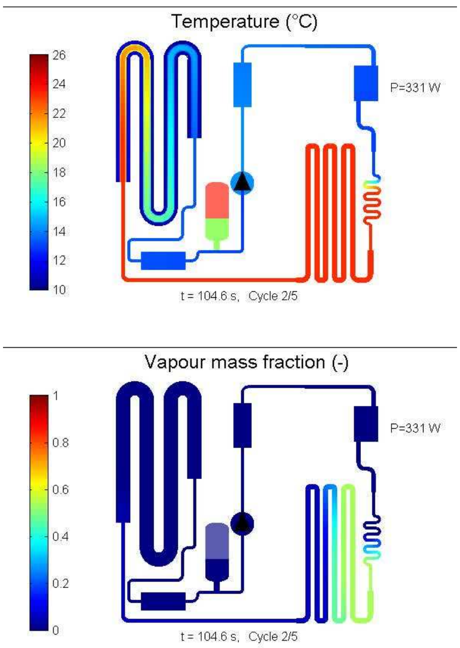
ESA-WPP-338
February 2014

Proceedings of the

27th European Space Thermal Analysis Workshop

ESA/ESTEC, Noordwijk, The Netherlands

3–4 December 2013



credits: National Aerospace Laboratory NLR

European Space Agency
Agence spatiale européenne

Abstract

This document contains the presentations of the 27th European Space Thermal Analysis Workshop held at ESA/ESTEC, Noordwijk, The Netherlands on 3–4 December 2013. 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.

Contents

Appendices

Programme Day 1

9:00 Registration

9:45 **Welcome and introduction**

Harrie Rooijackers (ESA/ESTEC, The Netherlands)

10:00 **Thermal Concept Design Tool** — Flux calculation results and the new tool presentation

Andrea Tosetto & Matteo Gorlani (Blue Engineering, Torino, Italy)
Harrie Rooijackers (ESA/ESTEC, The Netherlands)

10:25 **Evaluation of Heat Transfer Parameters from CFD for Use in TMM in Case of Gas Convection in Vented Cavities**

Christian Wendt (Astrium Space Transportation, Bremen, Germany)

10:50 **Introduction to Simulation Data Management**

Peter Bartholomew (MDAO Technologies, United Kingdom)

11:15 Coffee break in the Foyer

11:45 **EVATHERM for Early Validation of Thermal Control**

Fabrice Mena (Astrium SAS, France)

12:10 **Thermo-electrical Detailed Analysis**

François Mercier & B. Samaniego & V. Gineste & L. Gajewski & A. du Jeu (Astrium SAS, Toulouse, France)

12:35 **Correlating thermal balance test results with a thermal mathematical model using evolutionary algorithms**

Niek van Zijl & B. Zandbergen (Delft University of Technology, The Netherlands)
Bruin Benthem (Dutch Space B.V., The Netherlands)

13:00 Lunch in the ESTEC Restaurant

14:00 **Exchange of Thermal Models** — Challenges and Solutions

Stefan Kasper (Jena-Optronik GmbH, Germany)

14:25 **The KT Thermal Mapping Tool** — an semi-automated temperature transfer between structural and thermal models

Anton Zhukov & Markus Czupalla & Alexander Kuisl & Gerhard Bleicher & Winfried Gambietz
(Kayser-Threde GmbH, Müchen, Germany)

14:50 **Mapping nodal properties between dissimilar nodal representations of S/C structures using ESATAN-TMS**

Alexander Maas (Dutch Space, The Netherlands)

15:15 **MASCOT** — Thermal subsystem design

Luca Celotti & Riccardo Nadalini & Małgorzata Sołyga (ActiveSpace Technologies GmbH, Germany)
Volodymyr Baturkin (DLR Institut für Raumfahrsysteme, Germany)
Sergey Khairnasov & Vladimir Kravets (National Technical University of Ukraine, Ukraine)

15:40 Coffee break in the Foyer

16:00 **LHP MODULE SOFTWARE** — Application at System Level
Paul Atinsounon & David Valentini (Thales Alenia Space, France)

16:25 **Time dependent behaviour of pumped two-phase cooling systems** — Experiments and Simulations
Henk Jan van Gerner (NLR, The Netherlands)

16:50 **Study on the utilization of the FHTS extension of ESATAN-TMS for the thermal modeling of a bi-propellant satellite propulsion system**
Martin Schröder (OHB System AG, Germany)

17:15 **Thermal Modeling of CubeSats and Small Satellites**
Anwar Ali & M. Rizwan Mughal & Haider Ali & Leonardo M. Reyneri
(Department of Electronics and Telecommunications, Politecnico di Torino, Italy)

17:40 Social Gathering in the Foyer

19:30 Dinner in *La Toscana*

Programme Day 2

9:00 **E-THERM POLICY**

Thierry Basset & Patrick Hugonnot (Thales Alenia Space, France)

9:25 **ESATAN Thermal Modelling Suite** — Product Developments and Demonstration

Chris Kirtley & Henri Brouquet (ITP Engines UK Ltd, United Kingdom)

movies/media6

10:10 **SYSTEMA-THERMICA** — Launcher Case Set-up and Thermal Analysis

Timothée Soriano & Rose Nerriere (Astrium SAS, Toulouse, France)

10:55 Coffee break in the Foyer

11:20 **First Application of Esatan-TMS r6 Solids for a Launcher Upper Stage Thermal Model**

Harold Rathjen (Atrium, Bremen, Germany)

11:45 **Enhancement of ray tracing method for radiative heat transfer with new Isocell quasi-Monte Carlo technique and application to EUI space instrument baffle**

Lionel Jacques (Centre Spatial de Liège, Belgium)
Luc Masset & Gaetan Kerschen (University of Liège, Space Structures and Systems Laboratory, Belgium)

12:10 **Calculation of Optimal Solar Array Steering Laws for Temperature Critical Missions**

Andreas Brandl (Astrium GmbH Ottobrunn, Germany)
Jan-Hendrik Webert (Universität der Bundeswehr Müchen, Germany)

12:35 **BepiColombo MTM STM Thermal Test**

Scott Morgan (Astrium EADS, United Kingdom)

13:00 Closure

13:00 Lunch in the ESTEC Restaurant

Appendix A

Welcome and introduction

Harrie Rooijackers
(ESA/ESTEC, The Netherlands)

esa

27th European Space Thermal Analysis Workshop

3-4 December 2013, ESA ESTEC, Noordwijk

Welcome & Introduction

Harrie Rooijackers
Thermal Division
Analysis and Verification Section
ESA ESTEC

European Space Agency

Workshop objectives

esa

- 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.

European Space Agency

27th European Space Thermal Analysis Workshop 2/11

ESA Team

Benoit Laine	Head of Section
James Etchells	
Duncan Gibson	Workshop Secretary
Harrie Rooijackers	Workshop Organiser

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

European Space Agency

27th European Space Thermal Analysis Workshop 3/11

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 Duncan or Harrie before the end of Workshop.
- No copyrights, please!
- Workshop Proceedings will be supplied to participants afterwards, on the Web.

European Space Agency

27th European Space Thermal Analysis Workshop 4/11

Practical information

esa

- Lunch: 13:00 - 14:00
- Cocktail today around 17:45 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!

European Space Agency

27th European Space Thermal Analysis Workshop 5/11

Workshop diner

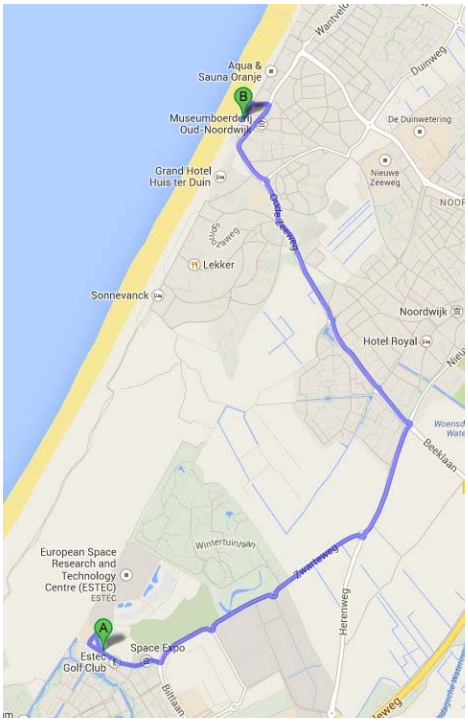
esa

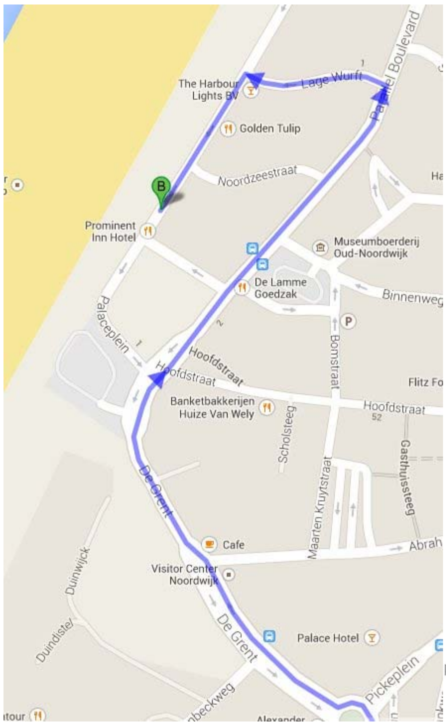
- in “La Toscana", Koningin Wilhelmina Boulevard 5,
  2202 GR Noordwijk, ☎ +31(0)71 3616 555
- fixed menu with choice of main course (fish, meat or vegetarian) for €29,50 excl. drinks
  drinks are charged individually.
- Restaurant booked today for 19:30
- Please arrange your own transport
- "Dutch" 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

European Space Agency

27th European Space Thermal Analysis Workshop 6/11

Restaurant “La Toscana”





European Space Agency

Menu (€ 29,50 p.p. excluding drinks)

CARPACCIO
Thinly sliced raw fillet of beef with parmesan cheese, rocket salad and pine nuts
or
VITELLO TONNATO
Thinly sliced veal with tuna mayonnaise
~~~~~~~~~~~~

SALMONE CON SALSA DI ANETO
Grilled salmon with a dill sauce
or
POLLO CAPRICCIOSO
Grilled fillet of chicken with mushrooms, peppers and tomato sauce
~~~~~~~~~~~~

DAME "VICE VERSA“
Chocolate ice cream with vanilla ice cream, vanilla sauce and whipped cream
or
TIRAMISU
Famous Italian dessert

European Space Agency

27th European Space Thermal Analysis Workshop 8/11

ICES 2013

- The 44th International Conference on Environmental Systems (ICES) will be held 13-17 July, 2014, Tucson, Arizona, USA.
- Deadline for submitting abstracts: 18 November, 2013
- 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

European Space Agency

26th European Space Thermal Analysis Workshop 9/11

Workshop

Next year: 28th workshop, 14-15 October 2014

Current workshop:

23 very interesting presentations covering:

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

European Space Agency

27th European Space Thermal Analysis Workshop 10/11

Workshop

Listen, Ask, Discuss

most of all: Enjoy

European Space Agency

27th European Space Thermal Analysis Workshop 11/11

Appendix B

Thermal Concept Design Tool
Flux calculation results and the new tool presentation

Andrea Tosetto Matteo Gorlani
(Blue Engineering, Torino, Italy)

Harrie Rooijackers
(ESA/ESTEC, The Netherlands)

Abstract

During its lifetime the TCDT has evolved both through improvements suggested or required by users all over the ESA member states and enhancements as part of the development and maintenance contract with ESA.
The current release 1.6.0 of the TCDT is already available to the European Thermal Community and contains an internal flux calculator for TCDT models. This flux calculator has been validated through comparison of results with ESATAN-TMS r5.
The evolution of the tool that is now under development will be a portable stand-alone application, independent of Excel, that can be more easily integrated in existing workflows. Skilled engineers will be able to easily extend the tool with their only script, re-using the existing functionality, in order to perform their analysis in an easier way. To maximise the functionality available in the basic tool, participants are invite to discuss their ideas and suggestions with us directly during the breaks or contact us after the workshop.

Thermal Concept Design Tool

Future developments

Andrea Tosetto
Matteo Gorlani
Blue Engineering, Torino, Italy
Harrie Rooijackers
European Space Agency, Noordwijk, The Netherlands

27th European Space Thermal Analysis Workshop
3-4 December 2013, ESA/ESTEC
Sheet 1

Overview

- Background
- TCDT 1.6.0 Flux Calculator: Results Evaluation vs Radiative module of ESATAN-TMS
- Version 2.0: concepts of the new tool

27th European Space Thermal Analysis Workshop
3-4 December 2013, ESA/ESTEC
Sheet 2

Background

NEW DISTRIBUTION & MAINTENANCE CONTRACT STARTED NOVEMBER 2013

- TCDT is distributed FREE of CHARGE to the European Thermal Community
- TCDT web pages available for download, PR, FR
- TCDT is regularly maintained by BLUE
- Small developments are regularly implemented to improve operability
- TCDT version 1.6.0 is available since July 2013

27th European Space Thermal Analysis Workshop
3-4 December 2013, ESA/ESTEC
Sheet 3

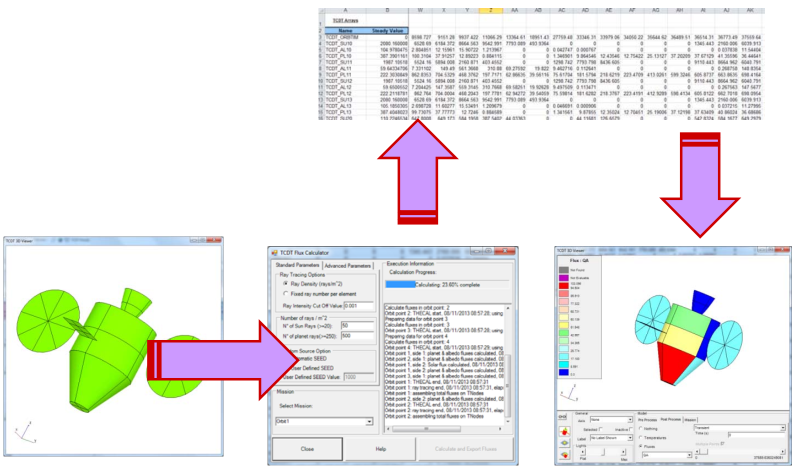
TCDT 1.6.0 Flux Calculator

TCDT 1.6.0 contains a simplified flux calculator algorithm able to evaluate direct absorbed solar, albedo and planet infrared fluxes on the geometrical model surfaces.

The main catacteristics of the TCDT calculator are:

- Direct Incident Fluxes are evaluated with analytical functions
- Shadows are Evaluated with MCRT

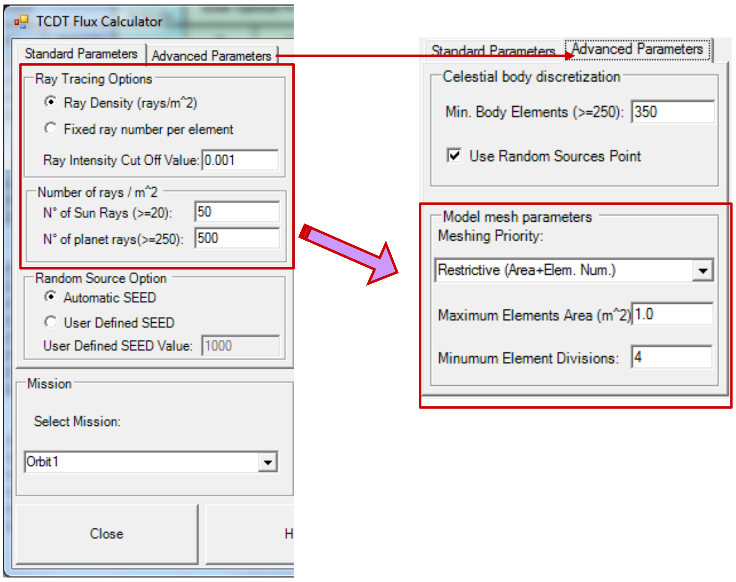
User point of view workflow



27th European Space Thermal Analysis Workshop
3-4 December 2013, ESA/ESTEC
Sheet 4

TCDT 1.6.0 Flux Calculator

The User can access both to the standard parameters and the advanced parameters

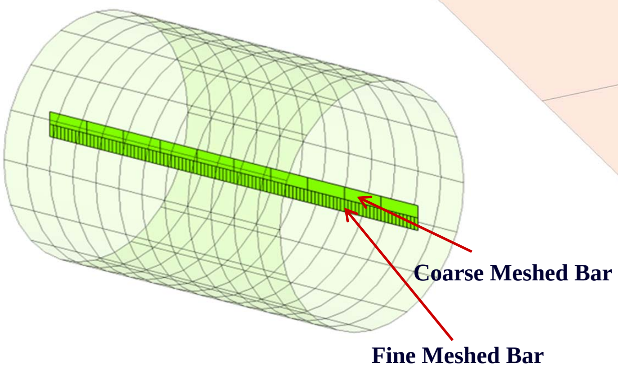


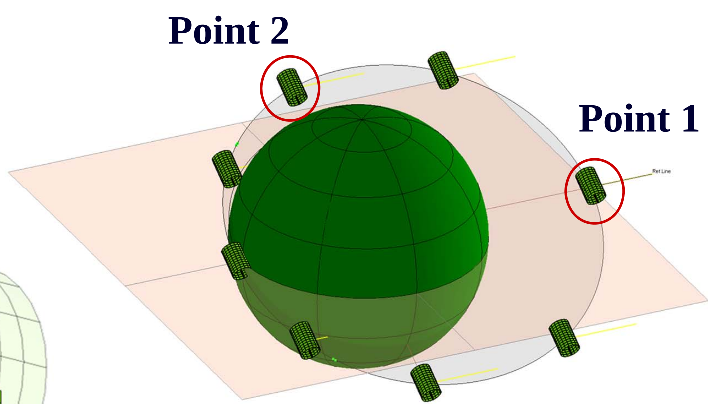
27th European Space Thermal Analysis Workshop
3-4 December 2013, ESA/ESTEC
Sheet 5

TCDT 1.6.0 Flux Calculator: Results Evaluation vs ESARAD

Test Case 1.

Optical properties:
Alpha = 1
Epsilon = 1

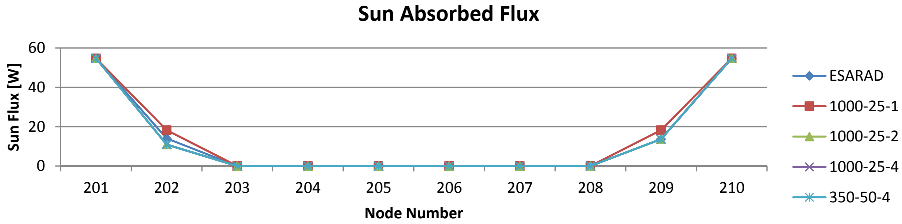




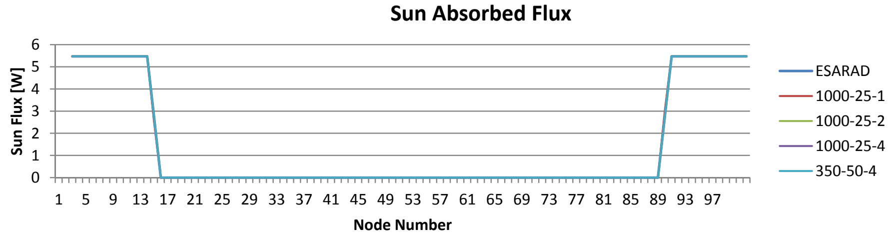
27th European Space Thermal Analysis Workshop
3-4 December 2013, ESA/ESTEC
Sheet 6

TCDT 1.6.0 Flux Calculator: Results Evaluation

Sun Flux Results on Test Point 1



Sun fluxes on the coarse meshed strip.

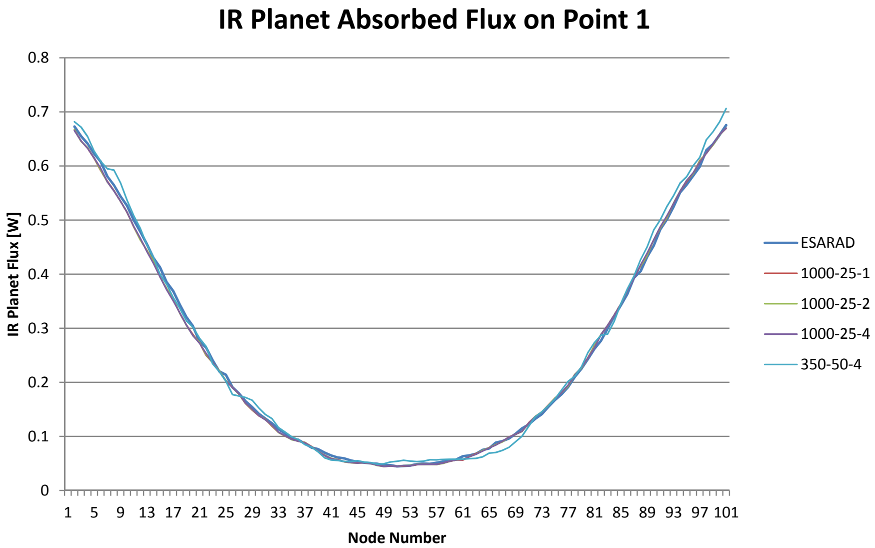


Sun fluxes on the fine meshed strip.

27th European Space Thermal Analysis Workshop
3-4 December 2013, ESA/ESTEC
Sheet 7

esa blue engineering

TCDT 1.6.0 Flux Calculator: Results Evaluation



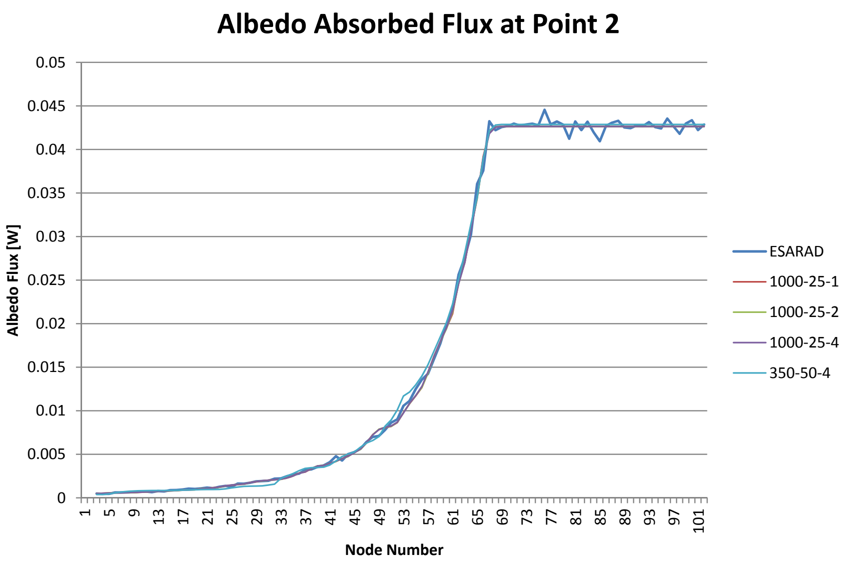
IR Planet fluxes Test Point 1:

Earth flux on the fine meshed strip of the bar using different mesh discretizations.

27th European Space Thermal Analysis Workshop
3-4 December 2013, ESA/ESTEC
Sheet 8

esa blue engineering

TCDT 1.6.0 Flux Calculator: Results Evaluation



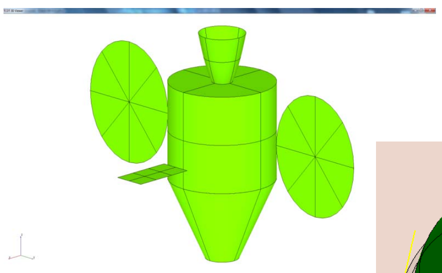
Albedo flux Test Point 2:

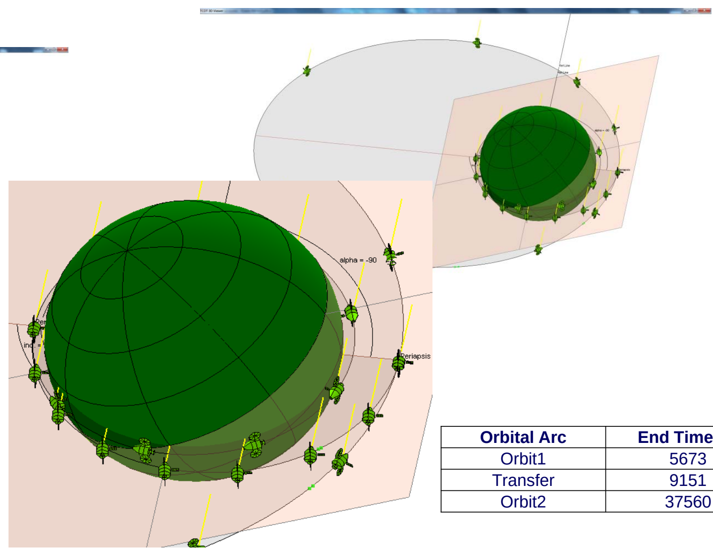
Albedo heat flux on the Z- strip of the bar at different mesh discretizations

27th European Space Thermal Analysis Workshop
3-4 December 2013, ESA/ESTEC
Sheet 9

TCDT 1.6.0 Flux Calculator: Results Evaluation vs ESARAD

Test Case 2.





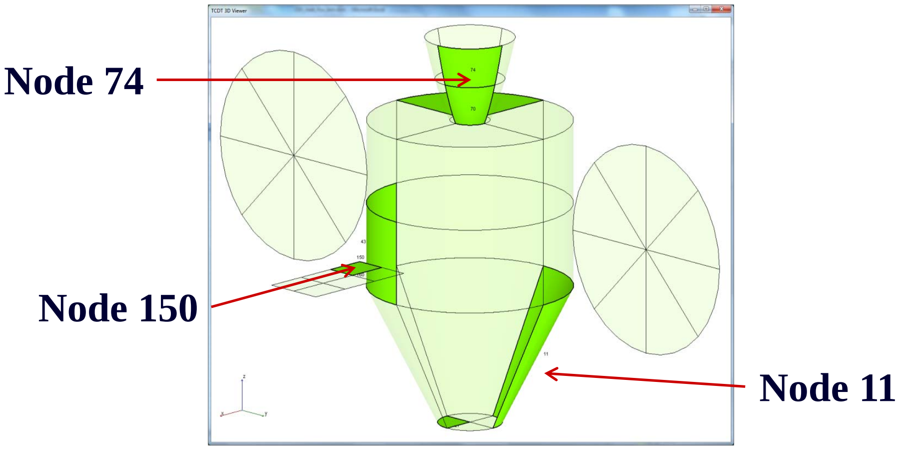
Optical properties:
Alpha = 1
Epsilon = 1

Orbital Arc	End Time (s)
Orbit1	5673
Transfer	9151
Orbit2	37560

27th European Space Thermal Analysis Workshop
3-4 December 2013, ESA/ESTEC
Sheet 10

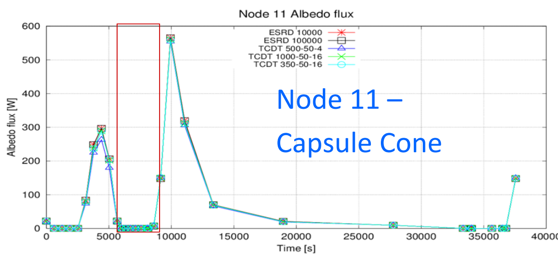
TCDT 1.6.0 Flux Calculator: Results Evaluation

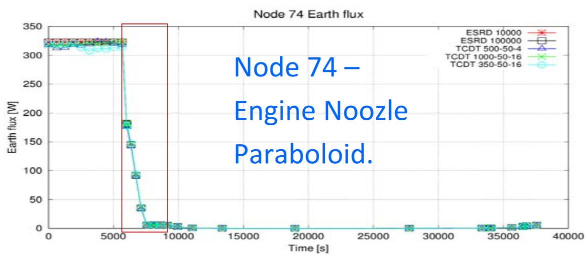
Test Case 2. Results



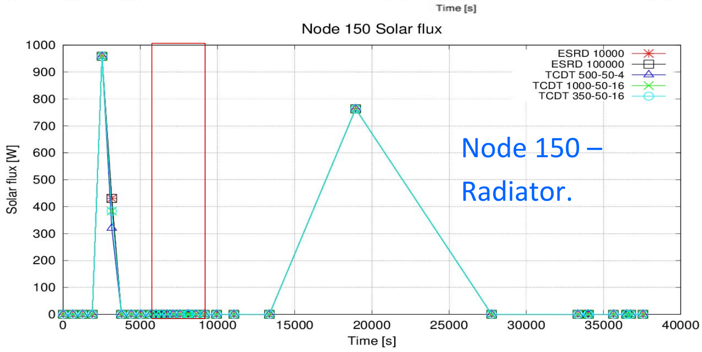
27th European Space Thermal Analysis Workshop
3-4 December 2013, ESA/ESTEC
Sheet 11

TCDT 1.6.0 Flux Calculator: Results Evaluation





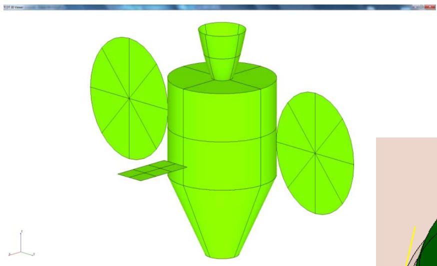
Orbital Arc	End Time (s)
Orbit1	5673
Transfer	9151
Orbit2	37560



27th European Space Thermal Analysis Workshop
3-4 December 2013, ESA/ESTEC
Sheet 12

TCDT 1.6.0 Flux Calculator: Results Evaluation vs ESARAD

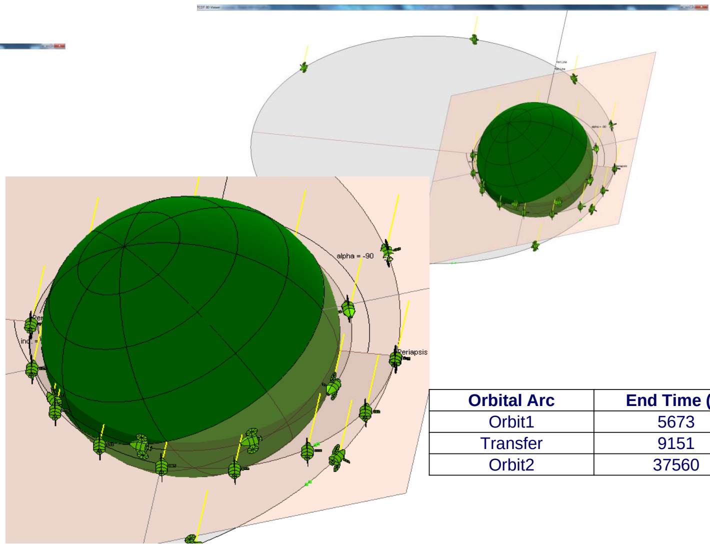
Test Case 2.1



Optical properties:

Alpha = 0.5

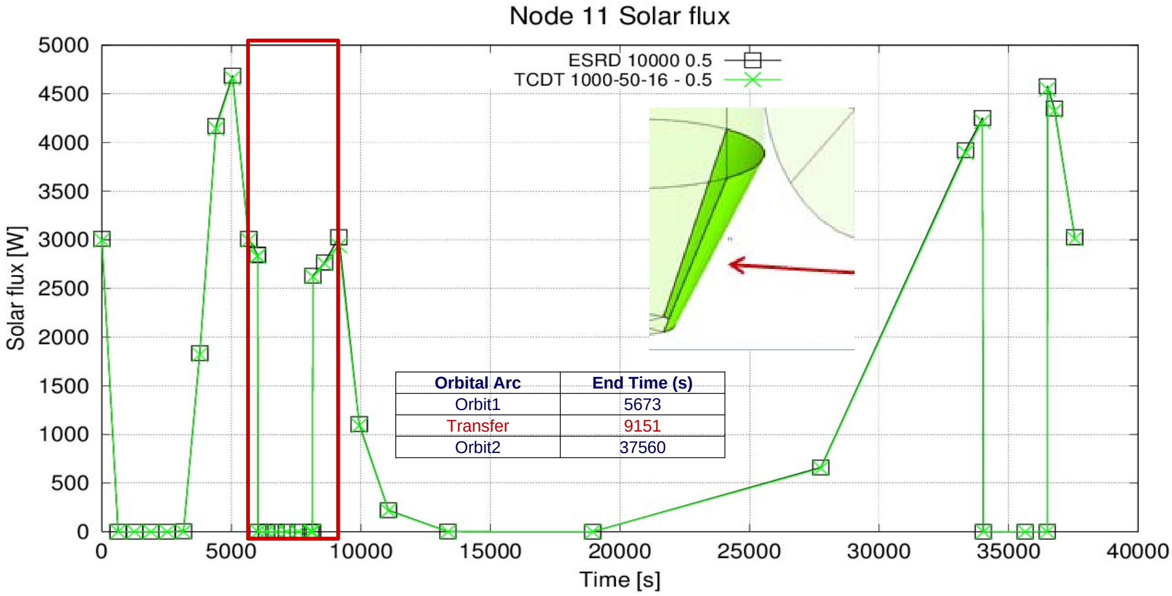
Epsilon = 0.5



Orbital Arc	End Time (s)
Orbit1	5673
Transfer	9151
Orbit2	37560

27th European Space Thermal Analysis Workshop
3-4 December 2013, ESA/ESTEC
Sheet 13

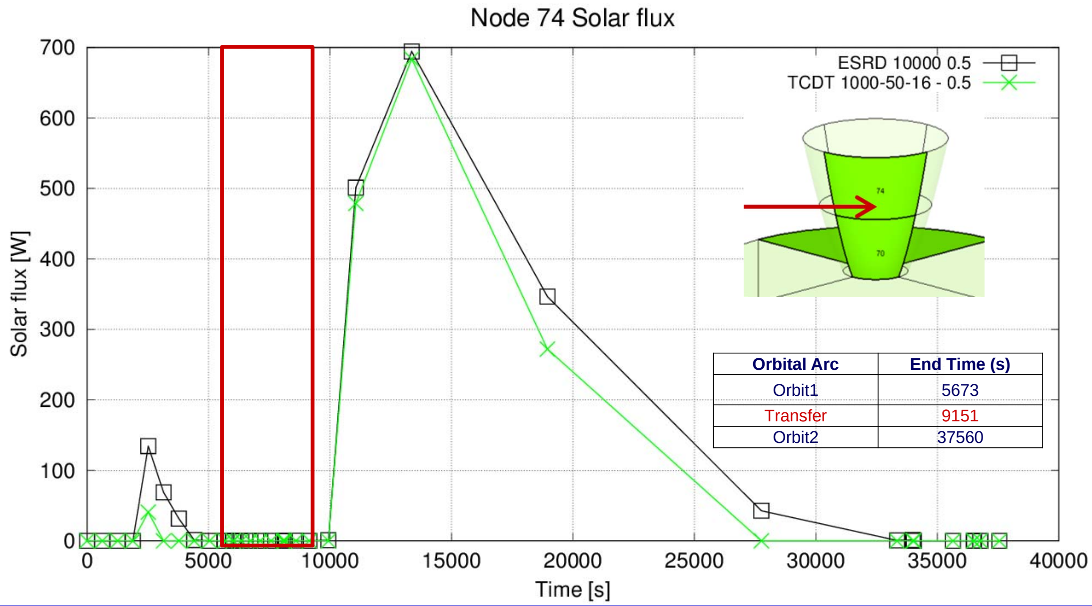
TCDT 1.6.0 Flux Calculator: Results Evaluation



Orbital Arc	End Time (s)
Orbit1	5673
Transfer	9151
Orbit2	37560

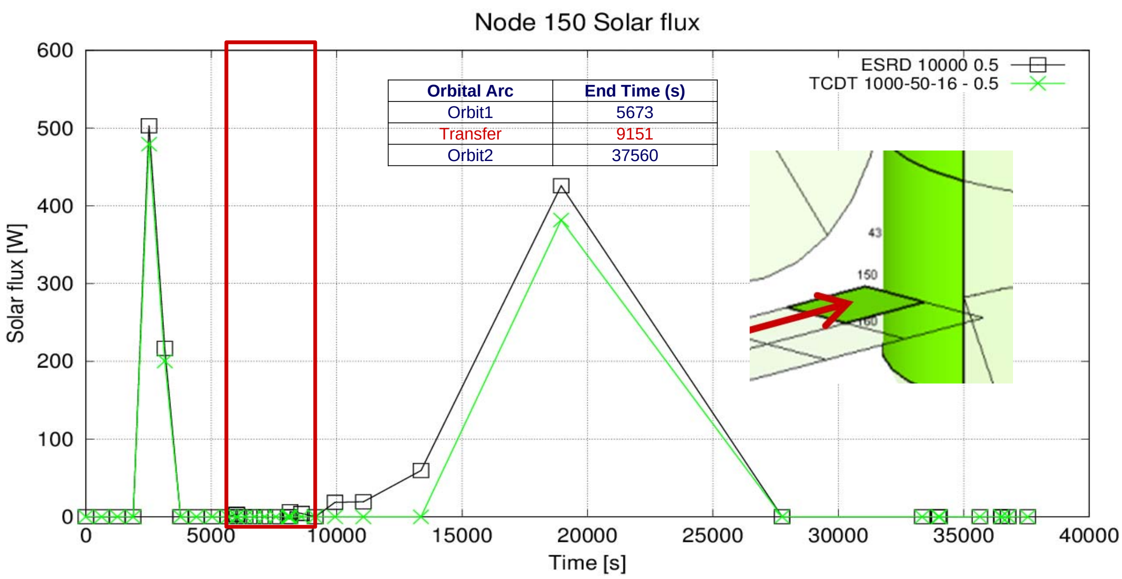
27th European Space Thermal Analysis Workshop
3-4 December 2013, ESA/ESTEC
Sheet 14

TCDT 1.6.0 Flux Calculator: Results Evaluation



27th European Space Thermal Analysis Workshop
3-4 December 2013, ESA/ESTEC
Sheet 15

TCDT 1.6.0 Flux Calculator: Results Evaluation



27th European Space Thermal Analysis Workshop
3-4 December 2013, ESA/ESTEC
Sheet 16

TCDT 1.6.0 Flux Calculator: Results Evaluation

CONCLUSIONS:

The results show a good fit with the ESATAN-TMS results. Care should be taken with low absorption thermo-optical properties

It is possible to note that, due to the complex shapes of the model, an increase of the number of sub-elements used by the TCDT tool generates a better solution

The performances of the TCDT in terms of speed vs ESATAN-TMS vary according the complexity of the model, TCDT is 1 to 4 time slower

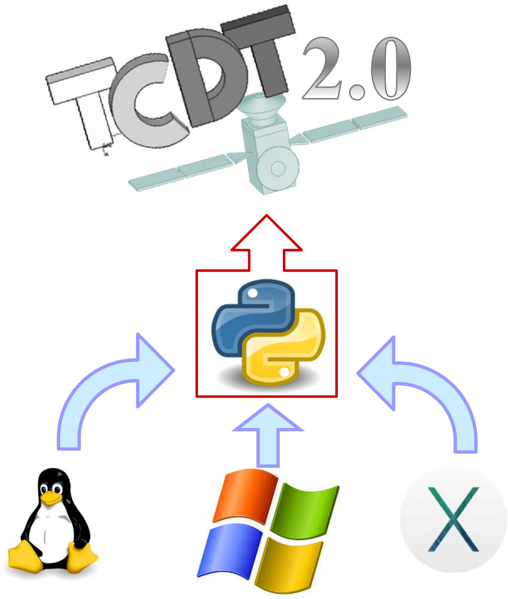
The default parameters provide results that differ slightly from ESATAN-TMS with acceptable performance (averagely 2 times slower)

27th European Space Thermal Analysis Workshop
3-4 December 2013, ESA/ESTEC
Sheet 17

Version 2.0: A New Tool.

Highlights

- Stand Alone
- Multiplatform
- Parametric
- Scriptable
- Extensible



27th European Space Thermal Analysis Workshop
3-4 December 2013, ESA/ESTEC
Sheet 18

Version 2.0: A New Tool.

TCDT 2.0, what is new:

- GUI, workflow.
- TCDT classes, objects and functions will be used in python scripts within the GUI or externally.
- User skilled in python can make their own scripts to automate processes.

27th European Space Thermal Analysis Workshop
3-4 December 2013, ESA/ESTEC
Sheet 19

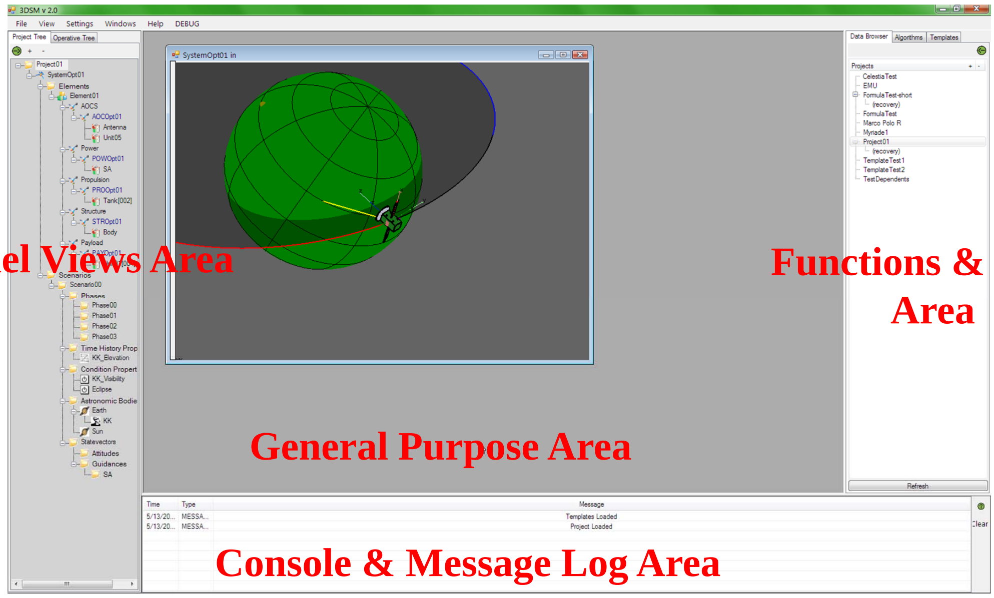
Version 2.0: A New Tool.

TCDT 2.0, inherited features:

- TCDT will be full parametric.
- Basic users can manage the TCDT with a short learning curve.
- Skilled users can customize the TCDT and make their own scripts to automatize processes.

27th European Space Thermal Analysis Workshop
3-4 December 2013, ESA/ESTEC
Sheet 20

Version 2.0: A New Tool.



27th European Space Thermal Analysis Workshop
3-4 December 2013, ESA/ESTEC
Sheet 21

esa blue engineering

Version 2.0: A New Tool.

Functionalities that will be transferred to the new version:

- **Thermal community suggestions: SURVEY**

- Base classes development
- THECAL Model Based and non Model based functions
- GUI for THECAL functions

- GTMM data structure and GUI
- External Tools Managements

27th European Space Thermal Analysis Workshop
3-4 December 2013, ESA/ESTEC
Sheet 22

esa blue engineering

TCDT 2.0

TCDT Team

DISTRIBUTION & MAINTENANCE

BLUE ENGINEERING S.R.L.

Matteo Gorlani - Project Manager
m.gorlani@blue-group.it
Andrea Tosetto - Software Development
a.tosetto@blue-group.it
Support
tcdtsw@blue-group.it

Blue Group - Engineering & Design
WEB: http://www.blue-group.it

ESA - ESTEC

Benoit Laine - Head of Thermal Analysis and Verification Section
Benoit.Laine@esa.int
Dr. Harrie Rooijackers - Project Manager
harrie.rooijackers@esa.int

ESTEC-D/TEC-MTV
WEB: http://www.esa.int

WEB: www.blue-group.it/TCDT
EMAIL: tcdtsw@blue-group.it

27th European Space Thermal Analysis Workshop
3-4 December 2013, ESA/ESTEC
Sheet 23

TCDT 2.0

Version 2.0: A New Tool.

Workshop Survey:

http://www.blue-group.it/TCDT/survey.php

27th European Space Thermal Analysis Workshop
3-4 December 2013, ESA/ESTEC
Sheet 24


TCDT 2.0
Version 2.0:
A New Tool.
Workshop Survey:
Alternative url:
https://docs.google.com/spreadsheet/viewform?usp=drive_web&formkey=dHZLQ3dwREQ1bEFOVFltaDNWeGVuX0E6MA#gid=0
27th European Space Thermal Analysis Workshop
3-4 December 2013, ESA/ESTEC
Sheet 25
esa
blue engineering

Appendix C

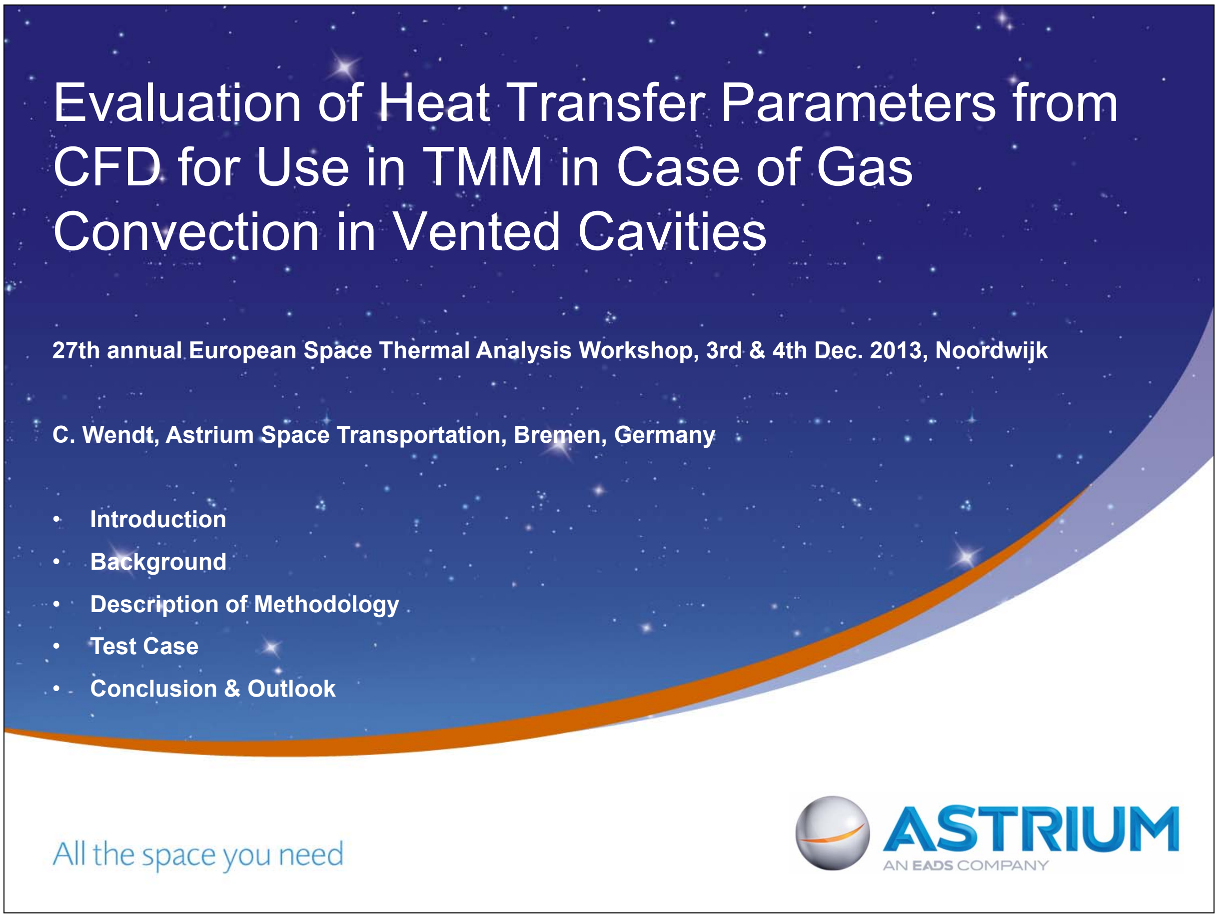
Evaluation of Heat Transfer Parameters from CFD for Use in TMM in Case of Gas Convection in Vented Cavities

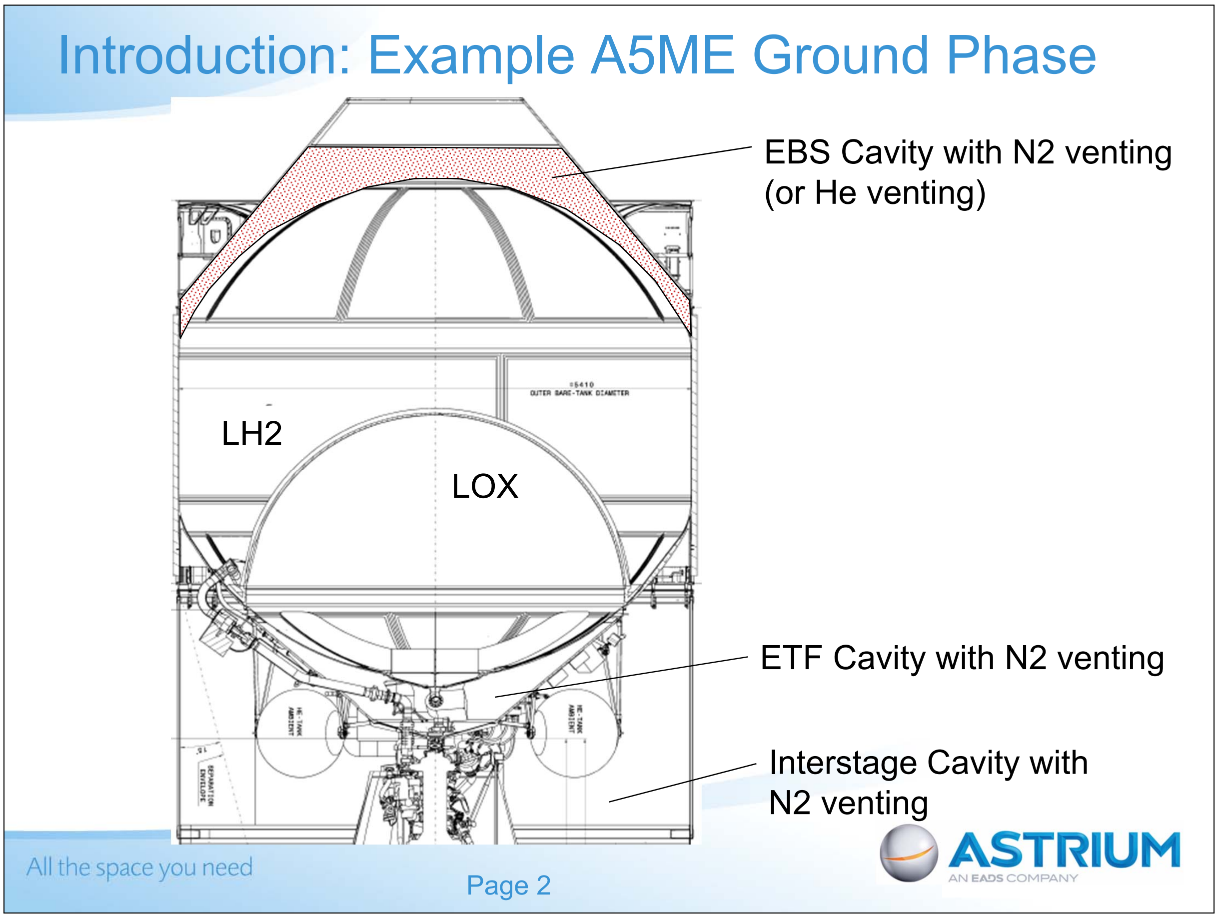
Christian Wendt
(Astrium Space Transportation, Bremen, Germany)

Abstract

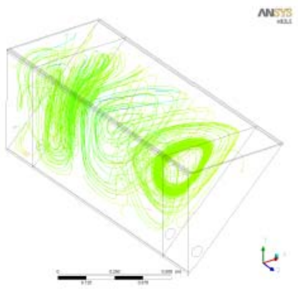
The analysis of the convection in Ariane 5 launcher's vented cavities on ground and during ascent is important for the thermal control of the equipments and of the propellants during flight phase. For the according analysis of the upper stage, a lumped parameter Thermal Mathematical Model (TMM) has been established within ESATAN.

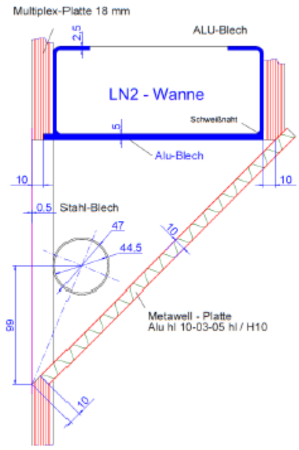
As an input, heat transfer parameters (HTPs) have been derived from two related Computational Fluid Dynamic (CFD) analysis cases, the so called hot and cold case. The methodology for evaluation of these HTPs from the CFD analysis is described for one and more gas nodes based on steady state results. For a representative launcher cavity with laminar/turbulent buoyancy influenced flow, a comparison is provided between the TMM results and the CFD results obtained with the commercial tool ANSYS Fluent. Exact agreement is achieved between TMM and CFD for the hot and the cold case. Deviations for the analyzed intermediate cases turned out to be less than 5K in case of a one gas node TMM and less than 3K in case of a seven gas node TMM.

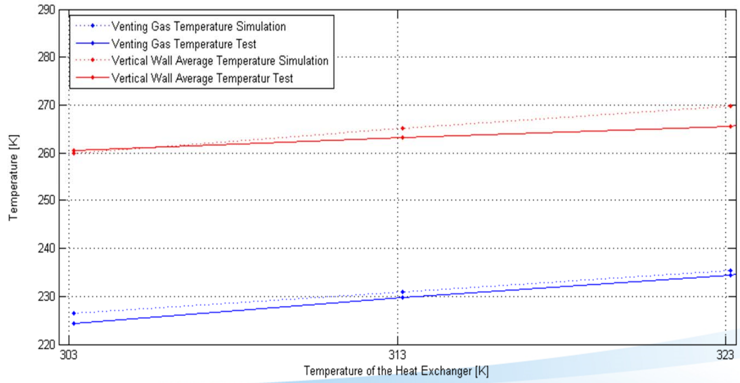

Evaluation of Heat Transfer Parameters from CFD for Use in TMM in Case of Gas Convection in Vented Cavities
27th annual European Space Thermal Analysis Workshop, 3rd & 4th Dec. 2013, Noordwijk
C. Wendt, Astrium Space Transportation, Bremen, Germany
• Introduction
• Background
• Description of Methodology
• Test Case
• Conclusion & Outlook
All the space you need
ASTRIUM
AN EADS COMPANY


Introduction: Example A5ME Ground Phase
EBS Cavity with N2 venting
(or He venting)
LH2
LOX
ETF Cavity with N2 venting
Interstage Cavity with
N2 venting
All the space you need
Page 2
ASTRIUM
AN EADS COMPANY

Background: Check of CFD with Cryo-Tests







- N2 vented cavity with a simplified typical geometry
- Variable temperature of heat exchanger to realize several test cases
- Good agreement between CFD and test

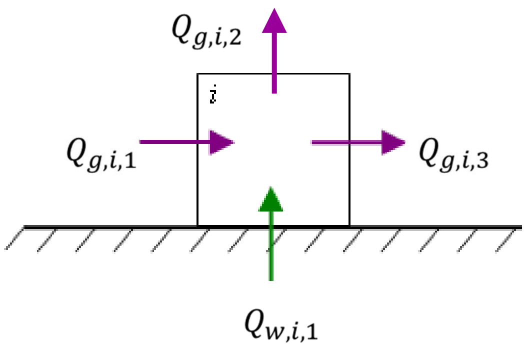
All the space you need

Page 3

ASTRIUM AN EADS COMPANY

Method: Approach for HTPs from CFD

- Two CFD results: Hot and cold case (more intervals possible)
- Steady state:
  - Sum of all heat fluxes entering the gas is zero
  - For more than one gas node $0 = \sum_k Q_{w,i,k} + \sum_k Q_{g,i,k}$



All the space you need

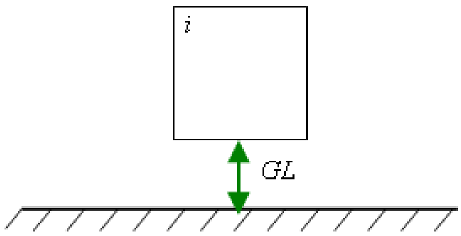
Page 4

ASTRIUM AN EADS COMPANY

Method: Gas/Wall Heat Transfer ⇒ GLs from CFD

$$GL_{w,i}^{cold} = \frac{Q_{w,i}^{cold}}{T_i^{cold} - T_{w,i}^{cold}} \qquad GL_{w,i}^{hot} = \frac{Q_{w,i}^{hot}}{T_i^{hot} - T_{w,i}^{hot}}$$

$$\Rightarrow \quad GL_{w,i} = GL_{w,i}^{cold} + \frac{GL_{w,i}^{hot} - GL_{w,i}^{cold}}{\dot{m}_{in}^{hot} - \dot{m}_{in}^{cold}} \cdot (\dot{m}_{in} - \dot{m}_{in}^{cold})$$



All the space you need

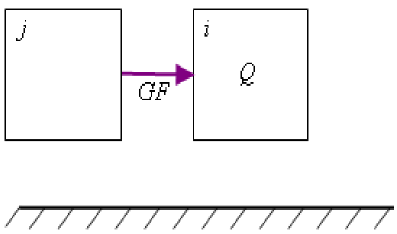
Page 5

Method: Gas/Gas Heat Transfer ⇒ GFs and Qs from CFD

$$Q_{g,i}(T_i, T_j) = Q_{g,i}^{cold} + \frac{Q_{g,i}^{hot} - Q_{g,i}^{cold}}{(T_j^{hot} - T_i^{hot}) - (T_j^{cold} - T_i^{cold})} \left[(T_j - T_i) - (T_j^{cold} - T_i^{cold}) \right]$$

$$\Rightarrow \quad GF_i = \frac{Q_{g,i}^{hot} - Q_{g,i}^{cold}}{(T_j^{hot} - T_i^{hot}) - (T_j^{cold} - T_i^{cold})}$$

$$\Rightarrow \quad Q_i = Q_{g,i}^{cold} - \frac{Q_{g,i}^{hot} - Q_{g,i}^{cold}}{(T_j^{hot} - T_i^{hot}) - (T_j^{cold} - T_i^{cold})} \cdot (T_j^{cold} - T_i^{cold})$$



All the space you need

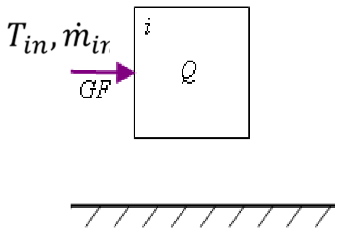
Page 6

Method: Venting Inlet/Gas Heat Transfer ⇒ GFs and Qs from CFD

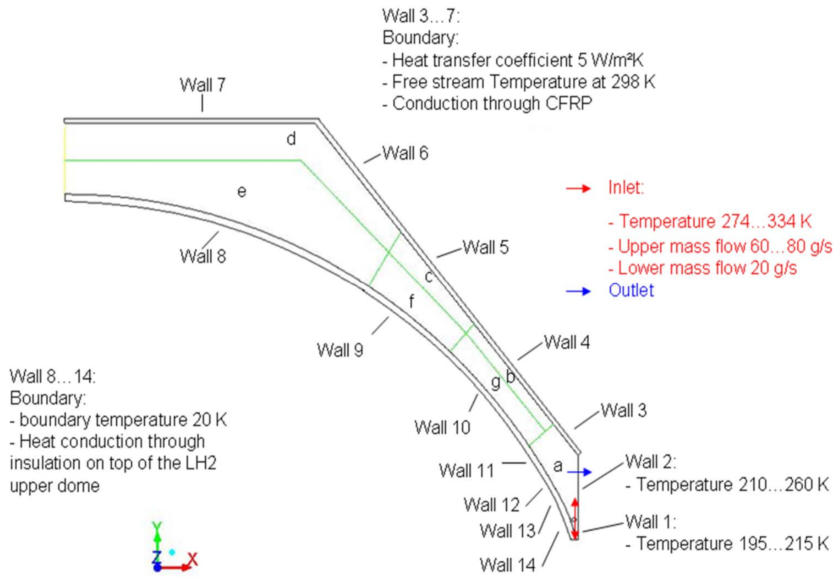
$$Q_{g,i}(\dot m_{in},T_{in},T_i)=Q_{g,i}^{cold}+\frac{Q_{g,i}^{hot}-Q_{g,i}^{cold}}{\dot m_{in}^{hot}(T_{in}^{hot}-T_i^{hot})-\dot m_{in}^{cold}(T_{in}^{cold}-T_i^{cold})}\left[\dot m_{in}(T_{in}-T_i)-\dot m_{in}^{cold}(T_{in}^{cold}-T_i^{cold})\right]$$

$$\Rightarrow \quad GF_i=\dot m_{in}\frac{Q_{g,i}^{hot}-Q_{g,i}^{cold}}{\dot m_{in}^{hot}(T_{in}^{hot}-T_i^{hot})-\dot m_{in}^{cold}(T_{in}^{cold}-T_i^{cold})}$$

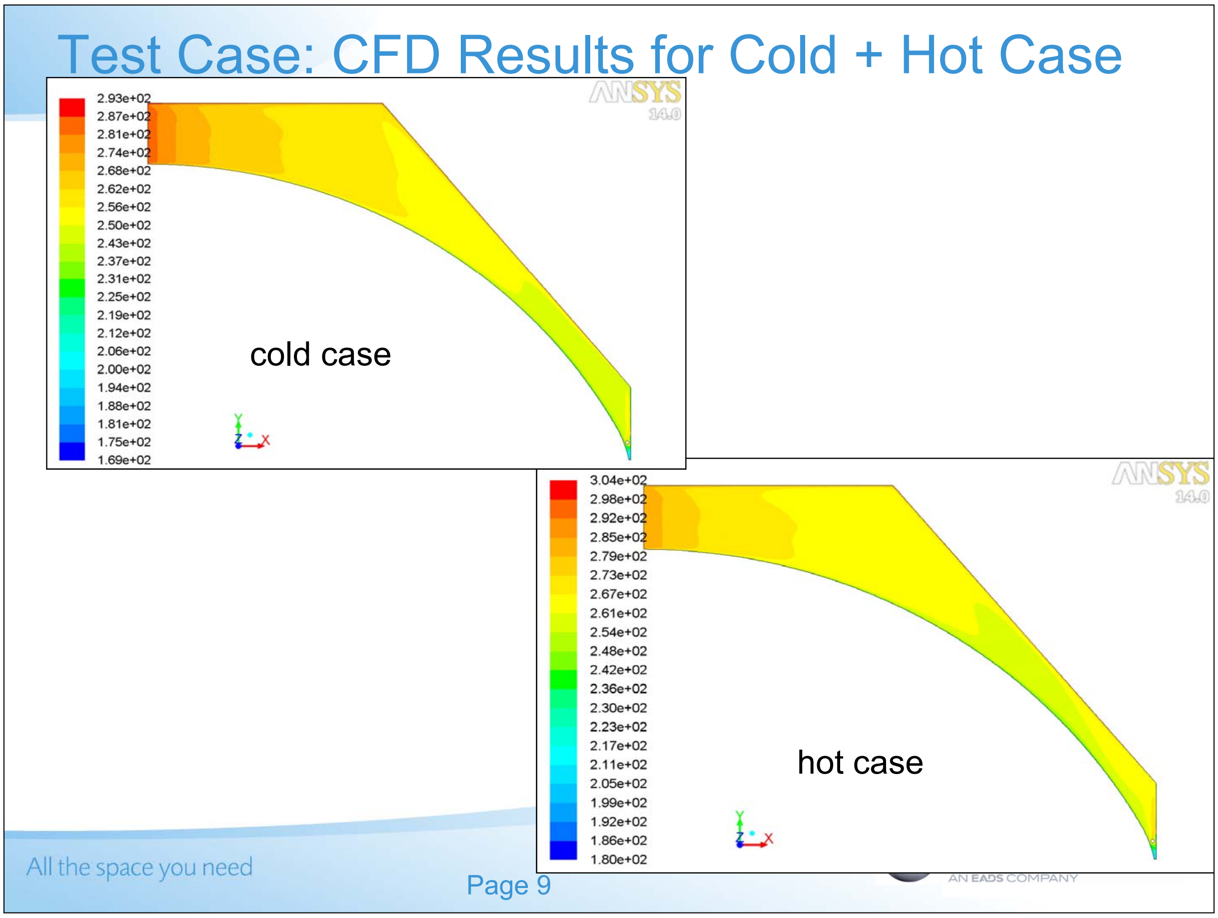
$$\Rightarrow \quad Q_i=Q_{g,i}^{cold}-\frac{Q_{g,i}^{hot}-Q_{g,i}^{cold}}{\dot m_{in}^{hot}(T_{in}^{hot}-T_i^{hot})-\dot m_{in}^{cold}(T_{in}^{cold}-T_i^{cold})}\cdot\dot m_{in}^{cold}\cdot(T_{in}^{cold}-T_i^{cold})$$

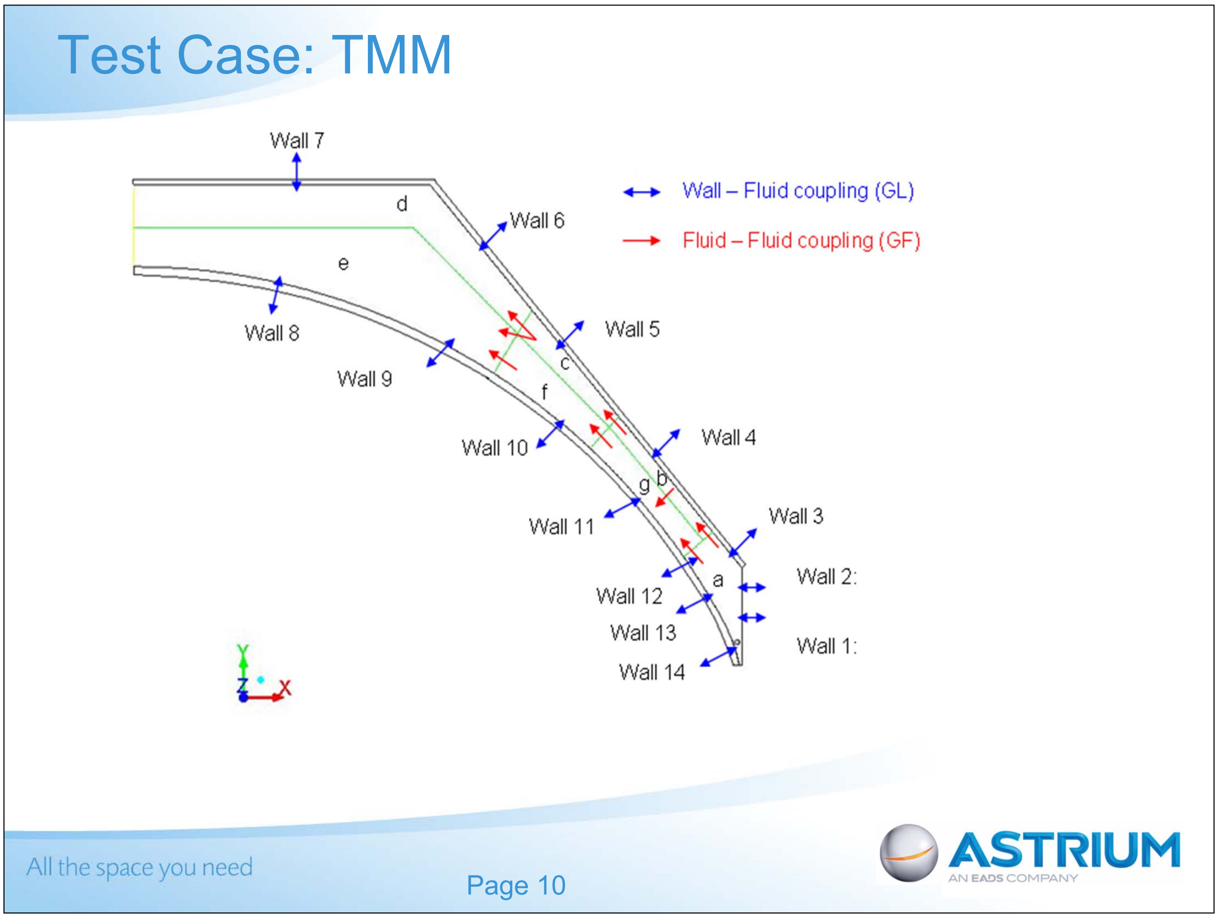


Test Case: EBS Cavity

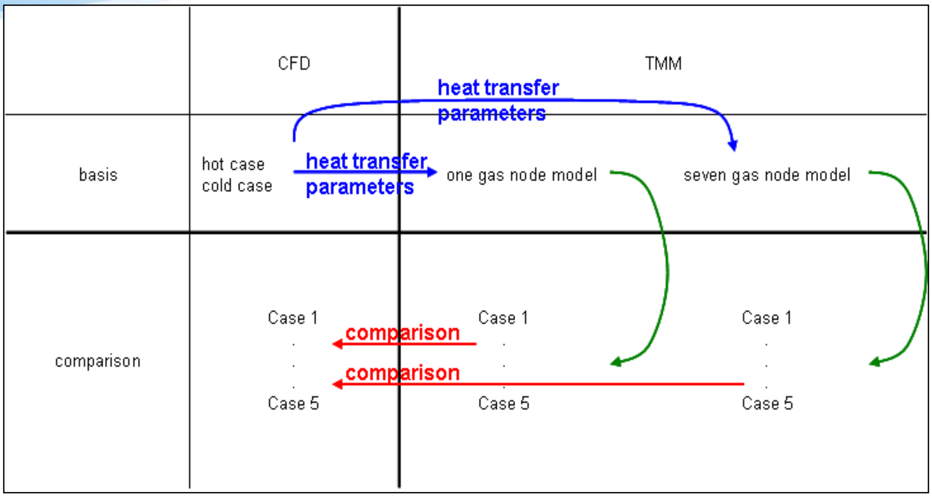


Description	Temperature Wall 1 [K]	Temperature Wall 2 [K]	Mass Flow Temperature [K]	Mass Flowrate up [g/s]
cold	200	220	294	60
hot	210	250	314	80


Test Case: CFD Results for Cold + Hot Case
cold case
hot case
All the space you need
Page 9
AN EADS COMPANY


Test Case: TMM
Wall – Fluid coupling (GL)
Fluid – Fluid coupling (GF)
Wall 7
Wall 6
Wall 5
Wall 4
Wall 3
Wall 2:
Wall 1:
Wall 8
Wall 9
Wall 10
Wall 11
Wall 12
Wall 13
Wall 14
All the space you need
Page 10
ASTRIUM
AN EADS COMPANY

Test Case:Comparison between TMM and CFD



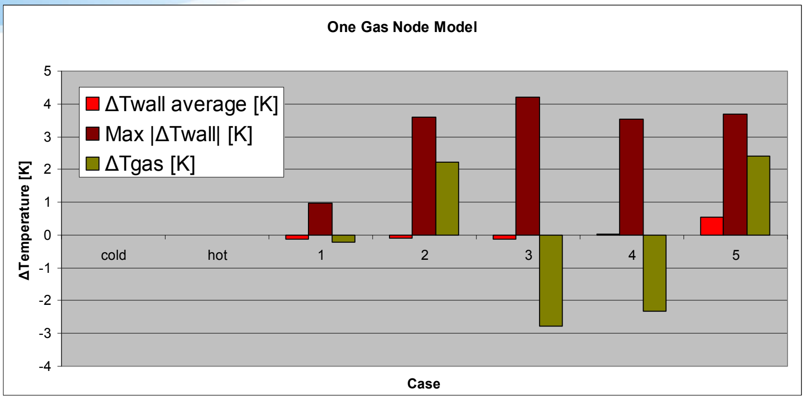
Case Nr.	Temperature Wall 1 [K]	Temperature Wall 2 [K]	InletTemperature [K]	Mass Flowrate up [g/s]
1	205	235	304	70
2	205	235	314	60
3	205	235	294	80
4	195	210	274	60
5	215	260	334	80

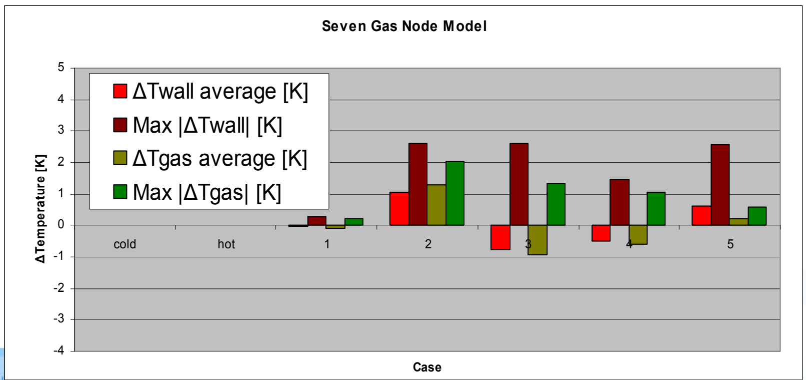
All the space you need

Page 11

ASTRIUM
AN EADS COMPANY

Test Case:Comparison between TMM and CFD





All the space you need

Page 12

ASTRIUM
AN EADS COMPANY

Conclusion & Outlook

- Methodology for transfer from CFD to TMM explained for vented cavities
- Comparison beween TMM and CFD showed good overall agreement for EBS Cavity for the One Node and Seven Nodes Model as well: Seven Gas Node Model about ~40% better than One Gase Node Model

	One Node Model	Seven Node Model
maximum temperature deviation	~4K	~2.5K
maximum LH2 heat flux deviation	~1%	~0.5%

- Method is currently enhanced to include time dependency, as needed e.g. for propellant stratification phenomena

All the space you need

Page 13

ASTRIUM
AN EADS COMPANY

Appendix D

Introduction to Simulation Data Management

Peter Bartholomew
(MDAO Technologies, United Kingdom)

Abstract

This presentation will give an introduction to the topic of Simulation Data Management. This is currently a hot topic in industrial areas such as automotive or aeronautics, however, for the space thermal analysis community it is still quite new. The objective of the presentation is to give an overview of the field and to stimulate discussion about how space thermal analysis models could be managed and how the analysis tools could be developed to facilitate this.

An introduction to Simulation Data Management

Peter Bartholomew
(MDAO Technologies Ltd UK)

Background

- Consultancy relating to data management issues across the traditional mechanical engineering disciplines
  - (e.g. structures, thermal, mechanisms, propulsion)
  - and also the link between those disciplines and Systems Engineering
  - includes test results
- Organisational scope potentially includes
  - Specific departments within ESTEC
  - Technical support contractors
  - Deliverables from supply chain companies

Phase I – Discussion with ESTEC

- Capture of requirements
  - review existing methods used for identifying and accessing data – (hidden metadata†)
  - Priority
    - internal processes
    - Interaction with industry
- Existing initiatives to be accommodated
- Relationship with supply chain
  - What is delivered
  - Who owns data and IP
  - Access and Distribution rights

†Metadata = "data about data" *or* "the things you know about your data"

Phase II – Supply chain companies

- Gain understanding of the data management processes being introduced within industry
  - Where you would see the master data residing
    - Location
    - Software
  - How to apply metadata to information held at remote sites

Phase III – Vendor companies

- Match vendor offerings against requirements

alternatively

- Identify contributing technologies and discuss options with relevant domain experts

Core Requirements

Simulation Data Management

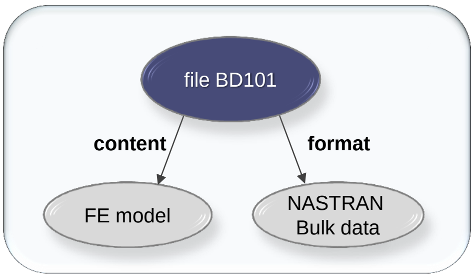
The need to define the SDM domain

- SDM is an emerging technology
- What constitutes SDM was thought to be understood
  - but we rapidly discovered that different people had different understandings of the definition
- High level definition:
  - **Simulation Data Management (SDM)** is a breakthrough technology which uses database solutions to enable users to manage simulation data and processes across the complete product lifecycle
- Capabilities defined under 3 headings
  - Data
  - Access
  - Security and Integrity

Classification of data items

For any data object / file we need to know

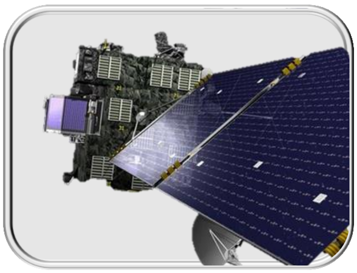
- What it represents – examples being:
  - Shape information of product
  - Pressure distribution over shape
- What format is used
  - STEP AP 203
  - Nastran bulk data
- Administrative: owner, creation date, ILM info.



- Classification is required to identify Data items

Links to product

For each data item links are needed to tie it back to the real world objects it represents:



- For some this will imply a link to PLM
- For others, simulation precedes CAD and the link may be to an SDM object or other business object

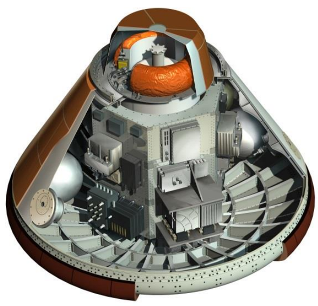
This includes loading environment with the relevant service/test cases recorded

- **Links are required between the simulation and real world objects**

Capture of process

Confidence in an engineering simulation requires an understanding of the process

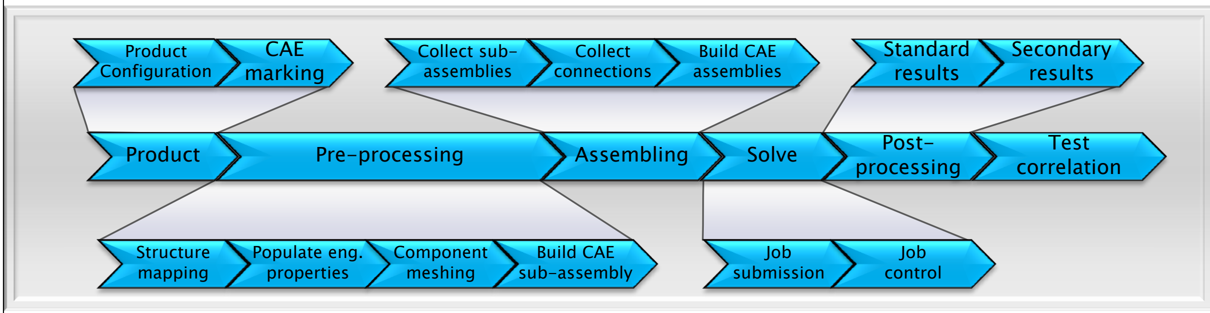
- What codes were used?
- What product (and product configuration) was analysed?
- What loading scenarios were modelled?



- Who performed the analysis?
- What past experience did they have?
- Is there service or test information available for similar products?
- What degree of correlation is achieved with analysis?

Simulation Process

The processes are often complex multi-step sequences



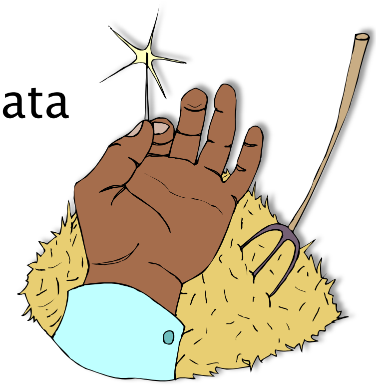
Complex CAE process – Ulrich Fox, Ford
NAFEMS SDM Conference, Frankfurt November 2010

- The process context needs to be recorded
  - to provide an audit trail for verification and
  - to support navigation as a means for search

User access and search

Even if you have annotated data and know what it is…

… can you find it?



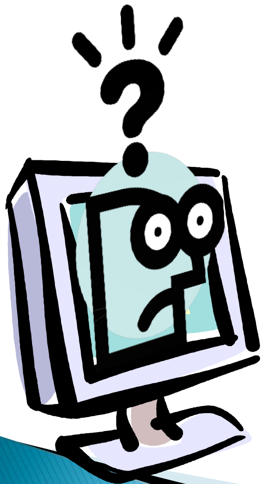
- Both keyword search (metadata & files) and navigation are needed to locate data items

- Both metadata and vaulted data files must be directly accessible to the user

Access – software application

The data management may be expected to underpin higher level functionality

- The metadata must be machine intelligible



Typically this is achieved through building a web of relationships between data objects, including:

- the classes they belong to
- project identifiers
- the processes that created them
- the team conducting the work and their clients

Integrity

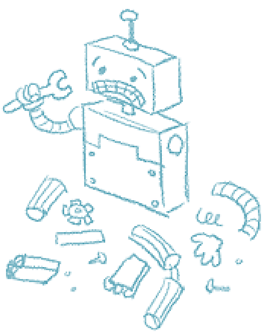
Integrity requirements are standard features of relational databases

Entity integrity

- requires there to be a unique identifier for every information object

Referential integrity

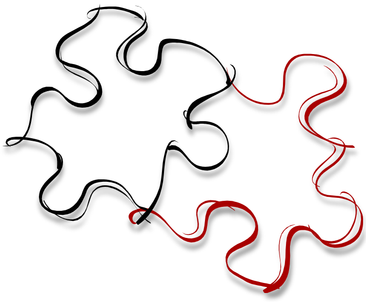
- requires that no references to missing data should exist
- *it is the lack of Referential integrity in the WWW that gives rise to Error 404 (and pain)*



Integrity

To achieve this both data and metadata must only be accessible through the SPDM system

- the user cannot be expected to create unique identifiers
- metadata needs to be protected from uncontrolled deletion to avoid a breakdown of referential integrity



(It will be necessary to delete data objects but essential metadata should be maintained and the policy/authority for their deletion should be recorded)

- **The system must ensure its own integrity, in particular entity and referential integrity**

Security

Companies will have procedures in place to control the release of their data by denying unauthorised access to data objects

- **It is required that an SDM system work within the constraints of corporate security and business rules**

(It may be possible to supply an alternative system to many clients provided it offers an equivalent level of security)

Core requirements – summary

Data Items: Metadata

1. SDM needs to manage and classify data items in all CAE formats
2. Data Items need to be linked back to real world objects
3. Process context needs to be recorded

Data Access: Function

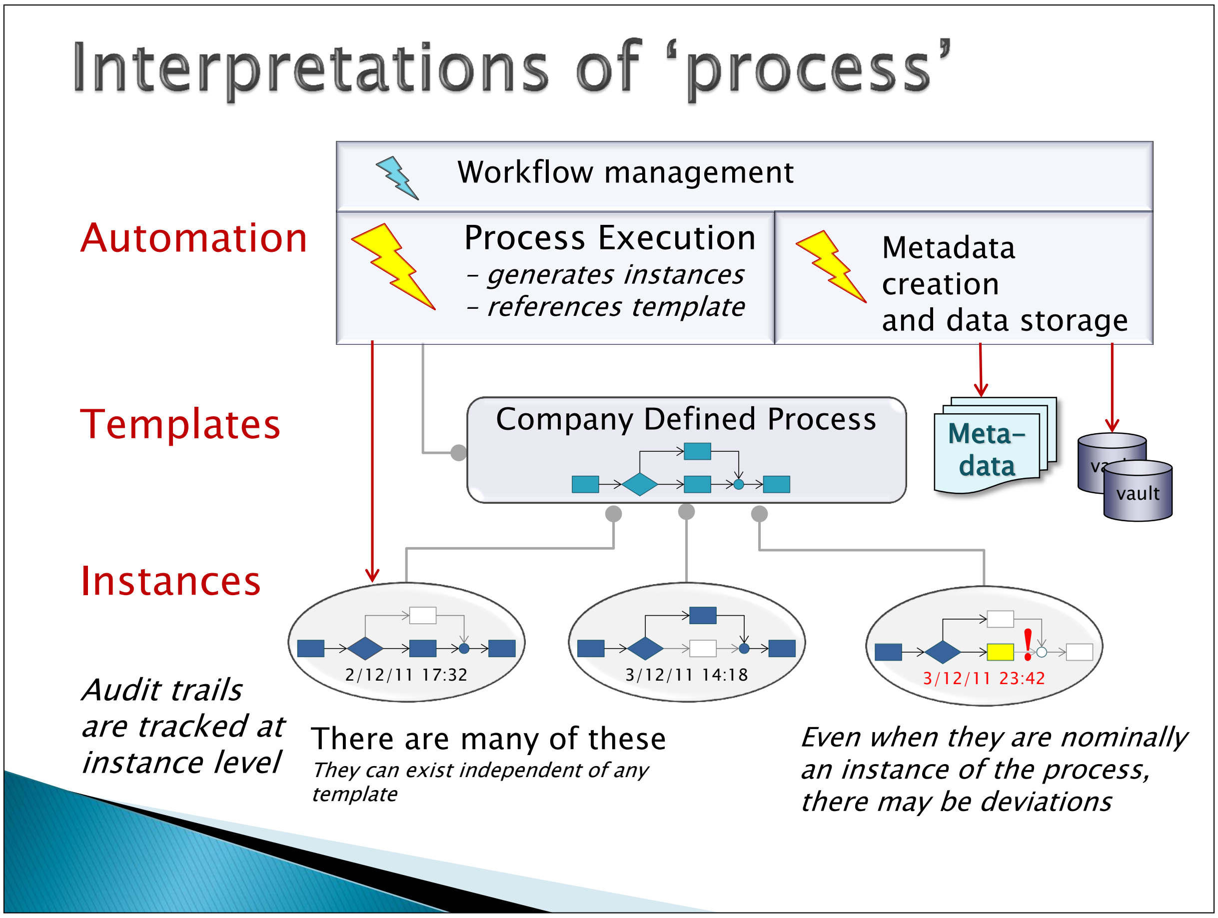
4. It should be accessible to human beings *Search*
5. It should be available to software applications *Database*

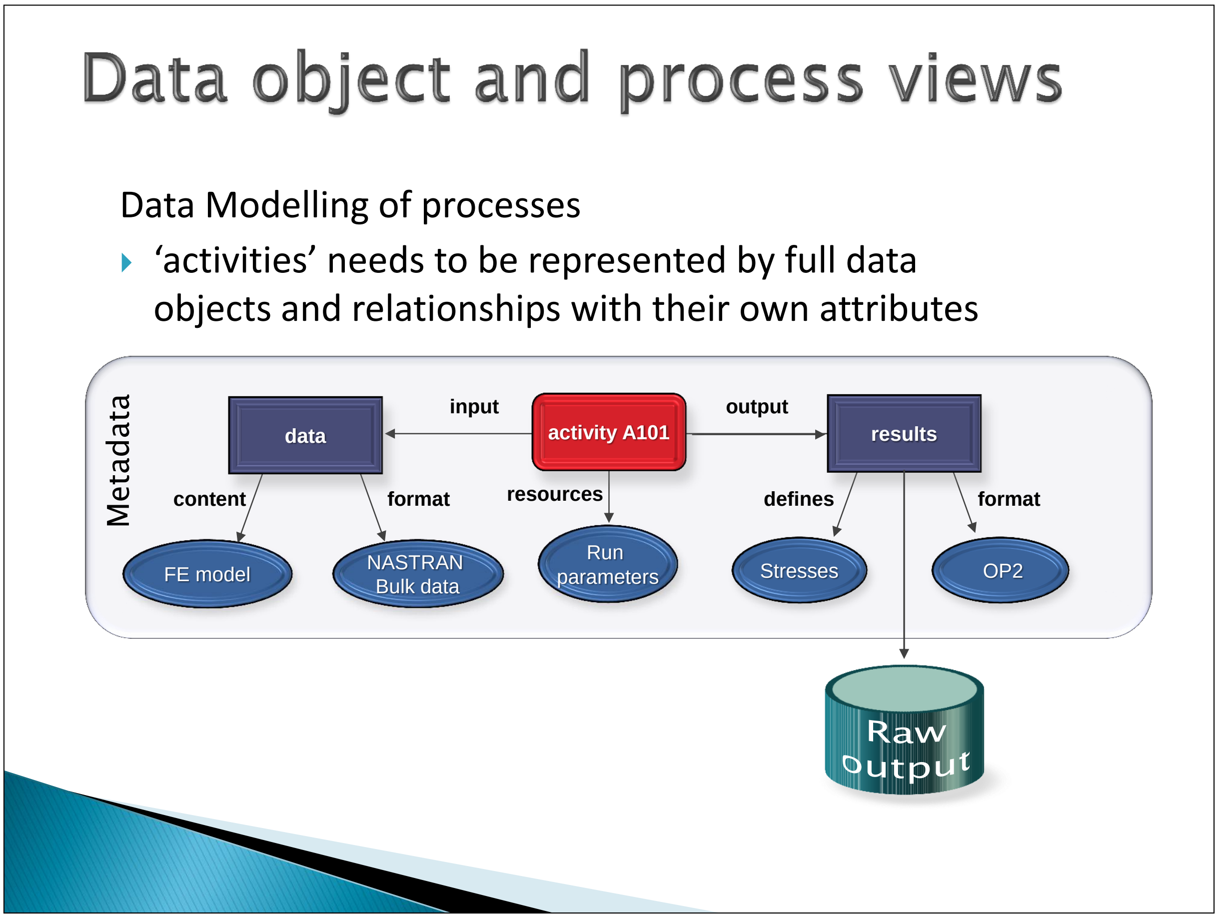
Security & integrity:

6. The system should maintain the consistency of data sets
7. The system must comply with business and security rules

PROCESS

Simulation Data Management


Interpretations of 'process'
Workflow management
Automation
Process Execution
– generates instances
– references template
Metadata
creation
and data storage
Templates
Company Defined Process
Meta–
data
vault
Instances
2/12/11 17:32
3/12/11 14:18
3/12/11 23:42
Audit trails
are tracked at
instance level
There are many of these
They can exist independent of any
template
Even when they are nominally
an instance of the process,
there may be deviations


Data object and process views
Data Modelling of processes
'activities' needs to be represented by full data
objects and relationships with their own attributes
Metadata
data
input
activity A101
output
results
content
format
resources
defines
format
FE model
NASTRAN
Bulk data
Run
parameters
Stresses
OP2
Raw
output

Solution Approaches

Simulation Data Management

Solution Strategies

Software packages – compatibility with industry?

1. PLM systems
   – CAD focus with enhancements
2. Simulation Process Data Management systems
   – engineering analysis focus, data and process

Emerging technology

3. Links between objects defined using Semantic Web technologies
   (the W3C standard for the semantic web uses RDF triples)
   – supports semantic search
   – computer interpretable

Questions?

Web of simulation information

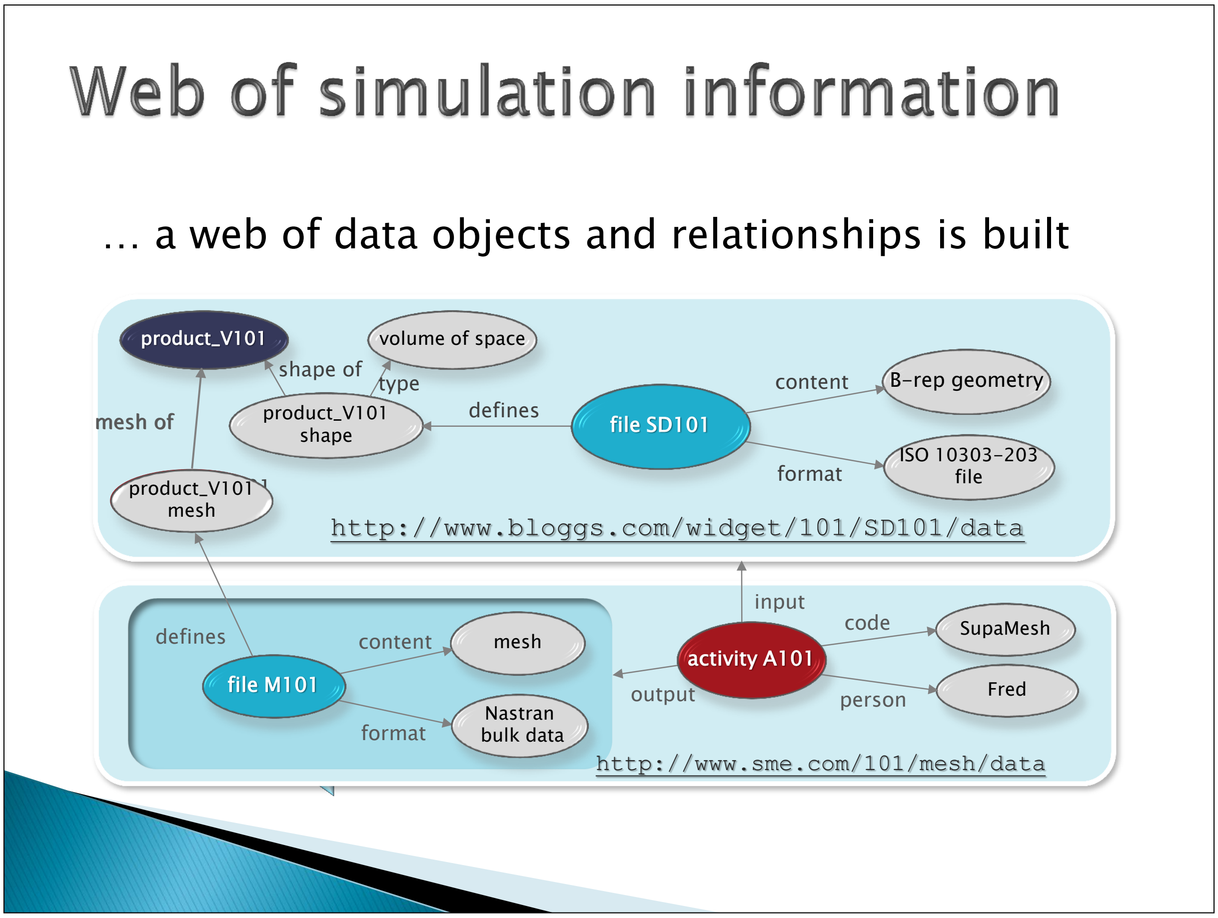
Through a sequence of simple business transactions…

Bloggs and Co, puts data set SD_v101 on the Web

"Hi Fred – can you define *widget_V101 mesh* using the data in http://www.bloggs.com/widget/101/SD101/data"

"Done – see the data file http://www.sme.com/101/mesh/data"

The analysis supplier uses it


Web of simulation information
… a web of data objects and relationships is built
product_V101
volume of space
shape of
type
content
B-rep geometry
mesh of
product_V101 shape
defines
file SD101
format
ISO 10303-203 file
product_V101 mesh
http://www.bloggs.com/widget/101/SD101/data
input
defines
content
mesh
code
SupaMesh
activity A101
file M101
output
person
Fred
format
Nastran bulk data
http://www.sme.com/101/mesh/data

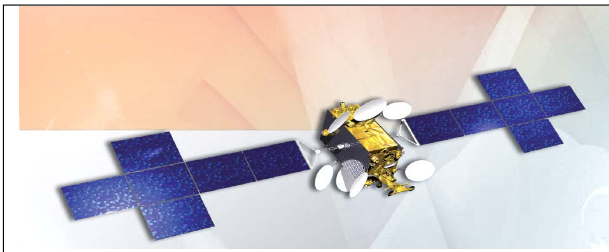
Appendix E

EVATHERM for Early Validation of Thermal Control

Fabrice Mena
(Astrium SAS, France)

Abstract

Commercial telecommunication programs require a more and more demanding reduced schedule for the integration & validation phases of the satellites.
The validation of the Thermal Control System (TCS) which is mission dependant represents a major activity which drives the schedule competitiveness. This aspect becomes a key challenge especially when the satellite is a prototype such as Alphabus PFM platform or Neosat, with new features and enhanced architectures, implying higher technical risks to be removed at the earliest in the program.
The analysis of a typical satellite Assembly, Integration & Test sequence gives the evidence that considering the *extensive system testing in clean room at ambient pressure & temperature*, there is an opportunity to perform an *early validation and correlation* of the satellite Thermal Mathematical Model (TMM) prior to the Thermal Vacuum & Thermal Balance testing.
Thus, the presentation will give an overview of the Evatherm method for Early Validation of the Thermal Control, developed together with ESA in the frame of Artes 3-4 and implemented in a real industrial and challenging Satcom program as Alphasat.
This engineering approach and associated software tools allow first to perform temperatures predictions and model correlation of the satellite system through testing in clean room, all along the AIT sequence, and second to implement Real time, Innovative & Improved Analysis methods (IAMITT) during the satellite Thermal Vacuum test itself.
The benefit in terms of thermal architecture performances justification or workmanship verification has been substantial and the methodology and the tools are now intended to be used as a standard.

