Proceedings of the

29th European
Space Thermal Analysis
Workshop

ESA/ESTEC, Noordwijk, The Netherlands

3–4 November 2015
Abstract

This document contains the presentations of the 29th European Space Thermal Analysis Workshop held at ESA/ESTEC, Noordwijk, The Netherlands on 3–4 November 2015. 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’.

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Programme Day 1

9:00 Registration

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

10:00 OrbEnv — A tool for Albedo/Earth Infra-Red environment parameter determination
   Alex Green (University College London, United Kingdom)
   Romain Peyrou-Lauga (ESA-ESTEC, The Netherlands)

10:25 Mercury Retro-Reflection — Modelling and Effects on MPO Solar Array
   Anja Frey & Giulio Tonellotto (ESA/ESTEC, The Netherlands)

10:50 On the thermal design and modelling of calibration blackbodies for the FCI and IRS instruments on MTG
   Nicole Melzack (RAL Space, United Kingdom)

11:15 Coffee break in the Foyer

11:45 Development of methodologies for Brightness Temperature evaluation for the MetOp-SG MWI radiometer
   Alberto Franzoso (CGS, Italy)
   Sylvain Vey (ESA/ESTEC, The Netherlands)

12:10 MASCOT thermal design — how to deal with late and critical changes
   Luca Celotti & Malgorzata Solyga (Active Space Technologies GmbH, Germany)
   Volodymyr Baturkin & Kaname Sasaki & Christian Ziach (DLR, Germany)

   Samuel Tustain (RAL Space, United Kingdom)

13:00 Lunch in the ESTEC Restaurant

14:00 Spatial Temperature Extrapolation Case Study — Gaia in-flight
   Matthew Vaughan (ESA/ESTEC, The Netherlands, Airbus Defence and Space, France)

14:25 Accelerating ESATAN-TMS Thermal Convergence for Strongly Coupled Problems
   Christian Wendt & Sébastien Girard (Airbus Defence and Space, Germany)

14:50 OHB System — Thermal Result Viewer
   Markus Czupalla & S. Rockstein & C. Scharl & M. Matz (OHB System, Germany)

15:15 Overview of ECSS Activities for Space Thermal Analysis
   James Etchells (ESA/ESTEC, The Netherlands)

15:45 Coffee break in the Foyer

16:15 Improve thermal analysis process with Systema V4 and Python
   Alexandre Darrau (Airbus Defence and Space, France)

16:40 Finite element model reduction for spacecraft thermal analysis
   Lionel Jacques & Luc Masset & Gaetan Kerschen
   (Space Structures and Systems Laboratory, University of Liège, Belgium)

17:05 The Thermal Design of the KONTUR-2 Force Feedback Joystick
   Ralph Bayer (DLR, Germany)

17:30 Social Gathering in the Foyer

19:30 Dinner in La Galleria
Programme Day 2

9:15  **ESATAN Thermal Modelling Suite** — Product Developments and Demonstration  
     Chris Kirtley & Nicolas Bures (ITP Engines UK Ltd, United Kingdom)

10:00 **SYSTEMA — THERMICA**  
     Timothée Soriano & Rose Nerriere (Airbus Defense and Space SAS, France)

10:45 **Thermal Spacecraft Simulator Based on TMM Nodal Model — Return of Experience**  
     Sandrine Leroy & François Brunetti (DOREA, France)

11:10 Coffee break in the Foyer

11:40 **Correlation of two thermal models**  
     Marije Bakker & Roel van Benthem (NLR, The Netherlands)

12:05 **Experience of Co-simulation for Space Thermal Analysis**  
     François Brunetti (DOREA, France)

12:30 **GENETIK+ — Introducing genetic algorithm into thermal control development process**  
     Guillaume Mas (CNES, France)

12:55 Closure

13:00 Lunch in the ESTEC Restaurant

14:00 Lab visits

15:30
Appendix A

Welcome and introduction

Harrie Rooijackers
(ESA/ESTEC, The Netherlands)
Welcome and introduction

Workshop objectives

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

ESA Team

Benoit Laine Head of Section
James Etchells
Duncan Gibson
Harrie Rooijackers

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

Programme

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

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

Workshop dinner

- in “La Galleria”, Kon. Wilhemia Boulevard 18, 2202 GT Noordwijk, ☎ +31(0)71 19 17196
- 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
The 46th International Conference on Environmental Systems (ICES) will be held 10-14 July, 2016, Vienna, Austria.

Deadline for submitting abstracts: 16 November, 2015

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
Next year: 30th workshop, 5-6 October 2016
Wed – Thu !!!

Why not Tue as usual?
On 3 October 1574 the siege of Leiden ended. This is still annually celebrated in Leiden with festivities in the centre with herring and white bread and "hutspot" (carrot and onion stew), the available liberation food at that time.

Public transport is a mess and even road transport in the area suffers.

On 4 October they can clean up the mess.

On 5 October everything is back to normal again.
In the war (eventually called the Eighty Years’ War) that had broken out, Dutch rebels took up arms against the king of Spain, whose family had inherited the Seventeen Provinces of the Netherlands. Most of the counties of Holland and Zeeland were occupied by rebels in 1572, who sought to end the harsh rule of the Spanish Duke of Alba, governor-general of the Netherlands.

See also:

- en.wikipedia.org/wiki/Dutch_Revolt
The territory had a very high density of cities, which were protected by huge defense works and by the low-lying boglands, which could easily be flooded by opening the dykes and letting in the sea.
The picture on the left shows a current altitude map of the Netherlands.
The picture on the right shows the part of the country above sea level in green and the part below in red.
Here is a zoom in on the current area of Leiden showing the sealevel.
Current workshop:
19 very interesting presentations covering:
- Range of general applications
- New tools
- Existing thermal tools
  • Enhancements
  • Applications
  • User experiences

Listen, Ask, Discuss

most of all: Enjoy
Appendix B

OrbEnv
A tool for Albedo/Earth Infra-Red environment parameter determination

Alex Green
(University College London, United Kingdom)

Romain Peyrou-Lauga
(ESA-ESTEC, The Netherlands)
Abstract

OrbEnv is a tool developed for ESA missions to provide realistic and less enveloping albedo coefficient and Earth temperature range for an orbit using data measured by satellites. The tool is able to treat the most common orbit types (LEO, SSO, HEO, MEO...) and is able to calculate impinging albedo and Earth fluxes for several basic geometries and several time steps. Data comes from the CERES instrument on NASA’s Terra satellite and covers more than 6 years of measurement.
Why develop such a tool?

OrbEnv tool development was initiated by several facts:

1. Thermal analyses of spacecraft in low Earth orbit rely on thermal environment parameters coming from various standards, not always in accordance.

2. Such environmental parameters are generally expected to cover the worst hot/cold cases for thermal analysis and design.

3. Environmental parameters are sometimes assumed regardless of the orbit definition, the season, the time constant of the spacecraft (or of local parts exposed to the external environment...)

4. For more than a decade, extensive and continuous measurements of Earth radiated and reflected flux have been performed by spaceborne instruments (CERES) and data are available.

Illustration of available Earth radiant energy data (Credit: CERES/NASA)
Objectives of OrbEnv tool

OrbEnv activity and tool development objectives:

1. Understanding CERES data (albedo, IR flux) and compare them with existing standards

2. Find a method to use CERES data and determine albedo / IR flux depending on:
   - the orbit definition,
   - the season,
   - the time constant of the spacecraft (or of local parts exposed to the external environment.)

3. Develop a tool to determine albedo / IR flux for any Earth orbit with several options:
   - basic geometry of the spacecraft (plane, sphere, cube)
   - time step

Earth Infra-Red equivalent temperature depending on season and latitude (NASA CERES measured data)

Earth Infra-Red equivalent temperature depending on season and latitude (NASA CERES measured data)

- Winter solstice
- Summer solstice
- Spring equinox
- Autumn equinox

Earth temperature in K

OrbEnv — A tool for Albedo/Earth Infra-Red environment parameter determination
Albedo coefficient depending on season and latitude (NASA CERES measured data)

Albedo depending on season and latitude (NASA CERES measured data)

Spring equinox

Winter solstice

Summer solstice

Autumn equinox

Earth temperature in K
Real data was obtained for every day during the period of interest. Given as a map with 1 degree by 1 degree grid points. The planetary IR emission is given in W/m². The same features can be seen in both maps, for example clouds tend to be more reflective than land so have a higher albedo, but are colder so have lower thermal IR emission.
The movement of cloud features can be seen in this 10 day period. The lack of sunlight at the pole due to the northern hemisphere winter can be also be seen.
Save the attachment to disk or (double) click on the picture to run the movie.
Model: Spacecraft orbit

Single orbit overlaid on map data

Separation of data points is 1 minute in this case

• Two examples of ground visibility 25 minutes apart:

The flux received at each point of the orbit varies according the features visible at each instant. In one of these two examples the spacecraft is over the coast of Brazil and sees mainly low albedo ocean and forest, but later is over ocean with lots of cloud cover and thus a much higher average albedo.
Where there is missing data the average value for the month is used. If a time period outside the data range is requested then the date can be be mapped around into the range, or average values can also be used.
The data is taken by the satellite in a sun-synchronous orbit by building up ground tracks that have an equator crossing at 10:30 am local time. When integrating over the area visible to the satellite the data for the grid point should therefore be the one taken closest to 10:30 am local time even if it was taken on the previous or next calendar day according to UTC.
The data is provided as a single value for each day, but thermal IR emission has a strong variation during the day which must be allowed for. This also depends on location; ocean sees little variation due to the large thermal inertia of water, while desert sees a much bigger cycle. Also some areas experience different cycles due to cloud cover changes, e.g. clouds tend to form over rainforests in the afternoon, reducing IR emission. To estimate this cycle, data was processed that shows how IR emission varies during the day for each grid point, by each month of the year. So for example we can say that on a typical March day the IR emission from a grid point in the Sahara is 5% greater at 1:30 pm than at 11:30 am when the satellite data was taken. This is combined with the satellite data for that day to provide an estimate of the emission at any time during the day in question.
At every grid square on the map the contribution to the flux received at the spacecraft location is calculated if the spacecraft is visible (the angle between the grid point normal and the grid-to-spacecraft vector is < 90 deg). Both albedo and IR fluxes are calculated for each face on the spacecraft. In addition the flux is calculated for two cases:

1. If the Earth had a uniform value for albedo/IR
2. With the real, varying albedo/IR values measured by satellite.
The sunlit portion of one orbit is shown. The albedo flux (in units of the solar constant) at the spacecraft position is shown for two cases:

1. Earth has a uniform albedo value of 0.3
2. An actual flux with albedo varying according to satellite measurements for the relevant day.

By comparing the two we can calculate an effective albedo value at each point - a uniform value for the earth that would produce the same heating as predicted using the varying albedo data. For example if the predicted (actual) flux at the spacecraft position is higher than the calculation for the uniform (0.3) case then we can infer that the effective albedo at that moment must have been proportionally greater than 0.3. It can be seen that on this orbit the effective albedo during the orbit is around 0.3 on average, with some variation between 0.2 and 0.4 due to the features the spacecraft passes over.
A front end for the model has been written to make it easy for engineers to set up and study cases of interest. The orbit can be specified in several ways, or imported from a file (e.g. output from STK). The spacecraft geometry and orientation (earth/velocity/sun/polar/ecliptic) can also be specified.
Back end calculations performed in Fortran

Specify duration of interest:
• By time
• By number of orbits

Simulation time step
Fully multi-threaded:
~300 orbits / min

The model calculations are implemented in Fortran for speed. The simulation can be completed in under an hour on a reasonably powerful computer, so does not have a significant impact on workflow.
The results can be explored graphically or exported to file for further study.
Environment hypotheses vary between satellites...

<table>
<thead>
<tr>
<th>Albedo</th>
<th>Cold Case</th>
<th>Hot Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>0.20</td>
<td>0.40</td>
</tr>
<tr>
<td>“Low polar”</td>
<td>0.16</td>
<td>0.34</td>
</tr>
<tr>
<td>“Polar sso”</td>
<td>0.25</td>
<td>0.35</td>
</tr>
</tbody>
</table>

- What is the reason for these choices?
- Is it possible to find some evidence to support them?

Or alternatively: Make recommendations for future missions

- Calculate worst cases from orbit with real albedo data
- Use those values as hot and cold case in thermal modelling tools

The issue has been raised lately of why certain values for Earth’s thermal environment are used; why the chosen values are not consistent, and what justifies the choices. Earth's albedo is approximately 0.3 when averaged over the entire globe, so values of 0.2 - 0.4 are common choices for the cold and hot cases. But for example, in the case of some polar spacecraft, flying over areas with greater albedo on average, we see lower values are chosen, why?

Instead the model that has been developed can be used to combine spacecraft orbits with real Earth observation data to estimate the range of environment variables that would have been experienced in reality. This can provide evidence to support the choice of values for thermal modelling.
Orbits

Altitude = 420 km
Period   = 92.8 min
Eccentricity = 0

Inclination:
1) “ISS”: 51.6°
2) “Polar”: 87.4°

Model: 5 years of orbits -> 28326 revolutions
Drifting ascending node – samples all possible orientations

Two orbits have been chosen for comparative purposes; one orbit similar to the ISS, and one with the same altitude but in a polar orbit. Five years are modelled, providing a large number of revolutions to give a large statistical sample.
The data can be averaged over different timescales, here an average over one orbit is calculated. This shows what uniform value of albedo the earth would have needed for the spacecraft to receive the same energy over one orbit as it does in the case when actual albedo data is used. For the ISS orbit a range of 0.2 - 0.4 appears sensible for the extreme cases. There appear to be two peaks of albedo per year.
In the polar case the effective albedo range observed is much higher, the ranges assumed for polar spacecraft earlier does not appear to be appropriate. The distribution also appears to be somewhat bimodal.
The same calculations can be done for thermal IR emission in the ISS case. There is only one peak per year.
Polar orbit, IR.

Range: 245.1 - 255.5 K
Mean = 250.1 K
MetOp-A has an orbit typical of sun-synchronous earth observation satellites. It was launched in 2006 so here the real spacecraft position data for the period 2007-2011 could be imported into the simulation. This allows us to observe the actual features/weather the spacecraft flew over.
The range of effective albedo averaged over one orbit is observed to vary between 0.24 and 0.41. We can see that the normal range of 0.2 - 0.4 would perhaps be a little too conservative in the cold case.
For IR emission the effective surface temperature varies between 246 and 256 K.
The results so far have shown effective surface parameters when averaged over a single orbit. The model can also output the instantaneous albedo/IR heating received by the spacecraft, and perform averaging over different timescales.
Timescale variation

Timescale is important...

- Need to choose appropriate hot and cold cases matched to system size
- Per orbit averaging in this case had range 245 - 255 K
- Range changes greatly over small timescales!

It can be seen that the variations are much greater when averaged over smaller timescales.
In addition to albedo and planetary IR, the other major parameter of the orbital thermal environment is direct solar heating. In recent years the value of solar "constant" has been questioned due to new measurements. The commonly employed, old values of solar irradiance appear to be in error due to scattering and diffraction internal to the instruments used.
The Total Irradiance Monitor on NASA’s SOlar Radiation and Climate Experiment satellite measures the Total Solar Irradiance much more accurately and gives a new lower figure. This value is now accepted by climate scientists and is recommended in the latest report from the United Nations Intergovernmental Panel on Climate Change.
New TSI value

Uncertainties:
± 0.5 W/m² (measurement)
± 0.05 W/m² (solar variation)

Earth orbit:
1 AU: 1361 W/m²
Perihelion: 1407 W/m²
Aphelion: 1316 W/m²

Extra margin: 1 W/m²

Recommendation:
Hot case: **1410 W/m²**
Average: **1361 W/m²**
Cold case: **1310 W/m²**

When taking into account Earth’s orbit, the solar cycle, and the uncertainties, then new values of solar heating for hot and cold cases are recommended for a spacecraft in orbit around the Earth.
Thank you!

Questions?

http://www.kuu.org.uk/orbenv/
Appendix C

Mercury Retro-Reflection
Modelling and Effects on MPO Solar Array

Anja Frey        Giulio Tonellotto
(ESA/ESTEC, The Netherlands)
Abstract

Mercury’s regolith might reflect the incident sun light preferably in the direction of the Sun, causing a retro-reflection effect. In the case of the BepiColombo Mercury Planetary Orbiter solar array this deviation from the bond albedo, which is implemented in most thermal analysis software, may cause significant temperature differences. This causes power losses since the solar array is continuously steered throughout the orbit in order to optimize its sun aspect angle (maximum sun power) without exceeded the design temperatures.

To estimate the influence of this albedo variation the mathCAD sheet Mercury Orbital Heat Fluxes Assessment (Merflux), developed by ESTEC’s D. Stramaccioni, was adapted to calculate the heat fluxes that a spacecraft experiences in orbit around Mercury when considering the retro-reflection. Different albedo modelling options were implemented and finally the diffusive reflection modelling was compared with a directional reflection case, where sunlight is reflected back into the direction of the Sun more than into the other directions. The directional reflection modelling was considered the most realistic, based on findings in literature.

The peak albedo flux, impinging on a nadir-pointing cube, calculated with this directional model, was found to be more than twice the flux calculated with the diffusive approach, while the integral remains the same (energy balance of the planet). An extensive parametric study, with different solar panel models and attitudes, concluded that the influence of the albedo modelling has a non-negligible influence on the solar array temperature. For a fixed solar aspect angle throughout the whole orbit, the biggest difference in temperature between the two albedo models was found to be +14°C/ -10°C. A more realistic approach used a steering profile provided by ESOC and found maximum ΔT of +8°C/ -5°C. These worst ΔT are local peaks, not applicable to the whole orbit, nor applicable to the most critical panel wing of the solar array, whose ΔT is only +4°C/ -4°C. Around the sub-solar point the directional albedo provides the highest temperatures, while they are lower at the poles.

This information will permit preparing the best approach for solar array in orbit steering functions definition and calibration.
Mercury Retro-Reflection: Modelling and Effects on MPO Solar Array

Anja Frey
Giulio Tonellotto
ESTEC
03/11/2015
BepiColombo (spacecraft/mission)

- Europe's first mission to the planet Mercury, planned launch 2017
- Three modules:
  - Mercury Planetary Orbiter (MPO, ESA): studies surface and internal composition
  - Mercury Magnetospheric Orbiter (MMO, JAXA) surrounded by the Sunshield (ESA): studies magnetosphere
  - Mercury Transfer Module (MTM, ESA): carries the whole SC to Mercury
- Journey to Mercury takes 7.5 years with eight gravity-assist manovers at Earth, Venus, and Mercury
- Planned mission duration in orbit around Mercury is minimum one year

Save the attachment to disk or (double) click on the picture to run the movie.
**Scope of the Activity**

1. **Modelling of Mercury retro-reflection effects**: this was obtained by adapting the Merflux Worksheet (*) to account for retro-reflection in the albedo calculation.

2. **Estimation of retro-reflection effects on MPO Solar Array**: a simplified two nodes model of the SA was analyzed in order to determine the change in the predicted solar panel temperatures.

(*) Merflux Worksheet is a MathCAD tool created by D. Stramaccioni for in orbit heat fluxes calculation. This tool was validated against Esatan-TMS by J. Etchells, "MathCAD Heat Flux Calculator Verification Report" [2006, TEC-MCV/2006/3176/In/JE]

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**Environmental Specification:**
**BC-EST-TN-00112**

- **Bond albedo**: 0.119
  - Bond albedo is the fraction of incident solar energy that is reflected back to space by a spherical body over all wavelengths. [...] Origin of this value and its derivation can be found in reference [3.1] below.

- **Visual geometric albedo**: 0.138
  - Geometric albedo (or head-on reflectance) is the fraction of incident solar energy that is reflected back by a planet into the direction of the Sun (phase angle equal to 0). It can be also thought as the amount of radiation reflected from a planet relative to that from a flat Lambertian surface, which is a diffuse perfect reflector at all wavelength. The reported value is taken from reference [3.1].

Mercury Albedo

TABLE III
Estimates of Bond Albedo

<table>
<thead>
<tr>
<th></th>
<th>$p_v$</th>
<th>$q_v$</th>
<th>$A_B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moon</td>
<td>0.113</td>
<td>0.611</td>
<td>0.123 ± 0.002</td>
</tr>
<tr>
<td>Mercury</td>
<td>0.138</td>
<td>0.486</td>
<td>0.119</td>
</tr>
</tbody>
</table>

$^a$Values from Lane and Irvine 1973.
$^b$This work.

$P_v$ geometric albedo in the V filter of the UBV system

$q_v$ phase integral in the V filter of the UBV system

$A_v = p_vq_v$ spherical albedo in the V filter of the UBV system

$A_B$ bond albedo

$\left(\frac{A_B}{A_V}\right)_v \approx \left(\frac{A_B}{A_V}\right)_g$

UBV: a wide band photometric system for classifying stars according to their colors.
U: ultraviolet
B: blue
V: visual


UBV photometric system, also called the Johnson system (or Johnson-Morgan system), is a wide band photometric system for classifying stars according to their colors. It is the first known standardized photoelectric photometric system. The letters U, B, and V stand for ultraviolet, blue, and visual magnitudes.

Lane and Irvine (1973), who determined $p$ and $q$ as a function of wavelength, between 350 and 1000 nm, and used these values to calculate the radiometric Bond albedo shown in Table 111. In the case of Mercury, we lack sufficient information to derive the wavelength dependence of $q$, and as far as $p$ is concerned, an adequate first approximation is that the wavelength behavior is similar to that of the Moon.
1. Solar flux: \( Q_{S, k, j} = S_C \cdot \alpha_k \cdot A_k \cdot F_{ss, k, j} \left( 1 - \delta_{ecl, j} \right) \)

2. Planet IR flux: \( Q_{IR, k, j} = \Sigma_{grid} \sigma \cdot T_{grid}^4 \cdot S_{grid} \cdot \epsilon_k \cdot A_k \cdot \frac{C_1 \cdot C_2}{\pi \cdot d^2} \)

3. Directional emissivity: \( \frac{\epsilon(\varphi)}{\epsilon_H} = 0.9 \left( \cos(\varphi) \right)^m / \epsilon_H \)

4. Albedo flux: \( Q_{A, k, j} = \Sigma_{grid, sunlit} S_C \cdot a \cdot C_3 \cdot S_{grid} \cdot \alpha_k \cdot A_k \cdot \frac{C_1 \cdot C_2}{\pi \cdot d^2} \)

Albedo Models alternatives

1. Diffusive Model:
   a. Incident flux is reflected diffusively in all directions
   b. The spatial distribution is even in all directions

2. Retro-reflection Model:
   a. The solar flux is reflected back into the direction of the Sun
   b. The reflection resembles that of a flat mirror

3. Directional Reflection Model:
   a. Compromise between diffusive and retro-reflection
   b. Light is primarily reflected into one direction while some of it is still reflected diffusively
**Directional Emissivity**

"Radiation: Processes and Properties Surface Radiative Properties", 
http://me.queensu.ca/Courses/346/

- The spectral, directional emissivity:

\[
\varepsilon_{\lambda,\theta}(\lambda, \theta, \phi, T) \equiv \frac{I_{\lambda,\varepsilon}(\lambda, \theta, \phi, T)}{I_{\lambda,\varepsilon}(\lambda, T)}
\]

- The spectral, hemispherical emissivity (a directional average):

\[
\varepsilon_{\lambda}(\lambda, T) \equiv \frac{E_{\lambda}(\lambda, T)}{E_{\lambda,\varepsilon}(\lambda, T)} = \frac{\int_0^{2\pi} \int_0^{\pi/2} I_{\lambda,\varepsilon}(\lambda, \theta, \phi, T) \cos \theta \sin \theta \, d\phi \, d\theta}{\int_0^{2\pi} \int_0^{\pi/2} I_{\lambda,\varepsilon}(\lambda, T) \cos \theta \sin \theta \, d\phi \, d\theta}
\]


**Directional reflection**

Note: tear drop shapes are dimensionless representations of Albedo directional reflection

C1 angle between reflection direction and spacecraft position

C2 angle between S/C surface and grid point on the planet's surface
**Directional reflection**

### 6. ALBEDO RADIATION

#### 6.1 Constants and Planet Environment Parameters

- Planet Albedo coefficient: \( \alpha = 0.12 \)
- Directional reflection distribution: \( a \).
- Geometric albedo: \( \alpha_n \).

