Low Mass Calibration Load

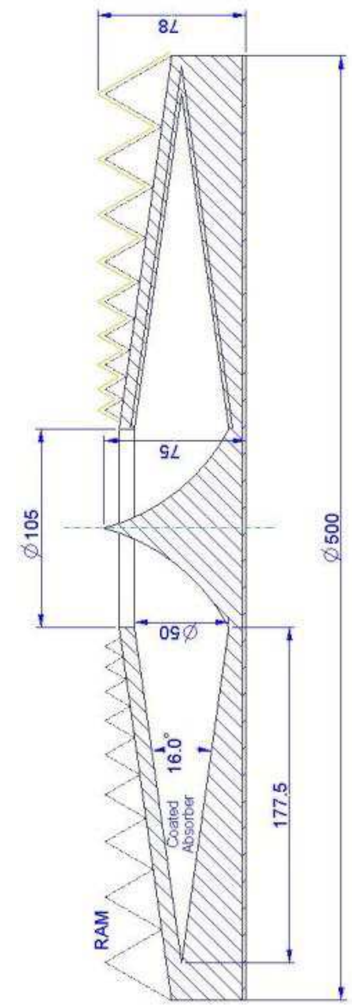
ABSL Final Presentation to ESTEC
12th December 2011

This presentation is divided into two parts:

1. Executive Summary
2. Technical Details

Introduction

- The project was undertaken under TRP funding to address critical aspects of calibration for missions with limited resources in volume and mass whilst trying to accommodate ultimate instrument performance
- The Team’s bidding proposal put forward a novel design, to combine the benefits of our scale-less cone designs   with constrains upon the load’s height
- The load would need to be broadband in nature, taking advantage of the design principles drawing upon ABSL team’s previous calibration experience



Introduction

- The objective was to develop a generic load but to focus design effort the project has been targeted at post-EPS needs
- While the Team was aware of the evolution of the Post-EPS requirements as the work progressed, the decision was made not to change the direction of the project, but to build a sound set of design, manufacture, test and analysis capabilities while maintaining a project-oriented set of requirements

Design, Development and Manufacturing

The following were the very challenging requirements for the load:

Req.	Performance Requirements
1	Applicable bandwidth : 18 to 300 GHz
2	Brightness temperature : > 300K
3	Emissivity : >0.999
4	Variation in brightness temperature : < 100mK over aperture
5	Error in brightness temperature versus physical temperature : < 500 mK
6	Beam form : corresponds to standard feed-horn
7	Phase centre of beam form : coincides with aperture plane
8	Coupling (CHL – next stage) : <-30dB
9	Temperature range : 20 - 50 deg C
10	Survival Temperature : >48h @-40….50degC. In air and vacuum
11	Stability (drift) : <1 mK/s

Design, Development and Manufacturing

The following were the accommodation constraints on the load

	Constraints
	Diameter : 0.4<d<0.5m
	Height : <75mm goal < 50mm
	Mass : <10kg goal 7.5 kg

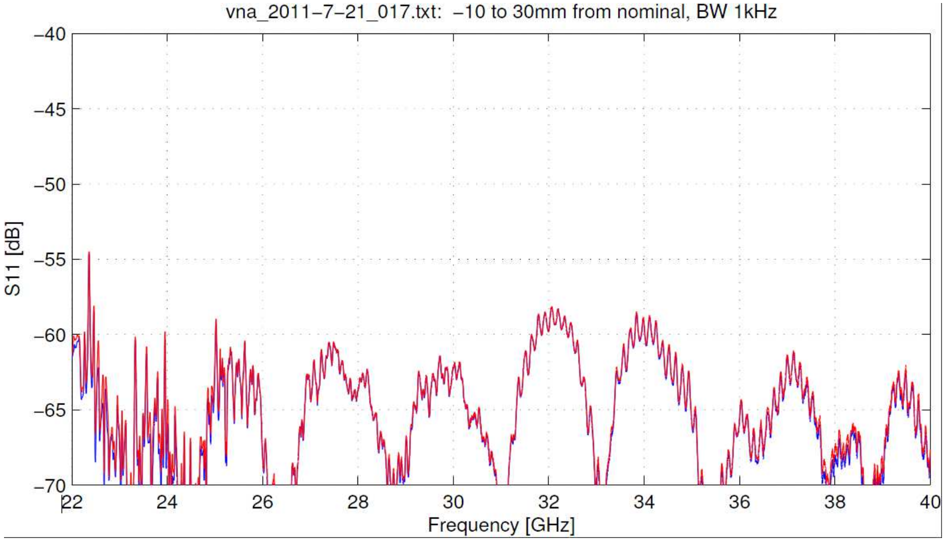
Other microwave load designs could be produced, but they would not come close to meeting the accommodation requirements above. This can be justified by reference to other current microwave calibrator designs, such as one for the Sentinel-3 Microwave Radiometer which the Team is currently building for CASA

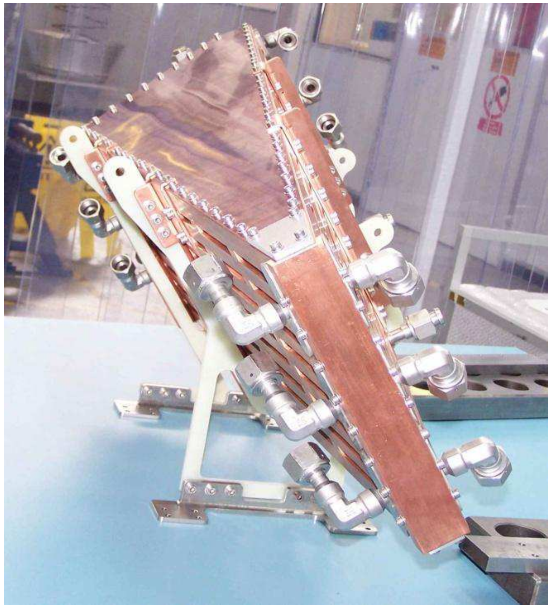
Comparison Between Simple Cone and Current Design

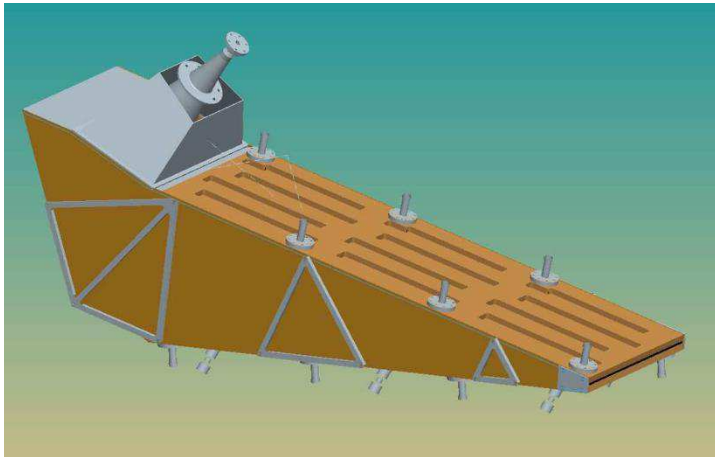
- Current design emphasises low-mass and volume
- Other current microwave loads perform better radiometrically and thermally, but mass of the order of 70kg and length >1m
- Current design is a good compromise between flight accommodation and flight performance
- Further design iterations have been identified during the LMCL project to suit evolving Post-EPS instrument requirements
- LMCL project has provided the flexibility to satisfy future calibration hardware needs
- The design work has emphasised radiometric performance rather than thermal control, taking the view that if thermal performance becomes an issue, active control could be considered

Alternative , albeit related, technologies

- The Team's S3 MWR ground based calibration target - >1M in length, and >70 Kg in mass but with an S11 of -60dB at 22-40 GHz







Importance of S11: Error in BrightnessTemperature due to coherent standing waves

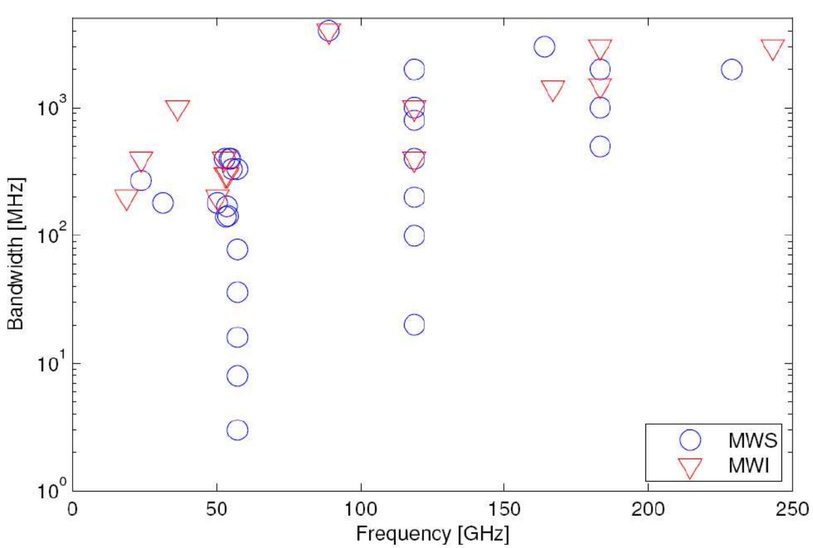
- Coherent backscatter leads to standing waves between the receiver and calibration load.
- This causes a periodic baseline ripple given by:

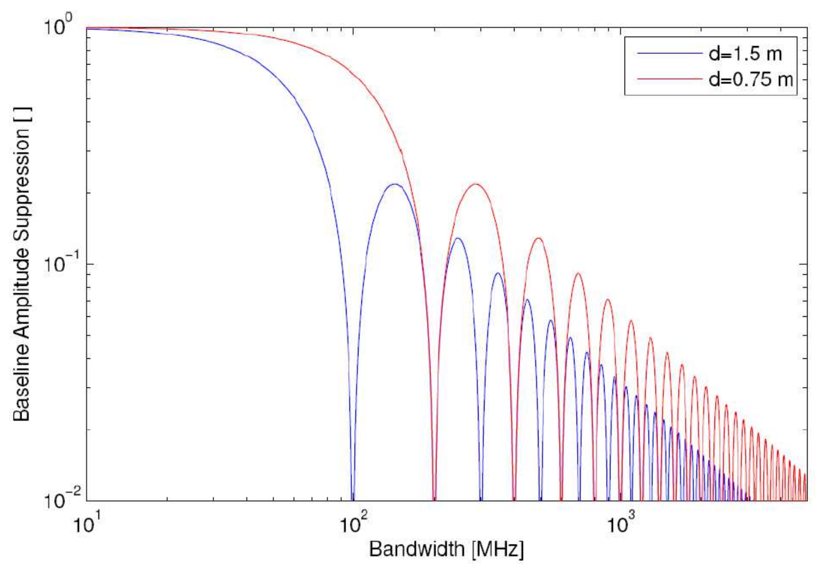
$$\Delta_{TB} = 2\ |\Gamma_1|\ |\Gamma_2|\ (T_1 - T_2) \cos(\ 4\pi\ d/\lambda + \phi)$$

- Taking 57 GHz MWS channel – narrow band and harder to achieve good Load S11, we have
  - $\Gamma_1 = 0.32$ (-10 dB) for receiver
  - $\Gamma_2 = 0.0056$ (-45 dB) for the calibration load – see results displayed later
  - $T_1 - T_2 = 23$ K (assumes brightness temperature emitted by the receiver is close to the physical receiver temperature, as an isolator-protected LNA would be)
- Gives a maximum standing wave error of ~ 82 mK

Channel Bandwidth and Standing Wave Suppression

- Broadband channels may average over several standing wave periods, leading to suppression of baseline ripple.
- Narrow MWS bands at 57 GHz and 118 GHz will not benefit from suppression. MWI channels will benefit by ~ factor of 5 for a 1.5 m path length. This argues for a long distance to be placed between the Rx and the Load, though the use of "relay optics" .

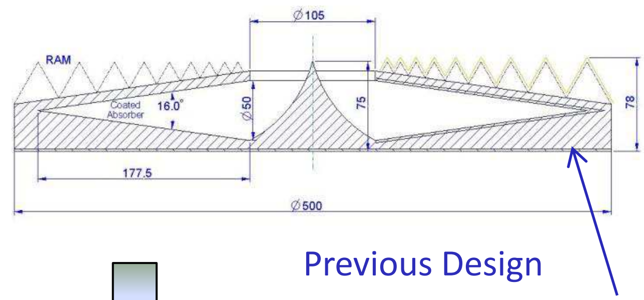




Design, Development and Manufacturing

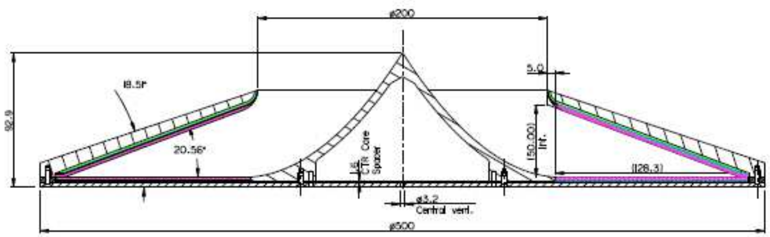
- Although a cone configuration is preferred from the performance stand-point, such a solution cannot be accommodated in a flight load
- Two loads have been manufactured and tested during the project to address the challenging requirements
- The design was updated to improve blackness performance
- Second load has performed well and justified the decision to modify the design - at no extra cost to ESA
- Load now has flat back plate design (design iteration)
- Internal surfaces are lined with multi-layered absorber

Design, Development and Manufacturing – Second Design Iteration



Previous Design

Support Structure



Current Design

- Design modified at breadboard PDR in order to improve the thermal performance
- Overall size of load has increased
- Central cone increased in size
- Height constraint observed
- The move to a multi-layered absorber was a major achievement for the project (drawing on experience from other projects. This enables better performance to be provided at lower frequencies

Base Plate with Central Spike

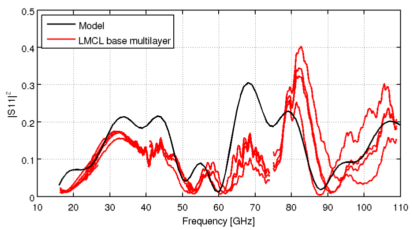
Spreader in Moulding Support prior to Casting

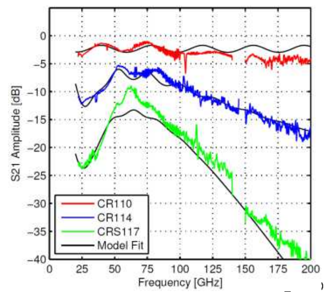
Overflow Channels in Mould, Allowing the Thickness to be Controlled

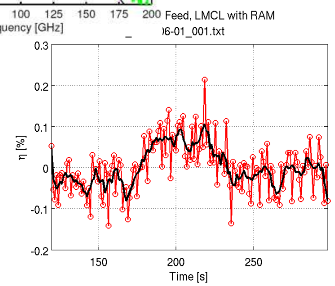
Extent of Testing - Electromagnetic

- A significant amount of both active and passive radiometric testing has been undertaken to characterise the load.
- Measurements have been done over an extended set of frequency ranges, up to 200 GHz
- Measurements have been backed up by analysis
- Overlays of measured and predicted data have consistently shown good agreement
- Background experience on other scale-less (cone) loads has been a factor
- The above gives confidence that wide-band operation has been achieved

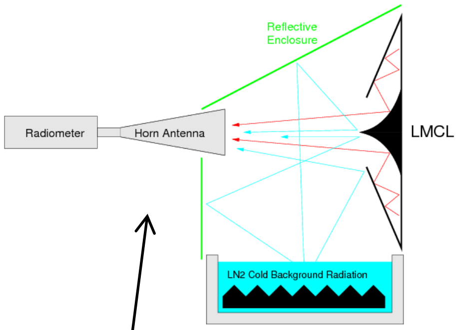
Extent of Testing - Electromagnetic

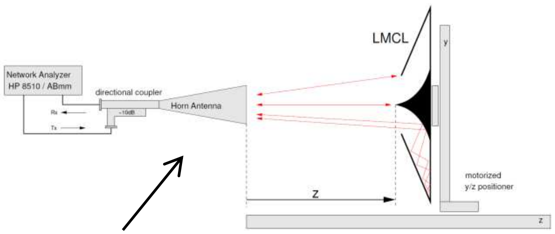




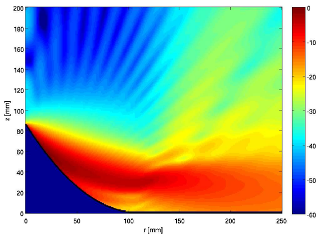


Broadband test results show good agreement with analysis

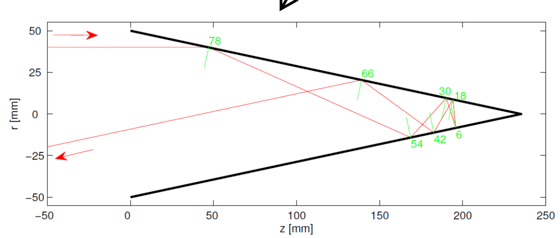




Both passive and active measurements completed to fully characterise breadboard load and verify analysis /modelling results



Modelling confirms how load will perform radiometrically



Complete set of theoretical and physical investigations carried out during the project to verify load radiometric characteristics

Vital Importance of the radiometer’s probing beam

The load performance cannot be decoupled from the nature of the probing beam

- Measurements done by the team have indicated that side-lobes will have a significant effect on reflectivity of the load
- This is due to over-spill of the beam
- Beam needs to be concentrated on the central area of the load for good calibration
- Team have had to make some assumptions about the shape of the beam and thereby the region of the load ‘seen’ by the receiver