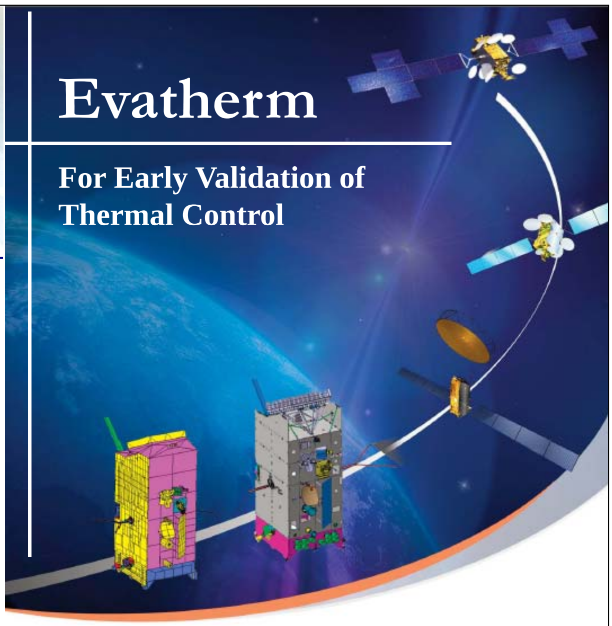


27th annual European Space Thermal Analysis Workshop

ESTEC, 3 & 4 December 2013

James Etchells	(ESA Estec)
François BALME	(ESA Estec)
Stéphane IUGOVICH	(EADS Astrium)
André CAPITAINE	(EADS Astrium)
Fabrice MENA	(EADS Astrium)

ASTRIUM AN EADS COMPANY



Ref : ASA.AST.PS.14348
date : Dec 2013

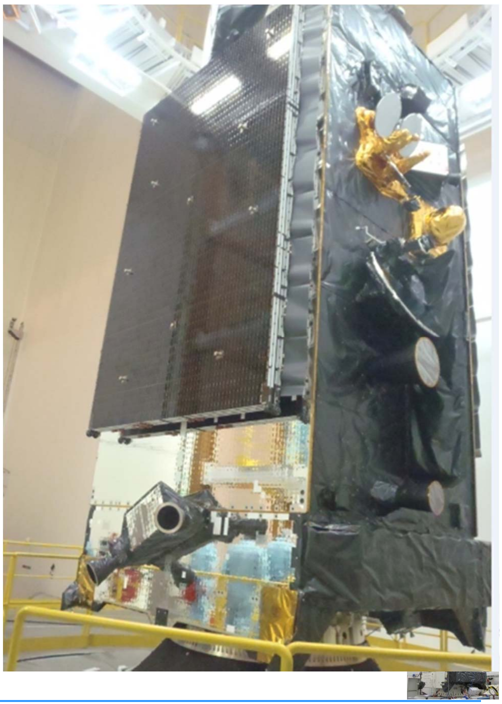
All the space you need

ASTRIUM

Overview	Ambient	IAMITT	Synthesis

Alphasat Program Context

- GEO Satcom built by Astrium as prime contractor
- Alphasat used the protoflight model of new Alphabus platform, and carry an advanced commercial geomobile communications mission for Inmarsat, as well as demonstration payloads for ESA.
  - Launch mass of 6550kg (AR5 & Proton) & P/L mass capability of 2500kg
  - Electrical power of 12kW (P/L ~10kW)
  - Design lifetime of 15 years
  - P/L & Processors developped by Astrium (L band & C band)
- Alphasat was launched in July 2013 and is now operational
- The Alphabus platform was & is jointly developed by Astrium and Thales Alenia Space, & supported by ESA & CNES



27th annual European Space Thermal Analysis Workshop, ESTEC, 3&4 December 2013 ASA.AST.PS.14348 Dec 2013 page 2/20

Overview | Ambient | IAMITT | Synthesis

ASTRIUM AN EADS COMPANY

Context & Needs of the development for TCS enhanced validation

- Alphabus SC Thermal Control Architecture included new design features :
  - New Platform with TAS thermal hardware & structure, new thermal designs

  Alphabus & Alphasat TCS integrates a number of challenging design features which were demanding in terms of extended validations & thermal model correlation

- Alphasat Spacecraft AIT schedule was challenging regarding to the validation content
  - AIT phase took place from 2010 to 2013

  There was a substantial time slot between first functional tests in clean room and SC TVTB which gave the opportunity to anticipate thermal system validations

- Alphabus TCS design justification is based on integrated System Thermal Analysis
  - The System thermal team (astrium) was responsible for the design of all subsystems & appendages, at Platform & Repeater Module levels
  - The Alphasat TMM integrates therefore all subsystems, specially the propulsion equipments & tubing, the thrusters, the sensors, the antennas, the equipments

  The Integrated S/C thermal model required an extended & extensive test correlation approach in Thermal Vacuum , & gives the opportunity to improve the validations scope & schedule

27th annual European Space Thermal Analysis Workshop, ESTEC, 3&4 December 2013 ASA.AST.PS.14348 Dec 2013 page 3/20

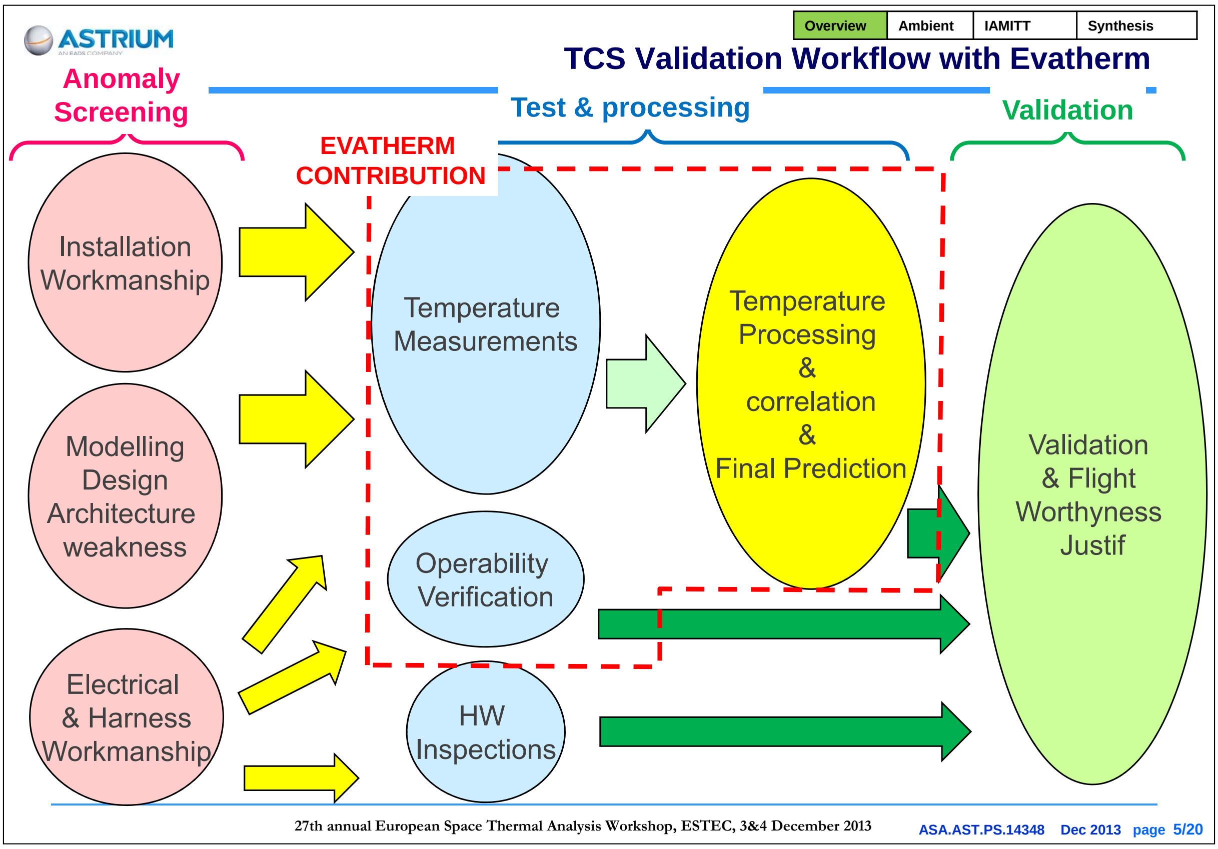
Overview | Ambient | IAMITT | Synthesis

ASTRIUM AN EADS COMPANY

Guideline of the Evatherm methodology

- Evatherm for Early Validation of the THERMal control
- Considering the Alphabus program context & exiting R&D activities & expertise, Evatherm ARTES 3-4 development was contracted with ESA.
- Two Master Objectives :
  - A) With an Integrated S/C system thermal modelling reflecting Convective heat Exchanges:
    - Anticipate model comparison & correlation at various stage of the SC AIT process during clean room tests at Ambient
    - Development of Clean Room Thermal predictions for Early validation of the Architecture with the system integrated thermal model
  - B) IAMITT for Inovative Analysis Method for Improved Thermal Testing (not only TVTB)
    - Implementation of the efficient thermal test management tools & method in real time for the SC Tvac using the TMM & GMM
    - Tvac is demanding in terms of data exchanges, instrumentation, monitoring & correlation efforts

27th annual European Space Thermal Analysis Workshop, ESTEC, 3&4 December 2013 ASA.AST.PS.14348 Dec 2013 page 4/20



ASTRIUM

Overview | Ambient | IAMITT | Synthesis

A) Development of Clean Room Thermal predictions for Early validation of TCS

- **Content :**
  - From Flight S/C TMM , implementation as a generic approach of the relevant routines with Esatan / Thermica / Thermisol to reproduce heat exchanges in clean room conditions
  - Prediction of the temperature levels of the equipments during partial SFTs in clean room or open door, depending of the S/C assembly configuration, & verification of the mains gradients of the thermal chain by model preliminary correlation or comparison
  - Targeted correlation status is +/-3° C & appeared to be achievable
  - Prediction of the behaviour of the thermal regulations in clean room in order to perform preliminary validation of the SW functions
- **Interest**
  - Be able to define to AIT the test conditions which are permitted
  - Define the appropriated thermal alarms for AIT tests, and consolidate the test set up requirements (cooling devices, ventilation …)
  - Validate as far as possible and as soon as possible the thermal architecture and associated hardware workmanship (e.g lack of thermal gaskets or torquing, heaters wiring, thermistors locations, S/W behaviour …)
  - Minimise the risks associated to the SC TVTB and make lighter if possible the content on the TB objectives in vacuum
  - Perform System launch pad predictions to anticipate critical operation phases ..

27th annual European Space Thermal Analysis Workshop, ESTEC, 3&4 December 2013 ASA.AST.PS.14348 Dec 2013 page 6/20

Overview | Ambient | IAMITT | Synthesis

ASTRIUM

B) Implementation of the IAMITT improvements to the Alphabus / Alphasat TVTB

- **Content :**
  - **Develop a dissipation model tool (SST) for real time generation of the power values, for SM & RM**
  - **Implement this innovative test management techniques, specially for the understanding & the processing of the S/C test conditions, management of the alarms, monitoring, thermal model ..**
    - **Perform quasi Real time model correlation of Tvac System Tests (thermal balances)**
    - **Extend the model correlation exercice to all subsystems, specially the tubing and the appendages which will have a poor instrumentation, with spatial extrapolation approaches**
- **Interest**
  - **Minimise the risks related to the Prototype Platform testing, specially for the Tvac**
  - **Perform a model correlation at the beginning of the TVTB test campaign in order to :**
    - **Adjust the T° objectives for SFTs**
    - **Anticipate the corrective actions on the design and workmanship**
  - **Achieve a completed & exhaustive thermal architecture validation & correlation, even in the areas where the instrumentation is poor, e.g CPS/XPS piping, tanks, thrusters, structure**

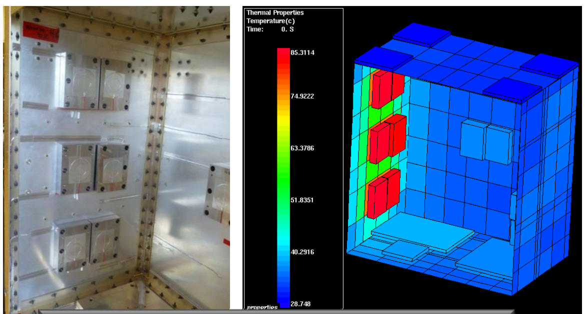
27th annual European Space Thermal Analysis Workshop, ESTEC, 3&4 December 2013 ASA.AST.PS.14348 Dec 2013 page 7/20

Overview | Ambient | IAMITT | Synthesis

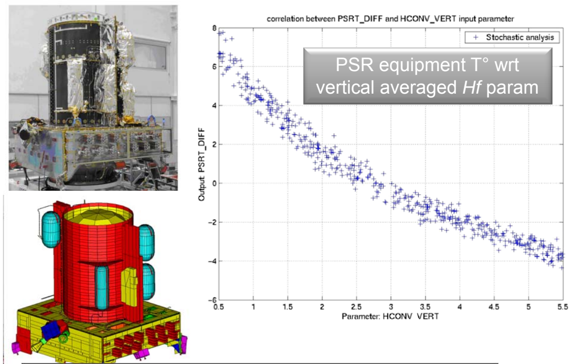
ASTRIUM

Physical & Modelling approach

- **Development based on a pragmatic method :**
  - **Easy to implement in thermal solvers**
  - **Heat balance computed as usual with** $GL_{convectif} = h.S$ **and** $h = Hf * \left|T_{node} - T_{fluid}\right|^{0.25}$
  - **Several approaches to identify the best "*Hf*" coefficient that matches with measures:**
    - Mac Adams theoritical approach with averaged coefficients (averaged over ΔT, characteristic lengthes, shapes orientation…) confronted to Micado breadboard experiment
    - Empirical approach: using S/L coupled to launcher analysis experience (*Hf*~3W.m^{-2}.K$^{-1.25}$)
    - Stochastic approach: identification of the best Hf value that correlates Alphasat ambient tests



Micado breadboard & thermal simulation



Alphasat stochastic application

27th annual European Space Thermal Analysis Workshop, ESTEC, 3&4 December 2013 ASA.AST.PS.14348 Dec 2013 page 8/20

ASTRIUM
AN EADS COMPANY

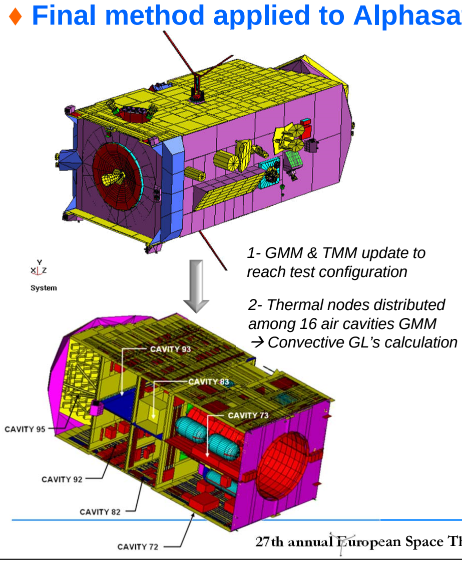
Overview | **Ambient** | IAMITT | Synthesis

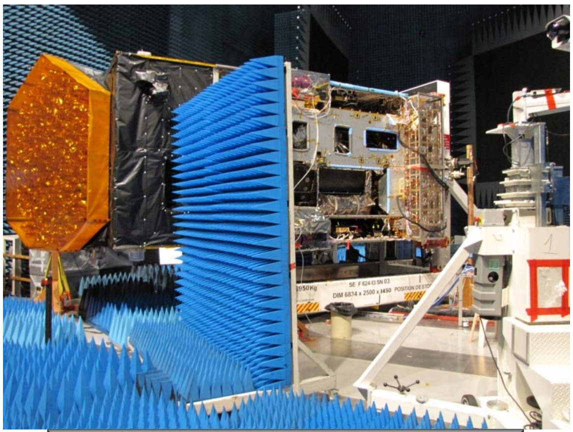
Method definition and application

- ♦ **Methods tuned thanks to :**
  - **Micado breadboard test**
  - **Alphasat SM SFT test**
  - **Alphasat RM alignment test**

Best compromise reached with $Hf=3W.m^{-2}.K^{-1.25}$
- Easy to implement in the Esatan/Thermisol file
- Provides conservative results

- ♦ **Final method applied to Alphasat Pim & Probes tests prediction & correlation**





Alphasat in RF test chamber (Intespace)

27th annual European Space Thermal Analysis Workshop, ESTEC, 3&4 December 2013 ASA.AST.PS.14348 Dec 2013 page 9/20

ASTRIUM
AN EADS COMPANY

Overview | **Ambient** | IAMITT | Synthesis

Ambient test prediction and correlation - synthesis

- ♦ **Main results:**
  - **Method based with $Hf=3W.m^{-2}.K^{-1.25}$ easy to set up**
  - **Thanks to ambient test predictions: air cooling device not mounted for PIM & Probes test: positive impact on S/L schedule!**
  - **Good global correlation status 85% of predicted temperatures below 3°C from the measurements (TC+TM)**
  - **Thermal Control System early validation thanks to ambient correlation**
- ♦ **Lessons learnt:**
  - **Air temperature modelling in the cavities is a driving parameter and is difficult to predict:**
    - **Take advantage of the thermistors (or TC) on non dissipative equipments to defined as a Boundary the air T° in the SC cavities → for correlation and TCS early validation**
    - **Or compute the air T° as a Diffusive node to remain conservative but generate larger uncertainties (air stratification difficult to simulate) → for ambient test predictions**
- ♦ **Next step:**
  - **Application to other Telecom S/C clean room tests**

27th annual European Space Thermal Analysis Workshop, ESTEC, 3&4 December 2013 ASA.AST.PS.14348 Dec 2013 page 10/20

ASTRIUM

Overview | Ambient | IAMITT | Synthesis

Using Iamitt in SC Tvac conditions

- **Setup of a centralized database using**
  - **TMM / GMM data**
  - **Test Predictions & load cases**
  - **Test instrumentation (flight + test)**
- **Iamitt modules usage during Alphasat or SC Tvac:**
  - ***3D display module :***
    - **Monitor in real time all the test parameters through the GMM**
      - Temperature
      - Margins vs limits
      - Delta measured / Predicted temperatures
      - Dissipations of heater Status
  - ***Spatial Extrapolation :***
    - **From TMM & discrete measurements points, compute in real time the full T° maps of the HW & vizualize on GMM (eg piping, structure …)**
  - ***TMUT (Thermal Model Updating & correlation) :***
    - **Implement tools to tune the physical parameters (after identification) of the TMM**
    - **Run in real time thousand of runs to achieve the best correlation compromise**
    - **Systematic approach for all modelled subsystems**

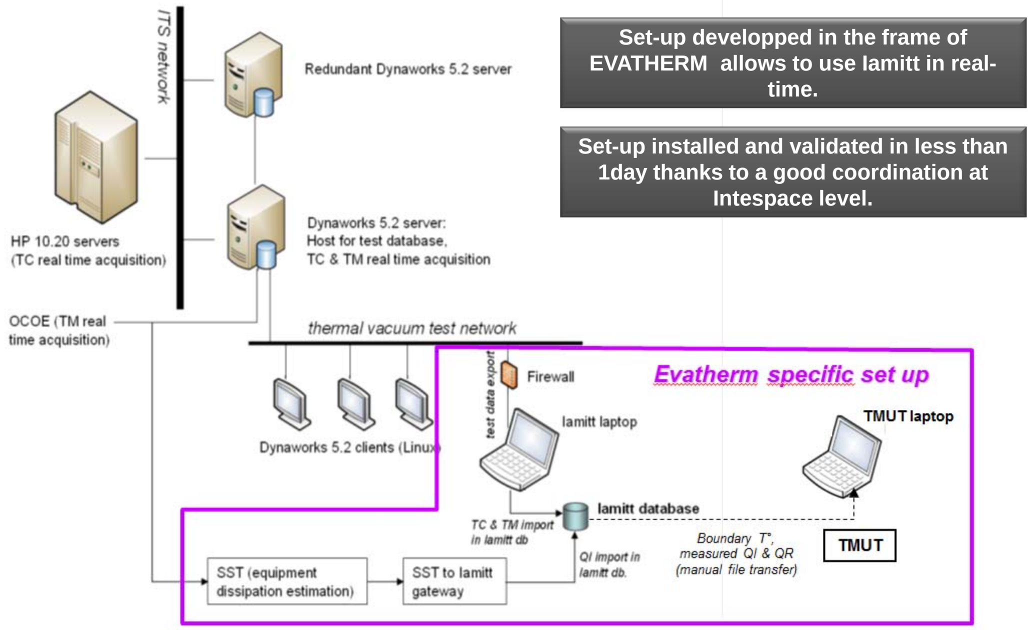
27th annual European Space Thermal Analysis Workshop, ESTEC, 3&4 December 2013 ASA.AST.PS.14348 Dec 2013 page 11/20

ASTRIUM

Overview | Ambient | IAMITT | Synthesis

Using Iamitt in Tvac conditions

- **EVATHERM: Iamitt architecture for Alphasat Tvac test at Intespace:**



27th annual European Space Thermal Analysis Workshop, ESTEC, 3&4 December 2013 ASA.AST.PS.14348 Dec 2013 page 12/20

ASTRIUM

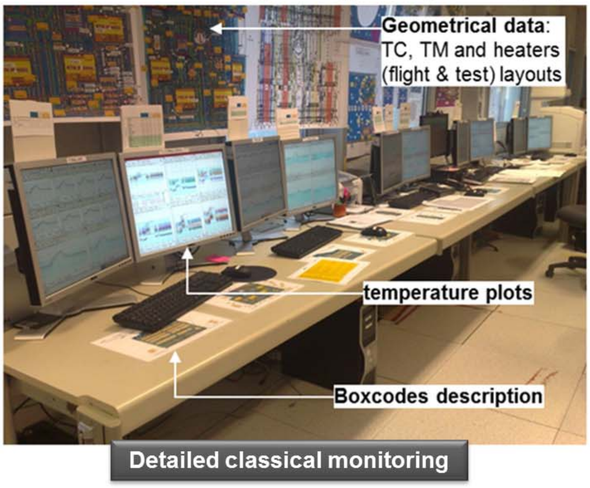
Overview | Ambient | IAMITT | Synthesis

Using Iamitt in Tvac conditions

♦ Tvac test monitoring improved with Iamitt:

- Real time test data monitoring with direct access to temperatures, alarms on the geometry
- Iamitt used as helper tool: good complementary to classical monitoring

Classical thermal monitoring during Tvac (Simmer, Alphasat)



3D monitoring (Alphasat)

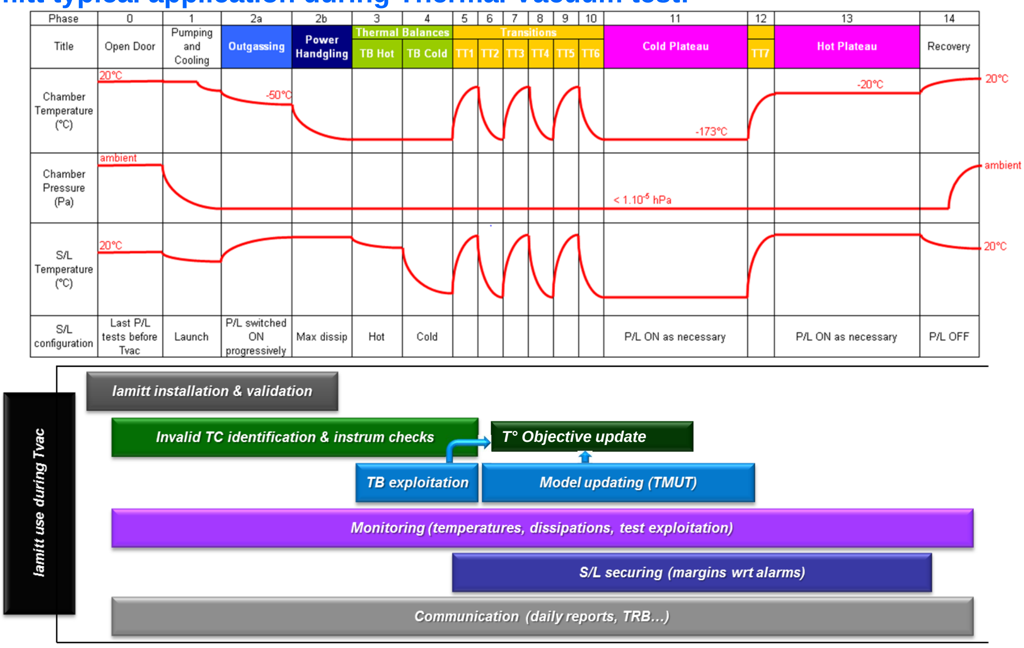
27th annual European Space Thermal Analysis Workshop, ESTEC, 3&4 December 2013 ASA.AST.PS.14348 Dec 2013 page 13/20

ASTRIUM

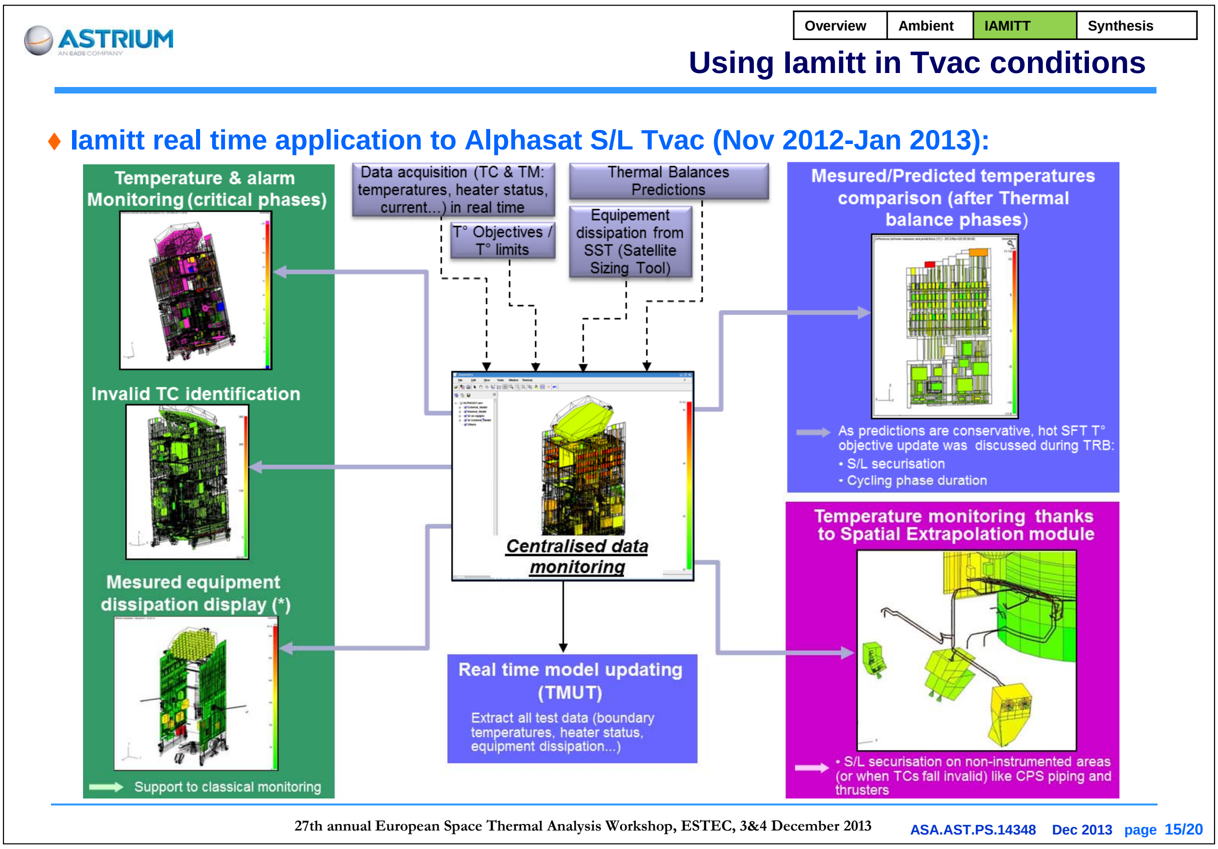
Overview | Ambient | IAMITT | Synthesis

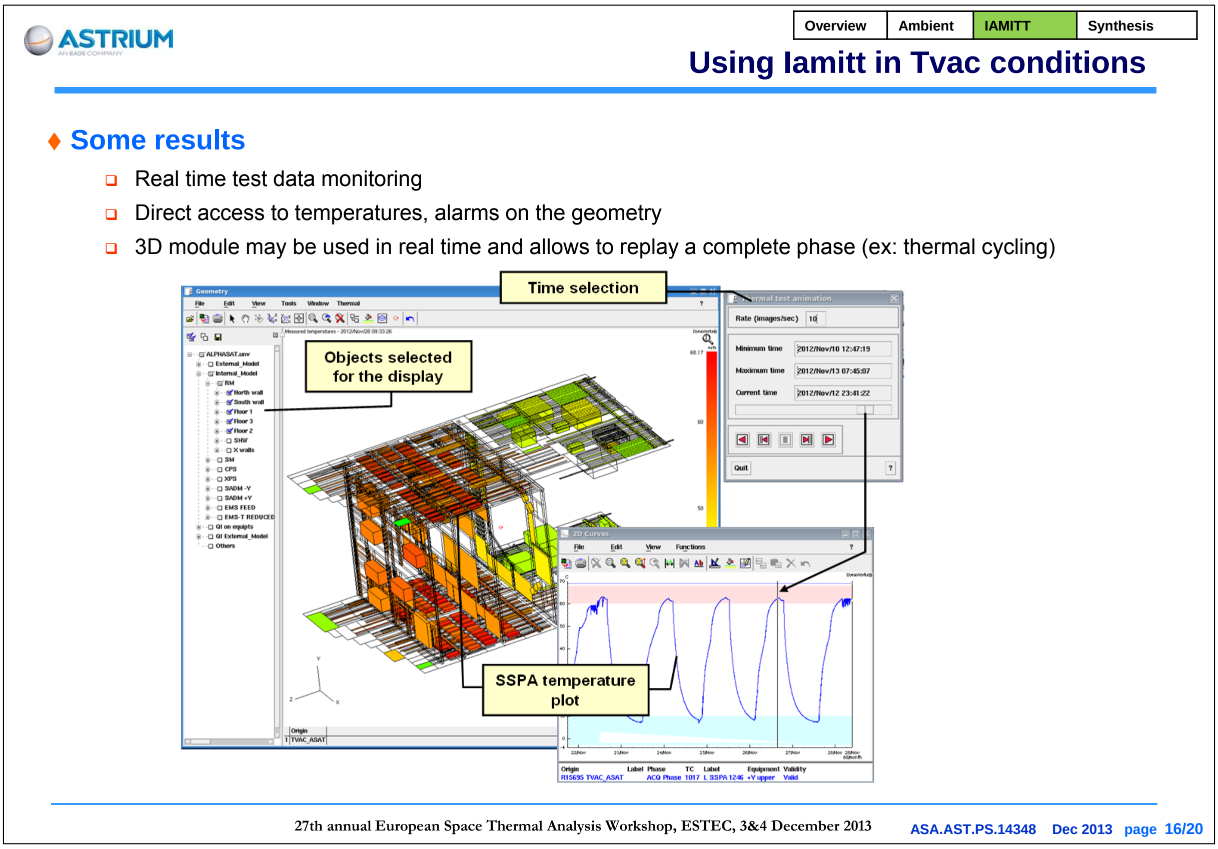
Using Iamitt in Tvac conditions

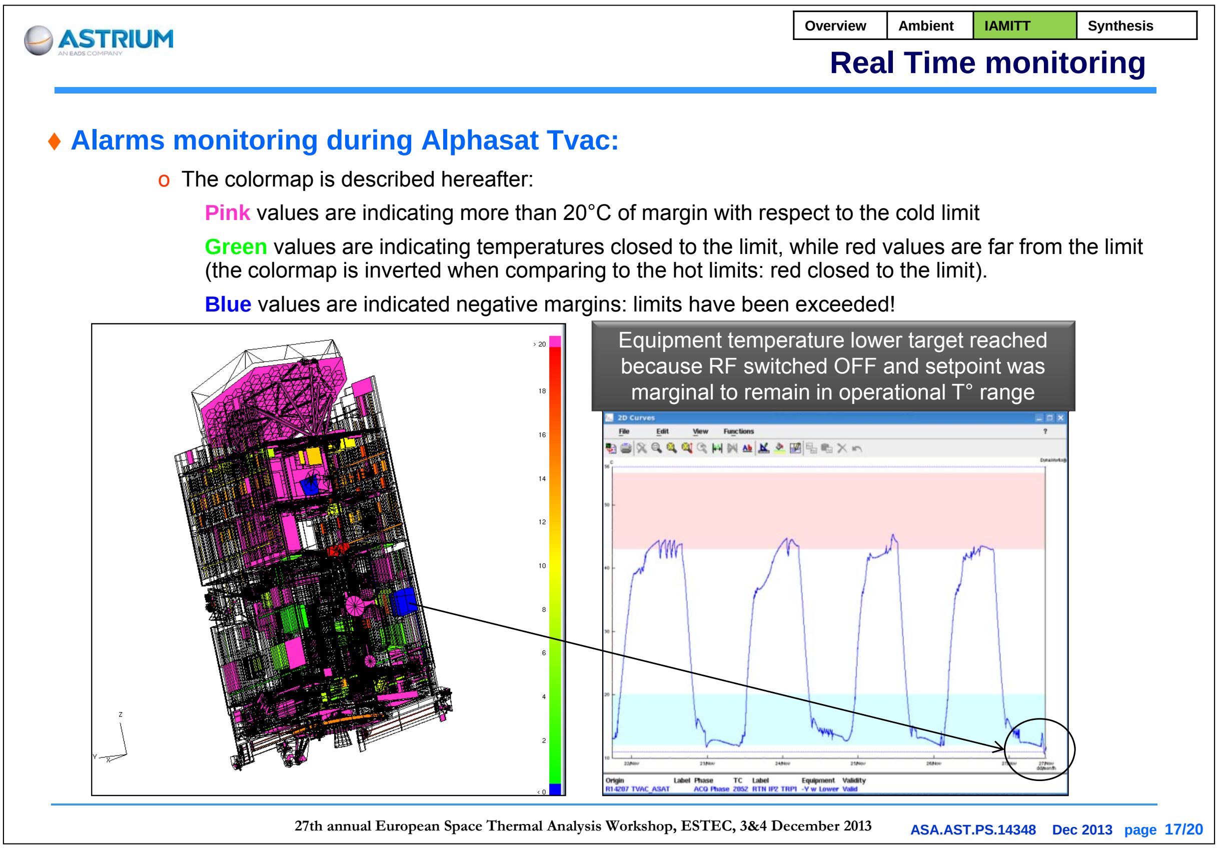
♦ Iamitt typical application during Thermal Vacuum test:

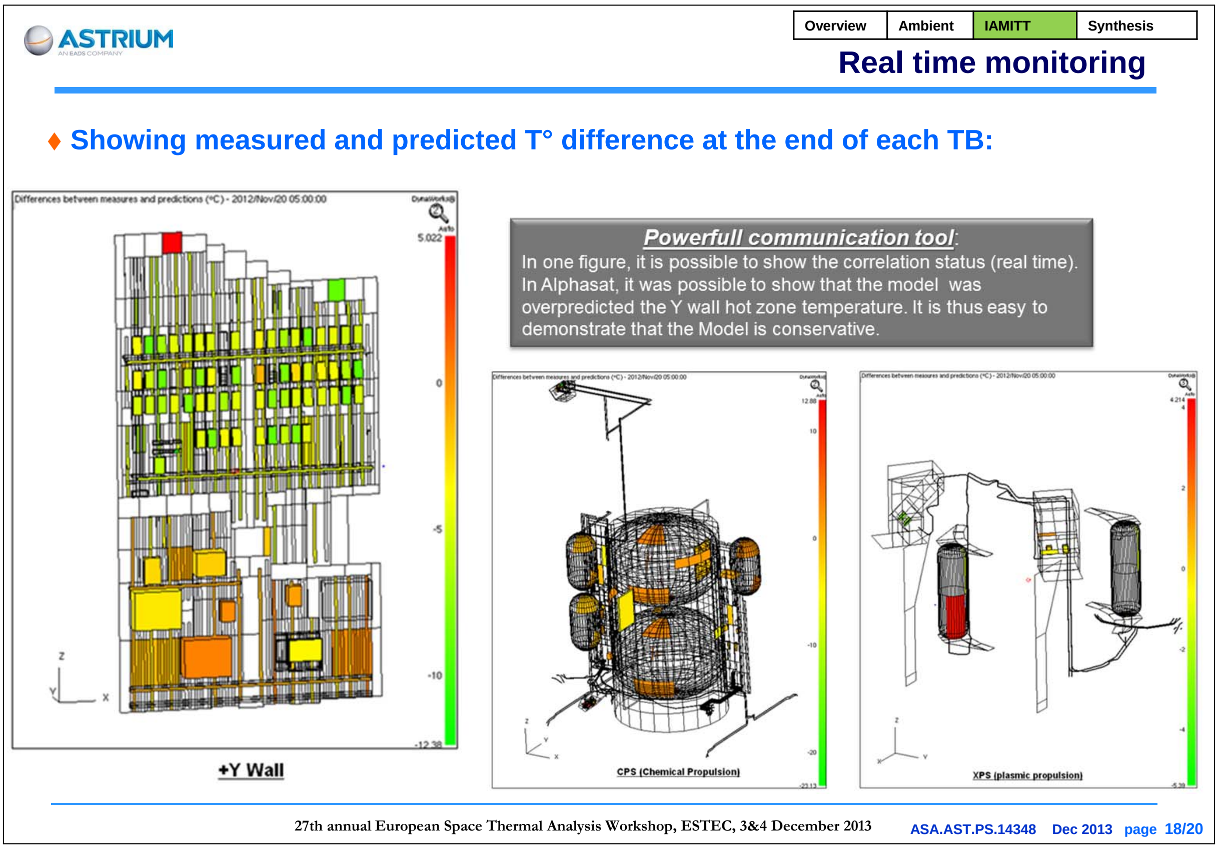


27th annual European Space Thermal Analysis Workshop, ESTEC, 3&4 December 2013 ASA.AST.PS.14348 Dec 2013 page 14/20


ASTRIUM
AN EADS COMPANY
Overview
Ambient
IAMITT
Synthesis
Using Iamitt in Tvac conditions
Iamitt real time application to Alphasat S/L Tvac (Nov 2012-Jan 2013):
Temperature & alarm Monitoring (critical phases)
Invalid TC identification
Mesured equipment dissipation display (*)
Support to classical monitoring
Data acquisition (TC & TM: temperatures, heater status, current…) in real time
T° Objectives / T° limits
Thermal Balances Predictions
Equipement dissipation from SST (Satellite Sizing Tool)
Centralised data monitoring
Real time model updating (TMUT)
Extract all test data (boundary temperatures, heater status, equipment dissipation…)
Mesured/Predicted temperatures comparison (after Thermal balance phases)
As predictions are conservative, hot SFT T° objective update was discussed during TRB:
• S/L securisation
• Cycling phase duration
Temperature monitoring thanks to Spatial Extrapolation module
• S/L securisation on non-instrumented areas (or when TCs fall invalid) like CPS piping and thrusters
27th annual European Space Thermal Analysis Workshop, ESTEC, 3&4 December 2013
ASA.AST.PS.14348 Dec 2013 page 15/20


ASTRIUM
AN EADS COMPANY
Overview
Ambient
IAMITT
Synthesis
Using Iamitt in Tvac conditions
Some results
Real time test data monitoring
Direct access to temperatures, alarms on the geometry
3D module may be used in real time and allows to replay a complete phase (ex: thermal cycling)
Time selection
Objects selected for the display
SSPA temperature plot
27th annual European Space Thermal Analysis Workshop, ESTEC, 3&4 December 2013
ASA.AST.PS.14348 Dec 2013 page 16/20


ASTRIUM
Overview
Ambient
IAMITT
Synthesis
Real Time monitoring
Alarms monitoring during Alphasat Tvac:
The colormap is described hereafter:
Pink values are indicating more than 20°C of margin with respect to the cold limit
Green values are indicating temperatures closed to the limit, while red values are far from the limit (the colormap is inverted when comparing to the hot limits: red closed to the limit).
Blue values are indicated negative margins: limits have been exceeded!
Equipment temperature lower target reached because RF switched OFF and setpoint was marginal to remain in operational T° range
2D Curves
27th annual European Space Thermal Analysis Workshop, ESTEC, 3&4 December 2013
ASA.AST.PS.14348 Dec 2013 page 17/20

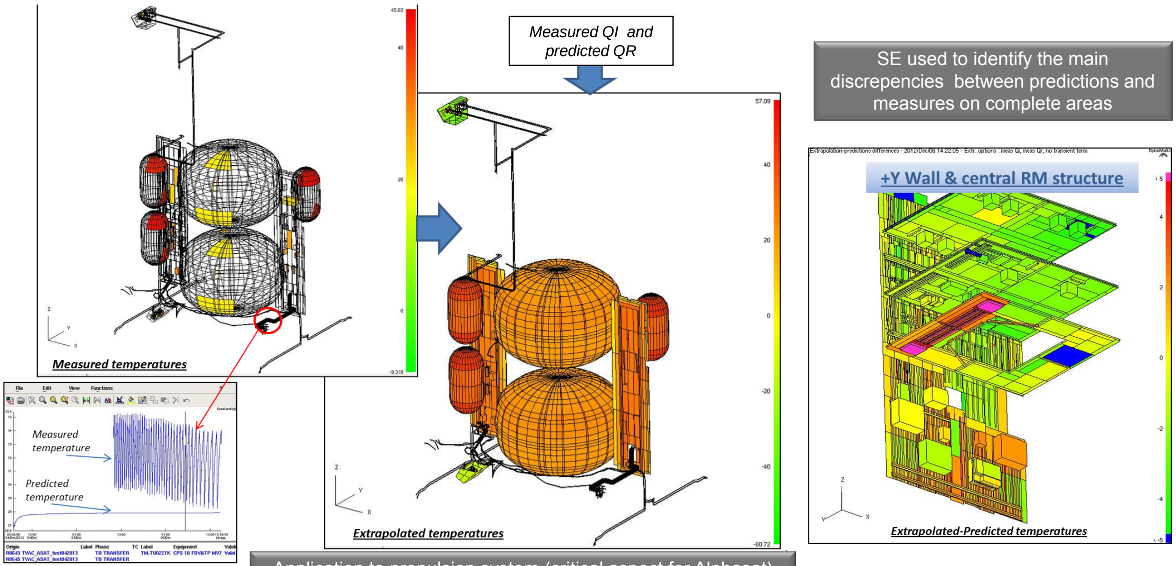

ASTRIUM
Overview
Ambient
IAMITT
Synthesis
Real time monitoring
Showing measured and predicted T° difference at the end of each TB:
Differences between measures and predictions (°C) - 2012/Nov/20 05:00:00
Powerfull communication tool:
In one figure, it is possible to show the correlation status (real time). In Alphasat, it was possible to show that the model was overpredicted the Y wall hot zone temperature. It is thus easy to demonstrate that the Model is conservative.
+Y Wall
CPS (Chemical Propulsion)
XPS (plasmic propulsion)
27th annual European Space Thermal Analysis Workshop, ESTEC, 3&4 December 2013
ASA.AST.PS.14348 Dec 2013 page 18/20

ASTRIUM

Overview | Ambient | IAMITT | Synthesis

Using Iamitt in Tvac conditions

- **Spatial extrapolation of some sub assemblies temperatures**
  - **Exhaustive monitoring of all subsystems in test, even the ones not instrumented**



Application to propulsion system (critical aspect for Alphasat)

27th annual European Space Thermal Analysis Workshop, ESTEC, 3&4 December 2013 ASA.AST.PS.14348 Dec 2013 page 19/20

ASTRIUM

Overview | Ambient | IAMITT | Synthesis

Iamitt improvement - Synthesis

- **Main results:**
  - **Iamitt operationally used in real time on Alphasat TVAC and:**
    - On an **E3000 Telecom S/C Tvac** in sept. 2012 prior to Alphasat (Evatherm Dry Run)
    - On an **Earth Observation S/L Tvac** in May 2013 (Evatherm post-activities)
  - **Early validation of the TCS (invalid TC, alarms & workmanship errors)**
- **Lessons learnt:**
  - **Spatial Extrapolation module is promising but needs improvements (robustness wrt transient phases, heating regulation cycling)**
- **Next step:**
  - **Astrium FDH wants to apply Iamitt in one of their next Earth-Obs / Science Satellite tests**

27th annual European Space Thermal Analysis Workshop, ESTEC, 3&4 December 2013 ASA.AST.PS.14348 Dec 2013 page 20/20

ASTRIUM

Overview | Ambient | IAMITT | Synthesis

Assisted Thermal Model Update during Tvac (TMUT)

♦ Scope

- Joint application of Error Localisation (TMELT, CNES R&T) and Thermal Model Update (TMUT, Iamitt ESA R&D) automated approaches

♦ Objectives

- Automated Test conditions update of the Thermal Model (with real test configuration from Iamitt: equipt status and dissip, boundary T°) in “pseudo real time”: at the end of each TB phase. Allows to get quickly an initial up to date correlation status
- Apply the assisted Error Localisation tool (CNES R&T) to help identifying the main parameters for the correlation exercise
- Run the assisted Thermal Model Update Tool (TMUT), based on a stochastic optimisation method, to reduce the gap between predictions and measures by automatically changing the main parameters values.

♦ Outcomes from Alphasat Tvac application:

- Successful Test conditions update of the Thermal Model
- TMELT approach not efficient: not designed to identify modelling lacks (or measurement errors); not suited to complex multiple-errors situations
- First TMUT/Alphasat application (during Tvac) not successful due to this remaining errors (modelling-measurements)
  - Temperature gap fitness function cannot be significantly reduced by changing parameters value

27th annual European Space Thermal Analysis Workshop, ESTEC, 3&4 December 2013 ASA.AST.PS.14348 Dec 2013 page 21/20

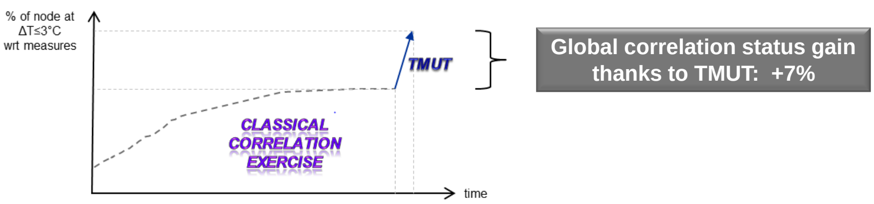
ASTRIUM

Overview | Ambient | IAMITT | Synthesis

Assisted Thermal Model Update during Tvac (TMUT)

♦ Post-Tvac activites:

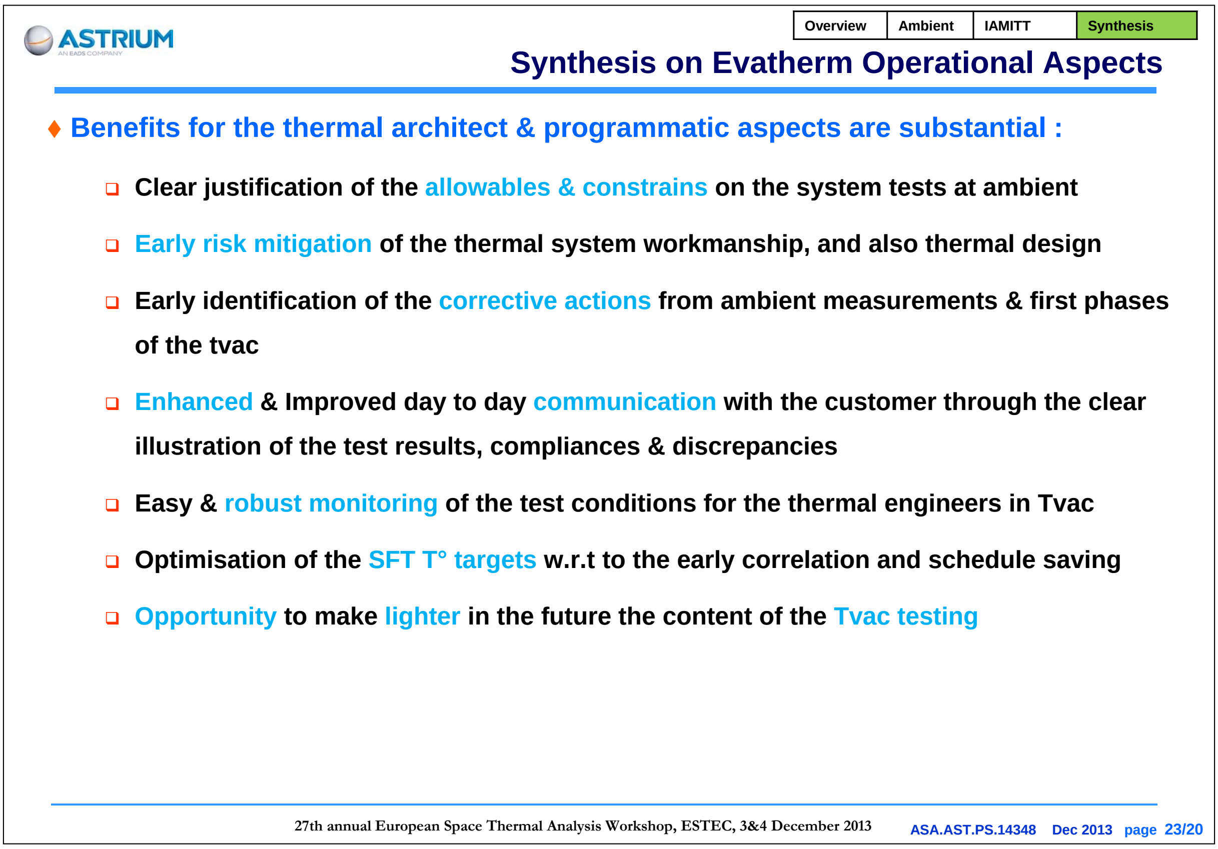
- Taking advantage of the classical manual correlation results, TMUT exercised on two subset of driving parameters: CPS (24 params) then global (77 params)
- Results improvement:
  - Temperature gap (between predictions and measures) reduced by 0.5°C
  - Number of the TC in the criteria (<3°C) increased by an average of 7%



♦ Lessons learnt:

- Algorithm parallelisation : allows to run about 10.000 steady state TMM shots in 20h (Alphasat thermal model is composed by 16.000 nodes & ~2.000.000 couplings)
- Needs to filter non influent parameters and invalid measures to get a successful optimisation
- Differential Evolution algorithm preferred to Genetic one: much better convergence

27th annual European Space Thermal Analysis Workshop, ESTEC, 3&4 December 2013 ASA.AST.PS.14348 Dec 2013 page 22/20


ASTRIUM
Overview
Ambient
IAMITT
Synthesis
Synthesis on Evatherm Operational Aspects
Benefits for the thermal architect & programmatic aspects are substantial :
Clear justification of the allowables & constrains on the system tests at ambient
Early risk mitigation of the thermal system workmanship, and also thermal design
Early identification of the corrective actions from ambient measurements & first phases of the tvac
Enhanced & Improved day to day communication with the customer through the clear illustration of the test results, compliances & discrepancies
Easy & robust monitoring of the test conditions for the thermal engineers in Tvac
Optimisation of the SFT T° targets w.r.t to the early correlation and schedule saving
Opportunity to make lighter in the future the content of the Tvac testing
27th annual European Space Thermal Analysis Workshop, ESTEC, 3&4 December 2013
ASA.AST.PS.14348 Dec 2013 page 23/20

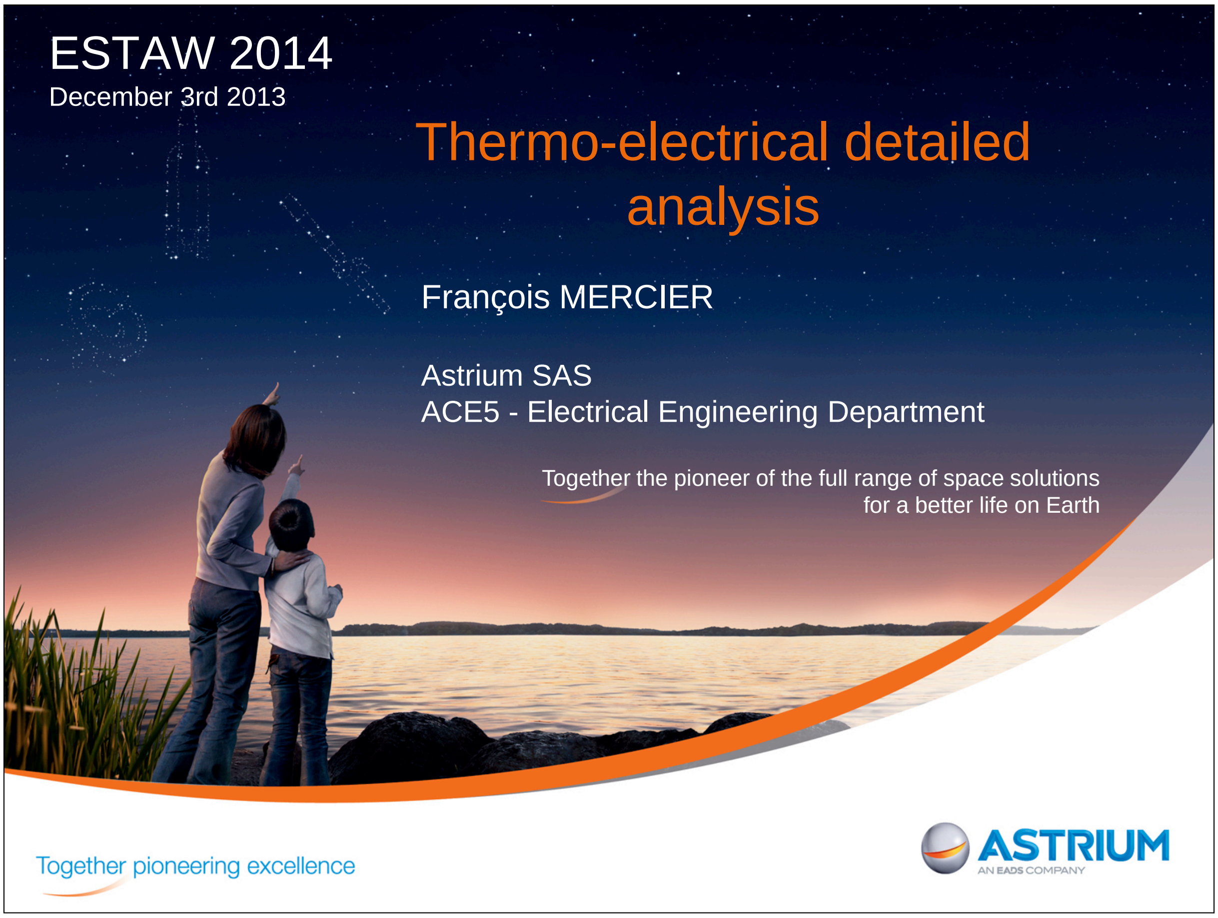
Appendix F

Thermo-electrical Detailed Analysis

François Mercier B. Samaniego V. Gineste L. Gajewski A. du Jeu
(Astrium SAS, Toulouse, France)

Abstract

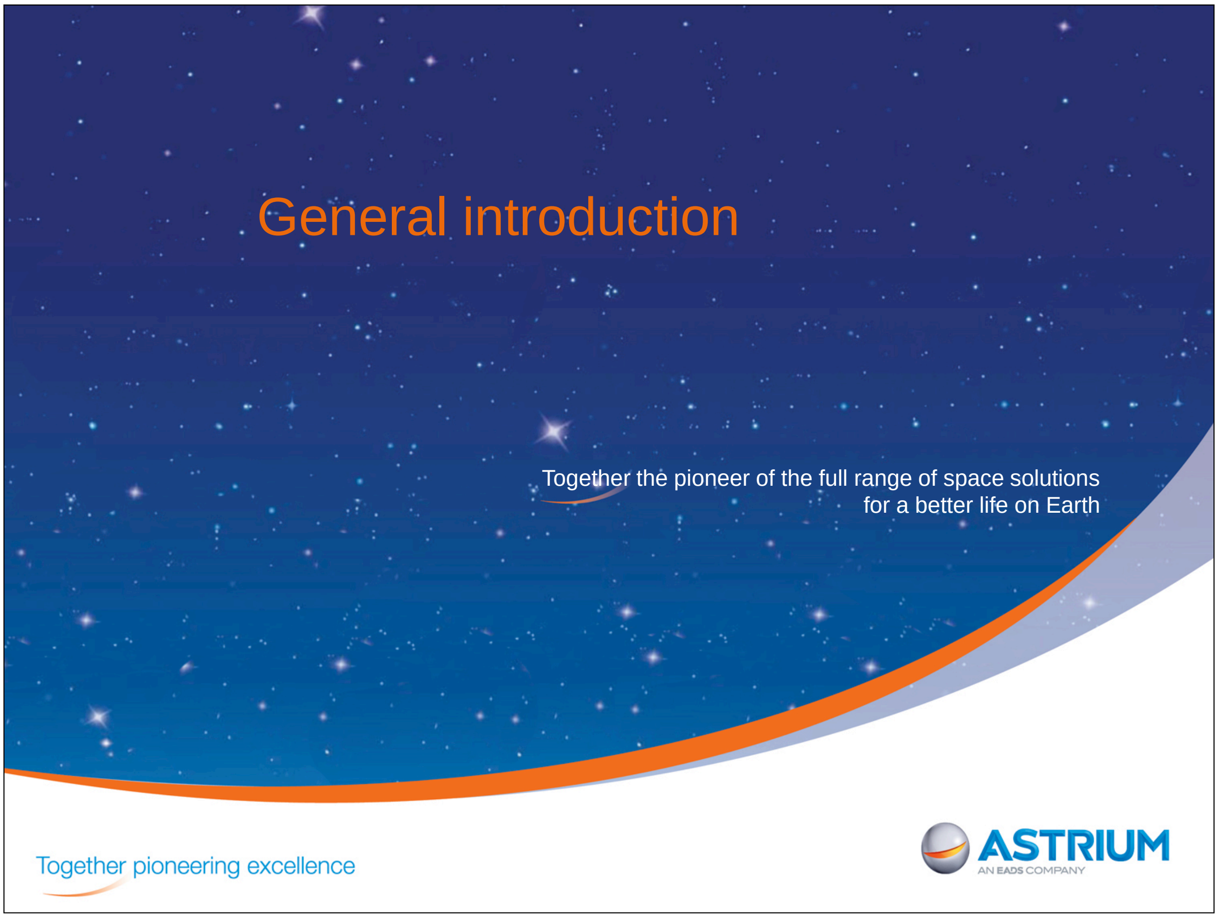
An important part of the power system engineering work is deeply linked to the thermal aspects of the various power components like batteries and solar panels. With the help of an internally developed coupled thermo-electrical solver, previously untried detailed analyses on various power systems were performed in Astrium, stemming interesting results.
The wide-spread Thermisol thermal solver in the Systema software suite was extended with a power add-on. The principle was to add an electrical layer through dedicated nodes complementary to the existing thermal nodes. It allowed the power users to code electrical systems and user components on the same environment as the existing Thermisol codes.
This new solver was applied for a full satellite power system analysis. The coupling with the thermal aspect allowed the re-use of thermal files and designs to prepare the analysis. An electrical layer composed of the user components of a classical power system (battery, solar array, power regulation and distribution) was added to perform fully coupled thermo-electrical analysis, adding higher accuracy to the battery, solar array and regulation modeling.
In the frame of an ESA study to investigate on solar array thermal / electrical imbalance in power systems equipped with MPPT, in-depth modeling of solar panels were also performed on both electrical and thermal aspects. This allowed cell level analysis for very fine phenomenon like the local cell gradients created by dissipation of back panel diodes and harness during orbit cycles, sensitivity studies to default or accurate local and global shadowing analyses.
The solver was also included in a software loop with coupled SAS/MPPT hardware for validation testing.

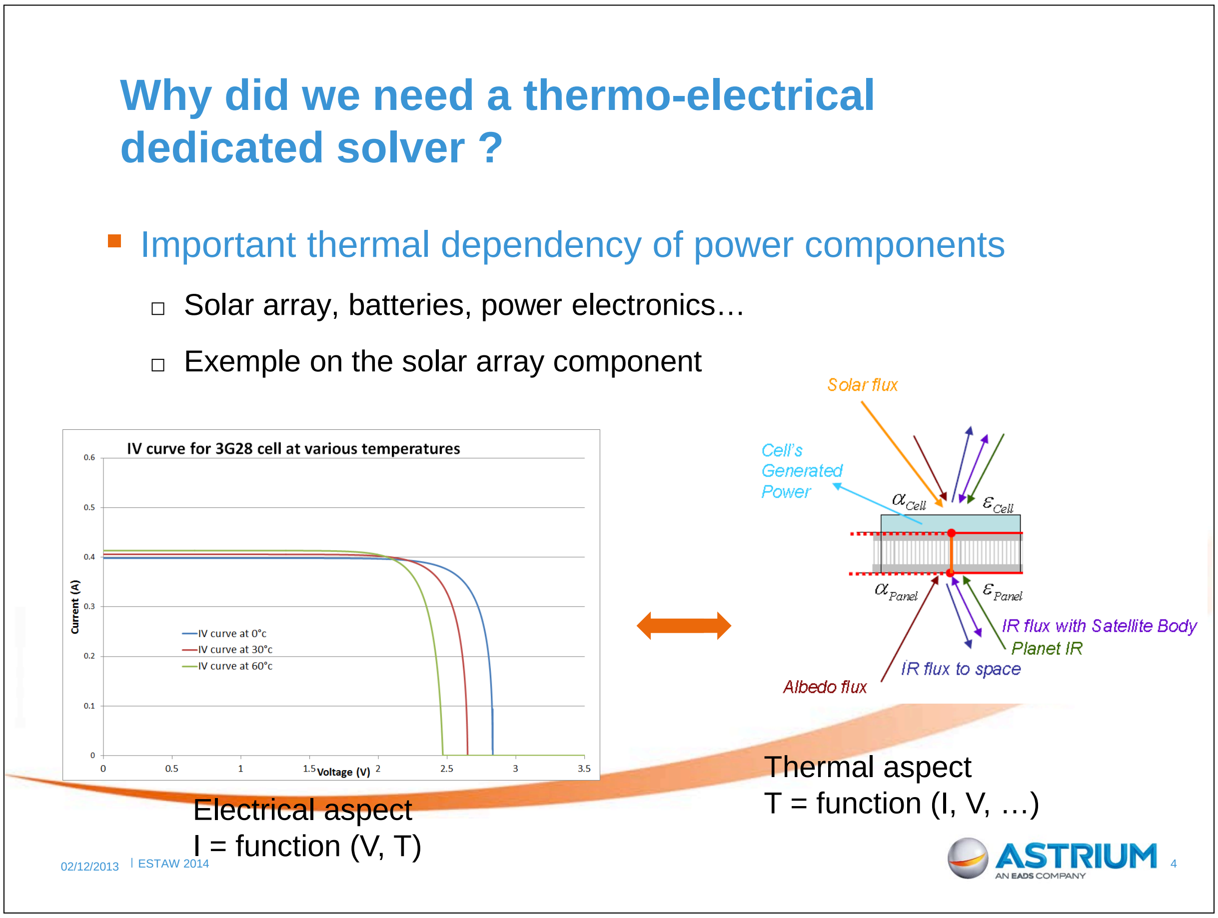


Contents

- General introduction
  - Why did we need a thermo-electrical dedicated solver ?
  - Solver architecture
- Application to satellite power system analysis
  - Example on satellite energy budget
- Application to Solar Array thermo-electrical analysis
  - ESA study context
  - Modelling on solar panel
  - Examples of various detailed analyses
- Conclusion

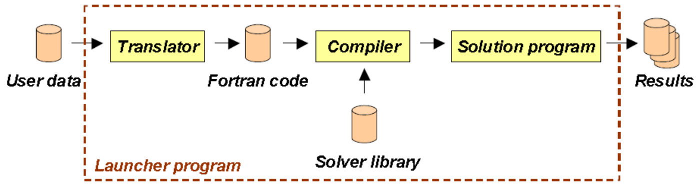
02/12/2013 | ESTAW 2014 ASTRIUM AN EADS COMPANY 2


General introduction
Together the pioneer of the full range of space solutions
for a better life on Earth
Together pioneering excellence
ASTRIUM
AN EADS COMPANY

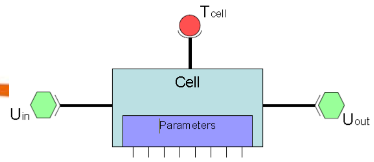

Why did we need a thermo-electrical dedicated solver ?
Important thermal dependency of power components
Solar array, batteries, power electronics…
Exemple on the solar array component
IV curve for 3G28 cell at various temperatures
Current (A)
Voltage (V)
IV curve at 0°c
IV curve at 30°c
IV curve at 60°c
Solar flux
Cell's Generated Power
α_{Cell}
ε_{Cell}
α_{Panel}
ε_{Panel}
IR flux with Satellite Body
Planet IR
IR flux to space
Albedo flux
Electrical aspect
I = function (V, T)
Thermal aspect
T = function (I, V, …)
02/12/2013
ESTAW 2014
ASTRIUM
AN EADS COMPANY
4

Solver architecture

- Based on THERMISOL, the Astrium thermal solver (from SYSTEMA)
  - Package includes translator (or pre-processor), computation library and dedicated solution program
  - Equivalent to using Thermisol as development environment



- A Power add-on layer was added, with new electrical nodes in addition to thermal nodes already in place



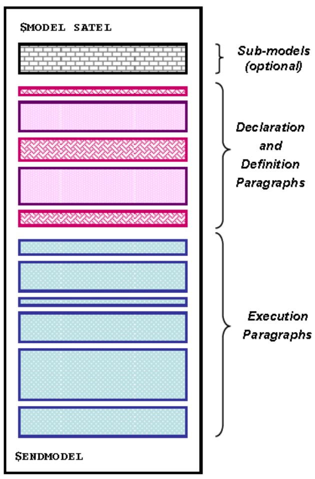
Example of a solar array cell component

02/12/2013 | ESTAW 2014

ASTRIUM AN EADS COMPANY 5

Solver architecture

- Some architecture advantages :
  - User components (importation of dedicated power models)
  - High performance – number of nodes, algorithms for thermo-electrical coupled calculation
  - Direct link with Systema suite for flexibility
  - Re-use of existing thermal analyses
  - A lot of freedom (ex: parametrical analysis)
- Architecture disadvantages :
  - No solver graphical interface (but in development)
  - Fortran coding and some thermal solver background needed for complex analysis



Typical code structure

02/12/2013 | ESTAW 2014

ASTRIUM AN EADS COMPANY 6

Application to power system analysis

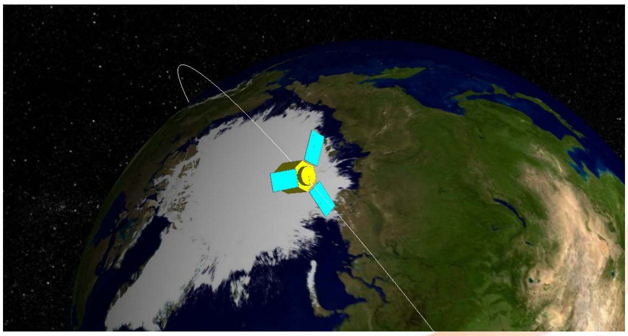
Together the pioneer of the full range of space solutions
for a better life on Earth

Together pioneering excellence

ASTRIUM
AN EADS COMPANY

Application to power system analysis

- Aim : to perform an energy budget on a typical LEO satellite mission
  - Outputs : Solar array and battery behaviour over one day of mission



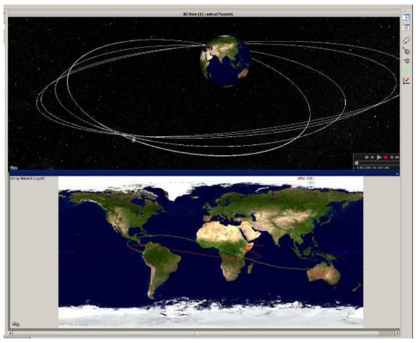
- Inputs :
  - Geometrical model
  - Orbit and kinematics
  - Thermal data on solar array and satellite external surfaces
  - Electrical data on satellite power system

02/12/2013 | ESTAW 2014

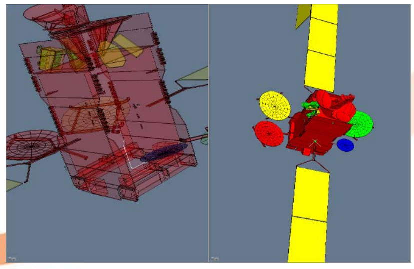
ASTRIUM
AN EADS COMPANY
8

Simulation process – Systema / Thermica part

- Geometrical modeling in Systema software
- Kinematics and orbit input



- Simulation to get required outputs
  - Albedo, IR and solar fluxes
  - Thermal fluxes
  - Radiative Couplings between surfaces

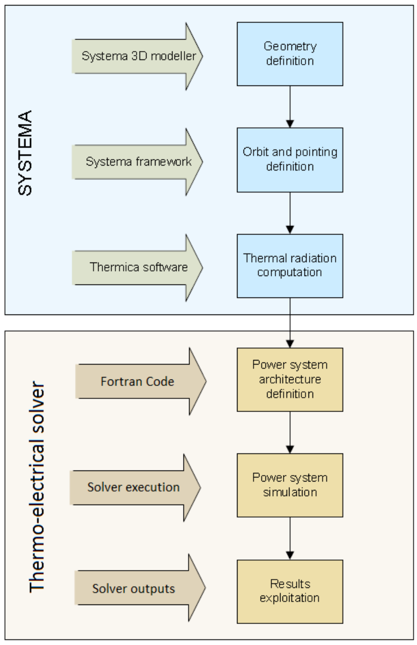


02/12/2013 | ESTAW 2014

ASTRIUM AN EADS COMPANY 9

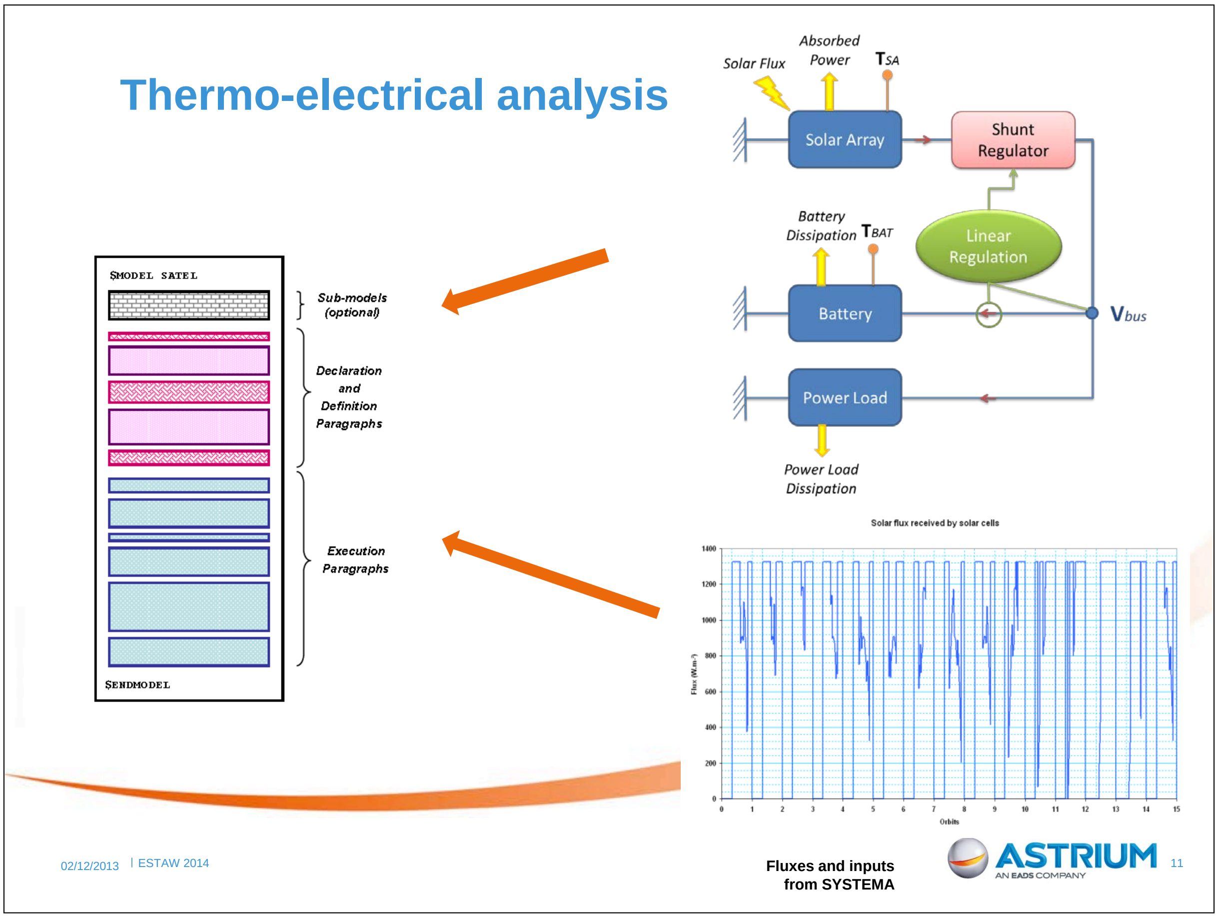
Electrical analysis

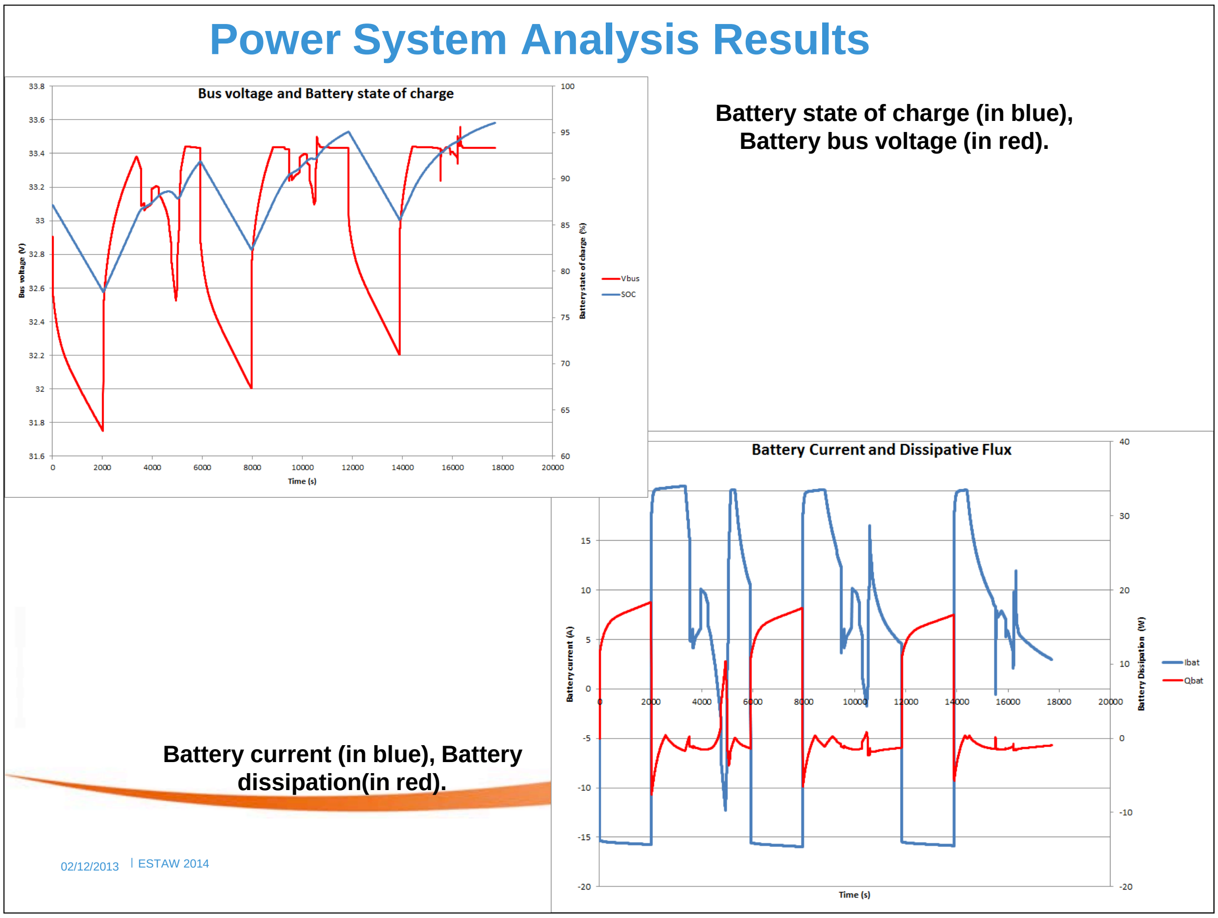
- The thermal data and fluxes are injected into the electrical modeling
  - User components of different electrical blocks
  - Links with fluxes from Systema simulation
- The thermo-electrical solver is applied on a chosen timeframe
  - Dedicated $CONTROLS and $EXECUTION routines



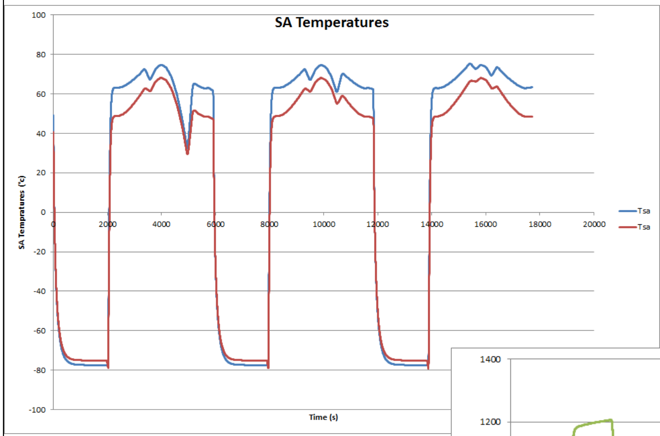
02/12/2013 |

ASTRIUM AN EADS COMPANY 10

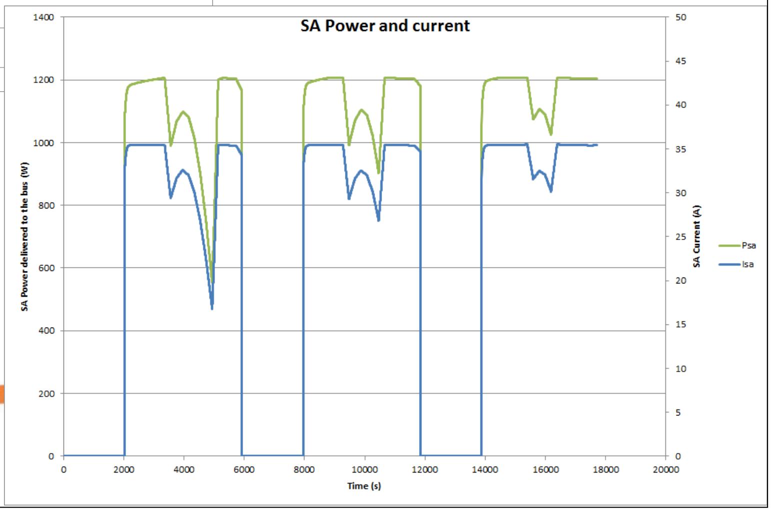

Thermo-electrical analysis
Solar Flux
Absorbed Power
T_{SA}
Solar Array
Shunt Regulator
Battery Dissipation
T_{BAT}
Linear Regulation
Battery
V_{bus}
Power Load
Power Load Dissipation
$MODEL SATEL
Sub-models (optional)
Declaration and Definition Paragraphs
Execution Paragraphs
$ENDMODEL
Solar flux received by solar cells
Orbits
Fluxes and inputs from SYSTEMA
ASTRIUM
AN EADS COMPANY
11
02/12/2013 | ESTAW 2014


Power System Analysis Results
Bus voltage and Battery state of charge
Bus voltage (V)
Battery state of charge (%)
Time (s)
Vbus
SOC
Battery state of charge (in blue), Battery bus voltage (in red).
Battery Current and Dissipative Flux
Battery current (A)
Battery Dissipation (W)
Time (s)
Ibat
Qbat
Battery current (in blue), Battery dissipation(in red).
02/12/2013 | ESTAW 2014

Power System Analysis Results



Solar Array temperatures (front SA in blue, Back SA in red).



Solar Array Power (in blue), Solar array current (in red).

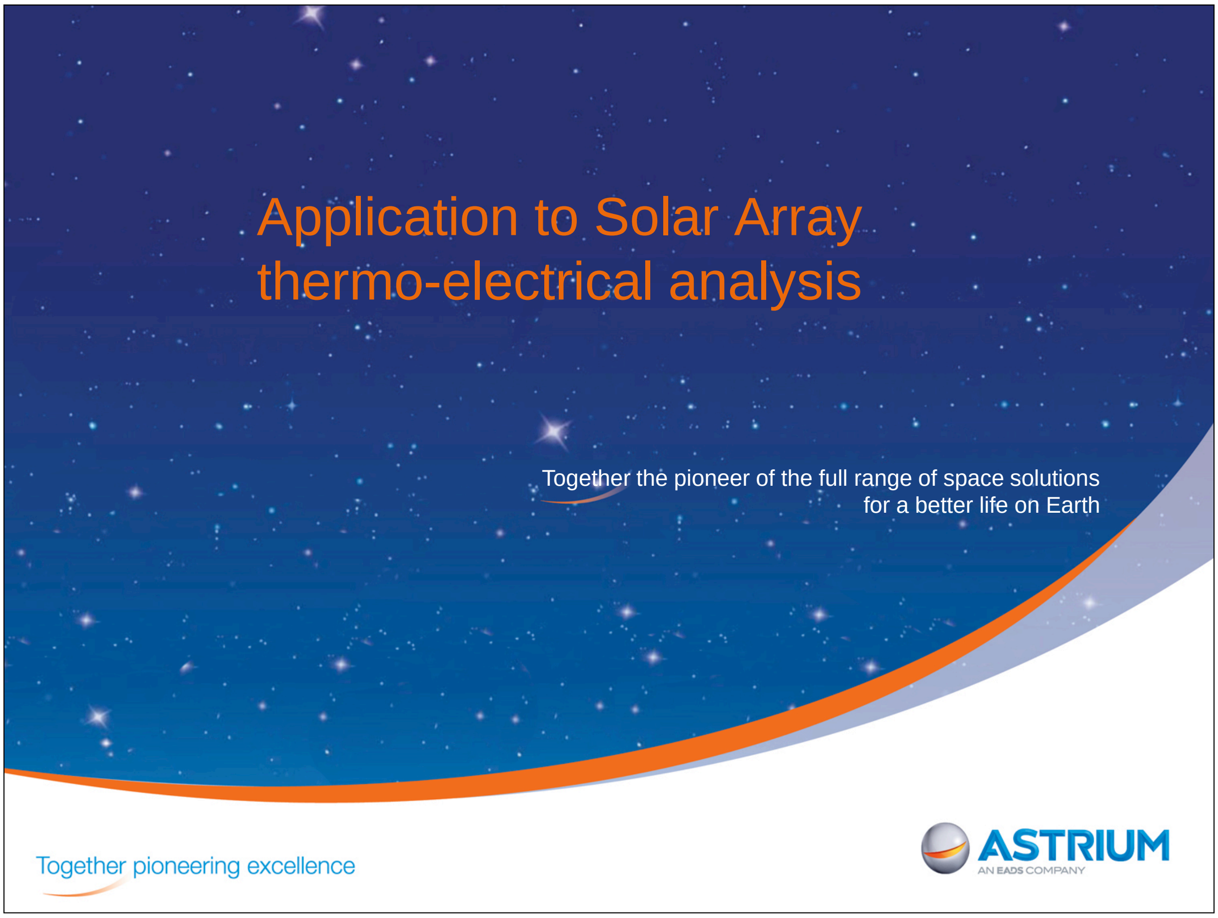
02/12/2013 | ESTAW 2014

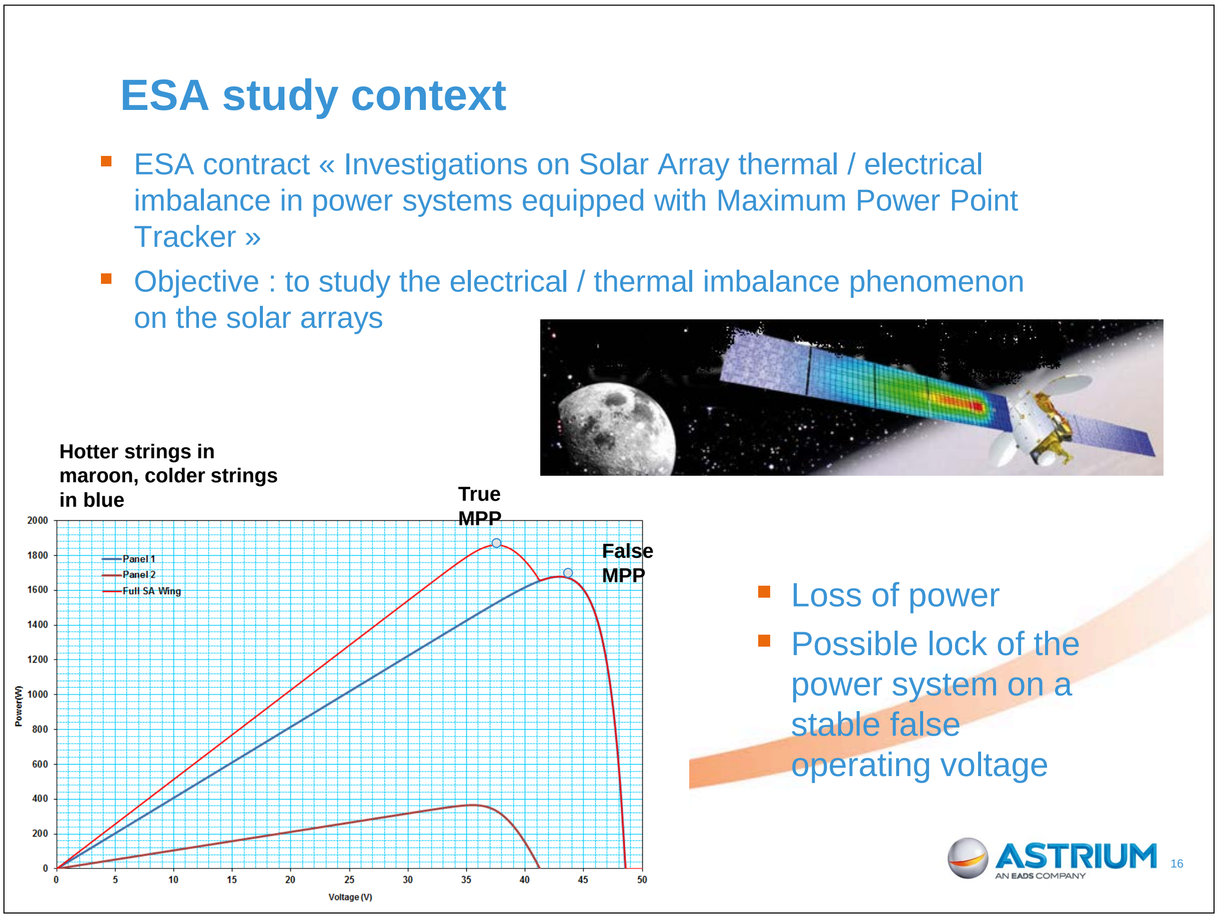
Conclusion for Power analysis

- Possibility to simulate whole power systems with thermo-electrical components
- High flexibility at every level
  - Mission and thermal inputs modifications
  - User components
  - Execution, controls and outputs

02/12/2013 | ESTAW 2014

ASTRIUM AN EADS COMPANY 14


Application to Solar Array
thermo-electrical analysis
Together the pioneer of the full range of space solutions
for a better life on Earth
Together pioneering excellence
ASTRIUM
AN EADS COMPANY

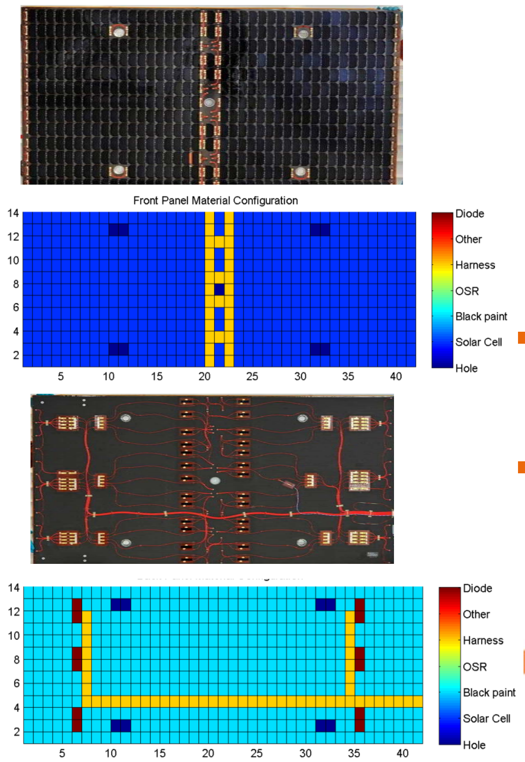

ESA study context
ESA contract « Investigations on Solar Array thermal / electrical imbalance in power systems equipped with Maximum Power Point Tracker »
Objective : to study the electrical / thermal imbalance phenomenon on the solar arrays
Hotter strings in maroon, colder strings in blue
True MPP
False MPP
Panel 1
Panel 2
Full SA Wing
Power(W)
Voltage (V)
Loss of power
Possible lock of the power system on a stable false operating voltage
ASTRIUM
AN EADS COMPANY
16

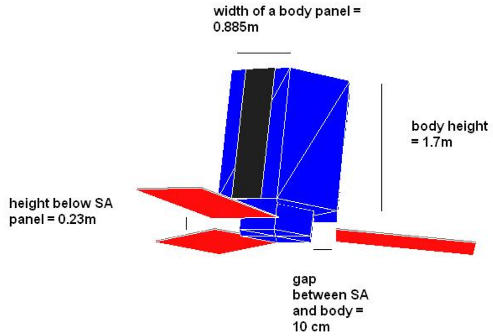
Development of a new solver

- A lot of factors come into play for this phenomenon
- Need for very extensive modelling :
  - High number of thermal / electrical nodes
  - High level of details on thermal effects (panel layout, effect of view factors)
  - Flexible environmental modelling : both LEO missions and scientific extraplanetary missions
  - High level of coding flexibility : various cell models to be studied, multiple thermal effects to simulate like misalignment, radiations, shadowing…

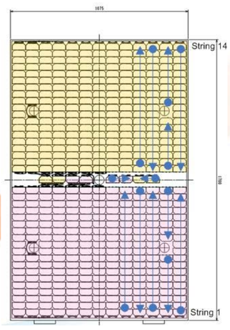
02/12/2013 | ESTAW 2014 ASTRIUM AN EADS COMPANY 17

Detailed modelling on solar panel





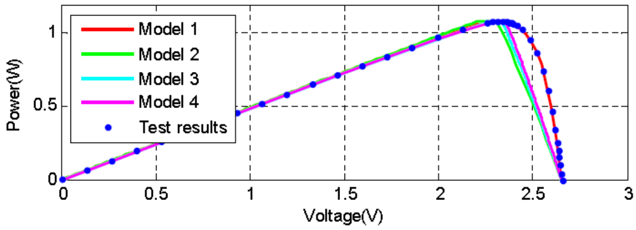
- Geometrical modelling of the body for view factor effects
- Very accurate modelling of panels layout (front and back) – including harness, diodes, and realistic stringing



ASTRIUM AN EADS COMPANY 18

Cell models inputs

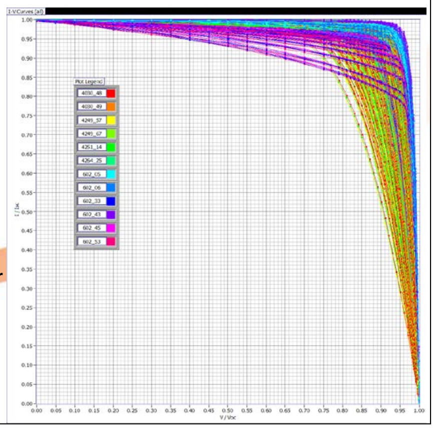
- Various classic cell models identified



PV curves of modelled solar cells (3G28 type) compared to test data

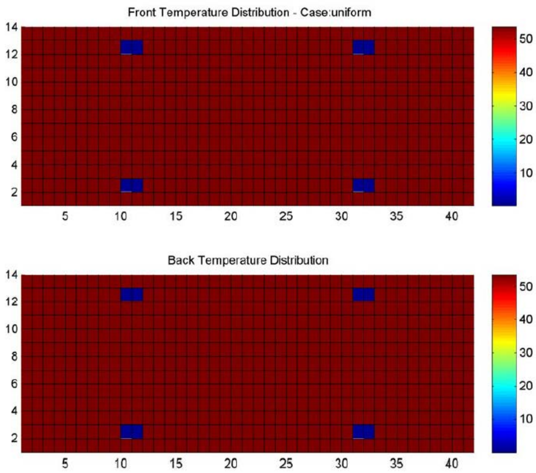
- Need to implement innovative cell model through data interpolation
  - Based on extensive test data from another part of the study

IV curves for various temperatures, solar fluxes and radiation levels for tested cells

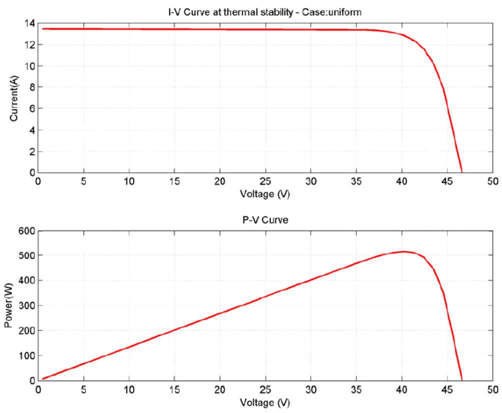


02/12/2013 | ESTAW 2014

Examples on various detailed analyses LEO case in sunlight – uniform temperature



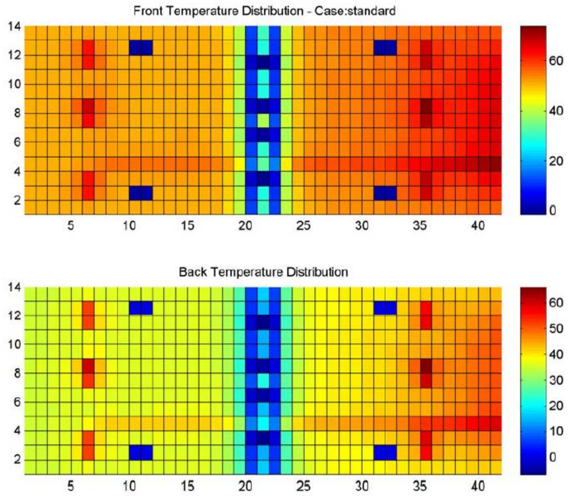
Temperature distribution – uniform temperature at 53.6°c



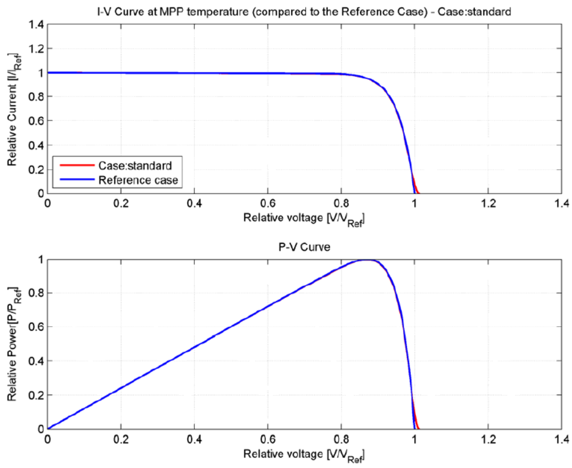
SA power characteristics

02/12/2013 | ESTAW 2014 ASTRIUM AN EADS COMPANY 20

Examples on various detailed analyses LEO case in sunlight - standard simulation



Temperature distribution



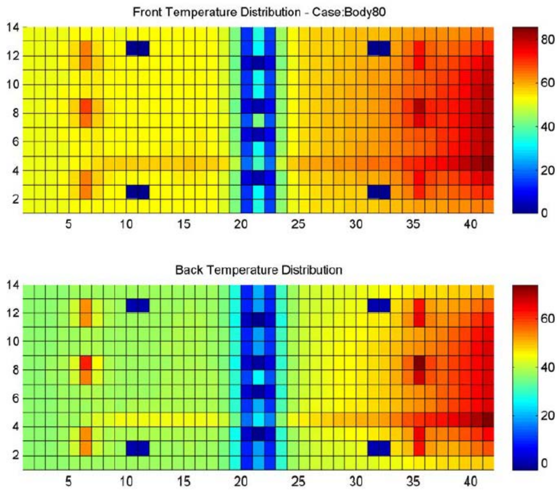
SA power characteristics compared to uniform case

	Cell Temperature (°c)	Vmp (mV)	Voc (mV)	Icc (mA)	Imp (mA)
Min value	28.12	2047.51	2368.65	508.81	486.54
Max value	73.79	2335.05	2646.19	539.80	516.25
Avg value	53.53	2175.06	2491.77	532.37	509.13

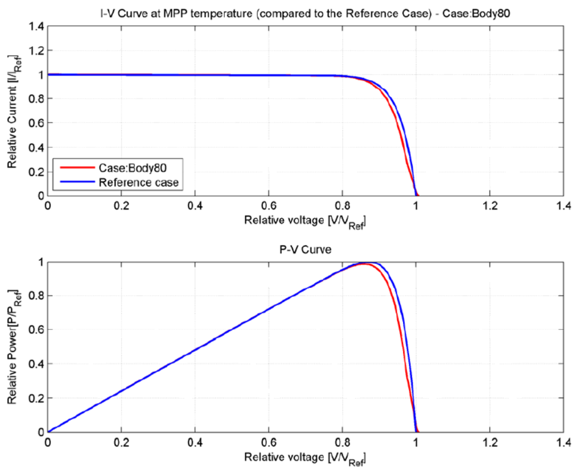
Summary of major Cell parameters

02/12/2013 | ESTAW 2014 ASTRIUM AN EADS COMPANY 21

Examples on various detailed analyses LEO case in sunlight - very hot body case



Temperature distribution



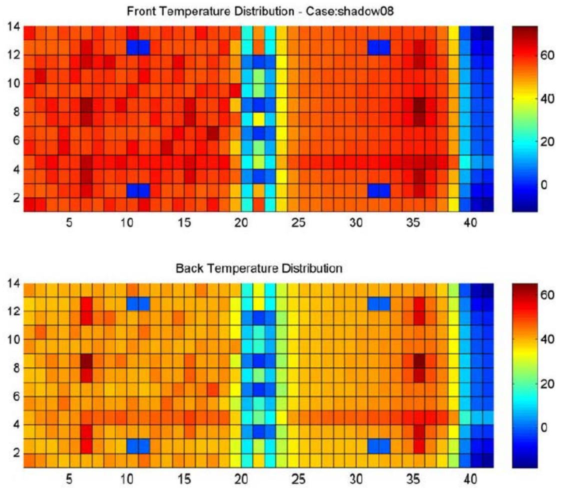
SA power characteristics compared to uniform case

	Cell Temperature (°c)	Vmp (mV)	Voc (mV)	Icc (mA)	Imp (mA)
Min value	31.53	1972.13	2295.90	509.48	487.18
Max value	85.75	2313.57	2625.46	541.03	517.43
Avg value	57.44	2150.48	2468.04	533.30	510.02

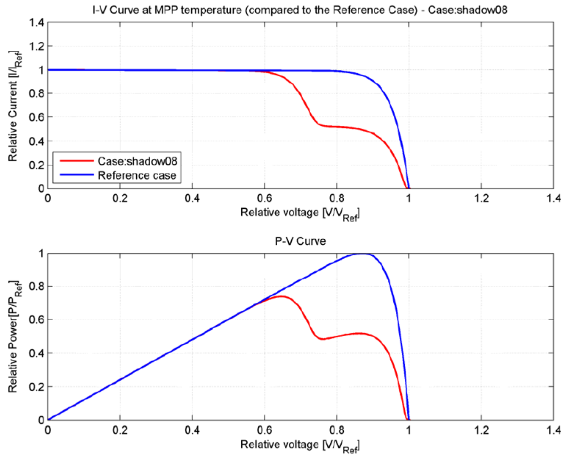
Summary of major Cell parameters

02/12/2013 | ESTAW 2014 ASTRIUM AN EADS COMPANY 22

Examples on various detailed analyses
LEO case in sunlight - shadowing of 8% of SA



Temperature distribution



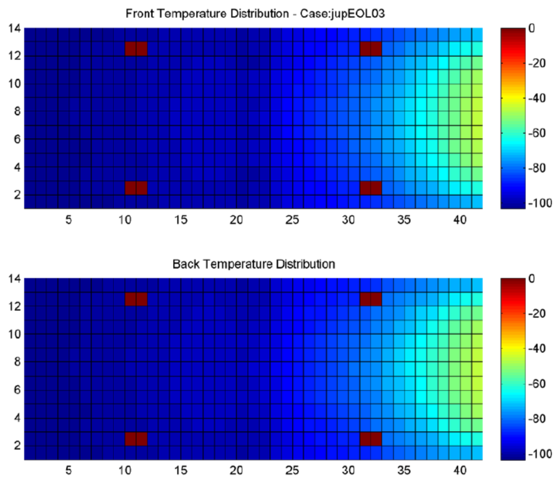
SA power characteristics compared to uniform case

	Cell Temperature (°c)	Vmp (mV)	Voc (mV)	Icc (mA)	Imp (mA)
Min value	-12.70	2048.96	2370.06	494.64	472.95
Max value	73.56	2592.39	2894.58	540.63	517.04
Avg value	52.15	2183.75	2500.15	532.06	508.83

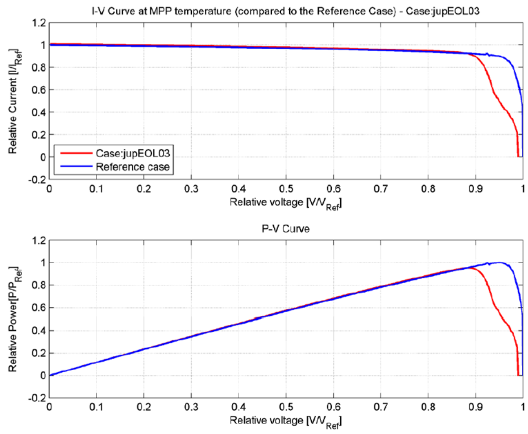
Table 7.1.26-2 - Summary of major Cell parameters

02/12/2013 | ESTAW 2014 ASTRIUM AN EADS COMPANY 23

Examples on various detailed analyses
Jupiter case – Europa flyby



Temperature distribution



SA power characteristics compared to uniform case

	Cell Temperature (°c)
Min value	-103.38
Max value	-46.49
Avg value	-89.42

Table 6.2.3-2 - Summary of major Cell parameters

02/12/2013 | ESTAW 2014 ASTRIUM AN EADS COMPANY 24

Conclusion

Together the pioneer of the full range of space solutions
for a better life on Earth

Together pioneering excellence

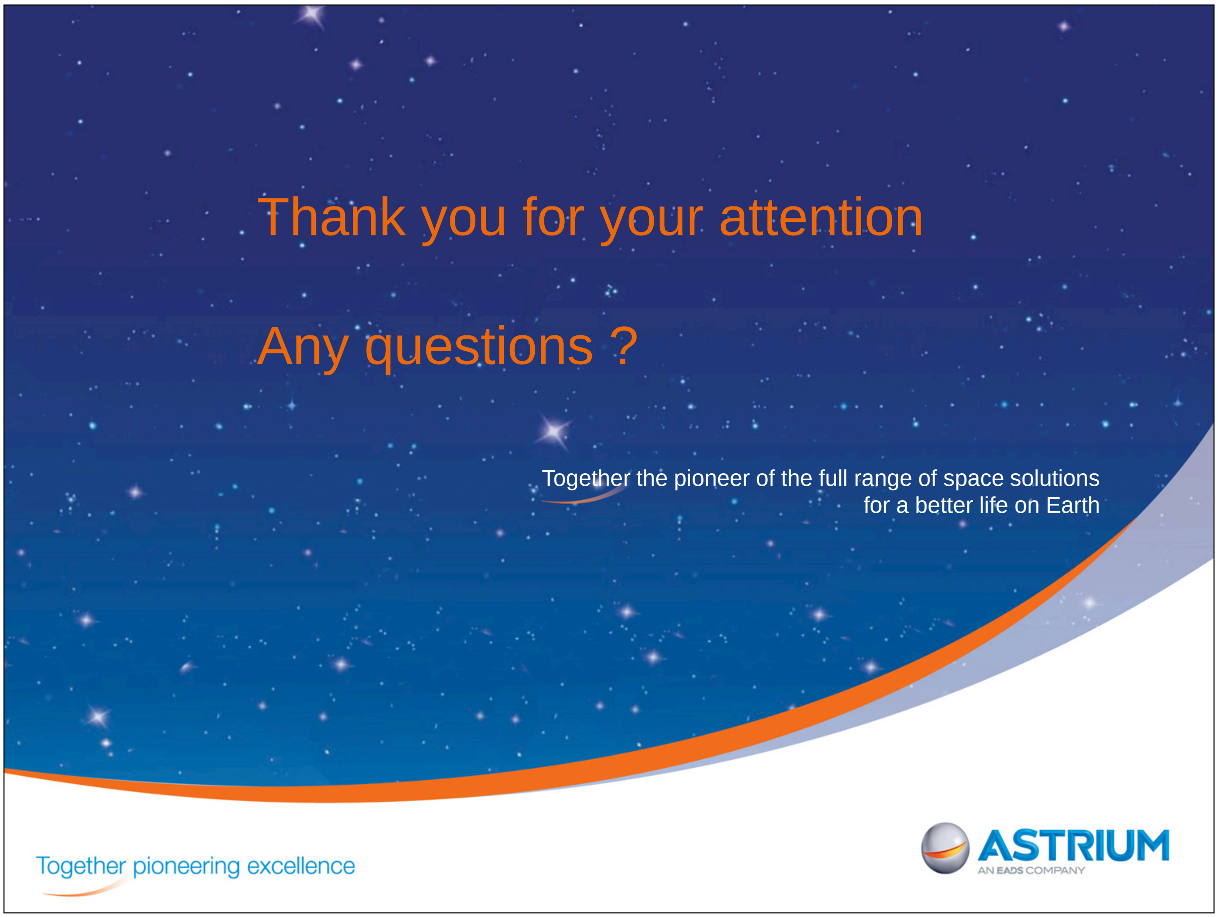
ASTRIUM
AN EADS COMPANY

Conclusion

- A new tool for thermo-electrical analyses
  - Validated and used in Astrium Toulouse
  - Two licenses available at ESA (see G. Beaufils)
- Interesting perks
  - Full link with Systema suite, high number of nodes, user components, re-use of existing thermal analyses, parametric analyses…
- Opening a new range of detailed analyses
  - For Solar Array / Battery / Power electronics / RFCS components
  - Multiple applications for current science missions (JUICE, BEPI, Rovers…)

02/12/2013 | ESTAW 2014

ASTRIUM
AN EADS COMPANY 26


Thank you for your attention
Any questions ?
Together the pioneer of the full range of space solutions
for a better life on Earth
Together pioneering excellence
ASTRIUM
AN EADS COMPANY

Appendix G

Correlating thermal balance test results with a thermal mathematical model using evolutionary algorithms

Niek van Zijl   B. Zandbergen
(Delft University of Technology, The Netherlands)

Bruin Benthem
(Dutch Space B.V., The Netherlands)

Abstract

The results of a series of thermal balance tests have been correlated with a thermal mathematical model. Three different optimization algorithms have been used for this: Monte Carlo simulation, Genetic Algorithm and Adaptive Particle Swarm Optimization. Based on a correlation criterion that minimizes the temperature difference between tests and model, the correlation can be optimized. APSO proved to be most useful, for its ability to optimize both locally and globally, its ability to search in a continuous search space, and its fast convergence. In this research, an average residual error of only 1.1°C was found. In general, optimization algorithms are feasible for thermal balance test results correlation. Comparing to manual correlation, optimization algorithms take less time, yield better results since they scan the entire search space, and are more flexible since several uncertain parameters can be varied at the same time. However, optimization techniques tend to find mathematical solutions rather than physical solutions, so boundaries on the parameter space are needed, for example from other tests. Even though this research indicates a good correlation, the set-up was relatively small (only 129 nodes and 24 relevant temperature measurements and comparisons) and comprehensible. For larger (satellite) test programs, the thermal network might be less easily understood and contain more unknowns and uncertainties. In that case a correlation using optimization techniques might be less optimal. Some engineering judgement of the thermal engineer will always be needed.

