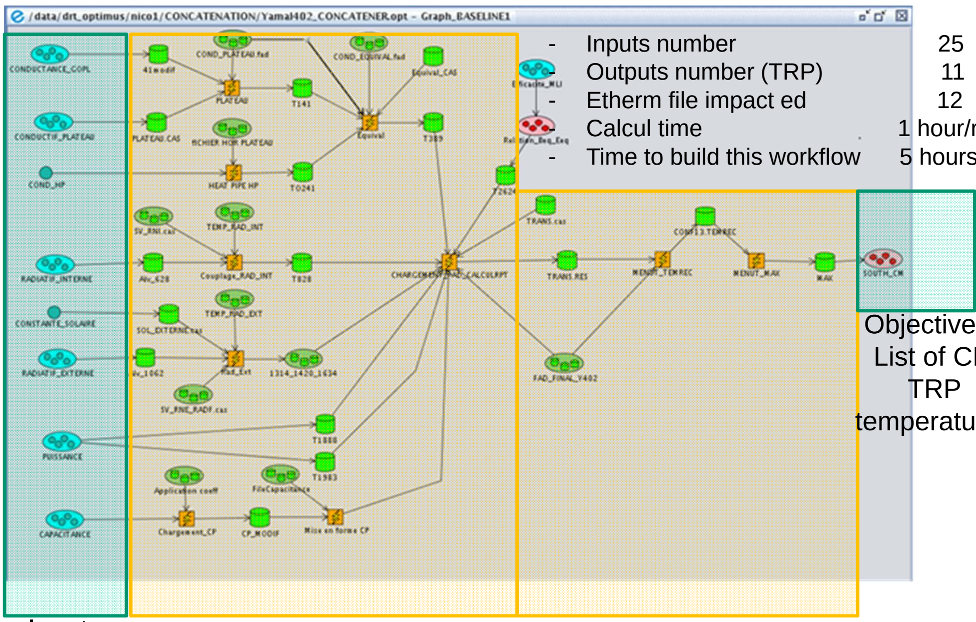
3- METHODOLOGY

OPTIMUS WORKFLOW with ETHERM thermal tool



-	Inputs number	25
-	Outputs number (TRP)	11
-	Etherm file impact ed	12
-	Calcul time	1 hour/run
-	Time to build this workflow	5 hours

Objectives : List of CM TRP temperatures

Inputs parameters

ETHERM input files and exe (cond, rad, solver, …)

ETHERM output files and thermal post processing

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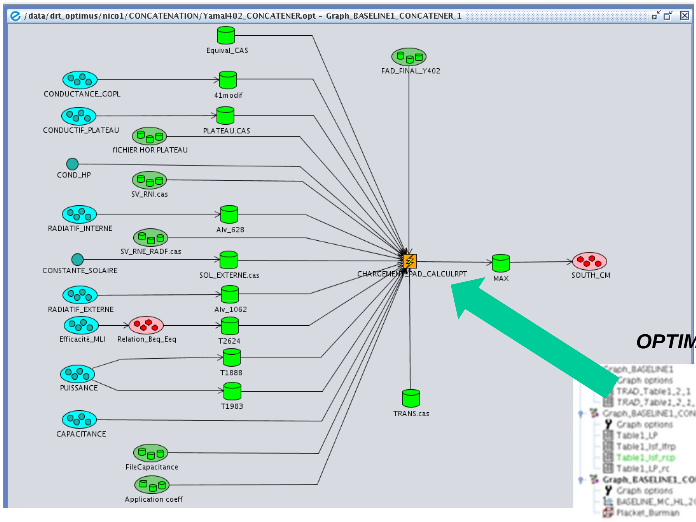
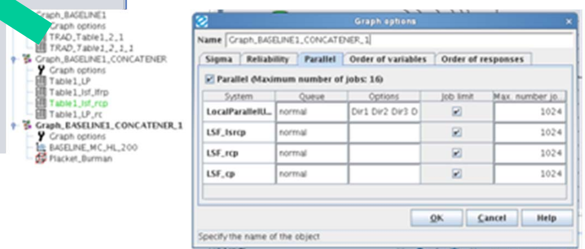
3- METHODOLOGY

OPTIMUS WORKFLOW for parallel computations



In order to optimize the computation time a parallel workflow was built to run 16 cases at a time
In nominal condition, **1000 computations are performed in 3 days for the whole CM model**

OPTIMUS option box for parallel computation



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3- METHODOLOGY

TRADITIONAL METHOD VS STOCHASTIC METHOD

TRADITIONAL APPROACH
Root Mean Square (RMS)

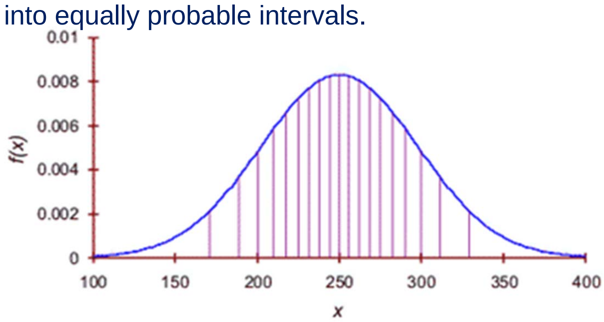
- The traditional approach to determine uncertainty is a root mean square :
- We consider each parameter one by one as input
- For each run, all the parameters have their nominal value except the current one which have his worst value.
- For each unit the global temperature uncertainty is defined as :

$$\Delta T^{RMS}{}_{unit} = \sum_{k}^{25} \sqrt{\Delta T_K{}^2}$$

with ΔT_k= T unit calc. with nominal value of parameter k - T unit calc.with worst value of k

STOCHASTIC APPROACH
MONTE CARLO WITH LATIN HYPERCUBE

MCS : N samples (N=1000) of K variables (K=25) are randomly produced and the thermal model is run N times with these samples.
Latin hypercube sampling (LHS) is a statistical method used to optimize efficiency of MCS and respect the initial distribution (gaussian, truncated or uniform). The range of each variable is divided into equally probable intervals.



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4- RESULTS

RMS uncertainty analysis results

11 units ➔

25 parameters

			Valeur nominal	Valeur	EPC	LDLA	RECEIVER	DOCON	BEACON	TWT	OMUX Northern (6ch)	TWT	OMUX Russia (9ch)	EPC	LDLA
					PAYLOAD South CM										
					Top 65°C					Top 85°C		Bottom 85°C		Bottom 65°C	
				Nomenclature	1EP403 (middle)	1CL2-08 (+x)	1RE3-05	1DC1-03	1BE2-01	1TE403A (+x)	1MS502(Northern)	1TE309B (-x)	1MS401 (Russian)	1EP307 (-x)	1CL2-09 (--x)
				Trp	**4766**	**4786**	**4707**	**4704**	**4844**	**4694**	**4140**	**4574**	**4145**	**4762**	**4796**
				Tnominal	44,7	44,26	45,33	44,91	42,51	60,72	54,43	59,46	56,01	32,8	30,01
CONDUCTIF	PANNEAU CM	Lx Ly	3,81	**3,43**	0,17	0,35	0,24	0,23	0,16	0,43	0,43	0,48	0,47	0,09	-0,10
		Lz	1,37	**1,23**	0,25	0,38	0,26	0,26	0,28	0,53	0,55	0,54	0,55	0,22	0,24
	CONDUCTANCE CONTACT	Heat-pipe/Stucture1	933,00	**700**	-0,02	0,00	-0,03	-0,02	-0,03	0,06	0,06	0,05	0,06	0,00	0,01
		Heat-pipe/Stucture2	2400,00	**1800**	0,08	0,03	0,06	0,08	0,05	0,01	0,01	0,01	0,00	0,06	0,03
		Unit/Aluminium	1200,00	**900**	0,19	0,28	0,38	0,33	0,20	0,00	0,00	0,00	0,00	0,17	0,15
		Heat-pipe/Xing	5000,00	**3750**	0,42	-0,21	0,08	0,25	-0,04	0,92	-0,47	0,39	-0,08	0,51	0,01
		Unit/Heat-pipe	5000,00	**3750**											
		coeff*	1,00	**0,75**											
RADIATIF	INTERNE	Eps CAMP	0,50	**0,53**	0,00	0,06	0,00	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,01
		Eps E_D_R_O **(Eps__085)**	0,85	**0,88**	-0,03	-0,01	-0,03	-0,03	-0,01	0,00	0,00	0,00	-0,01	-0,03	0,00
		Eps Z307_BEACON **(Eps_Z307)**	0,95	**0,98**	0,00	0,00	0,00	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,00
		Eps Z306_TWT **(Eps_Z306)**	0,90	**0,93**	0,00	0,00	0,00	0,00	0,00	0,00	0,00	-0,01	0,00	0,00	0,00
		Eps NIDA	0,80	**0,83**	0,02	0,04	0,01	0,02	0,02	-0,01	-0,01	0,00	0,00	0,00	0,01
		Eps MLI **(Epsl_MLI)**	0,05	**0,07**	0,06	0,06	0,05	0,07	0,05	-0,11	-0,12	-0,12	-0,13	0,06	0,06
		Beq MLI (W/°C,mm²)	1,0000E-07	**1,50E-07**	0,06	0,06	0,05	0,07	0,05	-0,09	-0,10	-0,09	-0,10	0,06	0,07
		Eps_eq MLI	0,0050	**7,50E-03**											
	EXTERNE	Alp OSR	0,255	**0,29**	2,54	2,52	2,54	2,54	2,62	2,62	2,69	2,61	2,69	2,57	2,73
		Eps OSR	0,84	**0,81**	2,05	2,04	2,04	2,04	2,11	2,24	2,30	2,21	2,30	1,83	1,98
		Eps TWT	0,80	**0,83**	0,03	0,03	0,03	0,03	0,03	0,21	0,15	0,21	0,15	0,02	0,04
		Alp TWT	0,70	**0,73**	0,01	0,01	0,01	0,01	0,01	0,07	0,05	0,07	0,05	0,00	0,02
		Eps MLI	0,84	**0,87**	-0,01	-0,01	-0,01	-0,01	-0,01	-0,02	-0,02	-0,02	-0,02	-0,01	0,00
		Alp MLI	0,93	**0,96**	0,01	0,01	0,01	0,01	0,01	0,01	0,02	0,01	0,01	0,01	0,01
		Beq MLI (W/°C,mm²)	2,0000E-08	**3,000E-08**	0,00	-0,01	0,00	0,00	0,01	0,02	0,02	0,01	0,01	-0,01	0,01
		Eps_eq MLI	0,0109	**1,629E-02**											
EXTERNE		Constante solaire	1418,00	**1439**	0,37	0,37	0,36	0,37	0,37	0,39	0,38	0,38	0,37	0,38	0,39
CAPACITANE	Cp	Equipement	1,00	**0,75**	0,01	0,00	0,00	0,01	0,01	0,00	0,02	0,03	0,01	0,01	0,02
		Structure	1,00	**0,85**	0,02	0,01	0,01	0,02	0,02	0,00	0,00	0,01	0,00	0,02	0,02
PUISSANCE	CM	Table Payload CM	1,00	**1,05**	2,43	2,39	2,45	2,44	2,36	3,03	2,82	2,97	2,91	1,86	1,85
		Table Harness	1,00	**1,05**	0,01	0,02	0,01	0,02	0,01	0,01	0,01	0,01	0,01	0,07	0,07
				RMS	**4,13**	**4,09**	**4,13**	**4,13**	**4,14**	**4,75**	**4,62**	**4,63**	**4,66**	**3,73**	**3,88**
		Prise en compte de l'erreur modèle (2°C)	**2**		2	2	2	2	2	2	2	2	2	2	2
				RMS 2°C	**4,58**	**4,56**	**4,59**	**4,58**	**4,60**	**5,16**	**5,04**	**5,04**	**5,07**	**4,23**	**4,37**
		RMS 2°C -RMS (pour étude stochastique)			**0,46**	**0,46**	**0,46**	**0,46**	**0,46**	**0,40**	**0,41**	**0,41**	**0,41**	**0,50**	**0,49**

Total RMS error for each unit ➔

A highly automated computation process that gives RMS uncertainty & confirms the list of influent parameters issued from RSM contribution (CM dissipations, α_{OSR} , ε_{OSR})

4- RESULTS

Stochastic uncertainty analysis results Glossary

Cumulative distribution function (CDF)
The cumulative distribution function describes the probability for the unit temperature to have a value less than or equal to a limit (nominal, design, acceptance, …)

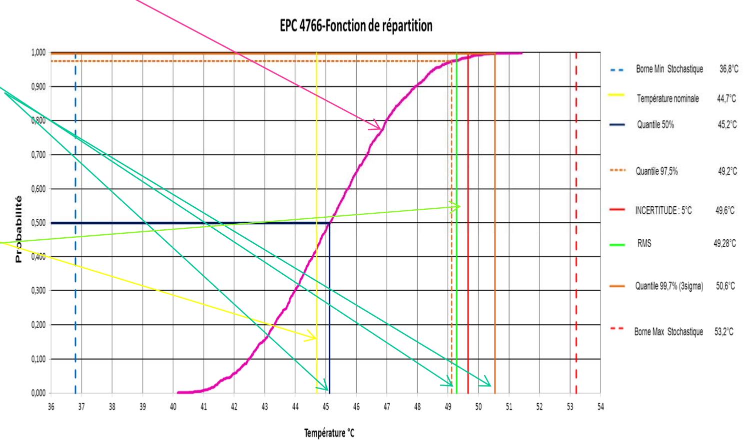
Quantiles (50% / 97.5% / 99.7%)
Quantile are points taken at regular intervals from the CDF.
99.7% quantile correspond to 3sigma design

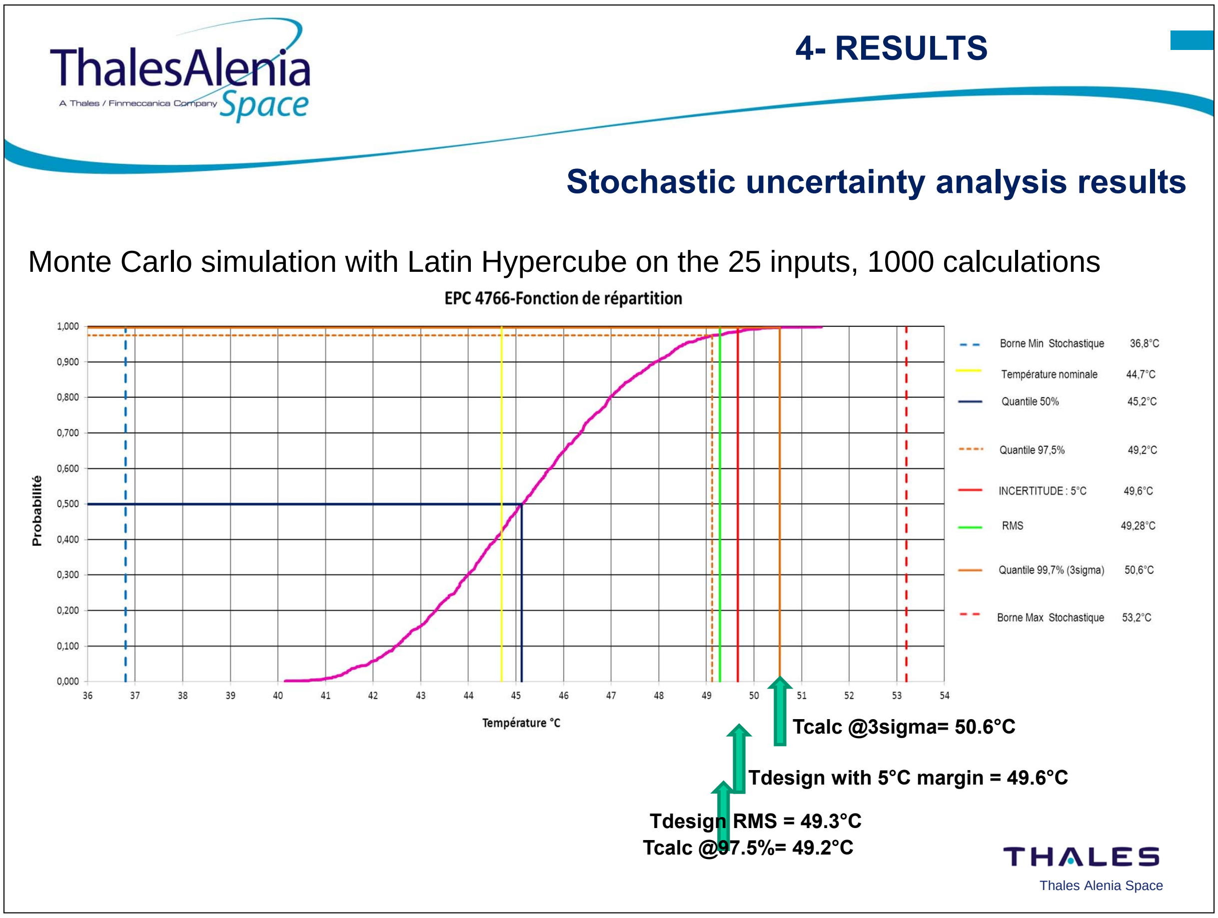
Nominal temperature
Temperature calculated when all the parameter have their nominal value.

RMS Temperature
Temperature error obtained with RMS method considering the accumulation of effect of all the input parameters of the study (added to nominal temp)

Uncertainty margin 5°C : Tnominal +5°C

Boundary temperature (min and max)
The lowest and highest temperature obtained over the 1000 runs

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4- RESULTS
Stochastic uncertainty analysis results
Monte Carlo simulation with Latin Hypercube on the 25 inputs, 1000 calculations
EPC 4766-Fonction de répartition
Probabilité
Température °C
Borne Min Stochastique 36,8°C
Température nominale 44,7°C
Quantile 50% 45,2°C
Quantile 97,5% 49,2°C
INCERTITUDE : 5°C 49,6°C
RMS 49,28°C
Quantile 99,7% (3sigma) 50,6°C
Borne Max Stochastique 53,2°C
Tcalc @3sigma= 50.6°C
Tdesign with 5°C margin = 49.6°C
Tdesign RMS = 49.3°C
Tcalc @97.5%= 49.2°C
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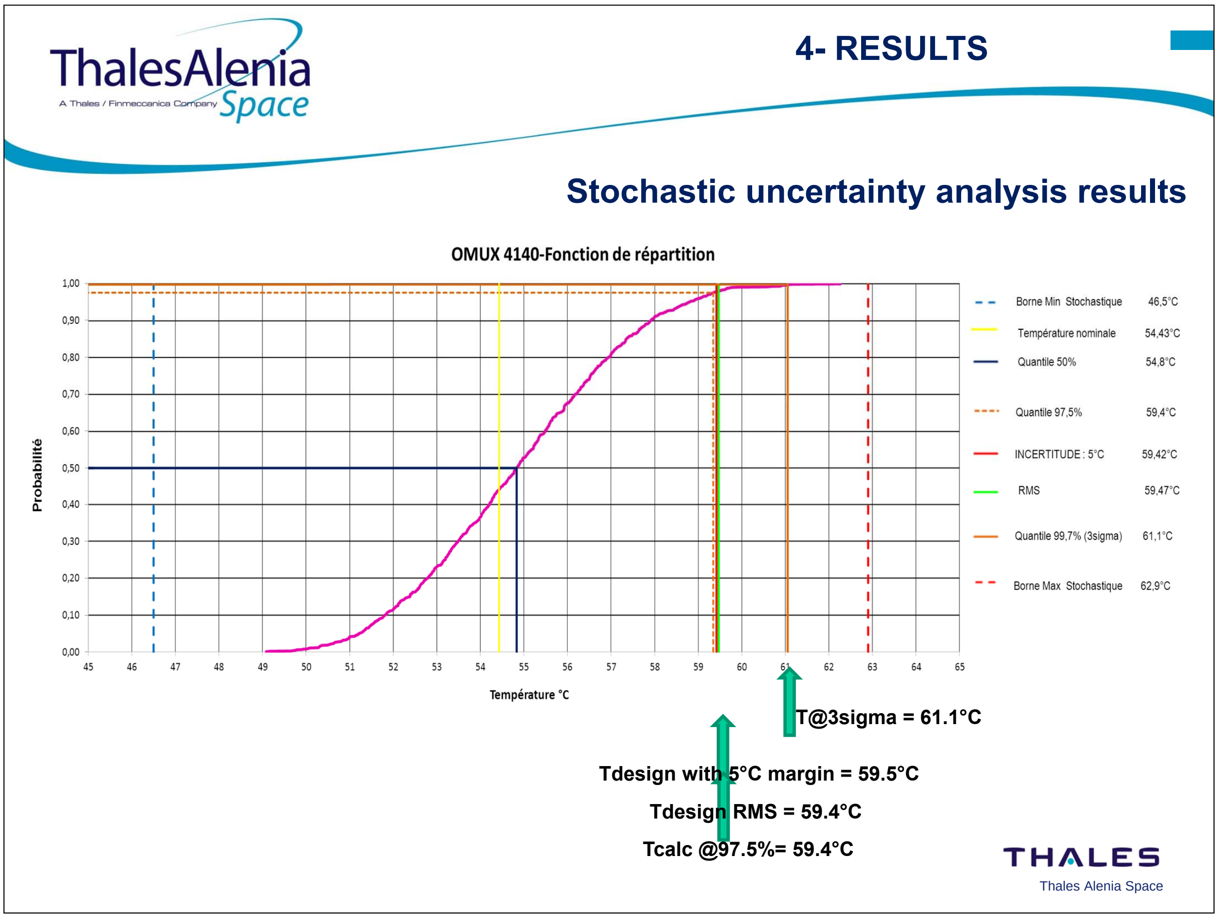
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4- RESULTS
Stochastic uncertainty analysis results
OMUX 4140-Fonction de répartition
Probabilité
Température °C
Borne Min Stochastique 46,5°C
Température nominale 54,43°C
Quantile 50% 54,8°C
Quantile 97,5% 59,4°C
INCERTITUDE : 5°C 59,42°C
RMS 59,47°C
Quantile 99,7% (3sigma) 61,1°C
Borne Max Stochastique 62,9°C
T@3sigma = 61.1°C
Tdesign with 5°C margin = 59.5°C
Tdesign RMS = 59.4°C
Tcalc @97.5%= 59.4°C
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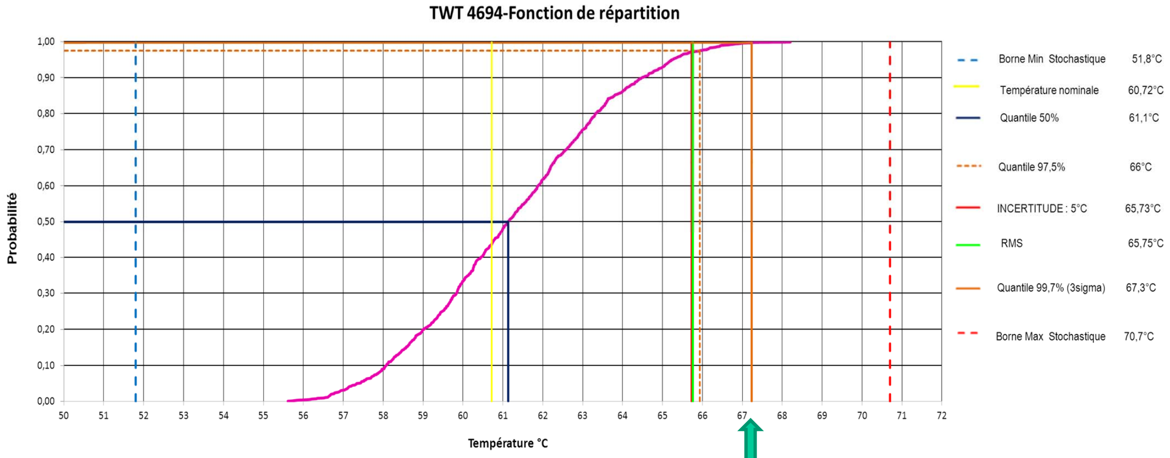
4- RESULTS

Stochastic uncertainty analysis results



T@3sigma = 67.3°C

Tdesign with 5°C margin = 65.8°C

Tdesign RMS = 65.7°C

Tcalc @97.5%= 66°C

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4- RESULTS

SUMMARY OF RESULTS

						INCERTITUDE CALCUL MODELE YAMAL 402 CONFIGURATION: WS EOL 100% Drive CONF 1-3								
						TRADITIONELLE			STOCHASTIQUE (T en °C)					
			Nomenclature	Trp	Tnominal °C	Incertitude:	RMS		50% (médian)		97,5% (		99% (3sigma)	
						+ 5°C	T °C	DT	T Calculé	Ecart (Tc-Tston)	T Calculé	Ecart (Tc-Tn)	T Calculé	Ecart (Tc-Tn)
South CM	Top 65°C	EPC	1EP403 (middle)	4766	44,7	49,7	49,3	4,6	45,2	0,5	49,2	4,5	50,6	5,9
		LDLA	1CL2-08 (+x)	4786	44,3	49,3	48,9	4,6	44,8	0,5	48,6	4,3	50,2	5,9
		RECEIVER	1RE3-05	4707	45,3	50,3	49,9	4,6	45,8	0,5	49,9	4,6	51,2	5,9
		DOCON	1DC1-03	4704	44,9	49,9	49,5	4,6	45,4	0,5	49,5	4,6	50,8	5,9
		BEACON	1BE2-01	4844	42,5	47,5	47,1	4,6	43,0	0,5	46,9	4,4	48,5	6,0
PAYLOAD	Top 85°C	TWT	1TE403A (+x)	4694	60,7	65,7	65,9	5,2	61,1	0,4	66,0	5,3	67,3	6,6
		OMUX Northern	1MS502(Northern)	4140	54,4	59,4	59,4	5,0	54,8	0,4	59,4	5,0	61,1	6,7
	Bottom 85°C	TWT	1TE309B (-x)	4574	59,5	64,5	64,5	5,0	59,9	0,4	64,5	5,0	66,0	6,5
		OMUX Russia	1MS401 (Russian)	4145	56,0	61,0	61,1	5,1	56,4	0,4	61,0	5,0	62,6	6,6
	Bottom 65°C	EPC	1EP307 (-x)	4762	32,9	37,9	37,1	4,2	33,4	0,5	37,0	4,1	38,1	5,2
		LDLA	1CL2-09 (--x)	4796	30,0	35,0	34,3	4,4	30,5	0,5	34,2	4,2	35,6	5,6

The first target of the study is reached : probability was associated to calculated unit temperatures within a telecom system by taking into account uncertainties on inputs. It points out that :

DT RMS ≈ DT stochastique @97.5% ≈ 5°C = design margin <≈ DT@3sigma

➔ In this case the stochastic approach does not allow to reduce the usual margin of 5°C.

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CONCLUSIONS

Globally this study pointed out the following major conclusions :

- Feasibility of intensive sensitivity analysis of a telecom thermal model at low computation cost with OPTIMUS (not presented)
- Feasibility to associate reliable probability distributions to unit temperatures using the same workflow than for sensitivity (1000 runs thanks to parallel mode)
- This approach did not allow to reduce the usual margin of 5°C for the design,
- However it pointed out that this margin currently in use for design is
    - in agreement with RMS « exhaustive » computation
    - Is overpassed in less than 2 % of cases (by less than 2°C)

    ➔ With the current margin the thermal design is conservative, but not clearly oversized !

- OPTIMUS process was optimized :
  - Better interface OPTIMUS/Etherm
  - Possibility to execute lots of runs in parallel (more than 1000 runs at all).

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ON GOING ACTIONS & PERSPECTIVES

Complete the first probabilist approach on CM by taking into account the uncertainty on spatial distribution for dissipations and for P/L failure cases (TBC)

Improve and optimize OSR area (on going)
- Optimisation methods and automated workflow capability
- Sensible saving expected on analysis duration

Telecom S/C model correlation (on going)
- Model exploration, Optimisation methods, automated workflow capability
- **Particular interest targeted** : performing correlation and flight prediction in a same coupled computation process (weeks of saving expected)

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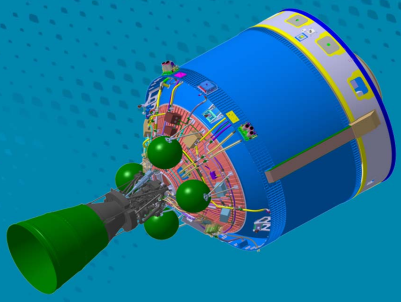
Appendix P

Development of an automated thermal model correlation tool

Martin Trinoga
(Airbus Defence and Space, Germany)

Abstract

A generally essential part in the development of a spacecraft is the implementation of a thermal model for the temperature predictions during the operation phase. In order to achieve a good accuracy of the assessed temperatures, the thermal model has to be correlated with measurements from predetermined thermal tests. Currently this correlation is only possible in a manual way at Airbus DS GmbH. As this manual method is often a time consuming process, a new method for solving this problem is currently under development. With this newly developed MATLAB® tool (TAUMEL = Tool for AUtomated Model correlation using Equation Linearization) it will be possible to correlate restricted thermal models from ESATAN-TMS automatically. The first master thesis regarding this automated approach was finished in December 2013, whose outcome will be presented. Because of the promising potential of this new correlation method, Airbus DS in Bremen is currently working within the frame of a second master thesis. The current status will be presented as well.



Development of an automated thermal model correlation tool

Name: Martin Trinoga
Date: 14.10.2014

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Contents

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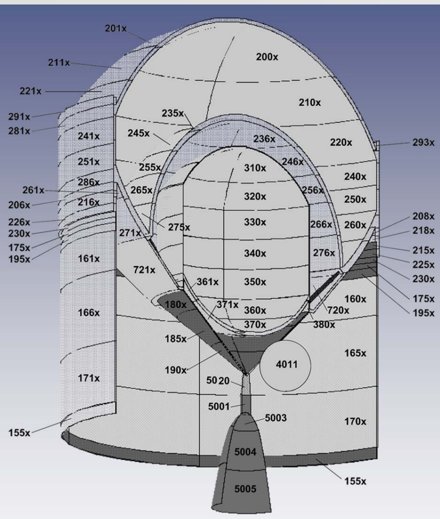
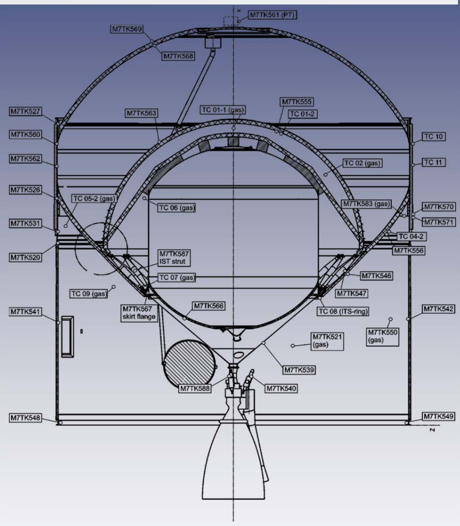
Fundamentals

Test vs. TMM





$$\begin{bmatrix} T_{model,1} \\ \vdots \\ T_{model,n} \end{bmatrix}_c = [T_{model}]_c \xleftrightarrow[\text{(mean absolute deviation)}]{\text{comparison criterion}} [T_{test}] = \begin{bmatrix} T_{test,1} \\ \vdots \\ T_{test,n} \end{bmatrix}$$

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Fundamentals

Parametric correlation

$$C_i \frac{dT_i}{dt} = \sum_{\substack{i=1 \\ j \neq i}}^{N} GL_{ij} PL_{ij} (T_j - T_i) + \sigma \sum_{\substack{i=1 \\ j \neq i}}^{N} GR_{ij} PR_{ij} (T_j^4 - T_i^4) + \dot{Q}_i$$

Uncertainties:

- Heat conduction ($GL_{ij} = \lambda_i \frac{A_{ij}}{d_{ij}}$): $\lambda: \pm 20\%$
- Heat radiation ($GR_{ij} = A_i \varphi_{ij} \varepsilon_i \alpha_j$): $\varepsilon, \alpha: \pm 20\%$
- Convection (GF) excluded in the current development stage

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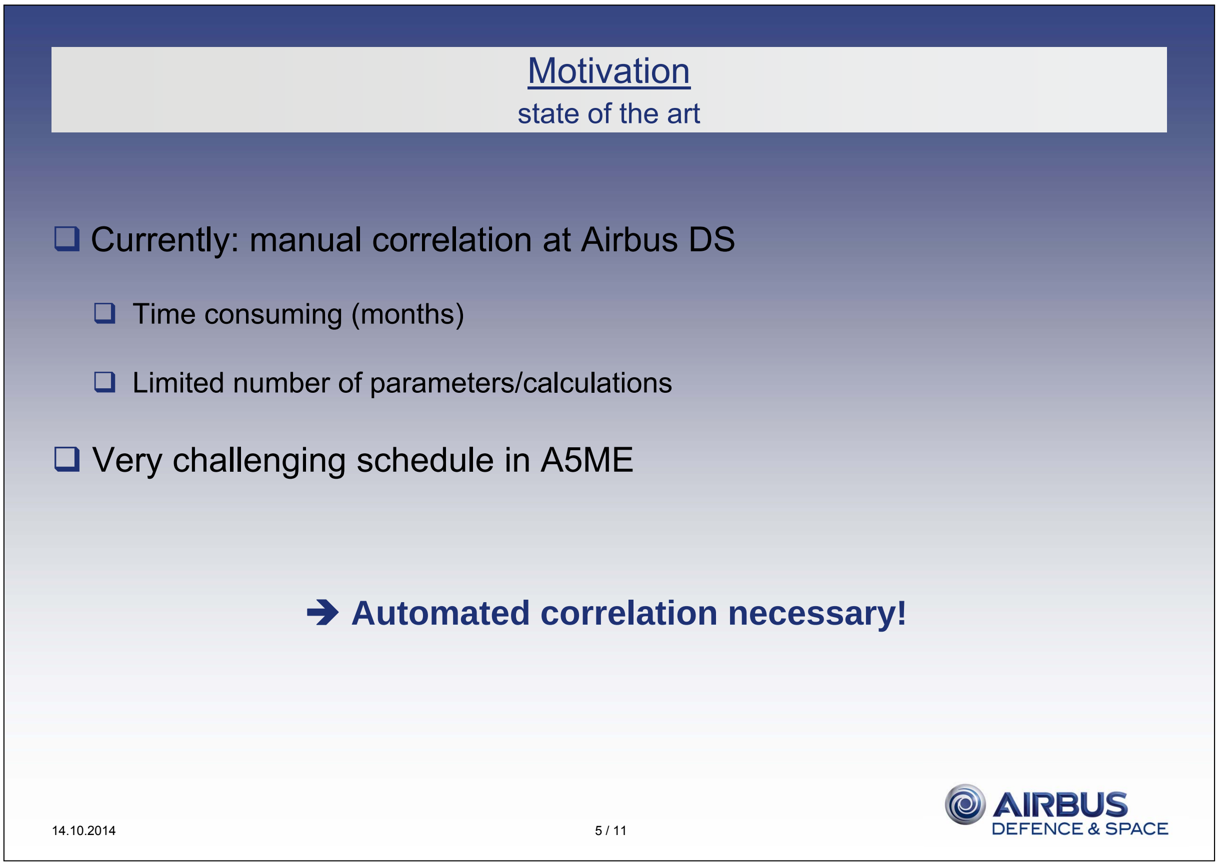
Motivation
state of the art
Currently: manual correlation at Airbus DS
Time consuming (months)
Limited number of parameters/calculations
Very challenging schedule in A5ME
➔ Automated correlation necessary!
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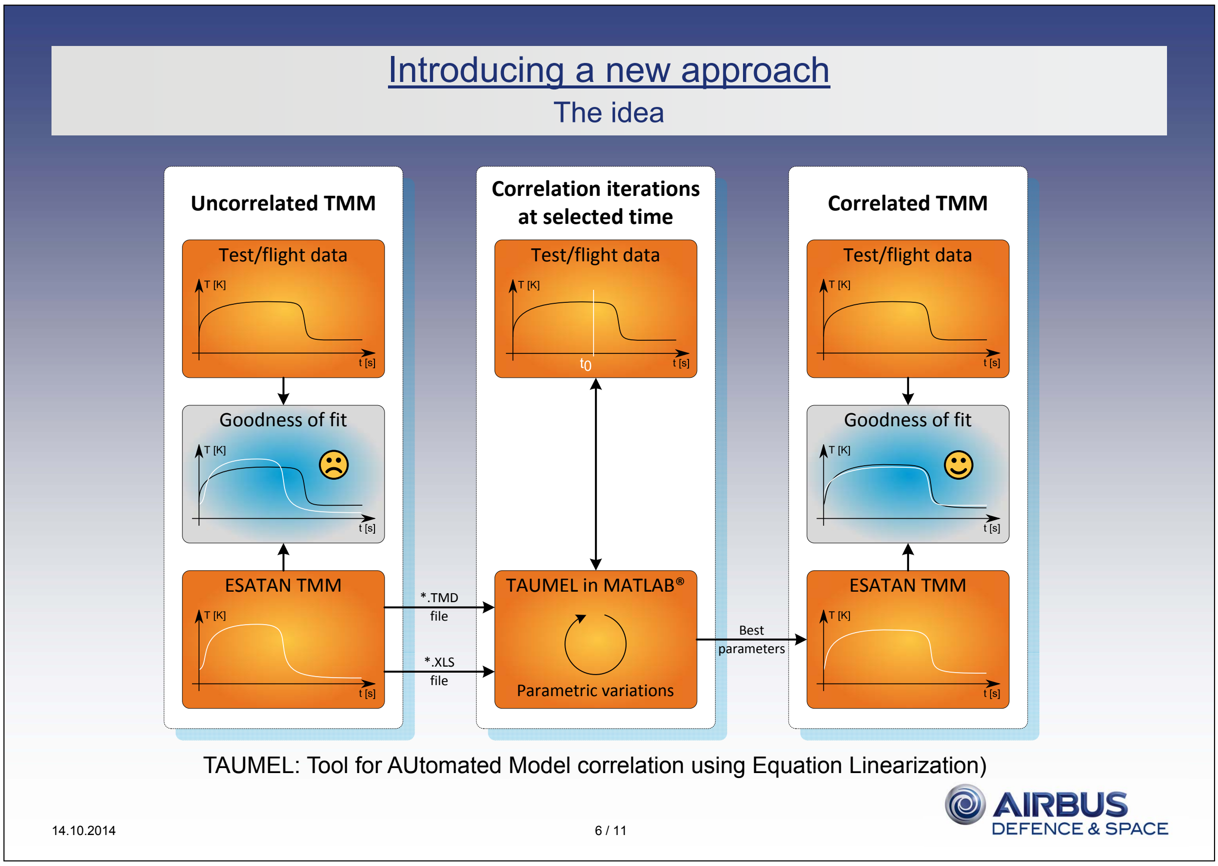
Introducing a new approach
The idea
Uncorrelated TMM
Test/flight data
T [K]
t [s]
Goodness of fit
ESATAN TMM
*.TMD file
*.XLS file
Correlation iterations at selected time
t0
TAUMEL in MATLAB®
Parametric variations
Best parameters
Correlated TMM
TAUMEL: Tool for AUtomated Model correlation using Equation Linearization)
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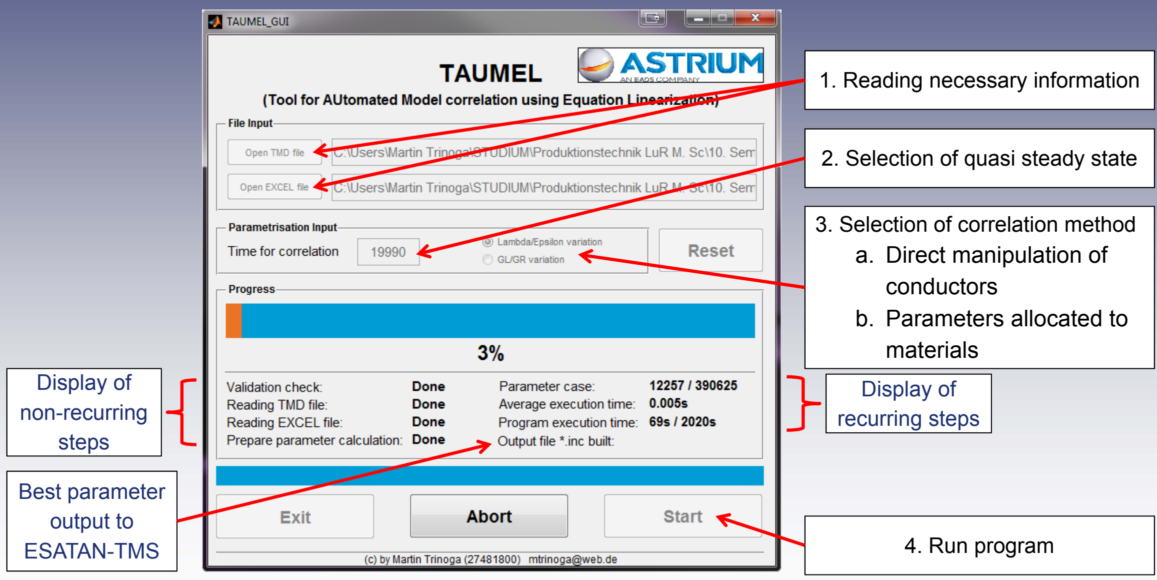
Current GUI in MATLAB®



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Results

Academic test case vs. reality

	Small models (15-150 nodes)	ESC-A (~1800 nodes)
MAD uncorrelated	14.5K	19.6K
MAD correlated	0.8K	14.8K
$\frac{\text{runs}}{\text{hour}}$	500000 - 60000	13000 - 4500

FAST !