Vital Importance of the radiometer's probing beam

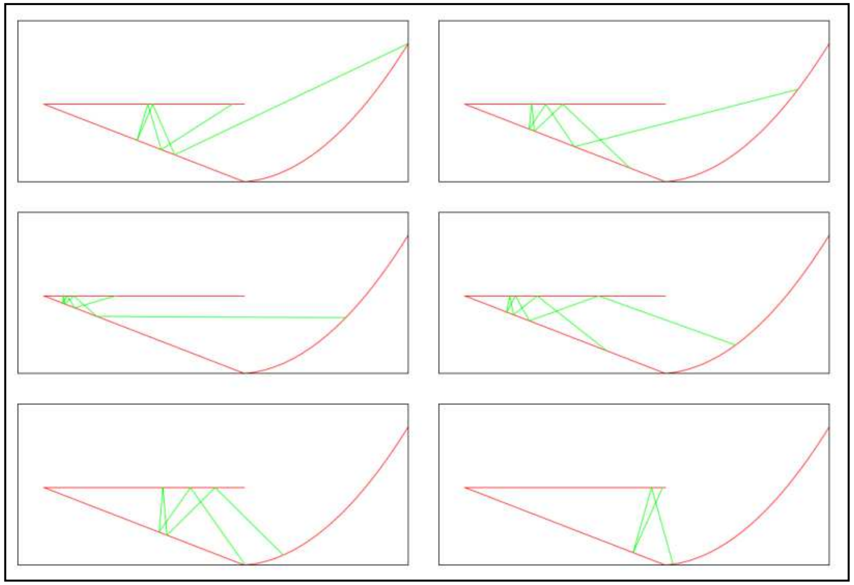
- Ultra-Gaussian beam used for testing (optimised over-spill)
- Recommended for use in operation
- Optimised feed-horns will be needed at operational frequencies
- For any appreciable energy hitting side area absorber or, ideally, pyramids would be needed
- Pyramids will require extra height
- This will also limit pyramid aspect ratio
- Simple absorber used instead of pyramids for testing

Ray Tracing Analysis to Support Model Concepts

- Ray-tracing technique used for modelling
- Geometry intended to maximise number of internal reflections
- Number of reflections given by N = 90°/α, where α is the ½-angle of the cone
- Simple 2-d ray-tracing method used
- Two other geometries analysed for comparison: symmetrical and inverted flat plate
- All have better performance at different distances from the central axis
- Thermal management would also be different leading to different compliance situations

Effect Of Internal Geometry

- Ray-tracing (to the right) used for comparison of geometries
- Inverted design used for comparison of likely performance
- Listed as good candidate for investigation in any future work
- Design would have more challenging thermal management scenario
- Three designs considered have better performance in some areas, worse in others



Example of Ray-Tracing Analysis ('Inverted Design' in This Case = Flat surface at the Top Instead of the Base)

Error in Brightness Temperature versus Physical Temperature

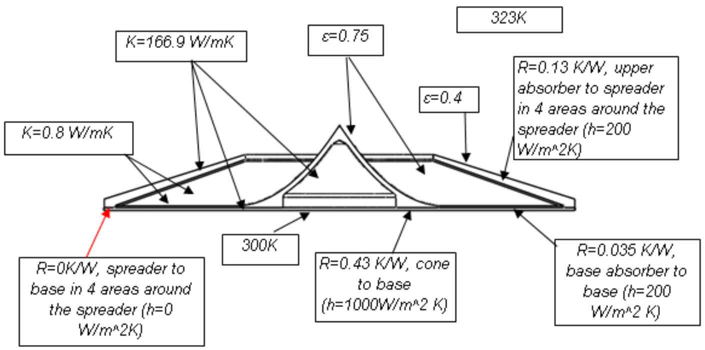
Source of Error	Temperature Uncertainty	Explanation
Incoherent backscatter	23 mK	23K temperature difference and 0.999 emissivity
Temperature non-uniformity	280 mK	From thermal simulations
Temperature readout	10 mK	For typical readout electronics
Standing waves	82 mK	Highly dependent on instrument characteristics

Extent of Testing - Thermal

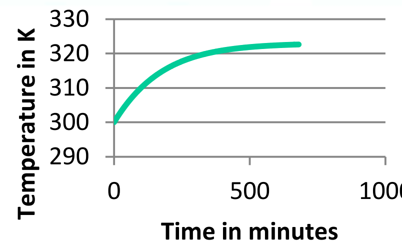
- Thermal testing has been carried out on manufactured material samples (shown above) to verify results of analysis
- Testing has been carried out in national standards facilities in the UK
- Measurement results have been used in parametric modelling to enable future design iterations to be carried out
- Important conclusion *that there is basically no contact resistance between layers and onto metal backing*

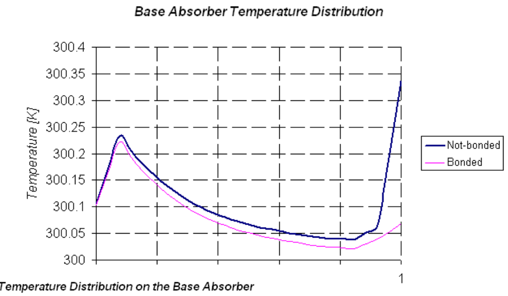
Extent of Testing - Thermal

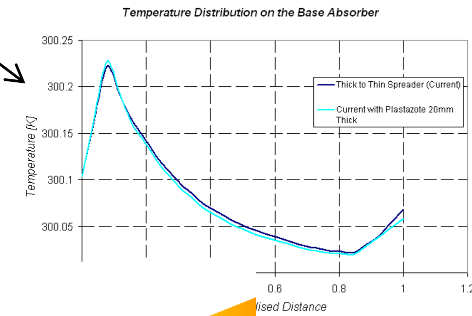
Materials properties thoroughly defined

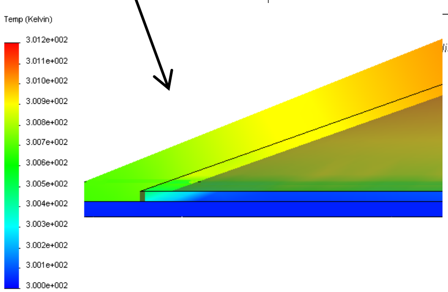


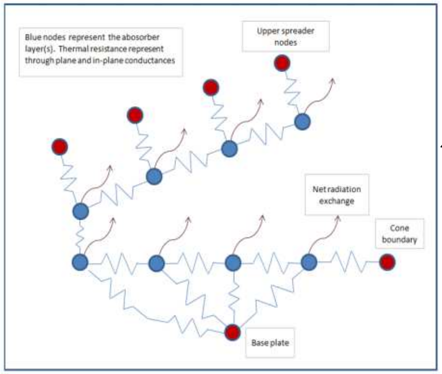
Static and transient thermal analyses and measurements conducted to characterise the load thermally and verify analysis results



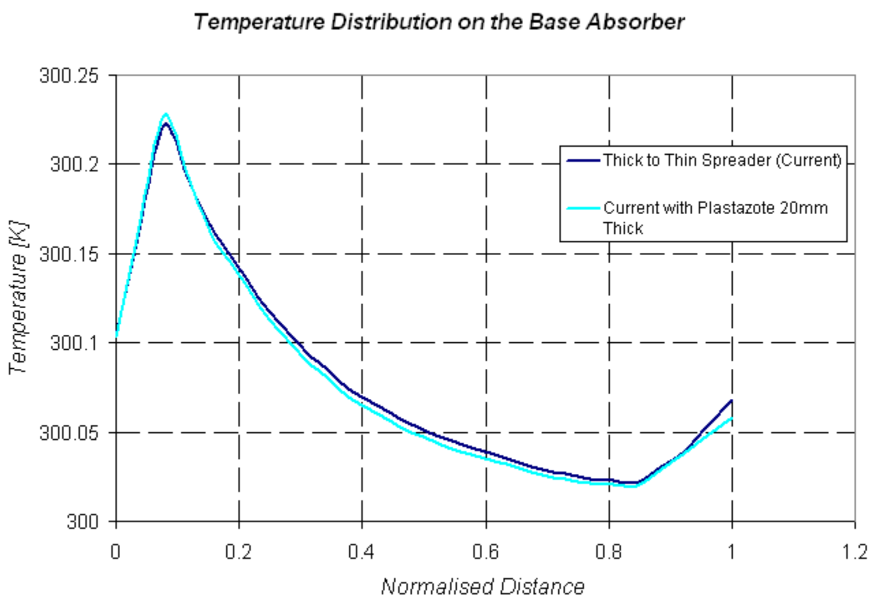


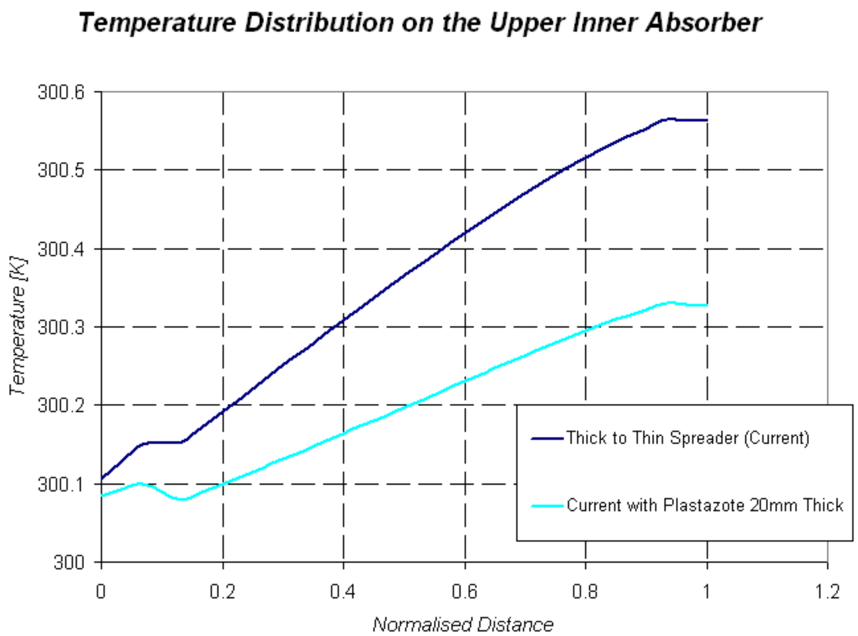






Bespoke physical property analysis method developed to enable the whole load to be thermally modelled


Temperature Distribution on the Base Absorber
300.25
300.2
300.15
300.1
300.05
300
Temperature [K]
0
0.2
0.4
0.6
0.8
1
1.2
Normalised Distance
Thick to Thin Spreader (Current)
Current with Plastazote 20mm Thick


Temperature Distribution on the Upper Inner Absorber
300.6
300.5
300.4
300.3
300.2
300.1
300
Temperature [K]
0
0.2
0.4
0.6
0.8
1
1.2
Normalised Distance
Thick to Thin Spreader (Current)
Current with Plastazote 20mm Thick

Summary of Design Status

PR = Per (original) Requirement

Technical Requirements	Compliance Against Original Spec	Adjusted Value (Neg'ns)	Design Goal (TN#2)	Compliance Against Adjusted Spec
Electrical Requirements				
Applicable bandwidth : 18 to 300 GHz	C		PR	C Geometrical design is broad-band, i.e. does not have feature sizes derived from the relevant wavelengths, however the absorber layers were optimized for specific bands of interest. They were numerically optimized for MWS bands 20, 30, 50-60, 90, 120 GHz
Brightness temperature : > 300K	C		PR	C With the specified high emissivity, this corresponds to the physical temperature of the absorber structures. In the current design it is assumed that the LMCL would be mounted on a temperature-controlled plate. However active heating would be required to achieve 300K at the low end of the temperature range (requirement 9, 20 degrees, i.e. 293K)
Emissivity : >0.999	C	0.9995	0.9999 (-40dB)	NC against design goal, but compliant against original spec

Summary of Design Status

Technical Requirements	Compliance Against Original Spec	Adjusted Value (Neg'ns)	Design Goal (TN#2)	Compliance Against Adjusted Spec
Error in brightness temperature versus physical temperature : < 500 mK	C	250mK	< 200 mK ex. S11 < 500mK @ 57GHz inc. S11	Compliant by analysis, but with an emissivity of 0.999 and an assumed cold space view of the remaining 0.001 (which is worst case) a result of 300mK bias + standing waves + thermometry/gradient errors would be indicated, so compliance indicated against original spec
S_{11} : <-30dB	C		PR	C

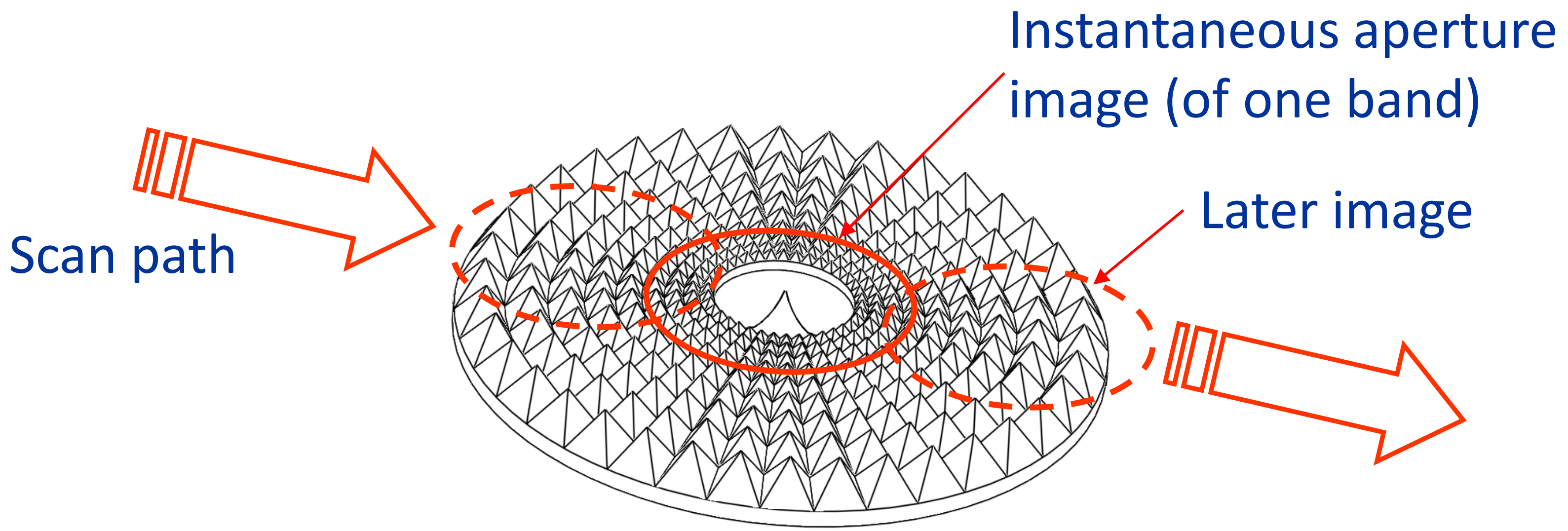
Summary of Design Status

Environmental Conditions				
Temperature range : 20 – 50degC	C		PR	C Will require either thermal control or thermal links to spacecraft at a suitable temperature, and sufficient shielding
Survival Temperature : >48h @-40….50degC. In air and vacuum	C		PR	NC Not tested for survival to -40degC. Different potting process could be necessary. May be possible to achieve compliance by changing the casting/potting order. May be possible to cast the CR layers first then pot onto the metal base at room temperature to reduce stresses at -40degC ALMA loads tested to -30degC, but smaller
Stability (drift) : <1 mK/s	C		PR	C Per analysis

Summary of Design Status

Technical Requirements	Compliance Against Original Spec	Adjusted Value (Neg'ns)	Design Goal (TN#2)	Compliance Against Adjusted Spec
Dimensions				
Diameter : 0.4<d<0.5m	C		PR	C
Height : <75mm goal < 50mm	NC		<100mm	C Compliant against modified requirement (breadboard height: 91.3mm)
Mass : <10kg goal 7.5 kg	PC		<7.5kg	NC Mass currently 10kg, but this is without the pyramidal absorber on the upper surface (cf CASA: Calibration load for Sentinel 3 MWR at 70kg)

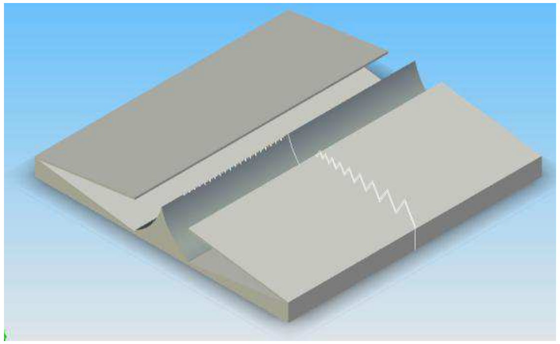
- As reported during WP1 Requirements Review meeting of 22nd January 2009, axially-symmetric design may not suit instrument needs
- May preclude the use of the proposed ‘hybrid’ design
- Depends on latency within most effective portion of LMCL (scan speed, detector integration time, ratio of aperture to LMCL diameter, etc)



Mission Requirements and Design Flexibility

- Stop-and-stare has, however, provided a vehicle for investigating design concept and measuring performance
- It is believed that stopping of the flight instrument (MWI; MWS..) will not be possible
- Further design evolutions will be needed
- Team has already proposed alternative load configurations, adapting to the likely needs of the instrument

