Appendix L

Thermo-elastic analysis of the LISA Pathfinder spacecraft

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LISA Pathfinder Thermo-Elastic Analysis

Presented by: J. Etchells

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21st European Workshop on Thermal and ECLS Software
30th – 31st October 2007

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Overview of Presentation

1. Background
2. Objectives of the Analysis
3. Thermal Analysis
4. Thermal to Structural Mapping – including demo
5. Structural Analysis
6. Results and Discussion

(Items 2–4: Focusing on methodologies)

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Background to the LPF Mission (1)

- LISA Pathfinder (LPF) is a pre-cursor mission for the LISA (Laser Interferometer Space Antenna) mission
- S/C will detect gravitational waves generated by massive objects (e.g. black holes)
- Objective is to demonstrate critical technologies for LISA such as:
  - Drag free and attitude control in S/C using two test masses
  - Test feasibility of laser interferometry at the level of accuracy envisaged for LISA
- LISA Technology Package (LTP) capable of measuring tiny movements of the test masses:
  - 1 nano-meters relative to the S/C ($1\text{x}10^{-9}$ m)
  - 10 pico-meters relative motion between test masses ($1\text{x}10^{-11}$ m)
- Direct consequence of this is that an extremely stable S/C structure is required
  - Thermo-elastic distortions are potentially very important

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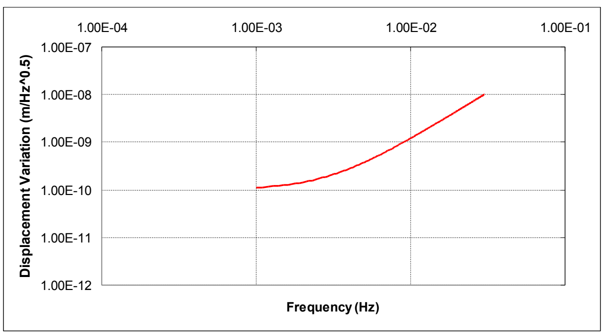
Background to the LPF Mission (2)

- Requirements for thermo-elastic stability are expressed as Power Spectral Density (PSD) or Linear Spectral Density (LSD)
- Example : Variation in distance between electrode housings (in x direction):

$$x_{dist} \le 100 \times 10^{-12} \left(1 + \left(\frac{f}{0.003}\right)^2\right) \frac{m}{\sqrt{Hz}} \quad \text{for} \quad 1 \times 10^{-3} \le f \le 3 \times 10^{-2}\, Hz$$



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Objectives of the Analysis

- Objective to carry out a thermo-elastic analysis of the full LPF S/C in order to verify the stability requirements
  - Some questions existed about the analysis methodology used in industry
  - Typical kind of “shadow engineering” task carried out at ESTEC
  - Verify the results/predictions produced by industry
- Analysis was originally envisaged as an ***analysis*** task not a ***modelling*** task
  - Re-use of industrial thermal models meant minimal modelling
    - Just combine industrial models into single S/C model
  - Main task was to be the thermal to structural mapping
- Analysis would be carried out using standard ESA tools:
  - ESARAD, ESATAN, SINAS, NASTRAN

