Methodology for Applying a Probabilistic Thermal Analysis Approach to Mars Odyssey Aerobraking

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I. Introduction

Aerobraking (AB) is a cost effective method for making orbit changes using atmospheric drag. It has become useful on recent missions for obtaining the desired destination orbit about a given planet for various scientific motivations. Atmospheric drag is utilized to create an effective ΔV at the periapsis of the orbit and thusly reduces the apoapsis altitude and velocity. Atmospheric drag during AB is created by the spacecraft passing through the upper atmosphere of a planetary body at hypersonic speeds. In all AB missions to date, the solar arrays on the spacecrafts have been used as the primary drag surface. The amount of effective ΔV created by passing through the atmosphere can be controlled by the depth of the drag pass into the atmosphere and the length of the drag pass. However, for an increase in atmospheric density and pass duration, the incident heat flux on the spacecraft and its solar arrays is greatly increased. As expected, an increase in the incident heat flux results in higher temperatures on the solar arrays. In AB, predicting these temperatures is imperative given the solar arrays' finite thermal limit.

The first application of AB took place in 1993 during the Venus Magellan mission[1]. This application was referenced as a "Transition Experiment" being the first of its kind and was not necessary for mission success. The reason for AB in this mission was to reduce the highly elliptic insertion orbit so that the resolution of the gravity data being collected would be increased at non-equatorial regions for the proposed experiment. During AB, Magellan's orbit was reduced from an eccentricity of 0.3 to 0.03 over a period of 70 days and 750 orbital passes. This experiment essentially reduced the orbital velocity by 1,221 m/s while only using 31.6 kg of fuel. The Magellan spacecraft is shown below in Figure 1. Throughout AB, the solar arrays were oriented normal to the aerodynamic flow to increase the drag surface. This AB configuration placed the large High Gain Antenna behind the spacecraft bus to ensure longitudinal stability while in the atmosphere[2]. It is important to note that for this and all subsequent missions that the spacecraft was oriented so that the backside of the solar panels rather than the cell side faced the aerodynamic flow. For the early AB design phase of Magellan, the heating rate was the primary upper design limit. However, a dynamic pressure constraint was also introduced to keep the attitude rates small in case of a sideways entry. At the time of AB, the Magellan spacecraft only had a total of four temperature sensors that would aid in temperature prediction for the solar panels. These sensors were located on the front side of the solar panels[3]. By today's standards, a rudimentary finite element model of the entire spacecraft was utilized to predict the maximum temperatures experienced by the solar panels. This method most likely contained significant errors due the computational capabilities available at the time[4]. While AB was not essential to mission success for Magellan, it was so for the subsequent AB missions: Mars Global Surveyor (MGS), Mars Odyssey, and Mars Reconnaissance Orbiter (MRO).

MGS, the second application of AB, saved approximately 1,220 m/s of impulsive ΔV by AB for over 850 passes. AB was necessary on this mission for the spacecraft to reach the desired science orbit. This spacecraft can be seen in Figure 1 in its AB configuration. As can be seen in the diagram, drag flaps were added to the ends of the solar panels to increase the overall drag of the spacecraft when in its AB

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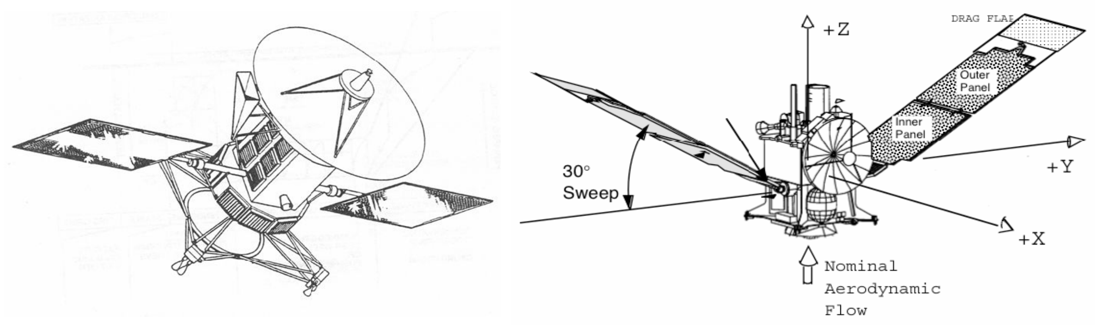
configuration. During AB, the solar panels were to be swept back by 30 degrees to assure aerodynamic stability. However following launch, it was discovered that one of the solar panels did not fully deploy and was thus tilted by approximately 20 degrees. This phenomenon added a new element to this AB mission. To proceed with AB, the broken solar panel was aligned with the cells and directed into the aerodynamic flow. While the AB could continue, a much lower dynamic pressure constraint was introduced causing the AB phase to require an additional year[2]. MGS had four thermocouples located on its solar panels. Two of the sensors were on the cell side of the panels, and two were located on the "hot" side or the side facing the aerodynamic flow. These thermocouples were used as an input to a 1-dimensional thermal analysis that determined the heat rate that the solar arrays experienced during previous drag passes[4].

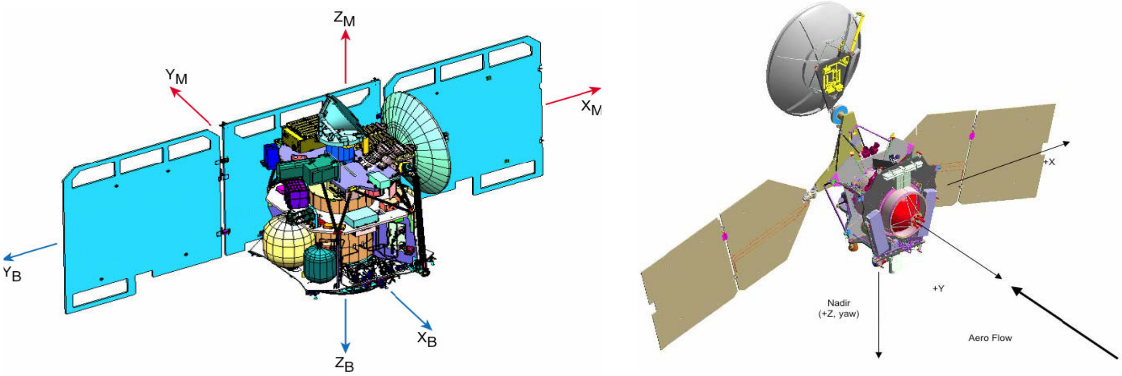
Mars Odyssey, currently the most aggressive AB mission, saved an effective impulsive ΔV of approximately 1,090 m/s over 300 AB passes to enter into a 400 km circular orbit. The spacecraft is shown in Figure 1 in its AB configuration. As with the previous AB missions, Odyssey was oriented so that the cell side of the solar arrays faced away from the flow. This configuration results in a high stability about the body z-axis which nominally points towards the center of Mars during AB[2]. As can be seen in the diagram, the solar array is a three panel, layered construction. Five temperature sensors were utilized in the thermal analysis of the solar panels during the AB phase. Two of the sensors are located on the exposed hot facesheet side, while the other three are located on the cell side. The thermal analysis method used during operations for Mars Odyssey AB exceeded prior methods in its accuracy by utilizing a 3-dimensional finite element thermal model to predict solar array temperatures for future drag passes as well as reconstruct the temperatures from past orbits[4]. Further details into this thermal analysis method and the actual sensor locations will be discussed in detail in subsequent sections.

