COMPUTER MODELING OF SPACECRAFT PERFORMANCE FOR FLIGHT OPERATIONS: LESSONS LEARNED

Richard A. Dragonette

Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723 (USA)
Fax: 301-953-1093. E-mail: richard_dragonette@jhuapl.edu

ABSTRACT. A large satellite is a complex problem from the perspective of modeling its thermal response and the response of its power distribution subsystem to strenuous data collection experiments (DCEs). If it is desired to execute several DCEs closely spaced in time, a model that predicts the spacecraft's response during data collection and during its recovery is required to ensure the satellite can execute the desired task and be satisfactorily recovered before the start of the next DCE.

This paper presents some of the lessons learned during the evolution of such an automated software model for a large Earth-observing satellite. I discuss defining what the model needs to do versus what it could do given infinite resources, the need for simplification even with powerful computing tools, short-term single DCE simulation versus longer-term simulation, and on-orbit model parameter modification.

1.0 THE MIDCOURSE SPACE EXPERIMENT POWER–THERMAL OVERVIEW

The Midcourse Space Experiment (MSX) satellite is 5.2 m tall, has a square cross section 1.8 m on a side, and weighs approximately 2700 kg. The satellite operates 11 optical sensors that can view wavelengths between the very-long-wave infrared (28 μm) and the far ultraviolet (110 nm). The satellite consists of three primary sections (see Fig. 1): (1) the instrument section, which houses the optics for the 11 optical sensors; (2) the electronics section, which houses the electronics comprising the attitude control system and the command and data handling system; and (3) a connecting truss, which thermally isolates the hot electronics section from the cold instrument section and which houses the large solid hydrogen cryogen dewar used to cool the infrared telescope.

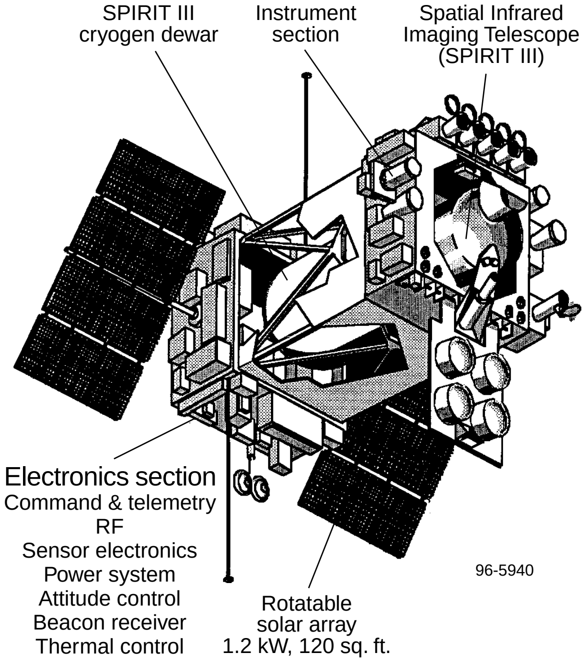

Figure 1. The MSX spacecraft.

Figure 1 illustrates the layout of the 11 optical sensors incorporated into the MSX satellite. The sensors are all aligned such that their lines of sight point along the spacecraft's +*x*-axis. The initial primary telescope is the Spatial Infrared Imaging Telescope (SPIRIT III), a cryogenically cooled infrared telescope. The operational life of the SPIRIT III is limited to approximately 14 months, with a 20% duty cycle, by the supply of solid hydrogen cryogen carried onboard the satellite. The remaining ultraviolet and visible sensors are designed for a 4-year operating life, with a 5-year goal.

The SPIRIT III telescope optics are designed to operate near 0 K. The internal optics of the telescope are protected from stray light energy by the SPIRIT III forebaffle, a mechanical structure spatially separating the aperture at the front of the telescope from the SPIRIT III primary light-collecting mirror. Figure 2 shows the mechanical layout of the SPIRIT III telescope. Because the SPIRIT III forebaffle is directly exposed to incident light and because it is physically located farthest from the solid hydrogen cryogen, it heats faster and cools more slowly than any other part of the cryogen-cooled optics.