#### Exponent for Directional Reflection

- \( \alpha_n = 0.2 \)
- \( a = 0.3 \)

#### Area of the Planet's Surface Grid

- \( S_{grid} \)

#### Solar Absorptivity

- \( \alpha_s \)

**Reminder: Diffusive Albedo**

\[
Q_{A,k,j} = \sum_{\substack{\text{grid} \text{, sunlit} \\text{cells}}} \alpha_s \cdot C_1 \cdot C_2 \cdot \alpha \cdot a \cdot S_{grid} \cdot C_3 \cdot \alpha_{k,j} \cdot A_{k,j}
\]

**NP** Unit vector normal to planet's surface

**an** Exponent for directional reflection

**Sgrid** Area of the planet’s surface grid

**\( \alpha_s \)** Solar absorptivity

---

**Reference Orbit Case**

**Perihelion case:**

Diffusive Albedo (as considered so far for BepiColombo analyses)

#### 2.1 Input Orbital Parameters

- Altitude of periapsis: \( h_p = 400 \times 10^3 \) m
- Altitude of apoapsis: \( h_a = 1508 \times 10^3 \) m
- Orbit inclination: \( i = 90 \) deg

**Nadir pointing**
**Albedo heat fluxes comparison**

(nadir-pointing cube)

- Directional albedo is considered the most realistic approach
- Differences in peak Albedo fluxes can be significant between the different models

![Graph showing albedo heat fluxes comparison](image)

**Steering profiles provided by ESOC**

![Graph showing steering profiles](image)
**Albedo heat fluxes comparison**

(Steering profile)

- Directional albedo is considered the most realistic approach
- Differences in peak Albedo fluxes can be significant between the different models

---

**Solar Panel Thermal Model**

1. 2 Nodes: Front and back
2. Front covered with optical solar reflector (OSR)
3. Back is bare CFC or covered with OSR
4. Solar Panel Area = 1322 mm * 2065 mm, thickness = 22.8 mm
5. Consist of CFC Honeycomb between CFC Sheets
6. Thermal inertia is null

<table>
<thead>
<tr>
<th>Panel</th>
<th>Front Side</th>
<th>Back Side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Panels</td>
<td>a) OSR 47% EOL:</td>
<td>1) Bare CFC EOL:</td>
</tr>
<tr>
<td></td>
<td>( \alpha/\varepsilon = 0.601/0.827 )</td>
<td>( \alpha/\varepsilon = 0.92/0.825 )</td>
</tr>
<tr>
<td>Inner Panel</td>
<td>b) OSR 82% EOL:</td>
<td>2) OSR 100% EOL:</td>
</tr>
<tr>
<td></td>
<td>( \alpha/\varepsilon = 0.372/0.803 )</td>
<td>( \alpha/\varepsilon = 0.25/0.79 )</td>
</tr>
</tbody>
</table>

**NB1**: Case a1 represents Cells/OSR ratio of the outermost panels (2 and 3). Case b2 represent inner panel.

**NB2**: Null thermal inertia considered: only slightly conservative assumption and closer to real operational mode where SA temperatures are kept close to constant values

[See BC-ASO-AN-116068 Is.3 par.5.1.3 and 5.3 (selected values)]
Thermal Analysis Cases

Analysis cases are combinations of the following points:
1. 3 SA combinations of optical properties (front/back) have been considered (outer panel, inner panel, and worst case optical properties combination): a1, b2, b1.
2. Solar Panel is at constant angle to the Sun: 90°, 78°, and 65°
3. Perihelion and Aphelion orbits
4. 4 different Albedo modelling approaches:
   a. bond albedo 0.119 (fully diffused)
   b. full retro-reflection 0.12
   c. full retro-reflection 0.138
   d. directional albedo
5. 2 realistic steering profiles (perihelion & aphelion) provided by ESOC

Note: ThermXL and Esatan software (part of Esatan-TMS suite) has been used for SA temperatures calculation.

Temperature of inner panel with ESOC SAA profile at Perihelion

---

Temperature of Solar Panel Front

![Temperature of Solar Panel Front](image1)

Temperature Difference of Solar Panel Front

![Temperature Difference of Solar Panel Front](image2)

---

29th European Space Thermal Analysis Workshop
3–4 November 2015
Temperature of outer panel with ESOC SAA profile at Perihelion

Temperature of Solar Panel Front

True Anomaly [°]
Temperature [°C]
Time [s]

Temperature Difference of Solar Panel Front

True Anomaly [°]
Temperature Difference [°C]
Time [s]

Temperature of inner panel with ESOC SAA profile at Aphelion

Temperature of Solar Panel Front

True Anomaly [°]
Temperature [°C]
Time [s]

Temperature Difference of Solar Panel Front

True Anomaly [°]
Temperature Difference [°C]
Time [s]
Summary

1. A simplified model of Mercury Albedo has been built
2. Environmental heat fluxes have been calculated
3. The impact on MPO SA temperatures has been studied for:
   • Perihelion and Aphelion orbits
   • 4 different Albedo modelling approaches (diffusive vs retro-reflection)
   • 3 SA combinations of optical front/back properties
   • 3 fixed SAA: 90deg, 78deg and 65deg angles
   • 2 realistic steering profiles (perihelion & aphelion) provided by ESOC

Note: The most realistic Albedo modelling approach is considered the one with Albedo directional reflection (i.e. diffused reflection with much higher energy concentration around the direction of retro-reflection).
Conclusions 1/2

1. Albedo modelling has a negligible influence on SA temperatures
2. Fixed SA SAA (not realistic case): for the directional retro-reflection (considered the best engineering case), the SA front side worst \( \Delta T \) (directional minus diffusive albedo) during orbit is \( \sim +14/-10 \text{degC} \) for outermost panels and \( \sim +10/-5 \text{degC} \) for the innermost panel
3. Variable SAA (realistic steering profile case): for the directional retro-reflection, the SA front side worst \( \Delta T \) during orbit is less than \( +8 \text{degC}/-5 \text{degC} \) for outermost panels and less than \( +4/-4 \text{degC} \) for the innermost panel
4. Worst \( \Delta T \) is a peak (limited time duration), not applicable to the whole orbit: around sub-solar point the directional albedo provides the highest temperatures.

Conclusions 2/2

5. There are parts of the orbit where the diffusive albedo approach is conservative: in those areas Industry models are conservative (safe in temperature), but SAA steering profile might not be optimized at best (reduced power generation).
6. Results are preliminary estimations based on simplified models of planet and SA (e.g. 2 nodes for SA), averaged optical properties for SCA+OSR, albedo modelling approach for Mercury not consolidated.
7. Worst cases occur in SA panels with bare CFC on the backside (outermost panels) and are usually more pronounced in cases with bigger SAA (as visible within analysis cases with fixed SAA).
1. Using thermal models for definition of SA steering profile at Mercury is very challenging and was never done before.

2. In this study is estimated the effect that albedo might have on SA. This effect changes based on real environment to be found at Mercury and on modelling assumptions: an improvement of models themselves might help, but will not solve the problem (thermal models limitations, software limitations in retro-reflection modelling, and limited knowledge of Mercury albedo itself).

3. The albedo predictions can be also influenced by Mercury albedo coefficients variations over the planet surface: this is an additional source of uncertainty, partially covered by the Planet IR compensation (higher albedo → lower IR). The overall effect was considered negligible by Industry but never quantified.
4. The SA steering calibration at beginning of MPO orbit phases (after MOI) shall be carefully planned by taking extra margins: i.e. started with a target T lower than nominal and fine tuned once SA simplified model is considered properly validated with flight data.

5. A predefined table of sensitivity to SAA variations at different orbit positions and seasons might help the calibration itself and it is recommended (e.g. sensitivity to 1deg angle variation along mission). Simplified SA thermal model profiles might be corrected based on flight T measurements and these sensitivity tables.

6. Impact on SA thermal control, power budgets and operations should be discussed

<table>
<thead>
<tr>
<th>Case</th>
<th>Max/min ∆T Diffusive and Directional Reflection [K]</th>
<th>Max/min ∆T Diffusive and Retro- Reflection 0.12 [K]</th>
<th>Max/min ∆T Diffusive and Retro- Reflection 0.138 [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perihelion a1y 90 deg</td>
<td>+13.9/-10.0</td>
<td>0.00/-12.33</td>
<td>0.00/-12.33</td>
</tr>
<tr>
<td>Perihelion a1y 88 deg</td>
<td>+7.6/-5.3</td>
<td>+5.37/-8.34</td>
<td>+6.79/-8.34</td>
</tr>
<tr>
<td>Perihelion a1y 75 deg</td>
<td>+5.5/-3.4</td>
<td>+9.99/-6.40</td>
<td>+11.82/-6.40</td>
</tr>
<tr>
<td>Perihelion a1y SAA profile</td>
<td>+7.6/-5.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perihelion b1y 90 deg</td>
<td>+12.2/-10.1</td>
<td>+0.02/-12.37</td>
<td>+0.00/-12.37</td>
</tr>
<tr>
<td>Perihelion b1y 88 deg</td>
<td>+8.4/-6.3</td>
<td>+8.03/-9.62</td>
<td>+9.74/-9.62</td>
</tr>
<tr>
<td>Perihelion b1y 75 deg</td>
<td>+6.9/-4.4</td>
<td>+14.32/-7.92</td>
<td>+16.71/-7.92</td>
</tr>
<tr>
<td>Perihelion b1y SAA profile</td>
<td>+8.4/-7.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perihelion b2y 90 deg</td>
<td>+6.8/-5.0</td>
<td>+0.00/-6.67</td>
<td>+0.00/-6.67</td>
</tr>
<tr>
<td>Perihelion b2y 88 deg</td>
<td>+3.8/-3.5</td>
<td>+1.20/-4.71</td>
<td>+1.72/-4.71</td>
</tr>
<tr>
<td>Perihelion b2y 75 deg</td>
<td>+2.4/-2.6</td>
<td>+3.34/-3.28</td>
<td>+4.08/-3.28</td>
</tr>
<tr>
<td>Perihelion b2y SAA profile</td>
<td>+3.7/-3.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Temperature Differences between Albedo Models (2/2)

<table>
<thead>
<tr>
<th>Case</th>
<th>Max/min ΔT Diffusive and Directional Reflection [K]</th>
<th>Max/min ΔT Diffusive and Retro-Reflection 0.12 [K]</th>
<th>Max/min ΔT Diffusive and Retro-Reflection 0.138 [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aphelion a1y 90 deg</td>
<td>+13.4/-8.6</td>
<td>+0.00/-11.81</td>
<td>+0.00/-11.81</td>
</tr>
<tr>
<td>Aphelion a1y 88 deg</td>
<td>+9.0/-4.4</td>
<td>+0.00/-6.51</td>
<td>+0.00/-6.51</td>
</tr>
<tr>
<td>Aphelion a1y 75 deg</td>
<td>+6.9/-2.9</td>
<td>+2.50/-4.78</td>
<td>+3.52/-4.78</td>
</tr>
<tr>
<td>Aphelion a1y SAA profile</td>
<td></td>
<td>+7.3/-2.8</td>
<td></td>
</tr>
<tr>
<td>Aphelion b1y 90 deg</td>
<td>+11.5/-8.6</td>
<td>+0.00/-11.75</td>
<td>+0.00/-11.75</td>
</tr>
<tr>
<td>Aphelion b1y 88 deg</td>
<td>+7.2/-4.4</td>
<td>+0.00/-6.51</td>
<td>+0.00/-6.51</td>
</tr>
<tr>
<td>Aphelion b1y 75 deg</td>
<td>+5.0/-2.9</td>
<td>+0.00/-4.08</td>
<td>+0.64/-4.08</td>
</tr>
<tr>
<td>Aphelion b1y SAA profile</td>
<td></td>
<td>+5.5/-2.7</td>
<td></td>
</tr>
<tr>
<td>Aphelion b2y 90 deg</td>
<td>+6.4/-4.0</td>
<td>+0.00/-6.05</td>
<td>+0.00/-6.05</td>
</tr>
<tr>
<td>Aphelion b2y 88 deg</td>
<td>+5.8/-3.1</td>
<td>+0.68/-5.02</td>
<td>+1.21/-5.02</td>
</tr>
<tr>
<td>Aphelion b2y 75 deg</td>
<td>+6.2/-4.5</td>
<td>+4.43/-4.47</td>
<td>+5.42/-4.47</td>
</tr>
<tr>
<td>Aphelion b2y SAA profile</td>
<td></td>
<td>+5.6/-2.3</td>
<td></td>
</tr>
</tbody>
</table>

Results (1/24): perihelion/outer panel/SAA 90deg

<table>
<thead>
<tr>
<th>Front Side</th>
<th>Back Side</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSR 47% EOL: $\alpha/\epsilon = 0.601/0.827$</td>
<td>Bare CFC EOL: $\alpha/\epsilon = 0.92/0.825$</td>
</tr>
</tbody>
</table>

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection.
### Results (2/24): perihelion/outer panel/ SAA 78deg

**Front Side**

- OSR 47% EOL: \( \alpha/\varepsilon = 0.601/0.827 \)
- Bare CFC EOL: \( \alpha/\varepsilon = 0.92/0.825 \)

**Back Side**

**Temperature of Solar Panel Front**

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>201.6</td>
</tr>
<tr>
<td>2000</td>
<td>207.82</td>
</tr>
<tr>
<td>4000</td>
<td>197.16</td>
</tr>
<tr>
<td>8000</td>
<td></td>
</tr>
</tbody>
</table>

**Temperature Difference of Solar Panel Front**

**ΔT logic:** \( ΔT \) positive means that the retro-reflection approach gives higher \( T \) than the diffusive (Lambertian) reflection.

### Results (3/24): perihelion/outer panel/ SAA 65deg

**Front Side**

- OSR 47% EOL: \( \alpha/\varepsilon = 0.601/0.827 \)
- Bare CFC EOL: \( \alpha/\varepsilon = 0.92/0.825 \)

**Back Side**

**Temperature of Solar Panel Front**

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>258.98</td>
</tr>
<tr>
<td>2000</td>
<td>257.37</td>
</tr>
<tr>
<td>4000</td>
<td>254.4</td>
</tr>
<tr>
<td>8000</td>
<td></td>
</tr>
</tbody>
</table>

**Temperature Difference of Solar Panel Front**

**ΔT logic:** \( ΔT \) positive means that the retro-reflection approach gives higher \( T \) than the diffusive (Lambertian) reflection.
### Results (4/24): perihelion/outer panel/SAA profile

**Front Side**
- OSR 47% EOL: $\alpha/\varepsilon = 0.601/0.827$

**Back Side**
- Bare CFC EOL: $\alpha/\varepsilon = 0.92/0.825$

#### Temperature of Solar Panel Front

**Temperature Difference of Solar Panel Front**

$\Delta T_{\text{log}}$: $\Delta T$ positive means that the retro-reflection approach gives higher $T$ than the diffusive (Lambertian) reflection.

### Results (5/24): perihelion/b1/SAA 90deg

**Front Side**
- OSR 82% EOL: $\alpha/\varepsilon = 0.372/0.803$

**Back Side**
- Bare CFC EOL: $\alpha/\varepsilon = 0.92/0.825$

Case a2 is not realistic and not considered. Case b1 might apply to areas of panels 2 and 3 where locally the OSR percentage is higher than the average 47% (TBC if realistic).

#### Temperature of Solar Panel Front

#### Temperature Difference of Solar Panel Front

$\Delta T_{\text{log}}$: $\Delta T$ positive means that the retro-reflection approach gives higher $T$ than the diffusive (Lambertian) reflection.
Mercury Retro-Reflection — Modelling and Effects on MPO Solar Array

Results (6/24): perihelion/b1/SAA 78deg

<table>
<thead>
<tr>
<th>Front Side</th>
<th>Back Side</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSR 82% EOL:</td>
<td>Bare CFC EOL:</td>
</tr>
<tr>
<td>$a/e = 0.372/0.803$</td>
<td>$a/e = 0.92/0.825$</td>
</tr>
</tbody>
</table>

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection

Results (7/24): perihelion/b1/SAA 65deg

<table>
<thead>
<tr>
<th>Front Side</th>
<th>Back Side</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSR 82% EOL:</td>
<td>Bare CFC EOL:</td>
</tr>
<tr>
<td>$a/e = 0.372/0.803$</td>
<td>$a/e = 0.92/0.825$</td>
</tr>
</tbody>
</table>

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection
### Results (8/24): perihelion/b1/SAA profile

<table>
<thead>
<tr>
<th>Front Side</th>
<th>Back Side</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OSR 82% EOL:</strong></td>
<td><strong>Bare CFC EOL:</strong></td>
</tr>
<tr>
<td>$\alpha/\varepsilon = 0.372/0.803$</td>
<td>$\alpha/\varepsilon = 0.92/0.825$</td>
</tr>
</tbody>
</table>

**Temperature of Solar Panel Front**

Temperature Difference of Solar Panel Front

- **Diffusive Reflection**
- **Directional Reflection**
- **Eclipse**
- **True Anomaly**

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2000</td>
<td>200</td>
</tr>
<tr>
<td>4000</td>
<td>400</td>
</tr>
<tr>
<td>6000</td>
<td>600</td>
</tr>
<tr>
<td>8000</td>
<td>800</td>
</tr>
</tbody>
</table>

**True Anomaly [°]**

**Temperature Difference [°C]**

**ΔT logic:** $\Delta T$ positive means that the retro-reflection approach gives higher $T$ than the diffusive (Lambertian) reflection.

### Results (9/24): perihelion/inner panel/ SAA 90deg

<table>
<thead>
<tr>
<th>Front Side</th>
<th>Back Side</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OSR 82% EOL:</strong></td>
<td><strong>OSR 100% EOL:</strong></td>
</tr>
<tr>
<td>$\alpha/\varepsilon = 0.372/0.803$</td>
<td>$\alpha/\varepsilon = 0.25/0.79$</td>
</tr>
</tbody>
</table>

**Temperature of Solar Panel Front**

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>200</td>
</tr>
<tr>
<td>400</td>
</tr>
<tr>
<td>600</td>
</tr>
<tr>
<td>800</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Temperature Difference [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2000</td>
<td>200</td>
</tr>
<tr>
<td>4000</td>
<td>400</td>
</tr>
<tr>
<td>6000</td>
<td>600</td>
</tr>
<tr>
<td>8000</td>
<td>800</td>
</tr>
</tbody>
</table>

**True Anomaly [°]**

**Temperature Difference of Solar Panel Front**

- **Diffusive Reflection**
- **Directional Reflection**
- **Retro Reflection 0.12**
- **Retro Reflection 0.138**
- **Eclipse**
- **True Anomaly**

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Temperature Difference [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2000</td>
<td>200</td>
</tr>
<tr>
<td>4000</td>
<td>400</td>
</tr>
<tr>
<td>6000</td>
<td>600</td>
</tr>
<tr>
<td>8000</td>
<td>800</td>
</tr>
</tbody>
</table>

**ΔT logic:** $\Delta T$ positive means that the retro-reflection approach gives higher $T$ than the diffusive (Lambertian) reflection.
Results (10/24): perihelion/inner panel/ SAA 78°

Front Side | Back Side
---|---
OSR 82% EOL: α/ε = 0.372/0.803
OSR 100% EOL: α/ε = 0.25/0.79

Temperature of Solar Panel Front

Temperature Difference of Solar Panel Front

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection.

Results (11/24): perihelion/inner panel/ SAA 65°

Front Side | Back Side
---|---
OSR 82% EOL: α/ε = 0.372/0.803
OSR 100% EOL: α/ε = 0.25/0.79

Temperature of Solar Panel Front

Temperature Difference of Solar Panel Front

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection.
Results (12/24): perihelion/inner panel/ SAA profile

Front Side | Back Side
---|---
OSR 82% EOL: \( \frac{\alpha}{\varepsilon} = 0.372/0.803 \) | OSR 100% EOL: \( \frac{\alpha}{\varepsilon} = 0.25/0.79 \)

\[\Delta T\] logic: \( \Delta T \) positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection.

Temperature of Solar Panel Front

Temperature Difference of Solar Panel Front

Results (13/24): aphelion/outer panel/ SAA 90deg

Front Side | Back Side
---|---
OSR 47% EOL: \( \frac{\alpha}{\varepsilon} = 0.601/0.827 \) | Bare CFC EOL: \( \frac{\alpha}{\varepsilon} = 0.92/0.825 \)

\[\Delta T\] logic: \( \Delta T \) positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection.

Temperature of Solar Panel Front

Temperature Difference of Solar Panel Front
Mercury Retro-Reflection — Modelling and Effects on MPO Solar Array

Results (14/24): aphelion/outer panel/ SAA

78deg

Front Side | Back Side
---|---
OSR 47% EOL: $\frac{\alpha}{\varepsilon} = 0.601/0.827$ | Bare CFC EOL: $\frac{\alpha}{\varepsilon} = 0.92/0.825$

$\Delta T$ logic: $\Delta T$ positive means that the retro-reflection approach gives higher $T$ than the diffusive (Lambertian) reflection

Temperature of Solar Panel Front

Temperature Difference of Solar Panel Front

Results (15/24): aphelion/outer panel/ SAA

65deg

Front Side | Back Side
---|---
OSR 47% EOL: $\frac{\alpha}{\varepsilon} = 0.601/0.827$ | Bare CFC EOL: $\frac{\alpha}{\varepsilon} = 0.92/0.825$

$\Delta T$ logic: $\Delta T$ positive means that the retro-reflection approach gives higher $T$ than the diffusive (Lambertian) reflection
Results (16/24): aphelion/outer panel/SAA profile

Front Side | Back Side
------------|-------------
OSR 47% EOL: $\alpha/\varepsilon = 0.601/0.827$ | Bare CFC EOL: $\alpha/\varepsilon = 0.92/0.825$

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection

Temperature of Solar Panel Front

Temperature Difference of Solar Panel Front

Results (17/24): aphelion/b1/SAA 90deg

Front Side | Back Side
------------|-------------
OSR 82% EOL: $\alpha/\varepsilon = 0.372/0.803$ | Bare CFC EOL: $\alpha/\varepsilon = 0.92/0.825$

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection

Temperature of Solar Panel Front

Temperature Difference of Solar Panel Front
Results (18/24): aphelion/b1/SAA 78deg

<table>
<thead>
<tr>
<th>Front Side</th>
<th>Back Side</th>
</tr>
</thead>
</table>
| OSR 82% EOL:  
\(\alpha/\varepsilon = 0.372/0.803\)  | Bare CFC EOL:  
\(\alpha/\varepsilon = 0.92/0.825\) |

\[\Delta T\] logic: \(\Delta T\) positive means that the retro-reflection approach gives higher \(T\) than the diffusive (Lambertian) reflection

Temperature of Solar Panel Front

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>200</td>
</tr>
<tr>
<td>2000</td>
<td>162.41</td>
</tr>
<tr>
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<tr>
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<td>162.41</td>
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<tr>
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<td>162.41</td>
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<table>
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<tr>
<th>True Anomaly [°]</th>
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<tbody>
<tr>
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Temperature Difference of Solar Panel Front

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Temperature Difference [°C]</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td>4000</td>
<td>-2</td>
</tr>
<tr>
<td>6000</td>
<td>-2</td>
</tr>
<tr>
<td>8000</td>
<td>-2</td>
</tr>
</tbody>
</table>

\[\Delta T\] Diffusive and Directional Reflection
\[\Delta T\] Diffusive and Retro-Reflection 0.12
\[\Delta T\] Diffusive and Retro-Reflection 0.138

\[\Delta T\] logic: \(\Delta T\) positive means that the retro-reflection approach gives higher \(T\) than the diffusive (Lambertian) reflection

Results (19/24): aphelion/b1/SAA 65deg

<table>
<thead>
<tr>
<th>Front Side</th>
<th>Back Side</th>
</tr>
</thead>
</table>
| OSR 82% EOL:  
\(\alpha/\varepsilon = 0.372/0.803\)  | Bare CFC EOL:  
\(\alpha/\varepsilon = 0.92/0.825\) |

Temperature of Solar Panel Front

<table>
<thead>
<tr>
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<th>Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>2000</td>
<td>205.24</td>
</tr>
<tr>
<td>4000</td>
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<tr>
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<td>205.24</td>
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<tr>
<td>8000</td>
<td>205.24</td>
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</table>

<table>
<thead>
<tr>
<th>True Anomaly [°]</th>
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<tbody>
<tr>
<td>0</td>
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Temperature Difference of Solar Panel Front

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Temperature Difference [°C]</th>
</tr>
</thead>
<tbody>
<tr>
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<td>4000</td>
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</tr>
<tr>
<td>6000</td>
<td>-4</td>
</tr>
<tr>
<td>8000</td>
<td>-4</td>
</tr>
</tbody>
</table>

\[\Delta T\] Diffusive and Directional Reflection
\[\Delta T\] Diffusive and Retro-Reflection 0.12
\[\Delta T\] Diffusive and Retro-Reflection 0.138

\[\Delta T\] logic: \(\Delta T\) positive means that the retro-reflection approach gives higher \(T\) than the diffusive (Lambertian) reflection
Results (20/24): aphelion/b1/SAA profile

<table>
<thead>
<tr>
<th>Front Side</th>
<th>Back Side</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSR 82% EOL:</td>
<td>OSR 100% EOL:</td>
</tr>
<tr>
<td>$\alpha/\varepsilon = 0.372/0.803$</td>
<td>$\alpha/\varepsilon = 0.25/0.79$</td>
</tr>
</tbody>
</table>

Temperature of Solar Panel Front

Time [s]

Temperature Difference of Solar Panel Front

$\Delta T$ positive means that the retro-reflection approach gives higher $T$ than the diffusive (Lambertian) reflection.