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Conclusion

Current state of the tool

- Reading TMD-files from ESATAN-TMS into MATLAB®
- Excellent correlation for academic cases (vacuum test)
- Only small models in an acceptable time due to exponentially increasing number of parameter cases

Open problems

- Selection of quasi steady state
- Fluid connected nodes / convection
- Temperature depending boundary conditions

Essential for correlation of “real” models!

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Outlook

Planning for further development

- Open problem treatment
- Implementation of intelligent numerical parameter solver
  - Simulated annealing
  - Threshold accepting
  - Genetic algorithm
- Validation of the method
- Application to projects (A5ME)

Second master thesis currently running

Third thesis/internship planned for 2015

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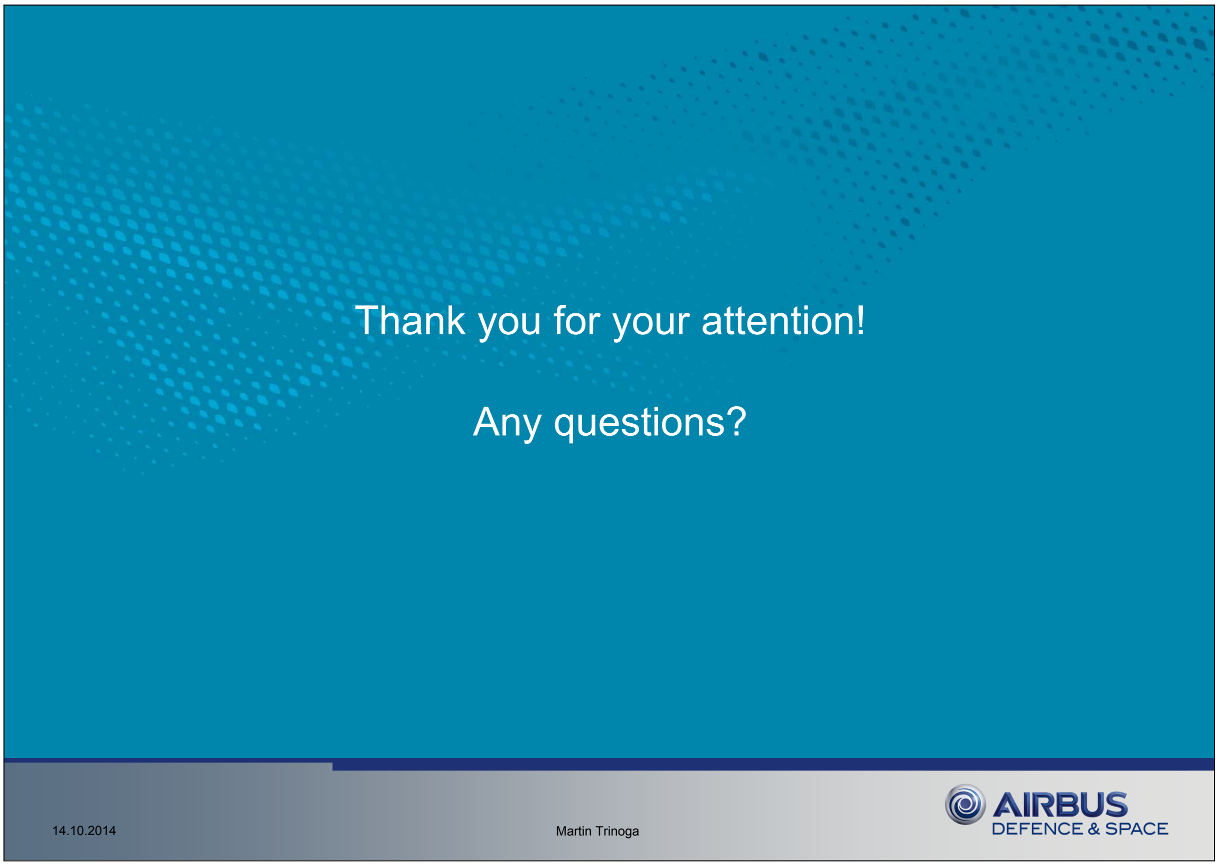
Thank you for your attention!
Any questions?
14.10.2014
Martin Trinoga
AIRBUS
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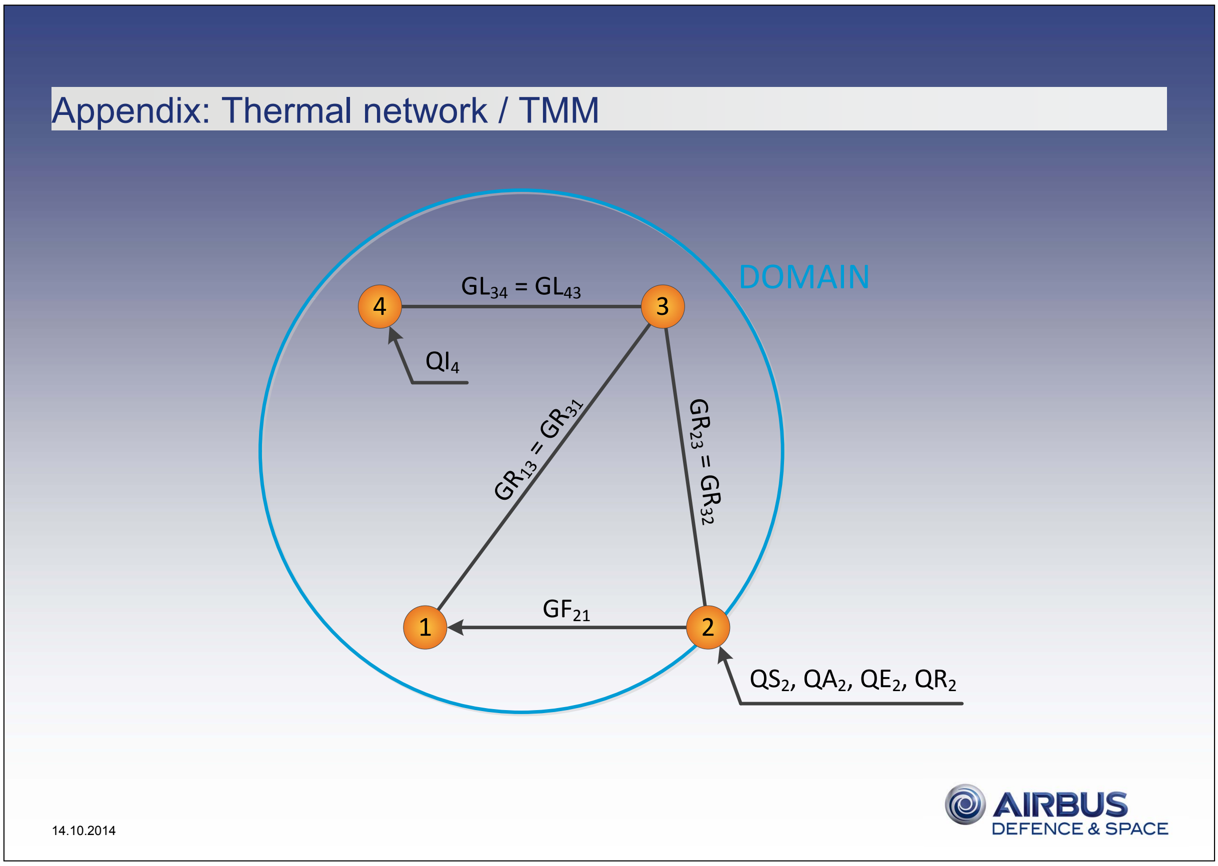
Appendix: Thermal network / TMM
DOMAIN
$GL_{34} = GL_{43}$
4
3
QI_4
$GR_{13} = GR_{31}$
$GR_{23} = GR_{32}$
1
2
GF_{21}
QS_2, QA_2, QE_2, QR_2
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Appendix: Mean absolute deviation

$$MAD = \frac{1}{n}\sum_{i=1}^{n}\left|T_{test,i} - T_{model,i}\right|$$

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Appendix: Parameter combinations

Case	Parameter 1	Parameter 2	Parameter 3	Case	Parameter 1	Parameter 2	Parameter 3
1	0.9	0.9	0.9	15	1.0	1.0	1.1
2	0.9	0.9	1.0	16	1.0	1.1	0.9
3	0.9	0.9	1.1	17	1.0	1.1	1.0
4	0.9	1.0	0.9	18	1.0	1.1	1.1
5	0.9	1.0	1.0	19	1.1	0.9	0.9
6	0.9	1.0	1.1	20	1.1	0.9	1.0
7	0.9	1.1	0.9	21	1.1	0.9	1.1
8	0.9	1.1	1.0	22	1.1	1.0	0.9
9	0.9	1.1	1.1	23	1.1	1.0	1.0
10	1.0	0.9	0.9	24	1.1	1.0	1.1
11	1.0	0.9	1.0	25	1.1	1.1	0.9
12	1.0	0.9	1.1	26	1.1	1.1	1.0
13	1.0	1.0	0.9	27	1.1	1.1	1.1
14	1.0	1.0	1.0				

```
$REAL
#----------------------------------------------------------
# Array of correlation parameters calculated with TAUMEL
#----------------------------------------------------------
Corr_Par(2,7) =
1.000000, 1.200000,
2.000000, 1.200000,
3.000000, 1.200000,
4.000000, 1.000000,
5.000000, 0.800000,
101.000000, 1.000000,
102.000000, 1.000000;
```

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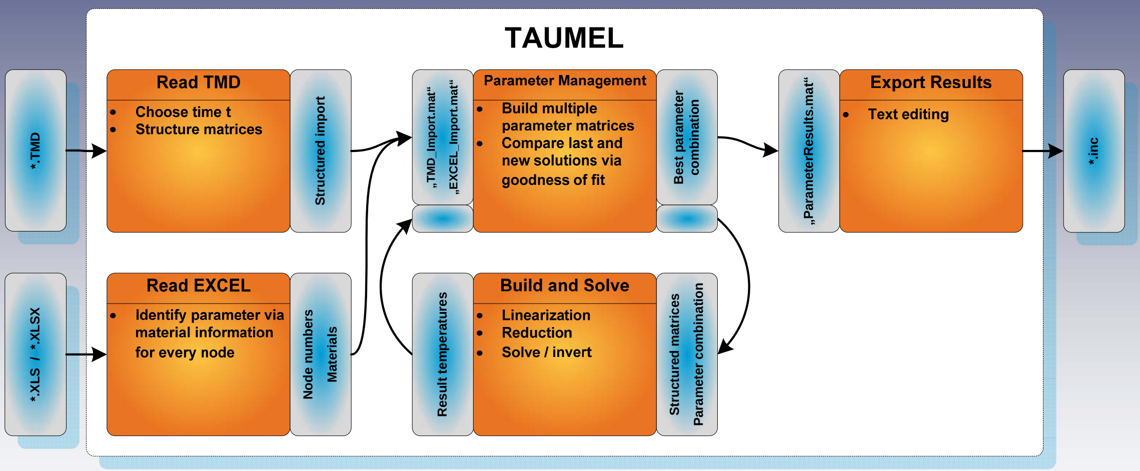
Appendix: New approach in MATLAB®



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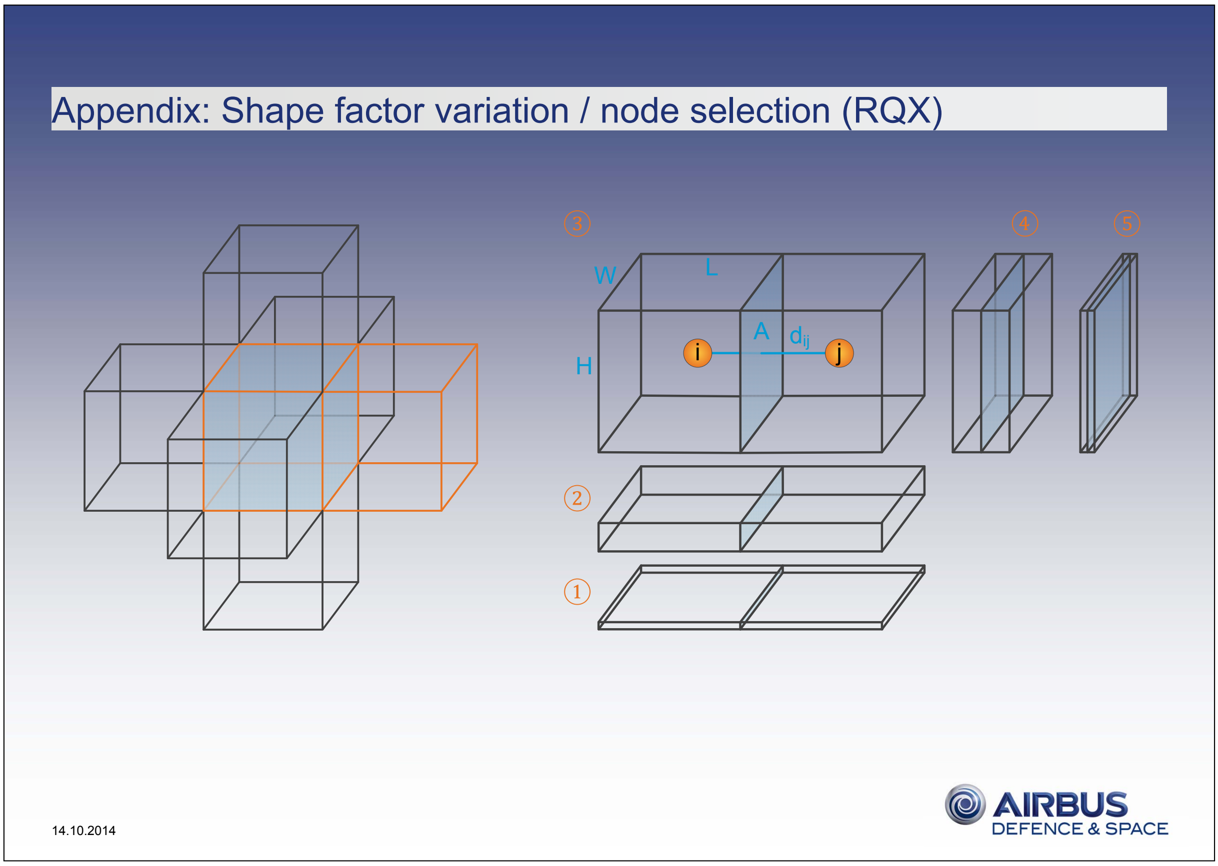
Appendix: Problematic of material depending parameter building

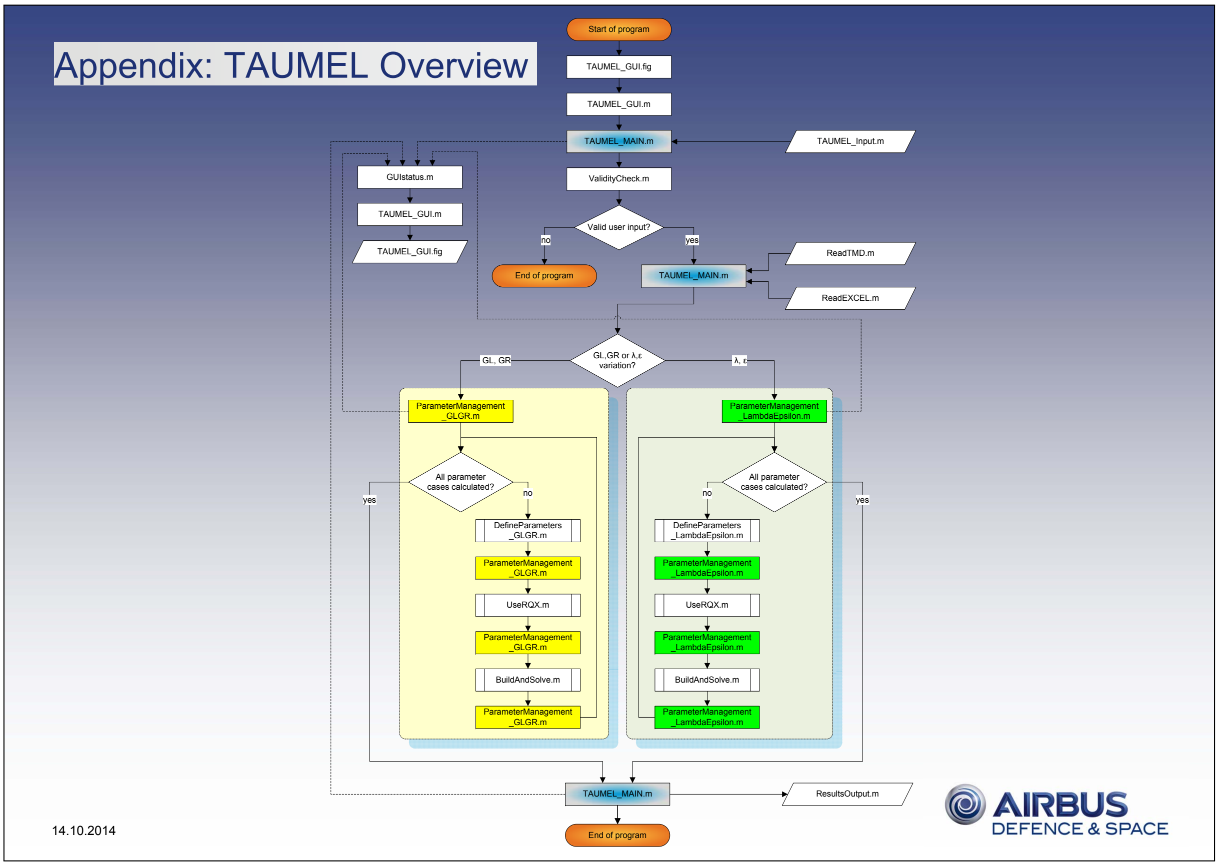
PL =

	1	2	3	4	5	6	7	
	-	1	0.9	1	1	1.1	1	1
	1	-	0.9	1	1	1.1	1	2
	0.9	0.9	-	0.9	0.9	?	0.9	3
	1	1	0.9	-	1	1.1	1	4
	1	1	0.9	1	-	1.1	1	5
	1.1	1.1	?	1.1	1.1	-	1.1	6
	1	1	0.9	1	1	1.1	-	7

14.10.2014

AIRBUS DEFENCE & SPACE


Appendix: Shape factor variation / node selection (RQX)
3
4
5
W
L
H
A
i
j
d_{ij}
2
1
14.10.2014
AIRBUS
DEFENCE & SPACE


Appendix: TAUMEL Overview
Start of program
TAUMEL_GUI.fig
TAUMEL_GUI.m
TAUMEL_MAIN.m
TAUMEL_Input.m
GUIstatus.m
TAUMEL_GUI.m
TAUMEL_GUI.fig
ValidityCheck.m
Valid user input?
no
yes
End of program
TAUMEL_MAIN.m
ReadTMD.m
ReadEXCEL.m
GL,GR or λ,ε variation?
GL, GR
λ, ε
ParameterManagement _GLGR.m
ParameterManagement _LambdaEpsilon.m
All parameter cases calculated?
yes
no
DefineParameters _GLGR.m
ParameterManagement _GLGR.m
UseRQX.m
ParameterManagement _GLGR.m
BuildAndSolve.m
ParameterManagement _GLGR.m
All parameter cases calculated?
no
yes
DefineParameters _LambdaEpsilon.m
ParameterManagement _LambdaEpsilon.m
UseRQX.m
ParameterManagement _LambdaEpsilon.m
BuildAndSolve.m
ParameterManagement _LambdaEpsilon.m
TAUMEL_MAIN.m
ResultsOutput.m
End of program
14.10.2014
AIRBUS
DEFENCE & SPACE

Appendix Q

On using quasi Newton algorithms of the Broyden class for model-to-test correlation

Jan Klement
(Tesat-Spacecom GmbH & Co. KG, Germany)

Abstract

The correlation of a model with test results is a common task in thermal spacecraft engineering. Often genetic algorithms or adaptive particle swarm algorithms are used for this task. A different approach has been developed at Tesat Spacecom using quasi Newton algorithms of the class defined by C. G. Broyden in 1965. A study is performed with thermal space industry models showing the performance of this approach. By comparing it to the results of other studies it is shown that this approach reduces the number of iterations by several orders of magnitude.

PIONEERING WITH PASSION

On using quasi Newton algorithms of the Broyden class for model-to-test correlation

Jan Klement, 15.10.2014

PIONEERING WITH PASSION

Using just one scalar

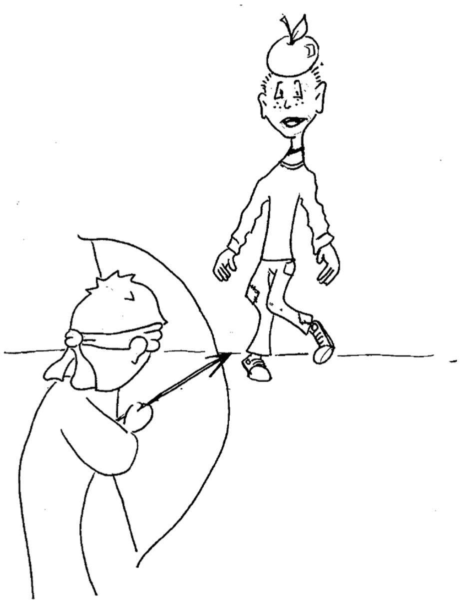


Illustration by Wiebke Klement

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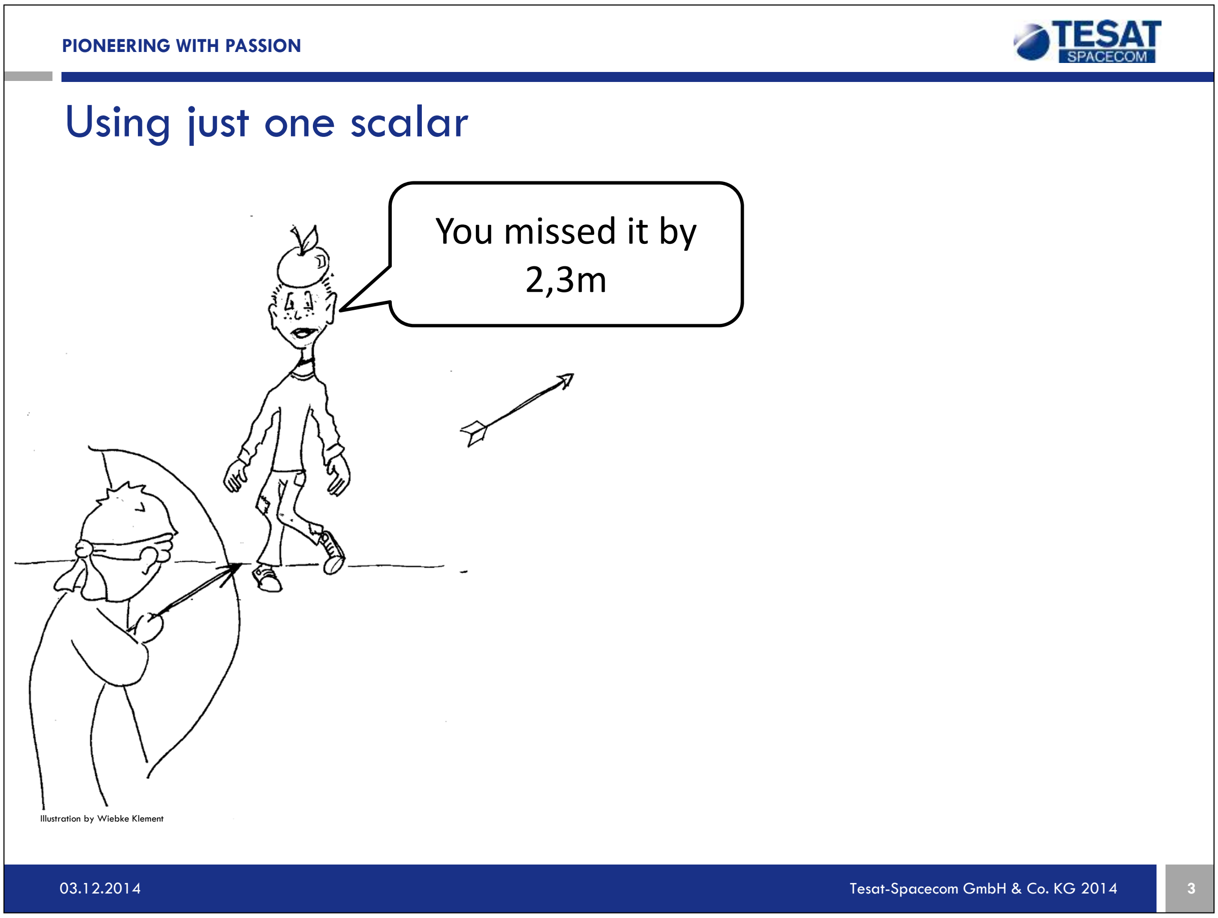
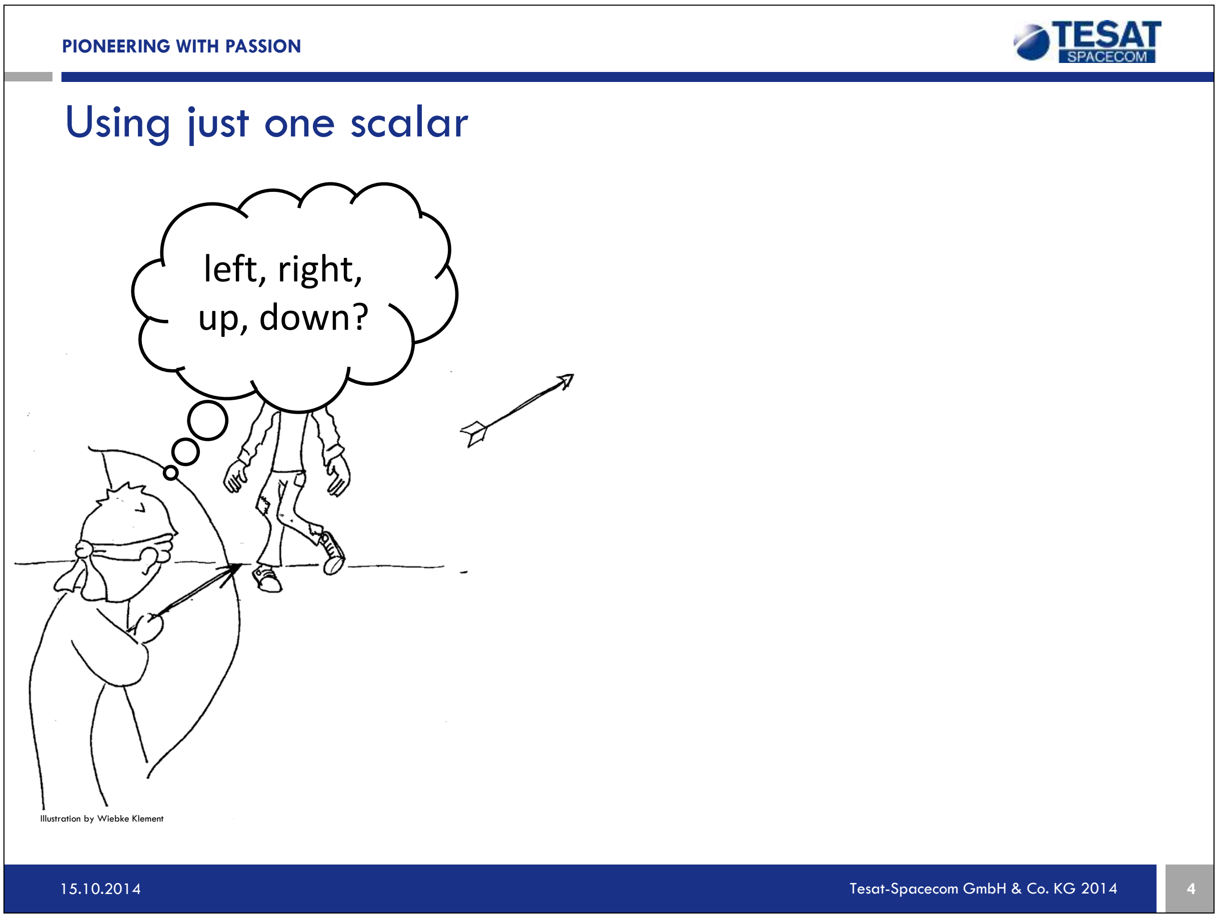

PIONEERING WITH PASSION
TESAT SPACECOM
Using just one scalar
You missed it by 2,3m
Illustration by Wiebke Klement
03.12.2014
Tesat-Spacecom GmbH & Co. KG 2014
3


PIONEERING WITH PASSION
TESAT SPACECOM
Using just one scalar
left, right, up, down?
Illustration by Wiebke Klement
15.10.2014
Tesat-Spacecom GmbH & Co. KG 2014
4

PIONEERING WITH PASSION

Using just one scalar

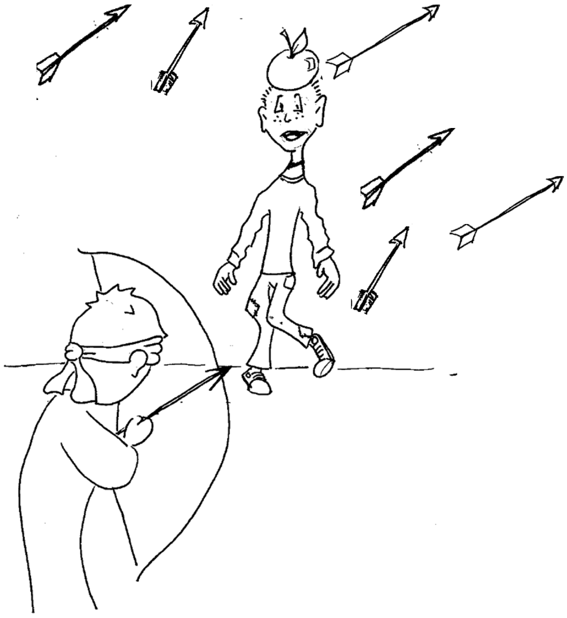


Illustration by Wiebke Klement

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PIONEERING WITH PASSION

Using an vector

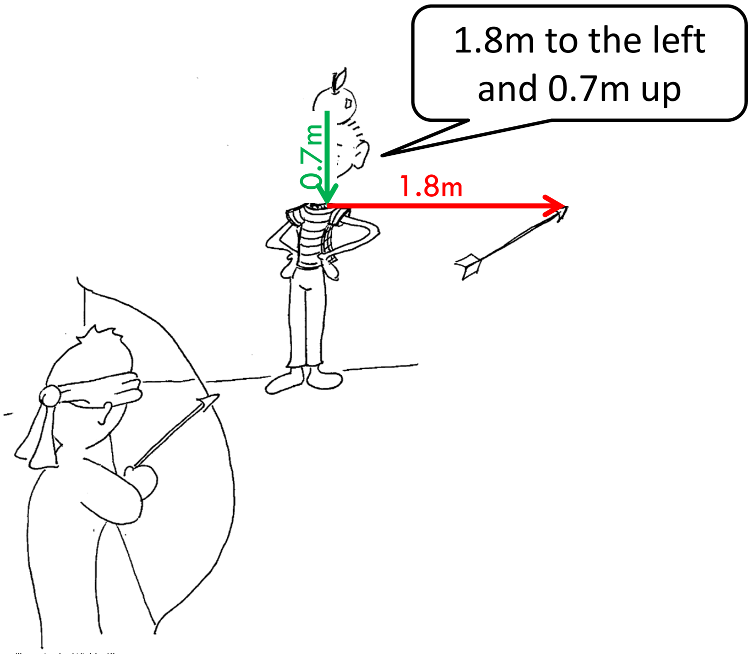

Illustration by Wiebke Klement

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PIONEERING WITH PASSION

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Definition of the parameters

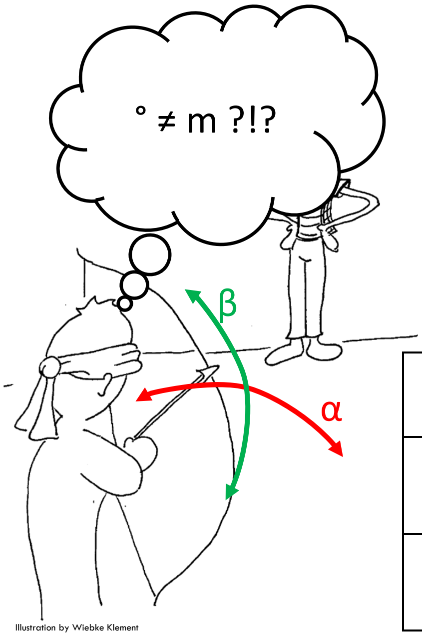
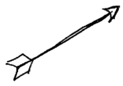


Illustration by Wiebke Klement



Equation system to be solved:

$$x(\alpha,\beta)=0$$
$$y(\alpha,\beta)=0$$

		1st arrow	2nd arrow	3rd arrow	4th arrow	5th arrow
parameter p	α	0°				
	β	0°				
target e	x	1.8m				
	y	-0.7m				

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PIONEERING WITH PASSION

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Calculation of the first partial derivatives

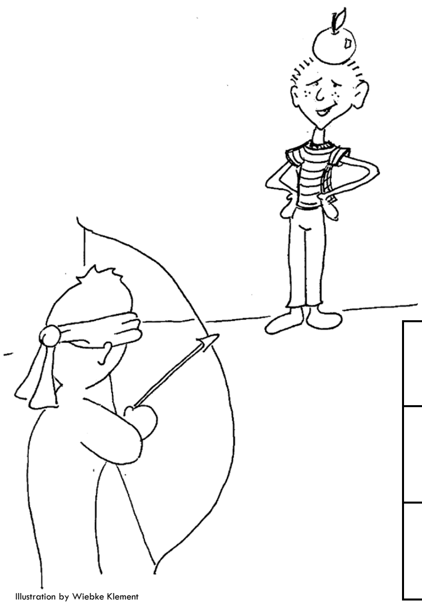
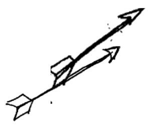


Illustration by Wiebke Klement



$$\frac{\Delta x}{\Delta\beta}=\frac{1.8m-1.8m}{1^\circ}=0m/^\circ\approx\frac{\partial x}{\partial\beta}$$

$$\frac{\Delta y}{\Delta\beta}=\frac{-0.5m-(-0.7)m}{1^\circ}=0.2m/^\circ\approx\frac{\partial y}{\partial\beta}$$

		1st arrow	2nd arrow	3rd arrow	4th arrow	5th arrow
parameter p	α	0°	0°			
	β	0°	1°			
target e	x	1.8m	1.8m			
	y	-0.7m	-0.5m			

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PIONEERING WITH PASSION

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Calculation of the first partial derivatives

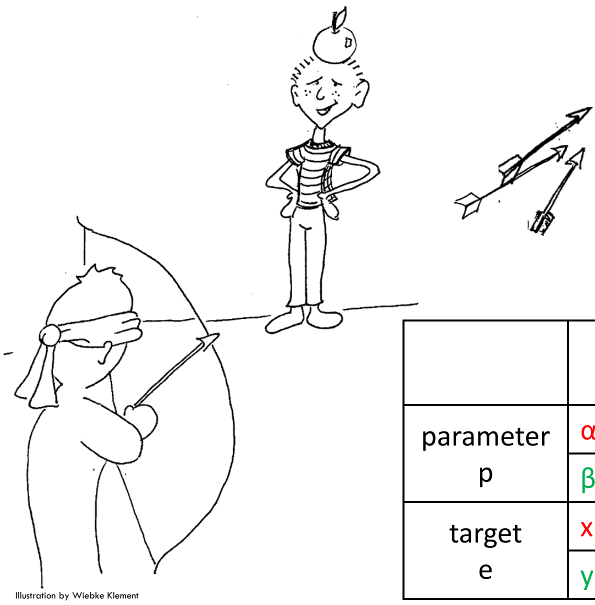
Illustration by Wiebke Klement

$$\frac{\Delta x}{\Delta \alpha} = \frac{1.9m - 1.8m}{1^\circ} = 0.1m/^\circ \approx \frac{\partial x}{\partial \alpha}$$

$$\frac{\Delta y}{\Delta \alpha} = \frac{-0.71m - (-0.7m)}{1^\circ} = 0.01m/^\circ \approx \frac{\partial y}{\partial \alpha}$$

		1st arrow	2nd arrow	3rd arrow	4th arrow	5th arrow
parameter p	α	0°	0°	1°		
	β	0°	1°	0°		
target e	x	1.8m	1.8m	1.9m		
	y	-0.7m	-0.5m	-0.71m		

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PIONEERING WITH PASSION

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Solving the linear equation system

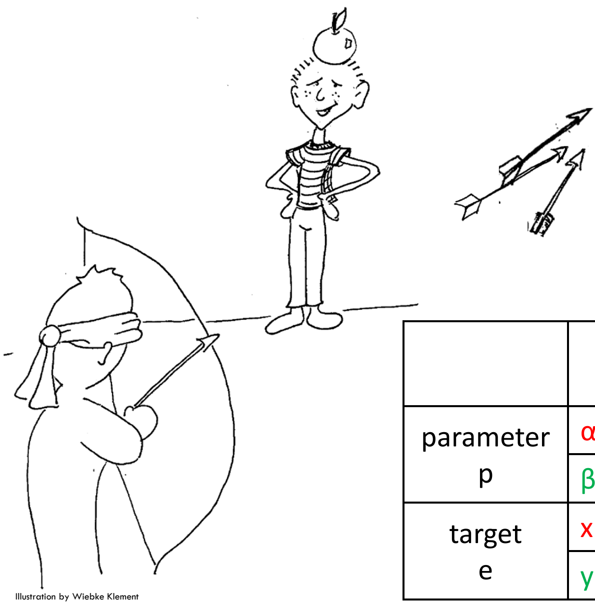
Illustration by Wiebke Klement

Jacobian matrix:

$$J_1 = \begin{bmatrix} \frac{\partial x}{\partial \alpha} & \frac{\partial x}{\partial \beta} \\ \frac{\partial y}{\partial \alpha} & \frac{\partial y}{\partial \beta} \end{bmatrix} \approx \begin{bmatrix} 0.1 & 0 \\ 0.01 & 0.2 \end{bmatrix} m/^\circ$$

$$p_4 = (-J^{-1}e_1) + p_1$$

		1st arrow	2nd arrow	3rd arrow	4th arrow	5th arrow
parameter p	α	0°	1°	0°	-18°	
	β	0°	0°	1°	4.4°	
target e	x	1.8m	1.9m	1.81m		
	y	-0.7m	-0.7m	-0.5m		

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PIONEERING WITH PASSION

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Testing the solution of the linear system

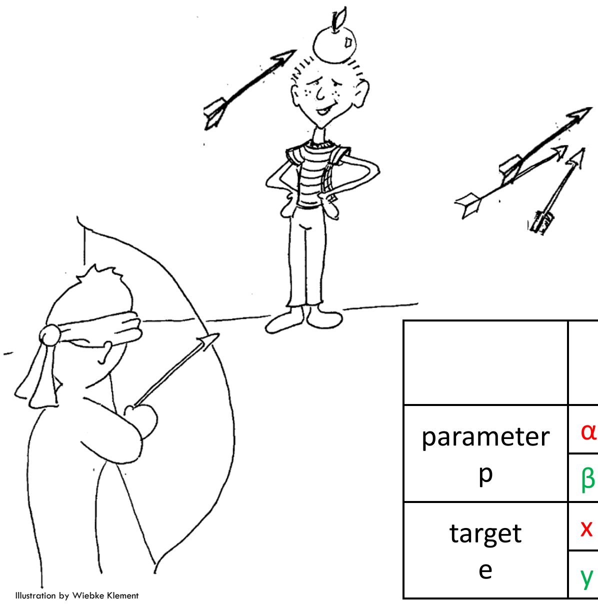

Illustration by Wiebke Klement

Missed because it is NOT Linear!

