Appendix D

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

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Abstract

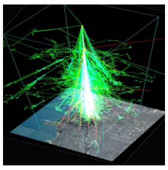
[1] The Meteosat series of spacecraft are meteorological satellites, providing a range of data that inform weather forecasts across Europe. First generation satellites have flown, second generation (MSG) are currently operational, and the third generation (or MTG) will provide data well into the 2030s. Two instruments going on the MTG satellites will be calibrated using the blackbody targets that are being designed at RAL Space.

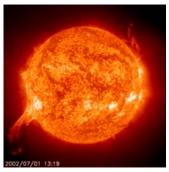
The blackbody targets are required to operate at temperatures between 100–370 K. The challenge involved in this includes providing single targets that can physically achieve and operate successfully at both thermal extremes, while also meeting stringent temperature gradient requirements. This presentation 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



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European Space Thermal Analysis Workshop
3-4th November 2015

Science & Technology Facilities Council

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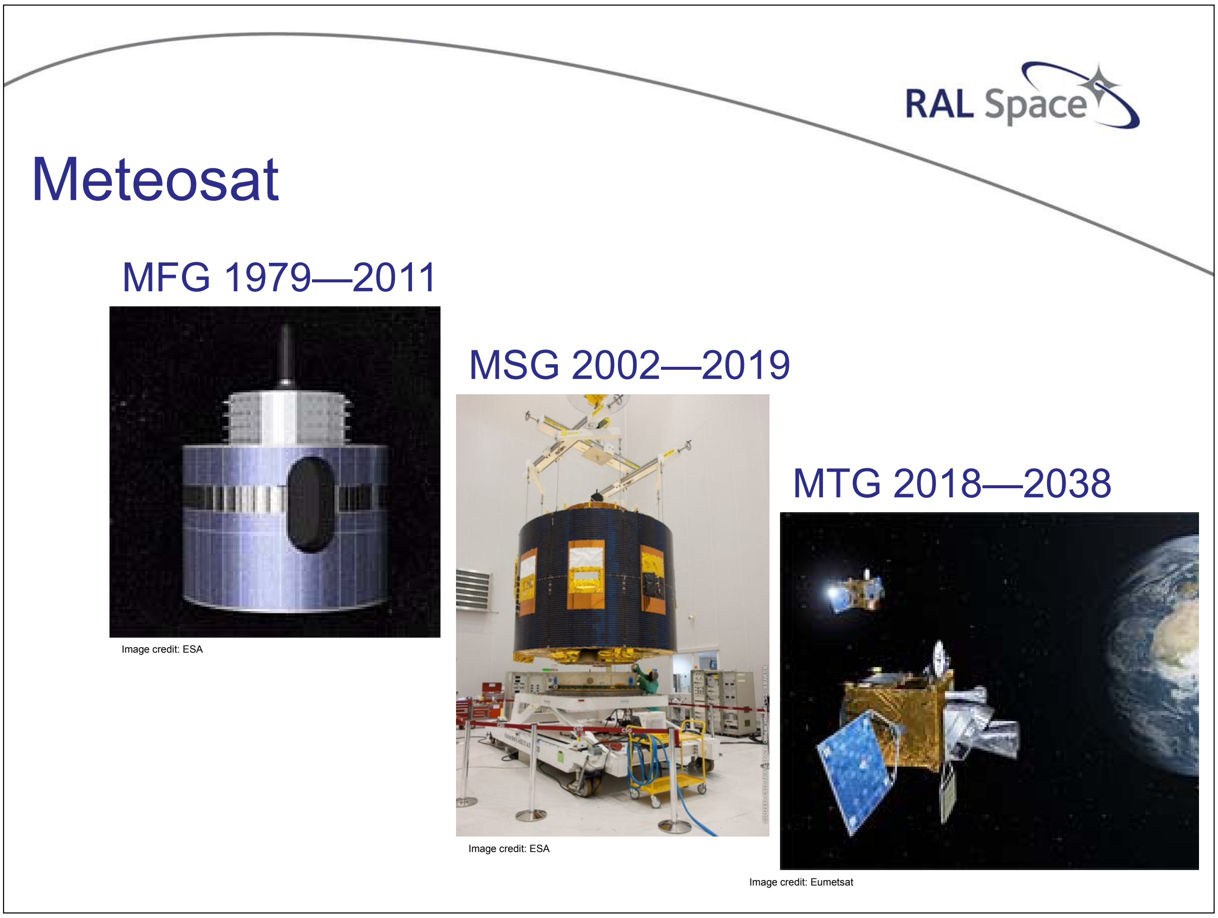
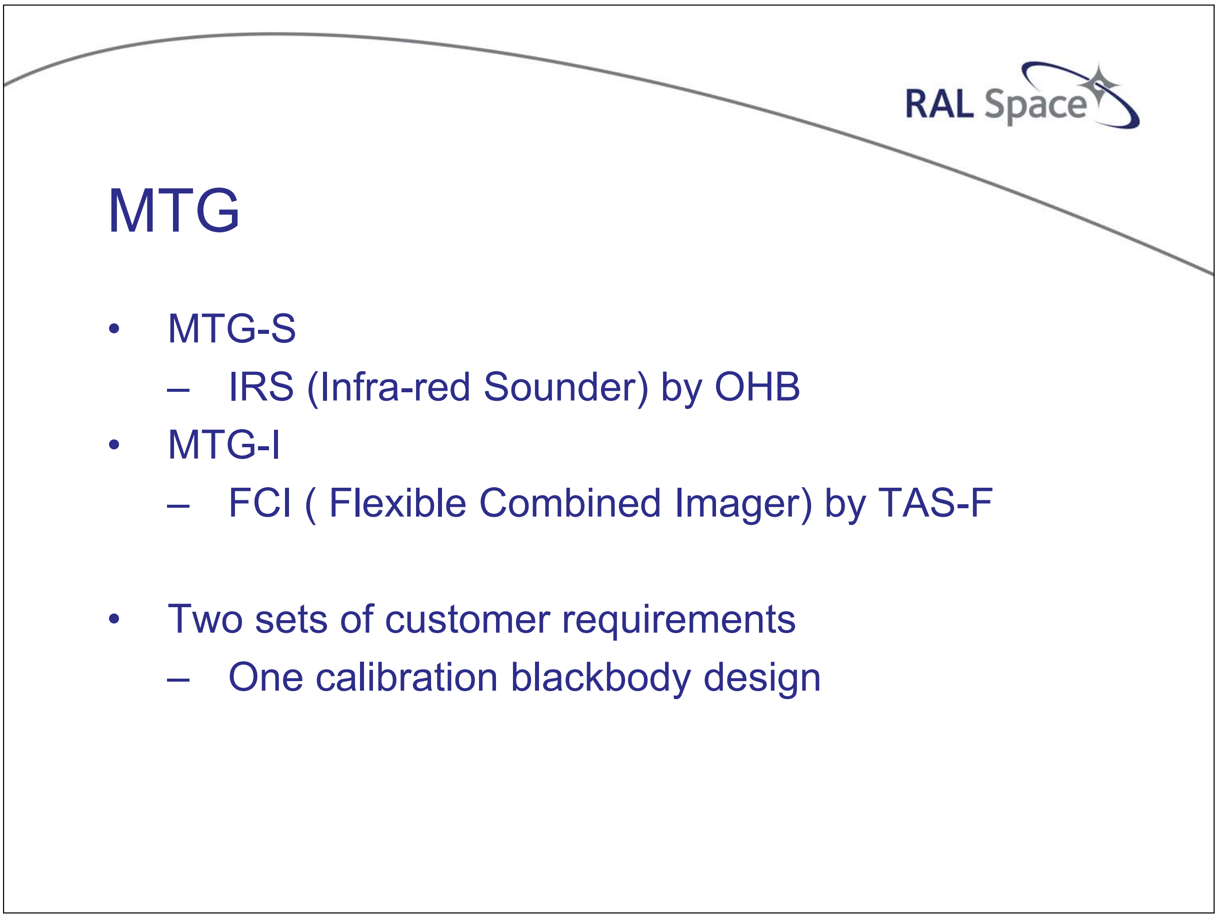
Outline