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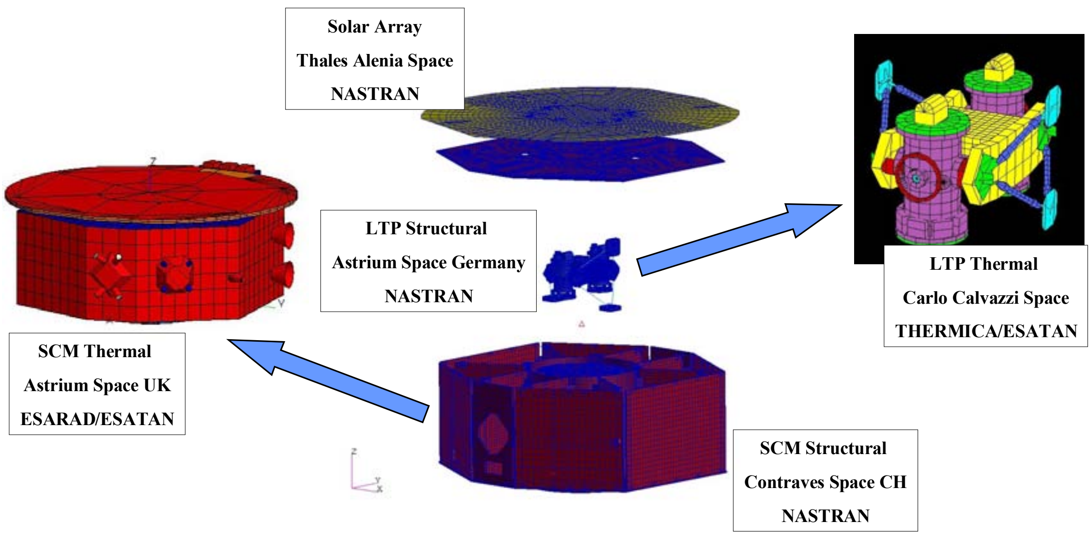
Industrial Consortium and Models Used



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Update of Thermal Models

- Originally minimal modelling was envisaged – analysis not modelling
  - thermal models already developed by industry
- Generally industrial models were of a high standard – but not up to date
  - in many cases industrial thermal models were still at PDR level
  - actual design baseline had evolved considerably
- Structural FEM models were generally more up-to-date than thermal models
  - FEM models can be produced mush more quickly from CAD
  - Structural analysis used in design process mush more – even driving it
- Therefore, two problems:
  - Thermal models out of sync with current design baseline
  - Thermal models out of sync with structural FEM
- Therefore much more modelling was required than initially expected
  - Thermal model updates represented the single largest effort expended

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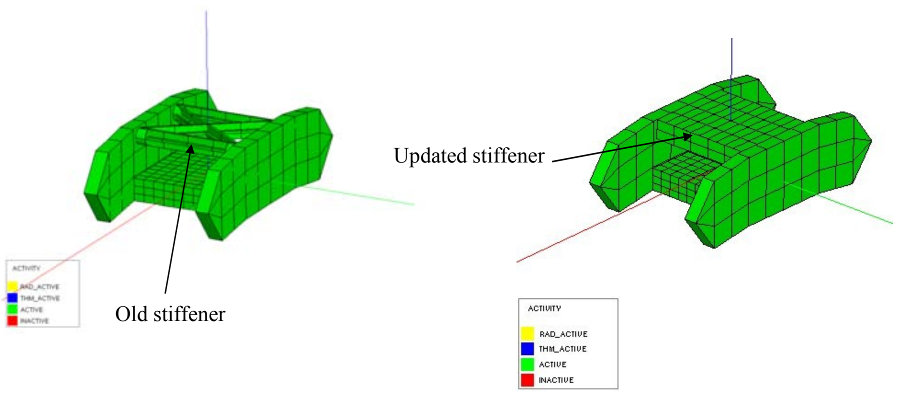
Update of Thermal Models
Example 1 : Optical Bench Stiffener



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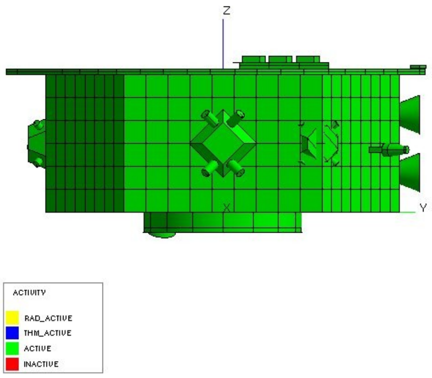
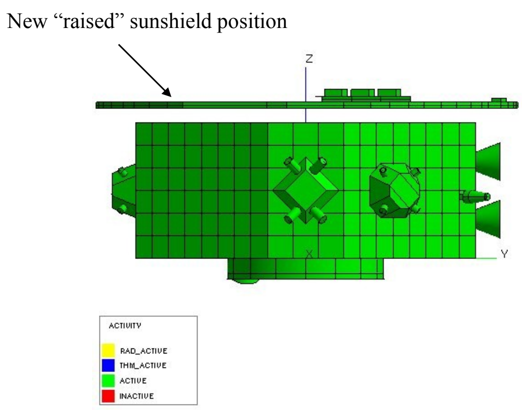
Update of Thermal Models
Example 2 : Solar Array/Sunshield Position