		1st arrow	2nd arrow	3rd arrow	4th arrow	5th arrow
parameter p	α	0°	1°	0°	-18°	
	β	0°	0°	1°	4.4°	
target e	x	1.8m	1.9m	1.81m	-0.2m	
	y	-0.7m	-0.7m	-0.5m	-0.1m	

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A new Jacobian matrix

Option 1 – Continue using the same Jacobian matrix

Option 2 – Calculate a new Jacobian matrix using 2 additional arrows (multidimensional Newton algorithm)

Option 3 – Guess a new Jacobian matrix using the secant condition (algorithms of the class defined by C. G. Broyden in 1965)

Quelle Wikipedia

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PIONEERING WITH PASSION

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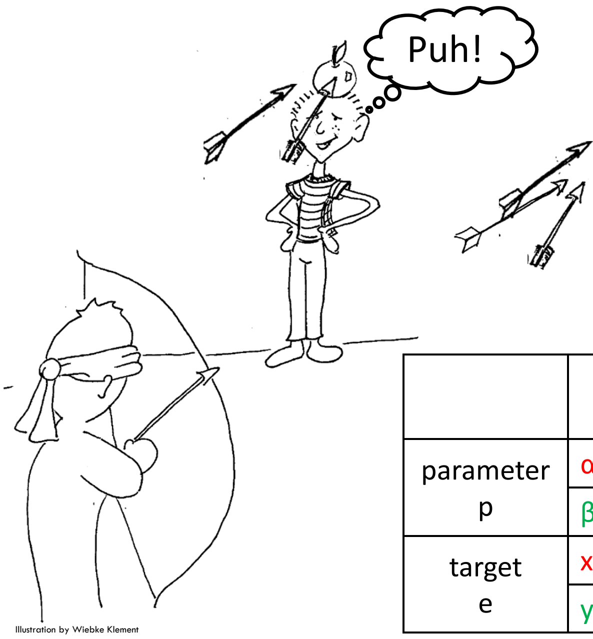
Testing the solution of the linear system



		1st arrow	2nd arrow	3rd arrow	4th arrow	5th arrow
parameter p	α	0°	1°	0°	-18°	-16°
	β	0°	0°	1°	4.4°	4.8
target e	x	1.8m	1.9m	1.81m	-0.2m	0.01m
	y	-0.7m	-0.7m	-0.5m	-0.1m	0.02m

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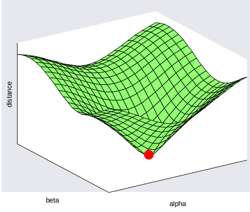
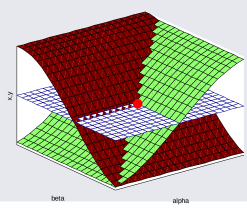
Comparision of the approches

	minimizing the distance	**solving an equation system**
Data per iteration	1 scalar	vector
Function	1 complex function 	2 nearly linear functions 

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Applying the method to thermal correlation

	blindfolded archer	thermal model correlation
	Arrows	Iterations
Input Parameters	α, β	λ, ε, α, c
Results	x, y	T_{calc}-T_{mes}
Function to be minimized	Distance to the Apple	RSS of temperature differences

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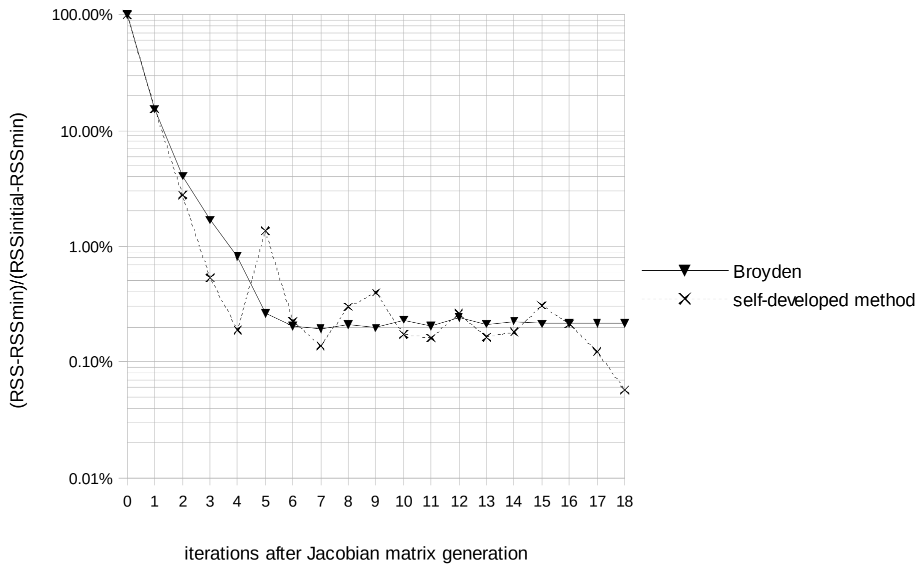
Results of a correlation of a transient complex system model with a TV test



2062 nodes , 156 temperatures (26 sensors 6 points in time)

13 parameters used for correlation

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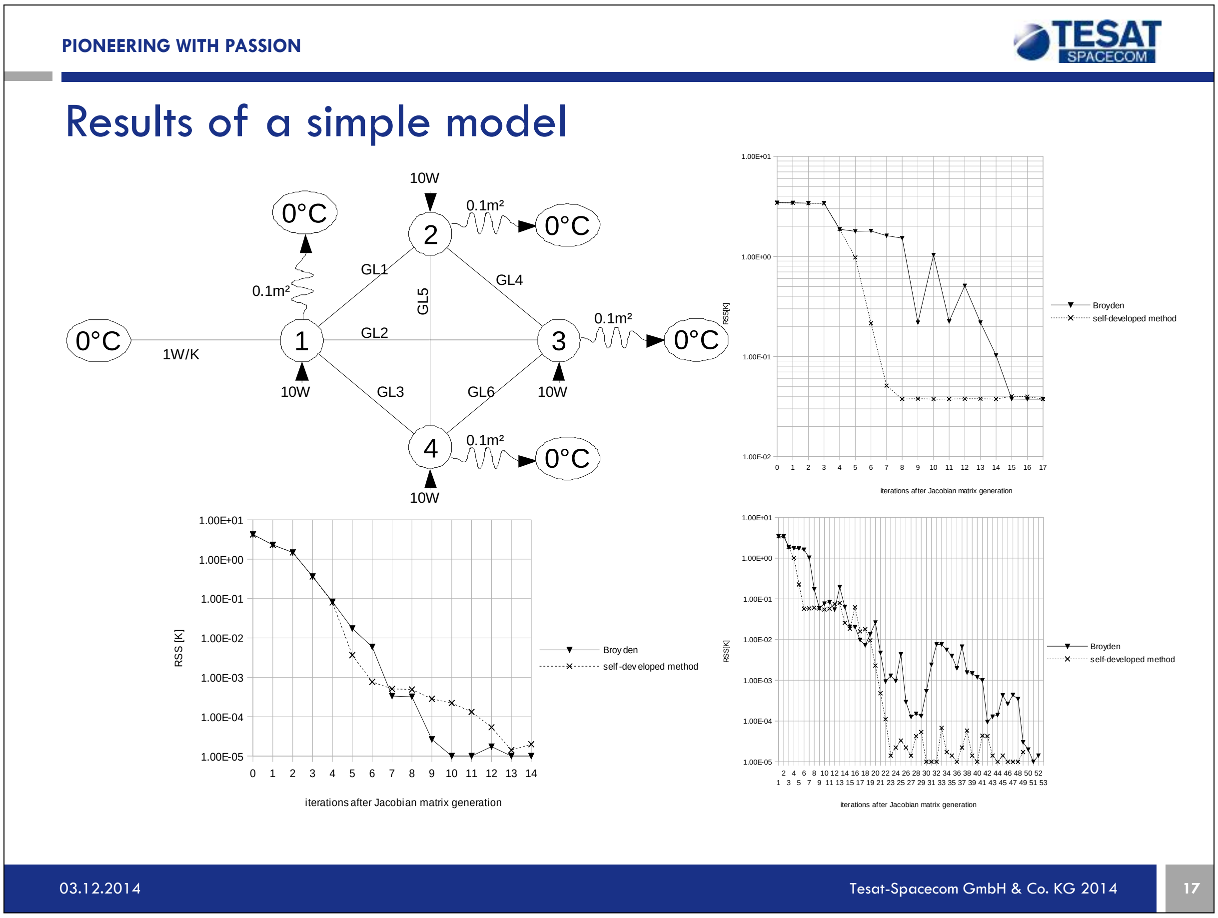
PIONEERING WITH PASSION
TESAT SPACECOM
Results of a simple model
10W
0.1m²
0°C
2
GL1
GL4
GL5
0.1m²
0°C
1W/K
1
GL2
3
0.1m²
0°C
10W
GL3
GL6
10W
4
0.1m²
0°C
10W
RSS [K]
iterations after Jacobian matrix generation
Broyden
self-developed method
03.12.2014
Tesat-Spacecom GmbH & Co. KG 2014
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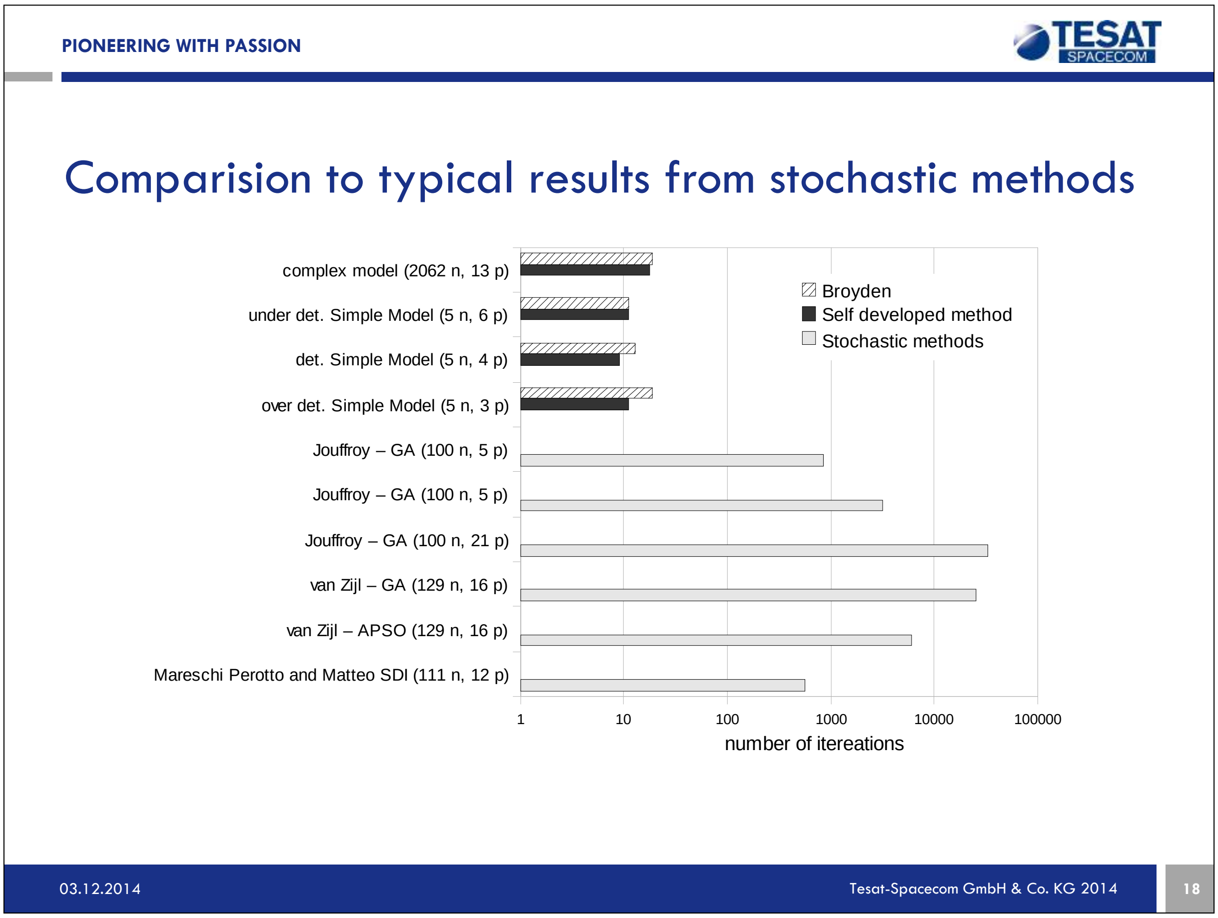
PIONEERING WITH PASSION
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Comparision to typical results from stochastic methods
complex model (2062 n, 13 p)
under det. Simple Model (5 n, 6 p)
det. Simple Model (5 n, 4 p)
over det. Simple Model (5 n, 3 p)
Jouffroy – GA (100 n, 5 p)
Jouffroy – GA (100 n, 5 p)
Jouffroy – GA (100 n, 21 p)
van Zijl – GA (129 n, 16 p)
van Zijl – APSO (129 n, 16 p)
Mareschi Perotto and Matteo SDI (111 n, 12 p)
Broyden
Self developed method
Stochastic methods
1
10
100
1000
10000
100000
number of itereations
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Limits of the algorithm

The method can be used as long as:

- The functions are monotone and differentiable
- Each parameter has an effect on at least one result
- Each result is influenced by at least one parameter

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Conclusion and Questions

See also:

- Klement, J. , 2014,"On using quasi-Newton algorithms of the Broyden class for model-to-test correlation", Journal of Aerospace Technology and Management www.jatm.com.br doi: 10.5028/jatm.v6i4.373, available online: http://www.jatm.com.br/ojs/index.php/jatm/article/view/373/pdf_38
- Klement, J, 2014, "Satelliten heiß-kalt Thermische Modelle an die realen Testergebnisse angleichen", Elektronik Industrie, 2014/11, pp 134-139, also available online: http://www.all-electronics.de/texte/anzeigen/56104/Modelle-von-Satelliten-Komponenten-an-reale-Testergebnisse-angleichen

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- WenLong , C., Na, L., Zhi, L., Qi, Z., AiMing, W., ZhiMin, Z. and ZongBo, H., 2011, "Application study of a correction method for a spacecraft thermal model with a Monte-Carlo hybrid algorithm", Chinese Science Bulletin, Vol. 56, No. 13, pp. 1407-1412. doi: 10.1007/s11434-010-4053-z.

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test2.ske

```
$MODEL CORRELA

# Model by Jan Klement to test correlation algorithms
# 4.11.2014
# further details see:
# Klement, J. ,to be published 2014, "On using quasi−Newton algorithms of the Broyden class for model−to−test correlation",
# Journal of Aerospace Technology and Management, http://www.jatm.com.br
# or
# Klement, J. ,2014,"Modelle von Satelliten−Komponenten an reale Testergebnisse angleichen",
# http://www.all−electronics.de/texte/anzeigen/56104/Modelle−von−Satelliten−Komponenten−an−reale−Testergebnisse−angleichen


$LOCALS
#READ "parameters.nwk"
$NODES
# Boudary:
B10 = 'boundary';
# dissipative  nodes:
D1 = '1',       T=0.0E+00,      C= 1.0, A= 0.00000E+00;
D2 = '2',       T=0.0E+00,      C= 1.0, A= 0.00000E+00;
D3 = '3',       T=0.0E+00,      C= 1.0, A= 0.00000E+00;
D4 = '4',       T=0.0E+00,      C= 1.0, A= 0.00000E+00;
$CONDUCTORS
GL(1,10) = 1.0;
GL(1,2) = cond_1;
GL(1,3) = cond_2;
GL(1,4) = cond_3;
GL(2,3)= cond_4;
GL(2,4)= cond_5;
GL(3,4)= cond_6;
GR(1,10)=0.1;
GR(2,10)=0.1;
GR(3,10)=0.1;
GR(4,10)=0.1;
$CONSTANTS
$REAL
$INTEGER
$CHARACTER
$CONTROL
  STEFAN = 5.6686D−08;
  RELXCA = 1.0000D−5;
  NLOOP  = 10000;
  TIMEO  = 0.D+00;
  TIMEND = 1000;
  DTIMEI = 1.D+00;
  OUTINT = 1.D+00;
$ARRAYS
$REAL
$SUBROUTINES
$INITIAL
  QI1=10.0;
  QI2=10.0;
  QI3=10.0;
  QI4=10.0;
$VARIABLES1
$VARIABLES2
$EXECUTION
          CALL SOLVIT
$OUTPUTS
# LIST OF ALL NODES TEMPERATURES
       CALL PRNDTB(' ',' L,T,C,QI',CURRENT)
       open(11,FILE='results.csv')
       write(11,*) 'Temp;T10;T1;T2;T3;T4'
       write(11,'(A3,";",16((F10.5),";"))') 'Tem',T10,T1−8.85234,T2−17.67466,T3−17.59433,T4−17.51947
$ENDMODEL
```

parameters.nwk

```
$LOCALS
$REALS
#target
 cond_1=0.11;
 cond_2=0.12;
 cond_3=0.13;
 cond_4=0.14;
 cond_5=0.15;
 cond_6=0.16;

#undetermined model initial conditions
 cond_1=0.5;
 cond_2=0.5;
 cond_3=0.5;
 cond_4=0.5;
 cond_5=0.5;
 cond_6=0.5;

#determined  model initial conditions
 cond_1=0.5;
 cond_2=0.5;
 cond_3=0.13; #const
 cond_4=0.5;
 cond_5=0.5;
 cond_6=0.16; #const

#overdetremined model initial conditions
 cond_1=0.5;
 cond_2=0.5;
 cond_3=0.13; #const
 cond_4=0.5;
 cond_5=0.5;  #const
 cond_6=0.16; #const
```

Appendix R

SYSTEMA – THERMICA 4.7.0 & THERMICALC 4.7.0

Timothée Soriano Rose Nerriere
(Astrium SAS, France)

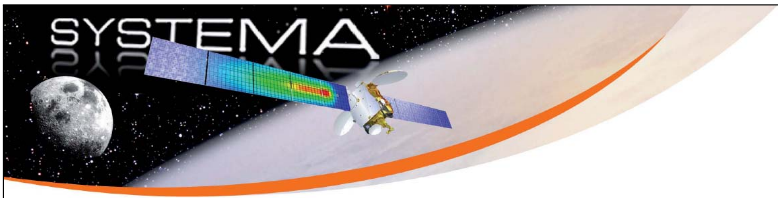
Abstract

SYSTEMA – THERMICA 4.7.0

The new 4.7.0 release includes new major functionalities.
A new CAD library is now embedded into SYSTEMA allowing the management of heavier CAD files. Thanks to several defeaturing options, it is possible to simplify a geometrical model with holes, chamfers and small volumes suppression. CAD shapes and SYSTEMA native shapes can then be used for thermal analysis.
A Post-Processing tab is now dedicated to the management of results. Mathematical operations, comparisons, min/max, margins, power budgets etc. can be linked together. The complete post-processing workflow can also be batched, including the generation of results into tables and graphs.

THERMICALC 4.7.0

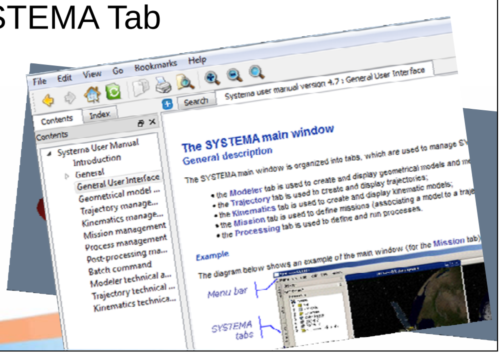
THERMICALC is a new product of the THERMICA suite which is designed to solve small thermal problems (up to 100 nodes). It has the powerful capabilities of THERMISOL accessible from an Excel spreadsheet.
Setting and running a thermal model within THERMICALC is very easy: declaration of nodes, couplings, plus a wizard mode to help setting thermostats, temperature or time dependencies.
THERMICALC also proposes the import of THERMICA outputs (such as nodes, couplings and external fluxes) and even THERMISOL inputs.
An advanced mode may be activated so to be able to set any user's code and so to perform more complex analysis.



Current status

- Long Time Support current version: v4.5.3a 04/2014
- Next Release: v4.7.0 11/2014
  - Integrates new major features:
    - ➢ CAD management
    - ➢ Post-Processing Tab
    - ➢ Extended Python interface to all SYSTEMA Tab
    - ➢ Upgrade of 3D performances
  - 64bits version for Windows and Linux
  - And lots of evolutions and corrections:

    Search tool on browser, Integrated help, Archiving option, New volumic shapes,…



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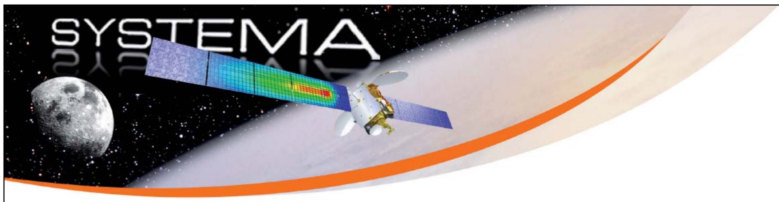

Content

- CAD management
  - New library
  - Defeaturing
- Post-Processing Tab
  - Toolboxes
  - How to use it in SYSTEMA
- ThermiCalc
  - Perform easy thermal analysis from Excel

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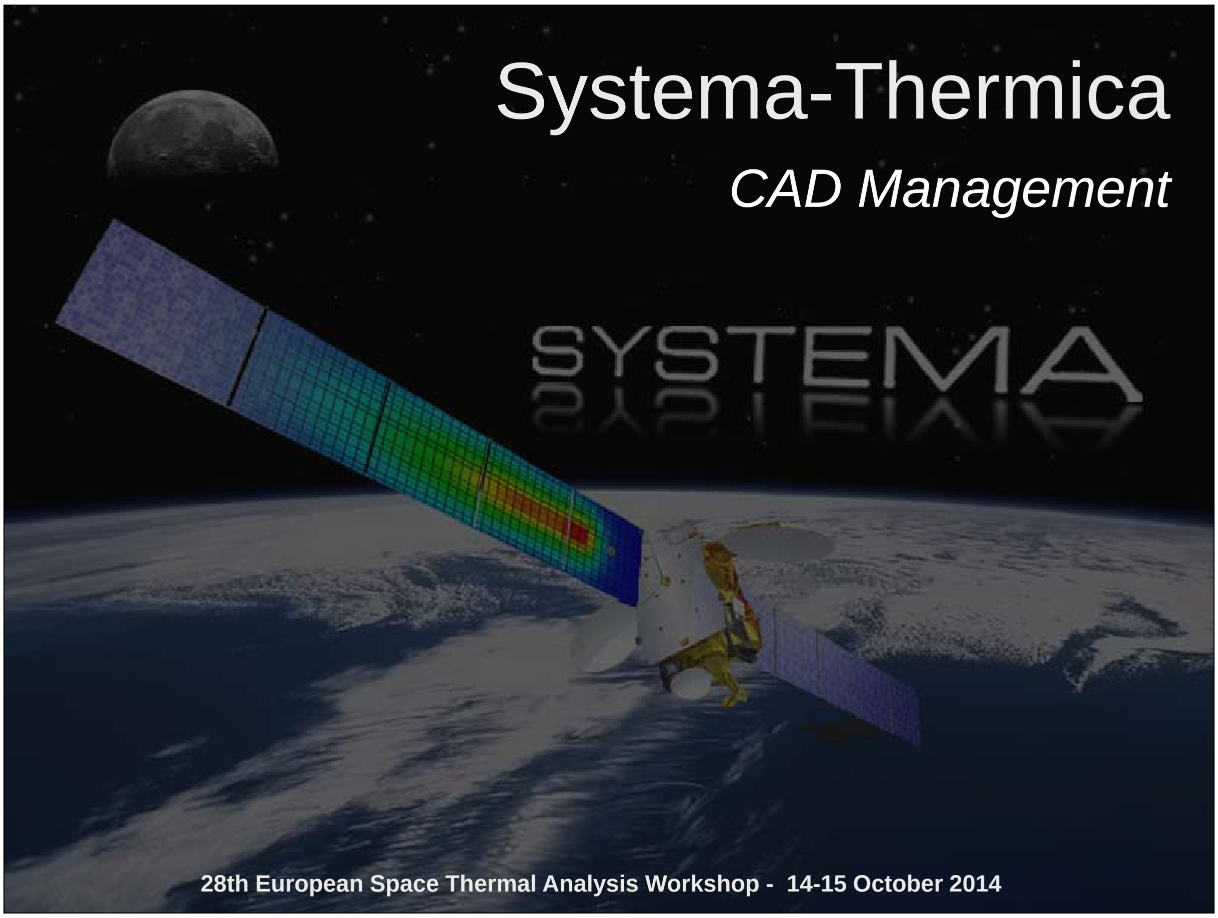

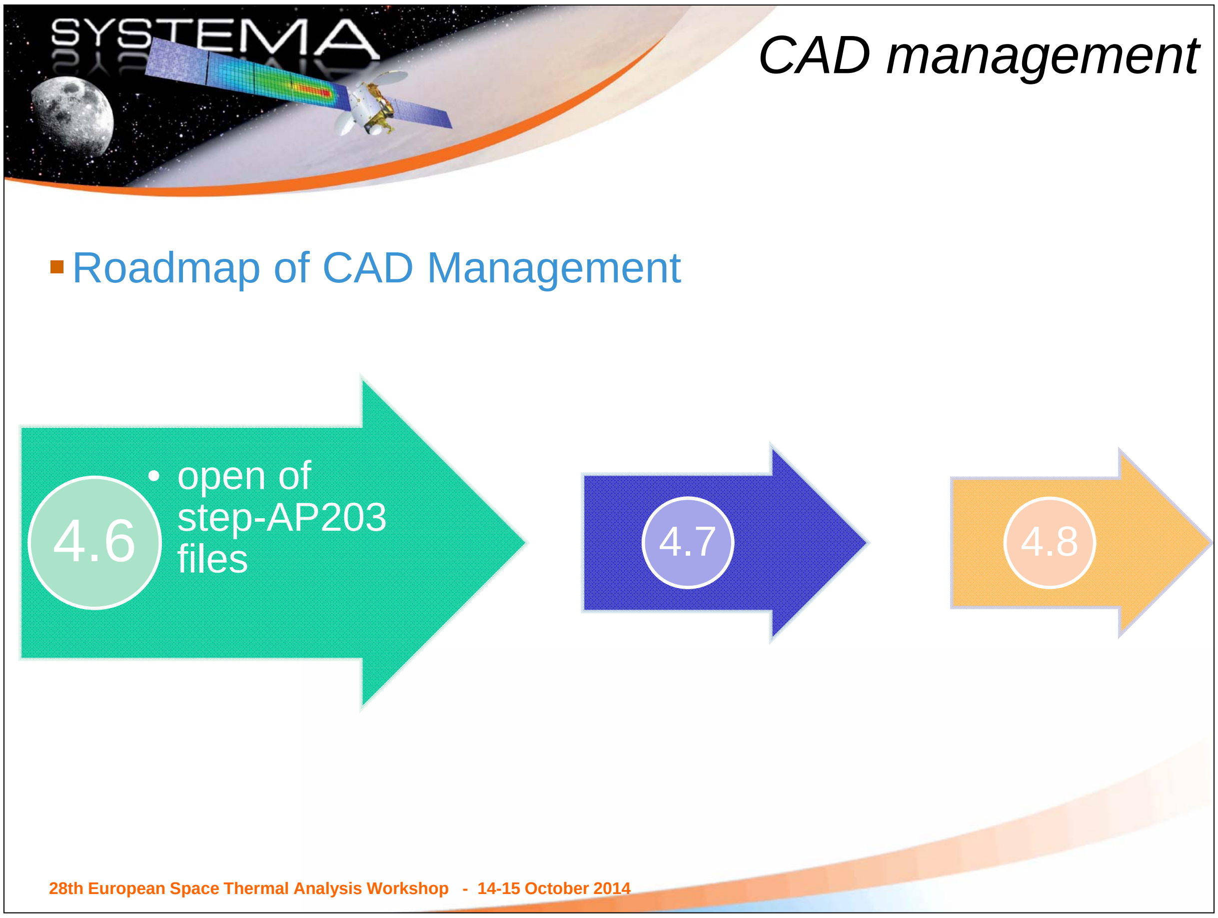
SYSTEMA
CAD management
Roadmap of CAD Management
4.6
open of step-AP203 files
4.7
4.8
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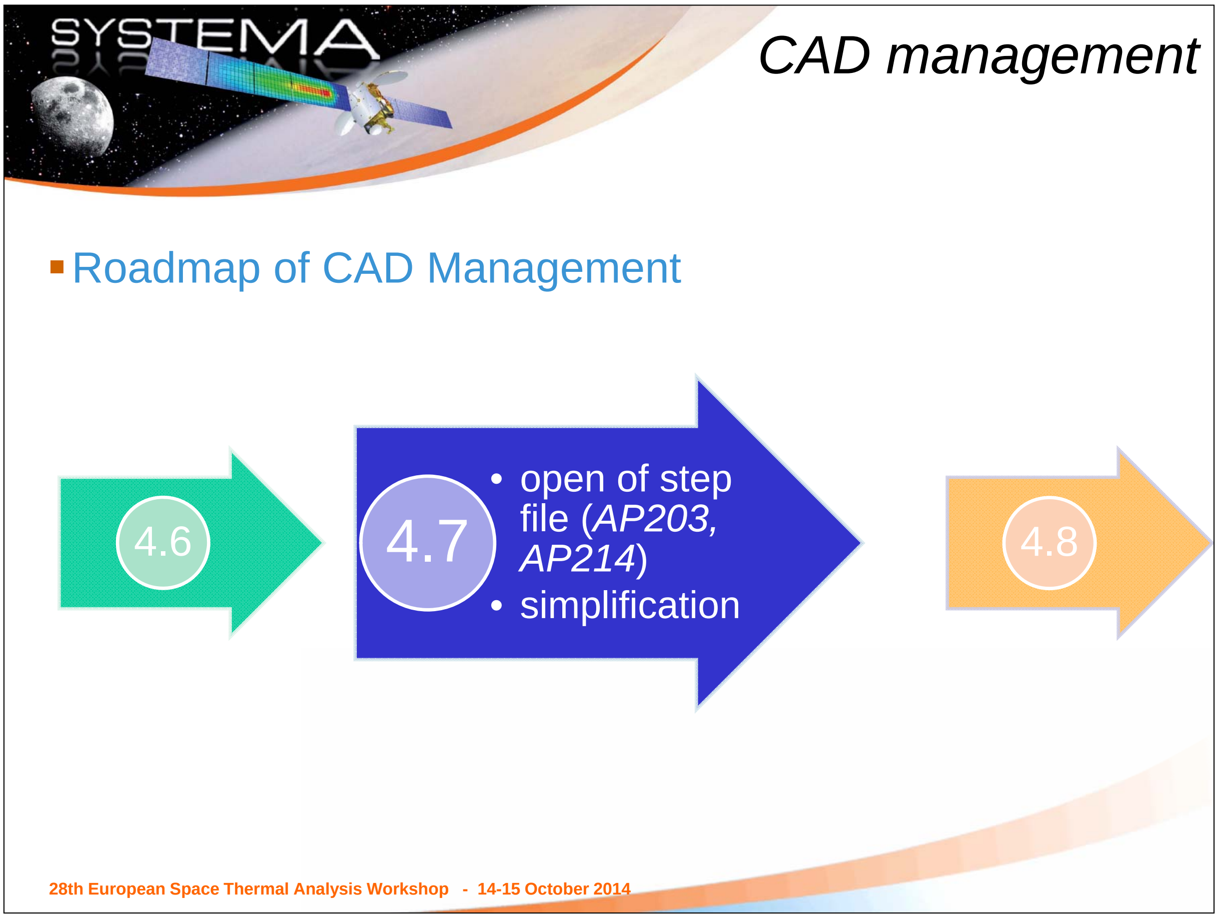
SYSTEMA
CAD management
Roadmap of CAD Management
4.6
4.7
open of step file (AP203, AP214)
simplification
4.8
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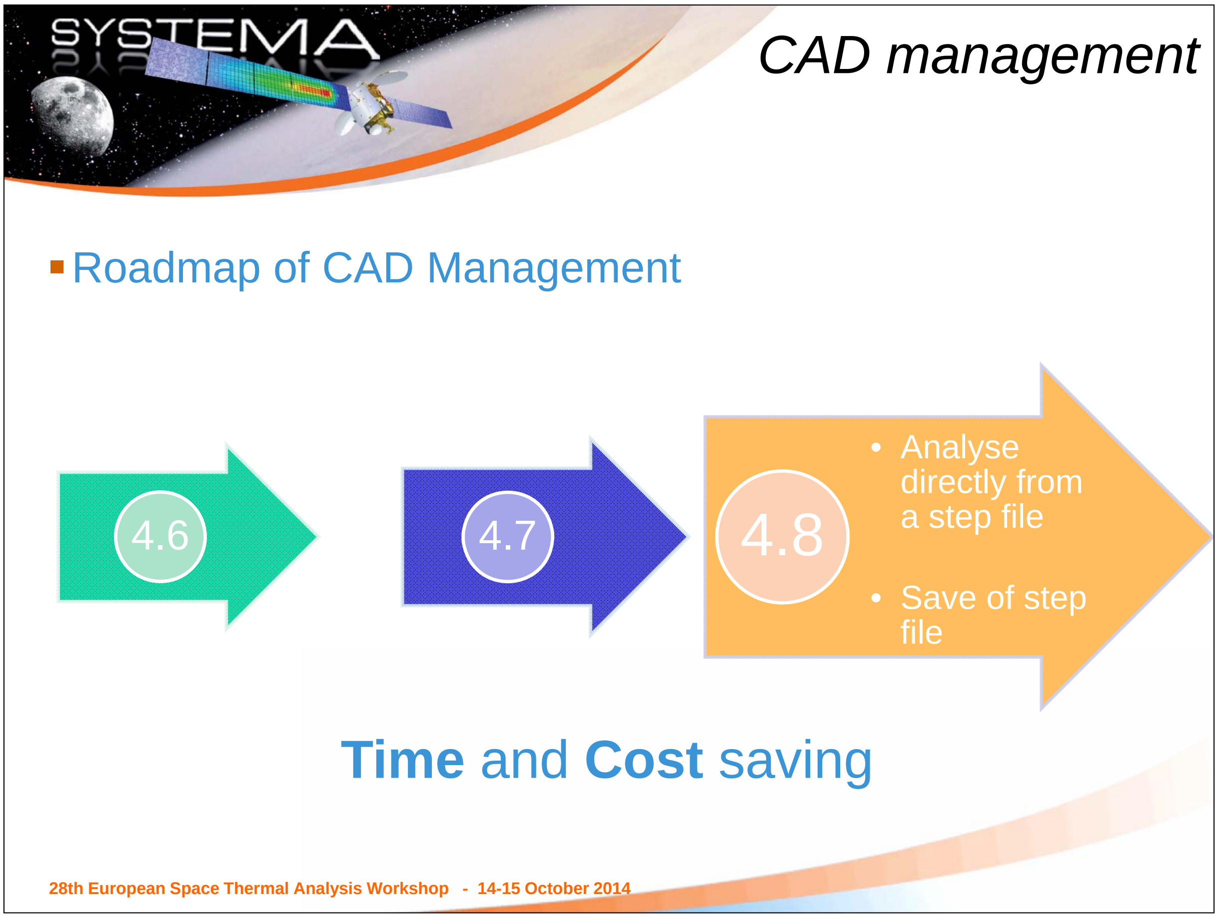
SYSTEMA
CAD management
Roadmap of CAD Management
4.6
4.7
4.8
Analyse directly from a step file
Save of step file
Time and Cost saving
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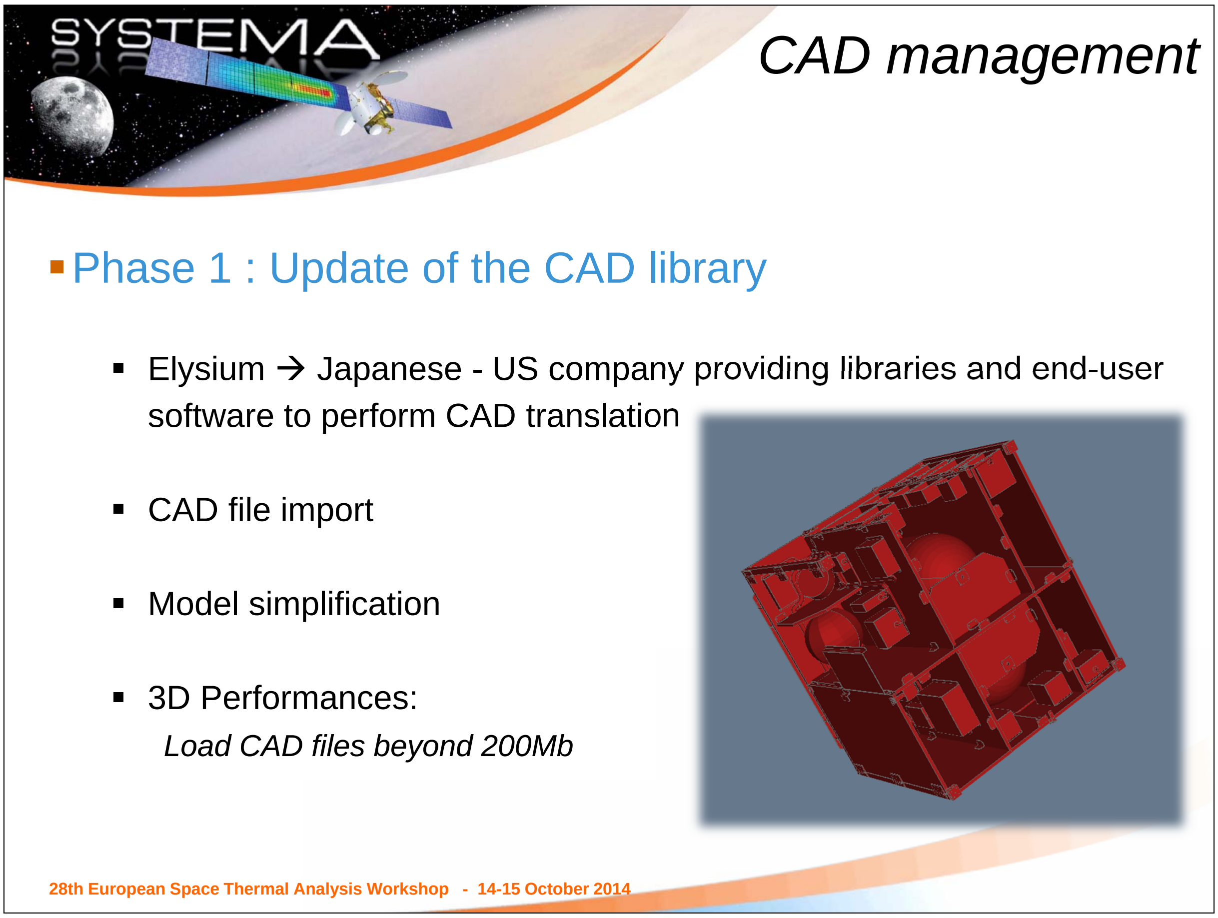
SYSTEMA
CAD management
Phase 1 : Update of the CAD library
Elysium → Japanese - US company providing libraries and end-user software to perform CAD translation
CAD file import
Model simplification
3D Performances:
Load CAD files beyond 200Mb
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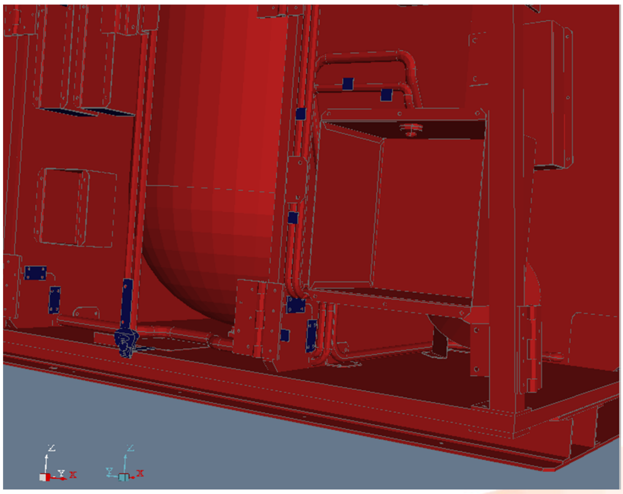
SYSTEMA