The SPIRIT III forebaffle has a quiescent operating temperature of 30 K and a maximum operating temperature of 70 K. Above 70 K, heat from the forebaffle itself will significantly degrade infrared image data quality. The forebaffle is expected to be heated to 70 K by some single data collection experiments (DCEs) that point the spacecraft's +*x*-axis near the Sun or at the hard sunlit Earth. It can take more than 1 day for the forebaffle to return to its quiescent temperature once it reaches 70 K.

The MSX satellite electronics section and instrument section are spatially separated because of thermal considerations. The instrument section is designed to operate at −30°C, and the electronics section is expected to operate near +20°C. The electronics section could see operating temperature fluctuations as large as −19°C to +55°C. The truss that connects the electronics and instrument sections is constructed of graphite epoxy, which thermally isolates the spacecraft sections and which houses and isolates the SPIRIT III cryogen dewar. Briefly, the dewar can be thought of as a large thermos bottle containing solid frozen hydrogen, which is melted to cool the SPIRIT III telescope connected to the top of the dewar. The outer shell of the dewar, which can be seen in Fig. 1, is expected to remain near −50°C (225 K) until the solid hydrogen is expended.

The MSX satellite has three primary data collection modes: (1) acquiring and tracking objects in space using the hard Earth and Earth-limb as backgrounds; (2) characterizing the Earth-limb and the Earth's

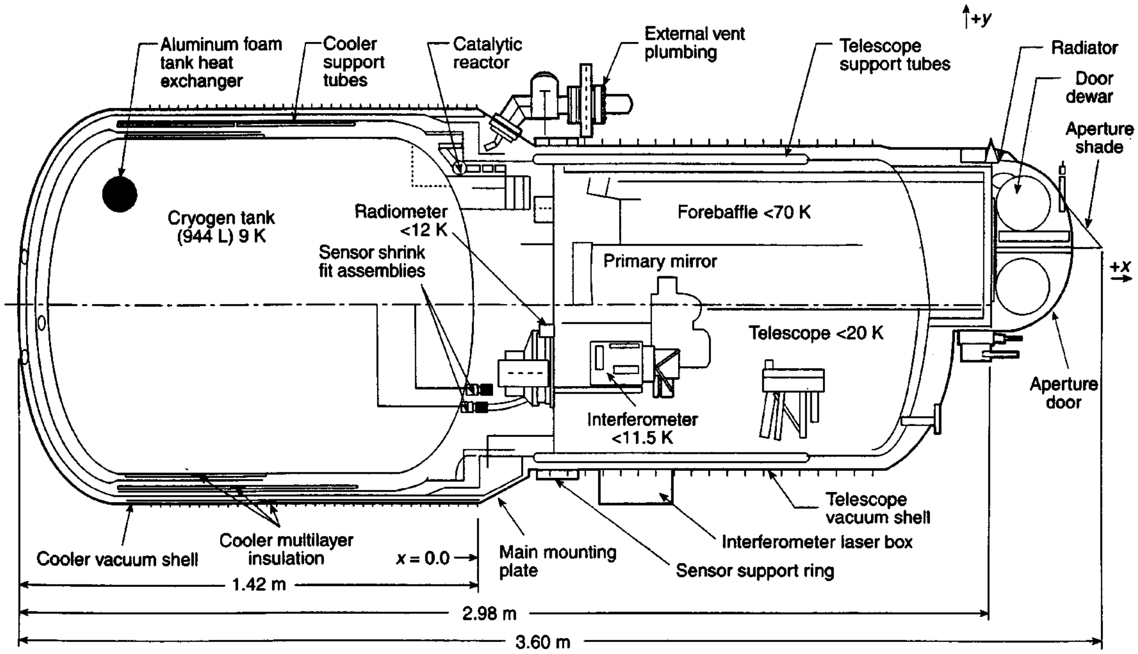

Figure 2. SPIRIT III mechanical configuration.

atmospheric phenomenology using one of many downward-looking preprogrammed scanning patterns; and (3) celestial scanning, which is intended to produce an infrared and far-ultraviolet map of the celestial sky.

The events that track a rapidly moving space object severely stress the spacecraft's resources from both a power and thermal standpoint. When such an event is completed, the satellite's battery is expected to be drained to a 70% depth of discharge, and many spacecraft components will be heated to the upper end of their respective operating temperature ranges. (A 70% depth of discharge implies that the battery has been drained of 70% of its available power.) The celestial events tend to be far less stressful on the spacecraft because these events point the telescopes' lines of sight toward deep space, keeping the instruments cool, and the solar arrays can be positioned to collect adequate solar power. The atmospheric and Earth-limb scan events can fall anywhere between these two extremes.