Note: An article explaining the method in more detail is included behind the presentation.

Correlating thermal balance test results using optimisation algorithms

Niek van Zijl, Bruin Benthem, Barry Zandbergen

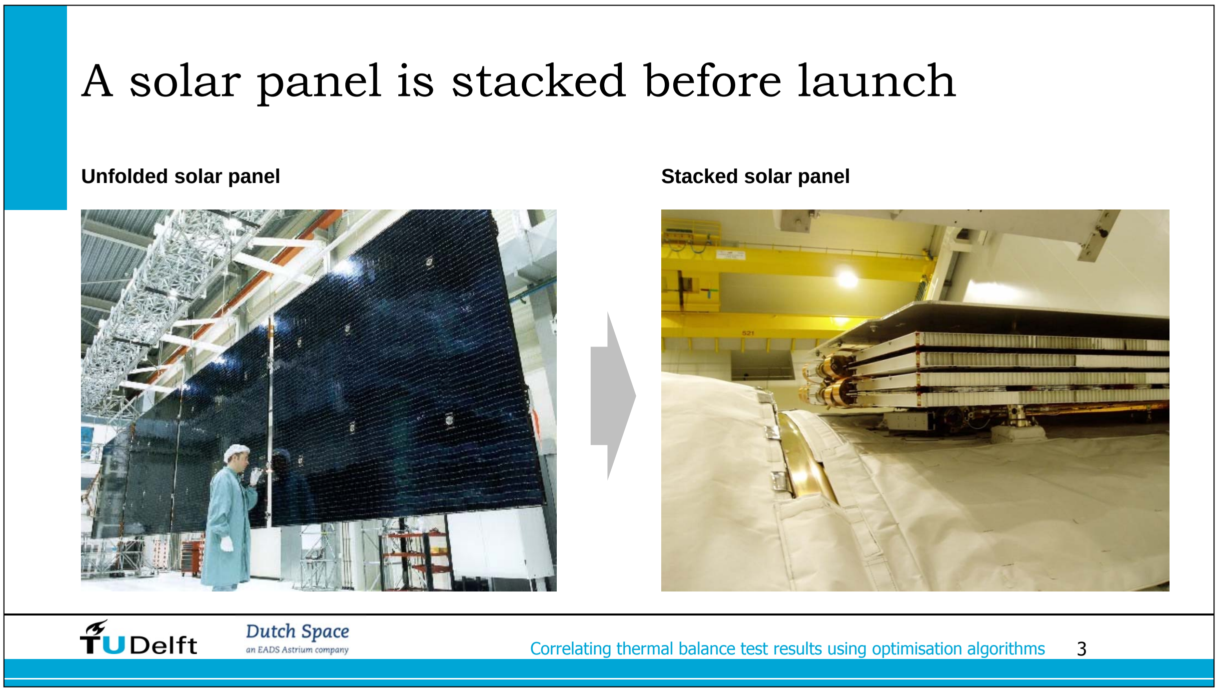
TU Delft · Dutch Space, an EADS Astrium company · Correlating thermal balance test results using optimisation algorithms 1

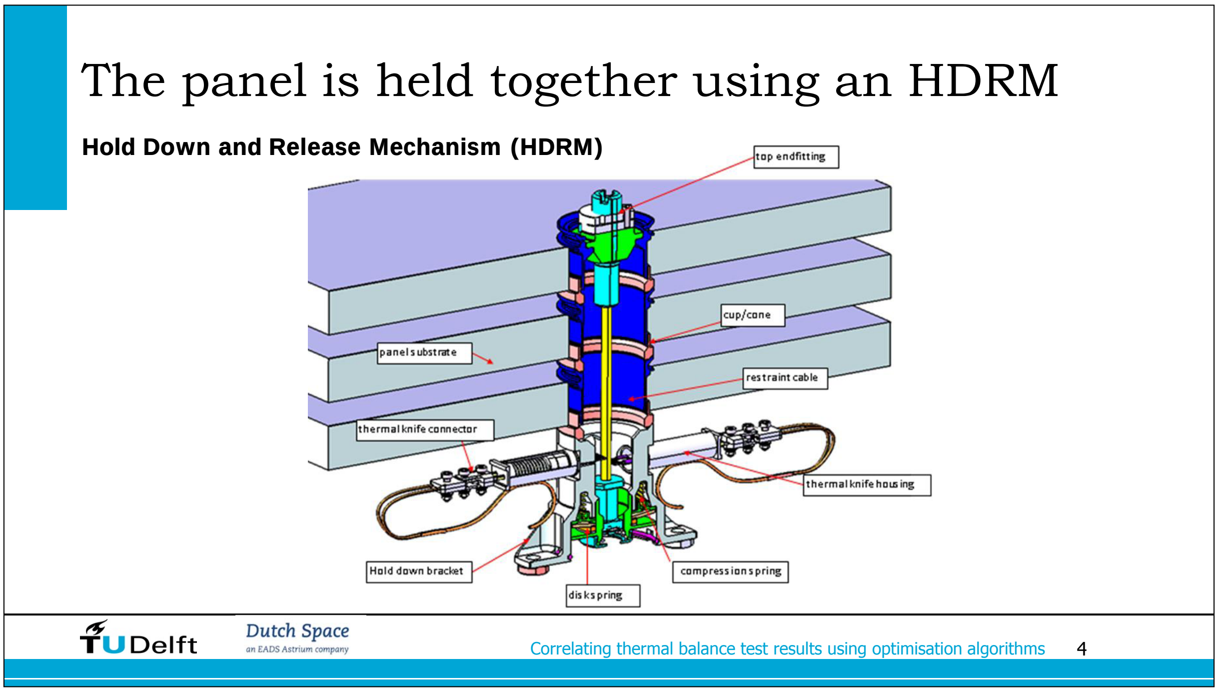
Use (evolutionary) optimisation algorithms for TB test correlation!

- In industry so far **TB test correlation** was always done **manually**
- Nowadays, with **increase in computer speed** optimisation algorithms are possible
- This research shows that **optimisation algorithms,** in particular **APSO**, are very much **suited for this correlation**!

- This presentation will prove this, based on a series of tests performed at Dutch Space

TU Delft · Dutch Space, an EADS Astrium company · Correlating thermal balance test results using optimisation algorithms 2


A solar panel is stacked before launch
Unfolded solar panel
Stacked solar panel
TU Delft
Dutch Space
an EADS Astrium company
Correlating thermal balance test results using optimisation algorithms
3


The panel is held together using an HDRM
Hold Down and Release Mechanism (HDRM)
top endfitting
cup/cone
panel substrate
restraint cable
thermal knife connector
thermal knife housing
Hold down bracket
compression spring
disk spring
TU Delft
Dutch Space
an EADS Astrium company
Correlating thermal balance test results using optimisation algorithms
4

Several TB tests were performed for TMM validation

Test goals

- Validate the TMM of the HDRM by determining the unknown couplings and optical properties
- Reduce endfitting temperature uncertainty

TU Delft Dutch Space an EADS Astrium company Correlating thermal balance test results using optimisation algorithms 5

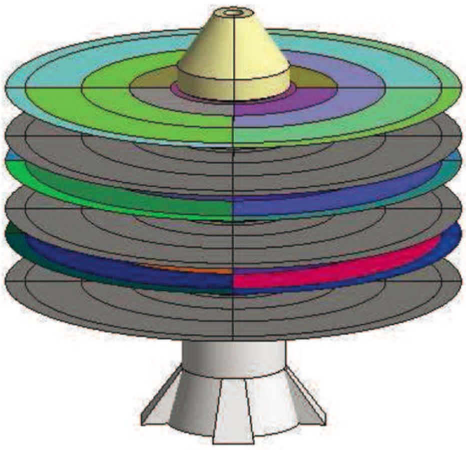
In total 4 dedicated tests were performed

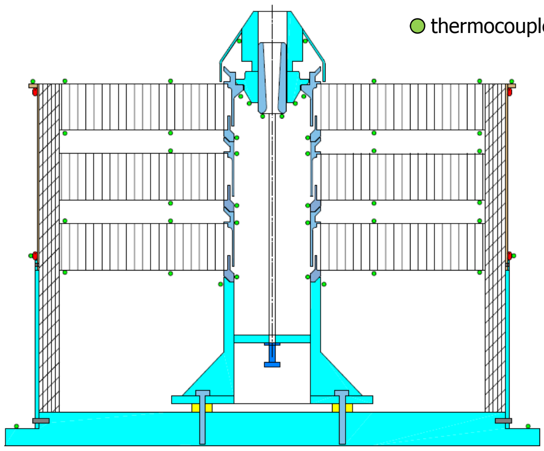
- In total 4 tests have been performed
  - 3 dedicated tests on parts of an HDRM to determine 8 thermal parameters
  - Final test on entire HDRM to validate earlier found values and correlate 8 other parameters
- First two tests at Dutch Space (1 week)
- Last two tests at ESTEC (2 weeks)

TU Delft Dutch Space an EADS Astrium company Correlating thermal balance test results using optimisation algorithms 6

Thermocouples were placed in accordance with the TMM

HDRM model versus measurement locations





TUDelft Dutch Space an EADS Astrium company Correlating thermal balance test results using optimisation algorithms 7

6 test phases have been performed on the total set-up

Phase	Cold plate [°C]	Solar simulator flux	White cap
D1 T1	60°C	1423 W/m²	no
D1 T2	60°C	1322 W/m²	no
D1 T3	40°C	1423 W/m²	no
D2 T1	60°C	1423 W/m²	yes
D2 T2	60°C	1322 W/m²	yes
D2 T3	40°C	1423 W/m²	yes

TUDelft Dutch Space an EADS Astrium company Correlating thermal balance test results using optimisation algorithms 8

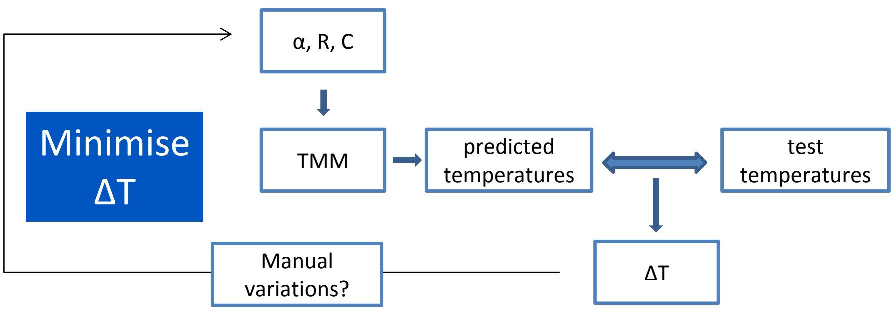
Thermal balance test correlation aims to minimise ΔT

Thermal balance test correlation:

*"The process of **adaptation of TMM parameters** in order to **minimise** the **difference** between the temperature **measurements** and the temperature **predictions** of the TMM"*

TU Delft Dutch Space an EADS Astrium company Correlating thermal balance test results using optimisation algorithms 9

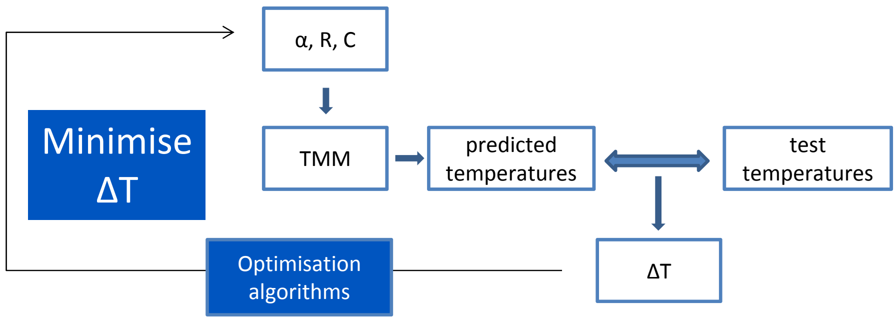
The correlation process: minimising through adaptation



Manual correlation:
1) It takes ages, 2) Goal of average ΔT < 3°C often not reached!

TU Delft Dutch Space an EADS Astrium company Correlating thermal balance test results using optimisation algorithms 10

The correlation process: minimising through adaptation



Use optimisation algortihms!

TU Delft Dutch Space an EADS Astrium company Correlating thermal balance test results using optimisation algorithms 11

Correlation goal is to minimise temperature difference over all 6 phases and all thermocouples

$$\min \Phi = \sqrt{\frac{\frac{1}{N}\sum_{i=1}^{N}(T_{model_i} - T_{test_i})^2 + (T_{model_{ef}} - T_{test_{ef}})^2}{2}}$$

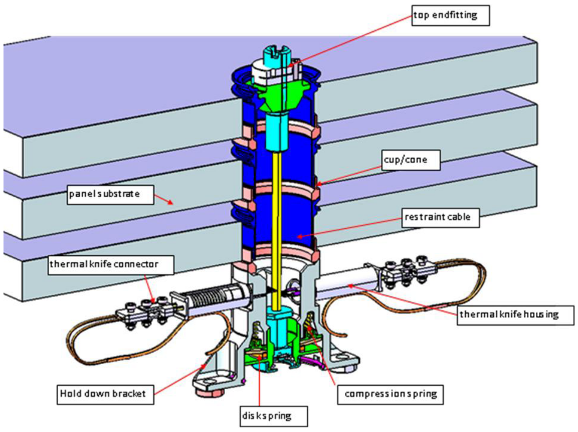
$$\min \Phi_{allPhases} = \sqrt{\frac{1}{6}\sum_{phase=1}^{6} \Phi_{phase}{}^2}$$

TU Delft Dutch Space an EADS Astrium company Correlating thermal balance test results using optimisation algorithms 13

In the correlation process, 16 thermal parameters were varied

Parameter
C_cup2panel
C_cone2panel
C_intra-panel
C_inter-panel
α_endfitting
ε_endfitting
α_WhiteCap
ε_WhiteCap

Parameter
C_bracket2baseplate
C_endfitting2cup
C_endfitting2whitecap
ε_baseplate
ε_TiCup
ε_Kapton
ε_CFRP
α_Kapton (outerPanel)



TU Delft Dutch Space an EADS Astrium company Correlating thermal balance test results using optimisation algorithms 14

Several optimisation algorithms have been compared

- Monte Carlo simulation
Random picking of parameter values

- Genetic Algorithm
Simulates natural selection (survival of the fittest)

- Adaptive Particle Swarm Optimisation
Simulates behaviour of school of fish

TU Delft Dutch Space an EADS Astrium company Correlating thermal balance test results using optimisation algorithms 15

APSO allows to search in a continuous search space

- Algorithm introduction by Zhan (2009), for TB tests by Beck (2012)
- APSO imitates the **swarm behavior** of fish or birds
- A set of **mathematical rules** allows the swarm to **explore**, but also **follow the 'best' particle**
- Advantage is it can **search in a continuous space**

TU Delft Dutch Space an EADS Astrium company Correlating thermal balance test results using optimisation algorithms 16

Genetic Algorithm is widely-used optimisation algorithm, based on natural selection

- Algorithm introduction for TB tests by Jouffroy (2007)
- GA mimics **natural selection**, allowing 'best fit' solutions to **survive and produce offspring**
- **Genetic operations** allow the population to **evolve** and differ slightly from the previous, **allowing new (better) solutions**
- Method is widely used, for example in orbit optimisation

TU Delft Dutch Space an EADS Astrium company Correlating thermal balance test results using optimisation algorithms 17

The practical application of these algorithms involved linearisation and .csv dump to MATLAB

- ESATAN-TMS model is linearised around test temperatures
- L, R and Q matrices dumped as .csv and imported in MATLAB

- TMM is evaluated and compared to test temperatures
- Thermal parameters are changed (linearly) using algorithms and substituted in L / R / Q matrices

- If model is converged, stop

Correlated model has average temperature difference of 1.1°C only, and almost 0 on the endfitting

Average temperature difference between model and test [°C]	
Endfitting	All nodes
0.24	1.1

From literature: a goal of average ΔT < 3°C, but it is often not even reached!

APSO is best algorithm to use for TB test correlation

	Monte Carlo	GA	APSO
Φ [K]	1.0171	0.789	0.783
Number of evaluations	10000	25600 (256 individuals x 100 generations)	6000 (20 particles x 300 iteration)
Search space	discrete	discrete	continuous
Required calculation time (s)	515	1298	263
Algorithm set-up	easy	difficult population operation	difficult swarm operations

APSO best algorithm to use:
- ability to optimise both locally and globally
- able to search in a continuous search space
- leads to fast convergence

TU Delft Dutch Space an EADS Astrium company Correlating thermal balance test results using optimisation algorithms 20

Discussion

- The first series of TB tests on parts only, have certainly helped in converging the result of the entire HDRM correlation
- Calculation time on this set-up was limited. With larger models, the thermal network grows, increasing computation time enormously
- Re-running the algorithm yielded the same objective function, but with different solution (thermal parameter set). Some of these sets were physically impossible, so engineering judgements is still important!

TU Delft Dutch Space an EADS Astrium company Correlating thermal balance test results using optimisation algorithms 21

Conclusion

- Established good correlation (1.1°C average) with test results
- Shown feasibility of optimisation algorithms
- APSO came out as best algorithm:
  - ability to optimise both locally and globally
  - able to search in a continuous search space
  - leads to fast convergence

TU Delft Dutch Space an EADS Astrium company Correlating thermal balance test results using optimisation algorithms 22

(Test) experience quotes

In theory, theory and practice are equal. In practice, theory and practice appear not to be equal

free from Flip Zijdemans, Dutch Space

TU Delft Dutch Space an EADS Astrium company Correlating thermal balance test results using optimisation algorithms 23

Correlating thermal balance test results with a thermal mathematical model using evolutionary algorithms

Niek van Zijl [#*1]

[#] *Faculty of Aerospace Engineering, Delft University of Technology*
Kluyverweg 1, 2629 HS Delft, The Netherlands

[*] *Dutch Space B.V.*
Mendelweg 30, 2333 CS Leiden, The Netherlands

[1] niekvanzijl@msn.com

***Abstract*— The results of a series of thermal balance tests have been correlated with a thermal mathematical model. Three different optimisation algorithms have been used for this: Monte Carlo simulation, Genetic Algorithm and Adaptive Particle Swarm Optimisation. Based on a correlation criterion that minimises the temperature difference between tests and model, the correlation can be optimised. APSO proved to be most useful, for its ability to optimise both locally and globally, its ability to search in a continuous search space, and its fast convergence. In this research, an average residual error of only 1.1°C was found. In general, optimisation algorithms are feasible for thermal balance test results correlation. Comparing to manual correlation, optimisation algorithms take less time, yield better results since they scan the entire search space, and are more flexible since several uncertain parameters can be varied at the same time. However, optimisation techniques tend to find mathematical solutions rather than physical solutions, so boundaries on the parameter space are needed, for example from other tests. Even though this research indicates a good correlation, the set-up was relatively small (only 129 nodes and 24 relevant temperature measurements and comparisons) and comprehensible. For larger (satellite) test programs, the thermal network might be less easily understood and contain more unknowns and uncertainties. In that case a correlation using optimisation techniques might be less optimal. Some engineering judgement of the thermal engineer will always be needed.**

I. Introduction

When a series of thermal balance tests is finished, the results need to be correlated with a thermal mathematical model. For long this correlation process has been a manual process as described clearly in [1], but the correlation often does not yield satisfactory results. The general correlation goal is a correlation within 3K [2],[3], but many correlations do not reach that criterion [1],[4]-[6]. Besides that, manual correlation can be very time consuming. As the correlation process actually is an optimisation problem, several optimisation techniques could be used to (semi-) automatically solve this problem. With computer speed increase over the past few years, optimisation algorithms have become more attractive to use. A literature study of several algorithms in [7] showed that Genetic Algorithm (GA) and Simulated Annealing (SA) proved promising for thermal correlation. In [8] a general study of GA parameters is performed. [9] is the first paper describing the use of Adaptive Particle Swarm Optimisation (APSO) for correlation.

In this paper the feasibility of the use of Monte Carlo techniques, GA and APSO is investigated. All techniques are tested using the results of a series of performed thermal balance tests.

II. Test Set-Up

A series of four thermal balance tests was performed on the Hold Down and Release Mechanism (HDRM). This system, developed by Dutch Space, clamps a stack of solar panels together during launch and deploys them once in orbit. The stack is held in place with a cable under tension, running through a hole in every panel. On both ends it is clamped with two endfittings. On the top part, the endfitting is exposed to solar radiation. To lower this endfitting temperature, also a white cap can be used.

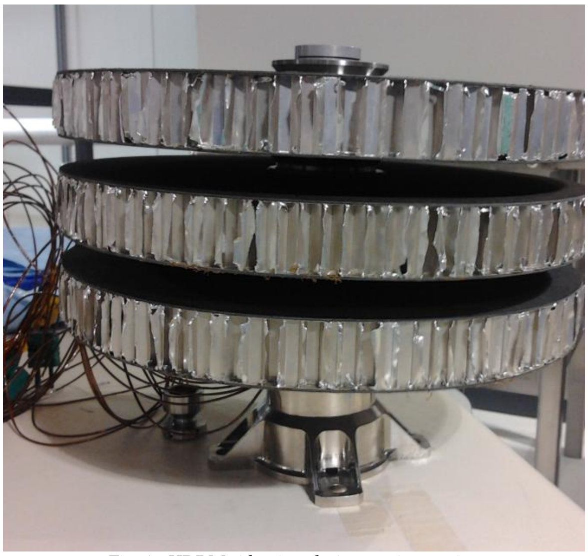


Fig. 1. HDRM side-view during test integration

The first three tests have been performed on parts of the HDRM, to determine 8 sensitive thermal parameters. Dedicated test set-ups and tests were designed to determine these values.

The last test was performed on an entire HDRM. The set-up consisted of an HDRM with 3 circular panel parts of 210 mm diameter as seen in Fig. 1. All around the panels 5 layers of 2-mm insulating foam and double-sided aluminised Kapton in between [10] are placed, while an Aluminum/CRES cylinder was placed around the foam, equipped with guard heaters, reaching the same temperature gradient as in the stack. This combination of foam and guard heating reduced the heat leak to the sides, leading to less than 0.3°C influence on the test temperatures.

On the bottom the HDRM was fixed to an aluminium baseplate, mounted on the chamber cold plate. A solar simulator was present to deliver the heat flux to the sample. It was calibrated using a solar cell.

Six different test phases were tested as described in TABLE I. Three tests phases are performed with white cap, and three without. Steady state (<0.1°C/ 2hrs) was reached for all test phases.

TABLE I
Test Phases

Phase	**Cold plate** [°C]	**Solar sim** [W/m^2]	**White cap**
D1 T1	60	1423	no
D1 T2	60	1322	no
D1 T3	40	1423	no
D2 T1	60	1423	yes
D2 T2	60	1322	yes
D2 T3	40	1423	yes

III. Correlation Problem/Criterion

A geometrical model of the test set-up was made in ESATAN-TMS, including the test chamber (shroud, door, window) and the insulating foam. The insulating foam was modelled as a fully IR-reflective surface. This geometrical model led to a thermal mathematical model of 109 nodes, plus 20 nodes for the environment. The test item was modelled rotationally symmetric and split in 4 quarters. Due to this rotational symmetry, a pair of thermocouples (for redundancy) was placed under 180° from the other. There were 48 thermocouples used on the set-up, plus about 10 in the chamber (facility thermocouples). Averaging redundant test thermocouples, and taking into account the shroud, door and window, there were 24 relevant locations of which the temperatures could be compared between test and model. As the model is rotationally symmetric, the temperatures of every four rotationally symmetric nodes were averaged as well.

To check the quality of the correlation, a correlation criterion was defined. [11] defines this as the average temperature difference, while [12] defines it in a least squares fashion. For this test two aspects were important: correlation over all nodes and the correlation of the endfitting temperature only (since this is the critical aspect of the HDRM). As a result, both aspects count for 50% in the correlation criterion, while still using a least squares approach:

$$\Phi = \sqrt{\frac{\frac{1}{N}\sum_{i=1}^{N}(T_{model_i} - T_{test_i})^2 + (T_{model_{ef}} - T_{test_{ef}})^2}{2}}$$

Where N is the amount of temperatures that are compared. As the shroud, door and baseplate serve as heat sinks, they are the boundary conditions of the system. Consequently these same temperatures are fed in the model as well, so they do not count for the correlation criterion. As a result, N = 20 when no white cap is present, and N = 21 if there is a white cap. The endfitting is included in N, since it then counts for the average error in the system.

As there are 6 test phases, this correlation needs to be checked for all 6 test phases (again root-mean-square, RMS), so:

$$\Phi_{allPhases} = \sqrt{\frac{1}{6}\sum_{phase=1}^{6}\Phi_{phase}^{\;2}}$$

IV. Implementation

To correlate the model, a set of 16 thermal parameters was varied. These consist of optical properties (UV absorption and IR emissivity) and conductive couplings (including some contact conductances). The different correlation methods were applied by making a .csv dump of the ESATAN-TMS model and reading these in MATLAB to accommodate for automatic correlation. This leads to three matrices: L, R and Q. L is the (square) matrix of conductive couplings, R is the (square) matrix of radiative couplings, and Q is the one-dimensional matrix of heat inputs (i.e. solar power, αAS).

The different algorithms (Fig. 2 and Fig. 3) work by varying parts of these matrices. If a conductive coupling is varied, it can just be replaced in the L-matrix. If the absorption α of a node is varied, the heat input on that node is scaled linearly with the new α. And if the emissivity ε of a node is varied, the entire radiative coupling from that node to all other nodes is scaled linearly with the new ε. Scaling these optical properties linearly with heat input or radiative couplings is not entirely representative, since reflections to other nodes are then not taken into account. This small error can be checked at the end of the correlation by back-substituting the found parameters from the optimal correlation in ESATAN-TMS and comparing the resulting temperatures.

The main advantage however is that varying optical properties becomes much faster this way, since not every time a new radiative analysis needs to be performed, like in ESATAN-TMS. There the entire geometrical model needs to be reloaded, after which a radiative analysis over all nodes needs to be performed. This is done by firing rays from every surface and counting the amount of rays that hit each other surface. The radiative analysis uses a Monte Carlo scheme, so a large amount of rays (~10000) per surface is fired, leading to a total 10-20 seconds needed per radiative analysis.

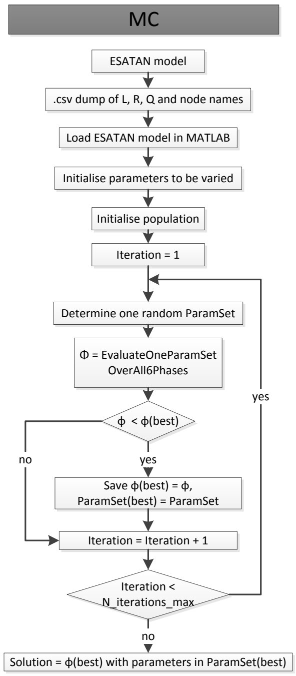


Fig. 2. Monte Carlo implementation

Besides the faster alterations of optical properties, MATLAB is also faster than ESATAN-TMS in calculating steady state results, because it is able to work with matrices better.

Variations of the parameters happened within certain limits. For 8 out of 16 parameters, their uncertainty ranges had been determined in the earlier 3 tests. Another 4 optical properties were known from Dutch Space heritage, while taking into account the guidelines from ESA [13] of ±0.03. The last 4 parameters were varied in a very large range: -100% to +100% of the estimated value. This allowed the search space to become limited, but large enough to find the optimal solution.

In the end, every algorithm chooses a set of parameters, which are then inserted in the model. The model is solved for steady state of each phase using the boundary conditions from TABLE I. The resulting temperatures are compared on the 24 relevant nodes, which gives a solution for the objective function.

Three algorithms are used for correlation: Monte Carlo (MC), Genetic Algorithm (GA) and Adaptive Particle Swarm Optimisation (APSO).

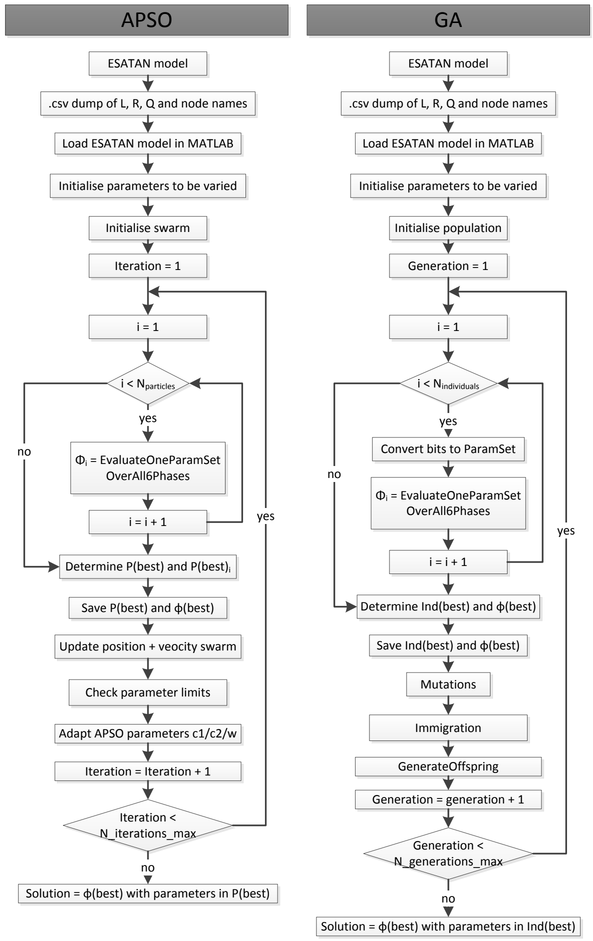


Fig. 3. GA and APSO implementation

V. Monte Carlo Method

The Monte Carlo method is quite straightforward. Per trial, each parameter value is randomly (uniform) chosen from its parameter range. This is evaluated and yields a value for the objective function. The more trials are performed, the larger the chance is a lower value for the objective function is found. On the other hand it is never clear whether this is a true optimum. A correlation with $\Phi = 1.0171$ is found, after 10000 trials, taking 515 seconds.

VI. Genetic Algorithm

The genetic algorithm simulates natural selection. A population consisting of solutions (parameter sets) evolves over generations, while the ones with the best fitness (lowest value for objective function) survive. Fig. 3 presents the algorithm in more detail.

In this research, each parameter had a resolution of 7 bits, leading to an individual length of 112 bits. A mutation rate of 0.1% per bit, an immigration rate of 2% and an elitist survival principle of 5% was used. On top of that, the most fit individual has a 2 times higher chance to generate offspring than the least fit individual. For all individuals in between this scales exponentially. In the next generation, parents are fully replaced with children (i.e. there is no fitness check, since this would require a full function evaluation, increasing the computation time).

In Fig. 4 the best correlation of 100 generations and a population size of 256 individuals is presented. This run took 1298 seconds and yielded a value for the objective function Φ = 0.789.

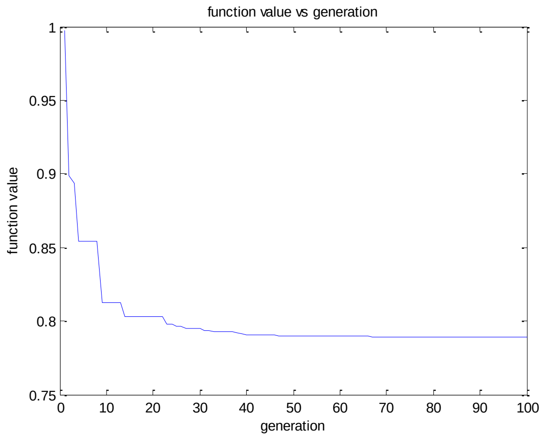


Fig. 4. Objective function improvement with more generations in GA correlation

VII. Adaptive Particle Swarm Optimisation

The APSO algorithm is described in [14]. APSO is an adaptation of Particle Swarm Optimisation (PSO) [15],[16]. PSO is based on the behavior of a flock of birds or school of fish. The movement of each particle (parameter set) is influenced by its local best known position but is also guided toward the best known position in the search space, which is updated when other particles find better solutions. The swarm searches the entire search space, but is also able to converge when an optimum has been found. This combination of both global and local optimum search makes PSO very useful.

The adaptive part in APSO comes from two extra parameters only, which identify the evolutionary state, and enforce an elitist learning principle. These parameters are adapted during the search. The evolutionary state determination increases the search efficiency and speed, while the elitist learning principle allows the swarm to jump out of the local optima.

The algorithm is presented in Fig. 3. During the correlation process, the swarm consisted of 20 particles, and the maximum amount of swarm iterations was 300. The development of the APSO parameters during the process is presented in Fig. 5. This resulted in Φ = 0.783 after 263 seconds.

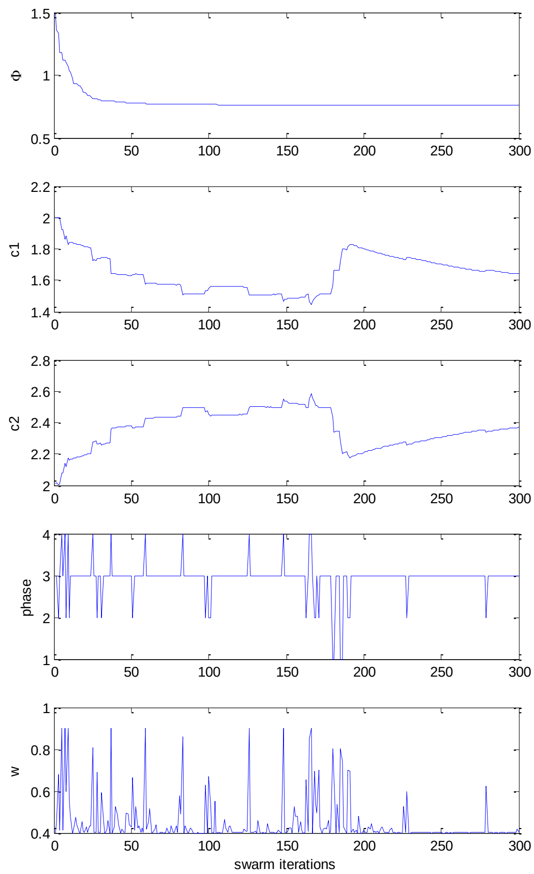


Fig. 5. Development of APSO parameters during correlation

VIII. Optimal Correlation

The optimal correlation can be found by selecting the one with the lowest value for the objective function, which is the one from APSO. The resulting temperature differences ΔT between model and test are presented in TABLE II.

TABLE II
REMAINING TEMPERATURE DIFFERENCES BETWEEN CORRELATED MODEL AND TEST FROM OPTIMAL CORRELATION (APSO)

Phase	ΔT on endfitting [°C]	ΔT over all nodes [°C] (RMS)
D1T1	0.16	1.20
D1T2	-0.17	1.11
D1T3	0.25	1.25
D2T1	-0.07	0.92
D2T2	-0.46	0.95
D2T3	0.05	1.04

The remaining ΔT over all nodes (RMS) is 1.1°C, which is far within the goal of correlation within 3°C [2],[3],[13]. So the correlation can be considered sufficient.

The residual between test and model temperatures is not zero. There always remains an error between test results and model. For now, several sources are:

- Errors in thermocouple measurements: even though the thermocouples are calibrated, still redundant thermocouples are now averaged, so there is always a residual error.
- Modelling errors which simplify reality: optical properties of finite surfaces and simplifications of the geometry.
- Material/manufacturing errors/assumptions: the panel is never fully homogene in all directions, for example due to different directions of the carbon fibres. On top of that, adhesives and/or pottings are not equally thick in all directions. This is assumed in the model however, so this might lead to errors.
- Couplings are linearised: the couplings through the panel are modeled as linear with temperature, whereas they are a combination of conduction (linear) and radiation (quartic).

IX. DISCUSSION

A comparison of the three different optimisation techniques is presented in TABLE III. From this table it becomes clear that APSO is the best method for correlating the test results. It reaches a better correlation due to its ability to combine both local and global search. On top of that, it can search the parameter space in a continuous search space, i.e. the parameter space does not have to be discretized and thus a global optimum is also a local optimum (you are in the Himalayas, but you also know you are exactly at the top of Mount Everest). APSO has a short calculation time, since the swarm can be very small, and there is no time involved in converting the parameters to bits and vice versa, like in GA. The solution also converges rather quickly, compared to GA. The main disadvantage of GA is the resolution of the parameters. More bits means a more accurate solution, but requires much more calculation power. Setting up the APSO correlation is not more difficult than setting up the GA correlation. Both methods have several swarm/population operations, but once the algorithm is set up, it can be applied rather easily.

TABLE III
COMPARISON OF DIFFERENT ALGORITHMS

	Monte Carlo	GA	APSO
Φ [K]	1.0171	0.789	0.783
Number of evaluations	10000	256 individuals x 100 generations = 25600	20 particles x 300 iterations = 6000
Search space	discrete	discrete	continuous
Required calculation time (s)	515	1298	263
Algorithm set-up	easy	difficult population operation	difficult swarm operations

However, some remarks can be made. Four aspects are considered.

A. *Amount of relevant temperature locations*

The amount of relevant temperature locations is limited in this test compared to large satellites programs. This means there are less nodes and couplings, which makes the correlation of the model easier. As a result, the correlation of the model can be on average 1.1°C, where several others have failed to correlate within 3°C [1],[4]-[6]. It can be concluded the correlation in this particular test has been good, but it cannot be concluded that this will hold for other (larger) satellite tests. The amount of temperature locations in this test was relatively small, compared to 49 in Monte Carlo correlation [11], 17 in APSO correlation [9], 35 in GA correlation [8] and 105 in manual correlation in [1]. For larger models or more measurement points the correlation might be more difficult.

On the other hand, in the correlation performed in this research, a set of 16 parameters was varied. This is relatively large, compared to 5 in Monte Carlo correlation [11], 10 in APSO correlation [9], and 5 in GA [8] (no data available from the manual correlation in [1]). More specific, using the optimisation techniques, the set of 16 parameters can easily be expanded. It will increase the computation time a little, but that is all. This makes optimisation algorithms again more favourable over manual correlation. Also, the total computation time is only in the order of several minutes, whereas [9] speaks of 50 hours for 600 iterations in a TMM with 650 nodes and only 10 varying parameters.

B. *Diversity in found correlations*

Running the different algorithms several times yielded several parameter sets with similar objective function values (0.783 to 0.790). These parameter sets however differed significantly. It shows that there are several solutions possible in this optimisation problem. Some of these parameter sets present mathematically possible solutions, but not physically possible ones, for example emissivities larger than 1. The challenge is to determine which of all these parameter sets is in fact the set that approached the physical parameters the best. In this research, three dedicated tests were performed to determine 8 of the 16 parameters. The values found with their uncertainty margins were used as inputs. The APSO solution that showed the best correspondence to these results (only few percent difference between earlier results and correlation results) was finally selected as the optimal correlation. However, if these 3 dedicated tests had not been performed, it would have been much harder to determine which physical solution to take. This is where ultimately also engineering judgement of the thermal engineer is needed!

A concrete example during this correlation process was the coupling of the HDRM to the baseplate. Normally the HDRM is isolated from the baseplate with some thermal washers, but mechanically fixed in place with several bolts. During the correlation, the temperature at the bottom part of the HDRM was always higher than was expected, in the order of 10°C. This showed in fact much less power was flowing to the baseplate than was predicted. By making this coupling a varying parameter, the optimisation algorithms directly converged to a solution a factor 3 lower than was expected. Inspection of the test set-up also revealed that the bolts had not been torqued properly, explaining this lower conduction. The fact that the correlation algorithms converged to this much lower value proves their strength. On the other hand, the thermal engineer should notice that the temperature is always higher during every correlation run, i.e. the optimisation algorithm cannot lower this temperature difference further (and the influence on the objective function of a 10°C difference is big!). The thermal engineering should thus know how the thermal model is built and which parameters could affect the correlation. A combination of engineering judgement and the optimisation algorithm yields the optimal correlation then.

C. Failure to reproduce found correlation

The result of running an optimisation algorithm is a certain set of values for all 16 parameters. But vice versa, the questions rises whether for a certain optimal correlation, this correlation can be reproduced? In a practical sense, this means the optimal correlation parameters yield the temperatures on the 20/21 (without/with white cap) relevant node locations (boundary conditions are kept the same). Now a correlation starts with these temperatures as reference temperatures, instead of the test temperatures. In a theoretical sense, this correlation should lead to an objective function of 0, since there exists a perfect fit to the temperatures.

This reproduction correlation process has been performed for GA and APSO. Fig. 6 presents these results. It is clear that the function value (i.e. the objective function) does not become 0, even after 1000 iterations, so both algorithms are not that perfect that they can always find the true optimum. This might have to do with the large set of parameters. Considering the 16 parameters and the 7 bits per parameter, an individual in GA consists of 112 bits, so there are $2^{112} = 5.2 \cdot 10^{33}$ parameter sets possible. For APSO, the amount of combinations is infinite due to its continuous search space.

On the other hand, already after 100 generations (GA) or 200 iterations (APSO) an objective function value of 0.1 has been found, which comes down to an average residual error per temperature location of 0.1°C. This residual error is so small, that it is also safe to say the correlation algorithm does find useable optima.

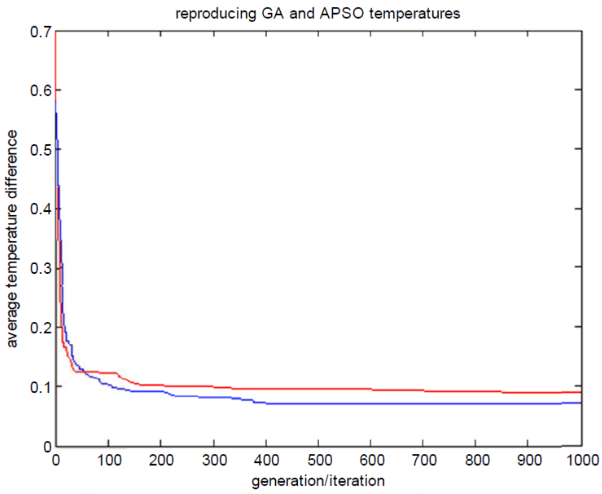


Fig. 6. Effort to reproduce the thermal parameters from the GA (blue) and APSO (red) optimal correlation

X. Conclusion

For the correlation of thermal balance test results with a thermal mathematical model, APSO proved to be most useful, for its ability to optimise both locally and globally, its ability to search in a continuous search space, and its fast convergence.

In comparing manual correlation with the use of optimisation techniques, it can be said that optimisation techniques are favourable: they take less time than manual correlation, they yield better results since they scan the entire search space, and they are more flexible since several uncertain parameters can be varied at the same time.

On the other hand, optimisation techniques tend to find mathematical solutions rather than physical solutions, so boundaries on the parameter space are needed, for example from other tests. As more parameters are being varied, the search space becomes very big. As there are several possible solutions, the algorithms do not necessarily find their own optimum again. And finally, the results from this research indicate a good correlation (average residual per node of

1.1°C), but the set-up was relatively small (only 129 nodes and 24 relevant temperature measurements and comparisons) and comprehensible. For larger (satellite) test programs, the thermal network might be less easily understood and contain more unknowns and uncertainties. In that case a correlation using optimisation techniques might be less optimal. Some engineering judgement of the thermal engineer will always be needed.

Acknowledgment

This research has been made possible by Dutch Space and Delft University of Technology. The author would like to thank Bruin Benthem and Barry Zandbergen for their suggestions and support, and their critical but true and honest feedback.

References

[1] Z. Jin, S. C. Joshi, G. J. J . Nesamani, P.K. Chan, T.M. Ying & C. H. Goh, "Data analysis and correlation for thermal balance test on a micro-satellite model," *Heat Transfer Engineering*, vol. 31, no. 2, pp. 222-233, 2010.

[2] D. G. Gilmore, *Satellite Thermal Control Handbook*. The Aerospace Corporation Press, 1994, ISBN 1-884989-00-4.

[3] R. D. Karam, *Satellite Thermal Control for Systems Engineers*. American Institute of Astronautics and Aeronautics, 1998, vol. 181 of Progress in Astronautics and Aeronautics, ISBN 1-56347-276-7.

[4] Z. Sherman, "The thermal balance test of AMOS-2 spacecraft," *Proceedings of the 5th International Symposium on Environmental Testing for Space Programmes, ESA SP-558*, pp. 127-135, 2004.

[5] E. van den Heuvel & J. Doornink, "Thermal balance testing of the European robotic arm," *Proceedings 4th International Symposium on Environmental Testing for Space Programmes, ESA SP-467*, pp. 439-444, 2001.

[6] S. Miller & E. Marotta, "Thermal modeling and testing of a nanosatellite's avionics board," *Journal of Thermophysics and Heat Transfer*, vol. 21, no. 3, pp. 496-504, 2007.

[7] F. Jouffroy, "Bibliographical study of optimisation methods with focus on genetic algorithm techniques wrt post-test thermal model correlation problem," document available from https://exchange.esa.int/restricted/model-correlation, 2006.

[8] F. Jouffroy & N. Durand, "Thermal model correlation using genetic algorithms," *21st European Workshop on Thermal and ECLS Software*, 2007.

[9] T. Beck, A. Bieler & N. Thomas, "Numerical thermal mathematical model correlation to thermal balance test using adaptive particle swarm optimization (APSO)," *Applied Thermal Engineering*, vol. 38, pp. 168-174, 2012.

[10] S. Tachikawa, R. Takagi, Y. Mizutani, Y. Hiasa, and A. Ohnishi, "Performance evaluation of new thermal insulation system with polyimide foams," in *41st International Conference on Environmental Systems*, pp. 52-57, 2011.

[11] W. Cheng, N. Liu, Z. Li, Q. Zhong, A. Wang, Z. Zhang & Z. He, "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, 2011.

[12] B. A. Cullimore, "Dealing with uncertainties and variations in thermal design," *Proceedings of InterPack '01, International Electronic Packaging Conference*, 2001, IPACK2001-15516.

[13] ECSS, "ECSS standard, Space Engineering, Mechanical Part 1: thermal control," ECSS-E-30 Part 1A, 2000.

[14] Z-H. Zhan, J. Zhang, Y. Li & H. S-H. Chung, "Adaptive particle swarm optimization," *IEEE Transactions on Systems, Man, and Cyberneticspart B: Cybernetics*, vol. 39, no. 6, pp. 1362-1381, 2009.

[15] J. Kennedy and R. C. Eberhart, “Particle swarm optimization,” in Proceedings of IEEE International Conference on Neural Networks, vol. 4, pp. 1942–1948, 1995.

[16] R. C. Eberhart and J. Kennedy, “A new optimizer using particle swarm theory,” in Proceedings of the 6th International Symposium on Micro Machine and Human Science, pp. 39–43, 1995.

Appendix H

Exchange of Thermal Models
Challenges and Solutions

Stefan Kasper
(Jena-Optronik GmbH, Germany)

Abstract

This presentation deals with the various challenges of exchanging thermal models that can be encountered by:

- use of different thermal software tools
- use of different ESATAN-TMS versions
- use of different modeling rules / model design standards
- differences in thermal modeling specification documents

jenaoptronik

Exchange of Thermal Models: Challenges and Solutions

Stefan Kasper, 3-4 December 2013 at ESA/ESTEC, Noordwijk, The Netherlands

space for success

---

jenaoptronik

The city of Jena

German Optical Valley: Tradition and Future

space for success

Jena-Optronik GmbH. Exchange of Thermal Models: Challenges and Solutions 2

jenaoptronik

The company.

Jena-Optronik GmbH

Jena-Optronik focuses on space applications with operational, commercial and scientific background:

- **Attitude and Orbit Control Systems (AOCS) sensors**
- **Optical space instruments for Earth observation**

- Jena-Optronik is EN/AS 9100 certified

EN 9100:2009
BUREAU VERITAS
Certification
N° DE002542-1

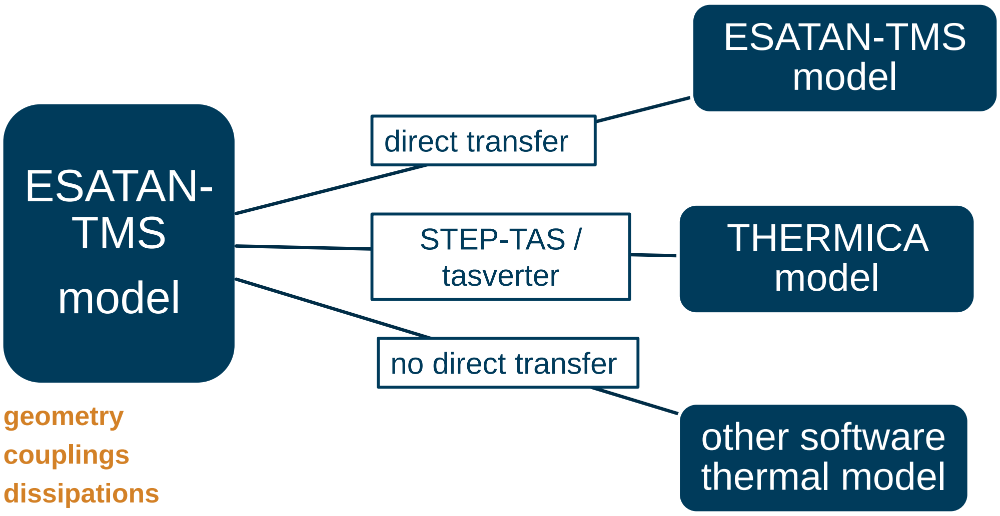
- **World-wide activities with a broad customer base**
- **High quality awareness** and well-qualified, motivated employees
- Strong future-proof technological basis in an **innovative environment**
- **40 years of experience** with optical instruments
- **Partner in international and national projects**

space for success

Jena-Optronik GmbH. Exchange of Thermal Models: Challenges and Solutions 3

jenaoptronik

Model Transfer Overview



geometry
couplings
dissipations
orbit
boundaries

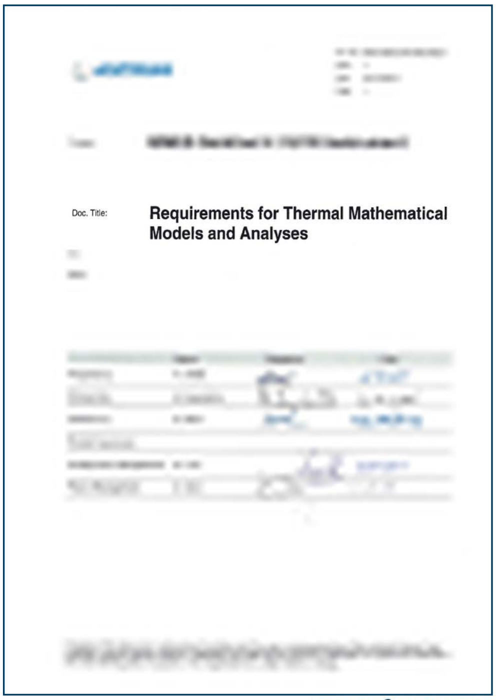
space for success

Jena-Optronik GmbH. Exchange of Thermal Models: Challenges and Solutions 4

jenaoptronik

Start of a Project

- Unit Specification
- Environment Specification
- GDIR
- Thermal Model Requirements
  - file naming
  - node number ranges
  - limited number of nodes
  - ESATAN file structure
  - …
- Reduced Thermal Model Delivery
- …


Doc. Title: Requirements for Thermal Mathematical Models and Analyses

space for success

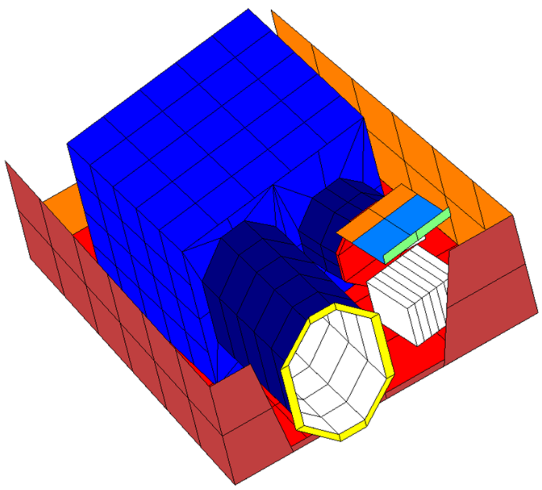
Jena-Optronik GmbH. Exchange of Thermal Models: Challenges and Solutions 5

jenaoptronik

Workflow in ESATAN-TMS

Geometry (*.erg)

- thermo-optical properties
- bulk properties
- shell definition
  - dimension
  - nodalisation
  - labels …
- node numbering (! FE method)
- translations, rotations
- non-geometric nodes
- conductive interfaces
- contact zones
- user-defined conductors
- groups



space for success

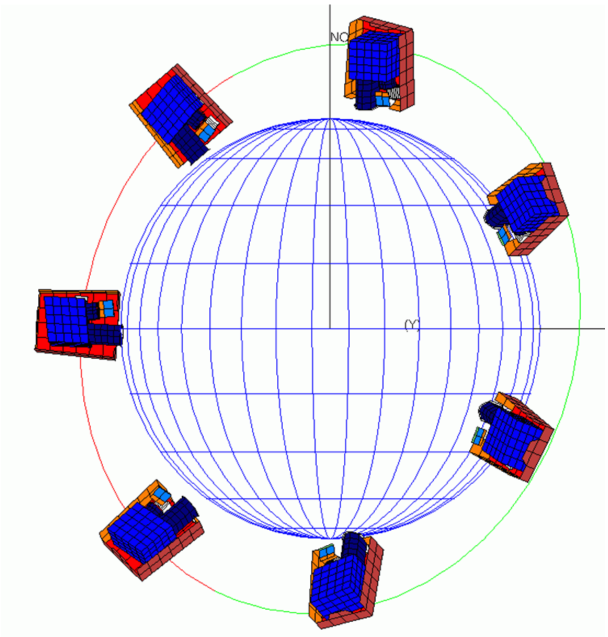
Jena-Optronik GmbH. Exchange of Thermal Models: Challenges and Solutions 6

Workflow in ESATAN-TMS

Kernel (*.erk) and Thermal (*.ere)

- orbit definition
- parameters for ray-tracing
- parameters for heat flux calculation
- call of GR calculation
- call of orbit load calculation

- boundary definition
- temperatures
- dissipations
- call of GL calculation
- call and run of analysis cases



space for success

Jena-Optronik GmbH. Exchange of Thermal Models: Challenges and Solutions 7

Workflow in ESATAN-TMS

The template file

- replaces the classical ESATAN file
- is a skeleton for the thermal model
- is the right place for all user subroutines
- use $INCLUDE in order to have a simple structure of the template
- different analysis cases need different template files → use "switch variables"

```
# template for
# analysis case 1
................
................
xxxxxxxxxxxx
$CONSTANTS
$INTEGER
analysis = 1;
...............
```

```
# template for
# analysis case 2
................
................
xxxxxxxxxxxx
$CONSTANTS
$INTEGER
analysis = 2;
...............
```

```
# template for
# analysis case 3
................
................
xxxxxxxxxxxx
$CONSTANTS
$INTEGER
analysis = 3;
...............
```

space for success

Jena-Optronik GmbH. Exchange of Thermal Models: Challenges and Solutions 8

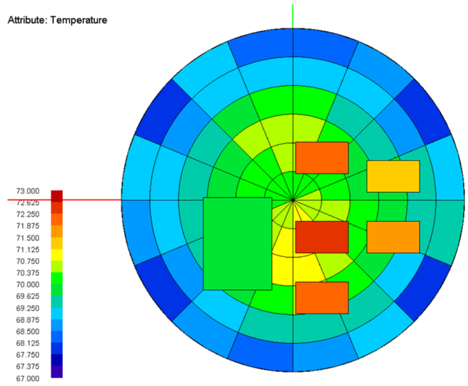
jenaoptronik

Workflow in ESATAN-TMS

Recommendations for Model Transfer

- use of $INCLUDE
- define all necessary nodes and couplings in geometry file
- avoid double code (use subroutines)
- keep the template file clean

- don't copy the thermal model requirements specification from a former project → consider the new features of ESATAN-TMS



space for success

Jena-Optronik GmbH. Exchange of Thermal Models: Challenges and Solutions 9

jenaoptronik

Workflow in ESATAN-TMS

Use of Different ESATAN-TMS Versions

- Project requires use of out-dated versions
- some features are not available
  - conductive interfaces along curved edges
  - contact zone
- manual re-calculation of the required conductive couplings

space for success

Jena-Optronik GmbH. Exchange of Thermal Models: Challenges and Solutions 10

jenaoptronik

Model Design Standards

Different Modelling Rules / Model Design Standards

- the classical ESATAN *model.d* file is no longer required
- don‘t make requirements on the ESATAN file itself
- node numbers are no longer significant when using the Finite Elements approach

space for success

Jena-Optronik GmbH. Exchange of Thermal Models: Challenges and Solutions 11

jenaoptronik

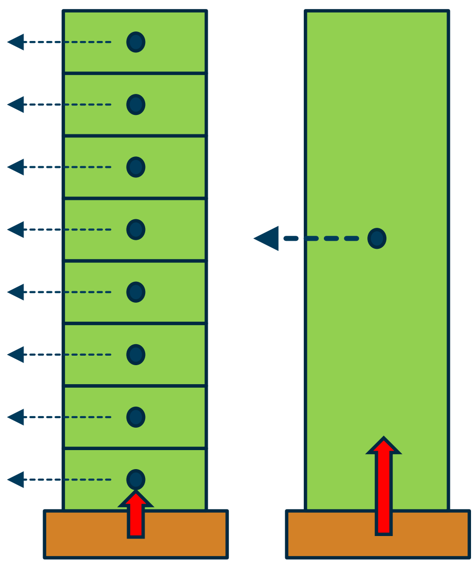
Specification

Accuracy of Reduced Thermal Models

Requirements (example):

- temperature (except MLI): the capacity weighted node temperature shall not differ by more than 3 K
- fluxes: the interface flux shall not differ by more than 5%
- heaters: the required heater power shall not differ by more than 5%
- dissipation: no difference allowed in dissipations
- thermal capacity: no difference allowed in the thermal capacities

→ temperature requirement is OK
→ flux requirement is impractical for external units



space for success

Jena-Optronik GmbH. Exchange of Thermal Models: Challenges and Solutions 12

jenaoptronik

Model Transfer

Transfer of Thermal Models with non-European companies

- no common software
- transfer via Excel sheet

	A	B	C	D	E
1	type	identifier	density	specific_capacity	conductivity
2	BULK	mat_alu	2700	900	141
3	BULK	mat_mli	2.7	900	141

- transfer via text file

NODE INFORMATION

surface number	node number	node name	capacity in Ws/K	internal heat dissipation in W		thermal optical property						remark	allowable temperature range in degree Celsius		
				off	on	solar absorbtivity		infrared emissivity		ratio: specular to total reflectivity			non-operating	turn-on	operating
						BOL	EOL	BOL	EOL	SOLAR	IR				
7, 8, 9, 10, 11	13	baseplate	117	0	0	n.a.	n.a.	0.1	0.1	n.a.	0.0	temperature reference point	-35…+65	-35…+60	-30…+55

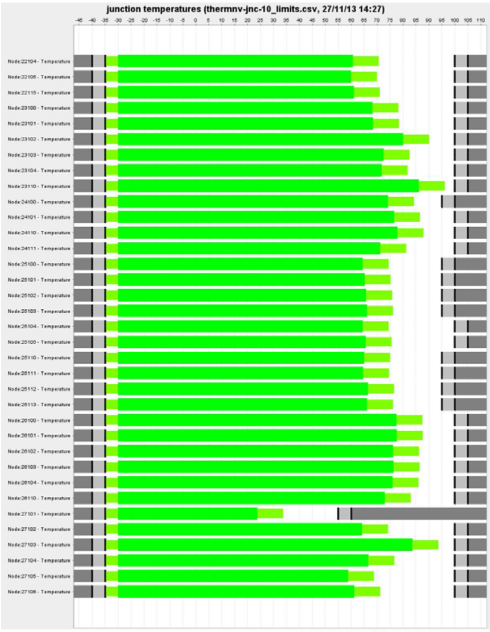
space for success

Jena-Optronik GmbH. Exchange of Thermal Models: Challenges and Solutions 13

jenaoptronik

Summary

- There is no common standard for exchange of thermal models.
  - We have company internal rules for modelling.
- Also inside the “ESATAN-TMS community” there are different modelling techniques.
- Consider the new software features by issuing thermal model specifications.
- Make practicable requirements for reduced thermal models.



space for success

Jena-Optronik GmbH. Exchange of Thermal Models: Challenges and Solutions 14

Appendix I

The KT Thermal Mapping Tool

an semi-automated temperature transfer between structural and thermal models

Anton Zhukov Markus Czupalla Alexander Kuisl Gerhard Bleicher
Winfried Gambietz
(Kayser-Threde GmbH, Müchen, Germany)

Abstract

The analysis of the thermo-opto-mechanical performance of optical instruments is a complex and time consuming process. It spans across multiple disciplines and multiple tools (e.g. ESATAN, NASTRAN, ZEMAX) which are not designed to interface with one another.
To allow precise end-to-end thermo-opto-mechanical analyses of instruments, without the loss of data, KT establishes a software suite (MULTIPAS), which inherently connects the thermal, structural and optical tools.
An important part of the MULTIPAS software suit is the Thermal Mapping Tool (TMT) providing the link between the thermal and structural model. The tool realize an automated temperature mapping process based on in-house interpolations routines and has the ability to handle mismatching meshes of the thermal and structural models.
To preserve thermal boundaries between the parts a recognition of single parts is built in the TMT, allowing to map geometrically adjacent but thermally decoupled parts correctly. Further, edge effects are covered in a way that guarantees no extrapolations at the edges, preserving the temperature range prescribed by the thermal model. A built in batch mode allows for handling of thousands of time steps, opening the door to transient stability analyses of entire orbits.
Demonstration of the TMT functionality, results from application experience will be presented and discussed in the presentation. Further, conclusions shall be presented and discussed for the build of GMMs which are to be used as mapping "templates".

KAYSER-THREDE

Kayser-Threde GmbH

Space

Industrial Applications

27th European Space Thermal Analysis Workshop

KT Thermal Mapping Tool

A. Zhukov, M. Czupalla, A. Kuisl, G. Bleicher, W. Gambietz

An OHB Company

MultiPAS thermal structural optical Performance Analysis Software

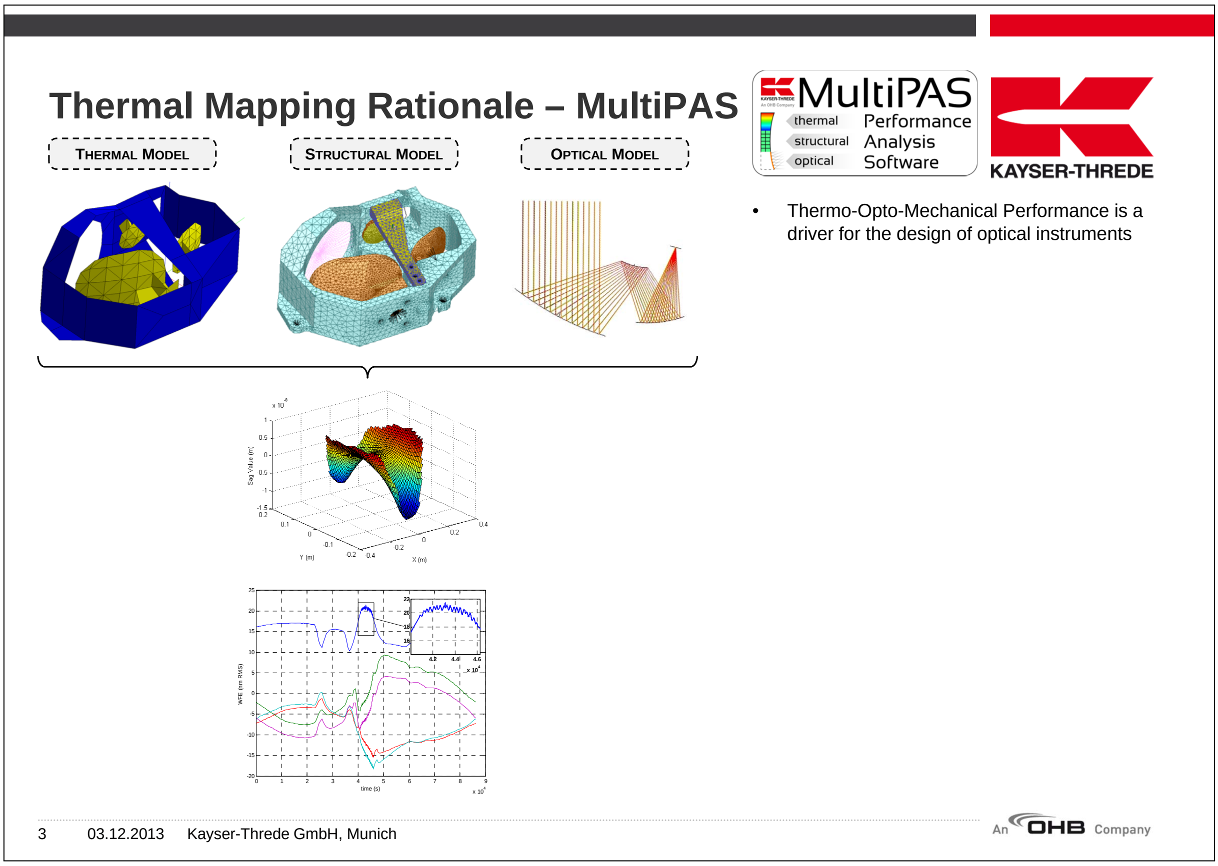
KAYSER-THREDE

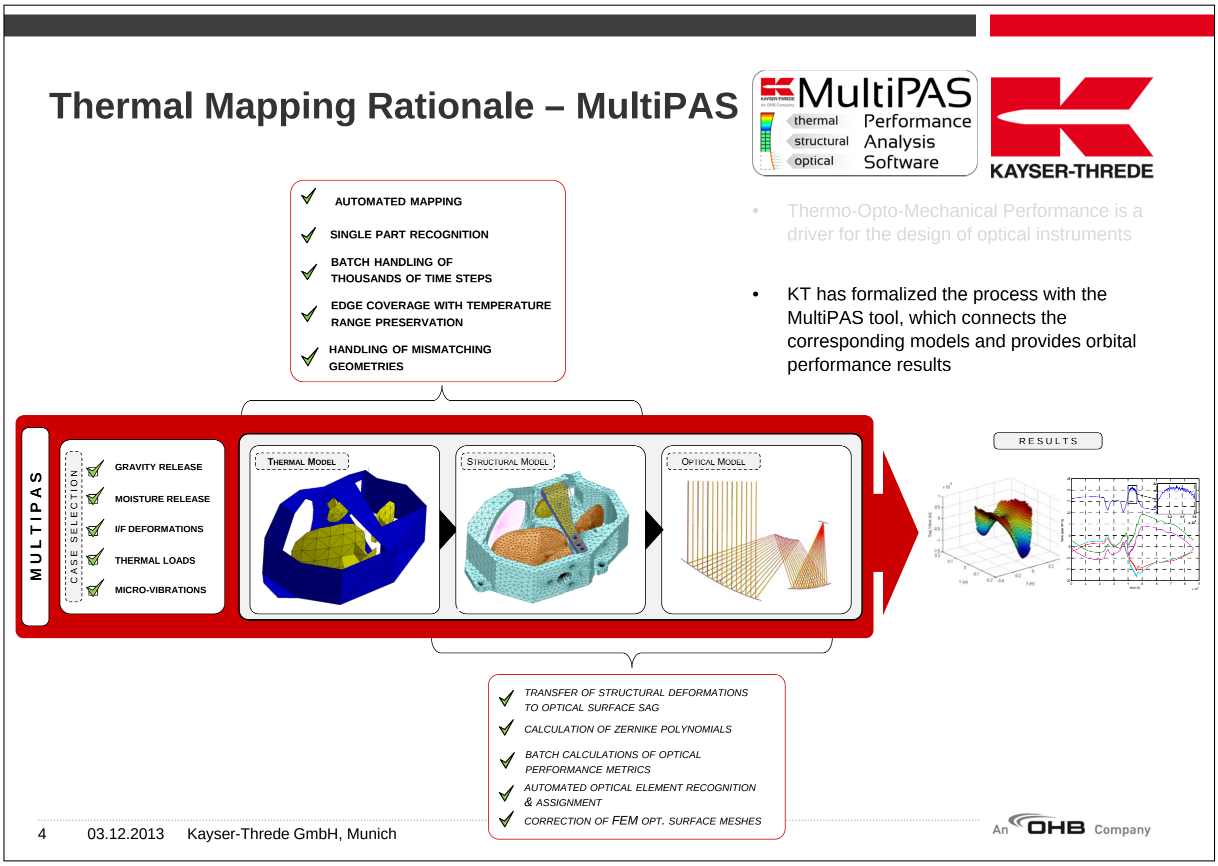
SUMMARY

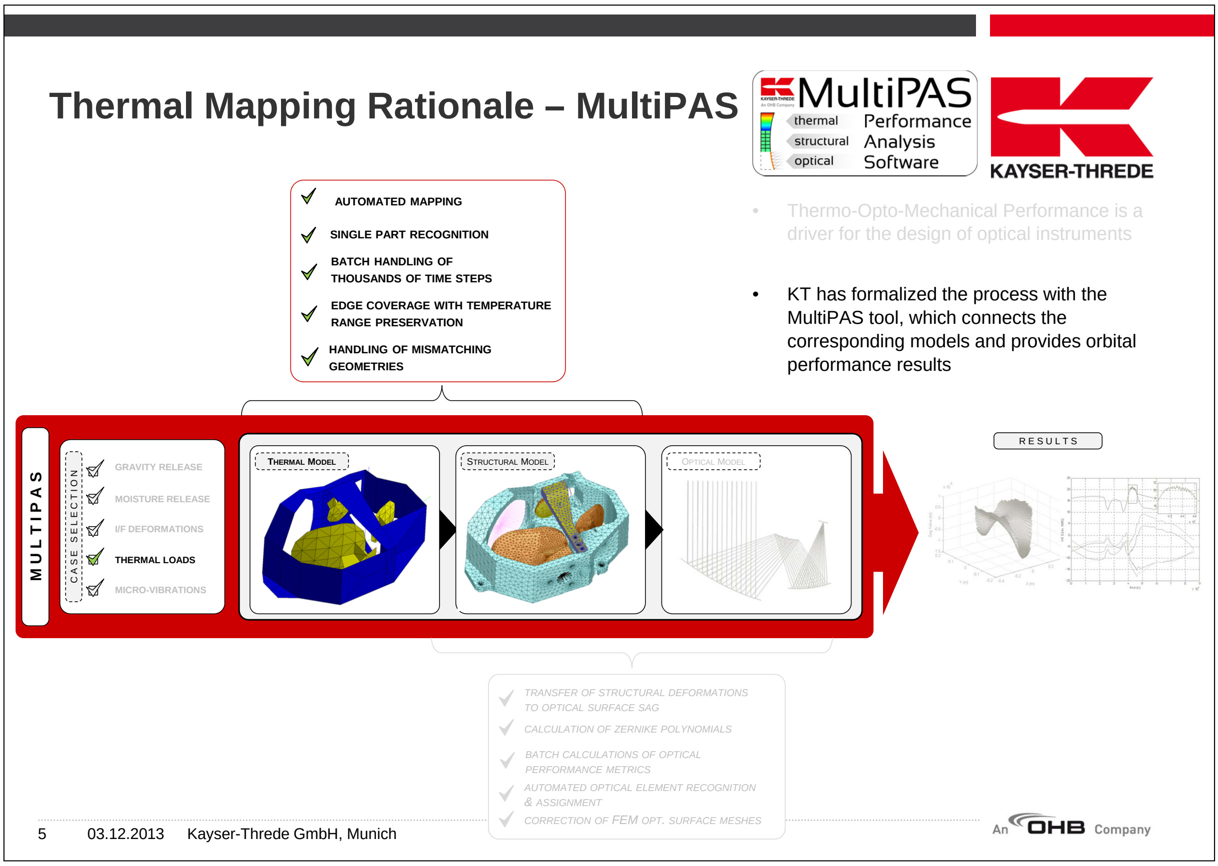
- **Thermal Mapping Rationale**
  - **KT MultiPAS Tool**
- **KT Thermal Mapping Tool (TMT) Introduction**
  - Mapping Process
  - Software Modules
- **Example**
  - Structural Model
  - Thermal Model
  - Model Comparison
  - Mapping Process
- **Mapping Verification**
- **Summary**

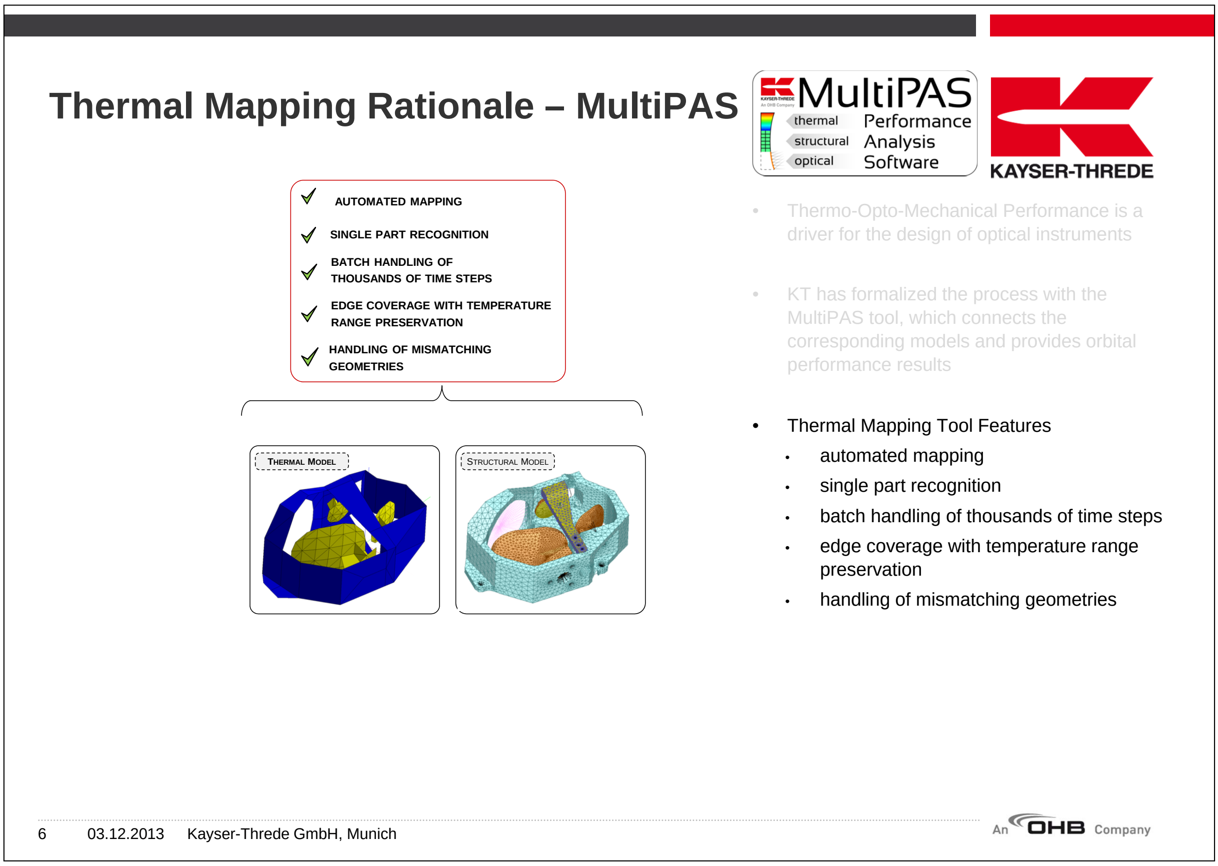
2 03.12.2013 Kayser-Threde GmbH, Munich

An OHB Company


Thermal Mapping Rationale – MultiPAS
MultiPAS
thermal Performance
structural Analysis
optical Software
KAYSER-THREDE
THERMAL MODEL
STRUCTURAL MODEL
OPTICAL MODEL
Thermo-Opto-Mechanical Performance is a driver for the design of optical instruments
3 03.12.2013 Kayser-Threde GmbH, Munich
An OHB Company


Thermal Mapping Rationale – MultiPAS
MultiPAS
thermal Performance
structural Analysis
optical Software
KAYSER-THREDE
Thermo-Opto-Mechanical Performance is a driver for the design of optical instruments
KT has formalized the process with the MultiPAS tool, which connects the corresponding models and provides orbital performance results
AUTOMATED MAPPING
SINGLE PART RECOGNITION
BATCH HANDLING OF THOUSANDS OF TIME STEPS
EDGE COVERAGE WITH TEMPERATURE RANGE PRESERVATION
HANDLING OF MISMATCHING GEOMETRIES
MULTIPAS
CASE SELECTION
GRAVITY RELEASE
MOISTURE RELEASE
I/F DEFORMATIONS
THERMAL LOADS
MICRO-VIBRATIONS
THERMAL MODEL
STRUCTURAL MODEL
OPTICAL MODEL
RESULTS
TRANSFER OF STRUCTURAL DEFORMATIONS TO OPTICAL SURFACE SAG
CALCULATION OF ZERNIKE POLYNOMIALS
BATCH CALCULATIONS OF OPTICAL PERFORMANCE METRICS
AUTOMATED OPTICAL ELEMENT RECOGNITION & ASSIGNMENT
CORRECTION OF FEM OPT. SURFACE MESHES
4 03.12.2013 Kayser-Threde GmbH, Munich
An OHB Company


Thermal Mapping Rationale – MultiPAS
MultiPAS
thermal
structural
optical
Performance
Analysis
Software
KAYSER-THREDE
AUTOMATED MAPPING
SINGLE PART RECOGNITION
BATCH HANDLING OF THOUSANDS OF TIME STEPS
EDGE COVERAGE WITH TEMPERATURE RANGE PRESERVATION
HANDLING OF MISMATCHING GEOMETRIES
MULTIPAS
CASE SELECTION
GRAVITY RELEASE
MOISTURE RELEASE
I/F DEFORMATIONS
THERMAL LOADS
MICRO-VIBRATIONS
THERMAL MODEL
STRUCTURAL MODEL
OPTICAL MODEL
RESULTS
TRANSFER OF STRUCTURAL DEFORMATIONS TO OPTICAL SURFACE SAG
CALCULATION OF ZERNIKE POLYNOMIALS
BATCH CALCULATIONS OF OPTICAL PERFORMANCE METRICS
AUTOMATED OPTICAL ELEMENT RECOGNITION & ASSIGNMENT
CORRECTION OF FEM OPT. SURFACE MESHES
• Thermo-Opto-Mechanical Performance is a driver for the design of optical instruments
• KT has formalized the process with the MultiPAS tool, which connects the corresponding models and provides orbital performance results
5 03.12.2013 Kayser-Threde GmbH, Munich
An OHB Company

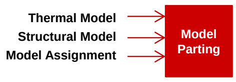

Thermal Mapping Rationale – MultiPAS
MultiPAS
thermal
structural
optical
Performance
Analysis
Software
KAYSER-THREDE
AUTOMATED MAPPING
SINGLE PART RECOGNITION
BATCH HANDLING OF THOUSANDS OF TIME STEPS
EDGE COVERAGE WITH TEMPERATURE RANGE PRESERVATION
HANDLING OF MISMATCHING GEOMETRIES
THERMAL MODEL
STRUCTURAL MODEL
• Thermo-Opto-Mechanical Performance is a driver for the design of optical instruments
• KT has formalized the process with the MultiPAS tool, which connects the corresponding models and provides orbital performance results
• Thermal Mapping Tool Features
• automated mapping
• single part recognition
• batch handling of thousands of time steps
• edge coverage with temperature range preservation
• handling of mismatching geometries
6 03.12.2013 Kayser-Threde GmbH, Munich
An OHB Company

TMT Introduction – Mapping Process

MultiPAS thermal structural optical Performance Analysis Software

KAYSER-THREDE

- TMT Mapping Process
  - **Model parting**: Models are separated into conductive units



7 03.12.2013 Kayser-Threde GmbH, Munich

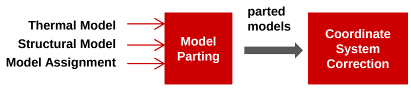
An OHB Company

TMT Introduction – Mapping Process

MultiPAS thermal structural optical Performance Analysis Software

KAYSER-THREDE

- TMT Mapping Process
  - **Model parting**: Models are separated into conductive units
  - **CS Correction:** Models are positioned to allow initial 3-D mapping



8 03.12.2013 Kayser-Threde GmbH, Munich

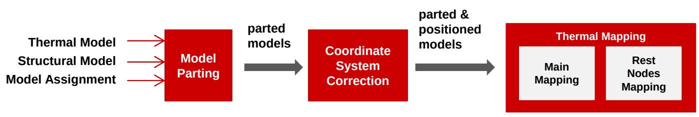
An OHB Company

TMT Introduction – Mapping Process

MultiPAS thermal structural optical Performance Analysis Software

KAYSER-THREDE

- TMT Mapping Process
  - Model parting: Models are separated into conductive units
  - CS Correction: Models are positioned to allow initial 3-D mapping
  - **Thermal Mapping:**
    - **Main Mapping:** Algorithm defines temperatures for main structural (FEM) nodes as a function of thermal elements
    - **Rest Node Mapping:** not covered structural areas are defined based on existing ones (no further use of the thermal model)



9 03.12.2013 Kayser-Threde GmbH, Munich

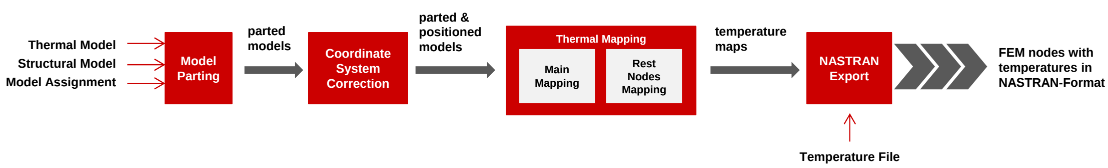
An OHB Company

TMT Introduction – Mapping Process

MultiPAS thermal structural optical Performance Analysis Software

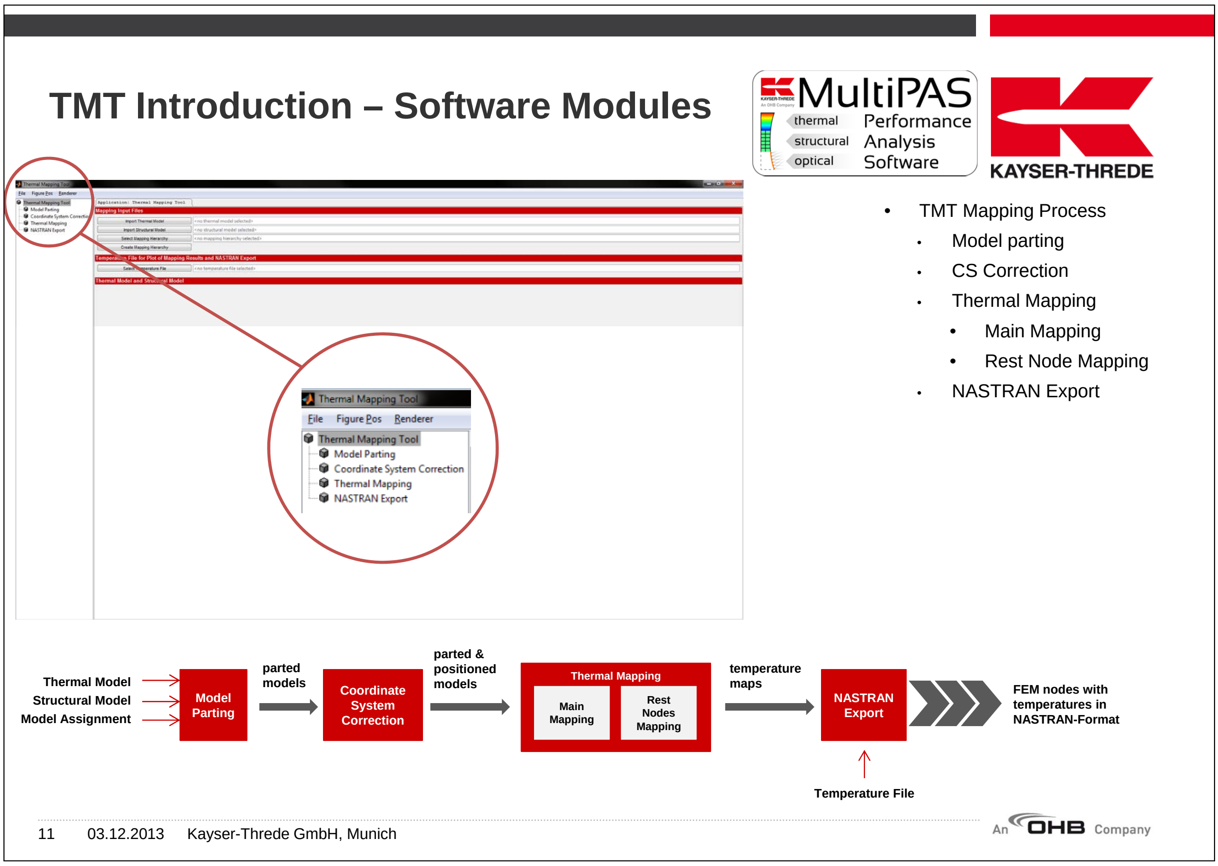
KAYSER-THREDE

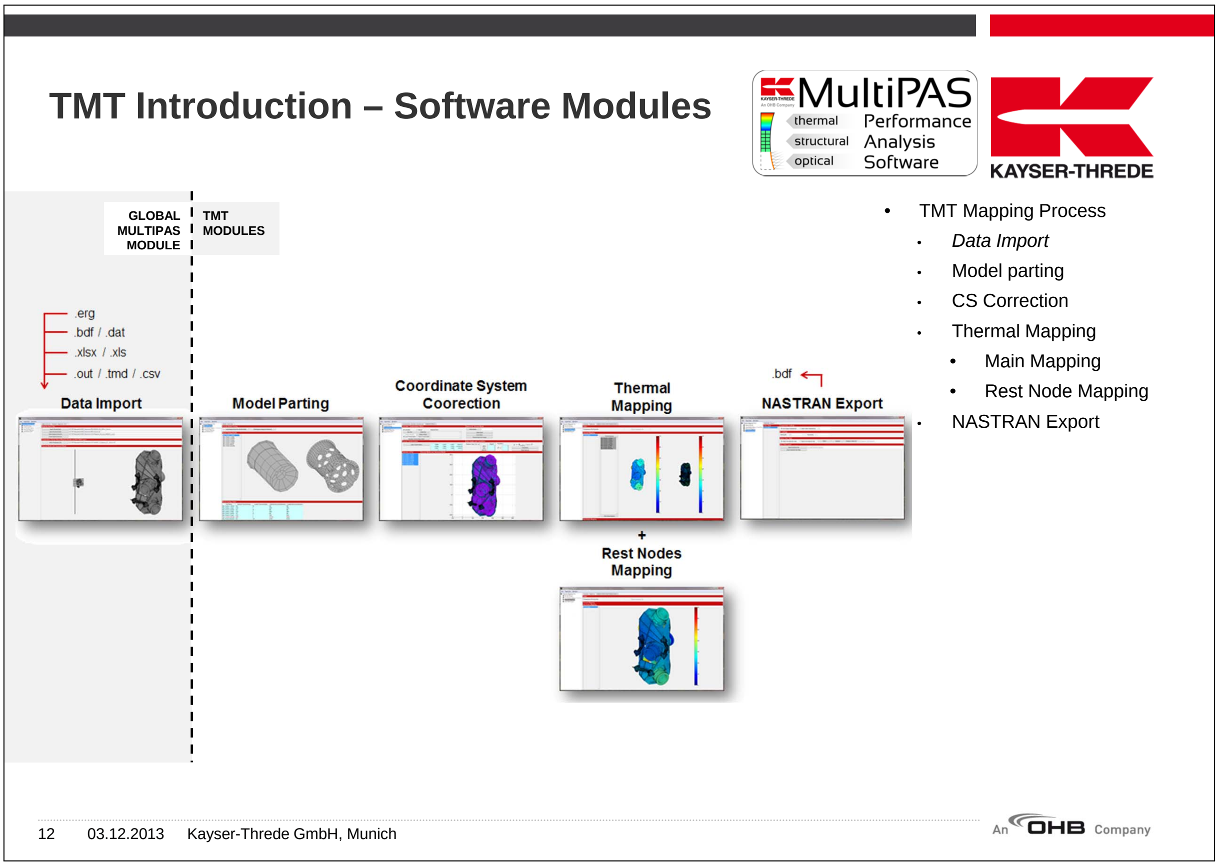
- TMT Mapping Process
  - Model parting: Models are separated into conductive units
  - CS Correction: Models are positioned to allow initial 3-D mapping
  - Thermal Mapping:
    - Main Mapping: Algorithm defines temperatures for main structural (FEM) nodes as a function of thermal elements
    - Rest Node Mapping: not covered structural areas are defined based on existing ones (no further use of the thermal model)
  - **NASTRAN Export:** Mapping Algorithm defines temperatures for structural (FEM) nodes as a function of thermal nodes



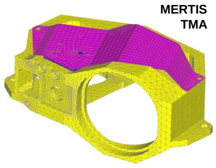
10 03.12.2013 Kayser-Threde GmbH, Munich

An OHB Company


TMT Introduction – Software Modules
MultiPAS
thermal Performance
structural Analysis
optical Software
KAYSER-THREDE
Thermal Mapping Tool
File Figure Pos Renderer
Thermal Mapping Tool
Model Parting
Coordinate System Correction
Thermal Mapping
NASTRAN Export
• TMT Mapping Process
• Model parting
• CS Correction
• Thermal Mapping
• Main Mapping
• Rest Node Mapping
• NASTRAN Export
Thermal Model
Structural Model
Model Assignment
Model Parting
parted models
Coordinate System Correction
parted & positioned models
Thermal Mapping
Main Mapping
Rest Nodes Mapping
temperature maps
NASTRAN Export
Temperature File
FEM nodes with temperatures in NASTRAN-Format
11 03.12.2013 Kayser-Threde GmbH, Munich
An OHB Company


TMT Introduction – Software Modules
MultiPAS
thermal Performance
structural Analysis
optical Software
KAYSER-THREDE
GLOBAL MULTIPAS MODULE
TMT MODULES
.erg
.bdf / .dat
.xlsx / .xls
.out / .tmd / .csv
Data Import
Model Parting
Coordinate System Coorection
Thermal Mapping
.bdf
NASTRAN Export
+
Rest Nodes Mapping
• TMT Mapping Process
• Data Import
• Model parting
• CS Correction
• Thermal Mapping
• Main Mapping
• Rest Node Mapping
• NASTRAN Export
12 03.12.2013 Kayser-Threde GmbH, Munich
An OHB Company

Example

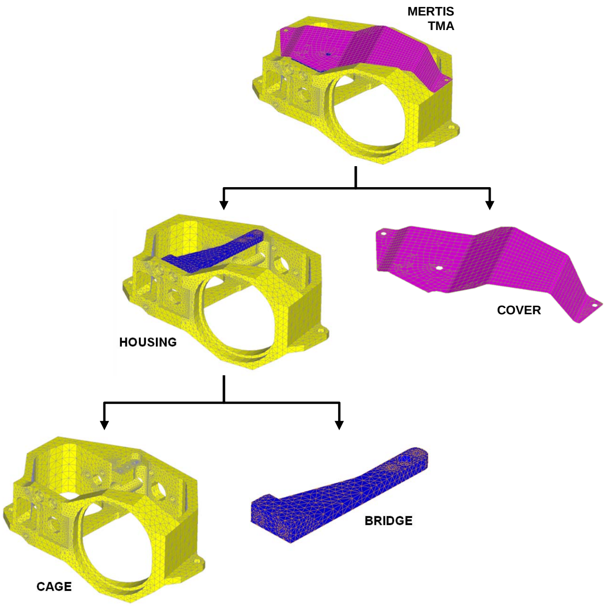


- Three Mirror Assembly of MERTIS
  - „complex“ 3-D structure
  - Bolted cover → high temperature gradient between housing and cover
  - Bolted “bridge” → danger of mapping from the wrong part

13 03.12.2013 Kayser-Threde GmbH, Munich

An OHB Company

Example – Structural Model



- Three Mirror Assembly of MERTIS
  - „complex“ 3-D structure
  - Bolted cover → high temperature gradient between housing and cover
  - Bolted “bridge” → danger of mapping from the wrong part
- Structural Model
  - Mixed mesh (solids (3-D) and shells (2-D))
  - High level of details (holes, chamfers, edges)

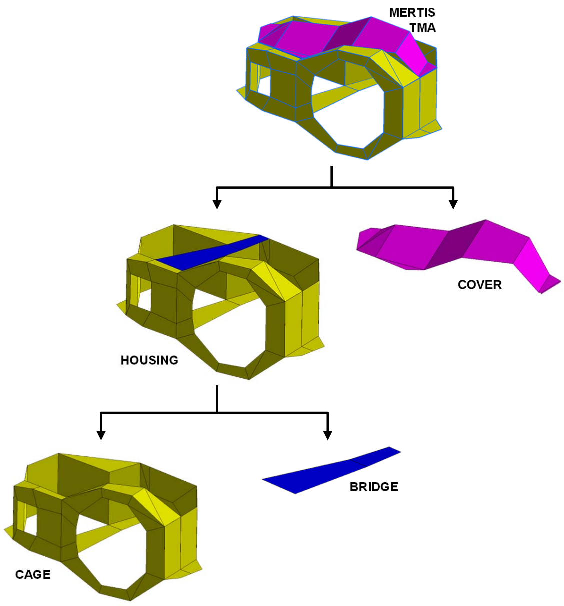
14 03.12.2013 Kayser-Threde GmbH, Munich

An OHB Company

Example – Thermal Model

MultiPAS thermal structural optical Performance Analysis Software

KAYSER-THREDE



- Three Mirror Assembly of MERTIS
  - „complex“ 3-D structure
  - Bolted cover → high temperature gradient between housing and cover
  - Bolted “bridge” → danger of mapping from the wrong part
- Structural Model
  - Mixed mesh (solids (3-D) and shells (2-D))
  - High level of details (holes, chamfers, edges)
- Thermal Model (GMM)
  - High degree of defeaturing → NO holes, chamfers, edges
  - No modeled depiction of bolted I/F (considered in TMM)

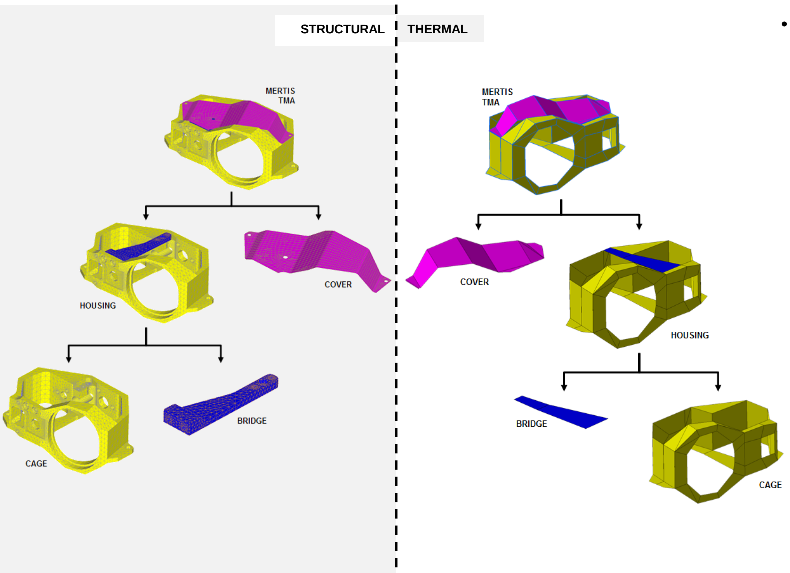
15 03.12.2013 Kayser-Threde GmbH, Munich

