Appendix F

Thermal Design and Analysis of the SPICE Primary Mirror

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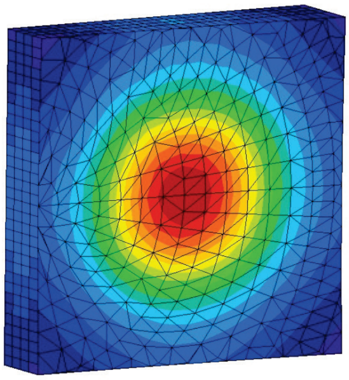
Abstract

The Spectral Imaging of the Coronal Environment (SPICE) is a payload on-board ESA's Solar Orbiter satellite. The instrument is a high resolution imaging spectrometer operating at ultraviolet wavelengths. The Rutherford Appleton Laboratory is responsible for the design and build of this instrument. Current design status for SPICE represents that at preliminary design review (PDR).

The primary mirror is a component on-board SPICE that is used to reflect EUV light to the detector assembly via a diffraction grating. The mirror is constructed from fused silica and has a boron carbide coating on the sun facing side. One of the key challenges of the SPICE instrument is for the primary mirror to manage the high heat load and resulting thermal deformations at perihelion (0.284AU). For this reason, the primary mirror has been designed to maximise the amount of EUV light (used for science observations) that is reflected whilst trying to minimise absorption in the remaining part of the spectrum. A detailed geometrical mathematical model (GMM) and thermal mathematical model has been created for this component using ESATAN-TMS. The GMM has utilised a CAD converter to ensure an accurate representation of the geometry of the mirror. The TMM has employed equations to model the spectral absorption through the silica medium of the mirror. The model is being used to provide inputs to the thermo-elastic deformation analysis of the mirror.

RAL Space

SPICE Primary Mirror Thermal Modelling



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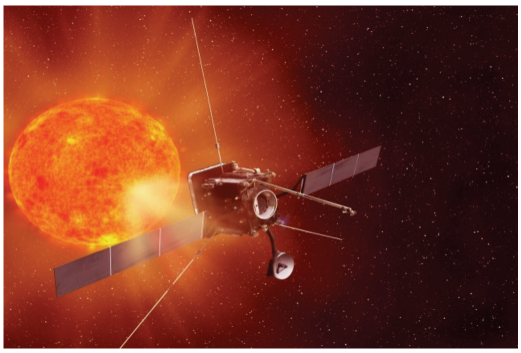
26th European Space Thermal Analysis Workshop, 20th -21st November

RAL Space

Agenda

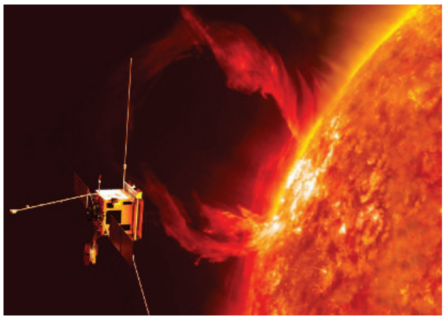
- SPICE overview
- Primary mirror overview
- Introduction
- Modelling challenges
- Geometrical Modelling
- Conductive heat transfer
- Thermo-optical properties
- Radiative attenuation
- Thermal predictions
- Summary of results
- Conclusions
- Questions