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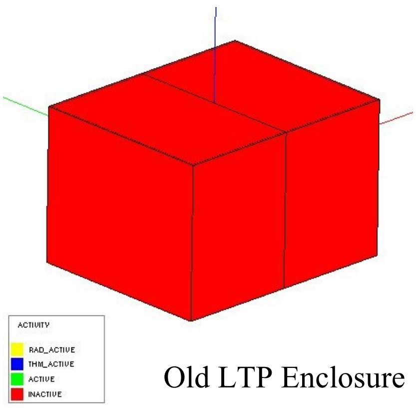
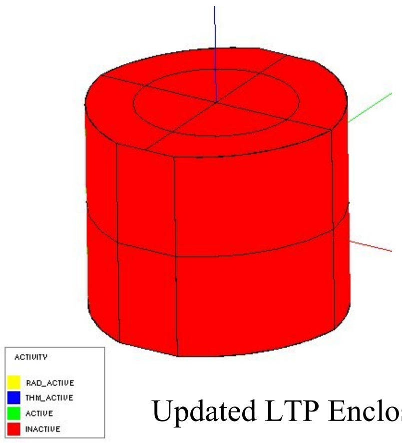
Update of Thermal Models
Example 3 : LTP Enclosure



Old LTP Enclosure



Updated LTP Enclosure

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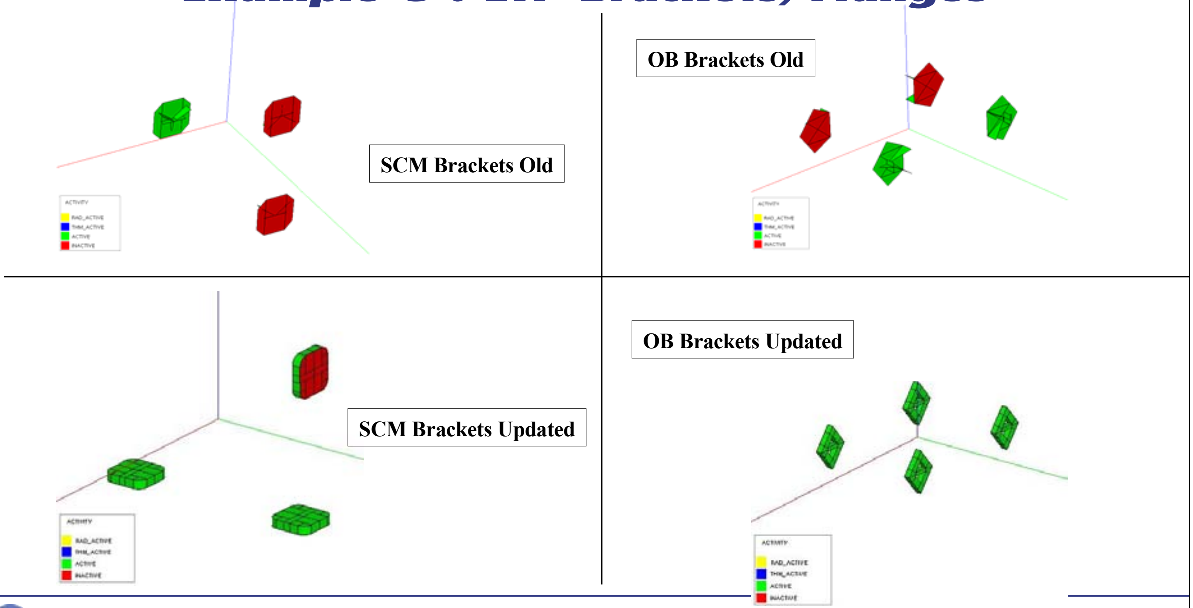
Update of Thermal Models
Example 3 : LTP Brackets/Flanges