- Meteosat
- Blackbodies
- Thermal challenges and design overview
- Breadboard model

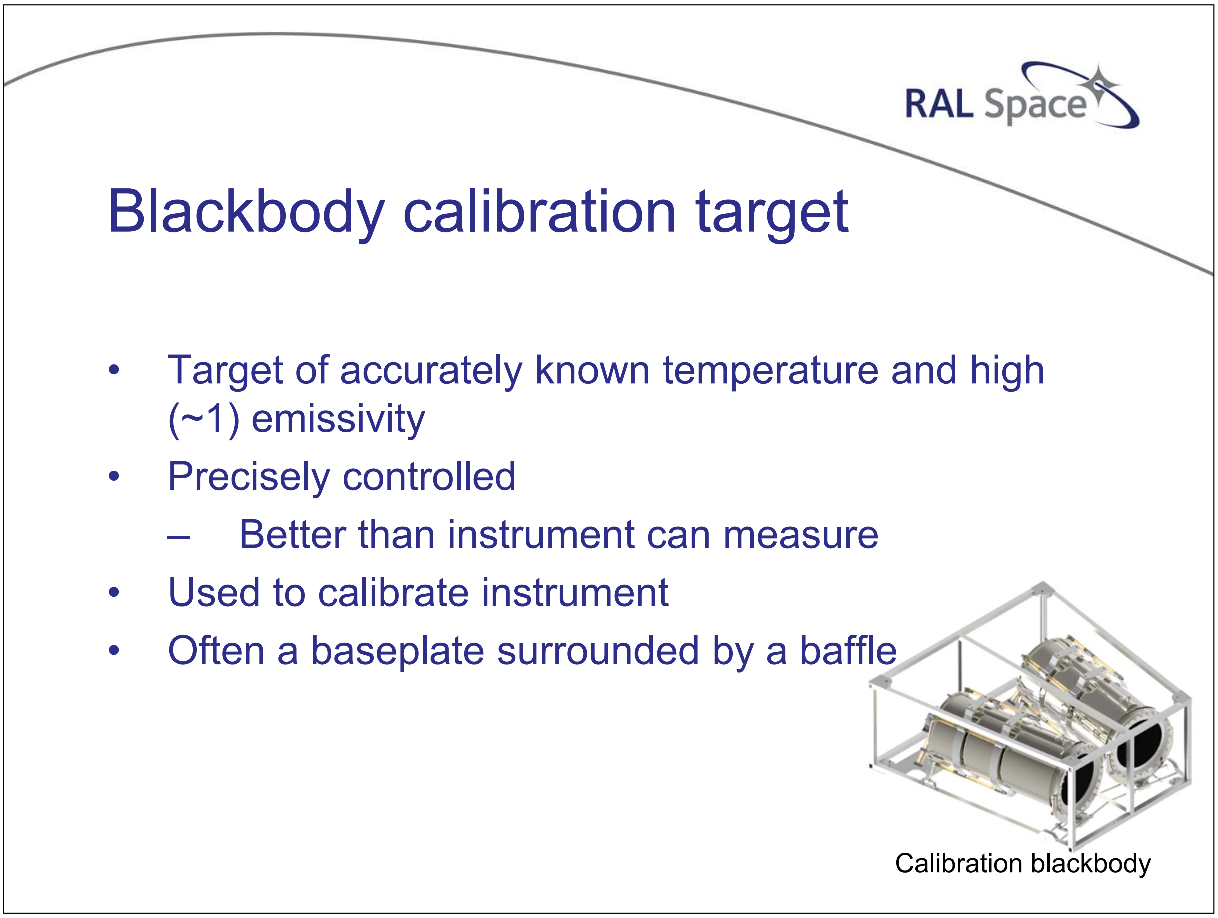


The Meteosat series of spacecraft are meteorological satellites, providing data that inform weather forecasts across Europe. The first generation satellites flew between 1979 and 2011, and the second generation is still operational – and expected to be until 2019.



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.



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.

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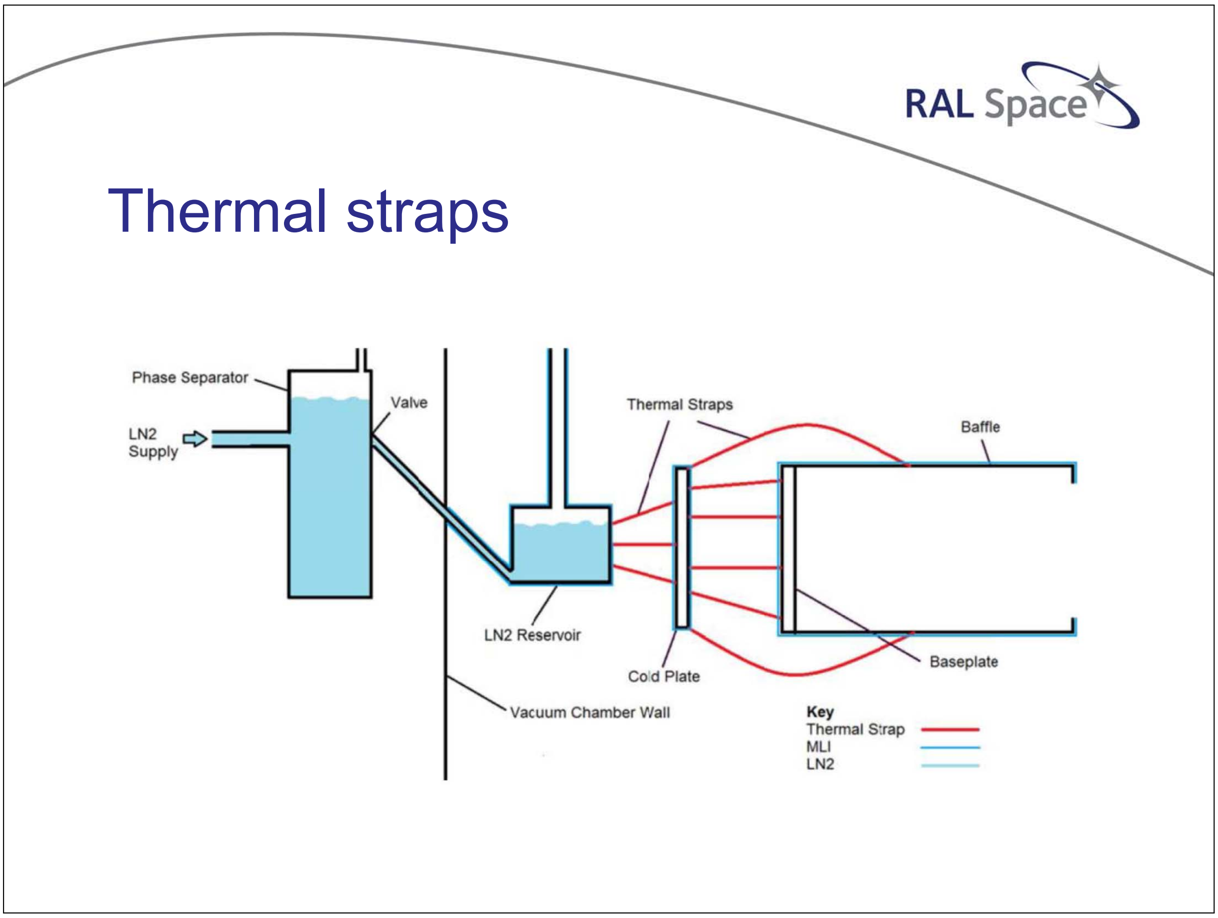
MTG blackbodies thermal challenges