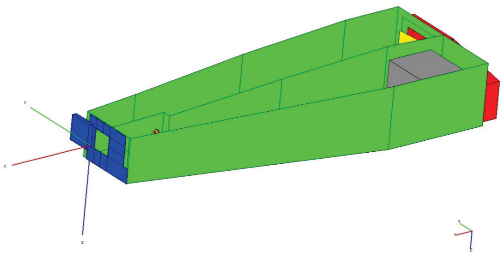


SPICE Overview

RAL Space

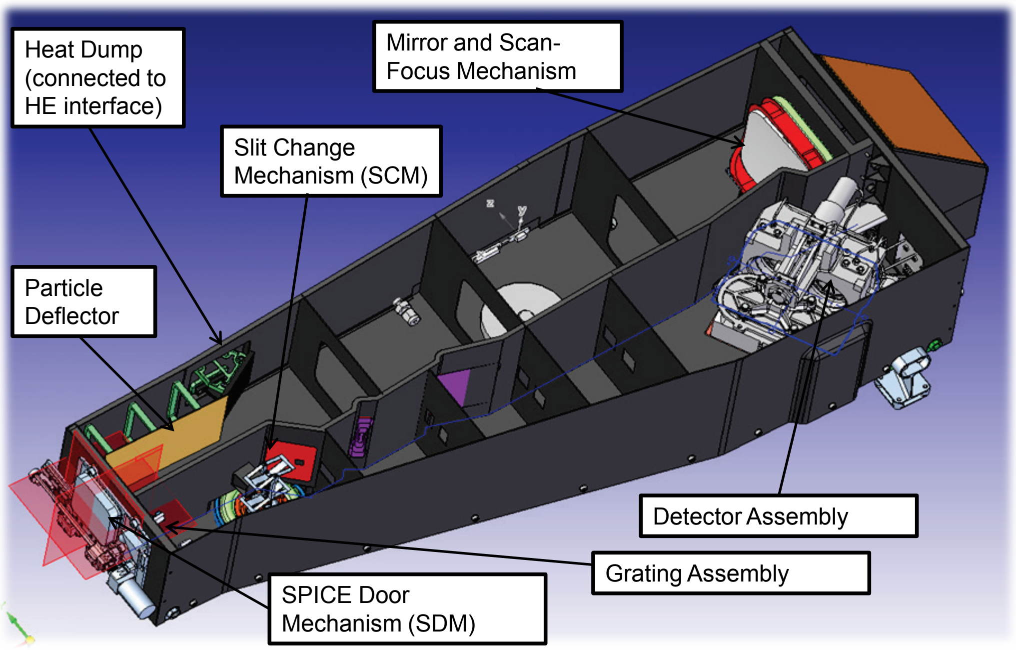
- Spectral imaging of the coronal environment (SPICE)
- High resolution spectrometer, recording EUV spectra and spectral lines from the Sun's atmosphere
- Payload on-board ESA's Solar Orbiter satellite
- Key science:
  - ➢ Solar wind
  - ➢ Coronal mass ejections
  - ➢ Solar dynamo





SPICE Overview

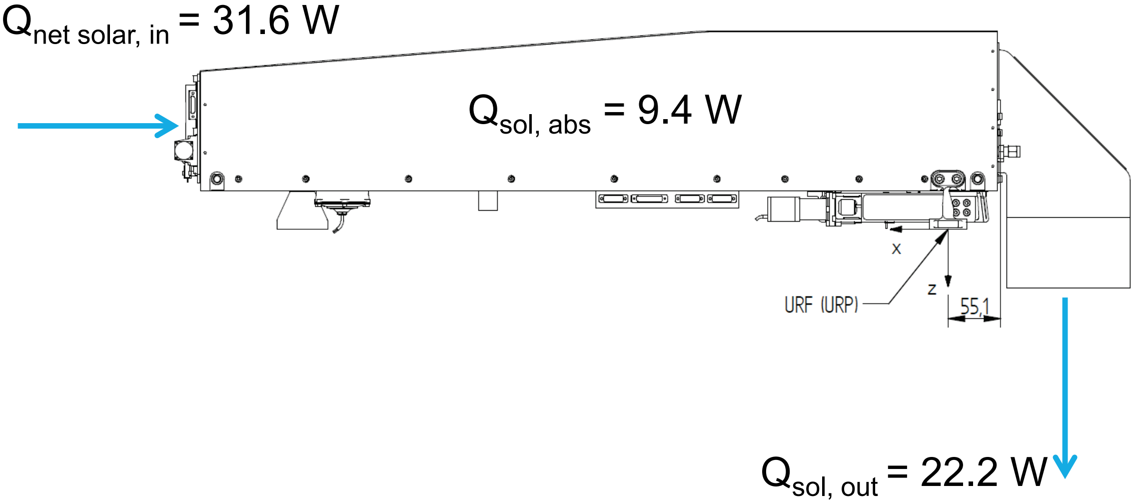
RAL Space



SPICE Overview

RAL Space

$Q_{net\ solar,\ in} = 31.6\ W$



$Q_{sol,\ out} = 22.2\ W$

Primary Mirror Overview

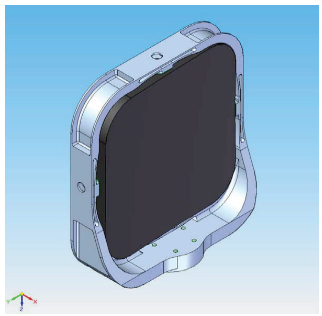
RAL Space

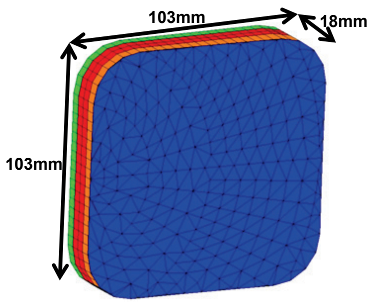
- Reflects EUV solar radiation (used for science observations), transmits unwanted solar energy which is then rejected to space

