Thermal Design Analysis of a Satellite with Articulating Solar Panels

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ABSTRACT

Nearly all satellites have articulating components such as solar panels or antennas that cause the geometry of the spacecraft to vary during the orbit. These satellites are earth oriented, except for the solar panels which are gimbaled with two axes of rotations to keep them perpendicular to the solar vector. Therefore, in the satellite design, the proximity of the solar panels to the radiators makes it necessary to consider the effects of the orbit-varying geometry on the absorbed heat loads and radiation network.

This paper describes the orbital thermal analysis of such types of satellites performed using the TRASYS interface in MSC/PATRAN THERMAL. This system proved to be an efficient simulation tool for thermal analysis of a satellite with a complex articulating motion during the various orbits.

INTRODUCTION

For advanced space-based communication systems, the large number of satellites required for global coverage makes it necessary to develop innovative concepts to reduce manufacturing costs as well as devise compact packaging for clustering multiple satellites within the launch vehicle payload volume. Also, with a number of competing systems planned for the next decade, shortening the design cycle becomes crucial in capturing market share. The ability to rapidly simulate the orbital thermal performance of a satellite early in the conceptual design phase can provide a competitive advantage.

A design concept proposed for one type of satellite poses some significant challenges for the thermal control system. Earth oriented satellites with solar panels have to undergo a 2-axes gimbaled motion during the orbit to keep them normal to the solar vector. To achieve compact packaging and keep costs down, the solar panels are mounted on a relatively short boom in close proximity to the radiators. During portions of the orbit the articulating solar panels partially block the space view from the radiators. A relatively high power dissipation density compounds the problem. The concept also envisions heat pipes to minimize temperature gradients; the requirements and locations of these heat pipes have to be assessed as part of the preliminary thermal analysis.

The orbital thermal analysis of the articulating spacecraft components was performed using the TRASYS interface in MSC/THERMAL[1]. The attractive features of this system for this application are the automated surface translation from PATRAN to TRASYS and a variable geometry package in TRASYS that automatically programs the spacecraft articulation during the orbit. In the course of the project, a customized enhancement to the interface was developed by MSC to handle the time-varying radiation network within MSC/THERMAL. MAN Technologie R&D funding sponsored this enhancement, with which MSC/THERMAL provides a unique system for thermal analysis of satellites within an integrated CAE environment. It is also useful for other thermal applications involving time-varying viewfactors.

This paper describes the orbital thermal analysis and the software enhancement that enables modeling the effects of the articulating solar panels in MSC/THERMAL.

Orbital Thermal Analysis

The ability to perform orbital thermal analysis in MSC/THERMAL was introduced approximately five years ago through interfaces with TRASYS[2] and NEVADA[3]. TRASYS has been around for nearly three decades and is considered a standard in aerospace for computing the thermal radiation environment for a spacecraft in orbit. The orbital environment consists of direct incident and reflected heat rates originating from solar and planetary sources as well as radiation interchange factors between surfaces. TRASYS version 27 includes routines that automatically handles orbit generation based on orbital parameters. This includes a variable geometry package that allows different parts of the spacecraft (up to 40 groups) to be continually oriented to different points in space. TRASYS outputs time varying and orbit averaged radiation networks and absorbed heat loads for use by a thermal solver such as MSC/THERMAL.

Traditionally, TRASYS models have been created from 13 primitives (e.g., discs, spheres, cones, paraboloids) that are assembled to build up the spacecraft geometry. In effect, the user is forced to recreate geometry that may already exist in the form of a CAD file. In some cases, trimmed surfaces, for example a parabolic antenna with cutouts, would be difficult to generate. To make matters worse, TRASYS is not interactive so there is no immediate feedback on the geometry that the user is generating.

The TRASYS and NEVADA interface in MSC/THERMAL greatly simplifies generating the orbital thermal model by automatically creating a TRASYS or NEVADA surface data input definition directly from the finite element model in MSC/PATRAN. Figure 1 illustrates this process. The interface provides the flexibility to submit different enclosures to the various radiation codes; for example, interior enclosures to MSC/THERMAL's Viewfactor code, diffuse external enclosures to TRASYS, and specular enclosures to NEVADA. The output from TRASYS or NEVADA can then be imported to define the orbital environment for the thermal response analysis. The translator can also output a ready-to-run SINDA[4] file including the radiation networks and orbital heat loads.

