Appendix H

Spatial Temperature Extrapolation Case Study
Gaia in-flight

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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

Spatial Extrapolation of Temperature. Case Study: Gaia In-Flight

Innovative Analysis Methods for Improved Thermal Testing (IAMITT)

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

IAMMIT - 26th European Space Thermal Analysis Workshop - Melanie Doolaeghe & Andre Capitaine (Astrium Satellites, France)

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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

Spatial Extrapolation of Temperature. Case Study: Gaia In-Flight

Spatial Extrapolation
Background

Thermal Network Model

☐ Non-instrumented thermal node

● Instrumented thermal node

▨ Extrapolated temperature (without invalid sensors)

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Background Slide

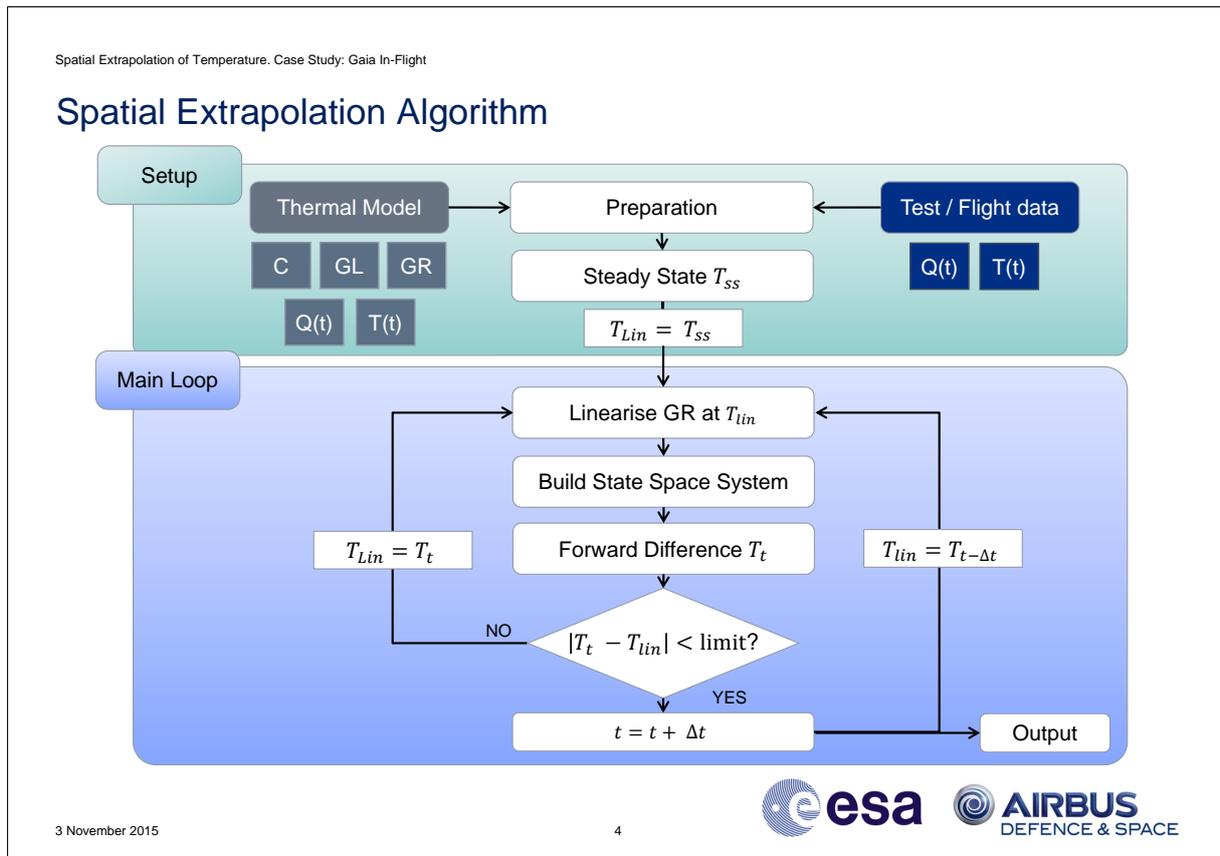Using the thermal network model with a sensor to node mapping we can extrapolate to find the remaining temperatures.