- 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

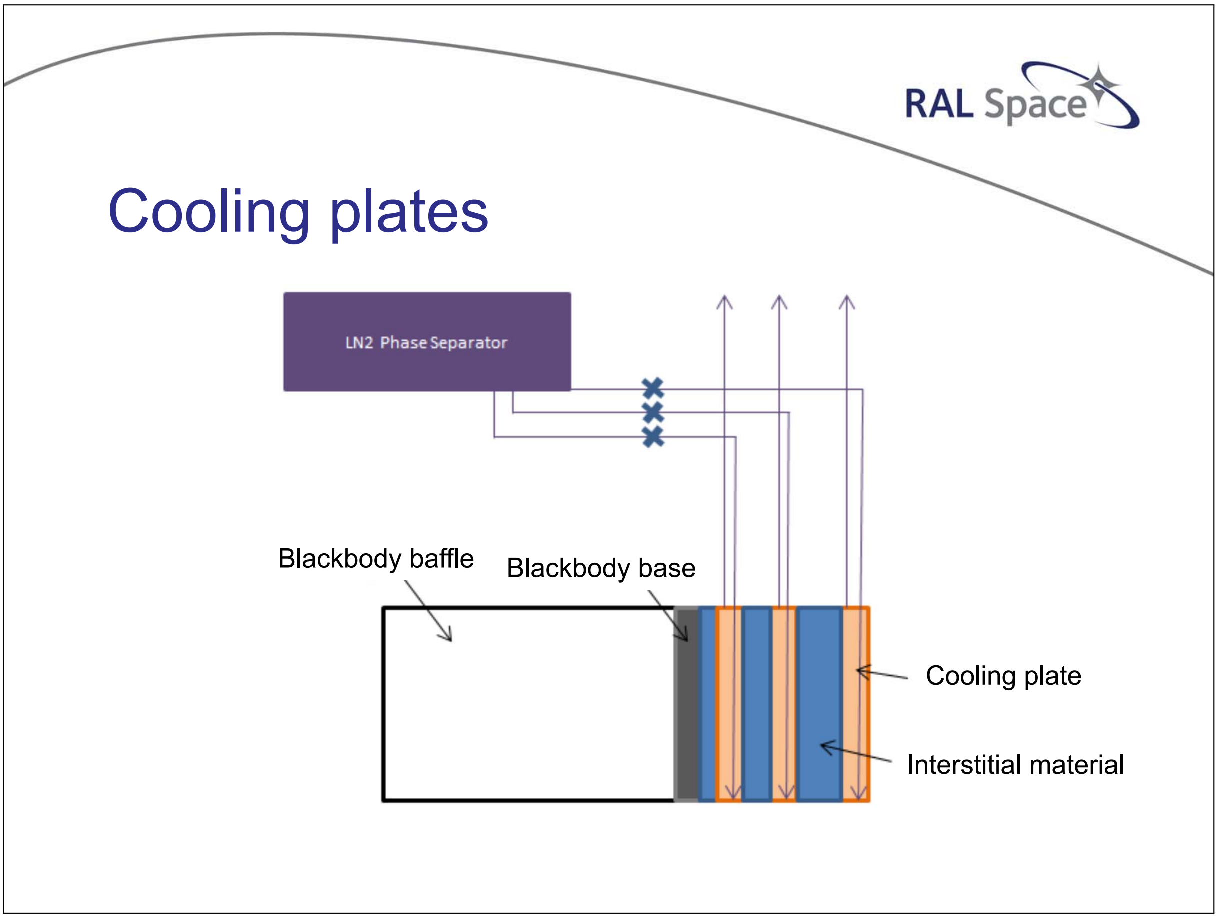
Taking both sets of customer requirements into account, the MTG blackbody design will need to: be able to operate between 100 – 370 K. Thus we need one design that can both physically achieve and operate successfully at this wide range of temperatures. The blackbodies also need to have a uniform temperature – 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.

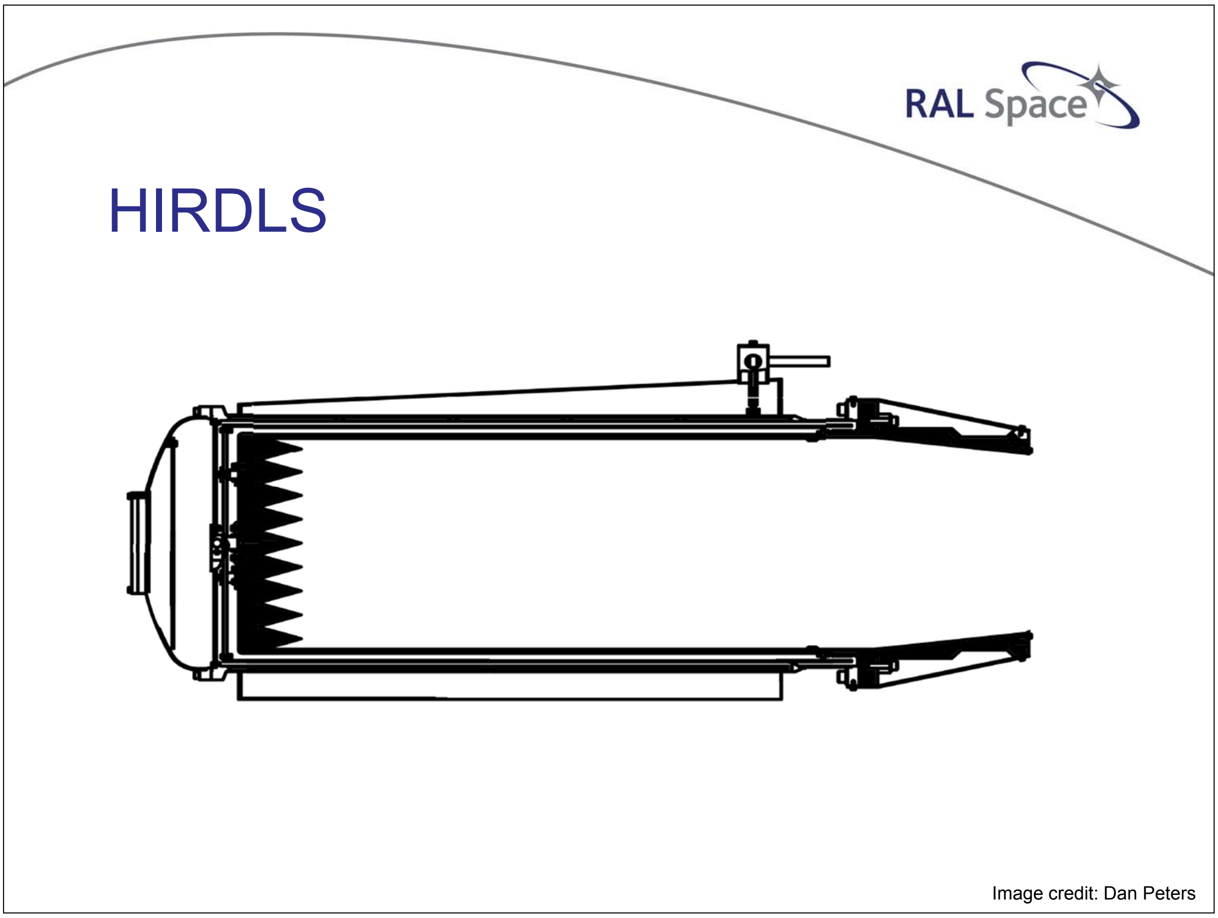
During the proposal stage it was identified that having a variable conductive link to the LN2 would allow us to save on heater power and nitrogen. So the next stage in the design was to investigate this.



