USE OF THE INTERFACE-BACKLOAD METHOD FOR SOLVING LISA AND OTHER LARGE, DIVIDED THERMAL PROBLEMS

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ABSTRACT

A new technique has been developed to include more conductors for a problem that has run out of addressable memory. This technique (Interface-Backload method) is valid for a subset of problems with a clear interface between an internal and external portion of a model. It is being developed for the LISA (Laser Interferometer Space Antenna) project through GSFC. With the strict thermal requirements on the optical bench for LISA, it may be necessary to include as many radiation paths as possible. The current thermal model far exceeds the maximum allowed number of couplings, even with filtering.

The Interface-Backload method includes the effects of an external portion on the internal portion through backloads, and vice versa. As such, the opposite model (couplings and nodes) is not directly included in the solution domain, allowing for additional conductors to be included in current solution. The process is iterated until a user-defined tolerance is reached.

The LISA design includes a Y-Tube, which serves as a physical barrier between the external model (e.g. Structure, electronics boxes) and the internal model (e.g. optics, telescope) and makes for an ideal test case. This technique was validated using a simple LISA model, for which the entire solution domain can be solved. This paper outlines the requirements and design of LISA, the derivation of the backload terms, and the results from the initial study using the simple LISA model.

1 INTRODUCTION

LISA (**L**aser **I**nterferometer **S**pace **A**ntenna) is a joint NASA-ESA constellation mission to detect the presence of gravitational waves using laser interferometry scheduled to launch in 2012. Each spacecraft contains two free floating proof masses used as targets to reflect the corresponding spacecraft's laser signal. As such, strict requirements exist to minimize any forces that may affect movement of the proof mass (so as not to be confused as a gravitational wave). To satisfy the requirements, end-to-end STOP-G (**S**tructural-**T**hermal-**O**ptical-**P**erformance-**G**ravity) analyses will be performed to evaluate the acceptability of any design.

Due to the tight thermal requirements, unprecedented precision and accuracy is required for the thermal analysis. Significant efforts must be taken to minimize all sources of error. A previous study provided the rationale to use a single mesh for all phases of the STOP-G analysis to eliminate temperature mapping errors. However, further work revealed a major drawback with this approach; the model becomes too large to solve using traditional thermal analysis software and methods.

This paper describes the mission and thermal requirements for LISA and describes a proposed technique to allow more conductors to be included in the solution domain. This task was performed by Swales Aerospace for NASA/GSFC and this particular effort was documented in SAI-TM-2555.

2 MISSION OVERVIEW

The LISA mission is designed to detect gravitational waves using laser interferometry. The mission consists of three identical spacecraft flying in a heliocentric orbit, 20° behind the Earth, in an equilateral triangle formation with 5 million kilometers separating each spacecraft. Each spacecraft is equipped with two laser/telescope/proof mass assemblies. The design of the spacecraft requires that all components be gravitationally balanced about the proof masses to minimize spacecraft influences/disturbances on the proof masses.

2.1 MISSION DETAILS AND SCIENCE

For a gravitational wave to be detected, the two points in space (i.e. proof masses) between the laser must be locally stationary with a known path length. A passing gravitational wave causes a change in the path length between distant proof masses, detected by monitoring the resulting change in the interference pattern from the interferometer. Therefore, motion of the proof mass needs to be minimized, since this will also cause a change in the interference pattern and may be confused as a gravitational wave. As such, it is mission critical to minimize the forces acting on the spacecraft and the proof masses. Once inserted into the science orbit, thermal distortions (as a result of a changing thermal environment or variations in dissipated power) may result in fluctuating forces on the proof mass, due to changes in the gravitational forces between the proof masses and surrounding objects. As such, the thermal design plays a large role in the success of the LISA mission. Figure 1 shows the current LISA design with the solar array and top plate removed for visibility.