Construction:

  - Fused **silica** substrate with **boron carbide** (B_4C) coating* on **parabolic** front face

- Critical component on SPICE instrument
- Low thermal conductivity (1.5 W/mK)
- Mounted with titanium mount
- Focus adjusted using scan focus mechanism (SFM)





*** Boron carbide coating data produced by the Max-Planck-Institut für Sonnensystemforschung (MPS)**

Introduction

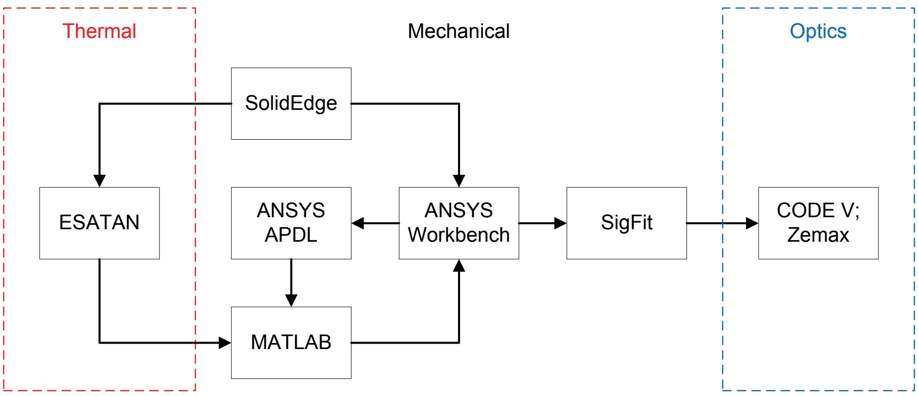
Aim:

- Create an accurate thermal model of the SPICE primary mirror to provide inputs for the thermo-elastic analysis
  - ➢ Thermal deformation of optical surface

Design drivers:

- Manage high heat load at perihelion (~31 W incident at 0.284 AU)
  - ➢ Minimise temperature gradients and differential thermal expansion
- Modelling using ESATAN-TMS R4

Introduction



Workflow diagram

Modelling Challenges

RAL Space

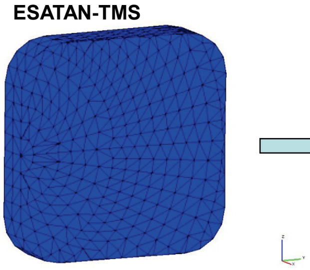
- Difficult geometry (parabolic front face)
- Wavelength-dependent thermo-optical properties:
  - ➢ Solar properties
  - ➢ Infrared properties
- Attenuation of solar load through silica medium:
  - ➢ Wavelength-dependence
  - ➢ Feature not available in ESATAN
- Transfer of data to ANSYS for thermo-elastic modelling
  - ➢ Efficient and accurate process

