Improvement in the Thermal-to-Structural Model Mapping Process for Integrated Modeling for the Roman Space Telescope

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Integrated Modeling has been a key component of verifying optical requirements for the Nancy Grace Roman Space Telescope (RST) that are either impossible or impractical to verify exclusively through ground testing. Two major areas for Integrated Modeling are Jitter and Thermal Distortion that require the exchanges of model performance predictions across disciplines. In both cases, distortions are impressed on optical models to evaluate the impact on boresight alignment and wave front error. In the case of Jitter, the disturbances are driven by reactions to motions most often from actuators; however, in the case of thermal distortion, the motions are driven by thermal expansion or contraction as a result of changing temperatures. This then requires a link further upstream to the thermal model, which is used to predict the thermal performance and temperature gradients and stability. The process for mapping temperatures from a thermal model to a corresponding structural model has been performed numerous times through the RST project lifecycle, with improvements in the accuracy, verification, and effort sought throughout. This paper describes some of the recent improvements to the process, including: capture of the visualization parameters, automatic generation of the mapped images for both the thermal and structural model groupings, and reduction in the effort to assemble the full set of mapped temperatures. These upgrades have greatly reduced the manual effort associated with thermal mapping and allowed for faster turn-around of Integrated Modeling predictions.

Acronyms and Nomenclature

CGI	=	CoronaGraph Instrument
DAC	=	Deployable Aperture Cover
FEM	=	Finite Element Model
GSFC	=	Goddard Space flight Center
IC	=	Instrument Carrier
IM	=	Integrated Modeling
LISS	=	Lower Instrument Sun Shade
OBA	=	Outer Barrel Assembly
OTA	=	Optical Telescope Assembly
RST	=	Roman Space Telescope
SASS	=	Solar Array Sun Shield
STIRU	=	Star Tracker and Inertial Reference Unit
STOP	=	Structural-Thermal-Optical-Performance
WFI	=	Wide Field Instrument

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I. Introduction

The Nancy Grace Roman Space Telescope (RST) is the current flagship astrophysics mission in development at the National Aeronautics and Space Administration's Goddard Space Flight Center (GSFC). With a field of view 100 times greater than the Hubble Space Telescope, stability is a challenging and driving requirement for both wave front error and boresight alignment for the image generation requirements of the planned surveys of the infrared sky. As such, Integrated Modeling (IM) has played a very important role in the design development and maturation throughout the last decade to evaluate the predicted observatory performance against requirements, since many of the requirements would be very costly or very challenging to verify during ground testing. Throughout the project life cycle, IM analyses have been executed many times and as schedule, staffing, and resources permit, tools have been developed to automate many of the tedious portions of the process that have required manual action or intervention.

These capabilities include a *ViewSave* tool, a *Mapping* tool, and a *ViewGenerate* tool. The *ViewSave* tool allows the user to capture particular information about the viewpoint, view target, zoom factor, and view twist angle directly from AutoCAD and stores the data in an Excel Workbook for later use by the *ViewGenerate* Tool. The *Mapping* tool takes the nodal temperature output from specified results files and the FEM Grid Point-to-Thermal-Node factors file and computes the associated mapped temperature based on the thermal files. While this process is also done automatically by Thermal Desktop®, the mapping interpolation factors are re-generated each time mapping is performed and sometimes these factors may differ slightly due to projected points that fall exactly on a boundary between two surfaces. In this case, the "noise" in the n^{th} digit may be the deciding factor and result in small, but potentially significant, differences. Lastly the *ViewGenerate* tool takes inputs from a spreadsheet populated by the user with view data, data range values, and group/Domain Tag Set associations and generates the images, acquires the screen image, and pastes it into a PowerPoint presentation. It does this first for the thermal contour and then repeats the process for the mapped contours on the structural model group and then repeats this process for each line in the input spreadsheet, automating what used to be a very time consuming, manual process.

Lastly, the paper concludes with some lessons learned throughout the project to improve the accuracy and repeatability of the mapping. In general, these focus on nuances to ensure that instead of data being mapped to all grid points, that the *best and most appropriate* data is mapped. Furthermore, with the development of new tools, repeatability is improved by utilizing the same interpolation factors file rather than generating new ones for each mapped results case, which may have minor differences based on the mapping algorithm.

II. Roman Space Telescope Design

The Roman Space Telescope (shown in Figure 1) features a 2.4 m primary mirror along with a 0.581 m secondary mirror that along with two fold mirrors and a third powered mirror for a three mirror anastigmatic design for the primary Wide Field Instrument (WFI), designed and built as a joint effort between BAE Systems and GSFC. A secondary pickoff mirror relays part of the incoming light through a Tertiary Collimator Assembly to a CoronaGraph Instrument (CGI), designed and built by the Jet Propulsion Laboratory. The Optical Telescope Assembly (OTA) was designed and built by L3Harris. The OTA, WFI and CGI are all supported by the Instrument Carrier, a composite, truss-like structure designed and built by GSFC. The Instrument Carrier (IC) also supports the Star Tracker and Inertial Reference Unit (STIRU) assembly for attitude and orientation determination. The Instrument Carrier is supported off the top deck of a hexagonal spacecraft bus structure that provides for typical spacecraft needs (Propulsion,