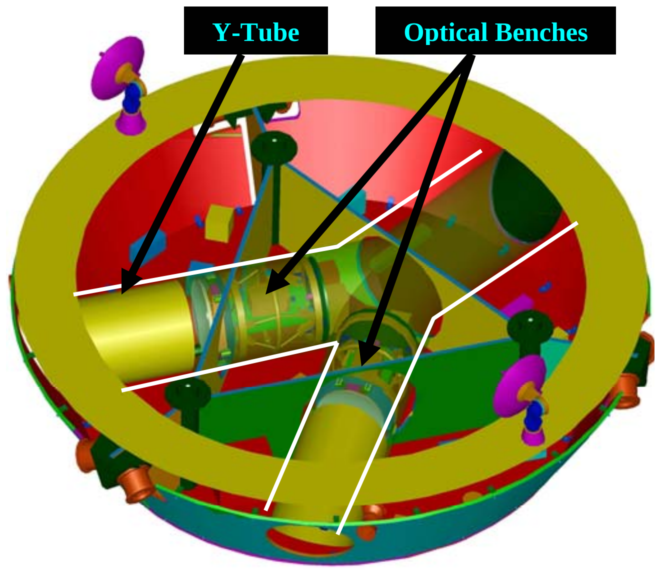

Figure 1 – LISA Spacecraft (Thermal Shield removed)

2.2 THERMAL REQUIREMENTS

The thermal requirements fall into two categories: fluctuations within a particular frequency range and temperatures that may cause component misalignment on the optical bench. The area of primary concern is temperature fluctuations that may cause the proof masses to move and appear to the sensors as a gravitational wave. The requirements are stated in terms of temperature fluctuations per root Hertz and should be evaluated by transforming a time varying temperature profile into the frequency domain and calculating the power spectral density.

2.3 THERMAL DESIGN

The thermal design requires minimization of any thermal fluctuations that could affect the optical bench and components near to the proof mass. Since gravitational forces are higher for closer objects, fluctuations in temperature (and consequently thermal distortions) further away from the proof mass are less of an influence than fluctuations of closer components. Two potential sources of thermal fluctuation have been anticipated: variation in the solar intensity and fluctuation of on-board power dissipations. To minimize these effects, various layers of conductive and radiative isolation exist in the internal heat paths of the spacecraft.

The solar array is isolated from the spacecraft structure using low conductivity stand offs and insulating foam in a honeycomb panel. This first layer of isolation allows very little of the absorbed solar heat to transfer through to the spacecraft. The second layer of isolation is achieved by using low conductivity mounts and goldized coatings to minimize radiation from the spacecraft to the Y-Tube (outside) and from the Y-Tube (inside) to the internal shield. Lastly, the internal shield is also goldized to minimize heat transfer to the optical bench.

3 THERMAL ANALYSIS

Due to an inability to ground test and include self-gravity effects, the LISA project will rely heavily on highly accurate, analytical efforts. The thermal analysis for LISA is currently performed using ThermalDesktop and SINDA/FLUINT v4.6 from Cullimore and Ring. As discussed in a previous TFAWS paper ("Use of a Single Finite Element Mesh for a STOP-G Analysis of the LISA Spacecraft"), the same mesh was intended to be used throughout the STOP-G process to eliminate temperature mapping errors. The major drawback to this approach is that it results in an extraordinarily large thermal model. The FEM submitted by the structures discipline included over 43000 nodes. While this is a very large number of nodes compared to a traditional thermal model, the conduction matrix generated is very manageable. The real problem is evident when radiation terms are included.

3.1 MODEL CHALLENGES

The RadCad output from ThermalDesktop generated 40+ million radiation couplings. Current limitations in the Windows XP operating system (based on 32-bit numbers) allow for up to 2GB (~2.1E9 with one bit for sign) of addressable memory locations for a single process. For this model, that resulted in about 25 million total couplings that could be loaded until the memory address needed was larger than what could be represented with a 32-bit number. Unfortunately, this problem cannot be fixed by the software provider, as it is a limitation in the capabilities of the operating system.

This limitation requires significant filtering of the radiation couplings upon output to reduce the number of terms to what could be loaded; this consequently results in a source of error that is very difficult to quantify.

3.2 PROPOSED APPROACH

The question remains as to how many couplings can be eliminated without significantly affecting the accuracy of the solution. To help address this, a new approach has been proposed which takes advantage of a physical interface between the "internal" and "external" portions of the model. This method uses backloads to provide the inputs of one model to the interface, allowing the remaining portion of the model to be solved with the inclusion of more radiation couplings. This process is then repeated for the other side of the interface and iterated until a sufficient number of iterations have been performed to allow solution convergence.