The most recent AB mission, MRO, which attained its science orbit in August 2007, performed 450 AB passes to circularize and reduce its orbit about Mars and in turn saved approximately 1,190 m/s of impulsive ΔV. The spacecraft's AB orientation can be seen in Figure 1. MRO is the first multiple pass AB spacecraft to have a nearly asymmetric AB configuration. Utilizing the HGA as an additional drag surface does introduce a bias in the spacecraft's angle of attack but also increases its stability[2]. MRO had a significant increase in the number of temperature sensors on the solar arrays. A total of eight sensors with four on the hot side and four on the cell side were located on the spacecraft's solar panels. Also, the sensors were placed in locations where the highest temperatures were expected. These improvements in planning allowed for a more accurate and credible thermal analysis of the solar panels. A new probabilistic thermal approach was used on MRO during AB operations. This approach uses a high fidelity finite element thermal model to create a thermal response surface. The response surface methodology reduces the complex 3-dimensional thermal model into a simple equation that can be used to predict the temperatures at various locations on the solar arrays. Further, a Monte Carlo analysis was used to give a mean temperature prediction as well as a standard deviation from which $\pm 3\sigma$ uncertainty bounds were calculated[5]. As this is the method being applied to the Mars Odyssey mission in this project, it will be explained in much more detail in the following sections.



Magellan

Mars Global Surveyor



Mars Odyssey

Mars Reconnaissance Orbiter

Figure 1. Aerobraking missions

As evidenced in the all of the multiple pass AB missions above, much concern has been placed on predicting accurate solar array temperatures during operations. This process has proved to be a difficult endeavor due to the various uncertainties involved in an AB thermal analysis. The probabilistic method that was previously mentioned as being used for the MRO mission provides a very useful and efficient way of incorporating such uncertainties and determining solar array temperature predictions. This thermal response surface methodology can include environmental uncertainties in the solar array's expected heat loads as well as physical uncertainties associated with the geometry and composition of the spacecraft and solar arrays. The primary environmental uncertainty that has been identified is the density variability in the Martian atmosphere. In addition to environmental and physical uncertainties, computer modeling uncertainties from numerically modeling physical components can also be included in the analysis. Using this method, the most significant uncertainties can all be included in designing the thermal response surface for an AB mission. The response surface equation is most useful when utilized in a Monte Carlo simulation. By statistically varying specific parameters to be used in a single repeated calculation, the Monte Carlo simulation can determine a mean predicted temperature, a standard deviation in the temperature estimation, and the probability of falling within the $\pm 3\sigma$ temperature bounds. Using a simple response surface equation rather than a high fidelity finite element model for the Monte Carlo simulation makes this type of thermal analysis practical for temperature predictions during AB operations.

II. Motivation

As addressed in the previous section, a probabilistic thermal prediction model is a necessary component for a safe and robust AB mission. Furthermore, the model needs to perform fast enough so that a full thermal analysis of the solar array can be performed during each drag pass of AB operations. For Magellan and MGS, the thermal models were quite rudimentary compared to the 3-dimensional finite element thermal models utilized directly on Mars Odyssey and indirectly on MRO. Mars Odyssey was the first AB mission to attempt using a complex model to predict temperatures on the solar array for future drag passes as well as reconstruct temperature distributions for past passes. This method resulted in the detailed temperature distribution predictions seen below in Figure 2. While this method was a vast improvement over those used in previous AB missions, it was a somewhat slow process and provided no method for determining uncertainties in the predictions as well as for calculating the probability of the actual temperature falling within a $\pm 3\sigma$ temperature bound of the estimate. Performing such studies with the high fidelity model would have been extremely time intensive requiring approximately 10,000 hours for a 10,000 case Monte Carlo simulation of one drag pass[5].

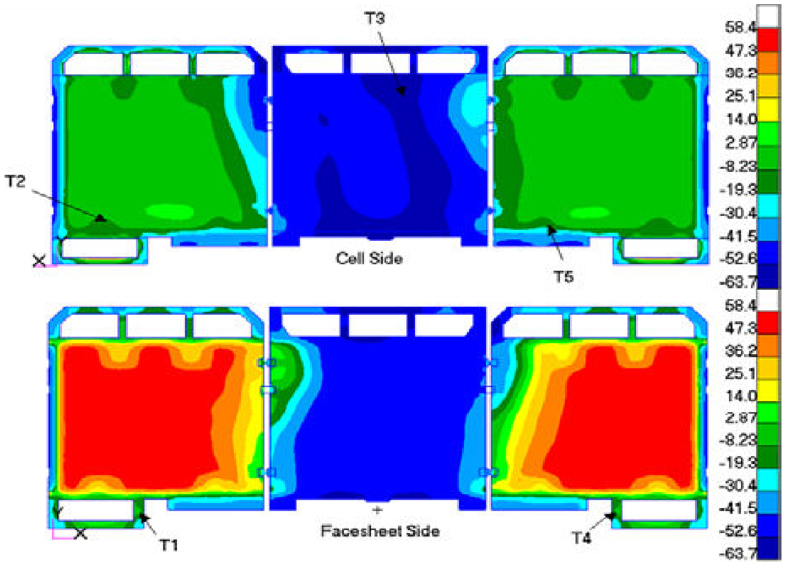


Figure 2. Predicted temperature distribution on the solar array[6] (drag pass 40)

However, since this detailed analysis was performed for each orbit during operations, it makes Mars Odyssey a prime candidate for testing and studying the probabilistic thermal model that utilizes a response surface equation in place of the high fidelity 3-dimensional finite element model. The model used during Odyssey AB operations also provided hot spots and maximum temperatures on the solar arrays independent of the temperature sensor locations. While the response surface methodology has been applied to the MRO mission, 3-dimensional finite element thermal model predictions do not exist for each orbit during MRO AB.

Another motivation for applying the response surface methodology to the Odyssey mission is because of its aggressive AB. Compared to Odyssey, MRO was a fairly benign and far less aggressive AB mission. During Odyssey AB, a maximum solar array temperature was estimated to reach 90°C on orbit 106 while MRO's peak solar array temperature was estimated to reach only 40°C. This aggressive Odyssey AB will no doubt push the solar array temperatures much closer to their thermal limit. Attaining $\pm 3\sigma$ uncertainty bounds and the probabilities associated with the bounds will provide great insight into the robustness of using a probabilistic thermal prediction model.

