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MESSENGER Power and Thermal Systems Operations

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The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft launched on 3 August 2004 and is en route to orbit Mercury. MESSENGER is passively cooled, uses a peak-power tracking system, and is able to operate both near Earth and at Mercury. The operations of the MESSENGER power and thermal systems, from launch through three Mercury flybys, provide lessons for the exploration of the inner solar system.

Since launch, MESSENGER has experienced solar distances ranging from 1.0 AU to 0.3 AU, equivalent to 1 to 11 Suns. The widely varying solar distance makes for a challenging operational environment for the power and thermal systems. MESSENGER's sunshade provides the main thermal protection from solar heating. For most solar distances, spacecraft attitude is maintained to keep the sunshade pointed within 12 to 15° of the sunward direction. However, at near-Earth solar distances, having the shade between the Sun and the spacecraft resulted in excessive radiative cooling of the spacecraft. To counteract this effect, a series of attitude maneuvers referred to as "flips" and "flops" were performed to point the spacecraft's sunshade respectively away from and back toward the Sun. These "flips" and "flops" were a complex set of maneuvers involving not only changes to the spacecraft attitude but also updates to on-board autonomy rules meant to keep the sunshade pointed at the Sun as well as rotations of the solar array panels by 180°. These maneuvers were considered high-risk events, as they temporarily disabled on-board protection systems designed to preserve spacecraft safety, and they required coordination and sequencing among multiple subsystems (power, guidance and control, and autonomy) to complete execution without violating flight constraints. These activities were not developed until the need arose after launch.

As the solar distance changes, the solar arrays are operated to balance power production with thermal protection for the array panels. This balance involves commanding the solar arrays to maintain a fixed offset from pointing directly at the Sun. The limits on off-pointing angles that yield sufficient power and yet protect the solar arrays thermally change with solar distance, so periodic commanded updates are required. For solar distances less than 0.4 AU, the safe off-pointing-angle range increasingly narrows. At its lowest, the range is only 8° wide. Within such a narrow range, operations requiring the spacecraft attitude to change in the same direction as the solar-array rotation can become difficult, because small excursions outside the off-pointing range can cause solar-array temperatures to rise quickly.

Since launch, one Earth flyby, two Venus flybys, and three Mercury flybys have been performed. Each of these encounters has been challenging because of solar eclipses and rapid changes in the spacecraft attitude to permit targeted science observations while fully operating the science payload and communication equipment, a combination of circumstances that potentially could cause a greater demand for power than the solar arrays can supply. The Mercury flybys have been especially challenging because they took place at a solar distance of ~0.3 AU, at which the range in off-Sun pointing angle for the solar arrays

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is the tightest. In addition, during some of the science operations, the solar array motion had to be stopped so that motion (jitter) would not interfere with image acquisition.

I. Introduction

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft launched on 3 August 2004 and is currently en route to orbit Mercury. MESSENGER is passively cooled, uses a peak-power tracking system, and is able to operate both near Earth and at Mercury. The operations of the MESSENGER power and thermal systems, from launch through three Mercury flybys, provide lessons for the exploration of the inner solar system.

The mission can be broken into four distinct operational phases: near-Earth, outer-cruise, inner-cruise, and Mercury orbit. The operational boundaries for the phases are based on MESSENGER's distance from the Sun. The near-Earth solar distance is greater than 0.9 AU. Outer cruise is at 0.7 through 0.9 AU and inner cruise is when the solar distance is less than 0.7 AU. This paper presents an overview of the near-Earth, outer-cruise, and inner-cruise operations that have already been completed. First, the MESSENGER power and thermal systems is summarized. Then, the near-Earth attitude maneuvers performed to keep the body of the spacecraft from becoming too cold are described. Next, the general operational philosophy and limits for cruise operations are explained. Lastly, three specific activities during the inner-cruise timeframe are examined in detail to illustrate the different challenges in operating in changing power and thermal environments.