4 BACKLOADS

Backloads are a method for providing a complicated geometrical environmental around a surface via a simple heat load. This is the same technique employed by radiation solvers to compute the planetary heat load. The derivation is as follows.

4.1 BACKLOAD DERIVATION

Beginning with the basic exchange of heat for node i, the following equation summarizes the heat flow (*Eqn 1*) where the solution domain is contained in (1 ≤ i ≤ N):

$$Q_{stored,i} = Q_{applied,i} + \sum_{j=1}^{N} G_{Lin,ij} * \left(T_j - T_i\right) + \sigma * \sum_{j=1}^{N} G_{Rad,ij} * \left(T_j^4 - T_i^4\right)$$

The backload terms can be derived by extracting the radiation portion of the general equation. The following equation shows the heat transferred by radiation (*Eqn 2*):

$$Q_{radiation,i} = \sigma * \sum_{j=1}^{N} G_{Rad,ij} * \left(T_j^4 - T_i^4\right)$$

For a subset of nodes in the "Backload" range (1 ≤ i ≤ n), terms can be grouped into radiation between nodes that are both in the "Backload" range and radiation where only one node is in the "Backload" range (*Eqn 3*):

$$Q_{radiation,i} = \sigma * \sum_{j=1}^{n} G_{Rad,ij} * \left(T_j^4 - T_i^4\right) + \sigma * \sum_{j=n+1}^{N} G_{Rad,ij} * \left(T_j^4\right) - \sigma * \left(T_i^4\right) * \sum_{j=n+1}^{N} G_{Rad,ij}$$

Defining the second term as the Backload yields (*Eqns 4,5*):

$$Q_{Backload,i} = \sigma * \sum_{j=n+1}^{N} G_{Rad,ij} * \left(T_j^4\right)$$

$$Q_{radiation,i} = \sigma * \sum_{j=1}^{n} G_{Rad,ij} * \left(T_j^4 - T_i^4\right) - \sigma * \left(T_i^4\right) * \sum_{j=n+1}^{N} G_{Rad,ij} + Q_{Backload,i}$$

Note that $Q_{backload,i}$ is independent of the temperature of node i. For this system of equations, the nodes once contained outside of the "Backload" range are no longer included in the solution domain. However, the second term in *Eqn 5* still includes an effect of these nodes based on the $G_{rad,ij}$. This parameter can be derived by running the free-standing model containing only surfaces in the backload range, which would provide a view to space where a non-backload surface once was (*Eqn 6*). A alternate method would be to sum all the $G_{Rad,ij}$ terms during the calculation of the backload terms and redirect that view to space.

$$\left(T_i^4\right) * \sum_{j=n+1}^{N} G_{Rad,ij} \approx G_{Rad,Space(FreeFlyer)} * \left(T_i^4 - T_{space}^4\right)$$

Assuming that the space temperature is absolute zero and combining *Eqn 5* and *Eqn 6* yields (*Eqn 7*):

$$Q_{radiation,i} = \left\{\sigma * \sum_{j=1}^{n} G_{Rad,ij} * \left(T_j^4 - T_i^4\right) - \sigma * \left(T_i^4\right) * G_{Rad,Space(FreeFlyer)}\right\} + Q_{Backload,i}$$

This now includes only nodes in the backload range (1 ≤ i ≤ n), but via the backload term includes the *effects* of nodes from outside the backload range. This approach has been used on numerous large spacecraft projects with good success to provide the spacecraft environment from an integrated model run to instrument contractors without the need to provide the entire spacecraft model.