Results (21/24): aphelion/inner panel/SAA 90deg

<table>
<thead>
<tr>
<th>Front Side</th>
<th>Back Side</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSR 82% EOL:</td>
<td>OSR 100% EOL:</td>
</tr>
<tr>
<td>$\alpha/\varepsilon = 0.372/0.803$</td>
<td>$\alpha/\varepsilon = 0.25/0.79$</td>
</tr>
</tbody>
</table>

Temperature of Solar Panel Front

Time [s]

Temperature Difference of Solar Panel Front

$\Delta T$ positive means that the retro-reflection approach gives higher $T$ than the diffusive (Lambertian) reflection.
Results (22/24): aphelion/inner panel/ SAA 78deg

<table>
<thead>
<tr>
<th>Front Side</th>
<th>Back Side</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSR 82% EOL:</td>
<td>OSR 100% EOL:</td>
</tr>
<tr>
<td>$\alpha/\varepsilon = 0.372/0.803$</td>
<td>$\alpha/\varepsilon = 0.25/0.79$</td>
</tr>
</tbody>
</table>

Temperature of Solar Panel Front

Temperature Difference of Solar Panel Front

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection.

Results (23/24): aphelion/inner panel/ SAA 65deg

<table>
<thead>
<tr>
<th>Front Side</th>
<th>Back Side</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSR 82% EOL:</td>
<td>OSR 100% EOL:</td>
</tr>
<tr>
<td>$\alpha/\varepsilon = 0.372/0.803$</td>
<td>$\alpha/\varepsilon = 0.25/0.79$</td>
</tr>
</tbody>
</table>

Temperature of Solar Panel Front

Temperature Difference of Solar Panel Front

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection.
The orbit is divided in three regions with $\delta_{\text{retro}}$ as the indicator function:

\[
\delta_{\text{retro}} = \begin{cases} 
0 & \text{if } \mathbf{O}_S \cdot \mathbf{\hat{d}} \cdot \mathbf{\hat{\text{sun}}} < 0 \\
0 & \text{if } |\mathbf{\hat{d}}| > R_p \\
1 & \text{otherwise}
\end{cases}
\]

\[
\text{OSS} = (\mathbf{O}_S \cdot \mathbf{\hat{\text{sun}}}) \cdot \mathbf{\hat{\text{sun}}}
\]

\[
\mathbf{d} = \mathbf{O}_S - \text{OSS}
\]

**OS**  Position vector  
**$R_p$**  Planet’s mean radius  
**sun**  Solar unit vector (unit vector from the center of the planet pointing to the sun)
• The orbit is allocated into a number of points along the orbit (different positions).
• The start and end points of the retro-reflection cylinder are found by counting along the orbit until $\delta_{\text{retro}}$ becomes 1 and then 0, respectively.
• The respective points represent positions along the orbit and therefore specific times.

![Graph of orbit time and retro-reflection vs. time](image)

• Albedo is assumed to be reflected back in the direction of the sun
• Like the eclipse, it is assumed as a cylinder
Only retro-reflection

\[ C2 \alpha A \cdot n \cdot \text{Normal to the surfaces} \]

\[ QA \cdot a \cdot \alpha \cdot A \cdot C2 \cdot A_{k,j} \cdot \text{Normal to Orbit} \]

QA: Absorbed Albedo flux
\( n \): Normal to the surfaces
SC: Solar flux
\( \alpha \): Visible, hemispherical absorptance
A: Area
C2: Aspect angle of the surface
a: Planet Albedo coefficient

Only retro-reflection – reference case

\[ a = 0.12 \]

\[ a = 0.138 \]

A1 – Anti-Velocity
A2 – Normal to Orbit
A3 – Nadir
A4 – Velocity
A5 – Normal to Orbit
A6 – Zenith
Perihelion case: incident (*) Solar heat fluxes calculated on a nadir pointing orbiting cube of 1m side

A1 – Anti-Velocity
A2 – Normal to Orbit
A3 – Nadir
A4 – Velocity
A5 – Normal to Orbit
A6 – Zenith

(*) incident \(\rightarrow\) absorbed by 1sqm black body surface

---

Perihelion case: incident (*) IR heat fluxes calculated on a nadir pointing orbiting cube of 1m side

A1 – Anti-Velocity
A2 – Normal to Orbit
A3 – Nadir
A4 – Velocity
A5 – Normal to Orbit
A6 – Zenith

(*) incident \(\rightarrow\) absorbed by 1sqm black body surface
Albedo Heat Fluxes (diffusive model) – reference case

Perihelion case: incident (*) Albedo heat fluxes calculated on a nadir pointing orbiting cube of 1m side

- A1 – Anti-Velocity
- A2 – Normal to Orbit
- A3 – Nadir
- A4 – Velocity
- A5 – Normal to Orbit
- A6 – Zenith

(*) incident → absorbed by 1sqm black body surface

Solar Panel Attitude

SAA (Sun Aspect Angle): angle between solar panel and sun vector
- Solar array plane is represented by the XZ plane
- SAA=90° means Sun lies within the XZ plane (no energy)
Solar Flux – SAA = 65°

IR Planetary Radiation – SAA = 65°
Albedo heat fluxes comparison (SA with SAA=65°)

- Directional albedo is considered the most realistic approach
- Differences in peak Albedo fluxes can be significant between the different models

| Diffusive, a = 0.12 | Retro-reflection, a = 0.12 | Retro-reflection, a = 0.138 | Directional reflection, a = 0.138 (\cos(\phi))^{0.3} |

QA6: Albedo flux incident on SA front side
QA3: Albedo flux incident on SA back side
Appendix D

On the thermal design and modelling of calibration blackbodies for the FCI and IRS instruments on MTG

Nicole Melzack
(RAL Space, United Kingdom)
Abstract

The Meteosat series of spacecraft are meteorological satellites, providing a range of data that inform weather forecasts across Europe. First generation satellites have flown, second generation (MSG) are currently operational, and the third generation (or MTG) will provide data well into the 2030s. Two instruments going on the MTG satellites will be calibrated using the blackbody targets that are being designed at RAL Space. The blackbody targets are required to operate at temperatures between 100–370 K. The challenge involved in this includes providing single targets that can physically achieve and operate successfully at both thermal extremes, while also meeting stringent temperature gradient requirements. This presentation will cover the thermal design solution, which involves using helium gas conduction, and how it has been modelled in ESATAN-TMS. The testing of the prototype and the limitations of modelling gas conduction in ESATAN-TMS will also be discussed.

1 Due to severe weather conditions the author was unable to attend the workshop and present this material.
On the thermal design and modelling of calibration blackbodies for the FCI and IRS instruments on MTG.

Nicole Melzack, RAL Space, STFC

Outline

• Meteosat
• Blackbodies
• Thermal challenges and design overview
• Breadboard model
The Meteosat series of spacecraft are meteorological satellites, providing data that inform weather forecasts across Europe. The first generation satellites flew between 1979 and 2011, and the second generation is still operational – and expected to be until 2019.
Meteosat third generation, or MTG, will be taking over and the first satellites should be launching in 2018. MTG has two types of spacecraft: Sounding – MTG-S and Imaging – MTG-I. Instruments that will be going on both spacecraft are being designed and produced by OHB in Germany and TAS-F in France.

In order to calibrate their instruments on the ground, both TAS-F and OHB will be using the calibration targets that we’re designing at RAL Space. So we are combining two sets of customer requirements in order to deliver a single blackbody design.
Blackbody calibration target

- Target of accurately known temperature and high (~1) emissivity
- Precisely controlled
  - Better than instrument can measure
- Used to calibrate instrument
- Often a baseplate surrounded by a baffle

A blackbody calibration target is a target that an instrument views, that is controlled to a very accurate temperature and emissivity (ideally 1). Normally they comprise of a baseplate that the instrument views surrounded by a baffle to protect it from the environment. The calibration target needs to be controlled more precisely than what the instrument can measure, which is how it is used as a calibration source, and so the requirements can be quite stringent.
On the thermal design and modelling of calibration blackbodies for the FCI and IRS instruments on MTG

MTG blackbodies thermal challenges

- Large operating temperature range
  - 100–370 K
- Small temperature gradient requirements
- Transition between temperatures in 0.1 K steps
- Transition 16 K in 30 minutes
- 3 kW power limit

Taking both sets of customer requirements into account, the MTG blackbody design will need to: be able to operate between 100 – 370 K. Thus we need one design that can both physically achieve and operate successfully at this wide range of temperatures. The blackbodies also need to have a uniform temperature – so what instrument sees can’t vary by more than 200 mK. Furthermore, the blackbodies need to be able to transition between temperatures relatively accurately and quickly, and with only a 3 kW power limit.
To get down to the colder temperatures, the customer requirements specify that we should use liquid nitrogen. LN2 is about 77 K, so being able to thermally link the blackbody to it will allow us to run the whole thing cold, and still be able to use heaters to control the temperature. The first idea was to have a reservoir of LN2, connected to a cold plate, which then connected to the cavity with copper thermal straps. This was the proposed solution that won us the work. The cold plate would be used for coarse control and would have heaters on it. The cavity itself would be used for finer temperature control.

However, with this design there was no way to turn off this LN2 link for when the blackbodies needed to be at the hotter temperatures, this would lead to a high demand for heater power, and the potential waste of nitrogen. The boiling LN2 could cause vibration issues – although the flexibility of the thermal straps allow them to dampen this effect. Furthermore, the straps would provide point source cooling, which would make it harder to achieve the required uniformity.

During the proposal stage it was identified that having a variable conductive link to the LN2 would allow us to save on heater power and nitrogen. So the next stage in the design was to investigate this.
The idea progressed to having three cooling plates (instead of the one cold plate shown previously). The plates would have piping in which could be filled with LN2, and be at different distances from the back of the cavity. Controlling which plates were filled with nitrogen achieved different conductive links to the cold LN2. This design gave the uniformity in temperature required at the base of the blackbody, but didn’t address the uniformity of the baffle – which is required for the radiometric design.

We needed a way that we could have a variable conductive link to the LN2 surrounding the entire cavity.

Then we started looking at the HIRDLS blackbody targets, which were developed at Oxford University by Bob Watkins, and Dan Peters who now works at RAL Space.
HIRDLS is an instrument that flew on the NASA Aura mission. The ground calibration target for this instrument covered the blackbody in a jacket of LN2, with a He gas gap between it and the cavity, and is the design that we have taken forward for the MTG calibration targets.
Helium’s thermal conductivity changes with pressure, and so with 1 bar of He we get the maximum conductive link, with 0 bar, we get a vacuum and effectively no conductive link through the gas gap. At pressures in between we get varying conductance – hence the idea to operate the gap as a variable conductance gas gap heat switch.
Main thermal control aspects

- Helium conductivity
- Heater control to minimise gradients
- Radiation shield thermo-optical properties
On the thermal design and modelling of calibration blackbodies for the FCI and IRS instruments on MTG

Helium conductivity in a gas gap

Helium thermal conductivity in a helium gas gap

\[ k(T) = k_{\text{bulk}}(T) \cdot \left( 1 + \frac{8}{3} \cdot k_{\text{bulk}}(T) \cdot \frac{T}{e \cdot p \cdot \sqrt{3} \cdot R \cdot T} \cdot \left( \frac{1}{\alpha_1} + \frac{1}{\alpha_2} - 1 \right) \right)^{-1} \]

- \( k_{\text{bulk}} \) is the bulk conductivity of He
- \( T \) is temperature
- \( e \) is the gap thickness
- \( p \) is the pressure of the gas
- \( R \) is the specific gas constant
- \( \alpha \) is the thermal accommodation factor

Equation from:

The thermal conductivity we get from gaseous helium in a gap depends not only on its pressure. The temperature of the helium gas itself is a big contributor. The size of the gap we’re using also plays a role – the smaller the gas gap the better the thermal conductivity. We also need to take into account the energy exchange between the solid surface and the gas at either side of the gas gap – which is represented by the thermal accommodation factor.

All of these factors are taken into account in this equation. So this is what I used to calculate the thermal conductivity value, \( k \), and then plugged that into the equation for the conductive link, or GL to use with the ESATAN software.
Helium gas conduction modelling

For the other conductive links in the thermal model, such as the bolted interfaces, I used the ESATAN Workbench to define a contact conductance. However, I did not define any geometry to be the helium, and so all the helium conduction modelling was done through the ESATAN file.

I treated either side of the radiation shield as its own helium gas gap, and calculated the GLs required for each gap.

\[ \text{GL1} = \frac{k \cdot A}{x} \]

\[ \text{GL2} = \frac{k \cdot A}{x} \]
I then used these in the template file, and made node-node GL links between the relevant surfaces in the $CONDUCTORS block.
On a practical level it’s easier to control the power input into heaters, than it is to control the pressure in a gas gap. So once I’d set up the model, I looked to see the smallest number of helium pressures I could use to control over the entire temperature range – given the 3 kW power limit.

I looked at the two easier options first, 1 bar for the cold cases, and 0 bar for the hot cases. I looked into what the maximum controllable temperature was for each set point (using ’full power’) and the minimum controllable temperature (using about 300 W in total). But there was a gap here. And with a bit of trial and error I found a helium pressure that would bridge the gap and allow us to control over the entire range.
You may notice that 0.025 mbar is a very low pressure to use here, and that’s because the relationship between conductivity and pressure is extremely non-linear, this is a log plot of the relationship at 260 K.
With regards to the heater powers, we needed to be careful that we weren’t micro managing the gradients, we didn’t want to be putting heat inputs into each node, as that makes the system far too reliant on the power input, and ultimately we want something that is inherently uniform.

The solution here was to control the cavity temperature using the radiation shield. The control heaters on here would make the heat reaching the cavity more uniform. Modelling and analysing this in ESATAN again took trial and error. I initially used the workbench to add boundary condition at potential ‘heater’ nodes, however I found this took too long and started writing the inputs into the template files myself, I also experimented with parametric cases – running one case after another and just changing the heater location or heat input, which did speed up my analysis.

There is a conflict in the customer requirements. The uniformity requirement lends itself to a high thermal mass, however the fast transition time between temperatures would be easier to meet with less mass.

Meeting the uniformity requirements has meant that there is a need for boost heaters on the cavity, which will only be used when temperature transitions are taking place, to speed up the time taken to go between set-points.
Since the main control heaters are on the radiation shield, we need to ensure that there is always a thermal link between the heated shield and the cavity, even when there is no helium in the gas gap. Conversely, on the other side of the shield, we want the thermal link between the cold liquid nitrogen and the shield to be dominated by the gas conduction.

The solution here was to use surface coatings, so the cavity and shield surfaces which face each other are painted black with a high emissivity and good thermal link at all times. However, low emissivity coatings on the LN2 jacket and shield surfaces which face each other will help save heater power and LN2 when running at hotter temperatures.
Thermal Model in ESATAN-TMS Workbench

I’ve used this thermal model for the helium pressures and to optimise the heater distributions, and most recently to create the test predictions for the upcoming breadboard model tests.
The breadboard model is a prototype of the blackbody that is being used to de-risk the design. It will provide loads of useful data to help me correlate the model and start on the more detailed CDR analysis.

In theory the blackbody will operate at the thermal extremes, but we need to make sure it will be manufactured to withstand those temperatures.
As I said earlier, I’ve used thermal analysis to size the power requirements and also the locations of the heaters on the blackbody. But in reality, ensuring the heaters maintain a good thermal contact with the structure is down to the adhesive working across the range of operational temperatures.

As a pre-BBM test, four different adhesives were used to attach heaters onto aluminium plates and then curved sections of aluminium. I then helped with the thermal cycling of the samples – using an oven and a bucket of liquid nitrogen to make sure the samples saw the conditions they would in operation. Some of the adhesives failed, we could see blackening on the heaters when we turned them on in the extreme environments. However one of the adhesives, the transfer tape, seemed to survive the best over the course of thermal cycling, and so it has been chosen to attach the heaters to the BBM.
Limitations of model

- Temperature of helium
- Perpendicular conduction modelled only
- No account for possible convection
- Gas gap modelled O(1mm) much larger than conventional gas gaps
- Larger surface area than a conventional gas gap heat switch
- Curved surface

That was one way I’ve tried to make sure the model and the reality will be as similar as possible. However the main area of uncertainty here will be the helium conduction. There are limitations on the analysis that I have performed, and the equation that I have used to do the initial calculations.

As I’m not modelling the helium gas as nodes in the GMM, I have no way of knowing what the temperature of the gas really is inside the gap. I can make an educated guess on the temperature, and I know that it will be in the range of 77 K and the temperatures reached at the heaters, but I don’t know for sure. The temperature will affect the conductivity and I expect this to be a reason for inconsistency with the breadboard model and my predictions at the lower temperatures.

The equation I’ve used only accounts for the perpendicular conduction across the gap, which is fair enough given that most gas gap heat switches use gaps smaller than a millimetre and don’t really need to take anything else into account.

However I’ve scaled this equation up, and so don’t know if the fact that the gap is over a very large and curved surface area will affect its validity. I am optimistic that the breadboard model testing will show that the design works though, as the HIRDLS blackbody targets were successful.

I am looking forward to investigating the results of the tests and correlating my model, not only to progress with the design of these blackbodies, but to further the understanding of how scaled up gas gap heat switches can be used for precise thermal control.
Thank you

Nicole Melzack, RAL Space, STFC
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Tel: +441235 567147
Appendix E

Development of methodologies for Brightness Temperature evaluation for the MetOp-SG MWI radiometer

Alberto Franzoso  
(CGS, Italy)

Sylvain Vey  
(ESA/ESTEC, The Netherlands)
Abstract

The MicroWave Instrument (MWI) is a conical scanning radiometer, which shall be embarked on MetOp Second Generation satellite. MWI will provide precipitation monitoring as well as sea ice extent information. It is now entering the detailed design phase.

Conical scanning radiometers are characterized by a continuous instrument calibration, with the sensors passing, at every rotation, below two calibration sources: a cold sky reflector providing 3K reference, and an On Board Calibration Target (OBCT) which provides an Hot temperature reference.

The high performance required to the instrument implies that the OBCT temperature is known with high accuracy, and that the gradients along its surface are suppressed. However, gradients are intrinsic to the structure of the OBCT, and driven by the day-night induced temperature cycles of its environment. Gradients can therefore only be minimized through a very extensive use of active control on the OBCT thermal environment.

The development of a Brightness Temperature computation method, i.e. the computation of the temperature sensed by the radiometer in the RadioFrequency (RF) band, was therefore a necessary step for the instrument thermal control optimization. It allowed to assign the limited instrument resources in the most efficient way, and to justify the design solutions.

In this presentation the details of the Brightness Temperature (BT) computation are provided. The OBCT temperature maps are generated by Thermica 4.6.1 using its fast-spin feature and are then post-processed with MatLab, filtering them with the Feed Horns Patterns. This results in the BT profiles along the orbit, with their associated errors. The method is then extended to the High Frequency analysis in order to assess the influence of each position of the rotation cycle on the BT. Results are shown, demonstrating that a passive thermal control is suitable to meet the strict performance requirements.
Development of methodologies for Brightness Temperature evaluation for MetOp-SG MWI radiometer

Alberto Franzoso (CGS), Sylvain Vey (ESA/ESTEC), 3-4 November 2015, ESTEC

Presentation Content

- MetOp & MWI instrument introduction
- Conical scanning concept and Instrument calibration
- OBCT: features and temperature knowledge
- Standard thermal analysis: gradients requirements and Modelling detail effect
- Brightness temperature approach: concept an implementation
**METOP Second Generation overview**

- MetOp-Second Generation: follow-on system to the 1st gen. series of MetOp (Meteorological Operational) satellites, which currently provide operational meteorological observations from polar orbit.

- To provide operational observations and measurements from polar orbit for numerical weather prediction and climate monitoring in the early 2020’s to mid-2040’s timeframe.

- To provide services to atmospheric chemistry, operational oceanography and hydrology.

- With respect to First Generation:
  - To ensure continuity
  - to improve the accuracy / resolution of the measurements;
  - to add new measurements / missions.

---

**MWI instrument introduction**

- **Development of methodologies for Brightness Temperature evaluation for the MetOp-SG MWI radiometer**

- **Launcher**: Soyuz in Kourou / Falcon 9 / Ariane 5 / Ariane 6
- **Orbit**: MetOp Sun Synchronous Orbit 835 km mean altitude, 9h30 Local Time at Descending Node
- **Controlled re-entry into the South Pacific Ocean Uninhabited Area**
**MWI instrument overview**

**MicroWave Imager:**
- Conical scanning radiometer
- Cloud and precipitation, snow and sea-ice, profiles of water vapor and temperatures
- Collects MW radiation from Earth and atmosphere
- Frequency range of 18.7GHz to 183.3GHz
- Constant speed rotation at 45rpm

---

**MWI instrument introduction**

- Tube Structure (Rotating Part)
- Racetrack (Rotating Part)
- Rotating Deck (Rotating Part)
- Thermal Skirt (Fixed Part)
- Baseplate (Fixed Part)

  1. Main Reflector (Rotating Part)
  2. Front End Sub-Assembly (Rotating Part)
  3. Calibration Assembly (Fixed Part)
  4. Low Frequency Equipment, FEE and CDPU (Rotating Part)
  5. Scan Mechanism (Joint between Rotating and Fixed Part)
  6. Launch Locking Devices (Fixed Part)
**Instrument Calibration**

- Calibration principle based on linearity of receiver chain.
- Linear interpolation used to calculate the scene brightness temperature from 2 known reference temperatures
  - Cold Sky Target, i.e. calibration reflector @ 3K
  - On Board Calibration Target (OBCT): hot RF source at known temperature
- The antenna rotation (45 RPM) creates observation cycles
- Necessity of accurate knowledge of OBCT temperature

---

**OBCT structure**

- Regular pyramidal pattern to have a RF perfect absorber (-40dB return loss)
- ECCOSORB RF coating
- Baffling system for protection from environment
OBCT requirements

- First Issue:
  - Derived from initial system level error apportionment
  - Attempt to translate the temperature knowledge accuracy into gradients & stability requirements

<table>
<thead>
<tr>
<th>OBCT specific requirements (operational cases)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity</td>
</tr>
<tr>
<td>OP temperature variation over one orbit</td>
</tr>
<tr>
<td>OP temperature variation over lifetime</td>
</tr>
<tr>
<td>Surface temperature variation over one orbit</td>
</tr>
<tr>
<td>Nominal gradient across the surface</td>
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<tr>
<td>Gradient variation across the surface</td>
</tr>
<tr>
<td>Gradient variation across the surface</td>
</tr>
<tr>
<td>Surface temperature knowledge</td>
</tr>
</tbody>
</table>

OBCT environment

- Sun Intrusion: avoid direct and reflected Solar Fluxes on Pyramids (local hot spots)
  - Solutions: “Racetrack” baffling system
- Orbital oscillation of environment
  - Variable sink temperatures
  - Massive base is stable
  - Lighter peaks have wider oscillation
- Result: typical gradient along pyramids, in top-bottom direction
Model detail level and gradients

- **Step 0:** Initial Phase A model: 4 pyramid layers,
  - 1 node for bulk
  - 1 node for epoxy layer, with mass

- **Step 1:** Final Phase A model:
  - 1 node for bulk
  - 1 node with $C_p$ for epoxy core
  - 1 node, massless, for epoxy surface

- **Step 2:** Phase B1 model:
  - 1 node for bulk
  - 4 nodes for each side, with $C_p$ for epoxy core
  - 4 nodes for each side, massless, for epoxy surface

- Gradient estimation: $\sim 0.15-0.3K$ (COMPLIANT)
- OBCT: for final OBCT $\sim 4000$ nodes

---

- **Step 3:** Phase B2 model:
  - Tip area with NO aluminum core
  - Base area with discontinuity (epoxy)

---

Level 1: No aluminum below epoxy surface
Level 2: Aluminum and epoxy
Level 3
Level 4: last pyramid “geometrical” level
Level 5: Aluminum is not continuous
Level 6: pure aluminum layer
The tips, once modelled in a more realistic way, amplify the already known «tip-bottom» gradient by about one order of magnitude.

Gradients have a very regular pattern (no local hot spots), all tips are typically at the same temperature with a dispersion of ~0.5K

Requirements are far from being respected in the current configuration

Corrective actions to reduce (but not realistically a by factor 10) the gradients are:
- [...] (long list of unfeasible options for other system constraints)
- Racetrack active heater control to damp its oscillations
  - ROM estimation: ~200W heater (150% of entire instrument budget)
- Alternative: coupled RF&Thermal analysis
  - temperature maps post-processing to verify brightness temperature, the real quantity of interest
  - To investigate the effect of the «Shape» of the gradient pattern, not only its max value

OBCT brightness temperature, detected by each feed horn, in any operational condition, shall not deviate from the PRT temperatures by more than ±0.25K
NEW ANALYTICAL APPROACHES

At the core of the approach there is the consideration that each feed horn is actually "filtering" the pyramids temperature, combining them in a unique «Brightness Temperature» (BT) reading.

This is achieved through a kind of weighted average of the physical temperatures.

The real meaningful information, important to assess the performance of the instrument, is not really the gradient along the surface, but the difference between the PRT temperature and the BT acquired by the horns.

In this sense, NOT ALL THE GRADIENTS are equivalent; a periodic gradient is much less harmful than a uniform gradient, because the horn is a low-pass filter.

A Gaussian horn beam is considered, according to ADS-Tolouse inputs (responsible of Radiofrequency Assembly).

- Different for each of the 7 horns;
- Function of r, z

The beam is the weighting factor for the physical temperatures.

The beam is projected on the pyramids, at several different instrument rotation angles, weighting it to its view factor to the horn.

Per each rotation angle, each pyramid surface element is weighted in a different way.

Per each angle (and per each horn) the BT is calculated.

The BT is compared to the PRT temperatures.