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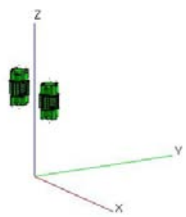
Integration of Thermal Models

TMM

- Integration of ESATAN models of LTP and SCM was simple
  - Conductive interface through LTP enclosure support cleats
  - Existing harness/fibre optic conductances from existing LTP model
  - ESARAD GRs

GMM

- Position updated LTP model inside updated SCM model
- Split into several (6) enclosures - like a Russian doll
  - Reduces computation time for raytracing



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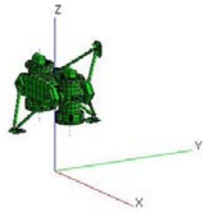

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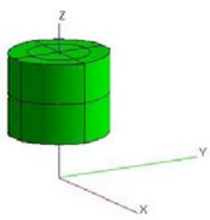

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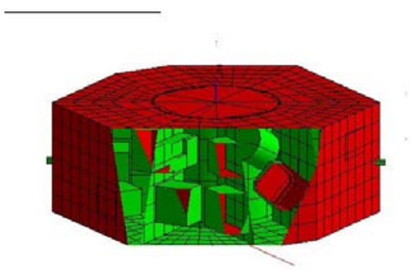

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Integration of Thermal Models

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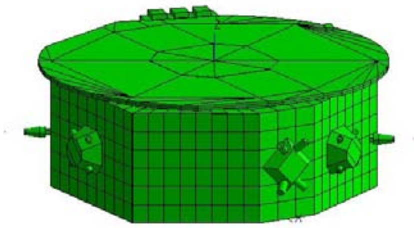

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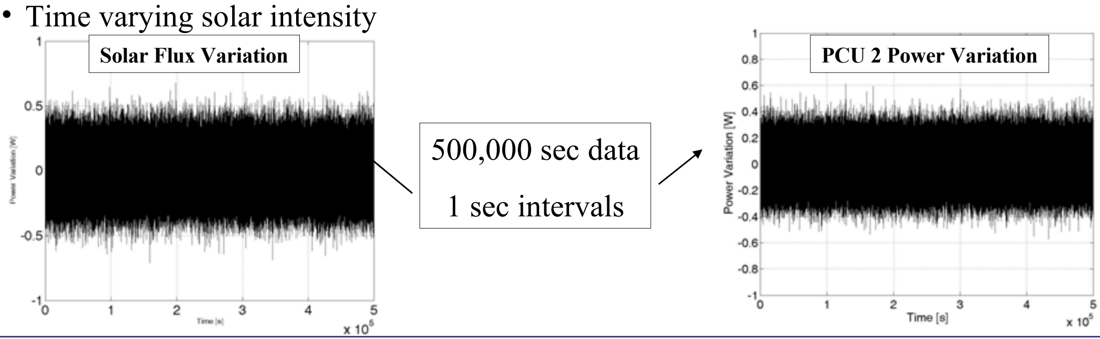
Thermal Loads and Boundary Conditions

Boundary Conditions

- BCs in industrial models replaced with single deep space node
  - Industrial LTP model had extra boundary nodes for conductive/radiative interfaces

Thermal Loads (Provided by ASU)

- Time varying (white noise) power dissipation from 5 units (PCUx3, PCDU, OBC)
- Time varying solar intensity



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TMM Issues (1): Convergence

- Using full S/C model SS solver could not converge beyond RELXCA < 10^{-5} K
- Observation of monitor file revealed good convergence followed by sudden instability
  - Different solvers tried (SOLVIT, SOLVFM) but to no avail
  - Temperature damping helped but still had instability + very slow convergence
- Eventually problem identified as energy imbalance in the test masses
  - TMs are very well isolated so residual energy is slow to “dissipate”
  - Dummy GLs were introduced between TMs and housings to speed up convergence – then removed for final “clean” steady state run
  - Allowed convergence to RELXCA < 10^{-8} K in steady state