Geometrical Modelling

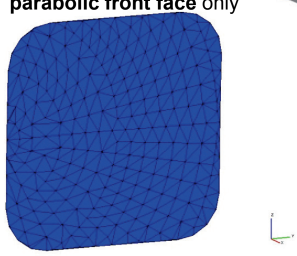
RAL Space

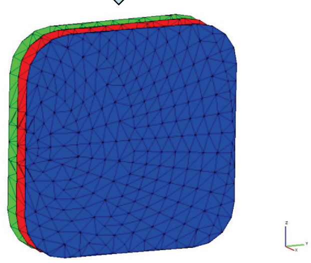
1. Import geometry into **CADbench**

2. Convert & import into **ESATAN-TMS**

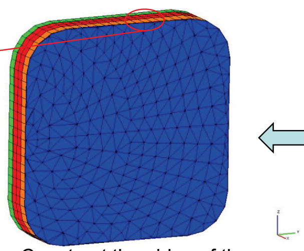


3. Break model down into **parabolic front face** only

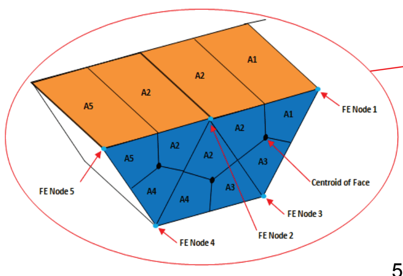




4. Build **nodal layers** through the thickness of the mirror

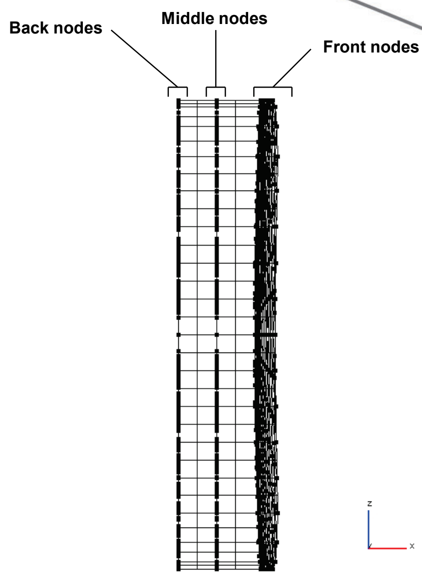


5. Construct the sides of the mirror to coincide with **FE nodal boundaries**



Conductive Heat Transfer

- Mirror broken down into **3** layers of finite element (FE) nodes through the thickness
  - *Front* nodes (269 nodes)
  - *Middle* nodes (269 nodes)
  - *Back* nodes (269 nodes)
- Thickness of each set of nodes set appropriately
- Conductive links across each layer of nodes generated by ESATAN-TMS using FE analysis
- Conductive links between layers input into the model using lumped parameter analysis

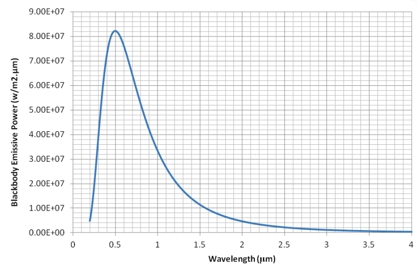


Thermo-optical Properties

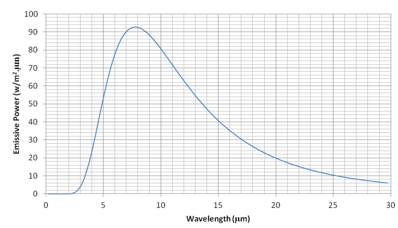
- Wavelength-dependent solar and IR properties:
  - B_4C coating*
  - Silica
- Simulated using weighted average values (not ESATAN function):

$$X_\theta \approx \frac{\int_0^\infty X_\theta(\theta,T)E_{\theta,b}(\theta,T)d\theta}{\int_0^\infty E_{\theta,b}(\theta,T)d\theta}$$

- Calculated values used within ESATAN-TMS:
  - Transmissivity (B_4C) = ~ 0.8
  - Reflectivity (B_4C) = ~ 0.1
  - Absorptivity (B_4C) = ~ 0.1
  - Emissivity (silica) = ~ 0.97



Planck blackbody emissive power for the Sun (5770K)



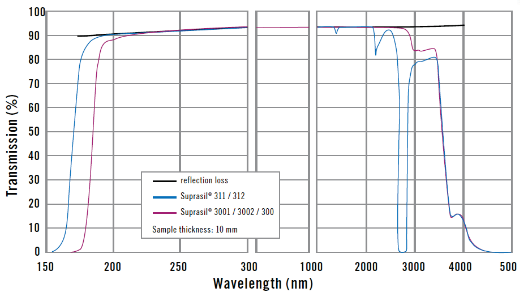
Planck blackbody emissive power for an object at 100°C (approx. Temperature of the mirror)

* Boron carbide coating data produced by the Max-Planck-Institut für Sonnensystemforschung (MPS)

Radiative Attenuation

Theory:

- High internal transmissivity (95-98%) between 0.2µm - 2.0µm
  - ➢ 94% (29.1 W) of the incident solar energy is distributed in this spectral band
- The internal transmissivity decreases between 2.0µm - 5.0µm
  - ➢ 5.5% (1.7 W) of the incident solar energy
- At wavelengths greater than 5.0µm the silica is essentially opaque
  - ➢ 0.5% (0.2 W) of the incident solar energy



External transmissivity for Heraeus Suprasil silica

Radiative Attenuation

Theory:

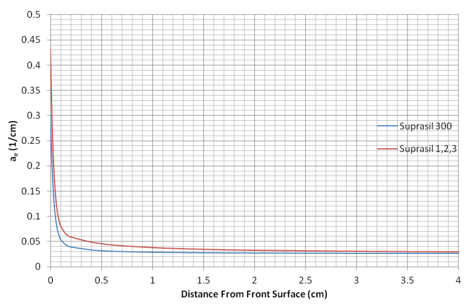
- Solar radiation is attenuated through the silica medium according to linear absorption coefficients , a_θ
  - ➢ Wavelength-dependent property
- Beer-lambert law used to calculate internal transmissivity:

$$\tau_I(\theta,T) = \exp\left(-a_\theta(\theta,T)t\right)$$

- Mean absorption coefficient, a_e, calculated using a weighted average that varies through the thickness of the silica medium

$$\tau_I(\theta,T) = \exp\left(-a_e(\theta,T)t\right)$$

$$\underbrace{a_e(t,T)}_{\text{Mean absorption coefficient}} \approx \frac{\int_0^\infty \overbrace{a_\theta(\theta,T)}^{\text{Absorption coefficient}} \overbrace{E_{\theta,b}(\theta,5770K)}^{\text{Black body emissive power}} \overbrace{e^{(-a_\theta(\theta,T)t)}}^{\text{Internal Transmissivity}} \overbrace{\tau_S(\theta)}^{B_4C\text{ Transmissivity}} d\theta}{\int_0^\infty E_{\theta,b}(\theta,5770K)e^{(-a_\theta(\theta,T)t)}\tau_S(\theta)d\theta}$$



Mean absorption coefficient through the thickness of the mirror

Radiative Attenuation

RAL Space

Modelling:

- TMM splits the mirror thickness into 28 segments
  - Constant a_e through each segment
  - 17 segments for first 1mm
- Nodal absorption attributed as follows:
  - Front nodes → **Boron carbide absorbed + internal absorption (0-1mm)**
  - Middle nodes → **Internal absorption (1-10mm)**
  - Back nodes → **Internal absorption (10-18mm)**

Radiative Attenuation

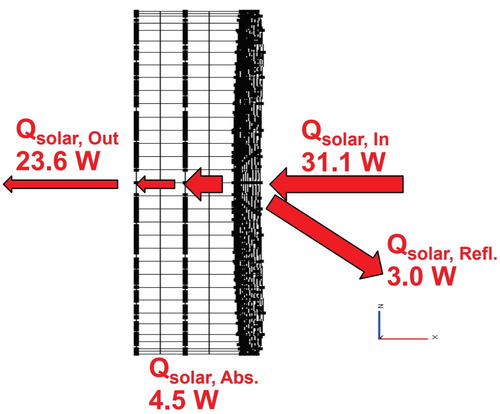
RAL Space

Modelling:

- Total solar absorption (4.5 W) broken down as follows:
  - Front nodes = 3.1 W
  - Middle nodes = 0.8 W
  - Back nodes = 0.6 W

Mirror Segment	Solar Absorbed (W)		
	0.2μm - 2.0μm	2.0μm – 5.0μm	>5.0μm
10nm B4C layer	**2.80**	0.00	0.00
0-1mm	0.08	0.09	0.15
1-10mm	0.57	0.18	0.01
10-18mm	0.52	0.07	0.00

Absorbed solar loads through the mirror

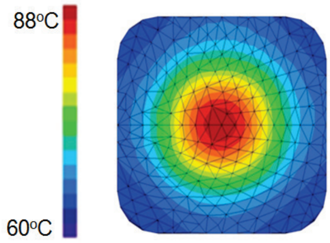


Thermal Predictions

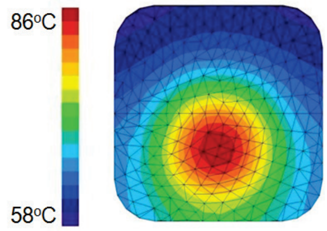
RAL Space

At perihelion (on-axis pointing):

- Solar footprint:
  - ➢ ~70mm x 70mm square centred on mirror
  - ➢ Differential solar flux across footprint
- Temperature predictions:
  - ➢ Peak temperature = **88°C**
  - ➢ Max gradient through thickness = **7°C**
  - ➢ Max gradient across nodal layers = **24°C**