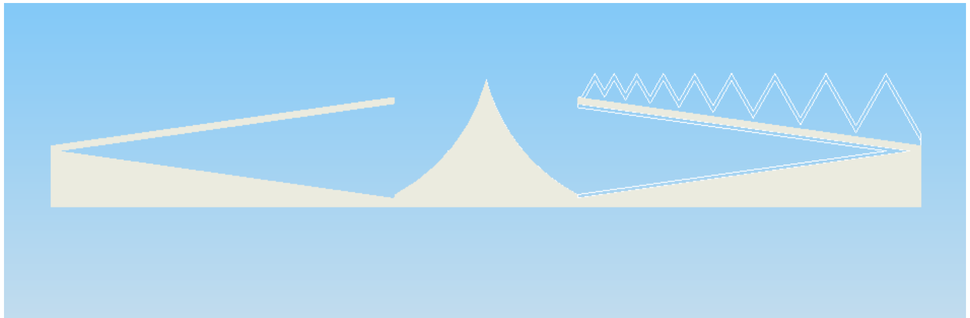
Linearized Version of LMCL



Mission Requirements and Design Flexibility

- Further design investigations could bring improvements
- Original load design incorporated pyramids around the outer (annular) wall – removed due to height restrictions of original specifications
- Interaction with instrument teams could resolve mechanical constraints and enable further optimisation to be undertaken

Cross-section of Linearized Version of LMCL



Summary of Design Status

- Novel load has been designed, manufactured and tested and shown to be largely compliant to the requirements
- The design is based on a compacted scale-less wide-band load technology, using recently-developed multiple absorbing layers
- Although a better performing load could be designed, the present configuration is the best performing within the constraints of a space mission
- Needed design iterations have been identified as part of the LMCL project
- Fundamental design concepts and underlying technologies are understood and have been verified by ABSL team

Conclusions

- The project has built up a sound knowledge base for future load design, development, manufacture and test projects
- The project has enabled the performance requirements that can be achieved by such loads to be determined
- The project has generated both measured and analysis data which agree well and enable the load to be fully characterised
- While the project has taken longer than expected, benefits have been gained from other European projects (ALMA's calibration loads) and has provided design knowledge, experience and test results
- The project has resulted in comprehensive documentation that can be used to launch future low mass calibration load projects

We consider that the LMCL project has been very worthwhile, and the team would wish to:

1. design the flight load for the EPS SG mission, using the techniques developed on the current LMCL project
2. start work in the near future to determine what the requirements for such a flight load might be, so that gaps in terms of load design can be addressed. This will reduce risk by addressing the needed design modifications as early as possible
3. interact with the instrument design teams to enable requirements to be re-defined and load modified accordingly, and
4. adapt the design to suit the need for calibration of moving beams.

The work performed on the LMCL project provides a sound basis future space-borne calibration load designs and their manufacture and testing

This presentation is divided into two parts:

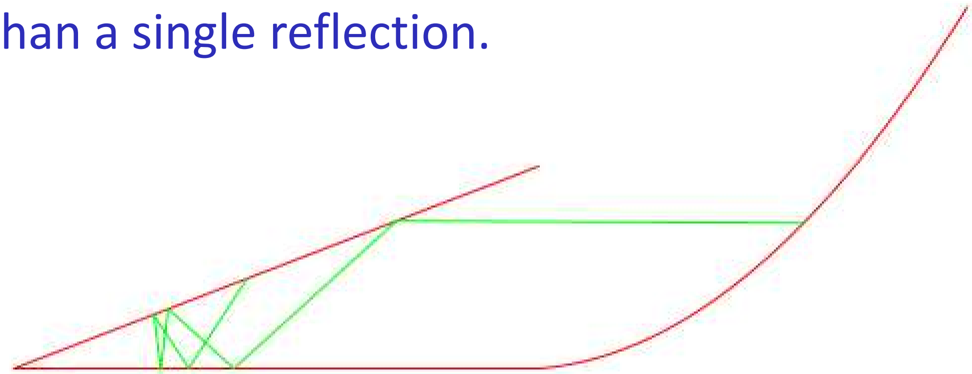
1. Executive Summary
2. Technical Details

The Physics of the LMCL

1) Why use a conical cavity?

- Internal geometry has no scale lengths
  - Different from pyramidal structures (fixed size / height).
  - Design is inherently broad-band (not wavelength dependent).

- Multiple reflections
  - Total reflection is product of all bounce reflections.
  - Much better performance than a single reflection.



The Physics of the LMCL

2) Multi-layered Absorber

- Choice of thickness is a trade-off between thermal and RF performance.

Thin Layer		Thick Layer
+ Good thermal performance	⟺	− Poor thermal performance
− Insufficient absorption		− Thermal gradient present
− Poor emissivity		− Brightness temperature error
− Standing waves		+ Good absorption

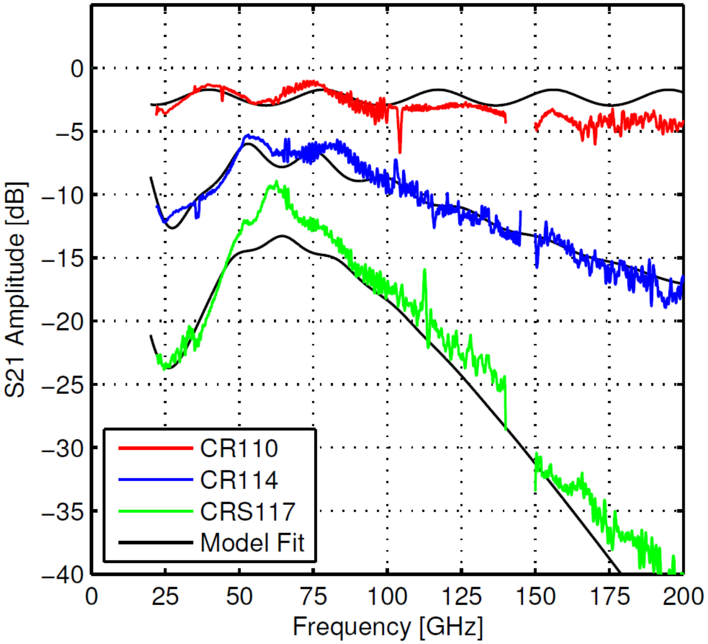
- Multi-layered absorbers offer enhanced performance at lower thickness.
  - Graduation in refractive index improves matching to free space.
  - Layer structure can be tuned for specific frequencies.

The Physics of the LMCL

3) Need for magnetically loaded absorber material

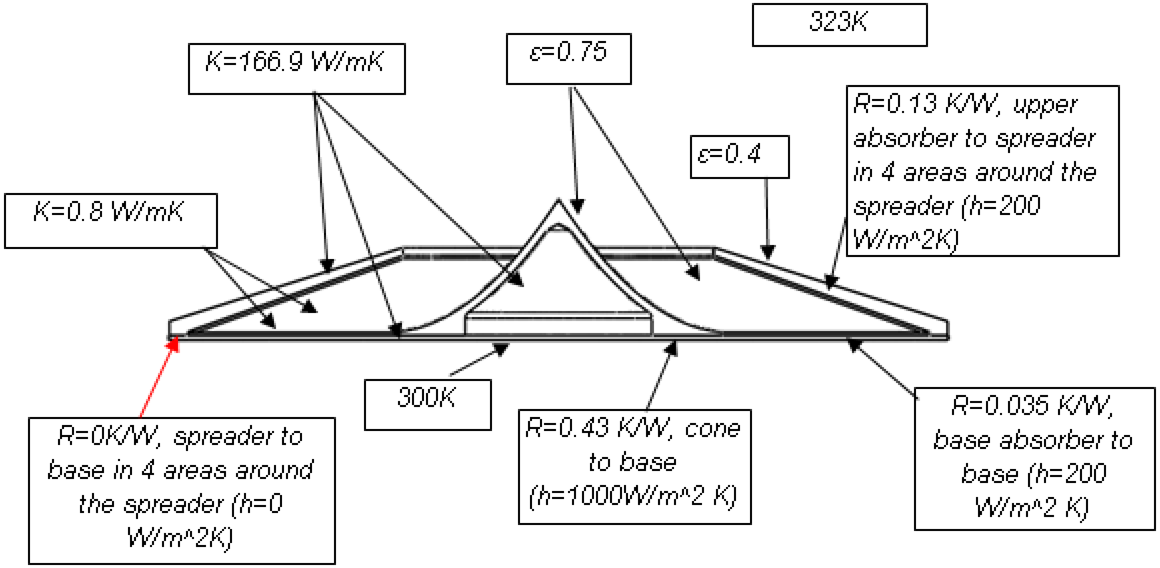
- Transverse electric field is zero at metal surface.
  - No significant dielectric absorption within λ/4 of backing structure.
  - Magnetic absorption is therefore important at low frequency (long wavelength).

- At higher frequencies (> 60 GHz) magnetic absorption is no longer significant.
  - Rising dielectric absorption takes over.



Magnetic absorption → Dielectric absorption

- Baseline geometry and material properties



- Thick-to-thin spreader (current)

Design, Development and Manufacturing

The absorbing layers inside the load were finalised for testing as follows, as the design evolved from the first to second iteration

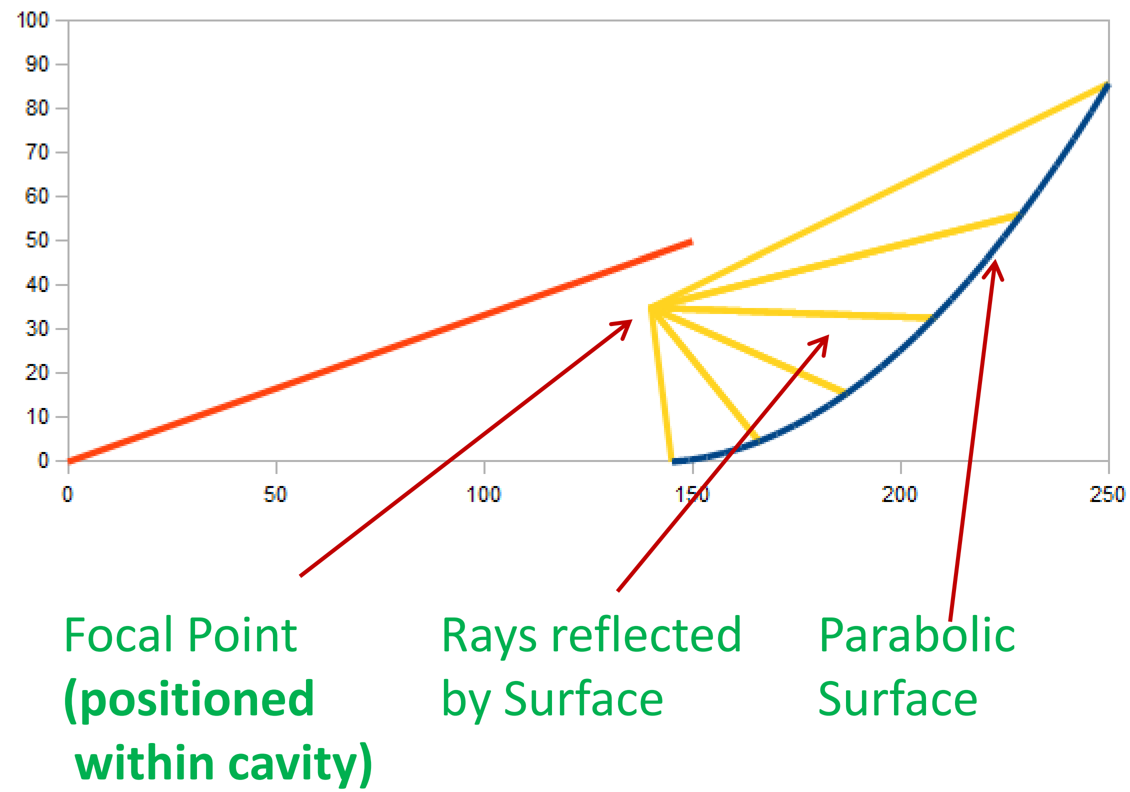
New Base Layers Added		
Layer Material	Second iteration	First Iteration
CRS-117	1.4mm	0.5mm
CR-114	0.7mm	1.0mm
CR-110	2.0mm	1.0mm
New Spreader Layers Added		
CRS-117	Remains at 2.0mm	
CR-114	0.7mm	
CR-110	2.1mm	

Design of Central Spike

- Initial design of spike based on ray-tracing.

- Parabola chosen for surface.
  - All rays entering along its axis converge at the focus.
  - Focus then placed within cavity.

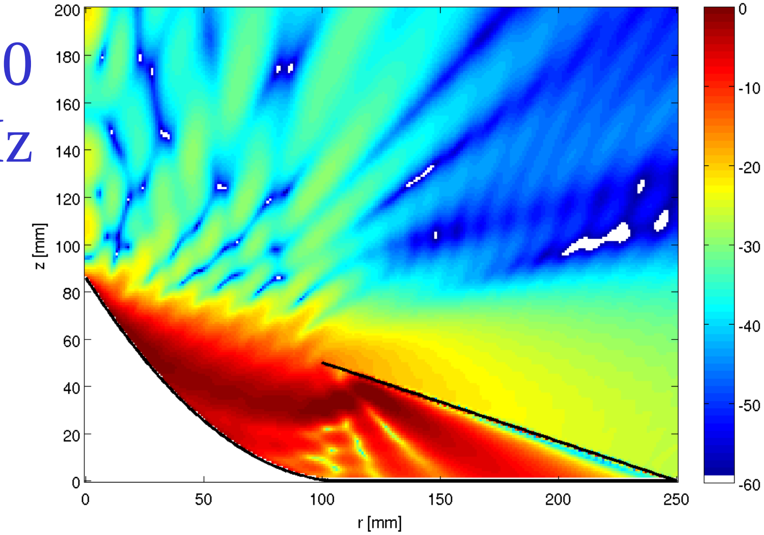
- Rays from all points on the reflector must enter the internal cavity.
  - Must avoid edge of upper surface.



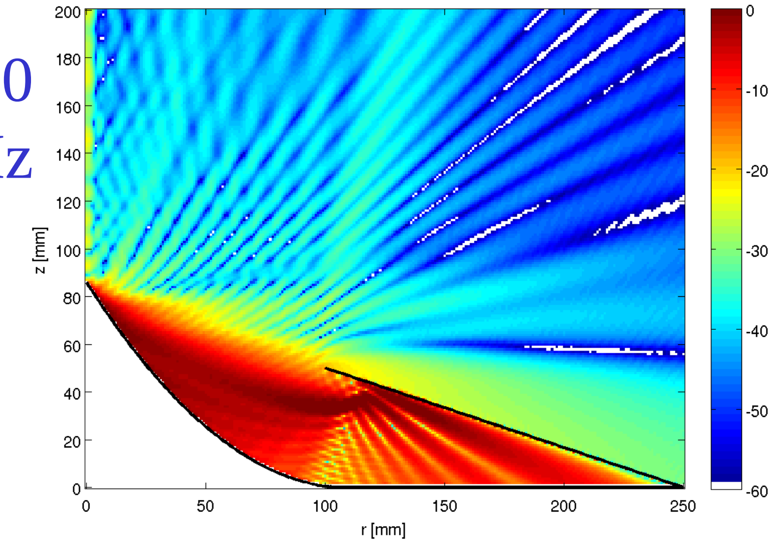
GRASP Analysis

- Design then checked via GRASP simulations.
  - Based on PO (physical optics).
- Plots show results for:
  - Beam waist: w_0 = 70 mm
  - Input distance: z = 200 mm

20 GHz



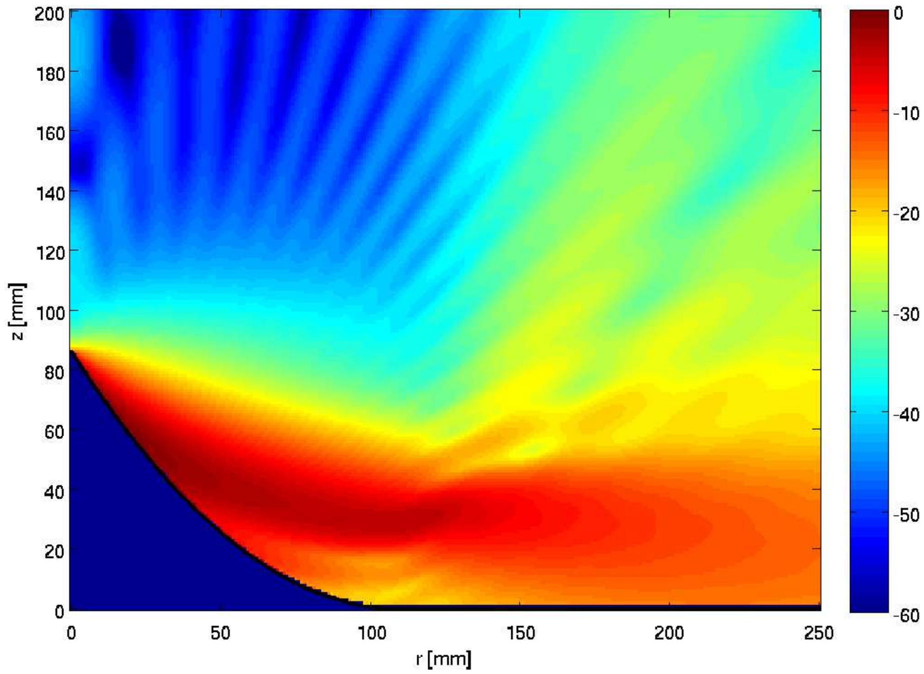
50 GHz



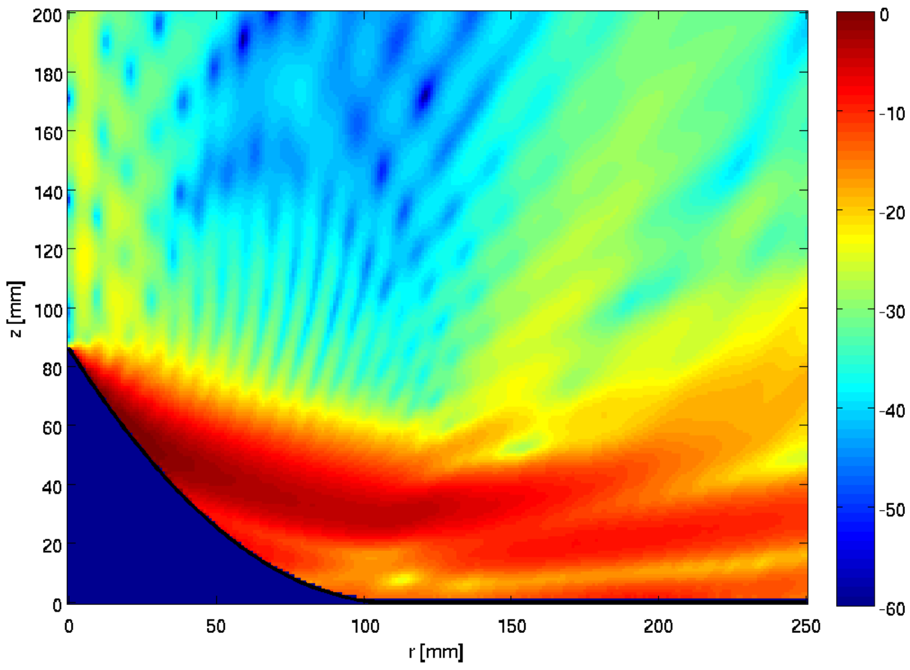
GRASP MoM Simulations

- Additional simulations performed to better understand the test results.
- Use of the Method-of-Moments (MoM) GRASP add-on.
- Inclusion of the actual K-band feed horn.