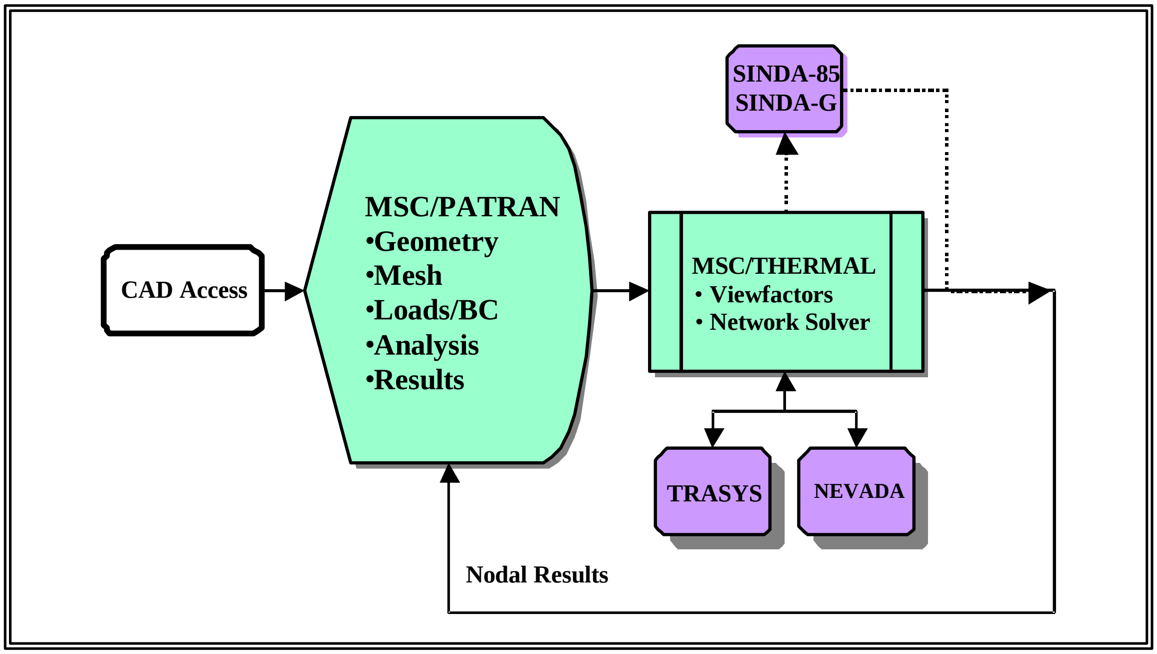

Figure 1. Orbital Heating Analysis Process in MSC/THERMAL

The new enhancement funded through this project allows MSC/THERMAL to handle time-dependent radiation networks generated by TRASYS for articulating spacecraft. The case study below shows how this new capability was applied.

Spacecraft Model

The studied satellite configuration is illustrated in Figure 2. The bus is shaped as a truncated prism to maximize the number of satellites that can be packed in the launch vehicle volume. The +X face of the bus contains a hexagonal shaped antenna and is earth oriented during the orbit. The radiators are mounted on the +Y, -Y, and –X faces of the bus with views of the solar panels. The solar arrays are gimbaled on a relatively short boom with the panels able to rotate about the X- and Z-axes. With the close proximity of the solar panels, the space view from the radiators can be blocked significantly under some orbit configurations as the panels articulate to track the sun. This is particularly true for the battery radiator (-X) where the space view can vary by up to 30 percent during the orbit. In preparing the model, it is convenient to select the PATRAN global origin at the gimbal to help simplify defining the solar panel articulation in TRASYS.