An OHB Company

Example – Model Comparison

MultiPAS thermal structural optical Performance Analysis Software

KAYSER-THREDE



- Three Mirror Assembly of MERTIS
  - „complex“ 3-D structure
  - Bolted cover → high temperature gradient between housing and cover
  - Bolted “bridge” → danger of mapping from the wrong part
- Structural Model
  - Mixed mesh (solids (3-D) and shells (2-D))
  - High level of details (holes, chamfers, edges)
- Thermal Model (GMM)
  - High degree of defeaturing → NO holes, chamfers, edges
  - No modeled depiction of bolted I/F (considered in TMM)
- Model comparison
  - Model parting must detect/prescribe part limits
  - Algorithm must deal with mismatching meshes

16 03.12.2013 Kayser-Threde GmbH, Munich

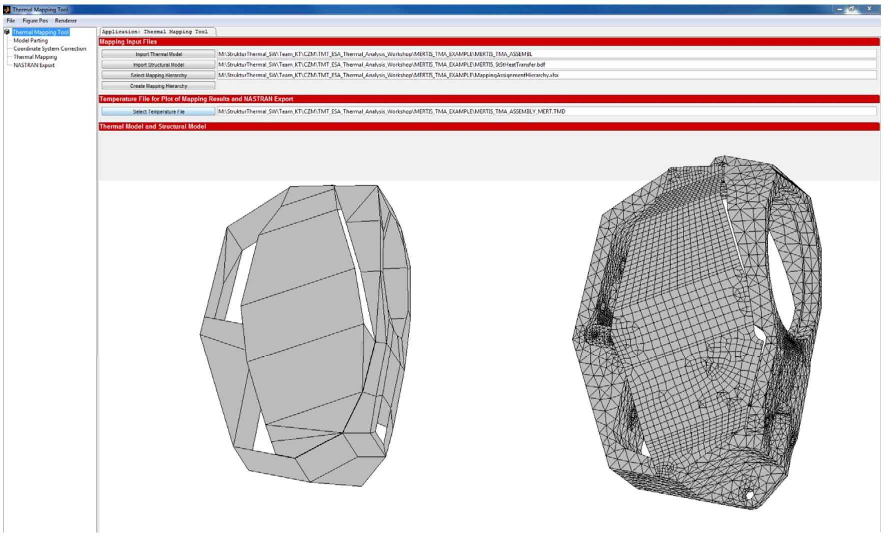
An OHB Company

Example – Mapping Process

MultiPAS thermal structural optical Performance Analysis Software

KAYSER-THREDE

- TMT Mapping Process
  - *Data Import*



17 03.12.2013 Kayser-Threde GmbH, Munich

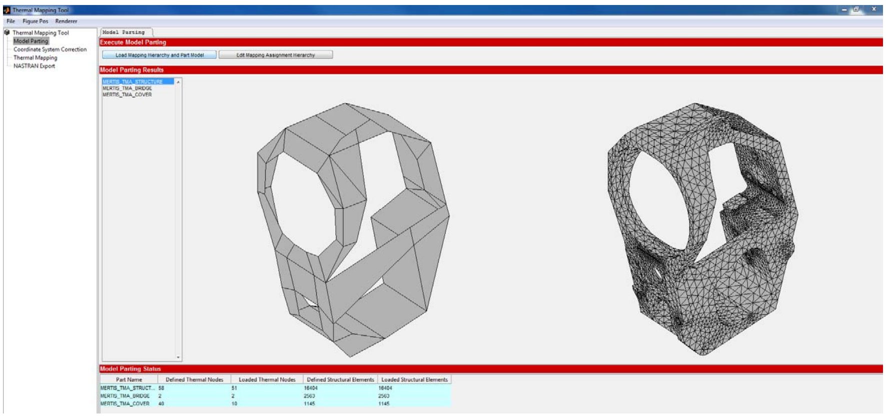
An OHB Company

Example – Mapping Process

MultiPAS thermal structural optical Performance Analysis Software

KAYSER-THREDE

- TMT Mapping Process
  - Data Import
  - Model parting



18 03.12.2013 Kayser-Threde GmbH, Munich

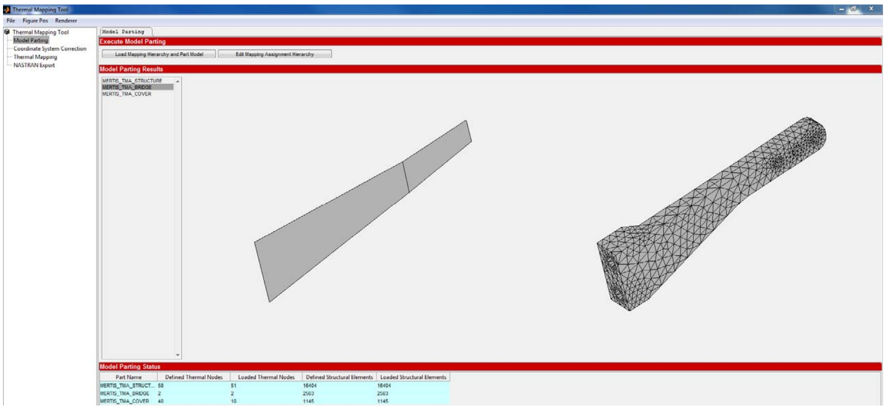
An OHB Company

Example – Mapping Process

MultiPAS thermal structural optical Performance Analysis Software

KAYSER-THREDE

- TMT Mapping Process
  - Data Import
  - Model parting



19 03.12.2013 Kayser-Threde GmbH, Munich

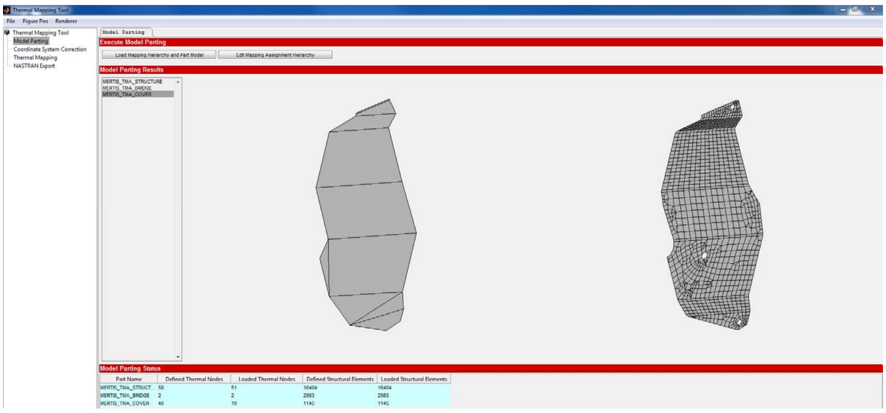
An OHB Company

Example – Mapping Process

MultiPAS thermal structural optical Performance Analysis Software

KAYSER-THREDE

- TMT Mapping Process
  - Data Import
  - Model parting



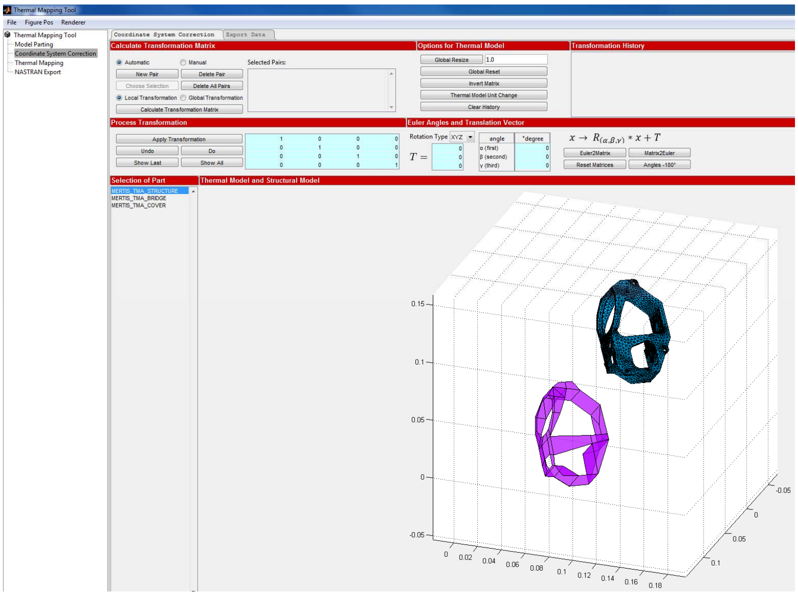
20 03.12.2013 Kayser-Threde GmbH, Munich

An OHB Company

Example – Mapping Process

MultiPAS thermal structural optical Performance Analysis Software

KAYSER-THREDE



- TMT Mapping Process
  - Data Import
  - Model parting
  - CS Correction

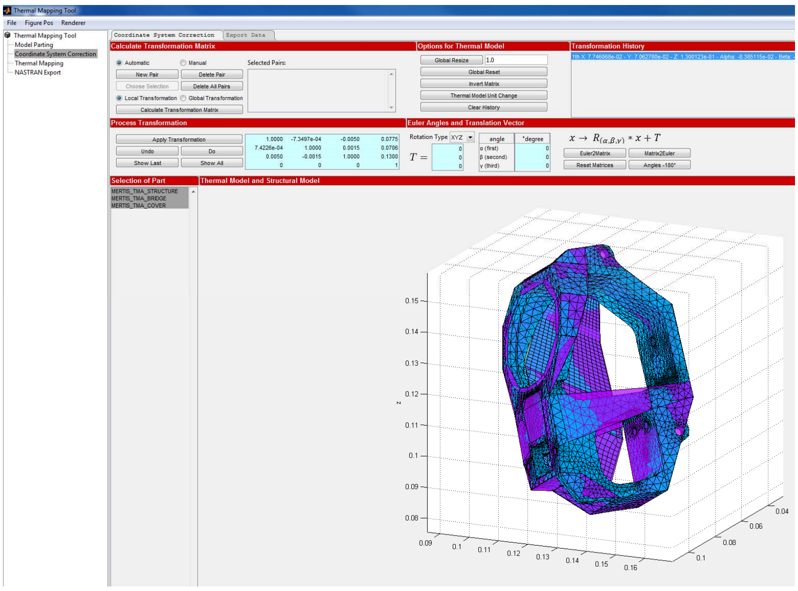
21 03.12.2013 Kayser-Threde GmbH, Munich

An OHB Company

Example – Mapping Process

MultiPAS thermal structural optical Performance Analysis Software

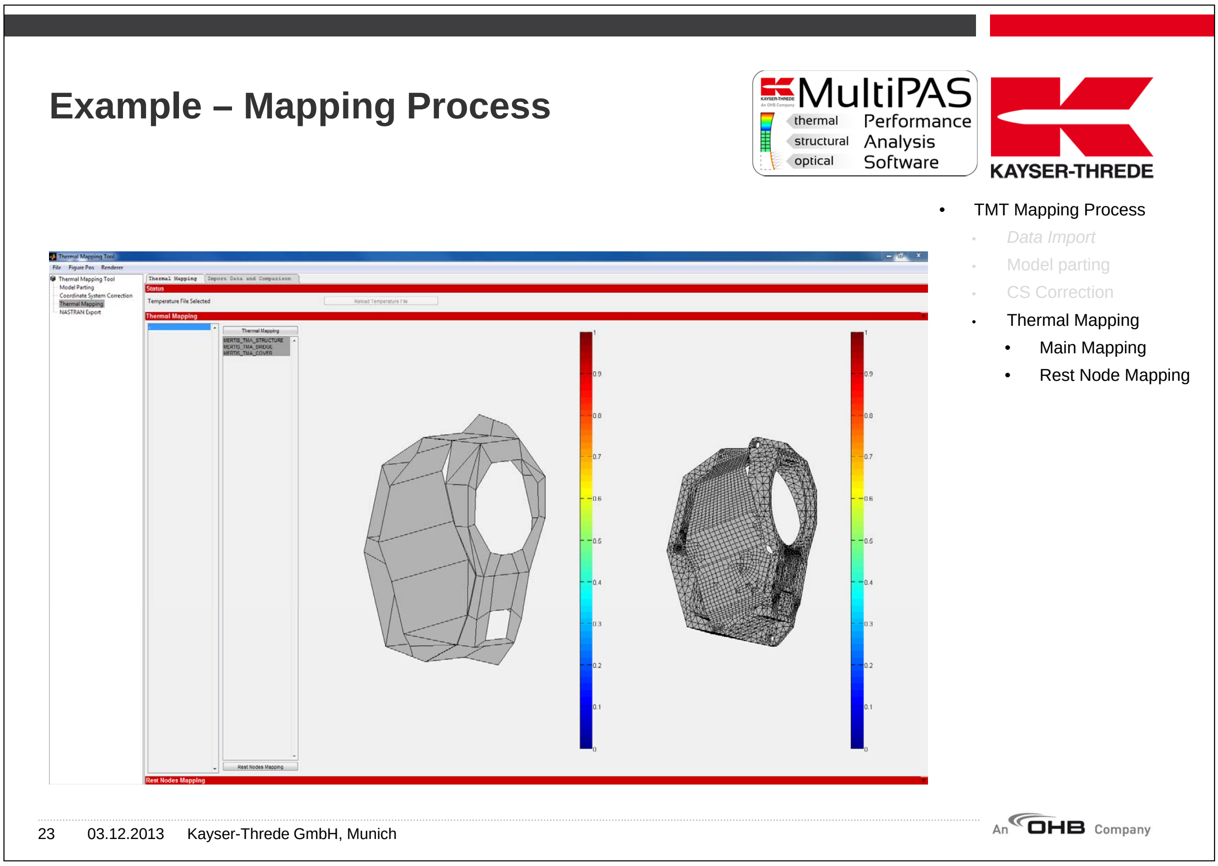
KAYSER-THREDE

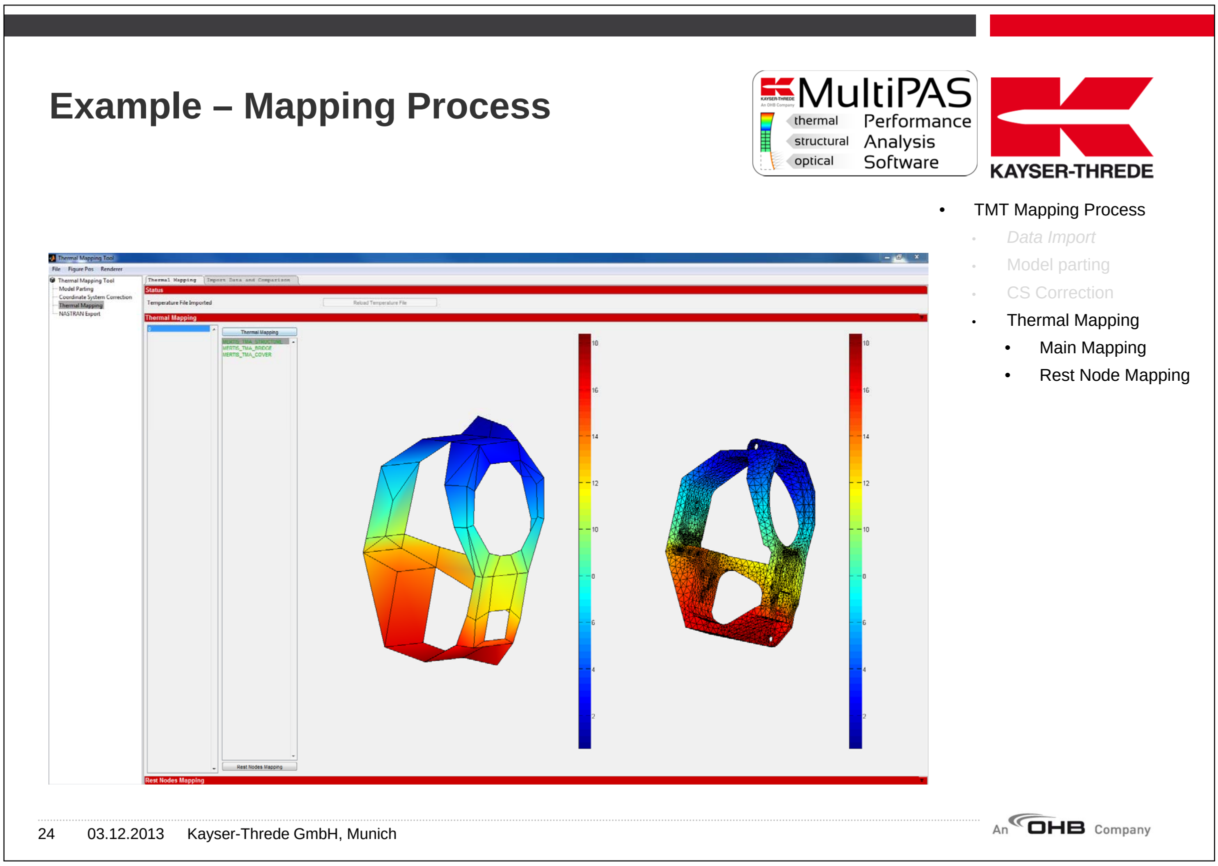


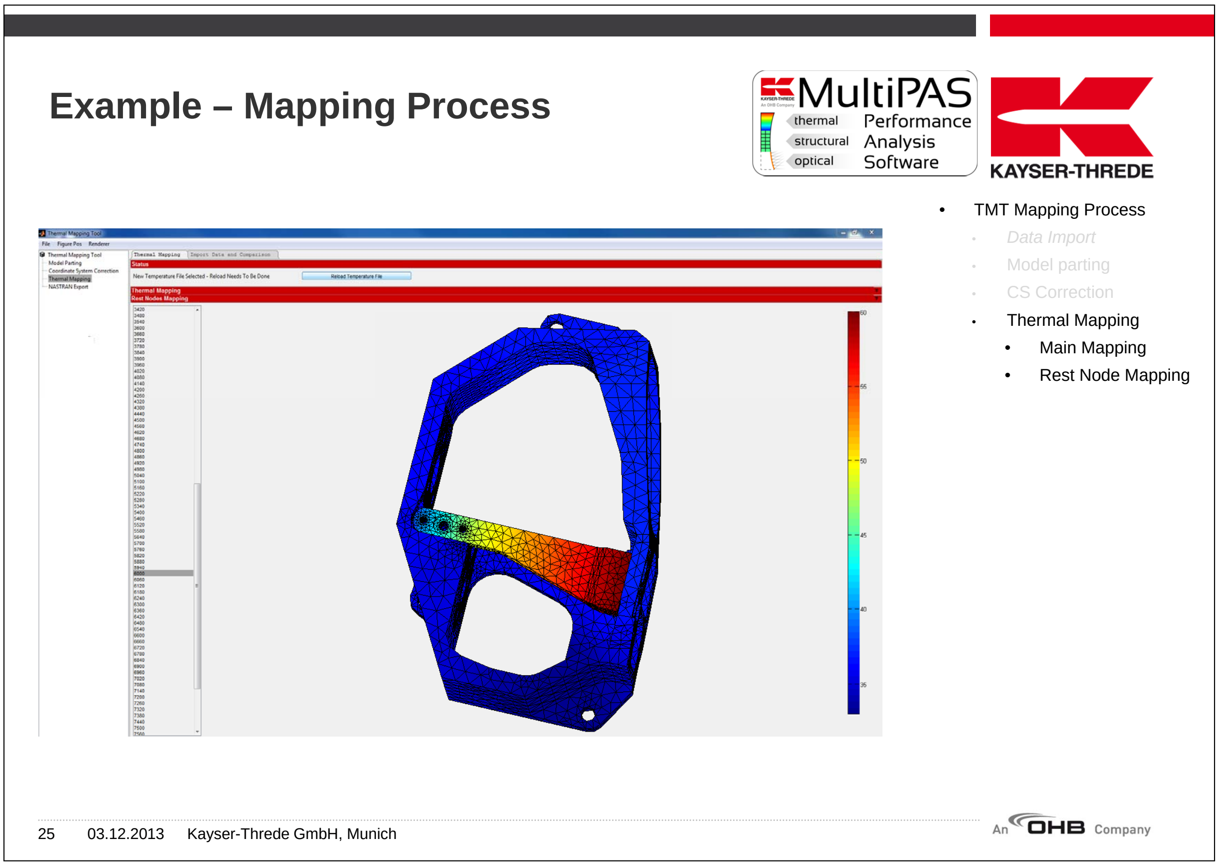
- TMT Mapping Process
  - Data Import
  - Model parting
  - CS Correction

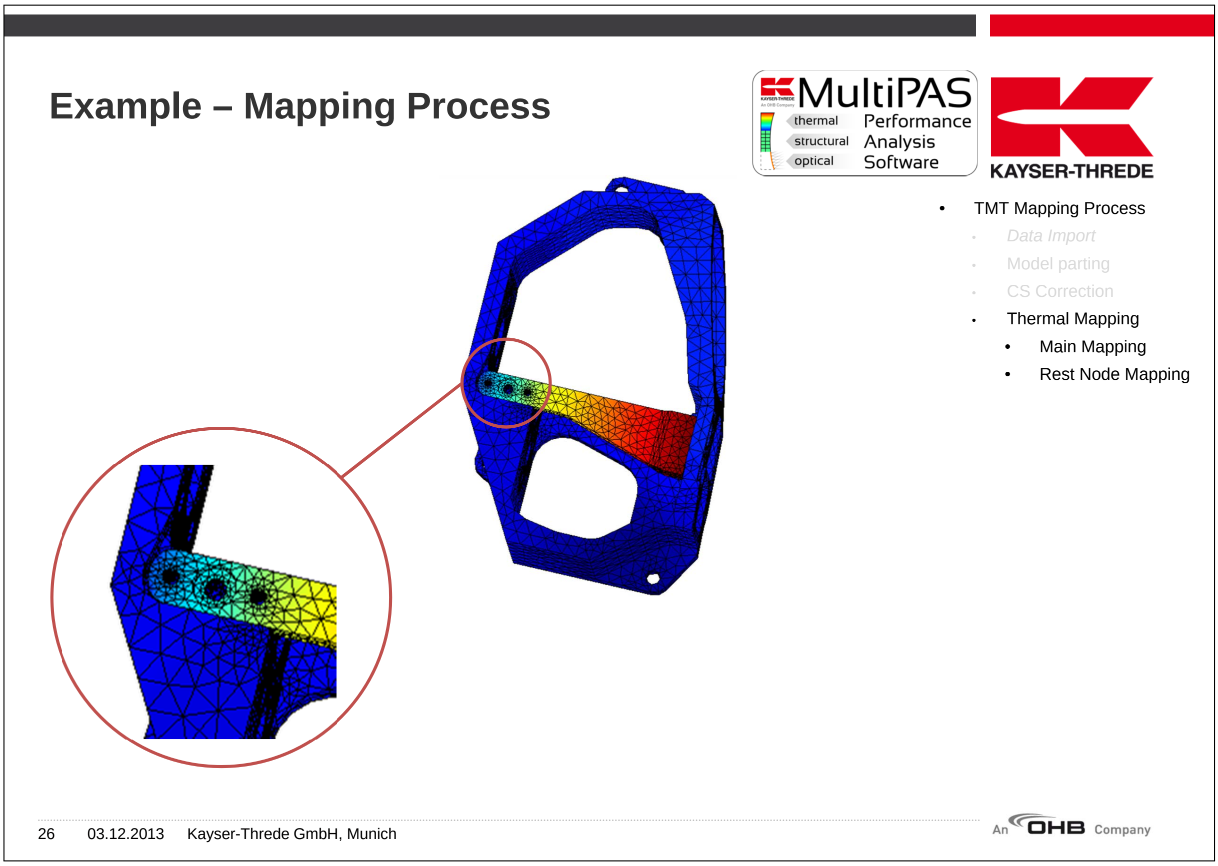
22 03.12.2013 Kayser-Threde GmbH, Munich

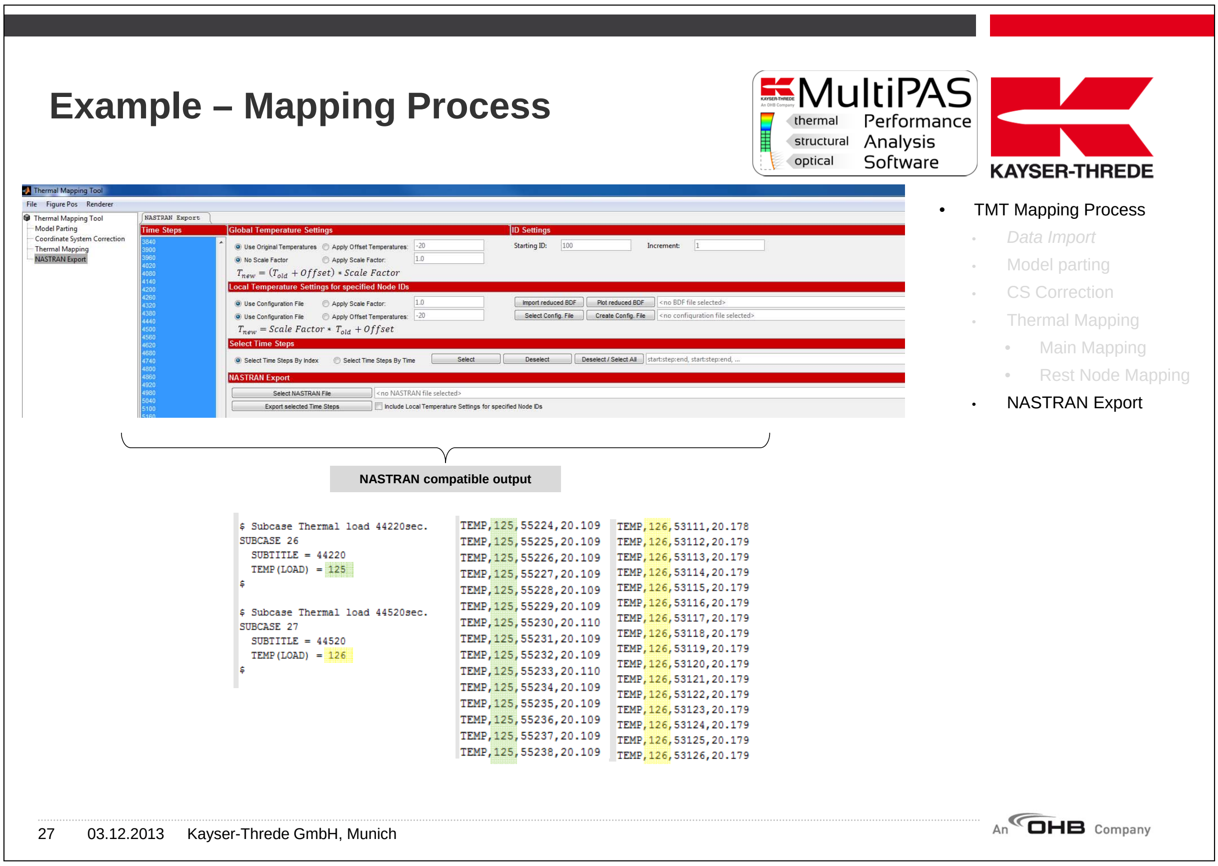
An OHB Company

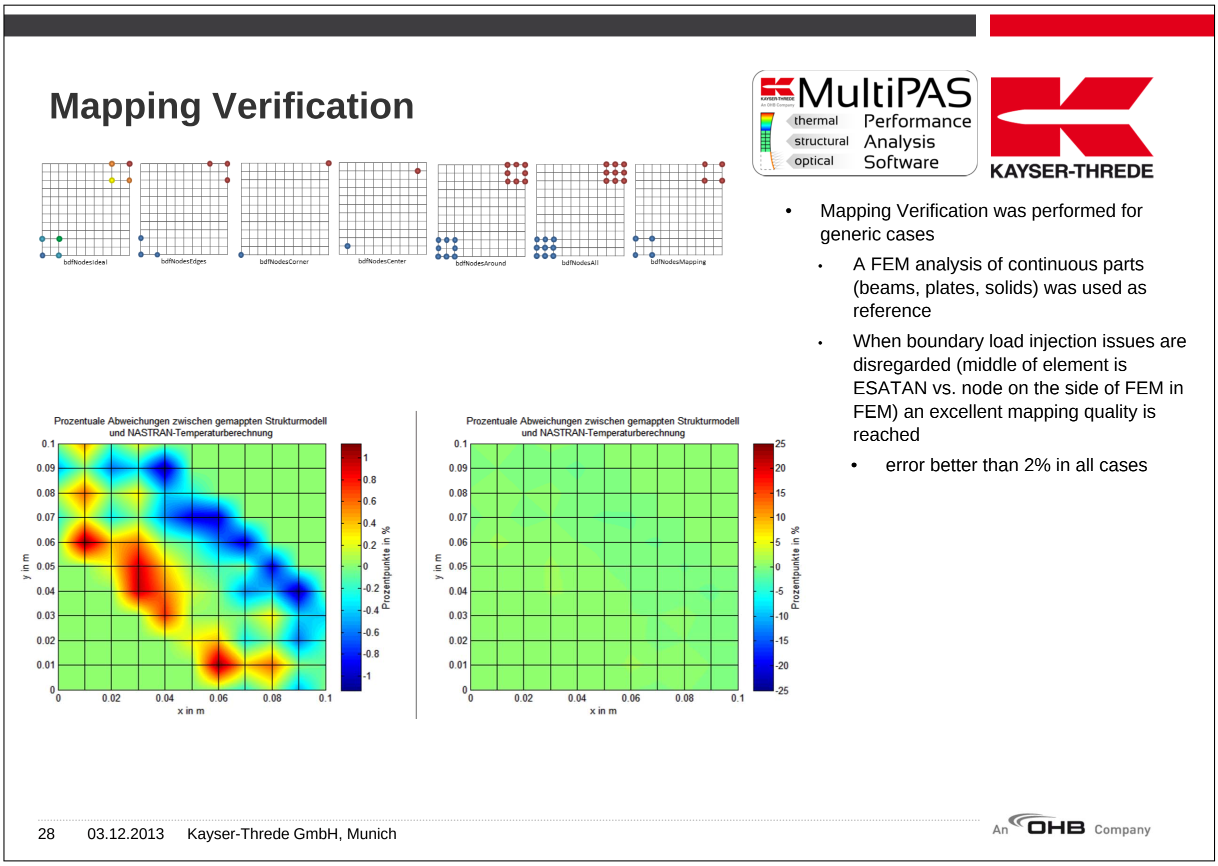

Example – Mapping Process
MultiPAS
thermal
structural
optical
Performance
Analysis
Software
KAYSER-THREDE
TMT Mapping Process
Data Import
Model parting
CS Correction
Thermal Mapping
Main Mapping
Rest Node Mapping
23 03.12.2013 Kayser-Threde GmbH, Munich
An OHB Company


Example – Mapping Process
MultiPAS
thermal
structural
optical
Performance
Analysis
Software
KAYSER-THREDE
TMT Mapping Process
Data Import
Model parting
CS Correction
Thermal Mapping
Main Mapping
Rest Node Mapping
24 03.12.2013 Kayser-Threde GmbH, Munich
An OHB Company


Example – Mapping Process
MultiPAS
thermal
structural
optical
Performance
Analysis
Software
KAYSER-THREDE
TMT Mapping Process
Data Import
Model parting
CS Correction
Thermal Mapping
Main Mapping
Rest Node Mapping
25
03.12.2013
Kayser-Threde GmbH, Munich
An OHB Company


Example – Mapping Process
MultiPAS
thermal
structural
optical
Performance
Analysis
Software
KAYSER-THREDE
TMT Mapping Process
Data Import
Model parting
CS Correction
Thermal Mapping
Main Mapping
Rest Node Mapping
26
03.12.2013
Kayser-Threde GmbH, Munich
An OHB Company


Example – Mapping Process
MultiPAS
thermal
structural
optical
Performance
Analysis
Software
KAYSER-THREDE
TMT Mapping Process
Data Import
Model parting
CS Correction
Thermal Mapping
Main Mapping
Rest Node Mapping
NASTRAN Export
NASTRAN compatible output
$ Subcase Thermal load 44220sec.
SUBCASE 26
SUBTITLE = 44220
TEMP(LOAD) = 125
$ Subcase Thermal load 44520sec.
SUBCASE 27
SUBTITLE = 44520
TEMP(LOAD) = 126
TEMP,125,55224,20.109
TEMP,126,53111,20.178
27 03.12.2013 Kayser-Threde GmbH, Munich
An OHB Company

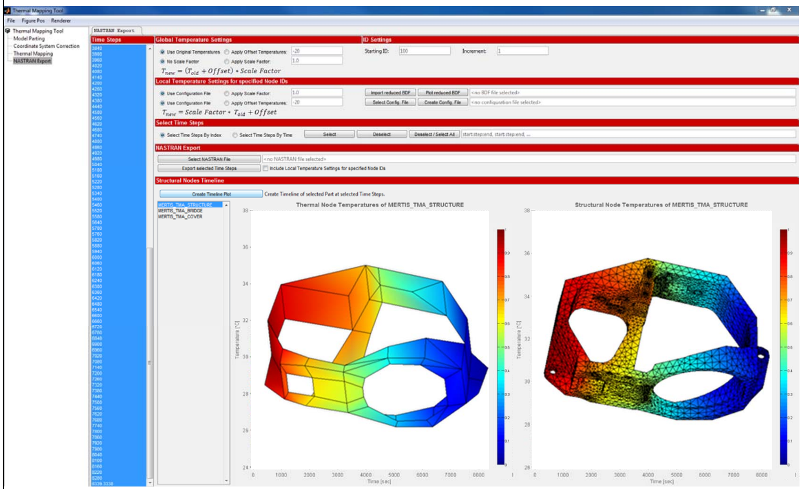

Mapping Verification
MultiPAS
thermal
structural
optical
Performance
Analysis
Software
KAYSER-THREDE
Mapping Verification was performed for generic cases
A FEM analysis of continuous parts (beams, plates, solids) was used as reference
When boundary load injection issues are disregarded (middle of element is ESATAN vs. node on the side of FEM in FEM) an excellent mapping quality is reached
error better than 2% in all cases
Prozentuale Abweichungen zwischen gemappten Strukturmodell und NASTRAN-Temperaturberechnung
x in m
y in m
Prozentpunkte in %
28 03.12.2013 Kayser-Threde GmbH, Munich
An OHB Company

Mapping Verification

MultiPAS thermal structural optical Performance Analysis Software

KAYSER-THREDE

- Mapping Verification was performed for generic cases
  - A FEM analysis of continuous parts (beams, plates, solids) was used as reference
    - error better than 2% in all cases
  - When boundary load injection issues are disregarded (middle of element is ESATAN vs. node on the side of FEM in FEM) an excellent mapping quality is reached
  - In “every-day” mapping the success of the process is verified by visual inspection
    - comparison of 2-D maps → part by part)



29 03.12.2013 Kayser-Threde GmbH, Munich

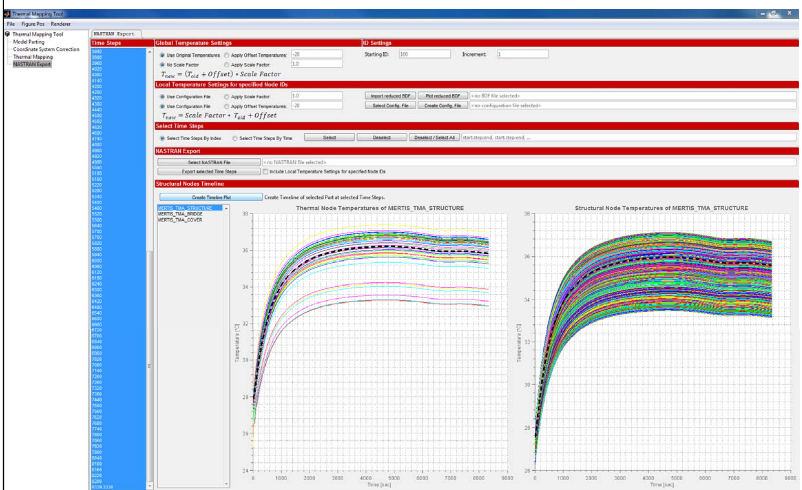
An OHB Company

Mapping Verification

MultiPAS thermal structural optical Performance Analysis Software

KAYSER-THREDE

- Mapping Verification was performed for generic cases
  - A FEM analysis of continuous parts (beams, plates, solids) was used as reference
    - error better than 2% in all cases
  - When boundary load injection issues are disregarded (middle of element is ESATAN vs. node on the side of FEM in FEM) an excellent mapping quality is reached
  - In “every-day” mapping the success of the process is verified by visual inspection
    - comparison of 2-D maps → part by part)
    - Comparison of transient plots → part by part



30 03.12.2013 Kayser-Threde GmbH, Munich

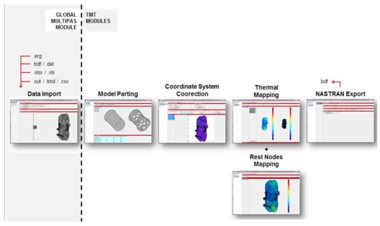
An OHB Company

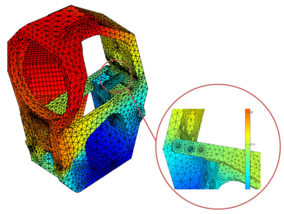
Summary

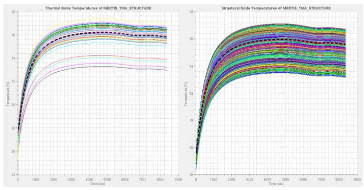
- KT has generated an highly automated Temperature Mapping Process
- The Process is reflected in a corresponding software → Thermal Mapping Tool
- The TMT is part of a bigger Optical Performance Analysis Software Suite (MultiPAS)

- The TMT allows a fast and precise transfer of temperatures from thermal models onto FE Models for multiple time points over the orbit
- The process is broken down into four main parts
  - Model Parting
  - Coordinate System Correction
  - Thermal Mapping
    - Main Mapping
    - Rest Node Mapping
  - NASTRAN Export (incl. verification)

- The mapping preserves
  - temperature boundaries defined by the thermal model
  - edge temperatures (temperature regions) defined by the thermal model
- The mapping algorithm was successfully verified against FEM thermal analyses







31 03.12.2013 Kayser-Threde GmbH, Munich

Appendix J

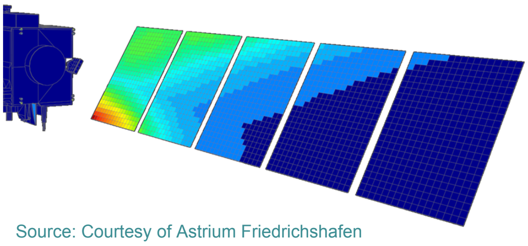
Mapping nodal properties between dissimilar nodal representations of S/C structures using ESATAN-TMS

Alexander Maas
(Dutch Space, The Netherlands)

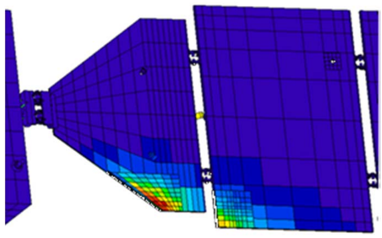
Abstract

When multiple parties are involved in a single project, they often use different (thermal) models to represent a particular part or structure. As the nodal distribution is not always the same, it can be difficult to exchange data (e.g. flux distributions and temperature profiles) from one party to another. Clever use of a standard ESATAN-TMS tool can simplify the mapping of nodal data from one nodal representation to another for some of these applications, i.e. where the geometric models are sufficiently similar such that the conductive interfaces between the different node systems can be calculated by ESATAN-TMS. By using the conductive area calculation tool, the contact area between the different nodal representations can be determined. By means of area averaging, any nodal parameter can be projected onto the other nodal representation system. This process requires a few manual steps that can be performed automatically by means of a script. The method has been successfully applied in a detailed S/A plume flux analysis, where plume flux distributions determined in one nodal system were applied to a more detailed model to determine the S/A temperatures. This application is used as an example to show all required steps.

Dutch Space
an EADS Astrium company



Source: Courtesy of Astrium Friedrichshafen



Mapping nodal properties between dissimilar nodal representations of S/C structures using ESATAN-TMS

27th European Space Thermal Analysis Workshop (3-4 Dec 2013)

Alexander Maas (Dutch Space B.V.)
A.S.Maas@dutchspace.nl

-1-

Dutch Space
an EADS Astrium company

Introduction

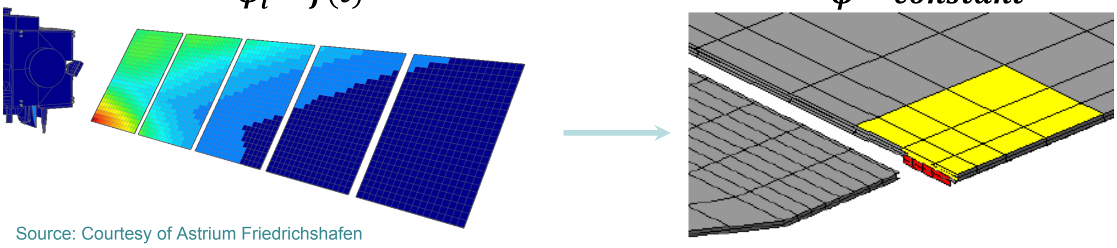
- Usually multiple parties are involved in a single project
  - Company X / Company Y
  - Mechanical / Thermal / Other
- Complexity of analyses is high
- Exchanging data between parties is difficult and leads to ‘worst-case’ assumptions
- Inherently this leads to overly conservative results
- Design optimization is possible if data exchange could be simplified

-2-

Dutch Space
an EADS Astrium company

Example of typical data exchange – Plume flux distribution

$\phi_i = f(t)$ $\phi = constant$



Source: Courtesy of Astrium Friedrichshafen

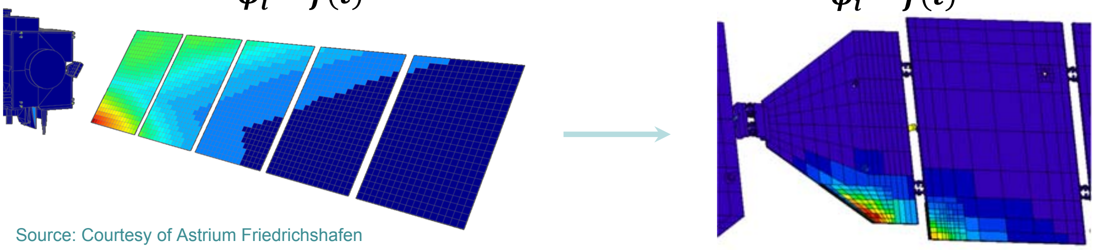
- Actual plume distribution is not taken into account
- Not problematic for steady-state
- For transient analysis when plume hot-spot changes, this is too worst-case

-3-

Dutch Space
an EADS Astrium company

Example of optimal data exchange – Plume flux distribution

$\phi_i = f(t)$ $\phi_i = f(t)$



Source: Courtesy of Astrium Friedrichshafen

- Actual plume distribution is taken into account
- Plume hot spot is accurately modeled in transient analysis
- Less conservative analysis

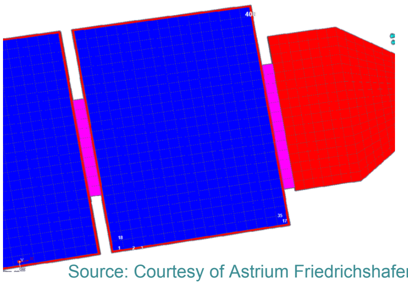
-4-

Dutch Space
an EADS Astrium company

Problem statement

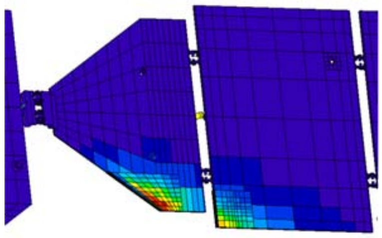
How can you easily work with multiple nodal systems using ESATAN-TMS

Node system X



Source: Courtesy of Astrium Friedrichshafen

Node system Y

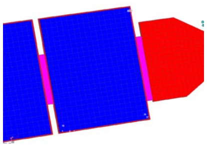


-5-

Dutch Space
an EADS Astrium company

High level overview

Node system X



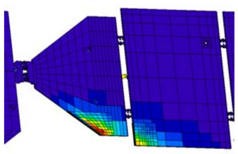
Source: Courtesy of Astrium Friedrichshafen

Nodal properties α_i

Determine nodal properties $ß_i$ from nodal properties α_i

Nodal properties $ß_i$

Node system Y

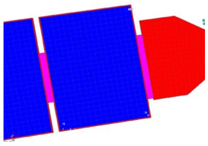


-6-

Dutch Space
an EADS Astrium company

High level overview

Node system X



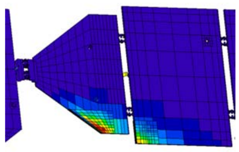
Source: Courtesy of Astrium Friedrichshafen

Nodal properties α_i

Define $ß_i$ as area average of α_i

Nodal properties $ß_i$

Node system Y



-7-

Dutch Space
an EADS Astrium company

Method to connect nodes

Straightforward solution

Area average of nodal data

$$ß_m = \sum_{i=n}^{n+3} \frac{A_{m,i}\alpha_i}{A_m}$$

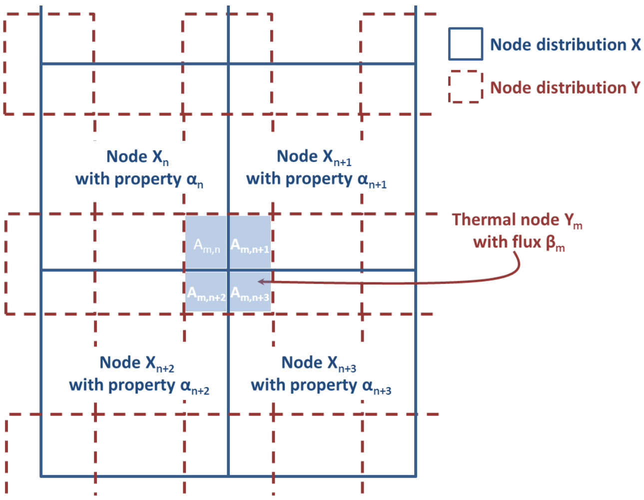
$A_{m,i}$=Overlapping area node X_i and Y_m

A_m =Total node area of node Y_m

α_i =Node property of node X_i

$ß_m$ =Node property of node Y_m

Can be tedious to determine $A_{m,i}$ for large models



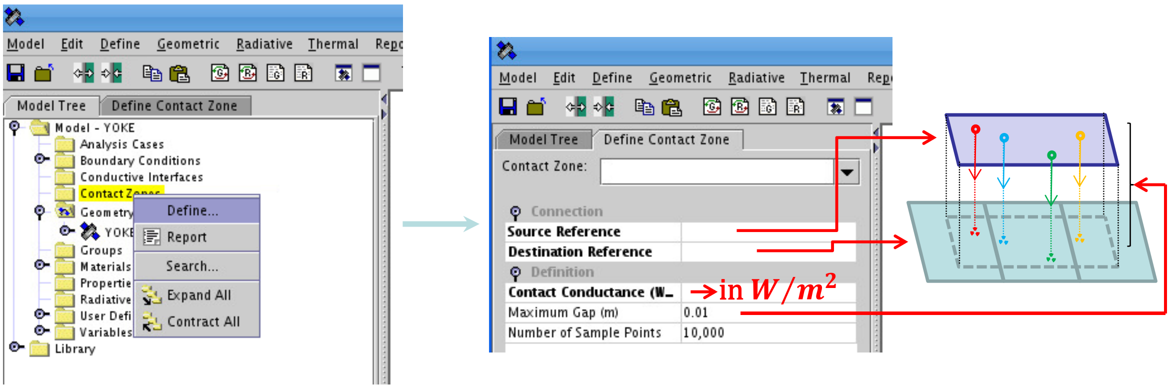
Luckily ESATAN-TMS has an automatic function for this!

-8-

Dutch Space
an EADS Astrium company

ESATAN-TMS contact zone calculator

- Added in ESATAN-TMS r4



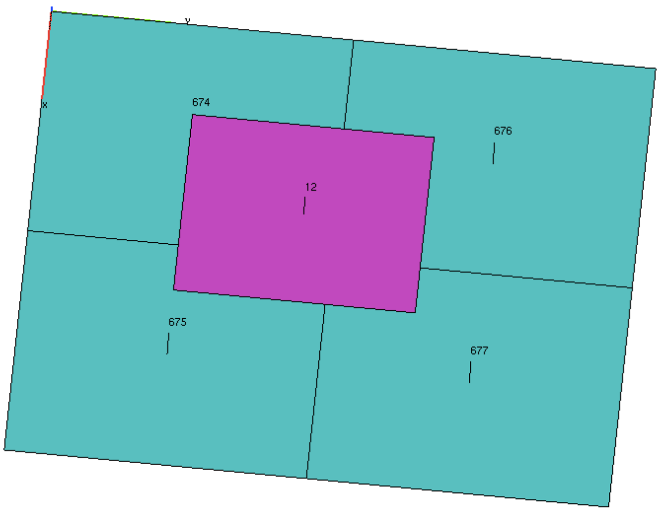
-9-

Dutch Space
an EADS Astrium company

ESATAN-TMS contact zone calculator

Determine contact conductance:

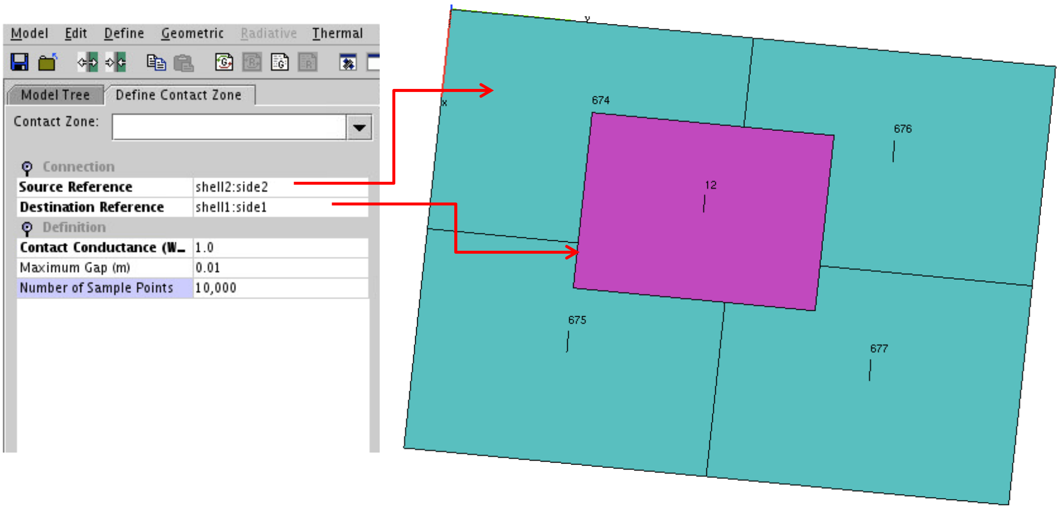
- 2 components
- Modelled geometrically
- Contact zones are also modelled
- Contact conductance 1[W/m^2]



-10-

Dutch Space
an EADS Astrium company

ESATAN-TMS contact zone calculator



-11-

Dutch Space
an EADS Astrium company

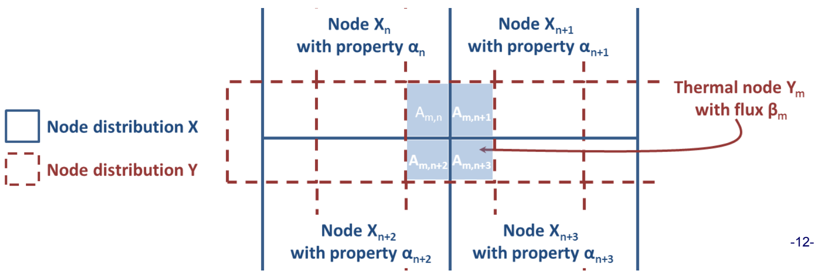
Determining area weight factors

- Perform calculation with contact conductance of 1 [W/m²K]

$$GL = A_{contact} \cdot h_{contact}$$

```
GL(12,674) = 7.20000E-05 * 1.00000; # from contact zone AreaFactors
GL(12,675) = 6.45000E-05 * 1.00000; # from contact zone AreaFactors
GL(12,676) = 6.95000E-05 * 1.00000; # from contact zone AreaFactors
GL(12,677) = 6.00000E-05 * 1.00000; # from contact zone AreaFactors
```

- Note that $A_{contact} = A_{m,i}$



-12-

Dutch Space
an EADS Astrium company

Calculating the nodal properties in the other system

- Perform calculation with contact conductance of 1 [W/m²K]

$$GL = A_{contact} \cdot h_{contact}$$

```
GL(12,674) = 7.20000E-05 * 1.00000; # from contact zone AreaFactors
GL(12,675) = 6.45000E-05 * 1.00000; # from contact zone AreaFactors
GL(12,676) = 6.95000E-05 * 1.00000; # from contact zone AreaFactors
GL(12,677) = 6.00000E-05 * 1.00000; # from contact zone AreaFactors
```

- Note that $A_{contact} = A_{m,i}$
- We can thus apply these factors in the area averaging

$$ß_m = \sum_{i=n}^{n+3} \frac{A_{m,i}\alpha_i}{A_m}$$

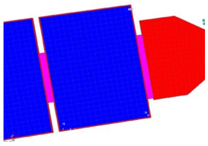
```
T 12= 0.0
T 12= T 12+ 7.20000E-05 * T 674 / A 12
T 12= T 12+ 6.45000E-05 * T 675 / A 12
T 12= T 12+ 6.95000E-05 * T 676 / A 12
T 12= T 12+ 6.00000E-05 * T 677 / A 12
```

-13-

Dutch Space
an EADS Astrium company

High level overview

Node system X



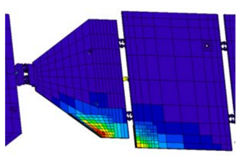
Source: Courtesy of Astrium Friedrichshafen

Nodal properties α_i

Define $ß_i$ as area average of α_i

Nodal properties $ß_i$

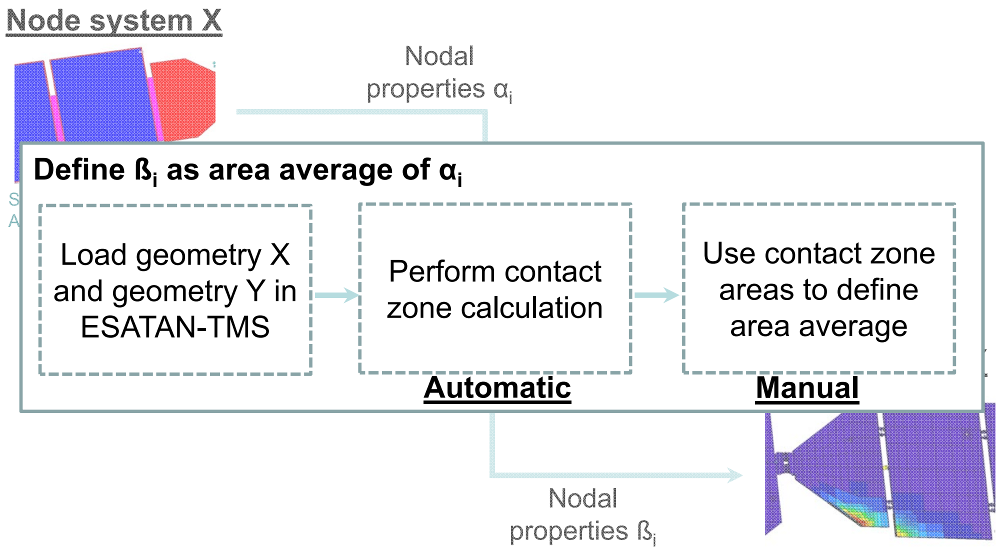
Node system Y



-14-

Dutch Space
an EADS Astrium company

High level overview



-15-

Dutch Space
an EADS Astrium company

Prerequisites

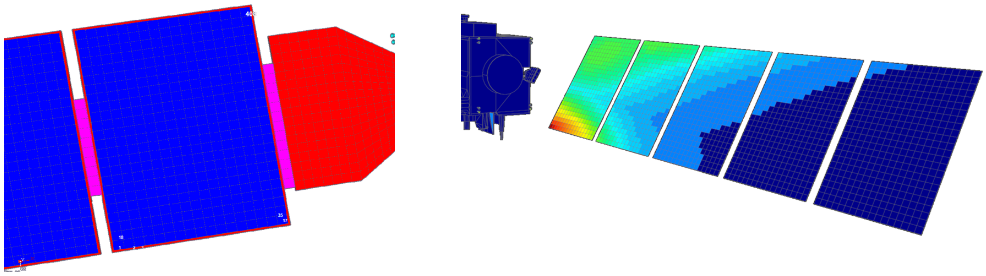
- Both nodal distributions must be available in ESATAN-TMS
- Geometries must be sufficiently similar to allow contact zones to be calculated using ray tracing.

-16-

Dutch Space
an EADS Astrium company

Example 1 – Plume flux distribution

Situation: Plume flux distribution over a part needs to be modeled in high detail. Discretization for which plume flux data is available does not correspond to thermal node distribution



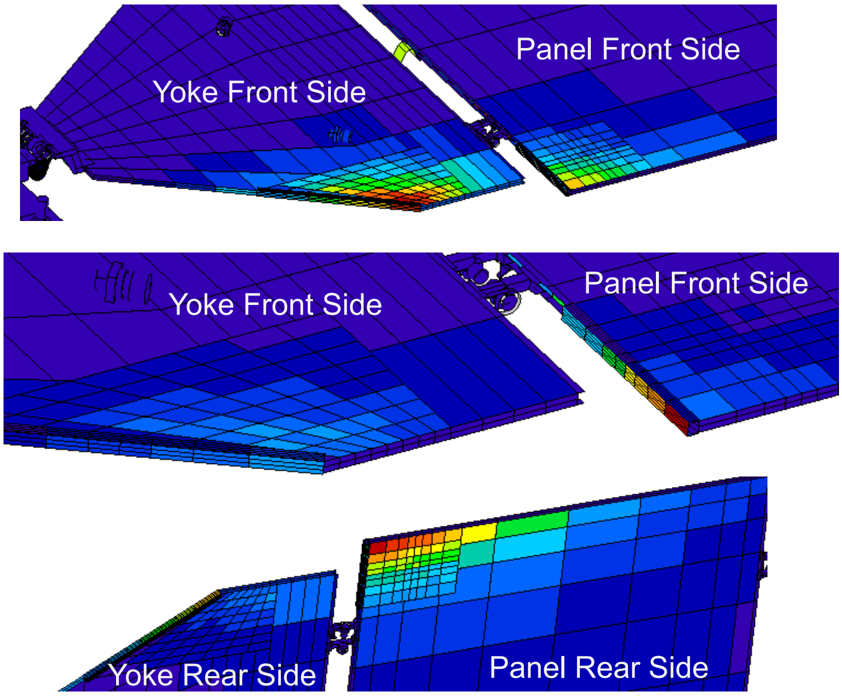
Source: Courtesy of Astrium Friedrichshafen

-17-

Dutch Space
an EADS Astrium company

Example 1 – Plume flux distribution

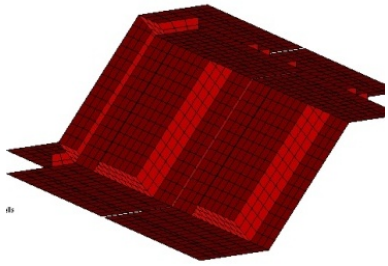
Full flux distribution can be taken into account in the thermal analysis

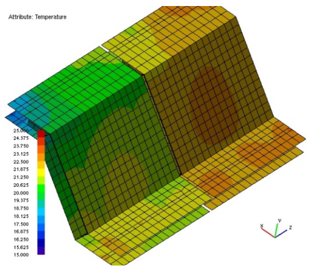


Dutch Space
an EADS Astrium company

Example 2 – Temperature distribution

Situation: To determine thermal distortion of a part, the NASTRAN model requires temperature data. The mechanical model is highly detailed. Thermal calculations with same node distribution would require (too much) time.



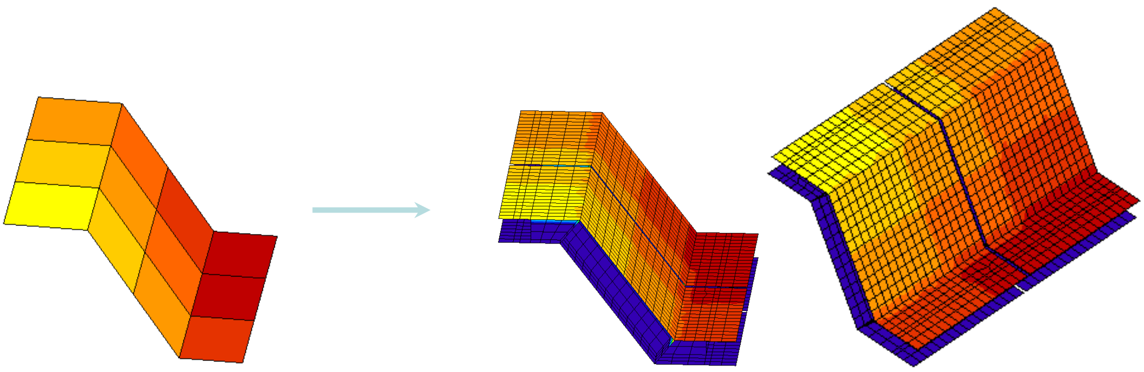


-19-

Dutch Space
an EADS Astrium company

Example 2 – Temperature distribution

Temperature map of ESATAN-TMS can be converted to NASTRAN by using this method to map temperatures



-20-

Dutch Space
an EADS Astrium company

Summary

The ESATAN-TMS contact zone calculation tool simplifies mapping of nodal properties between dissimilar nodal representations, as long as:

- Both node distributions are available in ESATAN-TMS format
- Geometries are be sufficiently similar to allow contact zones to be calculated using ray tracing.

-21-

Appendix K

MASCOT
Thermal subsystem design

Luca Celotti   Riccardo Nadalini   Małgorzata Sołyga
(ActiveSpace Technologies GmbH, Germany)

Volodymyr Baturkin
(DLR Institut für Raumfahrsysteme, Germany)

Sergey Khairnasov   Vladimir Kravets
(National Technical University of Ukraine, Ukraine)

Abstract

MASCOT is a lander built by DLR, embarked on JAXA's Hayabusa-2, a scientific mission to study the asteroid 162173 1999 JU3. It is a small lander, less than 300x300x200mm?, with onboard payloads (camera, magnetometer, radiometer and IR spectrometer), developed in collaboration by DLR and CNES. MASCOT lands on the asteroid surface, after being released by Hayabusa-2 from a very close position above the asteroid surface, and investigates the asteroid surface. The thermal design of the lander represents one of the main challenges in the whole project because of multiple constraints, depending on the mission phase, mass, power and free space available.

MASCOT, notwithstanding its small size, is equipped with redundant heat-pipe system, MLI blanket, heaters. The thermal design of the lander has been chosen after a trade-off phase concerning the technology which could suit better the opposing requirements of the mission: low heat exchange between the lander and the exterior (including the main spacecraft) in cruise, possibility to transfer all the heat dissipated by the internal paylaods and electronic boards during operations on asteroid surface. After selecting the heat-pipe technology as baseline, a development phase was undertaken by the partners both in terms of manufacturing, testing, thermal characterization phase and analitical modelling in order to match the thermal requirements.

Heaters are used to assure the survival of the most delicated parts of the lander during cold cruise phases: the battery cells (only primary battery on-board), the electronic boards and the main payload. Strict requirements are given by the main spacecraft in terms of maximum power available to heat the lander during cruise. MLI blankets are used where the available space allows it, e.g. to extra insulate the Ebox from the rest of the lander creating a „hot compartment" and between the lander and the main spacecraft to reduce the heat exchange with it during cruise below the given limits. The whole thermal concept in all its parts undertook a detailed modelling phase in parallel to an experimental phase in vacuum chamber to improve the model and to qualify the system.

MASCOT thermal design is here presented through the following points:

- MASCOT as part of HY-2 mission: mission, constraints, challenges
- Challenging thermal requirements
- Main thermal strategy and trade-offs: available technologies, constant conductance heat-pipes
- Thermal design
- Vacuum chamber testing
- Thermal model results
- Conclusions and future steps

MASCOT
Thermal subsystem design

European Space Thermal Analysis Workshop 2013

Luca Celotti

3-4 December 2013

Estec, Nordwijk - The Netherlands

making space a global endeavour

Luca Celotti, Riccardo Nadalini, Małgorzata Sołyga
ActiveSpace Technologies GmbH

Volodymyr Baturkin
DLR Institut für Raumfahrtsysteme
Explorationssysteme RY-ES

Vladimir Kravets , Sergey Khairnasov
National Technical University of Ukraine
Heat and power engineering department
Heat Pipes Laboratory

Outline

MASCOT thermal design is here presented through the following points:

- MASCOT as part of HY-2 mission: mission, constraints, challenges
- Challenging thermal requirements
- Main thermal strategy and trade-offs: available technologies, constant conductance heat-pipes
- Thermal design
- Vacuum chamber testing
- Thermal model results
- Conclusions and future steps

2

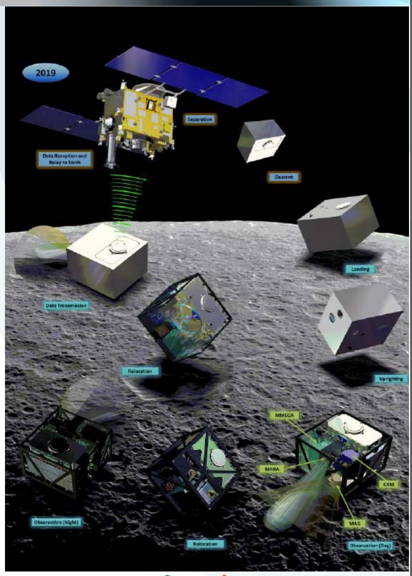
MASCOT as part of HY-2 mission

MASCOT (Mobile Asteroid Surface Scout) is a lander built by DLR, in collaboration with CNES and JAXA, embarked on JAXA's Hayabusa-2, a scientific mission to study the asteroid 162173 1999 JU3.

It is a small lander, less than 300x300x200mm³, with onboard payloads (camera, magnetometer, radiometer and IR spectrometer), developed by DLR, CNES and IAS.

During cruise phases MASCOT is cradled by the support structure MESS inside HY-2 spacecraft.

MASCOT lands on the asteroid surface, after being released by Hayabusa-2 from a very close position above the asteroid surface, and investigates the asteroid surface.



Courtesy of DLR

activespace technologies

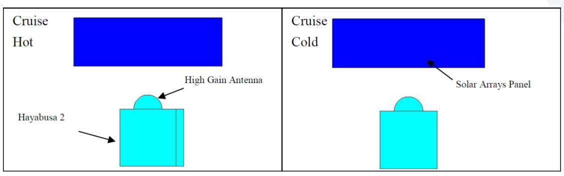
3

Challenging thermal requirements

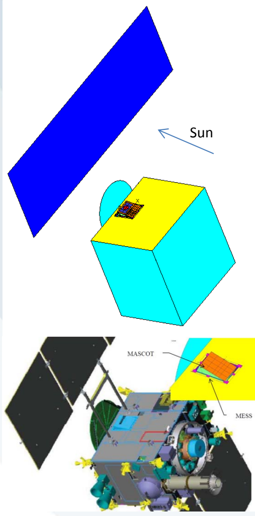
→ Different mission phases → Opposite thermal requirements:

4 years Cruise phase: **cold condition**

- MASCOT as much as possible insulated from the exterior
- Necessity to keep the internal components above minimum non-OP temperatures
- Reduced heat exchange (MASCOT+MESS, cruise and return cruise) with the main S/C (max +/-5W)
- Reduced power consumption (cruise) for heaters (max 5W always ON)



Cruise phase, as seen form the Sun

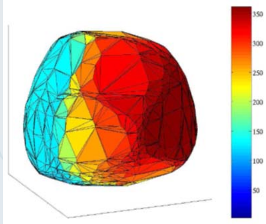


activespace technologies

4

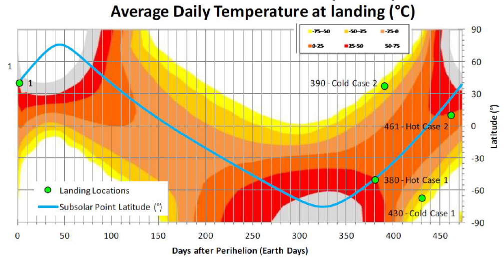
Challenging thermal requirements

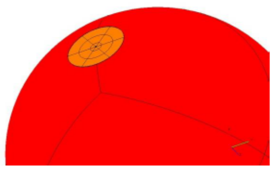
→ Different mission phases → Opposite thermal requirements:

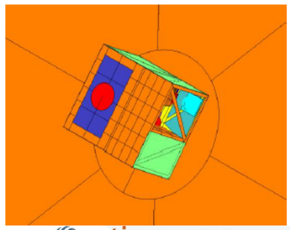


On asteroid phase: **„hot“ condition**

- Landing site evaluation
- Dissipate as much as possible heat from the payloads and internal subsystems to the deep space via the lander radiator
- Asteroid environment, temperature of the ground, sun illumination







activespace technologies

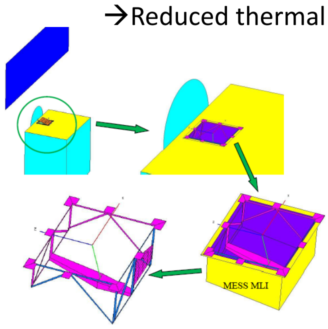
5

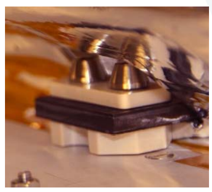
Main thermal strategy for MESS / S/C

Insulate as much as possible the lander and MESS from the main S/C in order to fulfill JAXA requirements for cruise „on board“ and „empty“ cases (for heat fluxes).

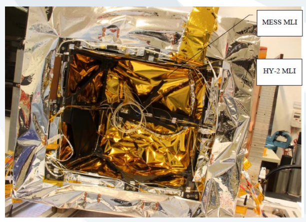
Strategy:

→MLI blanket to protect the S/C from external heat exchanges (+/-5W radiative)
→Reduced thermal coupling between MESS and S/C (+/-5W conductive)
→Reduced thermal coupling between MASCOT and MESS (+/-5W conductive)





Courtesy of DLR



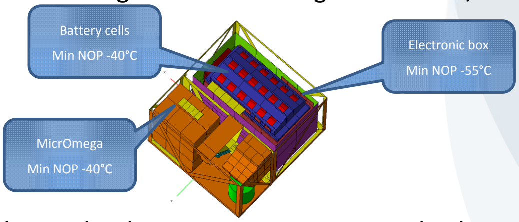
Courtesy of DLR

activespace technologies

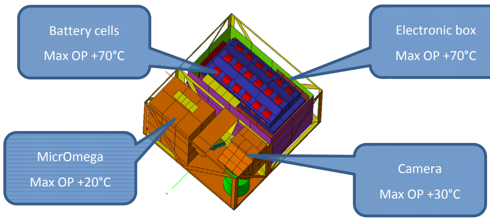
6

Main thermal strategy for MASCOT

Surviving temperatures must be guaranteed during hibernation/cruise mode.



On asteroid surface, the paylaods and subsystems must be kept within their minimal and maximum temperature limits to guarantee the success of the mission (2 asteroid „day-nights“, 15 hours).



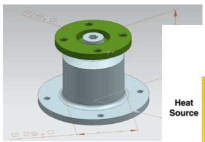
activespace technologies 7

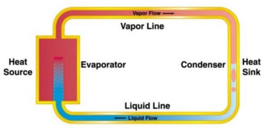
Main thermal strategy for MASCOT

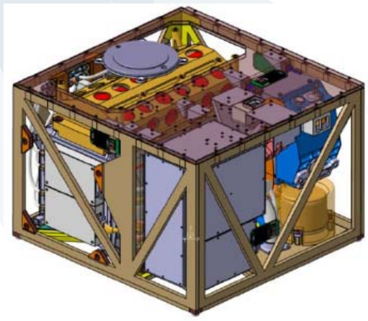
Two opposite requirements present for the two main mission phases, cruise and on-asteroid

→Technology for thermal control able to fulfill both the requirements

Possible solutions:







- Heat-switch
- Loop heat-pipes
- Variable conductance heat-pipes
- Evapoartive systems with storage of consumable liquib
- „Constant“ conductance heat-pipes

Trade-off in terms of mass, maturity of the technology, available space in the lander, simpler design, performances, eventual heating power by the main S/C, short lead time.

activespace technologies 8

Main thermal strategy for MASCOT

„Constant“ conductance heat-pipes (Heat Pipes Laboratory)

- No use of a reservoir
- No non condensable gas inside
- Independent from the value of the radiator face-sheet conductivity

→ Solution based on the selection of the work fluid in order to have a passive regualtion system and to fulfil:
  - Low heat transfer and small GL at temepratures below -20°C
  - Enough heat transfer and large GL above +20°C

activespace technologies 9

Main thermal strategy for MASCOT

„Constant“ conductance heat-pipes (Heat Pipes Laboratory)

→ Methanol used for MASCOT heat-pipes

→ Flight heirtage of combination copper+methanol/water/acetone
  - → Fragment, 1980
  - → Skala, 1983
  - → Magion-4, 1995
  - → Magion-5, 1996

→ Appearance of variable heat conductance properties, function of the operative temperature, for methanol and acetone
  - → on-flight check on microsatellites Magion-4 and Magion-5

activespace technologies 10

Main thermal strategy for MASCOT

„Constant“ conductance heat-pipes (Heat Pipes Laboratory)

- Copper shell and capillary structure instead of aluminium:
  - Faster design and selection of wicks with different parameters
  - Flexibility for bending at small radii

- 8 different wick types manufactured and tested to fulfil the requirements, final result:
  - Porosity 85%
  - Sintered copper metal felt wick with artery effect

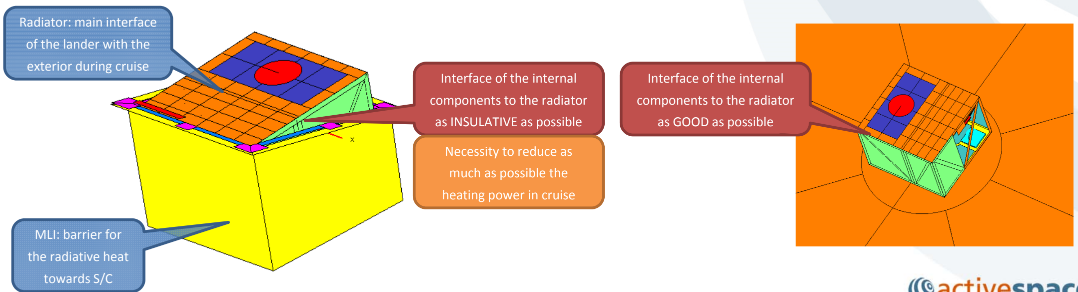
- Preparation of the materials and parts:
  - Methanol preliminary purified via degassing
  - Case and wick purification with solvents, vacuum, high T >950°C
  - Corrosion protection via nickel-plating

activespace technologies 11

Thermal design

The whole thermal design is based on a very delicate equilibrium:

- surviving temperatures must be guaranteed during hibernation/cruise mode
  → thermal design with minimal heat exchange with the exterior
- distribution of the available heating power and temperature sensor in cruise
- on asteroid condition, the heat produced by the internal components must be rejected as efficiently as possible

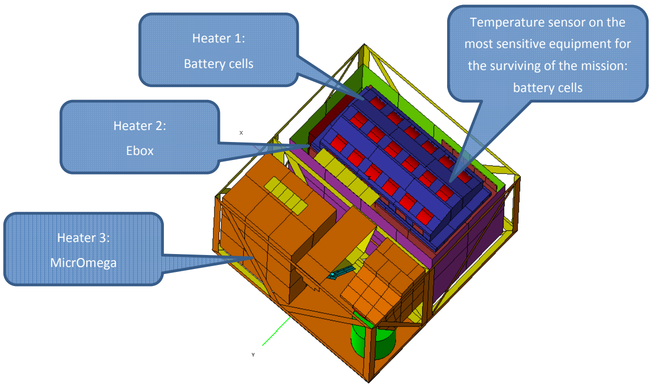


activespace technologies 12

Thermal design

The thermal design of MASCOT is mainly **passive** (heaters only during cruise).

Heater line available from the S/C, but only **one temperature sensor usable**.



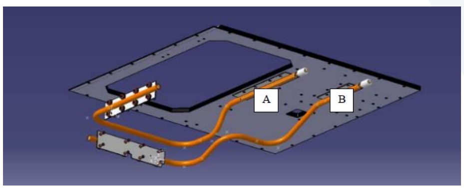
- Temperature of the other sensitive equipments is estimated by thermal model.
- Total heater power available: 10W with duty cycle < 50%.

activespace technologies 13

Thermal design

Heat-pipes model created in accordance with heat-pipes manufacturer and DLR expert; then tuned with the data obtained from thermal characterization of the prototypes.

Another requirements for cruise phases: commissioning/check-out: the system must be able to switch ON during cruise and operate a system check-out:
→ the heat-pipes must be able to change their behaviour **also** in cruise.



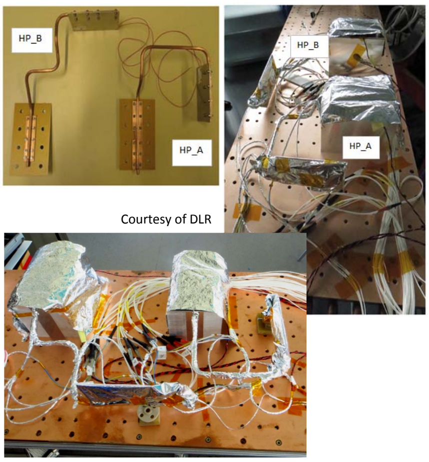
Courtesy of DLR

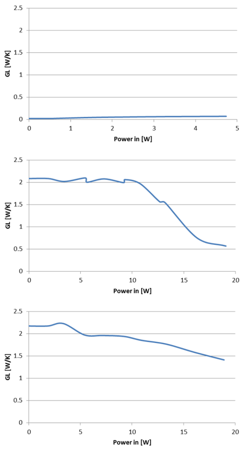
Two different designs of the heat-pipes (configuration constraints): MSCHPA and MSCHPB.

activespace technologies 14

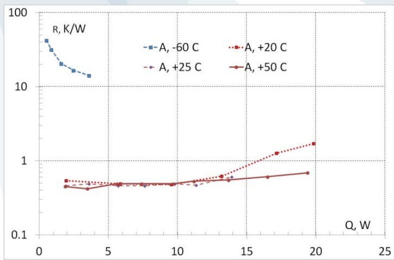
Thermal design

Heat-pipe thermal characterization





Different temperature levels (-60°C, +20°C, +50°C)

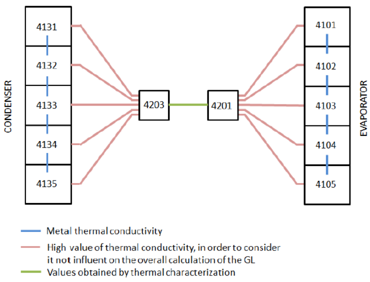


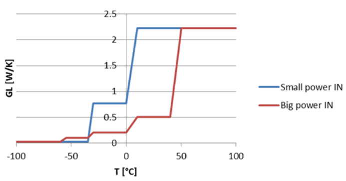
Partial results obtained for MSCHPA

activespace technologies 15

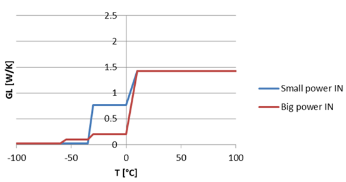
Thermal design

Heat-pipe modelling





P_HPA	[W]	<0.5	>0.5	<5.5	>5.5	<10	>10	independent
TCHPA [°C]	GLHPA [W/K]							
-100	0.022323							
-60	0.022323							
-55		0.022323	0.1					
-35		0.022323	0.1					
-30				0.769231	0.2			
0				0.769231	0.2			
10						2.222222	0.5	
40						2.222222	0.5	
50								2.222222
100								2.222222



P_HPB	[W]	<0.5	>0.5	<5.5	>5.5	<10	>10	independent
TCHPB [°C]	GLHPB [W/K]							
-100	0.02809							
-60	0.02809							
-55		0.02809	0.1					
-35		0.02809	0.1					
-30				0.769231	0.2			
0				0.769231	0.2			
10						1.428571	1.428571	
40						1.428571	1.428571	
50								1.428571
100								1.428571

activespace technologies 16

Vacuum chamber testing

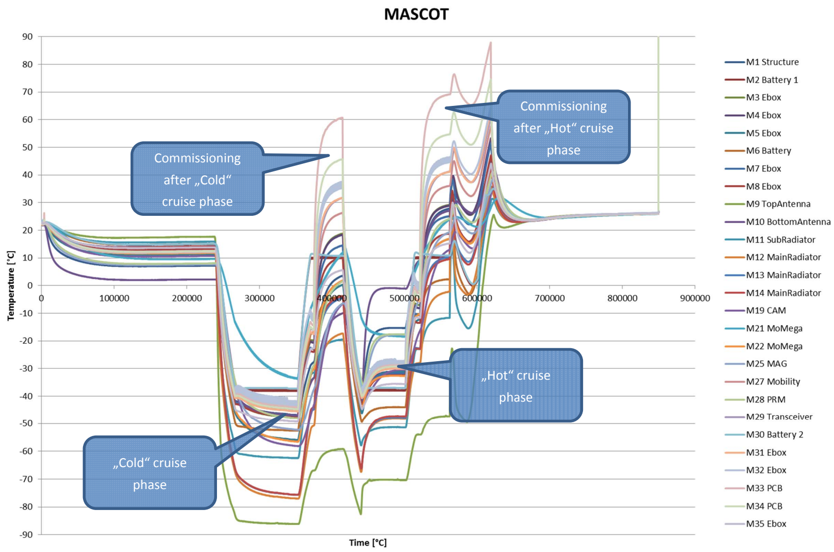
Apart from the thermal characterization tests perfomed specifically on the heat-pipes, dedicated tests have been performed for the lander in cruise condition (on asteroid testing phase at the end of November 2013).

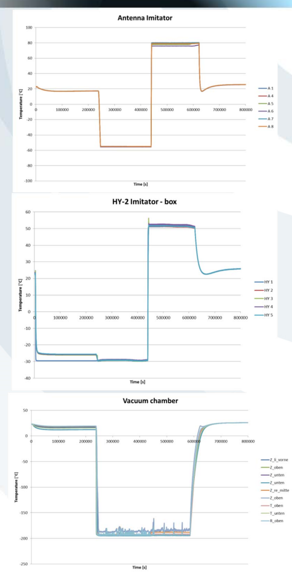
The S/C is represented by proper imitators for the same boundary conditions as in cruise phase.

Courtesy of DLR

activespace technologies 17

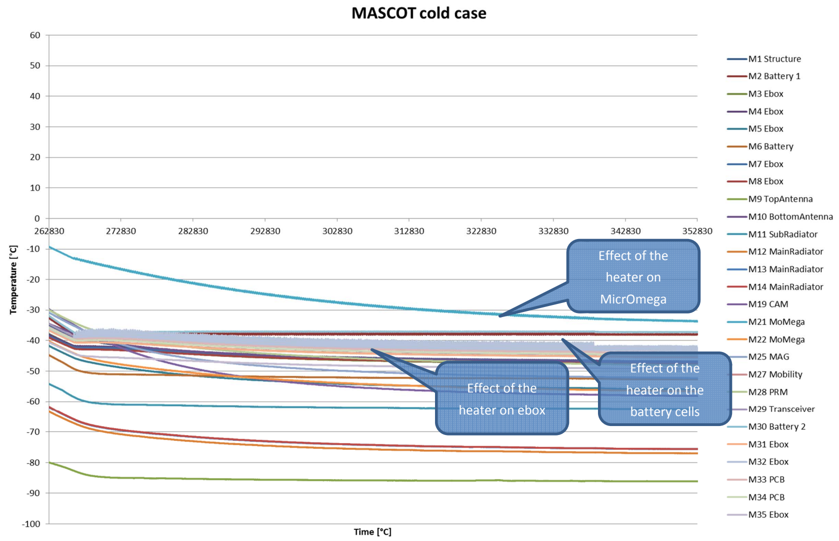
Vacuum chamber testing





activespace technologies 18

Vacuum chamber testing

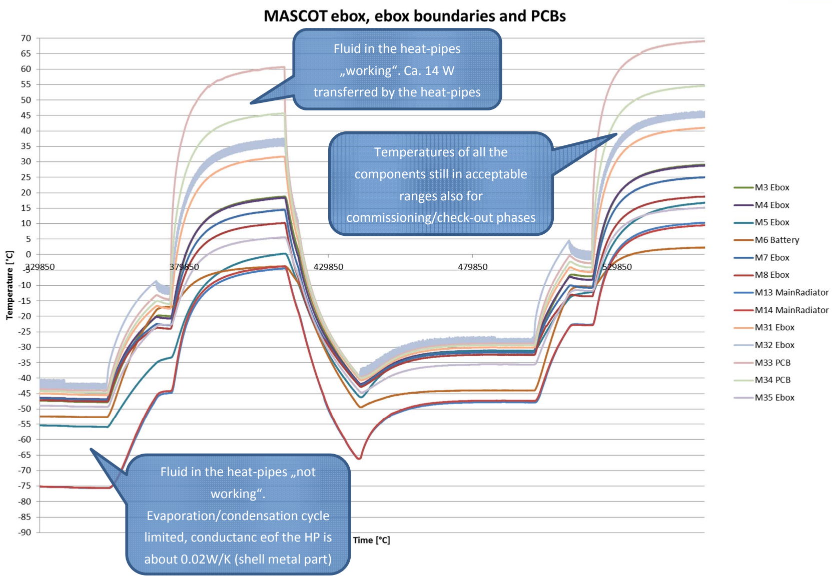


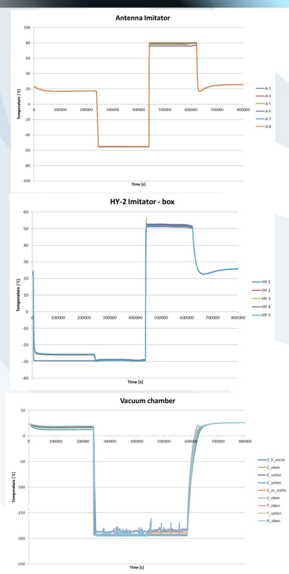
All the components within their nonOP temperature requirements, as predicted by the thermal model

activespace technologies

19

Vacuum chamber testing



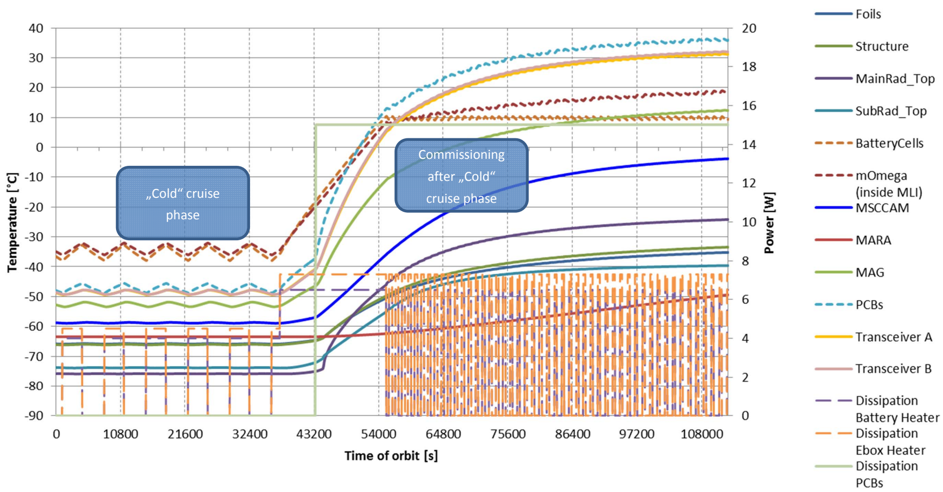


activespace technologies

20

Thermal model results

CA02 - Cruise cold transient analysis



activespace technologies 21

Thermal model results

Case	Heater power battery [W]	Heater power Ebox [W]	Heater power mOmega [W]	Total heaters power [W]	Duty cycle
Nominal cold cruise (52V HY-2)	8.3	9.3	3.0	20.6	21.6-23.4%
Safe cold cruise (36V HY-2)	4.0	4.5	1.5	10.0	45.1-48.7%
Nominal hot cruise (52V HY-2)	8.3	9.3	3.0	20.6	8.8-10.4%
Safe hot cruise (36V HY-2)	4.0	4.5	1.5	10.0	18.0-19.3%

Test results

Simulated case	Heater power battery [W]	Heater power Ebox [W]	Heater power mOmega [W]	Total heaters power [W]	Duty cycle
Continuous power COLD	1.95	2.14	0.68	4.77	-
Nominal cold cruise (52V HY-2)	-	-	-	-	23.2%
Safe cold cruise (36V HY-2)	-	-	-	-	47.7%
Continuous power HOT	0.8	0.25	0.85	1.9	-
Nominal hot cruise (52V HY-2)	-	-	-	-	9.2%
Safe hot cruise (36V HY-2)	-	-	-	-	19%

Model results

activespace technologies 22

Conclusions and future work

- The tests perfromed as cruise phase were succesful
- All the components are within the acceptable temperatures, as predicted by the model
- Heat exchange between S/C and lander as predicted by the model
- Duty cycles of the heaters within the limits and as predicted by the model
- „ON/OFF“ heat-pipes behaviour verified during cruise and commissioning/check-out simulated phases

- Heat-pipes are still to be verified for on asteroid conditions, with higher heat to be transferred and a last tuning phase about the performances may be necessary
- Improvements in the heat-pipes modelling foreseen taking into account new tests performed on QM HPs

activespace technologies 23

Thank you for the attention!

For further information, please visit our website

www.activespacetech.com

Riccardo Nadalini
Riccardo.nadalini@activespacetech.com

Tel: +49 (0) 30 6392 6059
Fax: +49 (0) 30 201 632 829

Rudower Chaussee 29
12489 Berlin
Germany

activespace technologies

Appendix L

LHP MODULE SOFTWARE
Application at System Level

Paul Atinsounon David Valentini
(Thales Alenia Space, France)

Abstract

Loop Heat Pipes (LHPs) are more and more used for spacecraft thermal control thanks to its performances and ability to transport heat load on a long distance.
In the frame of CSO program, LHPs are implemented on Visible and Infra-Red Detection Sub-assemblies.
In order to simulate LHPs behaviour at system level, specific software was developed by Astrium / Thales Alenia Space under CNES and ESA fundings. The LHP Module is compatible with many thermal softwares and works as a sub-model of ESATAN-TMS Thermal Mathematical Model (TMM).
The objectives of the presentation are to describe briefly the LHP Module inputs/outputs and functional blocks. Main performances of Visible and Infra-Red Assemblies are simulated using the LHP Module. Breadboard test exploitations are compared with predictions in order to validate the LHP Module accuracy. The software limits and constraints will also be presented.

Summary

2

- Introduction
- LHP operating principles
- LHP Module Software
- LHP Module application
- Validation with breadboard tests
- Limits and constraints
- Conclusion

OPEN

3rd - 4th December 2013

ThalesAlenia Space

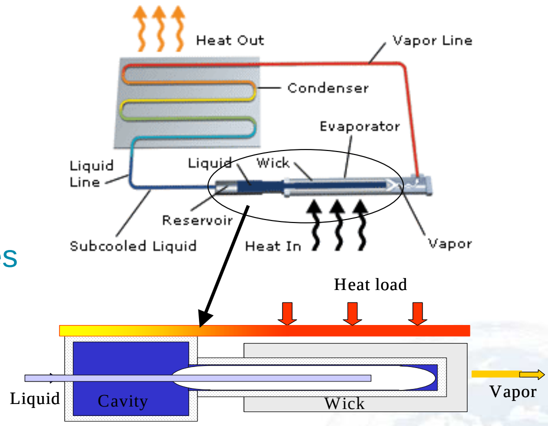
Introduction

- Tool development to simulate biphasic product at system level
- Development made by Astrium / Thales Alenia Space under CNES and ESA fundings
  - « Simplified » thermal model
  - Interface as a sub-model with ESATAN-TMS Thermal Mathematical Model
- LHP Module Software version V2.4 firstly used on CSO program

LHP Module Software developed for use at System Level

LHP operating principles

- LHP : two-phase (vapor and liquid) heat transfer device, using the evaporation and condensation of a working fluid (ammonia), and the capillary forces developed by evaporator wick
- Main elements :
  - Reservoir,
  - Evaporator,
  - Condenser,
  - Vapor and Liquid transport lines



Main Elements involved in LHP Performances

LHP Module Software (1/6)

5

- Simulating the LHP functioning by computing the main parameters:
  - Heat transfers through the LHP (fluid heat transported, heat flux at evaporator,flux exchanged at condenser level…)
  - Temperatures of LHP elements
  - Conductances (evaporator, condenser and total LHP conductances)
  - Sub-cooling (Tsat-Toutlet condenser)
  - Front position in condenser
  - LHP status (ON or OFF)
  - Thermo-hydraulic parameters (pressure losses, mass flow, fluid speed…)

Access to thermal and thermo-hydraulic Inputs/Outputs at System Level

OPEN

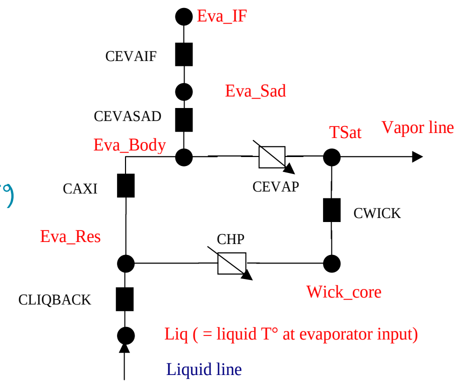
3rd - 4th December 2013

ThalesAlenia Space

LHP Module Software (2/6)

6

- Insertion in an ESATAN program
  - LHP Module Software used as sub-model
  - Sub-model modeling
    - Evaporator : 3 nodes or 5 nodes (**baseline**)
    - Vapor line : 1 node (adiabatic at saturation T°)
    - Condenser : N nodes
    - Liquid line : N nodes
    - LHP parameters



  - System modeling
    - Radiative and conductive couplings between the model and the LHP sub-model
    - Reservoir and liquid line regulation

Sharing functionalities between LHP Module and System Model

OPEN

3rd - 4th December 2013

ThalesAlenia Space

LHP Module Software (3/6)

7

- An elemuser.dat file : file with computing algorithms and subroutines
- System inputs (power, temperature initialization, nodal breakdown, modeling and numerical parameters) in the specific data file (XXX.LHP)
- Loop heat pipe inputs, describing the hardware of elements of the loop in generic data files:
  - XXX.EVAPHW for evaporator (capacitances, stop/start criteria, conductances)
  - XXX.CONDHW for condenser (number of branches, tubing properties)
  - XXX.VAPLHW for vapor line (number of sections, properties of branch)
  - XXX.LIQLHW for liquid line (number of sections, properties of branch)
  - XXX.PPTY for working fluid (thermodynamic properties)

LHP Module generic algorithms and input files

OPEN

3rd - 4th December 2013

ThalesAlenia Space

LHP Module Software (4/6)

8

System model

$MODEL SATELLITE, GLOBALFILE=ELEMUSER.DAT

$ ELEMENT LHP
Call of the specific data file "LHP"

$NODES
Definition of system and LHP I/F nodes

$CONDUCTORS
Definition of the link between system I/F nodes and LHP nodes
...