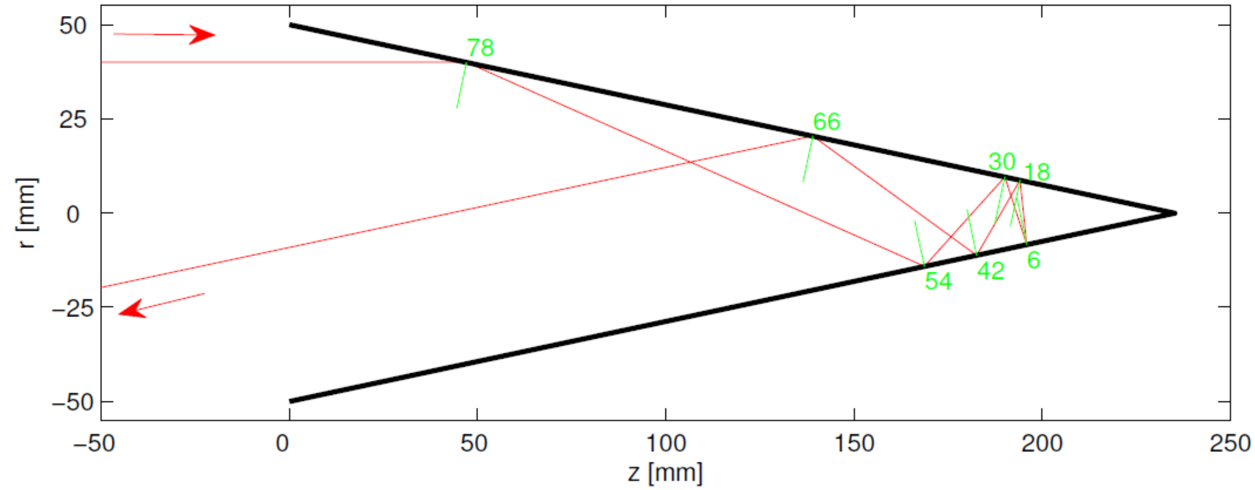
PO



MoM

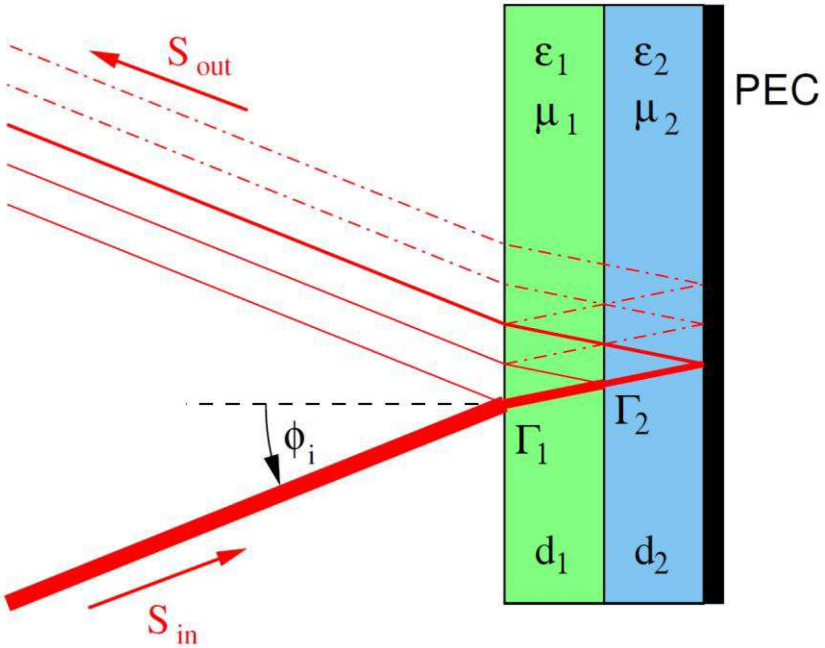


RF Model Implementation



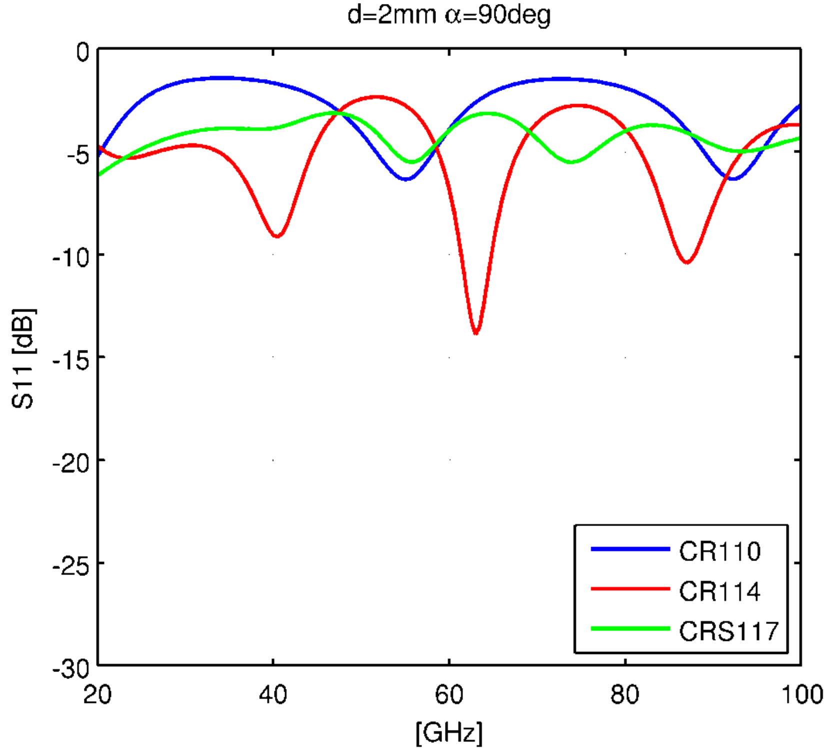
Example of Ray Tracing Model with Half-Cone Angle of α=12deg

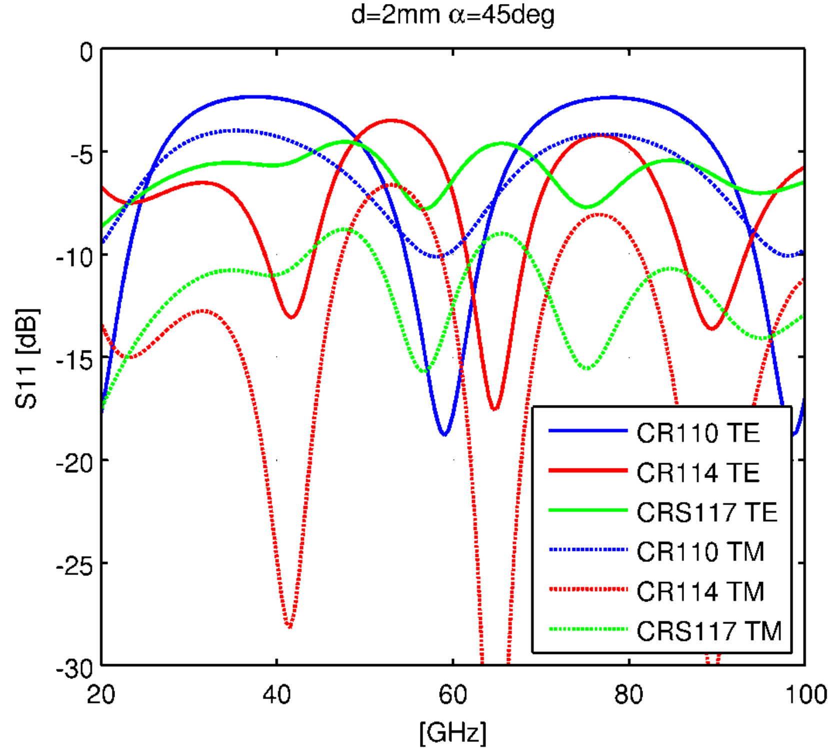
RF Model Implementation



Model of Reflectivity of Lossy Multilayer on a Perfect Electric Conductor

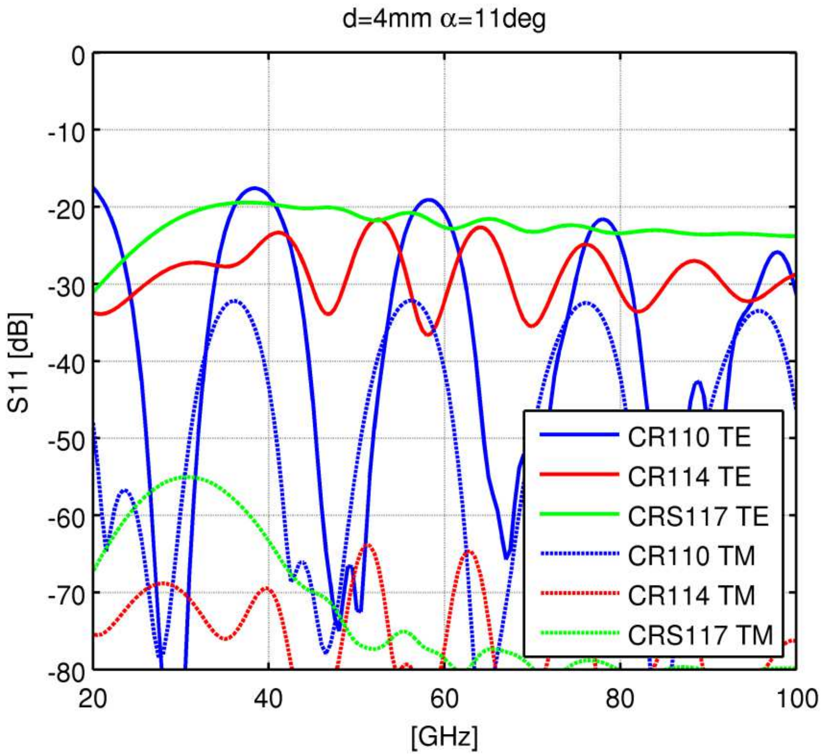
RF Model Examples

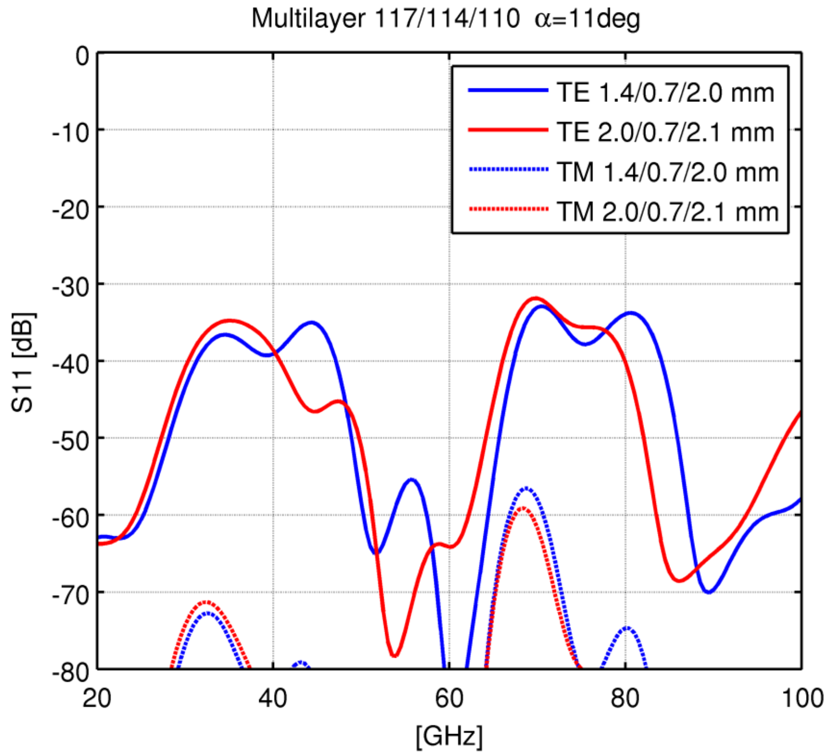




Simulated reflectivity for a single 2mm layer of CR110, CR114 and CRS117 at normal incidence (single bounce) and 45deg TE/TM incidence (two bounces)

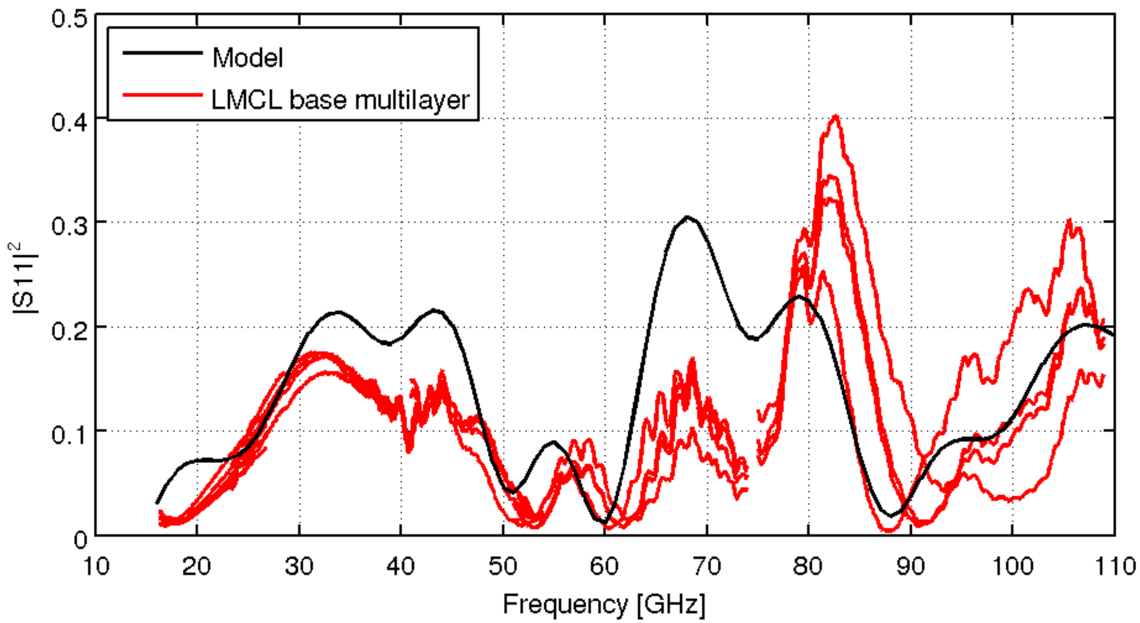
RF Model Examples





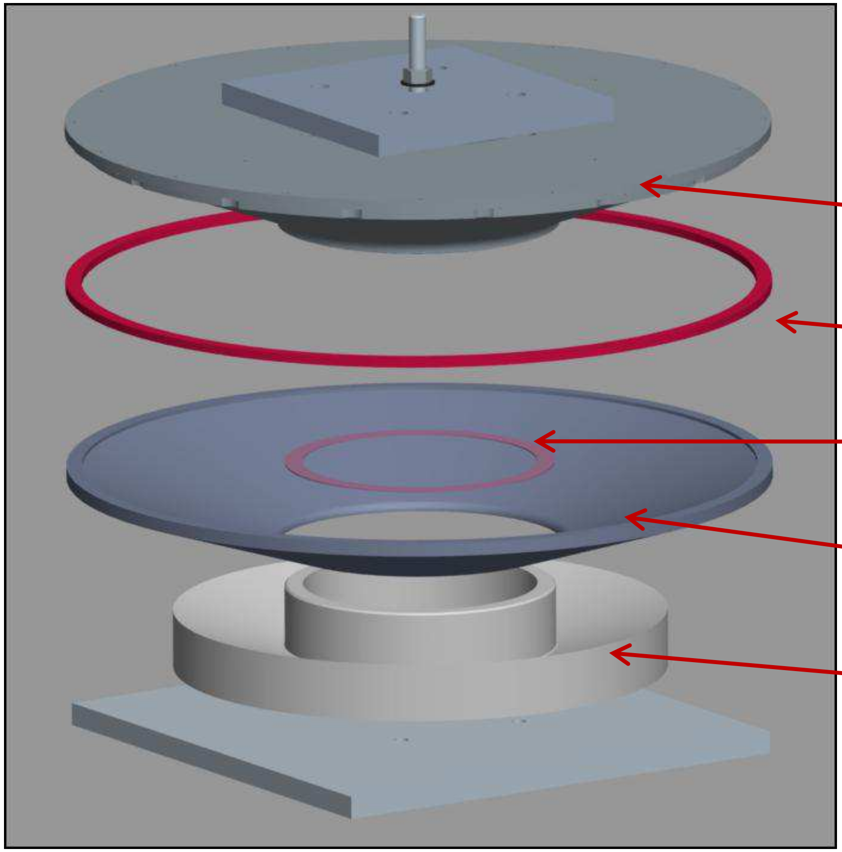
Simulations for the LMCL half angle α=11deg with different uniform absorber 4mm layers and with the final LMCL multilayer composition tuned to the most relevant PostEPS bands