In order to help the spacecraft recover quickly from stressful DCEs and return to its power–thermal equilibrium, the MSX spends roughly 80% of its time in "Park Mode." In Park Mode the spacecraft's +*x*-axis is pointed away from the Sun and Earth to promote rapid cooling of the instruments, especially the SPIRIT III forebaffle, and to quickly recharge the battery; the solar panels are positioned to collect maximum power; and the instruments are powered down.

In Park Mode, the MSX battery can require two orbits to recharge fully from a 40% depth of discharge, and even longer to recover from deeper battery drains. For much of its mission life the MSX orbit causes the spacecraft to be in solar eclipse for 20–27 minutes out of each 103-minute orbit. Even when in Park Mode, the spacecraft operates entirely from its battery for 20 or more minutes each orbit, inducing a 12% to 18% battery depth of discharge each orbit that must be accounted for by the MSX power–thermal model.

2.0 REQUIREMENTS FOR THE MSX OPERATIONS POWER–THERMAL MODEL

The two requirements of the MSX operations power–thermal model are as follows:

1. To enable operations to ensure that no individual DCE will overheat the MSX thermal system and that the DCE does not cause the MSX battery to drain below 45% depth of discharge for a normal event and 70% for a high-priority DCE.

2. To allow operations to determine if the concatenation of many DCEs over a period of days and weeks will create a cumulative effect that causes the battery's depth of discharge, or any of the spacecraft's critical temperatures, to increase over time to unacceptable levels.

The second requirement is important because the spacecraft does not always return to power–thermal equilibrium between DCEs. The MSX executes between four and eight DCEs per day, and it can take longer than 24 hours for the SPIRIT III forebaffle to equilibrate from a stressful event. Therefore, it is possible to overheat the forebaffle by executing four DCEs in one day, each of which would not exceed the SPIRIT III operating constraints by themselves if the spacecraft had started each respective DCE from thermal equilibrium. The ability to predict the battery depth of discharge over the long term is critical because the battery is often not fully charged at the start of a DCE, and this initial battery depth of discharge must be predicted and accounted for.

3.0 LESSONS LEARNED

Most of the lessons learned developing the power–thermal model were learned in the thermal portion of the model. The power system is easier to quantify; the wattage consumed by each component can be measured, and modeling the power supplied by the solar arrays is made easier by existing software and textbook analytical models.

Thermal performance is unique to each spacecraft and is difficult to quantify in absolute terms using an operations suitable computer model. Fortunately, thermal behavior can be satisfactorily predicted and analyzed in relative terms, making accurate predictions of absolute spacecraft temperatures less important. If one can precisely predict that the temperature of a component will rise by 2 degrees, it may not be important to predict if the temperature rise will be from 10 to 12 degrees or from 14 to 16 degrees.

3.1 POWER SYSTEM MODEL LESSONS LEARNED

Of the many lessons learned developing the power system model, the four most important, and universally applicable to other applications, concerned (1) database dependency, (2) time step averaging, (3) simplifying assumptions, and (4) spacecraft constants.

1. REDUCE DATABASE DEPENDENCY. In the MSX power model, each spacecraft command is reduced to only an associated number of watts, that is, the command has no effect on the power consumed (0 watts) or it turns something on, increasing power by $+x$ watts, or it turns something off, decreasing power by $-y$ watts. The function of the command and the subsystem executing the command is ignored.

For each spacecraft command in a DCE, the software had to make a database inquiry to determine the power consumption associated with the command. This severely limited software execution speed because many MSX DCEs consist of over 500 commands, requiring 500 database inquiries. To alleviate this problem, an additional step was added to the definition of MSX DCE command sequences. When a command sequence is specified months or weeks prior to the first time it is executed, it is simulated using the power model. As the model checks the database for the power associated with each command, the software stores in a data file the command name, the associated power, and the time relative to the start of the event that the command added or subtracted power.