II. Power and Thermal System Overview

An overview of the MESSENGER spacecraft is shown in Fig. 1. The sunshade provides the main thermal protection for the spacecraft. During both outer and inner cruise, the spacecraft attitude is controlled to keep the sunshade between the body of the spacecraft and the Sun. This restricts the spacecraft pitch to ±12° and yaw to -17° through +13.5°. While in inner cruise near Mercury, the temperature of the sunshade can reach several hundred degrees Centigrade, but the temperature of the rest of the spacecraft behind the sunshade remains at approximately room temperature. The MESSENGER thermal system also includes heaters for the fuel tanks, battery, spacecraft core, and instruments and heat pipes to connect high-power boxes to the radiator.

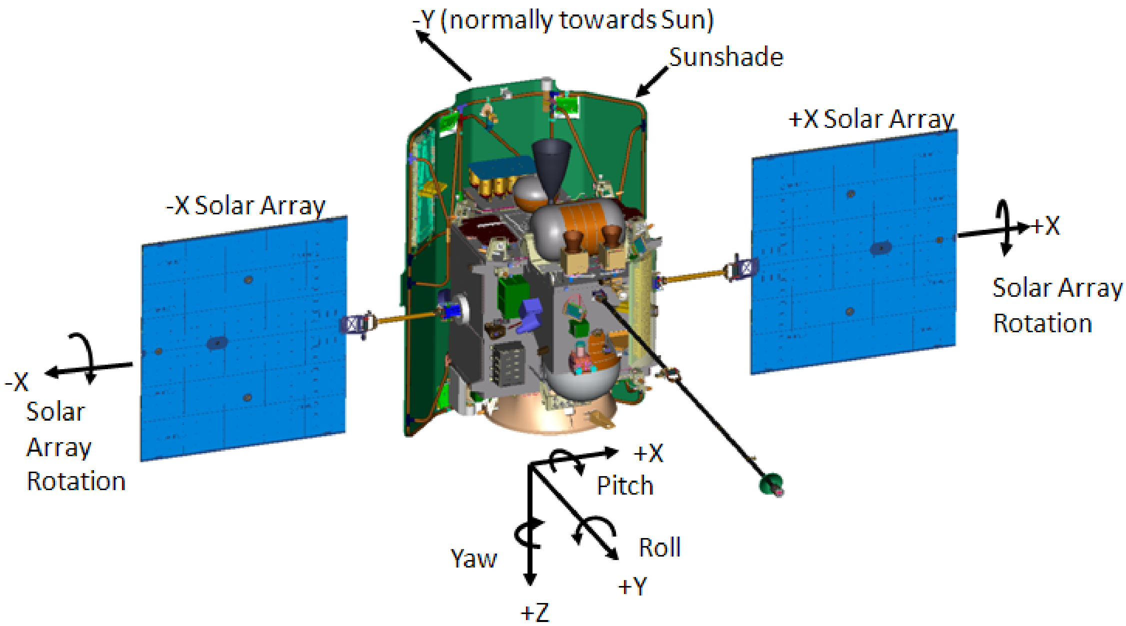

Figure 1. MESSENGER Spacecraft

Two Sun-tracking solar arrays provide power generation for MESSENGER. The solar arrays rotate about the spacecraft X-axis. Each solar array has a 220° range of motion that extends from when the normal vector of the solar array is 20° below the -Y-axis to 200° above the –Y-axis. The solar arrays can rotate independently. Since the solar arrays are on either side of the X-axis, they are referred to as the +X and -X panels. The MESSENGER power system uses a peak-power tracking system that will vary the solar array operating voltage as required. The power system also includes one 23 A-hr NiH_2 battery.

The solar array control has two main modes of operation: Sun-offset and body-fixed position. When in Sun-offset mode, the arrays move as the spacecraft attitude changes to keep the normal vector to the active surface of the panels a commanded offset angle from the Sun vector. In body-fixed position, the arrays remain at a commanded body-relative position regardless of changes to the spacecraft attitude.

III. Near-Earth and Outer-Cruise Operations

Since launch, MESSENGER has gone through solar distances ranging from 1.0 AU to 0.3 AU. The original mission plan was for the spacecraft to be oriented with the sunshade pointed away from the Sun after launch. Then the attitude would be “flipped” and the sunshade pointed towards the Sun when the spacecraft reached a solar distance of 0.85 AU. The timeframe from launch through 0.85 AU was called outer cruise.