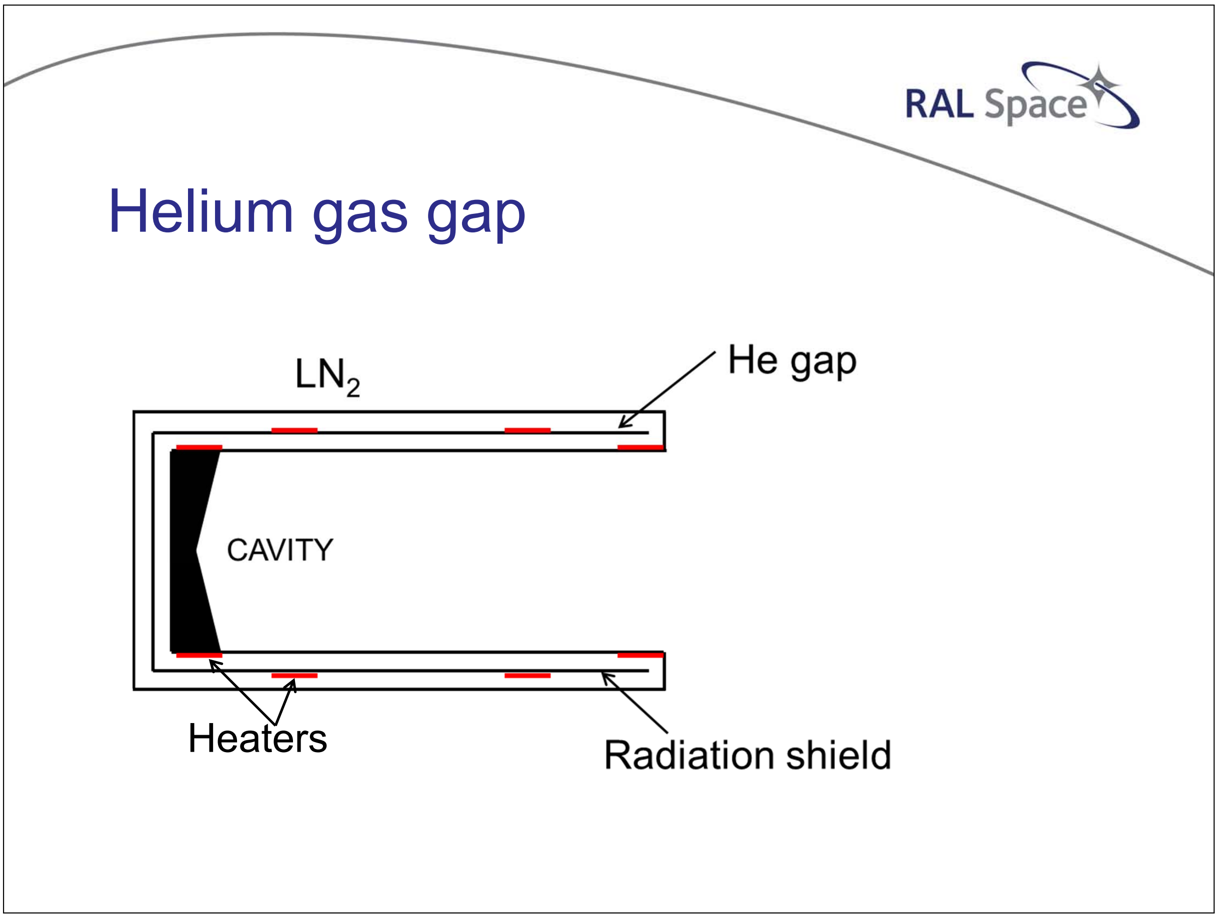
The idea progressed to having three cooling plates (instead of the one cold plate shown previously). The plates would have piping in which could be filled with LN2, and be at different distances from the back of the cavity. Controlling which plates were filled with nitrogen achieved different conductive 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

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Helium conductivity in a gas gap

Helium thermal conductivity in a helium gas gap

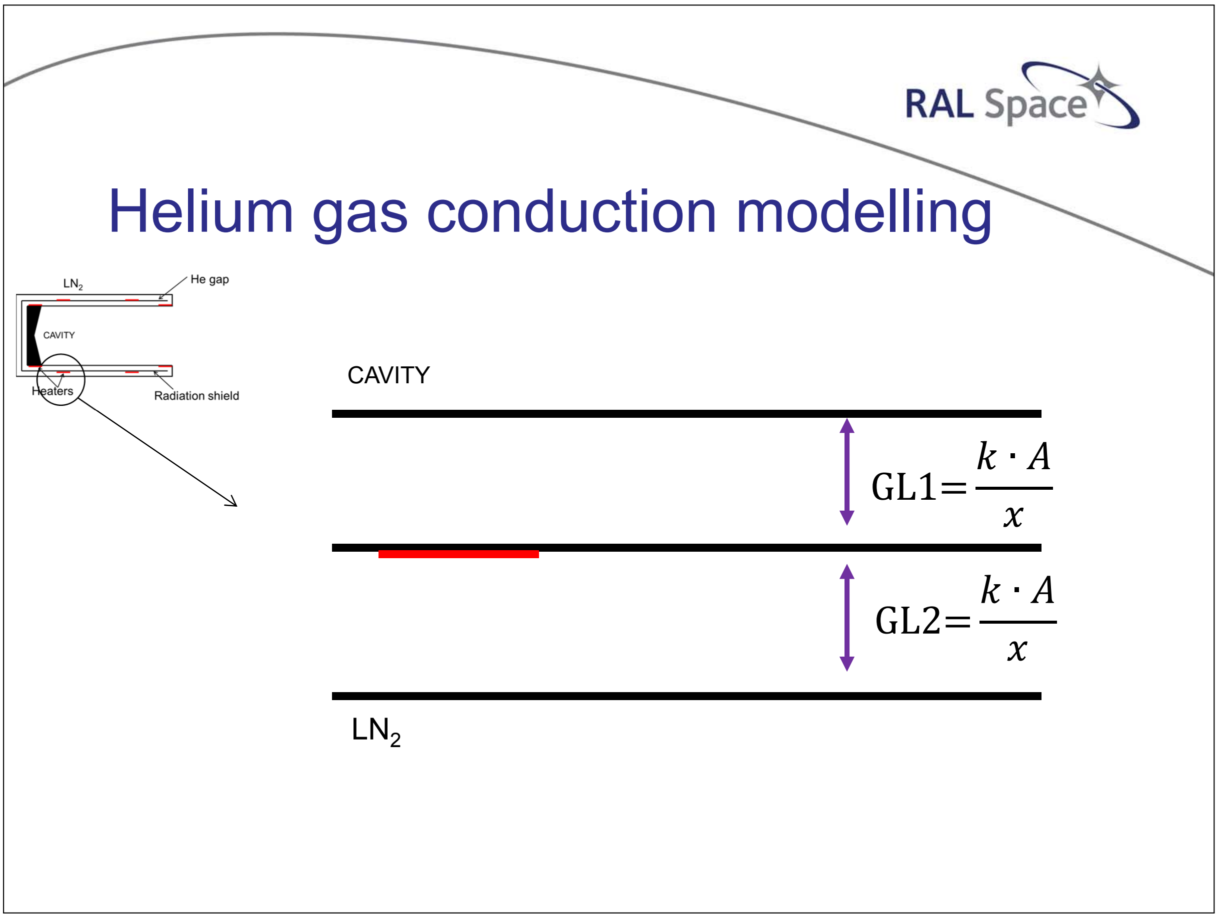
$$k(T) = k_{bulk}(T) \cdot \left(1 + \frac{8}{3} \cdot \frac{k_{bulk}(T) \cdot T}{e \cdot p \cdot \sqrt{3 \cdot R \cdot T}} \cdot \left(\frac{1}{\alpha_1} + \frac{1}{\alpha_2} - 1\right)\right)^{-1}$$

k_{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
α is the thermal accommodation factor

Equation from:
'Active-mirror-laser-amplifier thermal management with tuneable helium pressure at cryogenic temperatures', A. Lucianetti et al., Optics Express, Vol 19, Issue 13, pp. 12766 – 12780, 2011.