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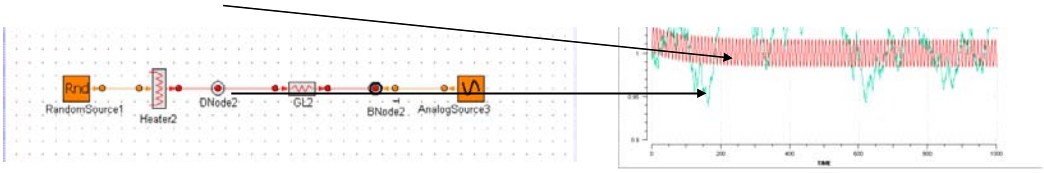
TMM Issues (2): Drift

- After steady state run, temperature drift observed in transient solution using same "mean" power dissipations
- Two different kinds of drift can be identified
  - Drift due to a systematic heat load such as a sine wave
  - Drift due to residual energy imbalance after the steady state solution



- In the LPF model only random power variations were considered therefore drift must be due to residual energy imbalance : three solutions identified
  - Obtain a better convergence (↓ RELXCA, ↓ INBALA) – Difficult due to convergence
  - Obtain a quasi-steady state using transient run with average heat load - Implemented
  - De-trend output temperatures to remove drift - Implemented

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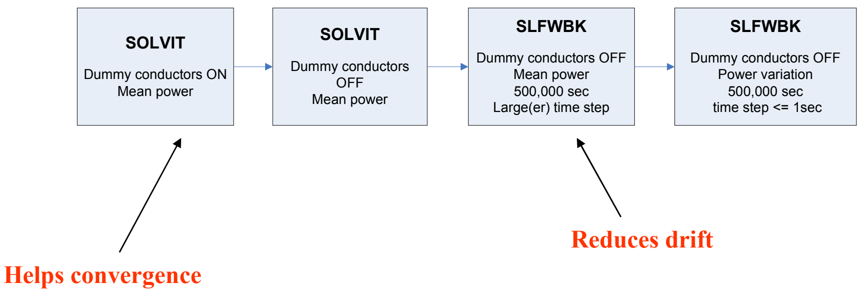
Final Analysis Case

- After overcoming convergence and drift problems the following analysis case was used:



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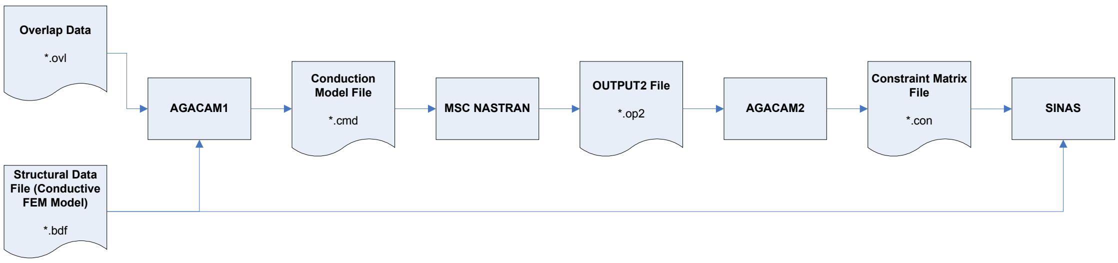
Thermal to Structural Mapping

Objective

- To build up correspondence (***overlap data***) between thermal nodes and structural FEM nodes
  - Allows temperatures to be applied as loads in structural model

Chosen Method

- Use SINAS and GMM geometry to map thermal nodes to structural FEM
  - SINAS presented at 2006 workshop (see proceedings)
    - http://mechanical-engineering.esa.int/thermal/tools/attachments/workshop2006/