However due to launch delays, the mission profile changed so that MESSENGER would return to solar distances above 0.85 AU. Post-launch analysis determined that having the sunshade between the body of the spacecraft and the Sun at distances greater than ~0.95 AU would result in excessive cooling of the spacecraft. To counteract the cooling, a series of “flips” and “flops” were planned. The “flip” maneuvers positioned the sunshade towards the Sun. The “flop” mauervers turned the spacecraft and pointed the sunshade away from the Sun. Each maneuver included a positive 180° rotation about the X-axis with the +Z deck rotating through the Sun, a 180° rotation of the solar arrays, and lastly a 180° spacecraft rotation about the Y-axis to set the radio frequency (RF) antennas in the proper quadrants. These were complex manuevers requiring coordination and sequencing among the power, guidance and control, and autonomy subsystems. The maneuvers had to be carefully planned to ensure that sunlight did not directly enter any of the critical insturment or star tracker apertures on the +Z and -Z decks of the spacecraft. Another constraint was to avoid shadowing the arrays. The temperature differential caused by a shadow could potentially cause array string failures. Additionally, the solar array rotation had to be carefully timed to coordinate with the spacecraft body motion to avoid the software declaring that a solar array “slew failed.” The software declares an array “slew failed” if the array does not reach the commanded position in the expected amount of time. During the “flips” and “flops” this was a concern because of how quickly the array target position was changing when the spacecraft was performing the 180° pitch maneuver around the X-axis. In later maneuvers, spacecraft momentum control was also incorporated. This was performed by updating the spacecraft pitch in addition to positioning the solar arrays. Adding another level of complexity, since the spacecraft was being turned 180°, the communications system had to be reconfigured in the middle of the turn. The manuevers were executed with onboard macros to control the absolute timing between activities. At the time, on-board autonomy parameters could only be redefined from the ground, so these various rules and parameters had to be updated immediately before and after a specific “flip” or “flop” to reduce the time the spacecraft was vulnerable to a fault that could point the spacecraft in the wrong sunward direction - potentially un-doing the maneuver just performed. Due to this all or nothing approach, the first “flip” was performed with the arrays in the body-fixed position mode oriented edge on to the Sun to make sure the sequence performed corrently and no array shadowing occurred. After the manuevers, the heater configurations had to be updated to suport the new attitude. Three “flips” and two “flops” were performed between 8 March 2005 and 21 June 2006. Figure 2 shows MESSENGER’s solar distance from launch through 31 December 2009. The “flips” and “flops” and other flight activities are marked as squares on the plot.