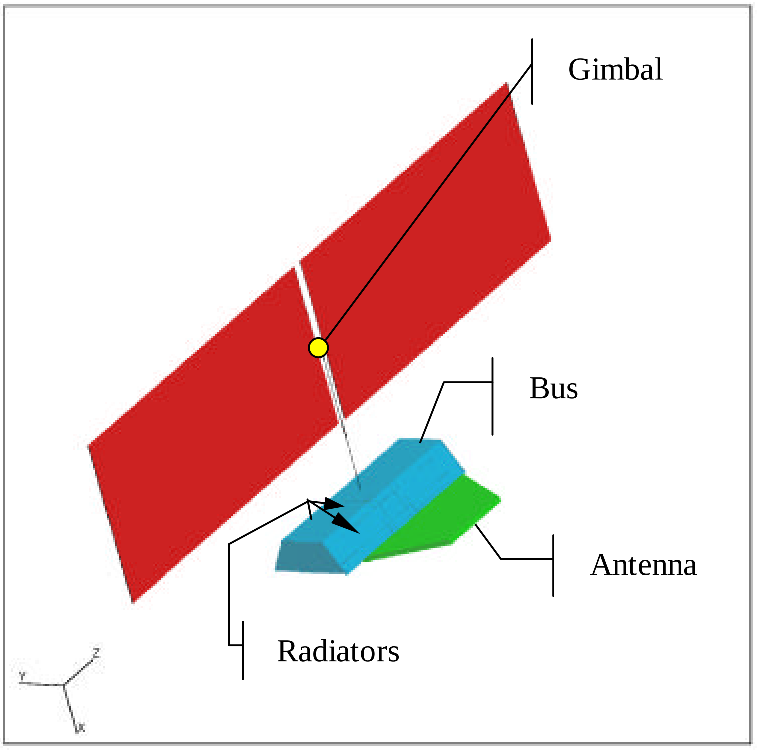

Figure 2. Satellite Configuration

The objective of the analysis was to determine the thermal response of the spacecraft for the given design and operation concepts. The thermal design is relatively complex involving articulating solar panels that may partially block the space view from the radiators, heat pipes being utilized to improve the effectiveness of the radiators and to minimize temperature gradients, and relatively high component heat dissipation with duty cycles synchronized to orbit position. A 3-D model of the satellite was used to simulate the on-orbit transient thermal response of the spacecraft. The PATRAN finite element model is illustrated in Figure 3. Included in the FEM model is a space node (7314) used for the exterior radiation network. Also shown in Figure 3 are LBC radiation markers confirming proper application of boundary condition on the sun side of the solar array.

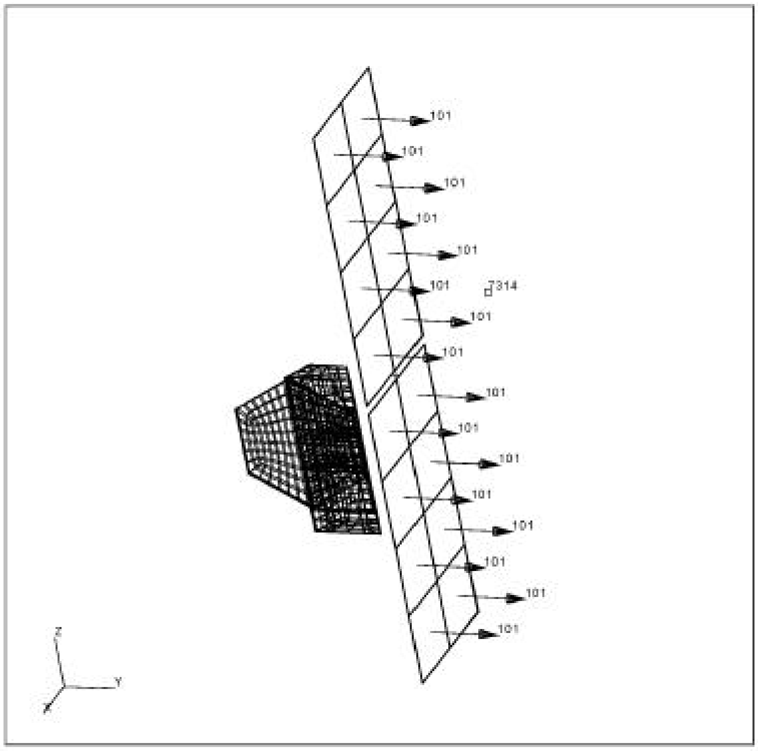

Figure 3. PATRAN FE Model of Satellite

This preliminary analysis considered two "worst case design" orbit configurations, Beta-77 and Beta-0, anticipated to result in the worst case hot and cold extremes. The Beta-77 orbit configuration is also expected to result in the worst case temperature gradients between the sun and anti-sun sides of the satellite. The model included the effects of the solar panel articulation on the absorbed heat loads and the radiation network. The internal power dissipations included duty cycles timed to the orbit positions, such as entering and exiting earth eclipse.

External Radiation Model

The surface data used by TRASYS were automatically translated by the TRASYS interface utility in MSC/THERMAL. The participating surfaces consist of the element faces on the exterior of the spacecraft that are assigned solar absorptivity and IR emissivity properties. The quadrilateral and triangular faces are converted to polygons in TRASYS as illustrated in Figure 4.