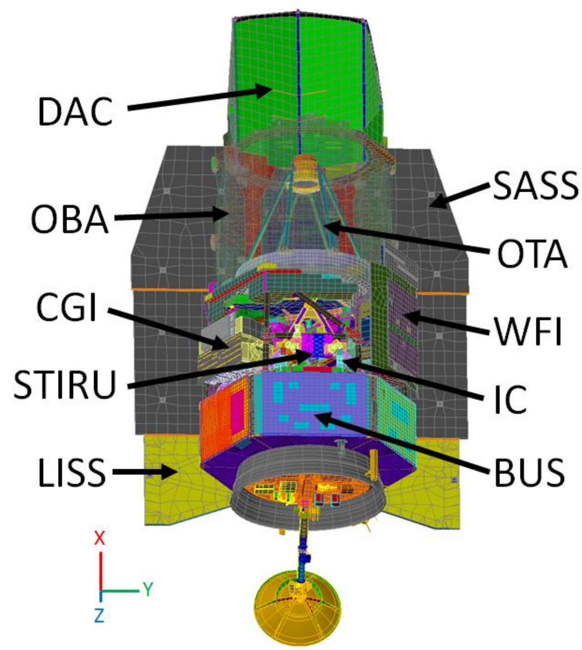

Figure 1. Major Subsystems of the Roman Space Telescope: *The OTA relays light to the WFI and CGI instruments. The OBA, DAC, LISS, and SASS provide a stable thermal scene as the observatory slews overs its Field of Regard, while the BUS handles major spacecraft functions (Communications, Attitude Control, Power Generation, Data Storage, Commanding, etc)*

Communications, Attitude Control, Power Distribution, Command and Data Handling, etc.). Surrounding the telescope and portions of the rest of the payload is the Outer Barrel Assembly (OBA), which provides a stable, temperature-controlled scene for the optics. A one-time actuation of the Deployable Aperture Cover (DAC) provides shielding to prevent direct solar impingement into the OBA. Mounted to the OBA, is the Solar Array SunShield (SASS) assembly, which provides both power generation from solar cells on the sun facing side and isolation from the solar environmental flux. Lastly. the Lower Instrument Sun Shade (LISS) provides isolation for direct solar heating when the observatory pitches in its Field-of-Regard. The observatory is allowed to roll from -15° to +15° about the X axis, pitch from -36° to +36° about the y-axis, and yaw at any angle about the Z-Axis. RST orbits the Sun-Earth Lagrange Point L2 and maintains all pointing and observations within the specified Field of Regard.

In order to achieve the desired science to study dark energy, complete a survey of exoplanets, detect primordial black holes, and demonstrate the technology of the CGI, thermal stability of the imaging systems is of utmost importance as the observatory slews from one target to the next. Therefore, a large number of Proportional-Integral-Derivative controlled heater zones are employed to maintain stable temperatures as the environmental conditions change as a result of attitude changes. The thermal modeling can predict the thermal performance and stability for the analyzed simulations, but in the end, it is really wave front error requirements that must be met. This requires a complex set of simulations that begin with thermal predictions, map those temperature predictions onto a structural Finite Element Model (FEM) mesh, perform thermal distortion analysis, transfer the distortions to an optical model and eventually evaluate the impact on wave front error stability. This is often referred to as STOP analysis: Structural-Thermal-Optical-Performance analysis. A second analysis chain involves disturbances from moving parts (Reaction Wheels, High Gain Antenna pointing) that can lead to distortions and also impact wave front error stability and is often referred to as Jitter Analysis. Furthermore, cumulative moisture desorption (outgassing of water, especially from composite materials) and creep of Invar parts may also lead to distortions that can impact wave front error stability. All of these multi-discipline analyses fall under an umbrella term of Integrated Modeling at GSFC, although thermal is most heavily involved with the STOP analysis.

III. Integrated Modeling Process

The general IM mapping process to compute thermal distortion effects has been consistent and well established throughout the years on RST. This process begins by imposing the thermal temperature field predicted by the thermal model onto the structural FEM through thermal mapping and subsequently computing the thermal distortion. These distortions are then passed to either a lightweight Linear Optical Model or a combination of more advanced optical codes to perform the ray trace, like SigFit, Code-V, or Zemax. The Thermal Desktop Post Processing Data Mapper object has been used since the early days of IM on RST to perform the thermal to structural mapping.

This initially started off with individual models for each sub-component to be mapped within a subsystem, but eventually migrated to single subsystem model and use of the Mapping Group Associations to accomplish the same effect, which reduced the number of files to be generated. During all this, comparisons between like groups for thermal contours and mapped structural contours were often generated, which was a very labor-intensive process to try to best align the viewpoints, generate the images, and then paste them into PowerPoint sides by side. Furthermore, it was not always prudent to map every FEM grid point as some times the structural and thermal representations of a given component may not align well. For example, structures might need to model a strut in detail whereas thermal may just be able to represent it with a simple conductor. As such, a fill-in run is performed in NASTRAN to ensure that all grid points are assigned an appropriate temperature. The algorithm used by the Thermal Desktop Post Processing Data Mapper is described next.