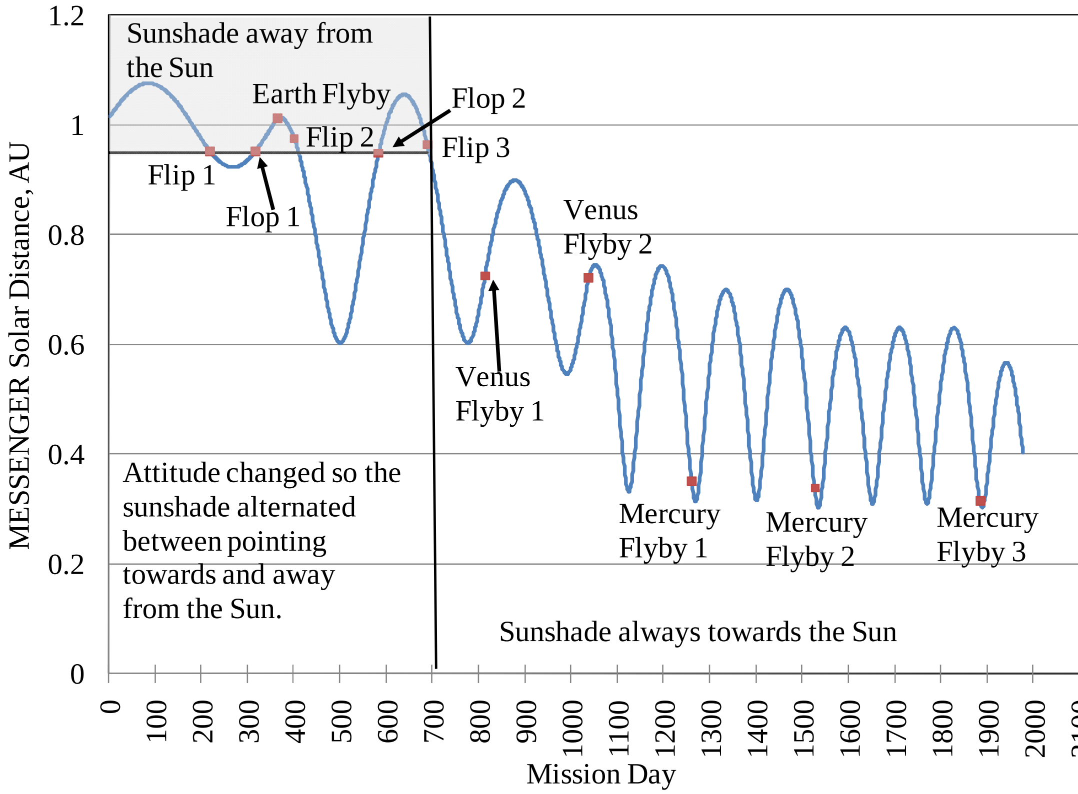

Figure 2. MESSENGER Solar Distance from Launch through 31 December 2009, with Critical Events

IV. Inner Cruise Operations

A. Power and Thermal Systems Inner-Cruise Operations Overview

Since completing the last "flip" on 21 June 2006, MESSENGER has been in the cruise phase of the mission with the spacecraft oriented so the sunshade remains towards the Sun. Additionally, since the first Mercury flyby MESSENGER has been in the inner-cruise phase, with the solar distance remaining below 0.7 AU. Normal daily operation of the MESSENGER power and thermal systems mostly involves managing the solar array positions to keep their steady state temperature below 150°C while providing ~800 W of power for spacecraft operations. The thermal management of the solar arrays is done by off-pointing the solar arrays from the Sun. The allowable range of angles for the solar array positions depends mostly on the spacecraft's distance from the Sun. Most of the time, the arrays are operated in the Sun-offset mode, and the commanded offset angle is periodically updated on the basis of the spacecraft's solar distance. However, during some of the science operations, the solar array motion is stopped so the motion will not interfere with image acquisitions. In this case, the solar arrays are prepositioned at a body-fixed angle specifically chosen for the event that allows the solar arrays to remain in a safe operations zone for the duration of the activity. During times of high activity, such as flybys, the array management can be quite challenging, with individual solar array angles required for several different spacecraft events. For example, during the second Mercury flyby sequence, the solar array positions were updated 23 times in five days.

The operational limits on the solar array Sun-offset angles vary significantly as the solar distance changes. A plot of the solar array Sun-offset angle limits for array steady-state temperature and power generation are shown in Fig. 3. The allowable operational angles are between the two plots.