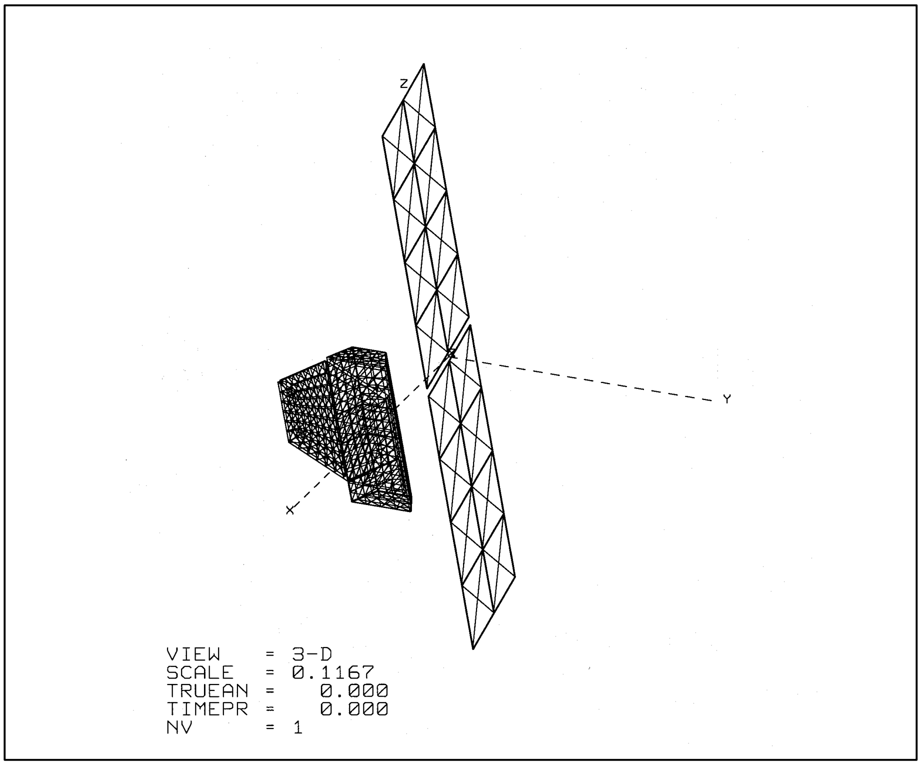

Figure 4. Translation of PATRAN Model to TRASYS (Beta-77, Truean=0.)

Note that the geometry in Figure 4 varies with orbit configuration and true anomaly. The TRASYS input deck created by this interface utility was edited as required to add the orbit definitions and control cards. The orbit definitions included descriptions of the solar panel gimbaling motion relative to the earth oriented spacecraft. The translator automatically correlates the space node number in the PATRAN model with the default space number in TRASYS. The PATRAN model was built in millimeters then converted to meters under Analysis Translation Parameter. The MSC/THERMAL material properties were defined in SI unit. Since TRASYS is hard-coded for British units (BTU, hours, feet) the forward and reverse translation includes appropriate scale factor prompts to convert to SI units (Watts, seconds, and meters). First, a steady-state run was made with the orbit averaged absorbed heat loads. This was used as the initial temperature for the transient cases.

The exterior vehicle radiation model consists of approximately 524 TRASYS polygon surfaces, each having a one-for-one correspondence with the external faces of hex/quad elements in the MSC/PATRAN model. For calculation purposes, TRASYS subdivides the quadrilateral surfaces into two tris, but they are recombined in the TRASYS output (*.bcd) file. Thermo-optical properties assigned to external surfaces are based on values available or reasonable estimates where a value has not yet been determined. Solar absorptivity and IR emissivity for the various parts of the satellite are listed in the table below.

Table 1. Thermo-optical Coatings on Vehicle Exterior

Region	Absorptivity	Emissivity
Radiators (5 mil silver Teflon SSM)	0.2	0.74
Antenna Front	0.6	0.8
Antenna Back (Sheldahl black/Kapton)	0.9	0.8
Structure MLI Cover (3 mil Kapton/VDA)	0.45	0.82
Solar Panel (facing sun)	0.67	0.8
Solar Panel (anti-sun) (Sheldalh black/Kapton)	0.9	0.8

Heat Pipe Modeling

Although the design of the envisaged satellite example would require heat pipes, it was decided to first run the model without any heat pipes to determine the critical areas. Indeed, the temperature gradient between the sun and anti-sun sides of the spacecraft (Beta 77) turned out to be milder than expected and it might not be necessary to employ these cross-bay heat pipe sets. However, a need was clearly established for heat pipes on the battery radiators, dictated by the Beta 0 condition.