4.2 BACKLOAD USAGE

To ensue the validity of results, the following criteria should be met before using backloads:

1. In general, it is assumed that the temperatures of nodes in the backload range do not have a great effect on increasing or decreasing temperatures of nodes outside of the backload range. (i.e. the radiation exchange between two nodes is small)
2. It is assumed that the G_{rad}'s between two nodes in the backload range are not greatly affected by the presence of the surrounding environment. Two ways that this may happen are if a non-backload surface intrudes into the view between backload surfaces (i.e. obscures the view between two backload surfaces) or if the G_{rad}'s between two backload surfaces are significantly affected by reflections from a non-backload surface.
3. The $Q_{applied,i}$ term in *Eqn 1* is not significantly affected by reflections/blockages by non-backload surfaces
4. The conduction to nodes outside the backload range is small or negligible.
5. All radiative terms are included in the backload (i.e. no filtering).

Assumptions 1, 2, and 5 generally hold true without much further investigation by the user.

To address assumption 3 above, it is often best to provide the environments from the integrated model run so that any blockages or reflections may be included. Furthermore, it is advised to provide these heat loads in UV and IR terms so that appropriate scalings may be applied if optical property adjustments are made.

To address assumption 4 above, the conduction couplings to a specified range of nodes ("Spacecraft Range") and the temperatures of those nodes may be included. In general, the heat transfer across the interface between the surrounding surfaces and the backload surfaces is included in the thermal model and not a product of the radiation model. The thermal model should be read and couplings where one node is in the Backload range and the other is in the Spacecraft range should be included. A user must be careful not to include radiation transfer across the interface multiple times (e.g. MLI coupling generated by the radiation model may be included as a separate coupling and in the backload term).

5 INTERFACE-BACKLOAD PROGRAM

A existing program used for calculating backloads was modified to create the Interface-Backload Program. The goal was to provide a method for solving the LISA model using backloads applied to interface nodes. For the "External" model, the backloads applied would be based on "Internal" temperatures, and vice versa. The previous view to the opposing model would be redirected to space, and conductive couplings would be included. Both steady-state and quasi-steady transient responses may be used.

5.1 PROGRAM APPROACH

The basic approach of the Interface-Backload program is shown in Figure 2.