$END MODEL

→

LHP specific data file

$FLUID
Call of the generic data file

$EVAPORATOR
Call of the generic data file

$VAPOR LINE
Call of the generic data file

$CONDENSER
Call of the generic data file

$LIQUID LINE
Call of the generic data file

$NUMERICAL PARAMETER
Definition of the numerical & modelling parameter

FLUID generic data file	**EVAP generic data file**	**COND generic data file**	**LIQ generic data file**	**VAP generic data file**
Definition of the fluid property	Definition of the evaporator	Definition of the condenser	Definition of the liquid line	Definition of the vapor line

Input data implementation in an ESATAN TMM

OPEN

3rd - 4th December 2013

ThalesAlenia Space

LHP Module Software (5/6)

9

- Main subroutines
  - Calch : diphasic and monophasic heat transfer coefficients (HTC) computation for each cell
  - ComputeLHP : permanent and transient temperatures computation
  - DeltaP : pressure losses computation in vapor, liquid lines and condenser
- Main function
  - Glfluid : heat transfers between tubing and fluid

LHP Module subroutines and functions

OPEN

3rd - 4th December 2013

ThalesAlenia Space

LHP Module Software (6/6)

10

1. Fluid transported heat computation → mass flow computation
2. Pressure losses computation in LHP (DeltaP subroutine) → Tsat computation, using the Clausius-Clapeyron curve dP/dT
   - Pressure losses=f(mass flow, tubing geometrical parameters)
3. Heat transfer coefficients computation at cell level (Calch subroutine)
   - HTC=f(mass flow, tubing geometrical parameters)
4. Exchanged power computation at cell level (Glfluid function)
   - Exchanged power=f(HTC, fluid input temperature, tubing temperature)
5. Enthalpy and fluid output temperature of each cell (ComputeLHP subroutine)

LHP Module computation sequences

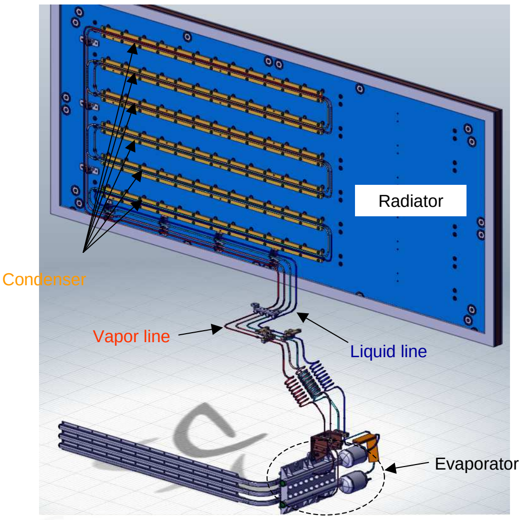
OPEN

3rd - 4th December 2013

ThalesAlenia Space

LHP Module Application (1/3)

11



- LEO Mission
- Cold Redundancy (1 LHP ON – 1 LHP OFF)
- LHP requirements
  - Transported heat power range : [50W,80W]
  - LHP conductance CLHP : 3W/K@min power, 7.5W/K@max power
  - Sub-cooling : >10℃
  - 1W < Operating reservoir heating power < 7W (Operating reservoir regulated @12℃)

Implementation of LHP to control electronic box (Visible assembly)

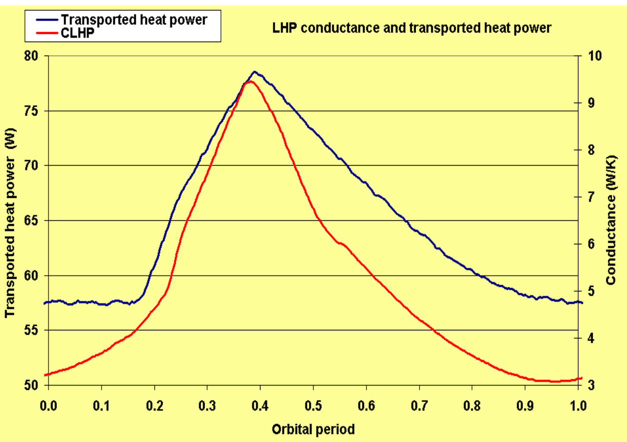
OPEN

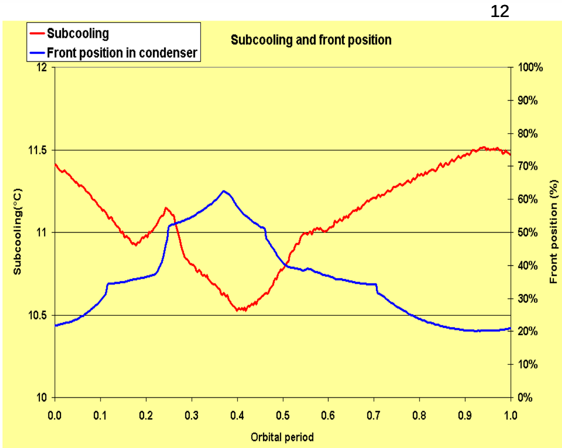
3rd - 4th December 2013

ThalesAlenia Space

LHP Module Application (2/3)

12





- Access to thermo-hydraulic outputs and LHP performances simulation
- LHP design optimization : evaporator length = 182 mm / max CLHP≈ 10 W/K / sub-cooling >10℃

LHP design compliant with thermal requirements

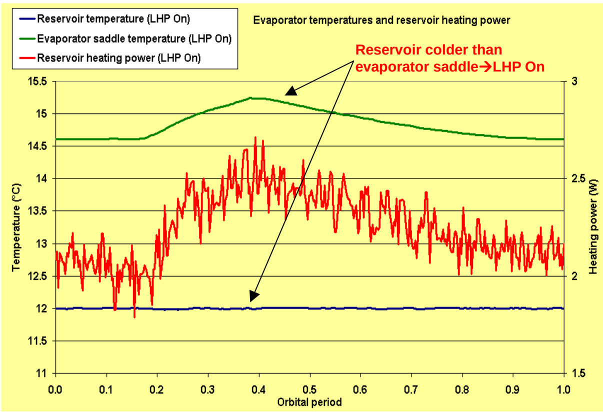
OPEN

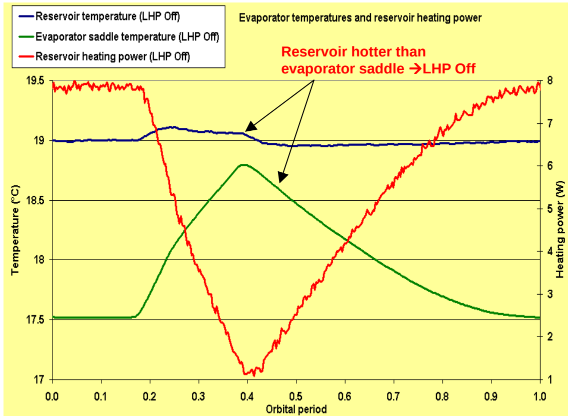
3rd - 4th December 2013

ThalesAlenia Space

LHP Module Application (3/3)

13





- Electronic TRP stability along the orbit < 20℃ tha nks to CLHP variation
- Verification of LHPs behavior (ON and OFF)

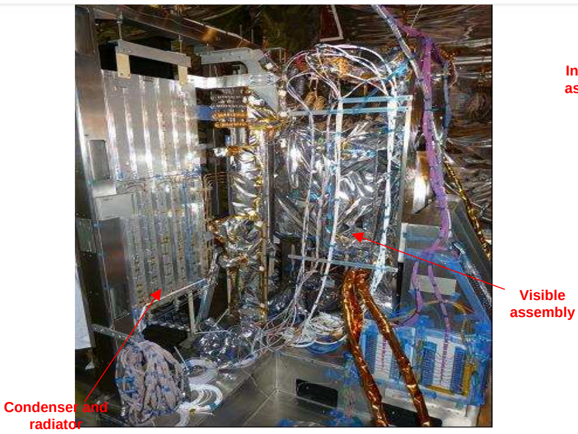
Design optimization to fulfill system budget (power consumption,…)

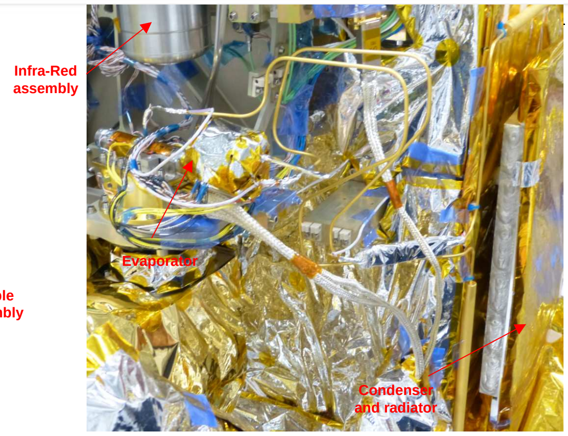
OPEN

3rd - 4th December 2013

ThalesAlenia Space

Validation with breadboard tests (1/4)





Visible Sub-Assembly breadboard tests   Infra-Red Sub-Assembly breadboard tests

- Breadboard tests objectives
  - Verification of LHP performances under 0g or 1g configuration
  - Vacuum test condition (<5.10 $^{-5}$ mbar)
  - TBT duration (10 days)

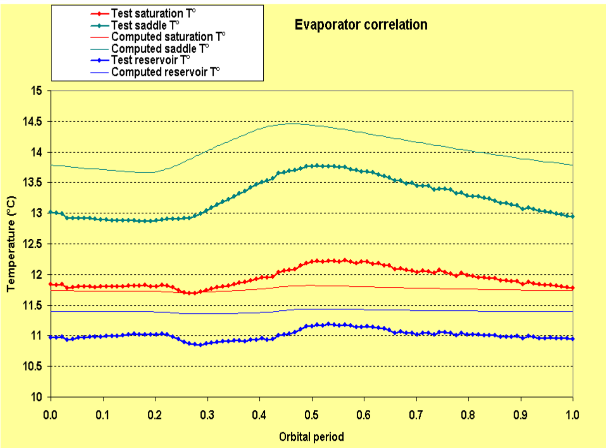
Breadboard Thermal Balance Test configuration

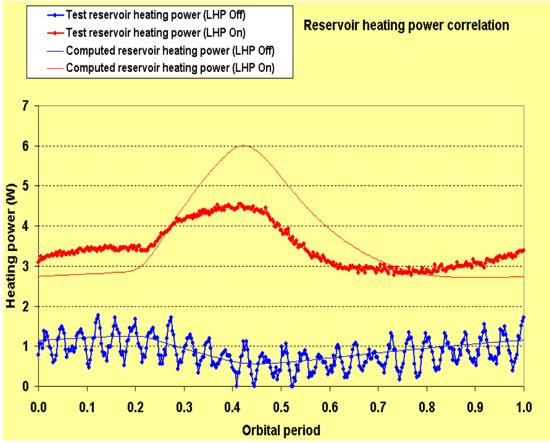
OPEN

3rd - 4th December 2013

ThalesAlenia Space

Validation with breadboard tests (2/4)





- Comparison between Visible Sub-Assembly TBT and correlated results
  - Less than 1℃ of difference on evaporator temperatu res
  - Less than 10% of difference on average power consumption
  - Equivalent thermal behavior along the orbit in hot and cold cases

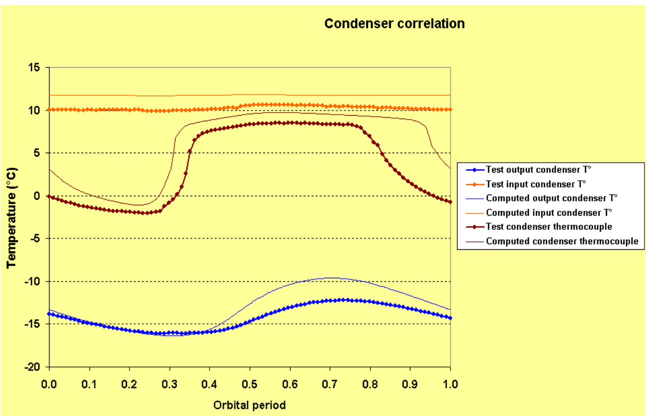
LHP Module validation and thermal model correlation

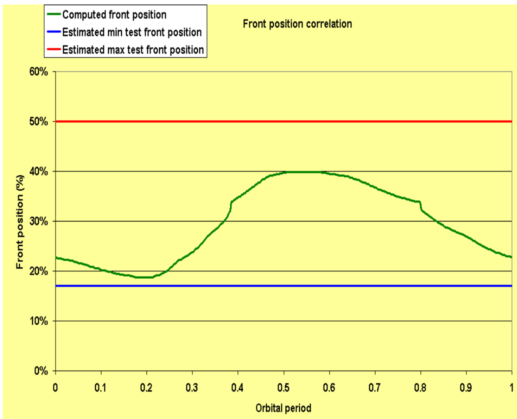
OPEN

3rd - 4th December 2013

ThalesAlenia Space

Validation with breadboard tests (3/4)





- Comparison between Visible Sub-Assembly TBT and correlated results
  - Front position correlated less than 5% at minimum transported heat power
  - Front position correlated less than 10% at maximum transported heat power

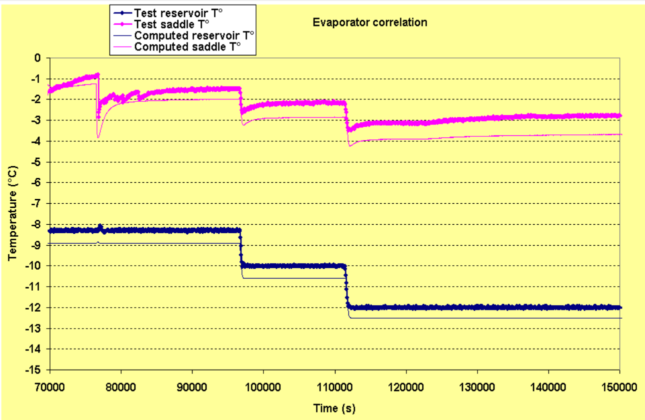
LHP Module validation and thermal model correlation

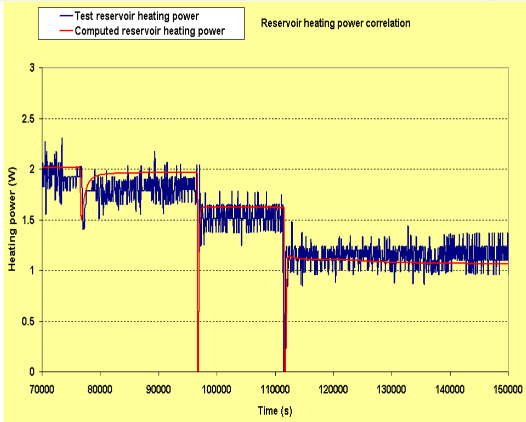
OPEN

3rd - 4th December 2013

ThalesAlenia Space

Validation with breadboard tests (4/4)





- Comparison between Infra-Red Sub-Assembly TBT and correlated results
  - Less than 1℃ of difference on evaporator temperatu res
  - Less than 10% of difference on average power consumption

LHP Module validation and thermal model correlation

OPEN

3rd - 4th December 2013

ThalesAlenia Space

Limits and constraints

18

- Long computation time
  - Small time step required for convergence (dt<2s)
- Permanent case
  - Steady state computations not available
- Vapor line nodal breakdown
  - Vapor line should be considered adiabatic and simulated by 1 single thermal node (otherwise convergence problem occurs)
- Evaporator saddle modeling
  - 1 node could not be sufficient for a large evaporator length due to gradient along the saddle
- Condenser modeling
  - Fine nodal breakdown must be made to simulate the front position and gradients in condenser

Constraints identified without impact on the presented application

OPEN

3rd - 4th December 2013

ThalesAlenia Space

Conclusion

19

- LHP Module Software allows to :
  - Simulate the behavior of biphasic LHP within a system model
  - Optimize a thermal design
  - Necessary to characterize performances (LHP module input) at sub-contractor level (0g and 1g configurations)
- Simulation results validated by thermal tests
- Discussion on-going with CNES/ESA to update LHP Module Software :
  - New technologies (Pressure Regulation Valve, Multi-condensors,…)
  - Gravity effect

Benefit to use LHP Module at System Level

Update of software functionalities identified

OPEN

3rd - 4th December 2013

ThalesAlenia Space

20

- Thank you for your attention

- Any questions?

OPEN

3rd - 4th December 2013

ThalesAlenia Space

Appendix M

Time dependent behaviour of pumped two-phase cooling systems

Experiments and Simulations

Henk Jan van Gerner
(NLR, The Netherlands)

Abstract

Two-phase pumped cooling systems (see figure M.1) are applied when it is required to maintain a very stable temperature in a system, for example in the AMS02, which was launched with the space shuttle (in May 2011) and subsequently mounted on the International Space. However, a two-phase pumped cooling system can show complex dynamic behaviour in response to rapid heat load variations. For example, when the heat load is increased, a large volume of vapour is suddenly created, which results in a liquid flow into the accumulator and an increase in the pressure drop. This will result in variations in the pressure and therefore temperature in the system, which are undesired. It is difficult to predict and understand this behaviour without an accurate dynamic model. For this reason, such a model has been developed by NLR. The model numerically solves the one-dimensional time-dependent compressible Navier-Stokes equations, and includes the thermal masses of all the components (see figure M.2 for an example). The model has been used for different projects, and the numerical results show an excellent agreement with experiments. During the presentation, I will discuss different pumped two-phase cooling systems, and a comparison between simulations and experiments.

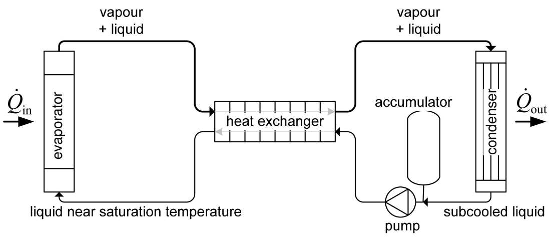


Figure M.1: Schematic drawing of a two-phase pumped cooling system

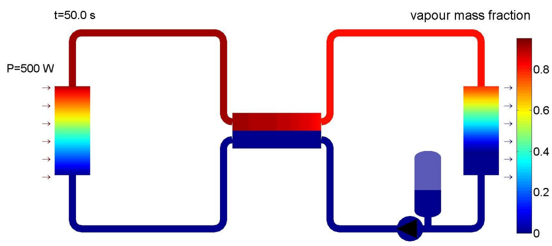
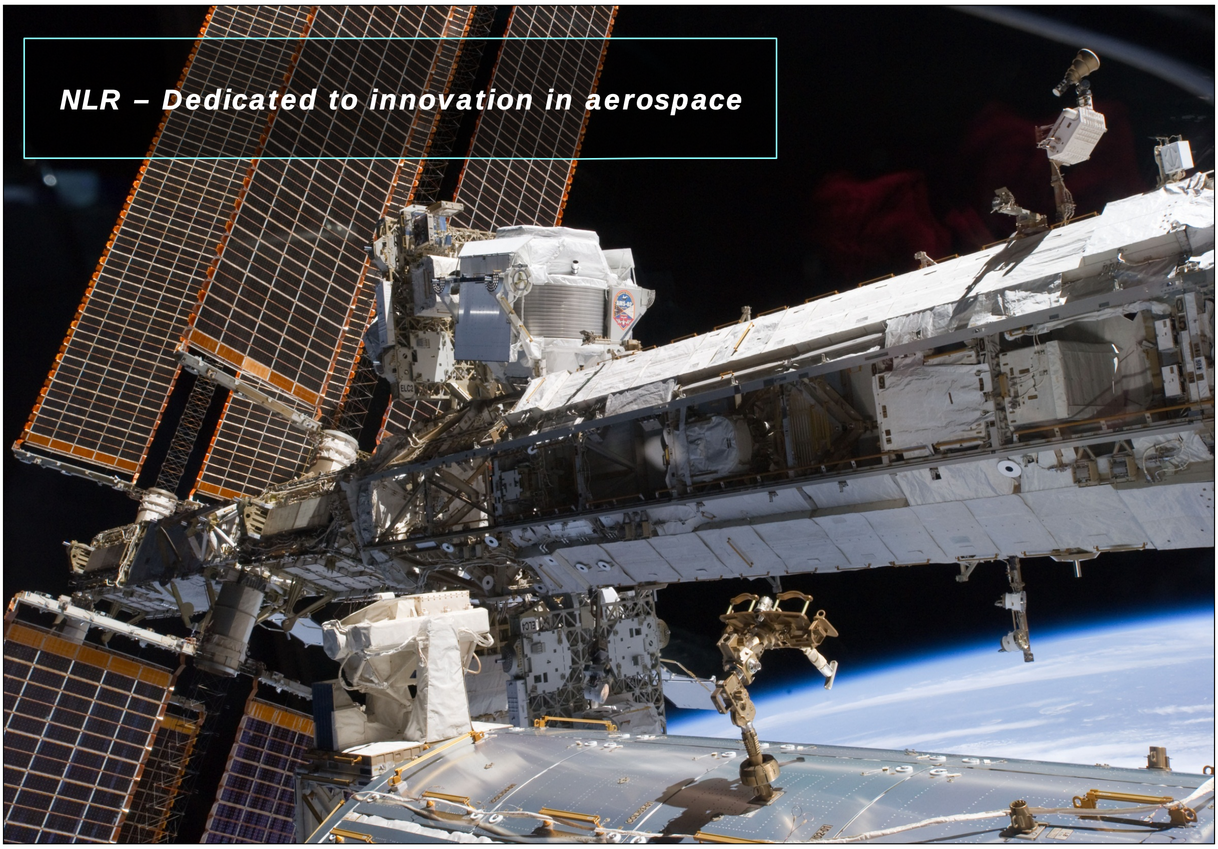


Figure M.2: Calculated vapour mass fraction



NLR Dedicated to innovation in aerospace

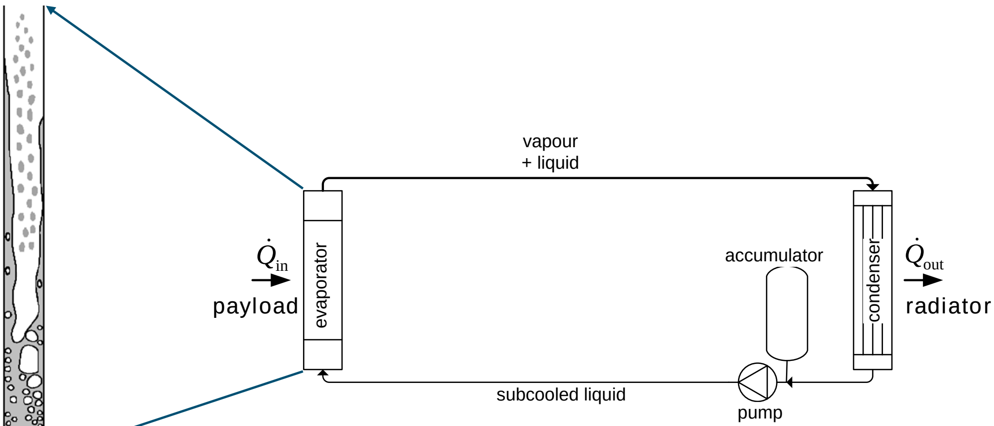
Time-dependent behaviour of pumped two-phase cooling systems: Experiments and Simulations

Henk Jan van Gerner, Niels Braaksma

Nationaal Lucht- en Ruimtevaartlaboratorium – National Aerospace Laboratory NLR

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

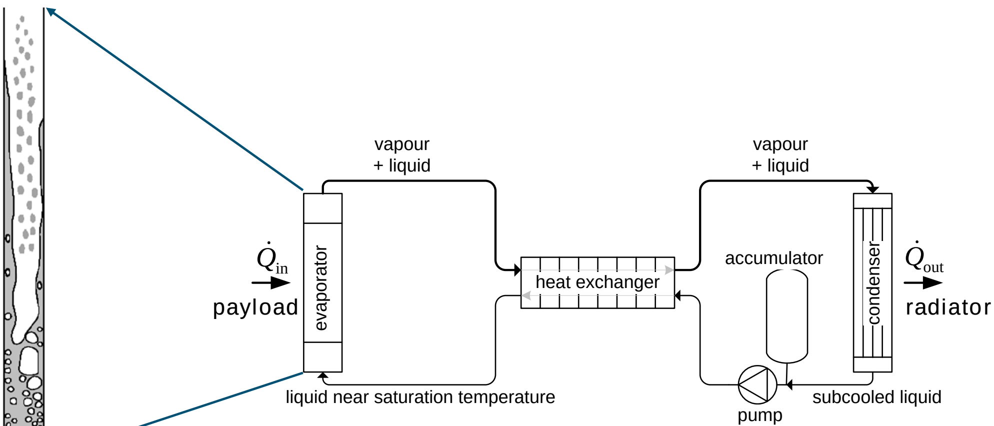


Schematic drawing of a 2Φ-MPFL

NLR *- Dedicated to innovation in aerospace* 3

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

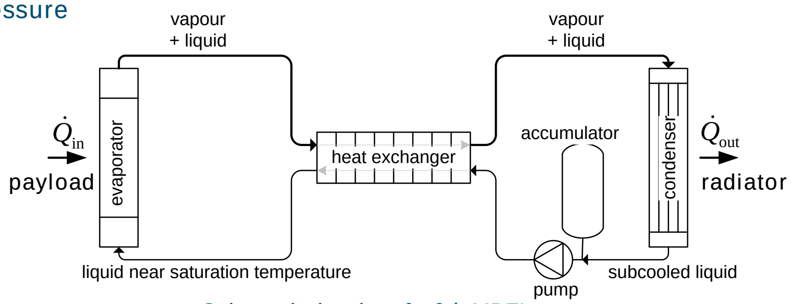


Schematic drawing of a 2Φ-MPFL

NLR *- Dedicated to innovation in aerospace* 4

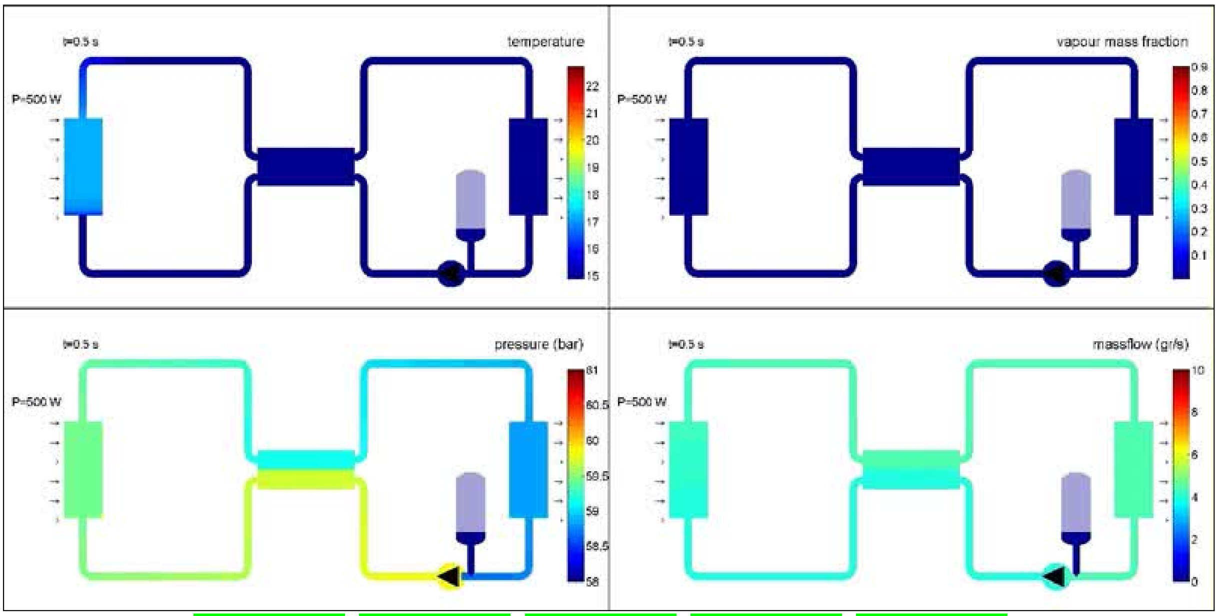
Two-phase Mechanically Pumped Fluid Loop

- 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
- Accumulator controls the saturation temperature/pressure in the loop



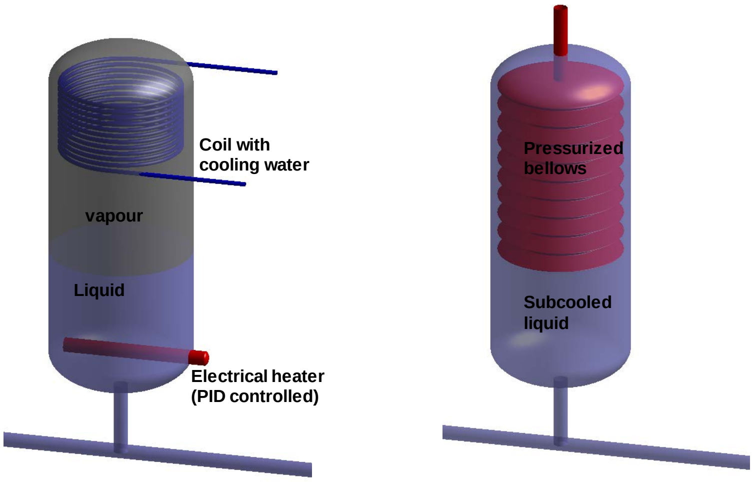
Schematic drawing of a 2Φ-MPFL

NLR - Dedicated to innovation in aerospace 5



Slow Normal Fast Play/Pause Stop

Two basic types of accumulators



Heat Controlled Accumulator (HCA)
- responds slower
  (depending on cooling capacity)
- simple, low mass, reliable
- Most often used

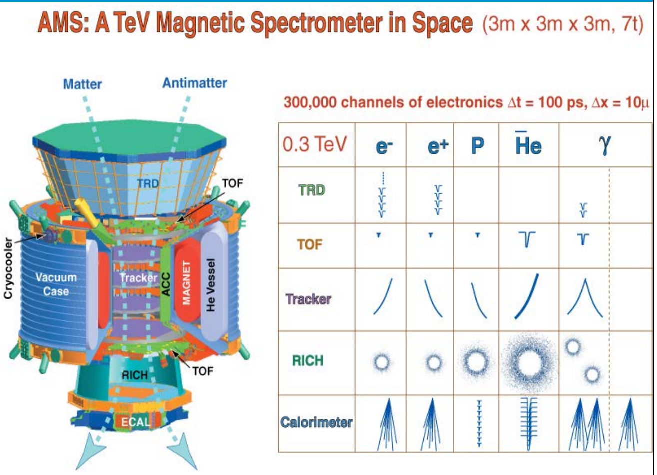
Pressure Controlled Accumulator (PCA)
- responds very fast
- heavy, complex

NLR - Dedicated to innovation in aerospace 6

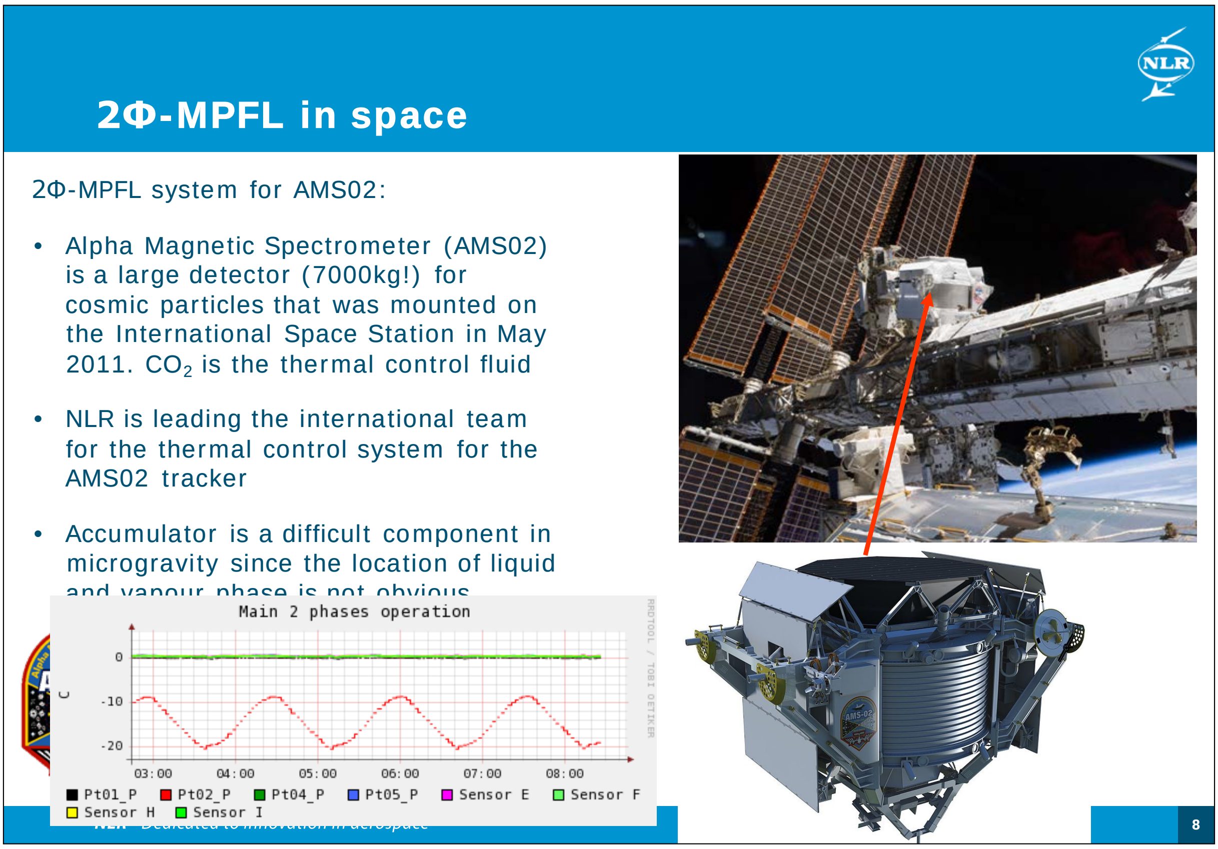
2Φ-MPFL in space

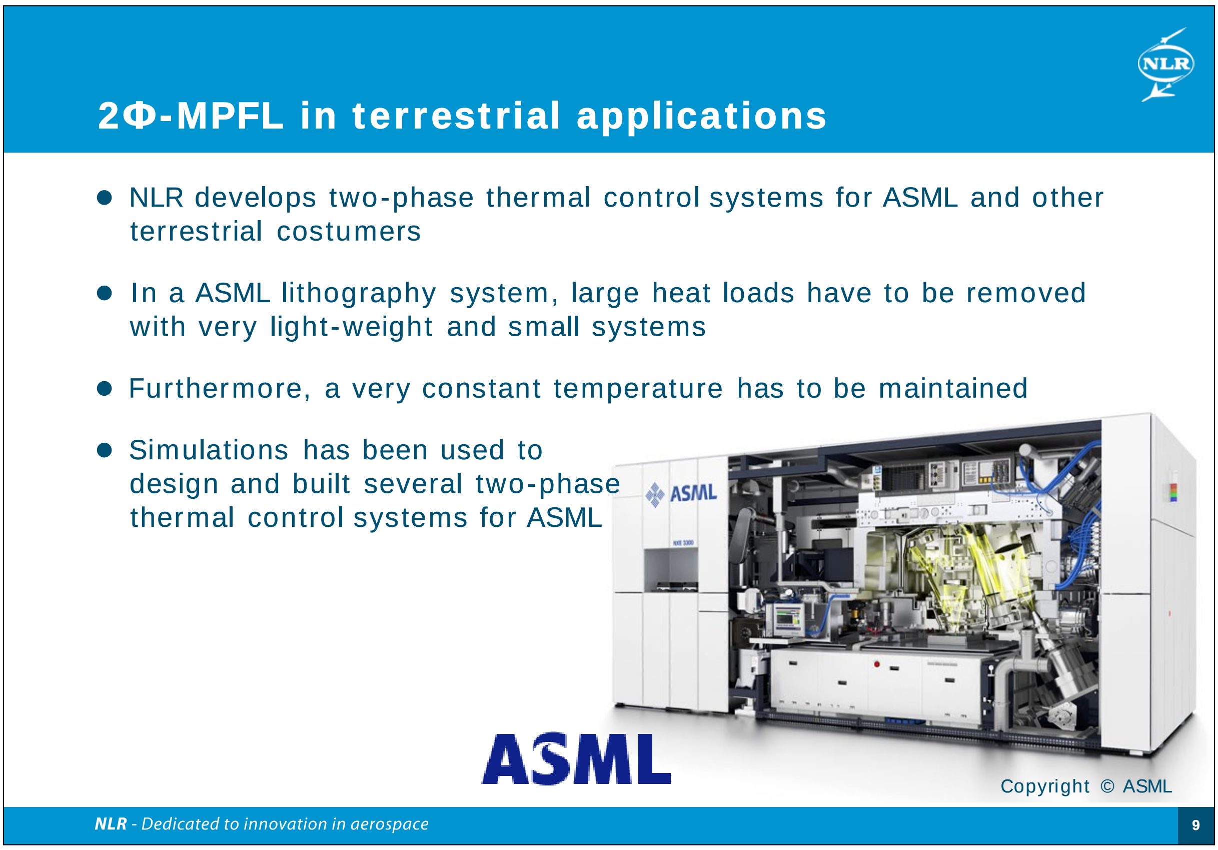
2Φ-MPFL system for AMS02:

- 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
- Accumulator is a difficult component in microgravity since the location of liquid and vapour phase is not obvious



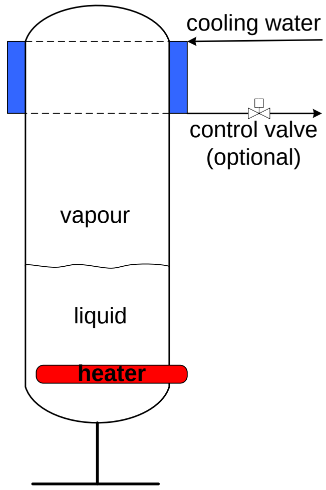
NLR - Dedicated to innovation in aerospace 7


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
Accumulator is a difficult component in microgravity since the location of liquid
Main 2 phases operation
0
-10
-20
C
03:00
04:00
05:00
06:00
07:00
08:00
Pt01_P
Pt02_P
Pt04_P
Pt05_P
Sensor E
Sensor F
Sensor H
Sensor I
8


2Φ-MPFL in terrestrial applications
NLR develops two-phase thermal control systems for ASML and other terrestrial costumers
In a ASML lithography system, large heat loads have to be removed with very light-weight and small systems
Furthermore, a very constant temperature has to be maintained
Simulations has been used to design and built several two-phase thermal control systems for ASML
ASML
ASML
Copyright © ASML
NLR - Dedicated to innovation in aerospace
9

Why do we need a model?

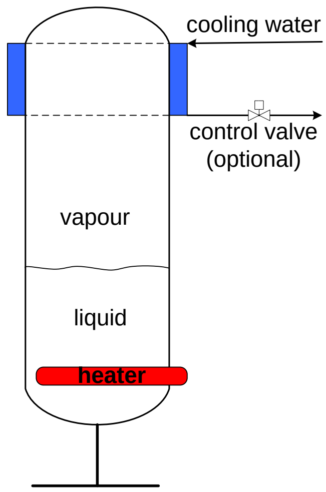
- When the heat load or the heat sink temperature changes (e.g. varying radiator temperature in space application), liquid will flow in/out the accumulator
- As a result, the pressure in the accumulator will change, and therefore the system saturation temperature
- A HCA will respond by heating/cooling inside the accumulator in order to return to the desired pressure/temperature



NLR - Dedicated to innovation in aerospace 10

Why do we need a model?

- In principle, the accumulator can keep exactly the desired temperature when the cooling capacity is very large or when the accumulator is very big
- In practice, cooling capacity and accumulator size are limited and the system temperature will vary
- An accurate model of the complete system is required to calculate how much the temperature will vary
- Furthermore, when 'warm' liquid flows out of the accumulator, the pump can cavitate. This can also be predicted by the model
- NB: A HCA does not have to be in thermal equilibrium (i.e. the liquid can be cooler than the vapour)



NLR - Dedicated to innovation in aerospace 11

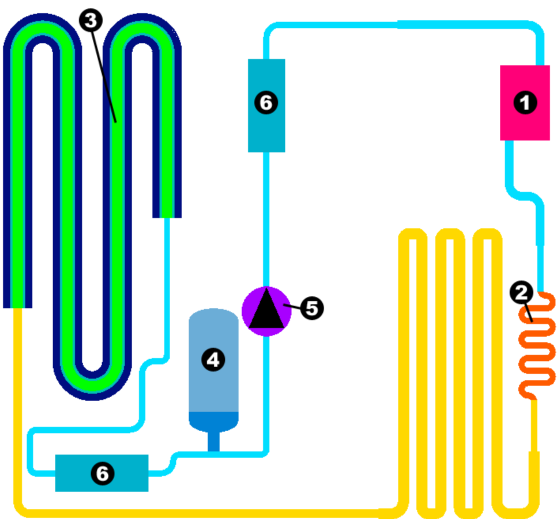
About the model

- The dynamic model numerically solves (in matlab) the time-dependent 1D Navier-Stokes equations
- The Navier-Stokes equations are slightly modified, such that the maximum timestep is not determined by the sound velocity, but by the fluid velocity. This reduces the calculation time with a factor of ~500 (but soundwaves cannot be modelled)
- The Navier-Stokes equations are discretized using the explicit MacCormack predictor-corrector method
- Thermal masses of the components and tubing are included
- Equations of state (i.e. fluid properties) are obtained from REFPROP
- Heat transfer coefficients for turbulent flow are calculated with empirical relations:
  - Single-phase: Gnielinski
  - Condensation: Updated Shah correlation
  - Evaporation: Kandlikar or Cooper's pool boiling correlation with dryout model
- Frictional pressure drop for turbulent flow is calculated with empirical relations
  - Single-phase: Coolebrook
  - Two-phase: Müller-Steinhagen and Heck, Friedel, or linear relation
- Different types of accumulators are implemented

***NLR** - Dedicated to innovation in aerospace* 12

Comparison between the model and experiments

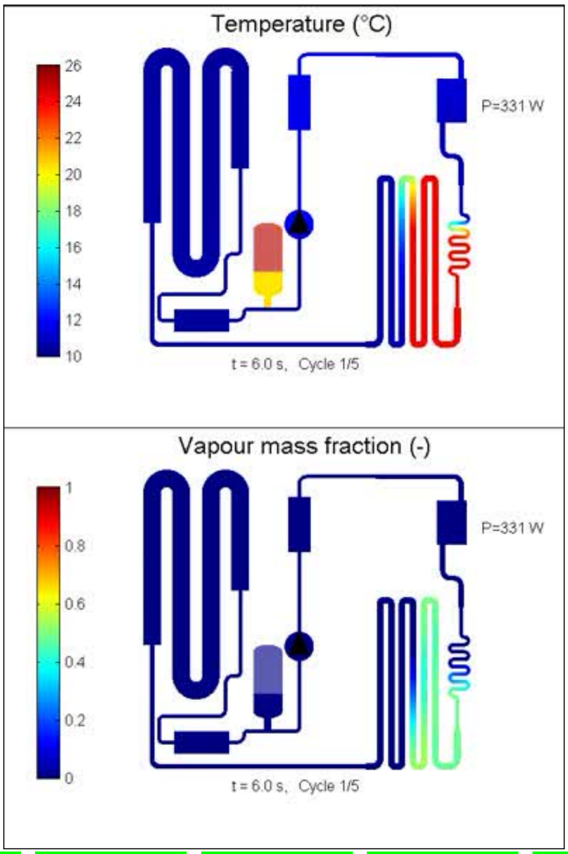
- In order to validate the model, experiments were carried out with a system filled with CO_2



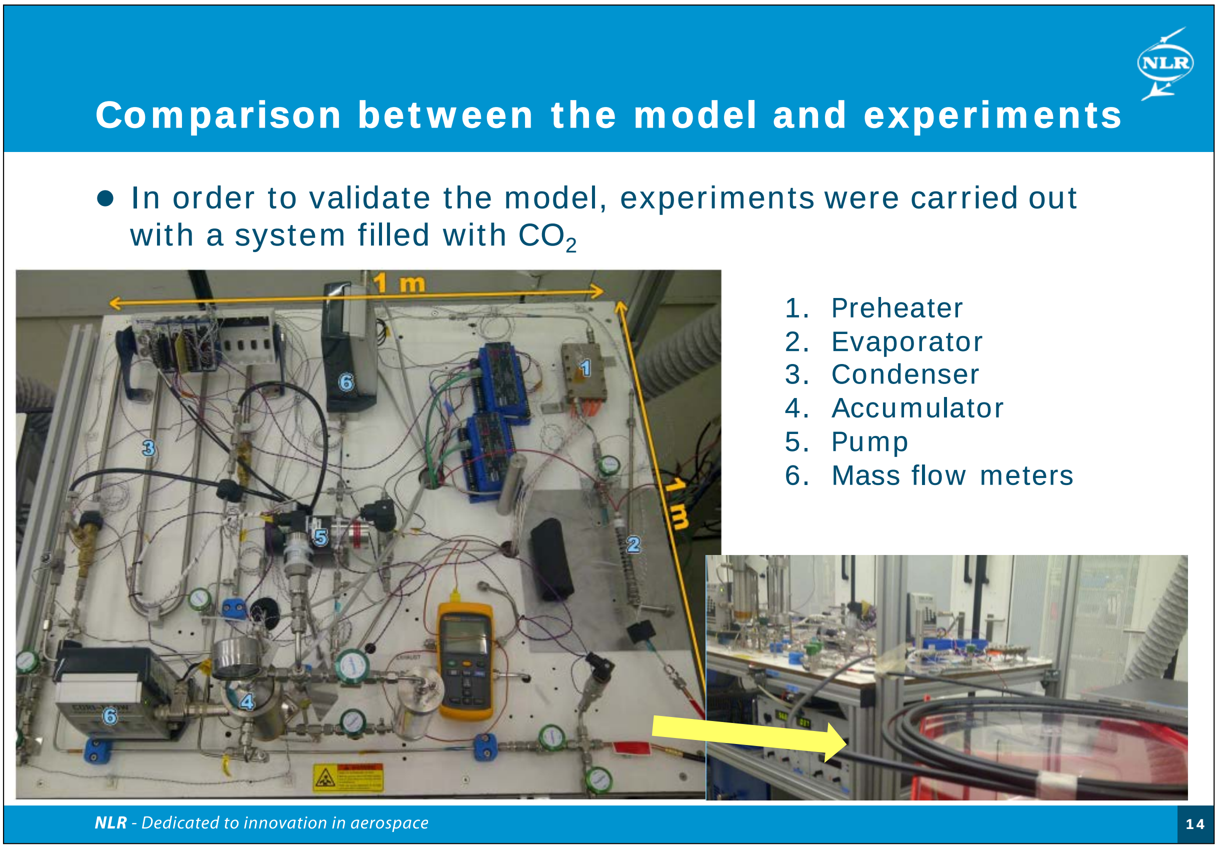
1. Preheater
2. Evaporator
3. Condenser
4. Accumulator
5. Pump
6. Mass flow meters

Schematic drawing of the test setup

***NLR** - Dedicated to innovation in aerospace* 13

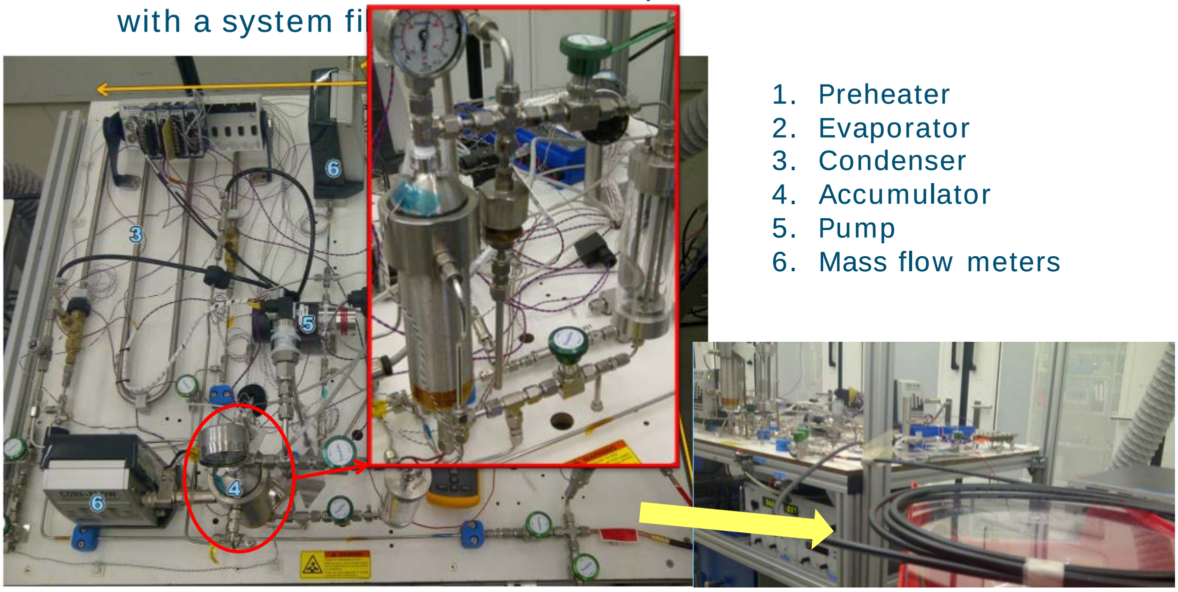


Slow Normal Fast Play/Pause Stop



Comparison between the model and experiments

- In order to validate the model, experiments were carried out with a system fi



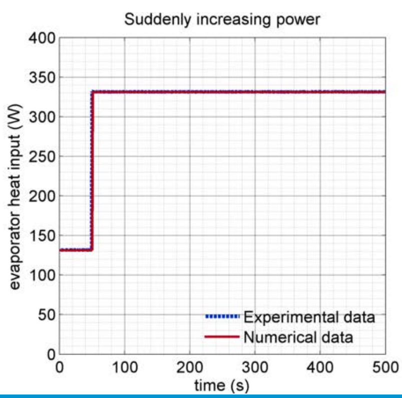
1. Preheater
2. Evaporator
3. Condenser
4. Accumulator
5. Pump
6. Mass flow meters

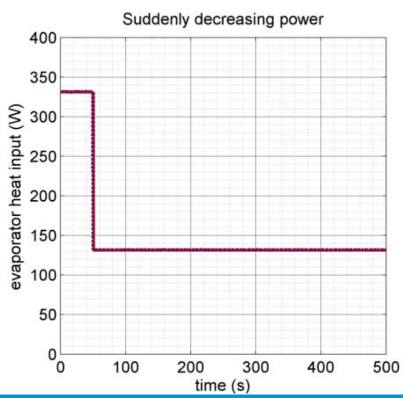
NLR - Dedicated to innovation in aerospace 15

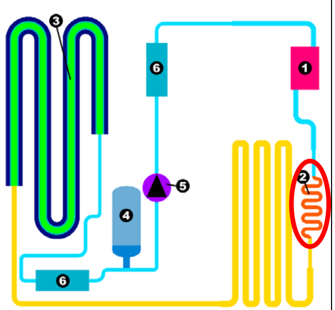
Comparison between the model and experiments

Power:

- The heat input in the evaporator is changed from 131W to 331W
- The preheater is not used → it is just a thermal mass





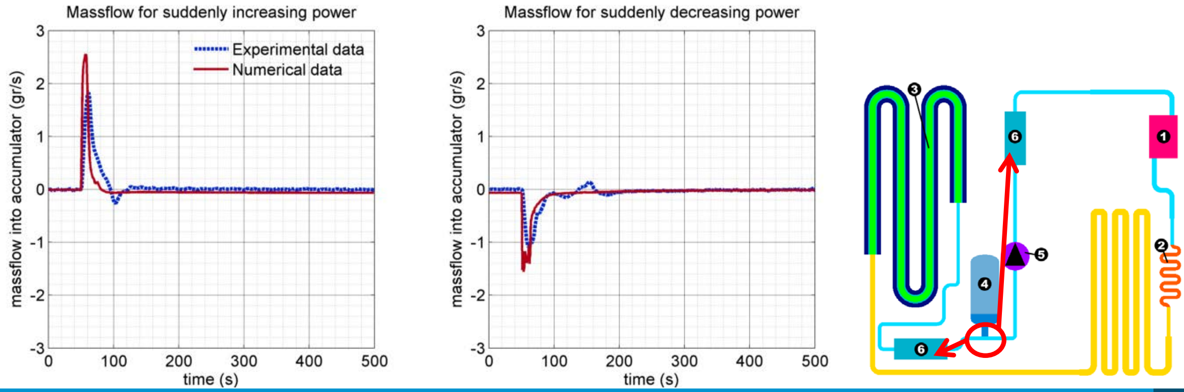


NLR - Dedicated to innovation in aerospace 16

Comparison between the model and experiments

Massflow:

- Massflow into the accu is the difference between the two massflow meters
- As a result of an increase in evaporator power, liquid will flow into the accumulator
- A decrease in evaporator power result in liquid flowing out of the evaporator

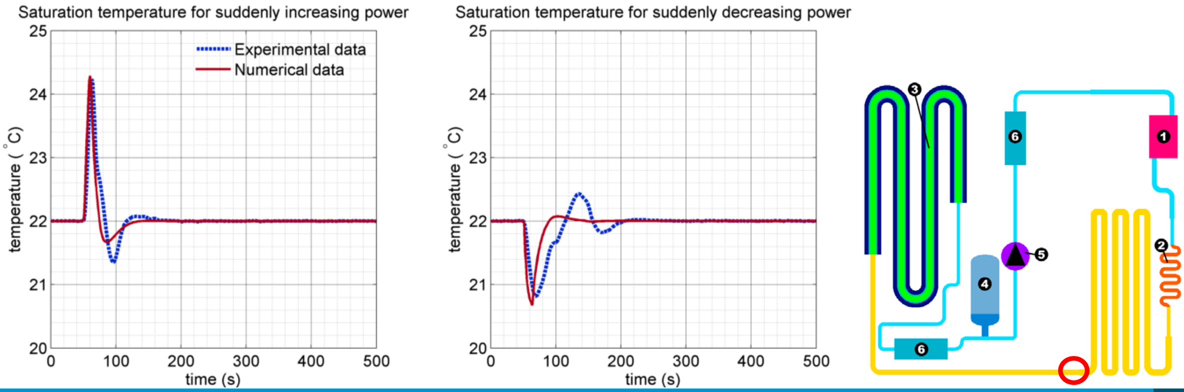


NLR - Dedicated to innovation in aerospace 17

Comparison between the model and experiments

System saturation temperature:

- Due to liquid inflow in the accu (after evaporator power increase), the system pressure and thus temperature will rise
- The accumulator will react and return the temperature to the desired value
- There is an excellent agreement between experiment and simulation

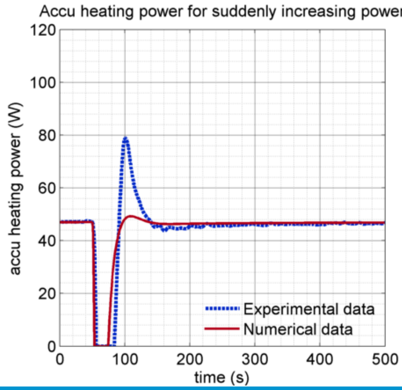


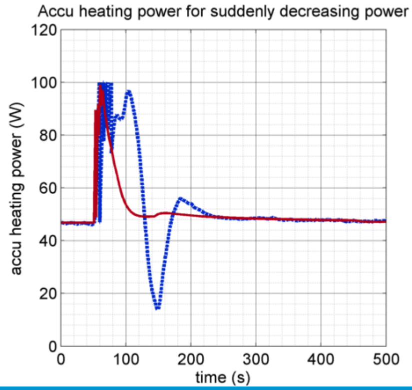
NLR - Dedicated to innovation in aerospace 18

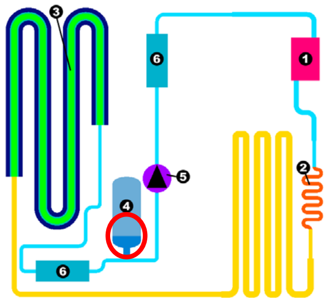
Comparison between the model and experiments

Accu heat/cooling power:

- The accu cooling capacity is 43W. This was known from previous experiments, but this can also be calculated directly. The steady-state heating power compensates for the cooling power
- The accu heating power is PID controlled. The PID parameters in the model and experiment are the same
- More accu cooling power results in better temperature stability





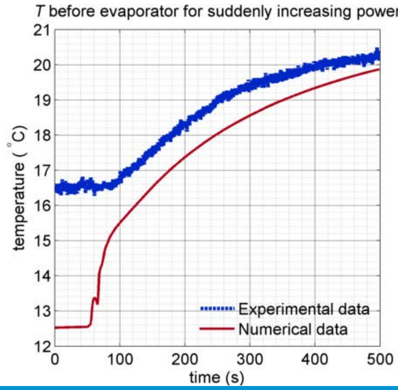


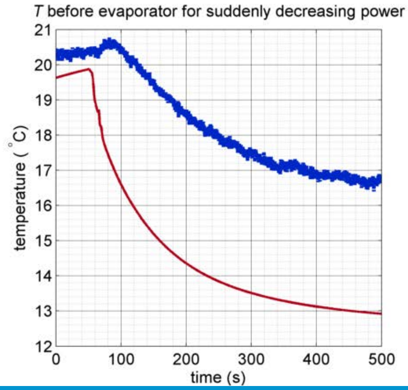
NLR - Dedicated to innovation in aerospace 19

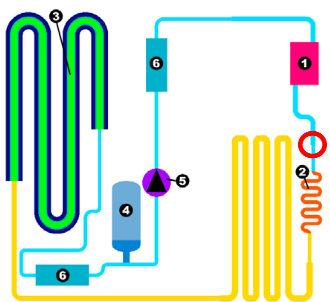
Comparison between the model and experiments

Evaporator inlet temperature:

- There is a large difference between the simulated and experimental inlet temperature
- This is caused by a difference in pump efficiency and inaccuracy in HTC:
  - Simulation: Efficiency assumed to be constant at 15%
  - Experiment: Gear pump with variable efficiency, cooling water massflow not known
- However, the difference does not influence the system behavior → $\Delta x = \frac{C_p \Delta T}{H_{lv}} \approx 0.1$
- Result could be improved by adjusting some parameters (i.e. tuning)



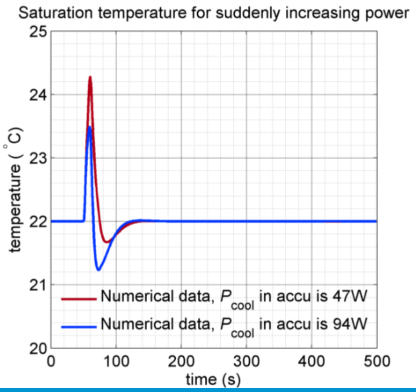


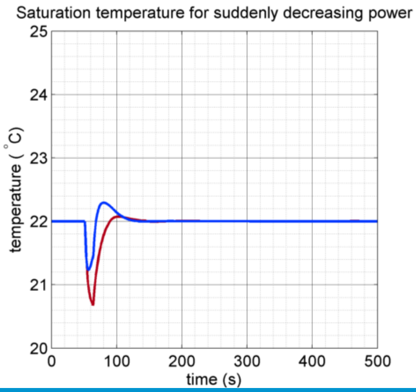


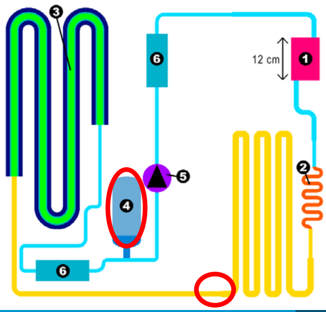
NLR - Dedicated to innovation in aerospace 20

Effect of accumulator cooling power

- Increasing the accu cooling power, results in smaller variations in the system temperature
- However, this is often difficult to achieve in practice, and it results in an increase in steady-state heating power
- When a low energy consumption is important, Peltier elements are used to provide both heating and cooling in the accu (as in AMS02)







NLR - *Dedicated to innovation in aerospace* 21

Conclusions and further developments

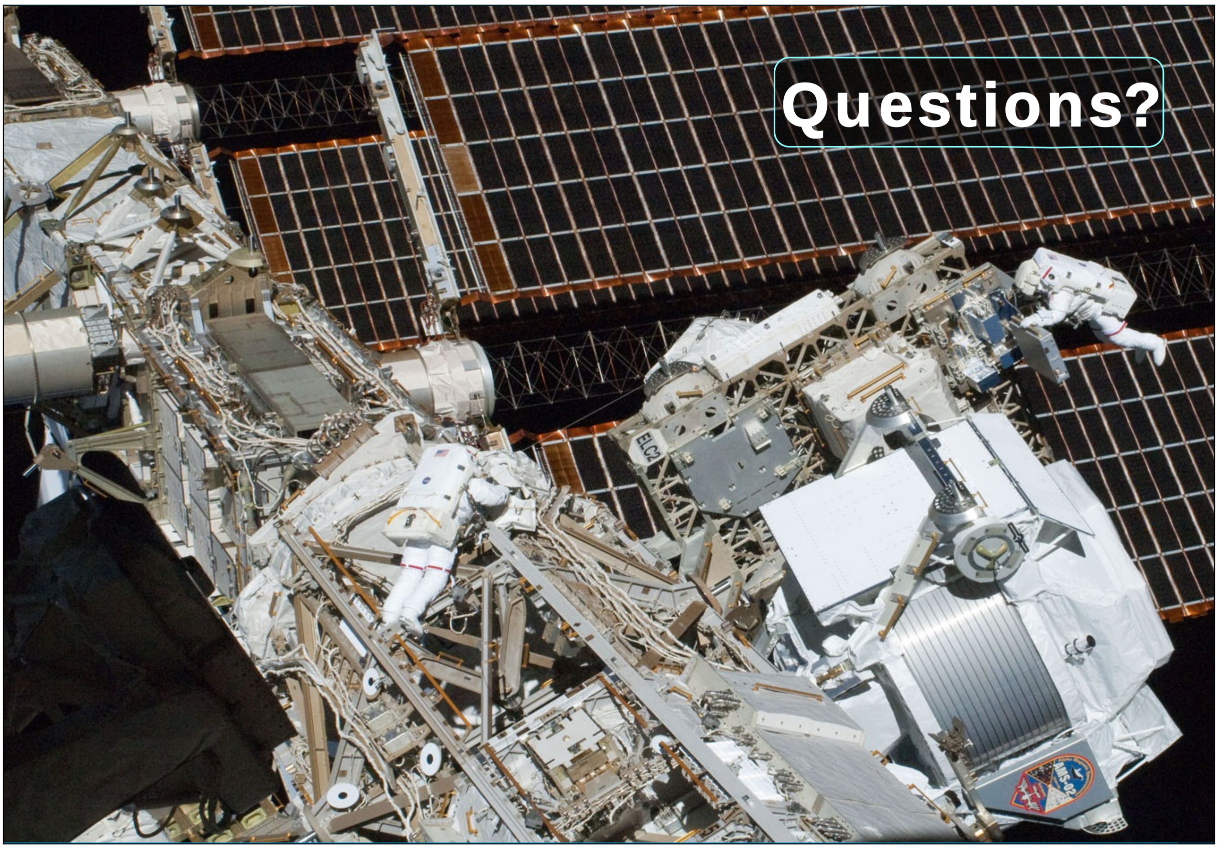
Conclusions

- The saturation temperature in a system will vary as a result of heat load variations
- The model is able to predict the saturation temperature variations accurately

Further developments

- Simulations have been carried out with different fluids (CO_2, R134a, R152a, R245fa). However, tests have only been carried out with CO_2
  → Validate model with other fluids
- Use the model for Heat Pump applications (i.e. refrigerator loops)
- Implement accumulator with Peltier heating/cooling instead of water cooling

NLR - *Dedicated to innovation in aerospace* 22


Questions?


NLR
Dedicated to innovation in aerospace
DEFENSE & PEACEKEEPING MISSIONS
INNOVATION
JOB CREATION
MOBILITY
SAFETY
ENVIRONMENT
www.nlr.nl - info@nlr.nl

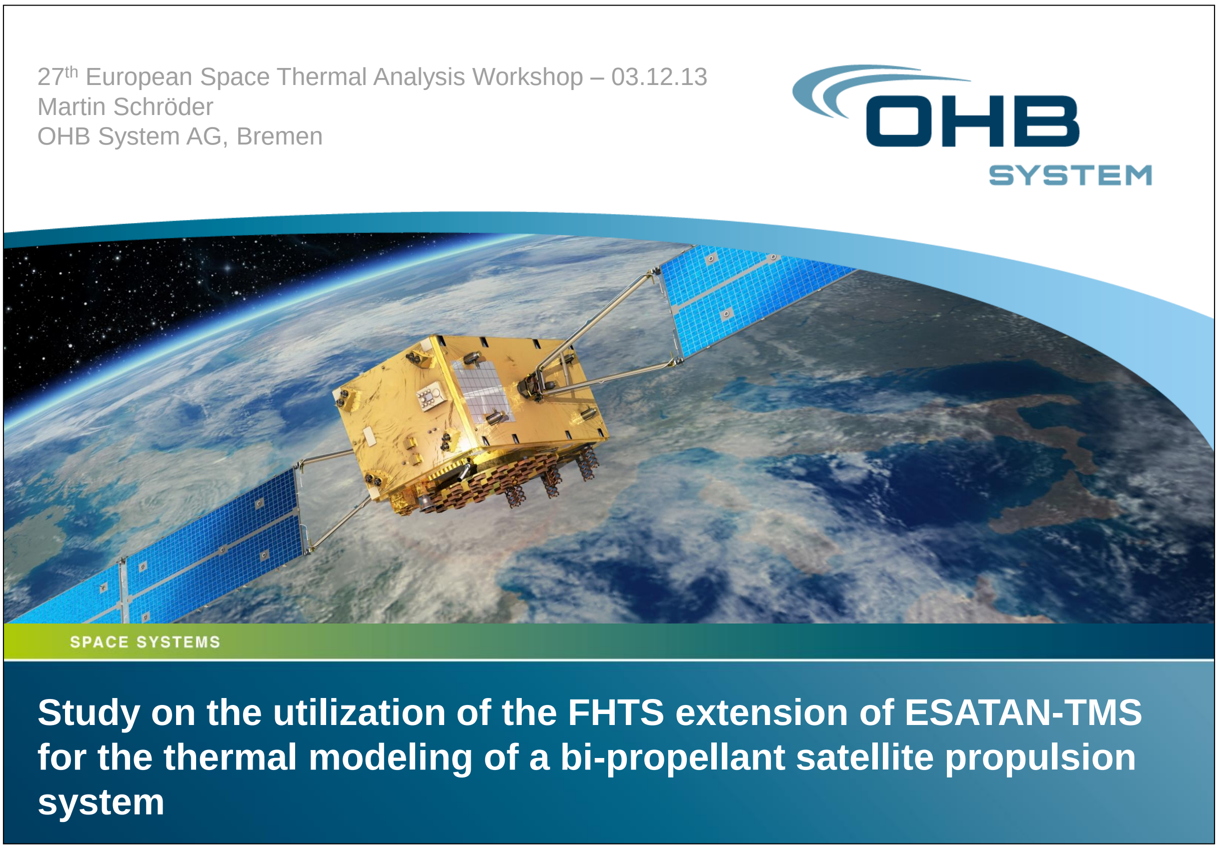
Appendix N

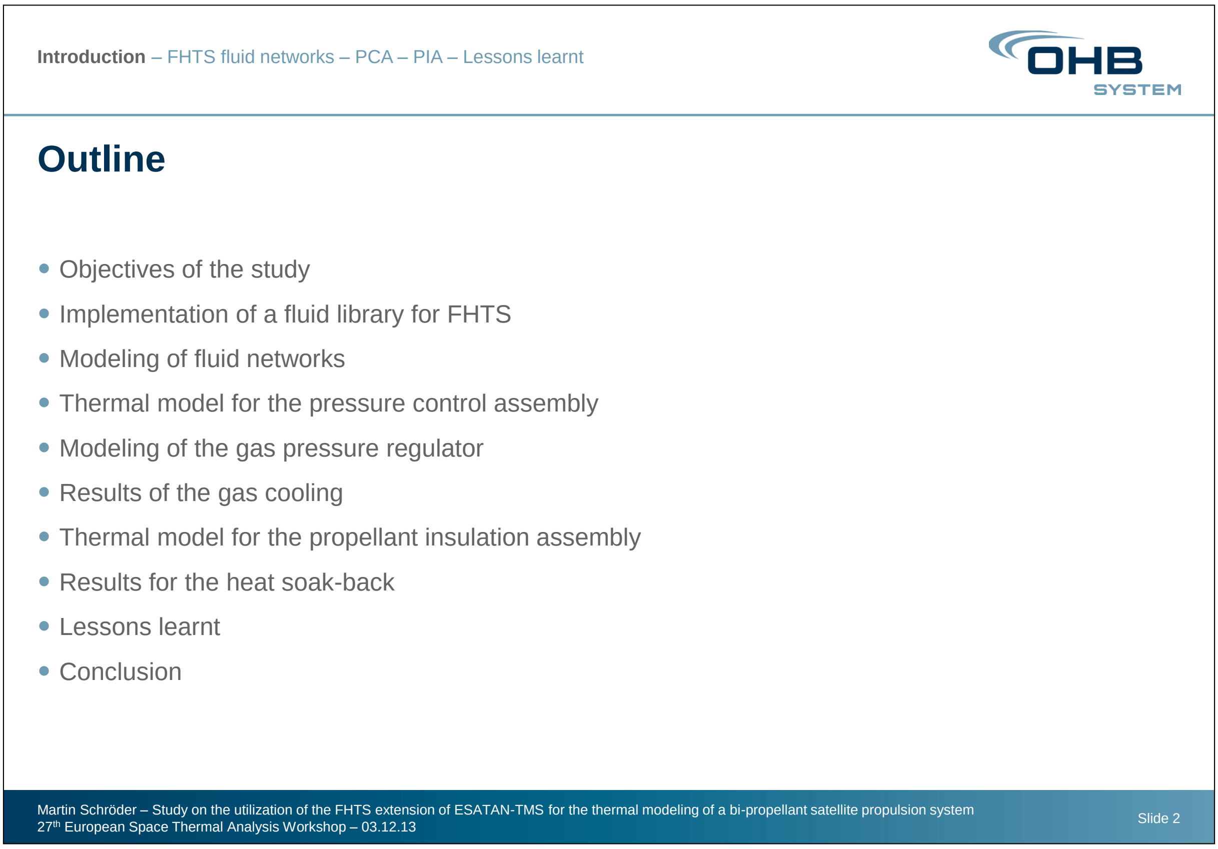
Study on the utilization of the FHTS extension of ESATAN-TMS for the thermal modeling of a bi-propellant satellite propulsion system

Martin Schröder
(OHB System AG, Germany)

Abstract

The presentation will contain the findings of my diploma thesis done in cooperation with OHB System AG. Its aim was to investigate if the FHTS extension of ESATAN-TMS could be used to model the fluid inside a bi-propellant chemical propulsion system with regard to the thermal control system. At first, a FHTS fluid library for propellants and pressurizing agents was implemented in order to model the fluids in the propulsion system accurately. After that, two simplified thermal models using the fluid library were developed, one for the pressure control assembly (PCA) and another for the propellant insulation assembly (PIA). For both models inputs from a reference geostationary telecommunication satellite were used. The presentation will mainly deal with the modeling of the effect of gas cooling by the expansion of Helium gas through the gas pressure regulator of the PCA. The solution found will be explained and the results of the simulations shown. Eventually several best practices and lessons learnt shall be presented with regard to the use of FHTS for propulsion systems.


27th European Space Thermal Analysis Workshop – 03.12.13
Martin Schröder
OHB System AG, Bremen
OHB SYSTEM
SPACE SYSTEMS
Study on the utilization of the FHTS extension of ESATAN-TMS for the thermal modeling of a bi-propellant satellite propulsion system


Introduction – FHTS fluid networks – PCA – PIA – Lessons learnt
OHB SYSTEM
Outline
• Objectives of the study
• Implementation of a fluid library for FHTS
• Modeling of fluid networks
• Thermal model for the pressure control assembly
• Modeling of the gas pressure regulator
• Results of the gas cooling
• Thermal model for the propellant insulation assembly
• Results for the heat soak-back
• Lessons learnt
• Conclusion
Martin Schröder – Study on the utilization of the FHTS extension of ESATAN-TMS for the thermal modeling of a bi-propellant satellite propulsion system
27th European Space Thermal Analysis Workshop – 03.12.13
Slide 2

Objectives of the study

In order to study the influence of some relevant thermal problems of the propulsion subsystem, like:

- Flowing and standing fluid in piping
- Helium gas cooling
- Heat soak-back

→ Possibility to model different states of the propulsion system within an ESATAN thermal model by the use of the FHTS extension

- Implementation, verification and validation of a fluid library for FHTS
- Development of thermal models including fluid networks for the pressure control and propellant assemblies
- Simulation of relevant states and analysis of results

Implementation of a fluid library for FHTS

- Database for the fluid properties to be used in FHTS fluid networks
- For example: density, specific heat capacity, conductivity etc.
- Included substances: **Helium**, **Nitrogen**, **Hydrazine**, **Monomethylhydrazine** and **Nitrogen Tetroxide**

Compound / Element	Temperature range	Pressure range
Helium	-80 - 60 °C	0 - 400 bar
Nitrogen	-30 - 60 °C	0 - 400 bar
Hydrazine	2 - 60 °C	0 - 20 bar
Monomethylhydrazine (MMH)	-53 - 60 °C	0 - 20 bar
Nitrogen Tetroxide (NTO)	-12 - 60 °C	0 - 20 bar

- Verification and selection of properties from different sources
- Partly insufficient reference situation, especially for the gaseous phase
- Limiting the area of application to the liquid phase for the fuels and the oxidizer

OHB SYSTEM

Modeling of fluid networks

- Fluid Node = Volume with a fluid state (temperature, pressure, mass flow)
- Boundary conditions for each solver and each loop
- Courant criterion for optimized piping discretization

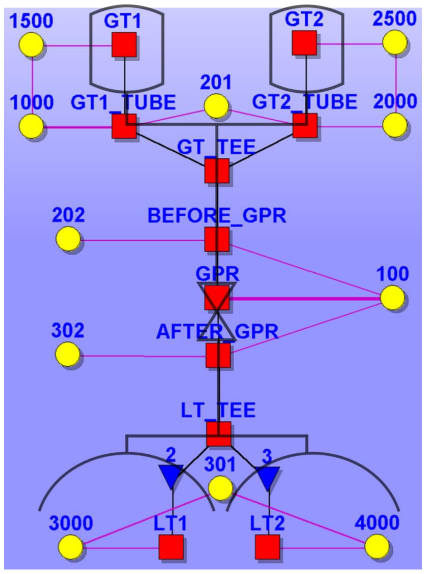
$$Co = \frac{v\Delta t}{L} \qquad v = \frac{\dot{m}}{\rho A}$$

- Single-phase solver:
  - Two boundaries for open and one boundary for closed loops
  - Pressure boundaries or defined mass sources or sinks
- Two-phase solver (full-transient FGENFI):
  - QTRSOL = 'NO'
  - No boundaries needed
  - Including compressible effects, like the Joule-Thomson-Effect
  - Suitable for non-stationary states, like the outflow of a tank

OHB SYSTEM

Thermal model for the pressure control assembly

- Pressure control assembly with two gas tanks and the gas pressure regulator
- Simplified model
- Representative lengths of the piping optimized with the Courant criterion
- 60 thermal nodes and 64 fluid nodes
- Use of the provided FHTS elements:
  - Non-ideal accumulator
  - Pipe
  - Valve
- Expansion of the Helium at the GPR
- Simulation of the gas cooling
- Two relevant states in GTO transfer:
  - Burning
  - Coasting



Introduction – FHTS fluid networks – **PCA** – PIA – Lessons learnt

OHB SYSTEM

Modeling of the gas pressure regulator

- FHTS valve element
- Divides the high pressure zone from the one with low pressure
- Pressure in the gas tanks decreases with the outflow during the firings
- Defined mass flow through the regulator
- Solution: regulated opening fraction of the valve

$$X = \frac{\dot{m}}{\rho}\sqrt{\frac{1}{\Delta p}}$$

- Value is continuously updated in $VARIABLES1
- Valve element allows the separation of the two zones in independent fluid loops
- Allowing for two closed loops with one pressure boundary during coasting phase
- FGENFI for the burning state
- FLTNTS for the coasting state

Martin Schröder – Study on the utilization of the FHTS extension of ESATAN-TMS for the thermal modeling of a bi-propellant satellite propulsion system
27th European Space Thermal Analysis Workshop – 03.12.13 Slide 7

Introduction – FHTS fluid networks – **PCA** – PIA – Lessons learnt

OHB SYSTEM

Workaround for the conservation of mass

- Because of the used pressure boundary, mass is removed form the system during the coasting phase, resulting in a change of density
- Conservation of mass is ensured with a workaround

$$\rho = \frac{m}{V} = f(T, p) = const$$

$$p = f(T, V, m) \longrightarrow f(T)$$

- The density has to remain constant, while the pressure will rise during the temperature increase in the coasting phase
- Correct pressure increase or decrease through the use of the fluid properties of the library

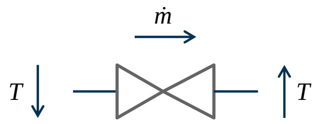
- The adjusted pressure is found in a while-loop:
  1. Check if the deviation of the density compared to the reference value is greater than a defined threshold
  2. Incremental raise or lower the pressure value and calculate a new density value with the given temperature using the fluid library
  3. If a matching value is found, the corresponding pressure is set as the new boundary value

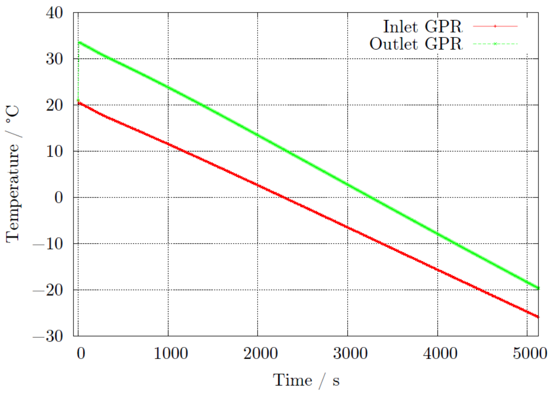
Martin Schröder – Study on the utilization of the FHTS extension of ESATAN-TMS for the thermal modeling of a bi-propellant satellite propulsion system
27th European Space Thermal Analysis Workshop – 03.12.13 Slide 8

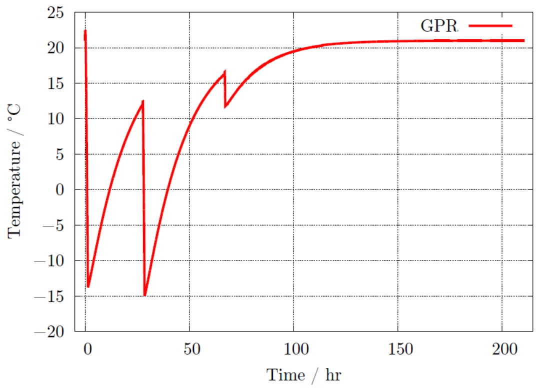
Introduction – FHTS fluid networks – **PCA** – PIA – Lessons learnt

Results of the gas cooling

- Joule-Thomson effect at the gas pressure regulator
- Helium expanding through the throttling valve
- Isenthalpic expansion





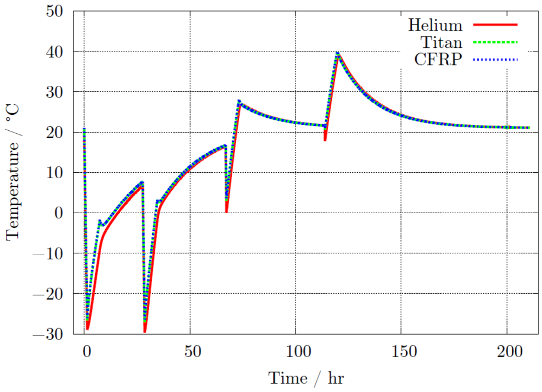


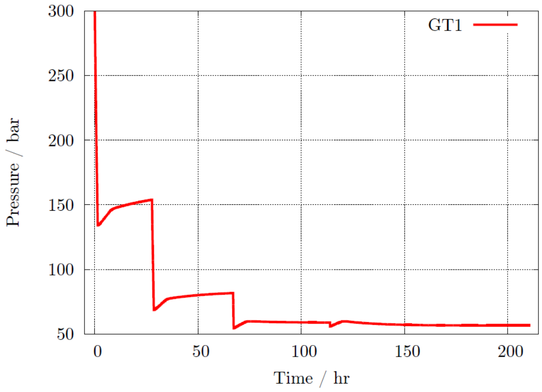
Martin Schröder – Study on the utilization of the FHTS extension of ESATAN-TMS for the thermal modeling of a bi-propellant satellite propulsion system
27th European Space Thermal Analysis Workshop – 03.12.13
Slide 9

Introduction – FHTS fluid networks – **PCA** – PIA – Lessons learnt

Results of the gas cooling

- Gas cooling effect has a large impact on the temperature of the whole pressure control assembly during GTO transfer phase
- Pressure evolution including the workaround for the conservation of mass





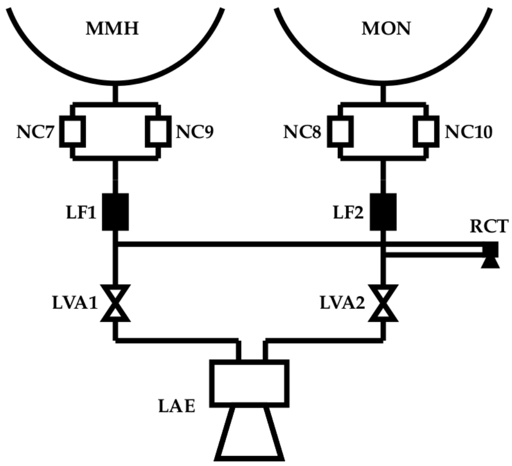
Martin Schröder – Study on the utilization of the FHTS extension of ESATAN-TMS for the thermal modeling of a bi-propellant satellite propulsion system
27th European Space Thermal Analysis Workshop – 03.12.13
Slide 10

Introduction – FHTS fluid networks – PCA – **PIA** – Lessons learnt

OHB SYSTEM

Thermal model for the propellant insulation assembly

- Propellant insulation assembly with the main engine and an RCT
- Simplified model
- Other components included:
  - Redundant pyro-valve
  - Liquid filter
  - Latching valve
- 255 thermal nodes and 158 fluid nodes
- Simulation of the heat soak-back



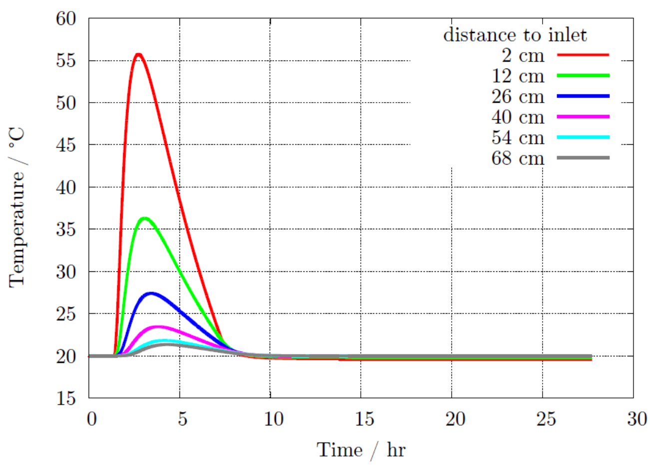
Martin Schröder – Study on the utilization of the FHTS extension of ESATAN-TMS for the thermal modeling of a bi-propellant satellite propulsion system
27th European Space Thermal Analysis Workshop – 03.12.13
Slide 11

Introduction – FHTS fluid networks – PCA – **PIA** – Lessons learnt

OHB SYSTEM

Results of the heat soak-back

- The effect of the heat soak-back is local and affects mainly the feeding lines connected to the inlet valves



Martin Schröder – Study on the utilization of the FHTS extension of ESATAN-TMS for the thermal modeling of a bi-propellant satellite propulsion system
27th European Space Thermal Analysis Workshop – 03.12.13
Slide 12

Introduction – FHTS fluid networks – PCA – PIA – **Lessons learnt**

OHB SYSTEM

Lessons learnt

- FGENFI for non-stationary states is more stable when larger time steps are used
- For the standing fluid case the solver failed to converge with the given model

- Single-phase solver are in general more robust than two-phase solver
- Single-phase solver with pressure boundaries have no conservation of mass without a workaround

- Stability of the solution can be improved when the discretization of the piping is done under consideration of the Courant criterion and for the worst case (finer meshing for slow mass flows)

- Comparison of the number of used iterations for the fluid and thermal networks (SUMFLL and SUMTHL) gives a hint which solution hinders the other → consider the use of corresponding damping factors (DAMPT and DAMPM)

- After the use of a single-phase solver, the two-phase FGENFI solver needs a call of the FINITS function to initialize the fluid state properties

Martin Schröder – Study on the utilization of the FHTS extension of ESATAN-TMS for the thermal modeling of a bi-propellant satellite propulsion system
27th European Space Thermal Analysis Workshop – 03.12.13
Slide 13

Introduction – FHTS fluid networks – PCA – PIA – **Lessons learnt**

OHB SYSTEM

Proven control constants for the used solver

- Damping factors: DAMPT = DAMPM = 0.5

- Execution times:
  - Pressure control assembly model: ca. 1 hour
  - Propellant insulation assembly model: ca. 4 hours

Control constant / variable	FGENFI	FLTNTS
RELXCA, FRLXCA, RELXMA	0.001	0.001
DTIMEI	10.0	1.0
LOOPCT	29 – 76	29 – 54
SUMFLL	29 – 76	2
SUMTHL	109 – 389	1 – 11

Martin Schröder – Study on the utilization of the FHTS extension of ESATAN-TMS for the thermal modeling of a bi-propellant satellite propulsion system
27th European Space Thermal Analysis Workshop – 03.12.13
Slide 14

OHB SYSTEM

Conclusion

- Fluid library for relevant pressurizing agents, fuels and an oxidizer for a bi-propellant satellite propulsion system
- Extension of the ESATAN/FHTS area of application for the integrated simulation of states of the propulsion subsystem

- Non-stationary states with compressible effects with FGENFI-Solver in full-transient mode
- Stationary states with FLTNTS-Solver including the mass workaround

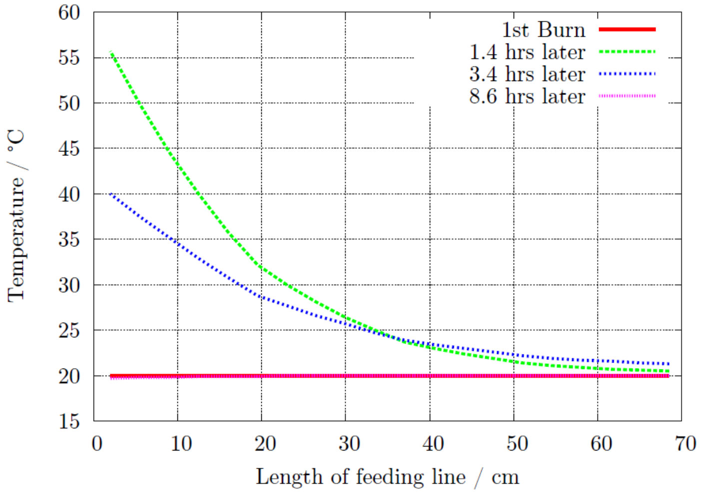
- Significant influence of the Helium gas cooling on the whole pressure control assembly during the GTO transfer
- Local influence of the heat soak-back at the feeding lines

OHB SYSTEM

Thank you for your attention!

OHB SYSTEM

Heat soak-back temperature gradient in the feeding line



Martin Schröder – Study on the utilization of the FHTS extension of ESATAN-TMS for the thermal modeling of a bi-propellant satellite propulsion system
27th European Space Thermal Analysis Workshop – 03.12.13
Slide 17

OHB SYSTEM

References

(1) ITP ENGINES UK LTD.: ESATAN-TMS Thermal Engineering Manual, October 2012

(2) ITP ENGINES UK LTD.: ESATAN-TMS Thermal User Manual, October 2012

(3) Schröder, Martin: Untersuchung des Fluideinflusses im Hinblick auf die Auslegung des Thermalkontrollsystems eines Zweistoff-Antriebssystems für Satelliten, November 2013

Martin Schröder – Study on the utilization of the FHTS extension of ESATAN-TMS for the thermal modeling of a bi-propellant satellite propulsion system
27th European Space Thermal Analysis Workshop – 03.12.13
Slide 18

Appendix O

Thermal Modeling of CubeSats and Small Satellites

Anwar Ali M. Rizwan Mughal Haider Ali Leonardo M. Reyneri
(Department of Electronics and Telecommunications, Politecnico di Torino, Italy)

Abstract

Recently universities and SMEs (Small and Medium Enterprises) have initiated the development of nanosatellites because of their low cost, small size and short development time. The challenging aspects for these satellites are their small surface area for heat dissipation due to their limited size. There is not enough space for mounting radiators for heat dissipation. As a result thermal modeling becomes a very important element in designing a small satellite. A generic thermal model of a CubeSat satellite is presented in this paper. Detailed and simplified thermal models for nanosatellites have been discussed. The detailed model takes into account all the thermal resistors associated with the respective layer while in the simplified model the layers with similar materials have been combined together and represented by a single thermal resistor. The thermal model of complete CubeSat has been presented. The proposed models have been applied to CubeSat standard nanosatellite called AraMiS-C1, developed at Politecnico di Torino. Thermal resistances measured through both models are compared and the results are in close agreement. The absorbed power and the corresponding temperature differences between different points of the single panel and complete satellite are measured. In order to verify the theoretical results, the thermal resistance of the AraMiS-C1 is measured through an experimental setup. Both values are in close agreement.
Detailed thermal model of the CubeSat panel from top to bottom is shown in figure O.1 and will be further explained in the presentation. Simplified thermal model of the CubeSat panel from top to bottom is shown in figure O.2 and will be further explained in the presentation.

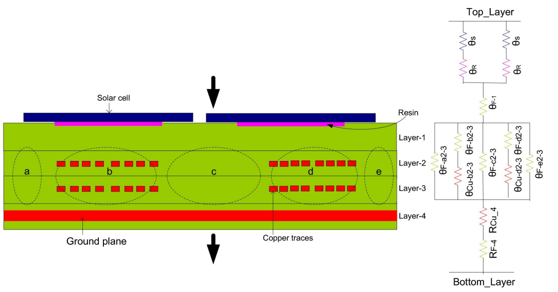


Figure O.1: CubeSat panel cross sectional view and detailed thermal model

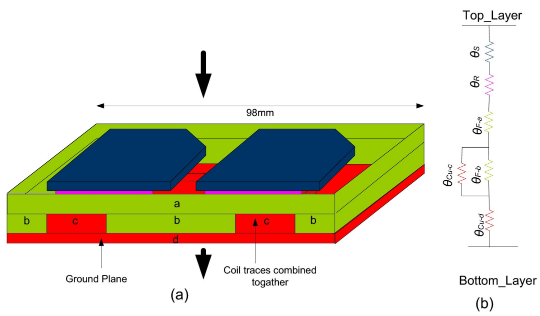


Figure O.2: Panel top to bottom cross sectional view and simplified model

Thermal model of the complete CubeSat is shown in figure O.3 and will be further explained in the presentation.

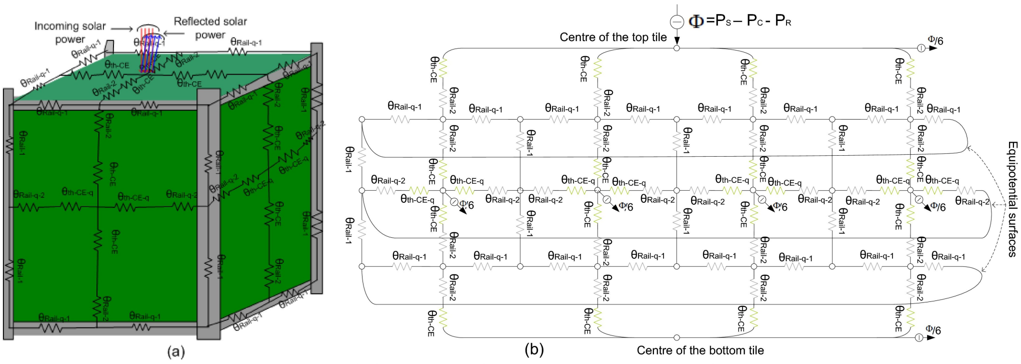


Figure O.3: CubeSat satellite and top to bottom thermal model

Thernal Modeling of CubeSat Standard NanoSatellites

Anwar Ali, M. Rizwan Mughal, Haider Ali, Leonardo M. Reyneri

Department of Electronics and Telecommunications
Politecnico di Torino, Italy.