III. Development of Method

Applying a probabilistic thermal analysis to Mars Odyssey AB requires the use of high fidelity 3-dimensional finite element model. This type of model was used for determining the thermal limits during the design phase of the mission and for temperature predictions during AB operations. For this study, the high fidelity model was used to create a response surface model of solar array temperatures at specific locations. This response surface model can then be utilized in a Monte Carlo simulation to obtain a mean temperature estimate along with a standard deviation of the estimate for positions on the solar array. As mentioned before, the Monte Carlo simulation can also provide a probability of the temperature being within a specified corridor.

The high fidelity thermal model used to create the response surface is strategic in the accuracy of the response surface temperature estimates. Three primary components comprise the thermal model used on Mars Odyssey. The Thermal Desktop model is the first of these components and is used to determine radiation view factors and the orbital heating for each drag pass. The second component is the Patran Thermal finite element model which is used to calculate the solar array temperatures encountered during each drag pass. The Thermal Desktop model and Patran Thermal model of Mars Odyssey used in the thermal analyses are shown below in Figure 3.

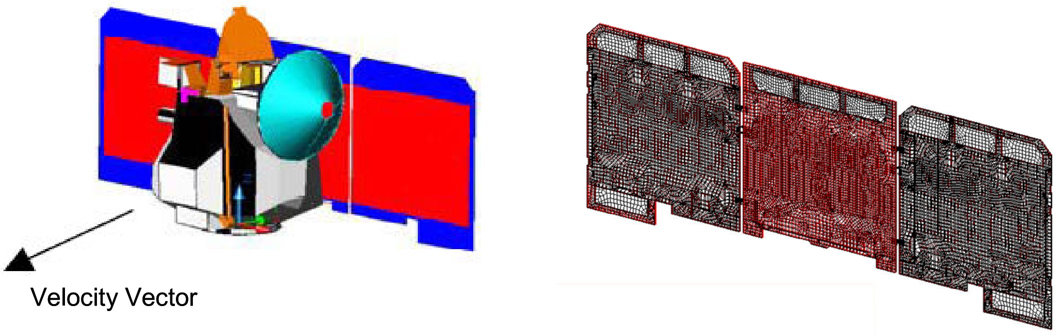


Figure 3. Thermal Desktop model (left) and Patran Thermal model (right) of Mars Odyssey

A Direct Simulation Monte Carlo model of the Odyssey spacecraft and solar arrays is the third component and is used to calculate the heat transfer coefficients as a function of the atmospheric density. A sample heat transfer coefficient distribution on the Mars Odyssey solar arrays for a density of 32 kg/km^3 is shown below in Figure 4. Also in the figure below, the approximate temperature sensor locations are identified. As shown, sensors one and four appear on the hot facesheet side, and sensor two, three, and five appear on the cell side. These locations are important in this study as they are the primary source for validating the proposed thermal analysis method.

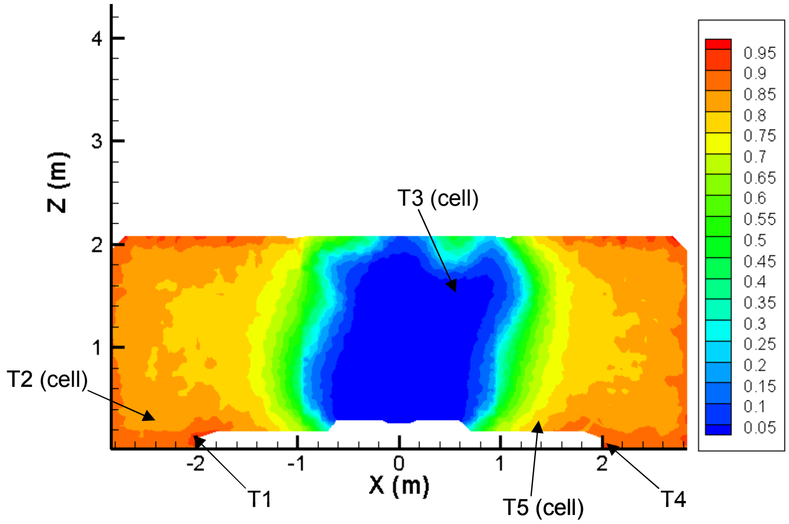


Figure 4. Odyssey heat transfer coefficient distribution with temperature sensor locations for a density of 32 kg/km^3

The boundary conditions for the thermal model come from the provided POST trajectories as well as the Thermal Desktop and DSMC outputs. The three primary components of the high fidelity thermal model used during Odyssey AB operations can be combined to predict temperatures on the spacecraft's solar arrays. A sample temperature distribution using this methodology can be seen by referring back to Figure 2. As is evident by viewing the distribution, the temperature sensors were placed in rather poor positions for determining the maximum temperatures on the solar arrays. For this particular orbit, the thermocouples indicated temperatures around 0°C while there are obviously locations on the facesheet side of the array that reach temperatures near 50°C. These errant sensor positions further necessitate an accurate and robust thermal model for determining maximum temperatures.

During Odyssey AB operations the thermal model was correlated to flight data. Doing this revealed that the error in the temperature predictions was directly related to the uncertainties in the density profile predictions. An error in the predicted density profile will lead to errors in both the predicted peak heat flux reached and total heat load; both of which will lead to inaccurate temperature predictions. This large variation in the density profile from the assumed normal distribution can be seen in Figure 5 for an individual orbit.

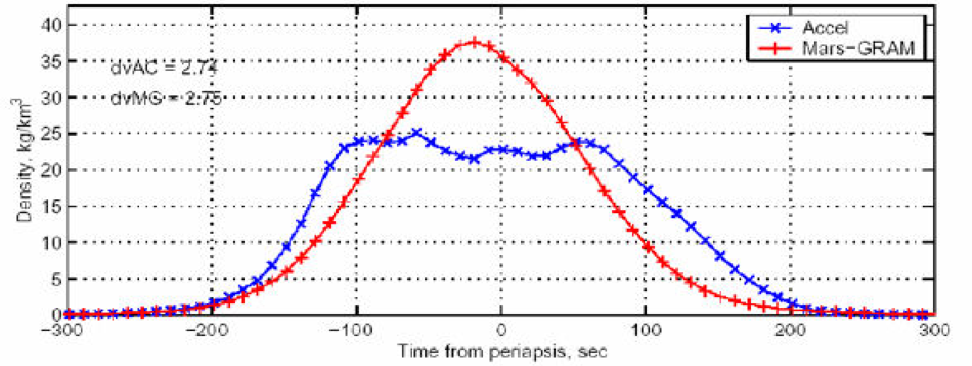


Figure 5. Mars Odyssey density profile for orbit 157

In addition to density uncertainties, many other uncertainties contribute to unreliable solar array temperature predictions. A new and more useful method of temperature prediction was deemed necessary and was utilized for MRO AB operations. This method, as previously mentioned, utilizes a Monte Carlo simulation to statistically vary inputs into the thermal model and thus provides a way of quantifying the uncertainties involved in the thermal predictions and calculating the probability of exceeding a thermal limit. This type of Monte Carlo simulation cannot be simply applied to the high fidelity thermal model used for Odyssey operations because of the length of time involved in predicting the solar array temperature distribution for each case. As mentioned before, one set of predictions would require approximately 10,000 hours for a 10,000 case Monte Carlo simulation. To make a Monte Carlo simulation practical, temperature predictions must be calculated in a few seconds rather than several hours. Using a thermal response surface model in place of the high fidelity thermal model, allows for the necessary rapid temperature predictions.