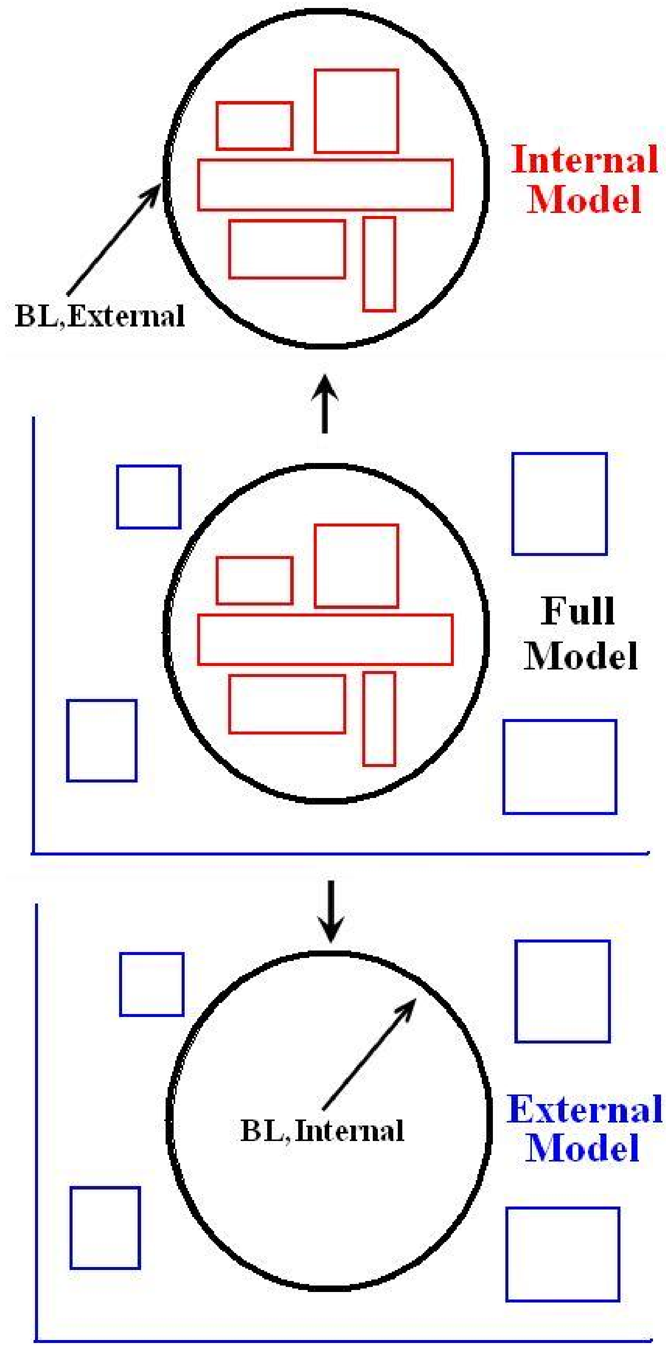

Figure 2 – Interface-Backload Approach

The ring in black represents a physical boundary between the internal and external model. The complete model may be solved by solving the External model and applying backloads generated from the internal model temperatures. Following this, the Internal model (with backloads generated from the External model) is solved. This process may be repeated as necessary until the tolerance goal is met.

5.2 GRAPHICAL USER INTERFACE (GUI)

The graphical user interfaces are shown in Figure 3 (Main Interface) and Figure 4 (Backload Options).

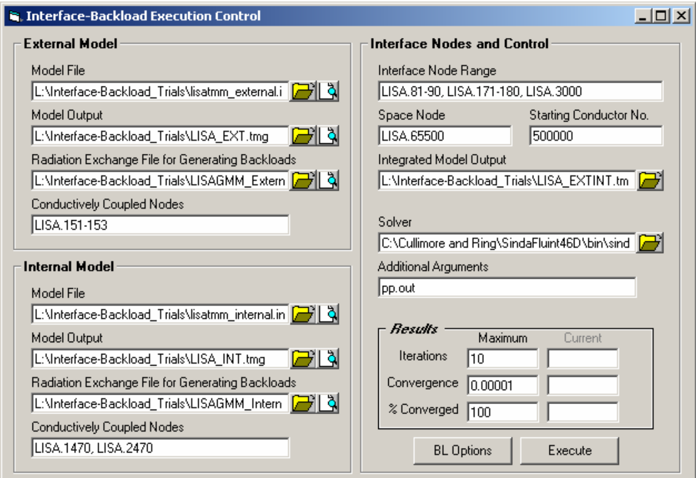

Figure 3 – Main Interface

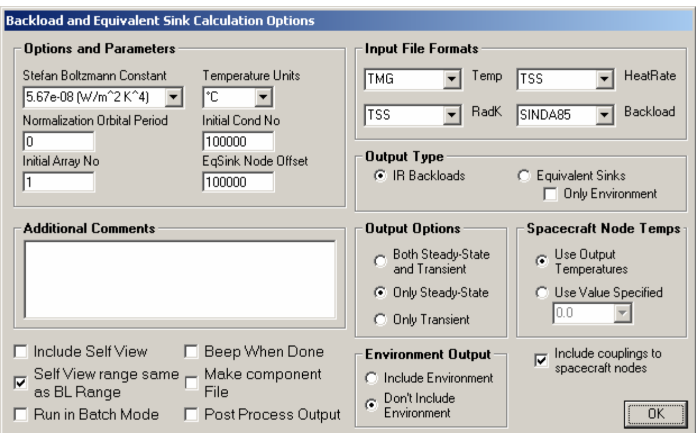

Figure 4 – Backload Calculation Options

The program was developed using Visual Basic 6.0 under the PC Windows® XP operating system.

5.3 PROGRAM INPUTS

The program expects as inputs: the thermal model input file, the thermal model output file, the radiation exchange file (e.g. radks), and any conductively coupled nodes for both the internal and external models. In addition, the user must specify the nodes to be considered as the interface, the space node (for redirection of backload radiation couplings), and an initial condition file for the generation of the initial backload values.

The thermal model input files must be specifically modified for use by the Interface-Backload program. The External input model must include: all external nodes, all interface nodes, and boundary nodes for conductively coupled nodes from the Internal model. The Internal input model has similar, but opposing, requirements. In addition, the input files should have INCLUDE directives to add in the results from the backload generation outputs. For simplicity, the INCLUDE directives were place in a "BL" submodel in each input file and included in the model build.