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 of Temperature. Case Study: Gaia In-Flight

Spatial Extrapolation Algorithm

Setup

| Thermal Model | $\rightarrow$ | Preparation | $\leftarrow$ | Test / Flight data |

| C | GL | GR | | Steady State T_{ss} | | Q(t) | T(t) |

| Q(t) | T(t) |

$$T_{Lin} = T_{ss}$$

Main Loop

Linearise GR at T_{lin}

Build State Space System

$T_{Lin} = T_t$ — Forward Difference T_t — $T_{lin} = T_{t-\Delta t}$

NO — $|T_t - T_{lin}| < \text{limit?}$

YES

$t = t + \Delta t$ — Output

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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.

Spatial Extrapolation of Temperature. Case Study: Gaia In-Flight

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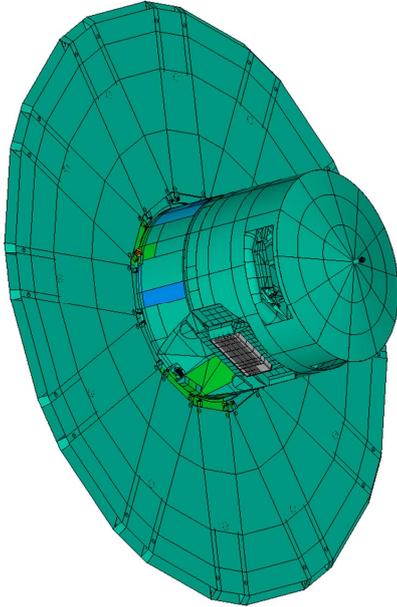
1. Define a use case for the spatial extrapolation
   Gaia – in-flight

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

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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

Spatial Extrapolation of Temperature. Case Study: Gaia In-Flight

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
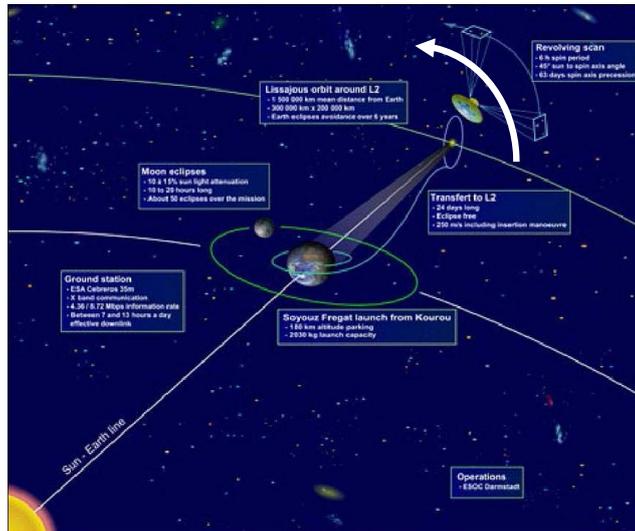Albedo and IR fluxes negligible

Solar constant at L2 :
1293 – 1388 W/m^2

Image Ref: ESA, https://directory.eoportal.org/web/eoportal/satellite-missions/g/gaia, accessed 15/10/2015

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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