A response surface equation can appear in various mathematical forms. For this study, a polynomial equation was used. The general form of a polynomial response surface equation can be seen below with both the two and three-variable interactions. The primary reason for choosing a polynomial equation for this study is that this form can be evaluated several times per second as opposed to a more computationally demanding form. Also, the actual equation used in the Odyssey temperature prediction only involves the two-variable interactions.

$$T_m = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} b_{ii} x_i^2 + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} b_{ij} x_i x_j + \sum_{i=1}^{n-2} \sum_{j=i+1}^{n-1} \sum_{k=j+1}^{n} b_{ijk} x_i x_j x_k \qquad \textbf{(1)}$$

In the response surface equation used for this analysis, the dependent variable is the temperature of the solar array at a specific location. Since, there are five sensor locations and a maximum temperature being calculated, six separate response surface equations were required. Deciding which independent variables to include in the equation is a matter of determining which variables have the most effect on the temperature of the solar array. This is typically done by a group of discipline experts brainstorming about the various affects on solar array temperatures during AB. While this is the most commonly used method for this type of analysis, it is also the most subject to error as an important variable may be inadvertently omitted. Ideally, a sensitivity analysis would be performed to determine the variables that most impact the dependent variable. This type of study would also reveal any correlation between variables. However, a sensitivity analysis of this style is extremely time intensive and not practical for this study. In this case, the discipline experts included those responsible for the development, use, and correlation of the thermal models for both MGS and Mars Odyssey[5]. The independent variable results that were used for this Odyssey response surface development were originally determined for use during MRO AB. Since the AB portions of the two missions were similar, these variables were determined relevant for use with Odyssey AB data. While a response surface equation would be the most accurate if each and every temperature impacting element were included, each additional variable greatly increases the number of Patran Thermal runs required. An increase in the Patran Thermal runs greatly increases the time required for building the response surface. Therefore, the 15 independent variables selected for the study are displayed below in Table 1 alongside their 3σ uncertainty as estimated by the panel of experts. The response surface bounds column of the table displays the upper and lower bounds used for each variable when building the response surface. ±6σ was used for all variables where such values were realistic. ±5σ was used for the variables where ±6σ exceeded the possible range such as when the emissivity value goes above 1. The chosen factors are divided below into environmental factors, material property factors, and modeling factors.

Table 1. Odyssey analysis variables used in developing the response surface equation

Category	Factor	3σ uncertainty	Response Surface Bounds	Distribution
Environmental	Drag pass duration	±3%	±6σ	Normal
	Density	±30%	±6σ	Normal
	Heat transfer coefficient	±14%	±6σ	Normal
	Periapsis velocity	±0.05 km/s	±6σ	Normal
	Initial solar array temperature	±20°C	±6σ	Normal
	Orbital heat flux	±30%	±6σ	Normal
Material Property	M55J graphite emissivity	±4%	±6σ	Normal
	ITJ solar cell emissivity	±5%	±6σ	Normal
	M55J graphite thermal conductivity	±25%	±6σ	Normal
	M55J graphite specific heat	±15%	±6σ	Normal
	Aluminum honeycomb core thermal conductivity	±30%	±6σ	Normal
	Aluminum honeycomb core specific heat	±5%	±6σ	Normal
Modeling	Outboard solar panel mass distribution	±50%	(±6σ)	Normal
	Solar cell layer mass distribution	±10%	(±6σ)	Normal
	Contact resistance between panel layers	±50%	±6σ	Normal

As mentioned above, the number of Patran Thermal runs must be minimized to create the response surface in a practical amount of time. The best way to do this is using a statistical design of experiments (DOE). The most thorough method is the full factorial design in which all variable combinations are analyzed. However, this can result in far too many Patran Thermal runs to make it practical for this study. For the 15 selected factors with three levels (high, low, and midpoint value) each, a full factorial analysis would result in 3^{15} or 14,348,907 Patran Thermal runs. A full factorial analysis increases exponentially based on the number of variables and levels making this method entirely impractical. However, a statistical software package, JMP, allows for various DOE's that minimize the number of required runs. To allow for a more timely processing time, JMP was used to form a face centered central composite design. Using the face centered central composite design, the number of runs could be drastically reduced while maintaining an acceptable degree of accuracy. For the 15 independent variables with three levels each, the number of Patran runs was reduced from 14,348,907 to 296 by using the face centered central composite design. To further increase the accuracy of this methodology, the peak density was handled as three completely separate response surface equations and was then varied on a smaller scale within each response surface. This was done to reduce the impact of the large variance in peak density throughout the mission. Thus, for the full range of density values, 888 cases are required. After running each of the three sets of the 296 runs where the 15 variables were set to different combinations of values, the maximum temperatures for each of the five sensor locations along with the maximum temperature for the entire array were entered into JMP. Then, using JMP's step-wise regression function, the coefficients to the response surface equation were determined. These are represented by the letter *b* in equation 1.

After obtaining the response surface equations, the final step in the probabilistic thermal analysis approach is to perform a Monte Carlo simulation. The most difficult part of performing the Monte Carlo simulation is determining the uncertainties for all of the variables. As with determining the 15 response surface variables, the MRO uncertainty values were utilized and simply applied to the Mars Odyssey AB mission. For MRO, the drag pass duration, atmospheric density, heat transfer coefficient, and periapsis velocity uncertainties were determined by analyzing past Mars AB mission data and calculating the mean and standard error of the data for each. This is the best and most accurate method for determining the uncertainties and was therefore used for these integral analysis variables. However, the remaining 11 variables' uncertainties were approximated by expert judgment. Using expert judgment as opposed to the more rigorous method can lead to increased error in the Monte Carlo results. Therefore, very conservative estimates were used for these remaining variables to increase in the fidelity of the results. The following sections will provide detailed instruction on implementing this study and on utilizing the required analysis tools.

The flow of the entire study is represented in Figure 6. The left side of the diagram lists the various analyses and files that are required for input into Patran and the response surface. As shown, JMP is utilized to generate the cases for Patran. Patran is then used for estimating the temperature profiles for the specific cases. These temperatures are then fed into JMP where the response surface equation is generated using stepwise regression of the data. Finally, the response surface equation is utilized in a Monte Carlo analysis to generate estimates of maximum temperatures for the Odyssey solar panels as well as the probability of exceeding the thermal limit of the panels.