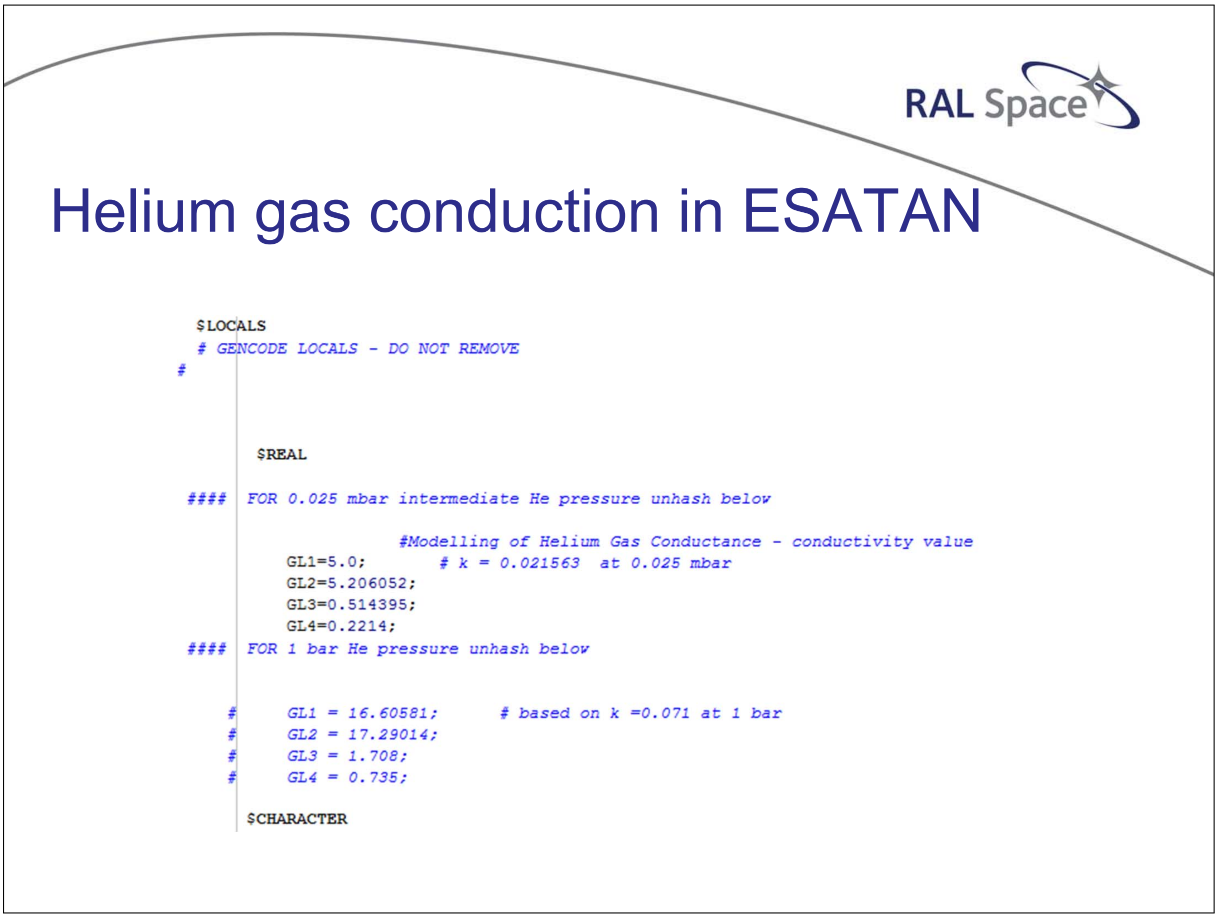
The thermal conductivity we get from gaseous helium in a gap depends not only on its pressure. The temperature of the helium gas itself is a big contributor. The size of the gap we're using also plays a role – the smaller the gas gap the better the thermal conductivity. We also need to take into account 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.

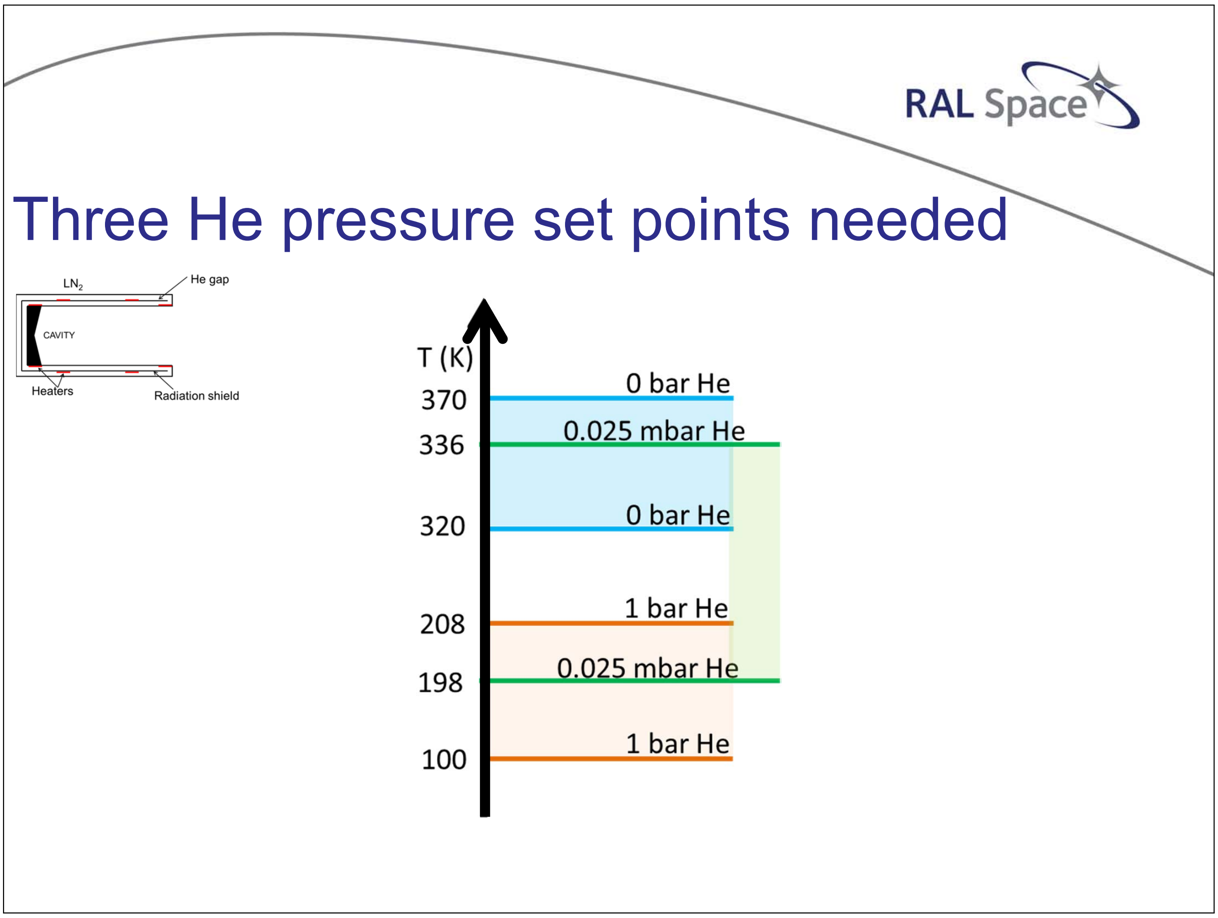


For the other conductive links in the thermal model, such as the bolted interfaces, I used the ESATAN Workbench to define a contact conductance. However, I did not define any geometry to be the helium, and so all the helium conduction modelling was done through the ESATAN file