Four files should be included in each model. These files, and their contents, are listed in Table 1, where *Base* is the base name of the input file.

Included Filename	Contains
*Base*_SelfView.rdk	Redirected views to space from radks in backload
Base.arr	Array data for transient backloads and boundary temperatures for conductively coupled nodes
Base.qav	Steady State calls for backload heating terms and boundary temperatures for conductively coupled nodes
Base.da1	Transient calls for backload heating terms and boundary temperatures for conductively coupled nodes

Table 1 – Included Files generated by Backload Calculation to be included in Preconditioned Model Files

Lastly, a special output file must be written upon completion of each solver run to indicate to the Interface-Backload program that the solver process is complete. This file was named "RunComplete.stat" and contained the string "Run Complete" once the model run was finished

5.4 PROGRAM EXECUTION

The program will run the specified solver with the filename as the argument. For the trial and development of this program, SINDA/FLUINT v4.6 was used, but it could be adapted to work with other solvers if necessary.

The temperatures from an integrated model run are first processed to generate the Internal backloads. The integrated model results should typically come from a model containing as many radiation couplings as possible to produce reasonably accurate results. In essence, these temperatures are used to generate the initial set of backloads for the solution. The output files from the Internal backload calculation are now included in the run for the External model (simulating the internal portion of the model via backloads).

Next, new backloads are computed based on the results from the External run and included in the Internal model run. After completion of the Internal model (using External backloads), a comparison of temperatures is made for all interface nodes, and the maximum difference is displayed to the GUI. This process is repeated until a maximum loop count is reached. The percentage of interface nodes that have reached convergence is also displayed. The maximum values may be changed at run-time if needed or to force completion of the Interface-Backload run.

6 TRIAL RUN

A simplistic rapid analysis model of LISA was used to test the validity of the Interface-Backload approach. The model was based on a TSS geometry model and a SINDA/ FLUINT thermal model, converted from the ESARAD/ ESATAN models submitted by RAL from the Pre Phase A analysis. The geometry model was broken into two separate models for the purposes of generating radiation couplings for each distinct model.

Figure 5 shows the External model and includes the surrounding spacecraft structure up to the outside of the "Y-Tube". Figure 6 shows the Internal model and includes everything from the inside of the Y-Tube to the optical bench. Since the entire system can be run as an integrated model, it provided a means to validate the results from the proposed approach.