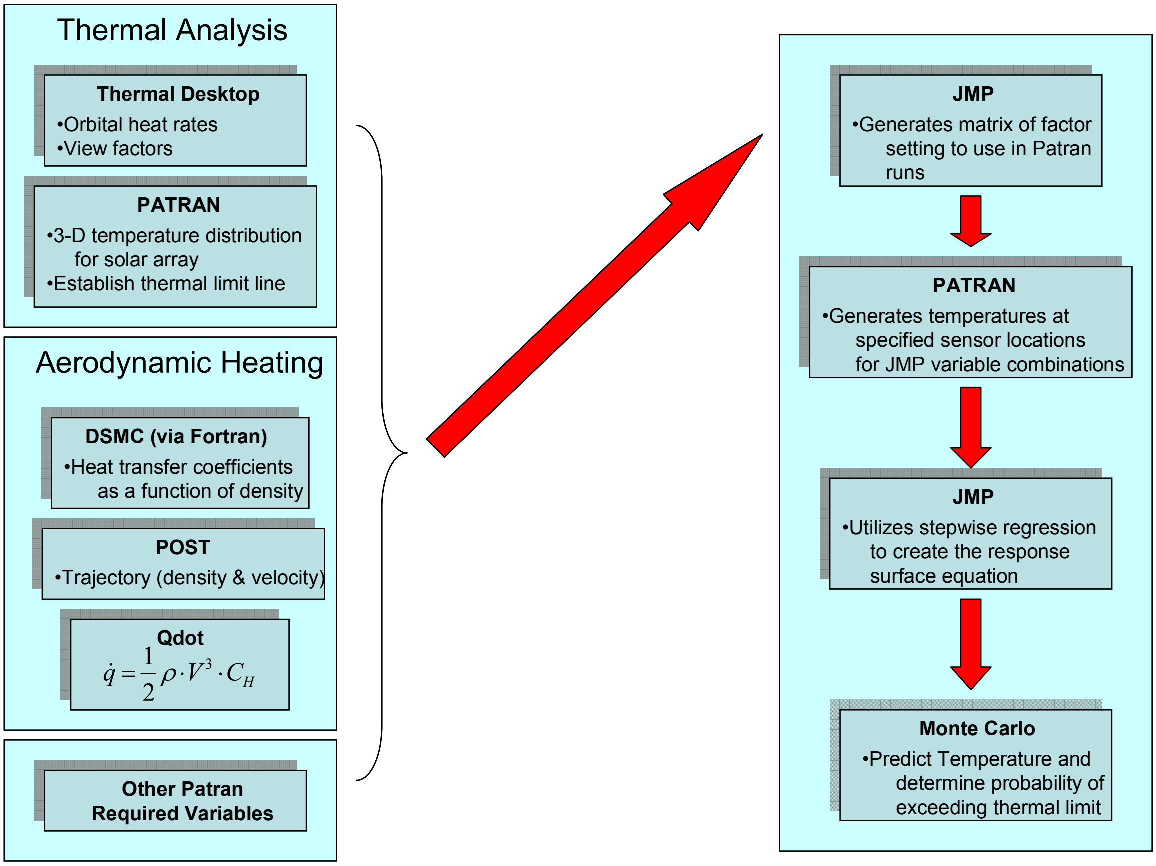


Figure 6. Flow of Required Analyses for the Study

IV. Instruction on the Creation and Modification of Required Files for Patran

Many files are necessary for producing a temperature prediction profile for a specified Odyssey drag pass using Patran. Foremost is the finite element model of the solar panel. The Odyssey finite element model is called *mars_ody_rev5.db*. In addition to this model, several other data files are required by the Patran simulation. These files include the DSMC data files for accounting for the heat transfer coefficient, trajectory files, orbital files (view factors and orbital heat flux) obtained from Thermal Desktop, material property files, Fortran code for modifying the solar heat flux, initial temperature files, and files associated with modeling uncertainties. In addition to these data files, there are several Patran required control files and drivers necessary for proper execution. In addition to nominal files, off-nominal versions of the data files were also created to accommodate the high, mid, and low variable variations. Figure 7 displays the various files and the files respective names that are required by Patran for producing the case specific temperature profiles. In the filenames that have a 'z', the 'z' represents the nominal version of the file or variable associated with the file. A 'p1' or 'm1' can replace the 'z' for high and low cases, respectively. The 'z' represents zero, the 'p1' represents plus one, and the 'm1' represents minus one. The following sections will explain how these files were obtained or constructed.