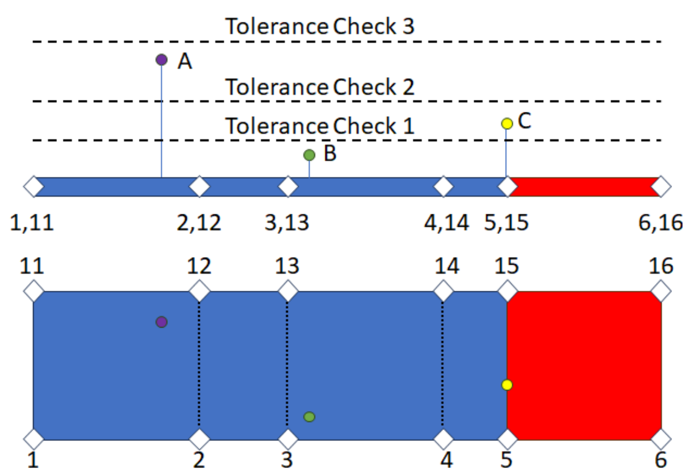

Figure 2. Thermal Desktop Mapping Algorithm: *(Top) Edge View displaying projection of Grid Points onto Thermal surfaces and their node definitions within allowable tolerances (Bottom) Top view of Grid Point locations*

Thermal Desktop identifies all the FEM grid points in the "From" mapping set from the structural model data. Next, it identifies all the solids and surfaces in the "To" mapping set from the thermal model data. As shown in Figure 2, three selected grid points (circles: A, B, and C) are illustrated as being in the "From" set. The "To" set contains two surfaces (Blue-left and Red-right), which includes in their definition the thermal nodes {diamonds: 1, 2, 3, 4, 5, 6, 11, 12, 13, 14, 15, and 16}. Grid Points A, B, and C are projected onto the plane for each surface and if it falls within the boundaries of the surface, the distance between the Grid Point and the Projected Grid Point is compared to the Tolerance Check. If this distance is less than the Tolerance Check, then that Grid Point is then mapped to the temperature at that projected location. In the case of Finite Elements (or finite difference with multiple nodes within a surface), the temperature is computed using shape functions with contributions from each node that defines the sub-area. For Grid Point B in Figure 2, this would include contributions from Thermal Nodes {3, 4, 13, and 14}, with node 3 having a higher contribution than the other nodes based on the shape functions. This produces a mapping relation of Grid Point B Temp = Factor1 * T3 + Factor2 * T4 + Factor3 * T13 + Factor4 * T14, where the sum of FactorX terms equals 1. For Tolerance Check 1, neither Grid Point A nor C would meet the criteria and would not get mapped if no further increases of the tolerance was performed. However, Thermal Desktop also allows for progressive tolerance checking, where increasingly larger tolerances may be used to first find the closest projections and gradually expand the allowed projection distance until all Grid Points are mapped or allowing some Grid Points to be unmapped. Increasing the tolerance to Tolerance Check 2 would map Grid Point C; likewise, further increasing it to Tolerance Check 3 would capture Grid Point A.

Two other subtleties with the mapping are also worth a discussion. Grid Point C in Figure 2 presents an interesting case where the Grid Point falls exactly on the boundary line between the blue and red surfaces. In this case, it is unclear if it would consistently select the blue over the red surface or the red over the blue surface. It is hypothesized that the differences may be found in the nth decimal place, which for single precision calculations stored in a double precision variable may be random noise. This is judged as the primary reason that performing the same mapping at different times or with different results sets might result in slight differences in the interpolation factors, impacting repeatability. A second subtlety is how mapping is handled when the Grid Point is mapped to a solid or possibly a centroid based, multi-node surface and produces an extrapolation instead of an interpolation. This effect could also happen for a single surface with a centroid nodalization as shown in Figure 3. In this case the gradient of the contribution nodes is extrapolated instead of interpolated. This impact can be seen when investigating the interpolation factors and finding that some of them are either negative or greater than 1. For the yellow Grid Point in Figure 3, the factor for node 1 would be greater than 1 and the factor for node 2 would be negative to propagate the gradient to the mapped location. This can result in some mapped temperatures actually being higher or lower than any of the thermal nodes. This is also known to happen when a mapping Grid Points to a solid and where the Grid Point my lie outside of the volume of the solid, but still fall within the tolerance to allow it to be mapped. In this case, for an 8-noded brick element where the Grid Point is mapped to the front face, the back to front gradient would be propagated to the mapped location. This same approach is how contour plots are displayed and may also result in temperatures that are slightly outside of the computed range, but often the granularity of the color bar divisions may mask this impact.

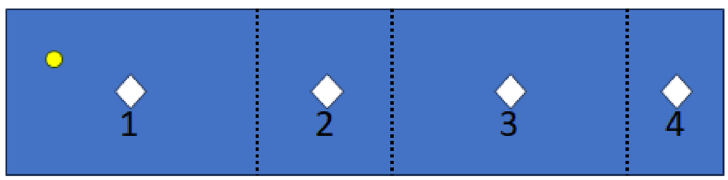

Figure 3. Centroid based, Multi-Node surface that may result in Extrapolation: *The temperature gradient from 2 to 1 is propagated to the mapped location in yellow, resulting in Extrapolation instead of Interpolation.*

IV. ViewSave Tool

The *ViewSave* tool (Figure 4) allows a user to connect to an existing instance of Thermal Desktop and capture view information. They also provide an output folder where the view information is stored in a file, whose name is based on the DWG filename. The *ViewSave* tool extracts the VIEWDIR,