The battery radiator consists of an aluminum honeycomb panel. In the proposed concept, a series of heat pipes would be embedded in the honeycomb core and bonded along it's entire length to both face sheets, thus allowing any portion of the heat pipe to serve as an evaporator or condenser. A similar type of heatpipe-honeycomb panel was used on the ATS-F[5] satellite. The reference study suggests treating the heat pipe vapor as an isothermal node connected with an effective conductance to the honeycomb panel facesheets. The effective conductance accounts for the heat transfer coefficient between the vapor and the heat pipe wall, a fin effectiveness to account for the fact that the heat pipe is bonded to the facesheets on only 2-sides, and the resistance through the 0.003-inch epoxy bond line thickness.

Based on test data, the above referenced paper came up with a design recommendation of 0.26 W/deg-F per linear inch of pipe (18.4 W/K-m). This heat transfer value is actually an hA/L, where L is the length of heat pipe associated to each node in the path of the heat pipe. For this preliminary analysis, the heat pipes were modeled external to MSC/PATRAN by introducing a convective resistor file (heatpipe_convec.dat) and a node representing the vapor in each heat pipe (heatpipe_vap_nod.dat). These files are inserted in the qin.dat input stream by use of $INSERTs. Additional heat pipes can be added to the model by editing these two files. A schematic of the heat pipe model is shown in Figure 5 for one of the heat pipes.

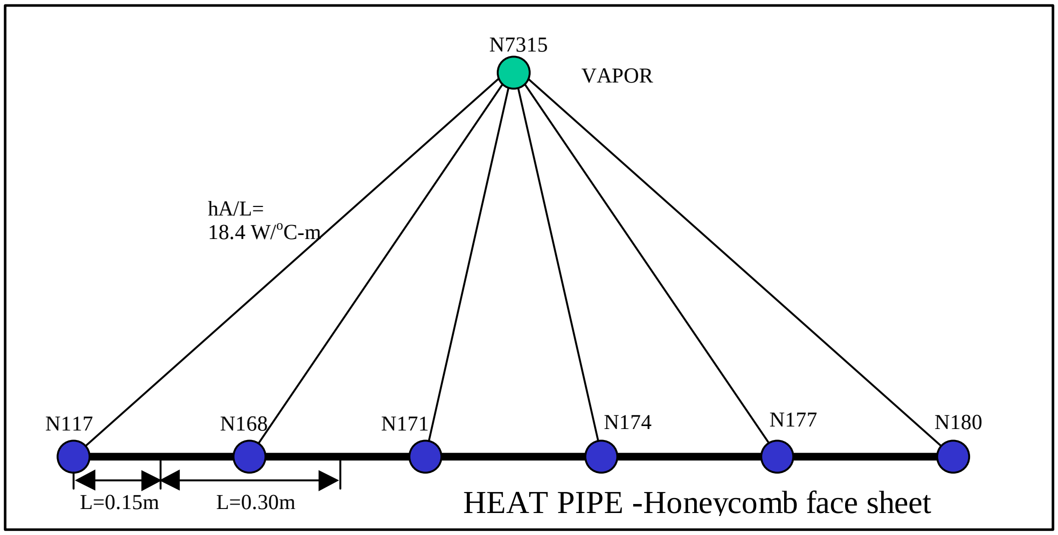

Figure 5. Battery Radiator Heat Pipe Model

The heat pipe nodes in Figure 5 correspond to the top facesheet of the honeycomb panel. For detailed analysis in a second loop, explicitly modeling of the heat pipe paths in MSC/PATRAN is foreseen, including heat pipe representing elements.

Heat Dissipation Model

The satellite has a relatively high dissipation of approximately 2475W average, 12,300W peak. The components heat dissipations were defined in the form of micro.dat files. For each of the design orbits, orbit averaged (constant) and time-dependent heat load were defined for each component. The constant dissipations were used in conjunction with the orbit averaged external heat load to determine a realistic initial temperature for the orbit transient. The time-dependent heat load data covered three full orbits. In the case of Beta-0, the duty cycles are synchronized to coincide with the satellite entering and leaving earth eclipse.

Orbit Configuration

Two orbit configurations were analyzed intended to represent the worst case hot and cold conditions. In both orbits the spacecraft is earth oriented with the solar panels articulating to keep them normal to the sun vector. In Orbit 1 (Beta-77), which occur during winter solstice, the spacecraft is constantly exposed to the sun. In Orbit 2 (Beta-0), which occurs during equinox, the spacecraft goes through an earth eclipse. The orbit parameters are listed in Table 2.