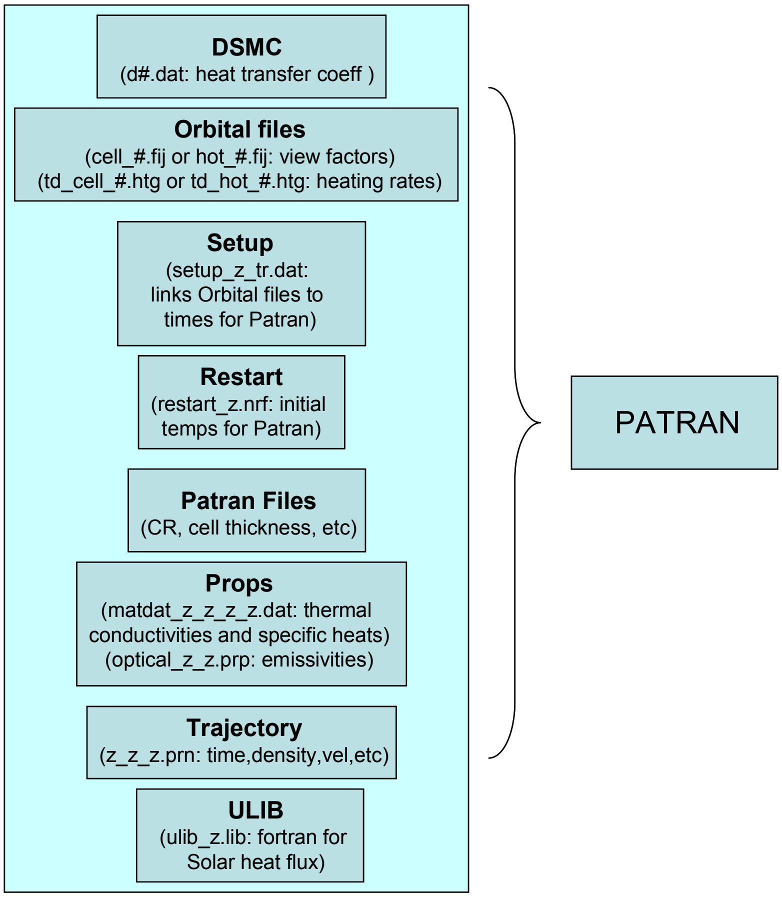


Figure 7. Files Required for the Operation of Patran

A. Heat Transfer Coefficients Using DSMC Data

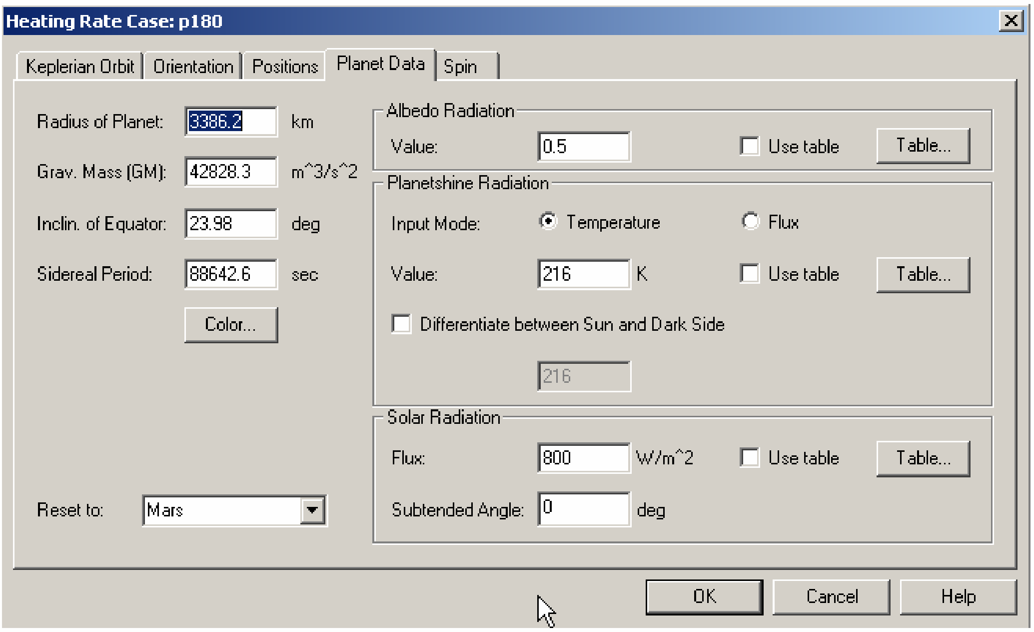
The Direct Simulation Monte Carlo files needed by Patran were obtained from aeroheating data provided by Dick Wilmoth. These files were then modified to the format required by Patran. This processing also involved mapping the heat transfer coefficients to the proper mesh for the Odyssey model and then varying the nominal heat transfer coefficient files to accommodate the high and low cases for the response surface. This process was performed using a Tecplot macro entitled *newmesh_DSMC.mcr*.

B. Trajectory Files

Five Odyssey-like trajectories are required for this study. Three are required for the cases needed to build the response surface, and all five are utilized for a fitting initial temperature to orbital period for the Monte Carlo analysis. The process involving the five orbits and curve-fitting the data for use in the Monte Carlo analysis will be explained in the section detailing the Monte Carlo simulation. The orbits were obtained using POST and provided by Jill Prince. In addition to the time based trajectory data, orbital elements for each of the orbits was provided for use in the Thermal Desktop analysis below. These nominal trajectory files then are modified to represent high, mid, and low variations in drag duration, peak density, and maximum velocity. For three nominal orbits, 27 trajectory files are needed for the specified variations. An Excel spreadsheet entitled *RS_traj_ody.xls* is used to modify and create the necessary files.

C. Orbital Files Obtained Using Thermal Desktop

The view factor and orbital heating files used in Patran are created using Thermal Desktop. The Thermal Desktop model of the Odyssey spacecraft is *MSP_01_stow.dwg*. To use this model, the short, medium, and long drag pass duration orbits must each be loaded into Thermal Desktop using the orbital elements provided with the trajectory data. The menu for entering the Keplerian orbital elements is accessed from *>Thermal>Orbit>Manage Orbits*. From this menu a new orbit can be added using the specified orbital elements. When entering the Right Ascension of the Ascending Node, note that the value must be converted to International Astronomical Units (IAU) using the internal conversion function. Also note that the Right Ascension of the Prime Meridian is not used and thus is arbitrary. Under the *Orientation* tab, verify that there are additional rotations of -90° about the z-axis and 180° about the x-axis. These rotations are controlled by the internal slew-to-aerobraking commands. In addition, the orientation should be referenced by +Z pointing in the Nadir direction. The Planet Data tab should be set as is shown in Figure 8. The *Radius of Planet* value can be slightly modified so that the periapsis and apoapsis altitudes under the *Keplerian Orbit* tab match the values provided with the orbital elements.



Radius of Planet: 3386.2 km
Grav. Mass (GM): 42828.3 m^3/s^2
Inclin. of Equator: 23.98 deg
Sidereal Period: 88642.6 sec
Reset to: Mars

Albedo Radiation
Value: 0.5 ☐ Use table

Planetshine Radiation
Input Mode: ● Temperature ○ Flux
Value: 216 K ☐ Use table
☐ Differentiate between Sun and Dark Side
216

Solar Radiation
Flux: 800 W/m^2 ☐ Use table
Subtended Angle: 0 deg

Figure 8. Thermal Desktop Planet Data Settings

Selecting the true anomalies under the *Positions* tab that correspond to the orbit positions to be analyzed is dependent on the orbit and requires some additional investigation to determine adequate values. To obtain sufficient data, orbit positions were chosen that represent 5 minutes prior to crossing into shadow, just prior to crossing into shadow, shadow entry, directly after shadow entry, periapsis, just prior to shadow exit, shadow exit, and directly after shadow exit. For determining proper true anomaly values corresponding to specific times in the orbit, a Matlab file, *time2trueAnomoly.m* was created that converts between true anomaly and time. Another easy way to obtain this correlation in Thermal Desktop is by highlighting the orbit and typing 'list' into the command prompt. This then prints the time and true anomaly for each of the specified orbit positions.

Once the orbits are loaded into Thermal Desktop, the view factor and orbital heating files can then be created. For creating the view factor files, select *>Thermal>Radiation Calculations>Calc View Factors*. Once the software has finished processing the view factor information, create a new post processing data set by selecting *>Thermal>Post Processing>Manage Datasets*. Then, a new *Form Factor* data set can be created based on orbit and orbit position. This process must be done for each position in each orbit. When creating the post processing data set, make sure that the *Fij/Bij to space* flag is set under *All node data*. Finally, the view factor data must be exported from Thermal Desktop for use in Patran. To do this, select *>Thermal>Export>Write Node Information,* and write to file the *Node Locations* and the *Current Post Processed Data* for *All nodes*. A very similar process is followed for producing the orbital heating files. For calculating the heating rates, select *>Thermal>Radiation Calculations>Calc Heating Rates Ray Trace*.

The Thermal Desktop *Post Processing* and *Exporting* of the data for the heating rate files is done as it was for the view factor files. For more details, refer to the Appendix under the section supplied for running Thermal Desktop.

The view factor and orbital heating files still require additional post processing after they have been exported from Thermal Desktop. This process is done using a set of Matlab files and Tecplot macros. The files have to first be modified using Matlab so that they are in the format needed by the mapping macros. These initial m-files are entitled *read_2_text_VF.m* and *read_2_text_HTG.m* for view factors and orbital heating. The Tecplot macros used to map the data to the proper mesh are entitled *hot_Macro.mcr* and *cell_Macro.mcr* as there is needed a mapping for the files representing the cell side and the hot facesheet side of the solar arrays. It should be noted that there are separate macros of the same titles for view factor data manipulation and orbital heating data manipulation. Finally, the data files are converted to the format required by Patran using *Cell_VF_afterMacro.m*, *Hot_VF_afterMacro.m*, *Cell_HTG_afterMacro.m*, and *Hot_HTG_afterMacro.m*. This entire process must be performed for each of the positions in each of the orbits being used in Patran.