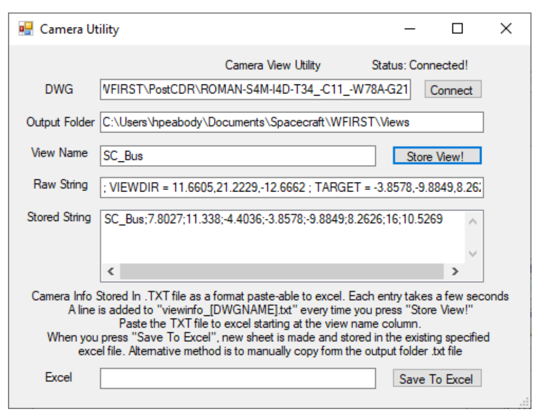

Figure 4. ViewSave Tool: *The ViewSave tool captures the view information directly from AutoCAD. This data is continuously written to a file for later import into a spreadsheet for further definitions and manipulation.*

TARGET, VIEWTWIST, and VIEWSIZE variables from AutoCAD for the current view, which are sufficient to fully define the view to be able to be re-created exactly using those parameters. In this case as shown in Figure 4, the VIEWDIR = 11.6605, 21.2229, -12.6662, TARGET = -3.8578, -9.8849, 8.2626, VIEWTWIST = 16, and VIEWSIZE = 10.5269.

Therefore, the user can simply orient their model in the desired view and zoom as intended and capture this information to display the model from exactly the same viewpoint later. Furthermore, this same information is utilized by another tool developed to reproduce the same view of the FEM model in FEMAP using the same parameters to define the viewpoint in that tool. Previously, this information was manually captured using the “view” command in AutoCAD, which displayed the information visually in a form as shown in Figure 5, however the information was not selectable and had to be manually transcribed to the spreadsheet rather than being captured and stored with a single click. It should be noted that the camera location is the VIEWDIR as a vector relative to the TARGET point. So, a VIEWDIR of {11.6605, 21.2229, -12.6662} added to a TARGET of {-3.8578, -9.8849, 8.2626} yields a Camera position of {7.8027, 11.338, -4.4036}, which matches the Camera X, Y, and Z shown in Figure 5. The tool does this conversion automatically and outputs the camera location, target location, twist angle, and height. However, the *ViewSave* tool captures only the view information and makes no attempt to identify or store the objects currently being displayed. The objects to be displayed are subsequently defined via Thermal Desktop Domain Tag Sets in the *ViewGenerate* tool described later in Section VI.

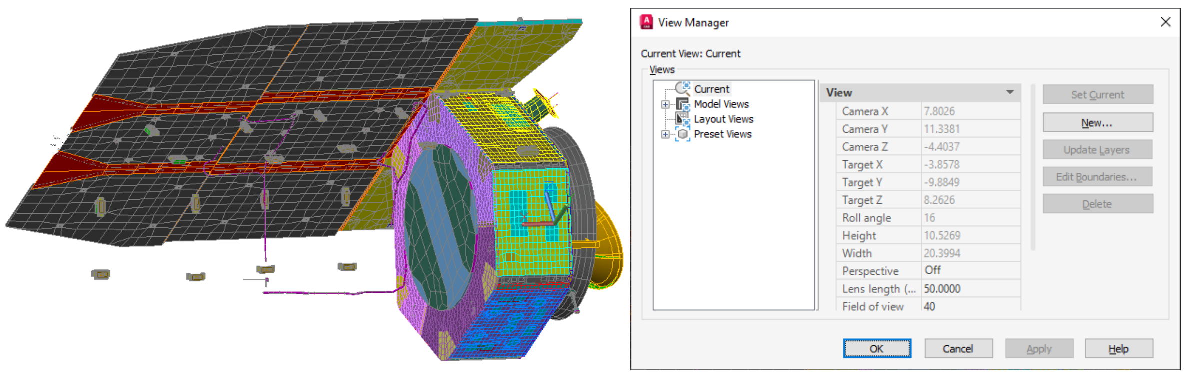

Figure 5. AutoCAD Inputs: *(Left) The orientation set by the user in AutoCAD and (Right) the AutoCAD View Manager displays the same information captured and stored by the ViewTool*

V. Mapping Tool

The *Mapping Tool* (Figure 6) allows usage of the same interpolation factor for multiple results sets. As described in Section III, the mapping algorithm does have the possibility of producing slightly different interpolation factors when Grid Points fall exactly on the boundary between surfaces. To circumvent this potential issue, the mapping is performed once to generate the interpolation factors file and then this file is utilized with multiple results sets to compute the mapped temperatures. Furthermore, this approach alleviates the need to have one single mapper that includes all the subsystems, since multiple interpolation factors files can be processed in sequence. Prior to this tool, each subsystem delivered a Post Processing Data Mapper for their components. These individual