Table 2. Thermal Design Orbit Parameters

Parameter	Orbit 1	Orbit 2
Longitude of ascending node (deg)	0	0
Argument of perifocus (deg)	90	0
Orbit inclination (deg)	53.5	53.5
Time of periapsis passage (hours)	0	0
Altitude at Periapsis (feet)	2.788E6	2.788E6
Altitude at apoapsis (feet)	2.788E6	2.788E6
Right ascention of sun (deg)	90	0
Declination of sun (deg)	-23	-0.5
Orientation type	Earth	Earth
Orientation • Vehicle +X • Vehicle +Y • Vehicle +Z	 Earth center Perp. to orbit Trailing vector	 Earth Center Perp. to Orbit Trailing vector
Solar Panel Gimbal Rotations • BCS X-axis • BCS Y-axis • BCS Z-axis	 Order=1 (0-360 deg.) No Rotations Order=2 (0-360 deg.)	 Order=1 (0-360 deg.) No Rotations Order=2 (0-360 deg.)
Orbit plane to solar vector angle (deg)	77	0
Orbit Period (minutes)	101.8	101.8
Earth eclipse (minutes)	None	35.0

The 2-axes articulation of the solar panels was modeled using the variable geometry subroutines in TRASYS v27. These routines allow different portions of the spacecraft (up to 40 groups) to be continually oriented to different points in space. In MSC/PATRAN, the solar panels were assigned a different Viewfactor enclosure number from the rest of the spacecraft, which results in these surfaces appearing as a different group (BCS) in the TRASYS input file. This BCS was then specified as having to remain solar inertial. At a specific point in the orbit (true anomaly), the desired orientations of the various groups are initially defined. For this purpose, it is best to pick a point in the orbit that will allow the simplest rotation definitions. Also, to minimize transformations, it is helpful to set the global origin at the gimbal point. Thereafter, TRASYS seeks to keep the various groups locked to the proper orientation (earth, sun, or point in space) during the orbit. The subroutine calls provide parameters for which axes are allowed to rotate, the order in which they should be rotated, and any limits in the angle of rotation. With these definitions, the TRASYS variable geometry package will automatically update the relative orientation of the blocks at each point in the orbit.

For Orbit 2, at exactly Beta 0, it turns out that only one axis of rotation would be required to keep the solar panels normal to the sun. Since that exact Beta 0 value occurs rarely, it was decided to actually model Beta 0.5 to force the solar panels to go through two axes of rotations.

The orbital fluxes were obtained at 8 points (45-degree intervals) around the orbit. Four additional orbit positions were added automatically by the program if the spacecraft enters earth eclipse (Beta-0). Sample orbit plots are shown in Figures 6 and 7.