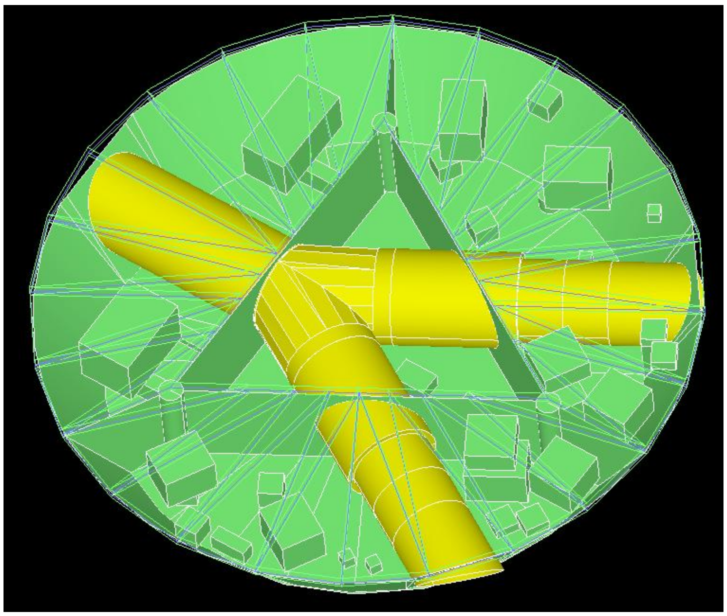

Figure 5 – External Model in TSS

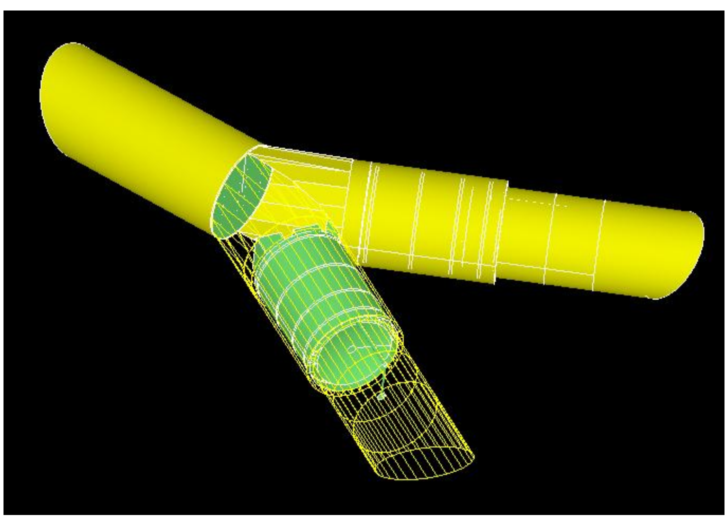

Figure 6 – Internal Model in TSS

6.1 RESULTS FROM TRIAL RUN

The output from both steady-state and transient responses to a sinusoidally fluctuating input solar function were compared for the interface nodes and are shown in Table 2. The EXTINT case represents the integrated model results; the EXT and INT represent the Interface-Backload approach for the External and Internal models respectively.

Node #	**Steady State Temperatures *[°C]***				
	Dif	EXT	EXTINT	INT	Dif
LISA.81	-0.31	18.25	17.93	18.02	-0.08
LISA.82	0.02	14.36	14.39	14.43	-0.04
LISA.83	-0.03	14.34	14.30	14.35	-0.04
LISA.86	-0.07	0.13	0.06	0.03	0.03
LISA.87	-0.09	0.15	0.06	0.02	0.03
LISA.88	0.36	-10.20	-9.83	-9.94	0.10
LISA.89	0.36	-10.19	-9.84	-9.94	0.10
LISA.90	0.67	-19.40	-18.73	-18.89	0.15
LISA.171	-0.22	17.93	17.71	17.79	-0.08
LISA.172	0.04	12.16	12.20	12.19	0.01
LISA.173	0.10	11.88	11.99	11.97	0.01
LISA.176	-0.04	-4.18	-4.22	-4.30	0.07
LISA.177	0.00	-4.65	-4.65	-4.73	0.07
LISA.178	0.43	-15.80	-15.37	-15.51	0.13
LISA.179	0.45	-16.20	-15.75	-15.89	0.14
LISA.180	0.74	-25.49	-24.74	-24.92	0.18
LISA.3000	0.28	-30.56	-30.27	-30.25	-0.02

Table 2 – Steady-State Temperature Results for Internal, External, and Integrated Models

For LISA, one of the more important results however is the magnitude of the *fluctuation* in temperature due to an input forcing function. These results are shown in Table3.

Node #	**Transient Fluctuations *[mK]***				
	Dif	EXT	EXTINT	INT	Dif
LISA.81	0.020	1.526	1.546	1.530	0.016
LISA.82	0.012	3.136	3.148	3.129	0.019
LISA.83	0.019	2.512	2.531	2.511	0.020
LISA.86	-0.003	6.054	6.051	6.035	0.016
LISA.87	0.035	4.628	4.663	4.644	0.019
LISA.88	-0.001	7.169	7.168	7.147	0.021
LISA.89	0.030	5.885	5.915	5.893	0.022
LISA.90	-0.017	8.283	8.265	8.249	0.016
LISA.171	0.019	1.521	1.541	1.525	0.016
LISA.172	0.012	3.071	3.083	3.064	0.019
LISA.173	0.019	2.494	2.513	2.492	0.020
LISA.176	-0.002	5.813	5.811	5.795	0.016
LISA.177	0.033	4.448	4.480	4.461	0.019
LISA.178	0.002	6.893	6.895	6.873	0.022
LISA.179	0.029	5.634	5.663	5.642	0.022
LISA.180	-0.013	7.962	7.949	7.931	0.018
LISA.3000	-0.014	5.252	5.238	5.223	0.015

Table 3 – Transient Temperature Fluctuations for Internal, External, and Integrated Models

6.2 *DISCUSSION OF RESULTS*

The agreement between the Interface-Backload approach and the integrated results for interface nodes is fairly close. In fact, further investigation of all nodes in the model showed that the agreement for the remaining nodes was even better than the interface nodes. Nodes unique to the Internal or External model were about an order of magnitude closer in temperature. Table 4 shows the Maximum, Minimum, Average, and Standard Deviation of differences in temperatures between a node from the Internal/External model and the integrated model run. Table 5 shows a similar comparison for the fluctuations.