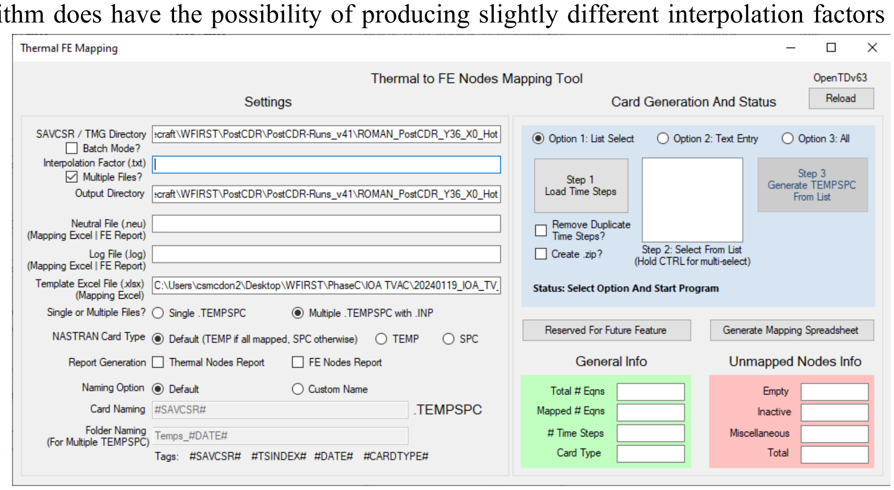

Figure 6. Mapping Tool: *The Mapping tool allows for the specification of multiple interpolation files and a thermal prediction file to compute the mapped Grid Point temperatures to thermal distortion analyses*

mappers had to be merged into a single mapper and all the Structural to Thermal Group associations re-created manually in a single mapper. That mapper was then the one used for production runs to produce the mapped temperature for the full observatory model. With the development of this tool, the individual mappers can be retained, and their individual interpolation factor files used. This also opens the possibility to allow for different revisions of the model and the mapper to be utilized.

Often, the IM model lags behind the discipline model, as newer subsystem models are integrated and validated prior to delivery to IM. After delivery to IM, the analysts may further refine the groups to improve the accuracy of the mapped results; however, these improvements generally do not flow back into the discipline model. Therefore, if any analyses performed at the discipline level are desired for IM purposes (such as a Thermal Vacuum test or launch analyses), these mapping improvements would not be reflected. Furthermore, the mapping of new subsystem components may not yet be available in the IM model. However, with the development of this tool, the interpolation factors files can be combined to produce intermediate IM results using some of the interpolation factors from improved mapping areas of subsystems common to both models while using newer mappers and their associated interpolation files that do not yet exist in the older IM delivered model.

VI. ViewGenerate Tool

9				FEM	View	Camera (Eye)			Target			Roll	Scale	Legend	
10	Slide Num	FEM Group Name	Thermal Domain Tag Set	Group ID	Name	X	Y	Z	X	Y	Z	Angle	Height	Min	Max
11	1	SC_BayPanel1	BUS_MAP_BAY1		BUS_Bay_1	1.37115	-0.00168	-2.2895	1.37115	-0.0017	-6.0595	89.947	1.50564		
12	2	SC_BayPanel2	BUS_MAP_BAY2		BUS_Bay_2	1.36956	1.72619	-1.3716	1.36669	4.84163	-3.4945	90	1.50564		
13	3	SC_BayPanel3	BUS_MAP_BAY3		BUS_Bay_3	1.36957	1.71027	0.87264	1.36661	4.92164	2.84747	90	1.50564		
14	4	SC_BayPanel3_Battery	BUS_MAP_BAY3_BAT		BUS_Bay_3	1.36957	1.71027	0.87264	1.36661	4.92164	2.84747	90	1.50564		
15	5	SC_BayPanel4	BUS_MAP_BAY4		BUS_Bay_4	1.37144	-0.31941	1.91163	1.37184	-0.7499	5.65697	270	1.50564		
16	6	SC_BayPanel5	BUS_MAP_BAY5		BUS_Bay_5	1.27926	15.55505	-9.2616	1.29173	12.412	-7.3616	269.847	1.46679		
17	7	SC_BayPanel6	BUS_MAP_BAY6		BUS_Bay_6	1.36294	-1.89599	-1.084	1.36591	-5.1176	-3.0421	270	1.50564		
18	8	SC_Longeron1	BUS_MAP_LONGERON_1		BUS_Longeron_1	3.76763	-1.50861	4.87527	1.9744	-1.0561	2.63586	161.068	1.15993		
19	9	SC_Longeron 2	BUS_MAP_LONGERON_2		BUS_Longeron_2	3.42157	-7.36803	1.78099	2.02542	-3.8059	0.23314	98.166	1.32516		
20	10	SC_Longeron 3	BUS_MAP_LONGERON_3		BUS_Longeron_3	3.20127	-4.41019	-7.1413	2.18704	-2.5202	-4.1427	66.633	1.4724		

Figure 7. ViewGenerate Input Spreadsheet: *This spreadsheet contains the view information and Structural-to-Thermal group associations to automatically generate the desired views*