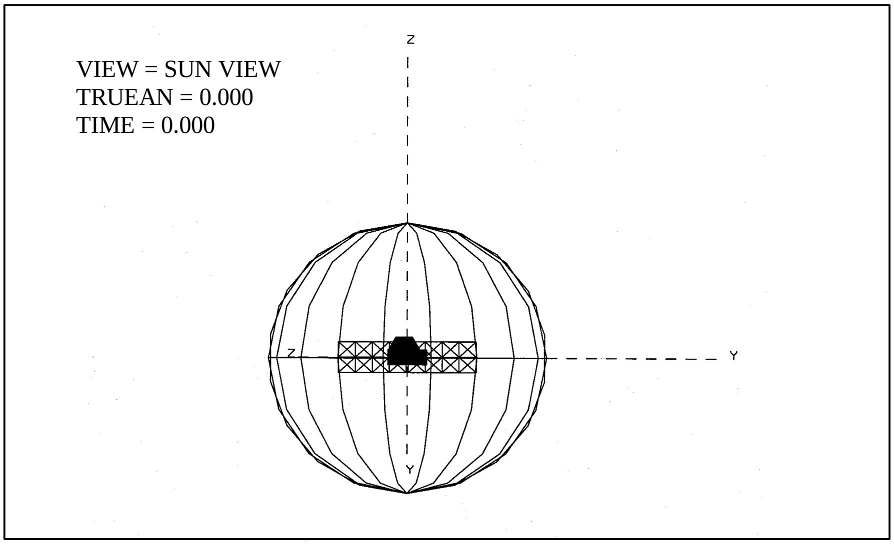

Figure 6. Satellite at Sub-solar Point (truean=0.), Beta-0 Orbit

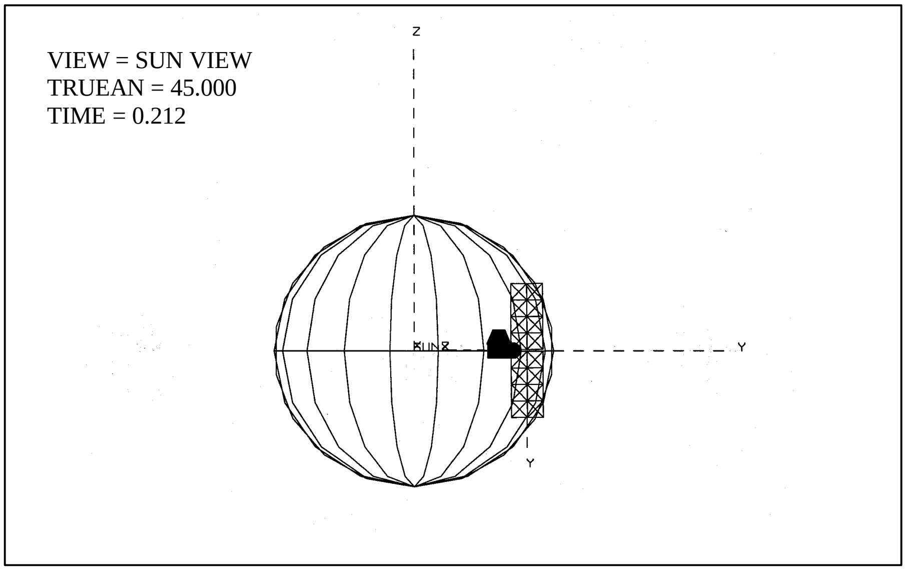

Figure 7. Satellite at Truean=45, Beta-0 Orbit

Time-Varying Radiation Network

TRASYS takes into consideration the effects of the variable geometry by generating a new set of radiation couplings (RADKs) at each orbit point. This variable radiosity network affects the absorbed heating, which is a function of the incident and reflected heat load. The radiosity network is also part of the thermal analyzer network. As part of this project, MAN Technologie funded an enhancement in MSC/THERMAL to support time varying radiation networks.

For the thermal analyzer, TRASYS produces a file (bcd) with the following blocks for a variable geometry model (separated by “C$END”):

(1) Variable radiation conductor arrays (RADKs vs. time)
(2) Radiation conductor interpolation calls
(3) Radiation conductors constant during the orbit
(4) Orbit averaged radiation conductors
(5) Heating arrays
(6) Heating interpolation calls
(7) Orbit averaged heating

By default, TRASYS will produce a variable conductor array for any RADK that varies by more than 10 percent during the orbit. As an example, for Beta-77 there are 11,548 radiation conductors of which 7130 are time varying. However, MSC/THERMAL could only support blocks (4) through (7) listed above. The initial work-around was to use the time-varying heating rate (blocks 5 and 6) with an orbit averaged radiosity network (block 4) for the transient response. Using time varying heating with orbit averaged RADKs is an approximation since at a specific orbit point the viewfactors may differ from the average.

The enhancement required defining a new script-FA radiation resistor type (Subtype 14) in MSC/THERMAL that references a material property where the viewfactors are a periodic function of time. Also, the reverse translator was upgraded to recognize the additional data blocks from TRASYS. The effects of this enhancement are illustrated in Figure 8 which compares the temperatures at a node located on the Battery Radiator (-X) with and without the time varying radiation network.