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

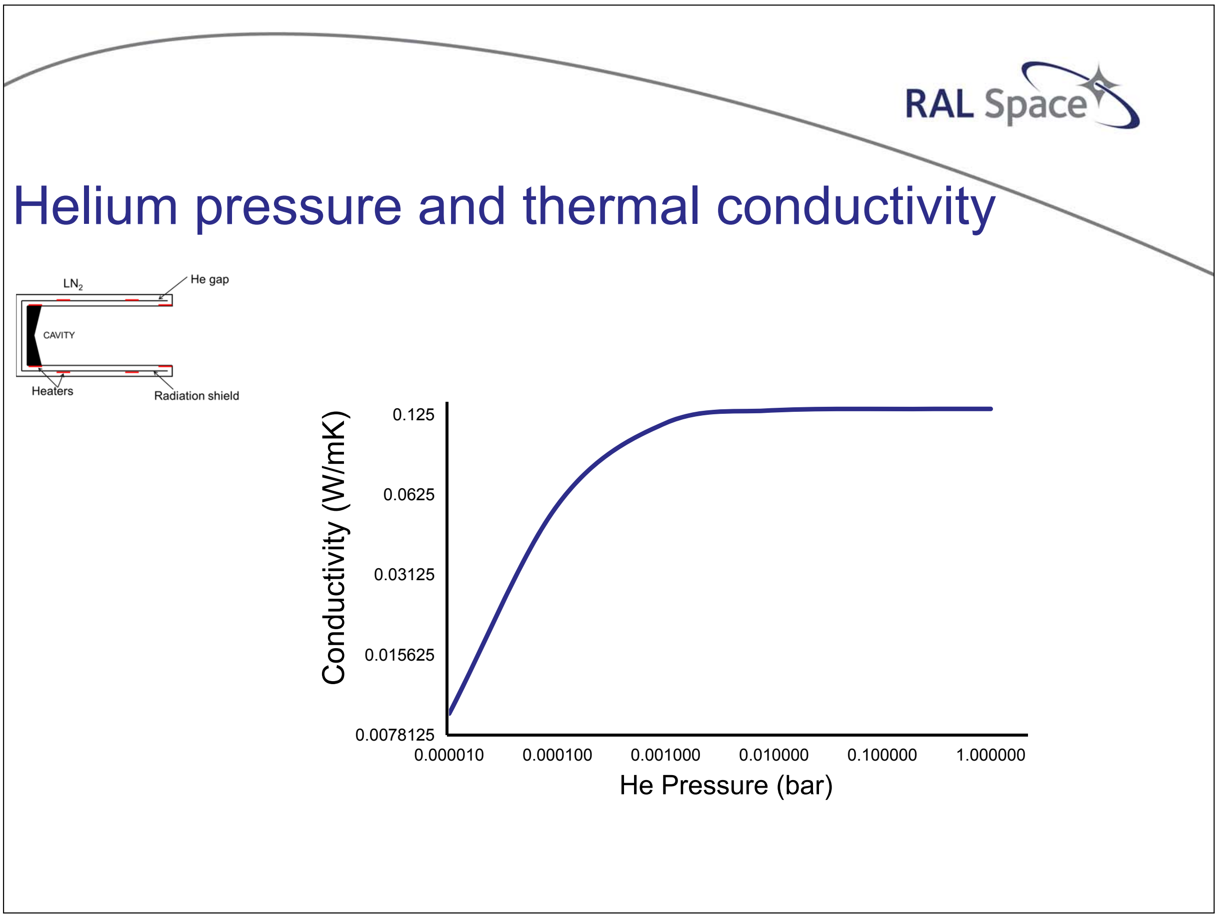


I then used these in the template file, and made node-node GL links between the relevant surfaces in the $CONDUCTORS block.

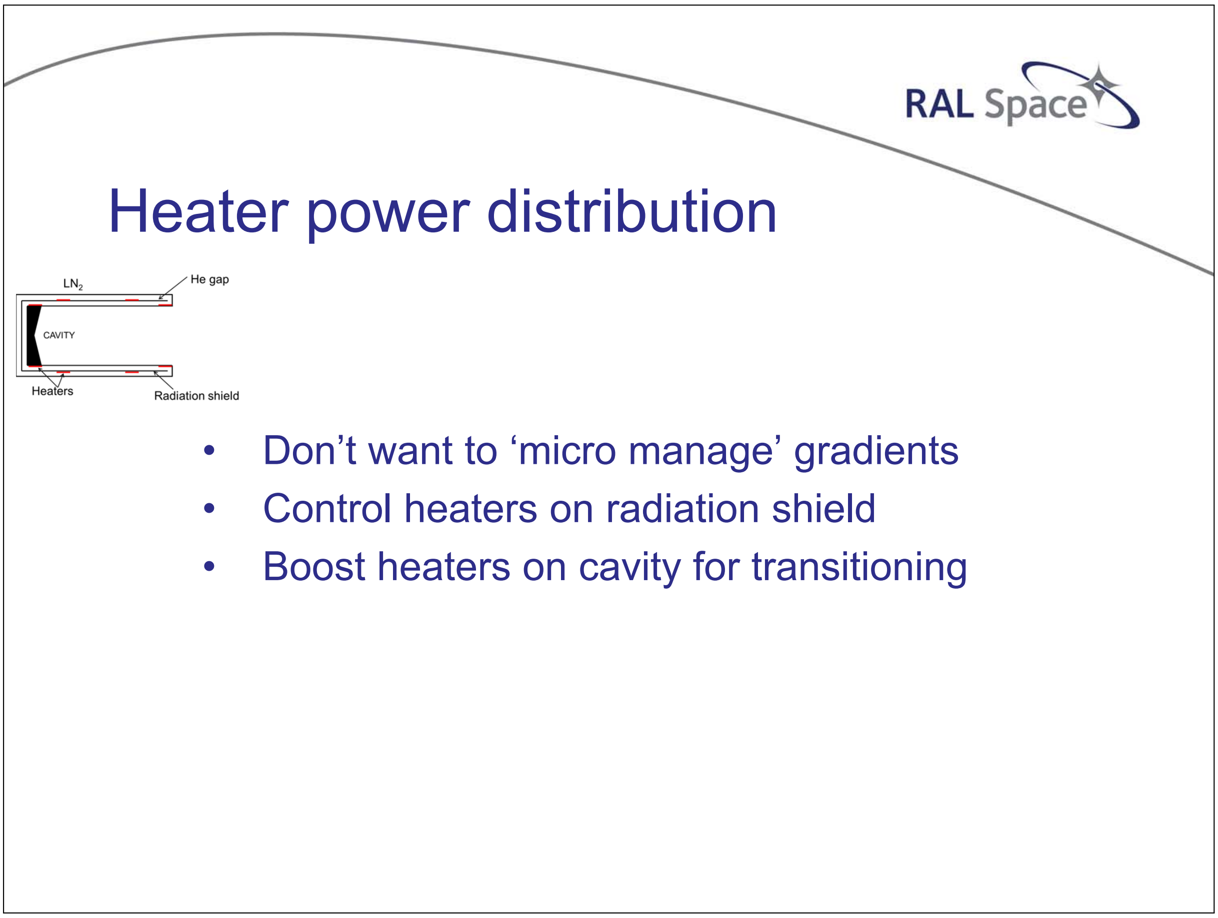


On a practical level it's easier to control the power input into heaters, than it is to control the pressure in a gas gap. So once I'd set up the model, I looked to see the smallest number of helium pressures I could use to control over the entire temperature range – given the 3 kW power limit.