The difference is the error contribution to the BT evaluation.
Method implementation

BT Mask Calculation (performed once)

Dedicated GMM of OBCT+Horns only (THERMICA)

Horn Model Parameters (RF, CAD)

View Factors Horn-Pyra (theta-dep)

MATLAB

Projected Horn pattern (theta-dep)

MATLAB

BT mask (Horn beam-weighted View Factors)

MATLAB

BT (time-dep)

Standard Thermal analysis

Complete GMM/TMM (THERMICA)

Temperature maps (time-dep)

MATLAB

BT (time-dep)

NEW ANALYTICAL APPROACHES

BT during the rotation of the instrument

Individual PRT

Brightness temperature at time t=050516.7

BT during the rotation of the instrument

Individual PRT
NEW ANALYTICAL APPROACHES

- The BT evaluation is performed at each orbital position of standard thermal analysis.
- A profile of the ERROR PRT--BT is available in function of orbital time.
- The profile is typically presented as the profile of the Average ERROR value + standard deviation band.
  - Average error over the central area of the feed horn path below the OBCT (typically, 5° wide).
  - Standard deviation is the deviation of the error computed all over this 5° wide window (typically, with a step of 1°).

Conclusions

- Generic Temperature Gradient requirements results are often dependent on Model Detail.
- In case of MWI OBCT, gradient requirement could no longer be met, unless a big amount of resources are assigned to thermal control.
- A re-discussion of requirements was needed (should be a general good practice).
- A joint RF-thermal analysis was carried, developing routines to compute the Brightness Temperature profiles along the orbit and comparing to the PRT readings.
- Analysis allowed to demonstrate that the proposed design was compatible with performance targets.
- Method allowed to refine thermal control system and to correctly assign the instrument resources.
Appendix F

MASCOT thermal design
how to deal with late and critical changes

Luca Celotti  Małgorzata Sołyga
(Active Space Technologies GmbH, Germany)

Volodymyr Baturkin  Kaname Sasaki  Christian Ziach
(DLR, Germany)
Abstract

MASCOT is a lander built by DLR, embarqued on JAXA's Hayabusa-2, a scientific mission to study the asteroid 162173 1999 JU3, launched on the 3rd of December 2014. As part of the project challenges, the short schedule for the whole development of the lander (2.5 years from PDR to launch), the strict and contrasting thermal requirements for different phases of the mission, mass&power/technology/volume limitations put the thermal design at the edge of the state of art technology solutions. As a result, the thermal system development has been on-going until the last phases of the project, on order to cope with late changes and technologies development.

This presentation focusses on the thermal control system evolution during the last months before launch and just after it and the tight schedule available to cope with late system changes. It shows the design modifications and updates, together with thermal modelling changes following intensive testing phases, in particular for the lander battery pack and the heating/pre-heating strategy for different mission phases. Many thermal vacuum campaigns, modelling re-iterations, better understanding of the main S/C thermal behaviour, together with the great team determination helped reaching a succesfull launch followed by an on-flight system verification.
MASCOT thermal design: how to deal with late and critical changes

Luca Celotti
November, 3-4 2015
ESTEC, Nordwijk - The Netherlands

Outline of the presentation

- MASCOT Mission
- Thermal Requirements
- Thermal Design
- Battery design
- Thermal Vacuum Tests – Battery Temperature Results
- Extra Battery Tests
- MASCOT Preheating Strategy
- Conclusion
MASCOT Mission

MASCOT (Mobile Asteroid surface SCOuT)

- A lander built by DLR (in collaboration with CNES)
- On-board JAXA’s Hayabusa-2 mission, a scientific mission to study the asteroid “Ryugu” (former 162173 1999 JU3)
- Smaller than 300x300x200mm³
- Carries 4 payloads for scientific investigation of the asteroid surface:
  - IR spectrometer (mOmega)
  - Camera
  - Magnetometer
  - Radiometer
- Will be released by the mothership and “fall” on the asteroid surface

Thermal requirements

The thermal requirements MASCOT must satisfy and the environment in which it will operate vary significantly, depending on the mission phase:

- Cruise Phase: MASCOT is attached to HY-Z on its way to the asteroid
  → In this phase, the lander should limit as much as possible the heat exchange with the S/C and with the environment
- Near-Asteroid Phase: MASCOT is still attached to HY-Z, which is hovering above the asteroid
- On-Asteroid Phase: In this Phase MASCOT is performing its operations on the asteroid surface (after free-fall phase)
  → In those two phases, the lander should reject as much heat as possible in order not to reach maximum operational temperature limits.
The design should fulfill the contrasting requirements during different mission phases and it should insulate MASCOT from HY-2 as much as possible and be passive (due to the limited power provided by HY-2).

Thus, it was decided to use variable conductance heat transfer technology from the electronic box (the most dissipative element) to the radiator. Heating power available is going to be distributed to the most critical parts (mOmega, EBOX, battery).

The heating strategy for the battery unit and its design has evolved during the whole project, making crucial parts of the thermal subsystem.
The STM model of MASCOT has been tested, including the battery STM model.

Thermal Vacuum Test (TVAC-2)

Different battery cells reach quite similar temperatures in all test phases.

Thermal Vacuum Test (TVAC-4)

In TVAC-4 test campaign, the temperatures on the battery STM2 were measured by the facility sensors as well as by the sensors read by on-board computer and HY-2 sensor (first time in which all these sensors were used).

The test results showed that there is big difference between measured values from difference systems (in some cases almost 10°C).
After the test campaign (TVAC-4) an extra test has been performed by DLR in order to verify the measurements coming from different sensors on the battery STM2.

Temperature sensors (HY-2 and OBC) differences fixed via re-calibration and new temperature/resistance curves.

### Sensors calibration

After the test campaign (TVAC-4) an extra test has been performed by DLR in order to verify the measurements coming from different sensors on the battery STM2.

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>Set up</th>
<th>Main HY PT1000</th>
<th>RET OBC PT1000</th>
<th>Main OBC PT1000</th>
<th>RET OBC PT1000</th>
<th>OBC PT1000 (average for 4 sensors)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.0</td>
<td>18.50</td>
<td>18.06</td>
<td>18.46</td>
<td>18.75</td>
<td>18.93</td>
<td></td>
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<tr>
<td>0.0</td>
<td>0.34</td>
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<td>0.05</td>
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<tr>
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<td>22.32</td>
<td>21.60</td>
<td>21.70</td>
<td>22.99</td>
<td></td>
</tr>
<tr>
<td>50.0</td>
<td>50.05</td>
<td>50.54</td>
<td>54.95</td>
<td>54.73</td>
<td>53.20</td>
<td></td>
</tr>
</tbody>
</table>

Temperature sensors (HY-2 and OBC) differences fixed via re-calibration and new temperature/resistance curves.

### Flight simulation test in JAXA

First use of battery EQM

Regardless for the calibration fixed, temperature differences between the HY-2 sensors are present, moreover an anomalous long duration of pre-heating phases appeared.
In this test the FM of MASCOT has been tested with the FM model of the battery. During this test the big temperature difference between the cells have been noticed as well as a much longer preheating duration.

A clear HW issue is present, appearing in the EQM and FM, not present in the STMs. Further investigations were necessary!

Deep evaluation of the design changes implemented by the battery supplier
- IR test performed on the FM by DLR to evaluate the heaters efficiency

The heaters and spreaders do not provide enough heating uniformity to the battery pack generating a longitudinal temperature difference. The position of the temperature sensors controlling the heating lines generates a temperature difference along the cells.
Comparative heating test for FM and FS model has been performed. Test results showed that the thermal behaviour of both battery models is very similar. Battery FS is chosen for flight, while the FM unit will be used for testing in order to investigate the thermal behaviour of the current battery design. EQM heaters positioning is confirmed equal to FM/FS and different from STMs by the supplier.

Extra battery tests – FM/FS test

Thermal Vacuum Test (TVAC-6)

In TVAC-6 test campaign the FS of MASCOT has been tested with the battery FM. The main objective of this test was better thermal characterisation of the battery (as the idea of a stand-alone test of the battery was discarded due to difficulties in replicating similar boundary conditions) – due to this fact on the battery almost 30 temperature sensors have been mounted.

29th European Space Thermal Analysis Workshop 3–4 November 2015
Thermal Vacuum Test (TVAC-6)

After the test, correlation performed and battery thermal model updated to represent also the real hardware behaviour.

As this vacuum campaign happened after launch, a strategy for the launch and the first health-check had to be evaluated, together with the pre-heating strategy.

In order to keep MASCOT within the temperature limits, a heating and pre-heating strategy has been prepared (together with HY-2).

The MASCOT global thermal behaviour is kept within the ranges controlling the temperature of the battery pack (2 sensors) via two independent heating lines (A, B).

For health-checks the temperature of the whole lander has to be raised via raising the temperature set controlling the battery.
Each of the heaters within the battery has a different temperature set up:

- For cruise phase: -33/-38°C
- For preheating phases: -5/-10°C

The heaters’ temperature set-ups defined were decided to be kept as a baseline also for the mission, reducing the ON time for both the heating lines at the same time.

Preheating strategy for the HC

Few days before the first MASCOT health check (switch ON of the lander on flight): detailed communication from JAXA about how the duty-cycle is applied to the heaters.

- Review of the heating and pre-heating strategy before the health check.
Preheating strategy for the HC

After the understanding how the HY-2 operates the heaters, different options for health check temperature set-ups have been analysed.

Thermal simulations (including the temperature gradient on the battery cells) allowed to prepare the procedures to follow during the first health check of MASCOT.
Conclusion

MASCOT is a lander built by DLR, embarqued on JAXA’s Hayabusa-2, a scientific mission to study the asteroid “Ryugu” (former 162173 1999 JU3), launched on the 3rd of December 2014. As part of the project challenges, the short schedule for the whole development of the lander (2.5 years from PDR to launch), the strict and contrasting thermal requirements for different phases of the mission, mass&power/technology/volume limitations put the thermal design at the edge of the state of art technology solutions. As a result, the thermal system development has been on-going until the last phases of the project, on order to cope with late changes and technologies development.

This presentation focusses on the thermal control system evolution during the last months before launch and even just after it. Thermal vacuum campaigns, modelling re-iterations, better understanding of the main S/C thermal behaviour, together with the great team determination helped reaching a succesfull launch followed by an on-flight system verification.


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Thank you for the attention!

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Appendix G

Solar Orbiter SPICE
Thermal Design, Analysis and Testing

Samuel Tustain
(RAL Space, United Kingdom)
Abstract

1 The Spectral Imaging of the Coronal Environment (SPICE) is one of ten instruments comprising the ESA Solar Orbiter payload. The instrument, currently being built at the STFC Rutherford Appleton Laboratory, is a high resolution imaging spectrometer operating at extreme ultraviolet wavelengths. We are currently in the build phase, with thermal testing of the flight model instrument due to commence shortly.

At an orbital perihelion of just 0.28 AU, there are numerous key design challenges that must be overcome for the instrument to survive the harsh thermal environment that it will be subjected to. In the last 18 months, the instrument has already undergone considerable thermal testing to qualify the design. The results of the tests completed thus far have provided essential inputs into the existing detailed thermal model, which is constructed using ESATAN-TMS. This presentation will discuss how the thermal analysis and testing have complemented each other for this project, while also providing impressions of ESATAN-TMS from the perspective of a relatively early user.

1Due to severe weather conditions the author was unable to attend the workshop and present this material.
Solar Orbiter SPICE — Thermal Design, Analysis and Testing

Samuel Tustain
Thermal Engineer, STFC Rutherford Appleton Laboratory
Solar Orbiter SPICE — Thermal Design, Analysis and Testing
29th European Space Thermal Analysis Workshop, 3rd-4th November 2015

Solar Orbiter - Overview

• Scheduled to launch in 2018
• Science goals are to address how the Sun creates and controls the heliosphere
  – Achieved by observing polar regions of the Sun from as close as 0.28 AU
• Payload comprised of ten instruments:
  – Six remote sensing, including the Spectral Imaging of the Coronal Environment (SPICE) instrument
  – Four in-situ instruments
• Heatshield provides main defence against solar load
  – Contains feedthroughs for remote-sensing payload

Image credit: ESA
SPICE – Overview

- High resolution imaging spectrometer operating at EUV wavelengths (70.2-105 nm)
- Objective is to provide data on the plasma composition of the Sun
  - Investigate links between the solar surface, corona and inner heliosphere
- Precise optics reflect light beam to detector assembly
- Currently in build phase of project
- Instrument mechanisms being provided by collaborating organisations

SPICE – Thermal Design

- Solar load is roughly 13 times greater than on Earth orbit
- Spacecraft heatshield blocks most incoming radiation
- Primary mirror has a 10 nm boron carbide (B₄C) coating
  - Reflective to UV radiation, but mostly transparent to visible and IR
- Secondary mirror (HRM) rejects this unnecessary load to deep space
- Only a small fraction of reflected UV load required, so pre-slit mirrors and heat dump radiator used to further reject heat
- Cold element interface maintains detectors at -20 ºC

Boron carbide wavelength dependent thermo-optical properties, data obtained by MPS
Detailed Thermal Model

- Constructed using ESATAN-TMS r7sp2
- Sub-models used for each subsystem
- Numerous configurations:
  - BOL/EOL
  - Door open/closed
  - Operational/Non-operational
- Three primary radiative cases:
  - Hot operational (0.28 AU)
  - Cold operational (0.91 AU)
  - Cold non-operational (1.5 AU)
Test Objectives and Plan

- To verify the thermal design, specifically:
  - Management of solar load
  - Key internal thermal interfaces (e.g. across mirror mounts)
  - External thermal interfaces
  - Minimum and maximum temperatures
- Key tests to achieve this:
  - STM
    - High Flux Mirror Test
    - Thermal Balance Test
  - FM
    - Detector Assembly Thermal Balance Test (in progress)
    - Thermal Balance Test (to be completed)
- Thermal Vacuum Test on STM and FM to qualify the thermal design over predicted temperature range

High Flux Mirror Test

- Designed to simulate the primary mirror in the worst case hot environment
- Objectives:
  - To experimentally determine thermo-optical properties of mirror
  - Observe impact on mirror temperatures
- High intensity lamp used as the test source to provide solar-like flux
  - Intensity roughly 20% of flight load
- Heat dump positioned behind mirror
  - Heat load absorbed from the lamp is deduced by replicating temperatures using heaters
- Test completed both with and without mirror
  - Difference in values indicates transmitted heat load
High Flux Mirror Test

- Results showed that ~80% of the incoming beam was transmitted
- Analysis of the incident spectrum show that this closely matched the expected transmission from the MPS data

SPICE – Test Rig

- Specialised test rig built for thermal testing of SPICE, to simulate spacecraft cavity
- Fluid pipes around shroud allow interface temperatures to be simulated
- Heaters simulate heat flows from instrument to spacecraft
- Shroud is wrapped in multi-layer insulation (MLI) to minimise heat flow from vacuum chamber
- Test rig successfully completed commissioning tests prior to instrument testing
STM Thermal Balance Test

- Eight test cases in total
  - Two involving mercury lamp (less intensity than previous lamp, but more flight-representative UV spectrum)
  - Six use test heaters to simulate absorbed loads
- ‘Beam dump’ maintained at 100 K by cryocooler to simulate deep space view from heat rejection mirror
- STM thermal model built to provide test predictions and inform test inputs

Detector Assembly Thermal Test

- Thermal vacuum and thermal balance testing on GSFC produced Detector Assembly (DA)
  - Verify thermal design (particularly cold element interface) and functional performance
  - Correlate DA submodel (not included in STM)
- DA has its own separate test rig
- Submodel extracted from flight model to generate test predictions
- Test is ongoing
Correlation

- ECSS standard used:
  - Temperature deviation < 5 °C
  - Mean deviation of temperature difference within ±2 °C
  - Standard deviation of temperature difference < 3 °C
- Particularly essential for this instrument because a realistic solar load cannot be easily replicated during testing
- Submodel structure has proven useful

Future Tests

- Upcoming tests on flight instrument
  - Thermal balance and thermal vacuum
  - First test with instrument and DA together
- No test heaters available for instrument structure
- Mercury lamp to be used once more for hot operational test cases
ESATAN-TMS Impressions

• Generally good!
• Workbench is relatively user friendly
• Library system should be reviewed
  – Store data in text format? Easier to modify
  – Update process between ESATAN-TMS versions is not well documented
• Performing cutting operations can sometimes be frustrating
• Undo button!

Conclusion

• SPICE must withstand extreme thermal environment
• Tests carried out:
  – High Flux Mirror Test
  – Thermal Rig Commissioning Test
  – STM Thermal Balance Test
• Future tests:
  – FM Detector Assembly Thermal Test
  – FM Thermal Balance Test
Contact Details

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Appendix H

Spatial Temperature Extrapolation Case Study
Gaia in-flight

Matthew Vaughan
(ESA/ESTEC, The Netherlands, Airbus Defence and Space, France)
Abstract

The project IAMITT (Innovative Analysis Methods for Improved Thermal Testing) was defined by ESA to address the issues of thermal test quality, cost and schedule reduction. One aspect of this project concerns the application of the techniques of spatial extrapolation with the aim to provide a full thermal map of a spacecraft given input temperature sensor data. This information is of particular interest during spacecraft thermal testing where a temperature may be recovered in the case of a sensor malfunction. It could also be useful in the prediction of temperatures for areas of the spacecraft that are normally difficult to instrument or to give the thermal engineer a more informed choice on the positioning of sensors.

A novel case study was proposed using the Gaia spacecraft to perform an extrapolation using the thermal model and in-flight telemetry. Firstly the thermal environment of Gaia’s orbit at L2 is considered together with the requirements for an extrapolation. The algorithms behind the extrapolation are then highlighted together with the techniques used to combine in-flight telemetry with a correlated thermal model. The procedure of synchronising the time in the model with the flight data is then discussed including the assumptions made with respect to solar fluxes and internal dissipations. The results are then presented comparing the differences between the model predicted and in-flight extrapolated temperatures. A heat balance on the boundary nodes is also used as an additional method to check the method against predicted values. Finally the extrapolated temperatures are visualised on the thermal model and possible benefits to the thermal engineer are reviewed.

This work has been carried out under the Young Graduate Trainee in Industry scheme of ESA in cooperation with Airbus Defence and Space, Toulouse, France.
Spatial Extrapolation of Temperatures
Case Study: Gaia In-flight

This work has been conducted in the framework of the Young Graduate Trainee (YGT) Programme of the European Space Agency (ESA) during a secondment to Airbus Defence and Space, Toulouse, France from the 1st April 2015 until the 31st December 2015.

Matthew VAUGHAN
03 Nov 2015

Title and introduction slide

• Work carried out during the Young Graduate Trainee scheme at ESTEC, ESA
• There are about 80 positions available each year for recent graduates in all areas of space
• Worked within the ESTEC Thermal analysis and verification department
• Seconded to industry in cooperation with Airbus Defence and Space, Toulouse, France, in the mechanical and thermal department.
• The work carried out consisted of mainly R&D projects and new techniques to aide thermal testing
Innovative Analysis Methods for Improved Thermal Testing (IAMITT)

<table>
<thead>
<tr>
<th>Module</th>
<th>Objective</th>
<th>Interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Test Database (TTD)</td>
<td>Complete and centralised database (all data, real-time)</td>
<td>Support to other modules</td>
</tr>
<tr>
<td>3D display (3D)</td>
<td>Real time 3D visualization of all data (Temperatures, Dissipations)</td>
<td>Better understanding and monitoring, quality enhancement and risk mitigation.</td>
</tr>
<tr>
<td>Spatial extrapolation (SE)</td>
<td>Complete map of temperatures (all nodes of thermal model).</td>
<td>Quality enhancement, risk mitigation, sensor reduction (for recurrent models of satellites).</td>
</tr>
<tr>
<td>Temporal extrapolation (TE)</td>
<td>Equilibrium temperature prediction Estimation of TB end of phase date.</td>
<td>Time and cost savings.</td>
</tr>
<tr>
<td>Thermal model updating Tool (TMUT)</td>
<td>Near real time thermal model test conditions and parameters updating.</td>
<td>Time and cost savings, quality enhancement</td>
</tr>
</tbody>
</table>

IAMITT Slide

- So how does the spatial extrapolation of temperature module fit into the bigger picture?
- Under umbrella of the bigger project called IAMITT (Innovative Analysis Methods for Improved Thermal Testing)
- Techniques developed to improve test quality, cost, schedule reduction and to provide more information for the thermal engineer
- Some are connected for example viewing live results of an extrapolation on 3D model during test
- The spatial extrapolation project started 10 years ago with a internship project at Airbus Defence and Space, Toulouse, France
- It has been continually developed and over the last 8 months applied to case studies.
- For more information see the presentation on IAMMIT during the 26th European Space Thermal Analysis Workshop: https://exchange.esa.int/thermal-workshop/attachments/workshop2012/index.htm
Background Slide
Using the thermal network model with a sensor to node mapping we can extrapolate to find the remaining temperatures.

How are these techniques useful?

- Information on areas of the spacecraft that are difficult to instrument
- Recover the temperature of malfunctioning thermocouples
- Improve the positioning of sensors on recurrent designs of satellites

Example: Telecoms satellite during transient TVAC:

- Extrapolation performed with 100% of available thermocouples
- Extrapolation then recomputed with only 50%
- Results: On average 90% of the removed sensor temperatures are extrapolated to within 5 degrees of the measured

To understand this firstly we need to take a look at the algorithm.
Spatial Extrapolation Algorithm

**Algorithm**

Q: How can we fuse the two data sources (Thermal Mathematical Model and Test/Flight data)?

A: Using a state space representation of our thermal model driven by the sensor readings.

Setup:

- Left: CSV dumped matrices from a thermal solver describing the thermal network
- Right: Test or flight data with temperature and heat readings
- Prepare system - removal inactive nodes - locate arithmetic nodes - sample sensors using mapping to nodes.
- The data acts as a transient boundary condition in the model.
- Steady State, average of current sensor T

Main loop (transient):

- Linearisation non linear conductors (T to the 4th power term)
- Build state space system and perform a forward difference to obtain the next T
- Check convergence on linearisation temperature
- Output timestep

The extrapolated temperatures are evaluated using the model driven by the inputs, which are heat sources and sensor temperatures.
Objectives

1. Define a use case for the spatial extrapolation
   "Gaia – in-flight"

2. Demonstrate the potential for a thermal engineer
   - Useful for model correlation checks
   - Full temperature map of un-sensored zones

3. Use flight data for the extrapolation of temperatures
   with a correlated model

4. Visualise the extrapolation results on a thermal
   model

Objectives

- Understanding of the prediction quality of the extrapolation
- Map of a spacecraft already in-flight
- Possibly provide information to help other disciplines
- Extrapolation only using flight telemetries (several hundred in comparison to a thermal balance
  test of several thousand)
- Perform heat balances on the extrapolation as a check
- Display results back onto the thermal model
Gaia
Background

3D dynamic map of the Milky Way

Launched December 2013

Lissajous orbit around L2
(1.5 X10^6 km from the COE)

Spin period 6 hours around central axis
45° to sun-earth line

Stable thermal environment
Albedo and IR fluxes negligible

Solar constant at L2 :
1293 – 1388 W/m²

Background on Gaia

- Positioned in a stable thermal environment
- Solar constant is a function of distance from the sun and position within orbit - slightly weaker than at earth
- For the extrapolation data, 6 hour rotations around the spacecraft central axis are taken into account
- The position in the Lissajous orbit over several rotations is considered to have a negligible impact
Extrapolation with in-flight data:
Requirements

1. Thermal Model: 
   TBTV correlated model with updated 
in-flight dissipations

2. Sensor temperature data: 
   During nominal operation mode

3. Sensor to thermal node mapping

4. Internal dissipations and heater powers: 
   Constant values used

5. Data to synchronise the thermal radiative 
environment

How do we process the sensor data?

Requirements

- TBTV correlated model with updated in-flight dissipations
- During nominal operation mode there are small standard deviations in the dissipations, in June 2014
- 7 x 6 hour rotations of telemetry considered with 147 temperature sensors
- Mapping file, multiple telemetries to thermal nodes
- Spacecraft ancillary data to synchronise the orbit in the model and in flight
Extrapolation with in-flight data:
Using the flight data as sensor nodes

Processing the flight data

- Start with 147 on board telemetries
- These are reduced to only 84 thermal nodes in the model by averaging multiple sensors to nodes
- Important to note that some of the nodes have a dissipation set in the model
- Finally any boundaries not instrumented must be included from the model for example the space environment node.
- Sampled approximately every 30 seconds for 42 hours
- Almost ready to extrapolate, we just need to synchronise the solar fluxes on the model
Extrapolation with in-flight data: Synchronising model and in-flight time

- Synchronised to June 2014
- Sun azimuth angle = 0° when the model +Z axis receives maximum solar flux
- In-flight parameter synced with a single rotation in the model
- Solar constant for the sun fluxes

Synchronising the model and in-flight time

- Synchronised to June 2014
- We have the ancillary parameter, sun azimuth angle which is equal to zero when the Z-axis of the spacecraft is pointing towards the sun.
- Therefore we can plot the flux on these surfaces and conclude that the maximum flux corresponds to an angle of 0 degrees.
- The solar fluxes are then synchronised with the in-flight time
- Finally the solar constant requires scaling for the day of the year and position within the orbit
- IR and albedo fluxes are considered negligible.
Differences on sensor nodes:

\[ \Delta T = |T_{Sensor} - T_{Pred}| \]

- \( T_{Pred} \) = the correlated TBTV model with updated dissipations
- 84 sensor nodes considered
- Averaging many sensors to one thermal node can cause discrepancies
- Noise on flight data

Comparison of sensor nodes

- Which checks can we provide to the thermal engineer?
- 84 Sensor nodes difference to measured averaged over 7 rotations
- Absolute difference sensor and predicted

Cause of discrepancies:

- Averaging many sensor nodes to one thermal node
- Dissipations not exactly constant and can cause large discrepancies with small nodal capacities
- Comparing two types of thermal node: boundary and diffusion
- Sensor nodes with a heat flux present
- Poor representation of zones with distributed heat flux

Now we move onto the rest of the temperatures, the extrapolated ones:
Extrapolation with in-flight data: How close are we to the model predicted?

\[ \Delta T = |T_{Extrap} - T_{Pred}| \]

- \(T_{Pred}\) = correlated TBTV model with updated dissipations
- 8100 diffusion nodes extrapolated
- 7 rotations averaged

Comparison of extrapolated nodes

- Difference between extrapolated and correlated TBTV model on 8100 nodes
- 90% of the nodes under 5 degrees
- On the one hand maybe many of the nodes are not impacted by small changes in temperature seen on the sensors
- But it shows a good level of accuracy around sensor zones, useful if we lose a telemetry during flight / thermocouple during test.