Spatial Extrapolation of Temperature. Case Study: Gaia In-Flight

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

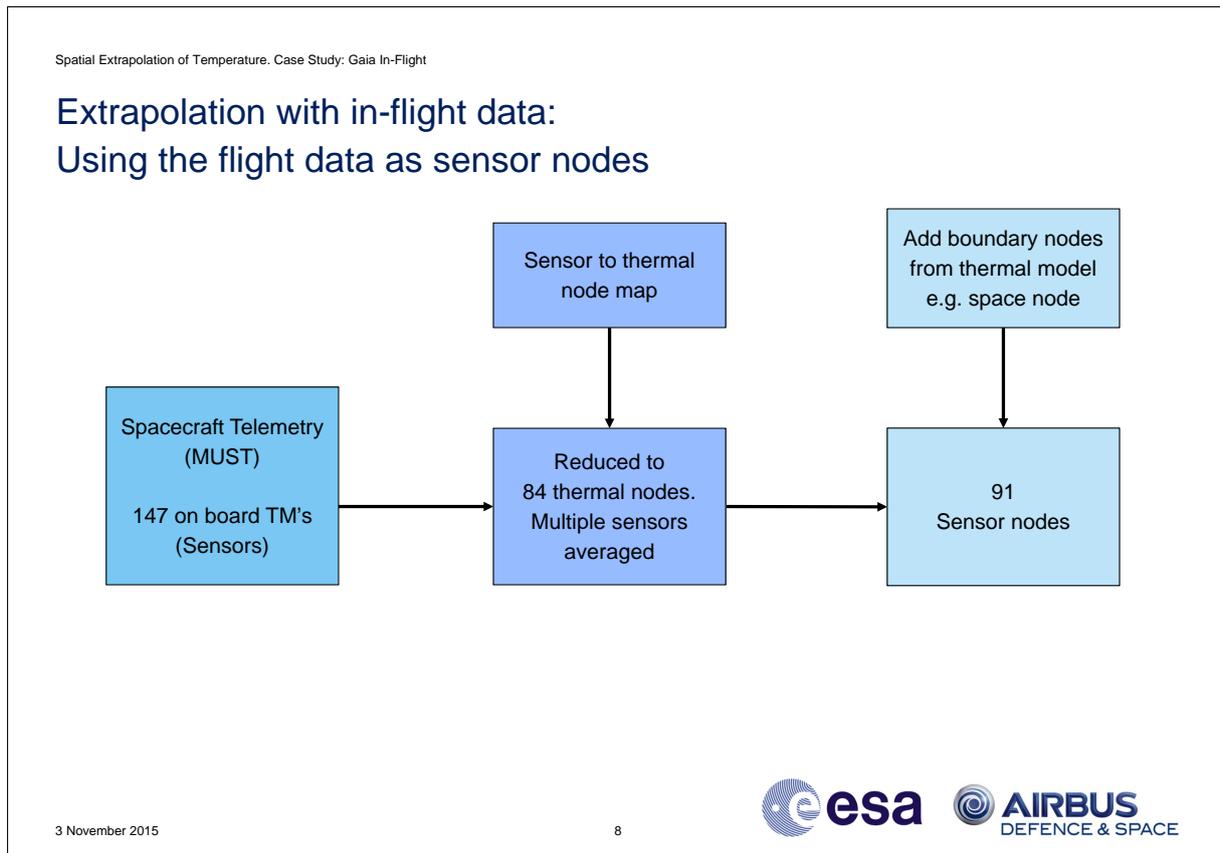5. Data to synchronise the thermal radiative environment

In-flight Temperature Data – 7 x 6 Hour Rotations

T [K]

Time [s]
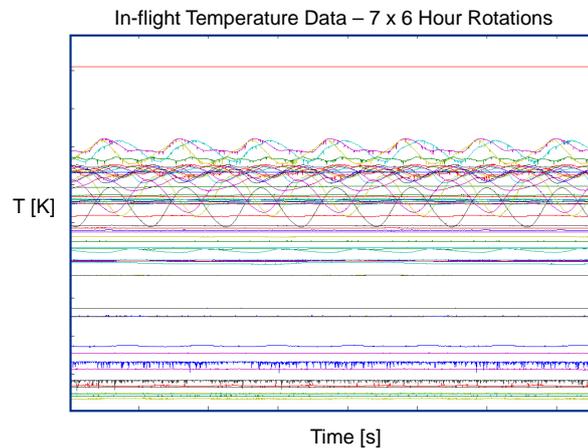
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Requirements

- 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

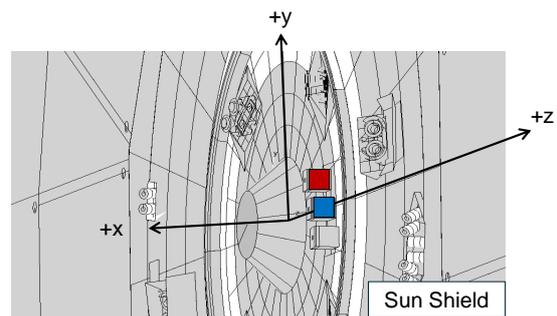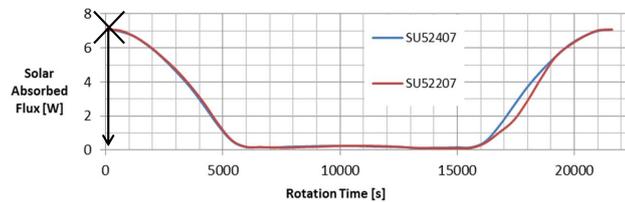How do we process the sensor data?