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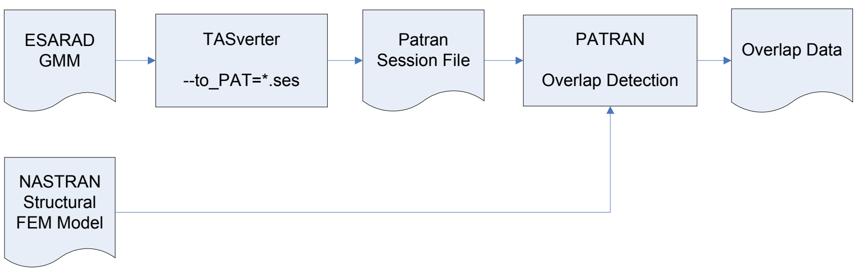
SINAS : Building Overlap Data



- Building overlap data is most time consuming part of the process
- It is the process of finding correspondence between thermal nodes and finite elements
- For LPF analysis overlap data was needed for entire S/C
  - huge task approx. 6800 thermal nodes 120,000 grids, 140,000 elems.– impossible to do the whole S/C at once

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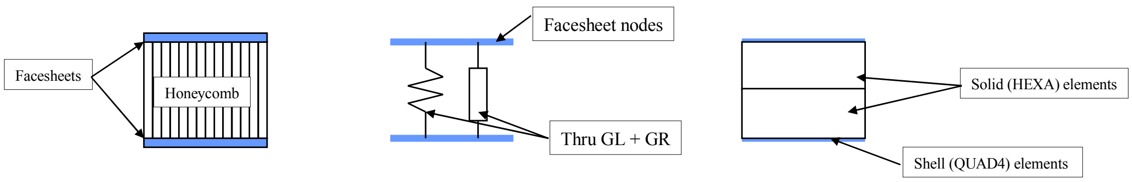
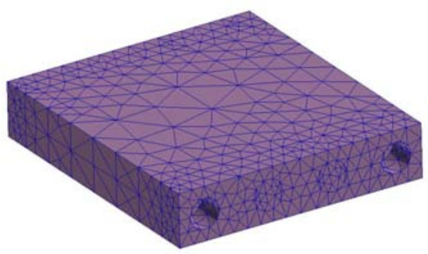
SINAS : Building Overlap Data

- ESARAD GMM was split up into total of 14 zones e.g. shear panels, outer panels, optical bench, LTP enclosure…
- Corresponding FEM topology extracted from the full NASTRAN model
  - Heavy use of Patran utilities such as the invaluable "***Group Extend***"
- Overlap data built up on a zone-by-zone basis using SINAS Patran interface
  - Combined at the end using text editor
- Gradient areas not required for sandwich panels due to modelling approach used
  - Panels modelled in FEM : 2 facesheets (shells elements) and honycomb (solid elements)
  - Temperatures from ESATAN facesheet node mapped to shells elements only

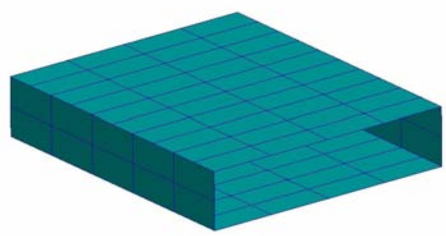


SINAS : Building Overlap Data

- Mapping process is complicated when solid elements are used in the structural FEM
  - Shells used for thermal GMMs representing "surfaces"
  - Further complicated when unstructured FEM meshes are used (e.g. tet mesh)
- Luckily SINAS uses ***FEM Topology*** for interpolation so adequate mapping can be built up



Optical Bench Stiffener FEM



Optical Bench Stiffener TLP

SINAS : The Rest of the Process

- In order for SINAS to carry out interpolation user must build a conductive representation of the structural FEM model
  - So called "Structural Data File"
  - Typically replace MAT1 cards with MAT4 cards, PCOMP with PSHELL etc
  - Replace RBEx/MPC with CELAS elements – but not always obvious what value to use
- Using overlap data and conductive FEM model run through other SINAS modules
  - Max memory limits were hit in a few places – had to increase array sizes
  - Problems with gradient areas were identified due to changes in MSC NASTRAN DMAP