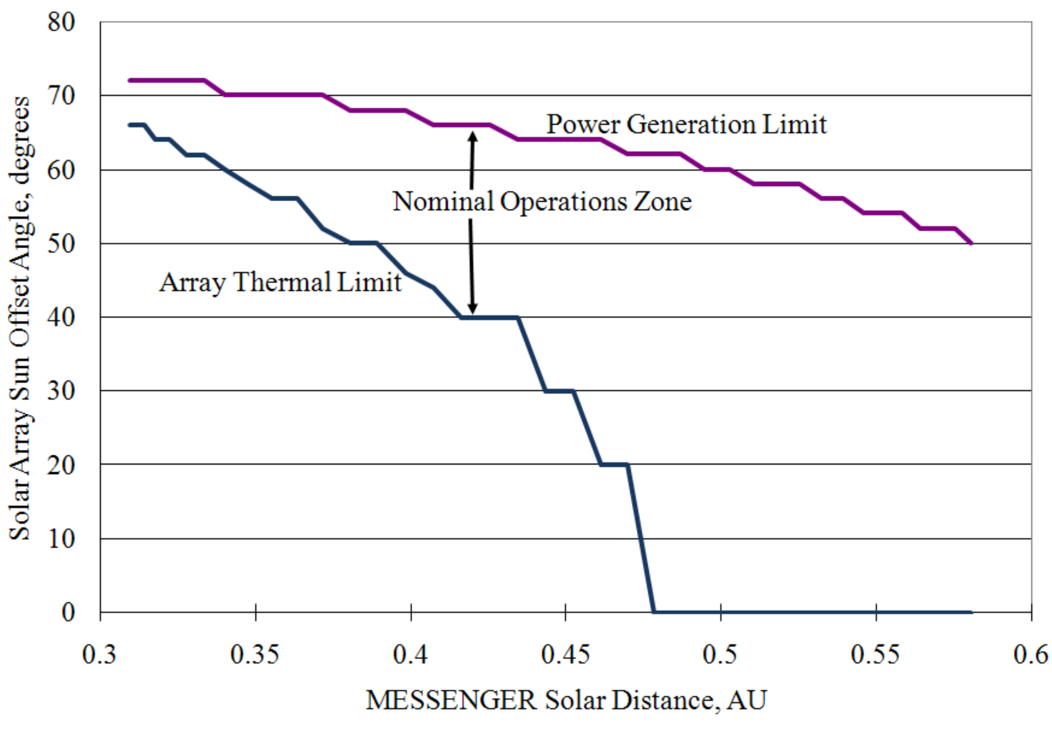

Figure 3. MESSENGER Solar Array Sun-Offset Angle Limits

The solar array Sun-offset angles are adjusted about 15 times a year as MESSENGER's solar distance changes. An example of the sun-offset limits and planned solar array position updates for solar distance for the first six months of 2009 are shown in Fig. 4. Since the normal spacecraft power consumption is below 800 W, the preference in choosing the position is to stay closer to the power boundary and, as the plot indicates, the position updates sometimes limits generation to slightly below 800 W.

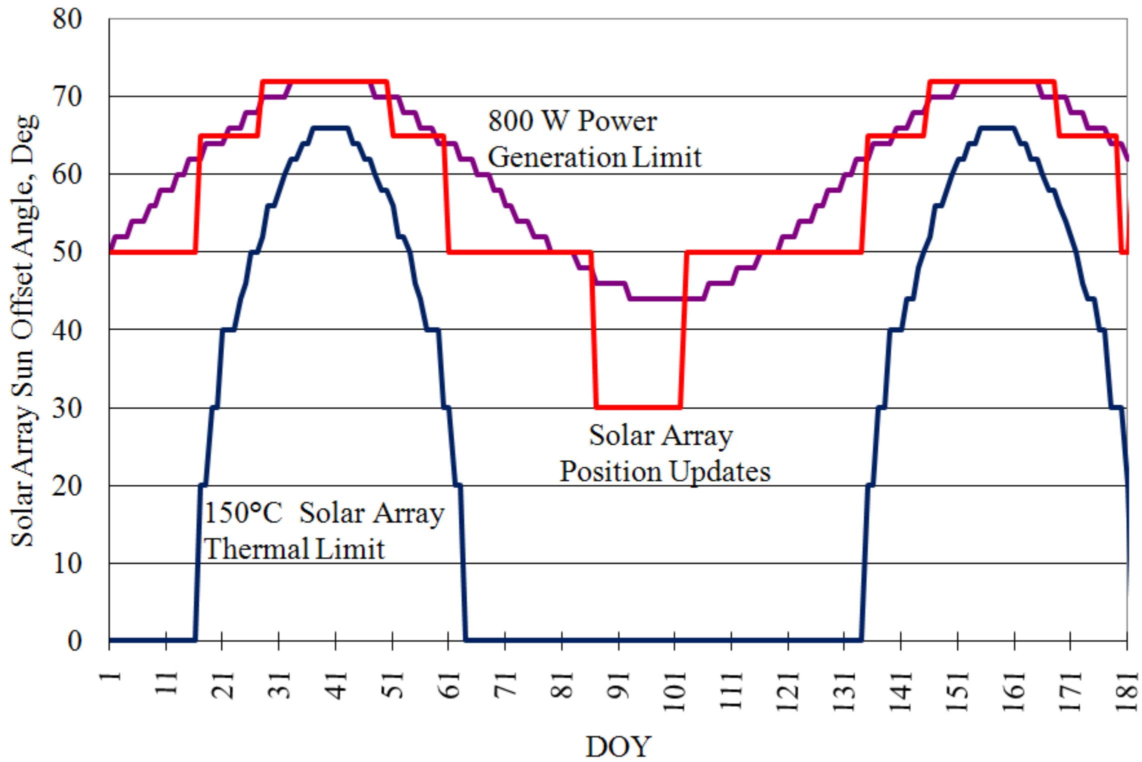

Figure 4. MESSENGER Operational Solar Array Sun-Offset Angles for January – June 2009