Perihelion temperature plot
On-axis



Perihelion temperature plot
Off-axis +0.95° rotation about y-axis

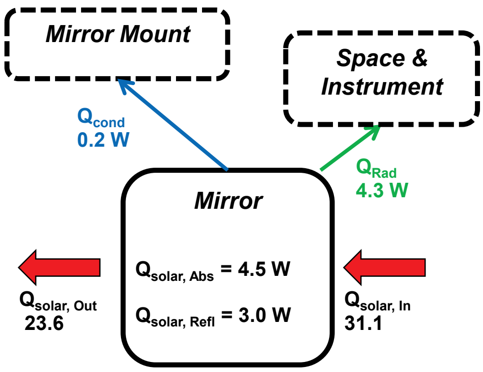
Summary of Results

RAL Space

- High peak temperatures and gradients at perihelion:
  - ➢ Large solar absorbed load
  - ➢ **Low thermal conductivity** of the silica
  - ➢ Differential solar flux across footprint

  → **BUT silica has a very low CTE so can cope with these gradients**

- Radiation is the dominant mode of heat transfer for the mirror
  - ➢ **Low conductance** from mirror to mount (undesirable feature)
  - ➢ **High emissivity** (desirable feature)

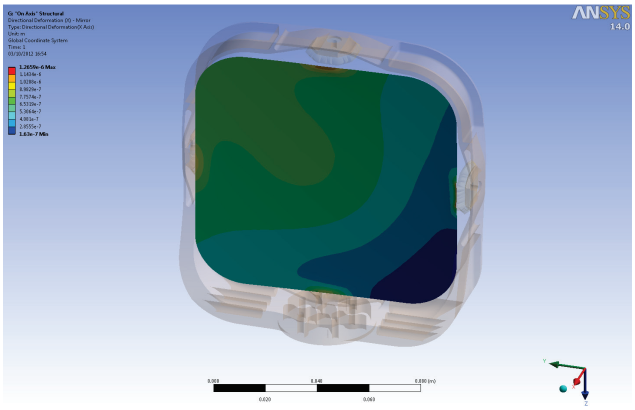


Mirror energy balance

Summary of Results

RAL Space

- Mounting configuration has little impact on thermal gradients
- Mirror surface deformation: curvature ~**0.2 µm**
  - ➢ Focus adjusted using ~**100 µm** linear motion of the SFM
    - ➢ Within the **±0.5mm** allowable linear focus adjustment of the SFM

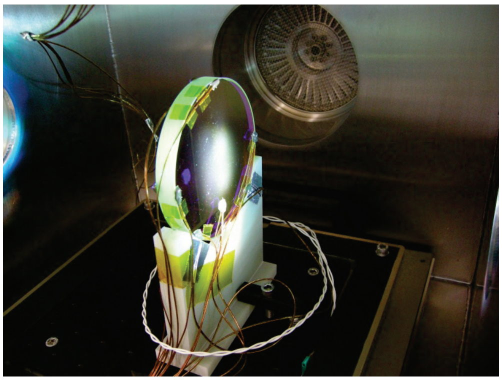


Mirror thermal deformations (ANSYS)

Conclusions

RAL Space

- Detailed thermal model of the primary mirror created
- Model provides temperature and nodal coordinate data for thermo-elastic analysis of mirror
- Predictions show large thermal gradients exist in the mirror
  - ➢ Focus adjustments calculated
- Analysis is on-going:
  - ➢ Anti-reflection coatings
  - ➢ Boron carbide coverage

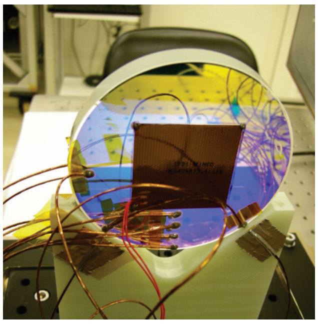


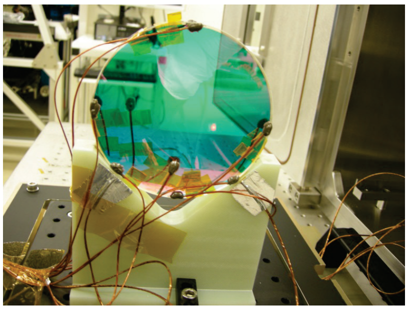
Conclusions

- Thermal testing is on-going
  - ➢ Ohmic heating test
  - ➢ Solar lamp test

ESATAN modelling:

- First year using the software
- Generally impressed with the software, areas for improvement:
  - ➢ FE nodal areas and node numbers
  - ➢ Wavelength-dependent thermo-optical property explanations/examples





Acknowledgements

- This work was funded by ESA contract number: **SOL.S.ASTR.CON.00070**
- I would like to acknowledge the Max-Planck-Institut für Sonnensystemforschung (MPS) for data relating to the boron carbide coating

Questions?