So what is the effect of adding many more boundary/sensor nodes to the thermal model?
Extrapolation with in-flight data:
Heat Balances

Net heat flow into boundary nodes
Averaged over 7 rotations

<table>
<thead>
<tr>
<th>Method</th>
<th>No. of boundary nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extrapolation</td>
<td>91</td>
</tr>
<tr>
<td>ESATAN</td>
<td>7</td>
</tr>
</tbody>
</table>

Heat Balances on boundary nodes

- Plot shows the net heat flux into the boundary nodes averaged over 7 rotations for one rotation
- Most of the heat flux is attributed to the space node, sun flux immediately lost to environment.
- Correlations are very close, the scale on the right shows around a 7 or 8 W max difference on the rotation.
- The boundary nodes are pushing and pulling the model, adding heat where it is needed and removing where it’s in excess
- There is an effect from distributed heat loads with one sensor node poorly representing a fraction of this heat load.

We have provided a few checks for the engineer and now we would like to view our results back on the original model:
Visualisation - sensor positions

- Interested mainly in the service module where most of the electronics and units are housed.
- Red is a sensored node (note that some are internal and do not have a visualisation available)
- Able to see the zones which are well sensored and therefore can be more confident of the prediction around these zones
- Structure and areas around the tanks are not sensored
**Extrapolation with in-flight data:**

**Visualisation: Extrapolated temperatures**

- Plotted are the extrapolated results along with the sensor temperatures.
- It is possible to plot other information for example variation of temperature over one rotation.
- The software can currently provide a live solution when each set of sensor readings are available, test or flight.
- Typically only a few fast iterations are required when the data has been processed.

One final interesting visualisation is the difference between the predicted and extrapolated...
Extrapolation with in-flight data:
Visualisation: Comparison with the prediction

\[ \Delta T \ [°C] = T_{\text{Extr}ap} - T_{\text{Pred}} \]

Visualisation - Differences

- So the turquoise / green colour shows a small near zero difference
- It can be seen that there is a uniform distribution across the satellite
- Some units are seen to be hotter and colder than predicted
- The thermal engineer can then revisit the dissipations or modelling assumptions
- Gives the engineer a fast check during a correlation to view localised effects.
Conclusions

1. Improvements made to the software:
   • Reduction of arithmetic nodes
   • Application to in-flight case

2. Successfully extrapolated in-flight temperatures

3. Multiple checks made available to aide the thermal engineer:
   • Heat balances on boundary nodes
   • Comparisons with predictions

4. Visualisations with the model for:
   • Location of sensor nodes
   • Extrapolated temperatures
   • Differences with a predictive model

Conclusions

• We generated a full flight map of temperatures as an aide for the thermal engineer.

• This could help in the correlation process to identify temperatures of units with malfunctioning sensors

• We note that in the case of flight where fewer temperature sensors are available, the overall temperatures are not greatly impacted by the change seen on the sensor nodes. However it could be useful for localised checks in the vicinity of units.

• We have been able to reproduce a live thermal view of an in-flight spacecraft with software that can be run live as telemetry is downloaded.
Questions received during the workshop

Q: Have you performed any tests on a unit level to verify the results?

A: We have not performed tests on a unit level but instead on a spacecraft level during thermal balance testing. The techniques have shown good results on a variety of telecommunications and earth observation spacecraft. During these case studies we typically have more thermocouples available and therefore able to produce a better quality map of temperatures.

Q: How can you be sure that the temperatures you calculate are ‘real’?

A: This comes down to the equations used in the algorithm. The algorithm is based on solving a system of differential equations representing a collection of nodal heat balances similar to a thermal solver. The physics of the extrapolation are captured inside of the thermal model using the sensor data as transient boundary conditions.
Appendix I

Accelerating ESATAN-TMS Thermal Convergence for Strongly Coupled Problems

Christian Wendt     Sébastien Girard
(Airbus Defence and Space, Germany)
ESATAN-TMS Thermal solves the heat conductance differential equation (DE) for the lumped parameter thermal network node temperatures considering heat sources as well as linear (also one way) and quartic (radiative) heat exchanges between the nodes. Extensions to this modeling are available for fluid loops and ablation, namely FHTS and ABLAT. However, embedding other relevant thermodynamic phenomena, as e.g. ice sublimation during ascent of a launcher or pressurization/depressurization of a vessel, may provoke other strongly coupled heat sources and additional, segregated DE, which may impact the accuracy of the result. Even then one will usually succeed in reaching the required accuracy by choosing sufficient small time-steps, but at the cost of significantly increased CPU time. An innovative method based on a predictor-corrector-method (PCM), representing a workaround for accelerating the convergence, has been implemented and will be explained here. This method uses standard ESATAN entities only, i.e. auxiliary nodes, heat sources and one way linear conductors. For the example of ice sublimation during launcher’s ascent this method is explained in detail and the benefit is demonstrated in conjunction with a specific solver option provided by ESATAN-TMS Thermal software developers in the frame of this work. Using this innovative method the time-step can be increased by nearly a factor of 100 for the given example.
Accelerating ESATAN’s Convergence for Strongly Coupled Problems

Christian Wendt, Sébastien Girard, Airbus DS
03.11.2015

Agenda

• Introduction
• Proposed Predictor-Corrector Method (PCM)
• Demonstration case: Ice sublimation
• Improvement for ice sublimation induced by the method
• Conclusion and next steps
Introduction

• Problem
  – Strongly coupled heat sources and additional, segregated Differential Equations (DE) within ESATAN (which solely solves for the heat conductance DE) may impact the accuracy of the results
  – Usually, sufficient small time-steps succeed in reaching the required accuracy, BUT at the cost of CPU time
  – Thus, ways have been studied to accelerate ESATAN’s convergence for a required time-step
  – Example outlined here is for ice sublimation during launcher’s ascent (strong coupling comes from huge amount of latent heat of ice sublimation of about 3 MJ/kg)

• Methods studied
  – Enabling SLCRNC, benefit from control-constant METHOD has been systematically studied:
    – METHOD=0 (default): $VARIABLES1$ is called once for the forward step and twice for the backward step
    – METHOD=2: $VARIABLES1$ is called at every iteration, BUT at the cost of CPU time
  – Workaround to accelerate convergence by linear approximation (predictor-corrector-method PCM) is based on ESATAN basic features:
    \[
    Y = Y|_{T_{old}} + \frac{\partial Y}{\partial T}|_{T_{old}} \Delta T
    \]
    where \( \Delta T = T - T_{old} \) is the difference of temperature \( T_{old} \) at $VARIABLES1$ access and the current temperature \( T \) of the iteration

Proposed PCM

Recall of the general Lumped Parameter heat conductance DE:

\[
C \frac{dT_i}{dt} = Q_i + \sum_{j \neq i} GL(T_j, T_i)(T_j - T_i) + \sum_{j \neq i} GF(T_j, T_i)(T_j - T_i) + \sum_{j \neq i} GR(T_j, T_i)(T_j^4 - T_i^4)
\]

PCM for an affected temperature node:

\[
C \frac{dT_{old}}{dt} = Q + GF(T_{old}, T)(T_{old} - T)
\]

where:

- \( T_{old} \) temperature at $VARIABLES1$ access
- \( T \) current temperature of the iteration
- \( Q = f(T_{old}) \) heat source
- \( GF(T_{old}, T) = -\frac{\partial f}{\partial T} \)
Proposed PCM, cont’d

PCM for an affected auxiliary variable node with C=0 (arithmetic node):

\[ 0 = Q + GF(0, X)(0 - X) + GF(\delta T/2, X)(\delta T/2 - X) \]
\[ \Rightarrow X = X^{\text{old}} + \frac{\partial X}{\partial T} \delta T \]

where:

- \( X \) auxiliary variable
- \( \delta T/2 = \left( T^{\text{old}} - T \right)/2 \)

derived from an arithmetic node containing \( \delta T/2 \):

\[ 0 = GF(T, \delta T/2)(T - \delta T/2) + GF(T^{\text{old}}, \delta T/2)(T^{\text{old}} - \delta T/2) \]

with \( GF(T, \delta T/2) = GF(T^{\text{old}}, \delta T/2) = 1 \)

\[ Q = X^{\text{old}} \left( 1 + \left( \frac{1}{2 \frac{\partial X}{\partial T}} - 1 \right)^{-1} \right) \]
\[ GF(0, X) = 1 \]
\[ GF(\delta T/2, X) = \left( \frac{1}{2 \frac{\partial X}{\partial T}} - 1 \right)^{-1} \]

Proposed PCM: Explanation of \( \delta T/2 \) Calculation-Scheme

- \( D1 : T1 \) current ice surface temperature of the iteration
- \( B2 : T2 = -T^{\text{old}} \) at \$VARIABLES1\$ access
- \( D3 : T3 \) half of temperature difference, \( C3 = 0 \)

\[ 0 = GF(1,3)(T1-T3) + GF(2,3)(T2-T3) \]
with
\[ GF(1,3) = 1 \]
\[ GF(2,3) = 1 \]
\[ \Rightarrow T3 = (T1+T2)/2 \]
\[ \equiv T3 = (T - T^{\text{old}})/2 \]
\[ \Rightarrow T3 = \delta T/2 \]
Proposed PCM: Explanation of $X$ Calculation-Scheme

**D1:** $T_1 = X$ auxiliary variable, $C_1 = 0$

**B2:** $T_2 = 0$

**D3:** $T_3 = \delta T/2$ half of temperature difference, $C_3 = 0$

$\theta = Q_1 + GF(2,1) (T_2 - T_1) + GF(3,1) (T_3 - T_1)$

with

$$Q_1 = X^{old} \left( 1 + \left( \frac{1}{\frac{\partial X}{\partial T}} - 1 \right)^{-1} \right)$$

at $VARIABLES1$ access

$$GF(2,1) = 1$$

$$GF(3,1) = \left( \frac{1}{\frac{\partial X}{\partial T}} - 1 \right)^{-1}$$

$\Rightarrow 0 = X^{old} \left( 1 + \left( \frac{1}{\frac{\partial X}{\partial T}} - 1 \right)^{-1} \right) - T_1 + \left( \frac{1}{\frac{\partial X}{\partial T}} - 1 \right)^{-1} (T_3 - T_1)$

$\Rightarrow T_1 = X^{old} \left( 1 + \left( \frac{1}{\frac{\partial X}{\partial T}} - 1 \right)^{-1} \right) \left( 1 + \left( \frac{1}{\frac{\partial X}{\partial T}} - 1 \right)^{-1} \right) T_3$

$\Rightarrow T_1 = X^{old} + \frac{\partial X}{\partial T} \delta T$

---

Ice Sublimation during Ascent: Description

Ice sublimation flow rate (Hertz-Knudsen) [kg/s/m²]

$$\dot{m} = \frac{\gamma \left( P_{\text{sat}} - P_{\text{ambient}} \right)}{\sqrt{2 \pi R T}}$$

Ice cooling rate [W]

$$Q = A \cdot \dot{m} \cdot H$$

Ice thickness reduction rate [m/s] (additional, segregated DE)

$$\dot{t} = \frac{\dot{m}}{\rho}$$
Ice Sublimation during Ascent: Implementation of PCM

Ice surface temperature T-PCM:
\[ C \frac{dT}{dt} = Q + GF(T_{old}, T)(T_{old} - T) \]

Ice sublimation rate M-PCM:
\[ 0 = Q + GF(0, \dot{m})(0 - \dot{m}) + GF(\Delta T/2, \dot{m})(\Delta T/2 - \dot{m}) \]
\[ \Rightarrow \dot{m} = \dot{m}_{old} + \frac{\partial \dot{m}}{\partial T} \Delta T \]

Ice vapor pressure P-PCM:
\[ 0 = Q + GF(0, p)(0 - p) + GF(\Delta T/2, p)(\Delta T/2 - p) \]
\[ \Rightarrow p = p_{old} + \frac{\partial p}{\partial T} \Delta T \]

where:
\[ Q = A \dot{m}_{old} \]
\[ GF(T_{old}, T) = -H \frac{\partial m}{\partial T} \]

where:
\[ GF(0, \dot{m}) = 1 \]
\[ Q = \dot{m}_{old} \left( 1 + \left( \frac{1}{2} \frac{\partial m}{\partial T} - 1 \right)^{-1} \right) \]
\[ GF(\Delta T/2, \dot{m}) = \left( \frac{1}{2} \frac{\partial m}{\partial T} - 1 \right)^{-1} \]

where:
\[ GF(0, p) = 1 \]
\[ Q = p_{old} \left( 1 + \left( \frac{1}{2} \frac{\partial p}{\partial T} - 1 \right)^{-1} \right) \]
\[ GF(\Delta T/2, p) = \left( \frac{1}{2} \frac{\partial p}{\partial T} - 1 \right)^{-1} \]

Ice Sublimation during Ascent: Network

Environment:
- \( P_{amb} \)
- \( T_{amb} \)

- Top ice layer (600)
- 4th ice layer (6000)
- 3rd ice layer (500)
- 2nd ice layer (300)
- 1st ice layer (200)
- Substrate (100)

- \( \delta T/2 \)
- Vapor pressure (8000)
- Evaporation rate (7000)

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Accelerating ESATAN’s Convergence for Strongly Coupled Problems

Ice Sublimation during Ascent: Cases

Duration: 0 \ldots 550s
Required time resolution: 1s
Time steps: 0.0001s (reference) 0.01s 0.1s 0.5s 1s

<table>
<thead>
<tr>
<th>SLCRNC</th>
<th>Convergence Acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>METHOD=0 NOMINAL (w/o PCM) T-PCM TMP-PCM</td>
<td></td>
</tr>
<tr>
<td>METHOD=2 NOMINAL (w/o PCM) T-PCM TMP-PCM</td>
<td></td>
</tr>
</tbody>
</table>

Ice Sublimation during Ascent: Max Deviations for METHOD=0

![Graph showing comparison of deviations for different time steps METHOD=0](chart.png)
Ice Sublimation during Ascent: Max Deviations for METHOD=2

No significant benefit from M-PCM und P-PCM correction

Conclusion

- PCM workaround for strongly coupled and additional DE generally explained:
  - PCM for temperature node
  - PCM for auxiliary variable node (arithmetical)

- Example given concerning ice sublimation during ascent:
  - SLCRNC with METHOD=0 and METHOD=2 studied
  - Ice surface temperature correction: T-PCM
  - Ice sublimation rate correction: M-PCM (arithmetical)
  - Ice vapor pressure correction: P-PCM (arithmetical)
  - Ice thickness reduction DE

  - Exact results are obtained without PCM with a time-step of 0.01s
  - With a time-step of 1s correct results have been achieved
    - For METHOD=0 with TMP-PCM
    - For METHOD=2 with T-PCM (M-PCM and P-PCM in addition give no significant improvement)

  - Need for dedicated System Elements and a general way to couple more thermodynamic equations to ESATAN’s heat conductance DE, as e.g. ice sublimation, pressurization / depressurization of a vessel, …
Appendix J

OHB System
Thermal Result Viewer

Markus Czupalla  S. Rockstein  C. Scharl  M. Matz
(OHB System, Germany)
Abstract

Driven by mission demands for improved performance, more precise prediction etc. a trend is observed to bigger thermal models simulated with a high transient resolution. The built-in post-processing capabilities of commercial software codes often cannot cope with the model and result file sizes. Further the necessary post-processing is split over multiple tools which are often not easy to handle.

Over the last couple of years an integral thermal post-processing tool has been developed at OHB Munich, which combined the necessary capabilities and offers a convenient and fast user I/F. The Thermal Result Viewer (TRV) has among others the following main features:

- Import of result files in different formats:
  - *.TMD
  - *.out
  - *.csv

- Import of the model structure from different sources:
  - GMM model (*.erg)
  - TMM result file (*.TMD)
  - Excel list (*.xlsx)
  - Manual setting in the program

- Simultaneous visualization of 3-D and 2-D temperature and heat flux maps and plots for selected groups

- Transient group based visualization of the internal heat fluxes in a model (conductive and radiative) without the necessity to program it into the TMM beforehand.

- Easy and intuitive graphical user Interface (GUI)

A Demonstration of the TRV functionality will be presented and discussed in the presentation.

![Example Temperatures Visualization in TRV](image1)

![Example Heat Flux Visualization in TRV](image2)
Table of Contents

- Thermal Result Viewer (TRV)
  - Rationale

- Tool modules
  - Data Files
  - Quick Result Viewer
    - Temperatures (2-D and 3-D)
    - Environmental Fluxes
  - Flux Viewer
  - Reporting

- Future Work
- Summary
Thermal Result Viewer - Rationale

- Need to quickly and efficiently post-process and visualize:
  - Temperatures:
    - transient evolutions
    - 3-D maps
  - Fluxes:
    - Environmental (QS, QA, QE, etc.)
    - Heat flows between parts (conductive, radiative) → establish heat flux budgets in post-processing
- Be able to work with or without GMM
- Allow easy grouping
  - re-using of available model structure
  - customized groups from excel
  - Manual group setup in GUI
- All is also possible with other tools (in ESATAN-TMS, Excel, Therm-NV etc.) but with significant effort.

→ Efficiency increase and ease of use were and are the main targets for the TRV

Thermal Result Viewer – Modules

- TRV is setup in a modular object oriented fashion
- Development is centralized on a server accessible to all OHB colleagues
- The TRV modules are:
  - Data files → import of data and sorting (optional)
Thermal Result Viewer – Modules

- TRV is setup in a modular object oriented fashion
- Development is centralized on a server accessible to all OHB colleagues
- The TRV modules are:
  - Data files → import of data and sorting (optional)
  - Quick Result Viewer → temperature and environmental fluxes visualization
  - Flux viewer → heat flow visualization
Thermal Result Viewer – Modules

- TRV is setup in a modular object oriented fashion
- Development is centralized on a server accessible to all OHB colleagues
- The TRV modules are:
  - Data files → import of data and sorting (optional)
  - Quick Result Viewer → temperature and environmental fluxes visualization
  - Flux viewer → heat flow visualization
  - Reporting → fine post-processing of figures and export

To start a project/session name is requested

- Multiple projects/sessions can be started in parallel
- Each project/session contains the following modules
  - Date Files
  - Quick Result Viewer
  - Flux Viewer
  - Reporting
Thermal Result Viewer – Data Files

- Thermal Model Data:
  - Loading of GMMs in *.erg format
  - Multiple GMMs can be loaded simultaneously
  - GMMs can be named

- Thermal Result Data:
  - Loading of temperature and flux results in *.TMD format
  - Loading of custom node hierarchies
  - Multiple results can be loaded simultaneously
  - Results can be named
Thermal Result Viewer – Data Files

- Thermal Result Data:
  - Loading of TMDs in *.erg format
  - Loading of custom node hierarchies
  - Multiple results can be loaded simultaneously
  - Results can be named
  - Parts of results to be loaded and used can be selected (important for big files sizes)
  - Check is possible if needed data is available

Thermal Result Viewer – Quick Result Viewer

- Used model and used result file must be selected
- Views can be named and multiple can be created
Thermal Result Viewer – Quick Result Viewer

- Model hierarchy:
  - Imported from GMM or TMD or customized external files
  - Displayed as foldable tree
  - Shells with no temperatures are greyed out
  - Temperatures with no shells are combined in an “from_TMD” nodes group

- Shells/nodes can be grouped manually and become selectable
- The manual section is detached from the loaded and valid model structure
  → the model itself cannot be re-structured
Thermal Result Viewer – Quick Result Viewer

- **Data selection:**
  - Allows selection of items/data to be displayed
  - Model can be displayed stand-alone to visualize the shell thicknesses
  - Color map can be “flat” or “interpolated”
  - Shown time point for 3-D color map can be selected and is indicated in the 2-D plot
  - Type of results can be selected (Temperatures, Fluxes)
  - Min/max values and/or average values can be displayed
  - Sides of GMM are selectable (e.g. to show MLI)

- **Views 3-D/2-D:**
  - 3-D color map and 2-D are displayed simultaneously
  - Shown time point for 3-D color map can be selected and is indicated in the 2-D plot
  - 3-D view can be rotated, zoomed, and paned
Thermal Result Viewer – Quick Result Viewer

- Views 3-D/2-D:
  - 3-D color map and 2-D are displayed simultaneously
  - Shown time point for 3-D color map can be selected and is indicated in the 2-D plot
  - 3-D view can be rotated, zoomed, and panned
  - Plots can be "sent" to the report where they can be further post processed

- QRV can be "cloned" to generate multiple views of the same
  - Each view is fully independent of the others
  - Each view can be accessed from the data selection tree
Thermal Result Viewer – Flux Viewer

- Allows to visualize the exchanged heat flows between model parts in the POST-PROCESSING without the need to program it into the solver a priori
- Used model and used result file must be selected
- Based on Temperatures, GLs and GRs from TMD

Thermal Result Viewer – Flux Viewer

- Model Hierarchy:
  - Imported from GMM or TMD
  - Displayed as foldable trees ON BOTH SIDES
  - Allows easy selection of flux groups
    - Fluxes FROM → TO
• Collectors:
  • Custom node groups can be set up
  • Displayed in separate selection boxes
  • Allows to plot fluxes from one group to multiple groups in one plot
    • The top tree gives either a sum of all fluxes or single fluxes from all nodes
Thermal Result Viewer – Flux Viewer

• Collectors:
  • Custom node groups can be set up
  • Displayed in separate selection boxes
  • Allows to plot fluxes from one group to multiple groups in one plot
    • The top tree gives either a sum of all fluxes or single fluxes from all nodes
  • Sub-groups are needed to allow visualization of partial flux totals

Thermal Result Viewer – Flux Viewer

• Data selection:
  • Allows selection of items/data to be displayed
  • Heat flows or GL/GR values between groups can be displayed
  • GL and/or GR values/fluxes
  • Total and/or single results can be displayed
  • Shown time point can be selected
Thermal Result Viewer – Flux Viewer

- **Data selection:**
  - Allows selection of items/data to be displayed
  - Heat flows or GL/GR values between groups can be displayed
  - GL and/or GR values/fluxes can be displayed
  - Total and/or single results can be displayed
  - Shown time point can be selected
  - Precise values for selected time point are displayed as a pop-up table
  - Side 1 and/or side 2 of shells can be selected

Thermal Result Viewer – Reporting

- Allows fine-tuning of selected figures (e.g. annotations)
- Allows export to figures
- Allows export to word (under development)
Thermal Result Viewer – Reporting

Selection Tree:
- Allows selection of plots which were sent to the report from quick result viewer or flux viewer
- Each view can be accessed separately (2-D or 3-D)
- Each view can be post treated with MATLAB functionalities (e.g. add legend, change axis, annotate, etc.)

Thermal Result Viewer – Reporting

Work area:
- Each view can be post treated with MATLAB functionalities (e.g. add legend, change axis, annotate, etc.)
Thermal Result Viewer – Reporting

- Plot settings:
  - Allows to add watermark
  - Allows to set quality of plots
  - Allows to change font size globally

- Export section:
  - Allows export to picture file formats into dedicated folders
Thermal Result Viewer – Future Work

- **Batch mode:**
  - Re-use of post-processing templates for:
    - other cases
    - model versions
  - Enable an a priori creation of post-processing templates outside of GUI:
    - Pre-set which parameters of which nodes are to be displayed together in a figure
    - Import setting
    - Export figures

- **Automated Reporting:**
  - Auto export all created figures

- **Movies:**
  - Enable TRV to show movies of the temperature evolution

- **Model Comparison:**
  - Side by side views of different models or model versions

- **Miscellaneous:**
  - Allow node identification in the plots
    - 3-D → shell picking → highlight node in tree and curve in 2-D
    - 2-D → curve picking → highlight node in tree and in 3-D

Thermal Result Viewer – summary

- A Thermal Result Viewer has been developed at OHB

- **It allows:**
  - Quick review of thermal models and thermal results in an integrated environment
    - temperatures → 3-D and 2-D
    - environmental Fluxes → 3-D and 2-D

  - Quick and efficient review of heat flows between parts in a thermal model
    - purely in POST-PROCESSING
    - easy selection and collection options
    - conductive and radiative fluxes can be visualized

  - Automated export of plots into picture files

→ the efficiency of thermal result post-processing has been significantly increased compared to standard state-of the tool combinations
Appendix K

Overview of ECSS Activities for Space Thermal Analysis

James Etchells
(ESA/ESTEC, The Netherlands)
Abstract

This presentation will provide an overview of the two ongoing ECSS activities in the field of space thermal analysis, in particular:

- ECSS-E-HB-31-03: Thermal analysis handbook
- ECSS-E-ST-3104: Exchange of Thermal Model Data for Space Applications

The thermal analysis handbook will soon be sent out for public review and this workshop therefore provides an opportunity to make the community aware of it.