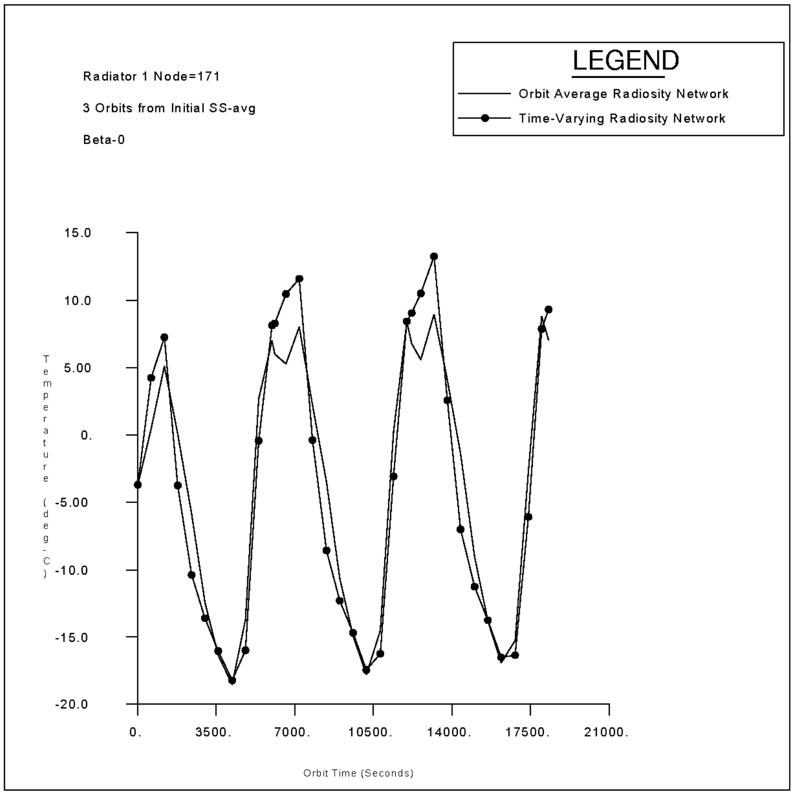

Figure 8. Effects of Considering Time-Varying Radiation Network

This plot shows three orbits starting at the sub-solar point (truean=0.) from an orbit averaged steady state condition. For Beta-0 orientations near the sub-solar point, the solar panels are rotated so that they block direct solar flux, but also nearly 30 percent of the space view from the battery radiator. As shown, using orbit-averaged viewfactors would have significantly under-estimated the radiator temperature during this period. The temperature dip near the sub-solar point can be explained by the fact that the radiator is correctly being treated as shaded from the sun by the solar panels, however, the view factor to space is based on an unrealistic high orbit averaged value. With the enhancement, the absorbed fluxes and radiation to space are consistent at every point in the orbit.

Transient temperature predictions have been obtained on the structure and components for the two design orbit environments, and for a case with and without heat pipes. An example of the component temperatures at one point in the orbit is illustrated in Figure 9.

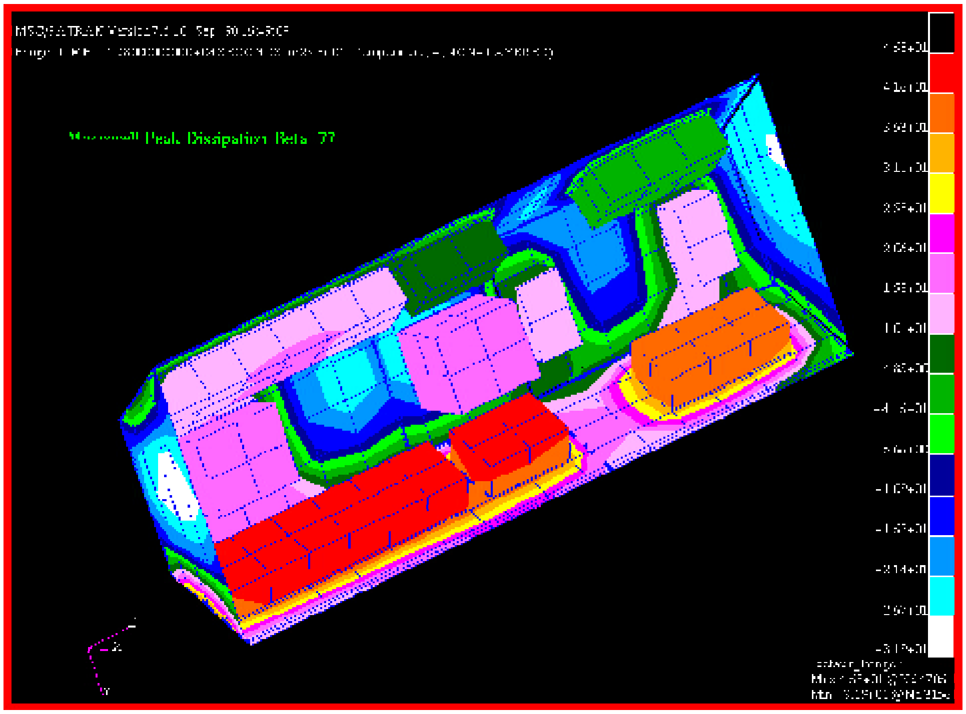

Figure 9. Predicted Component Temperatures in Satellite Bus at One Time Point

Conclusion

MSC/THERMAL-TRASYS has proven to be an effective tool for orbital heating analysis of satellites with articulating components such as solar panels. The effects of the variable geometry on the radiation network can be significant when the articulating components are in close proximity to the bus. The new capability to model articulating spacecraft, which should be available in an upcoming release of MSC/THERMAL, is becoming increasingly important as overall satellite sizes become more compact.

The MAN-sponsored enhancements made to MSC/THERMAL for this project are also useful for any thermal application where viewfactors vary with time, for example, a conveyer oven.

References

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