CAD management

- Phase 1: Opening Step files + defeaturing
  - Remove of
    - small shapes



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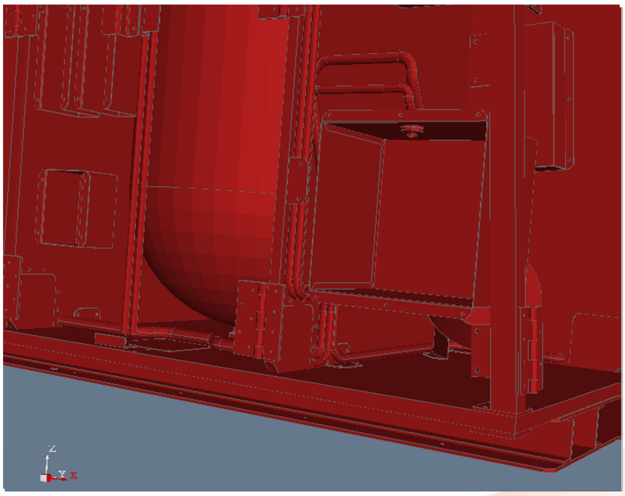
SYSTEMA

CAD management

- Phase 1: Opening Step files + defeaturing
  - Remove of
    - small shapes



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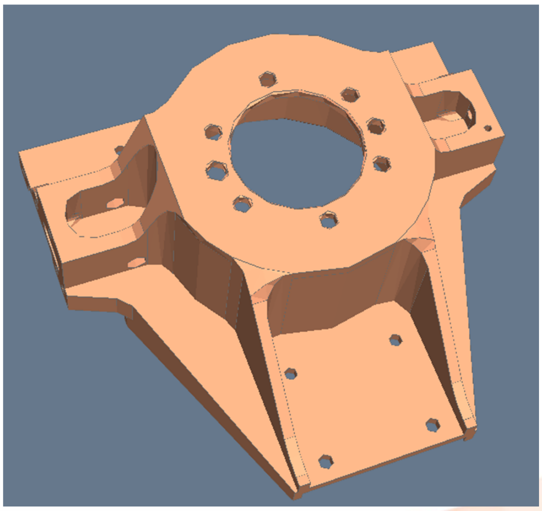
SYSTEMA

CAD management

- Phase 1: Opening Step files + defeaturing
  - Remove of
    - small shapes
    - holes



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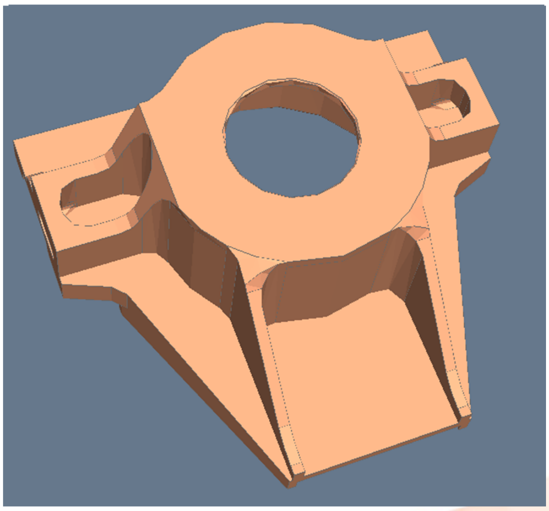
SYSTEMA

CAD management

- Phase 1: Opening Step files + defeaturing
  - Remove of
    - small shapes
    - holes



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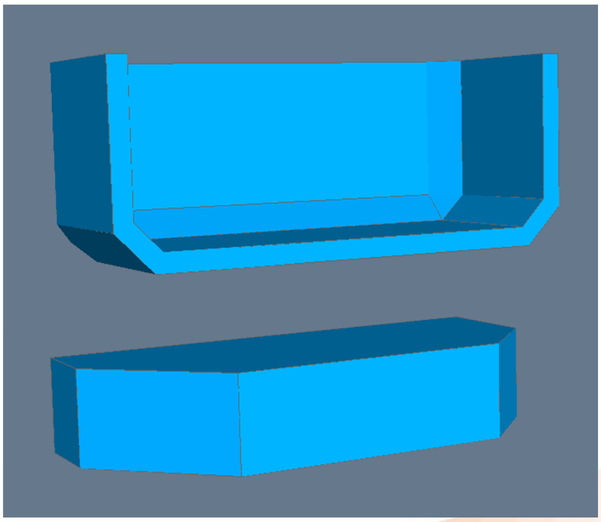
SYSTEMA

CAD management

- Phase 1: Opening Step files + defeaturing
  - Remove of
    - small shapes
    - holes
    - chamfers



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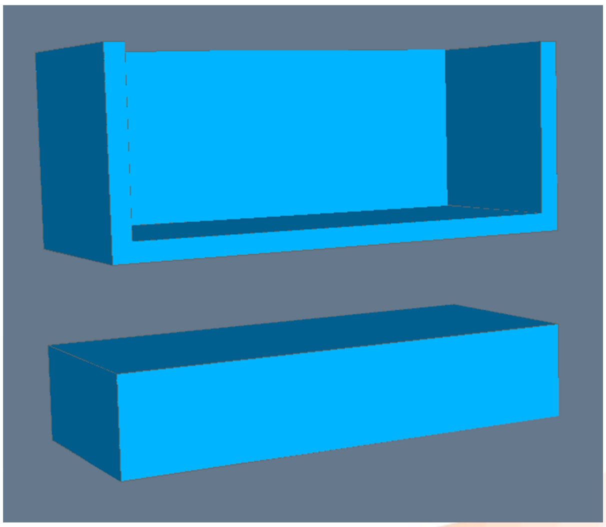
SYSTEMA

CAD management

- Phase 1: Opening Step files + defeaturing
  - Remove of
    - small shapes
    - holes
    - chamfers



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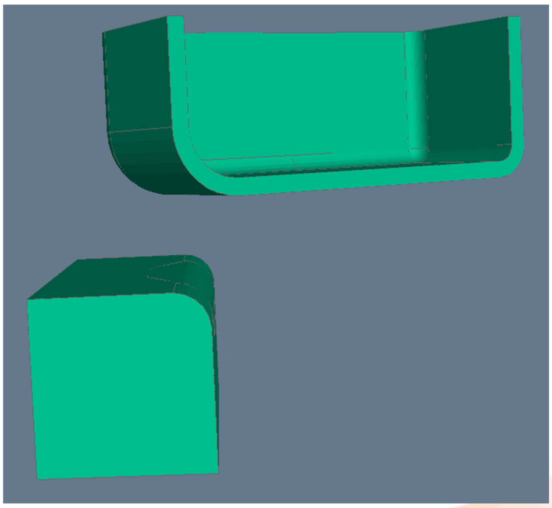
SYSTEMA

CAD management

Phase 1: Opening Step files + defeaturing

- Remove of
  - small shapes
  - holes
  - chamfers
  - fillets



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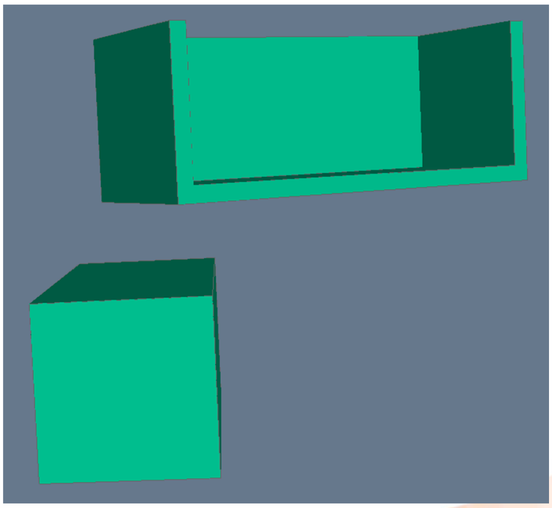
SYSTEMA

CAD management

Phase 1: Opening Step files + defeaturing

- Remove of
  - small shapes
  - holes
  - chamfers
  - fillets



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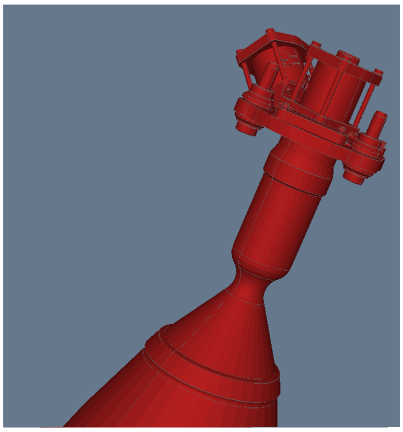
CAD management

Phase 1: Opening Step files + defeaturing

- Remove of
  - small shapes
  - holes
  - chamfers
  - fillets
- Tessellation

➢ *Python API available*



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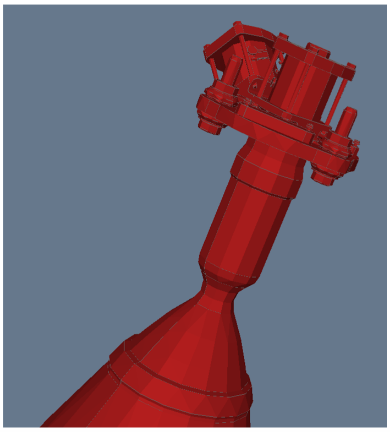
CAD management

Phase 1: Opening Step files + defeaturing

- Remove of
  - small shapes
  - holes
  - chamfers
  - fillets
- Tessellation

➢ *Python API available*



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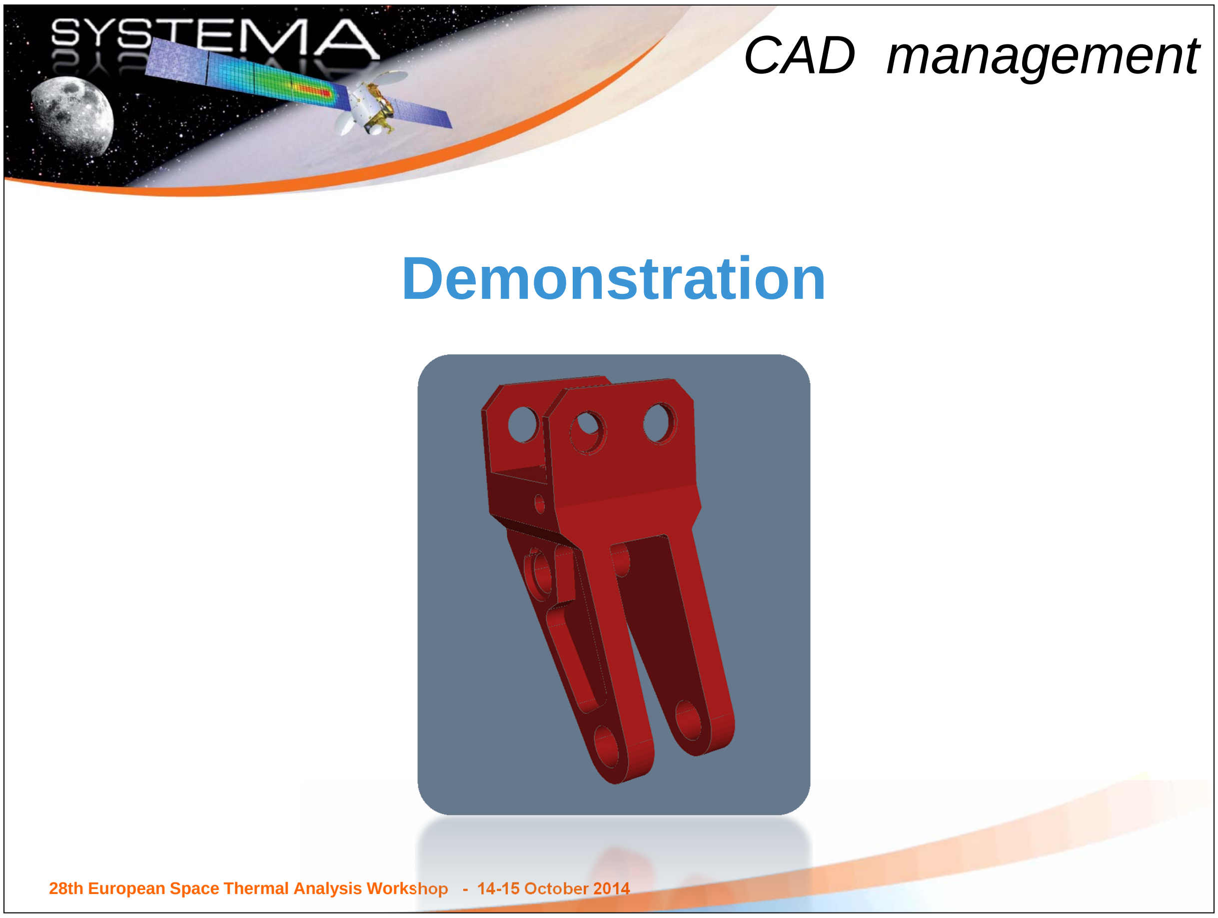
SYSTEMA
CAD management
Demonstration
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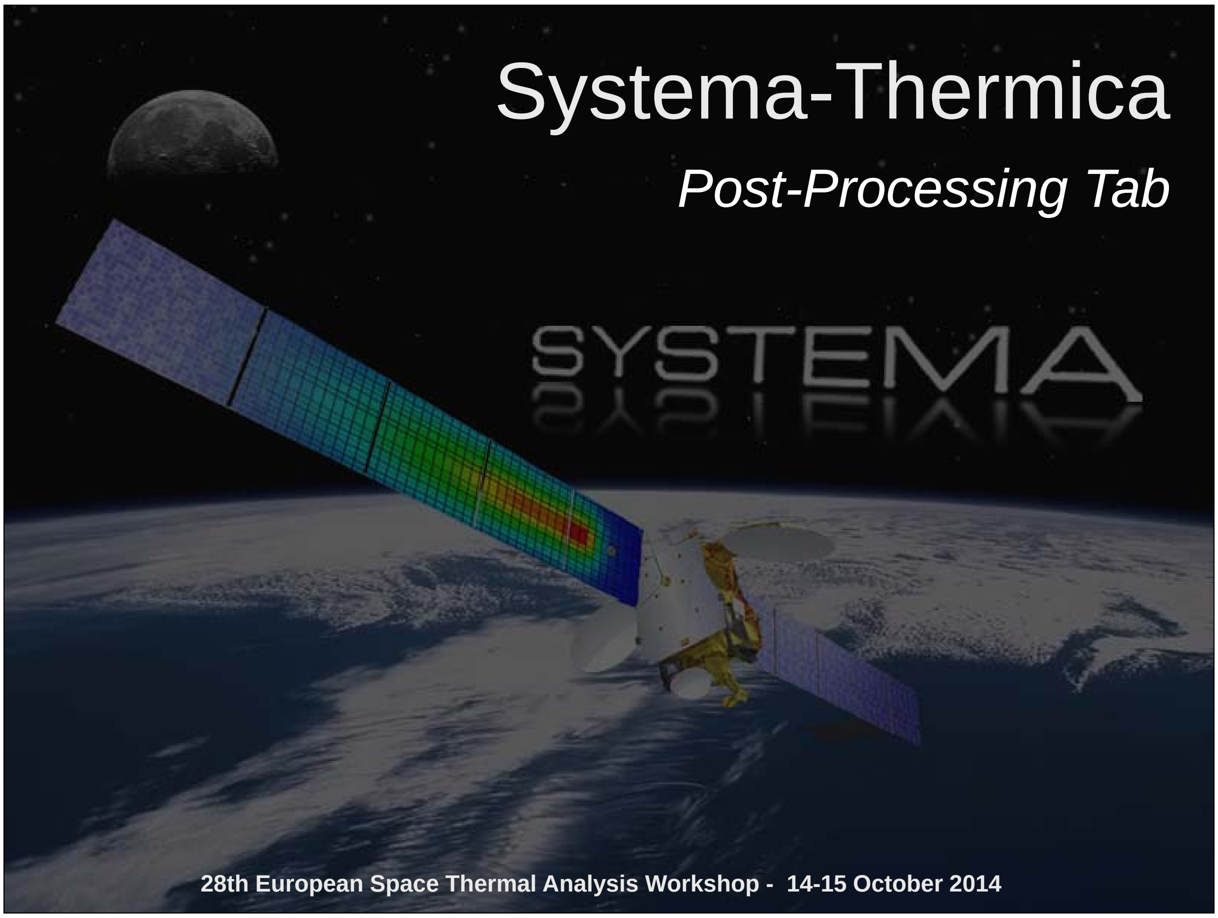
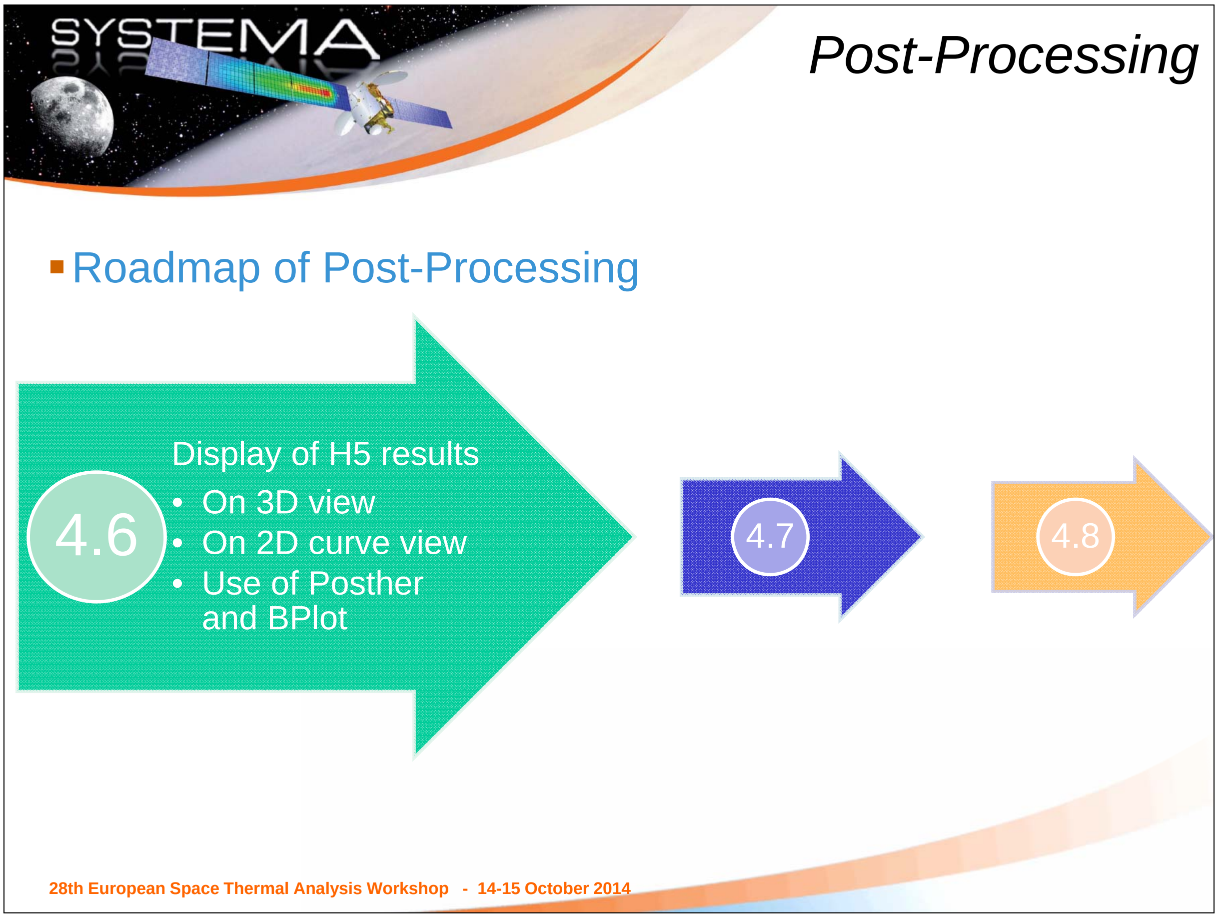

Systema-Thermica
Post-Processing Tab
SYSTEMA
28th European Space Thermal Analysis Workshop - 14-15 October 2014


SYSTEMA
Post-Processing
Roadmap of Post-Processing
4.6
Display of H5 results
• On 3D view
• On 2D curve view
• Use of Posther and BPlot
4.7
4.8
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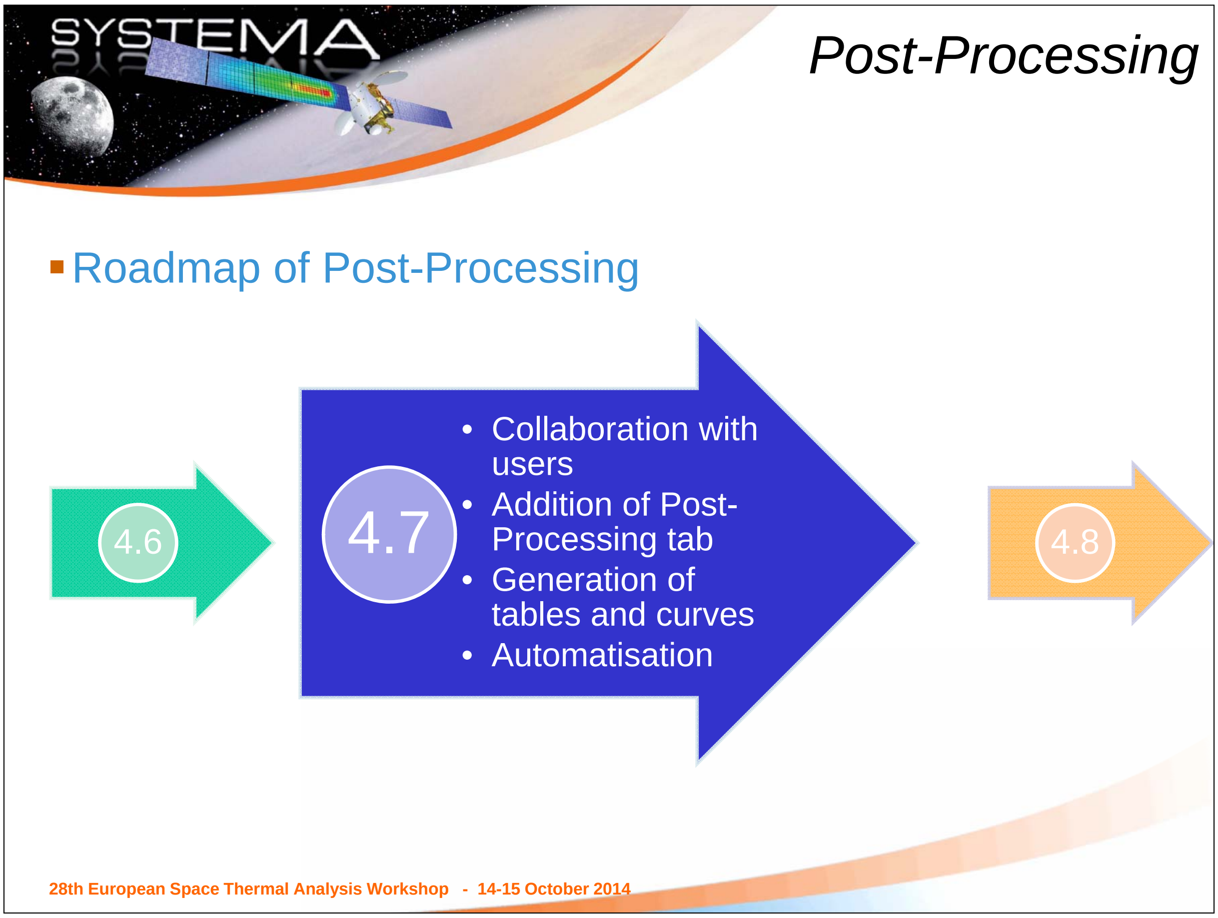
SYSTEMA
Post-Processing
Roadmap of Post-Processing
4.6
4.7
• Collaboration with users
• Addition of Post-Processing tab
• Generation of tables and curves
• Automatisation
4.8
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SYSTEMA

Post-Processing

- Roadmap of Post-Processing

4.6

4.7

4.8
- New toolboxes
  - Generation of 3D views
  - Generation of synthetic view
- Improvement on group management

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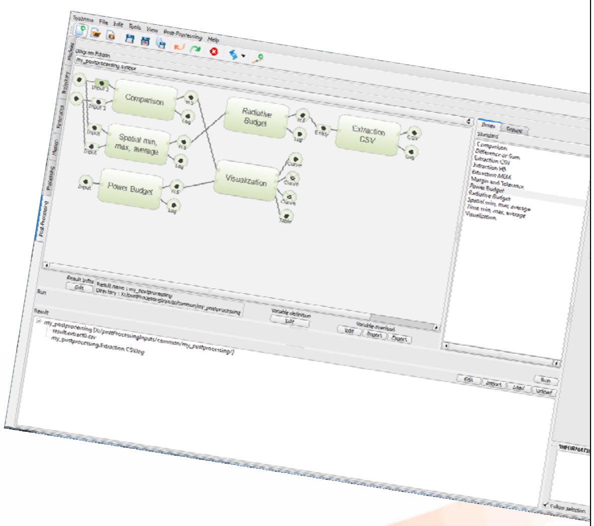
SYSTEMA

Post-Processing Tab

- New tab integrated in SYSTEMA
  - Diagram of Tool box
    - Drag&drop
    - Link
  - Group definition from node id
  - *Python API available*



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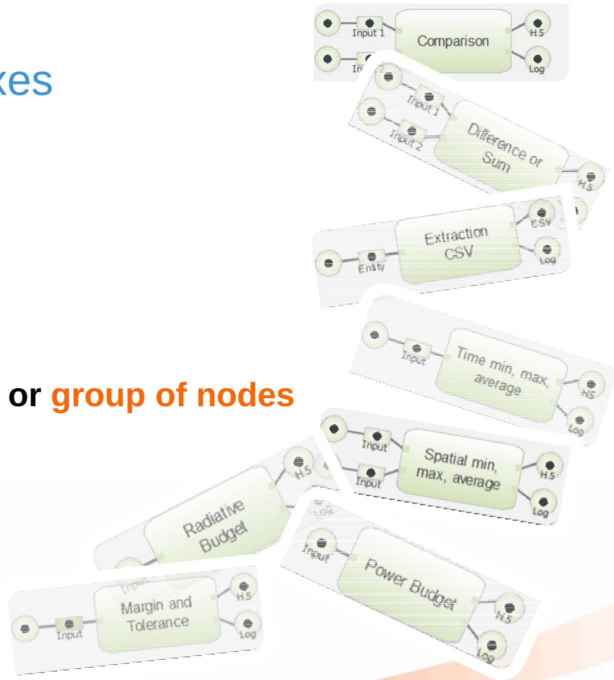
Post-Processing Tab

Post-Processing Tool boxes

- Input
  - H5 files
  - Entities from H5
- Filters
  - On a defined **node range or group of nodes**
  - On a defined time range



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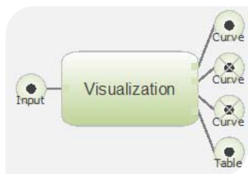
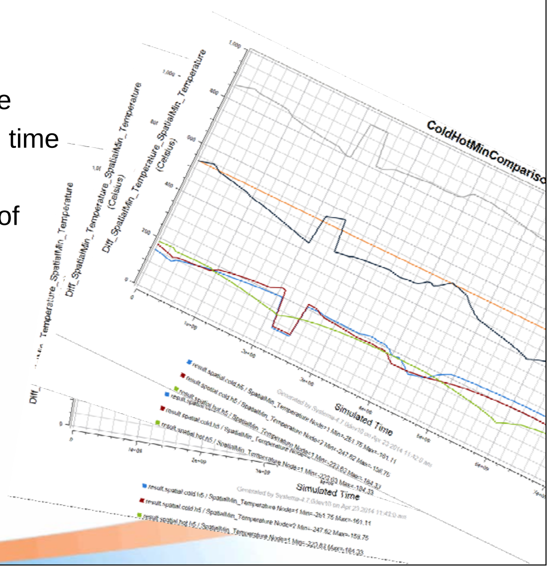
Post-Processing Tab

Post-Processing Tool boxes

- Visualization box
  - Generation of Tables and Curves
    - Result by nodes according to the time
    - Result for each nodes at one defined time
  - "Set of graph" option: Automatic generation of graphs from values defined in a file
  - Import/export from the 2D Curve View





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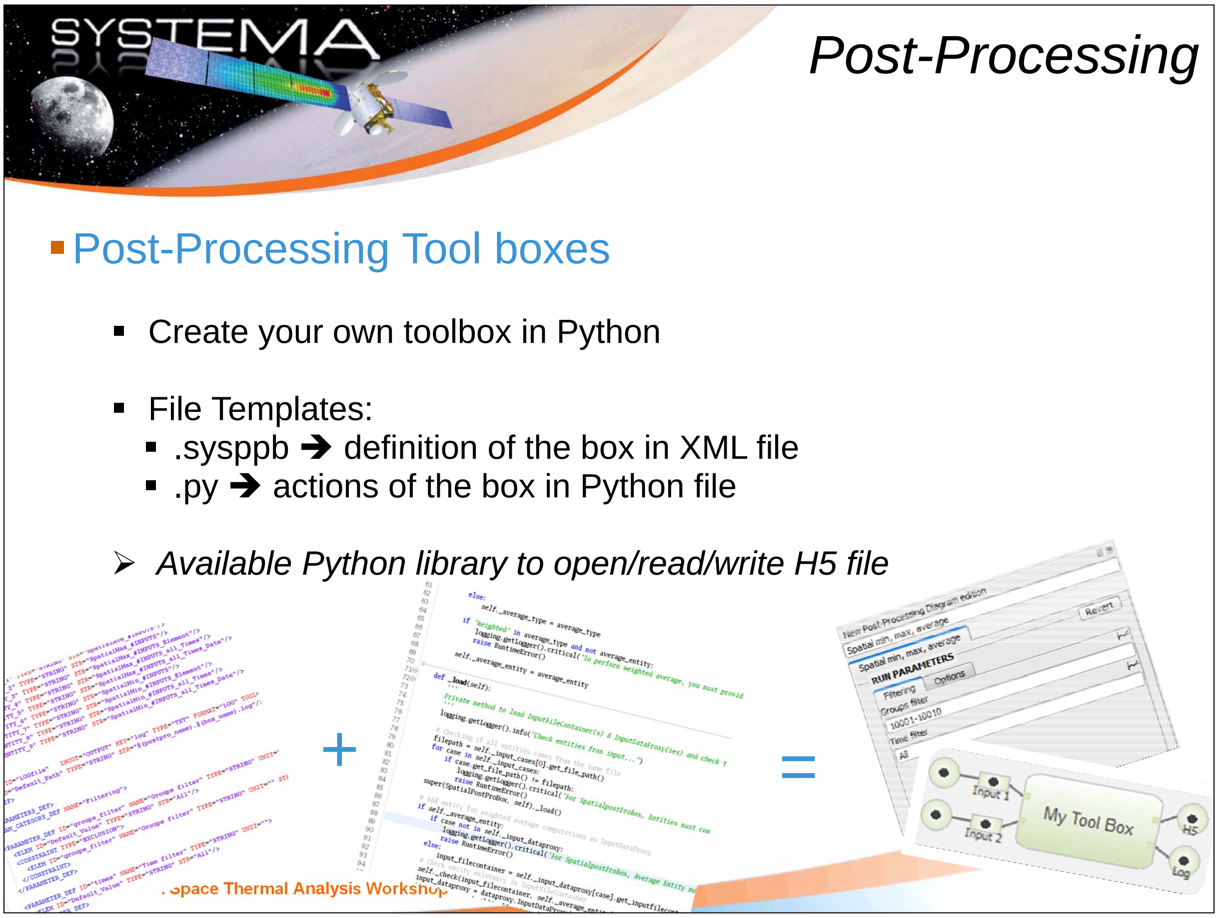
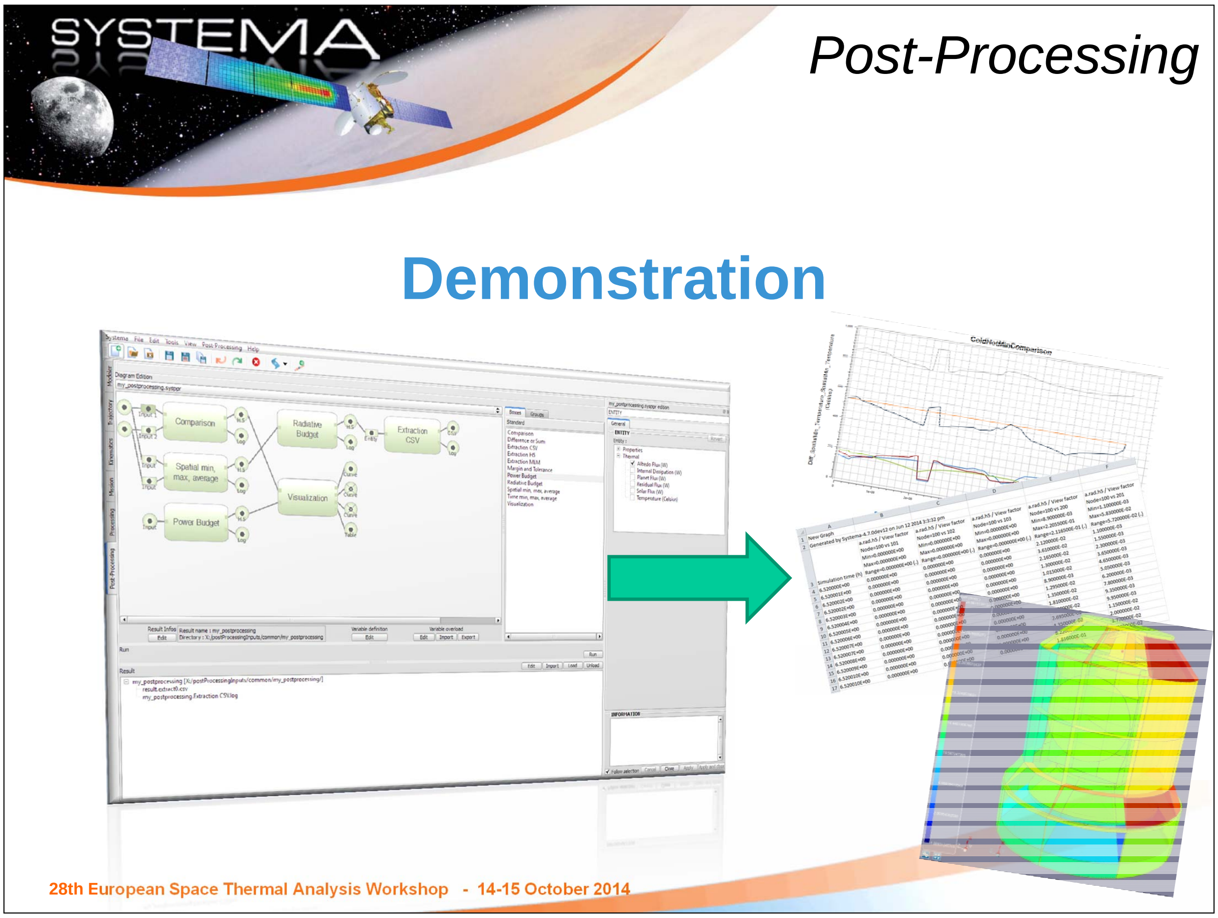

SYSTEMA
Post-Processing
Post-Processing Tool boxes
Create your own toolbox in Python
File Templates:
.sysppb ➔ definition of the box in XML file
.py ➔ actions of the box in Python file
Available Python library to open/read/write H5 file
+
=
My Tool Box
Input 1
Input 2
Spatial min, max, average
RUN PARAMETERS
Filtering
Options
Groups filter
Time filter
Revert
. Space Thermal Analysis Workshop