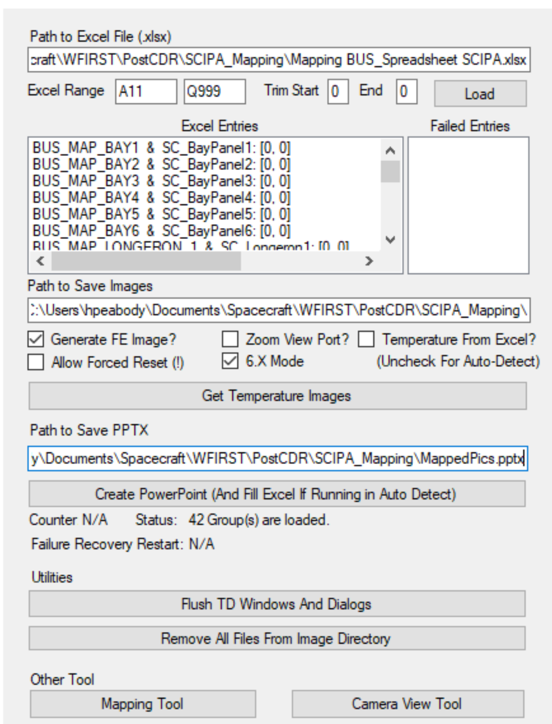

Figure 8. ViewGenerate Tool: *This tool takes data from an input spreadsheet and establishes a connection to Thermal Desktop to display the specified objects from the specified views.*

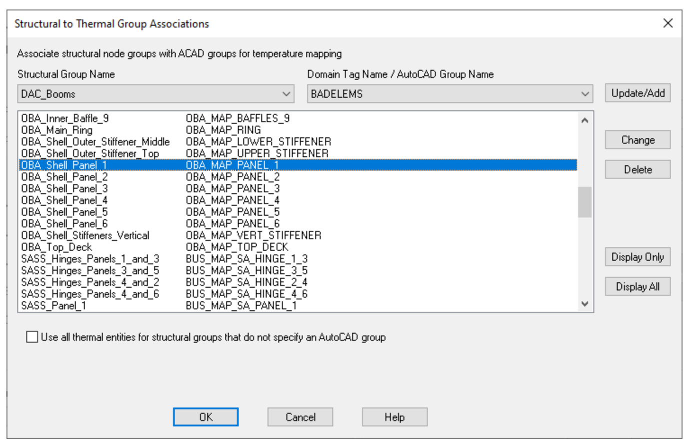

Figure 9. Thermal Desktop Post Processing Data Mapper Group Association form: *This form allows users to display* only *the selected group within a FEM and represents the only known method to allow this in Thermal Desktop*

The *ViewGenerate* tool (Figure 8) takes an input spreadsheet as shown in Figure 7 that defines the views (as saved by the *ViewSave* tool) as well as the FEM group from the structural model and the associated Domain Tag Set from the thermal model, with one entry per line. After connecting to a current session of Thermal Desktop, the tool finds the associated Post Processing Data Mapper, opens the form, navigates to the Structural to Thermal group Associations sub-form (Figure 9), selects the appropriate item in the list box, and lastly executes the *Display Only* button. The outcome of this action is to display the selected Domain Tag set in the post processing mode with the color bar auto-scaled for the range of temperatures associated with the surfaces, nodes, and solids in the selected Domain Tag Set. This capability was enabled using Automation Elements[1] and assistive technology and was not available in the OpenTD Application Programming Interface at the time of development. The values for the minimum and maximum temperature are extracted from the Post Processing color bar and entered in to the spreadsheet in the Legend columns to the right. This is used such that when the same spreadsheet data is used with the structural model, the range can be matched to the thermal image. The image of the thermal model is captured and stored as a file. The next step is the display of the mapped temperatures on the FEM while displaying only the selected FEM group. The color bar scale is set to manual input to prevent the full temperature scale for the entire FEM from being used and this image is also saved to a file. Lastly, an option exists to process all the generated images and post them into a PowerPoint file, with each line in the spreadsheet represented on one slide with the thermal image on the left and the structural image on the right for comparison. An example slide is shown in Figure 10. Currently for RST, it is not uncommon to have over 400 associations, which would be a major effort to generate manually, while the tool generates it overnight.