Another file that is required by Patran is *setup_tr.dat*. This file simply provides the Patran simulation information regarding the time tags associated with the view factor and orbital heating files. This file includes the periapsis time as well as the times of the other selected orbit positions.

D. Material Property Files

The material properties that are varied in the Patran cases for building the response surface are emissivity, thermal conductivity, and specific heat. The baseline or nominal emissivity data is contained in the *optical.prp* file. These files are modified by simply changing the emissivity values associated with the M55J graphite or the ITJ solar cell for the $\pm 6\sigma$ response surface bounds. This results in nine separate emissivity data files. The thermal conductivity and specific heat values for the M55J graphite and the aluminum honeycomb core are found in the file *matdat.dat*. The changes necessary to accommodate high, mid, and low values for all for of the variables result in having to create 81 different *matdat.dat* files with several modifications in each file. The tables requiring modification for M55J thermal conductivity uncertainty are 10401 and 10402. The table needing modification for M55J specific heat uncertainty is 10405. The tables needing modification for the aluminum honeycomb core thermal conductivity uncertainty are 10101, 10102, 10111, 10112, 10121, 10122, 10141, and 10142. The tables needing modification for the aluminum honeycomb core specific heat uncertainty are 10105, 10115, 10125, and 10145. Due to the large number of modifications, a Matlab file, *TCandSH_builder.m*, was created to implement and generate the various modified files. However, the m-file does require the user to calculate the $\pm 6\sigma$ values for each variable.

E. Fortran Code for Solar Heat Flux Accommodation

The solar heat flux is controlled in Patran using Fortran code. This code is in the file *ulib.lib* and needs only a multiplication factor applied to the solar heat flux calculations to vary its value as required in building the response surface equation with $\pm 6\sigma$ bounds.

F. Initial Temperature Files

The initial temperatures used by Patran are contained in a binary file called *restart.nrf*. This file is created by Patran and is necessary for obtaining an accurate temperature profile. To create the file, it is necessary to run a Patran simulation starting at a point in the orbit that is at least 5 minutes prior to when the actual Patran run will begin. When doing this, it is necessary to comment out the line in the Patran driver file, *qin.dat*, that reads the *restart.nrf* file. Doing this globally sets all of the nodes to 0°C at the beginning of the simulation. The additional time at the beginning of the orbit allows the spacecraft to reach a steady state temperature prior to the drag pass. When Patran is executed, *restart.nrf* files are created at 10 sec increments. So, the initial temperature file that corresponds to the time that the actual Patran simulation will begin can be obtained for each of the orbits. This file then needs to be further modified for the uncertainties in predicting the initial temperature by creating the high and low *restart.nrf* files. This is done by first converting the binary files to ASCII files. This conversion can be done by typing 'patq' from the command line. After selecting option 6, there is an option to convert output files from binary to ASCII format. The data in the *restart.nrf* file can then be modified for the uncertainty in the initial temperature using a Fortran macro called *nrMod.exe* or by other, more basic, methods. Then by typing 'patq' from the command line again and choosing the appropriate options, the file can be converted back to a binary format.

G. Files Associated with Modeling Uncertainties

Several uncertainties are created in the modeling of physical properties. To account for these errors in building the response surface, these uncertainties must be modeled. The primary modeling errors that are included in this study are contact resistance between panel layers, outboard solar panel mass distribution, and solar cell layer mass distribution. These variables must be accounted for from within Patran. For varying each of these parameters, the Patran model *mars_ody_rev5.db* must be opened in the Windows version of Patran. For modifying the contact resistance, select the *Loads & BC* tab and switch the *Action* to *Modify* and the *Object* to *Convection*. Then select *hot_facesheet_to_core* and modify as required. The same must then be done for the *core_to_upper_facesheet*. For varying the facesheet thickness, select the *Properties* tab and switch the *Action* to *Modify*. Then select *graphite_epoxy_standard* and modify the value associated with the shell corner thickness. For varying the solar cell thickness, select the *Properties* tab and switch the *Action* to *Modify*. Then select *Ga-As* and modify the value associated with the shell corner thickness. Once the changes have been made to the three variables, switch to the *Analysis* tab, enter a descriptive job name and click *Apply*. This will then create a directory with the necessary files for running Patran for the specified combination of variable values. Also, the primary Patran driver file *qin.dat* is created during this process and is thus associated with the specified combination of modeling uncertainties.

V. Methodology for Running Patran in Windows

Once all of the files have been created and modified as needed to cover the bounds of the response surface, the Patran runs can be performed as specified by the face centered central composite experiment design. The list of these cases is located in *RUN_Options.xls*. The *High*, *Mid*, and *Low* tabs represent the high, mid, and low density response surfaces with the column headers located in the *Column Names* worksheet. A Matlab file *DOS_create.m* is then used in conjunction with the case listings to create a batch file that autonomously cycles through and processes the 888 Patran runs. Great care should be taken when using this m-file as a wrong variable can yield the response surface invalid. The batch script simply copies the case specific files from the library of files created in Section IV into a run directory and then executes the Patran run commands producing the temperature profile for that particular case. This temperature profile for the various solar panel locations is located in the output file *trans.01*. This file is then used in conjunction with the case listing to build the response surface.

VI. Creating Response Surface Equations Using Patran Output

The *trans.01* Patran output temperature profile is then used directly in the creation of the response surface equation. However, only the maximum temperatures from each drag pass are needed for the response surface. These maximum temperatures are extracted from each temperature profile and placed into an Excel spreadsheet based on case number using a Matlab file called *trans2maxtemps.m*. The maximum temperature data is then copied into a JMP file where the cases are listed with the variable settings for each case. *15 factor CCD.jmp* is an example JMP file used for this type of analysis. Once the maximum temperature data is loaded into JMP, select the *Analyze* tab and choose *FitModel*. Be sure to remove all but one variable from the *Pick Role Variables* listing. The statistical analysis is then performed by selecting *RunModel* and then *Go*. This produces a table of ‘Estimates’. These ‘Estimates’ will be used as the coefficients for the response surface. Be sure to extract these estimates at this point and place them into an Excel sheet for use in the Monte Carlo analysis. The RMS of the Error and the R^2 adjusted values can also be obtained by selecting *MakeModel* and then running the model with Standard Least Squares. These values are a good indication of the response surfaces fit to the temperature data. Also, a graphical representation of the response surface’s match to the data is provided in JMP with an Actual vs. Predicted Plot as shown below in Figure 7.