SYSTEMA
Post-Processing
Demonstration
Comparison
Radiative Budget
Extraction CSV
Spatial min, max, average
Visualization
Power Budget
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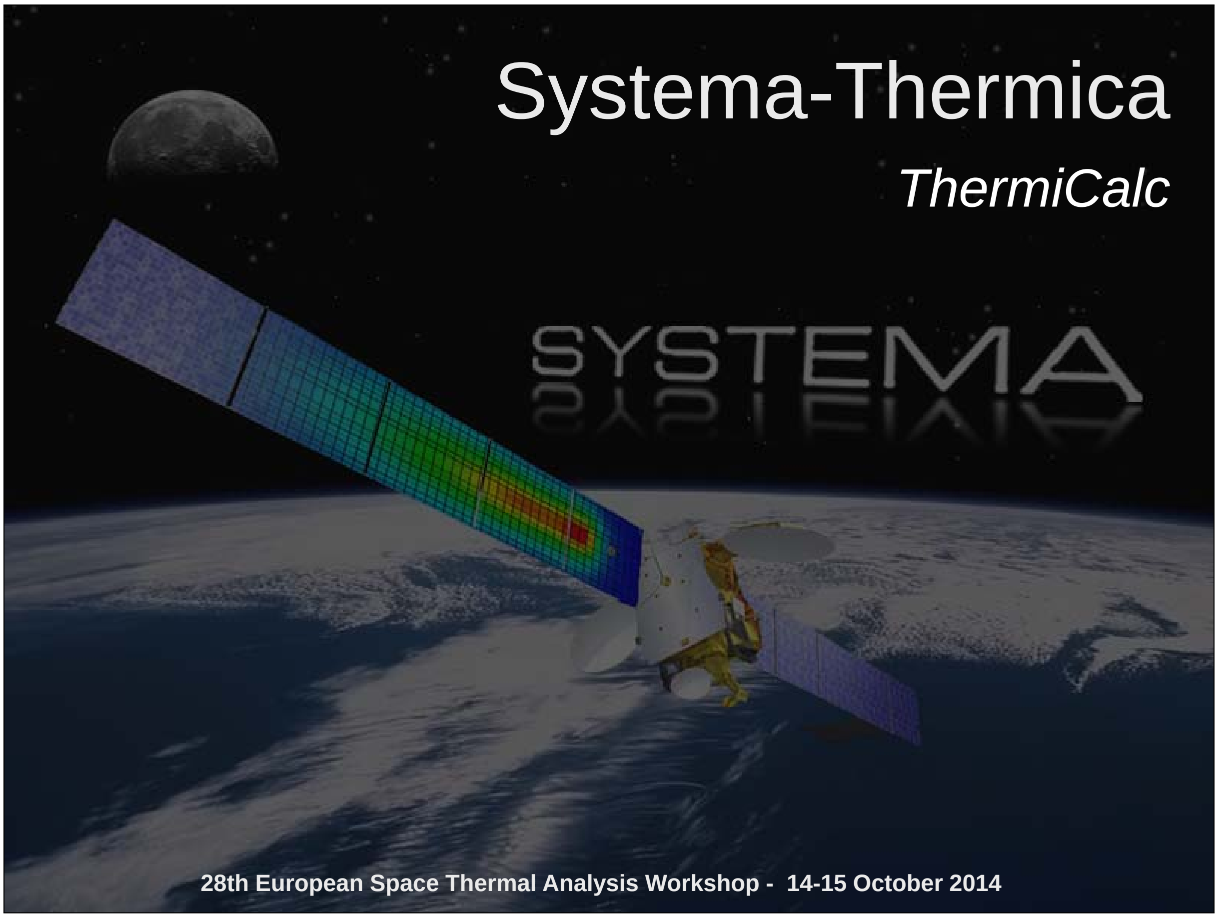
Systema-Thermica
ThermiCalc
SYSTEMA
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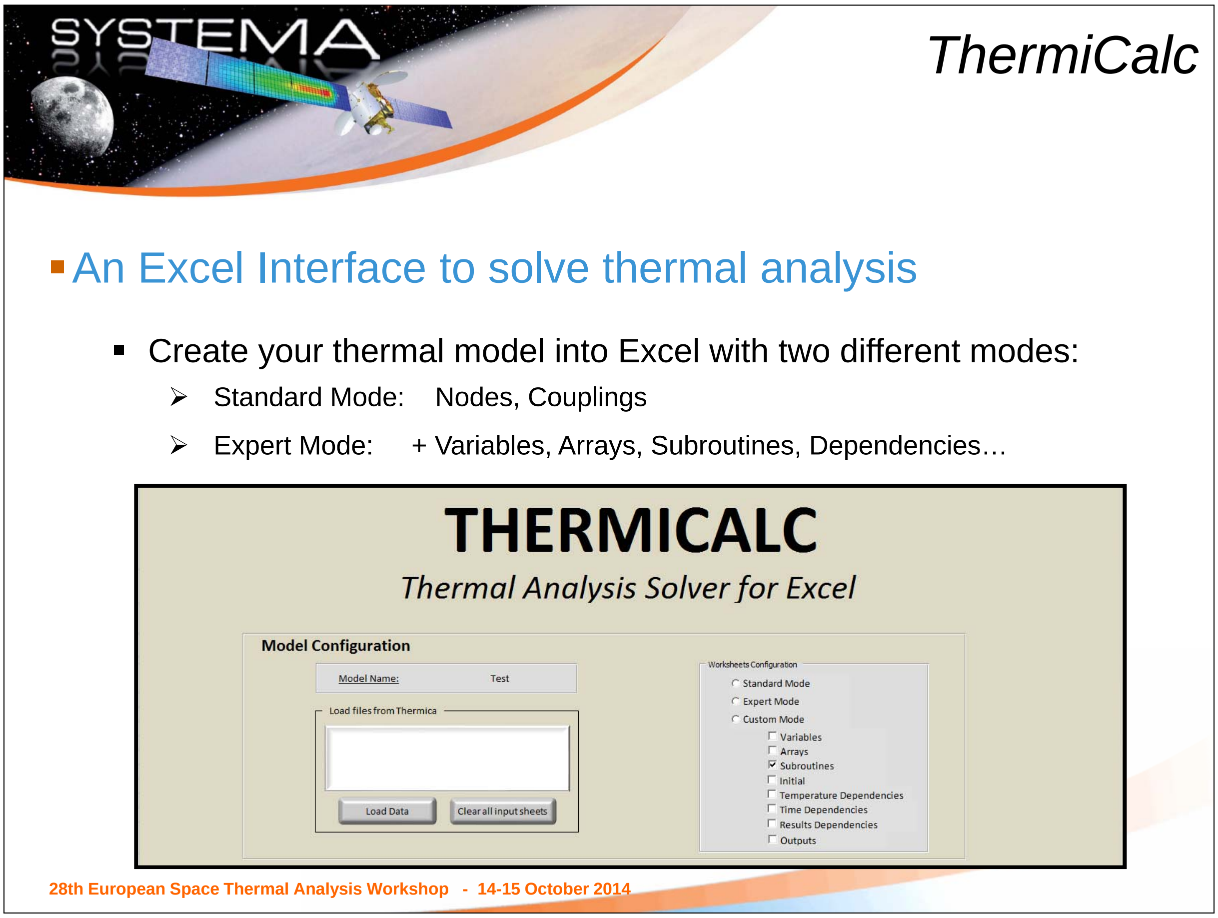
SYSTEMA
ThermiCalc
An Excel Interface to solve thermal analysis
Create your thermal model into Excel with two different modes:
Standard Mode: Nodes, Couplings
Expert Mode: + Variables, Arrays, Subroutines, Dependencies…
THERMICALC
Thermal Analysis Solver for Excel
Model Configuration
Model Name: Test
Load files from Thermica
Load Data
Clear all input sheets
Worksheets Configuration
Standard Mode
Expert Mode
Custom Mode
Variables
Arrays
Subroutines
Initial
Temperature Dependencies
Time Dependencies
Results Dependencies
Outputs
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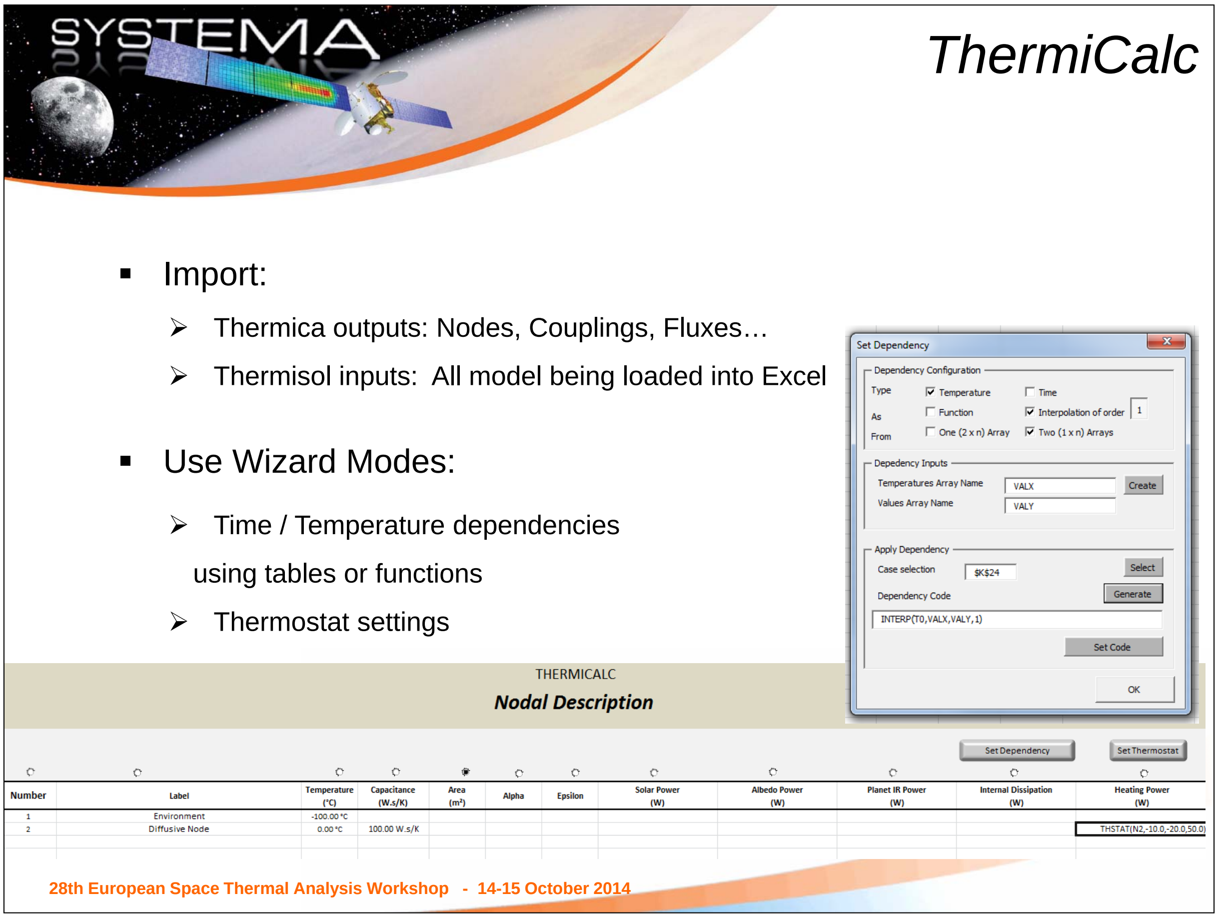
SYSTEMA
ThermiCalc
Import:
Thermica outputs: Nodes, Couplings, Fluxes…
Thermisol inputs: All model being loaded into Excel
Use Wizard Modes:
Time / Temperature dependencies
using tables or functions
Thermostat settings
Set Dependency
Dependency Configuration
Type
As
From
Temperature
Time
Function
Interpolation of order
One (2 x n) Array
Two (1 x n) Arrays
Depedency Inputs
Temperatures Array Name
Values Array Name
VALX
VALY
Create
Apply Dependency
Case selection
K24
Select
Dependency Code
Generate
INTERP(T0,VALX,VALY,1)
Set Code
OK
THERMICALC
Nodal Description
Set Dependency
Set Thermostat
Number
Label
Temperature (°C)
Capacitance (W.s/K)
Area (m²)
Alpha
Epsilon
Solar Power (W)
Albedo Power (W)
Planet IR Power (W)
Internal Dissipation (W)
Heating Power (W)
1
Environment
-100.00 °C
2
Diffusive Node
0.00 °C
100.00 W.s/K
THSTAT(N2,-10.0,-20.0,50.0)
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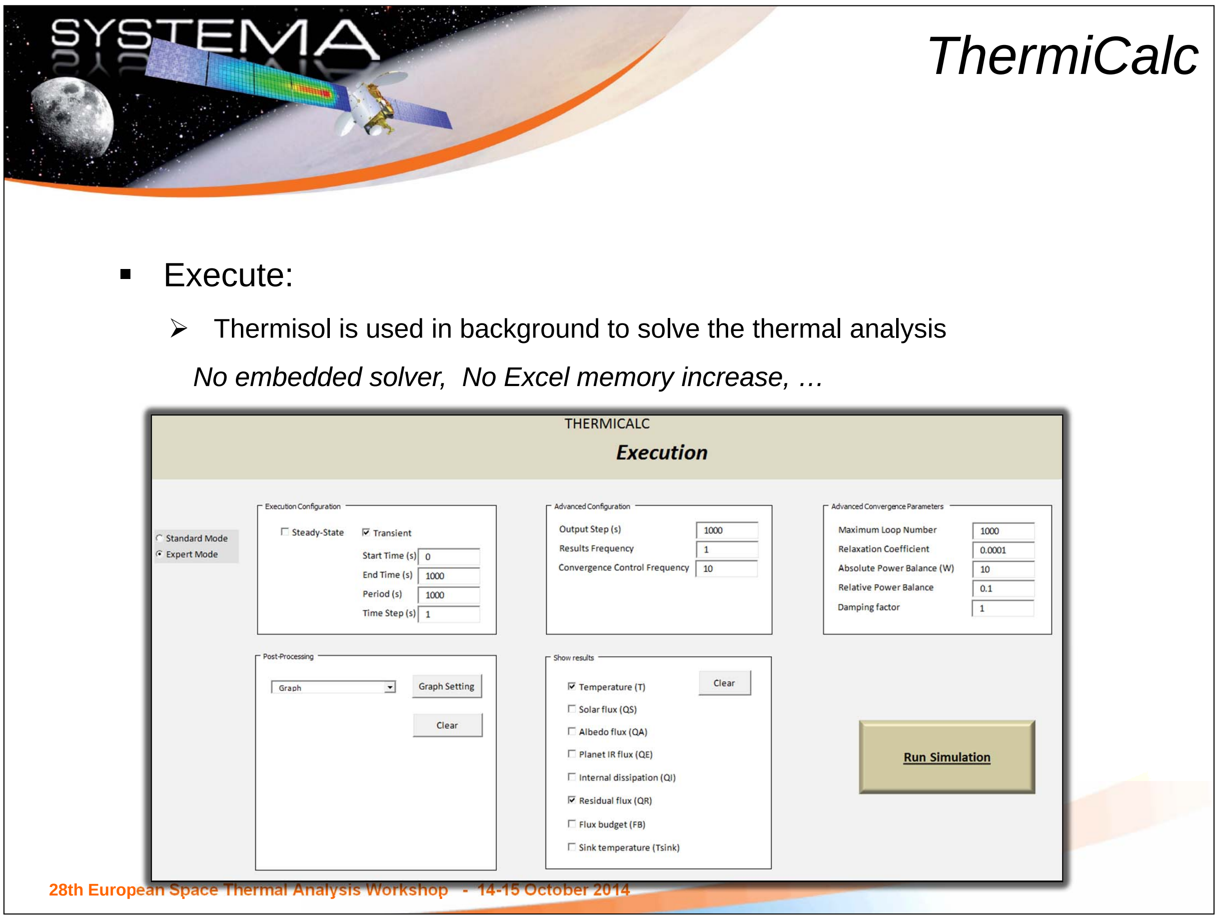
SYSTEMA
ThermiCalc
Execute:
Thermisol is used in background to solve the thermal analysis
No embedded solver, No Excel memory increase, …
THERMICALC
Execution
Standard Mode
Expert Mode
Execution Configuration
Steady-State
Transient
Start Time (s) 0
End Time (s) 1000
Period (s) 1000
Time Step (s) 1
Advanced Configuration
Output Step (s) 1000
Results Frequency 1
Convergence Control Frequency 10
Advanced Convergence Parameters
Maximum Loop Number 1000
Relaxation Coefficient 0.0001
Absolute Power Balance (W) 10
Relative Power Balance 0.1
Damping factor 1
Post-Processing
Graph
Graph Setting
Clear
Show results
Clear
Temperature (T)
Solar flux (QS)
Albedo flux (QA)
Planet IR flux (QE)
Internal dissipation (QI)
Residual flux (QR)
Flux budget (FB)
Sink temperature (Tsink)
Run Simulation
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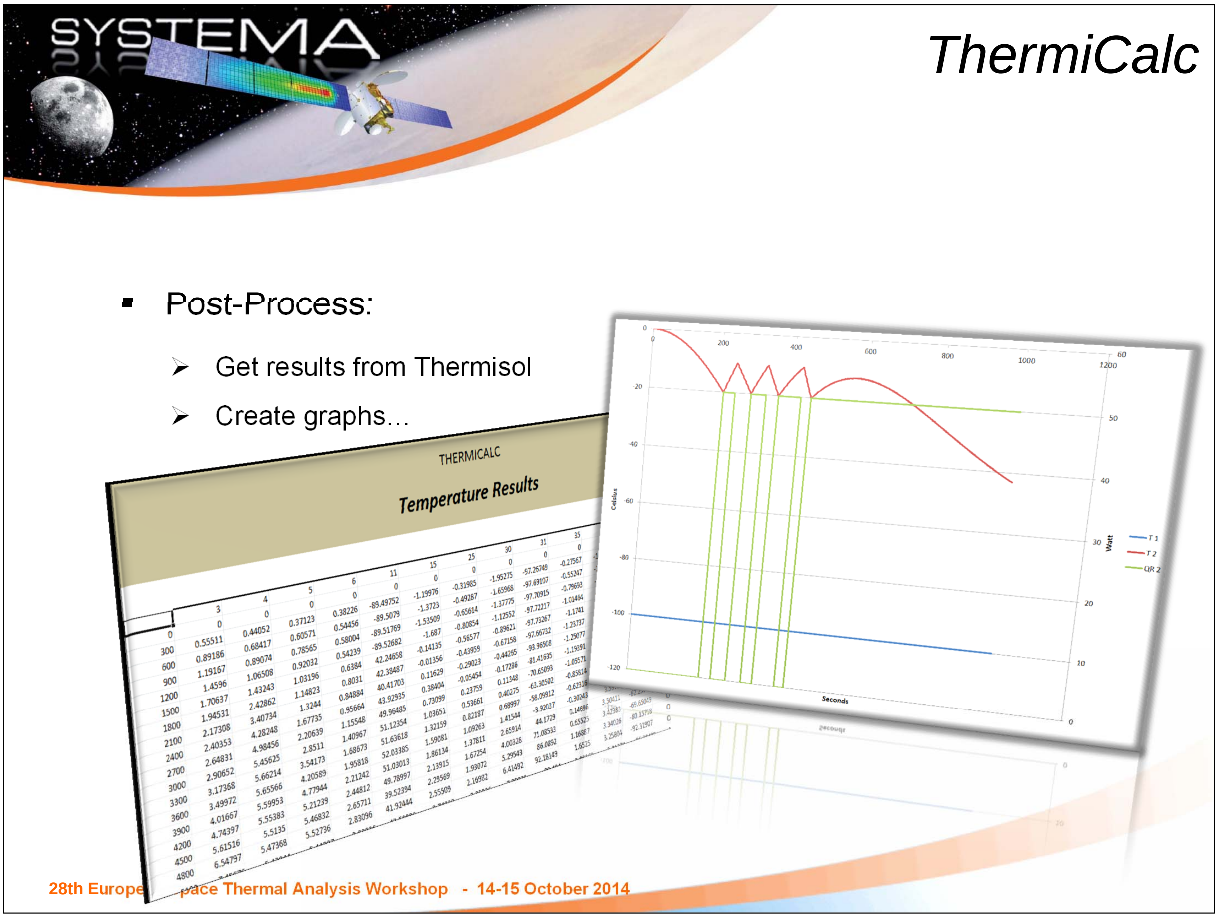
SYSTEMA
ThermiCalc
Post-Process:
Get results from Thermisol
Create graphs…
THERMICALC
Temperature Results
Celsius
Seconds
Watt
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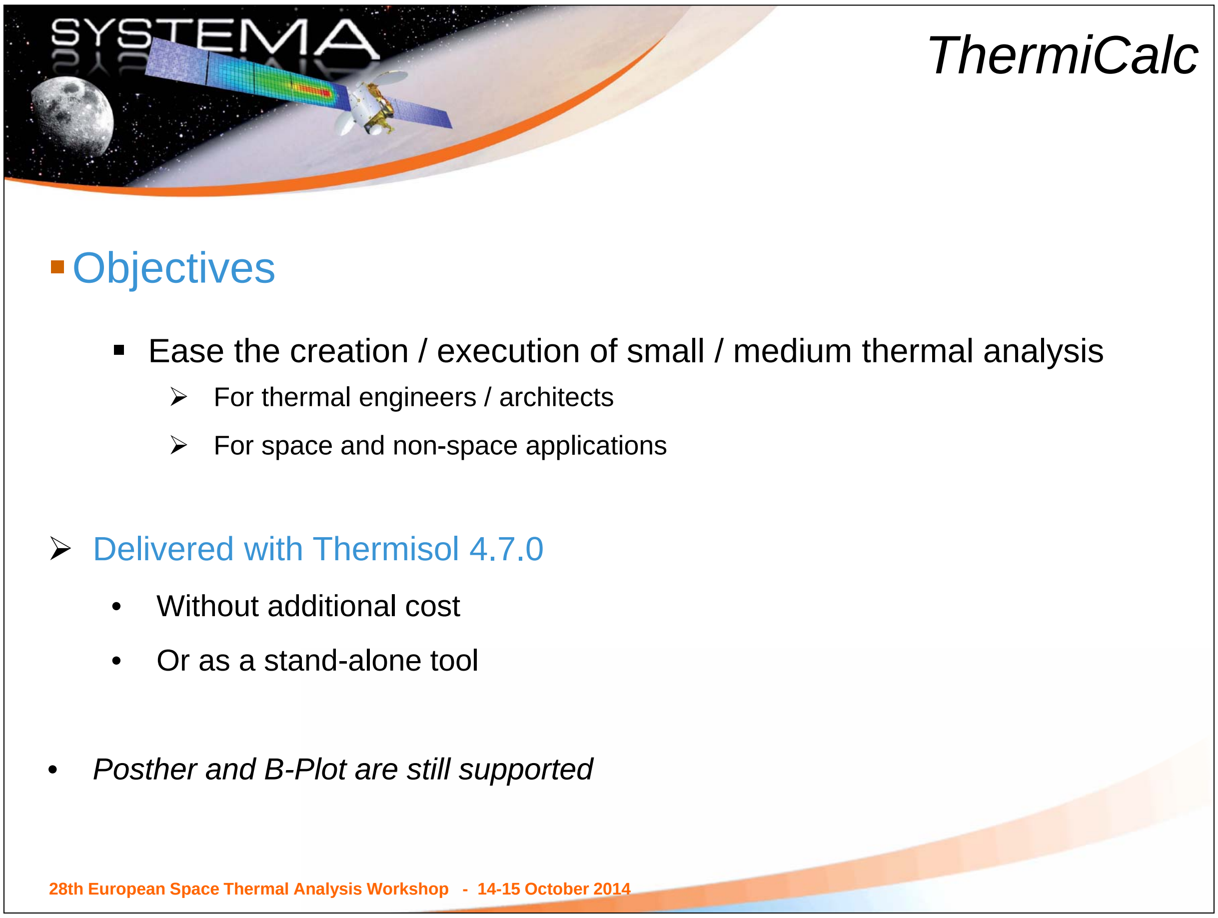
SYSTEMA
ThermiCalc
Objectives
Ease the creation / execution of small / medium thermal analysis
For thermal engineers / architects
For space and non-space applications
Delivered with Thermisol 4.7.0
Without additional cost
Or as a stand-alone tool
Posther and B-Plot are still supported
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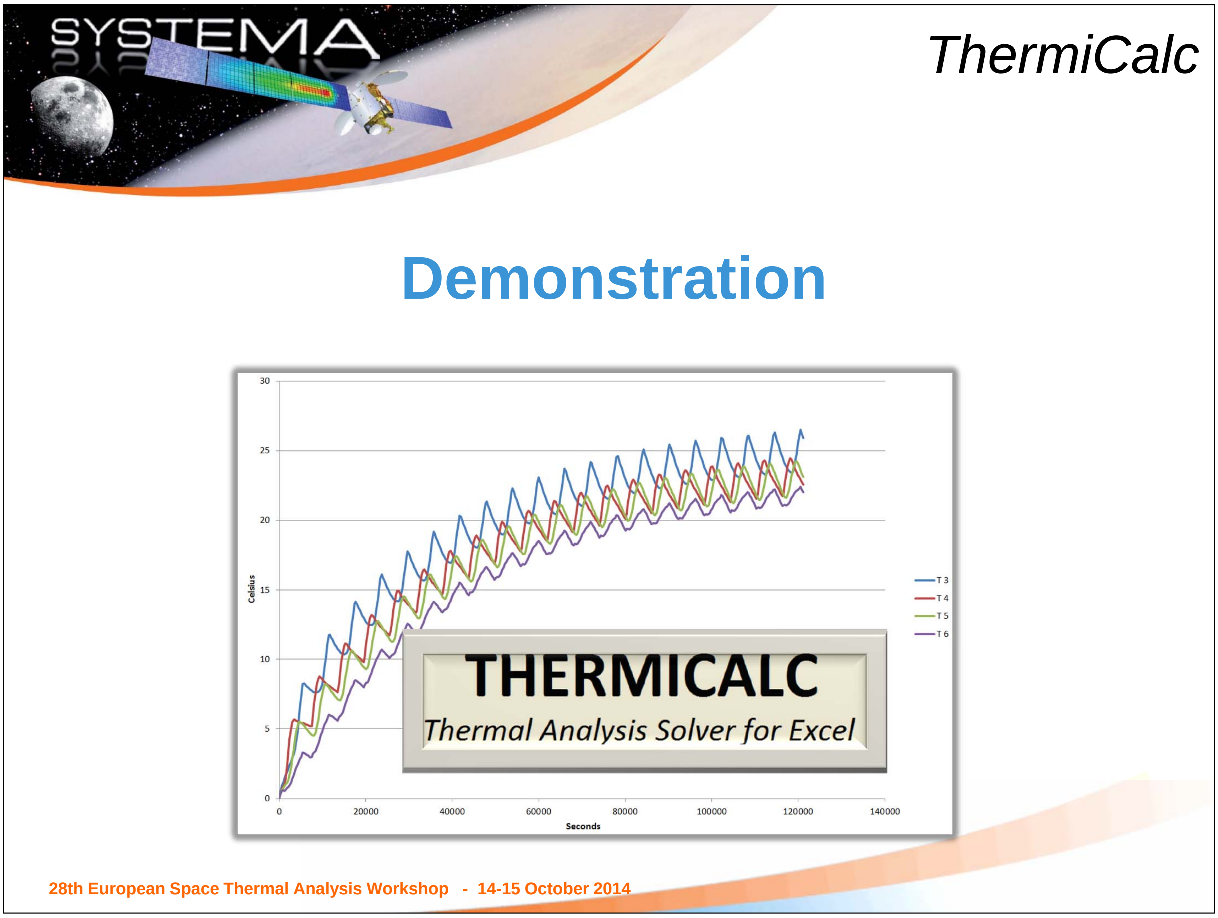
SYSTEMA
ThermiCalc
Demonstration
Celsius
Seconds
T 3
T 4
T 5
T 6
THERMICALC
Thermal Analysis Solver for Excel
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SYSTEMA
SYSTEMA
THERMICA
THERMISOL
Visit our Web site :
www.systema.astrium.eads.net
Contact :
timothee.soriano@astrium.eads.net
rose.nerriere@astrium.eads.net
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News & Events
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Partners
Support
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MORE
ALL PRODUCTS
FOCUS PRODUCTS
Thermica
Dosrad
Plume
Outgassing
NEWS & EVENTS
SOFTWARE PRODUCTS LINE FOR ENGINEERING
28th European Space Thermal Analysis Workshop - 14-15 October 2014

Appendix S

ESATAN Thermal Modelling Suite
Product Developments and Demonstration

Chris Kirtley Nicolas Bures
(ITP Engines UK Ltd, United Kingdom)

Abstract

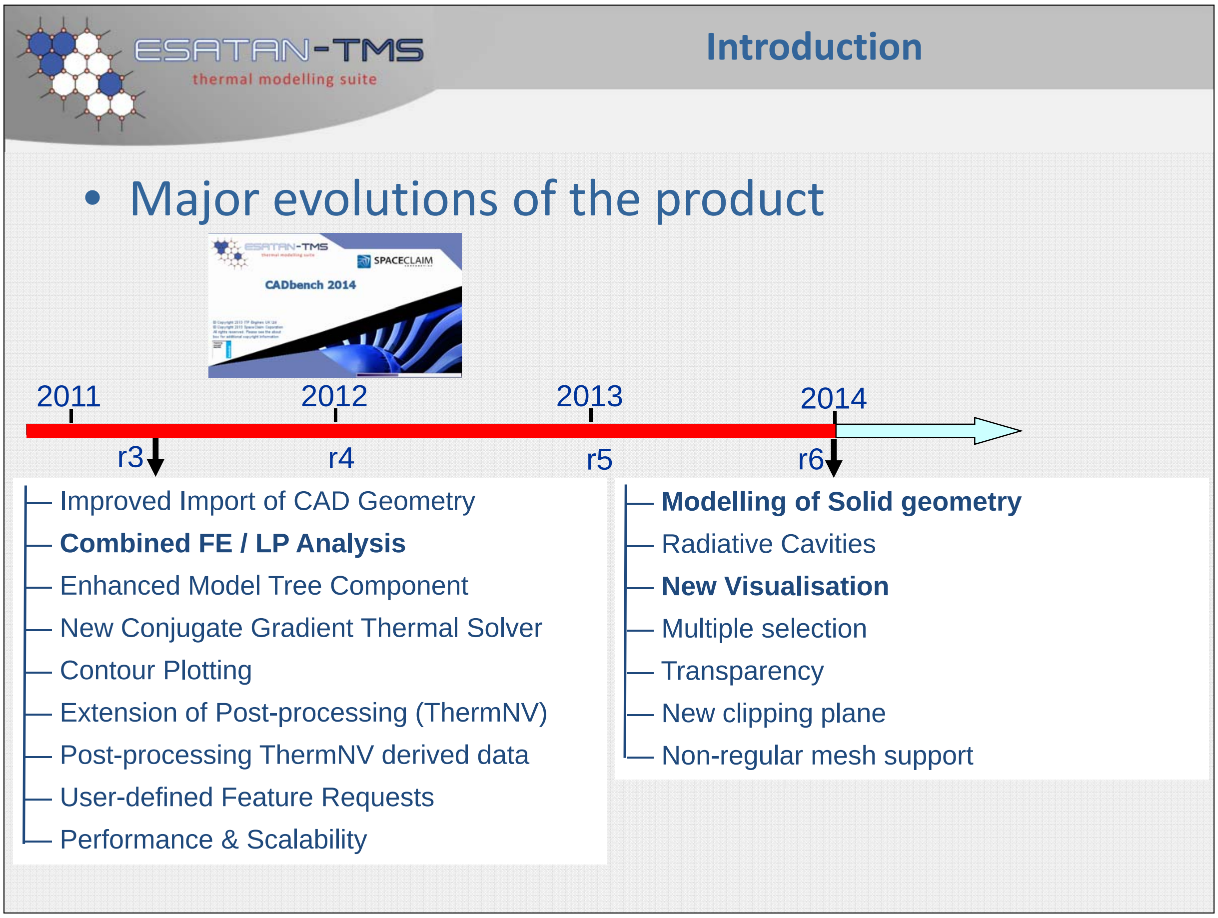
Product Developments

ESATAN-TMS provides the Engineer with a complete and powerful integrated thermal modelling environment. Version r6 was released at the end of last year and saw a significant evolution in its modelling capability. 3D solid geometry can now be modelled, performing ray-tracing on solid surfaces and allowing selection of either lumped parameter or finite element thermal analysis on the solid structure. With ESATAN-TMS r7 the focus of work of this release has been on a number of areas, including a tighter integration between Workbench and ESATAN, improvements to the layout of the user interface and general improvements directly raised by our customers.
This presentation outlines the new features to be included in the next release of ESATAN-TMS.

Thermal Modelling Demonstration

A demonstration of the new features included in ESATAN-TMS r7 will be given, building a thermal model to demonstrate the new functionality.

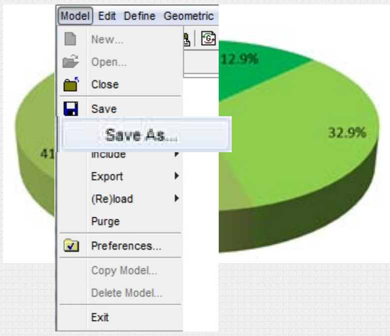

ESATAN-TMS
thermal modelling suite
ESATAN-TMS
Product Overview
Chris Kirtley
28th European Thermal & ECLS Software Workshop
ESA/Estec, Noordwijk, the Netherlands


ESATAN-TMS
thermal modelling suite
Introduction
• Major evolutions of the product
CADbench 2014
SPACECLAIM
2011
2012
2013
2014
r3
r4
r5
r6
Improved Import of CAD Geometry
Combined FE / LP Analysis
Enhanced Model Tree Component
New Conjugate Gradient Thermal Solver
Contour Plotting
Extension of Post-processing (ThermNV)
Post-processing ThermNV derived data
User-defined Feature Requests
Performance & Scalability
Modelling of Solid geometry
Radiative Cavities
New Visualisation
Multiple selection
Transparency
New clipping plane
Non-regular mesh support

ESATAN-TMS thermal modelling suite

Introduction

- User survey performed at the end of 2013
  - Feedback on how we are doing
    - Product functionality
    - Quality of user support
    - **What's important to you**

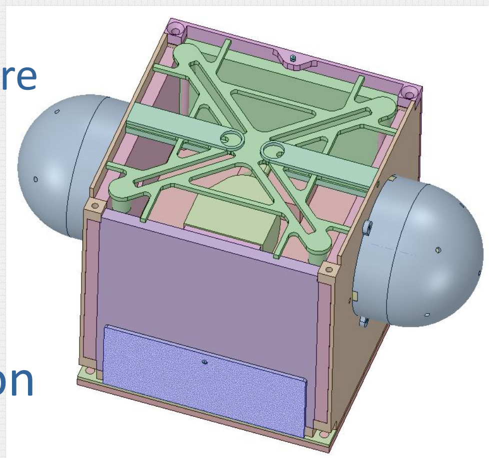


- Continued **major investment** on the product
- Focusing on points you raised
- Now finalising release for the end of the year

ESATAN-TMS thermal modelling suite

Contents

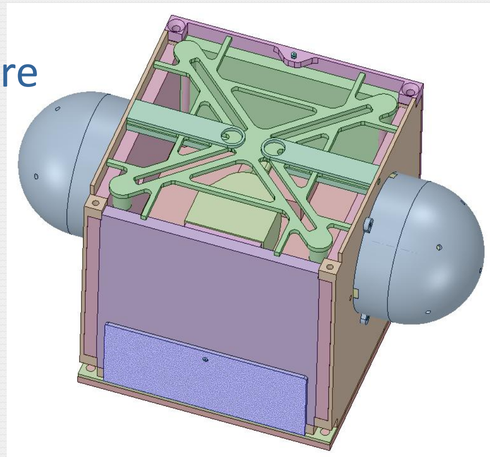
- Presentation of ESATAN-TMS development status
  - Model import from CAD
  - Further thermal integration
  - Improved user interface
  - Modelling time & temperature dependency
  - Model definition
  - Simplified user input



- Followed by a demonstration

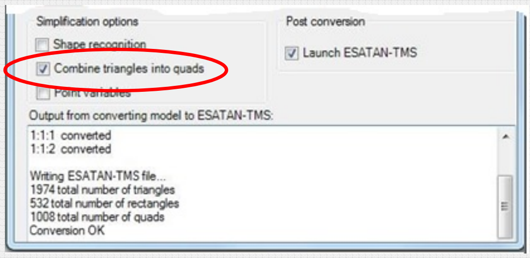
Contents

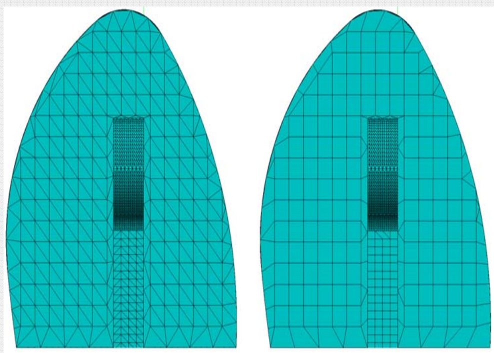
- Presentation of ESATAN-TMS development status
  - **Model import from CAD**
  - Further thermal integration
  - Improved user interface
  - Modelling time & temperature dependency
  - Model definition
  - Simplified user input



Model Import from CAD

- CADbench 2014 development
  - User feedback on conversion of CAD models
  - Handle more cases recognising primitives
  - Option to merge triangular element into quads
    - Merge triangles which are planar within a tolerance





ESATAN-TMS thermal modelling suite

Model Import from CAD

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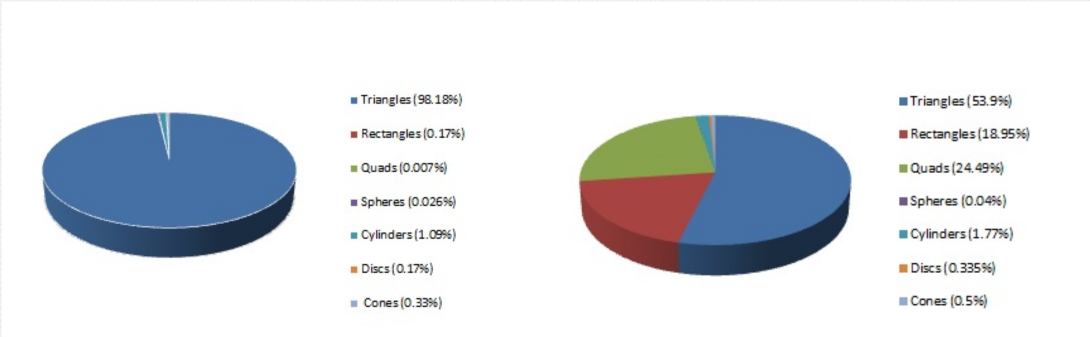
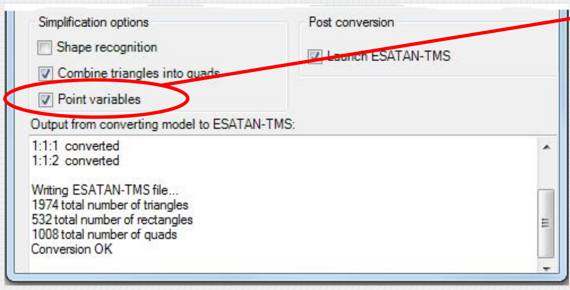
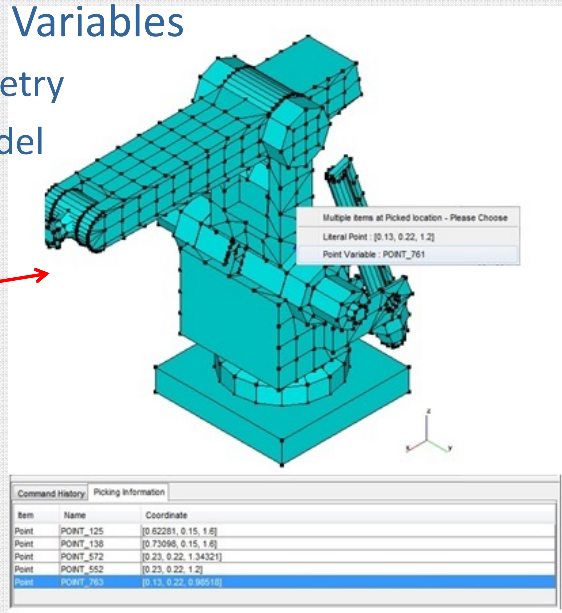


ESATAN-TMS thermal modelling suite

Model Import from CAD

- CADbench 2014 development
  - Option to generate Point Variables
    - Dynamic binding of geometry
    - Literal points reduces model complexity

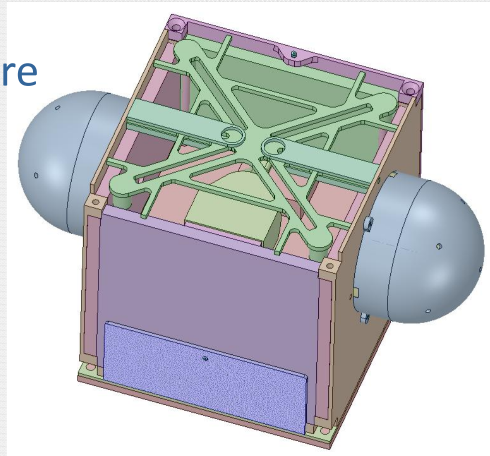




ESATAN-TMS thermal modelling suite

Contents

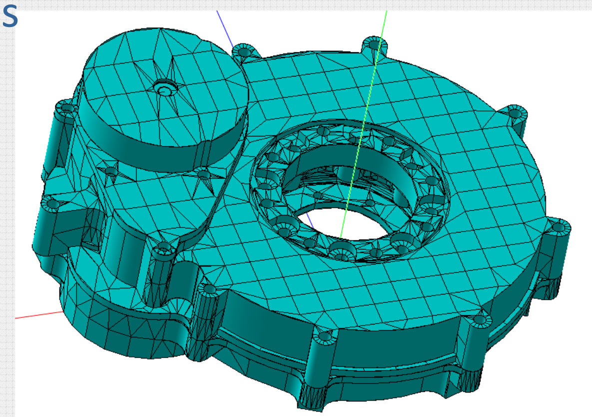
- Presentation of ESATAN-TMS development status
  - Model import from CAD
  - **Further thermal integration**
  - Improved user interface
  - Modelling time & temperature dependency
  - Model definition
  - Simplified user input



ESATAN-TMS thermal modelling suite

Thermal Integration

- Vision of an **fully integrated thermal modelling environment**
  - High-level thermal modelling through Workbench
  - Simplified interface, less error prone
  - Easier validation
  - More efficient
  - Availability of data
  - Consistency of data & concepts throughout