RF Model Verification



*Measured and simulated normal incidence reflectivity of the LMCL multilayer absorber, which has been tuned for the PostEPS bands 20-30GHz, **50-60GHz**, and 89GHz.*

Construction of the Load



Multi-layer casting of the spreader

Mould cone

Protection ring

Spacer **(Controls thickness)**

Spreader

Spreader support

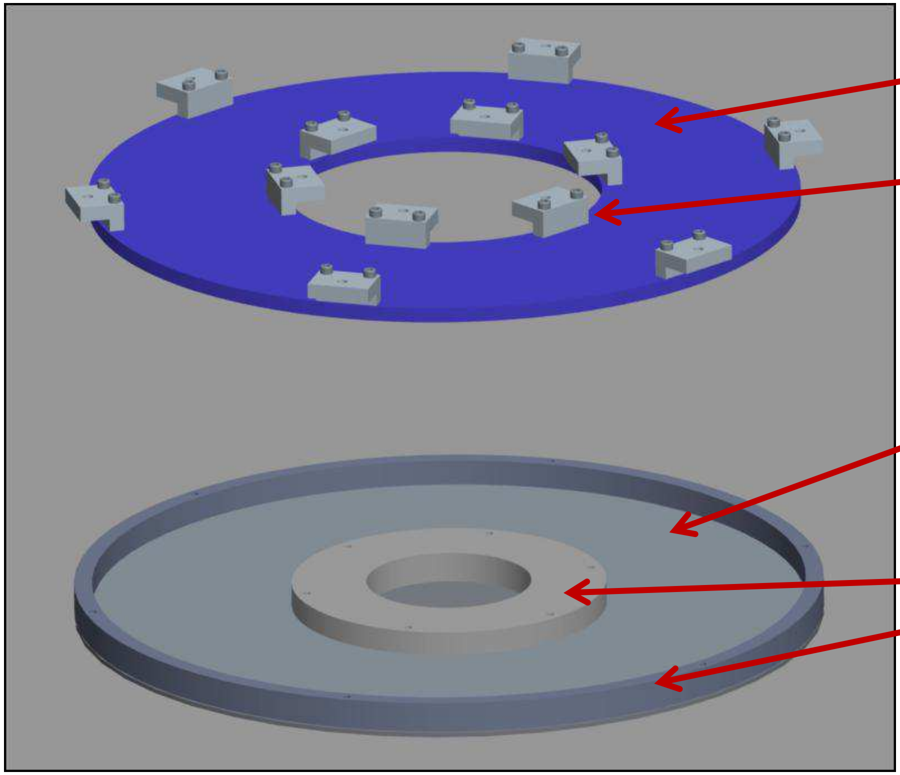
Absorber material

poured into cavity

between spreader

and support

Casting of the Base Plate



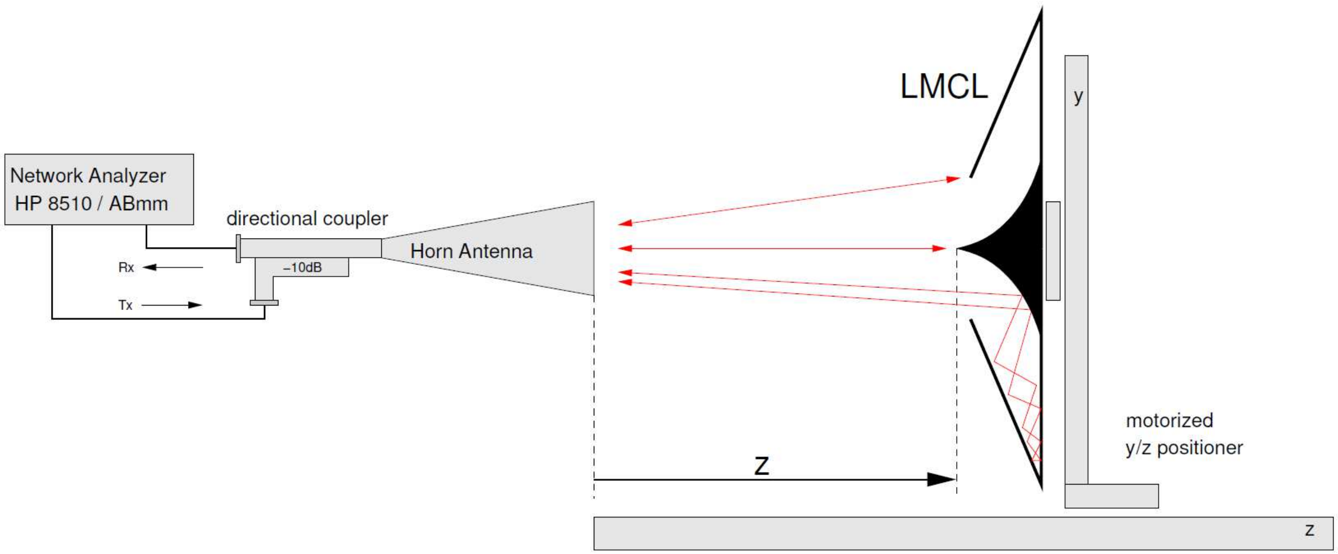
Mould plate

Spacers **(Controlling thickness)**

Base plate

Moulding rings

Active S11 Test Set-Up



The coherent backscatter or S_{11} of the target was determined using a Vector Network Analyzer (VNA) for varying distances z=0 to 0.5m between feed and LMCL aperture.

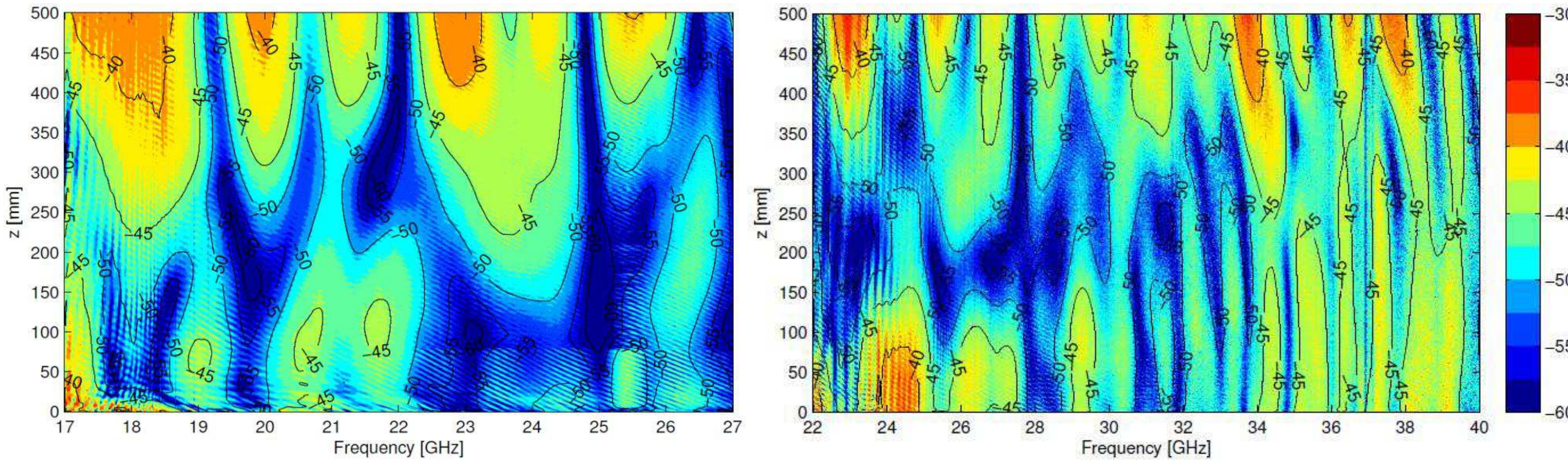
Active S11 Tests Performed

Frequency [GHz]	Waveguide Band	Aperture Diameter [mm]	Comment
17-27	K	120	Corrugated feed
22-40	Ka	80	Corrugated feed
40-65	U	53	Corrugated feed
70-100	W	90	Corrugated feed + blazed lens
160-210	G	60	Corrugated feed + elliptical reflector

This table shows the tests that were performed on the load and the feeds used

Example of Active S11 Test Results

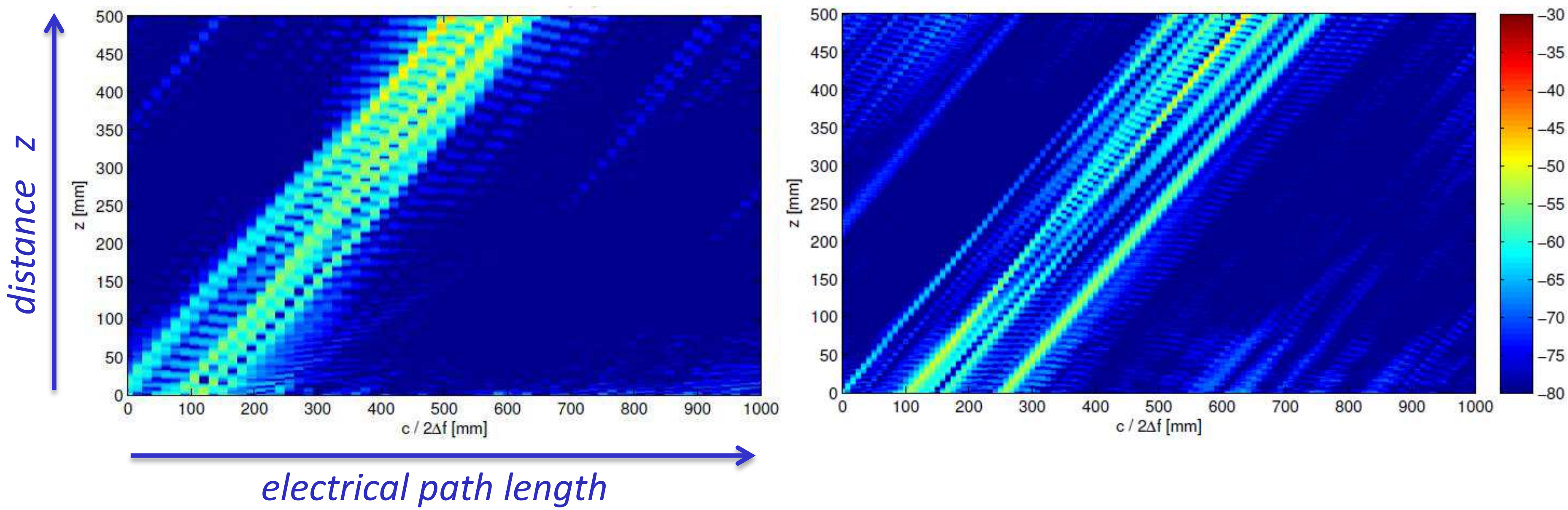
distance z



frequency

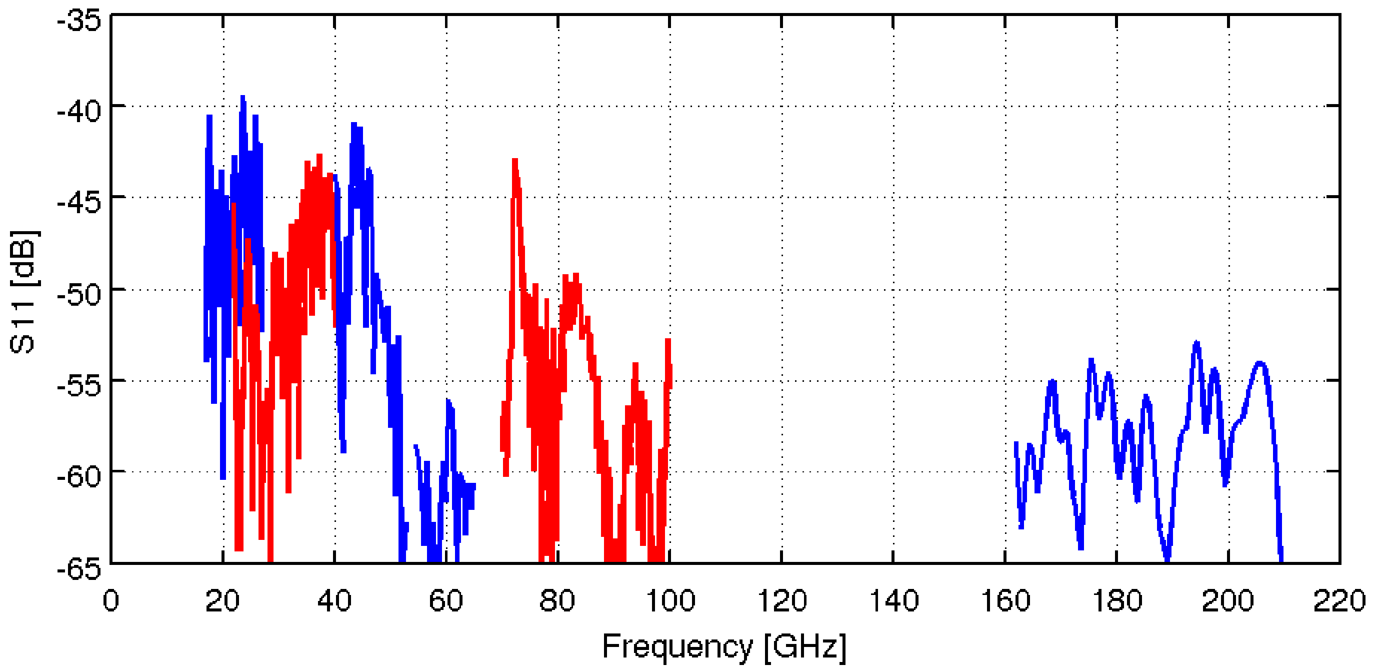
S_{11} amplitudes in K and Ka band depending on frequency and distance

Example of Active S11 Test Results (FFT Analysis)



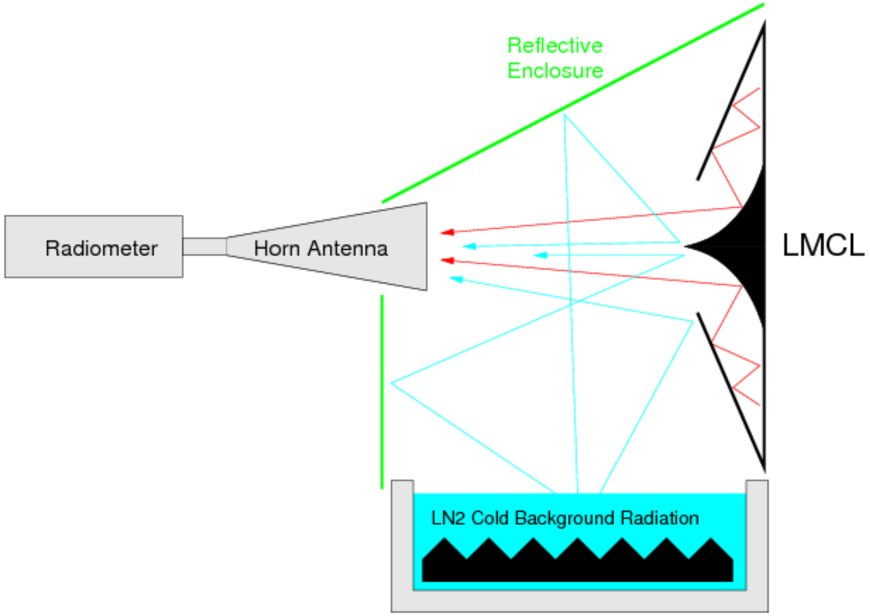
FFT Analysis of the K and Ka-band measurements allows to identify the origin of the S11

Summary of Active S11 Test Results (cf the S3 MWR at -60dB)