When the DCE is later simulated by MSX flight operations the day before its scheduled execution, the power model quickly reads the data file from the very fast system hard drive to obtain all power information without ever accessing the far slower database. This improvement also eliminates the need for the model to read the command sequence from the database since all DCE-related information is stored in a single file. When a DCE is simulated, the time each command turns power on or off is determined by adding the time relative to the DCE start time to the actual planned event start time. Eliminating 200–500 database inquiries increased the execution time of the model by at least an order of magnitude. A single command sequence for a DCE will typically be reused many times during the MSX mission, so the time spent running many simulations is greatly reduced by storing the results of the single first simulation.

2. TIME STEP AVERAGING. The MSX power model can be run using a time step of 1, 20, 30, or 60 s. Originally, the average power for each time step was assumed to be a constant equal to the maximum power consumed at any time during the interval. When the 60-s time step was used, the results of power simulations for many stressful DCEs indicated that the experiment would cause a 20% to 30% higher battery depth of discharge than would a simulation of the same DCE using a 1-s time step.

The MSX satellite uses four reaction wheels to point its telescopes; these wheels can cause power spikes, often lasting less than a second, with magnitudes larger than 1000 W. When such a power spike occurred, the power for the entire simulation time step was set equal to the nominal power drawn by the spacecraft plus the 1000-W wheel spike, causing the simulation to overestimate the power used. The model has been improved to integrate the power drawn by the spacecraft using a 1-s time step independent of the time step used by the simulation. When a 60-s time step is specified for the power–thermal model, the software integrates the power required using a 1-s time step over the entire 60-s interval. The power for each 60-s time step is set equal to the integrated average power.

With this change, the maximum battery depth of discharge calculated using a 1-s time step and using a 60-s time step consistently agree to within a 2% maximum depth of discharge. The lesson learned here is twofold: first, there is no need to simulate the power and thermal performance of the spacecraft with anything smaller than a 30-s or 60-s time step, and, second, care must be taken when averaging over the longer time steps.

3. SIMPLIFYING ASSUMPTIONS. Making simplifying assumptions allows software to run faster and makes code development easier. It is necessary to develop the extra code or realistic spacecraft test procedures to verify even seemingly benign simplifying assumptions. A lot of time and effort was spent

developing the solar array model for the MSX power–thermal model. A detailed model was developed to calculate the solar energy absorbed by the arrays and to determine how shadows generated by the three-dimensional spacecraft decrease the solar energy reaching one or both arrays. The solar arrays can be rotated 360 degrees around the spacecraft's *z*-axis, and to simplify calculations, the slow rotation speed of the arrays was ignored. Usually the arrays are locked in a desirable position at the start of a DCE, and the model assumed that the arrays instantly moved from their Park Mode position to the position commanded by the DCE.

This assumption saved a great deal of CPU time. If the slow rotational speed (at the time measured to be 0.24 degree per second) is taken into account, for each 1-s time step the software must rotate the arrays and calculate new spacecraft shadowing effects. Calculating shadowing effects is CPU intensive because it requires rotating both a three-dimensional model of the spacecraft and a separate model of the solar panels relative to the Sun. The arrays and spacecraft are separate models because they rotate with respect to each other. By assuming that the arrays move instantly, the model can reduce its calculations because the satellite and the arrays can be treated as a single fixed object instead of two separate objects that rotate about one another. The power–thermal model was improved to emulate the finite solar panel rotation rate. Eliminating this one seemingly minor simplifying assumption caused as much as a 15% difference in the calculated battery depth of discharge for the same DCE simulated with and without accounting for the panel rotation.

4. SPACECRAFT CONSTANTS. All constants associated with the spacecraft should be stored in text files that are read when the software is executed. Hard-coding the constants in the software code proved to be a mistake because it seems that no spacecraft constants remain constant. When on-orbit data are collected, and as the satellite ages, values that were expected to be constant are found to change. Placing all spacecraft constants in text files allows the model to be altered to match measured spacecraft performance without recompiling the software code. When the software is executed after the text file is updated with new values, it will run with the new constants without recompiling the code.

Some of the "constants" originally hard-coded into the software that we believed would never change include solar panel rotation rate, battery recharge current, average Park Mode heater power, battery operating temperatures, and the maximum solar array output power. The solar array rotation rate, for example, was measured on the ground to be 0.24 degree per second; however, on orbit it has been found to be 1.5 degrees per second. The MSX flight operations team has avoided repeatedly recompiling the model by editing a simple text file.