Concerning the standard on thermal model exchange, this is the formalisation under ECSS of the STEP-TAS protocol. The aims and objectives of the working group will be presented along with some discussion about the expected form of the final standard.
Overview of ECSS Activities for Space Thermal Analysis

James Etchells
James.Etchells@esa.int
02/11/2015

What is ECSS

- ECSS = European Cooperation for Space Standardization
  - Organization started in 1993
  - task is to develop a common set of consistent standards for hardware, software, information and activities to be applied in space projects
ECSS in the Thermal Control Area

ECSS-E-ST-31

Space engineering

Testing

Thermal design handbook - Part 1: View

ECSS-E-HB-31-01

ECSS in the Pipeline

Documents in the pipeline

Space-engineering

Thermal analysis handbook

SPACE-ENGINEERING

Space-engineering

Exchange of Thermal Model Data for Space Applications
Proposal at NESTA:
- Handbook on Thermal Model Validation

Conclusions:
- General agreement with idea
- Checklist would be useful
- Not a standard (not applicable doc)
- Don’t be too prescriptive
- Old ECSS standard content
- Observation that is a big undertaking
- Action on ESA to make 1st draft

In the context of computational analysis:
- Verification “did we solve the equations correctly?”
- Validation “did we solve the correct equations?”
# Thermal Analysis Handbook: Table of Contents

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### Current Status

- Draft reviewed by Working Group (Internal Assessment)
- Draft reviewed by TAAR (Parallel Assessment)
  - Comments/suggestions have been included
- Next step is **Public Review**, options:
  1. Limit review to NESTA members
  2. Full public review

29th European Space Thermal Analysis Workshop  
3–4 November 2015
ECSS-E-ST-31-04
EXCHANGE OF THERMAL MODEL DATA
aka STEP-TAS

Why STEP-TAS?

- CNES Initiative “Standard d’Exchange et Transfert – Application Thermique Spatiale”
- Based on French SET Z68-300 European aircraft industry

- ESA study to find common data models for exchanging thermal data between tools
- Identified “STEP” standard as most promising technology of the day

- 1st prototype in Europe and US in 1998
- Simplification and rigourisation of STEP-TAS internally at ESTEC
- Development of TASverter to facilitate exchange + validate protocol

- Industrial Implementation of STEP-TAS (Conformance Class 1 or 3)
- Interfaces in ESATAN-TMS, eTherm, Thermica, TMG, Thermal Desktop
What is STEP-TAS?

- **STEP** = Standard for the Exchange of Product Model Data, ISO 10303
  - There are a number of STEP standards - Application Protocols (APs)
  - Best known is AP203/214 for CAD
  - Uses a formal data model definition language called EXPRESS (ISO10303-11)
  - STEP protocol provides structure, but also algorithmic rules to ensure integrity of datasets

- **TAS** = Thermal Analysis for Space
  - Specific AP for space thermal analysis with 4 modules:
    - NRF : Network Results Format [TMM / Test data]
    - MGM : Meshed Geometric Module [GMM - static]
    - SKM : Space Kinematic Module [GMM - moving]
    - SMA : Space Mission Analysis [GMM - trajectory]
  - Protocol very generic, can be applied to other disciplines e.g. space environment (STEP-SPE)
  - Thermal specific information introduced via run-time dictionary specifying, e.g. what thermal nodes is, what a thermo-optical property is, etc.

Formalisation under ECSS

- Original plan was to formalise STEP-TAS standard under ISO
  - STEP-TAS is a fully conforming ISO 10303 application protocol
- Eventually ECSS was preferred over ISO
  - Lighter process, quicker to update if needed, more relevant to space domain
- Working Group starting in 2015:
  - H. Brouquet (ITP Engines)
  - K. Duffy (MAYA HTT)
  - J. Etchells (ESA)
  - A. Fagot (DOREA)
  - D. Gibson (ESA)
  - P. Hugonnot (TAS-F)
  - R. Muenstermann (Airbus DS (D))
  - T. Soriano (Airbus DS (F))
  - T van Eekelen (Samtech / Siemens)

- *But*, no precedent in ECSS for this kind of standard ... how to deal with it?
Formalisation under ECSS

ENTITY mgm_rectangle
  SUBTYPE OF(mgm_primitive_bounded_surface);
  p1 : mgm_3d_cartesian_point;
  p2 : mgm_3d_cartesian_point;
  p3 : mgm_3d_cartesian_point;
WHERE
  wr1: mgm_verify_points_use_context_length_quantity_type([p1, p2, p3], geometric_item.containing_model);
  wr2: mgm_verify_points_span_orthogonal_system(p1, p2, p3, mgm_get_context_uncertainty_value(geometric_item.containing_model, 'point_coincidence_length'));
END_ENTITY;

Difficult to reconcile these two styles

a. Inspection of the spacecraft (including structure and cable harnesses) shall be performed to verify that there are no ungrounded metal components.

b. Resistance testing shall be carried out on grounded metal components to ensure that their grounding meet the requirements in 9.2.2.

Expected Outputs

- Short set of ECSS style requirements targeted at tool developers
  - Focus on: validation, conformance, diagnostics
- STEP-TAS Protocol captured as a normative annex
  - Normative Annex must be a DRD description
- Change request to thermal standard

Where do you come in (as an end-user)?

- Use the STEP-TAS Interfaces
  - They work pretty well (last slide)
- Report any problems to tool developers and ESA
  - step-tas@thermal.esa.int
Future perspectives

- Make TASverter for TMM available soon
  - First issue supports SINDA <-> ESATAN
- Updates to STEP-TAS SDK
  - full validation
  - Improve diagnostics emitted by STEP-TAS SDK
- Web portal for STEP-TAS with forum, FAQ, recipes, downloads etc
- STEP-TAS viewer and validation
  - To replace BagheraView

Current Status

Overview of ECSS Activities for Space Thermal Analysis

29th European Space Thermal Analysis Workshop

European Space Agency
Overview of ECSS Activities for Space Thermal Analysis

END
Appendix L

Improve thermal analysis process with Systema V4 and Python

Alexandre Darrau
(Airbus Defence and Space, France)
Abstract

When performing analyses, thermal engineers follow a methodology to ensure results quality and traceability. However, some checking or/and post-processing operations are still manually done or are performed later in the analysis process, leading to error and time wasting.

The purpose of this presentation is to introduce how the Airbus Defence & Space Thermal Engineering department in Toulouse is working to overcome these difficulties using new Systema V4 functions and Python technology. An example for each thermal analysis stage is going to be presented to illustrate.
Improve thermal analyses process with
SystemaV4 + Python

Alexandre Darrau, Jean-Baptiste Bernaudin
Thermal Engineering - Airbus Defence & Space – Thermal Team

PLAN

• Objectives & Strategy
• Application on Thermal analysis process

01 - Model Geometry
02 - Model Pre-conditionning
03 - Model Conditionning
04 - Runs
05 - Model PostProcessing

WARG
GIMLI
RADYS
RADAGAST
TAPAS
POWERANGER

Systema
Python API
PySDS
PostProcessing Kernel

01 - Model Geometry
02 - Model Pre-conditionning
03 - Model Conditionning
04 - Runs
05 - Model PostProcessing
Objectives & Strategy (1/2)

Objectives: Support thermal engineer!

- Prevent time wasting + manual operations \(\rightarrow\) Automatisation (helper tools…)
- Ensure thermal analysis quality \(\rightarrow\) Check at each analysis stage
- Remove industrials softwares borders \(\rightarrow\) Object-Oriented + Modular approach
- Standardize data presentations.

Automatic tools will never replace engineer thermal but only optimize its time!

Objectives & Strategy (2/2)

Strategy:

- Set global methodology to pinpoint thermal engineer needs
- For each need, define a method to apply.
- When a tool is needed:
  - Use object oriented approach
  - Split data treatment from format
  - Category: modelling helper tool, checker, analysis tool

Thermal Team Tool

\[\text{SYSTEMA - API}\]
\[\text{Model/Meshing../PostPro} \quad \text{SDS}\]

\[\text{Thermal Team Python Modules}\]
\[\rightarrow \text{Export Data}\]
PLAN

- Objectives & Strategy
- Application on Thermal analysis process

01 - Model Geometry
02 - Model Pre-conditionning
03 - Model Conditionning
04 - Runs
05 - Model Post-processing

Model Geometry

GIMLI: Generation MLI
- Modelling Helper Tool
- Automatize MLI GMM and TMM model generation

GMM
TMM (.d)

 Nodes
 Boundaries
 GL
 GR
 Mesh coatings

CAO
SIMPLIFY MODEL
Simplify Model

11/03/2015

11/03/2015
Model Geometry

**WARG: Waveguide Rapid Generator**

- **Modelling Helper Tool:**
  - Automatize waveguide GMM and TMM model generation

CAO Neutral Line + Support Pos

Mesh coatings

GMM

TMM (.d)

Mesh

coatings

EXTRACT

DATA Nodes

Boundaries

GL

---

**PLAN**

- Objectives & Strategy
- Application on Thermal analysis process

01 - Model Geometry

02 - Model Pre-conditionning

03 - Model Conditionning

04 - Runs

05 - Model PostProcessing

---

AIRBUS DEFENCE & SPACE

29th European Space Thermal Analysis Workshop 3–4 November 2015
Model Preconditionning

RADYS: Radiative synthesis

- Checker tool: Check radiative cases data and generate report before run!

LAUNCH
Systema API + Thermal Team Module

Improve thermal analysis process with Systema V4 and Python

29th European Space Thermal Analysis Workshop 3–4 November 2015
Model Conditionning

RADAGAST: RADiAtive GebbArt Support Tool

- Checker tool: check gebbart factor consistency on geometry.

+ Gebbart Data
Model Conditionning

RADAGAST: RADiAtive GebbArt Support Tool

- Check gebbart factor consistency on geometry.

Face active see inactive one!

PLAN

- Objectives & Strategy
- Application on Thermal analysis process

01 - Model Geometry
02 - Model Pre-conditionning
03 - Model Conditionning
04 - Runs
05 - Model PostProcessing

WARG GIMLI RADYS RADAGAST TAPAS POWERANGER

Systema
Python API
PySDS
PostProcessing Kernel

29th European Space Thermal Analysis Workshop 3–4 November 2015
Model PostProcessing

POWERANGER: POWEr Range GEnerator
➤ Tool for thermal analysis
   - Perform power budget on groups after thermisol runs.
   - Steady-State and Transient cases on selected times.
   - Taking into account GL,GR variations and Edges elements.
   - Having graphical views of power exchanges and table synthesis.

Groups file
Solver File H5
HTML
PNG

SYSTEMA POSTPROCESSING + TSOEM43 Module

Model PostProcessing

POWERANGER: POWEr Range GEnerator
➤ Tool for thermal analysis
Model PostProcessing

POWERANGER: POWEr Range GEneratoR

TAPAS: Thermal Analysis PostProcessing Airbus Satellite

- Compute $T_{\text{min}}$/max/ave/Gradients on groups AFTER runs
- Compute $Q_{I}/QR/QS/QA/QE$ on groups AFTER runs
- Compute Mass Balance AFTER runs + Manage Equipment status
- Generate automatically charts (2d and horizontal bars), 3dviews
- Generate automatically Excel + HTML thermal reports
Model PostProcessing

TAPAS:

Improve thermal analysis process with Systema V4 and Python
Model PostProcessing

TAPAS:

1. Improve thermal analysis process with Systema V4 and Python

2. European Space Thermal Analysis Workshop: 3–4 November 2015
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Improve thermal analysis process with Systema V4 and Python
CONCLUSIONS

- Thanks to SYSTEMA API, it is possible to:
  - Optimize time model/meshing creations
  - Easily check thermal model.
  - Plotting user data on mesh.

- Thanks to Python, it is possible to:
  - Create simple tools without deep software engineering knowledge.
  - Wrap Systema API
  - Design tools with oriented object approach.
  - Create user friendly tools thanks to existing packages.

- Collaboration with Systema Team to improve existing functions and create new ones:
  - Materials data to be integrated in API
  - Implementing new box in postprocessing library
  - ...
QUESTIONS ?
Appendix M

Finite element model reduction for spacecraft thermal analysis

Lionel Jacques  Luc Masset  Gaetan Kerschen
(Space Structures and Systems Laboratory, University of Liège, Belgium)
Abstract

The finite element method (FEM) is widely used in mechanical engineering, especially for space structure design. However, FEM is not yet often used for thermal engineering of space structures where the lumped parameter method (LPM) is still dominant. Both methods offer advantages and disadvantages and the proposed global approach tries to combine both methods:

- The LPM conductive links are error-prone and still too often computed by hand. This is incompatible with the increasing accuracy required by the thermal control systems (TCS) and associated thermal models. Besides offering the automatic and accurate computation of the conductive links, the FEM also provides easy interaction between mechanical and thermal models, allowing better thermo-mechanical analyses.

- On another hand, due to the large number of elements composing a FE model, the computation of the radiative exchange factors (REFs) is prohibitively expensive. New methods to accelerate the REFs computation by ray-tracing are necessary. Ray-tracing enhancement methods were presented in the previous editions, providing at least a 50% reduction of the number of rays required for a given accuracy. Another way to speed up the REF computation consists in grouping the FE external facets into super-faces. Surfaces in FEM are approximated where primitives are used in the LPM. In parallel to super-faces, quadric surface fitting of selected regions in the FE mesh is therefore performed where high surface accuracy is required for the computation of the radiative links and environmental heat loads.

Last year’s presentation focused solely on the first point. Developments of super-face ray-tracing with quadrics fitting will be presented. In addition to REFs, orbital heat loads computation is also implemented with significant improvement. The presentation will also address the global process involving first the detailed FE model conductive reduction, then the super-faces generation with selective quadric fitting for the computation of REFs and orbital heat loads and finally the computation of the reduced model temperatures. Detailed FE model temperature field can then be computed back from the reduced ones and the reduction matrices for potential thermo-mechanical analyses.
**FINITE ELEMENT MODEL REDUCTION FOR SPACECRAFT THERMAL ANALYSIS**

Lionel Jacques$^{1,2}$, Luc Masset$^1$, Gaetan Kerschen$^1$

$^1$ Space Structures and Systems Laboratory, University of Liège  
$^2$ Centre Spatial de Liège

29th Space Thermal Analysis Workshop, ESTEC, Nov. 3rd, 2015

---

**Finite Element vs. Lumped Parameter**

<table>
<thead>
<tr>
<th></th>
<th>FEM</th>
<th>LPM</th>
</tr>
</thead>
<tbody>
<tr>
<td># nodes</td>
<td>$10^4 - 10^6$</td>
<td>$10^1 - 10^3$</td>
</tr>
<tr>
<td>Conductive links computation</td>
<td>Automatic</td>
<td>Manual, error-prone</td>
</tr>
<tr>
<td>Radiative links computation</td>
<td>Prohibitive</td>
<td>Affordable</td>
</tr>
<tr>
<td>Surface accuracy for ray-tracing</td>
<td>FE facets</td>
<td>Primitives</td>
</tr>
<tr>
<td>User-defined components</td>
<td>Difficult</td>
<td>Easy</td>
</tr>
<tr>
<td>Thermo-mech. analysis</td>
<td>Same mesh</td>
<td>Mesh extrapolation</td>
</tr>
</tbody>
</table>
Reconciliation through a global approach

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

Surface accuracy for ray-tracing
- Quadrics fitting

Conductive links, thermo-mech. analysis and user-defined compts.
- Reduce detailed FE mesh (keep conductive info. of the detailed geometry)
- Able to recover detailed T° from reduced
- Transform reduced FE model to LP model to enable user-defined comp.

Outline

Ray-tracing enhancement

FEM clustering & conductive reduction

Super-face ray-tracing

Integrating the developments

Conclusions & perspectives
Outline

Ray-tracing enhancement

FEM clustering & conductive reduction

Super-face ray-tracing

Integrating the developments

Conclusions & perspectives

Ray-tracing: origin + direction sampling

\[ F_{ij}(B_{ij}) = \frac{\text{Number of rays emitted by facet } i, \text{ directly (finally) hitting } j}{\text{total number of rays emitted by facet } i} \]

Ray direction sampling over hemisphere

Ray origin sampling over surface \( A_i \)

Reference solution: ESATAN-TMS
\[ \text{crude Monte Carlo: random direction & origin sampling, } 1 \text{ ray }/ \text{ origin} \]

\[ \text{error } \propto \frac{1}{\sqrt{N_{\text{rays}}}} \]
4-D QUASI-MC SAMPLING: 2 QUADRANGLES

![Graph showing relative error vs. number of rays for different sampling methods.](image)

4-D QUASI-MC SAMPLING

![Graph showing absolute error vs. number of rays for different sampling methods.](image)
Outline

Ray-tracing enhancement

FEM clustering & conductive reduction

Super-face ray-tracing

Integrating the developments

Conclusions & perspectives

Mesh clustering: 3 steps

K-mean clustering initialization (user input # cluster) → cluster center
Mesh clustering: 3 steps

K-mean clustering initialization (user input # cluster) $\rightarrow$ cluster center

Greedy region growing

Boundary smoothing
**Mesh clustering: 3 steps**

Heterogeneous mesh  
Material constraints

**Problem of Guyan condensation**

Cannot use cluster center as retained node  
No (or known) heat load on condensed nodes  
Heat load on selected node ≠ heat load on cluster

\[ Q_1 = 1 \text{W} \quad T_2 = 0^\circ \text{C} \]

**OK**  
**KO**
Create new “super-nodes”

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

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

\[ T_{SN} = AT \]

\[ T_{SNi} = \sum_{j=1}^{N} A_{ij} T_j \]

\[ \sum_{j=1}^{N} A_{ij} = 1 \]

More than 10% error

<table>
<thead>
<tr>
<th></th>
<th>Detailed</th>
<th>ESATAN</th>
<th>Reduced</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta T ) [K]</td>
<td>22.5</td>
<td>27.4</td>
<td>22.5</td>
</tr>
<tr>
<td># nodes</td>
<td>35k</td>
<td>422</td>
<td>397</td>
</tr>
<tr>
<td># links</td>
<td>&gt;200000</td>
<td>473</td>
<td>78600</td>
</tr>
</tbody>
</table>

Temperature [°C]

Temperature [°C]
Selective quadric fitting

Automatic quadric mesh fitting of user selected regions (e.g. optics)

\[ f(x) = C^T F \]
\[ F(x) = [1, x, y, z, xy, xz, yz, x^2, y^2, z^2]^T \]
\[ C = [c_0, ..., c_9]^T \]

\[ \text{error} \approx \sum_{S_l \in E} \int_{S_l} \frac{f(x)^2}{|\nabla f(x)|^2} \, d\sigma \approx \frac{C_0^T M C_0^T}{C_0^T N C_0^T} \]

With
\[ M = \frac{1}{n} \sum_{x_i \in E} F(x_i) F(x_i)^T \]
\[ N = \frac{1}{n} \sum_{x_i \in E} \nabla F(x_i) \nabla F(x_i)^T \]

\[ C \] is the eigen vector associated with minimum eigen value of
\[ M - \lambda N \]
Selective quadric fitting

Entrance baffle of EUI instrument onboard Solar Orbiter
Cone recognition
Shape error ~1nm

Ray-tracing with quadrics

Use directly the quadric for the intersection computation
→ avoid lost grazing rays
→ better shadow

Project normally to the quadric to determine which super-face
Fitted cylinder vs. ESARAD cylinder

Outline

Ray-tracing enhancement

FEM clustering & conductive reduction

Super-face ray-tracing

Integrating the developments

Conclusions & perspectives
## CONDUCTION + RADIATION

<table>
<thead>
<tr>
<th></th>
<th>Detailed</th>
<th>ESATAN</th>
<th>Reduced</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{id}$ [°C]</td>
<td>-11.9</td>
<td>-10.8</td>
<td>-12.4</td>
</tr>
<tr>
<td>$T_{min}$ [°C]</td>
<td>-20.2</td>
<td>-21.8</td>
<td>-20.6</td>
</tr>
<tr>
<td># nodes</td>
<td>35k</td>
<td>422</td>
<td>397</td>
</tr>
<tr>
<td># cond. links</td>
<td>&gt;200k</td>
<td>473</td>
<td>78.6k</td>
</tr>
<tr>
<td># rad. links</td>
<td>1500k</td>
<td>41k</td>
<td>55k</td>
</tr>
</tbody>
</table>

### Putting the building blocks together

- **CAD model / Structural FEM**
  - CAD cleaning / struct. FEM adaptation
  - Thermal properties

- **Thermal FEM**
  - (3) Selective quadric fitting
  - (2) FE mesh partitioning in super-faces/nodes

- **Partitioned thermal FEM with accurate surfaces**
  - (1) Conductive FEM reduction
  - (2) Ray-tracing (isocell) adapted to SF and quadrics

- **Reduced conductive and radiative model**
  - (4) User-defined components
  - LP iterative solver (ESATAN or Matlab)

- **Reduced temperatures**
  - (5) Detailed $T^*$ map recovery

- **Reduced heat flow map**
  - Detailed $T^*$ map

- **Thermo-mech. analysis**
  - (5) Straightforward mapping onto struct. FEM
Global tool development

CONCLUSIONS & PERSPECTIVES

Global approach for conduction and radiation

Takes advantages of both lumped parameter and finite element methods:

- More accurate conductive links
- Accurate shape recognition used for ray-tracing
- Reduce the gap between thermal and structural analyses

Perspectives:

- Iterative process with automatic refinement in high \( \Delta T \) regions
- GPUs with Matlab parallel computing toolbox\(^\text{®} \) and CUDA\(^\text{®} \)
- Quadric fitting \( \rightarrow \) opto-thermo-structural analyses
Thank you for your attention...

Any question?

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  B-4031 Angleur Belgium
  http://www.csl.ulg.ac.be
Appendix N

The Thermal Design of the KONTUR-2 Force Feedback Joystick

Ralph Bayer
(DLR, Germany)
Abstract

The KONTUR-2 Mission is a cooperation between the German Aerospace Center (DLR), ROSKOSMOS, RSC Energia and the Russian State Scientific Center for Robotics and Technical Cybernetics (RTC). Its purpose is to study the feasibility of using teleoperation to control robots for tasks such as remote planetary explorations. The operating human would be stationed in orbit around the celestial body in a spacecraft. For KONTUR-2, the earth is utilized as the celestial body, and the ISS as the spacecraft with the ISS crewmember as the operator. The main goals of this mission are the development of a space-qualified 2 degrees of freedom (DoF) force feedback joystick as the human machine interface (HMI), the study and implementation of underlying technologies to enable telepresence in space, and the analysis of telemanipulation performance of robotic systems. The DLR KONTUR force feedback joystick was upmassed and installed in the Russian Service Module of the ISS in August 2015. The first of a series of experiments to be completed by December 2016, were carried out successfully.

Meeting the thermal requirements of the joystick is one of the key challenges in the KONTUR-2 Mission. This presentation focuses on the thermal design for the force feedback joystick to cope with the unique conditions in a manned spacecraft. In order to reduce complexity, and further improve safety aspects for the integration on board the Russian segment of the ISS, active cooling has been eliminated in the force feedback joystick. Furthermore, as a safety measure, a temperature control system (TCS) has been developed and implemented able to respond to all unforeseen disturbances.