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Temperature Post-Processing

- Variations in temperature are extremely small + CTEs are also very small
  - Leads to tiny structural displacements - possible issues with NASTRAN numerical precision
  - Therefore decided to process temperatures before FEA
- Structural model is completely linear – no temperature dependent CTE
  - Therefore temperatures deltas were scaled to avoid numerical problems
- Temperature vector at each time step offset to give variations (deltas) around a nominal temperature vector $\{T_0\}$ (chosen to be start of final transient analysis)

$$\{\Delta T\} = \{T\} - \{T_0\}$$

- Temperature deltas then scaled up and provided for structural analysis
  - Equilibrium (zero strain temperature) for FEA is then 0ºC

$$\{\Delta T'\} = \{\Delta T\}.f$$

f = 1x10^6 for LPF analysis

- Must remember to scale down structural displacements by factor f !!

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Structural Analysis

- Carried out by E. Koekkoek (formally) from ESTEC TEC-MCS section
- Output of SINAS was provided
  - 600 time steps of 15 seconds - sufficient for the freq. range of interest
- Standard model checks carried out for thermo-elastic analysis
  - e.g. free eigenmodes, strain energy, free expansion
  - Some problems identified in the strain energy & free-expansion checks but we proceeded anyway
- Quasi static run carried out for each time step
  - Balance between administration time for NASTRAN and matrix decomposition
  - 25 subcases per run chosen as good compromise

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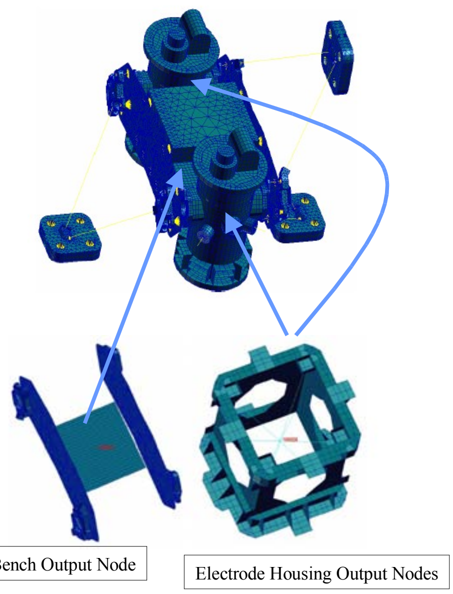
Post-processing to PSD/LSD

- Requirements for displacement are given in terms of Linear Spectral Density (LSD)
- Existing Matlab script (from ASD) was used to produce LSD plots of results
  - Results are de-trended using linear least square fit – removes some drift
  - Welch algorithm used for LSD
    - Blackman-Harris window
    - 7 segments (smoothing factor of 4)
    - 50% overlap between segments
- Output nodes on the optical bench, S/C interface flanges and electrode housings were chosen