3.2 THERMAL MODEL LESSONS LEARNED

Modeling the spacecraft thermally for flight operations proved to be an interesting challenge. There were many obstacles that, when overcome, led to a simple, fast model that enables MSX flight operations to ensure the satellite is not overstressed thermally. The MSX operations thermal model was originally envisioned as a smaller, faster, lower-fidelity version of the slower, higher-fidelity model used by the spacecraft thermal design team. The model was to calculate spacecraft temperatures at 241 points spread throughout the satellite as a function of time during a DCE. Model speed was expected to be better than real time because all 241 temperatures were to be calculated once every 60 s. Four of the more universally applicable lessons learned concerned (1) initialization, (2) absolute accuracy, (3) simplicity and rules of thumb, and (4) assessment of the relative cost of a DCE.

1. INITIALIZATION. Defining a suitable set of 241 initial values for the thermal model proved to be a major, and unexpected, challenge. An effort was made to define multiple sets of initial temperatures that accurately reflected spacecraft temperatures at different phases of its orbit. The spacecraft is kept warm by approximately 40 heater circuits that do not turn on and turn off at exactly the same phase of the orbit, even when MSX remains in Park Mode for multiple orbits. This means that spacecraft temperatures do not follow a pattern that repeats each orbit even in Park Mode. Each DCE executed by MSX heats the spacecraft, introducing even further irregularity to the MSX temperature profile.

Efforts to define accurate initial conditions were thwarted. The proposed solution was to initialize each temperature to the midpoint of its operating range and to start the thermal model three orbits prior to the start of the simulated DCE. The initial three Park Mode orbits were added to allow the 241 calculated temperatures to stabilize prior to the start of the simulated DCE. Experience demonstrated that it requires between 6 and 30 orbits for the calculated temperatures to stabilize. The thermal design team confirmed that, for a spacecraft of MSX's size and complexity, this is a reasonable amount of simulation time to expect an analytical thermal model to take to settle. The MSX orbit is 103 minutes long, so simulating 6 to 30 orbits requires the software to model the spacecraft in Park Mode 600 to 3000 minutes prior to the start of a 30-minute DCE. Even running at its fastest speed, this requires an execution time of 1 to 5 hours per DCE.

2. ABSOLUTE ACCURACY. There was poor agreement between the absolute value of the temperatures calculated by the MSX-flight-operations–241-node thermal model and the high-fidelity model used by the thermal engineering team. On the basis of discussions with thermal engineers, it became clear that a lower-fidelity model suitable for operations use should not be relied on to predict actual temperatures; it should be used to determine if the temperature of a spacecraft component would increase or decrease relative to its temperature at the start of the DCE. In other words, the model can predict that a component temperature would rise by 10 degrees, but not whether the temperature rise will be from 10 to 20 or from 15 to 25 degrees. This lack of absolute accuracy is common in analytical thermal models and should be accounted for in the intended application of an operations model.

3. SIMPLICITY AND RULES OF THUMB. The MSX thermal engineering team was consulted extensively to determine ways to simplify the effort required to thermally model the spacecraft. An effort was made to determine which components heat the fastest and which cool the slowest and to develop rules of thumb to ensure that these few thermally critical components are operated safely. The remaining spacecraft components should be operated safely if the thermal constraints of critical components are maintained. Despite its size and extreme thermal complexity, the thermal modeling requirements for MSX flight operations were reduced to the prediction of four temperatures: for the battery, cryogen dewar shell, tape recorder tape head, and SPIRIT III forebaffle. The 241-node thermal model was replaced by a set of four rules of thumb, only one of which requires extensive software to implement.

Empirically it was determined that normal operating modes of the spacecraft would not force the battery temperature to become too hot or too cold, so modeling the battery temperature has become a low priority; if a non-normal mode of operating the spacecraft is proposed, it will be reviewed on a case basis by the thermal engineers to determine its potential effects. The tape head temperature is linearly proportional to the time spent recording or playing back data. When not recording or playing, the tape is at standby and is cooling off. The tape head model uses linear equations to integrate the time spent recording or playing back the tape recorder as a function of time for 4-week intervals, using the MSX advance activities schedule, and plots the resulting temperatures.