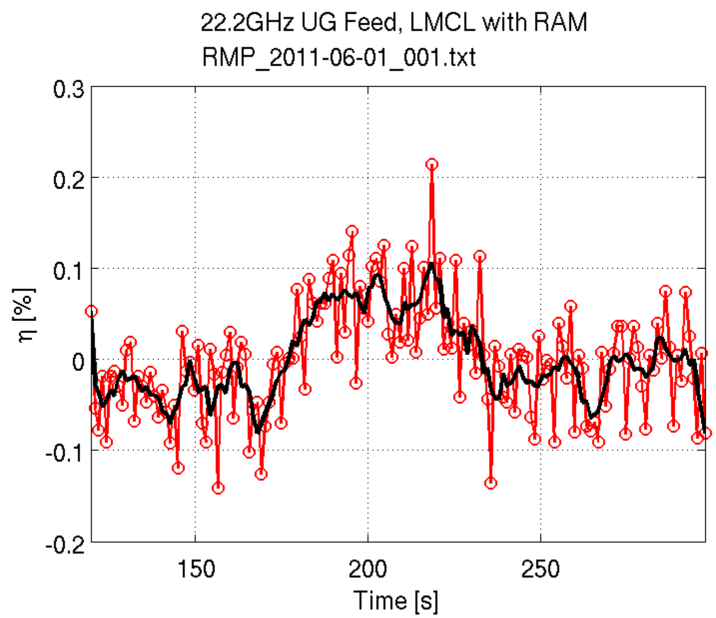
S11 test results of the LMCL target in different frequency bands at z=200mm

Passive Radiometric Test Set-Up



Schematic setup for radiometric tests with an extended LN2 background. This cold background is temporarily covered by an ambient temperature absorber

Passive Radiometric Test Example



Sample radiometric test result at 22GHz, using UG feed with Absorber Foam on the Outside of the LMCL Heat Spreader

Survival at Cold Temperatures

- One of the critical mechanical factors is the ability of the load to survive extremes of temperature
- Proof of survival has been based on experience with the Cone-based ALMA calibrators and ESA's Calibration Hot Load (CHL) testing
- Cracking and delamination are two likely failure conditions
- A number of strategies can be used from experience to protect the load from cold temperatures:
    - Casting temperature can be adjusted to mid-point of operating temperature range
    - Replacement of Eccosorb, a hard epoxy, with CRS - a softer, Silicon-based absorber
    - Change of metal structure to account for movement
- Design therefore considered safe so long as stresses relieved

LMCL Thermal study

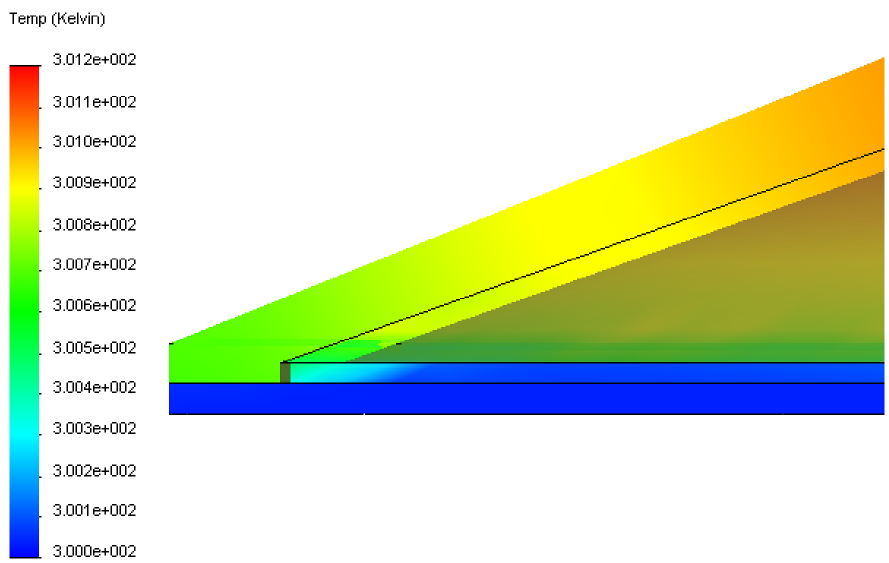
- Objective of the thermal design is to achieve the maximum temperature uniformity of the LMCL
- LMCL target temperature is 300K, environment varies from 293K to 323K
- Because of delta T, temperature gradients in the load will be present, objective is to minimise them so radiometric performance is maximised
- Two obvious approaches:
  - a) Passive thermal design
  - b) Active thermal control

LMCL Thermal study

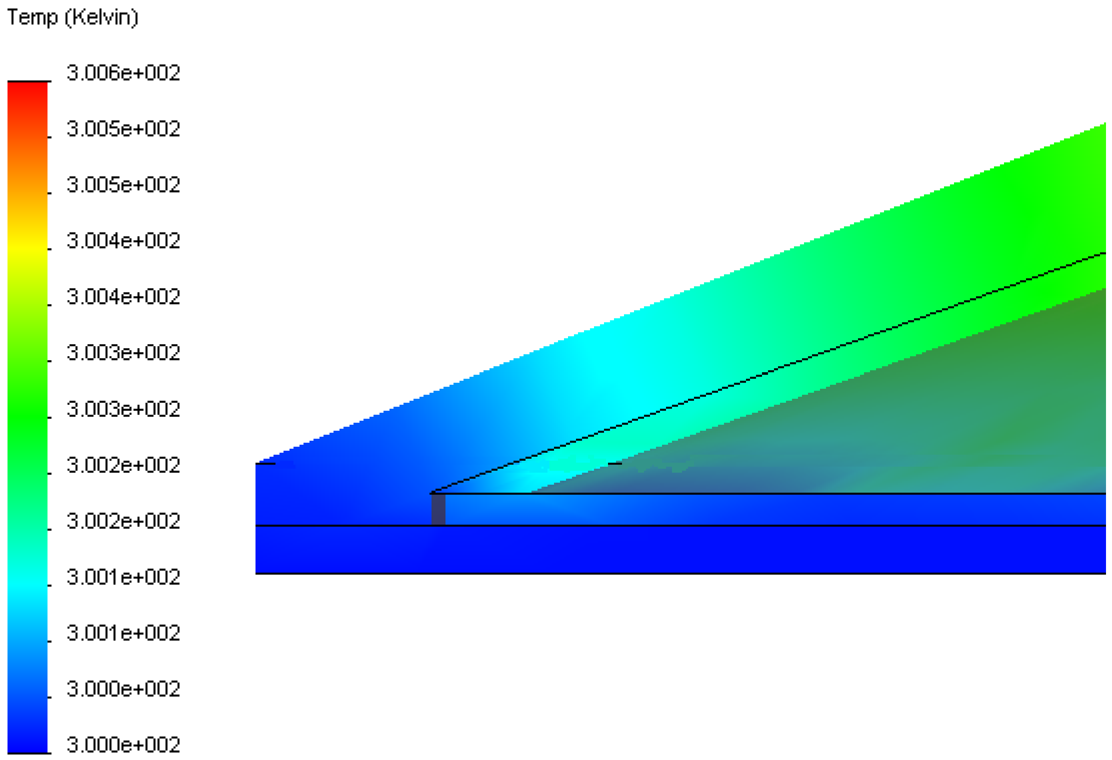
- Passive.-easier to implement, relies on careful selection of insulating materials such that load is thermally decoupled from radiative environment
- Active.- added complexity, power and mass budget (in the form of heaters and control logic), but better and finer thermal control overall
- Preferred avenue at this stage of LMCL development: passive
- In addition, thermal design was not main driver, LMCL had to perform radiometrically first and foremost

- Summary of sensitivity studies carried out:
  - Sensitivity to thermal resistance between upper body of LMCL (upper spreader) and lower body (base plate)
  - Sensitivity to upper spreader geometry
  - Sensitivity to IR emissivity of upper surface of LMCL

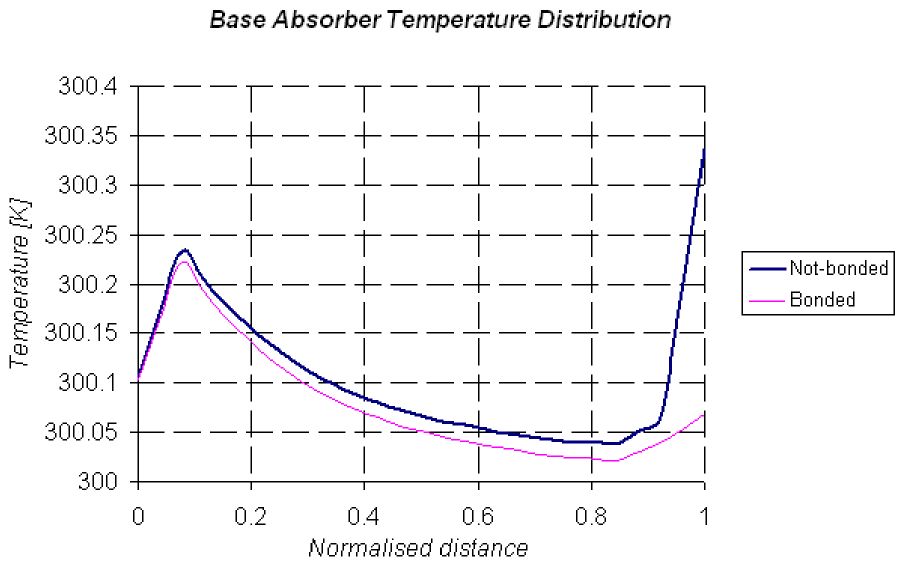
- Sensitivity to contact thermal resistance:
- Spread of results is wide depending on values of contact thermal resistance (i.e. From fully bonded to bolted: 850mK to 1150mK average lower-to-upper spreader gradient

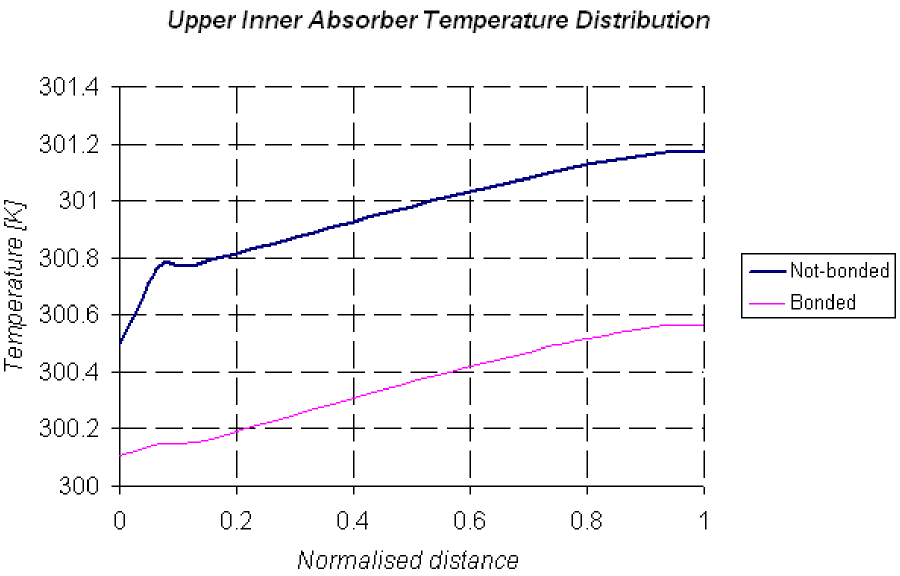


- Best performing configuration is when upper and lower spreaders are fully bonded~280mK maximum delta T



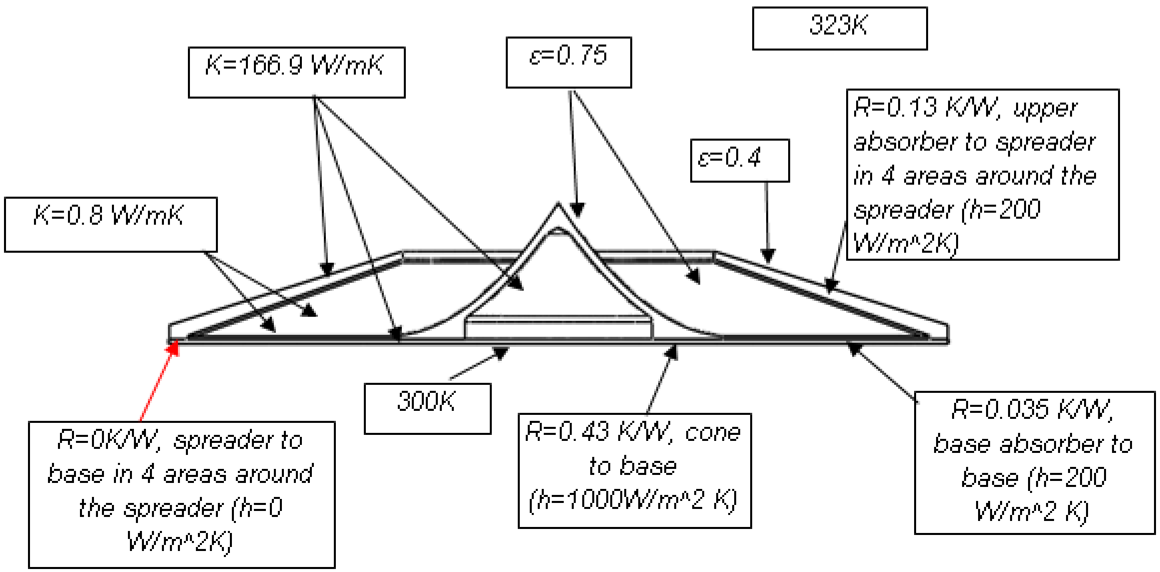
- Best performing configuration is when upper and lower spreaders are fully bonded~600mK maximum delta T





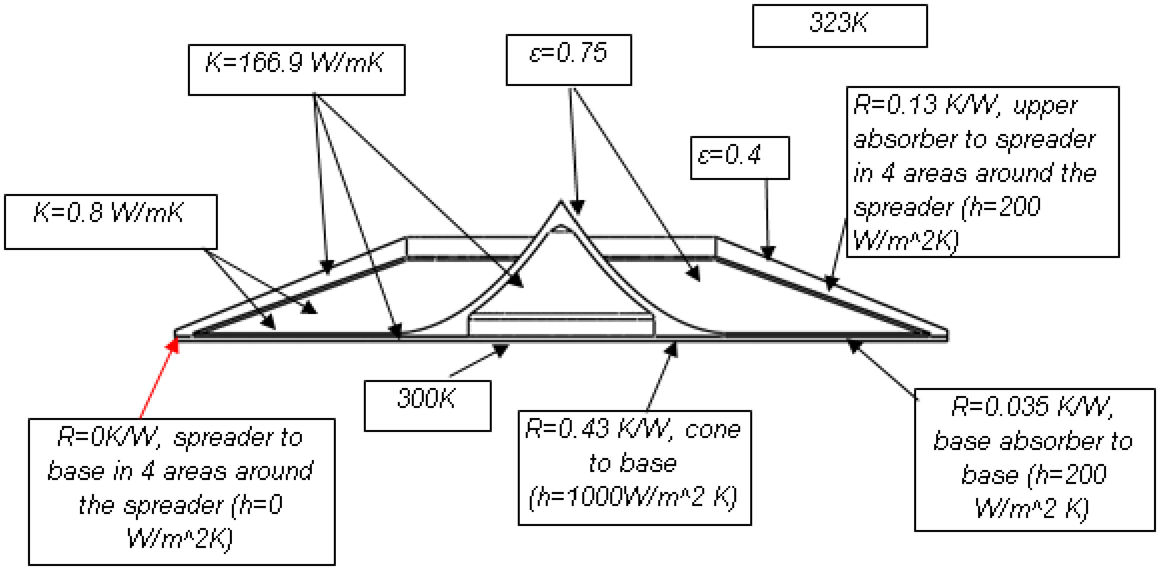
Minimising thermal resitance at bolted joint maximised temperature uniformity~300mK

- Several upper heat “spreader” geometries have been analysed:



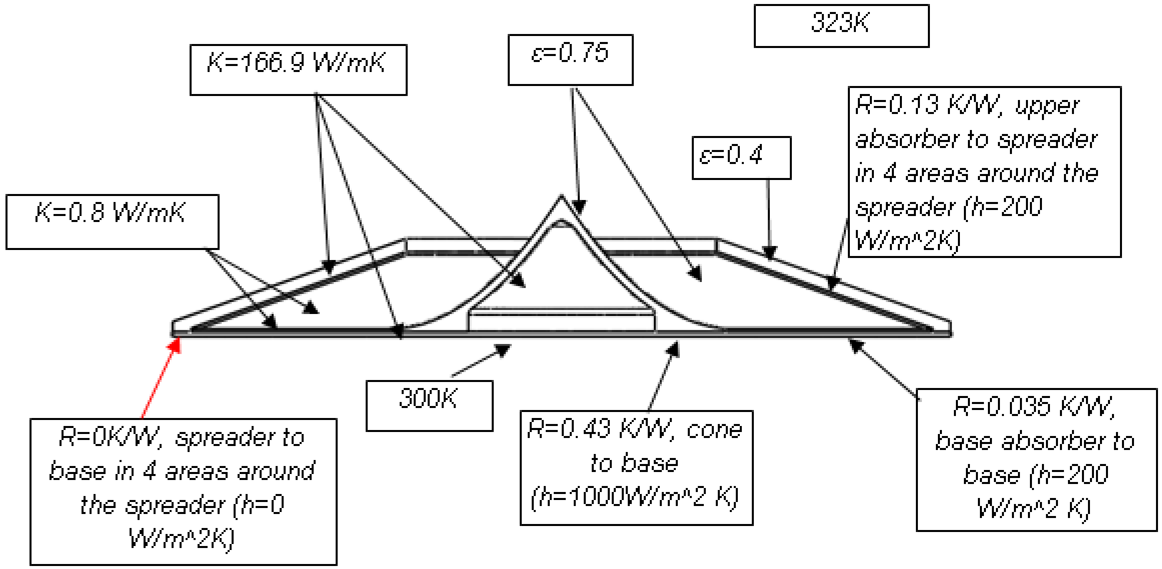
  - Thick-to-thin spreader (current)