ESATAN-TMS thermal modelling suite

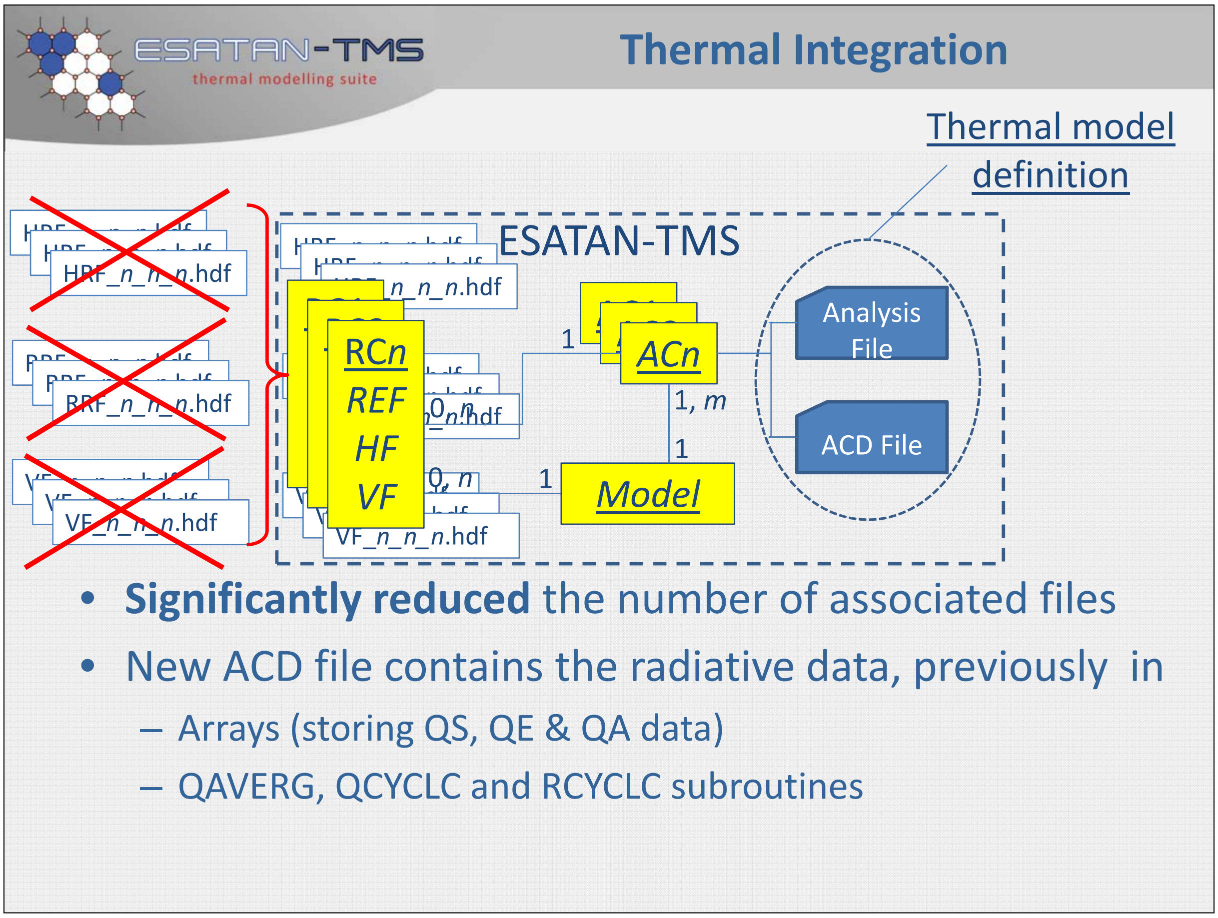
Thermal Integration

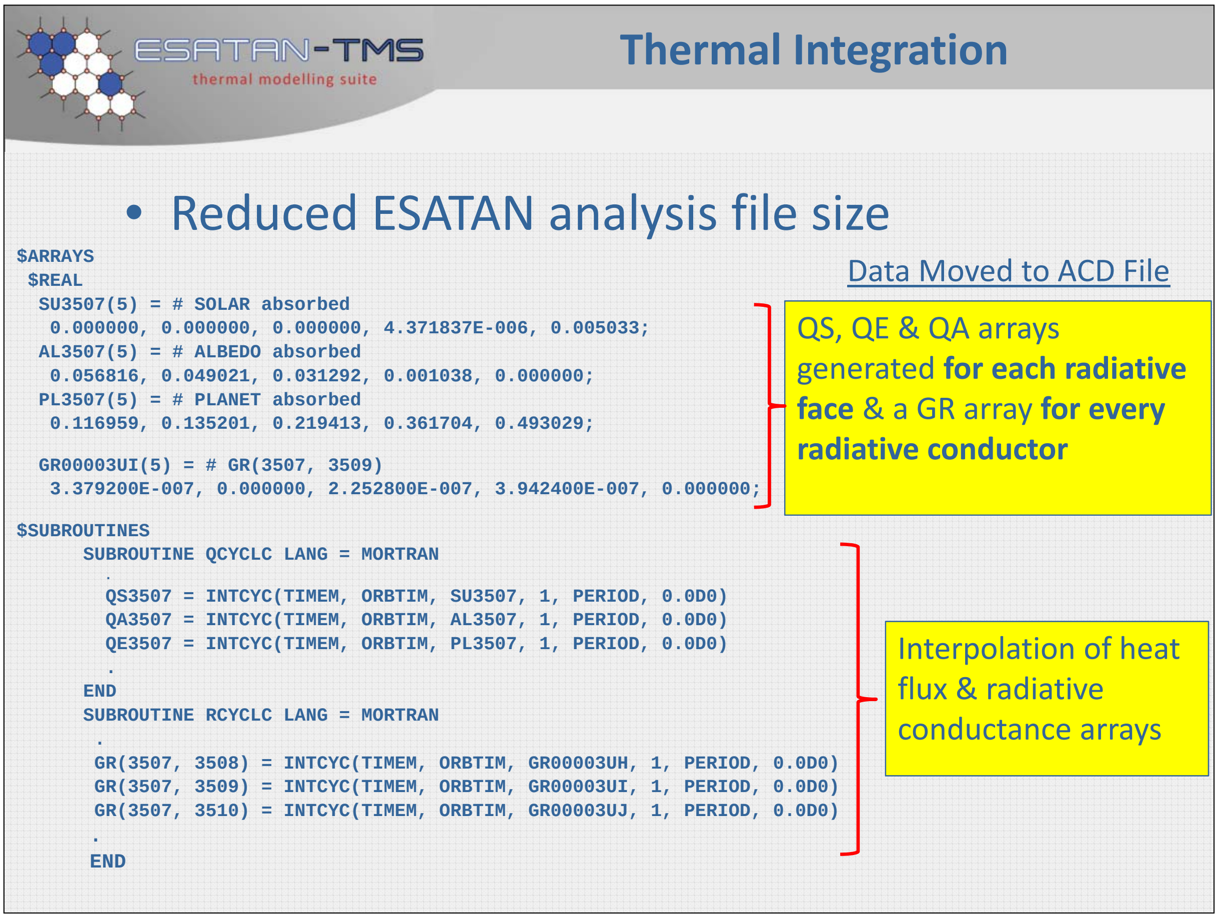
- Handling of Radiative Data (GRs & Qs)
  - Large number of generated radiative conductors
    - Data generated for each orbit position
    - Particularly models with moving geometry
  - Can lead to significant processing time
    - Data handling within Workbench
    - Exporting ESATAN analysis file
    - ESATAN Pre-process, compile, link & solve
  - In some cases file system or compiler limits reached

ESATAN-TMS thermal modelling suite

Thermal Integration

- In r7, redesigned storage of REF, VF, HF data
- Introduce **option** to write radiative data directly to a new ESATAN data file
  - Introduce **Analysis Case Definition (ACD) file**
  - ACD file goes hand-in-hand with ESATAN analysis file
  - Store radiative (GR & Q) data in ACD file
    - Node & conductor definitions retained in analysis file
  - ACD file uses HDF5 format
    - Platform independent binary file
    - Efficient structure & format


ESATAN-TMS
thermal modelling suite
Thermal Integration
Thermal model definition
HRF_n_n_n.hdf
RRF_n_n_n.hdf
VF_n_n_n.hdf
ESATAN-TMS
RCn
REF
HF
VF
ACn
Model
1
1, m
1
1
Analysis File
ACD File
• Significantly reduced the number of associated files
• New ACD file contains the radiative data, previously in
– Arrays (storing QS, QE & QA data)
– QAVERG, QCYCLC and RCYCLC subroutines


ESATAN-TMS
thermal modelling suite
Thermal Integration
• Reduced ESATAN analysis file size
Data Moved to ACD File
$ARRAYS
$REAL
SU3507(5) = # SOLAR absorbed
0.000000, 0.000000, 0.000000, 4.371837E-006, 0.005033;
AL3507(5) = # ALBEDO absorbed
0.056816, 0.049021, 0.031292, 0.001038, 0.000000;
PL3507(5) = # PLANET absorbed
0.116959, 0.135201, 0.219413, 0.361704, 0.493029;
GR00003UI(5) = # GR(3507, 3509)
3.379200E-007, 0.000000, 2.252800E-007, 3.942400E-007, 0.000000;
QS, QE & QA arrays generated for each radiative face & a GR array for every radiative conductor
$SUBROUTINES
SUBROUTINE QCYCLC LANG = MORTRAN
QS3507 = INTCYC(TIMEM, ORBTIM, SU3507, 1, PERIOD, 0.0D0)
QA3507 = INTCYC(TIMEM, ORBTIM, AL3507, 1, PERIOD, 0.0D0)
QE3507 = INTCYC(TIMEM, ORBTIM, PL3507, 1, PERIOD, 0.0D0)
END
SUBROUTINE RCYCLC LANG = MORTRAN
GR(3507, 3508) = INTCYC(TIMEM, ORBTIM, GR00003UH, 1, PERIOD, 0.0D0)
GR(3507, 3509) = INTCYC(TIMEM, ORBTIM, GR00003UI, 1, PERIOD, 0.0D0)
GR(3507, 3510) = INTCYC(TIMEM, ORBTIM, GR00003UJ, 1, PERIOD, 0.0D0)
END
Interpolation of heat flux & radiative conductance arrays

ESATAN-TMS thermal modelling suite

Thermal Integration

- ACD data is automatically read by the solution
  - Static heat flux read at the start of the analysis
  - Transient heat flux & conductance
    - Read in $VARIABLES1
    - Data only read into memory as required
    - Efficient interpolation of data
- Reminder, a full ESATAN analysis file can be generated if required

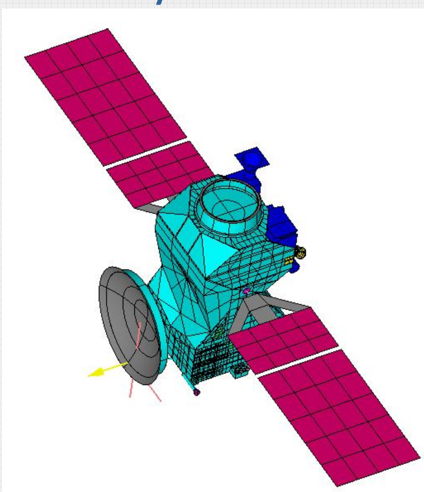
ESATAN-TMS thermal modelling suite

Thermal Integration

- Leads to **improved performance**, **reduced overall file size** & **reduction in memory**
- Example science model provided by OHB

Generated File Size (Mb)			
Data File	ESATAN-TMS		Δ (%)
	r6	r7	
Analysis File / ACD File	40	18	55%
MDB file	39	6	85%
Pre-processor log file	40	13	68%
Fortran file	15	6	60%
Model executable	18	5	72%
Total	**152**	**48**	**68%**

Performance (s)			
Process	ESATAN-TMS		Δ (%)
	r6	r7	
Pre-process	204	18	91%
Solution	133	67	50%
Total	**337**	**85**	**75%**



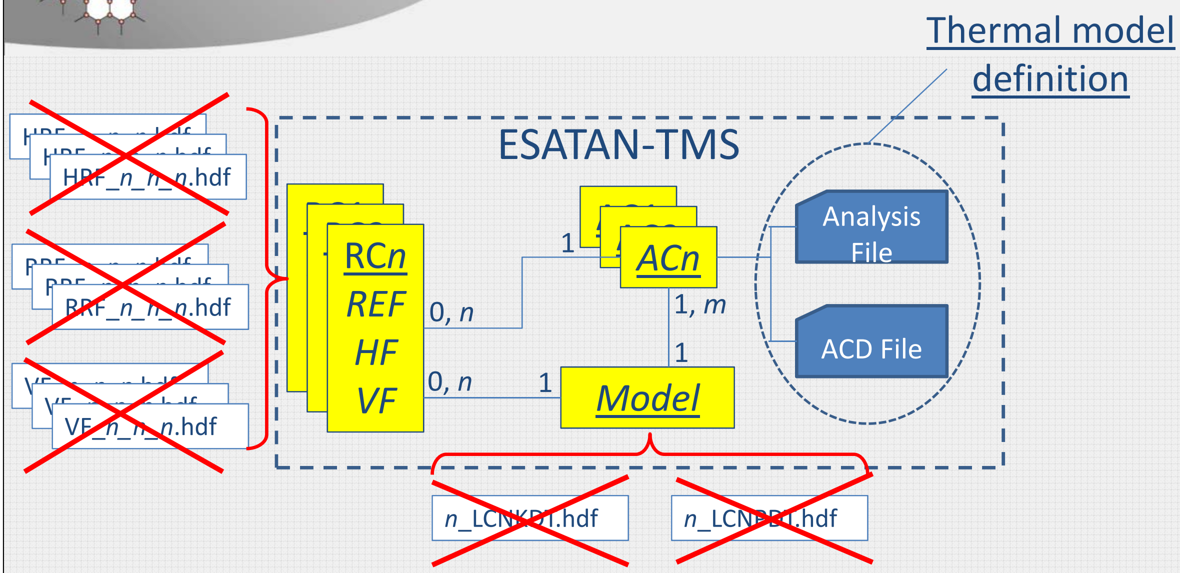
ESATAN-TMS thermal modelling suite

Thermal Integration

- In r7, handling of linear conductor data improved
  - Redesigned data storage within Workbench
  - Now store **all linear conductor data**
    - Previously stored only the LP conductors
    - Now store FE conductors and conductors generated from Contact Zones and User-Defined Conductors
  - Automatically calculate linear conductors on export to ESATAN, **only if they are out of date**

ESATAN-TMS thermal modelling suite

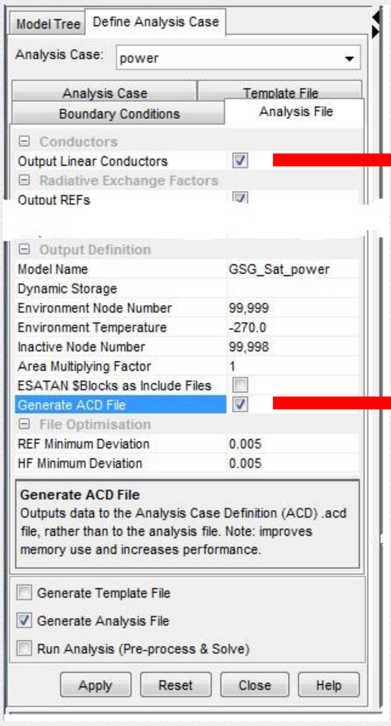
Thermal Integration



- Reduce the number of associated files
  - Linear conductors stored with the overall model data
- Now **store all conductor data**

ESATAN-TMS thermal modelling suite

Thermal Integration



Workbench GUI Changes

- Select to output **all linear conductors** (default)
- “Calculate Conductors” option removed
- **Option** to generate radiative data in Analysis Case Definition file (default)

ESATAN-TMS thermal modelling suite

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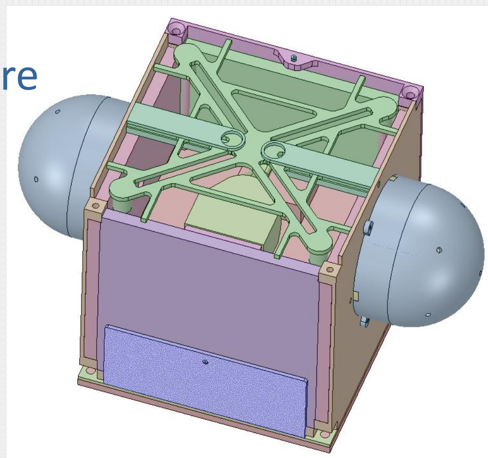
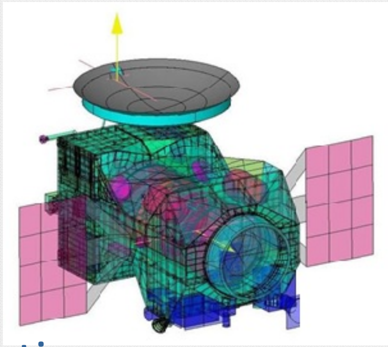


ESATAN-TMS thermal modelling suite

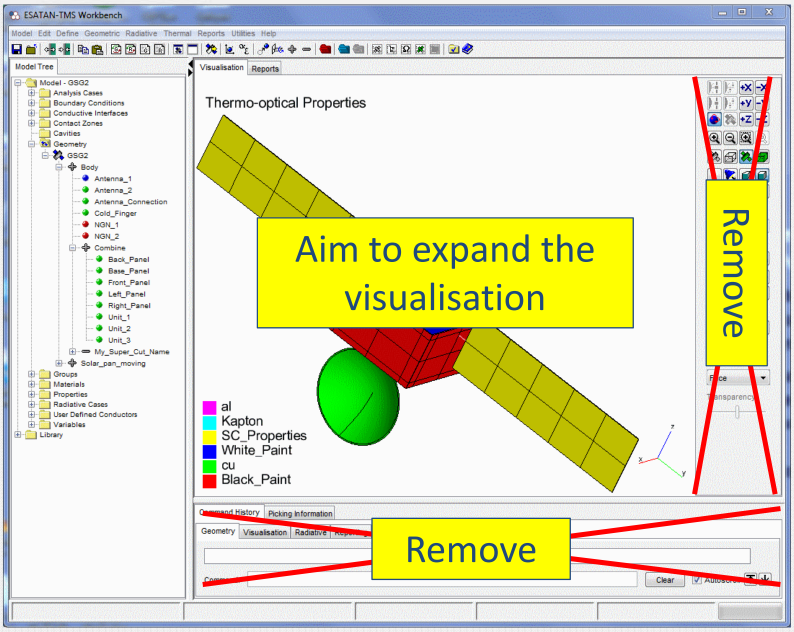
Improved User Interface

- ESATAN-TMS r6 saw a new visualisation
  - New visualisation technology
  - Take advantage of hardware
  - New functionality
    - Multiple selection, transparency & revised cutting plane
- Continue to build on this foundation
  - Improved user interface
  - More interactive model build
  - Pre- and post-processing of model data



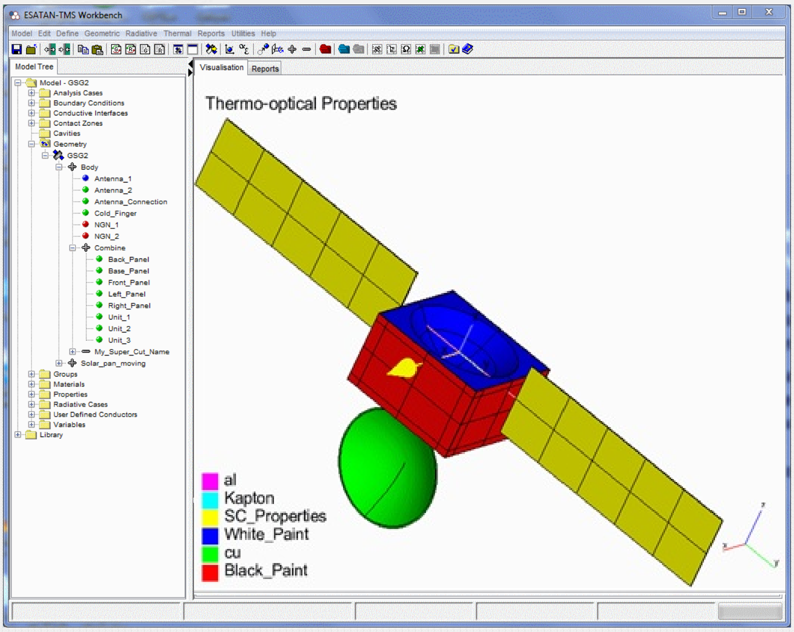
ESATAN-TMS thermal modelling suite

Improved User Interface



ESATAN-TMS thermal modelling suite

Improved User Interface

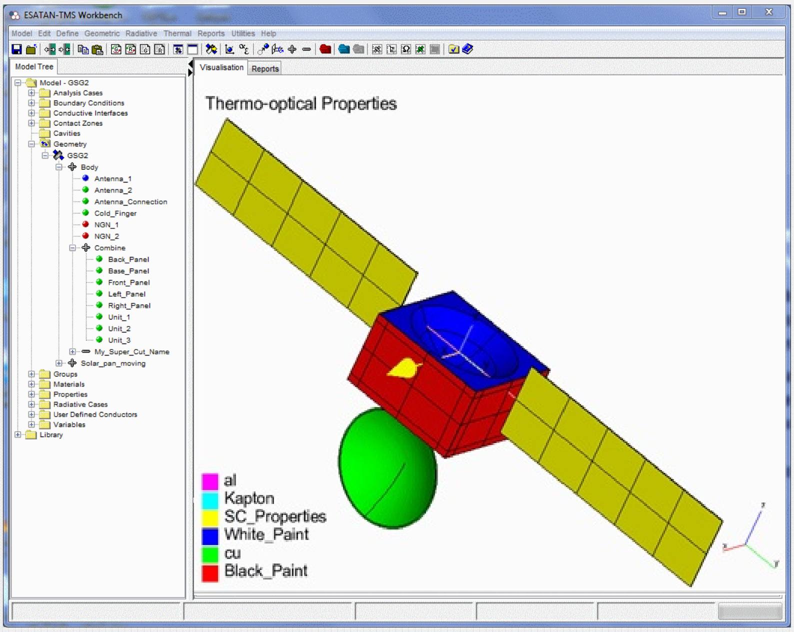


In r7 redesigned,

- Report Symbols
- Delete Environment
- Clipping Plane
- Include Model
- Custom Menu
- Report Case Results
- Process Conductor Interfaces
- Assembly
- Define Variables
- Cut / Combine
- Reporting Tab

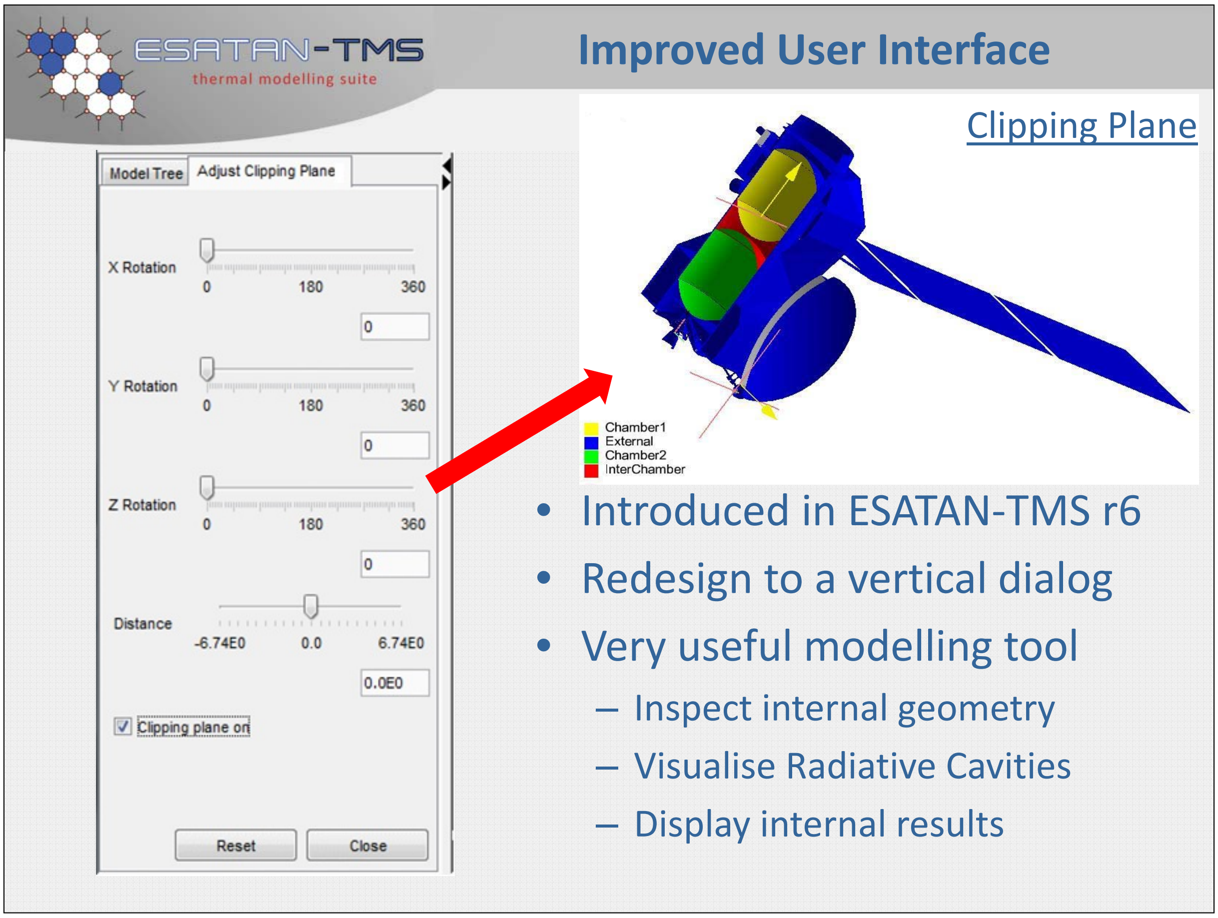
ESATAN-TMS thermal modelling suite

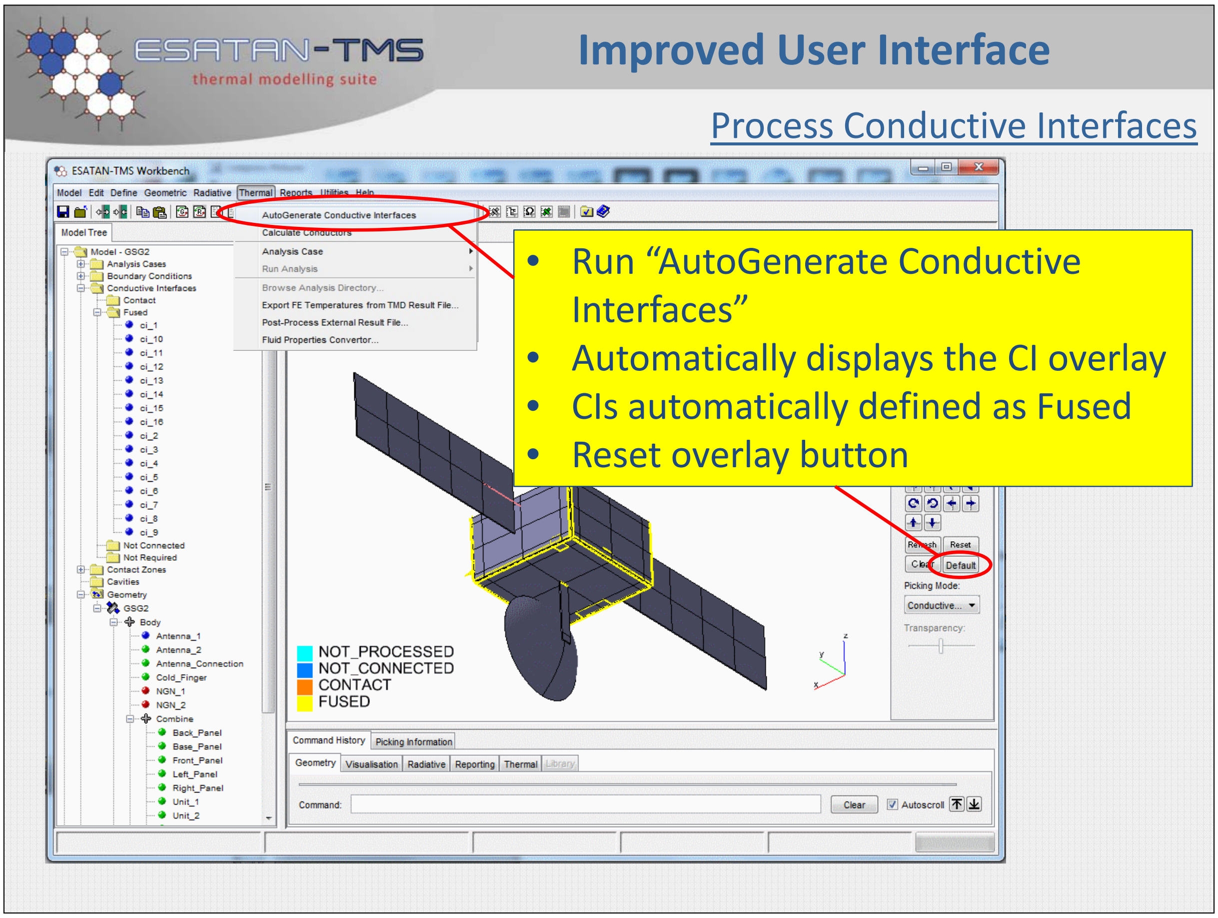
Improved User Interface

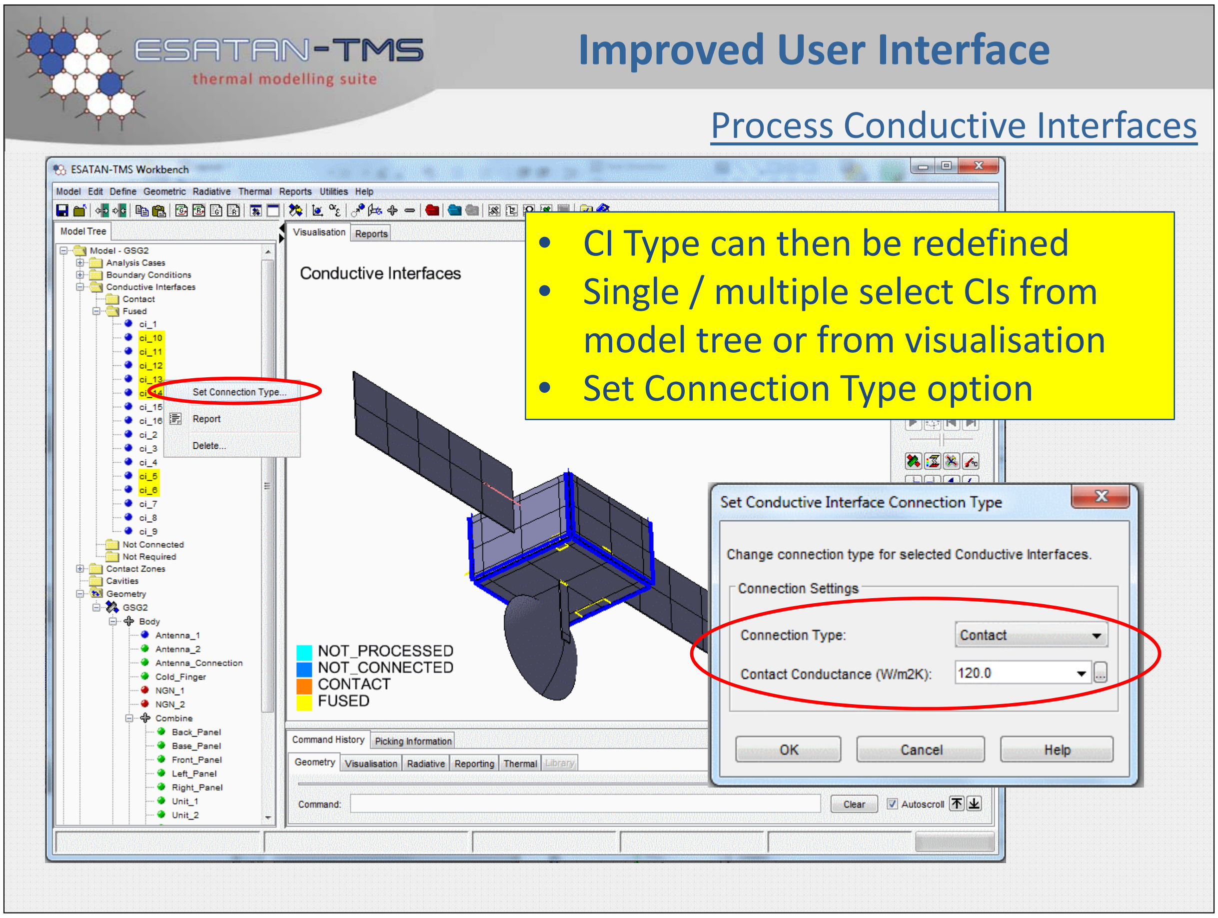


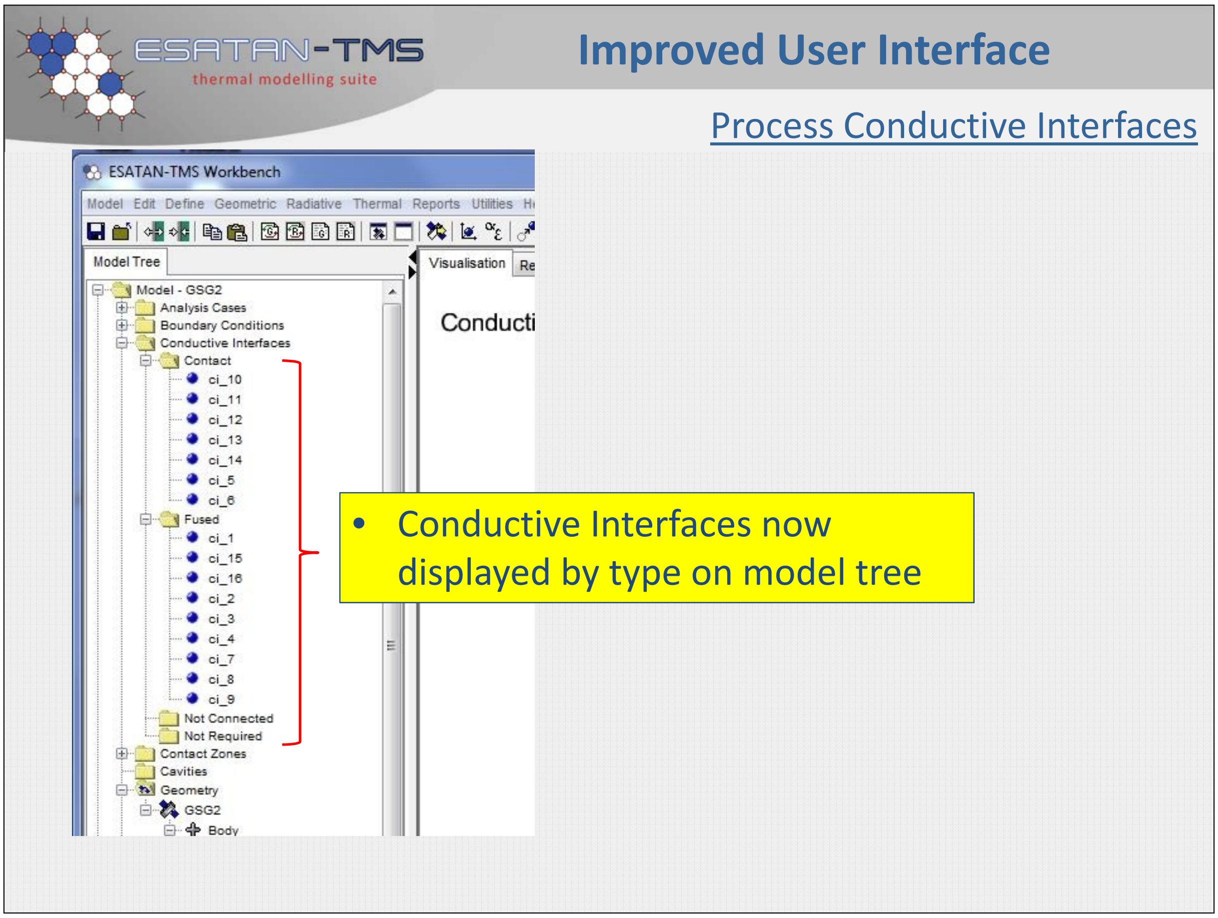
In r7 redesigned,

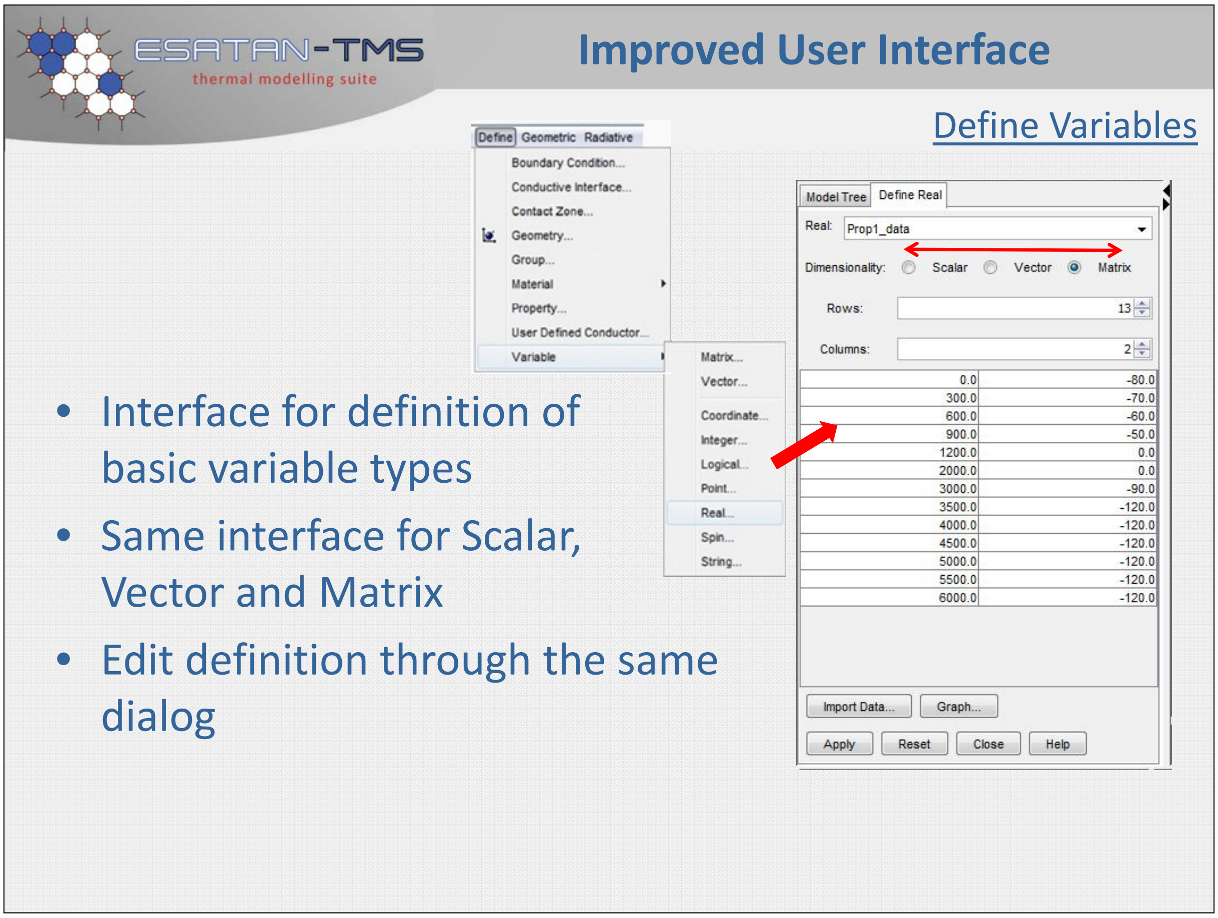
- Report Symbols
- Delete Environment
- **Clipping Plane**
- Include Model
- Custom Menu
- Report Case Results
- **Process Conductor Interfaces**
- Assembly
- **Define Variables**
- Cut / Combine
- **Reporting Tab**