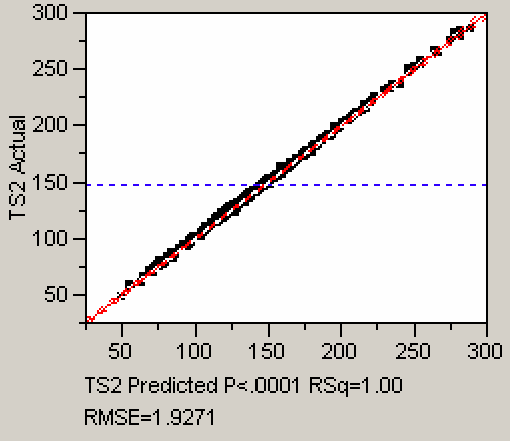


Figure 7. JMP Response Surface Equation Accuracy

VII. Performing the Monte Carlo Analysis

The Monte Carlo portion of this project takes a combination of parameters based on a per orbit basis and parameters that do not vary between orbits. The orbit dependent variables are drag pass duration, peak density, periapsis velocity, and orbital period. These variables are entered on a per orbit basis into the Monte Carlo driver *RespSurf_Driver_ODY.m*. This driver calls the function located in *RespSurfaceTemp_ODY.m*. This function performs the proper variable dispersions required for the Monte Carlo analysis. The function is also responsible for reading and processing the response surface equations. However, the response surface coefficients must first be loaded into a mat-file for use in this routine. This is done using the Excel spreadsheet containing the response surface coefficients and a matlab file called *Create_ODY_Coeff.m*. This file simply reads the Excel data a places it into a mat-file with the proper format and data orientation.

A few subtleties must be pointed out with regard to this Monte Carlo analysis. The first noteworthy point is the use of orbital period as an input parameter. This variable is used indirectly within the response surface. Initial temperature is the actual parameter used in the response surface equation. But because it is very difficult to predict initial temperature, a more easily predicted variable was chosen that can be used to define the initial temperature. This process is done by fitting the initial temperature to a polynomial equation with orbital period as the independent variable. It is important to note that this equation is in no means general and must be created for a particular mission occurring at a particular time. Fitting this data is a quite involved process requiring many of the tools used for producing the temperature profiles cited above. To obtain a useful and accurate equation, five representative Odyssey-like orbits are used. For each of these orbits the orbital files containing the view factor and heating rate data must be created using Thermal Desktop. This process is identical to that which was described in Section **IV.C**. Also, Patran must be utilized to produce temperature profiles for each of the orbits. It is important to note that all other parameters that were varied for building the response surface should be implemented with their nominal value. The process for running Patran was described in Section **V** and is applicable to this specific analysis. Once the temperature profiles are obtained, the initial temperature can easily be extracted for each orbit. Using the initial temperatures and corresponding orbital periods, a polynomial curve-fit can be performed to produce an equation that is easily entered in to the Matlab file used for the Monte Carlo analysis.

Also, it is important to comment on the thermal model correlation error used in *RespSurfaceTemp_ODY.m*. These values correspond to the error and standard deviation of the models ability to predict accurate temperatures. For the first three or four orbits, these values should be based on the temperature prediction capability of the response surface based on the data used to create the response surface in JMP. These values are easily obtained in JMP as described in the previous section. After the first several orbits, the error and standard deviation values can be calculated by comparing the output of the Monte Carlo analysis to flight data.

In the end, the Monte Carlo driver is used to produce a mean or predicted temperature and the standard deviation of the temperature. By keeping up with the output values from the various parameter dispersions, a probability of exceeding a specified corridor can easily be obtained. This type of analysis is very useful in pre-mission planning.

VIII. Conclusion

Further development on this approach could include a detailed analysis of response surface parameters. For this study, the variables chosen for MRO were utilized and applied to Odyssey to determine the sensitivities of this approach on a more aggressive AB mission. A more discerning selection of response surface parameters could greatly reduce the number of required cases for determining the equation coefficients. Strategically reducing the number parameters would in turn reduce the time involved in the response surface development without degrading the fidelity of the model.

The probabilistic thermal analysis approach outlined in this paper is integral in moving towards a more cost-effective, autonomous AB approach. Such an approach for thermal modeling greatly reduces the processing time during operations for predicting adequate solar panel temperatures and ensuring a safe and benign mission. As this process was first developed and used during MRO AB, this study is extremely important in determining the robustness and applicability of this approach to future AB missions.

References

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Appendix

Process for running Thermal Desktop

1. >Thermal>Orbits>Manage Orbits…. Then add a new orbit using the Keplerian Orbital elements…note: Convert_to_IAU and additional rotations….also, planet and sun position is controlled by RA of Sun…..Then set current
2. >Thermal>Radiation Calculations>Calc View Factors
3. >Thermal>Post Processing>Manage Datasets>Add New>choose Form Factors>Select appropriate database
4. >Thermal>Export>Write Node Information>write to file
5. >Thermal>Radiation Calculations>Calc Heating Rates Ray Trace
6. >Thermal>Post Processing>Manage Datasets>Add New>choose Heating Rates>Select appropriate database
7. >Thermal>Export>Write Node Information>write to file

note: orbit times for setup file are in "times.dat"
note: once all view factor and heating rate data has been exported from TD, they must be renumbered and then mapped to the appropriate ODY node locations.

- mapping done using "read_2_text_*VF*.m" then use tecplot macro "*hot*_Macro.mcr" then use matlab code for proper formatting "*Hot_VF*_afterMacro.m".

Process for running Patran from the command line:

- Refer to batch scipt located in Odyssey_test directory…..These are created using Matlab code "DOS_create.m" in MatlabCode on Jump.

Process for running Patran from Windows:

- Use "mars_ody_rev5.db"
- To create Patran files refer to notes located in red notebook or the following

Use mars_ody_rev5.db
For varying 'A' (contact resistance):

- Loads & BC
  ->Action->Modify
  Object->Convection
  1) - select hot_facesheet_to_core
     - mod data(z=52;m1=10.4;p1=93.6)
     - Apply
  2) - select core_to_upper_facesheet
     - mod data(z=26;m1=5.2;p1=46.8)
     - Apply

For varying 'B' (facesheet thickness):

- Properties
  ->Action->Modify
  Select graphite_epoxy_standard
  Mod shell corner thickness (z=0.0001905;m1=0.0000381;p1=0.0003429)
  Okay and Apply

For varying 'C' (solar cell thickness):

- Properties
  ->Action->Modify
  Select Ga-As
  Mod shell corner thickness (z=0.0005715;m1=0.0004572;p1=0.0006858)
  Okay and Apply

To Analyze:

- Analysis

Job name->ODY_RS_z_z_z
Apply
Shows up in directory
Place in Patran Files

Process for running JMP:

- Analyze->FitModel….remove all 'Y' but one
- Set personality to 'Stepwise'-> RunModel -> Go
- ->Make Data Table->extract 'Estimates' and use as coefficients
- ->MakeModel->Run Model with Standard Least Squares
- Record 'RMS of Error' and 'R2 adjusted'
- ->Save Columns->Predicted Values
- ->Save Columns->Residuals

Process for running Monte Carlo (Matlab version):

- Enter predictions for DragDuration, maxDensity, velocity, and (period) into "RespSurf_Driver_ODY.m"
- Make sure 'RSEdata' in "RespSurfTemp_ODY.m" is completely up to date by referring to notes
- Note the thermal model correlation error data!-use JMP error and std's for first three orbits and then recalculate an error and std based on results
- Set the number of samples
- Note: check density range and Period to IT equation