- Several upper heat “spreader” geometries have been analysed:



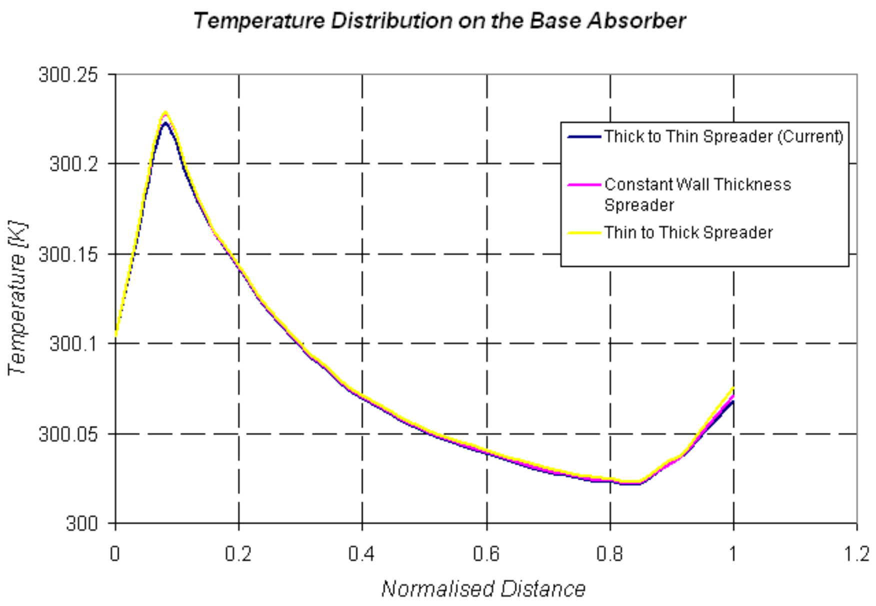
  - Thin-to-thick

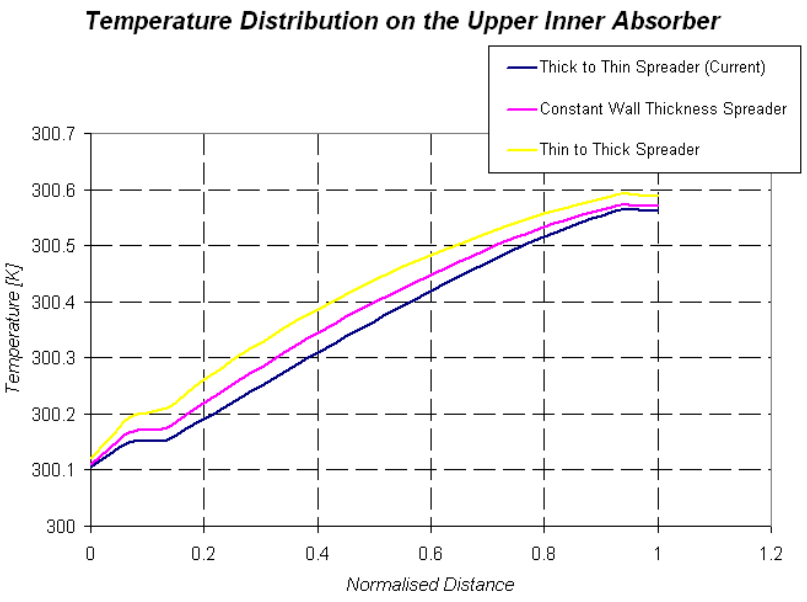
- Several upper heat “spreader” geometries have been analysed:



- Constant thickness

- Several upper heat "spreader" geometries have been analysed:



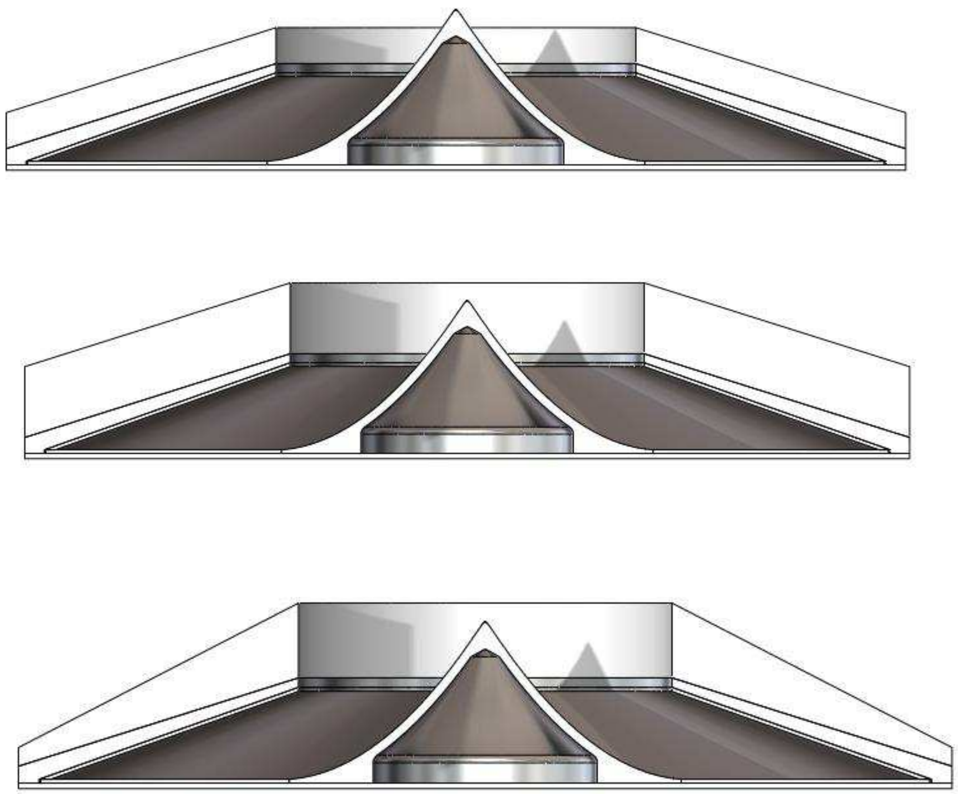


- Thick-to-thin upper spreader offers best performance

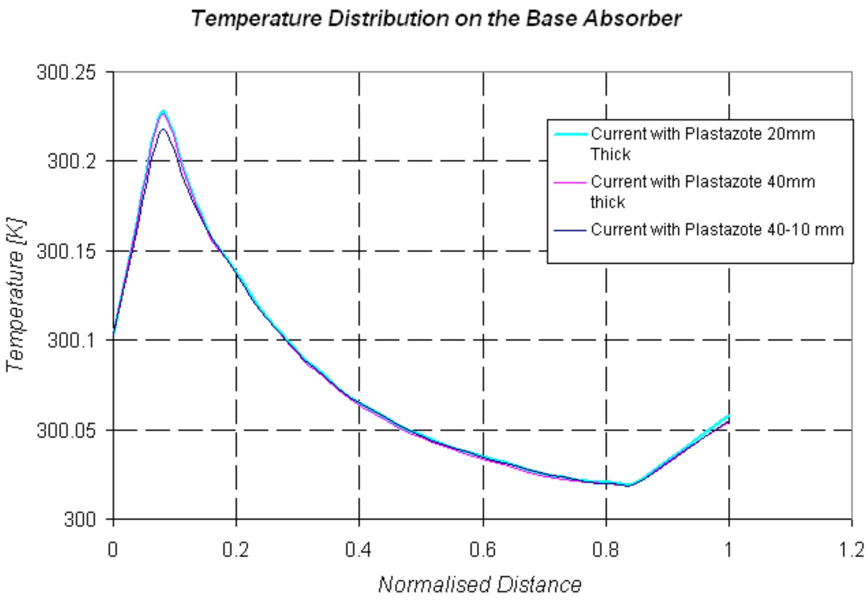
- Sensitivity to IR emissivity of upper surface of LMCL: Not feasible, IR emissivity of upper surface of load had to be very low, equivalent to highly reflective metallic surface this would have affected the radiometric performance of the load
- Last resource.- Insulate the load by means of a low conductivity material
- Cross linked polyethylene barrier has been shown to be an effective thermal insulator in a paper by Giovanni de Amici *et al: Stabilization of the Brightness Temperature of a Calibration Warm Load for Spaceborne Microwave Radiometers*

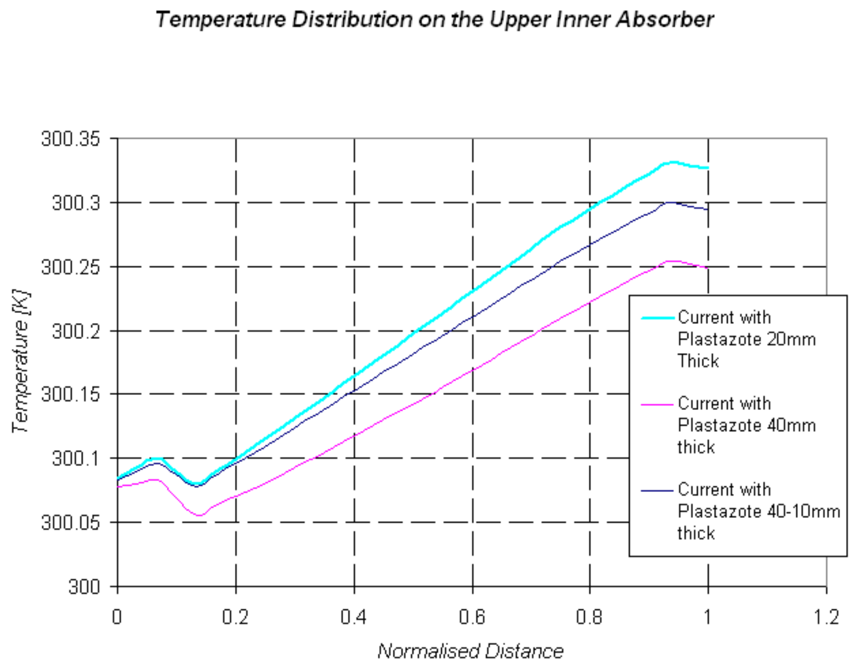
- This material has excellent radiometric performance (measurements were made at 180GHz) and good IR properties (the IR emissivity is lower than that of the bare microwave absorber: 0.5 vs 0.75)
- The lower emissivity of the polyethylene ensures the radiative coupling with ambient gets minimised
- In addition, the low conductivity of the polyethylene (0.0387 W/mk) isolates the load conductively from the upper surface exposed to ambient

- Several polyethylene slab geometries were analysed:

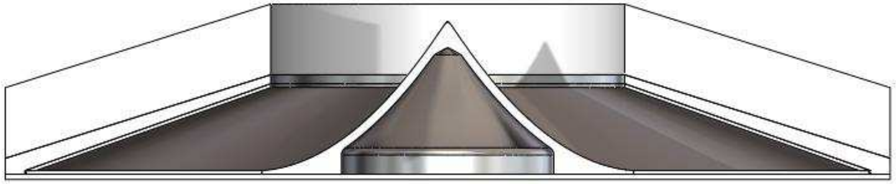


- Several polyethylene slab geometries were analysed:



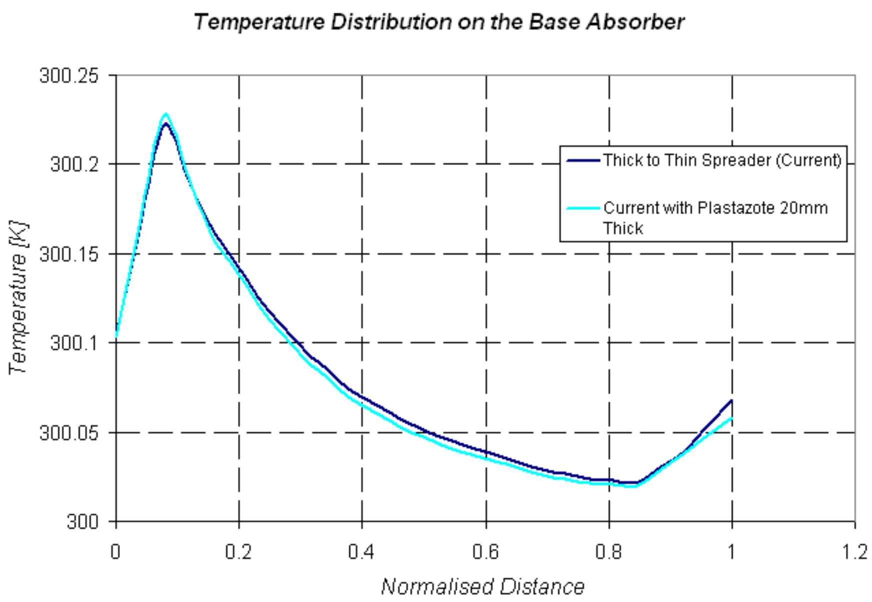


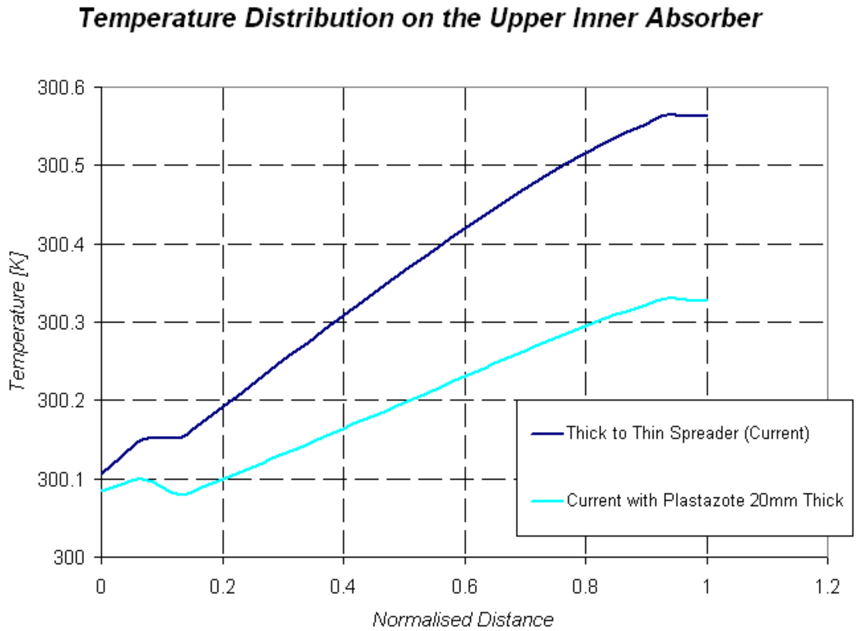
- Best performing from a thermal viewpoint (40mm thick):



- However, due to potential height limitations (20mm thick):

LMCL Thermal study



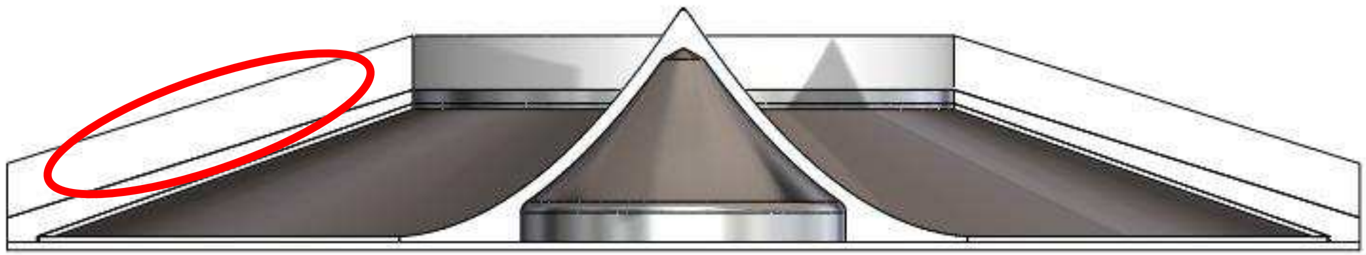


- Assuming that base of load is fully bonded to load upper spreader then temperature difference between absorber lower and upper average temperatures:280mK
- This is worst case as FE model assumed polyethylene barrier is bonded to upper spreader (i.e. No thermal contact resistance)

- Assumptions have been made on the values of contact resistances
- Thermal analysis can be fine-tuned if accurate values of thermal resistance were known:
  - For bolted interfaces if they were to be used
  - Thermal resistance between absorber and aluminium body has been estimated as negligible (through testing)

- Absorber –to-base contact resistance: negligible

- Polyethylene barrier thermal properties, real performance will improved due to added thermal resistance at interface (not considered in FE analysis)