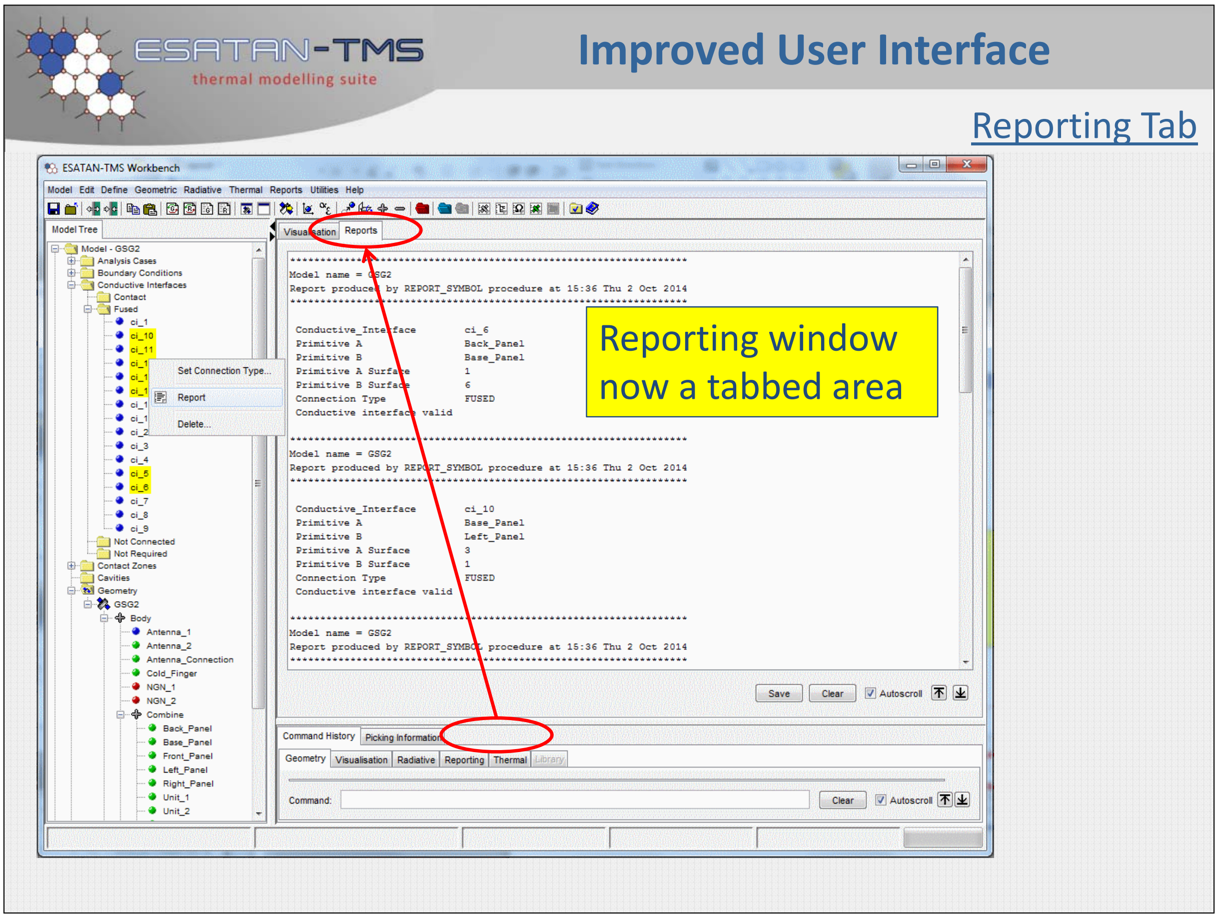

ESATAN-TMS
thermal modelling suite
Improved User Interface
Clipping Plane
Model Tree
Adjust Clipping Plane
X Rotation
0 180 360
Y Rotation
0 180 360
Z Rotation
0 180 360
Distance
-6.74E0 0.0 6.74E0
0.0E0
Clipping plane on
Reset
Close
Chamber1
External
Chamber2
InterChamber
• Introduced in ESATAN-TMS r6
• Redesign to a vertical dialog
• Very useful modelling tool
– Inspect internal geometry
– Visualise Radiative Cavities
– Display internal results


ESATAN-TMS
thermal modelling suite
Improved User Interface
Process Conductive Interfaces
ESATAN-TMS Workbench
AutoGenerate Conductive Interfaces
Calculate Conductors
Analysis Case
Run Analysis
Browse Analysis Directory...
Export FE Temperatures from TMD Result File...
Post-Process External Result File...
Fluid Properties Convertor...
• Run “AutoGenerate Conductive Interfaces”
• Automatically displays the CI overlay
• CIs automatically defined as Fused
• Reset overlay button
NOT_PROCESSED
NOT_CONNECTED
CONTACT
FUSED
Default
Reset
Picking Mode:
Transparency:
Command History
Picking Information
Geometry
Visualisation
Radiative
Reporting
Thermal
Command:
Clear
Autoscroll


ESATAN-TMS
thermal modelling suite
Improved User Interface
Process Conductive Interfaces
ESATAN-TMS Workbench
Model Edit Define Geometric Radiative Thermal Reports Utilities Help
Model Tree
Visualisation Reports
Conductive Interfaces
Set Connection Type...
Report
Delete...
NOT_PROCESSED
NOT_CONNECTED
CONTACT
FUSED
Command History Picking Information
Geometry Visualisation Radiative Reporting Thermal Library
Command:
Clear
Autoscroll
• CI Type can then be redefined
• Single / multiple select CIs from model tree or from visualisation
• Set Connection Type option
Set Conductive Interface Connection Type
Change connection type for selected Conductive Interfaces.
Connection Settings
Connection Type:
Contact
Contact Conductance (W/m2K):
120.0
OK
Cancel
Help


ESATAN-TMS
thermal modelling suite
Improved User Interface
Process Conductive Interfaces
ESATAN-TMS Workbench
Model Edit Define Geometric Radiative Thermal Reports Utilities
Model Tree
Visualisation
Conducti
Model - GSG2
Analysis Cases
Boundary Conditions
Conductive Interfaces
Contact
ci_10
ci_11
ci_12
ci_13
ci_14
ci_5
ci_6
Fused
ci_1
ci_15
ci_16
ci_2
ci_3
ci_4
ci_7
ci_8
ci_9
Not Connected
Not Required
Contact Zones
Cavities
Geometry
GSG2
Body
• Conductive Interfaces now displayed by type on model tree


ESATAN-TMS
thermal modelling suite
Improved User Interface
Define Variables
Define Geometric Radiative
Boundary Condition...
Conductive Interface...
Contact Zone...
Geometry...
Group...
Material
Property...
User Defined Conductor...
Variable
Matrix...
Vector...
Coordinate...
Integer...
Logical...
Point...
Real...
Spin...
String...
Model Tree
Define Real
Real: Prop1_data
Dimensionality: Scalar Vector Matrix
Rows: 13
Columns: 2
0.0 -80.0
300.0 -70.0
600.0 -60.0
900.0 -50.0
1200.0 0.0
2000.0 0.0
3000.0 -90.0
3500.0 -120.0
4000.0 -120.0
4500.0 -120.0
5000.0 -120.0
5500.0 -120.0
6000.0 -120.0
Import Data...
Graph...
Apply
Reset
Close
Help
• Interface for definition of basic variable types
• Same interface for Scalar, Vector and Matrix
• Edit definition through the same dialog

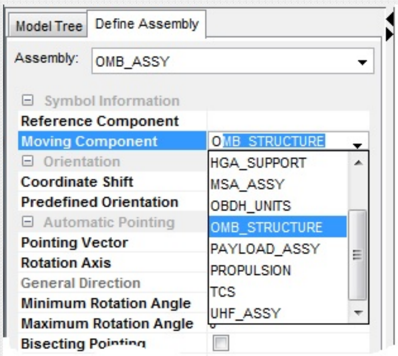

ESATAN-TMS
thermal modelling suite
Improved User Interface
Reporting Tab
ESATAN-TMS Workbench
Model Edit Define Geometric Radiative Thermal Reports Utilities Help
Model Tree
Visualisation Reports
Set Connection Type...
Report
Delete...
Reporting window now a tabbed area
Save Clear Autoscroll
Command History Picking Information
Geometry Visualisation Radiative Reporting Thermal Library
Command:

ESATAN-TMS thermal modelling suite

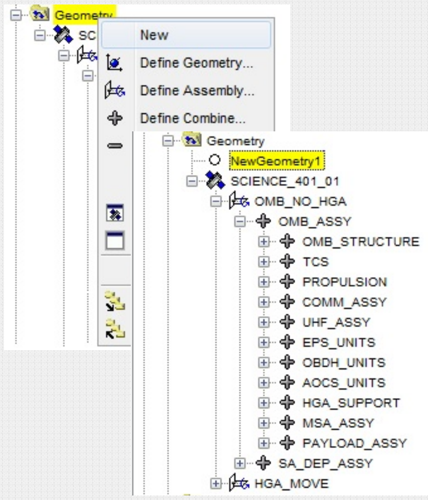
Improved User Interface

Other Items

- Auto-completion on dialogs



- Geometry New Command



ESATAN-TMS thermal modelling suite

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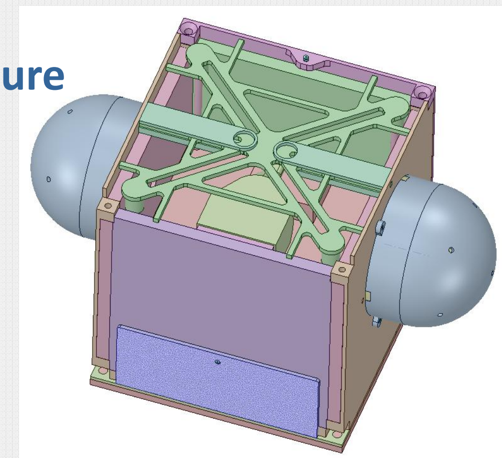
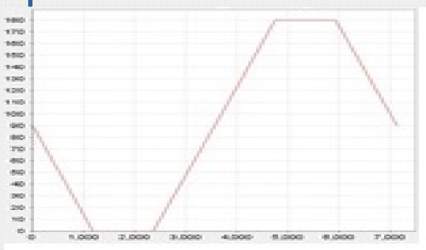


ESATAN-TMS thermal modelling suite

Time & Temperature Dependency

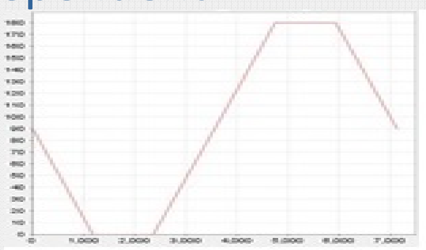
- Model time or temperature dependent properties in Workbench
  - Define Property
    - Time, temperature or time-cyclic
    - Plot profile
  - Additional support provided in ESATAN-TMS r7
    - Time or temperature dependent
      - All components of User-Defined Conductors
      - Conductance of Contact Conductor Interfaces
      - Capacitance of Non-Geometric Thermal Nodes
      - Shell through emissivity & conductance

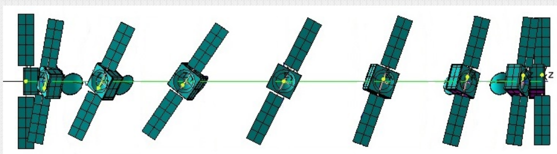


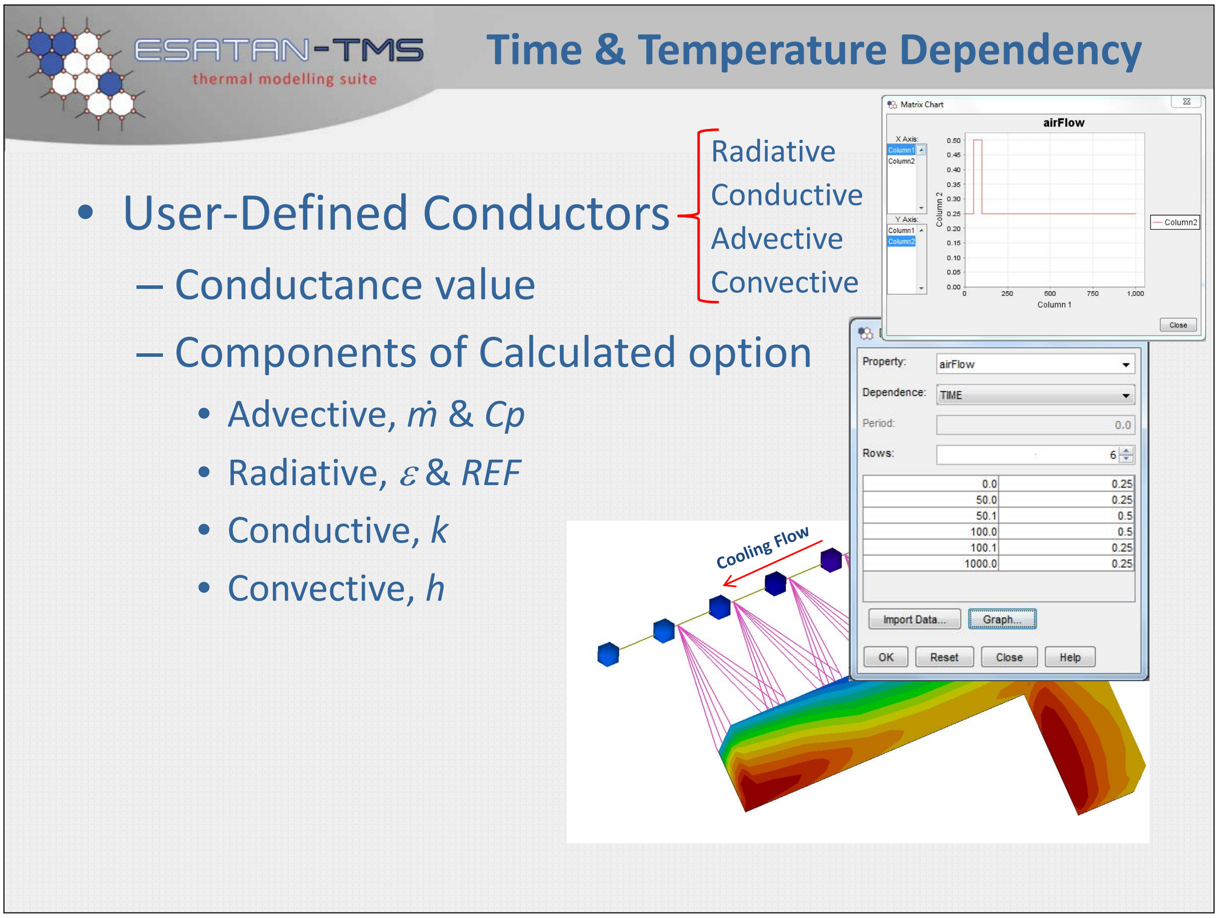
ESATAN-TMS thermal modelling suite

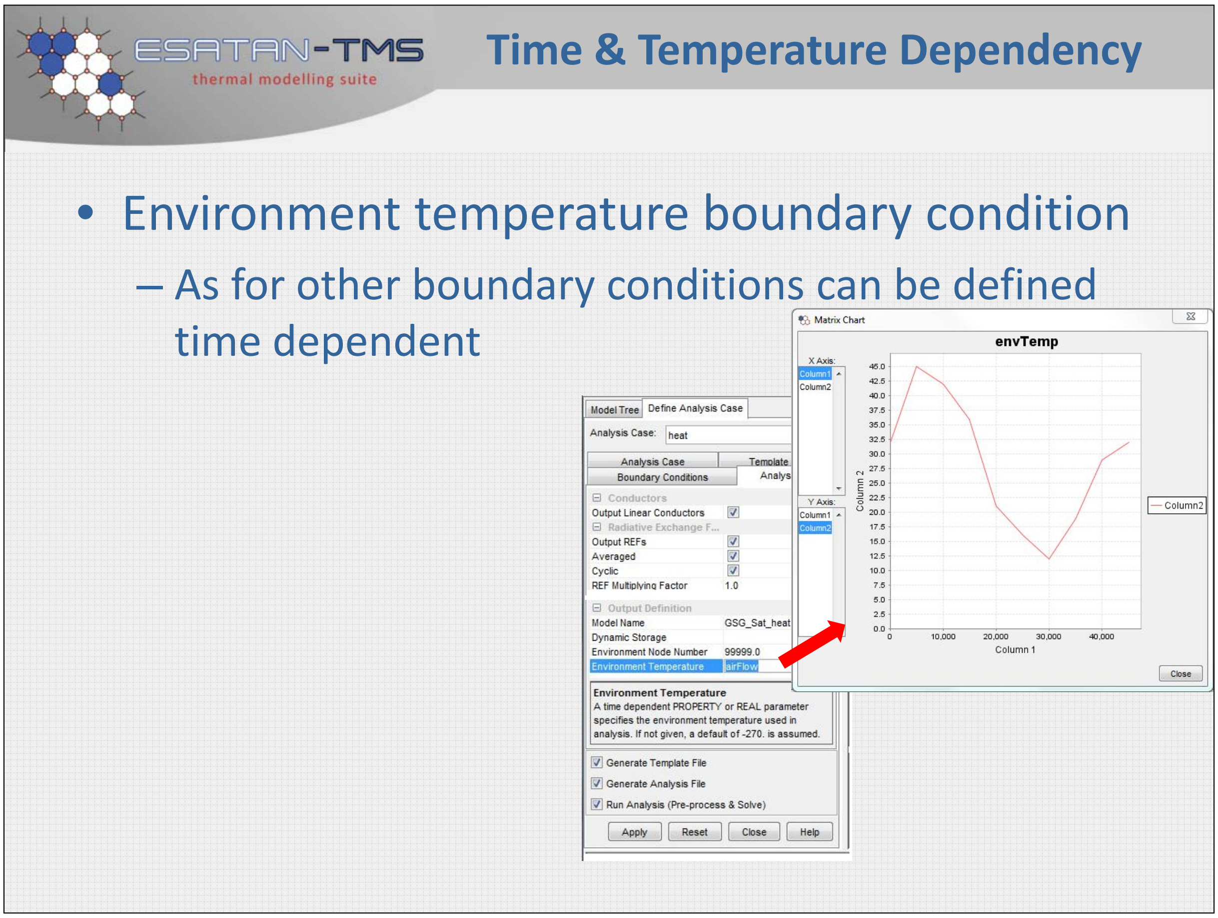
Time & Temperature Dependency

- Model time or temperature dependent properties in Workbench
  - Define Property
    - Time, temperature or time-cyclic
    - Plot profile
  - Additional support provided in ESATAN-TMS r7
    - Time dependent
      - Assembly pointing
      - Environment temperature






ESATAN-TMS
thermal modelling suite
Time & Temperature Dependency
• User-Defined Conductors
– Conductance value
– Components of Calculated option
• Advective, ṁ & Cp
• Radiative, ε & REF
• Conductive, k
• Convective, h
Radiative
Conductive
Advective
Convective
Cooling Flow
Matrix Chart
airFlow
Column 1
Column 2
Property:
airFlow
Dependence:
TIME
Period:
Rows:
Import Data...
Graph...
OK
Reset
Close
Help


ESATAN-TMS
thermal modelling suite
Time & Temperature Dependency
• Environment temperature boundary condition
– As for other boundary conditions can be defined time dependent
Matrix Chart
envTemp
Column 1
Column 2
Model Tree
Define Analysis Case
Analysis Case:
heat
Environment Temperature
A time dependent PROPERTY or REAL parameter specifies the environment temperature used in analysis. If not given, a default of -270. is assumed.
Generate Template File
Generate Analysis File
Run Analysis (Pre-process & Solve)
Apply
Reset
Close
Help

Contents

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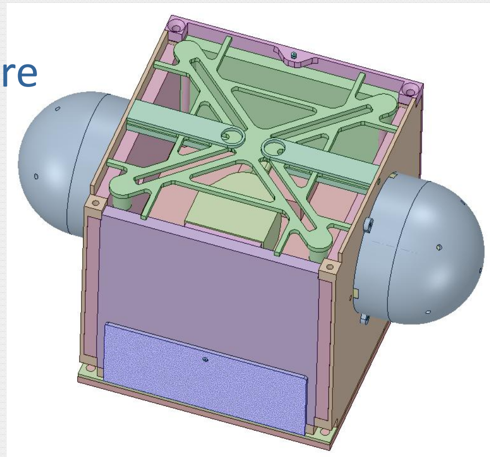
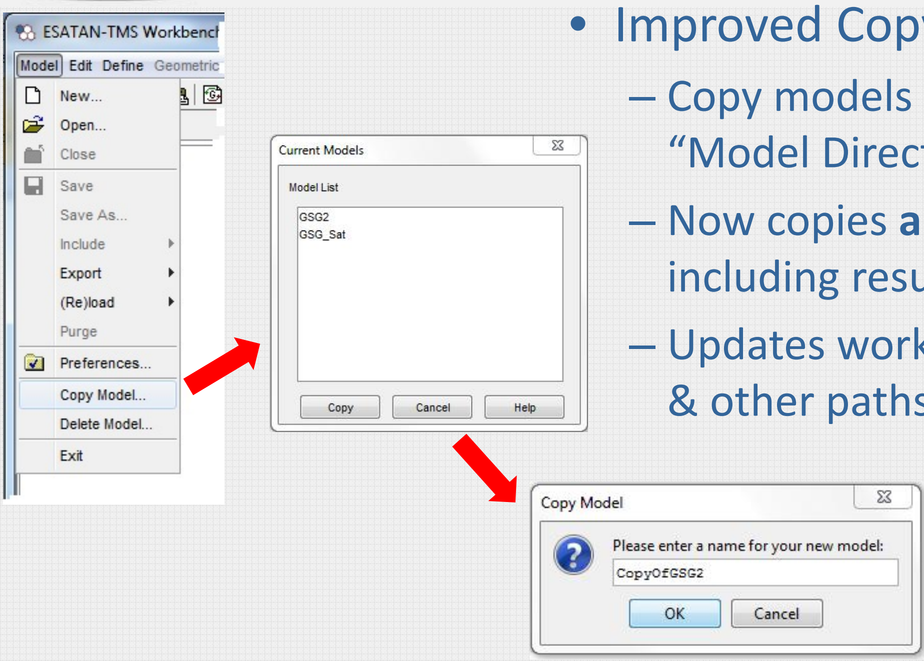
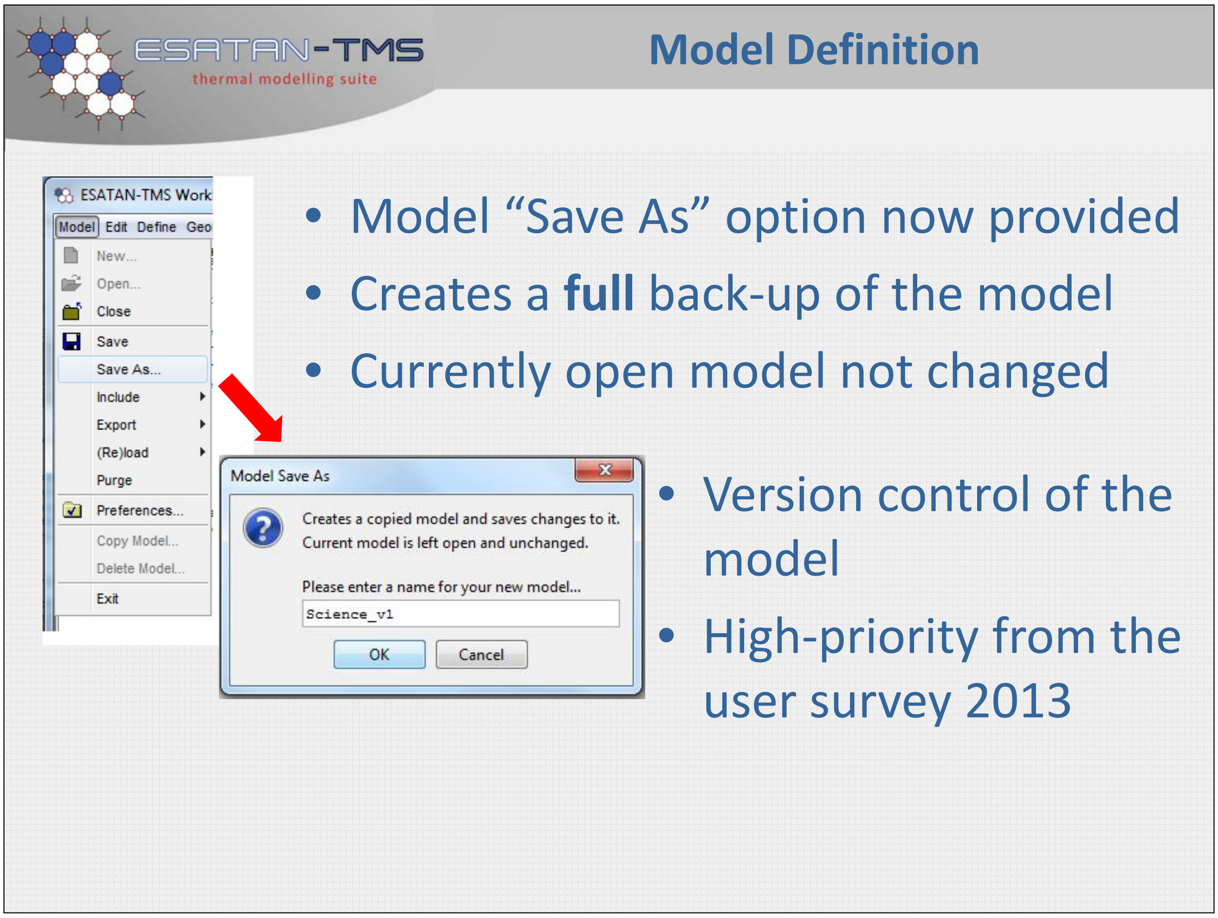
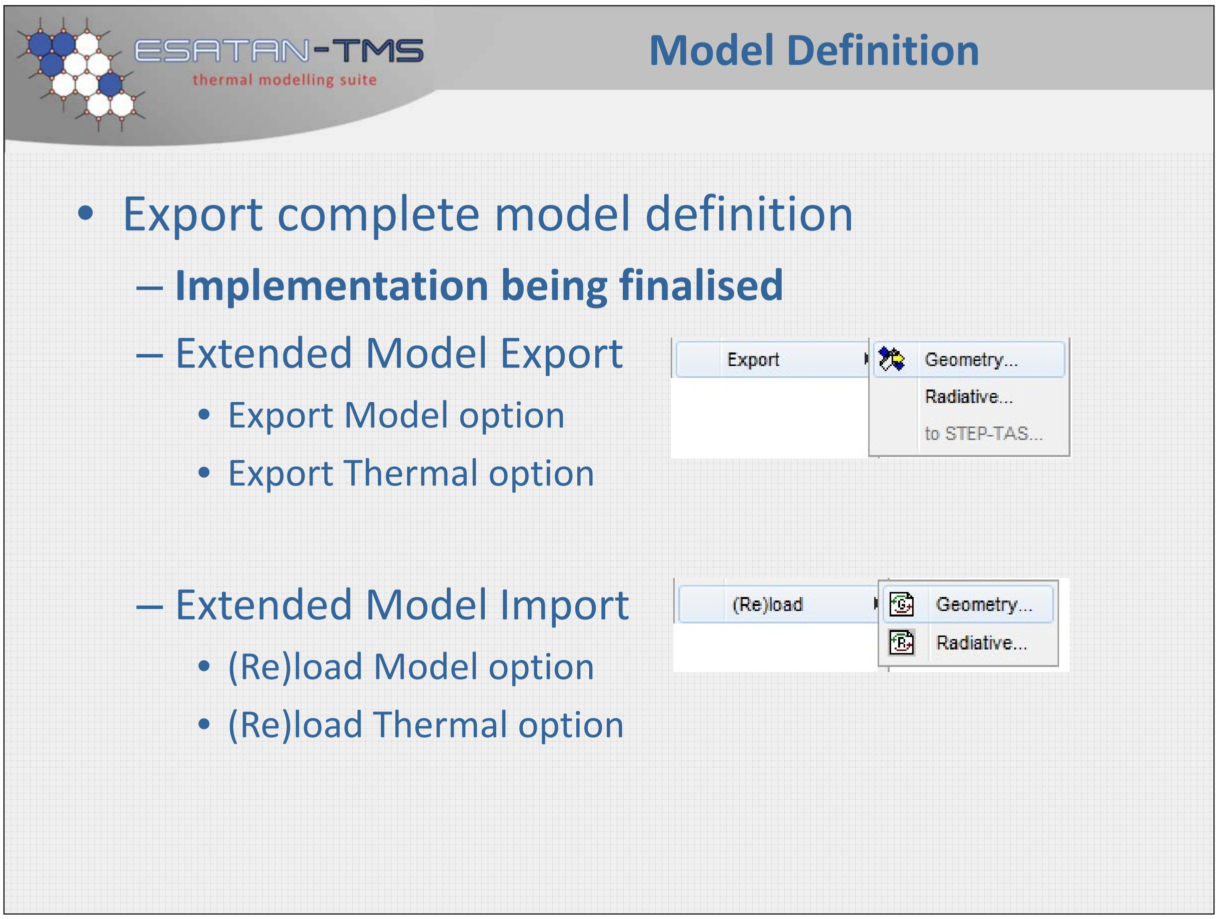


Model Definition

- Improved Copy Model
  - Copy models within the “Model Directory”
  - Now copies **all data**, including result data
  - Updates working directory & other paths




ESATAN-TMS
thermal modelling suite
Model Definition
ESATAN-TMS Work
Model Edit Define Geo
New...
Open...
Close
Save
Save As...
Include
Export
(Re)load
Purge
Preferences...
Copy Model...
Delete Model...
Exit
Model Save As
Creates a copied model and saves changes to it.
Current model is left open and unchanged.
Please enter a name for your new model...
Science_v1
OK
Cancel
• Model "Save As" option now provided
• Creates a **full** back-up of the model
• Currently open model not changed
• Version control of the model
• High-priority from the user survey 2013


ESATAN-TMS
thermal modelling suite
Model Definition
• Export complete model definition
– **Implementation being finalised**
– Extended Model Export
• Export Model option
• Export Thermal option
Export
Geometry...
Radiative...
to STEP-TAS...
– Extended Model Import
• (Re)load Model option
• (Re)load Thermal option
(Re)load
Geometry...
Radiative...

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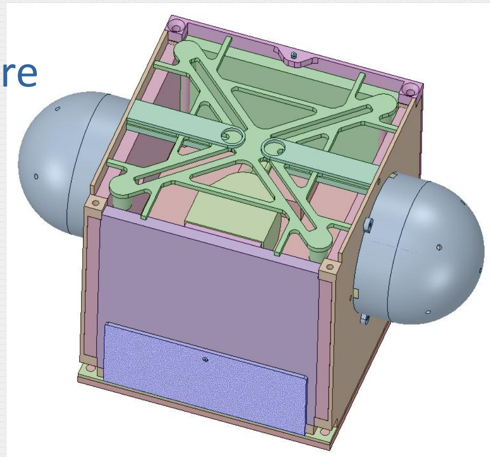
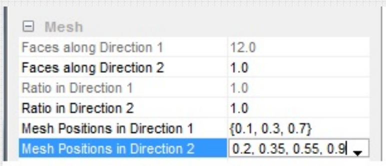
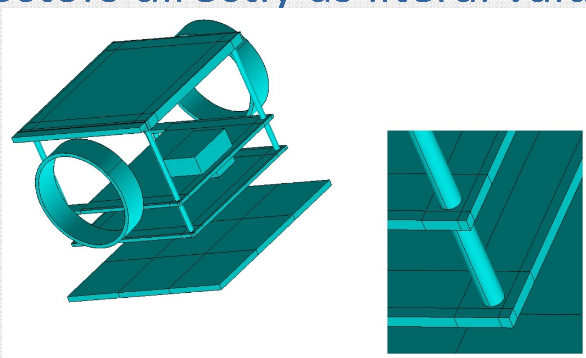


ESATAN-TMS thermal modelling suite

Simplified User Input

- Definition of Real Vectors directly as literal values
  - non-regular mesh



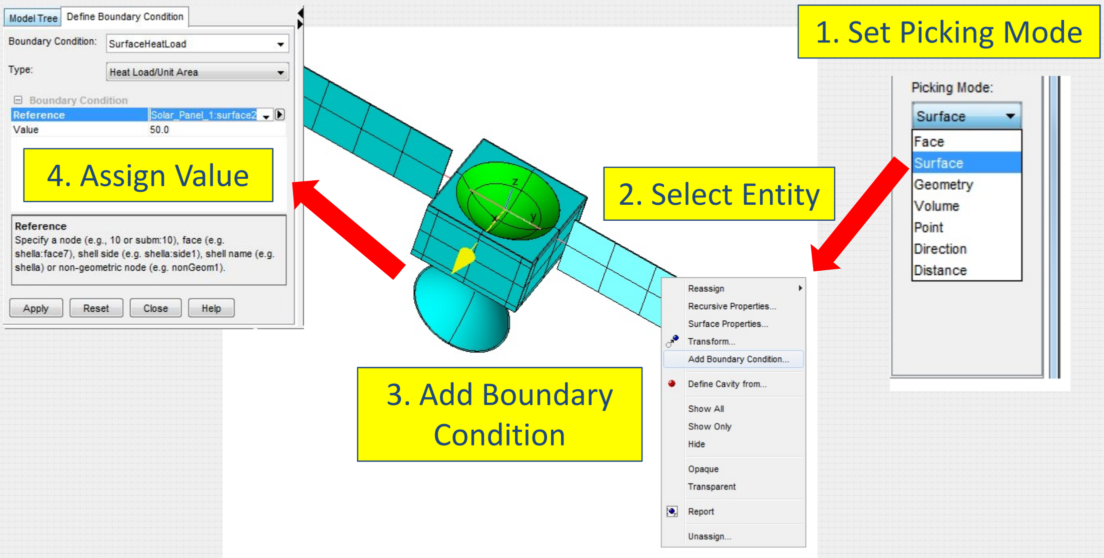


  - night-side temperature
  - orbit true anomaly
  - waveband frequency array

ESATAN-TMS thermal modelling suite

Simplified User Input

- Assignment of BCs directly onto selected entities in the visualisation



ESATAN-TMS thermal modelling suite

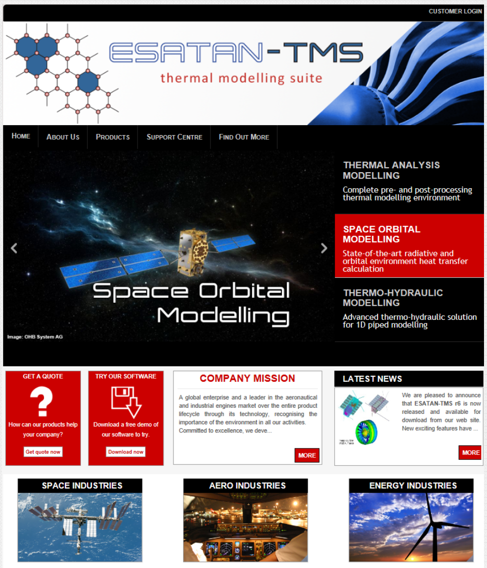
Conclusion

- ESATAN-TMS r7 **release at the end of the year**
- Continued **major investment** on the product
- Focus on input from **user survey 2013**
  - Improved thermal modelling environment
  - Time & temperature dependency
  - Control of model data
  - Improved performance
  - Simplified input
  - Improved visualisation

ESATAN-TMS thermal modelling suite

Product Support

- New web site, self help, short videos, …



- Extended Getting Started Guide
- Training courses at ITP
  - Nov 2014 Beginner
  - Jan 2015 Advanced
- On-site training on request
- Thermal consultancy

ESATAN-TMS thermal modelling suite

Product Support

- Maintenance & bug fixing of the product
  - General bug fixing, including STEP-TAS Import/Export
- Obtain feedback on priorities, both immediate and future requirements
  - Web report system
  - Customer visits
  - User survey
- … and the support team are here!

ESATAN-TMS
thermal modelling suite

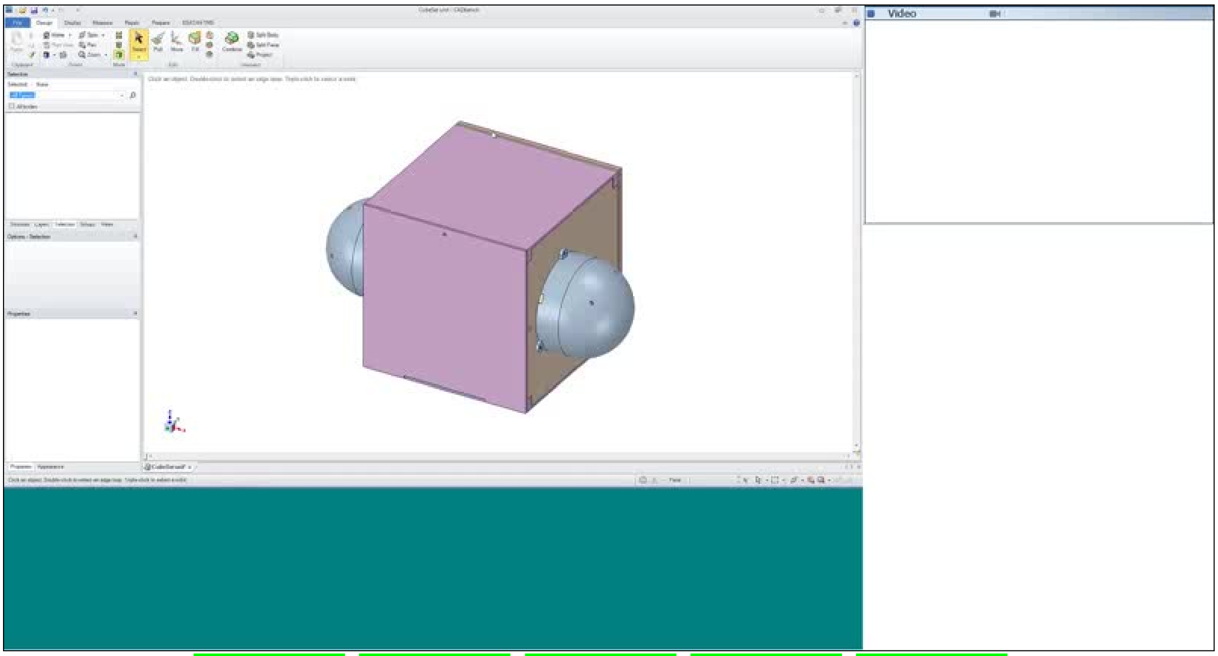
Thank You

Questions following the demonstration

ESATAN-TMS
thermal modelling suite

New Functionality (Summary)

- CAD Conversion
  - Shape recognition
  - Merge triangles
  - Option to generate Point Variables
- Thermal Integration
  - New Analysis Case Definition file
  - Control of output of all conductors
  - Automatically calculate conductors
  - Calculate conductors if out of date
- Redesign of dialogs
- Process Conductive Interfaces
- Reporting Tab
- Geometry New command
- Auto-completion on dialogs
- Extension of time & temperature dependency support
- Extended Copy Model
- Model Save As
- Export Complete Model Definition
- Define Vectors directly using literal values



Slow Normal Fast Play/Pause Stop

Appendix T

Tests of solids implementation in ESATAN TMS R6

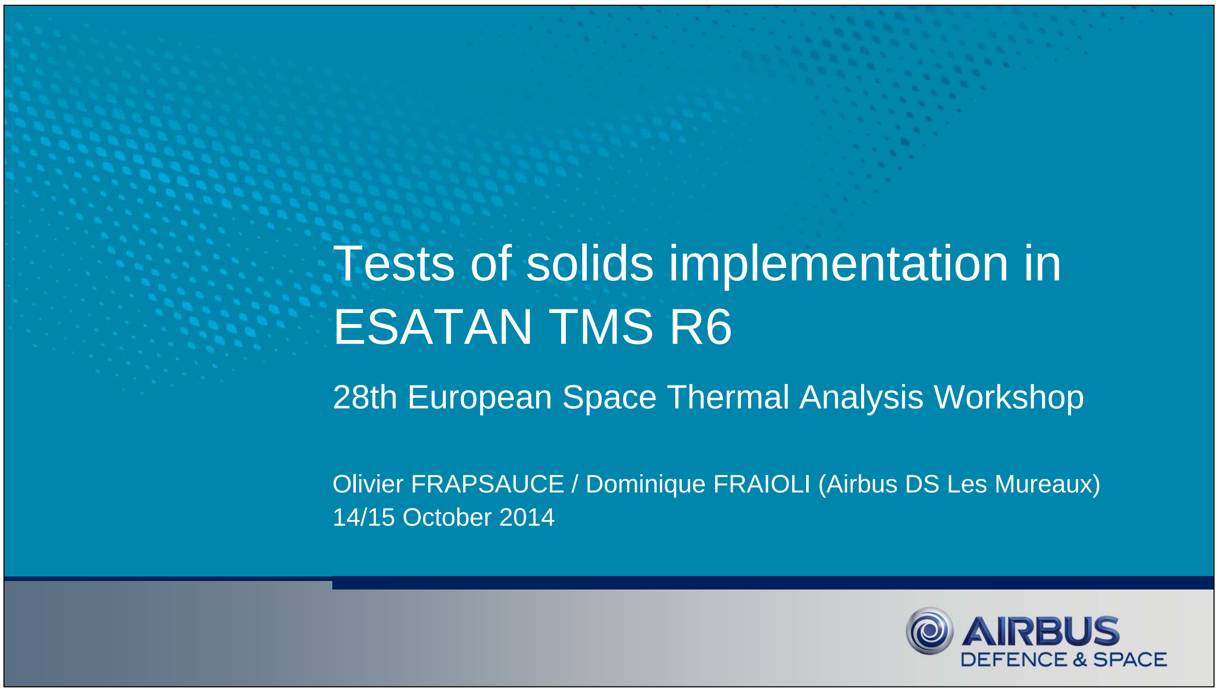
Olivier Frapsauce Dominique Fraioli
(Airbus DS Les Mureaux, France)

Abstract

For Airbus DS Launchers development, the modelisation of the thermal phenomena inside a space vehicle needs a 3D volumic approach, in particular to represent heat transfer inside thermal protections and cavities and complex geometries. The methods based on shell elements are not well adapted to system thermal analyses. The implementation of solids in the software ESATAN TMS aims to answer to the needs of Airbus DS Vehicles Engineering.