Spatial Extrapolation of Temperature. Case Study: Gaia In-Flight

Extrapolation with in-flight data:
Using the flight data as sensor nodes

| Sensor to thermal node map |

| Add boundary nodes from thermal model e.g. space node |

| Spacecraft Telemetry (MUST) 147 on board TM's (Sensors) | → | Reduced to 84 thermal nodes. Multiple sensors averaged | → | 91 Sensor nodes |

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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 syncronise the solar fluxes on the model

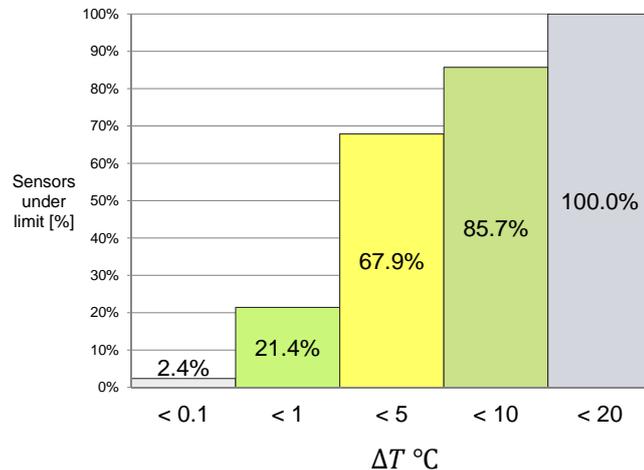*Synchronising the model and in-flight time*

- 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.

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:

Spatial Extrapolation of Temperature. Case Study: Gaia In-Flight

Extrapolation with in-flight data:
How close are we to the model predicted?