Region	Model	Transient Quasi-Steady Temperature Differences *[°C]*			
		Max	Min	Average	StDev
External	EXT	0.048	-0.088	0.014	0.017
Interface	EXT	0.745	-0.312	0.159	0.304
Interface	INT	0.179	-0.082	0.046	0.082
Internal	INT	0.048	-0.088	-0.035	0.012

Table 4 – Transient Quasi-Steady Temperatures for each Region (External, Interface, Internal)

Region	Model	Transient Quasi-Steady Temperature Fluctuations *[mK]*			
		Max	Min	Average	StDev
External	EXT	0.059	-0.019	0.003	0.010
Interface	EXT	0.035	-0.017	0.011	0.017
Interface	INT	0.022	0.015	0.019	0.002
Internal	INT	0.124	-0.010	0.032	0.012

Table 5 – Transient Temperature Fluctuations for each Region (External, Interface, Internal)

The LISA modeling environment is, overall, very benign with few sources of change. This probably contributes to the success of the approach. The differences in fluctuations (which are of most importance to LISA) are typically on the order of tens of micro-Kelvin different compared to the integrated model run. This error is judged to be acceptable compared to the expected error associated with filtering numerous radiation couplings.

One major source of error for the interface nodes is inherent in the approach itself. During an integrated model solution, changes in external and internal nodes both contribute simultaneously to the solution of the interface temperatures. The Interface-Backload approach holds one side fixed while the other side varies; therefore, at no time in the solution are both sides able to contribute due to variations in temperature during the solution.

7 CONCLUSIONS AND FUTURE WORK

The Interface-Backload technique appears to generate temperatures within acceptable error of the fully integrated model. This approach allows for the inclusion of more conductors in each solution domain as the conductors associated with the opposing model have been replaced with the backload terms. A further benefit is the ability to include *all* radiation terms in the backload calculation as well. This may provide better representation of the heat inputs to the interface from the opposing model than calculated at solve time (assuming that radk filtering still needed to be applied to each portion of the model).

Until 64-bit operating systems and larger blocks of memory are available for applications, the Interface-Backload method offers a means to handle larger models with a particular configuration. Employing this technique should allow more accurate modeling of the LISA spacecraft and limit the error associated with filtering radiation couplings necessary to get the model to run. This same approach may also be used for other spacecraft of similar configurations with a physical boundary separating an Internal and an External portion.

REFERENCES

The following papers contain additional information about the current design and analysis of LISA:

- “LISA Final Technical Report”, Astrium GmbH, April 2000
- “Use of a Single Finite Element Mesh for a STOP-G Analysis of the LISA Spacecraft”, Shelly Conkey and Hume Peabody, TFAWS 2003
- “Development of Interface Backload method for Solving the STOPG LISA FEM”, Swales Aerospace: SAI-TM-2555, Hume Peabody, May 2004

ACKNOWLEDGEMENTS

I would like to Shelly Conkey (Swales), for her efforts in revising the mesh to make it compatible with thermal needs. I would also like to thank Stephen Merkowitz (GSFC) for the opportunity to test this process and participate in the LISA design and analysis. This work was performed under contract number NAS5-01090, task number 0548.

ACRONYMS

NASA	National Aeronautics and Space Administration
ESA	European Space Agency
GSFC	Goddard Space Flight Center
LISA	Laser Interferometer Space Antenna
STOP-G	Structural, Thermal, Optical Performance, Self-Gravity
RAL	Rutherford Appleton Lab
FEM	Finite Element Model
FE	Finite Element
FTR	Final Technical Report
G_{rad} or radk	Radiation Coupling