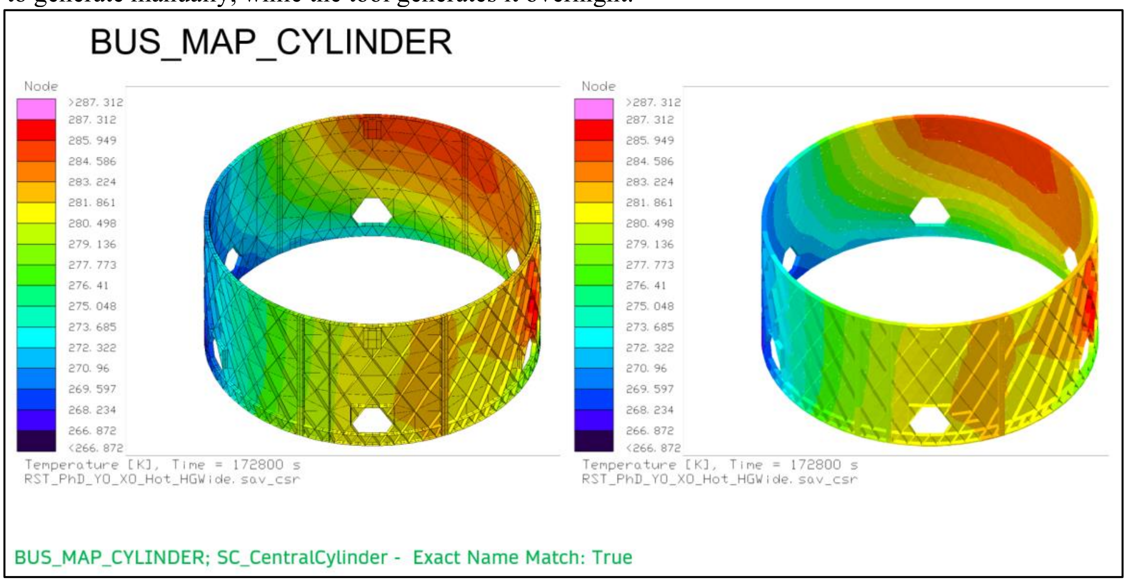

Figure 10. Sample Auto-generated Slide from ViewGenerate Tool: *From a single line in the input spreadsheet, the tool generates a slide such as this with the Group name as a title, the thermal image on the left and the FEM image on the right with identical color bar scales. View information is also stored in the notes section of the slide if needed, allowing thermal analysts to spend more time comparing and less time generating the comparisons.*

VII. Mapping Best Practices

Mapping best practices are generally focused on two main areas: accuracy and repeatability. RST opted early on to not attempt to map every FEM grid point using the Thermal Desktop mapper object due to inherent differences between how thermal and structures might model components. For any grid point not mapped, a structural "fill-in" thermal analysis is performed to populate the remaining grid point temperatures necessary for a thermal distortion analysis. This allowed subsystem analysts to determine whether to ensure that all their grid point were mapped or to allow the "fill-in" run to complete the temperature fields. Had the observatory forced all grid points to be mapped, this would have flowed down to subsystem requirements as well.

A "fill-in" run requires that the FEM utilizes element types that allow for heat transfer analyses to be performed by NASTRAN. For example, Rigid Body Elements have no thermal meaning and cannot be used. Assuming all element types are valid, NASTRAN can be configured to compute temperatures for all grid points based on input boundary conditions. If using NASTRAN for a stand-alone thermal analysis, this would require boundary condition assignments, such as imposed heat loads or temperature boundary conditions, but in the case of a "fill-in" run, it is just a number of grid point boundary temperature assignments. Based on the material properties, NASTRAN generates a conductive matrix and solves the energy balance to compute the temperature field for all grid points. In essence, with many grid points populated as boundary conditions, NASTRAN is really solving an interpolation problem to “fill in” the temperature gradient between assigned boundary temperatures; this does ensure that every grid point has a temperature, which is required for subsequent thermal distortion analyses.

After mapping is performed in Thermal Desktop, the color contours for the thermal representation (henceforth Thermal Group) and the associated mapped structures grids points and elements (henceforth Structural group) are displayed side by side for inspection. The color bar should be expanded to the maximum number of colors/levels allowed and the exact RGB values for each color should be identified such that the exact same colors can be used in the structural visualization tool. These contours are first compared within Thermal Desktop (Thermal Group versus Structural Group) and then compared between Thermal Desktop and the structural analysis code using results after the “fill-in” run.

For best comparison, there are two domains that should be minimized as much as practical: (1) the temperature range and (2) the number of points to compare. It would be possible to compare the full observatory thermal versus structural visually, but the range represented by each color in the color bar may smear and obscure local differences. Furthermore, comparing too many surfaces/grid points makes for difficulty in spotting discrepancies that may be hidden from view. Therefore, a break-down of Thermal Group to Structural Group at a near piece-part level is ideal for mapping checks. It is also important to ensure that appropriate thermal temperatures are mapped; light weight insulation type surfaces should generally not be included as they seldom contribute to thermal distortion but may be included in Thermal Group if not careful. For missions with challenging stability requirements, another useful approach is to map temperature differences between two orientations or analysis cases rather than bulk temperatures. Inherently these kinds of missions have designs that focus on insulation and isolation from stimuli; as such, the temporal gradients tend to be on a much smaller scale than the bulk temperatures. This approach can highlight areas where less-than-ideal mapping is present, since the overall color bar scale tends to be a narrower range. One nuance to note is that when Thermal Desktop performs its mapping and generates the interpolation factors, these values are stored internally. This means that even when a new temperature results set is loaded, the Grid Point temperatures are computed based on the current results set and do not need to be mapped again to display the FEM Grid Point contours. This nuance allows for processing of nodal temperature *differences* to be displayed on the FEM contour in addition to bulk temperature predictions.

For areas where the contours do not match well, the alignment between the Thermal Group and Structural Group should be more closely inspected. While they may appear close from a further-away viewpoints, closer inspection may highlight slight mismatches in alignment, which could lead to extrapolation and assignment of incorrect temperature fields, especially if the component has a sizable gradient. Another area where RST takes advantage of expected alignment differences is in flexures. It is typical that structures analysts model the top and bottom plates at the mid plane, whereas thermal often uses the two inner faces to not overestimate the isolation length. Therefore, for RST, only the top and bottom flexure surfaces are mapped, and the “fill-in” run linearly interpolates the gradient between them. Lastly, the tolerance should be checked to ensure the Grid Points map to the most appropriate thermal surface. A progressive tolerance is used starting with a very small value and subsequently increasing the tolerance by small amounts until the maximum allowed value is reached. It is important not to increase the tolerance too much between trials as it is optimum to find the not just the projected point that is within the tolerance, but the *closest* projected point that is within tolerance. It is not uncommon for RST to have as many as 100 mapping tolerances from zero up to about 11 cm. Anything outside of 11 cm is considered too far away to map accurately.