This presentation outlines DLR’s approach to handle the unpredictable thermal output of the mechatronic system, resulted from a complex combination of the specific task, and the operating handling of the Cosmonaut. This in turn directly influenced the design to meet the mission’s requirements, which includes the physical human-joystick interaction, storage on board the ISS, electronic components, operation time, and system performance.
The Thermal Design of the KONTUR-2 Force Feedback Joystick

Ralph Bayer

German Aerospace Center (DLR)
Robotic and Mechatronic Centrum (RMC)
Institute of Robotics and Mechatronics

Outline

• KONTUR-2 mission overview
• Thermal requirements
• Thermal design
• Analysis cases and results
• Temperature Control System (TCS)
• Thermal test and results
• Conclusion and Outlook
KONTUR-2 mission overview

Goals
- Development of a space-qualified force feedback joystick as the human machine interface (HMI)
- Development of telepresence technologies
- Study of ergonomics and human factors of the force feedback in microgravity

Joystick specifications
- Maximum force on joystick handle: 15 N
- Workspace: +/- 20°
- 2 Degrees of freedom

History: ROKVISS experiment
- Verification of robotic components in space

Feasibility study
Telepresence for remote planetary exploration

Experiment scenario
Teleoperating robot on the planetary surface from orbit
KONTUR-2 challenges

Difficult thermal conditions
Unpredictable motor load, which is a complex combination of
• Different tasks
• Operating behavior of the cosmonaut
• Side effects e.g. telepresence performance, friction modeling

Thermal requirements
Requirements
• Joystick housing maximum allowable temperature: 40°C
• Operational temperature range of on-board electronics and motors
• No active cooling system
• Continuous operating time: 30 minutes

Environmental qualification tests
• Humidity cycles
• Temperature cycles
• Offgassing (toxicity)
**Thermal design - model**

- **FEM analysis (ANSYS 14.0)**
- No printed circuit boards (PCBs)

**General boundary conditions**
- ISS ambient temperature condition ≤ 28°C
- Complete insulation between joystick and ISS structure
- Heat flows with +10% margin

**Conductive boundary conditions**
- Air inside the joystick appeals thermoconductive (neglected)
- Ideal thermal contact between mechanical parts
- Electronic components attached to the mechanical parts through interface materials (gap pads)

**Radiative boundary conditions**
- Heat radiation exchange in the environment
  - Joystick housing with electroplated chromium coating: $\varepsilon = 0.1$
  - Adapter plate with black anodized aluminium: $\varepsilon = 0.82$
- Heat radiation exchange inside the joystick

**Convective boundary conditions**
- Airflow (0.05 m/s) of the ISS air supply near the joystick
  - Similitude model of a plane plate in a longitudinal flow for specific plates and walls (worst case)
Thermal design – analysis cases

Analysis cases based on states

Standby
- Initial state after switching on and booting
- Passive mode – only communication possible
- Intended as pause mode

Idle
- Joystick is calibrated
- Motor Control Modules (MCM) are active but no torque is commanded
- Intermediate state between standby and operation

Operation
- All hard- and software components are active including force feedback control

<table>
<thead>
<tr>
<th>Electric Components</th>
<th>States</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Standby</td>
</tr>
<tr>
<td>Motors</td>
<td>None</td>
</tr>
<tr>
<td>Motor Control Module (MCM)</td>
<td>None</td>
</tr>
<tr>
<td>DCDC-Converter</td>
<td>≈ 1.9 W</td>
</tr>
<tr>
<td>Microcontroller Module (CPU)</td>
<td>≈ 5.0 W</td>
</tr>
</tbody>
</table>

Heat dissipation for basic states of the joystick

Thermal design – analysis cases

Thermal analysis cases for the KONTUR-2 Force Feedback Joystick

Pattern 1
- Motor-x
- Motor-y
- MCM-x
- MCM-y
- DCDC
- CPU

Pattern 2
- Motor-x
- Motor-y
- MCM-x
- MCM-y
- DCDC
- CPU

Pattern 3
- Motor-x
- Motor-y
- MCM-x
- MCM-y
- DCDC
- CPU

Heat flow [W] vs. Operation time [s]
### Analysis results

![3D model showing temperature distribution](image)

- **Top plate**
- **Outer walls**
- **Mechanism plate (MP)**
- **Adapter plate**
- **Base plate**
- **Characteristic joystick temperature distribution from the front side**
- **Characteristic hotspot from bottom side**

<table>
<thead>
<tr>
<th>Housing location</th>
<th>Standby</th>
<th>Idle</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Steady state &gt; 5 h</td>
<td>Steady state &gt; 2 h</td>
<td>30 min</td>
</tr>
<tr>
<td></td>
<td>°C</td>
<td>°C</td>
<td>°C</td>
</tr>
<tr>
<td>Base plate</td>
<td>37.70</td>
<td>46.38</td>
<td>34.60</td>
</tr>
<tr>
<td>Adapter plate</td>
<td>37.64</td>
<td>46.32</td>
<td>34.55</td>
</tr>
<tr>
<td>Outer walls</td>
<td>37.49</td>
<td>46.03</td>
<td>34.27</td>
</tr>
<tr>
<td>Mechanism plate</td>
<td>36.83</td>
<td>45.29</td>
<td>33.53</td>
</tr>
<tr>
<td>Top plate</td>
<td>36.68</td>
<td>44.72</td>
<td>33.10</td>
</tr>
</tbody>
</table>

### Temperature Control System (TCS)

**Objectives**

1. Observance of the temperature limits for the electronic components

2. Observance of max. housing temperature

   → Even when the joystick is operated incorrectly

- 9 temperature sensors are monitored every 1 sec.

![Temperature sensor of one motor housing](image)

![Temperature sensor near the CPU](image)
Temperature Control System (TCS)

Additional state: OpHalf

Statemachine conditions:
1: Calibrate AND T_CPU Crit 1 OR T_CASE Crit 1
2: Application activated AND T_CPU Crit 2 OR T_CASE Crit 2
3: Application activated AND T_CPU Crit 3 OR T_CASE Crit 3
4: T_CPU Crit 4 OR T_CASE Crit 4
5: T_CPU Crit 5 OR T_CASE Crit 5
6: Application deactivated
7: Standby
8: T_CPU Crit 8 OR T_CASE Crit 8

If T_CPU is invalid use T_DCDC
If T_CASE is invalid use T_MotorX OR T_MotorY

Thermal test

Test cases:
1. Standby state until steady state
2. Idle state until TCS switches to standby state
3. Operational state (stirring) with elastic band
   a. $F_H = 5$ N
   b. $F_H = 10$ N
   c. $F_H = 15$ N (max. force)
   → Higher load than normal usage!

- Joystick in thermal chamber
- No adapter plate
- Worst case ambient temperature is 28°C
- Housing isolated with polystyrene, foam and bubble wrap to reduce convectional heat transfer
Test results

Test case 1 - Standby state

Test results

Test case 2 - Idle state
Conclusion

Thermal design

- The thermal analysis model has been verified by thermal tests
- Thermal test have clearly proven that the joystick fulfills all thermal requirements under the assumed boundary conditions.
- The TCS has successfully been developed, implemented and tested.
- All environmental qualification and acceptance tests have been passed

KONTUR-2 mission

- The force feedback joystick was installed in the Russian service module in August 2015
- First experiments were conducted successfully
Outlook

• KONTUR-2 joystick shall operate until December 2015 on board the ISS
• During ongoing experiments all performance data will be recorded for each session
  → Ergonomic study for using force feedback in microgravital environment
  → Study of space related telepresence control performance
  → Evaluation of TCS-Concept for other robots
  → Further verification of thermal FEM-model

Haptics experiment with telepresence from space:
Handshake between cosmonaut on board the ISS and earth representative planned in December 2015

Thank you for your attention!

For further information, visit our website
http://www.dlr.de/rmc/rm/en

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Appendix O

ESATAN Thermal Modelling Suite
Product Developments and Demonstration

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

Product Developments

ESATAN-TMS r7 was released at the end of 2014 and focused on improvements throughout the thermal modelling process, taking into account feedback received through our customer survey. The work has continued at a high-level, with a significant number of developments being finalised which centre on improving both the effectiveness of the interface and the look and feel of the product. Through close discussions with customers, the next release will also see a series of developments, either extending existing functionality or providing exciting new modelling features. This presentation outlines the developments to be included within the next release of ESATAN-TMS.

Product Demonstration

A demonstration of the development version of ESATAN-TMS shall be provided, focusing on the new features of the product.
• **ESATAN-TMS 2016**
  - Major evolution of the product
  - Present main developments
  - Demonstration of new features
• ESATAN-TMS 2016 Developments
  – Improved Geometry Modelling
  – Bulk Material Definition
  – Radiative Analysis
  – Linear Conduction
  – Thermal Boundary Conditions
  – Thermal Analysis
  – Post-processing

• ESATAN-TMS 2016 Developments
  – New ESATAN-TMS Workbench
  – Improved Geometry Modelling
  – Bulk Material Definition
  – Radiative Analysis
  – Linear Conduction
  – Thermal Boundary Conditions
  – Thermal Analysis
  – Post-processing
• Aim to maximise the visualisation area was presented last year
• Large number of dialogs redesigned within ESATAN-TMS r7
• Concluded the work within ESATAN-TMS 2016
ESATAN Thermal Modelling Suite — Product Developments and Demonstration

ESATAN-TMS 2016 - Workbench

Reset Visualisation Display

Animation Controls

ESATAN-TMS 2016 - Workbench
ESATAN Thermal Modelling Suite — Product Developments and Demonstration

ESATAN-TMS 2016 - Workbench

- Geometry & Properties
- Radiative Analysis
- Linear Conduction
- Boundary Conditions
- Thermal Analysis
- Post Process

Presentation Contents

- ESATAN-TMS 2016 Developments
  - New ESATAN-TMS Workbench
  - Improved Geometry Modelling
  - Bulk Material Definition
  - Radiative Analysis
  - Linear Conduction
  - Thermal Boundary Conditions
  - Thermal Analysis
  - Post-processing

29th European Space Thermal Analysis Workshop

3–4 November 2015
• Interactive Combine operation
  – Aim, simplify geometry creation

Save the attachment to disk or (double) click on the picture to run the movie.
• Interactive Combine operation
  – Aim, simplify geometry creation

• New “Cut & Combine” dialog
  – Single dialog, clear operation
  – Cut & Combine in a single operation

Save the attachment to disk or (double) click on the picture to run the movie.
• Interactive Cut Operation
  – New “Cut by...” menu option
  – Cutters now displayed transparent
  – Option to switch cutting sense

Save the attachment to disk or (double) click on the picture to run the movie.
• Increased control of node numbering
  – Request from customers
  – Improved flexibility using Recursive Properties
• Node range across multiple geometry
  – Extension for LP & FE geometry

• ESATAN-TMS 2016 Developments
  – Redesign of ESATAN-TMS Workbench
  – Improved Geometry Modelling
  – Bulk Material Definition
  – Radiative Analysis
  – Linear Conduction
  – Thermal Boundary Conditions
  – Thermal Analysis
  – Post-processing
• Support for orthotropic material conductivity
  – Model composite materials, such as honeycomb
  – For orthotropic conductivity k1, k2 & k3 defined
  – Display “Material Orientation”, to validate application of material

• ESATAN-TMS 2016 Developments
  – New ESATAN-TMS Workbench
  – Improved Geometry Modelling
  – Bulk Material Definition
  – Radiative Analysis
    – Linear Conduction
    – Thermal Boundary Conditions
    – Thermal Analysis
    – Post-processing
• Support for solar emitter modelling
  – Requirement of Solar Orbiter & BepiColombo
  – Simulate solar lamps within a test chamber
  – Definition of multiple UV emitters
  – Easy validation of data
    • solar beam direction
    • applied emission

– Post-processing solar ray path & emitter flux
• Extended environment & mission definition
  – Time-dependent spacecraft orientation & assembly pointing
    • Request to support step change between positions
    • General extension, can be applied to temperature & heat load Boundary Conditions

• Extended environment & mission definition
  – Support for default planet data
  – Orbit definition by semi-major axis & eccentricity
  – Definition of mission for more than one orbit
  – Orbit positions defined by times
  – Support for planet image
Save the attachment to disk or (double) click on the picture to run the movie.

### Presentation Contents

- **ESATAN-TMS 2016 Developments**
  - New ESATAN-TMS Workbench
  - Improved Geometry Modelling
  - Bulk Material Definition
  - Radiative Analysis
  - **Linear Conduction**
  - Thermal Boundary Conditions
  - Thermal Analysis
  - Post-processing
• Extension of Conductor Interfaces identification
  – Identification of interfaces for displayed geometry
    • Increased flexibility to generate Conductive Interfaces between components
  – Interfaces now automatically identified on cut geometry

• Non-linear convective User-Defined Conductor
  – Request from AIRBUS D & S
  – Support for linear or non-linear convection

\[ Q_{conv} = kS(T_{fluid} - T_{wall})^{(1+\alpha)} \]

\[ K = \text{non-linear convective coefficient} \]
\[ S = \text{convective surface area} \]
\[ \alpha = \text{correction coefficient} \]
• ESATAN-TMS 2016 Developments
  – New ESATAN-TMS Workbench
  – Improved Geometry Modelling
  – Bulk Material Definition
  – Radiative Analysis
  – Linear Conduction
  – Thermal Boundary Conditions
  – Thermal Analysis
  – Post-processing

• Support for thermostat from Workbench
  – Heat load can now be controlled by a thermostat
  – Ability to control the thermostat based on Min, Max or Mean temp
• Support for thermostat from Workbench
  – Heat load can now be controlled by a thermostat
  – Ability to control the thermostat based on Min, Max or Mean temp

• Heat load multiplier can be defined
  – Request from customers
  – Apply the same heat load to multiple Boundary Conditions, with different scaling factors
• **ESATAN-TMS 2016 Developments**
  – New ESATAN-TMS Workbench
  – Improved Geometry Modelling
  – Bulk Material Definition
  – Radiative Analysis
  – Linear Conduction
  – Thermal Boundary Conditions
  – Thermal Analysis
  – Post-processing

• **Simplified interface for defining the thermal analysis**
  – Maintain template file
  – Single tab design
  • Select Boundary Conditions
  • Define thermal solution
  • Define thermal solution output
  • Select to Run Analysis...
• Analysis Monitor interface launched

Save the attachment to disk or (double) click on the picture to run the movie.
• ESATAN-TMS 2016 Developments
  – New ESATAN-TMS Workbench
  – Improved Geometry Modelling
  – Bulk Material Definition
  – Radiative Analysis
  – Linear Conduction
  – Thermal Boundary Conditions
  – Thermal Analysis
  – Post-processing

• Improved mechanism of displaying data
  – Right-click from model tree
  • Immediate display of data
• Improved mechanism of displaying data
  – Right-click from model tree
    • Immediate display of data

  – Simplified interface
    • Single dialog
    • Ordering of data per category
    • Common orbit display parameters

• ESATAN-TMS 2016
  – Major evolution of the product
  – Focus on user and project requests
  – Modelling process improved significantly
Save the attachment to disk or (double) click on the picture to run the movie.
Appendix P

SYSTEMA — THERMICA

Timothée Soriano     Rose Nerriere
(Airbus Defense and Space SAS, France)
Abstract

SYSTEMA, currently in version 4.7.1, is a framework for space physics applications including THERMICA, a package dedicated to thermal simulations. The next version will be the 4.8.0 and will include a new schematic module which will allow the definition of power systems and will ease the thermo-electrical simulation process. Besides, SYSTEMA has the ability to manage the solar system including different moons, like Ganymede, Europa and others for which orbits are approximated by Keplerian laws around a particular date of interest. A trajectory defined around a moon like Ganymede will lead to simulate fluxes both from the moon itself but also from other planets, like Jupiter in this example. Finally, a new applicative module within Systema, called Mapping, offers the possibility to transfer data from one model to another one: fluxes from a Plume analysis to a thermal model, temperatures to an outgassing model or to mechanical mesh. For the temperature mapping, a new method based on a "backward RCN" has been set-up. This method is capable of interpolating temperatures within a re-built quadratic profile onto the thermal mesh and offers then a very accurate mapping consistent with the hypothesis of the thermal simulation.
Content

Current status

Addition of Jupiter’s moons
• Ganymede use case

Mapping application
Current status

Long Term Support current version: v4.5.3 (08/2013)

Latest Release: v4.7.1 (06/2015)

- CAD simplification
- Windows 64bits
- 3D performance
- Post-Processing
- Python API extended

02 November 2015
v4.7.1

• Import/Export of ASCII Ephemeris files

• Follow the CIC exchange protocol: restriction of ESA standard CCSDS

• Trajectory Time-Position-Velocity

  - Import of Trajectory:
    - OEM files (Orbit Ephemeris Message) → x, y, z positions
v4.7.1

• Kinematics law “Transformation defined in a file”:

- Import of Kinematics:
  - AEM files for satellite attitude (Attitude Ephemeris Message) $\rightarrow$ quaternions
  - MEM files for moving bodies attitude (Mission Ephemeris Message) $\rightarrow$ rotation angle

• Export of HDF5 results:
  - MEM files (Mission Ephemeris Message) $\rightarrow$ thermal results

Next Release: v4.8.0 (S1 2016)
Jupiter’s moons

• Ganymede use case

Implementation of moons in Systema

• Texture of the moon
• Ephemeris information
  → Orbits approximated by Keplerian laws from a fixed date

Make mission and analyses around moons with Systema

JUICE mission

• Launch in 2022 and start of the mission in 2030
• Callisto and Europa flybys
• Orbit around Ganymede
Jupiter’s moons

Ganymede
• Available since version 4.7

Europa / Callisto
• Available in 4.8.0
Jupiter's moons

Ganymede Albedo Fluxes (Ganymede behind Jupiter)

Ganymede IR Fluxes (Ganymede in front of Jupiter)
Jupiter's moons

Jupiter is eclipsed by Ganymede

Satellite motion vs Jupiter

Jupiter is eclipsed by Ganymede

Satellite motion vs Jupiter
Conclusions
• Relative positions of planet / moon / sun
• Sun eclipses from both Ganymede and Jupiter
• Jupiter eclipse from Ganymede
• Ganymede and Jupiter fluxes simulated

Realistic simulations around any moons are possible

In the future
• update existing moon's properties
• add new moons
Mapping

Context: Multi-physics analysis

- **Need to transfer data**
  - Temperatures from *Thermal analysis* to *Mechanical mesh*
  - Fluxes from *Plume analysis* to *Thermal model*
  - Temperatures from *Thermal analysis* to *Outgassing model*

Geometrical associations

- **By projection from detailed to coarse model**
  - Detailed elements are projected to the nearest geometry of the coarse model (by ray-tracing)
  - The projection is normal to the coarse geometry
  - Correspondences between mesh are generated
  - Including parametric coordinates of projected points

1. Search closest impact by ray-tracing
2. Get normal direction of impacted point
3. Determine projection point
Mapping

Mapping of fluxes
• According to cross-section of projection

\[ Q_c \rightarrow \phi_c = \frac{Q_c}{A_c} \Rightarrow \phi d = \phi_c \cos \theta \quad \rightarrow \quad Q_d = A_d \phi d \]

02 November 2015

Mapping

Mapping of temperatures
• By a backward RCN method
  – The RCN method (Reduced Conductive Network) is an innovative algorithm that deals with the conduction in accordance with radiative and external fluxes ray-tracing methods. It is based on a finite volume integration of conductive fluxes computed through a model reduction of a detailed sub-mesh model.
  – The model reduction used by the RCN algorithm may also export “backward matrices” allowing to recover a detailed temperature profile from temperatures computed on the thermal model.
  – Using the RCN method for the conduction allows then to rebuild an accurate and detailed temperature profile and so to perform a temperature mapping of a very good quality
Mapping of temperatures

• Process
  – Import a Nastran file into Systema and save it as Systema native format
  – Create a process with the two models and the mapping module

The backward RCN method
Mapping

The backward RCN method

Consistency of the RCN Conduction and RCN backward Mapping

- **Coarse model**

  Boundary @ 0°C

<table>
<thead>
<tr>
<th>Mesh 1</th>
<th>Mesh 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q = 1W/m²</td>
<td>Q = 1W/m²</td>
</tr>
</tbody>
</table>

  - Computed average temperatures with the RCN conduction: T1 = 34.66 °C. T2 = 74.66 °C

- **Detailed model**
Mapping

Consistency of the RCN Conduction and RCN backward Mapping

• Detailed model: Results

Identical results between:
- Detailed simulation (RCN)
- Coarse simulation mapped to detailed model

Consistency of the RCN Conduction and RCN backward Mapping

• Coarse model: Results

The simplified RCN (classical lambda.S/I formulae) leads to a convergence of the temperatures with the mesh discretization.
Conclusion

- The new Mapping module allows to transfer data (temperatures, fluxes…) between different models
  - Projected areas may be used to be conservative on the powers
  - Backward RCN brings a complete solution and do not involve any extrapolation of temperatures
    (the temperature profile obtained is such as the really considered at temperature integration level)
Appendix Q

Thermal Spacecraft Simulator Based on TMM Nodal Model
Return of Experience

Sandrine Leroy    François Brunetti
(DOREA, France)
Abstract

Many advantages have been depicted to use the same thermal mathematical model from early design phases to operational phases of the satellite: higher reliability of the thermal model, cost reduction by reusing the model and adaptations work load minimisation.

The dynamic spacecraft system simulator is used to validate the spacecraft control center, but also to train operators. This last user case implies the simulator to react to not predictable events, unplanned scenarios while respecting the physics of the environment.

The thermal analysis model is used to validate the satellite design by predicting temperature ranges for embedded units by calculating temperatures of thermal control elements for given configurations of the environment. Because it is also important to simulate the logic of the flight software (such as thermal regulation), an implementation of the transient state based on simulated time cannot be avoided.

The implementation of a satellite simulator connected to the real flight software using the same thermal nodal model faces many challenges such as the recalculation "on the fly" of the view factors, solar, albedo and earth fluxes impacts on the external CAD model. Another challenge is to make the loop flight software - power dissipation generator - thermal calculator not hanging. For this reason, the thermal simulator regulation must be switched off in order to let the flight software drive the thermostats and thermal temperatures time response should also be adjusted in order to fit the physics time.

Thales Alenia Space Cannes asked DOREA to implement the thermal real-time simulator based on the thermal mathematical model (TMM) provided by thermal analysis team. Thanks to the very good time performances of the e-Therm thermal core calculator (external fluxes, view factors and temperatures calculations), a real time module with parallelism features have been implemented to fit the challenge.

After the success of the O3B Networks and Alphasat dynamic spacecraft simulators in 2013, Thales Alenia Space asked DOREA to implement all the following thermal simulators such as Iridium Next, TKM, SGDC and in the future T3S, K5 and KA7.
Thermal Spacecraft Simulator
Based on TMM Nodal Model
Return of Experience.

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**Purpose**
- A Dynamic Spacecraft System Simulator (DSSS) is a dedicated software tool that simulates the full satellite for operational phases.

**Use Cases**
- Used to train operators while handling the Spacecraft Control Center (SCC).
- It is also used to validate the development of the SCC.
- Used to validate the Check Out Equipment (OCOE) center.
**DSSS Components:**
- Real OnBoard flight Software (OBS).
- Payload / PLIU and TTC modeling,
- AOCS models,
- Power “dissipator” module,
- Thermal TMM Model (TCS).

**DSSS Characteristics :**
- It is a real time application,
- It should simulate the environment and physics as much as possible,
- Thermal is the subsystem that needs the simulation of physics. A processor is dedicated to the thermal simulator.

**Advantages**
- The scope is to reduce the development cost of the DSSS.
- Using the TMM provided at CDR or PSR has an enormous advantage to fit with the qualifications.

---

**Architecture of SCSIM-TCS**

**Thermal Simulator module (TCS):**
- DOREA implemented for Thales Alenia Space (TAS) a thermal simulator (SCSIM-TCS) part of the DSSS (SCSIM). The calculator is based on e-Therm CORE module.
- As it is CPU consuming, a dedicated processor is allocated to the thermal simulator.
- The architecture is using a co-simulation between the SCSIM (scheduler including the flight software) and the thermal simulator (SCSIM-TCS). The used protocol layer is TCP-IP with a native protocol interface (exchanging binary data values).
**SCSIM-TCS Characteristics**

- **Thermal Simulator module (TCS):**
  - SCSIM-TCS performs offline conductive and radiative couplings with a storage in a database of couplings according to the kinematics of the spacecraft.
  - SCSIM-TCS performs an online solar, albedo and earth flux calculation "on the fly".
  - Temperature calculation is calculated in a separate process in parallel of the external fluxes calculation.
  - Temperature regulation is performed by the control loop flight software <= TCS.

- **Customisation:**
  - The time constant of the thermal simulator is deduced from the thermal analysis (around 1s) and the meeting time with the flight software is not less than 32s (speed x1).
  - External fluxes calculation is performed with a threshold based on the Sun/Sat/Earth angles.

---

**Validation**

- **Successful deployment:**
  - The SCSIM-TCS thermal simulator has been validated in operational conditions for the satellites Alphasat (CNES/ESA/ADS/TAS) and O3B Networks, TKM, Iridium Next satellites (TAS Cannes).
  - It is currently running for SGDC and T3S, K7 and K5A are in preparation.
  - Requirements on $T^\circ$ : delta < 5°C on TM (telemetry = thermistances)

- **Validation approach:**
  - DOREA implemented an automated validation process able to compare given scenarii results provided by e-Therm (decided at KoM) with SCSIM-TCS with automated report generation.
  - DOREA provided a recorder mode enable to store all the flight software inputs in order to reproduce the orbital and powers dissipation "off line".
**Issues**

- **Main Issue:**
  - SCSIM-TCS does know nothing about the future of the scenario.
  - SCSIM-TCS has to calculate on the fly the moving of the sun and earth (for instance positioning to SAM). At thermal analysis level, the calculator knows at the start all the different modes.

- **Solutions:**
  - Both calculators (external fluxes and temperatures) are running in parallel.
  - Discretisation of the external geometry is tuned to reach a good compromise speed / fluxes error.
  - GMM is reduced in order to not decrease TH precision.
  - A CPU time of 20s is reached to a full external fluxes recalculation.

**Model Adaptation**

- **Adaptation of GMM**
  - If the model comes from other tools such as ESATAN TMS or SYSTEMA, models are converted thanks to STEP-TAS.
  - From the model provided at CDR or PSR, a GMM reduction should be performed to avoid previous issue (up to 1200 faces).