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.

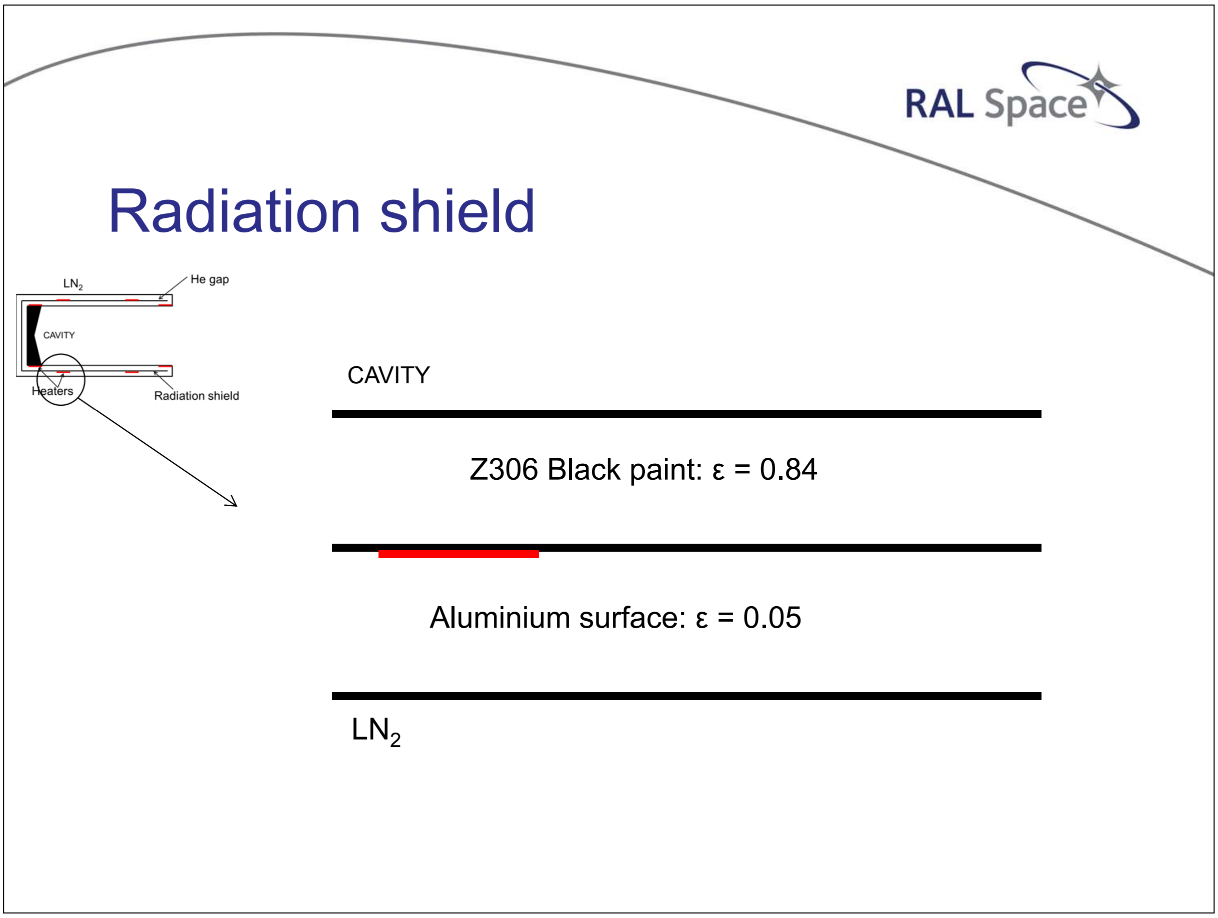


With regards to the heater powers, we needed to be careful that we weren't micro managing the gradients, we didn't want to be putting heat inputs into each node, as that makes the system far too reliant on the power input, and ultimately we want something that is inherently uniform.

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.

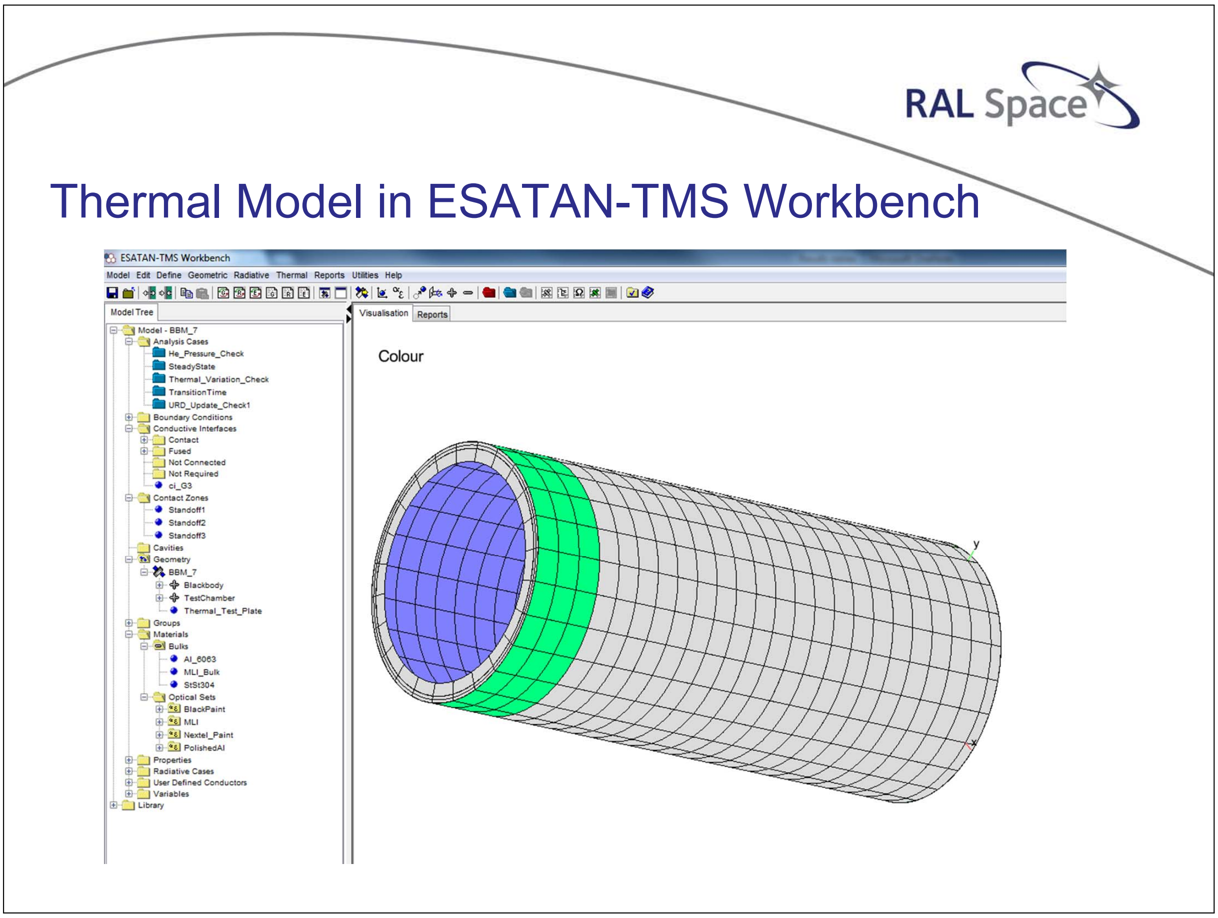
There is a conflict in the customer requirements. The uniformity requirement lends itself to a high thermal mass, however the fast transition time between temperatures would be easier to meet with less mass.