1

Outline

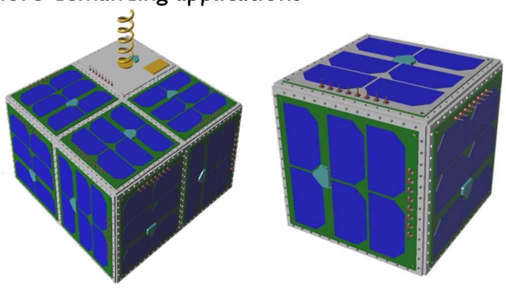
- Introduction to AraMiS project
- Thermal models
  - CubeSat solar panel
    - Detailed model
    - Simplified model
  - Two models applied to AraMiS-C1 tiles (CubePMT &CubeTCT)
- Thermal model of CubeSat
- Thermal resistance of AraMiS-C1
  - CubeSat model
  - Experimental
- Emissivity & absorption coefficient of AraMiS-C1
- Conclusion

2

Introduction to AraMiS (I)

- ARAMIS
  - Modular Architecture of NanoSatellites
  - Alternative to CubeSats, for larger and more demanding applications
- Modularity
  - Mechanical
  - Electronic
  - Testing level
  - Reduction of the overall budget

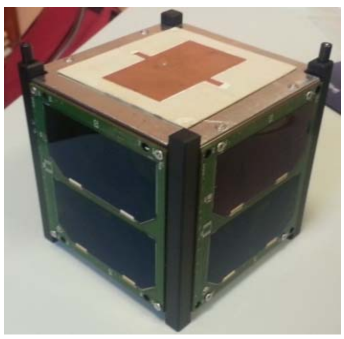
    development and testing time
- LEO Satellites
- Size
  - 16.5x16.5x16.5 cm3
  - 10x10x10 cm3
- 5 years expected life
- Commercial off the Shelf (COTS)



3

AraMiS-C1

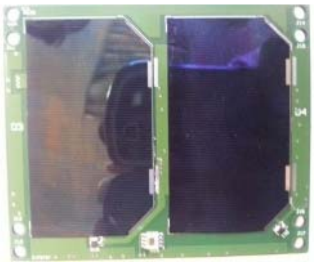
- CubeSat standard nano-satellites
- Based on tiles
- Four power management tiles (CubePMT): EPS & ADCS
- Two telecommunication tiles (CubeTCT): Antennas & RF subsystems
- Size 10x10x10 cm^3
- Mass is 1.3kg
- Room for batteries and payload boards

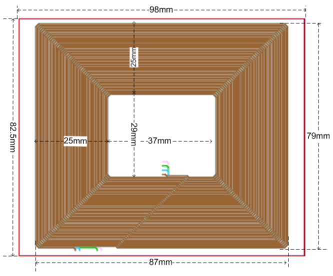


4

CubePMT

- CubeSat standard Power Management Tile
  - Dimensions 9.8 x 8.25 x 0.16 cm3
  - 8-layers PCB
  - Top layer : Solar panel and sun sensor
  - Bottom layer : electronic subsystems
  - Magnetorquer coil embedded in four internal layers





5

Thermal Modeling: Motivation

- Emphasis on nanosatellites (Universities & SMEs)
  - Low cost
  - Small size
  - Short development time
- Challenge
  - Small surface area for heat dissipation
  - Not enough space for mounting radiators
- Thermal modeling

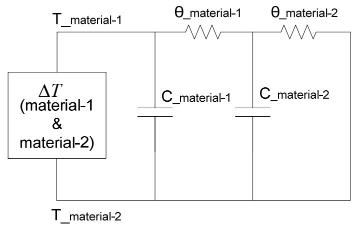
6

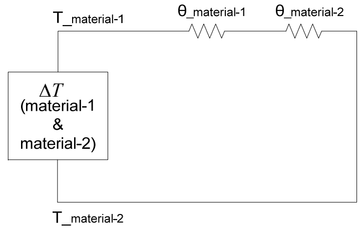
Thermal Resistace

- Heat sources
  - Generated by the satellite subsystems
  - Absorbed from the surrounding
- Some portion of heat is
  - Lost to the surrounding
  - Trapped inside the satellite
- Trapped heat energy
  - Increases temperature of the satellite
  - Depends on the thermal resistance
- Suppose two materials
- Fourier's law of heat conduction

$$\Delta T = P \cdot \theta_{th}$$

$$\theta_{th} = \frac{L}{K \times S}$$





7

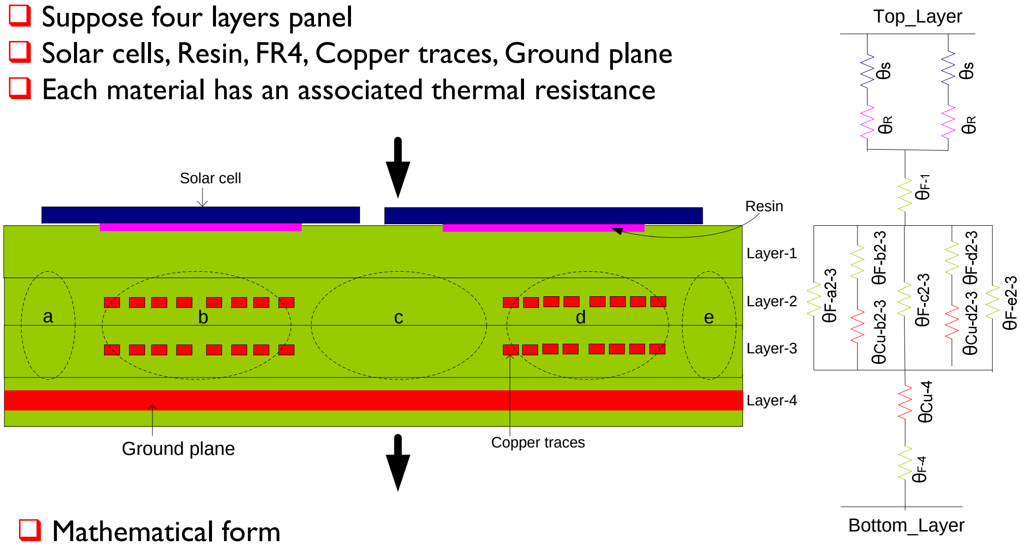
Thermal Modeling

- Thermal resistor representation
  - *θ* denotes thermal resistor
  - *F* represents FR4
  - *Cu* represents copper
  - Alphabets (*a, b, c, d,* e) represent the respective subsection and
  - Numbers (*1, 2, 3, 4*) represent the relevant layer
  - For example $\theta_{F\text{-}a2\text{-}3}$ represents the thermal resistor of FR4 material in subsection *a* of layers 2 and *3*

8

Top to bottom
Detailed thermal model of CubeSat panel

- Suppose four layers panel
- Solar cells, Resin, FR4, Copper traces, Ground plane
- Each material has an associated thermal resistance



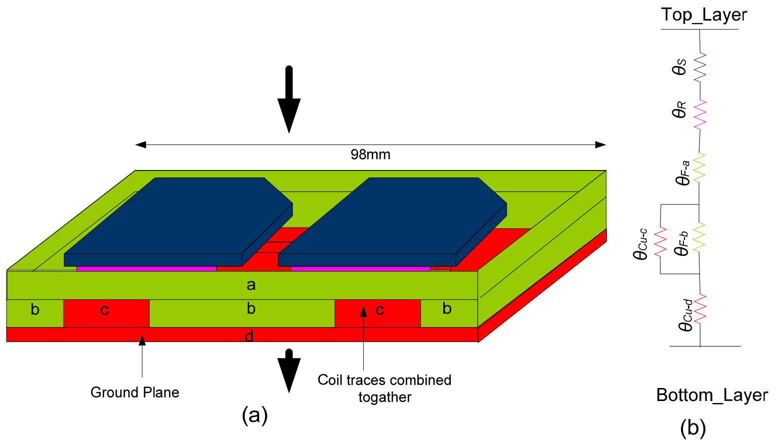
- Mathematical form

$$\theta_{th-S1S2} = \frac{\theta_S + \theta_R}{2} + \theta_{F-1} + \theta_{F-a2-3} // (\theta_{Cu-b2-3} + \theta_{F-b2-3}) // \theta_{F-c2-3} // (\theta_{Cu-d2-3} + \theta_{F-d2-3}) // \theta_{F-e2-3} + \theta_{Cu\_4} + \theta_{F-4}$$

9

Top to bottom
Simplified thermal model of CubeSat panel

- Layers with similar material combined together
- Assigned a single resistor



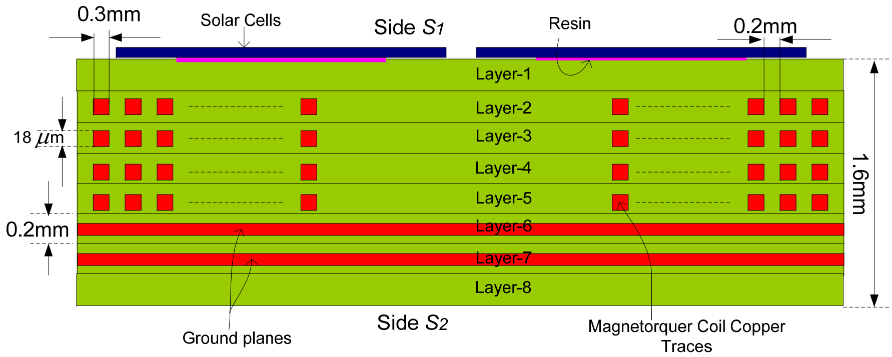
- Mathematical form

$$\theta_{th-S1S2} = \theta_S + \theta_R + \theta_{F-a} + \theta_{Cu-c} // \theta_{F-b} + \theta_{Cu-d}$$

10

Top to bottom
Resistance of CubePMT (AraMiS-C1)

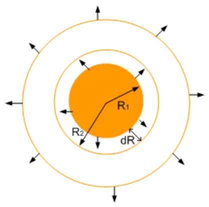
- CubePMT thermal resistance
  - Simplified Model
  - Detailed Model



- Applying the Detailed Model, $\theta_{th-S1S2} = 2.59K/W$
- Applying the Simplified Model, $\theta_{th-S1S2} = 2.58K/W$

11

Centre to Edge
Detailed thermal model of CubeSat Panel



$$dT = Pd\theta$$

$$d\theta = \frac{L}{KA} = \frac{dR}{K2\pi R.h}$$

$$P = P_d \alpha \pi R^2$$

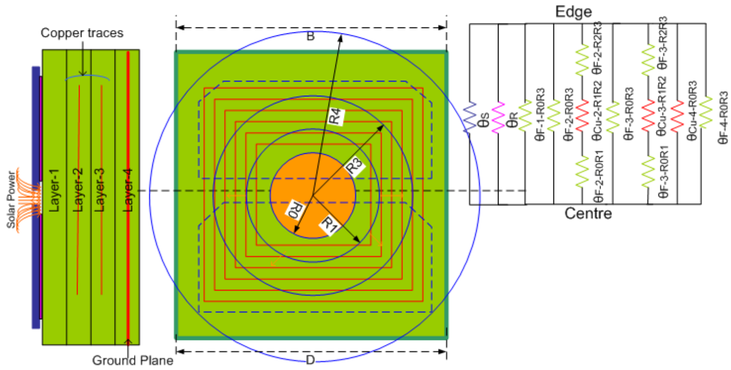
$$dT = P_d \alpha \pi R^2 \frac{dR}{K2\pi R.h} = \frac{P_d \alpha}{2Kh} RdR$$

$$\int_0^{R_T} dT = \frac{P_d \alpha}{2P_d Kh} \int_0^{R_T} RdR = \frac{\alpha R_T^2}{4K \cdot h}$$

$$\Delta T = \frac{\alpha P_d R_T^2}{4Kh}$$

$$\Delta T = P \cdot \Delta\theta$$

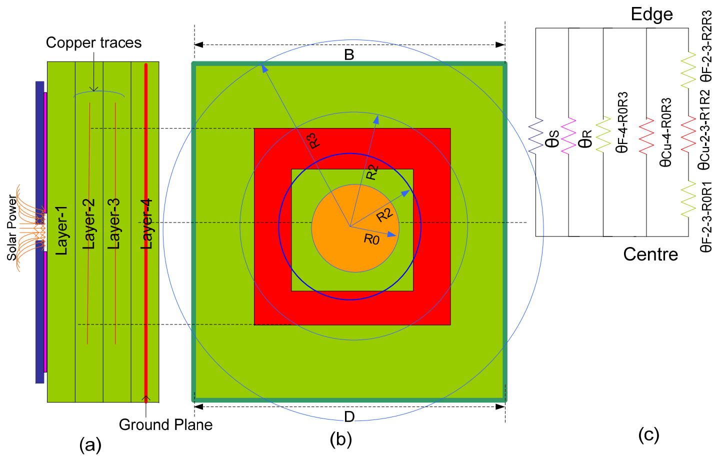
$$\Delta\theta = \frac{\Delta T}{P} = \frac{\frac{\alpha P_d R_T^2}{4Kh}}{P_d \cdot \pi \cdot R_T^2} = \frac{\alpha}{4\pi Kh}$$



$$\theta_{CE} = \theta_S // \theta_R // \theta_{F\_1} // \theta_{F\_2} //(\theta_{F\_2} + \theta_{Cu\_2} + \theta_{F\_2}) // \theta_{F\_3} //(\theta_{F\_3} + \theta_{Cu\_3} + \theta_{F\_3}) // \theta_{Cu\_4} // \theta_{F\_4}$$

12

Centre to Edge
Simplified Thermal Model of CubeSat Panel



$$\theta_{th-CE} = \theta_S \,//\, \theta_R \,//\, \theta_{F-4-R_0R_3} \,//\, \theta_{Cu-4-R_0R_3}$$
$$//(\theta_{F-2-3-R_0R_1} + \theta_{Cu-2-3-R_1R_2} + \theta_{F-2-3-R_2R_3})$$

13

Centre to Edge
Thermal Resistance of CubePMT & CubeTCT

- CubePMT
  - Detailed Model

$$\theta_{CE-P} = (\theta_{F-3} + \theta_{Cu-2} + \theta_{F-1}) \,//\, \theta_{Cu-4} \,//\, \theta_{F-5} \,//\, \theta_{Pos}$$

$$\boxed{\theta_{CE-P} = 3.45K/W}$$

  - Simplified Model,

$$\theta_{CE} = \theta_S \,//\, \theta_R \,//\, \theta_{F\_1} \,//\, \theta_{F\_2} \,//(\theta_{F\_2} + \theta_{Cu\_2} + \theta_{F\_2})$$
$$//\, \theta_{F\_3} \,//(\theta_{F\_3} + \theta_{Cu\_3} + \theta_{F\_3}) \,//\, \theta_{Cu\_4} \,//\, \theta_{F\_4}$$

$$\boxed{\theta_{CE-P} = 3.40K/W}$$

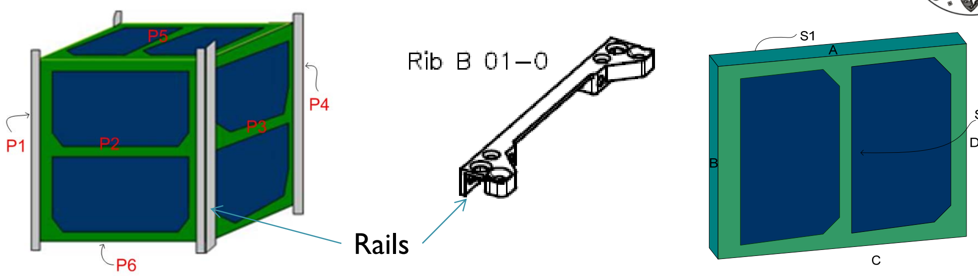
- CubeTCT
  - Simplified Model,

$$\theta_{CE-P} = \theta_{Cu} \,//\, \theta_F$$

$$\boxed{\theta_{CE-C} = 2.64K/W}$$

14

CubeSat thermal model (I)

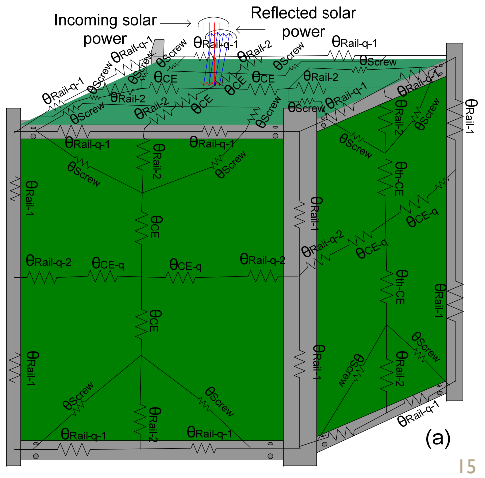


θCE: Centre to edge thermal resistance

θScrew : Screw thermal resistance

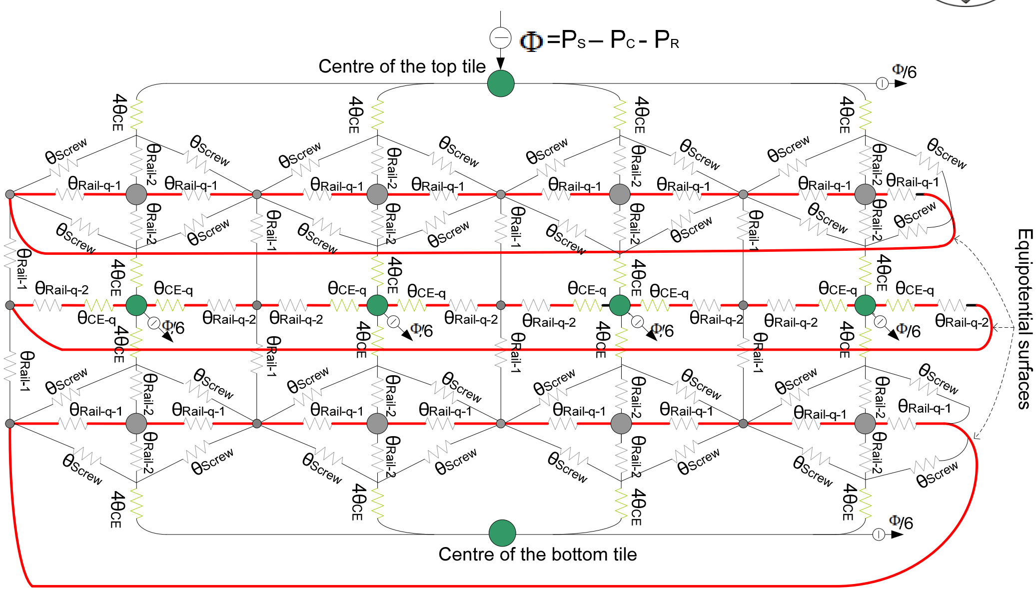
θRail: Rail thermal resistance

θX-q: Equipotential surface resistance



15

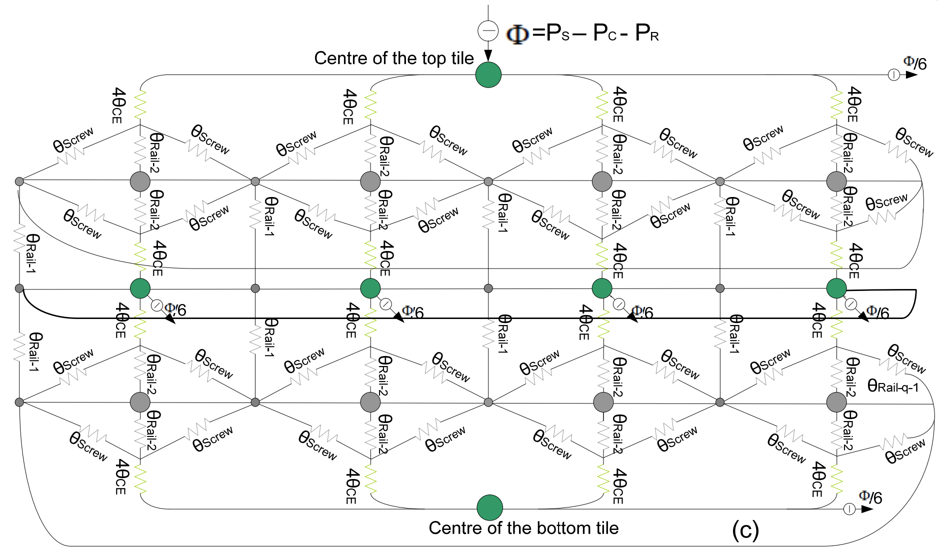
CubeSat thermal model (II)



- Solar panel is on: $\Phi = P_S - P_R - P_C = \alpha P_d S(1-\eta)$
- Solar panel is off: $\Phi = \alpha P_d S$

16

CubeSat thermal model (III)

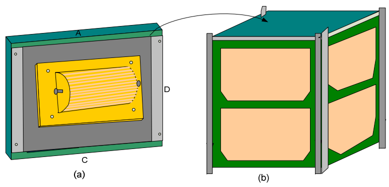


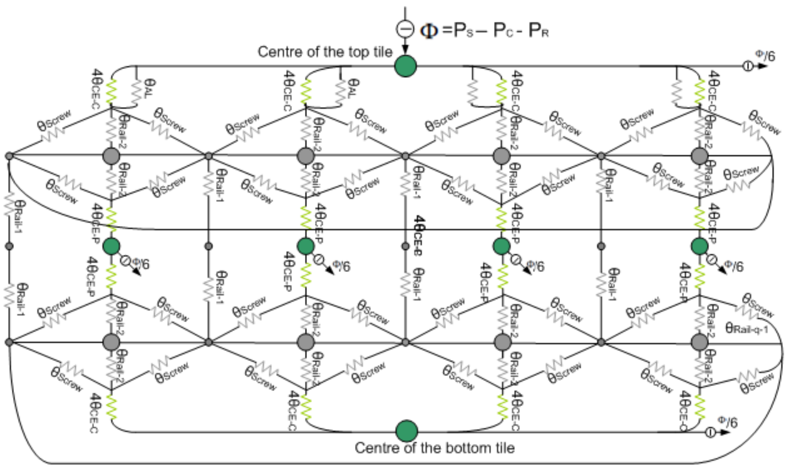
$$\theta_{th} = 2\left(\frac{4\theta_{CE} + \theta_{Rail-2} \, // \, \frac{\theta_{Screw}}{2}}{4}\right) + 2\left(\frac{4}{4\theta_{CE} + \theta_{Rail-2} \, // \, \frac{\theta_{Screw}}{2}} + \frac{4}{\theta_{Rail-1}}\right)^{-1}$$

17

Thermal Resistance of AraMiS-C1

- Theoretical Measurement using CubeSat Model
- Experimental Setup
  - Thermal Resistor with CubeTCT attached through aluminum tile.
  - Thermal model





18

AraMiS-C1 Thermal Resistance

$$\theta_{th} = \left(\frac{4\theta_{CE-C} // 4\theta_{Al-tile} + \theta_{Rail-2} // \frac{\theta_{Screw}}{2}}{4}\right) + \left(\frac{4\theta_{CE-C} + \theta_{Rail-2} // \frac{\theta_{Screw}}{2}}{4}\right) + 2\left(\frac{4}{4\theta_{CE-P} + \theta_{Rail-2} // \frac{\theta_{Screw}}{2}} + \frac{4}{\theta_{Rail-1}}\right)^{-1}$$

$$\theta_{CE-P} = 3.45K/W$$

$$\theta_{CE-C} = 2.64K/W$$

$$\theta_{Al-Tile} = \frac{0.11}{210W/(Km)\cdot 4\pi \cdot 6mm} = 0.018K/W$$

$$\theta_{Screw} = \frac{0.11}{210W/(Km)\times 4\pi \times 6mm} = 5.64K/W$$

$$\theta_{Rail-A} == \frac{100mm}{210W/mK\times(2mm\times 10mm + 2mm\times 8mm)} = 13.23K/W$$

$$\theta_{Rail-1} = \frac{\theta_{Rail-A}}{2} = 6.6K/W$$

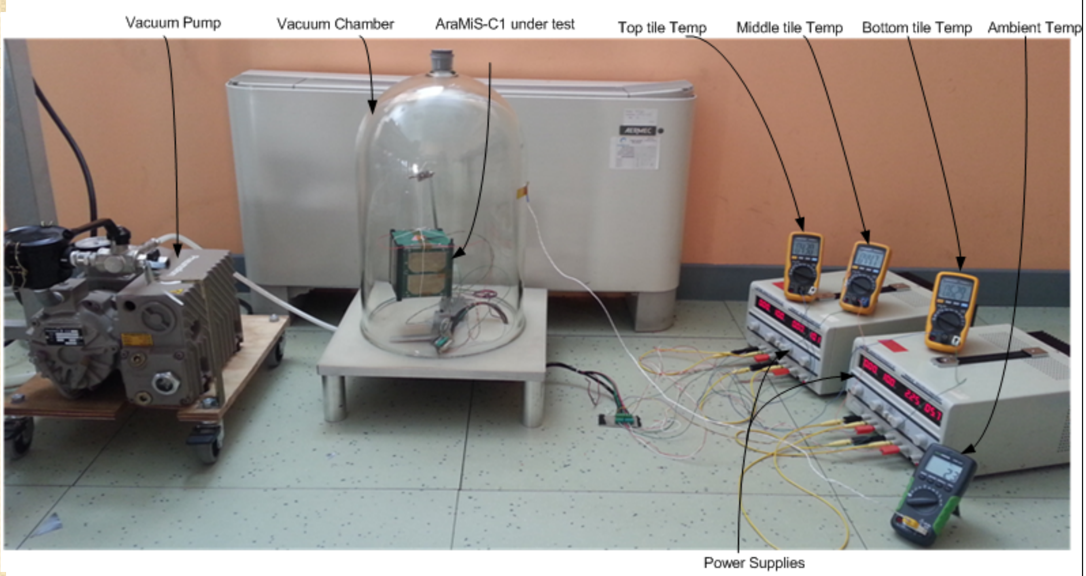
$$\theta_{Rail-B} = \frac{L}{K_{Al}\times S} = \frac{12mm}{210W/mK\times(2mm\times 100mm)} = 0.3K/W$$

$$\theta_{Rail-2} = 2*\theta_{Rail-B} = 0.6K/W$$

$$\theta_{th} = 5.15K/W$$

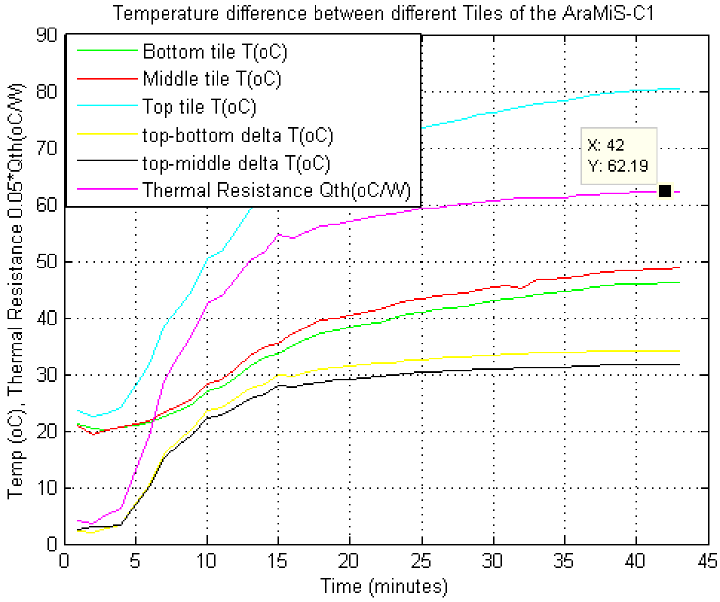
19

Practical Measurement Setup



20

Practical Results



$$\theta_{th} = \frac{\Delta T}{P} = \frac{\frac{\alpha P_d R_T^2}{4Kh}}{P_d \cdot \pi \cdot R_T^2} = \frac{\alpha}{4\pi Kh}$$

$$\theta_{th} = 3.1K/W$$

21

ACS: Magnetorquer Coil

- Magnetorquer coil is embedded in four internal layers
- Thermal Modeling

$$P_o = P_d + P_I$$

- Stefan-Boltzmann's law :

$$P_o = \alpha_o \sigma T_o^4 S + \alpha_L \sigma T_o^4 S_L$$

$$\alpha_o \sigma T_o^4 S + \alpha_L \sigma T_o^4 S_L = P_d + P_I$$

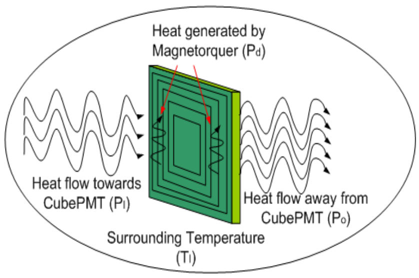
At steady state, Pd=0

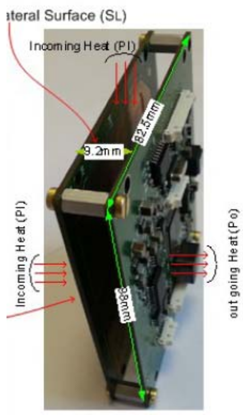
$$\alpha_I \sigma T_I^4 S + \alpha_L \sigma T_I^4 S_L = P_I$$

$$\alpha_o \sigma T_o^4 S + \alpha_L \sigma T_o^4 S_L = P_d + \alpha_I \sigma T_I^4 S + \alpha_L \sigma T_I^4 S_L$$

$$T_o = \sqrt[4]{\frac{P_d + \alpha \sigma T_I^4 S + \alpha_L \sigma T_I^4 S_L}{\alpha \sigma S + \alpha_L \sigma S_L}}$$

$$\alpha = \frac{P_d - \alpha_L \sigma S_L \left(T_o^4 - T_I^4\right)}{\sigma S \left(T_o^4 - T_I^4\right)}$$

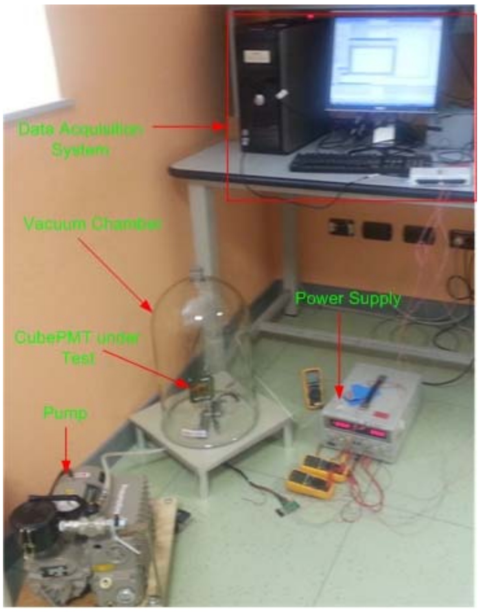




22

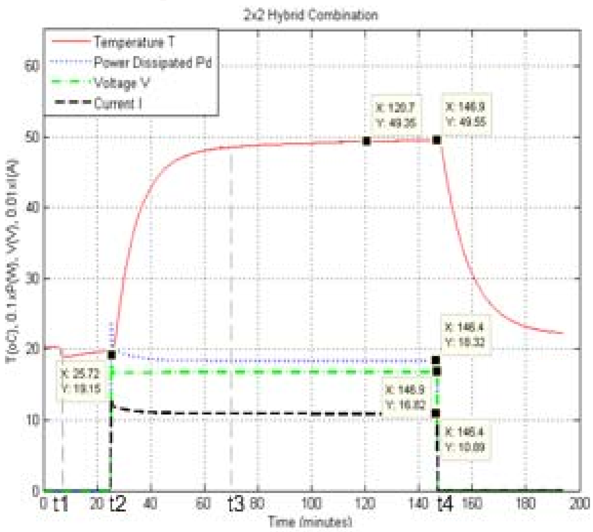
Magnetorquer Coil: Thermal Modeling

- Emissivity Measurement at Infra Red Wavelength
  - Ability of a surface to emit energy by radiation
  - Surfaces with different colors have different emissivity values
  - Voltage, current, temperature are captured



23

Magnetorquer Coil: Emissivity



Parameter	Value
σ	5.6703x10^{-8} Wm^{-2}K^{-4}
T_I	292.34K
T_o	322.69K
S	0.01617m^2
S_L	0.003321m^2
P_d	3.623W
α_L	1

$$\alpha = \frac{P_d - \alpha_L \sigma S_L \left(T_o^4 - T_I^4\right)}{\sigma S\left(T_o^4 - T_I^4\right)}$$

- The resulting emissivity (α) value 0.9.

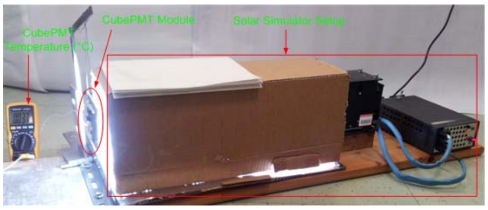
24

Absorption Coefficient (a) at Visible Light

- CubePMT was illuminated through a solar simulator (AM0 intensity)
- Temperature start increasing
- Temperature reached steady state (74˚C), solar simulator switched off.
- Voltage was applied to the magnetorquer coil,
- Increase voltage step by step, Current and temperature was measured. At 74˚C, the corresponding voltage and current

$$P_{solar} = P_{electrical} \quad \because P_{solar} = aP_d A, \quad P_{electrical} = VI$$

$$\Rightarrow a = \frac{VI}{P_d A}$$



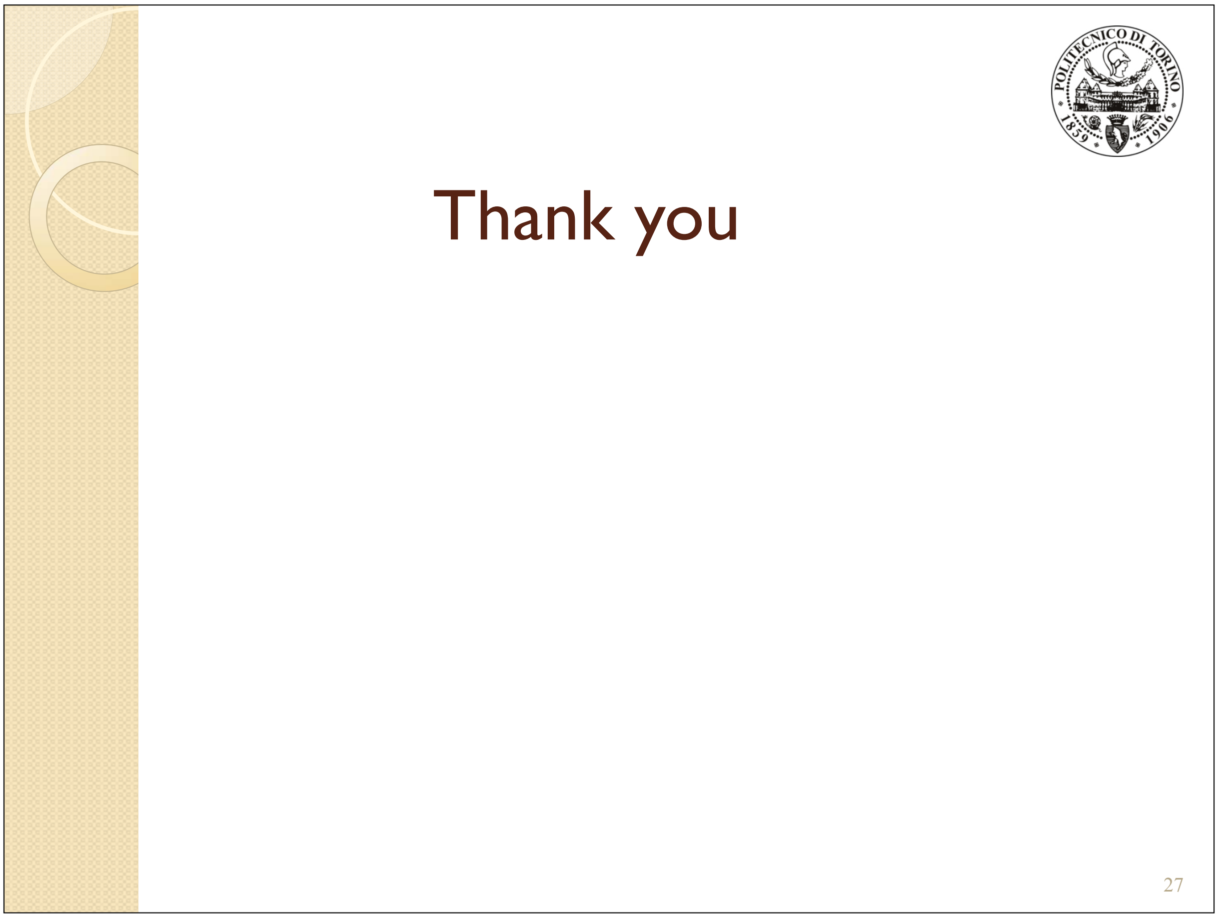
Parameter	Value
Applied voltage (V)	14.24 V
Current (I)	700 mA
Solar power density (P_d)	1366 W/m^2
CubePMT surface area (A)	0.008085 m^2

- The resulting emissivity (α) value 0.903

25

Conclusion

- Thermal resistance of CubePMT measured through detailed & simplified models
  - Have almost same value
  - Verify the authentication of the proposed models
- CubeSat model was applied to AraMiS-C1
  - Theoritical & practical thermal resistance have close value
  - Varify the validity of the proposed model


POLITECNICO DI TORINO
1859
1906
Thank you
27

Appendix P

E-THERM POLICY

Thierry Basset Patrick Hugonnot
(Thales Alenia Space, France)

Abstract

In Thales Alenia Space - Cannes, we have a long experience and expertise, in thermal software development. Concerning this point, we work with external companies in particular with DOREA. The subject concerns the presentation, the demonstration of a new thermal software in TAS-Cannes (= e-Therm release 1.4.c), and the associated policy. This tool is funded entirely by TAS-Cannes and it should not have to be commercialised but freely distributed.

Then, we will to talk about industrialization strategy especially based on using of our thermal software and on the integration of expert tools: Pre-processing, Orbitography module, 2D-3D Conductive module, Radiative module, Solver module, Thermal model reduction tool, PTA (which is a tool dedicated to preliminary phases and very well adapted to the telecom program), Post-processing. The general aim of these evolutions is to improve and standardize the analysis process, in order to gain in cost, quality and input/output traceability. This calculation chain is entirely compatible with thermal analysis COTS, main CAD and mechanical tools, thanks to powerful interfaces. These modules have been successfully used on following programs : Apstar, Yamal, W6A, O3B, Iridium Next, 8WB, TKM, CSO ...

Moreover, to improve quality and reliability of the dynamic spacecraft simulator and for performance reasons, TAS-Cannes chooses e-Therm to be the thermal real-time simulator engine based on the thermal mathematical model (TMM) provided by thermal analysis team. External powers calculator and temperatures resolution from internal e-Therm core module have been successfully improved to fit the real-time constraints. Parallelisation has been largely used to make the calculation most reactive in order to fit as much as possible the physics behaviour. New SCSIM based on TMM has been successfully validated on Alphasat (@bus platform) and O3B Networks satellite.

On another hand and to answer customer's needs, TAS-Cannes needed to provide a real time payload configuration simulator. A new session has been implemented into e-Therm. This session provides for each daily configuration a detailed thermal cartography for each channels based on powerful post-processing outputs (Barchart, CAD view ...). This session will be used on 8WB program planned to run all over the satellite lifetime.

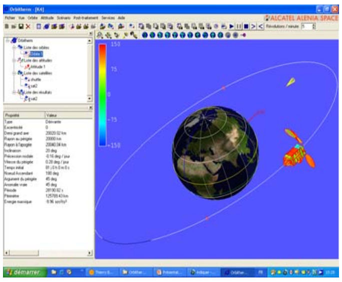
In parallel of industrialization strategy, we develop a strategy of openness of e-Therm by distributing software free of charge to TAS-Toulouse for antenna applications, TAS-Turin for infrastructures and instruments and more generally to TAS-Group and to others companies.

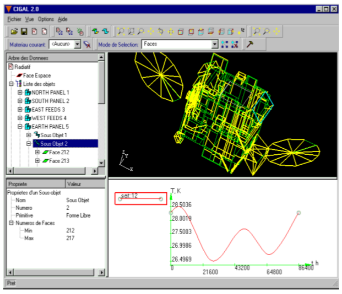
Furthermore, e-Therm can be used for concurrent design facility applications, and to other fields in physics: electronic board thermal behaviour calculation, ESD simulation on geostationary satellite.

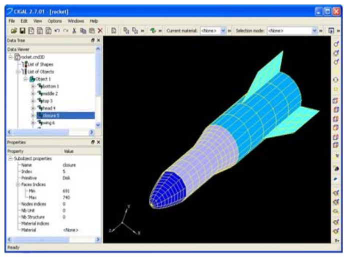
e-Therm
THERMAL SPATIAL TOOL

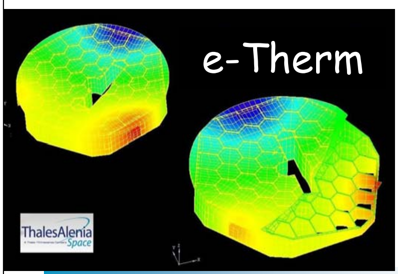
Page 1

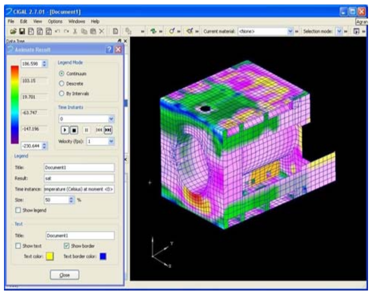
e-Therm Spatial thermal Tool :
Software functionalities & policy











THALES ALENIA SPACE CANNES

P. HUGONNOT, T. BASSET

27th annual European Space Thermal Analysis Workshop / 3-4 December 2013 - ESA/ESTEC

SUMMARY

Page 2

- INTRODUCTION
- e-Therm V1.4 ARCHITECTURE
- TAS-F TOOLS ROAD-MAP
- SOFTWARE ARCHITECTURE EVOLUTION
- MAIN INTEGRATED FUNCTIONALITIES
- CONCLUSION
- APPENDICES

27th annual European Space Thermal Analysis Workshop / 3-4 December 2013 - ESA/ESTEC

THALES

ThalesAlenia Space — A Thales / Finmeccanica Company

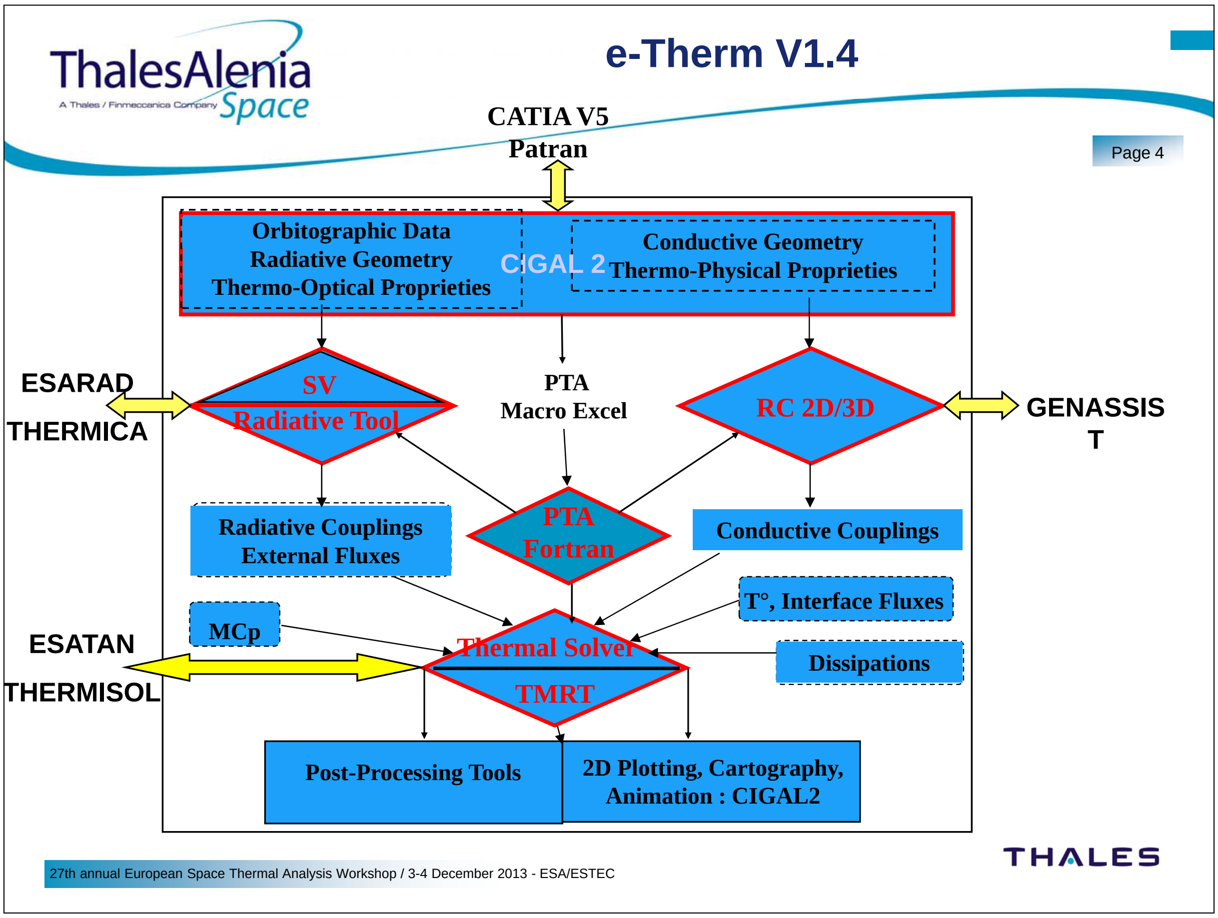
INTRODUCTION

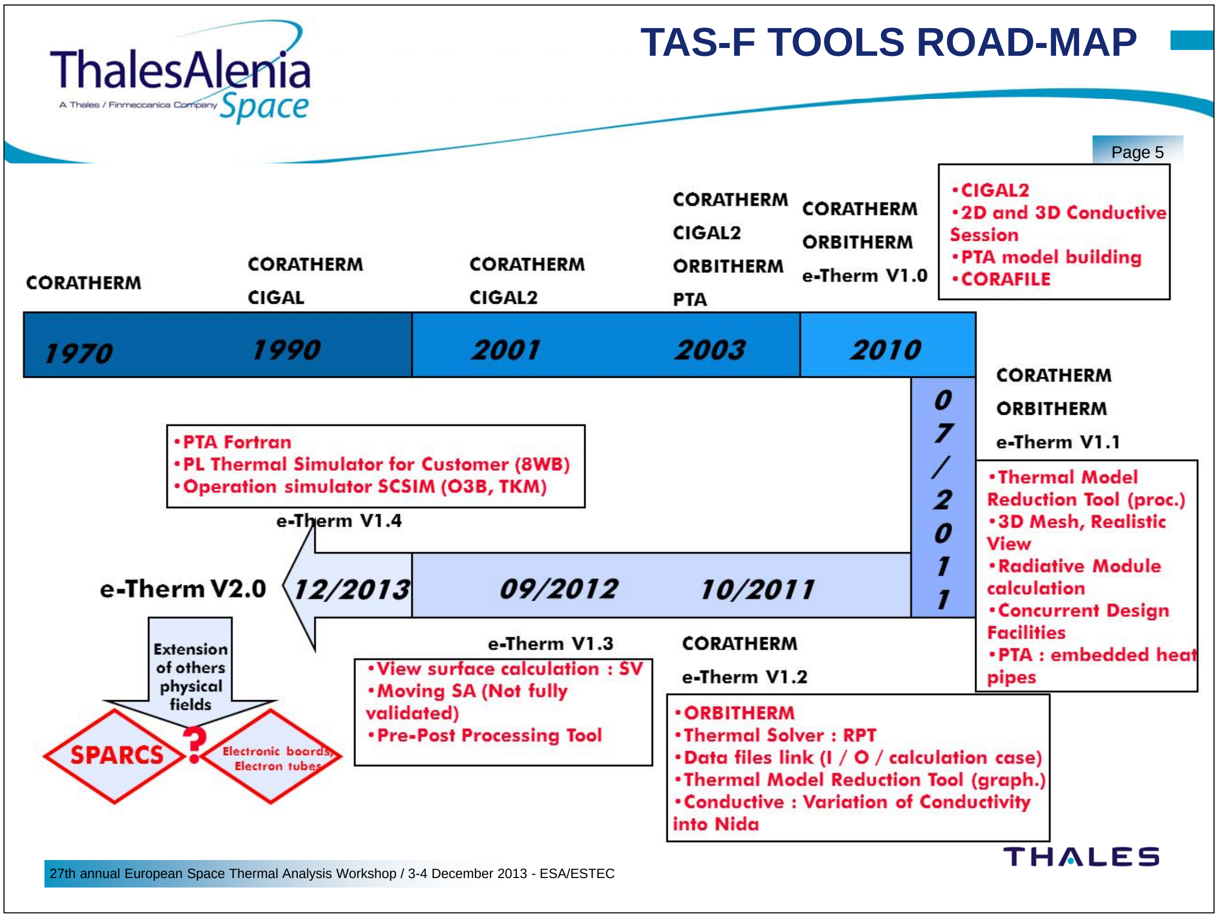
Page 3

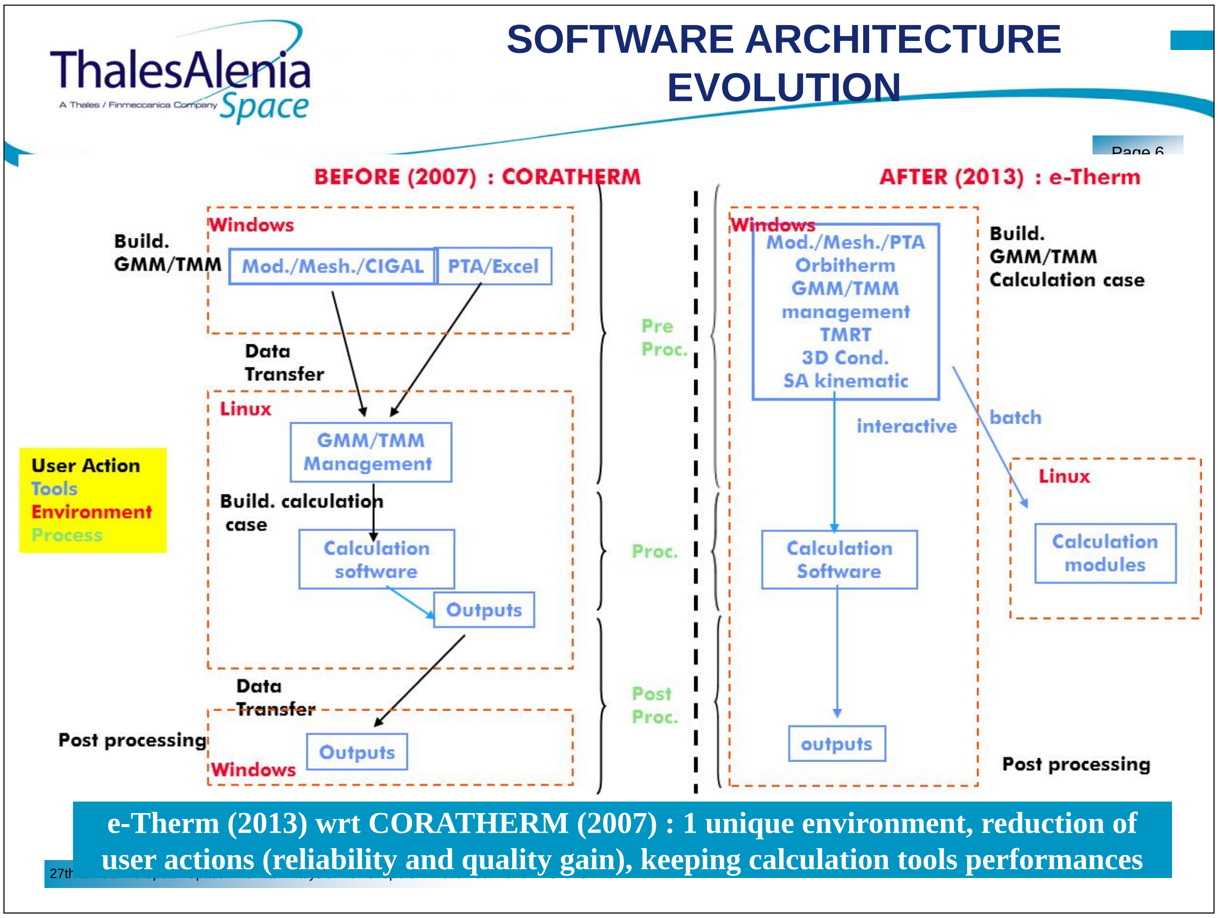
- In the 60's, Thales Alenia Space became prime on the satellite market :
  - Needs of analyses and sizing tools for the thermal control (Platforms, payloads, Scientific and telecommunication programs)
- Since more than 40 years :
  - CORATHERM evolution : CIGAL2 (pre / post), CORAFILE (data file management), ORBITHERM (visual orbitographic data) → e-Therm (since 2007)
  - Utilisation : 20 to 50 users
  - e-Therm tool :
    - Coherent and optimized relative to analyse process
    - Development of numerous pre and post-processing functionalities in order to simplify and to give back reliable the analysis process
- Reactivity in term of evolutions; flexibility of development and proximity in term of user support
- No licences

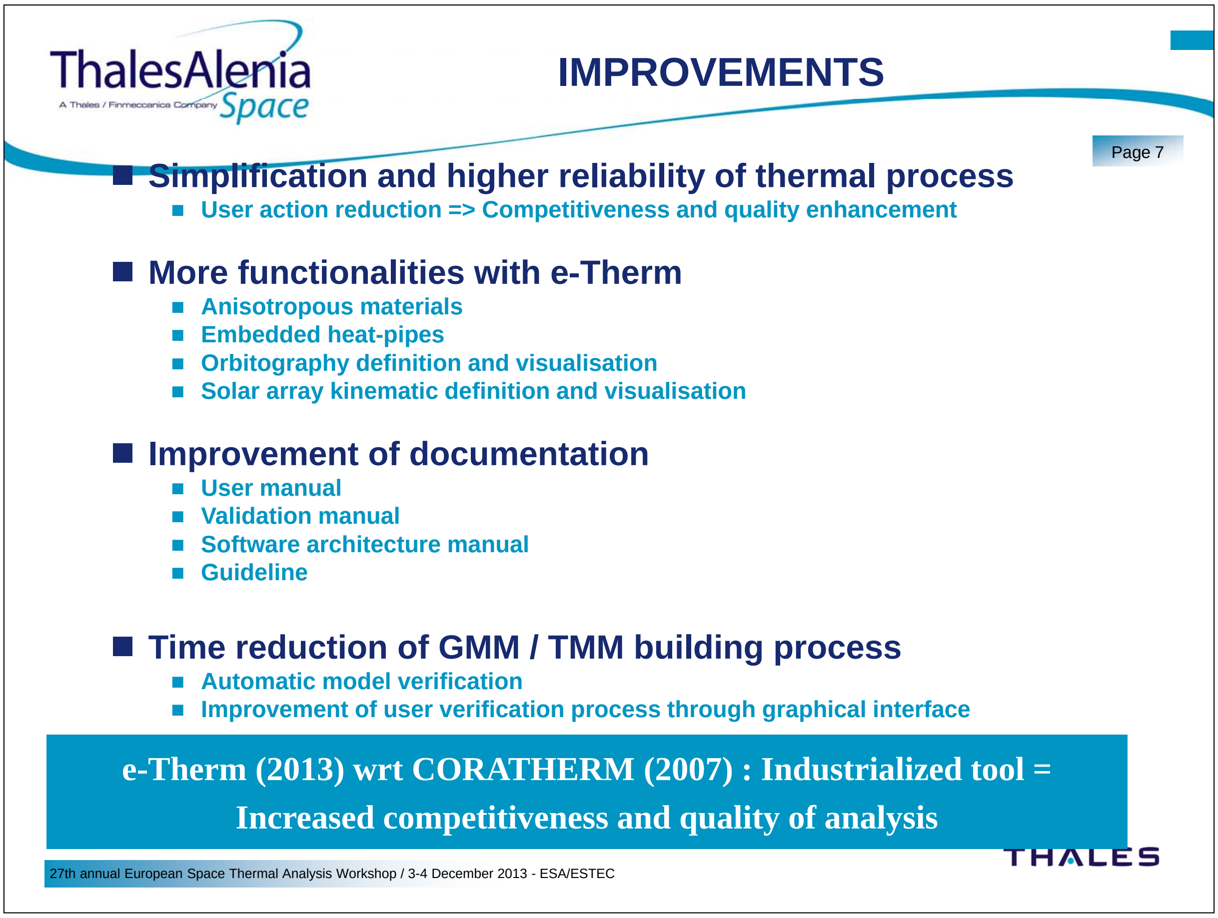
27th annual European Space Thermal Analysis Workshop / 3-4 December 2013 - ESA/ESTEC

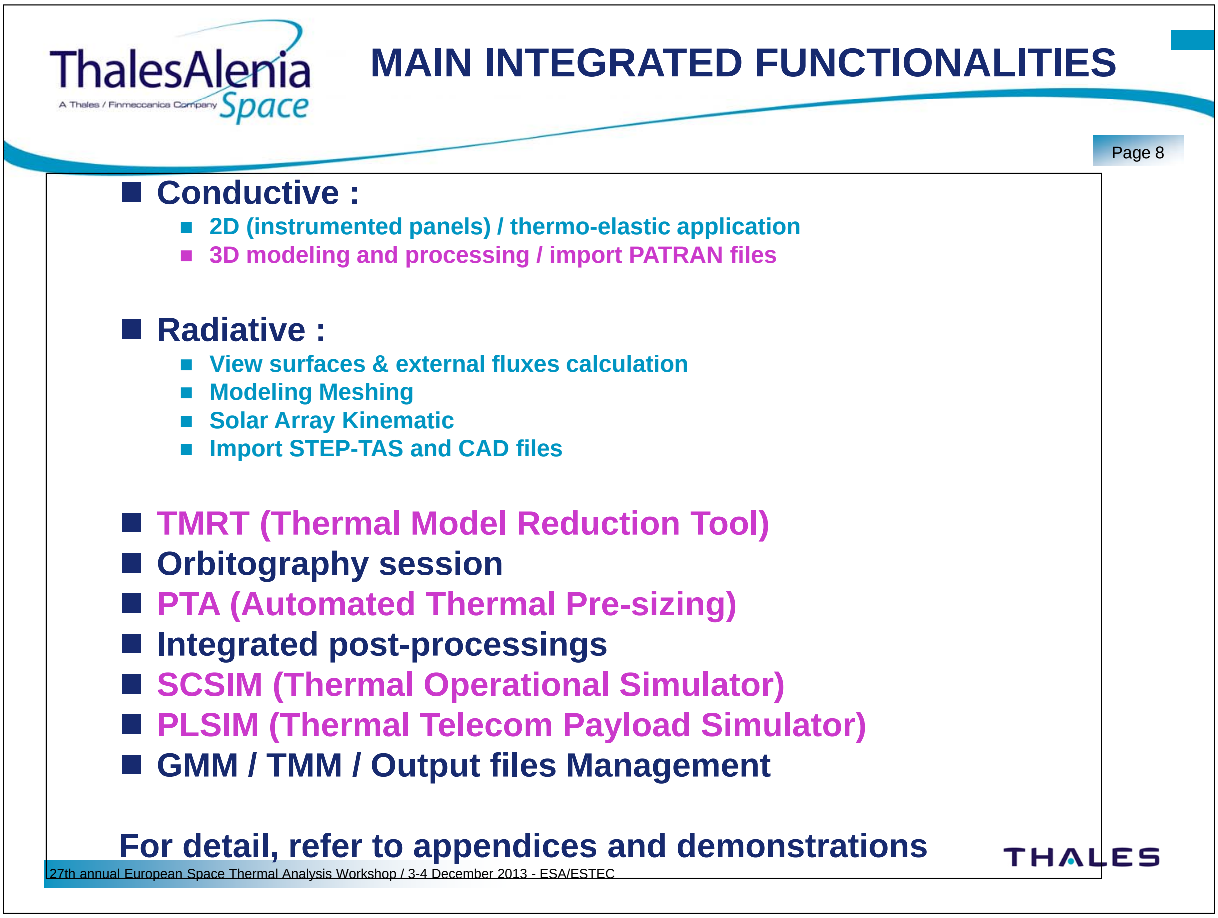
THALES




TAS-F TOOLS ROAD-MAP
ThalesAlenia Space
A Thales / Finmeccanica Company
Page 5
CORATHERM
CORATHERM
CIGAL
CORATHERM
CIGAL2
CORATHERM
CIGAL2
ORBITHERM
PTA
CORATHERM
ORBITHERM
e-Therm V1.0
•CIGAL2
•2D and 3D Conductive Session
•PTA model building
•CORAFILE
1970
1990
2001
2003
2010
07/2011
CORATHERM
ORBITHERM
e-Therm V1.1
•Thermal Model Reduction Tool (proc.)
•3D Mesh, Realistic View
•Radiative Module calculation
•Concurrent Design Facilities
•PTA : embedded heat pipes
•PTA Fortran
•PL Thermal Simulator for Customer (8WB)
•Operation simulator SCSIM (O3B, TKM)
e-Therm V1.4
e-Therm V2.0
12/2013
09/2012
10/2011
Extension of others physical fields
SPARCS
?
Electronic boards, Electron tubes
e-Therm V1.3
•View surface calculation : SV
•Moving SA (Not fully validated)
•Pre-Post Processing Tool
CORATHERM
e-Therm V1.2
•ORBITHERM
•Thermal Solver : RPT
•Data files link (I / O / calculation case)
•Thermal Model Reduction Tool (graph.)
•Conductive : Variation of Conductivity into Nida
THALES
27th annual European Space Thermal Analysis Workshop / 3-4 December 2013 - ESA/ESTEC


SOFTWARE ARCHITECTURE EVOLUTION
ThalesAlenia Space
A Thales / Finmeccanica Company
Page 6
BEFORE (2007) : CORATHERM
AFTER (2013) : e-Therm
Build. GMM/TMM
Windows
Mod./Mesh./CIGAL
PTA/Excel
Data Transfer
Linux
GMM/TMM Management
Build. calculation case
Calculation software
Outputs
Data Transfer
Post processing
Outputs
Windows
User Action
Tools
Environment
Process
Pre Proc.
Proc.
Post Proc.
Windows
Mod./Mesh./PTA
Orbitherm
GMM/TMM management
TMRT
3D Cond.
SA kinematic
Build. GMM/TMM Calculation case
interactive
batch
Linux
Calculation Software
Calculation modules
outputs
Post processing
e-Therm (2013) wrt CORATHERM (2007) : 1 unique environment, reduction of user actions (reliability and quality gain), keeping calculation tools performances


ThalesAlenia Space
A Thales / Finmeccanica Company
IMPROVEMENTS
Page 7
Simplification and higher reliability of thermal process
User action reduction => Competitiveness and quality enhancement
More functionalities with e-Therm
Anisotropous materials
Embedded heat-pipes
Orbitography definition and visualisation
Solar array kinematic definition and visualisation
Improvement of documentation
User manual
Validation manual
Software architecture manual
Guideline
Time reduction of GMM / TMM building process
Automatic model verification
Improvement of user verification process through graphical interface
e-Therm (2013) wrt CORATHERM (2007) : Industrialized tool =
Increased competitiveness and quality of analysis
27th annual European Space Thermal Analysis Workshop / 3-4 December 2013 - ESA/ESTEC
THALES


ThalesAlenia Space
A Thales / Finmeccanica Company
MAIN INTEGRATED FUNCTIONALITIES
Page 8
Conductive :
2D (instrumented panels) / thermo-elastic application
3D modeling and processing / import PATRAN files
Radiative :
View surfaces & external fluxes calculation
Modeling Meshing
Solar Array Kinematic
Import STEP-TAS and CAD files
TMRT (Thermal Model Reduction Tool)
Orbitography session
PTA (Automated Thermal Pre-sizing)
Integrated post-processings
SCSIM (Thermal Operational Simulator)
PLSIM (Thermal Telecom Payload Simulator)
GMM / TMM / Output files Management
For detail, refer to appendices and demonstrations
27th annual European Space Thermal Analysis Workshop / 3-4 December 2013 - ESA/ESTEC
THALES

CONCLUSION : TAS-CANNES POLICY SOFTWARE

Page 9

- Base : expert in-house tools (validated through ground and flight correlations) with 40 years of REX
- Tools and Analysis process industrialisation : improvement of quality and reliability / competitiveness
- Policy based on the opening of e-Therm
  - External free distribution of e-Therm : V1.4 distributed to WS participants
  - Maintenance funded :
    - By TAS for corrective
    - By customers for specific needs (evolutive / adaptative or training / support)
    - By agencies for general needs (evolutive)
  - Using of STEP-TAS exchange standard

Objective : External acknowledge of e-Therm as reference tools

27th annual European Space Thermal Analysis Workshop / 3-4 December 2013 - ESA/ESTEC

APPENDICES

Page 10

e-Therm MAIN NEW INTEGRATED FUNCTIONALITIES

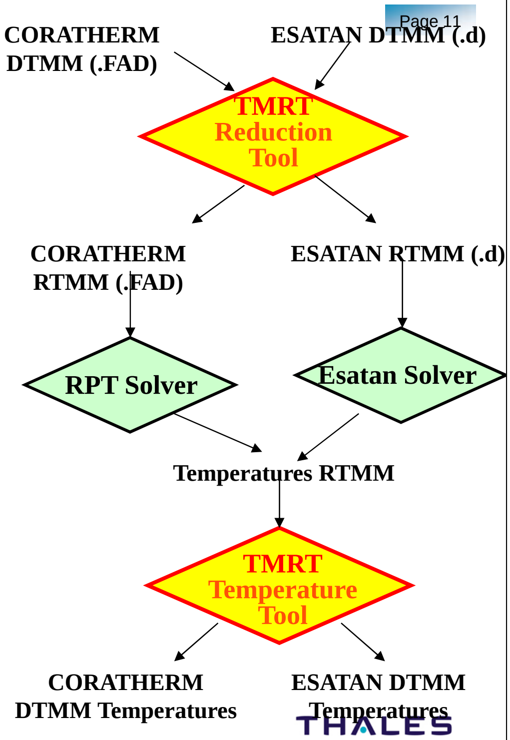
27th annual European Space Thermal Analysis Workshop / 3-4 December 2013 - ESA/ESTEC

ThalesAlenia Space — A Thales / Finmeccanica Company

THERMAL MODEL REDUCTION TOOL : TMRT

Page 11

- **Objectives and interests**
  - Go from a detailed model (DTMM) to a reduced model (RTMM) :
    - Reduce the number of nodes and exchanges
    - Automatic management of all exchanges and all the powers
  - Keep the physical consistency
    - Based on Plateau-Equivale method for conductive exchanges and capacitances
    - Summation of radiative exchanges and powers
  - Keep an acceptable accuracy
    - Grouping nodes requires experience and know-how to achieve a good compromise
  - Work in both formats e-Therm / ESATAN. Tool can be used as converter



27th annual European Space Thermal Analysis Workshop / 3-4 December 2013 - ESA/ESTEC

THALES

ThalesAlenia Space — A Thales / Finmeccanica Company

APPLICATIONS - TMRT

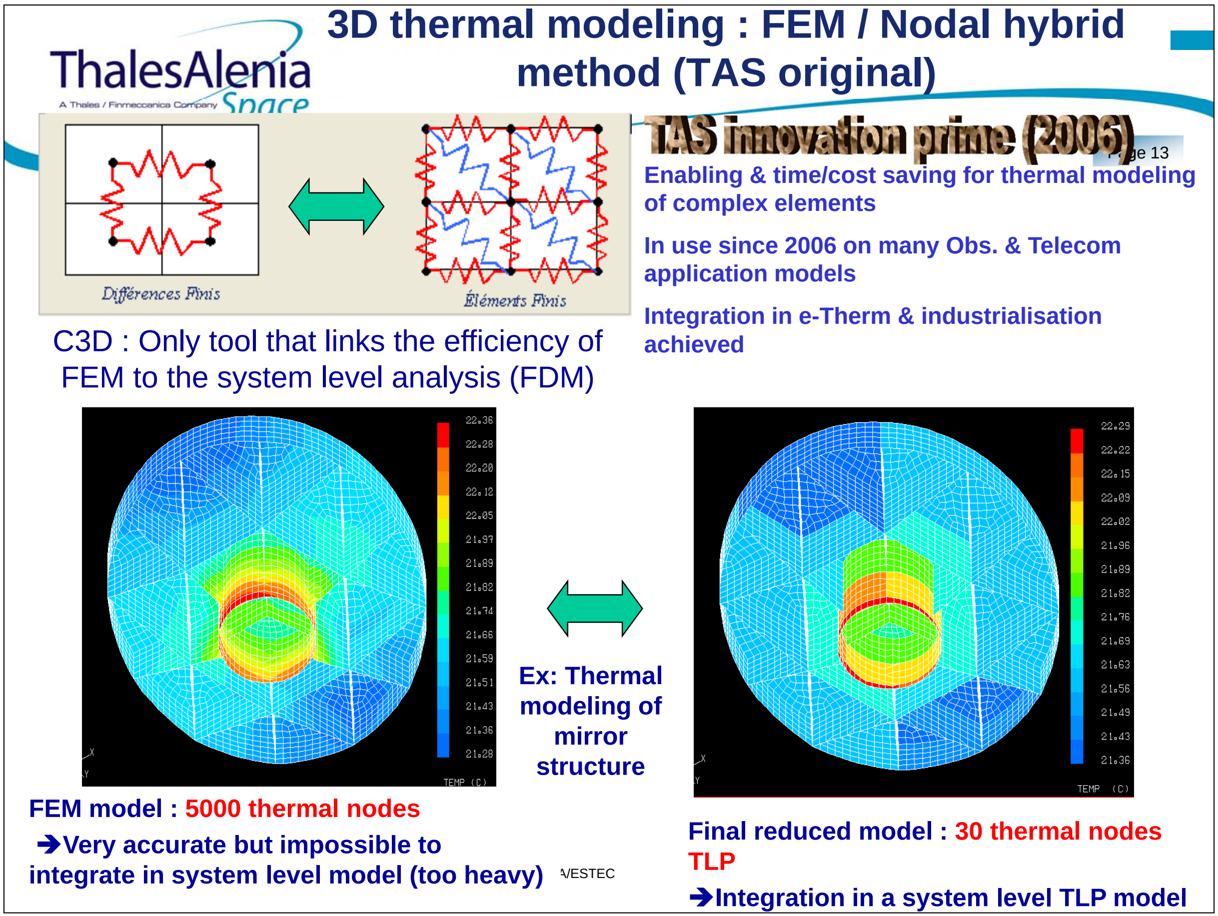
Page 12

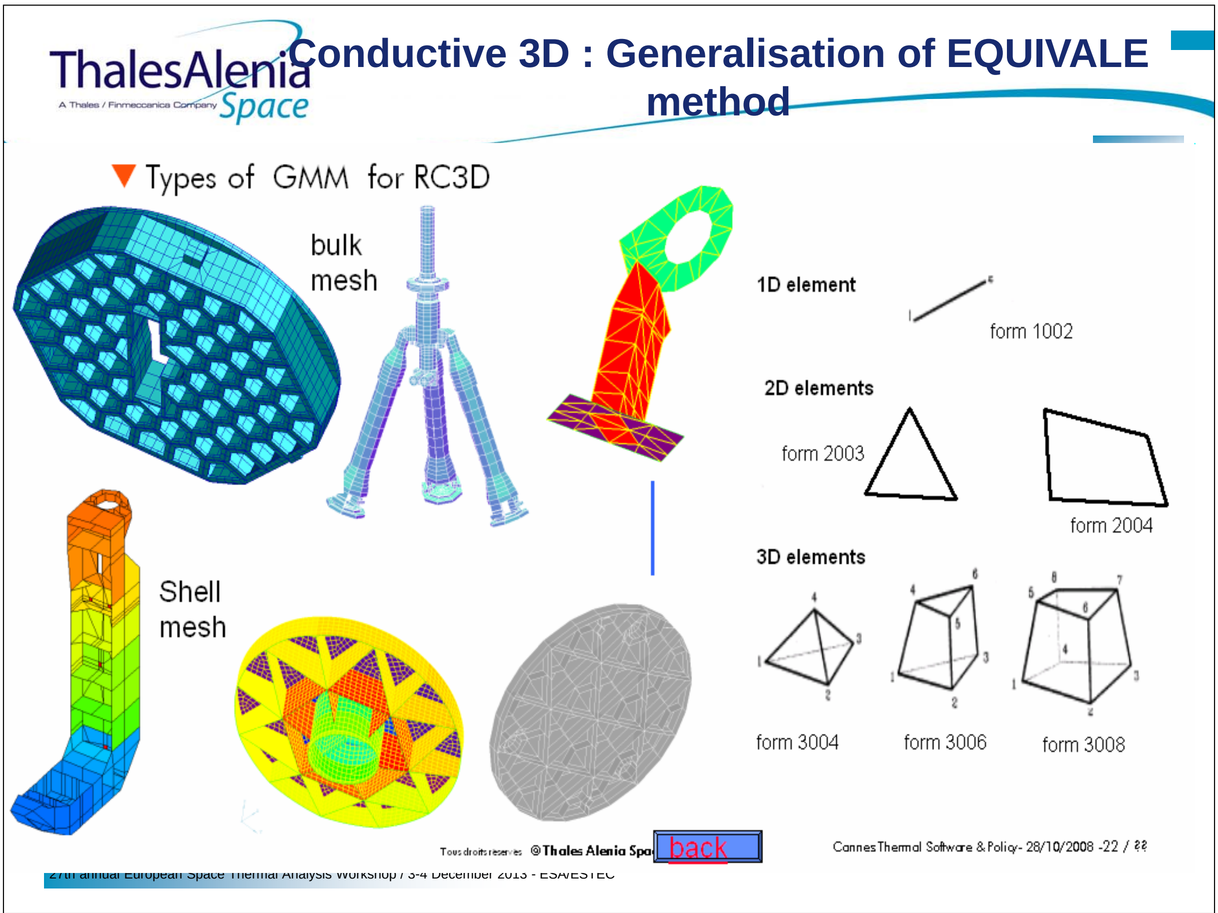
Launcher Interfaces Applications(CDR mathematical models) :

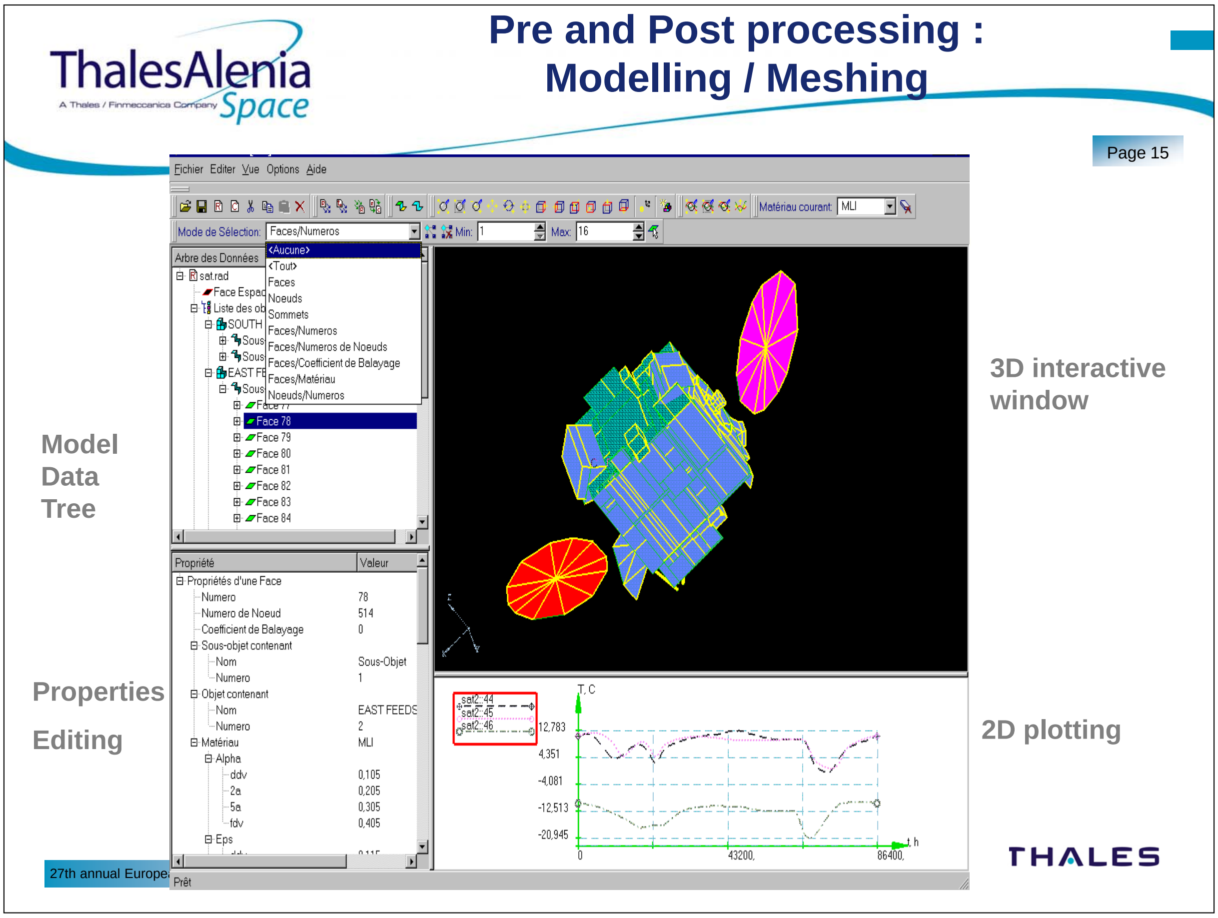
- AP7A (e-Therm V1.1)
  - 1rst application on telecommunication program
  - End of tool development and validation in live
  - RTMM delivered in 9 weeks
- YAMAL 402 (e-Therm V1.2-β)
  - Tool Finalisation and Validation in live
  - RTMM delivered in 10 weeks
- EUT W6A (e-Therm V1.2-β)
  - RTMM delivered in 6 weeks
  - Reduction from 3000 to 375 nodes
  - Accuracy : inferior to 2°C on the units, and average deviation near of 0°C on the residuum of model (TMM)
- ATHENA-FIDUS (e-Therm V1.3)
  - RTMM delivered in 4 weeks
- O3B (e-Therm V1.3)
  - RTMM delivered in less than 3 weeks

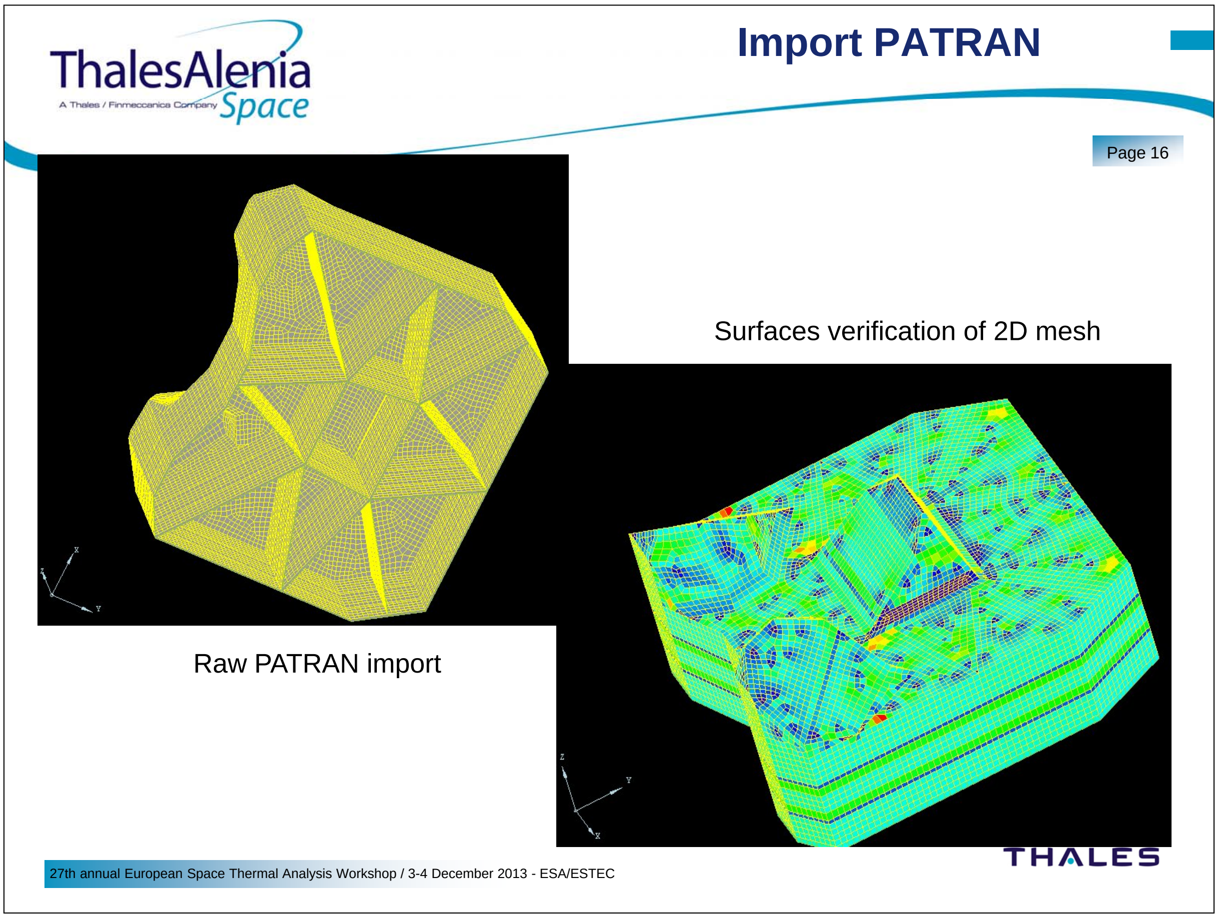
THALES

27th annual European Space Thermal Analysis Workshop / 3-4 December 2013 - ESA/ESTEC


ThalesAlenia Space
A Thales / Finmeccanica Company
3D thermal modeling : FEM / Nodal hybrid method (TAS original)
Différences Finis
Éléments Finis
TAS innovation prime (2006)
Page 13
Enabling & time/cost saving for thermal modeling of complex elements
In use since 2006 on many Obs. & Telecom application models
Integration in e-Therm & industrialisation achieved
C3D : Only tool that links the efficiency of FEM to the system level analysis (FDM)
Ex: Thermal modeling of mirror structure
FEM model : 5000 thermal nodes
➔Very accurate but impossible to integrate in system level model (too heavy)
Final reduced model : 30 thermal nodes TLP
➔Integration in a system level TLP model


ThalesAlenia Space
A Thales / Finmeccanica Company
Conductive 3D : Generalisation of EQUIVALE method
Types of GMM for RC3D
bulk mesh
Shell mesh
1D element
form 1002
2D elements
form 2003
form 2004
3D elements
form 3004
form 3006
form 3008
back
Cannes Thermal Software & Policy - 28/10/2008 -22
27th annual European Space Thermal Analysis Workshop / 3-4 December 2013 - ESA/ESTEC

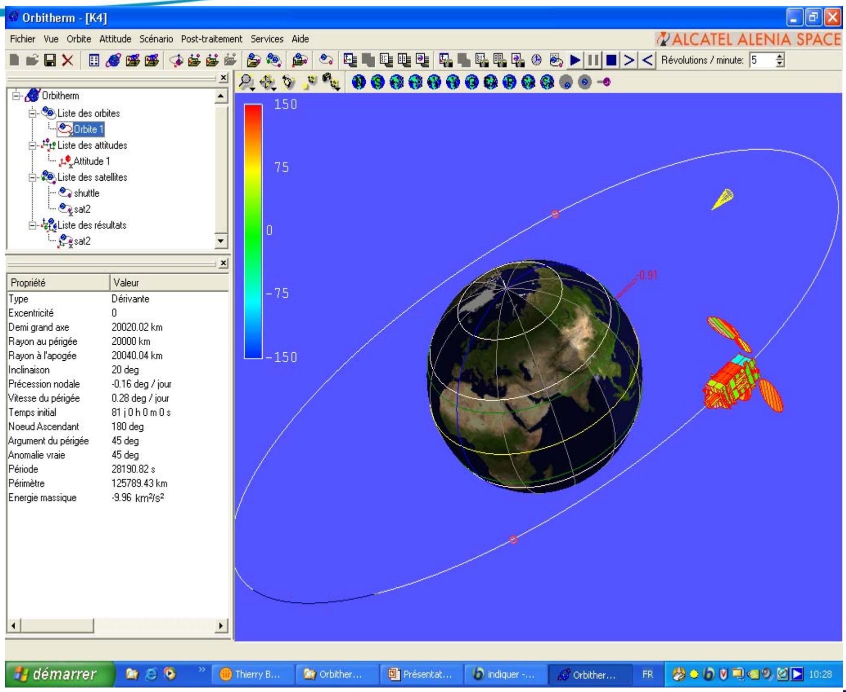

ThalesAlenia
A Thales / Finmeccanica Company Space
Pre and Post processing :
Modelling / Meshing
Page 15
Model
Data
Tree
Properties
Editing
3D interactive
window
2D plotting
27th annual Europe
THALES


ThalesAlenia
A Thales / Finmeccanica Company Space
Import PATRAN
Page 16
Surfaces verification of 2D mesh
Raw PATRAN import
27th annual European Space Thermal Analysis Workshop / 3-4 December 2013 - ESA/ESTEC
THALES

Pre and Post processing : ORBITHERM

Page 17

Model data tree



3D interactive window

Properties edition of the selected items

THALES

27th annual European Space Thermal Analysis Workshop / 3-4 December 2013 - ESA/ESTEC

AUTOMATED THERMAL PRE-SIZING (PTA)

Page 18

- Objectives and Interests
  - Generate a S/C TELECOM complete model including
    - A P/F generic part descended from database
    - A P/L generic part descended from CAO data (currently north and south panels, in the future all other panels with dissipative units)
  - Generate a north and south panels conductive mesh
  - Quickly and automatically include a large number of equipment or heat-pipes referenced with their specific thermal modeling
  - Management database
  - Automatically generate a consistent numbering for
    - Radiative and conductive geometries and associated couplings
    - Capacitances
    - Dissipations
  - Offer a friendly and ergonomic user interface

THALES

27th annual European Space Thermal Analysis Workshop / 3-4 December 2013 - ESA/ESTEC

ThalesAlenia Space
A Thales / Finmeccanica Company

APPLICATIONS - PTA

Page 19

- **Applications**
  - AP7A (e-Therm V1.0)
    - 1rst application on Telecommunication program
    - Tool Finalisation / Validation in progress
    - TMM delivered in 8 weeks
    - Nominal correlation S/C TMM
  - YAMAL 402 (e-Therm V1.1)
    - 1rst application on Telecommunication program including panels with integrated heat-pipes
    - Tool Finalisation / Validation in progress
    - TMM delivered in 10 weeks
  - EUT W6A (e-Therm V1.1)
    - TMM delivered in 6 weeks
  - ATHENA-FIDUS
    - TMM delivered in 3 weeks
- **Conclusion**
  - TMM delivered in 3-4 weeks
    - User manual and support
    - Completion and management of a database P / L Units / Heat pipes
  - Perspective : Extension to other panels

27th annual European Space Thermal Analysis Workshop / 3-4 December 2013 - ESA/ESTEC

THALES

ThalesAlenia Space
A Thales / Finmeccanica Company

SCSIM (Thermal Operational Simulator)

Page 20

- **Goal**
  - Thermal simulator real time operations. Solution based on the model resulting from the thermal analysis.
- **Prerequisites**
  - Thermal model developed in e-Therm
  - TMM reduced (max 3000 nodes)
  - Reduction of geometry (a thousand faces)
- **Process**
  - Receiving a request for calculating real-time temperatures from the following inputs :
    - Dissipations for a list of nodes,
    - Solar Vector and Flux,
    - Albedo Vector and Flux,
    - SATM and SADM Angles.
  - Selection of geometric configuration (/ SA kinematics).
  - Calculation of solar, albedo and earth fluxes in parallel of the temperatures calculation
  - Calculating the transient temperatures taking into account internal dissipations and external fluxes
  - Temperature outputs (thermistors)

27th annual European Space Thermal Analysis Workshop / 3-4 December 2013 - ESA/ESTEC

THALES

ThalesAlenia Space
A Thales / Finmeccanica Company

PLSIM (Thermal Telecom Payload Simulator)

Page 21

- **Scope**
  - Simulate one or more configurations of the payload at the desired date.
  - Temperature calculation from a TWT and OMUX configuration (ON / OFF + RF traffic)
- **Process**
  - Entering the payload configuration (eg, Excel)
  - Calculating power dissipation taking into account in particular RF losses all along the WG,
  - Calculating orbitographic data
  - Interpolation of thermo-optical parameters (α degradation)
  - Calculation of the solar, terrestrial and albedo fluxes
  - Calculation of steady state temperatures
  - Outputs :
    - Excel table outputs with TWT and OMUX temperatures with min and max,
    - Outputs with horizontal bar chart,
    - Outputs on CAD image with temperature mapping

27th annual European Space Thermal Analysis Workshop / 3-4 December 2013 - ESA/ESTEC

THALES

Appendix Q

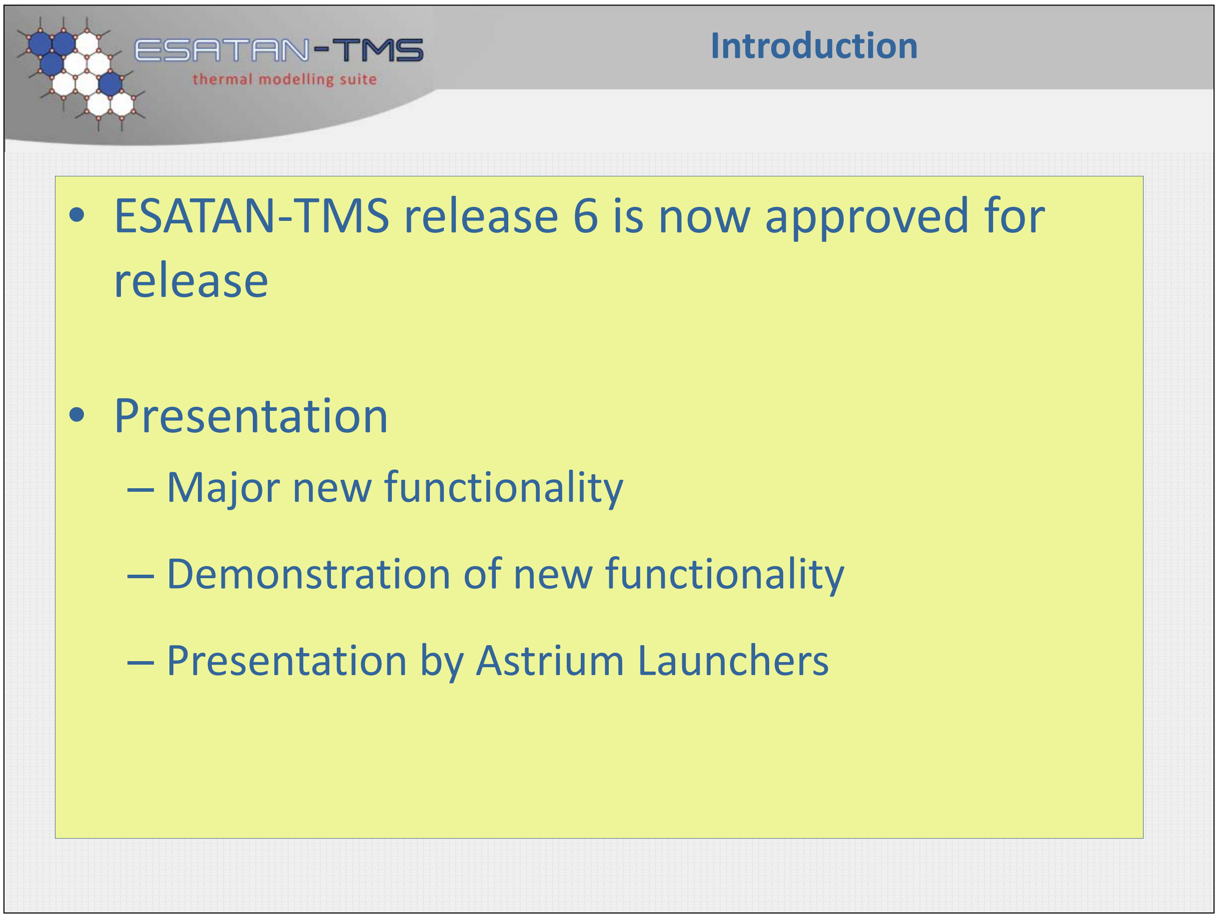
ESATAN Thermal Modelling Suite
Product Developments and Demonstration

Chris Kirtley Henri Brouquet
(ITP Engines UK Ltd, United Kingdom)

Abstract

ESATAN-TMS provides a complete and powerful integrated thermal modelling environment. ESATAN-TMS r6 sees a major evolution of the product, with advances to its geometry modelling and 3D visualisation capabilities. This presentation outlines the developments going into the new release of the product.
A demonstration of ESATAN-TMS r6 will be given, building a model to demonstrate the new functionality.


ESATAN-TMS
thermal modelling suite
ESATAN-TMS
Product Overview
Chris Kirtley
Henri Brouquet


ESATAN-TMS
thermal modelling suite
Introduction
• ESATAN-TMS release 6 is now approved for release
• Presentation
– Major new functionality
– Demonstration of new functionality
– Presentation by Astrium Launchers

ESATAN-TMS thermal modelling suite

Introduction

Our vision remains unchanged

- Provide a **complete** and **effective** thermal modelling environment
  - Functionality which meets customer's current & future modelling requirements
  - Provide a high-quality and fully validated product
- **Efficient** end-to-end integration within a multi-disciplinary engineering environment
- Backing this up with **professional** customer support services

New support Engineer: Nicolas Bures

ESATAN-TMS thermal modelling suite

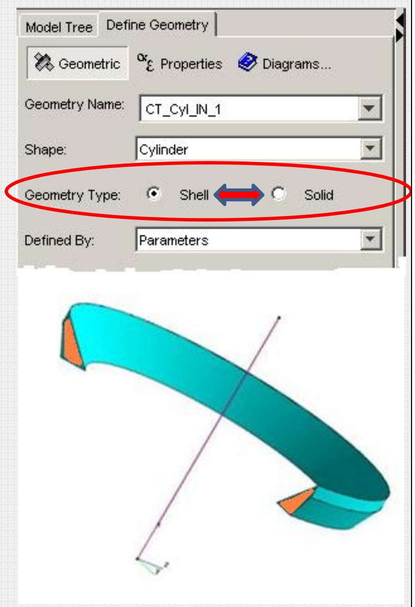
Modelling of Solids - Introduction

- Support modelling of solid (3D) geometry
  - Jointly funded ITP / ESA Contract
  - Immediate requirement from Astrium Launchers
  - Worked with Astrium Launchers
    - Definition of requirements
    - Feedback and testing via alpha and beta releases

ESATAN-TMS thermal modelling suite

Modelling of Solids - Solid Primitives

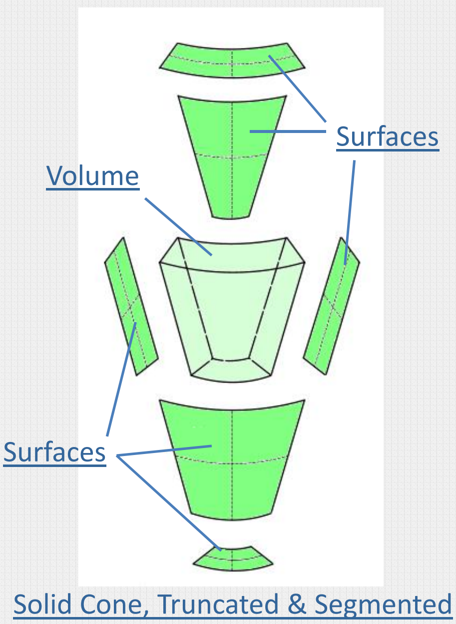
- Initial work performed on the product's architecture
- Ability to define a shell or solid primitives
- Logical extension to existing framework
- Solid cone, cylinder, paraboloid, quadrilateral, rectangle, sphere and triangle
- Definition by points or parameters
- Definition of a solid cone or cylinder by rotation of a quadrilateral
- Solid can be truncated or segmented

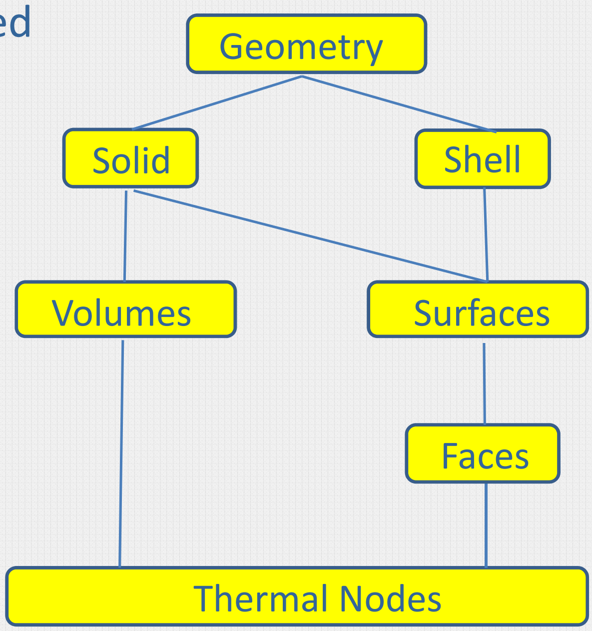


ESATAN-TMS thermal modelling suite

Modelling of Solids - Solid Primitives

- Terminology generalised

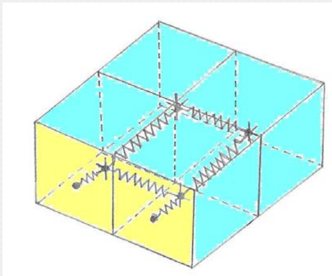


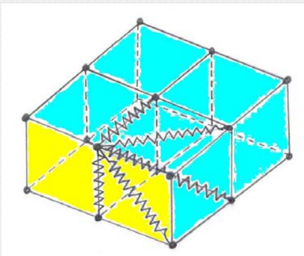


ESATAN-TMS thermal modelling suite

Modelling of Solids - Conductance

- **Lumped parameter** and **finite element** analysis supported through the Analysis Type
- Thermal network depends on the analysis type
- Lumped parameter
  - Single thermal node for each volume
  - Volume nodes connected within a solid
  - Arithmetic nodes on external faces
  - Solids connected via Conductive Interfaces



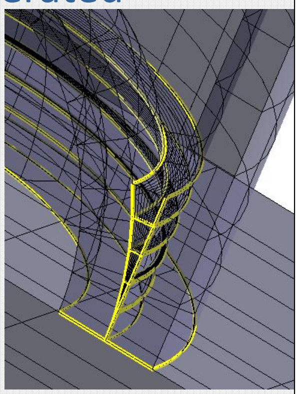


- Finite Element
  - Linear finite elements
  - Thermal nodes at each element vertices
  - Nodes connected to neighbouring nodes

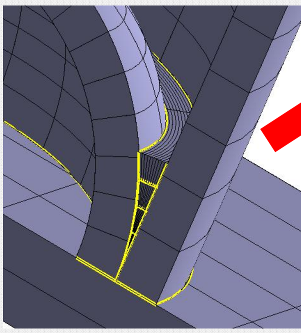
ESATAN-TMS thermal modelling suite

Modelling of Solids - Conductance

- Conductive interfaces are automatically generated
- Detects surfaces in contact
  - Geometry based
  - For LP or LP/FE no reliance on mesh congruency
  - POINT_COINCIDENT tolerance used
  - Fused by default
- Identifies interface exists
- Edit via Process Conductive Interface dialog
- Conductances calculated on output to analysis file



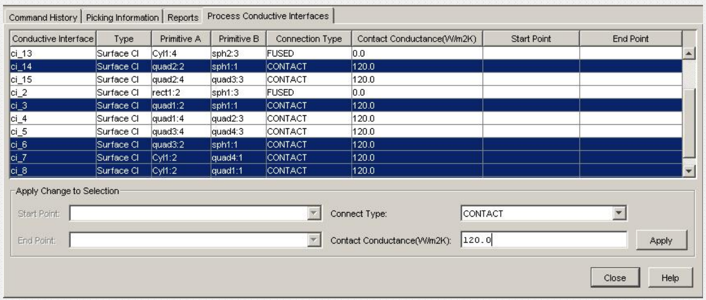
Transparency



Contact outlined

Modelling of Solids - Conductance

- Process Conductive Interfaces
  - Contact type introduced (point, edge & surface)
  - Select interface in the dialog or in the visualisation
  - Set the contact type (contact , fused or not connected)
  - Multiple selection of interfaces
  - Default type is fused



Command History | Picking Information | Reports | Process Conductive Interfaces

Conductive Interface	Type	Primitive A	Primitive B	Connection Type	Contact Conductance(W/m2K)	Start Point	End Point
ci_13	Surface CI	Cyl1:4	sph2:3	FUSED	0.0		
ci_14	Surface CI	quad2:2	sph1:1	CONTACT	120.0		
ci_15	Surface CI	quad2:4	quad3:3	CONTACT	120.0		
ci_2	Surface CI	rect1:2	sph1:3	FUSED	0.0		
ci_3	Surface CI	quad1:2	sph1:1	CONTACT	120.0		
ci_4	Surface CI	quad1:4	quad2:3	CONTACT	120.0		
ci_5	Surface CI	quad3:4	quad4:3	CONTACT	120.0		
ci_6	Surface CI	quad3:2	sph1:1	CONTACT	120.0		
ci_7	Surface CI	Cyl1:2	quad4:1	CONTACT	120.0		
ci_8	Surface CI	Cyl1:2	quad1:1	CONTACT	120.0		

Apply Change to Selection

Start Point:

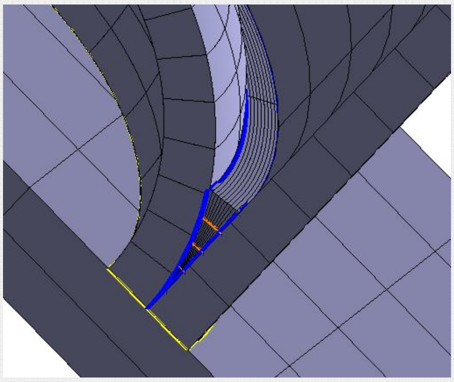
End Point:

Connect Type: CONTACT

Contact Conductance(W/m2K): 120.0

Apply

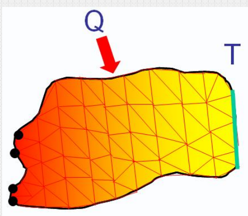
Close Help



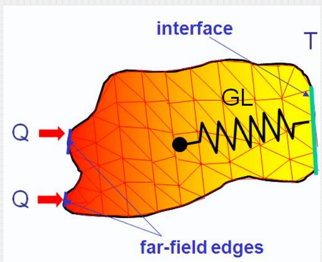
Modelling of Solids - Conductance

- Lumped parameter conductance calculation
  - Calculated on output to analysis file
  - Far-field method extended to 3D geometry
    - Implicit method, derives **understandable** conductances (≡ k.A/x)
    - Generated conductances **represent heat flows**
    - **Generic** method employed within primitives & across interfaces

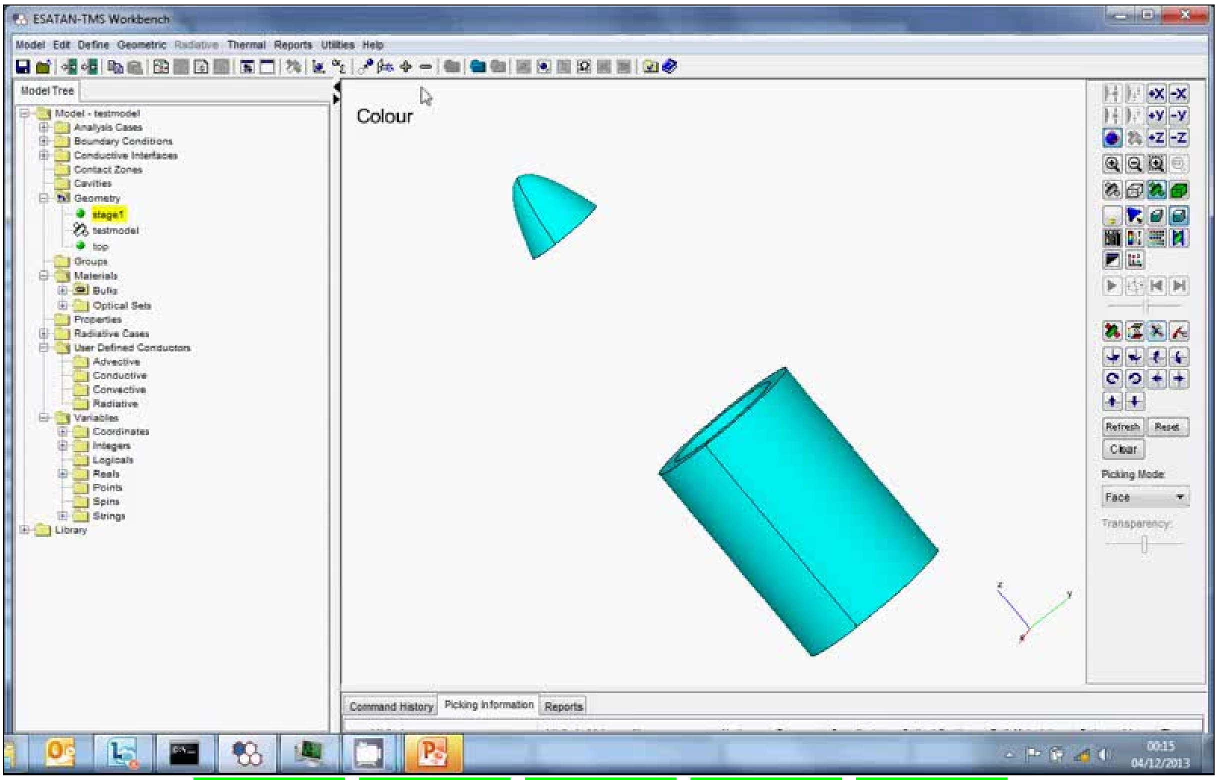
Calculate far-field nodes



Derive Conductance



- Ref. *Automatic Linear Conductor Generation Solution for Lumped Parameter Models*, ITP & ESA, ICES 2005-01-3059, 2005

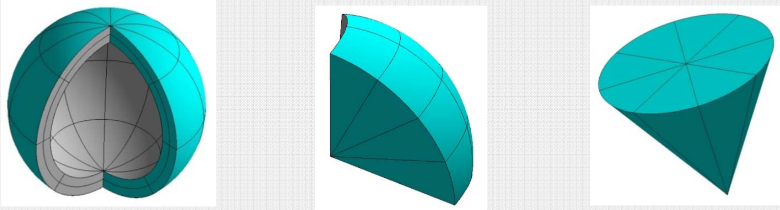


Slow Normal Fast Play/Pause Stop

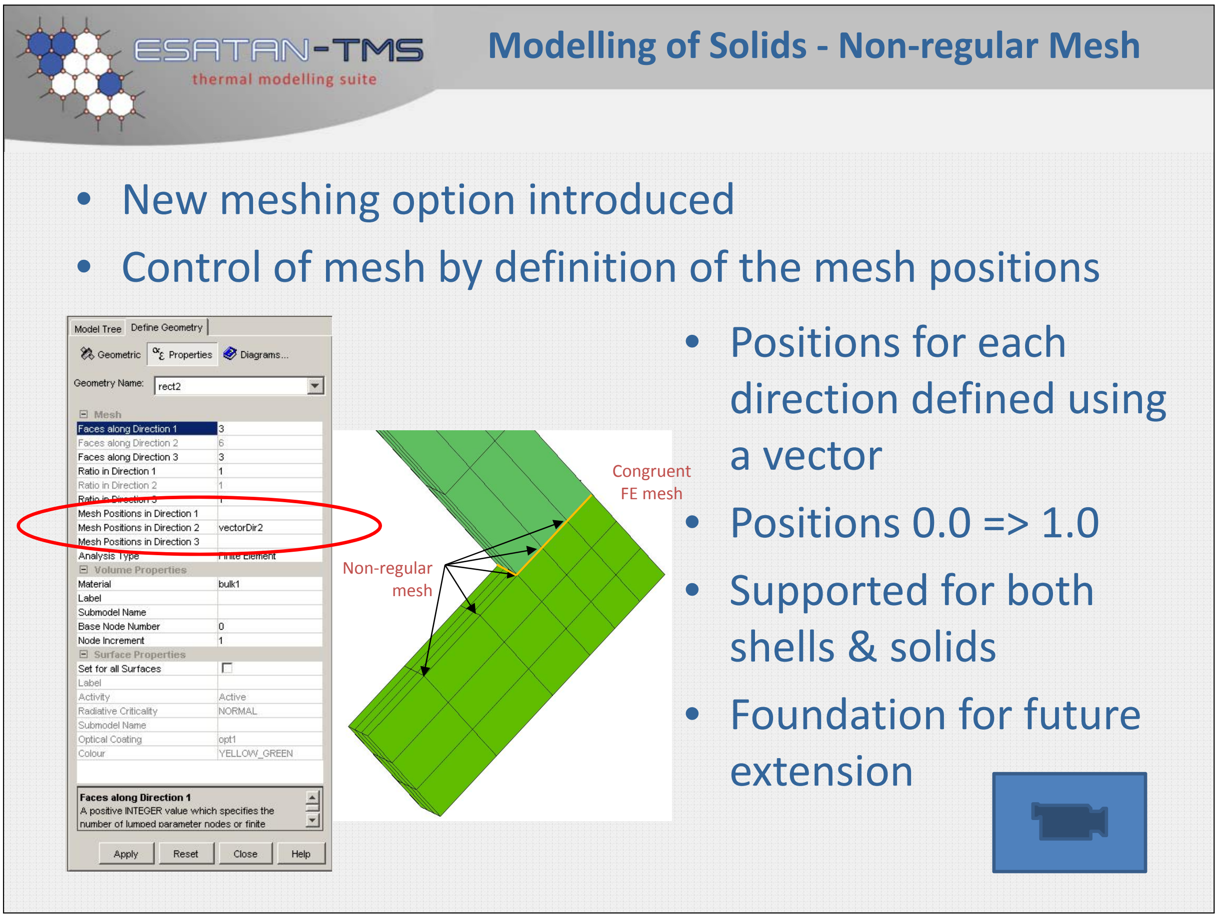
ESATAN-TMS thermal modelling suite

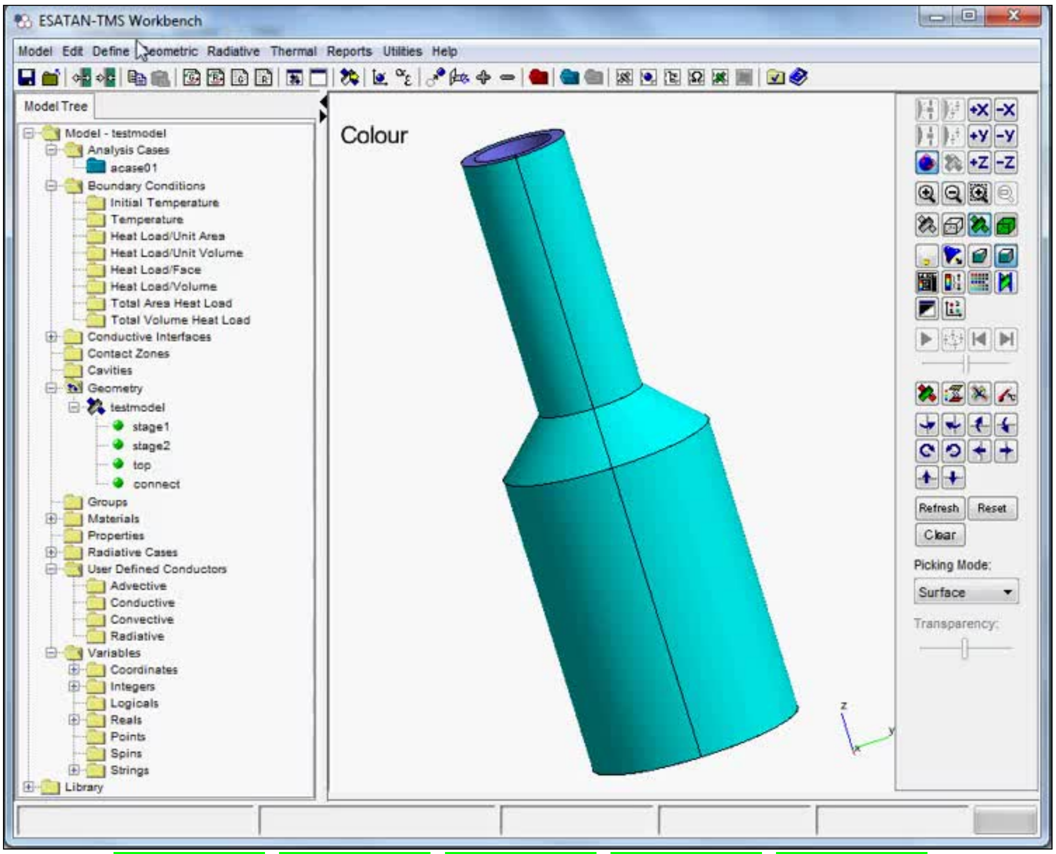
Modelling of Solids - Conductance

- Finite element solids
  - Each volume is a 3D FE element with nodes at the vertices
    - 8-node hexes, 6-node wedges,
    - 5-node quad-based pyramid & 4-node tets