The SPIRIT III forebaffle heats faster and cools more slowly than the rest of the MSX optical instruments, so if the thermal constraints of the forebaffle are maintained, the thermal requirements of remaining instruments should be maintained. Because of its complexity, a detailed analytical model of the SPIRIT III telescope had to be developed specifically for flight operations to calculate the SPIRIT III forebaffle temperature as well as the amount of cryogen depleted using SPIRIT III for a DCE. This effort ultimately is the only software-intensive piece of the thermal model. The model is used to ensure that a DCE does not raise the forebaffle temperature above 70 K. To model the long-term effects on the forebaffle, detailed simulations of DCEs are concatenated by assuming that the forebaffle cools linearly in Park Mode between DCEs. The linear cooling rate is determined by on-orbit data.

The SPIRIT III cryogen dewar shell temperature had to be specifically accounted for because it is critical to keep it cold, it is thermally isolated from the rest of the spacecraft, and it is exposed directly to space on the $+y$ side of the spacecraft. The cryogen dewar model integrates the cosine of the angle between the $+y$-axis and the Earth and the $+y$-axis and the Sun during each DCE. When the angle between the $+y$-axis and the Sun (or Earth) is less than 90 degrees, the thermal energy absorbed by the dewar shell is nearly directly proportional to the cosine of the angle multiplied by the time spent with the y-axis pointed at the angle.

These four simple rules of thumb make up the final MSX thermal model. There are two primary lessons learned from this effort. First, a good operations thermal model of a very complicated spacecraft can be derived from a few well-thought-out rules of thumb and simple analytical models if the spacecraft thermal design engineers are consulted to aid in the determination of the critical parameters. Second, to a first-order approximation, the heat absorbed by a spacecraft surface from a point source is proportional to the cosine of the angle between the surface normal and the point source. There is some inaccuracy induced by assuming the Earth is a point source since the satellite is relatively close to the Earth; even so, assuming the Earth to be a point source of heat, located at the center of the Earth, has proven satisfactory for MSX applications.

4. ASSESSING THE RELATIVE COST OF A DCE. The SPIRIT III model's primary outputs are the forebaffle temperature and the number of grams of solid hydrogen depleted as a result of the effects of a DCE. To compare the relative costs of DCEs, the amount of hydrogen depleted by a DCE is divided by the amount of hydrogen the model predicts would be used had MSX remained in Park Mode during the DCE. The simulation of a DCE starts at the beginning of the DCE, assuming that SPIRIT III is at equilibrium, and ends when SPIRIT III returns to equilibrium long after the DCE has completed. By assuming that the spacecraft starts and ends a DCE at equilibrium and by normalizing the event to Park Mode, the relative costs of very different DCEs can be reasonably compared.

Normalization has also improved the precision of the model's results because many of the biases in the model are canceled out when the model's results are normalized to Park Mode. The absolute number of grams the operations SPIRIT III model predicted would be used by a DCE differed by as much as 20% from the value predicted by the high-fidelity model used by the telescope builder for 15 representative DCEs. When the results of the two models were divided by the amount of cryogen that each respective model predicted would be depleted in Park Mode, the results of the two models differed by less than 5% for all 15 DCEs.

4.0 CONCLUSION

MSX is a large and thermally complex satellite that executes a wide variety of DCEs in an episodic manner; yet its thermal performance can be verified satisfactorily from an operations perspective using rules of thumb to model only four temperatures. In most cases, the rules of thumb can be implemented using simple linear, polynomial, or cosine equations that can be integrated over long or short periods of time. The operations thermal model should not be relied on to accurately predict spacecraft temperatures, but rather to determine relative temperature effects.

Lessons learned by the MSX flight operations team designing and implementing the MSX power–thermal model are (1) minimize interaction between the software and the command system database; (2) use a long time step, approximately 60 s, when running the model but use caution when averaging over the time step; (3) empirically verify any simplifying assumptions and initial conditions; (4) store spacecraft constants and initial conditions in a text file; (5) allow a lot of time for an analytical thermal model to settle if it is used; and (6) use the thermal model to determine relative effects, and try to normalize the model's results if the relative costs of DCEs are to be compared.