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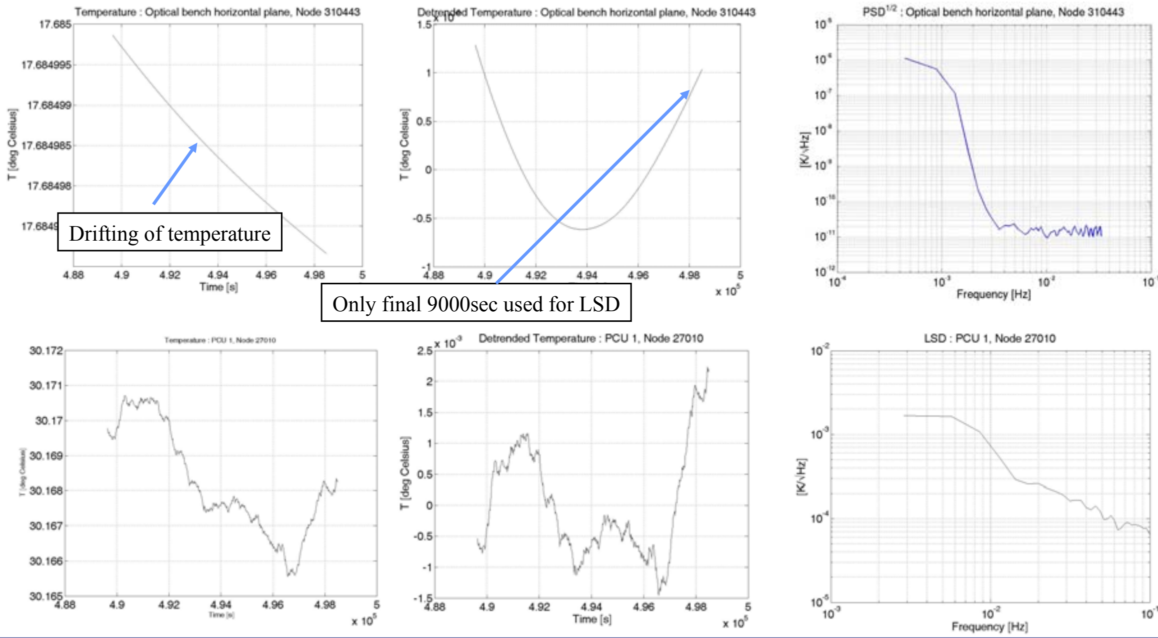
Sample Results: Temperatures



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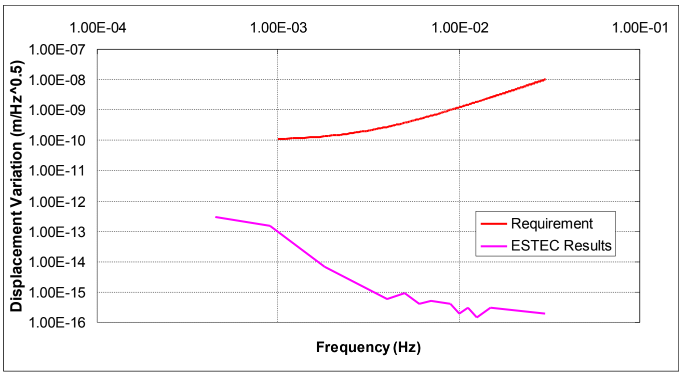
Sample Results: Electrode Housing Displacement Variation

- ESTEC results displayed smaller displacements than industrial analysis
  - Possible reasons for differences are different input data, different methodology used etc.



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Conclusions (1)

- Results of the ESTEC Analysis confirmed that LPF thermo-elastic distortions were within requirements
  - ESTEC analysis produced much ***smaller*** distortions than the industrial analysis predicted
  - Industrial methodology could be considered conservative
- Significant challenges overcome in terms of thermal analysis
  - High accuracy analysis required – presented many challenges
  - Many lessons learned which mirror experiences in industry (e.g. GAIA analysis)
    - One of the motivations for starting the ITAA with ASG
- SINAS used for an entire S/C
  - Use of TASverter module (link with Patran) was essential – available to all of you free!!
- Single biggest headache / time consuming operation was update of thermal model configurations – followed by mapping
  - Use of a common FEM model would have many advantages
    - Might take a few days to run – but it took weeks for modelling + mapping

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Conclusions (2)

- Self criticism – always important!:
  - Choice of solver (SFLWBK) – possible not the best
  - Smaller values of RELXCA/ENBALA should have been used

  } Both addressed in ITAA activity
    - Convergence problems prevented this – but problem now seems to be solved
- Use of transfer function type methods could be very interesting
  - As presented by D. Fertin (ESA), M. Molina at past workshop
    - Work on-going at ESTEC with trainee
  - Considering thermal-structural model as an I/O system is very useful for stability analysis
  - Model fidelity can be maintained but without numerical issues encountered with traditional tools

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