  - FE solids connected where mesh is congruent
    - Conductive Interfaces can be defined to break the connection or define a contact conductance
  - Generated conductances do not represent heat flow
    - Mathematically equivalent conductance matrix





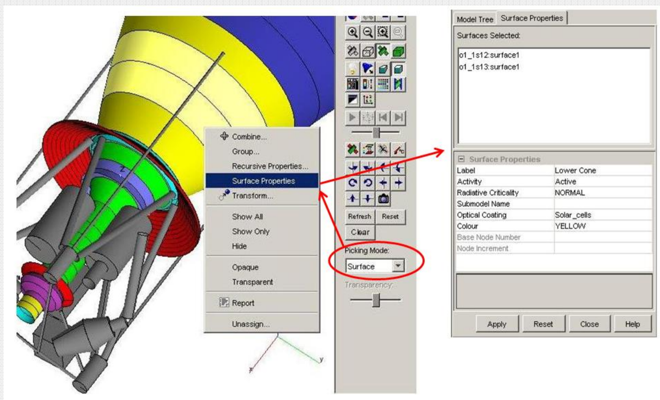
Slow Normal Fast Play/Pause Stop

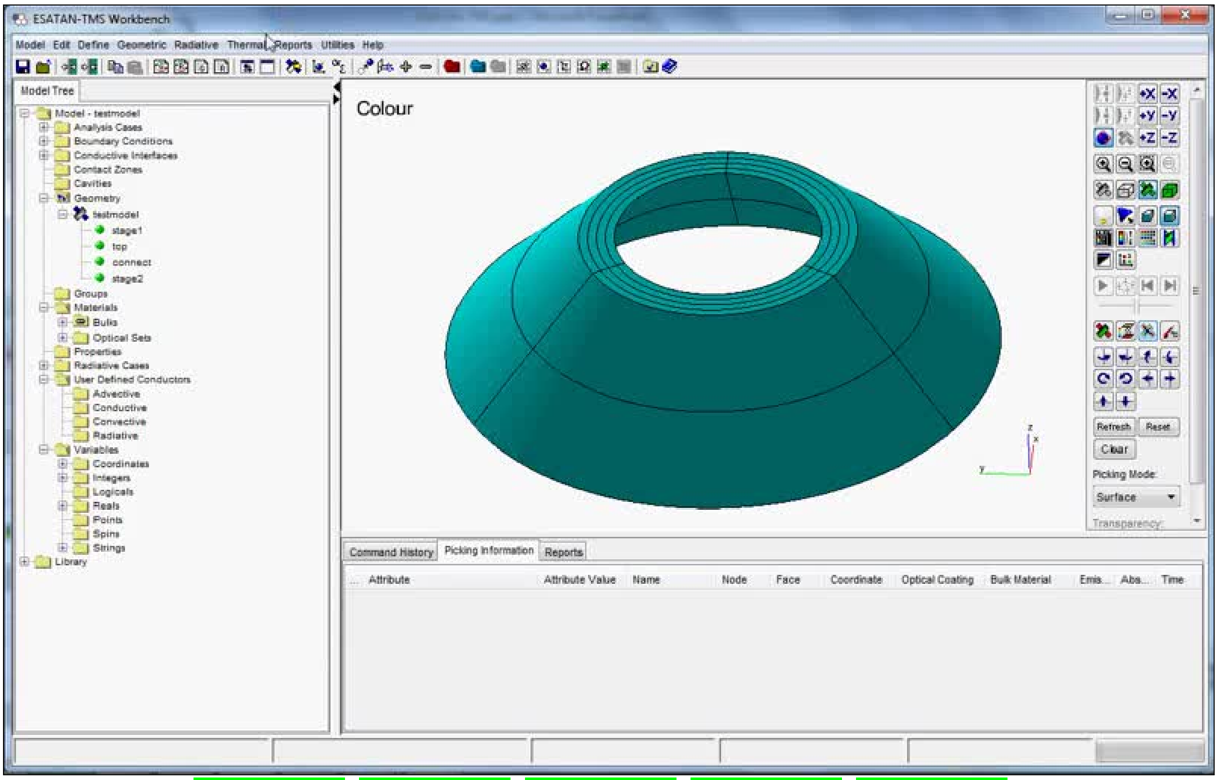
Modelling of Solids - Surface Properties

- Definition of surface properties
  - On definition of shells, individual surface properties can be defined
    - Surface 1 & Surface 2 (was Side1 & Side 2)
    - Optical, criticality, colour, label & submodel name
  - On definition of solids, the same surface properties are applied to all surfaces
  - Ability to set properties to specific surfaces is supported through the Surface Properties dialog

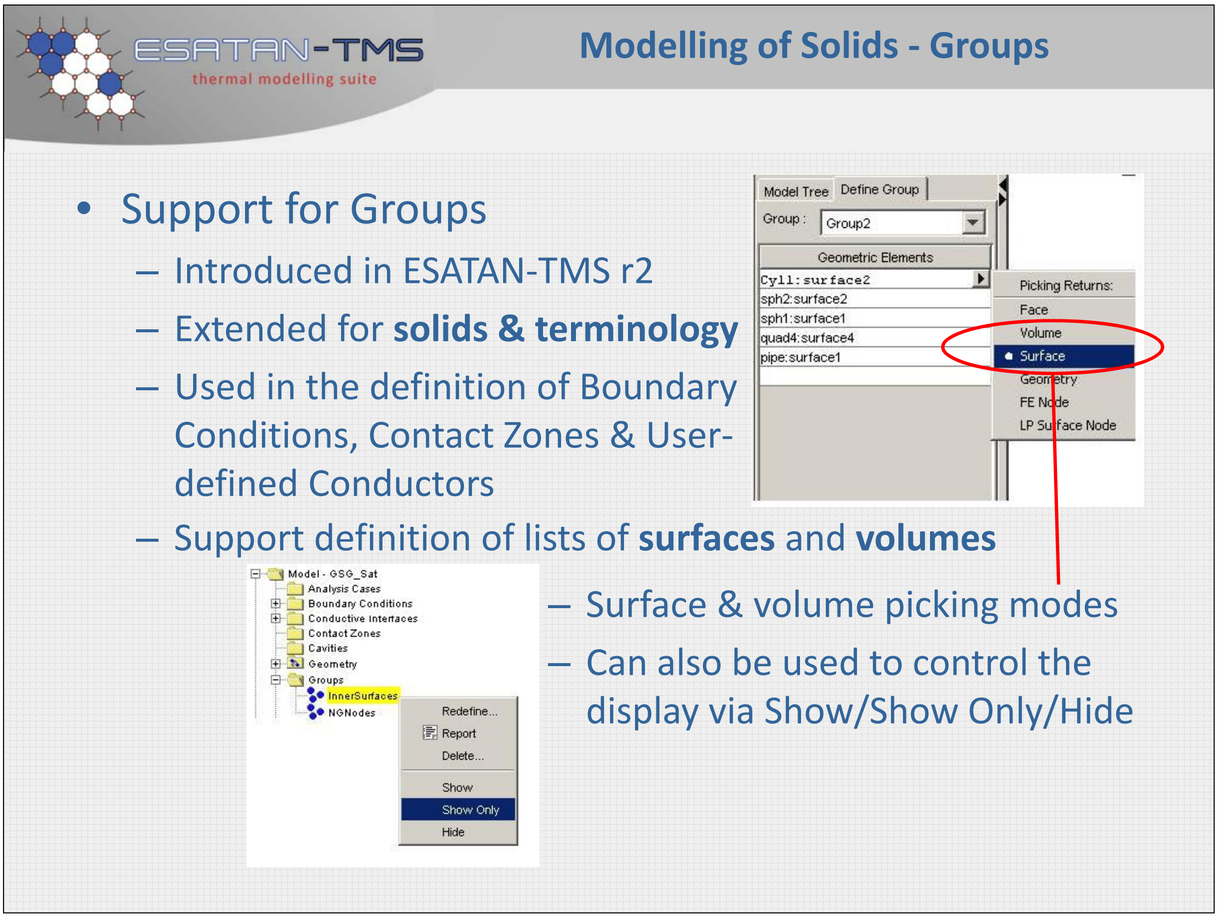
Modelling of Solids - Surface Properties

- Select surface(s)
  - New Surface picking mode available
    - Points, Faces, **Volumes**, **Surfaces**, Geometry, Points & Distance
  - Faces on the selected surface highlighted
  - Multiple selection of surfaces is supported
- Launch Surface Properties dialog
- Define surface properties
- Use pre-process overlays to validate the model





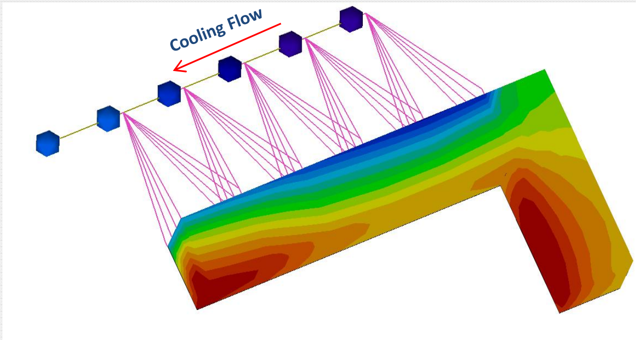
Slow Normal Fast Play/Pause Stop



ESATAN-TMS thermal modelling suite

Modelling of Solids - User-defined Conductors

- Support for User-defined Conductors
  - Introduced in ESATAN-TMS r1
  - Extended for **solids & terminology**
    - Links between solid & shell geometry
  - Generate thermal conductors (Conduction, Convection, Advection & Radiation)
  - Workbench to provide a complete thermal modelling environment



ESATAN-TMS thermal modelling suite

Modelling of Solids - Boundary Conditions

- Additional boundary condition support
  - Boundary conditions introduced within ESATAN-TMS r1
  - Extended for **new terminology**
  - Apply boundary conditions to surfaces & volumes
  - Extended for **boundary conditions on solid geometry**
    - Heat Load / Volume
    - Heat Load / Unit Volume
    - Total Volume Heat Load
  - Supported boundary conditions are:

Faces
Surfaces
Volumes
Geometry
(Groups)

Faces & Volumes →

Boundary Condition Type
Initial Temperature
Fixed Temperature

Thermal Nodes →

Set Temperature &
Node Status

ESATAN-TMS thermal modelling suite

Modelling of Solids - Boundary Conditions

- Additional boundary condition support
  - Boundary conditions introduced within ESATAN-TMS r1
  - Extended for **new terminology**
  - Apply boundary conditions to surfaces & volumes
  - Extended for **boundary conditions on solid geometry**
    - Heat Load / Volume
    - Heat Load / Unit Volume
    - Total Volume Heat Load
  - Supported boundary conditions are:

Faces
Surfaces
Geometry
(Groups)

Faces →

Boundary Condition Type

Heat Load / Face
Heat Load / Unit Area
Total Area Heat Load

Thermal Nodes →

Set internal heat load

ESATAN-TMS thermal modelling suite

Modelling of Solids - Boundary Conditions

- Additional boundary condition support
  - Boundary conditions introduced within ESATAN-TMS r1
  - Extended for **new terminology**
  - Apply boundary conditions to surfaces & volumes
  - Extended for **boundary conditions on solid geometry**
    - Heat Load / Volume
    - Heat Load / Unit Volume
    - Total Volume Heat Load
  - Supported boundary conditions are:

Volumes
Geometry
(Groups)

Volumes →

Boundary Condition Type

Heat Load / Volume
Heat Load / Unit Volume
Total Volume Heat Load

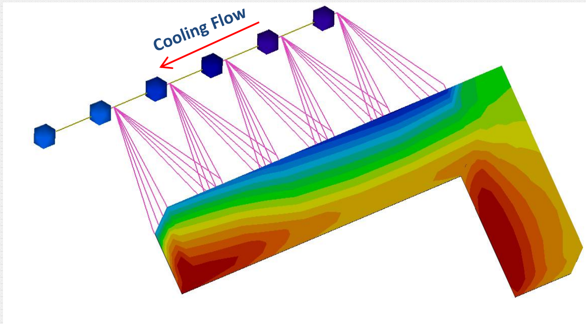
Thermal Nodes →

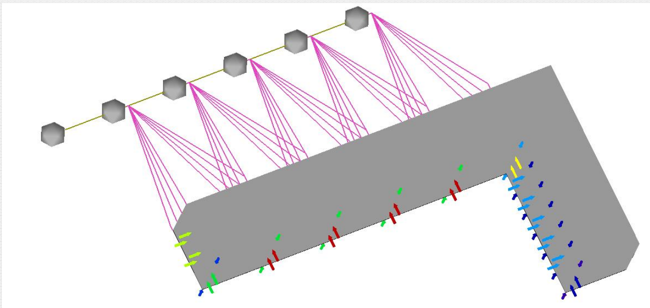
Set internal heat load

ESATAN-TMS thermal modelling suite

Modelling of Solids - Summary

- Solid geometry
- Non-geometric Nodes & User-defined Conductors representing cooling flow
- User-Defined Conductors modelling convection
- Finite element analysis type
- Non-regular mesh applied





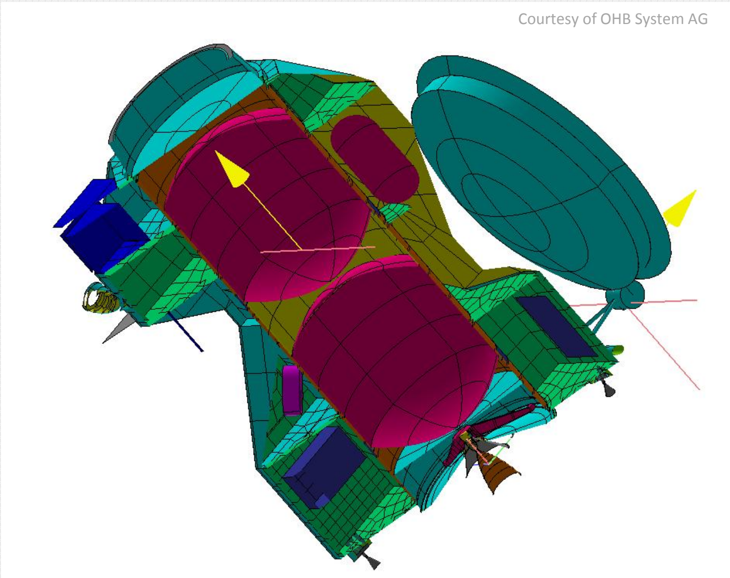
- Heat load applied to surfaces & volumes
- Post-processing temperatures & surface node heat loads
- Complete model built, run & post-processed within Workbench

ESATAN-TMS thermal modelling suite

Modelling of Solids - Conclusion

- Modelling of Solids, Conclusion
  - Major architectural development of the product
  - Clean & logical extension to the product
  - 3D version of the primitives
  - Supported throughout the modelling process
    - Groups, User-defined Conductors, Contact Zones, Boundary Conditions, Pre- & Post-process Radiative & Thermal, …
  - Conclusion of ESA contract
  - Meets the immediate needs of Astrium Launchers

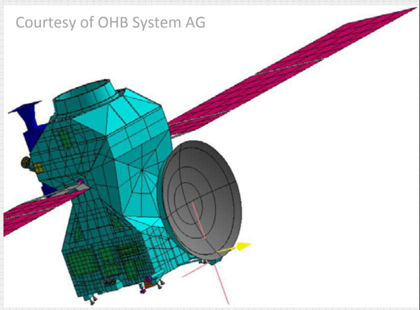
ESATAN-TMS thermal modelling suite



Radiative Cavities

ESATAN-TMS thermal modelling suite

Radiative Cavities - Introduction

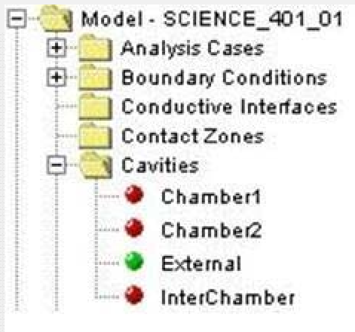


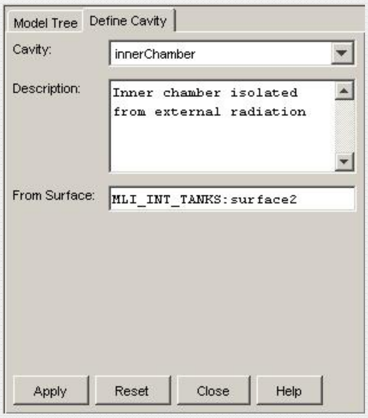
- Modelling of Radiative Cavities
  - Request from industry
  - Partition a model into cavities
  - Each cavity is radiatively isolated
    - Internal geometry can be modelled as enclosures
    - External geometry REFs depend on orbital position
  - Repeat radiative analysis only if cavity’s geometry or optical properties change
  - Leads to more efficient thermal modelling

ESATAN-TMS thermal modelling suite

Radiative Cavities - Definition

- Definition of a cavity
  - New Cavity symbol on the model tree
  - Create named cavities
  - Specify a surface to define a cavity



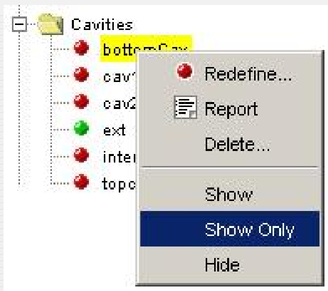


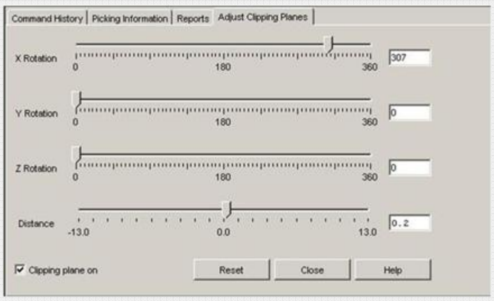
- View factor calculation performed on complete model
- VF results stored for future cavity def’n
- Cavity definition “out of date” only if cavity geometry or optical properties change
- Improved “sensitivity” of VF/REF/HF results

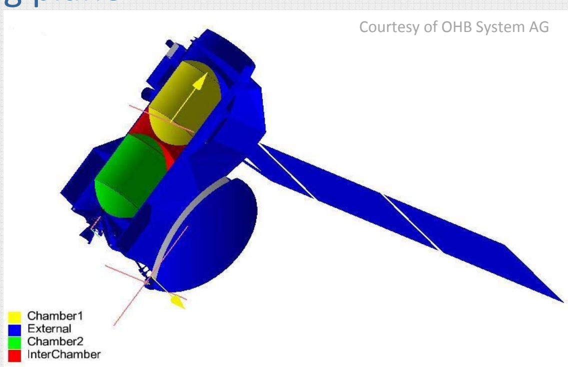
ESATAN-TMS thermal modelling suite

Radiative Cavities - Post-processing

- Report cavity definition
- Show/Hide cavity geometry
- New cavity overlay
- New “clipping planes” functionality
  - Fixed clipping plane w.r.t. model
  - Translate or rotate clipping plane
  - Clipping plane On / Off



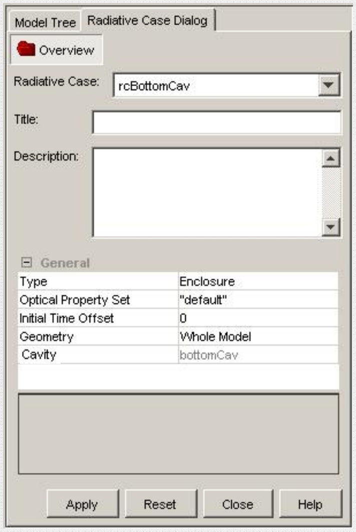




ESATAN-TMS thermal modelling suite

Radiative Cavities - Radiative Analysis

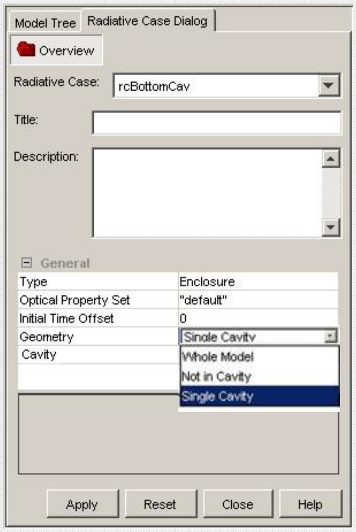
- Radiative analysis performed on each cavity
  - Introduced Geometry attribute on Radiative Case definition



ESATAN-TMS thermal modelling suite

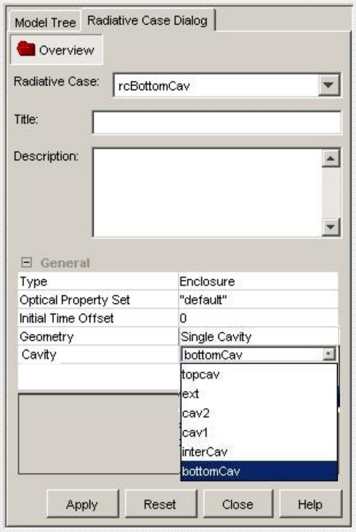
Radiative Cavities - Radiative Analysis

- Radiative analysis performed on each cavity
  - Introduced Geometry attribute on Radiative Case definition
  - Select geometry, Whole Model, Cavity or Not in Cavity
  - Default Whole Model



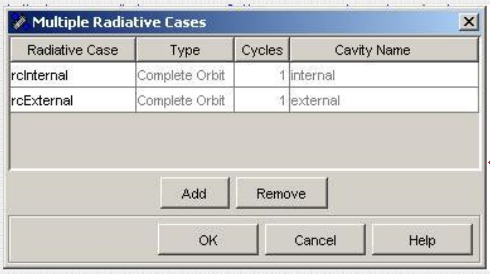
Radiative Cavities - Radiative Analysis

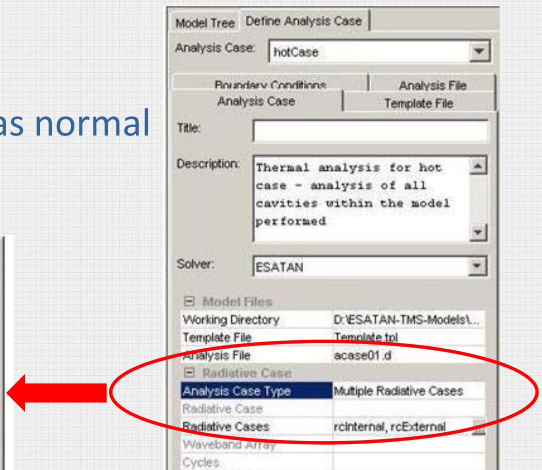
- Radiative analysis performed on each cavity
  - Introduced Geometry attribute on Radiative Case definition
  - Select geometry, Whole Model, Cavity or Not in Cavity
  - Default Whole Model
  - Select Cavity
  - VF/REF/HF results depend only on cavity geometry/properties

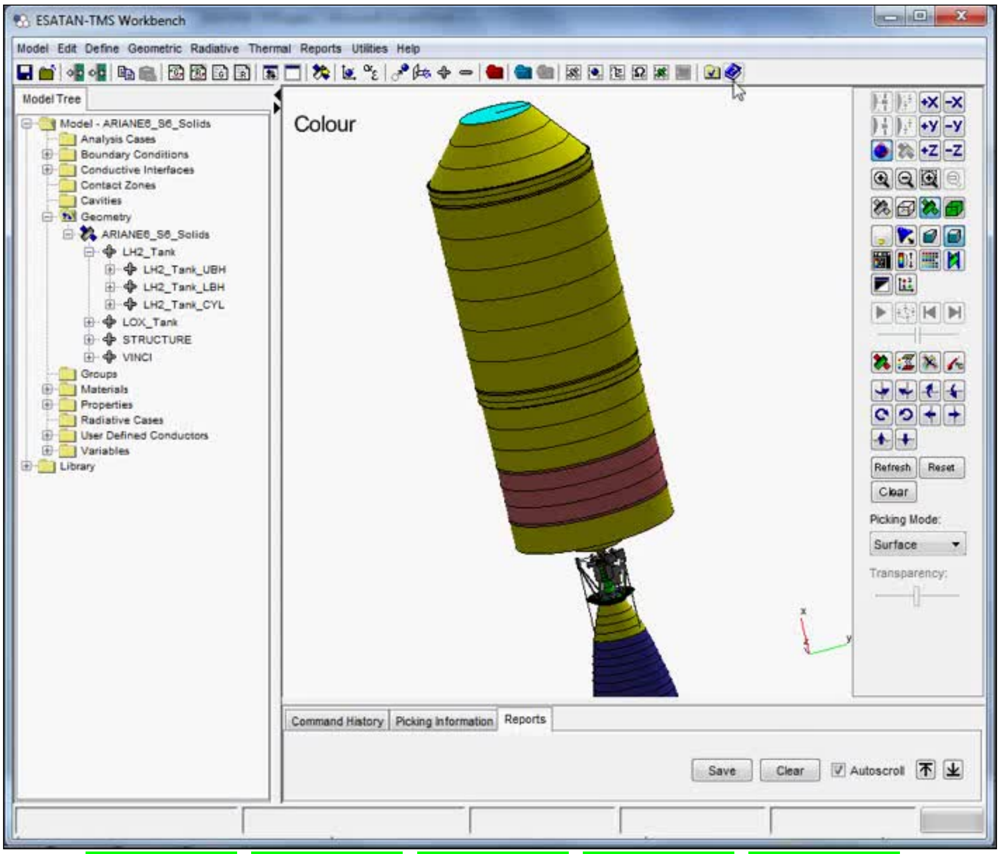


Radiative Cavities - Thermal Analysis

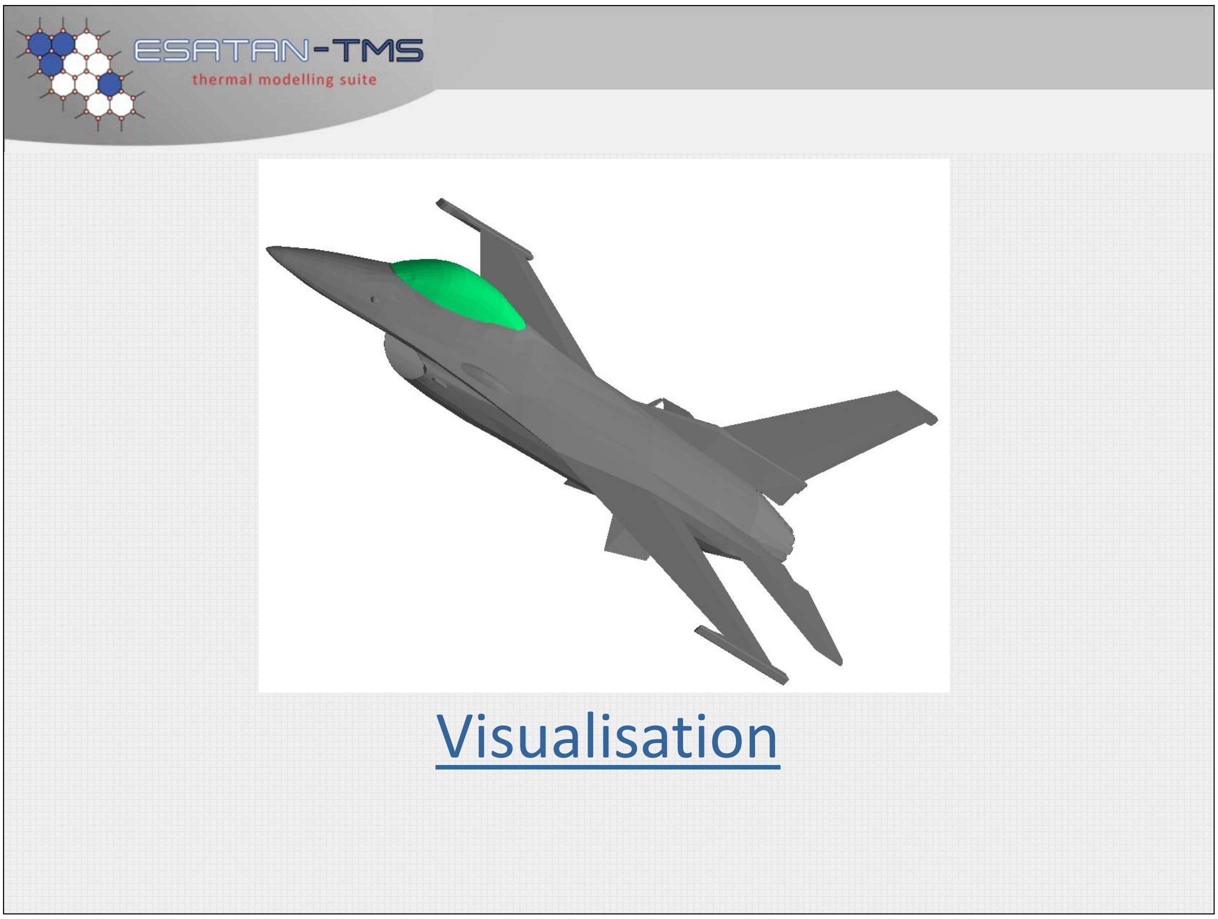
- Analysis Case used to run the analysis as a single case
  - New Analysis Case Type "Multiple Radiative Cases"
  - Select Radiative Cases
  - Generate single analysis file
  - Post-process thermal results as normal

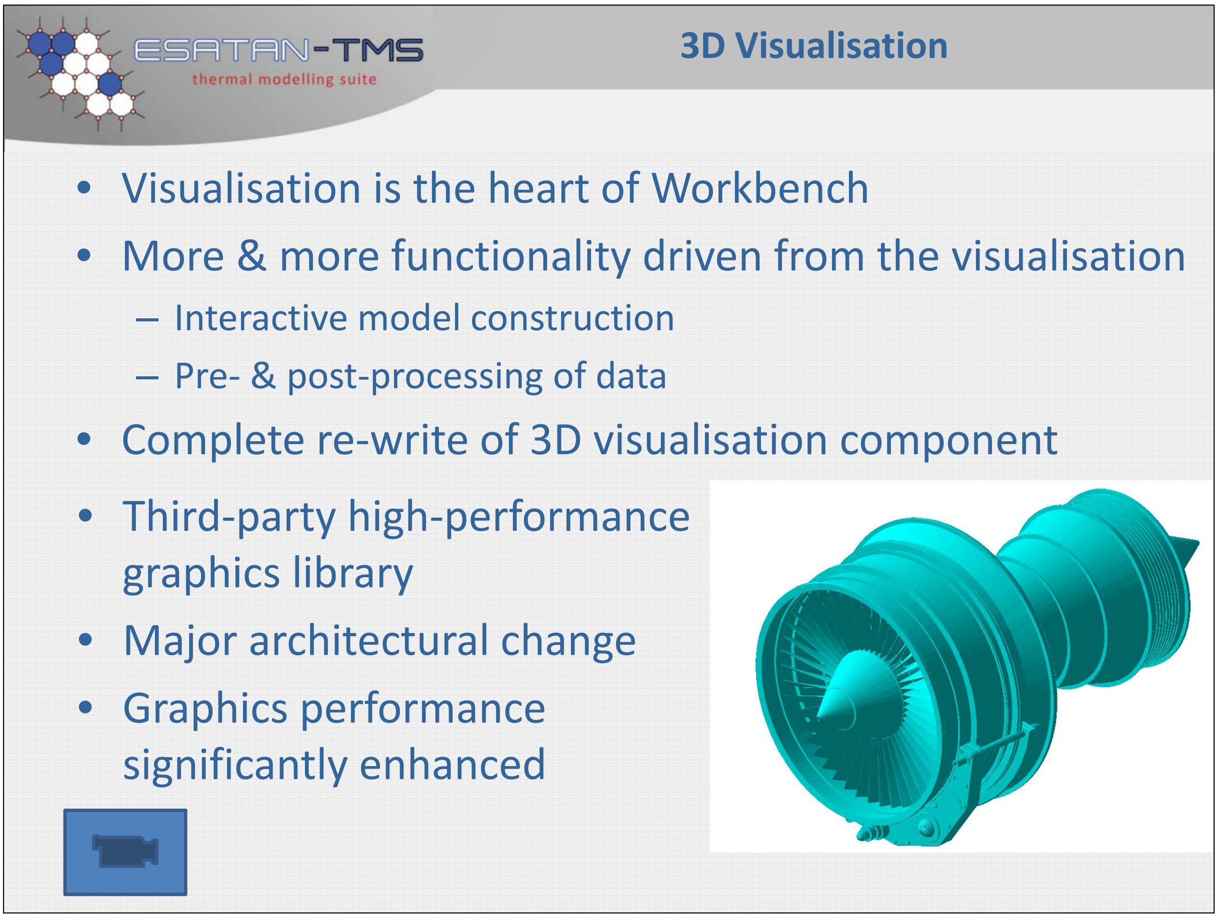






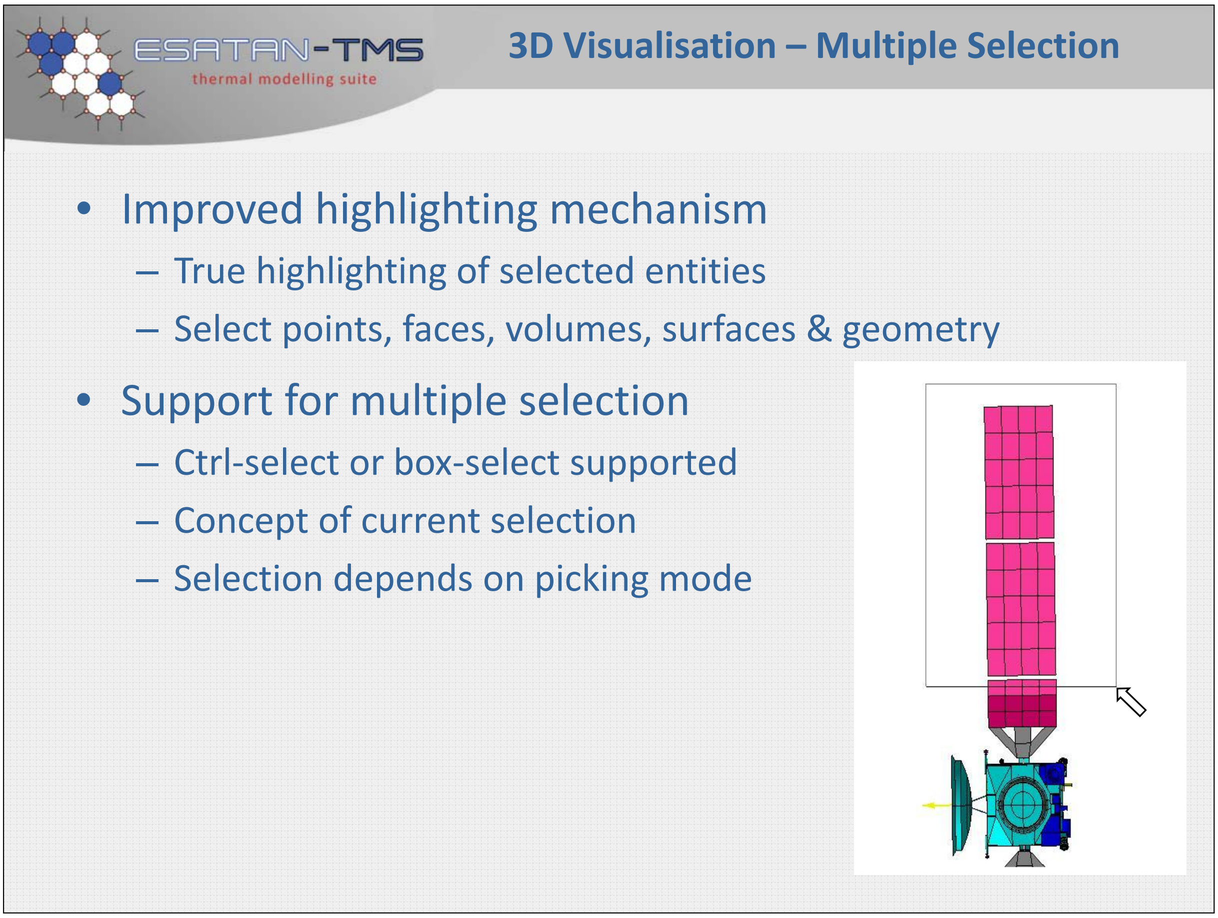
Slow Normal Fast Play/Pause Stop




ESATAN-TMS
thermal modelling suite
3D Visualisation
• Visualisation is the heart of Workbench
• More & more functionality driven from the visualisation
– Interactive model construction
– Pre- & post-processing of data
• Complete re-write of 3D visualisation component
• Third-party high-performance graphics library
• Major architectural change
• Graphics performance significantly enhanced


Colour
Slow
Normal
Fast
Play/Pause
Stop

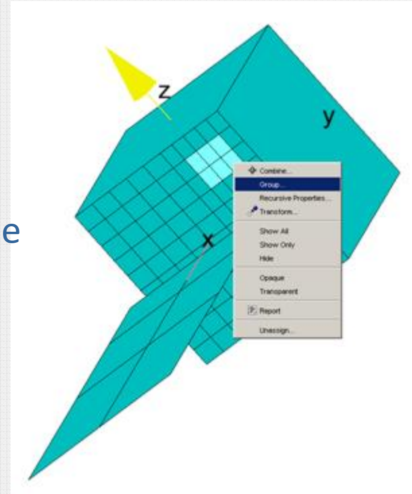
Slow | Normal | Fast | Play/Pause | Stop



ESATAN-TMS thermal modelling suite

3D Visualisation - Interactivity

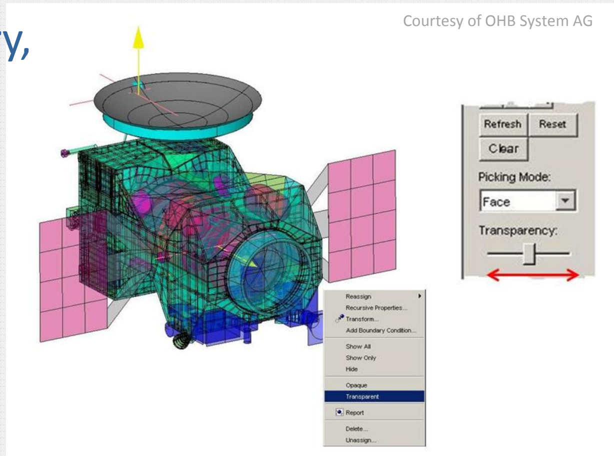
- Improved highlighting mechanism
  - True highlighting of selected entities
  - Select points, faces, volumes, surfaces & geometry
- Support for multiple selection
  - Ctrl-select or box-select supported
  - Concept of current selection
  - Selection depends on picking mode
  - Dialogs updated to work with multiple selection
    - Groups dialog
    - Combine Geometry dialog
    - Process Conductive Interfaces dialog

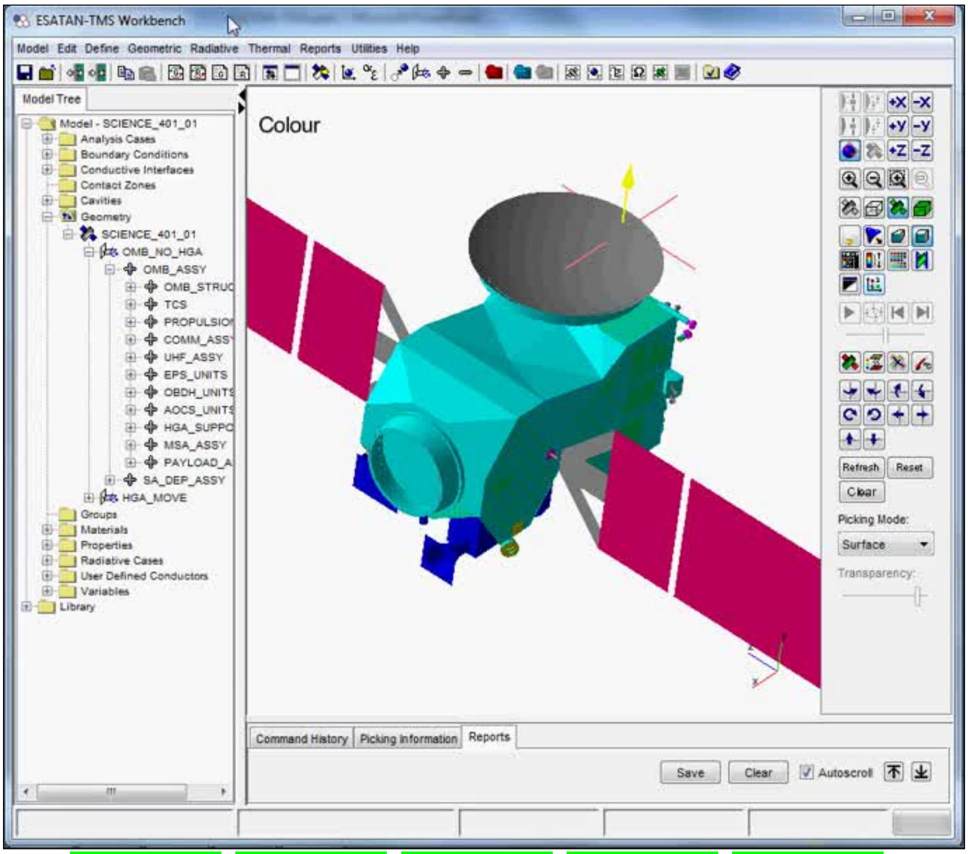


ESATAN-TMS thermal modelling suite

3D Visualisation - Transparency

- Support for transparency provided
- Select geometry from model tree or visualisation
- Global transparency level
- Expose internal geometry, conductive interfaces, cavities, ….





Slow | Normal | Fast | Play/Pause | Stop

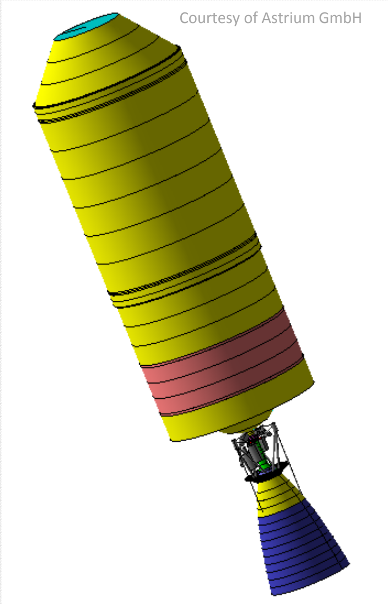
ESATAN-TMS r6 - Overall Conclusion

ESATAN-TMS
thermal modelling suite

- ESATAN-TMS release 6 is now approved for release
- >10 man-years of development
- Major architectural changes to the product

ESATAN-TMS r6 - Overall Conclusion

- Support for 2D and 3D geometry
  - Major architectural change
  - Clean & logical extension
  - Terminology & solids support extended through the product
  - Performed under joint ESA / ITP contract
  - Meets the primary requirements of Astrium Launchers
    - Involvement in the definition of the requirements
    - Provision of alpha & beta releases



ESATAN-TMS r6 - Overall Conclusion

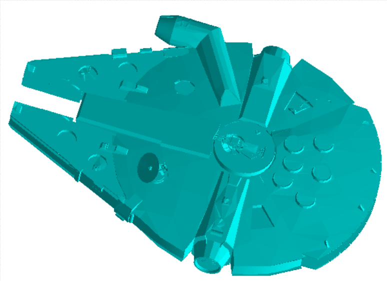
- New visualisation component
  - Major architectural change
  - High-performance graphics
  - Provide platform for future developments
  - Added transparency, revised clipping plane & multiple selection

The large investment demonstrates both ESA's and ITP's continued commitment to ESATAN-TMS

ESATAN-TMS thermal modelling suite

Future Development

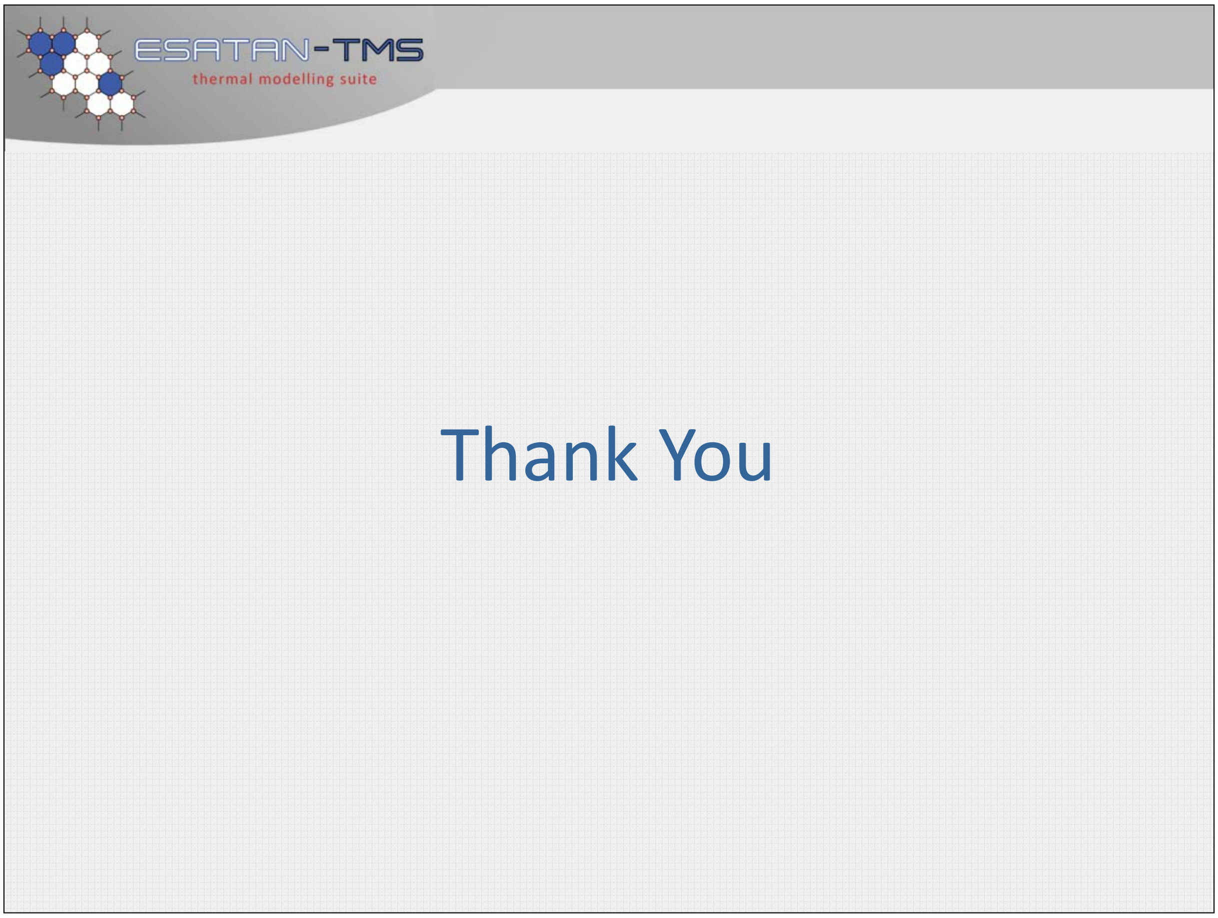
- Where are we going?
  - "Provide a **complete** and **effective** thermal modelling environment"
    - Further developments are already underway
    - Create more of the thermal model through Workbench
    - Efficient handling of the thermal data
    - Better pre- & post-processing of data, the right information at the right time of the process



ESATAN-TMS thermal modelling suite

Overall Conclusion

- Input through the customer survey
  - Currently processing results from recent survey
  - Thank you for your response to the survey
  - Information will be fed directly into our development plan
  - Prize winner is Bryan Shaughnessy, Head of the Thermal Engineering Department at RAL Space


ESATAN-TMS
thermal modelling suite
Thank You

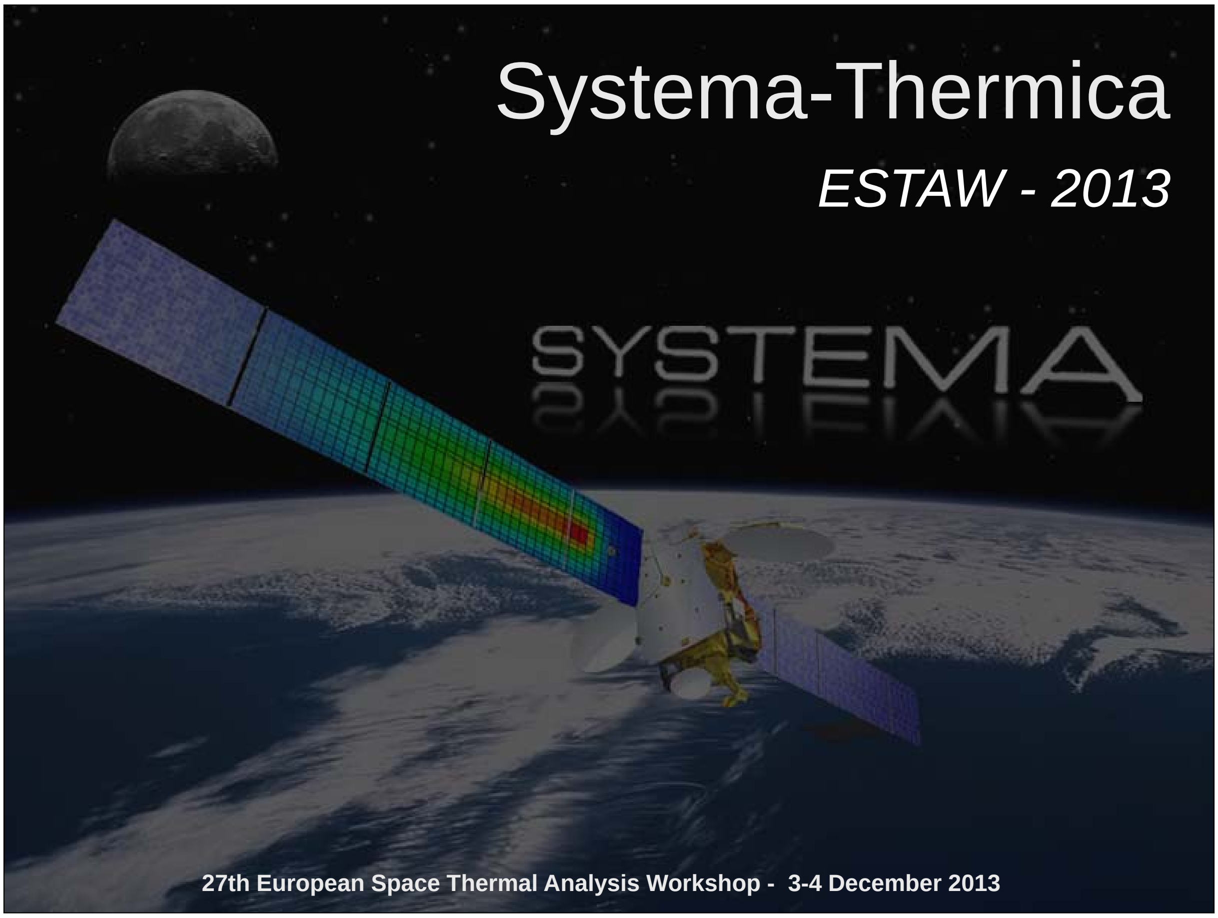
Appendix R

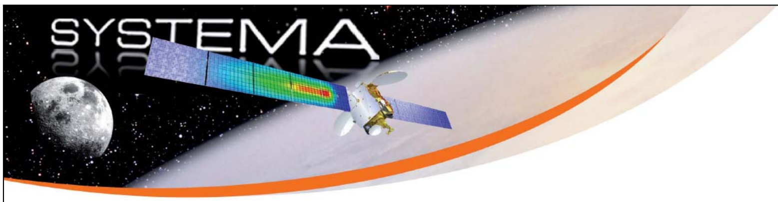
SYSTEMA-THERMICA
Launcher Case Set-up and Thermal Analysis

Timothée Soriano Rose Nerriere
(Astrium SAS, Toulouse, France)

Abstract

Thermal analyses of launchers have specific constraints which have been integrated in the up-coming release 4.7 of SYSTEMA-THERMICA. This presentation illustrates through a demonstration the newly integrated features allowing a launcher case set-up.
A new catalogue of volume primitives, required for modeling the launcher, has been added. The software handles the generation of external coating and internal bulk nodes and also automatically switches the activities according to contact detections.
On the mission aspects, launcher trajectories and attitudes are usually defined by discretized data expressed in complex inertial frames (synchronization of rotational frames related to the launcher base position).
Once the geometrical model and mission are set-up, the thermal analysis can start.
The thermal analysis of the previously defined launcher case requires the computation of the conduction into the volume structures as well as radiative exchanges between external coatings, planet Albedo and IR, solar and aero-thermal fluxes.
The presentation focuses on the volume management and on the new aero-thermal flux module which integrates an atmospheric model.
Besides, the new SYSTEMA version 4.7 has new post-processing features: from the generation of mission log data to the comparison of different thermal cases and margins set-up, results based on the launcher case are exploited.





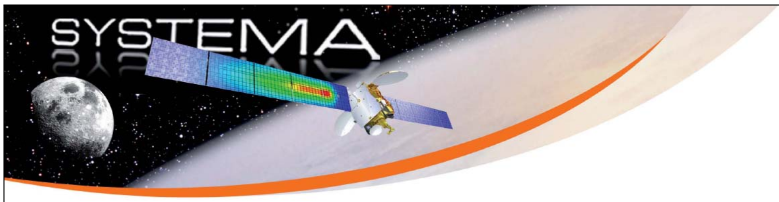
Current status

- Long Time Support current version: v4.5.3 08/2013
- Latest Release: v4.6.1 08/2013
  - Integrates new major features:
    - Volumes
    - Aero-Thermal Fluxes
    - EME2000 import
    - Frozen rotational frames
    - Mission Data
    - Upgrade of memory performances
  - 64bits version for Linux
  - And lots of evolutions and corrections:

    New icons & toolbars, New Python functions…

    Mercury eclipses corrected, Velocity interpolation…

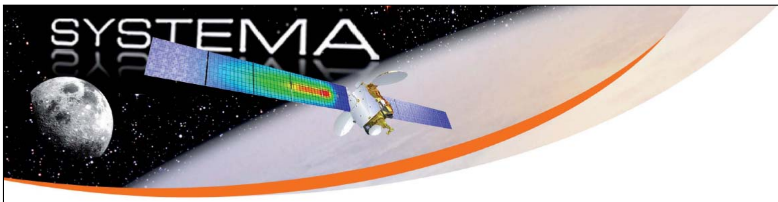
27th European Space Thermal Analysis Workshop - 3-4 December 2013



Current status

- **Next Release:** v4.7.0 06/2014
  - Integrates new features:
    - ➢ CAD management
      - Native import of CATIA files
      - Defeaturing
      - Tessellation
    - ➢ Post-Processing Tab
    - ➢ Extended Python interface to all SYSTEMA Tabs
  - 64bits version for Windows

27th European Space Thermal Analysis Workshop - 3-4 December 2013

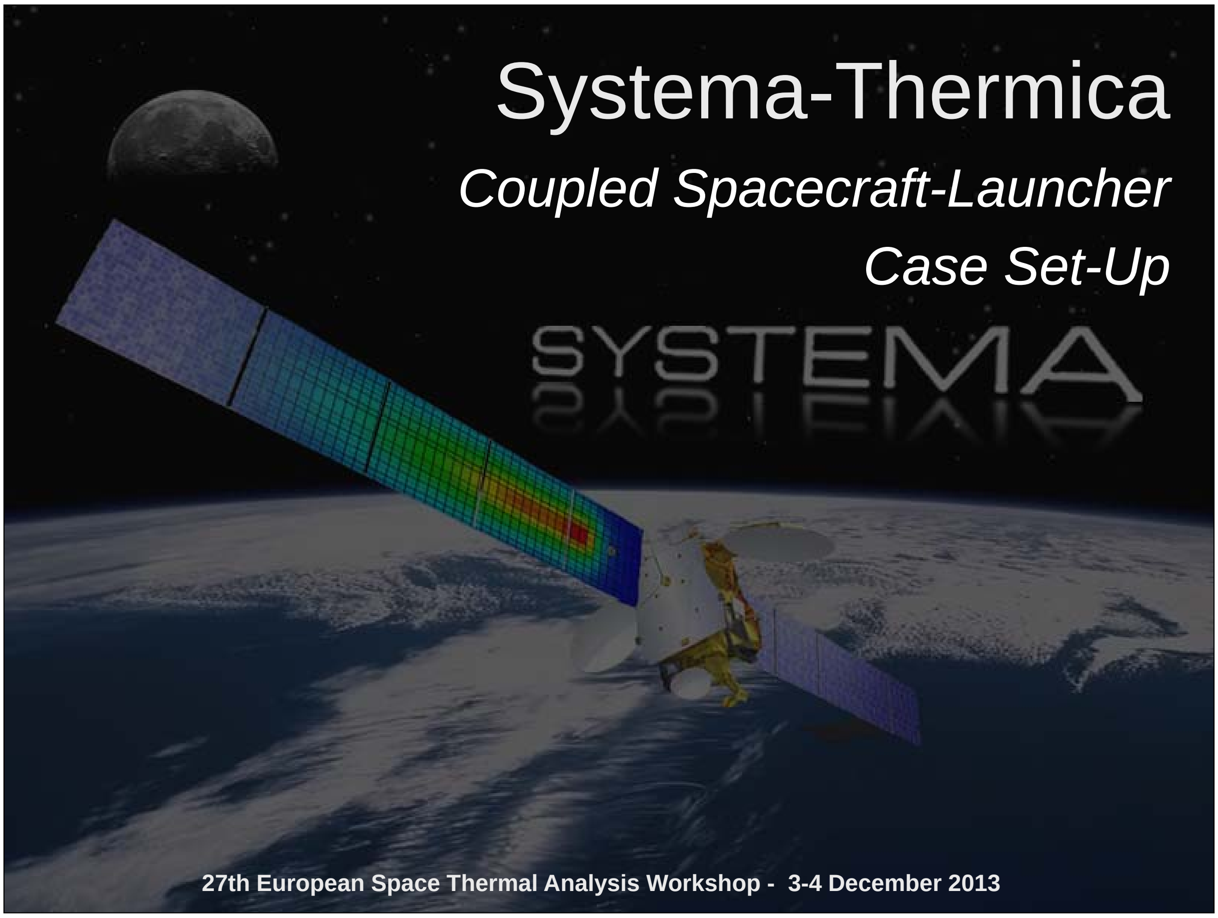


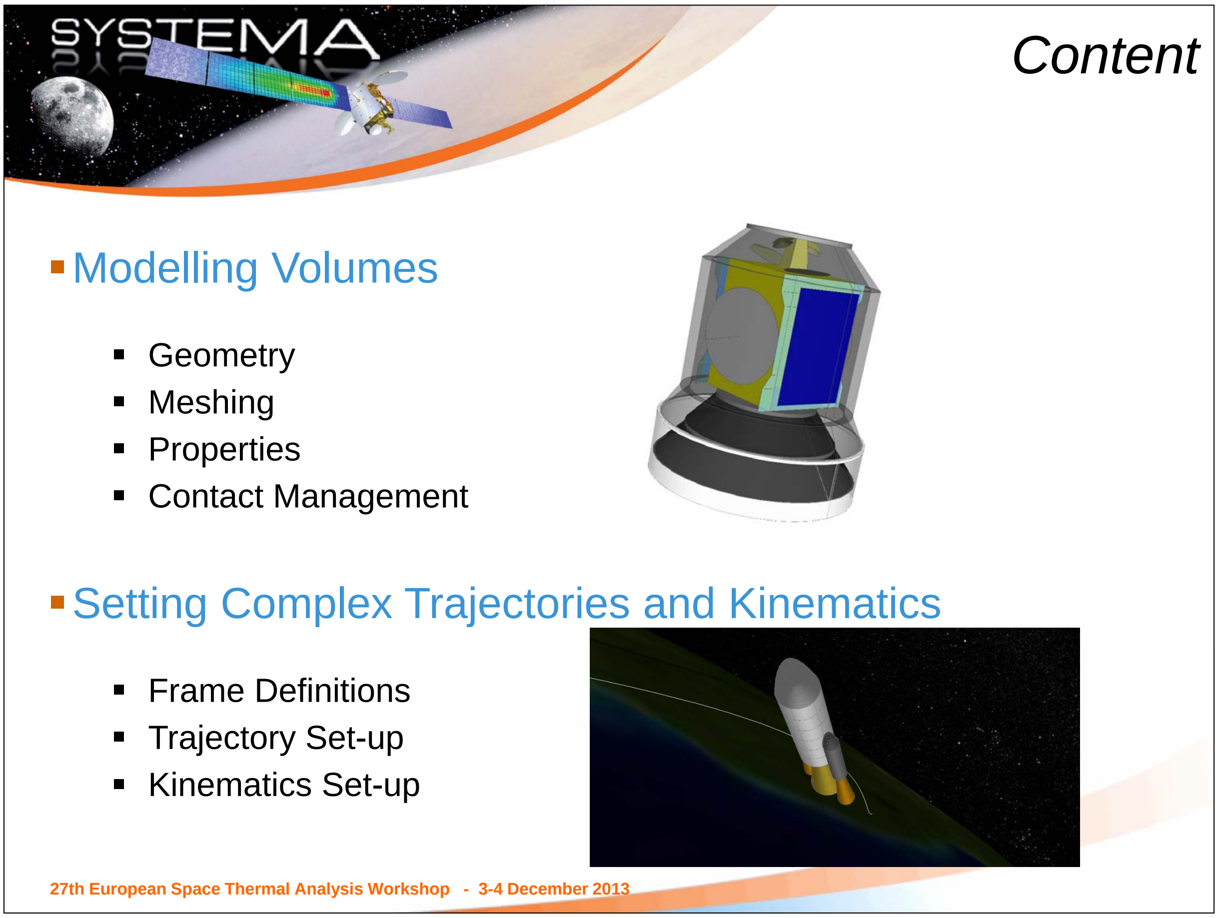
Content

- **Coupled Spacecraft – Launcher Case Set-Up**
  - Volumes
  - Mission
- **Coupled Spacecraft – Launcher Thermal Analysis**
  - THERMICA, THERMISOL
  - Post-Processing

This analysis scenario illustrates new features
of 4.6 and 4.7 releases
Also applicable to satellite thermal analysis

27th European Space Thermal Analysis Workshop - 3-4 December 2013


Systema-Thermica
Coupled Spacecraft-Launcher
Case Set-Up
SYSTEMA
27th European Space Thermal Analysis Workshop - 3-4 December 2013


SYSTEMA
Content
Modelling Volumes
Geometry
Meshing
Properties
Contact Management
Setting Complex Trajectories and Kinematics
Frame Definitions
Trajectory Set-up
Kinematics Set-up
27th European Space Thermal Analysis Workshop - 3-4 December 2013

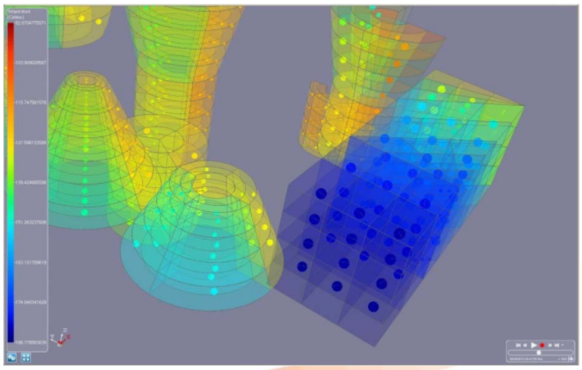
SYSTEMA

Volumes

New Volume Shapes

- **Boxes, Tetrahedrons**
  Extruded Triangles, Extruded Quadrangles
  Cylinders, Cones, Spheres
  Revolved Quadrangles

- Default & Interactive Creations



27th European Space Thermal Analysis Workshop - 3-4 December 2013

SYSTEMA

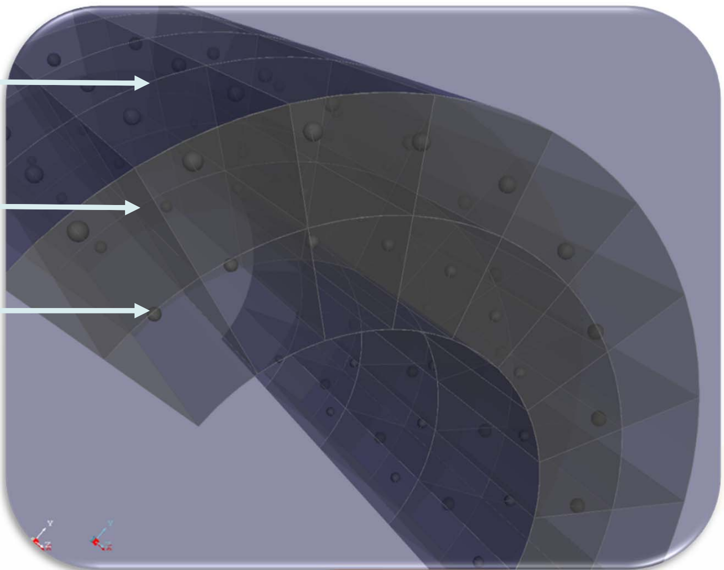
Volumes

Physical Properties & Meshing

- **External Faces**
  with Coating
  (external GR & Fluxes)

- **Internal Faces**
  (internal GL)

- **Volumes**
  with Bulk
  (Cp, Ql)



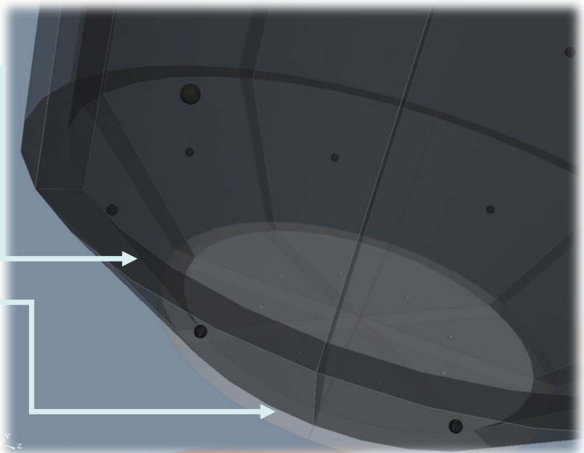
27th European Space Thermal Analysis Workshop - 3-4 December 2013

SYSTEMA

Volumes

Contact Management

- Conformant contact (without surface contact resistance):
  - *Automatic Merge of external nodes*
  - *Deactivation of coating activity*
- Using Surface Contact Resistance
  - *Creation of resistance couplings*

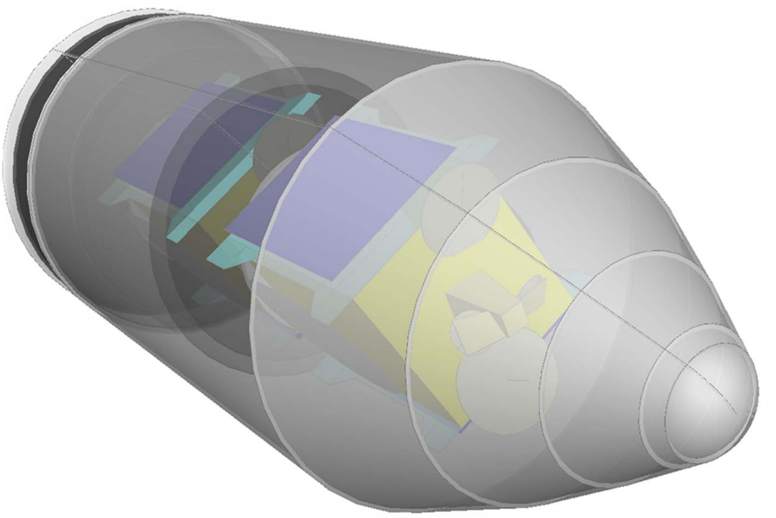


27th European Space Thermal Analysis Workshop - 3-4 December 2013

SYSTEMA

Volumes

Demonstration



27th European Space Thermal Analysis Workshop - 3-4 December 2013

Trajectories & Kinematics

Context

Launcher Mission Data are often expressed in complex frames
(inertial frames inherited from frozen rotational frames)

- *Equatorial Frame (Trajectory)*
- *Launch Pad Frame (Kinematics)*

These Data are usually not suitable for thermal tools and need a non-trivial conversion…

… except in SYSTEMA since the v4.6

27th European Space Thermal Analysis Workshop - 3-4 December 2013

Trajectories & Kinematics

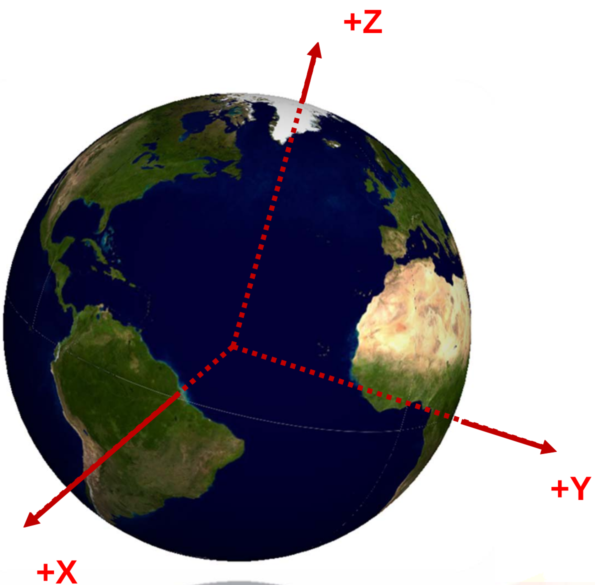
Frame Definitions

- Equatorial Frame:

Rotated Greenwich frame
with +X to Launch Pad Meridian

Fixed to Inertial frame at
Launch time minus x seconds

Used in Trajectories Data



27th European Space Thermal Analysis Workshop - 3-4 December 2013

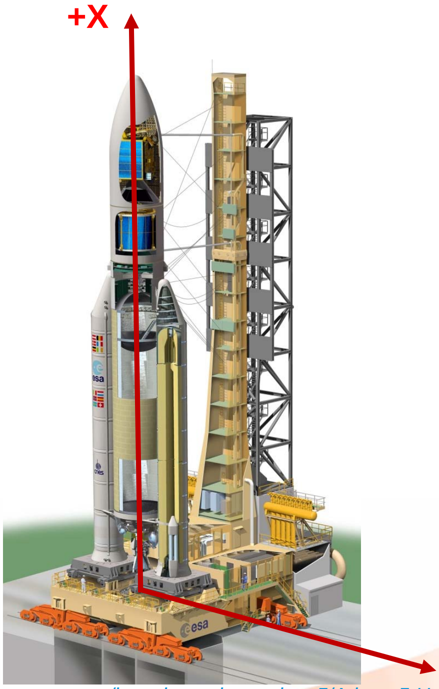
SYSTEMA

Trajectories & Kinematics

- Frame Definitions
  - Launch Pad Frame:

Fixed to Inertial frame at launch time minus *x* seconds

Used in Kinematics Data



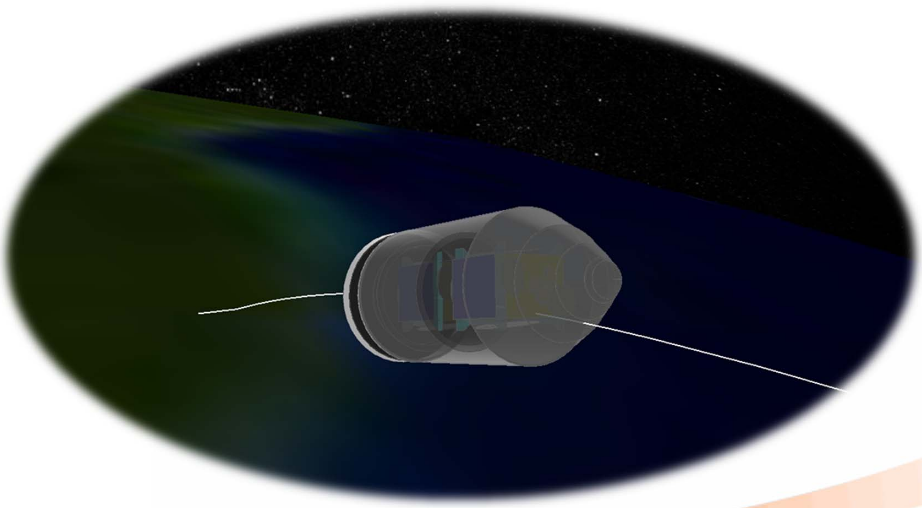
Source : www.arianespace.com/launch-services-ariane5/Ariane-5-User's-Manual.as

27th European Space Thermal Analysis Workshop - 3-4 December 2013

SYSTEMA

Trajectories & Kinematics

Demonstration



27th European Space Thermal Analysis Workshop - 3-4 December 2013

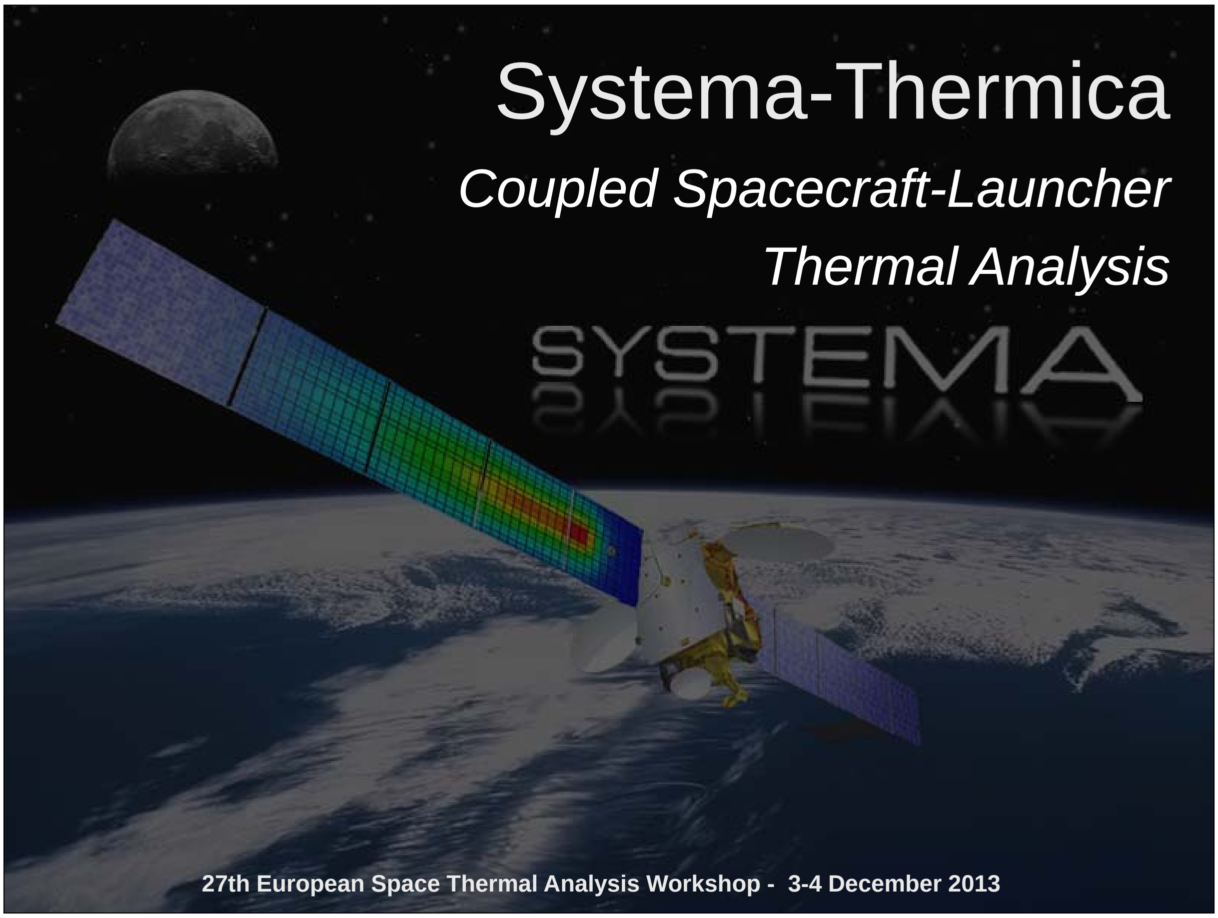
Trajectories & Kinematics

- Using Launcher Data directly into SYSTEMA

  - No Need to Convert in standard inertial references
  - Definition of Mission independent of a launch time
  - Suitable for all Launch Pads and all frame synchronisation specifications

In general, SYSTEMA is able to handle any complex mission
Observation satellite with manoeuvers, Transfer Orbits, Rovers, Interplanetary missions, …

27th European Space Thermal Analysis Workshop - 3-4 December 2013



Content

- THERMICA simulation
  - Nodal Description – Management of Volumes nodes and contacts
  - Conduction – Creation of Volume couplings
  - New Aero-Thermal flux module

- Post-Processing results in SYSTEMA
  - 2D curves and 3D animated results
  - Mission data
  - New Post-Processing dedicated tab

27th European Space Thermal Analysis Workshop - 3-4 December 2013

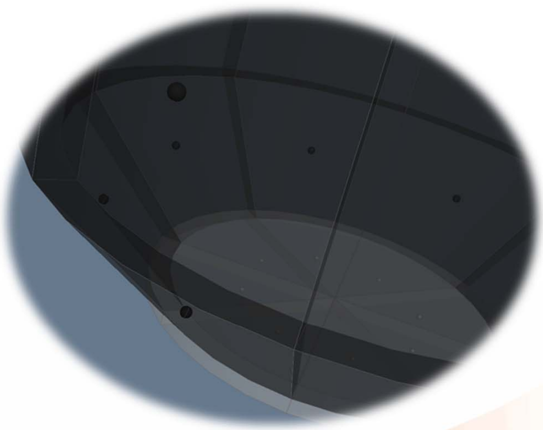
THERMICA

- Nodal Description:
  Management of Volumes nodes and contacts

```
# Volume surface contact: nodes merged
D   900000001 = CURRENT:425 + CURRENT:533;
D   900000002 = CURRENT:426 + CURRENT:534;
D   900000003 = CURRENT:427 + CURRENT:535;
D   900000004 = CURRENT:428 + CURRENT:536;
D   900000005 = CURRENT:429 + CURRENT:537;
D   900000006 = CURRENT:430 + CURRENT:538;
D   900000007 = CURRENT:431 + CURRENT:539;
D   900000008 = CURRENT:432 + CURRENT:540;
D   900000009 = CURRENT:850 + CURRENT:933;
D   900000010 = CURRENT:851 + CURRENT:934;
D   900000011 = CURRENT:852 + CURRENT:935;
```

```
$CONDUCTORS
    # Surface contacts
      GL( 125 , 233 )  =  3.619E+00;  #Cone3936_Bottom_Carbon_Alu_Contact
      GL( 126 , 234 )  =  3.619E+00;  #Cone3936_Bottom_Carbon_Alu_Contact
      GL( 127 , 235 )  =  3.619E+00;  #Cone3936_Bottom_Carbon_Alu_Contact
      GL( 128 , 236 )  =  3.619E+00;  #Cone3936_Bottom_Carbon_Alu_Contact
      GL( 129 , 237 )  =  3.619E+00;  #Cone3936_Bottom_Carbon_Alu_Contact
      GL( 130 , 238 )  =  3.619E+00;  #Cone3936_Bottom_Carbon_Alu_Contact
      GL( 131 , 239 )  =  3.619E+00;  #Cone3936_Bottom_Carbon_Alu_Contact
      GL( 132 , 240 )  =  3.619E+00;  #Cone3936_Bottom_Carbon_Alu_Contact

      GL( 133 , 325 )  =  2.331E+00;  #Cone3936_Top_Carbon_Alu_Contact
      GL( 134 , 326 )  =  2.331E+00;  #Cone3936_Top_Carbon_Alu_Contact
      GL( 135 , 327 )  =  2.331E+00;  #Cone3936_Top_Carbon_Alu_Contact
```



27th European Space Thermal Analysis Workshop - 3-4 December 2013

SYSTEMA THERMICA

▪ Conduction: Creation of volume Couplings

Using the **RCN** method on combined mid-planes
with thickness corrections

```
# Couplings from volume node 546
GL(546, 505) =   8.176E+01 * COND_Carbon;
GL(546, 513) =   8.294E+01 * COND_Carbon;
GL(546, 521) =   7.742E-02 * COND_Carbon;
GL(546, 522) =   7.742E-02 * COND_Carbon;
GL(546, 530) =   1.438E+00 * COND_Carbon;
GL(546, 538) =   1.438E+00 * COND_Carbon;
GL(505, 513) =  -2.350E+01 * COND_Carbon;
GL(505, 521) =  -7.705E-03 * COND_Carbon;
GL(505, 522) =  -7.705E-03 * COND_Carbon;
GL(513, 521) =  -7.400E-03 * COND_Carbon;
GL(513, 522) =  -7.400E-03 * COND_Carbon;
GL(521, 522) =  -2.085E-02 * COND_Carbon;
GL(530, 538) =  -4.795E-01 * COND_Carbon;
```

27th European Space Thermal Analysis Workshop - 3-4 December 2013

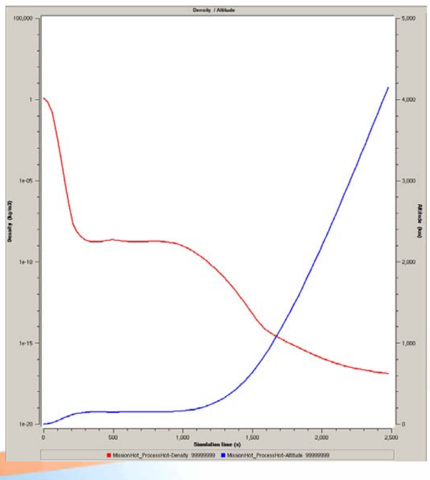
SYSTEMA THERMICA

▪ Aero-Thermal Flux *for free molecular atmosphere*

- Includes an Atmospheric Model (*US76*)
  May be by-passed to include custom tables
  Possibility to implement Msis models if required

- Computes Environmental Data vs Simulation Time:
  - *Altitude*
  - *Atmosphere Density*
  - ‘’ *Temperature*
  - *Aero-Thermal flux Constant*

  - *Cross Section with Velocity*



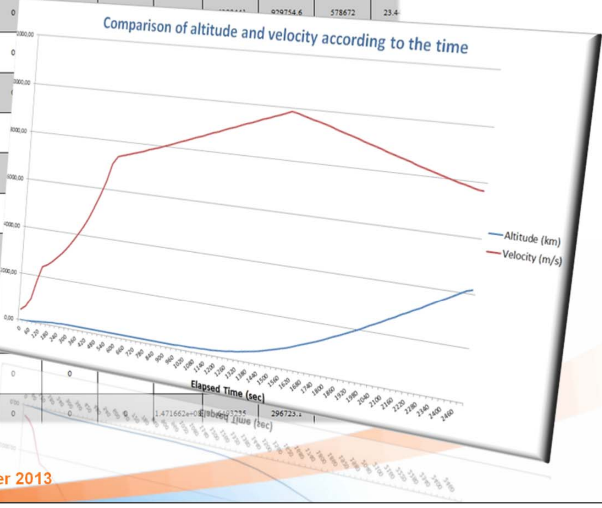
27th European Space Thermal Analysis Workshop - 3-4 December 2013

Post-Processing

- **Mission Data:** Exports all mission data to an html file

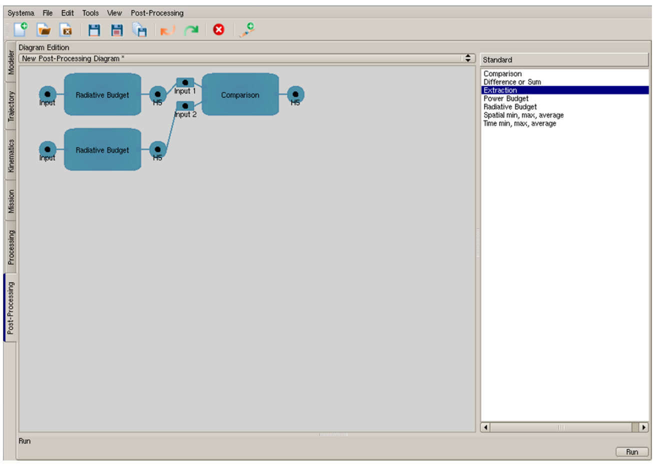
Mission

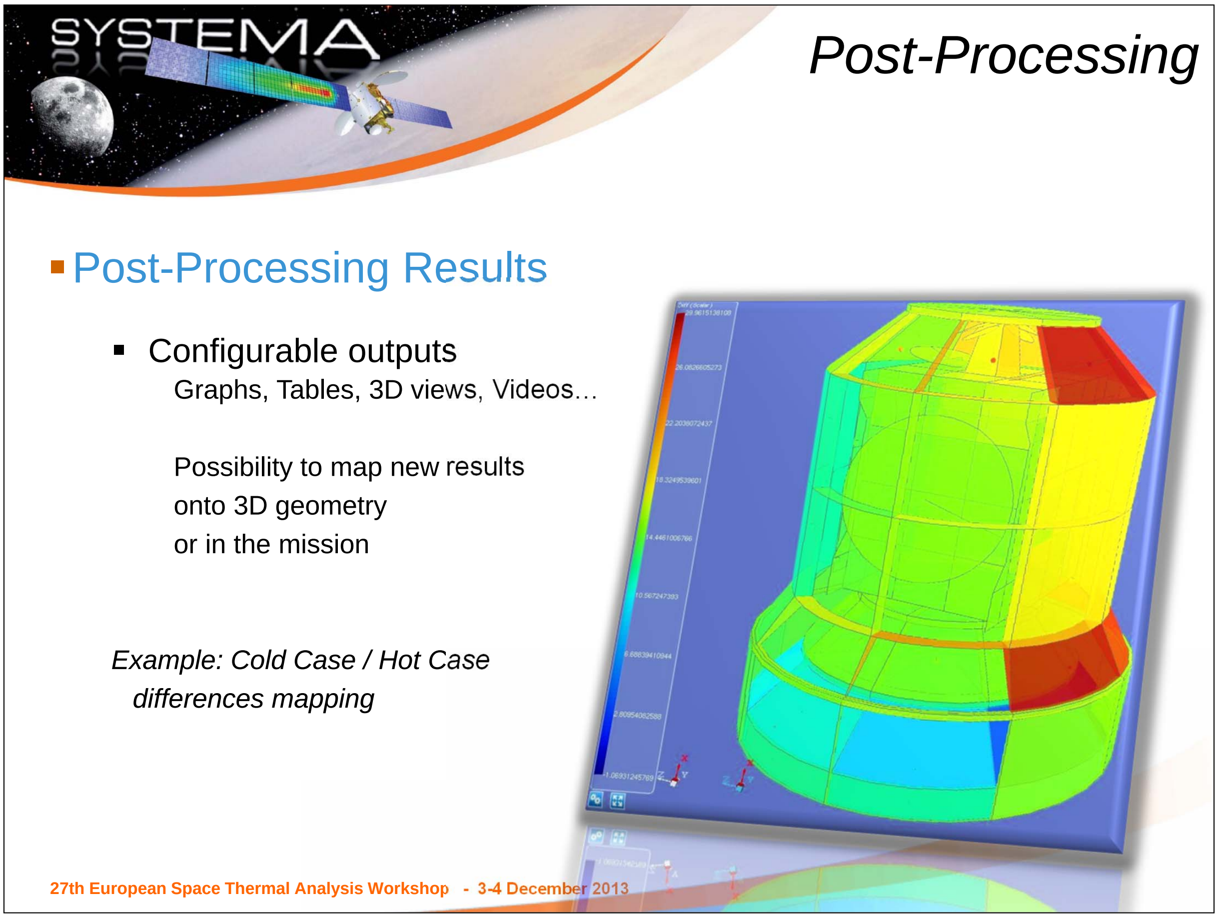
Computation point	Date	Date (Gamma 50)	Date (J2000)	Current Phase	Current Sequence	Current arc	Sun constant (W/m2)	Inertial transformation Sun to S/C (Ecliptic M50) - Tx (m)	Inertial transformation Sun to S/C (Ecliptic M50) - Ty (m)	Inertial transformation Sun to S/C (Ecliptic M50) - Tz (m)	Inertial transformation Sun to S/C (Ecliptic M50) - Rx (°)	Inertial transformation Sun to S/C (Ecliptic M50) - Ry (°)	Inertial transformation Sun to S/C (Ecliptic M50) - Rz (°)	Distance from Sun to S/C (km)	Inertial transformation Earth to S/C (M50) - Tx (m)	Inertial transformation Earth to S/C (M50) - Ty (m)	Inertial transformation Earth to S/C (M50) - Tz (m)	Inertial transfor… Earth… (M50) - …
Computation generated event (1)	21/12/2013 09:00:15.050	23365.37517419	5102.87517419	Default phase		New Time-Position-Velocity	1416.979	8.707879e+08	1.471643e+11	589335.7	0				[illegible]	929754.6	578672	23.4…
Computation generated event (2)	21/12/2013 09:00:45.050	23365.37552141	5102.87552141	Default phase		New Time-Position-Velocity	1416.979	8.698724e+08	1.471643e+11	595489.9	0							
Computation generated event (3)	21/12/2013 09:01:15.050	23365.37586863	5102.87586863	Default phase		New Time-Position-Velocity	1416.979	8.689509e+08	1.471642e+11	604093.9								
Computation generated event (4)	21/12/2013 09:01:45.050	23365.37621586	5102.87621586	Default phase		New Time-Position-Velocity	1416.98	8.680206e+08	1.471642e+11	618668								
Computation generated event (5)	21/12/2013 09:02:15.050	23365.37656308	5102.87656308	Default phase		New Time-Position-Velocity	1416.981	8.670791e+08	1.471642e+11	643072								
Computation generated event (6)	21/12/2013 09:02:45.050	23365.3769103	5102.8769103	Default phase		New Time-Position-Velocity	1416.982	8.661392e+08	1.471641e+11	671468.2								
Computation generated event (7)	21/12/2013 09:03:15.050	23365.37725752	5102.87725752	Default phase		New Time-Position-Velocity	1416.984	8.652033e+08	1.47164e+11	701708.4								
Computation generated event (8)	21/12/2013 09:03:45.050	23365.37760475	5102.87760475	Default phase		New Time-Position-Velocity	1416.985	8.642713e+08	1.47164e+11	733909.3								
Computation generated event (9)	21/12/2013 09:04:15.050	23365.37795197	5102.87795197	Default phase		New Time-Position-Velocity	1416.987	8.633432e+08	1.471639e+11	768244.5								
Computation generated event (10)	21/12/2013 09:04:45.050	23365.37829919	5102.87829919	Default phase		New Time-Position-Velocity	1416.989	8.62419e+08	1.471638e+11	804881.3	0							
Computation generated …	21/12/2013 09:05:15.050	23365.37864641	5102.87864641	Default phase		New Time-Position-…	1416.991	8.614986e+08	1.471637e+11	844006.7	0					296723.…		

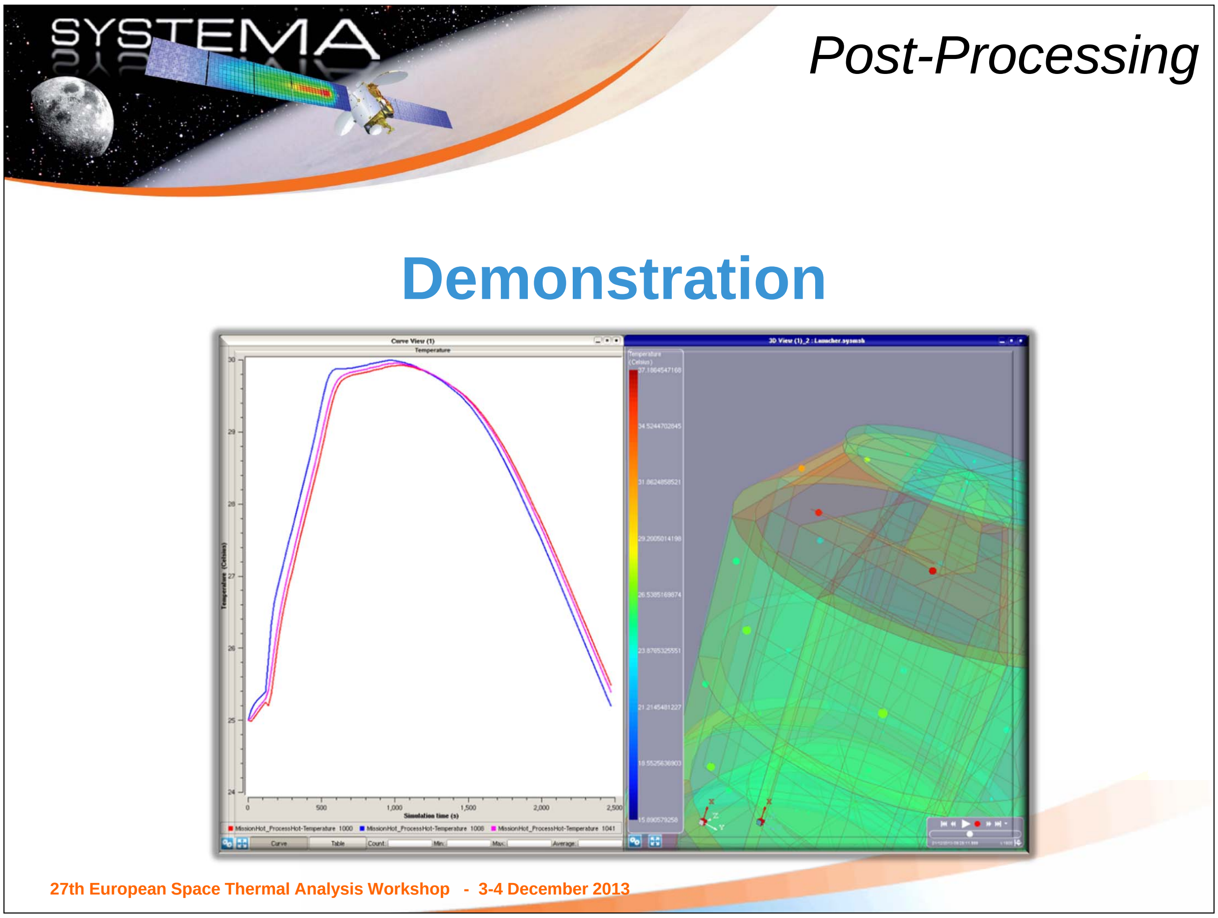


Post-Processing

- **Post-Processing Diagram**
  - Tool Box
    Min/Max, Flux Budget, Compare
    Extract, Tsink…
  - Possibility to set a diagram
    Example:
    Comparison of radiative budget
  - Possibility to create custom boxes
  - Configurable inputs
    Definition of groups and collections
    Time and data filters…




SYSTEMA
Post-Processing
Post-Processing Results
Configurable outputs
Graphs, Tables, 3D views, Videos…
Possibility to map new results
onto 3D geometry
or in the mission
Example: Cold Case / Hot Case
differences mapping
27th European Space Thermal Analysis Workshop - 3-4 December 2013


SYSTEMA
Post-Processing
Demonstration
27th European Space Thermal Analysis Workshop - 3-4 December 2013

SYSTEMA

Conclusion

▪ New features presented — *Usable for Launcher as for Satellite*

- Volumes
  - Automated Management of Coatings and Contacts
  - Conduction
- Management of complex Trajectories and Kinematics frames
  - Possibility to define inertial references derived from rotational frames
  - Customization of frame synchronisations
- Aero-Thermal Flux
  - For free molecular atmosphere (altitudes > 100km)
- Post-Processing Tab

27th European Space Thermal Analysis Workshop - 3-4 December 2013

SYSTEMA

THERMICA Advanced Training

▪ Next Class: 11-12 february 2014

- Advanced Model Setting
  - ➢ *Using Variables & Dependencies*
  - ➢ *Managing Distinct Sides Nodes*
- Using the RCN conductive module
- Advanced Mission Setting
  - ➢ *Opened / Closed Cavities & Complex Mission scenarios*
- Python interface & Batch executions
- Advanced THERMISOL features
  - ➢ *Using Events, Sub-models, User nodal entities*
  - ➢ *Parsing nodes & couplings: use of Mortran language & specific fonctions*
  - ➢ *Tuning the output data of the h5 file*

27th European Space Thermal Analysis Workshop - 3-4 December 2013

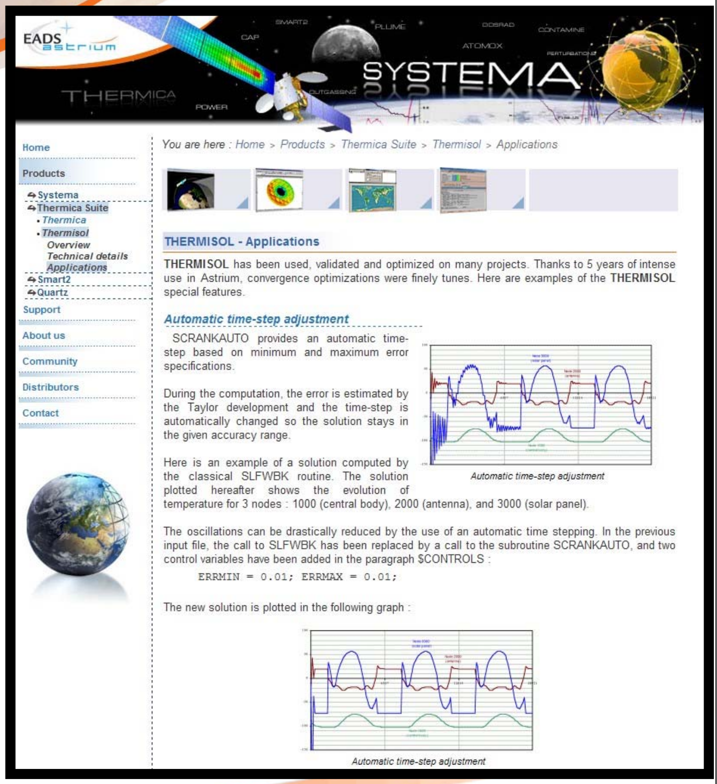
SYSTEMA
THERMICA
THERMISOL

Visit our Web site :

www.systema.astrium.eads.net

Contact :

timothee.soriano@astrium.eads.net
rose.nerriere@astrium.eads.net
maxime.jolliet@astrium.eads.net
anne.millet@astrium.eads.net



27th European Space Thermal Analysis Workshop - 3-4 December 2013

Trajectories

Setting the Trajectory in SYSTEMA

- Create a trajectory of type: “Time-Position-Velocity”
- Set the data format to: “Cartesian coordinates in a planet inertial reference (frozen planet rotational reference)”
- Set the coordinates to be frozen to:
  Latitude: 0°
  Longitude: -52.7686°
- Set the reference date to freeze the rotational reference

27th European Space Thermal Analysis Workshop - 3-4 December 2013

SYSTEMA

Kinematics

Setting the Kinematics in SYSTEMA

Launch Pad frame Setting:

- Create a “Free Connection”
- Select the kinematic law “Frozen Rotational Orientation”
- Set the reference date to freeze the rotational reference
- Set the rotation sequence in Z-Y’-X” axis with
  X rotation: + Launch Pad AZP angle
  Y rotation: - Launch Pad Latitude
  Z rotation: + Launch Pad Longitude

27th European Space Thermal Analysis Workshop - 3-4 December 2013

SYSTEMA

Kinematics

Setting the Kinematics in SYSTEMA

Launcher frame:

- Create a “Free Connection” from the Launch Pad Frame
- Select the kinematic law “Transformations defined in a file”
- Set the rotation sequence to Z-Y’-X”

Then the launcher attitude will be computed using the Azimuth and Elevation expressed in the Launch Pad Frame.