$$\Delta T \;=\; \left| T_{Extrap} - T_{Pred} \right|$$

- T_{Pred} = correlated TBTV model with updated dissipations

- 8100 diffusion nodes extrapolated

- 7 rotations averaged
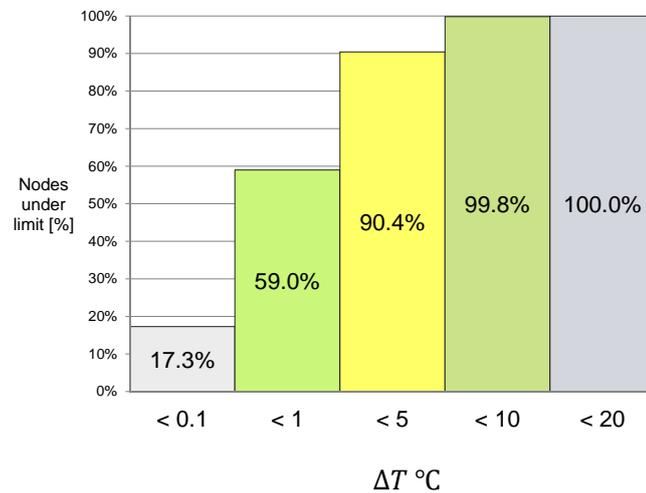
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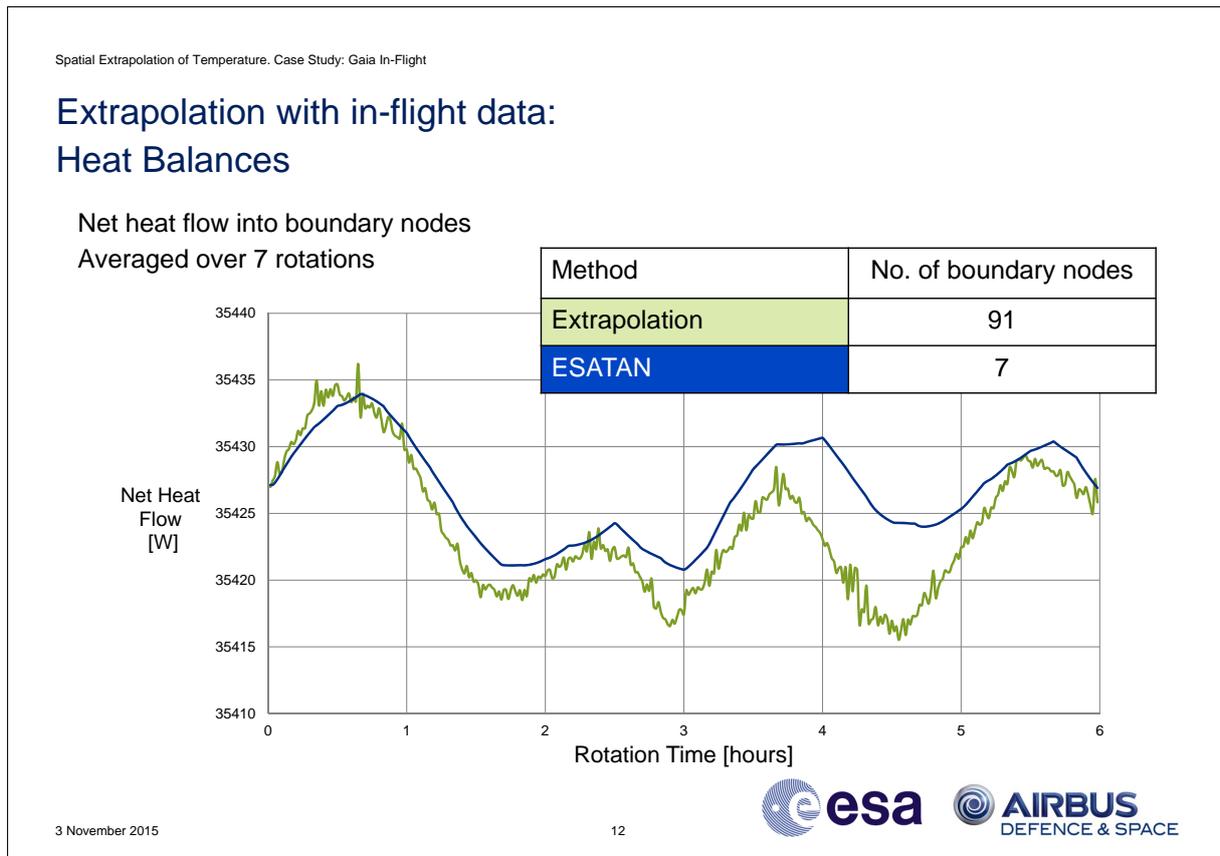
Comparison of extrapolated nodes