To improve repeatability, two techniques are employed. The first uses the same configuration of the model for mapping, regardless of the High Gain Antenna Dish pointing or the position of the Element Wheel for the WFI instrument. The same orientation is used that aligns with the structures model but may use *temperature predictions* from a different configuration. Since the mapping should be independent of mechanism orientations, this approach is judged acceptable and eliminates the need for multiple FEM models. Lastly, the use of single sets of interpolation files ensures consistency with mapping different results sets since the same factors are used for each set of predicts. Prior to the development of the *Mapping* Tool described in Section V, the mapper would need to be run for each thermal prediction case, potentially introducing errors due to small differences in the interpolation factors, especially for grid points that lie on boundaries between surfaces as described in Section III.

Lastly, another key aspect for RST has been the use of a pipe-cleaning effort, which refers to ensuring the data flow paths are cleared and vetted before sending large amounts of data through the full STOP process, which can be quite time consuming. The purpose of this is to ensure that data is mapped properly and not to determine if the predicted performance meets requirements. This important first step is where many of the errors associated with mapping are caught without pushing through all the data, then finding an error, and having to trace back to its cause. Effort spent up front to ensure that the predicted temperature field is properly mapped to the structural model can save considerable efforts on the back end trying to understand the discrepancies reflected in optical wave front error due to changing environments or configurations.

VIII. Conclusions and Path Forward

RST has made many improvements in the STOP mapping process since its early days. Beginning with many subsystem FEM files, manual generation of images from similar viewpoints, and numerous Data Mapper executions for various cases, then transitioning to a single mapper with many Thermal Group to Structural Group associations and eventually to subsystem dedicated mappers to generate the interpolation files and fully automated compare image generation, the process for RST has continuously improved. The development of the *ViewSave* tool, *Mapping* tool, and *ViewGenerate* tool, in addition to better understanding of the mapping algorithms and its nuances have enabled faster turn-around of STOP analyses with more accurate mappings and less effort required by the analyst.

That said, these process improvements do require more careful management of the files generated. While the *Mapping* tool, combined with an organized workflow, significantly improves the speed, flexibility, and traceability of the thermal-to-structural mapping process, users are well served to track which specific mappers have been vetted with specific thermal and structural models such that mapping predictions from a thermal model to a structural model can be executed with high confidence. While the *Mapping* tool does necessitate more careful organization and usage, it does allow for flexibility to combine individual mappers to generate maps for the full observatory. For example, if there is an update to one portion of the model, its associated updated mapper interpolation files can easily be swapped in without recalculating (or, most importantly, needing to revalidate) mapping associations for the rest of the observatory. Another use case currently being utilized is for thermal vacuum test models, where users can remove mappers representing hardware that is not present in the thermal vacuum test and add mappers for critical ground support equipment that is. Using the same exact mapping associations for test analysis as for flight also improves confidence that any differences between flight and test predicts are not due to an element of randomness introduced by Thermal Desktop's mapping algorithm. This combination of mapper interpolation files allows for much greater flexibility for evaluating models at different configurations or stages of subsystem integration. Another envisioned improvement utilizing this modular approach is to investigate component-specific mapping settings, such as varying tolerances or advanced mapping techniques, for distinct regions of the model (e.g., treating the faces of optical components differently from the spacecraft bus). Although this potential feature has not yet been fully explored, it offers the community another way to further improve mapping processes.

Organizing directories and workflows gives users flexibility and confidence when executing temperature mapping for integrated systems. For RST, vetted mappers are maintained in distinct directories which facilitates the selection of sets of interpolation files so the tool can process a batch of multiple cases with a single command. The key to implementing this capability is to carefully validate specific mapping interpolations between specific thermal models and specific structural models to ensure proper mapping relations, regardless of the analysis predictions. This directory-based organization is complemented by a naming convention that ensures all generated files are clearly and consistently identified; this is crucial because downstream analyses (structural, optical), rely on these names for proper case identification. For the most recent STOP analysis cycle for RST, this was leveraged mapping 27 hot cases simultaneously, as opposed to handling each case individually, which greatly simplified the process for the structural team, enabling them to plug the results directly into their models without additional reformatting. Furthermore, for transient simulations with potentially more output timesteps than desired for mapping, the use of a comma-separated list to specify desired timesteps has proven to be both faster and less error prone compared to previous approach of manual timestep selection within the mapper object. This approach not only accelerates the mapping process but also minimizes risk of human error during data handling. Overall, this methodology not only streamlines the mapping process but also provides a flexible framework for managing complex model integrations.

With a planned launch in September of 2026, the Roman Space Telescope seeks to unlock our understanding of dark energy and the role it plays in the expansion of the universe, demonstrate a new Coronagraph technology, and complete an infrared survey of exoplanets. Throughout the more than ten years of development, Integrated Modeling has played a key role in ensuring that the design is capable of meeting the requirements to perform the intended ground-breaking science. The dedicated Integrated Modeling team of engineers and analysts have continuously sought improvements in the accuracy and repeatability of the STOP process throughout the project life cycle. Whatever discoveries lie in Roman's future are owed to the dedication and hard work of an incredible team of scientists, engineers, technicians, and all the other support staff who made this observatory a reality.

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Addendum

Trade names and trademarks are used in this paper for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

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