- **Adaptation of TMM**
  - If the model comes from other tools such as ESATAN TMS or SYSTEMA, models are converted thanks to TMRT.
  - A simplified tubing model and a simplified recurrent part of the geometry will be inserted.
  - If needed (up to 6000 nodes) the TMM should be reduced thanks to TMRT.
  - Missing TH (thermistances) should be added.
e-Therm improvements
- The SCSIM-TCS, part of the SCSIM spacecraft simulator DSSS inherits of all e-Therm improvements (CORE) requiring a small cost of maintenance for DSSS.
- The DSSS global development costs have been reduced, and in particular the thermal simulator cost is reduced to the CDR/PSR model adaptation, the software itself is not impacted too much.

Models improvements
- New features to facilitate the GMM reduction are in process. e-Therm radiative session will provide a feature customised to the GMM reduction need for DSSS purpose.

Experimental
- Experimental solutions for automated GMM reduction based on the GMM but also TMM topology are studied at DOREA.
Appendix R

Correlation of two thermal models

Marije Bakker       Roel van Benthem
(NLR, The Netherlands)
Abstract

Reduced thermal models are often required in the design phase of projects. Reduced models have the advantage that they provide a reasonable level of accuracy while maintaining short calculation times. It is common to first build a detailed model, which is then reduced in the same software package. Grouping of nodes and thermal properties requires a lot of physical insight and can be a tedious job. This presentation will offer a different approach with the same advantages, but without the tedious node grouping in the reduction step. An analytical model for the thermal analysis of wiring is correlated with a more accurate numerical model. By this correlation, the level of accuracy of the analytical model is increased, while maintaining short calculation times. The model has been developed for aircraft applications, but can be used for aerospace applications as well. After a short introduction in the model and its applications, the presentation will mainly focus on the different steps in the correlation process.
Correlation of two thermal models

Marije Bakker, marije.bakker@nir.nl
Roel van Benthem, roel.van.benthem@nir.nl

Outline of the presentation

- Common way of model reduction
- Description of the models
- Correlation of the two models
- Using RMS as measure
- Fine-tuning of correlation using test results
- Conclusions and recommendations
Common way of model reduction

• Select approach, e.g. nodal model
• Build detailed model in ESATAN
  o If detailed FEM model is available, FEM model can be converted to ESATAN model
  o Depending on application the number of nodes can vary from a couple of dozens to over 1,000 nodes
  o For each node, the thermal properties have to be added
• Group nodes
  o Limited number of nodes allowed
  o Select nodes with similar properties and group them (TEDIOUS!)
  o Combine the thermal properties of all nodes in a group

Objective:
Use as much of the information from the detailed model as possible in the reduced model without increasing the calculation time of the reduced model

Reduced model is often used integrated in a larger model

Advantages reduced model:
• Fast results
• Decent level of accuracy despite limited level of detail

These advantages can also be obtained by correlation of two models
• Model 1: analytical model ('reduced' model)
• Model 2: numerical model ('detailed' model)
Description of the models

Application:
Thermal analysis of wiring bundle designs (of aircraft, but the model can also be used for (aero)space applications)

Objective:
Investigate weight reductions and improved safety

TDM – ‘reduced’ model
- Low level of detail
- Java model using a matrix solver (steady state)
- Network model
- Heat transfer calculated using analytical functions
- Typical calculation time per case: ~ 1 sec.

OOFELIE::Multiphysics numerical model (Open Engineering)
- High level of detail
- Fine grid
- 3D model
- Complex, detailed calculations for heat transfer
- Typical calculation time per case: ~ 1 hour
Correlation of the two models

Objective:
With the same inputs the models give the same outputs

INPUT

TDM

Output reduction
(to make results comparable)
Correlation of the two models

**Assumption:**
For the same set of inputs both models give the same output if each coupling $C$ (conductive, radiative and convective) from $i$ to $j$ is the same $\forall i, j$

**Approach:**
Find function $f(x)$ such that $f(x) \cdot C_{ij,TDM} = C_{ij,TNM}$

**Conditions:**
- Function $f(x)$ is different for conductive, radiative and convective couplings and for different combinations of $i$ and $j$
- Only one dependency is allowed in the function $f(x)$, i.e., $x$ can be e.g. pressure or power

**Question:** How can $C_{ij,TDM}$ and $C_{ij,TNM}$ be found?

**Answer:**
Sensitivity analysis

\[
P = C_{ij} \cdot (T_i - T_j) + C_{ik} \cdot (T_i - T_k)
\]

\[
T = \frac{1}{C_{ij} + C_{ik}} P_j + \frac{C_{ik}}{C_{ij} + C_{ik}} T_j + \frac{C_{ij}}{C_{ij} + C_{ik}} T_k
\]

\[
C_{ij} = \frac{C_{ik} + C_{jk}}{1}
\]

\[
\frac{\partial T_i}{\partial T_j} \approx \frac{T_i(T_j = T_j + \Delta T) - T_i(T_j = T_j)}{\Delta T}
\]

**Example:** 3 nodes, only conduction

**Diagram:**

- Node $i$ connected to nodes $j$ and $k$ with conductances $C_{ij}$ and $C_{ik}$, and pressures $P_j$ and $P_k$.
Correlation of the two models

Use the sensitivity to find all $C_{ij, TDM}$ and $C_{ij, TNM}$.

Assess what $x$ in $f(x)$ could be:

<table>
<thead>
<tr>
<th>Specific to this model:</th>
<th>Power [W]</th>
<th>Pressure [bar]</th>
<th>$T_1$ [°C]</th>
<th>$T_2$ [°C]</th>
<th>$T_3$ [°C]</th>
<th>$T_4$ [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(convective)</td>
<td>y</td>
<td>y</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
</tr>
<tr>
<td>(convective)</td>
<td>y</td>
<td>y</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
</tr>
<tr>
<td>(convective)</td>
<td>y</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
</tr>
<tr>
<td>(convective)</td>
<td>y</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
</tr>
<tr>
<td>(convective)</td>
<td>y</td>
<td>n</td>
<td>y</td>
<td>n</td>
<td>n</td>
<td>n</td>
</tr>
<tr>
<td>(radiative)</td>
<td>y</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>y</td>
<td>n</td>
</tr>
</tbody>
</table>

Correlation of the two models

To find the function $f(x)$ such that $f(x) \cdot C_{ij, TDM} = C_{ij, TNM}$ a comparison of the couplings is needed.
Correlation of the two models

If \( f(x) \cdot C_{ij,TDM} = C_{ij,TNM} \), then \( f(x) = \frac{C_{ij,TNM}}{C_{ij,TDM}} \)

Using RMS as a measure

- Implement all correlation functions (one for each coupling) in the TDM
- The root mean square can be used as a measure for how much the TDM has improved:

\[
RMS = \sqrt{\frac{\sum_{i=1}^{N}(T_{ij,TDM} - T_{ij,TNM})^2}{N}}
\]

- Calculate RMS using the complete subset of cases
- Result:

<table>
<thead>
<tr>
<th>Correlation step</th>
<th>RMS value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncorrelated TDM</td>
<td>10.51</td>
</tr>
<tr>
<td>Correlated TDM</td>
<td>16.38</td>
</tr>
<tr>
<td>Fine-tuned, correlated TDM</td>
<td>7.69</td>
</tr>
</tbody>
</table>
**Objective:**

Find factors $g$ such that changing the couplings to $g f(x) C_{ij \text{TDM}}$ gives improved correspondence between the TDM results and the test results for all cases.
Fine-tuning of correlation using test results

Measure to determine improvement of correlation:
Correlation Number

\[ RMS = \sqrt{\frac{\sum_{i=1}^{N} (T_{TDM,i} - T_{test,i})^2}{N}} \]

Results:

<table>
<thead>
<tr>
<th>Fine-tuning step</th>
<th>CN value</th>
<th>Fine-tuning improvements</th>
</tr>
</thead>
<tbody>
<tr>
<td>At start (after finishing TNM correlation)</td>
<td>13.67</td>
<td>*Fine-tuning inputs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*Slightly scale some correlation functions</td>
</tr>
<tr>
<td>After ~50 iterations</td>
<td>5.89</td>
<td>*Apply some additional minor changes</td>
</tr>
</tbody>
</table>
Conclusions

- Correlation of two models could be an alternative approach for model reduction, while tedious grouping and reducing step can be avoided.
- Sensitivity analyses are used to estimate heat transfer couplings.
- The number of investigated correlation functions has been reduced by a priori assessment of physical dependencies.
- Use of the sensitivity analysis leads to optimal correlation functions between the models. However, manual fine-tuning is still required.
- Correlated TDM gives results that are much better (±10°C) in line with the test results than previous TDM (±15°C).

Recommendations

- More research is required to generalize the methodology used.
- Automation of sensitivity analysis and calculation of correlation functions could be a valuable tool for model comparison without a priori physical understanding of the system.
Appendix S

Experience of Co-simulation for Space Thermal Analysis

François Brunetti
(DOREA, France)
Abstract

Thermal models for space analysis are more and more complex and the idea of having one homogenous model covering different physics such as heat transfer, fluid-dynamics, thermo-dynamics and thermo-elastic is difficult to support. One solution is to open the code to others tools dedicated to bring a complementary physics. The co-simulation is a good candidate to solve the exchange of heterogeneous calculation results but many different techniques and options should be considered at software design level. According to the performances and architecture of the simulators, a co-simulation can be generic or hybrid and impact of the choice of this option may be very expensive. Depending on the physics context, the developer should determine which code would be the master or slave, depending of physics time constants involved in both codes. More depending on computer constraints, an important choice is to specify the communication protocol (such as shared memory or TCP-IP). Some standards such as FMI (Functional Mock Up Interface) are pointing and seem to be pretty candidates, but most of tools provide their own interfaces.

In this presentation we would discuss about DOREA experience and chosen strategy while mixing both CAE simulators : e-Therm (thermal analysis software) bringing the satellite system nodal model and LMS Siemens AMESim (CFD), especially the dedicated AMERun module with the co-simulation option, to solve the fluids and thermo-dynamics (dysphasic fluxes of a fluid loop) for transient but also steady state calculations.
Objectives

- **What it is?**
  - Simulate a full system with mixed physics or mixed modeling techniques at subsystems level.

- **For what?**
  - Need to mix two heterogeneous subsystems for multiphysics purpose (Ex: nodal mathematical model with finite elements or finite volumes models).
  - Need to run two homogeneous subsystems in parallel.

- **Issues?**
  - Parallel simulations or embedded simulation (generic or hybrid)?
  - Different subsystems time constants.
  - Defining a master/slave to schedule meetings.
  - How to model and what type for the interface nodes?
  - Which communication protocol?
  - What about the steady state calculation?
  - What about initialisation?
**DOREA experience**

- **In the frame of a CNES project:**
  - For thermal analysis purpose, development of MPL dysphasic fluid loop simulation within the full spacecraft global system.
  - e-Therm (TAS thermal analysis software) should interface with Siemens LMS AMEsim (AMErun).
- **Actors:**
  - Thales Alenia Space implements the integration of MPL within the next generation of platforms.
  - Airbus Defence and Space improves its thermal analysis suite of tools: Systema (Thermisol).
  - DOREA develops the integration of MPL simulation within e-Therm.
- **State of the art:**
  - DOREA succeeded in connecting with LMS AMErun via generic co-simulation module, exchanging results between both tools by shared memory.

---

**Co-simulation architectures**

- **Generic co-simulation:**
  - deploys the both simulators (2 executables) in parallel, with a dedicated communication protocol on a given protocol layer.

  ![Generic co-simulation diagram](image)

  - Same machine, same architecture (32 or 64 bits)
  - Different machines, different architectures

- **Hybrid co-simulation:**
  - links the both simulations into one executable. Simulators exchanges thanks to an API (Application Programming Interface).

  ![Hybrid co-simulation diagram](image)

  - Same machine, same compilers, same architecture
Co-simulation architectures

<table>
<thead>
<tr>
<th></th>
<th>Generic</th>
<th>Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td>• CPU simulation times are done in parallel by several cores (faster).</td>
<td>• Only 1 executable to deploy.</td>
</tr>
<tr>
<td></td>
<td>• Both tools are safe to connect or reconnect without interferences.</td>
<td></td>
</tr>
<tr>
<td><strong>Drawbacks</strong></td>
<td>• TCP-IP may be unsafe and may increase simulation elapsed times</td>
<td>• Compilers, OS and architecture should be the same for both tools.</td>
</tr>
</tbody>
</table>

Dynamics of communication

- **Sequential approach:**
  - Simulator 1 is waiting results of Simulator 2 before calculating owns.

- **Parallel approach:**
  - Simulator 1 performs calculation with Simulator 2 previous time step results.
Master or Slave?

To share works, we need to define who is giving orders. Recall of the co-simulation protocol:

- **The master:**
  - « Take my inputs, perform your calculation, we will meet at this time. »

- **The slave:**
  - « I finished my calculation. It is time to meet. Take my outputs. »

Who should be the master:

- If one of the both simulators drives the full system, it is clear that this one should be the master.
- If one of the both systems has a biggest time constant, this one should be the master.
- If all subsystems are identical, it does not care who is master.

Nodes « interface »

To connect the physics with a nodal model (here thermal analysis mathematical model), we need to define nodes as « interfaces ».

- These nodes are shared by the both models.
- For the subsystem that is not « nodal », it is considered as a constant characteristic of the model (here temperature or exchanged power).
- If both subsystems are nodal models, we can consider conductive or radiative couplings to this node.
- For the subsystem that is « nodal », we need to define if the node is boundary or diffusive.

In our example (thermal analysis for space):

- The « interface » nodes are considered as an input characteristics at AMEsim level and diffusive into e-Therm.
- The temperature is given by e-Therm and the exchange power is returned by AMEsim.
- In our case (heat transfer), the exchange power of interface nodes are considered as internal powers within the equation.
Protocols and Layers

- Generic co-simulation protocol layers
  - The both executables may communicate thanks to shared memory. They should run on the same cluster node.
  - The both executables may also communicate via TCP-IP. Don't care about machines OS, memory or architecture (64 or 32 bits).

  Note: It is obvious that if the meeting time span is short (around the second), TCP-IP is not recommended because of network instabilities.

- Hybrid co-simulation protocols
  - No need of a dedicated protocol, the master calls routines from the API provided by the slave simulator. Warning: time CPU of simulation computation can be added (sequential).

- Existing protocols
  - The most common protocol is FMI (Functional Mock Up Interface), but native protocols (AMEsim, Simulink, ...) are also provided by developers.

Convergence (here with AMEsim)

- Transient State:
  - Based on the convergence of the slave simulation, results are taken into account for the calculation of the next time step.

- Steady State:
  - AMEsim does not provide a steady state calculation, a transient with a stop condition has to be considered.
Experience with AMEsim:

- Siemens LMS AMEsim has a co-simulation module, but more often used to co-simulate 2 AME models from AMEsim.
- Using a tierce application is not fully documented at AMEsim level.
- Challenge from DOREA is to make the global system simulator working in steady and transient state.
- For e-Therm / AMEsim co-simulation, a generic co-simulation has been selected because of time responses (time constant for the global system is about 1s)
- e-Therm has been selected as master because it handles all the system model.
- For time performances reasons, a SHM (shared memory) protocol layer has been chosen.
- Regarding to the simplicity of the AMEsim protocol (3 routines are needed), the AMEsim native protocol has been selected.
Appendix T

GENETIK+
Introducing genetic algorithm into thermal control development process

Guillaume Mas
(CNES, France)
Abstract

In 2014, GENETIK+, a tool that couples CNES genetic algorithm with SYSTEMA Software has been developed, showing great potential to help thermal engineers in their work. In 2015, new functionalities have been implemented to GENETIK+ to help analyzing physically the results of the optimization process such as visualization of the response surface and sensitivity analyses. Thanks to these updates, GENETIK+ has been used on real application cases to show the interest of using optimization algorithm in each steps of thermal control development process. From worst case analyses to in-flight model correlation, the results obtained with GENETIK+ open new possibilities for thermal engineers. The objectives of the presentation are to:

- Present GENETIK+ functionalities
- Show the potential of introducing optimization algorithms into thermal control development process
GENETIK+
INTRODUCING GENETIC ALGORITHM INTO THERMAL CONTROL DEVELOPMENT PROCESS

Guillaume MAS (CNES)
Marco SCARDINO (ISAE-SUPAERO Trainee)

03 – 04 November 2015

AGENDA
• CONTEXT OF THE STUDY
• GENETIK+ UPDATES OVERVIEW
• APPLICATION CASES
• PERSPECTIVES AND CONCLUSION
2014 creation of GENETIK+:

- GENETIK+ allows coupling between SYSTEMA and CNES algorithm GENETIK
- First tests on application cases show great possibilities
- 2014 work conclusions:
  - Full potential to investigate (model correlation, reduction, …)
  - Possibility to use GENETIK+ to explore the space of solution
  - Need post processing tool to understand optimisation process results
GENETIK+ — Introducing genetic algorithm into thermal control development process

AGENDA

- CONTEXT OF THE STUDY
- GENETIK+ UPDATES OVERVIEW
- APPLICATION CASES
- PERSPECTIVES AND CONCLUSION

GENETIK+ UPDATES OVERVIEW

2015 – Improvement of GENETIK+:

- Increase of GENETIK+ possibilities:
  - Integration of Multi-cases optimization ⇒ \( \text{Fitness}_{\text{TOT}} = \sum_{i=1}^{N} \alpha_i \text{Fitness}_i \)
    - model correlation on several cases (cold and hot configurations, …)
    - Research of optimum design for several orbital configurations
  - New user interface ⇒ User friendly
    - GENETIK+ can be used by non experts in optimisation process
  - Increase of source code robustness and validation ⇒ GENETIK+ able to be used in a real project context
2015 – Post processing Module – Library exploitation:

Visualization for understanding optimization solutions ➔ Physical analysis

- Scatter plots – preliminary results analysis

- Response surface Methodology – back to physics
  - 2 Interpolation Methods
    » Kriging
    » Radial Basis Function (RBF)
  - 2 Regression Methods
    » Multivariate Adaptive Regression Spline (MARS)
    » Ordinary Least Squares (OLS)
GENETIK+ UPDATES OVERVIEW

2015 – Post processing Module – Library exploitation:

- Sensitivity analyses on parameters
  - Integration of SOBOL Index method → Global sensitivity analysis on parameters
    - First order impact of each parameters on thermal model behaviour
    - Coupled impact of parameters on thermal model behaviour

- Parameters uncertainty analysis
  - Find the $\Delta T$ max. to cover all the parameters uncertainties
  - Link with parameters distribution law to determine $\Delta T$ for a given probability
**APPLICATION CASES**

**Optimisation algorithm - On which step of thermal control development?**

Thermal control development process – Simple overview

- **Worst case scenarios?**
- **TCS design**
- Model for thermal analysis
- **Level of uncertainties**

\[ \Delta T \]

- **Model correlation**
- **Model Reduction**

\[ T + \Delta T \]

---

**APPLICATION CASES**

**Optimisation algorithm – Worst cases definition of complex missions:**

**Universe observation mission**: Maximisation total flux absorbed by radiator

Drifting orbit, h=600 km, i=30°, two attitude laws:

- **B1** (two angles \( \alpha \) and \( \gamma \)) \[ \rightarrow \] \([\text{Day} - \alpha, R.A.A.N, \gamma] \]
- **GRB** (three angles \( \alpha, \beta \) and \( \gamma \)) \[ \rightarrow \] \([\alpha, \beta, \gamma, \text{Day}, R.A.A.N] \]

- **Model Reduction**

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3–4 November 2015
Optimisation algorithm - Worst cases definition of complex missions:

**Universe observation mission**: Maximisation total flux absorbed by radiator.

*Results*: B1/GRB opt. configuration = opt. configuration found 3 years ago.

*Sensitivity Analysis* is coherent with physics.

*Visualisation of response surface*

Low-Earth orbit observation mission: Minimisation Mass of TCS (thermal strap, spreader, radiator)

- Control in temperature placed on UNSTABLE thermal face
- Optimisation under constraints.
- Solution depends on thermal modelling.
- 1 days of computation → Abacus to lead discussion in project meeting
**APPLICATION CASES**

**Optimisation algorithm – Uncertainties calculation:**

- **Basic electronic equipment**: Find $\Delta T_{max}$ to cover all parameter uncertainties
- **Parameters**: coefficients of thermal contact and material properties. Introduction of uncertainties management vs. Probability.

**Focus on thermal model correlation process:**

- **Thermal control development process – Simple overview**
- **Model correlation**
- **Model Reduction**
APPLICATION CASES

THERME Experiment - Thermal Model Correlation on flight data:

- Characterise ageing of spatial coating
  - From maximal temperature reached in orbit, find $\alpha$ of coating $\rightarrow$ radiative equilibrium:
    $\phi_{\text{sol}}(\alpha, C_s, \beta) + \phi_{\text{alb}}(\alpha, C_s, C_a) + \phi_{\text{Earth}}(\varepsilon, C_t) - \phi_{\text{IR}}(\varepsilon, T) = 0$
  - On SDS-4, offset compared to previous in-flight data $\rightarrow$ Samples not isolated from spacecraft

- "Realistic" samples modelling
  - Thermal leaks: harness-samples (via simple contact and via adhesive tape), MLI-samples (adhesive tape), samples-temperature sensor and harness-SC panel.
  - $5$ contact coefficients as parameters.

- Correlation process:
  - First approach: Begin of Life (BOL) and End of Life (EOL).
    - BOL properties known / EOL properties unknown
  - Second approach: Begin of Life (BOL).

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<th>In Orbit (first value)</th>
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</tr>
<tr>
<td>SG122FD</td>
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<td>0,29</td>
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</table>

Solar absorptivity evolution

PSBN $0.16$  $0.3$
SG122FD $0.21$  $0.29$
APPLICATION CASES

THERME Experiment - Thermal Model Correlation on flight data:
- Sensor temperature evolution – comparison of the 2 approaches
  - BOL/EOL approach able to represent whole thermal model behaviour
  - BOL approach perfect representation in early mission phase

APPLICATION CASES

THERME Experiment - Thermal Model Correlation on flight data:
- Sensitivity Analysis – Improve THERME design?
  - Parameters play different roles on two samples, due to their different thermal conductivity.
    - PSBN (conductive substrate) most influential parameters: MLI-sample and sample-harness via tape
    - SG122 (Kapton substrate) most influential parameters: harness-wall and sample-harness

- New analytic formula for telemetry exploitation
  - Use of GENETIK+ to explore space of solution $\alpha = f(T_{wall}, \phi_{sol}, \phi_{Earth})$
  - Use of Post processing module to extract Response surface and its equation
APPLICATION CASES

Focus on thermal model reduction processes

Thermal control development process – Simple overview

Worst case scenarios? → TCS design → Model for thermal analysis → Level of uncertainties → ΔT

Model correlation

Thermal analysis → T + ΔT

Model Reduction

Thermal model reduction – Electronic equipment example:

- Classical electronic unit:
  - Composed by: Printed Circuit Board, internal structure, external structure and harnesses
  - Two sinks: 2 conductive sink (panel and external harness) and radiative sink

≈ 500 Thermal nodes
APPLICATION CASES

Thermal model reduction – Electronic equipment example:

- 3 working modes: ON, OFF and Stand-by.

- 2 configurations: both conductive sinks have the same temperature

<table>
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<tr>
<th>Case</th>
<th>T conductive (°)</th>
<th>T radiative (°)</th>
<th>Mode</th>
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<tbody>
<tr>
<td>Hot</td>
<td>50</td>
<td>50</td>
<td>ON</td>
</tr>
<tr>
<td>Cold</td>
<td>-10</td>
<td>0</td>
<td>OFF</td>
</tr>
</tbody>
</table>

Mode | PCB1 (W) | PCB2 (W) |
---|----------|----------|
ON  | 10,25    | 5        |
OFF | 0        | 0        |
Stand-by | 0 | 5        |

Δ\(T\) – Hot case: \(\Delta T_{max} = 3,63°\)
Cold case: \(\Delta T_{max} = 0,59°\)

**Conclusions:**
- Optimisation with high number of variables
- GENETIK+ allows to reduce thermal model (calculation time 24h)
Thermal model reduction – Electronic equipment example:

- Two reduction methods:
  2. Analytical reduction: Find an analytical formula of thermal model temperature

Steps of the analytical reduction method:
- Select TRPs (nodal description of reduced model)
- Build Response Surface with OLS in Steady-State, using GENETIK+ data points
- Find transient response

Application case – Electronic equipment:
- Steady-State Results: 3 TRPs, OLS second degree
- Transient Response:
  Hyp: Evolution on time as linear first-order system, system MISO (Multi Inputs – Single Output)

\[ TRP(t) = \sum_i TRP(t-1)_i + (TRP(\infty)_i - TRP(t-1)_i) \cdot (1 - e^{-t/\tau_i}) \]

Results analysis:
- Transient Response: 2°/min T\_cond, 10°/min T\_rad and ON after convergence
**Conclusions:**
- The new GENETIK+ version:
  - Optimisation on all steps of TCS definition process.
  - High performance with high number of parameters.
- GENETIK+ Post PRO.
  - *Sensitivity Analysis* is physical coherent → Most influential and non influential parameters.
- Principal actor is still Thermal engineer.
- Time reduction for model correlation, model reduction,……

**Future works:**
- Parallel coding → reduce calculation time
- Near Real Time model correlation → Extend analytical reduction approach
- Optimisation MultiCriteria
Appendix U

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