- 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.
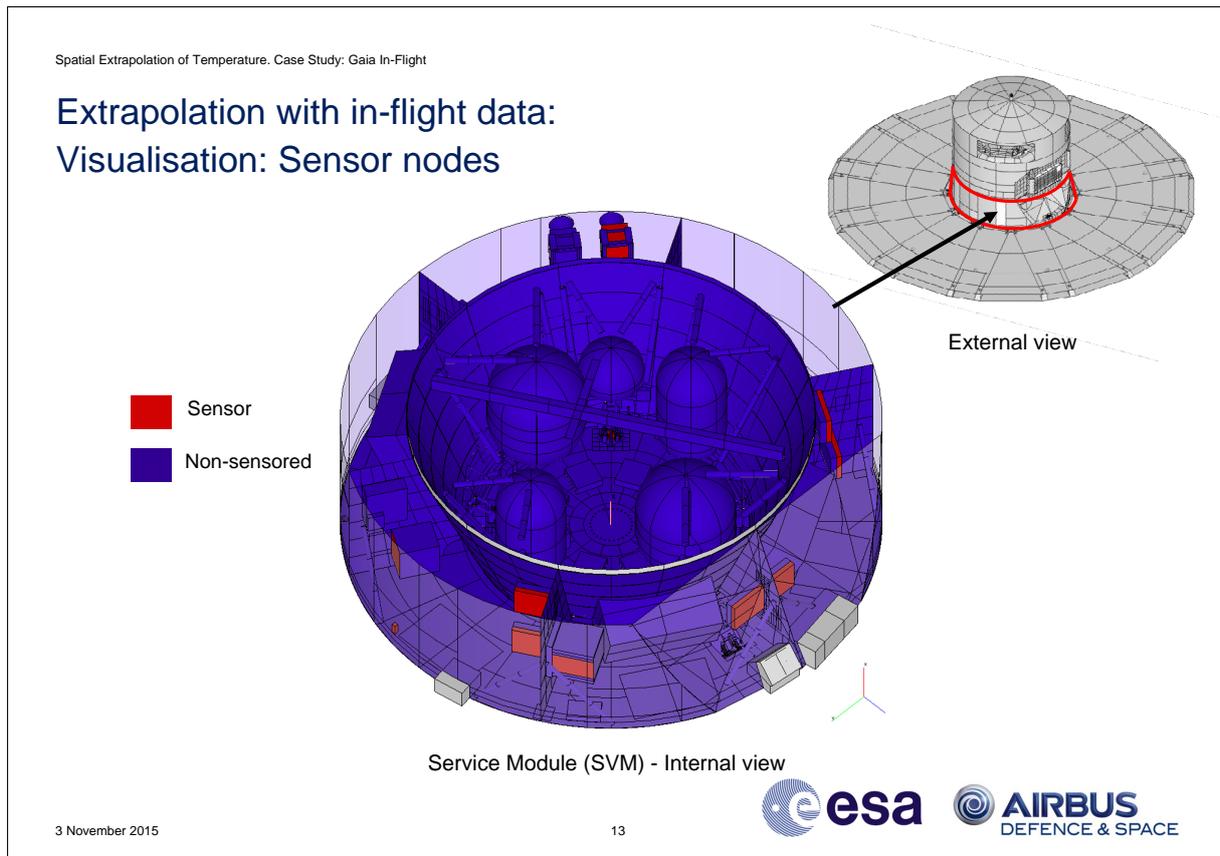
So what is the effect of adding many more boundary/sensor nodes to the thermal model?

Spatial Extrapolation of Temperature. Case Study: Gaia In-Flight

Extrapolation with in-flight data: Heat Balances

Net heat flow into boundary nodes
Averaged over 7 rotations

Method	No. of boundary nodes
Extrapolation	91
ESATAN	7

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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:

Spatial Extrapolation of Temperature. Case Study: Gaia In-Flight

Extrapolation with in-flight data:
Visualisation: Sensor nodes

External view

Sensor

Non-sensored

Service Module (SVM) - Internal view

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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
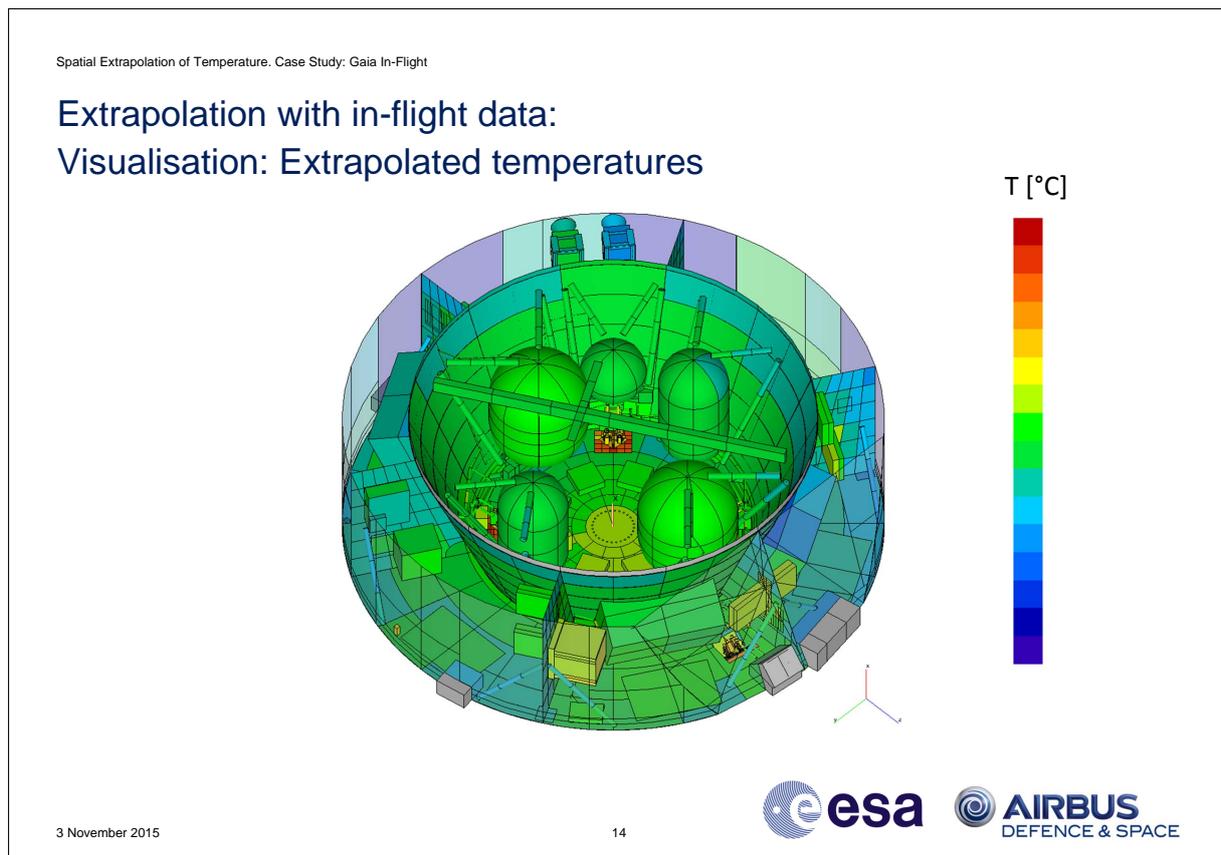
Visualisation - Extrapolated temperature

- 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

Spatial Extrapolation of Temperature. Case Study: Gaia In-Flight

Extrapolation with in-flight data:
Visualisation: Comparison with the prediction

$$\Delta T \ [°C] = T_{Extrap} - T_{Pred}$$
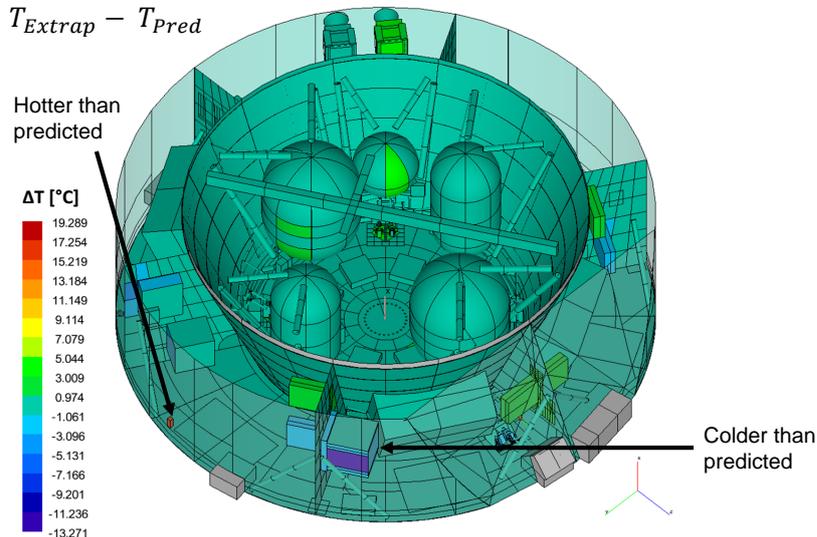
Visualisation - Differences

- 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.

Spatial Extrapolation of Temperature. Case Study: Gaia In-Flight

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

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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.