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.

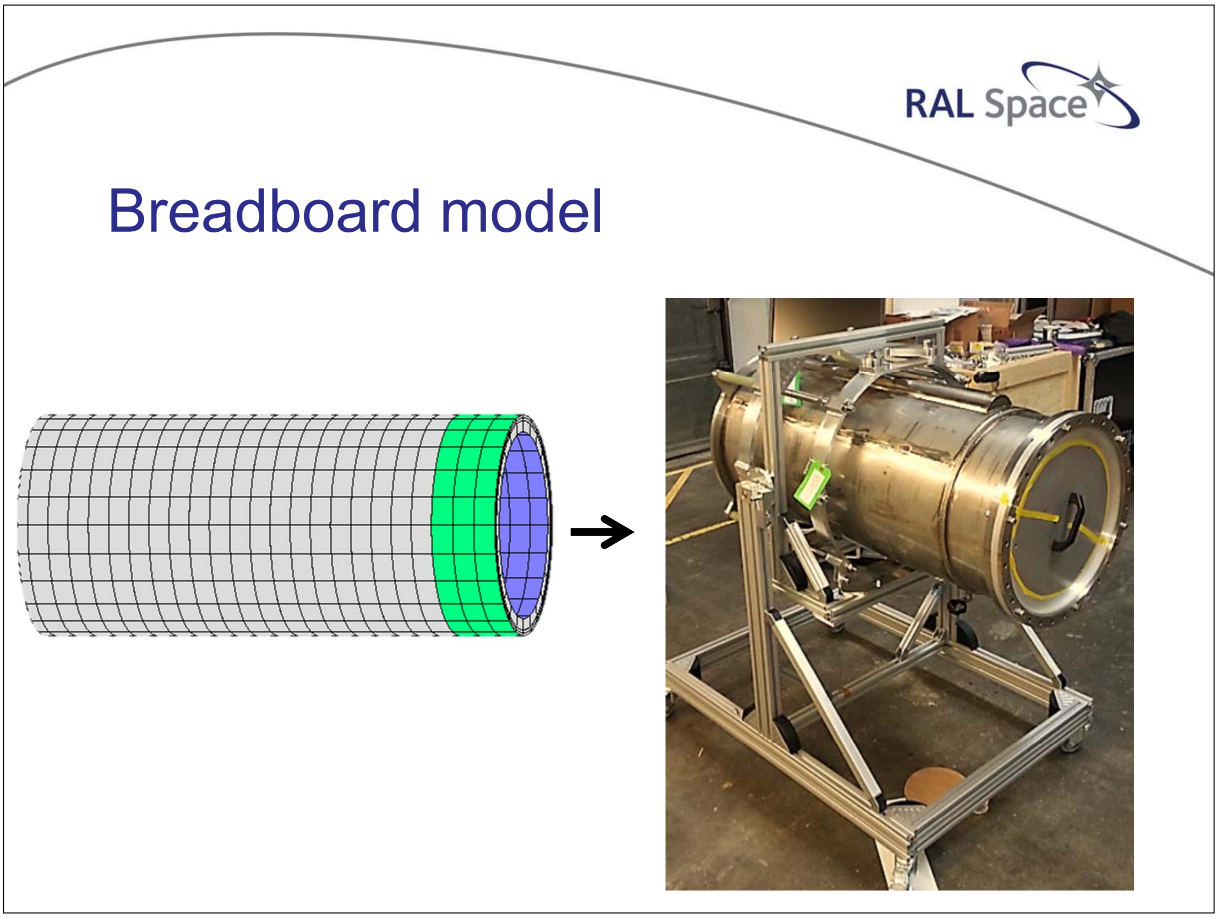


Since the main control heaters are on the radiation shield, we need to ensure that there is always a thermal link between the heated shield and the cavity, even when there is no helium in the gas gap. Conversely, on the other side of the shield, we want the thermal link between the cold liquid nitrogen 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.

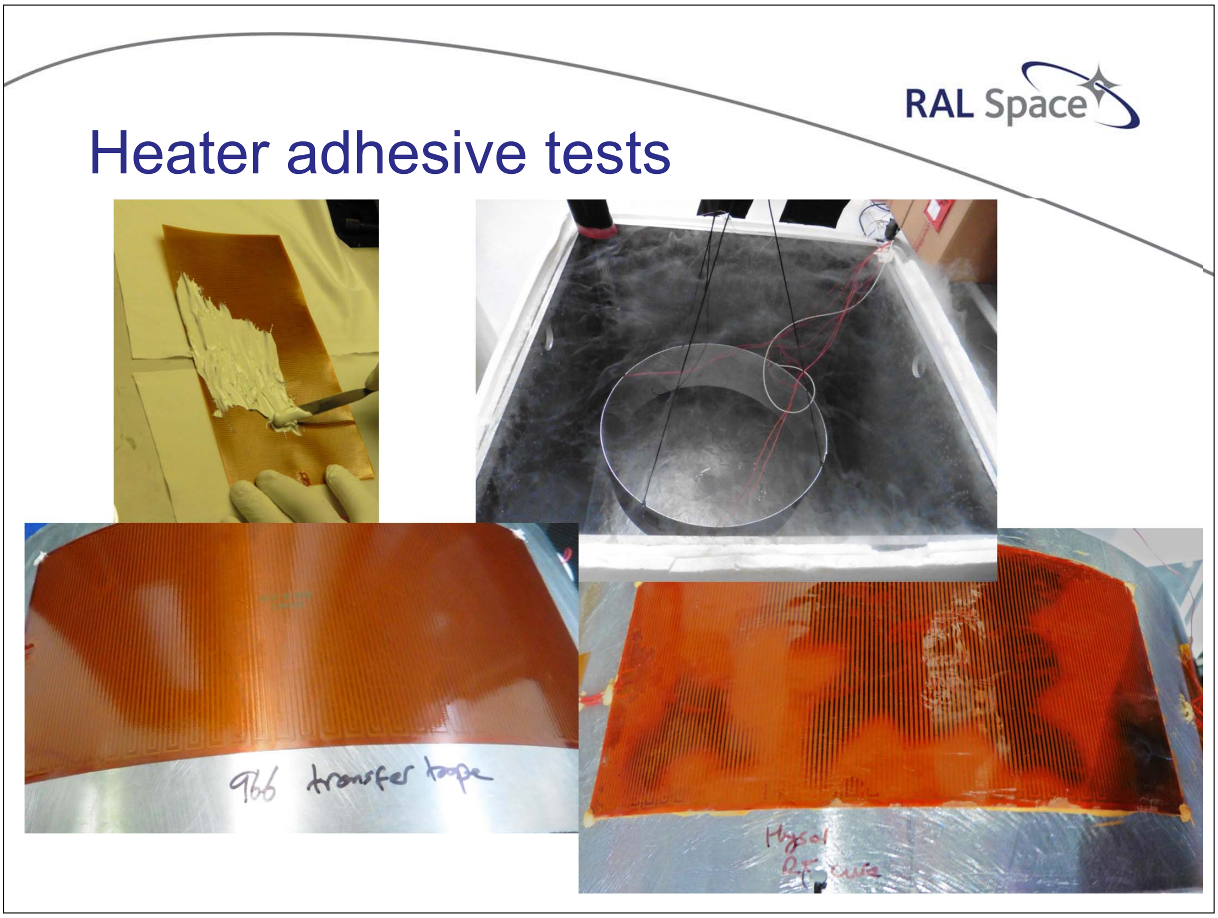


I've used this thermal model for the helium pressures and to optimise the heater distributions, and most recently to create the test predictions for the upcoming breadboard model tests.



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.

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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
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