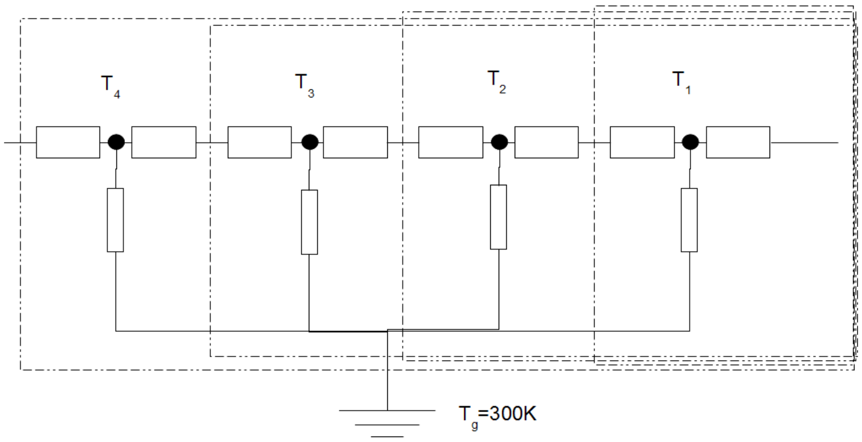


- However, best radiometric performance required a multi-layered absorber arrangement: gradients will get worse
- Parametric tool allows quick gradient assessment for up to three absorber layers
- Also, testing has shown thermal resistance between absorber layers is negligible
- Thermal problem complex but solvable, may require a combination of insulating materials (such as Plastazote) and active heaters in order to achieve the required 100mK gradient

Thermal Measurements

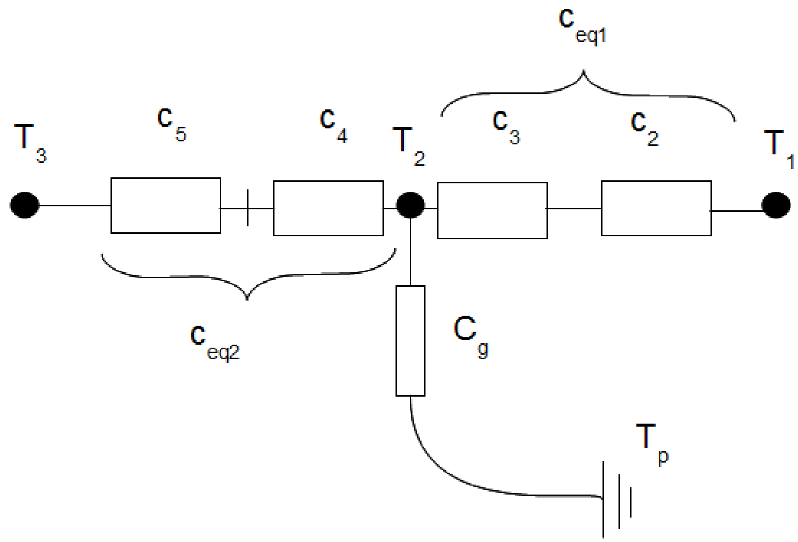
- Thermal conductivity measurements were undertaken at NPL in the UK
- Test measurement technique was guarded heat-flow
- Layered epoxy material used for the test at a mean ambient temperature of 27degC
- Material samples were held under compression between two polished metal surfaces, each controlled at a different temperature
- One surface is part of a heat flux transducer
- As heat flows from the upper surface to the lower, the temperature gradient is measured
- Using these values, the thermal conductivity of the samples can be calculated.

Model Development: Thermal model



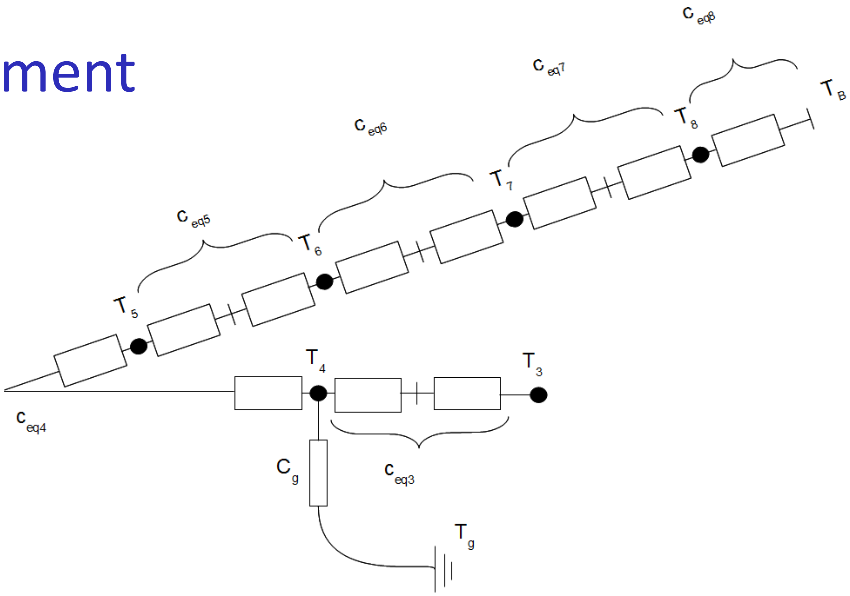
Thermal Mathematical Model consisted of four nodes conductively coupled across load base. Nodes also have conductive couplings between them and radiative coupling to the environment

Model Development



- *Thermal pathways in plane are analysed to calculate the steady-state nodal temperatures*
- *Equivalent conductances are calculated by combining the thermal paths and paths to ground plane*

Thermal Model Development



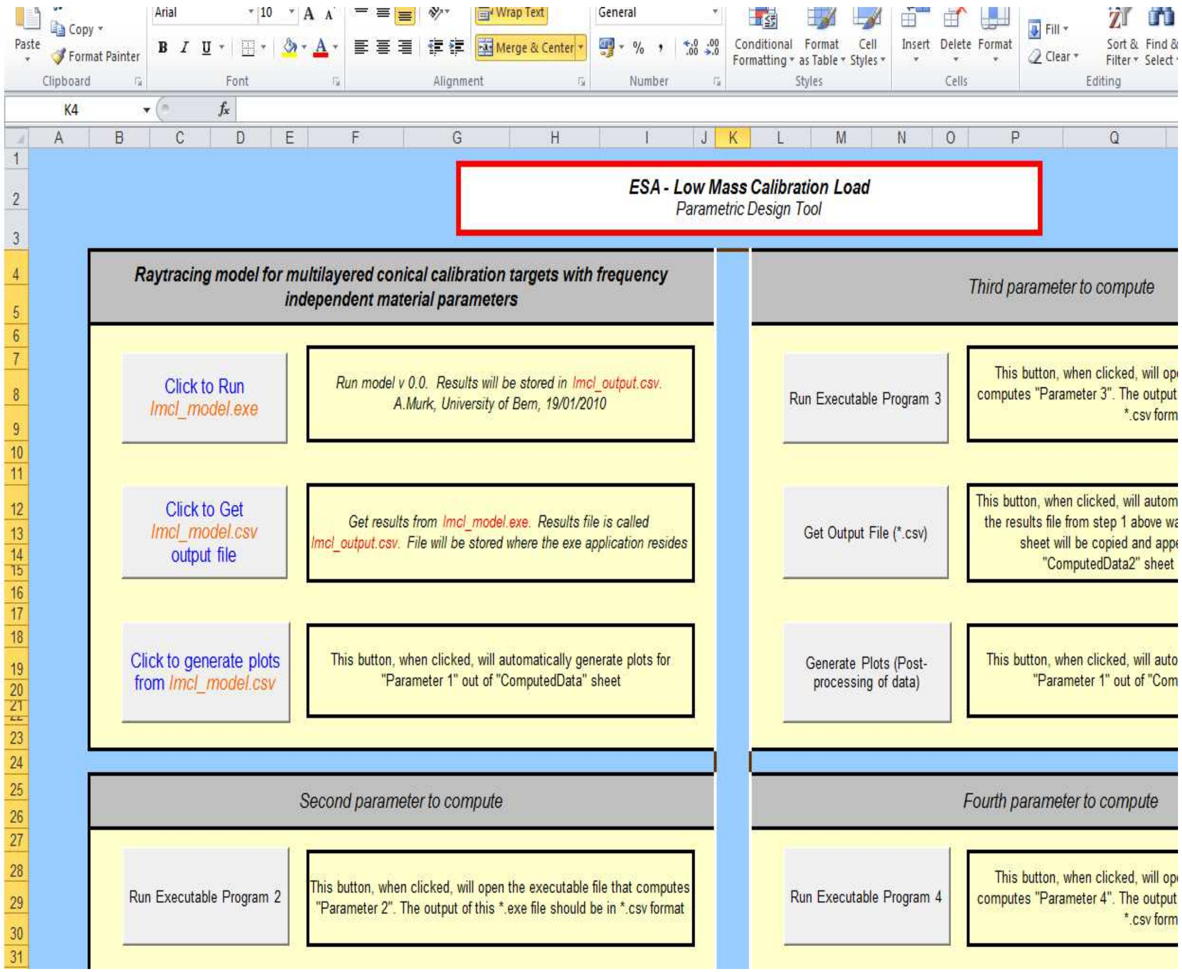
- *Analysis extended to side walls in similar manner, side wall consists of 4 thermal nodes (8 in total)*
- *Radiative coupling is then determined at each of the nodes taking FE analysis results as a baseline*
- *Radiative gains are held constant in parametric design tool, enabling absorber thickness effects to be analysed without creating intractable multi-variate scenario*

Model Implementation

Second step.- User runs radiometric subroutines, .csv input file is read automatically and output .csv file is generated which contains results

Third step.- User gets output .csv file and data gets copied automatically into master spreadsheet

Fourth step.- Plots are generated automatically



Model Implementation

User Input			
Conductivity of layer 1	0.7	W/mK	
Conductivity of layer 2	0.7	W/mK	
Conductivity of layer 3	0.7	W/mK	
Thickness of layer 1	0.002	m	
Thickness of layer 2	0	m	
Thickness of layer 3	0	m	

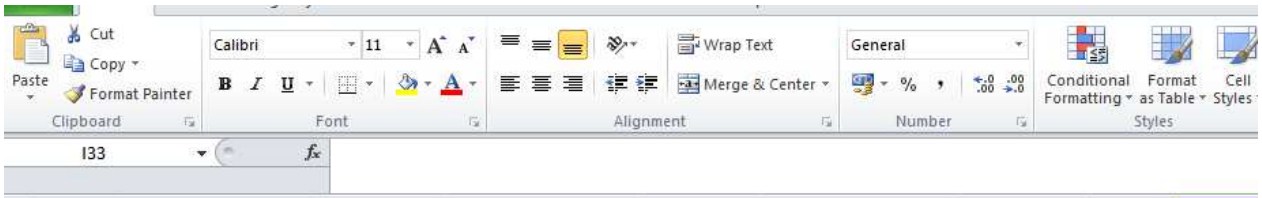
Step one.- User inputs material and layer geometric data

Model Implementation

Resistance-through-thickness calculation of base plate absorber					
Conductance between upper surface of absorber material and base plate, section 1					
Material 1		Material 2		Material 3	
Conductivity	0.7	Conductivity	0.7	Conductivity	0.7
Thickness	0.002	Thickness	0.003	Thickness	0.003
Area	0.0254	Area	0.0254	Area	0.0254
Thermal resistance	0.112485939	Thermal resistance	0.168728909	Thermal resistance	0.168728909
Total thermal resistance (in series)	0.449943757				
Total thermal conductance	2.2225				
Conductance between upper surface of absorber material and base plate, section 2					
Material 1		Material 2		Material 3	
Conductivity	0.7	Conductivity	0.7	Conductivity	0.7
Thickness	0.002	Thickness	0.003	Thickness	0.003
Area	0.03236	Area	0.03236	Area	0.03236

Step two.- In-plane and through-plane conductances get calculated for up to 3 layers

Model Implementation



	A	B	C	D	E	F	G	H
1								
2		Nodal temperature information, absorber conductivity and thickness, this data should never change, this is extracted from FE simulations						
3		T1	300.185	T9	300.0511	Conductivity	0.8	
4		T2	300.0725	T10	300.134	Thickness	0.002	
5		T3	300.0325	T11	300.205			
6		T4	300.0325	T12	300.25			
7		T5	300.086					
8		T6	300.16					
9		T7	300.241					
10		T8	300.318					
11		Tbaseplate	300	Tcone	300.1			
12		Tenvironment	323					
13		Tedge of section 8	300.3273					
14–15		Resistance-through-thickness calculation of base plate absorber						
16		Conductance between upper surface of absorber material and base plate, section 1						
17		Material 1		Material 2		Material 3		

Radiation input to Node 1	
To base plate	1.64465
To cone	0.005086
To node 2	0.004095
Q rad	1.653831

Radiation input to Node 2	
From node 1	0.004095
To base plate	0.821135
To node 3	0.001809
Q rad	0.818849

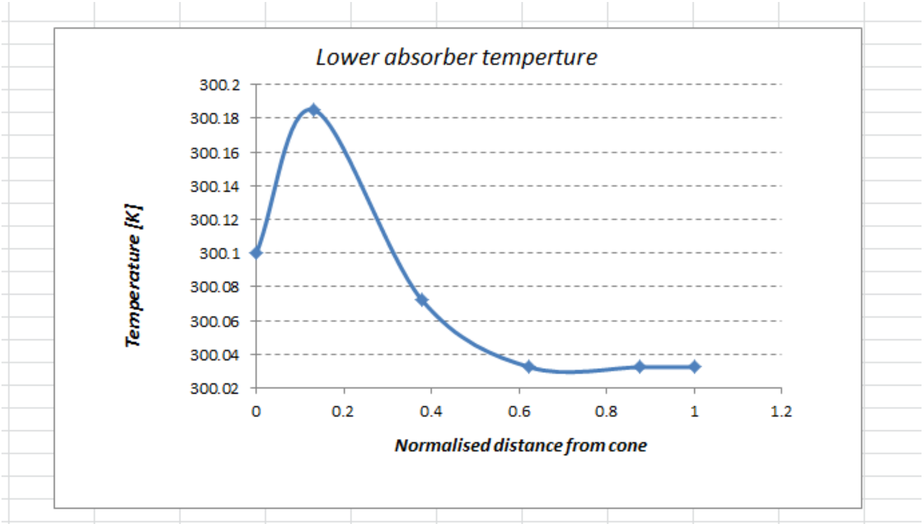
Step three.- Using data from FE thermal simulation, radiative couplings to ambient are calculated for known nodal temperatures and baseline geometry (1 two mm thick layer of absorber material)

Model Implementation

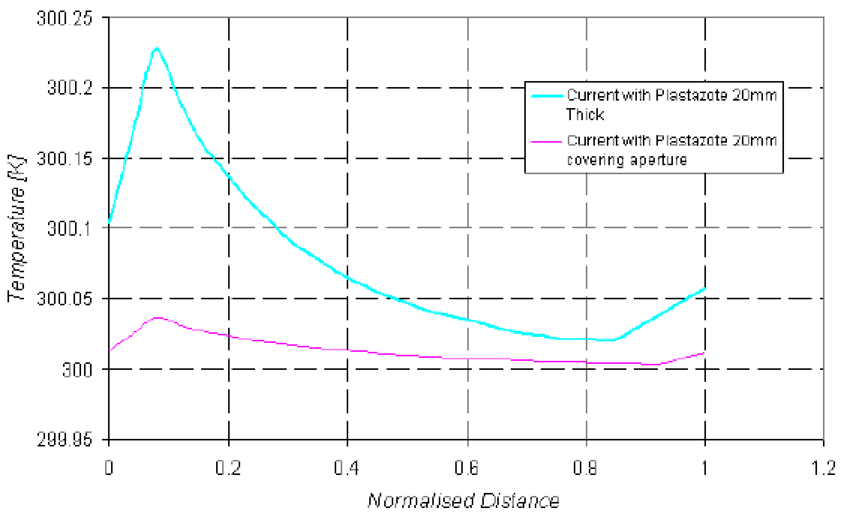
	L	M	N	O	P	Q	R	S	T	U	V	W
2												
3		Q	C	0	0	0	0	0	0	Alfa		
4		C	R	E	0	0	0	0	0	Beta		
5		0	E	S	G	0	0	0	0	Gamma		
6	INPUT	0	0	G	T	I	0	0	0	Delta		
7		0	0	0	I	U	O	0	0	Eta		
8		0	0	0	0	O	V	M	0	Theta		
9		0	0	0	0	0	M	W	K	Iota		
10		0	0	0	0	0	0	K	X	Kappa		
11												
12		T1	T2	T3	T4	T5	T6	T7	T8	Vector of loads for baseline	Vector of loads for case being simulated	Solution for case being simu
13	T1	-8.98623	0.036404	0	0	0	0	0	0	-2686.608969	-2686.608969	300.185
14	T2	0.036404	-11.4076	0.045229	0	0	0	0	0	-3398.618849	-3398.618849	300.0725
15	T3	0	0.045229	-13.8543	0.054049	0	0	0	0	-4126.945228	-4126.945228	300.0325
16	T4	0	0	0.054049	-16.3009	0.060069	0	0	0	-4856.562857	-4856.562857	300.0325
17	T5	0	0	0	0.060069	-16.9023	0.052717	0	0	-5038.29321	-5038.29321	300.086
18	T6	0	0	0	0	0.052717	-14.3014	0.043903	0	-4263.698105	-4263.698105	300.159987
19	T7	0	0	0	0	0	0.043903	-11.7046	0.03507	-3490.389776	-3490.432916	300.2367529
20	T8	0	0	0	0	0	0	0.03507	-9.13872	-2733.992394	-2733.992394	300.3179837
21												

Step four.- The user can specify any combination of absorbers and thermal properties (up to three layers) and the matrix of conductances and thermal loads is calculated automatically for him. Using a excel function, the system of equations gets solved for the 8 nodal temperatures

Model Implementation



Nodal Network



FE model (cyan)

Step five.- Temperature plots are generated

Model Implementation: Radiometric performance

- *Model uses a four-step process*
- *First step.- Model generates .csv file to be read by executable file based on user inputs*