27th European Space Thermal Analysis Workshop - 3-4 December 2013

Appendix S

First Application of Esatan-TMS r6 Solids for a Launcher Upper Stage Thermal Model

Harold Rathjen
(Atrium, Bremen, Germany)

Abstract

The development of this new feature of Esatan was driven by the need for thermal software that allows a volumetric modeling for heavy launcher structures and the applied thermal protection with thicknesses of up to several cm. This presentation assesses the first experiences with this tool applied on an existing upper stage model created within the Ariane 6 development program. Due to the early project status with a limited number of nodes this model is considered a good test. The advantages in particular of the automatic conductor generation (ACG) in comparison with the previous shell approach will be discussed.

First Application of Esatan-TMS r6 Solids for a Launcher Upper Stage Thermal Model

Harold Rathjen. Astrium Space Transportation TEB12. Bremen

Together the pioneer of the full range of space solutions
for a better life on Earth

27th European Space Thermal Analysis Workshop

Together pioneering excellence

ASTRIUM
AN EADS COMPANY

Esatan-TMS – Why Solid Modelling?

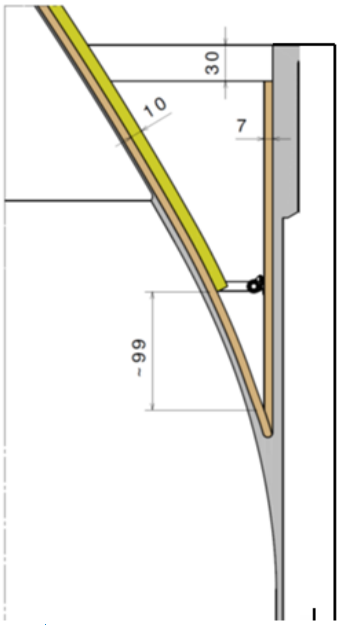
- The development of Esatan r6 was based on the needs of Astrium Les Mureaux and Bremen for a common thermal software for launcher development
- Special emphasis was laid on the introduction of solid type nodes in addition to the usual shell nodes
- It was of particular interest to get a software that was able to generate the majority of the linear conductors within a model (ACG)
- Experiences with ACG in r5 where a thickness and bulk properties were assigned to shells were not satisfying
- This is explained on the following slides

04.12.2013 | Esatan-TMS r6 Solids

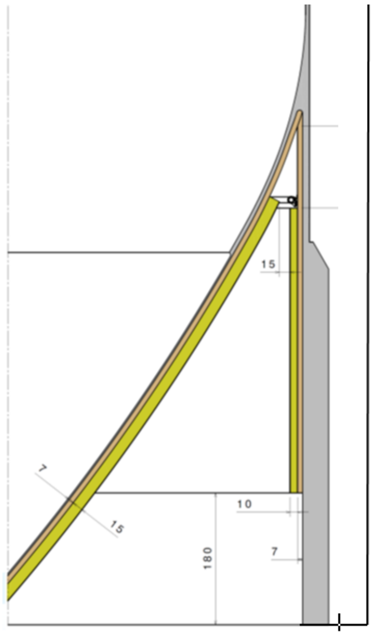
ASTRIUM
AN EADS COMPANY
2

Esatan-TMS – Why Solid Modelling?

- The sample below shows a typical configuration that requires Solid Modelling



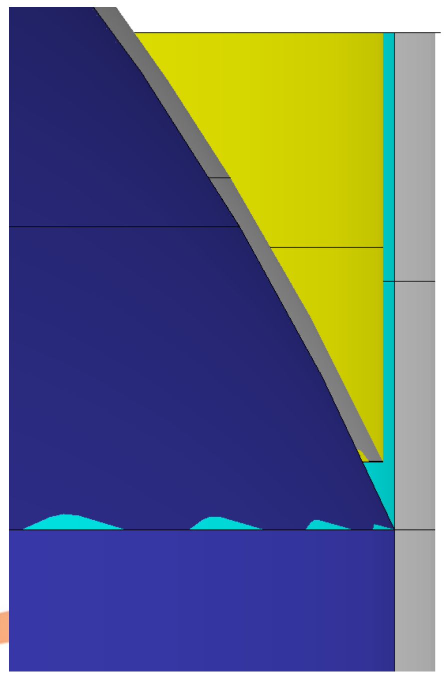
- Propellant tank upper skirt and bulkhead (left) and lower skirt and bulkhead (right)
- Structure with varying thickness
- Multiple layers of thermal insulation
- Thickness depending surface areas



04.12.2013 | Esatan-TMS r6 Solids

Esatan-TMS - Modelling with Shells in r5 - 1

- Insulation surfaces are represented by shells
- Structure is represented by shells (geometrical thickness neglected)
- Advantage of this approach:
  - Surface areas are defined correctly
- Disadvantage:
  - Only partial ACG application is possible due to conflicts with inner/outer area and node numbers
  - Work around was to use multiple GMMs for structure GLs, for insulation GLs and for radiation to be then combined in one TMM



04.12.2013 | Esatan-TMS r6 Solids

ASTRIUM AN EADS COMPANY 4

Esatan-TMS - Modelling with Shells in r5 - 2

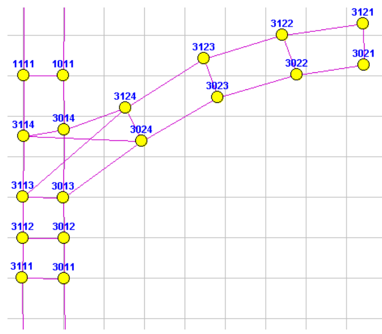
- In this approach the structure and the applied insulation layers are represented by one shell only.
- Advantage of this method:
  - All conductive links except in case of multiple insulation layers are automatically generated by ACG
- Disadvantage:
  - For the latter case only one conductor can be computed by ACG
  - Further disadvantage: Surface areas are not correctly computed
  - Wrong conductors are generated at junctions (next slide)

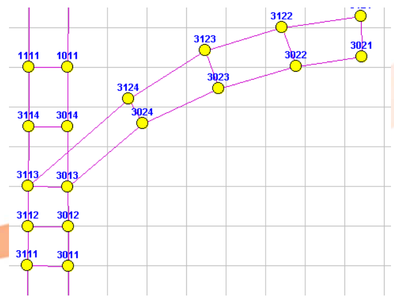
04.12.2013 | Esatan-TMS r6 Solids

ASTRIUM AN EADS COMPANY 5

Esatan-TMS - Modelling with Shells in r5 – 2 (cont'd)

- At the junction tank/skirt wrong conductors are generated as shown in the upper figure:
  - Bulkhead insulation node 3124 is connected to outer insulation node 3113
  - Bulkhead structure node 3024 is connected to outer insulation node 3114
- Redefining conductive interfaces as shown in the lower figure does not solve the problem
- Manual work around required, i.e. delete the relevant GLs from the results file



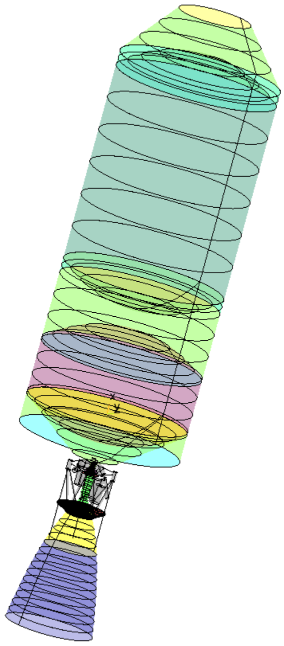


04.12.2013 | Esatan-TMS r6 Solids

ASTRIUM AN EADS COMPANY 6

Esatan-TMS - Solid Modelling in r6

- Testing was already done in Astrium with previous Alpha and Beta versions leading to some discussions with ITP
- The Esatan version that is subject of the current presentation is r6rc5 which is already quite close to the final release and was available since 3 weeks from today
- An existing simple model of an Upper Stage that consists of two propellant tanks, the structure and the engine was selected for the first application
- Due to the limited time frame only the upper (LH2-) tank was transformed into solids
- The figure is shown in the new transparent mode that allows a view inside without cutting

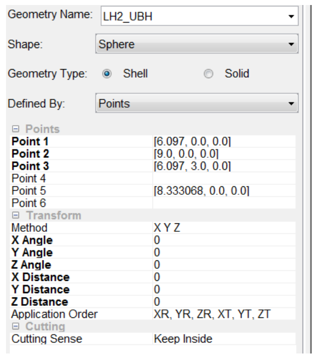


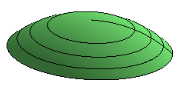
04.12.2013 | Esatan-TMS r6 Solids

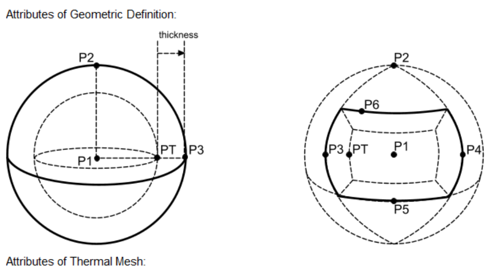
ASTRIUM AN EADS COMPANY 7

Esatan-TMS – Issue with Spheres in r6

- This issue concerns the definition of points 5 and 6 that cut a full sphere to a calotta
- In r5 only one coordinate is sufficient as shown in the sample
- Using this definition for solids leads to ignoring this point, i.e. the full sphere appears
- r6 requires a second coordinate to define the point laying on the sphere‘s surface although this could easily be computed by the software
- Problem: when one of the coordinates is wrong it is not clear where Esatan puts the cutting plane (no warning given)





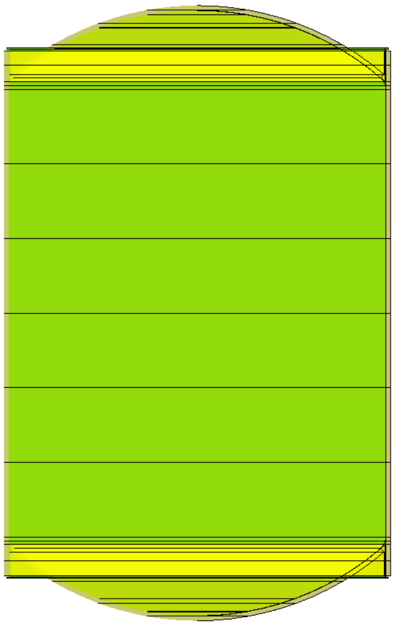


04.12.2013 | Esatan-TMS r6 Solids

ASTRIUM AN EADS COMPANY 8

Esatan-TMS - Solid Modelling in r6 (continued)

- The figure on the right shows the LH2 tank alone in transparent view
- It is characterised by the following:
  - Nodal discretisation in circumferential direction is one node only
  - Tank consists of the main cylinder and the identical upper and lower bulkheads with skirts including thermal insulation
  - Structure thicknesses are between 2mm (bulkheads) and 8mm (skirts), which is small compared to the diameter of 4m and makes it difficult to be recognised as solids
  - Insulation thickness on bulkheads and outer side of cylinder including skirts is 50mm, on skirts inner side 16mm.

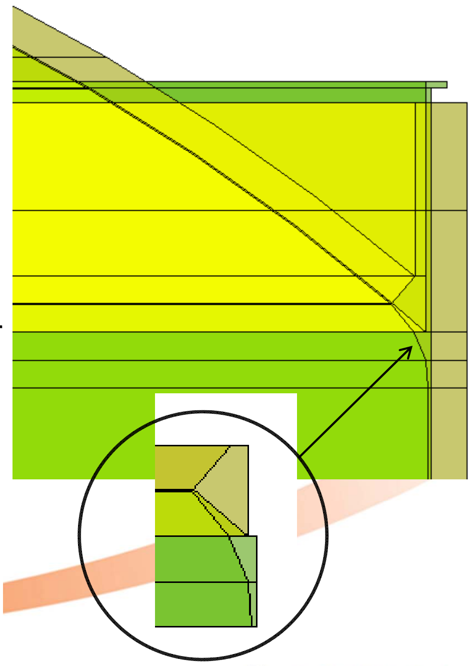


04.12.2013 Esatan-TMS r6 Solids

ASTRIUM AN EADS COMPANY 9

Esatan-TMS - Solid Modelling in r6 (continued)

- This figure shows a detailed view of the skirt area where the varying structural thicknesses can be seen
- The central y-ring to which cylinder, bulkhead and skirt are welded is approximated by a new type of primitive
- This new primitive is a cone generated by rotation of a quadrilateral about a user defined rotation axis
- Four of them are shown as sample in the detail figure: the y-ring and the gap between bulkhead and skirt insulation
- Dependant on the chosen quadrilateral this primitive can also be used to define a cylinder or a disc

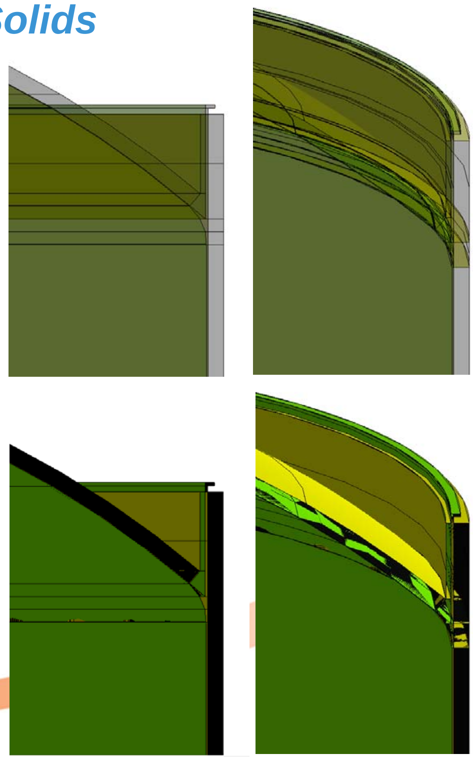


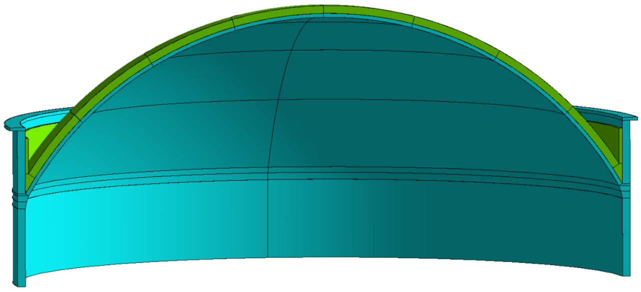
04.12.2013 | Esatan-TMS r6 Solids

ASTRIUM AN EADS COMPANY 10

Esatan-TMS - Visualisation of Solids

- Different options for visualisation available:
  - Samples on the right are with clipping plane on, in transparent mode (upper) and opaque mode (lower)
  - Half model (180° or any other angle) as in sample below that was used for 1st Alpha testing of r6



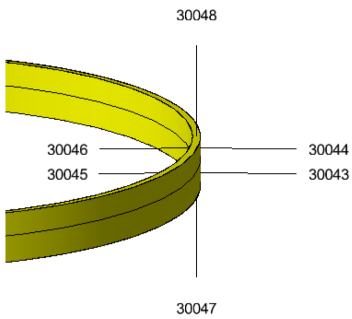


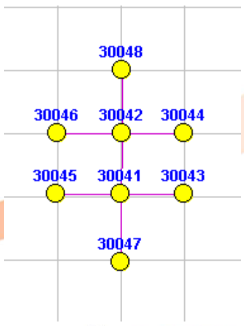
04.12.2013 | Esatan-TMS r6 Solids

ASTRIUM AN EADS COMPANY 11

Esatan-TMS – Solids Node Numbering

- In general each solid consists of 7 nodes: the central node representing the bulk properties, and one arithmetic node for each surface
- The sample on the right is a cylinder with two nodes in height direction, i.e. two bulk nodes and the corresponding surface nodes
- However, as it is a complete cylinder the surface nodes at 0° and 360° disappear and in fact makes it a two dimensional problem
- Node numbering starts with the bulk node using the initial number and increment as defined by the user
- Bulk node numbers are not displayed in Workbench but can be seen in ThermNV (in this case nodes 30041 and 30042)



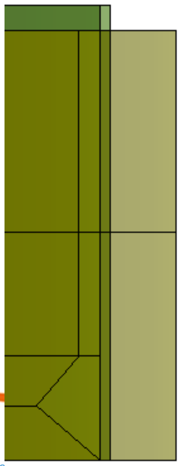


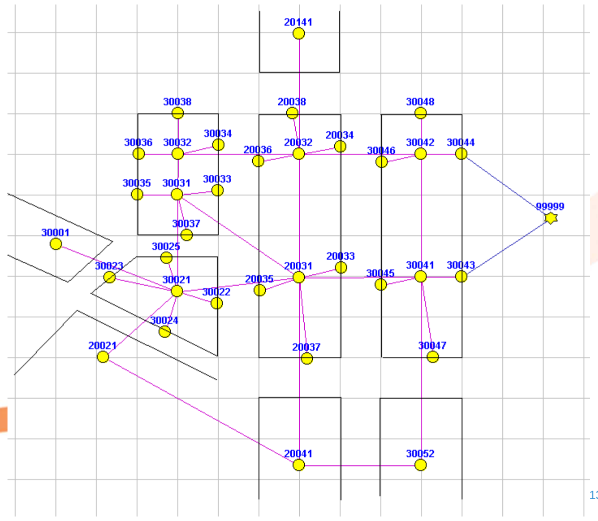
04.12.2013 Esatan-TMS r6 Solids

ASTRIUM AN EADS COMPANY 12

Esatan-TMS – Solids Linking in ACG

- The sample below shows the solid from the previous slide, which is the Upper Skirt outer insulation, in addition the skirt itself and the inner insulation in the gap plus some adjacent nodes
- It shows how solids are connected with each other by ACG





04.12.2013 | Es 13

Esatan-TMS – Solids Linking in ACG (cont'd)

- Before ACG is started, the AutoGenerate Conductive Interfaces Option has to be executed in Workbench. Different from Release5 the default setting is “fused“, so you can continue immediately
- As shown in above sample two solids that are in contact are linked by a direct conductor between the relevant bulk nodes
- The surface nodes that represent the contact area between the two remain nevertheless in the model and are linked with the bulk node
- These nodes and conductors are not used in the temperature calculation, but are needed for temperature overlay when these surfaces are displayed during post processing. They will then show the bulk temperature

04.12.2013 | Esatan-TMS r6 Solids 14

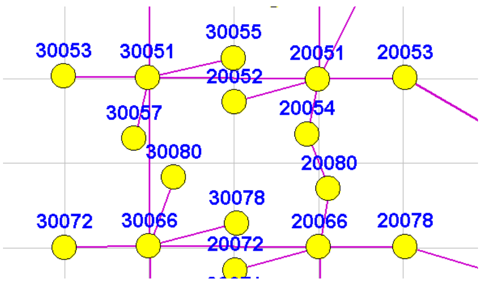
Esatan-TMS – Solids Linking in ACG (cont'd)

- From an analysis point of view the preferrable solution would be to have the surface nodes linked (or even better merged) instead of generating the direct link. This is for the following reasons:
  - To avoid useless information in the TMM. The number of nodes for the LH2 tank was doubled w.r.t. the modelling with shells only. Also the number of conductors is increased
  - In case of two different materials with temperature dependant conductivities the additional node is needed for more accurate temperature interpolation
  - Typical sample of such conductor:
  - GL(20051,30051) = 1.0 / (
    (1.0 / (113. * CNDFN1(T20051, T30051, k_A6_AL2219, 1))) +
    (1.0 / (20.7 * CNDFN1(T20051, T30051, k_A6_FOAM, 1))));

04.12.2013 | Esatan-TMS r6 Solids — ASTRIUM AN EADS COMPANY — 15

Esatan-TMS – Solids Linking in ACG (cont'd)

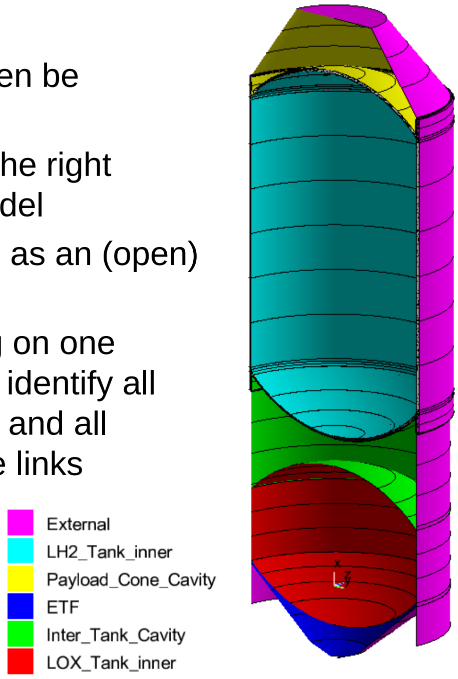
- When defining a conductive interface as "Contact" the additional contact conductor is placed between the two surface nodes (which is correct) as shown below between node 20054 and 20080
- In this case interpolation is done with the correct temperatures



04.12.2013 | Esatan-TMS r6 Solids — ASTRIUM AN EADS COMPANY — 16

Esatan-TMS – Cavities

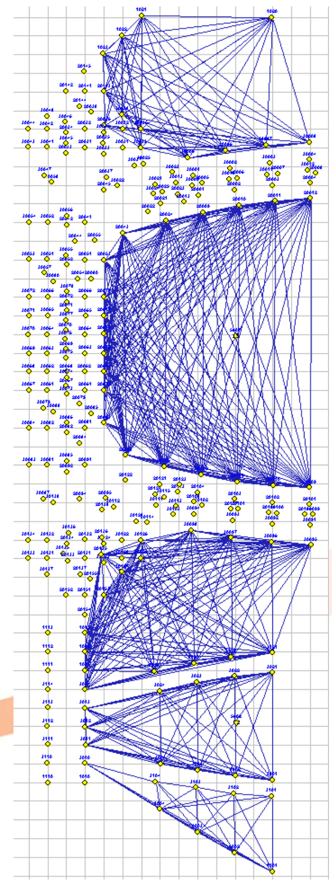
- r6 allows to define cavities that can then be computed independently
- The overlay applied on the model on the right shows the cavities defined for that model
- Also the external surfaces are defined as an (open) cavity
- Cavities are defined by simply clicking on one surface in that cavity. Esatan will then identify all surfaces to which it has radiative links and all surfaces to which these have radiative links



ASTRIUM
AN EADS COMPANY

Esatan-TMS – Cavities (continued)

- Loading the model with the radiative results of the 5 internal cavities in ThermNV shows that the cavity definition was correct because there is no radiation to outside
- Linear conductors have been switched off for a clearer view on GRs
- External GRs are also not shown here
- External radiation including natural radiation can now be re-computed as often as needed (for different orbits, solar aspect angles e.t.c) without re-computing the internal radiation.



Esatan-TMS – Conclusion

- First application of solid modelling on a real model shows that ACG can now generate the complete GL matrix except of links between shells and solids. These can be derived manually from the existing conductors
- Further discussions on how to treat the non connected surface nodes and their conductors deemed useful
- The cavity feature that allows separate calculation of separate cavities works for internal and external cavities
- A numerical validation of the ACG results was not yet performed
- Due to the limited time frame since delivery of the current version of r6, not all of the requested features have been tested. At least for solids and cavities and as far as current testing has shown r6 meets the requirements

04.12.2013 | Esatan-TMS r6 Solids

ASTRIUM AN EADS COMPANY 19

Esatan-TMS – Outlook

- Further features required for next release r7:
  - Allow cutting in ACG (shells and solids)
  - Extend perimeter of primitives: Torus (needed e.g. for line modelling), Ellipsoid (needed e.g. for special shape tank bulkheads)
  - Allow different properties for the surfaces of one solid
  - Provide compatibility of material libraries between different releases

04.12.2013 | Esatan-TMS r6 Solids

ASTRIUM AN EADS COMPANY 20

Appendix T

Enhancement of ray tracing method for radiative heat transfer with new Isocell quasi-Monte Carlo technique and application to EUI space instrument baffle

Lionel Jacques
(Centre Spatial de Liège, Belgium)

Luc Masset Gaetan Kerschen
(University of Liège, Space Structures and Systems Laboratory, 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 is still dominant. Radiative exchange factors (REFs), used to calculate radiative thermal exchanges in space, are usually computed through Monte Carlo ray-tracing. Due to the large number of elements composing a FE model, the computation of the REFs is prohibitively expensive. In the frame of a global approach, several research axes will be investigated to reduce the computational effort of the REFs with FEM. The first one focuses on accelerating the convergence and enhancing the accuracy of the ray-tracing process to decrease the number of rays required to achieve a given accuracy. The developments of the new Isocell quasi-Monte Carlo ray tracing method are presented. Based on Nusselt's analogy, the ray direction sampling is carried out by sampling the unit disc to derive the ray directions. The unit disc is divided into cells into which random points are then generated. The cells have the particularity of presenting almost the same area and shape. This enhances the uniformity of the generated quasi-random sequence of ray directions and leads to faster convergence. This Isocell method has been associated with different surface sampling to derive the REFs. The method is benchmarked against ESARAD, the standard thermal analysis software used in the European aerospace industry. Various geometries have been used. In particular, one entrance baffle of the Extreme Ultraviolet Imager (EUI) instrument developed at the Centre Spatial de Liège in Belgium is used. The EUI instrument of the Solar Orbiter European Space Agency mission and will be launched in a Sun-centered (0.28 perihelion) orbit in 2018.

Université de Liège

RAY TRACING ENHANCEMENT FOR SPACE THERMAL ANALYSIS: ISOCELL METHOD

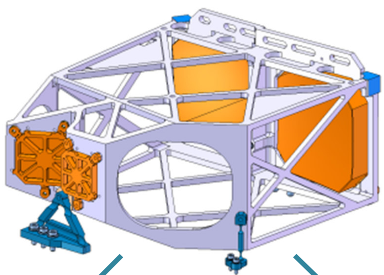
Lionel Jacques,

Luc Masset, Gaetan Kerschen

Space Structures and Systems Laboratory
University of Liège

27th Space Thermal Analysis Workshop, ESTEC, Dec. 4th, 2013

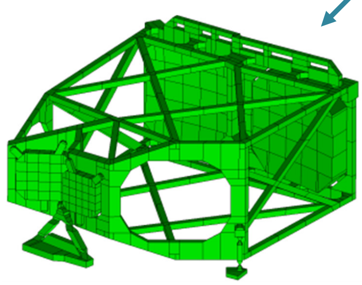
FINITE ELEMENT VS. LUMPED PARAMETER



MTG IRS BTA: strong thermal requirements

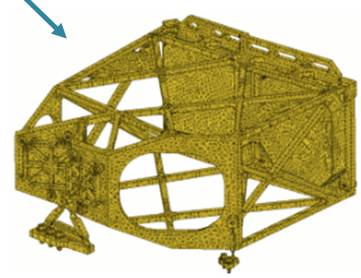
Detailed GMM and TMM necessary

Lumped parameter method



Error-prone manual inputs: geometry & conductive links
Thermo-mechanical: map the T° on the FEM

Finite Element method



Automatic meshing & conductive links
Thermo-mechanical analyses straightforward

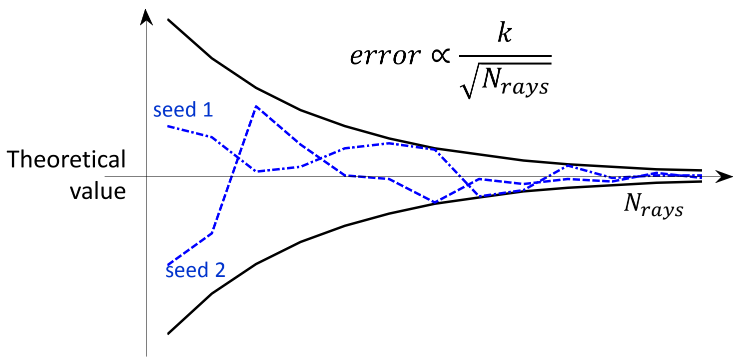
2

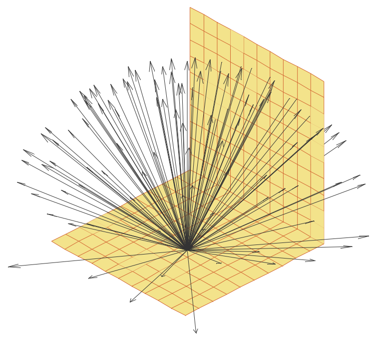
RADIATIVE THERMAL ANALYSIS IS EXPENSIVE

Radiative exchange factors: proportional to (# of elements)²

- × wavelength bands (infrared, visible, multispectral)
- × orbit positions & geometrical configurations

Computed mostly through Monte-Carlo ray-tracing:





3

HOW TO DECREASE COMPUTATION TIME?

1. Decrease the number of rays: **isocell ray direction sampling**

2. Decrease the number of faces: **super-faces**

4

Monte-Carlo ray direction sampling

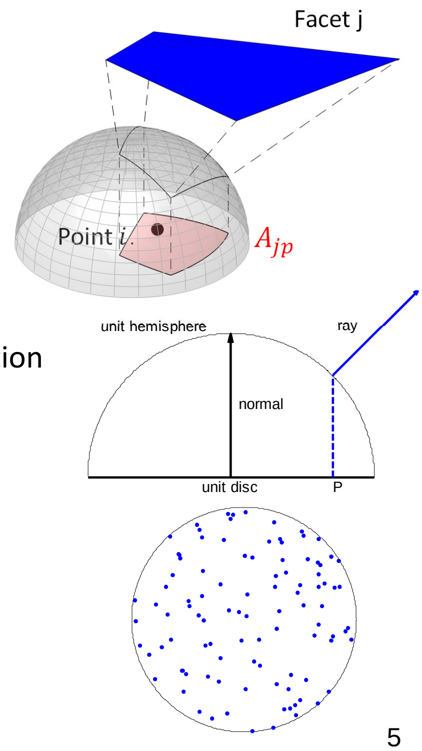
Based on Nusselt's analogy

$$F_{ij} = \frac{A_{jp}}{\pi}$$

And Malley's method:

- 1 point on the unit disc defines the ray direction
- Sampling of the unit disc

$$F_{ij} = \frac{\text{Number of rays emitted by facet i, hitting j}}{\text{total number of rays emitted by facet i}}$$

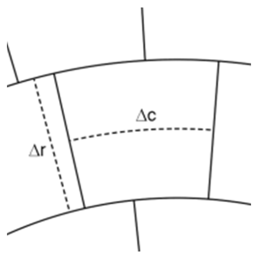


5

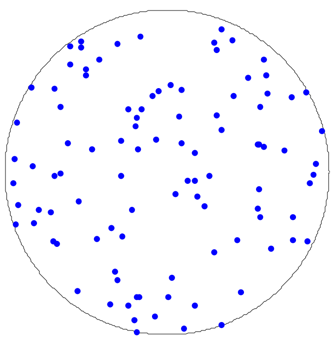
Isocell: More uniform direction sampling

More uniform ray direction sampling:

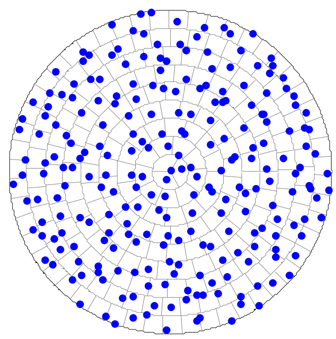
- Divide the unit disc into cells of equal area and aspect ratio $\frac{\Delta r}{\Delta c} \sim 1$
- Fire one ray per cell



Random (classic) sampling

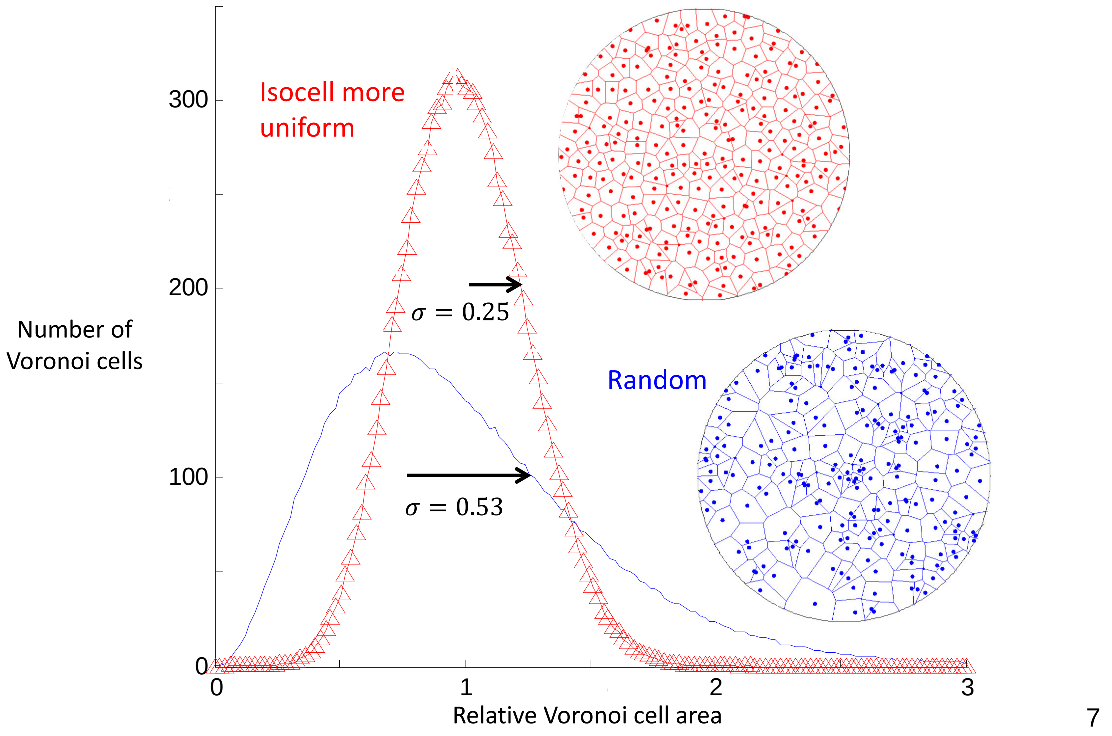


Isocell sampling

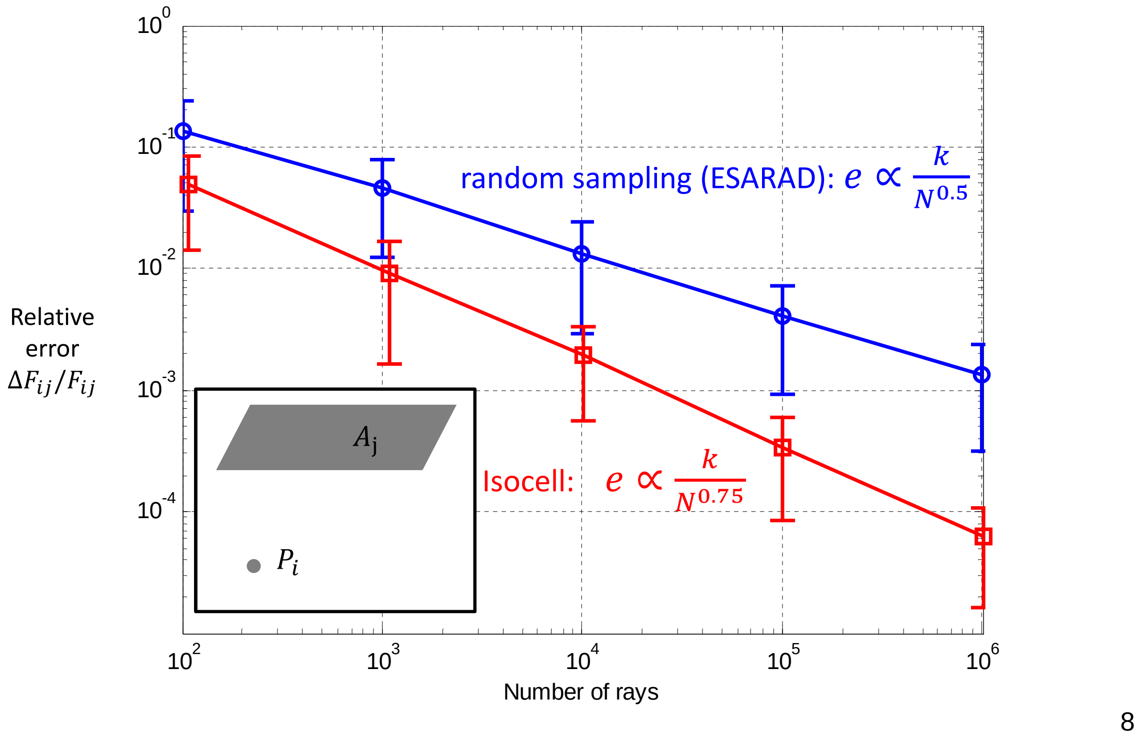


6

Confirmation: unit disc Voronoi cell area



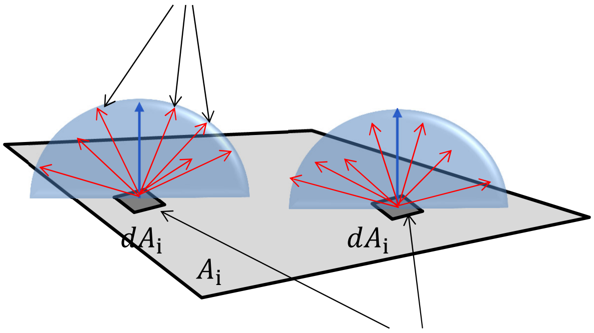
Point-wise VF: Isocell requires less rays



Surface & direction sampling

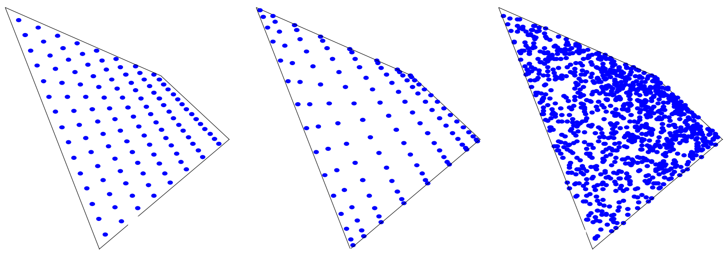
2 alternatives:

- Local direction sampling at each origin
- Global direction sampling & distribution among the origins



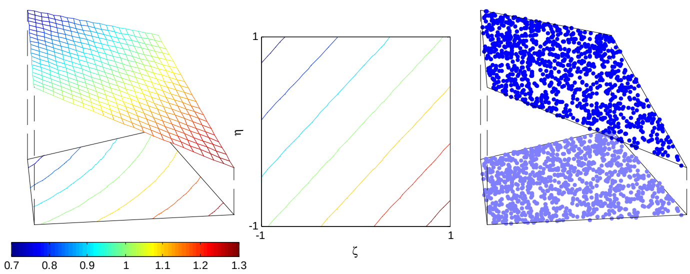
9

Different surface sampling strategies



Problem: concentration due to non area-preserving mapping of the face

Solution: each origin is weighted by the Jacobian of the mapping (origins in denser regions less weighted and vice-versa)



10

Gauss sampling: Gauss weights

Constant # of rays per origin

$$F_{i \to j} = \sum_{k=1}^{N_{rays}} W_k F_{di \to j}^k$$

Point-wise view factor

Uniform & random sampling: $W_k = 1 \ \forall k$

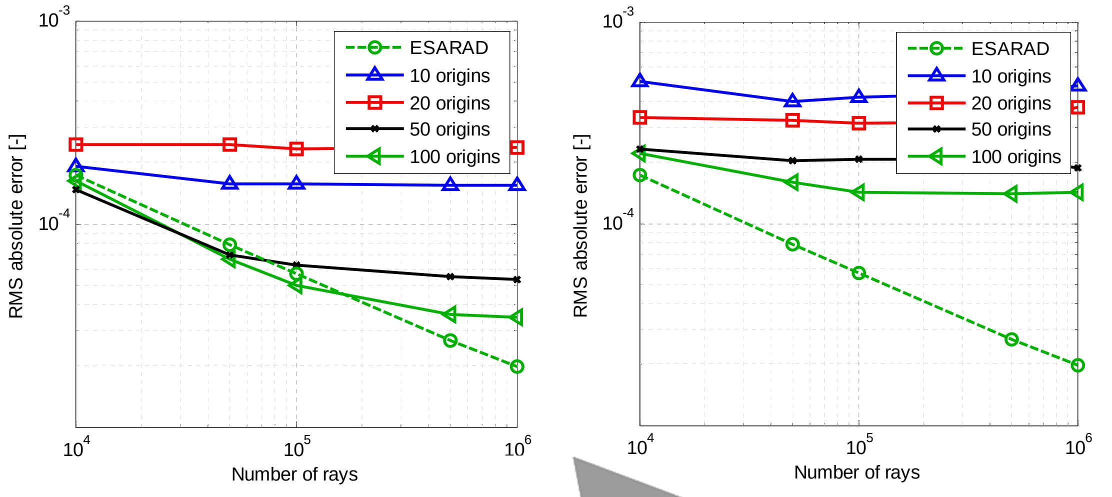
Gauss sampling: W_k = Gauss-Legendre quadrature weights

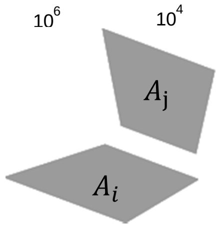
11

Surface sampling is critical

Uniform origin sampling & Local Isocell direction sampling

Random origin sampling & Local Isocell direction sampling

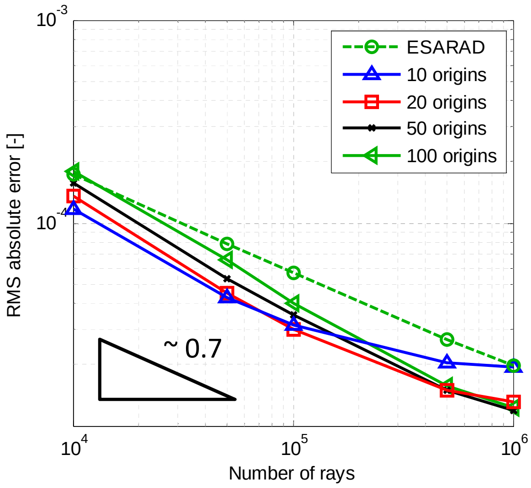




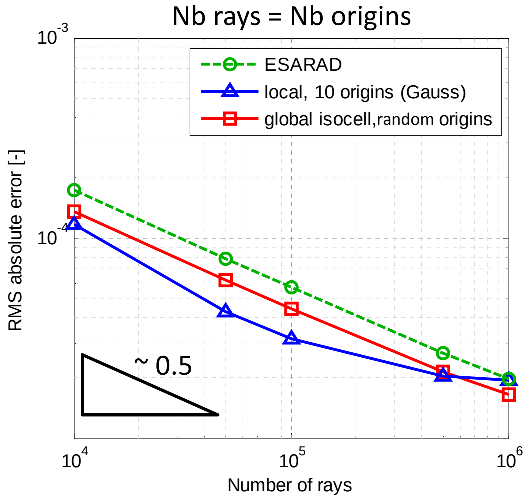
12

GAUSS SAMPLING GIVES BETTER RESULTS

Gauss origin sampling &
Local Isocell direction sampling



Random origin sampling &
Global Isocell direction sampling
Nb rays = Nb origins



Global direction sampling:

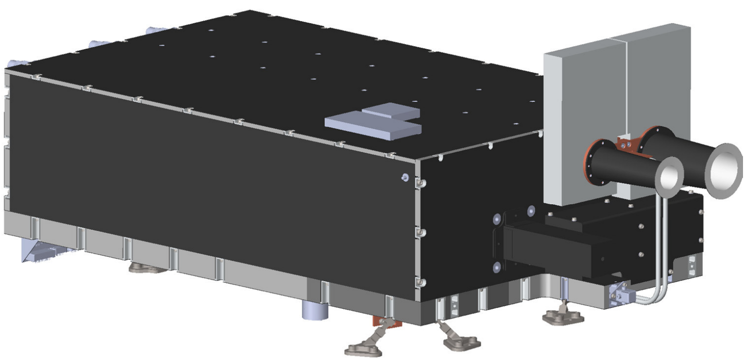
- Still ~2x better than ESARAD
- Does not need to specify a number of origins

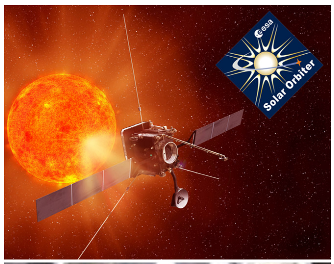
13

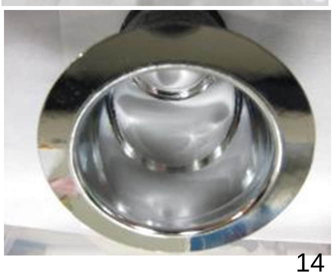
EUI ENTRANCE BAFFLE ON SOLAR ORBITER

0.28 AU perihelion: 17.5kW/m²

Coated CFRP entrance baffle and filter to reject unwanted light



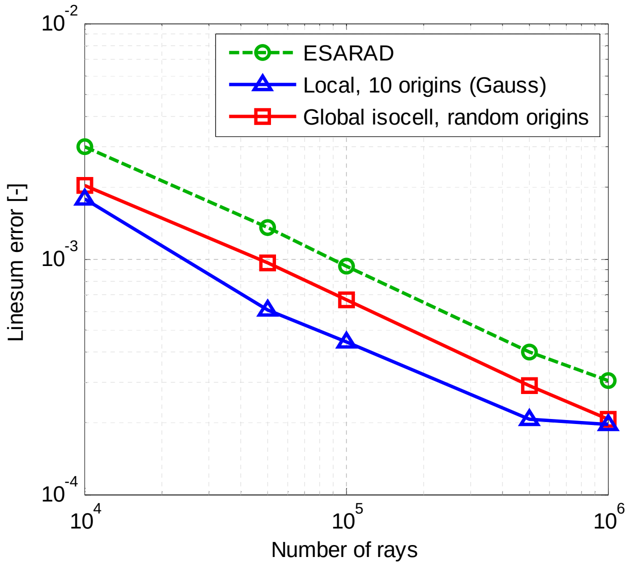


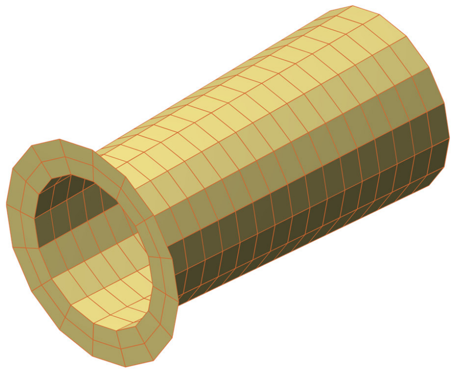


14

Radiative exchange factors global error

$$LSE_{RMS} = \sqrt{\frac{1}{N}\sum_i LSE_i^2} = \sqrt{\frac{1}{N}\sum_i \left(1 - \sum_j F_{ij}\right)^2}$$



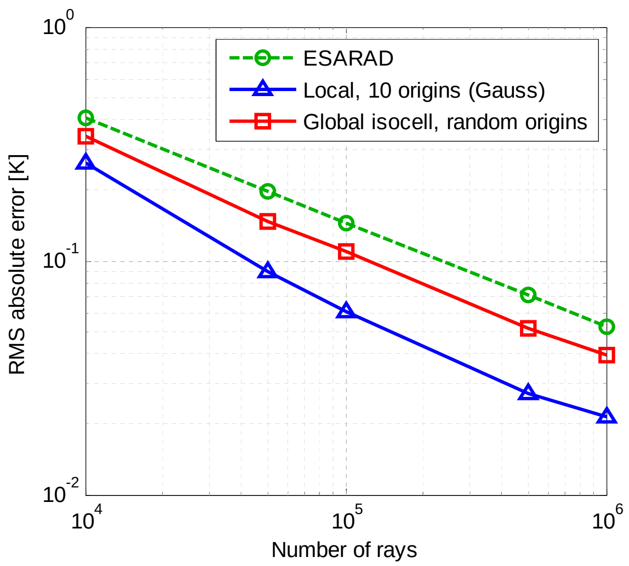


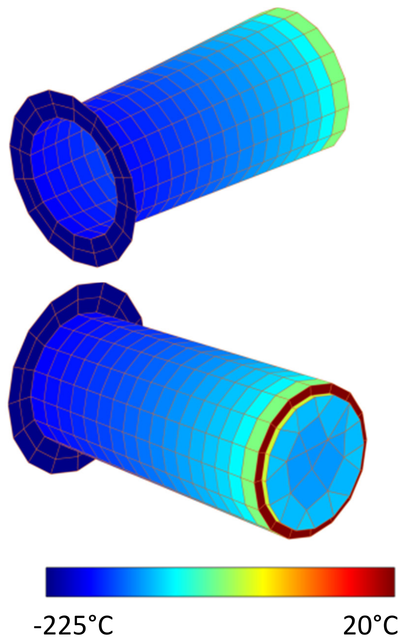
15

Convergence on Temperatures

Benchmark: pure radiative equilibrium

3K environment, 293K boundary





16

CONCLUSIONS

Isocell direction sampling offers significant improvement

Surface sampling is critical

50% reduction of number of rays with global direction sampling

Same performances on simple case and real-life space structure

First step to bridge the gap between structural and thermal analysis

17

Thank you for your attention…

Any question?

18

REFERENCES

[1] T.D. Panczak, The failure of finite element codes for spacecraft thermal analysis, Proceedings of the International Conference on Environmental Systems, Monterey, USA, 1996.

[2] J.-P. Halain, P. Rochus, T. Appourchaux, D. Berghmans, L. Harra, U. Schühle, F. Auchere, A. Zhukov, E. Renotte, J.-M. Defise, L. Rossi, K. Fleury-Frenette, L. Jacques, J.-F. Hochedez, and A. Ben Moussa, The technical challenges of the Solar-Orbiter EUI instrument, Proceedings of the SPIE, Vol. 7732, 2010, 77320R-77320R-10.

[3] L. Masset. "Thermal Model Reduction Using the Super-Face Concept." presented at the 25th European Workshop on Thermal and ECLS Software, ESA ESTEC, August 11, 2011.

[4] L. Masset, O. Brüls, and G. Kerschen. Partition of the Circle in Cells of Equal Area and Shape. University of Liège, 2012. http://orbi.ulg.ac.be/handle/2268/91953.

[5] T. Malley. A shading method for computer generated images. Master's thesis, University of Utah, June 1988

19

CONTACT

Lionel Jacques, ljacques@ulg.ac.be
Thermal Engineer & PhD student

- **University of Liège**
  Space Structures and Systems Lab
  1, Chemin des Chevreuils (B52/3)
  Liege, B-4000, Belgium
  http://www.ltas-s3l.ulg.ac.be/

- **Centre Spatial de Liège**
  Liège Science Park
  Avenue Pré-Aily
  B-4031 Angleur Belgium
  http://www.csl.ulg.ac.be

20

Appendix U

Calculation of Optimal Solar Array Steering Laws for Temperature Critical Missions

Andreas Brandl
(Astrium GmbH Ottobrunn, Germany)

Jan-Hendrik Webert
(Universität der Bundeswehr Müchen, Germany)

Abstract

For the Solar Orbiter and Bepi Colombo missions it is required to steer the solar arrays of the Spacecrafts in such a way that sensitive parts (like solar cells) do not exceed a maximum temperature, while keeping the electric power output as high as possible. This is usually done by adapting the sun aspect angle of the array in dependency of the actual heat input from the sun and if present from the planet.
In this presentation a fast and accurate method is discussed in which the optimized solar array rotation angles at each orbit position are calculated by a modified iteration-scheme with a detailed solar array thermal model.
With the developed iteration scheme it became possible to limit the total number of time consuming calculations of the time dependent radiation exchange factors to a minimum without losing the stability of the scheme. A further decrease of computational time was achieved by splitting the radiation calculation into sub-processes. Those have been distributed among the available computers, leading to an efficient parallelization of the radiation calculations.

Calculation of Optimal Solar Array Steering Laws for Temperature Critical Missions

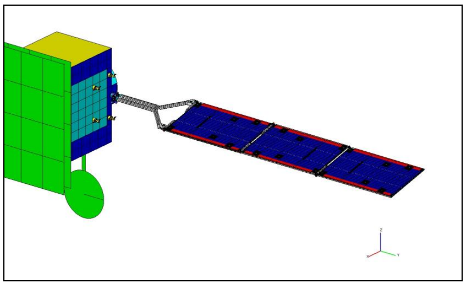
Solar Array Design
ASTRIUM GmbH Ottobrunn // Germany
Dr. Andreas Brandl

Universität der Bundeswehr
Munich // Germany
Jan-Hendrik Webert

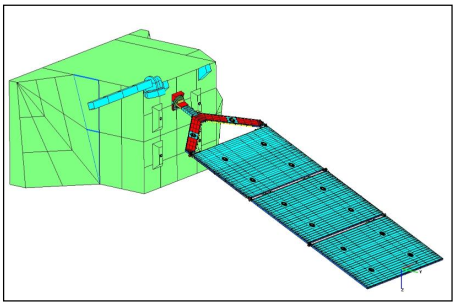
ASTRIUM AN EADS COMPANY

High temperature solar arrays

- Solar Orbiter



- Mercury Planetary Orbiter of the Bepi Colombo Mission



- Thermal / Geometrical Models
  - Modelled with ESATAN-TMS
  - Detailed (~5000 Nodes)
  - Time dependent radiation exchange factors → High computation time

ASTRIUM AN EADS COMPANY

Challenges

- Both solar arrays are exposed to high solar radiant flux
  - Bepi Colombo (MPO): S=14.5kW/m²
  - Solar Orbiter: S=17.5kW/m²
- Bepi Colombo MPO Orbiter
  - Additional Planetary IR & Albedo loads from Mercury
- Components of the solar array must not exceed certain temperature limits
  - Adhesives, Carbon Fibre Structure, wires/harness
  - Solar cells
- Temperature control
  - Only passive thermal control
  - Coatings / mirrors (OSR) / SSM foils / shields
  - Sun aspect angle by rotation of the solar array

Consequence:

At each orbit position the solar array rotation angle has to be steered to keep the temperature below a certain limit (BILD)

→Steering law

→Inverse problem

ASTRIUM AN EADS COMPANY 3

Classical solution method

Let {ϕ_i} the vector of the solar array rotation angles around an orbit

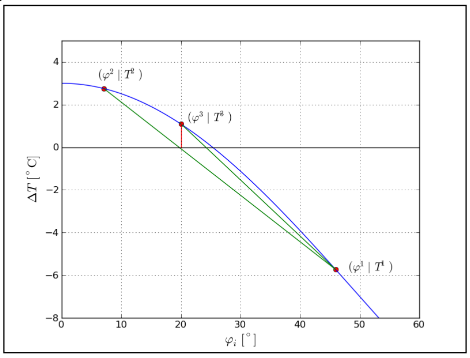
After GMM/TMM calculation that leads to a vector {T_i}

Goal: $T_i = T_{Target}$ for (almost) all orbit positions

→For each orbit position „i" the roots of $T_i(\phi_i) - T_{Target} = 0$ must be found

→Performed by „regula-falsi" or false-position method

→Better (faster): Anderson-Björk scheme

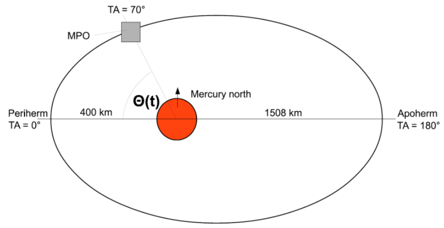


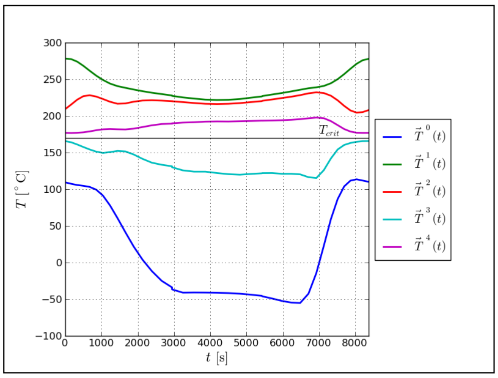
Procedure:

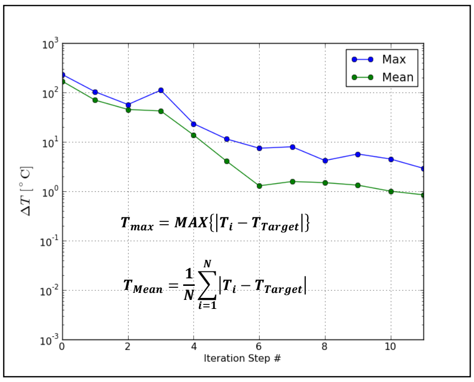
- First initial condition: edge on solar array → coldest possible temperature
- Second initial condition: face on solar array→ hottest possible temperature
- For each orbit position:
- Find approximate solar array rotation angle for which target temperature is reached
- Recalculate GMM/TMM with new set of sun aspect angles
- Repeat this iteration until maximum temperature of e.g. solar cells are within T_{Target} +/- 1.0°C

ASTRIUM AN EADS COMPANY 4

Example:
Mercury Planetary Orbiter







+ The iteration is stable
+ It converges, but there are cases where not
+ Easy to implement

- Slow (many iterations needed)
- Each iteration means one GMM/TMM calculation
- No complete convergence

→ Improvements necessary

ASTRIUM AN EADS COMPANY

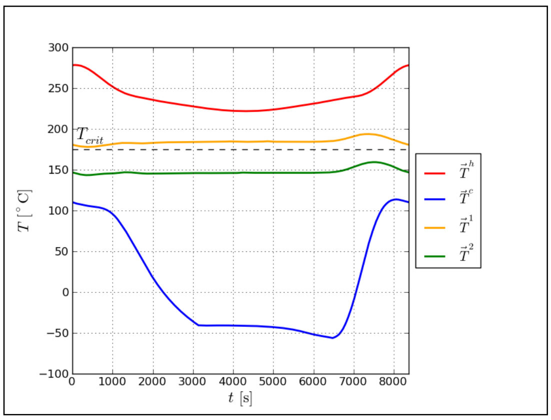
First Improvement

- Initial conditions

Start with initial conditions closer to the solution in order to lower the number of iterations needed

Usage of an „analytical“ model

- Thin plate approximation
- Neglecting reflections from the spacecraft



ASTRIUM AN EADS COMPANY

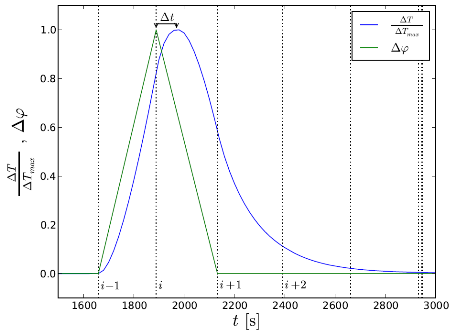
Second improvement I

- Acceleration of convergence & increase stability

If the thermal timescale τ of the solar array > t_{i+1}–t_i of the GMM time discretization

→classical method can break down or converges slowly

→Change of solar array rotation angle at position „i" has an influence on the temperature at position „i-1, i, i+1, i+2,…"



Responese function can be calculated by simulation or by analytical solution of the transient „linearized" heat equation

→False-position method doesn't work anymore

→Multi-dimensional root-finding method required

→Newton-scheme: $\vec{\boldsymbol{\varphi}}^{(k+1)} = \vec{\boldsymbol{\varphi}}^{(k)} - \boldsymbol{J}^{-1} \cdot \vec{\boldsymbol{T}}(\vec{\boldsymbol{\varphi}}^{(k)})$

→With the yet unknown Jacobi-matrix **J**

$$J_{ij} = \frac{\partial T_i}{\partial \varphi_j}$$

Physical meaning: change of temperature of position „i" due to the change of angle at position „j"

7

Second improvement II

- The calculation of the full Jacobi-matrix J can not be achieved in suitable time
- Approximation & assumptions has to be made
  - Key assumption: The shape of the temperature response at position „i" due to the change of angle at position „j" is independent from the position. It only depends on the relative distance „i-j"
  - Information available from unit response
  - Approximation of the Jacobian by:

$$J_{ij} = \frac{\partial T_i}{\partial \varphi_j} \sim c_{j-i} \frac{\Delta T_i}{\Delta \varphi_j}$$

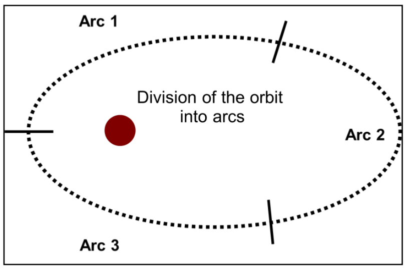
$$\boldsymbol{J} = diag(\Delta\vec{T})\boldsymbol{C_T} diag(\Delta\vec{\varphi})$$

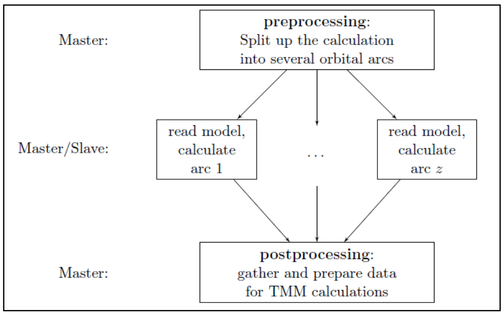
<u>Benefits:</u>
→Transient effects are covered
→At each orbit position more informations (from other positions) are used to calculate the roots→ faster
→Higher stability of the scheme

8

Third improvement

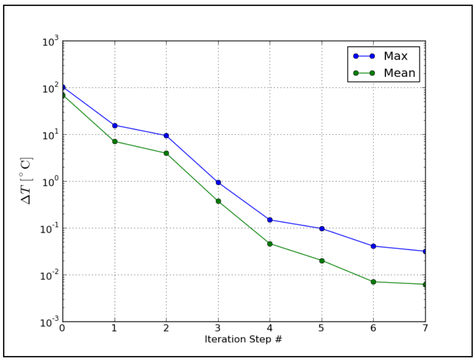
- The most effective measure to accelerate the calculation is achieved by the **parallelization** of the calculation of the view factors / heat loads (GMM)





- Method:
- Seperate the orbit into „N“ sub-arcs
- Distribute the calculation of the sub-arcs among the available computers
- Automated by the help of Python-scripts
- For the GMM $t_{calc} \sim 1/(N_{computers} * N_{cores})$
  - At the moment: 4 Computers with 4 cores each→ acceleration by a factor of 16
  - But: 16 ESATAN licenses needed

Putting all together / Summary



After using all the improvements

→After 4 iterations an accuarcy of +/-0.2K is achieved (Old: after 10 iterations: +/- 3K)

→Iteration is stable

→Calculation time

- → Now: 7h for complete generation of a steering law
- → Without improvements: 5-7 days

10

Appendix V

BepiColombo MTM STM Thermal Test

Scott Morgan
(Astrium EADS, United Kingdom)

Abstract

BepiColombo is a joint ESA/JAXA mission to Mercury, and will provide the best understanding of the planet to date. Mercury's proximity to the sun has called for significant thermal design work on the spacecraft, with many new technologies being developed specifically for the project. This in turn has demanded a large amount of spacecraft testing and validation. This presentation will describe the Mercury Transfer Module (MTM) system level STM thermal test, detail the specific challenges faced, and report the results and the lessons learned from the correlation of the associated thermal model.

BepiColombo MTM STM Test

S. Morgan
Astrium UK

Together pioneering excellence

ASTRIUM
AN EADS COMPANY

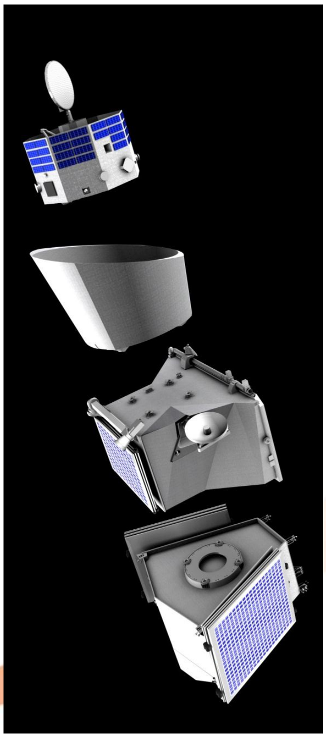
Contents

- Introduction
- Test Overview
- Specific Challenges and Lessons Learned
- Results

ASTRIUM
AN EADS COMPANY

Introduction

- BepiColombo is a joint ESA/JAXA mission to Mercury, launching in 2016
- It is effectively 3 spacecraft stacked on top of each other
  - MTM – Mercury Transfer Module
    - Propulsion module, including attitude control thrusters and Xenon electric propulsion system
  - MPO – Mercury Planetary Orbiter
    - ESA science module, studying the Internal structure, Geology, Element composition and Polar ice.
  - MMO – Mercury Magnetospheric Orbiter
    - JAXA science Module, studying the Magnetic field of Mercury and the inner solar system



ASTRIUM
AN EADS COMPANY

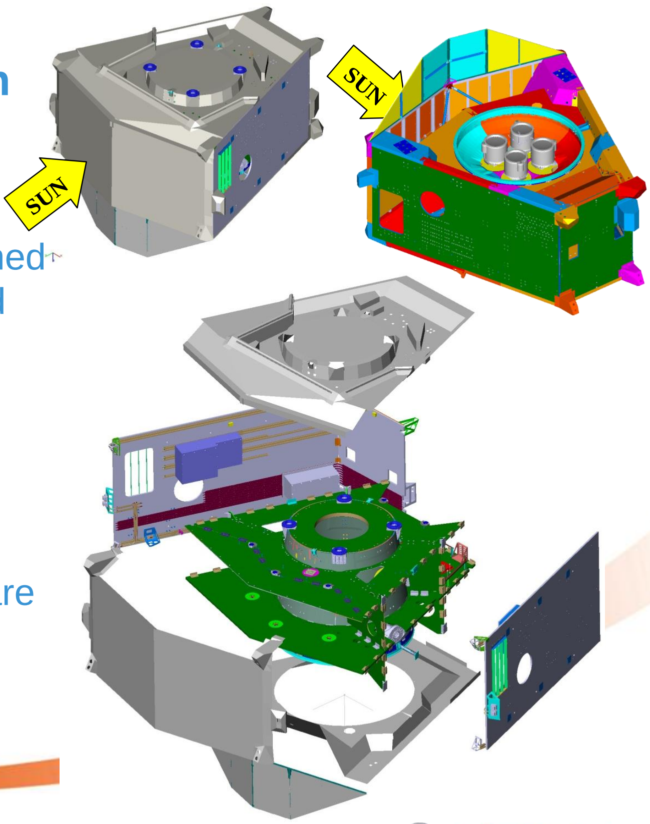
Introduction

- Flight Thermal Environment
  - Solar flux varies between 0.74SC and 11.4SC
  - Electric Propulsion system power use is >2x5.5KW
  - Total Thermal dissipation of ~2 KW
  - Mission timescale ~6 years
  - 7 Planet Flybys
    - 1 of Earth
    - 2 of Venus
    - 4 of Mercury

ASTRIUM
AN EADS COMPANY

MTM Thermal Design

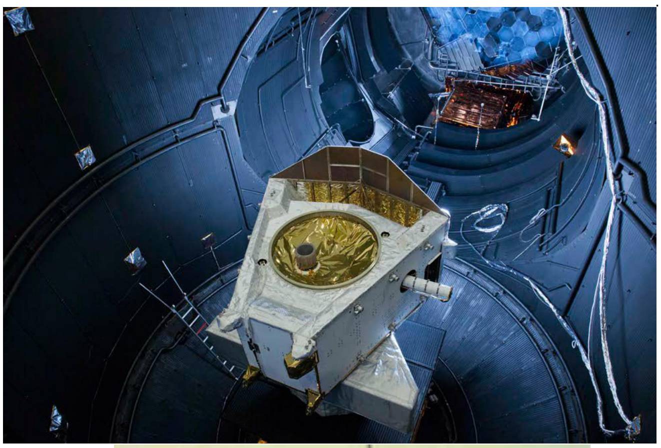
- Heat shield side always facing sun
- MLI and radiator cut-out designed to allow back face of heatshield to radiate
- 3 further sides are radiators
- Radiators are angled to allow rotations around z axis
- Major dissipating units are attached to heatpipes, which are directly on the radiators

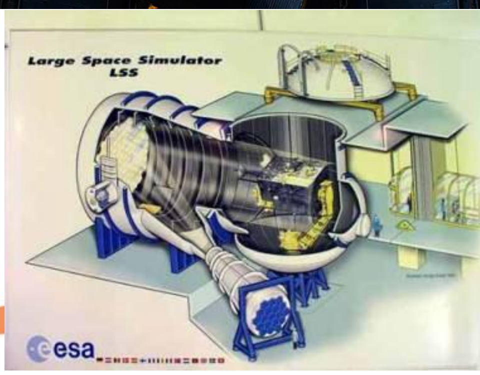


ASTRIUM
AN EADS COMPANY

Test Overview

- Test performed at ESTEC in the Large Sun Simulator (LSS)
- Test lasted for 11 days
- Only 1 Ion Thruster Installed
- Solar Array simulator Installed
- MPO dummy installed

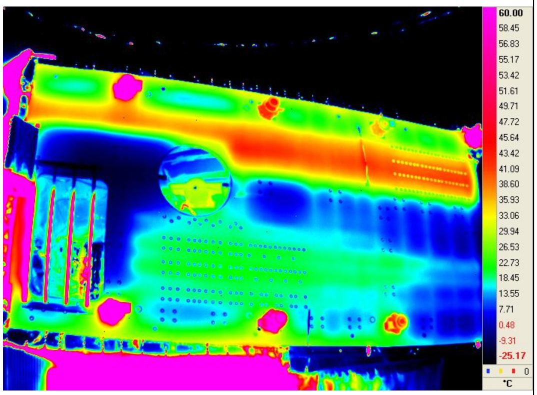


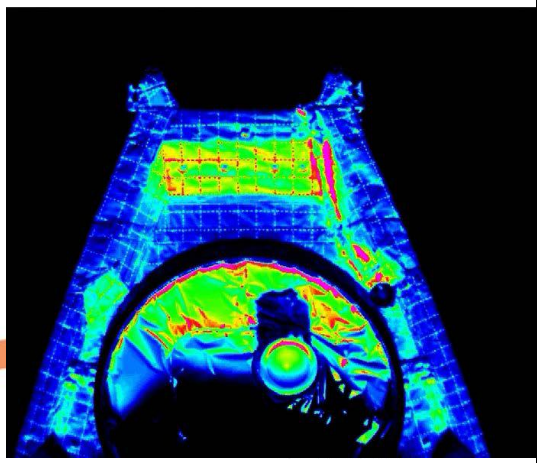


ASTRIUM
AN EADS COMPANY

Test Phases

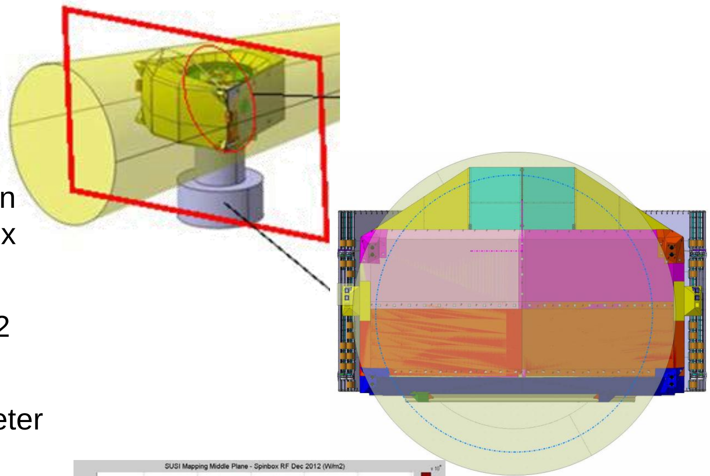
- 6 balance phases were run at different orientations and solar fluxes:
  - Warm Nominal
  - Hot Nominal
  - Hot Tilted (17°C)
  - Hot RCT Rotation (19°C)
  - Engine Bay Illumination
  - Cold Nominal
- Several transient phases were also run:
  - Venus eclipse
  - SEPS cool down
  - Attitude loss

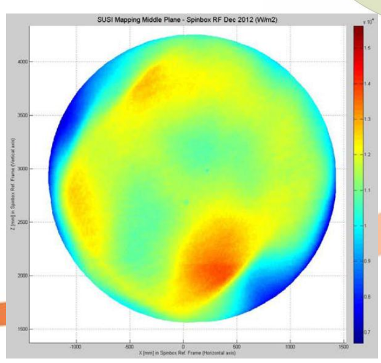




Challenges

- Convergent Solar Beam
  - Solar beam was convergent in order to increase the solar flux at the spacecraft
  - Maximum flux of 11,000W/m2 (8SC) was achieved
  - This reduces the beam diameter
- Non Uniform Solar Beam
  - The beam at high power was not completely uniform
  - This meant the variation had to be measured and implemented in the thermal model
  - Beam shape was idealised as a cone

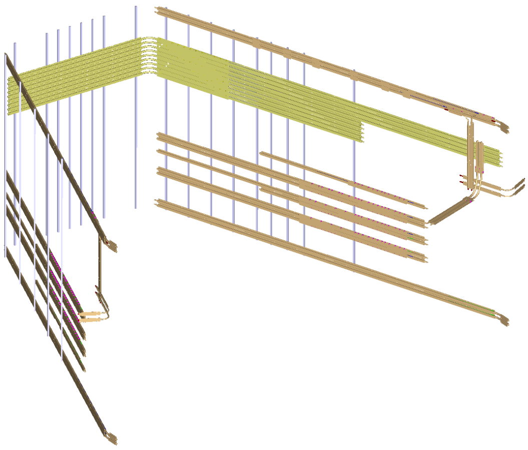


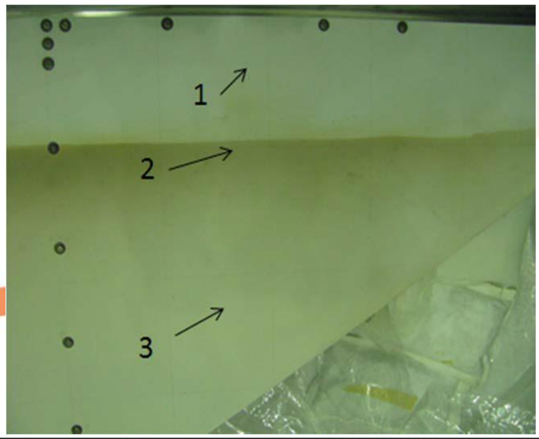


ASTRIUM
AN EADS COMPANY

Challenges

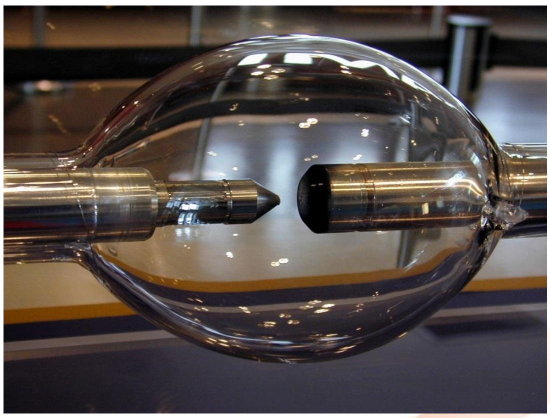
- 3D heatpipe network
  - Heatpipes on MTM cannot all be simultaneously horizontal
  - Vertical heatpipes only work if sufficient heat source at bottom to overcome gravity
  - Energy required is different in hot and cold phases
  - Lead to correlation challenges
- Optical Property Degradation
  - Some surfaces degraded during the test
  - Effect was visible during the balance phases





Challenges

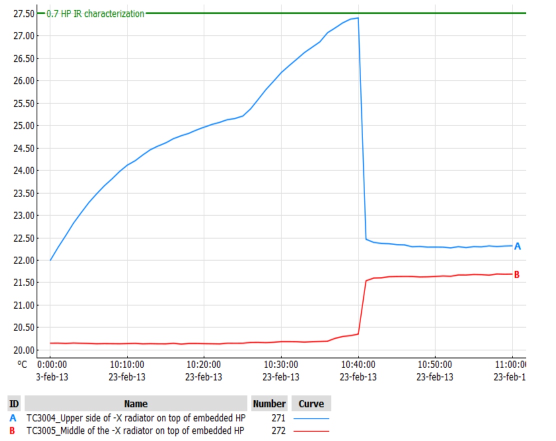
- Bulb Lifetime
  - Each bulb is used at 25kW
  - 19 bulbs
  - Limited Life time
  - Hot phases were done first
- Thermocouple read issues
  - Some thermocouples were electrically unstable
  - Had to be discounted in some phases

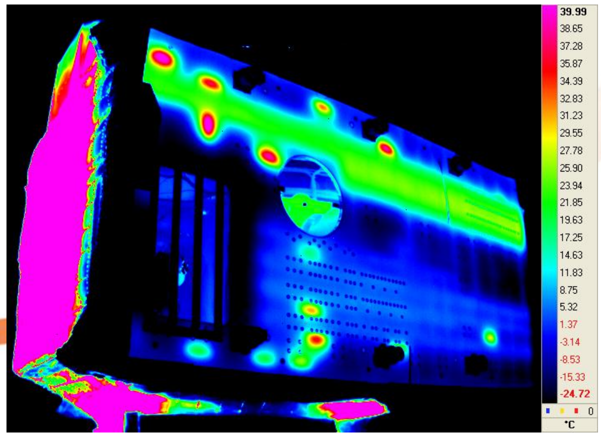


ASTRIUM
AN EADS COMPANY

Lessons Learned

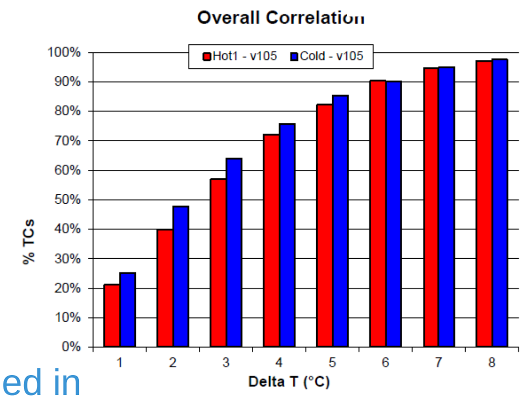
- Heatpipe thermocouples
- Ensure harness is correctly bundled (high power test harness was close to limits)
- The effect of IR flux simulation heaters was not as expected
- MPO simulator interface was too slow to heat or cool
- MY radiator needs heatpipe start-up heaters for vertical HPs





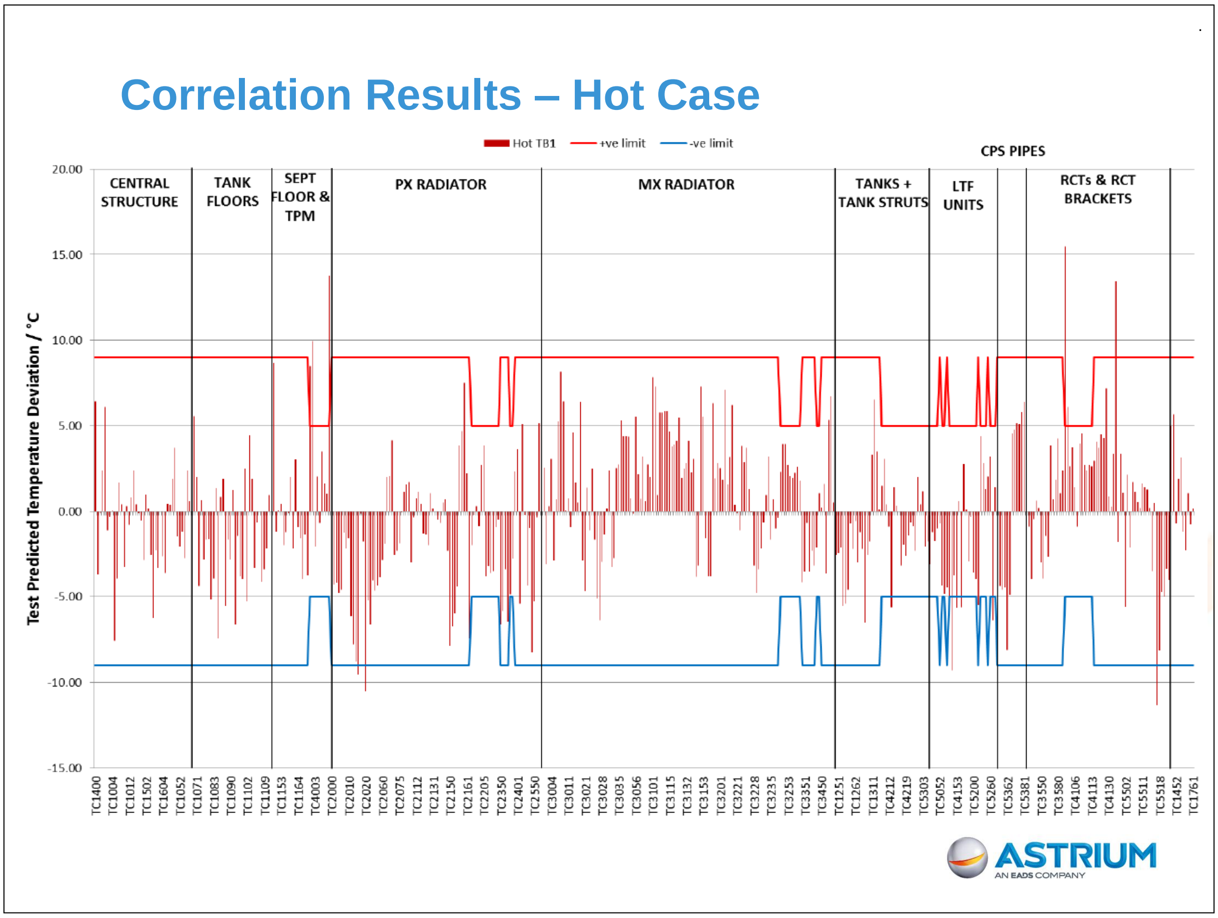
Correlation Results

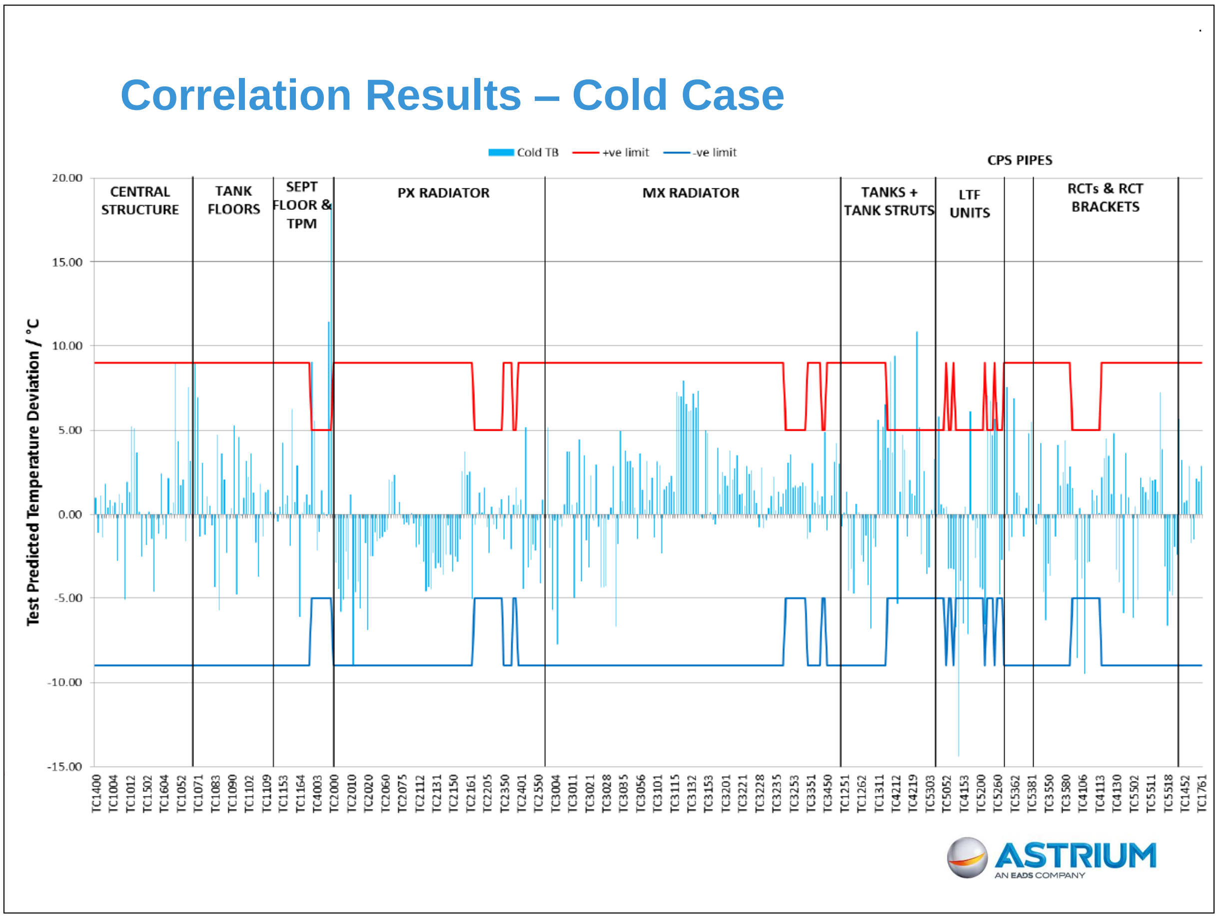
- 2 cases were chosen for full correlation
  - Hot Nominal
  - Cold Nominal
- Other balance phases were studied in local areas
- Overall Results:



Phase	Mean Δ	Standard Deviation of Δ	Number of Δ Exceedances
Hot	0.12°C	3.81°C	15/456
Cold	-0.44°C	3.60°C	19/456

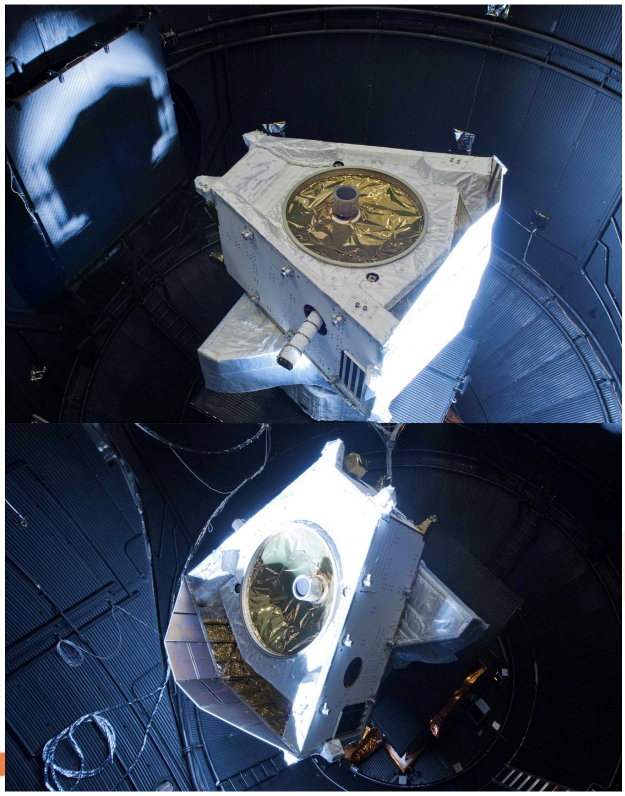
ASTRIUM
AN EADS COMPANY


Correlation Results – Hot Case
Hot TB1
+ve limit
-ve limit
CPS PIPES
CENTRAL STRUCTURE
TANK FLOORS
SEPT FLOOR & TPM
PX RADIATOR
MX RADIATOR
TANKS + TANK STRUTS
LTF UNITS
RCTs & RCT BRACKETS
Test Predicted Temperature Deviation / °C
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
ASTRIUM
AN EADS COMPANY


Correlation Results – Cold Case
Cold TB
+ve limit
-ve limit
CPS PIPES
CENTRAL STRUCTURE
TANK FLOORS
SEPT FLOOR & TPM
PX RADIATOR
MX RADIATOR
TANKS + TANK STRUTS
LTF UNITS
RCTs & RCT BRACKETS
Test Predicted Temperature Deviation / °C
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
ASTRIUM
AN EADS COMPANY

Conclusion

- The BepiColombo MTM STM was successfully tested and correlated
- Complex heatpipe network was verified
- Overall the system was slightly cooler than expected in the hot case, proving sufficient heat rejection capability
- The design has therefore been qualified
- Only very minor changes made for the PFM, which will be tested in Feb 2015



ASTRIUM
AN EADS COMPANY

Appendix W

List of Participants

Ali, Anwar
Politecnico
Politecnico di Torino - Corso Duca degli Abruzzi
10147 Torino
ITALY
✉ anwar.ali@polito.it

Atinsounon, Paul
THALES ALENIA SPACE
100, boulevard du Midi
06156 Cannes La Bocca
FRANCE
✉ paul.atinsounon@thalesaleniaspace.com

Bakker, Marije
National Aerospace Laboratory NLR
Voorsterweg 31
8316PR Marknesse
NETHERLANDS
✉ marije.bakker@nlr.nl

Bartholomew, Peter
MDAO Technologies
United Kingdom
✉ peter.bartholomew1@btconnect.com

Bascheri, Olivier
DOREA
Les Alisiers Bat B1 Route des Alisiers ZI des 3 Mo
06600 ANTIBES
FRANCE
✉ olivier.bascheri@dorea.fr

Basset, Thierry
TAS-Cannes
bd du midi
06150 Cannes la Bocca
FRANCE
✉ thierry.basset@thalesaleniaspace.com

Baturkin, Volodymyr
DLR, Institute of Space Systems
Robert-Hooke-Str. 7
28359 Bremen
GERMANY
✉ volodymyr.baturkin@dlr.de

Beaumont, Helen
ITP Engines UK Ltd
Cambridge Road, Whetstone
LE8 6LH Leicester
UNITED KINGDOM
✉ helen.beaumont@itp-engines.co.uk

Benthem, Roeland
National Aerospace Institute NLR
Antony Fokkerwegweg 2
1059 CM Amsterdam
NETHERLANDS
✉ roel.van.benthem@nlr.nl

Bodendieck, Frank
OHB System AG
Universitaetsallee 27-29
28359 Bremen
GERMANY
✉ frank.bodendieck@ohb-system.de

Brandl, Andreas
ASTRIUM GmbH
Robert-Koch-Str. 1
82024 Taufkirchen
GERMANY
✉ andreas.brandl@astrium.eads.net

Brouquet, Henri
ITP Engines UK Ltd
Cambridge Road, Whetstone
LE8 6LH Leicester
UNITED KINGDOM
✉ henri.brouquet@itp-engines.co.uk

Brunetti, François
DOREA
Les Alisiers Bat B1 Route des Alisiers ZI des 3 Mo
06600 ANTIBES
FRANCE
✉ francois.brunetti@dorea.fr

Capitaine, André
ASTRIUM
3 rue des Cosmonautes
Toulouse
FRANCE
✉ andre.capitaine@astrium.eads.net

Celotti, Luca
Active Space Technologies
GERMANY
✉ luca.celotti@activespacetech.eu

Checa, Elena
ESTEC/ESA
Keplerlaan 1
2200 AG Noordwijk
NETHERLANDS
✉ Elena.Checa@esa.int

Czupalla, Markus
Kayser-Threde Gmbh
GERMANY
✉ markus.czupalla@kayser-threde.com

De Palo, Savino
ThalesAlenia Space
Strada Antica di Collegno, 253
10146 Torino
ITALY
✉ savino.depalo@thalesaleniaspace.com

Etchells, James
ESA/ESTEC
Keplerlaan 1
2201 AZ Noordwijk
NETHERLANDS
✉ James.Etchells@esa.int

Fagot, Alain
DOREA
Les Alisiers Bat B1 Route des Alisiers ZI des 3 Mo
06600 ANTIBES
FRANCE
✉ alain.fagot@dorea.fr

Fernandez Rico, German
Universidad Politécnica de Madrid
plaza del cardenal cisneros, 3
28040 Madrid
SPAIN
✉ german.fernandez.rico@upm.es

Ferreira, Pedro
Max Planck Institute for Solar System Research (MP
Max-Planck-Str. 2
37191 Katlenburg-Lindau
GERMANY
✉ ferreira@mps.mpg.de

Fishwick, Nick
Astrium Ltd.
Gunnels Wood Road
SG1 2AS Stevenage
UNITED KINGDOM
✉ nicholas.fishwick@astrium.eads.net

Franzoso, Alberto
CGS SpA
Via Gallarate 150
20151 Milano
ITALY
✉ afranzoso@cgspace.it

Friso, Enrico
Independent Consulting Engineer
Via A.Pizzamano, 40/A
35127 PADOVA
ITALY
✉ enrico.friso@gmail.com

Gibson, Duncan
ESA/ESTEC
Keplerlaan 1
2201 AZ Noordwijk
NETHERLANDS
✉ Duncan.Gibson@esa.int

Gorlani, Matteo
Blue Engineering
via Albenga 98
10098 Cascine Vica, Rivoli
ITALY
✉ m.gorlani@blue-group.it

Hulier, Jean-Pierre
ASTRIUM
51-61 route de verneuil
78130 les mureaux
FRANCE
✉ jean-pierre.hulier@astrium.eads.net

Iugovich, Stéphane
ASTRIUM
FRANCE
✉ stephane.iugovich@astrium.eads.net

Kasper, Stefan
Jena-Optronik GmbH
Pruessingstrasse 41
07745 Jena
GERMANY
✉ stefan.kasper@jena-optronik.de

Jacques, Lionel
University of Lieges
BELGIUM
✉ ljacques@ulg.ac.be

Kirtley, Chris
ITP Engines UK Ltd
Cambridge Road, Whetstone
LE8 6LH Leicester
UNITED KINGDOM
✉ chris.kirtley@btinternet.com

Jahn, Gerd
Astrium GmbH
Claude-Dornier-Strasse
88090 Immenstaad
GERMANY
✉ gerd.jahn@astrium.eads.net

Laine, Benoit
ESA/ESTEC
Keplerlaan 1
2201 AZ Noordwijk
NETHERLANDS
✉ Benoit.Laine@esa.int

Jarrier, Antoine
DOREA
Les Alisiers Bat B1 Route des Alisiers ZI des 3 Mo
06600 ANTIBES
FRANCE
✉ antoine.jarrier@dorea.fr

Lardet, Paul
Sodern
Avenue Descartes
94451 Limeil-Brévannes Cedex
FRANCE
✉ paul.lardet@sodern.fr

Karaismail, F. N.
Turkish Aerospace Industries, Inc.
Fethiye Mah. Havacilik Blvd. No:17 Akýncý
06980 Ankara
TURKEY
✉ fnkaraismail@tai.com.tr

Laskowski, Jessica
DLR (Cologne)
Linder Höhe
51147 Cologne
GERMANY
✉ jessica.laskowski@dlr.de

Lein, Sebastian
Jena-Optronik GmbH
Prüssingstraße 41
07745 Jena
GERMANY
✉ sebastian.lein@jena-optronik.de

Leroy, Sandrine
DOREA
Les Alisiers Bat B1 Route des Alisiers ZI des 3 Mo
06600 ANTIBES
FRANCE
✉ sandrine.leroy@dorea.fr

Lindenmaier, Peter
HPS GmbH
Hofmannstr. 25-27
81379 München
GERMANY
✉ lindenmaier@hps-gmbh.com

Maas, Alexander
Dutch Space
Mendelweg 30
2333CS Leiden
NETHERLANDS
✉ a.s.maas@dutchspace.nl

Mena, Fabrice
EADS Astrium
FRANCE
✉ fabrice.mena@astrium.eads.net

Mercier, François
EADS ASTRIUM SAS
31 rue des cosmonautes
31402 Toulouse
FRANCE
✉ francois.mercier@astrium.eads.net

Molina, Marco
Selex ES
viale Europa
20014 NERVIANO
ITALY
✉ marco.molina@selex-es.com

Moroni, David
AVIO
C.SO GARIBALDI, 22
00034 COLLEFERRO
ITALY
✉ david.moroni@avio.com

Münstermann, Rolf
Astrium GmBH
Airbus-Allee 1
28199 Bremen
GERMANY
✉ rolf.muenstermann@astrium.eads.net

Nadalini, Riccardo
Active Space Technologies
ITALY
✉ riccardo.nadalini@activespacetech.com

Nerriere, Rose
EADS ASTIUM
31 avenue des Cosmonautes
31402 Toulouse
FRANCE
✉ rose.nerriere@astrium.eads.net

Okan, Altug
TUBITAK UZAY
ODTU Kampusu, Inonu Blv.
06531 Ankara
TURKEY
✉ altug.okan@tubitak.gov.tr

Pasquier, Marie-Hélène
CNES
18 AVENUE EDOUARD BELIN
31401 TOULOUSE
FRANCE
✉ helenem.pasquier@cnes.fr

Pin, Olivier
ESA
Keplerlaan 2
2200AG Noordwijk
NETHERLANDS
✉ olivier.pin@esa.int

Price, Steven
Astrium
Gunnels Wood Road
SG1 2AS Stevenage
UNITED KINGDOM
✉ steve.price@astrium.eads.net

Rathjen, Harold
Astrium GmbH Space Transportation
Airbus-Allee 1
28199 Bremen
GERMANY
✉ Harold.Rathjen@astrium.eads.net

Romera Perez, Jose Antonio
ESA/ESTEC
Keplerlaan, 1
2200 AG Noordwijk
NETHERLANDS
✉ jose.antonio.romera.perez@esa.int

Rooijackers, Harrie
ESA/ESTEC
Keplerlaan 1
2201 AZ Noordwijk
NETHERLANDS
✉ Harrie.Rooijackers@esa.int

Santoni, Massimo
Selex ES
Via A. Einstein
50013 Campi Bisenzio
ITALY
✉ massimo.santoni@selex-es.com

Schröder, Martin
OHB System AG
Universitätsallee 27-29
28359 Bremen
GERMANY
✉ martin.schroeder@ohb-system.de

Schwaller, David
ESA-ESTEC
Keplerlaan 1
2201 AZ Noordwijk
NETHERLANDS
✉ david.schwaller@esa.int

Scott, Morgan
Astrium UK
Gunnels Wood Road
SG1 2AS Stevenage
UNITED KINGDOM
✉ scott.morgan@astrium.eads.net

Selin, A.
TAI-TURKISH AEROSPACE INDUSTRIES
Fethiye Mahallesi, Havacilik Bulvari No:17
Kazan-
06980 ANKARA
TURKEY
✉ sarabaci@tai.com.tr

Shaenko, A.
Dauria Aerospace
st. Novaya, 100, Business center "Ural", Moscow re
143025 Technopark "Skolkovo"
RUSSIAN FEDERATION
✉ ark4110@mail.ru

Soriano, Timothée
Astrium SAS
3 rue des cosmonautes
31402 Toulouse
FRANCE
✉ timothee.soriano@astrium.eads.net

Stroom, Charles
MYOB
Gerrit van der Veenstraat 169-hs
1077EB Amsterdam
NETHERLANDS
✉ charles@stremen.xs4all.nl

Supper, Wolfgang
ESA/ESTEC
Keplerlaan 1
2201 AZ Noordwijk
NETHERLANDS
✉ wolfgang.supper@esa.int

Theroude, Christophe
Astrium Satellites
31 rue des cosmonautes
31402 Toulouse
FRANCE
✉ christophe.theroude@astrium.eads.net

Tosetto, Andrea
Blue Engineering
via Albenga 98
10098 Cascine Vica, Rivoli
ITALY
✉ a.tosetto@blue-group.it

Turkmenoglu, Mustafa
TUBITAK SPACE TECHNOLOGIES
RESEARCH INSTITUTE
ODTU KAMPUSU TUBITAK UZAY
06531 ANKARA
TURKEY
✉ mustafa.turkmenoglu@tubitak.gov.tr

Uygur, A. B.
Turkish Aerospace Industries, Inc.
Fethiye Mah. Havacýlýk Bul. No 17
06980 Ankara
TURKEY
✉ auygur@tai.com.tr

Zevenbergen, Paul
Dutch Space
Mendelweg 30
2333CS Leiden
NETHERLANDS
✉ p.zevenbergen@dutchspace.nl

Valentini, David
THALES ALENIA SPACE
100 boulevard du Midi
06156 Cannes la Bocca
FRANCE
✉ david.valentini@thalesaleniaspace.com

van Gerner, Henk Jan
NLR
Voorsterweg 31
8316PR Marknesse
NETHERLANDS
✉ Henk.Jan.van.Gerner@nlr.nl

Wendt, Christian
Astrium Space Transportation GmbH
Airbus Allee 1
28361 Bremen
GERMANY
✉ ChristianDr.Wendt@astrium.eads.net

Zamboni, Andrea
SELEX ES
Viale Europa SNC
20014 Nerviano
ITALY
✉ andrea.zamboni@selex-es.com