In the frame of the development of ESATAN TMS R6 (including solids approach), Airbus DS Vehicles Engineering has tested some new functionalities for solids: volumes generation, meshing of these volumes, conductive contacts inside and between volumes (ACG), fluid/wall contacts, fluid/fluid contacts, cavities identification, radiative computations based on cavities ...

For the 28th European Space Thermal Analysis Workshop, Airbus DS Vehicles Engineering will present the results of the close collaboration between Airbus DS Vehicles Engineering and ITP Engines (ESATAN Provider) in the implementation of solids in the software ESATAN TMS R6 based on the validation test cases.


Tests of solids implementation in ESATAN TMS R6
28th European Space Thermal Analysis Workshop
Olivier FRAPSAUCE / Dominique FRAIOLI (Airbus DS Les Mureaux)
14/15 October 2014
AIRBUS
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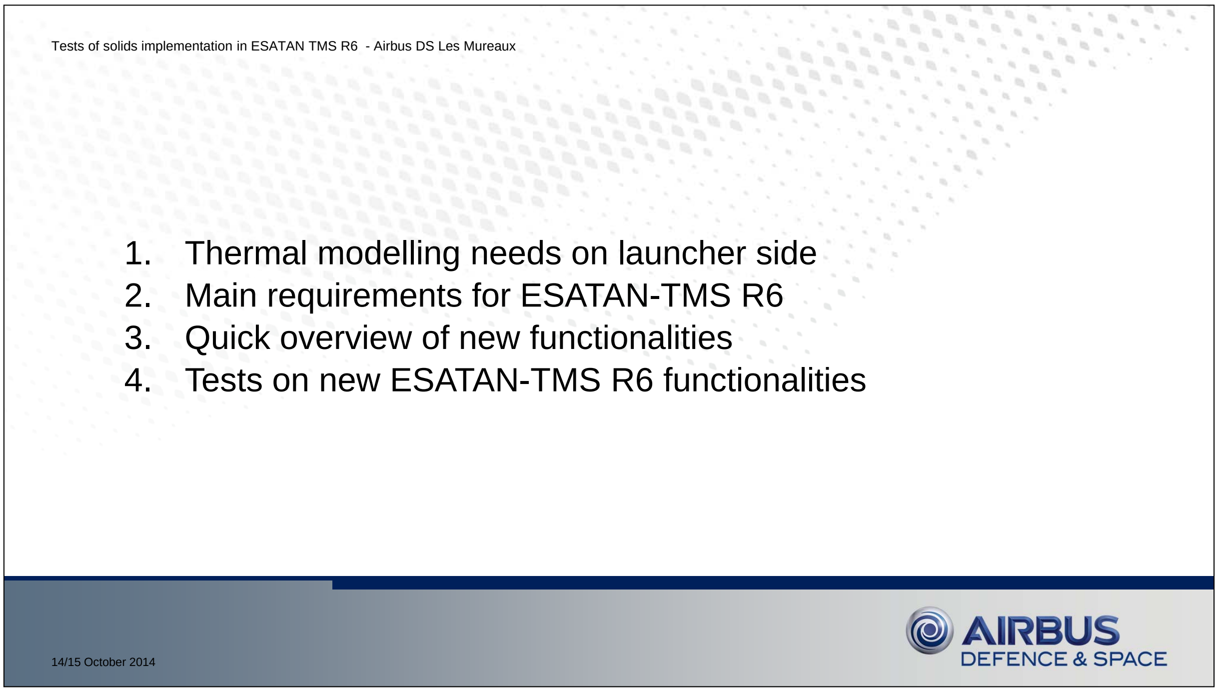
Tests of solids implementation in ESATAN TMS R6 - Airbus DS Les Mureaux
1. Thermal modelling needs on launcher side
2. Main requirements for ESATAN-TMS R6
3. Quick overview of new functionalities
4. Tests on new ESATAN-TMS R6 functionalities
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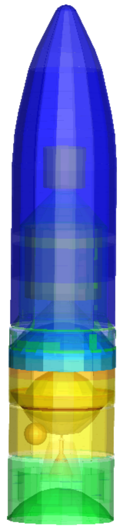
Tests of solids implementation in ESATAN TMS R6 - Airbus DS Les Mureaux

1. Thermal modelling needs on launcher side

On launcher side, the thermal model includes volumic conductive model associated to radiative and convective part.

The Airbus DS qualified (A5ECA version) process allows to use DMU to build the conductive model based on volumes and to generate automatically the geometrical mathematical model needed for radiative and convective exchanges.

The previous ESATAN TMS R5 version, using shell did not answer to the need > FDS for introduction of volumes into ESATAN TMS



FDS : Functional and Development Specification

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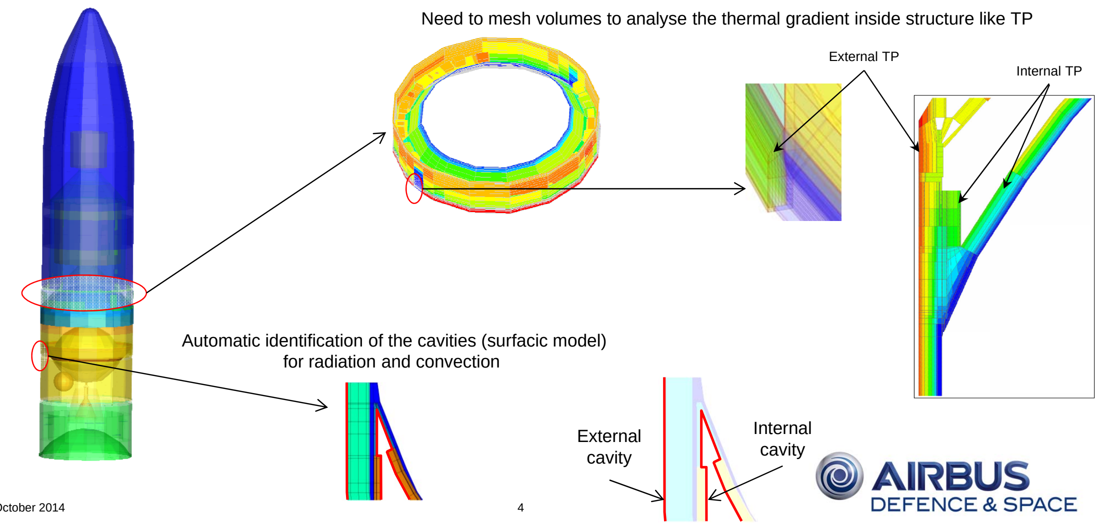
Tests of solids implementation in ESATAN TMS R6 - Airbus DS Les Mureaux

1. Thermal modelling needs on launcher side



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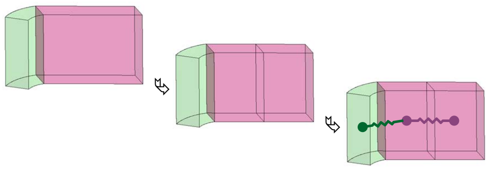
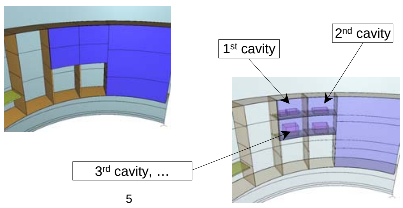
Tests of solids implementation in ESATAN TMS R6 - Airbus DS Les Mureaux

2. Main requirements for ESATAN-TMS R6

- To work with a volumic geometry in the graphical interface
  - Creation of solids
  - Meshing definition
  - Automatic Conductor Generation
    - Inside solids
    - Between two adjacent solids



- Creation of cavities
  - Cavity = set of surfaces used for a radiative and/or convective analysis
  - Automatic detection of the cavities



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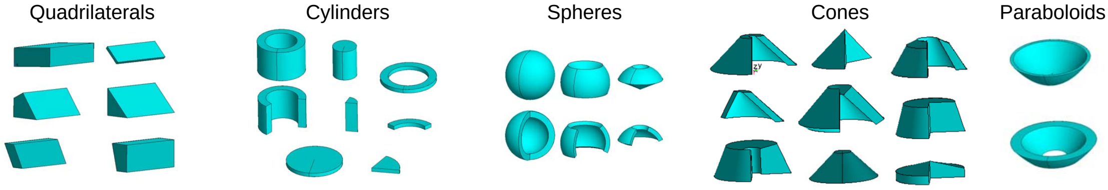
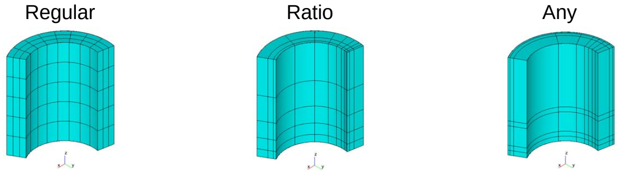
Tests of solids implementation in ESATAN TMS R6 - Airbus DS Les Mureaux

3. Quick overview of new functionalities

- Solid geometries



- Meshing



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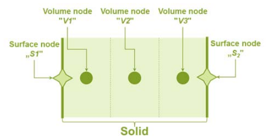
Tests of solids implementation in ESATAN TMS R6 - Airbus DS Les Mureaux

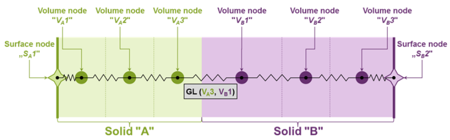
3. Quick overview of new functionalities

- Nodes definition
  - Solid geometry meshed in volumic nodes
  - External surfaces of the solid geometry defined as non-capacitive nodes *(6 surface nodes per solid)*

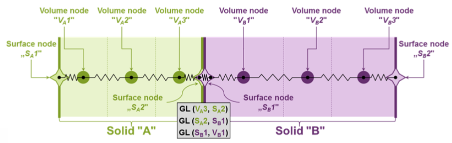


- ACG
  - Automatic contact recognition and couplings calculation using Far Field method
  - Contact processing :

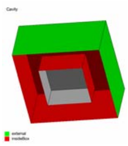
Fused option *(default option)*



Contact option



- Cavities recognition via view factors calculation



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Tests of solids implementation in ESATAN TMS R6 - Airbus DS Les Mureaux

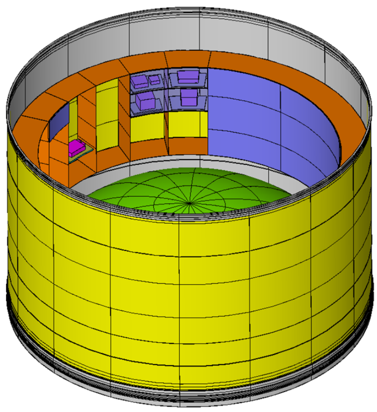
4. Tests on new ESATAN-TMS R6 functionalities

- Geometry & Meshing
  - Test case based on an Ariane 5 EPC upper part geometry

- Conductive couplings
  - Elementary tests with basic geometries (cylinders, spheres) :
    Comparison of calculated coupling values vs analytical formulae

    ↳In ESATAN-TMS R6 sp2, couplings values are considered valid.
  - Application on the Ariane 5 EPC upper part geometry

    ↳But the implementation of anisotropy is missing.



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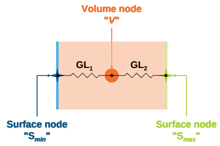
Elementary tests for conductive couplings

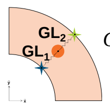
- Test Method
  - Creation of a single volume & Generation of the analysis file



  - Comparison of the calculated couplings (GL_1, GL_2 & GL_{eq}) with the analytical values

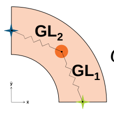
$$Deviation = \frac{GL^{analytical} - GL^{TMS\ R6sp2}}{GL^{analytical}} (\%)$$

- Example : Cylinder
  - Radial Direction (R)

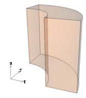


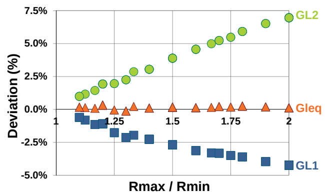
$$GL_{eq} = \frac{1}{\frac{1}{GL_1} + \frac{1}{GL_2}}$$

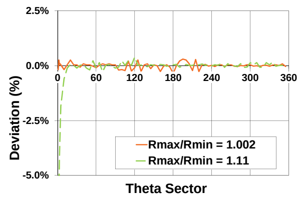
  - Angular Direction (θ)



$$GL_{eq} = GL_1 = GL_2$$







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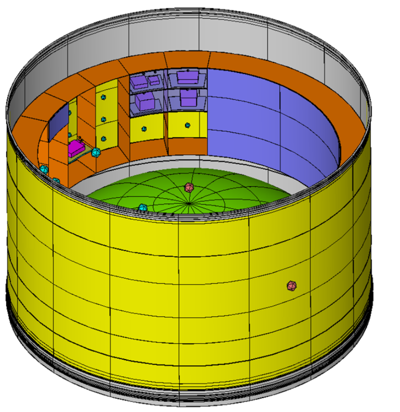
4. Tests on new ESATAN-TMS R6 functionalities

- Convective couplings
  - Application on the Ariane 5 EPC upper part geometry
  - Currently only direct convective coefficient h is available, the use of convective coefficient temperature dependent as $k.\Delta T^{\alpha}$ is not available in the interface.
- Advective couplings (fluid channels)
  - Application on the Ariane 5 EPC upper part geometry
  - Currently only fixed value of specific heat is available in the interface (no temperature dependance).



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Tests of solids implementation in ESATAN TMS R6 - Airbus DS Les Mureaux

4. Next steps

R6 fonctionnalities still to be tested

– Cavities identification for radiative/convective model generation and for radiative fluxes computations

Other validations for our new process

– capability to control that all the surfaces of the cavities are coupled with gas nodes
– Export capability (model exchange, model assembly, …)
– Compatibility with our internal tools (end to end process)

⇒According to these tests, new needs should be defined for addition in next ESATAN TMS version.

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Appendix U

Finite element model reduction for the determination of accurate conductive links and application to MTG IRS BTA

Lionel Jacques
(Space Structures and Systems Laboratory, University of Liège Centre Spatial de Liège, Belgium)

Luc Masset
(Space Structures and Systems Laboratory, University of Liège, Belgium)

Tanguy Thibert Pierre Jamotton Coraline Dalibot
(Centre Spatial de Liège, Belgium)

Gaetan Kerschen
(Space Structures and Systems Laboratory, University of Liège, Belgium)

Abstract

The finite element method (FEM) is widely used in mechanical engineering, especially for space structure design. However, FEM is not yet often used for thermal engineering of space structures where the lumped parameter method (LPM) is still dominant.
The two methods offer advantages and disadvantages and the proposed global approach tries to combine both. Whereas the LPM remains very versatile and allows easy integration of user-defined components, the computation of the conductive links is error-prone and still too often computed by hand. This is incompatible with the increasing accuracy required by the thermal control systems (TCS) and associated thermal models. Besides offering the automatic and accurate computation of the conductive links, the FEM also provides easy interaction between mechanical and thermal models, allowing better thermo-mechanical analyses. From this point of view, the FEM is complementary, offering the accuracy required by the always more stringent requirements of the TCS. In this framework, a FE mesh conductive reduction scheme has been developed. The detailed FE mesh is first fitted to the ESARAD geometry. The FE mesh is then partitioned, according to the ESARAD shells definition, before being reduced in an iterative procedure. The reduced conductive network, containing all the conductive information of the detailed FE mesh, and the ESARAD radiative links are then combined to form the TMM and compute the temperatures. The reduction method further allows the recovery of the detailed FE mesh temperatures back from the reduced one, therefore bridging the gap between thermal and mechanical analysis. The method has been tested and applied on the Back Telescope Assembly (BTA) on board MTG IRS.

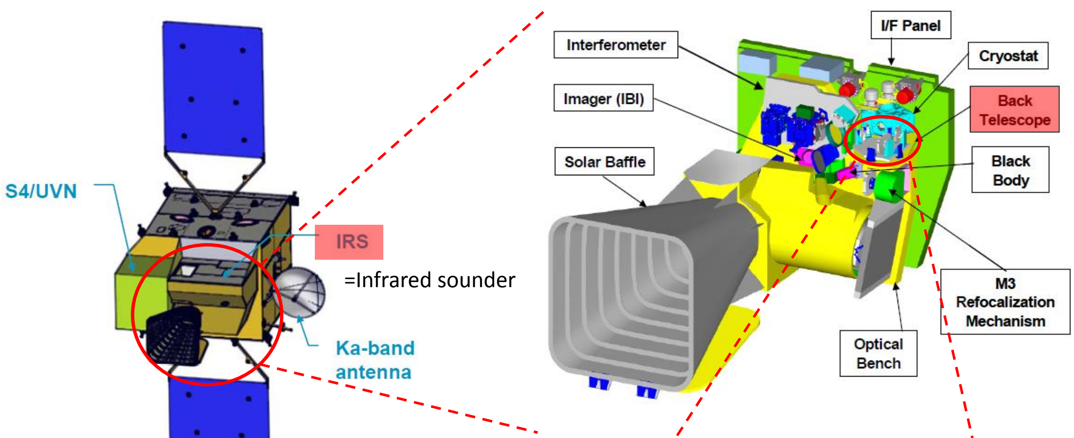
FINITE ELEMENT MODEL REDUCTION FOR THE DETERMINATION OF ACCURATE CONDUCTIVE LINKS AND APPLICATION TO MTG IRS BTA

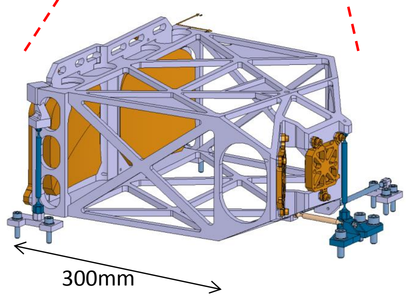
Lionel Jacques[1,2], Luc Masset[1], Tanguy Thibert[2], Pierre Jamotton[2], Coraline Dalibot[2], Gaetan Kerschen[1]

[1] Space Structures and Systems Laboratory, University of Liège
[2] Centre Spatial de Liège

28th Space Thermal Analysis Workshop, ESTEC, Oct. 15th, 2014

Requirements reach classical method limits





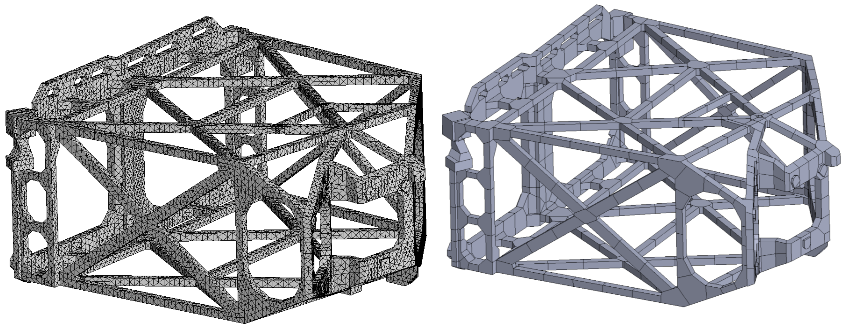
T° gradient < 1 °C

Conductive IF @ 20+/-5°C

Radiator @ [-70, -30]°C

2

Finite Element vs. Lumped Parameter



	FEM	LPM
Number of nodes	10^4 - 10^6	10^1 - 10^3
1. Conductive links computation	✔ Automatic	✘ Manual, error-prone
2. Radiative links computation	✘ Prohibitive	✔ Affordable
3. Surface accuracy for ray-tracing	✘ FE facets	✔ Primitives
4. User-defined components	✘ Difficult	✔ Easy
5. Thermo-mech. analysis	✔ Same mesh	✘ Mesh extrapolation

3

Global approach & proposed solutions

(2) Radiative links computation

- Reduce # of rays: quasi-Monte Carlo method (isocell, Halton)
- Reduce # of facets: super-face concept (mesh clustering)
- Parallelization: GPUs

(3) Surface accuracy for ray-tracing

- Quadrics fitting

(1,4,5) Conductive links, thermo-mech. analysis and user-defined compts.

- Reduce detailed FE mesh (keep conductive info. of the detailed geometry)
- Able to recover detailed T° from reduced
- Transform reduced FE model to LP model to enable user-defined comp.

4

Today's topic

(2) Radiative links computation

- Reduce # of rays: quasi-Monte Carlo method (isocell, Halton)
- Reduce # of facets: super-face concept (mesh clustering)
- Parallelization: GPUs

(3) Surface accuracy for ray-tracing

- Quadrics fitting

(1,4,5) Conductive links, thermo-mech. analysis and user-defined compts.

- Reduce detailed FE mesh (keep conductive info. of the detailed geometry)
- Able to recover detailed T° from reduced
- Transform reduced FE model to LP model to enable user-defined comp.

5

Outline

Mesh clustering

Mathematical reduction

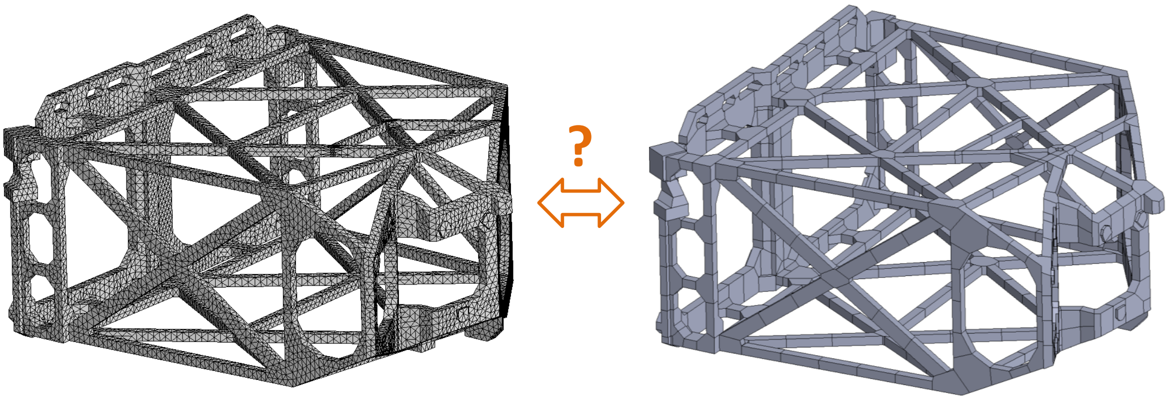
Step by step procedure

Benchmarking

Conclusions

6

How to reduce the system accurately?



2 step process:

- FE mesh partitioning matching ESARAD mesh
- FE mesh reduction to determine the GLs

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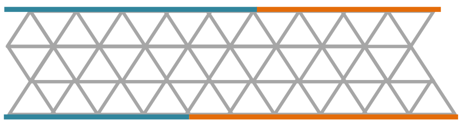
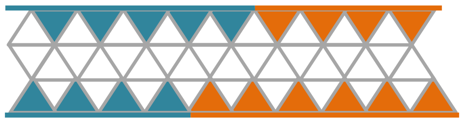
Merging meshes

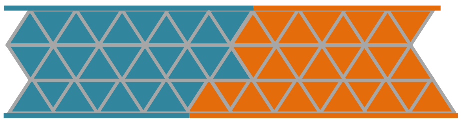
Superimpose ESARAD and FE meshes



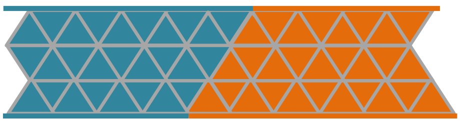
Assign skin FE to ESARAD shells



Greedy region growing



Cluster boundary smoothing



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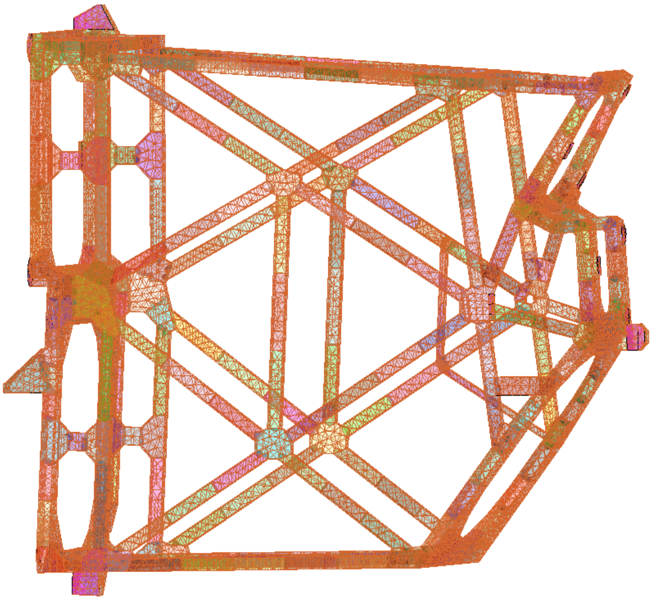
From FE clusters to GLs



$\mathbf{K_D}$ (65k × 65k) ? ⇔ $\mathbf{K_R}$ (340 × 340)

9

Guyan (static) condensation

Split the system

$$\mathbf{KT} = \mathbf{Q}$$

With retained and condensed nodes:

$$\begin{bmatrix} \mathbf{K}_{\mathrm{RR}} & \mathbf{K}_{\mathrm{RC}} \\ \mathbf{K}_{\mathrm{RC}}^{\mathrm{T}} & \mathbf{K}_{\mathrm{CC}} \end{bmatrix} \begin{Bmatrix} \mathbf{T}_{\mathrm{R}} \\ \mathbf{T}_{\mathrm{C}} \end{Bmatrix} = \begin{Bmatrix} \mathbf{Q}_{\mathrm{R}} \\ \mathbf{Q}_{\mathrm{C}} = 0 \end{Bmatrix}$$

Reduced system:

$$\mathbf{K}'\mathbf{T}_{\mathrm{R}} = \mathbf{Q}'$$

With

$$\mathbf{K}' = \mathbf{K}_{\mathrm{RR}} - \mathbf{K}_{\mathrm{RC}}\mathbf{K}_{\mathrm{CC}}^{-1}\mathbf{K}_{\mathrm{RC}}^{\mathrm{T}} = \mathbf{R}^{\mathrm{T}}\mathbf{K}\mathbf{R}$$

$$\mathbf{Q}' = \mathbf{Q}_{\mathrm{R}} - \mathbf{K}_{\mathrm{RC}}\mathbf{K}_{\mathrm{CC}}^{-1}\mathbf{Q}_{\mathrm{C}} = \mathbf{R}^{\mathrm{T}}\mathbf{Q} = \mathbf{Q}_{\mathrm{R}}$$

$$\mathbf{R} = \begin{bmatrix} \mathbf{I}_{\mathrm{RR}} \\ -\mathbf{K}_{\mathrm{RC}}\mathbf{K}_{\mathrm{CC}}^{-1} \end{bmatrix}$$

Condensed temperatures can be recovered: $\mathbf{T} = \mathbf{R}\mathbf{T}_{\mathrm{R}}$

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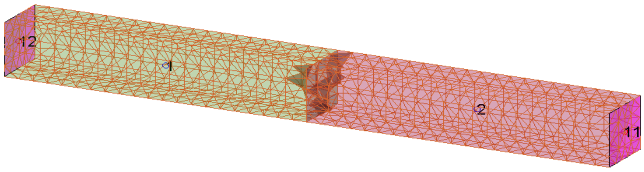
Problem of Guyan condensation

Need to select particular nodes to be retained

No (or known) heat load on condensed nodes



Heat load on selected node ≠ heat load on cluster represented by node

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Create new “super-nodes”

Not picking a representative node of the cluster but creating new nodes

A super-node = weighted (area, volume) average each node cluster

$$\mathbf{T_{SN}} = \mathbf{AT}$$

$$T_{SN_i} = \sum_{j=1}^{N} A_{ij} T_j \qquad \sum_{j=1}^{N} A_{ij} = 1$$

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Combining the relations

As done at element level in MSC Thermica®:

$$\begin{cases} \mathbf{KT} = \mathbf{Q} \\ \mathbf{T_{SN}} = \mathbf{AT} \end{cases} \Leftrightarrow \begin{bmatrix} \mathbf{K} & \mathbf{A^T} \\ \mathbf{A} & \mathbf{0} \end{bmatrix} \begin{Bmatrix} \mathbf{T} \\ \mathbf{0} \end{Bmatrix} = \mathbf{M} \begin{Bmatrix} \mathbf{T} \\ \mathbf{0} \end{Bmatrix} = \begin{Bmatrix} \mathbf{Q} \\ \mathbf{T_{SN}} \end{Bmatrix}$$

$$\begin{Bmatrix} \mathbf{T} \\ \mathbf{0} \end{Bmatrix} = \mathbf{M^{-1}} \begin{Bmatrix} \mathbf{Q} \\ \mathbf{T_{SN}} \end{Bmatrix} = \begin{bmatrix} \mathbf{X} & \mathbf{Y^T} \\ \mathbf{Y} & \mathbf{Z} \end{bmatrix} \begin{Bmatrix} \mathbf{Q} \\ \mathbf{T_{SN}} \end{Bmatrix}$$

$$\mathbf{YA^T} = \mathbf{I} = \mathbf{AY^T}$$

$$\mathbf{0} = \mathbf{YQ} + \mathbf{ZT_{SN}}$$

If the load is uniform over each super-node ($\mathbf{Q} = \mathbf{A^T Q_{SN}}$): $\mathbf{YQ} = \mathbf{Q_{SN}}$

$$-\mathbf{ZT_{SN}} = \mathbf{Q_{SN}}$$

$$\boxed{\mathbf{K_{SN}} = -\mathbf{Z}}$$

And the detailed T° can be recovered:

$$\mathbf{T} = \mathbf{XQ} + \mathbf{Y^T T_{SN}}$$

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You need to invert M to get $\mathbf{K_{SN}}$!

size($\mathbf{M}$) > size($\mathbf{K}$) → very expensive + $\mathbf{M}$ is not sparse!

Detailed T° not needed:

- LDL decomposition of $\mathbf{M}$ → selective inversion of sparse matrix and only $\mathbf{K_{SN}}$ is computed.

Detailed T° needed: $\mathbf{X}$ and $\mathbf{Y}$ are required (size($\mathbf{X}$)=size($\mathbf{K}$), not sparse)

- Local inversion of M for each super-node
- Global inversion for small problems.

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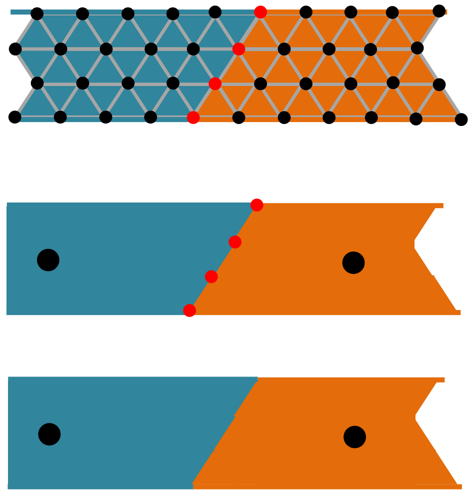
Local inversion of $\mathbf{M}$



Local inversion of M:

super-node + keep all detailed IF nodes

Guyan condensation to eliminate the

detailed IF nodes

Detailed T° recovery by inverse procedure:

no need to store the full $\mathbf{X}$ and $\mathbf{Y}$

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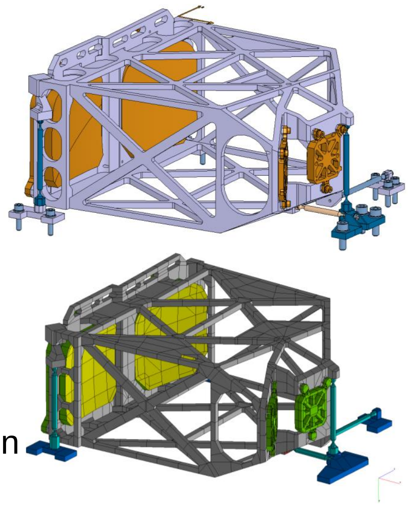
Overall procedure



- CAD cleaning + ESARAD shells drawing
- Import .step to ESARAD
- LPM nodes numbering in ESARAD
- FE meshing cleaned CAD
- Superimposition of FE & ESARAD meshes
- FE mesh partitioning
- FE assembly and detailed $\mathbf{K}$ matrix computation
- Reduction of $\mathbf{K}$ to $\mathbf{K}_{SN}$
- Export $\mathbf{K}_{SN}$ and super-nodal capacitances to ESATAN
- Compute the radiative links (with ESARAD or other)
- Combine radiative + conductive links and others → solve for $\mathbf{T}_{SN}$

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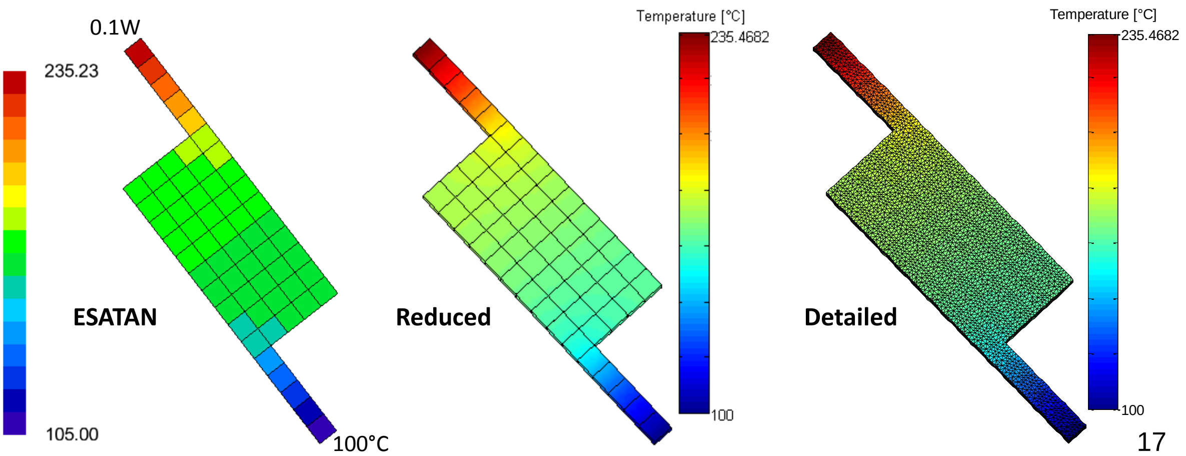
Benchmarking

	Detailed	ESATAN	Reduced
ΔT	235.47K	240.23 K	235.47 K
# nodes	11897	62	62
# GLs	71033	97	1891



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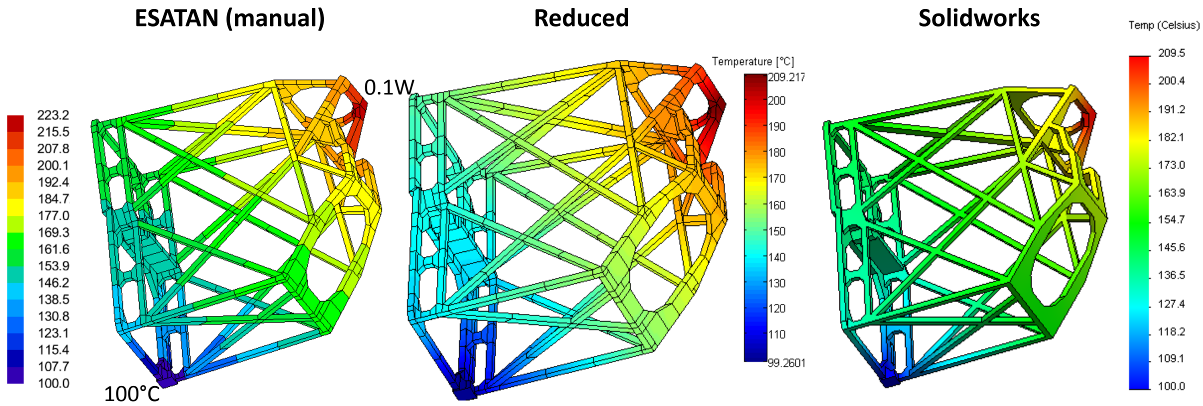
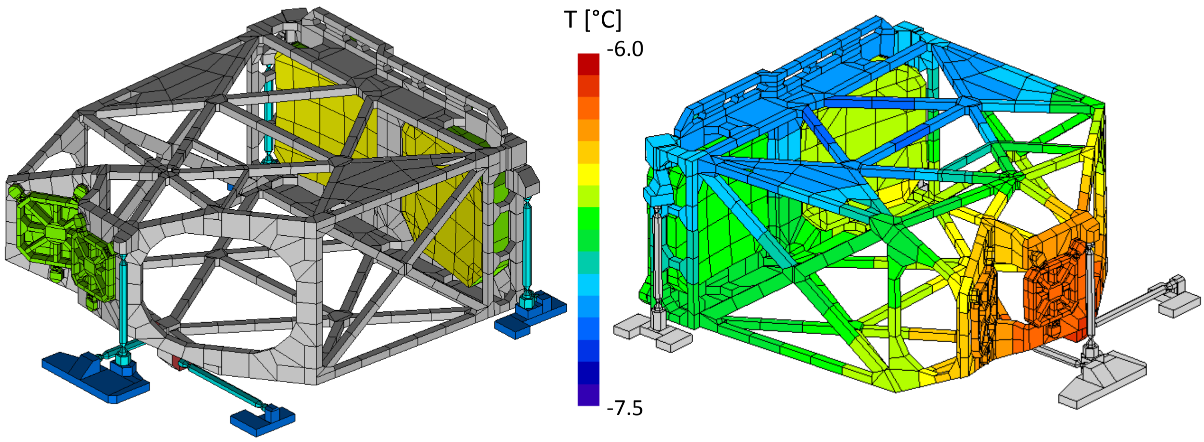
Manual GLs lead to 10% error

	Detailed (Solidworks)	ESATAN (manual)	Reduced
ΔT	107.4	123.2	107.7
# nodes	46405	280	280
# GLs	253004	402	39060



Integration of all components & run



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CONCLUSIONS

Conductive reduction method offers:

- better accuracy
- automatic GLs computation in complex 3D nodes
- detailed T° map recovery for thermo-mech. analyses

FEM vs. LPM: *Unity makes strength (Belgian motto)*

2^{nd} step to bridge the gap between structural and thermal analysis

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Thank you for your attention…

Any question?

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[2] MSC THERMICA User Manual, Version 4.5.1, 2012, ASTRI.UM.757138.ASTR

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Appendix V

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