During activities when the solar arrays cannot supply the power required to support the spacecraft load due to positioning for thermal constraints or eclipses, battery management can also be a challenge. MESSENGER has one 23A-hr NiH_2 battery. The operational constraints on battery management include keeping the discharge current below 14.5 A and the battery state-of-charge above 40%. The 14.5 A limit is based on acceptance testing values. Since the normal operating level during high-activity events with all of the instruments active is between 15A and 16 A, the 14.5 A requirement means the battery cannot carry the entire spacecraft load, so power-downs are required.

The 40% state-of-charge limit gives a 10% margin over a 30% state-of-charge limit where the system will go into a “last ditch” state. The “last ditch” state is based on the assumption that the spacecraft has lost knowledge of its position and has become off-pointed. It sets the operating voltage of the system at a predefined level instead of allowing peak-power tracking. Then it powers down heaters, commands the guidance and control system to no longer use the ephemeris files, resets the main processor, switches the remote terminal for the power distribution unit, switches the remote terminal for the power-switching electronics, and places the spacecraft into Earth-acquisition mode. An initial autonomy system response will place the spacecraft into Earth-acquisition mode at 40% state-of-charge prior to performing complete “last ditch.” During events when the solar arrays cannot provide power for long amounts of time, such as ~60-minute eclipses, the state of charge limit becomes an issue and power-downs are required.

To date, power-downs for MESSENGER are planned individually on the basis of activity. Generically, for activities where the arrays will not be providing power for less than 30 minutes, the main constraint is the 14.5 A battery current limit. In these cases, the spacecraft load is managed by turning off or changing set points for heaters. For longer activities, where the battery state-of-charge rule becomes a concern, the power-down is much larger and more intrusive. It includes not only heaters, but instruments and communication equipment as well. The following section goes into detail on three specific activities to demonstrate the different planning required.

B. Eclipses and Flybys

In addition to the nominal daily tasks, operating the MESSENGER power and thermal systems also involves preparing for and executing mission events such as planetary flybys. Since launch, MESSENGER has completed one Earth flyby, two Venus flybys, and three Mercury flybys as well as other instrument tests and surveys. The Venus and Mercury flybys were especially challenging from power and thermal perspectives because they included solar eclipses at or near the closest approach to the planet. The first Venus flyby and second Mercury flyby are discussed in detail, because they provide good representations of planning for a long eclipse and planning for array positioning due to thermal constraints. In addition to the two flybys, a vulcanoid survey performed in February 2009 is discussed to demonstrate solar array temperature behavior at small solar distances.

1. First Venus Flyby

The solar distance for the first Venus flyby was ~0.72 AU, so the solar arrays could be placed fully on the Sun to generate power without the solar array thermal limits being an issue. The first Venus flyby was challenging because the associated eclipse was 56 minutes long, so battery depth of discharge was the primary concern. For this eclipse, a major power-down was designed to keep the battery state-of-charge above 48%. It included the instruments, communications equipment, star trackers, and spacecraft heaters. The eclipse and recovery were broken into three phases - the eclipse itself, the battery recharge time after the eclipse, and the load recovery time after the battery reached 100% state-of-charge. Reactivating most of the loads was deferred until the battery reached 100% state-of-charge to ensure there was enough power to recharge the battery. The power-down and recovery were written into three on-board autonomy protection rules. The first powered off the spacecraft loads at eclipse entry. The second powered on select loads at eclipse exit. The third powered on the remaining loads once the battery reached full charge. Table 1 shows the state of the major spacecraft loads in the three phases.

Table 1. Planned Load States for Venus Flyby 1

Spacecraft Load	Phase A	Phase B	Phase C
Main Processor	On	On	On
RF Transponder A	On	On	On
RF Transponder B	On	On	On
RF Solid-State Power Amplifier A	Off	Off	***On***
RF Solid-State Power Amplifier B	Off	Off	Off
Primary Back Phased-Array Antenna Heater	Off	Off	***On***
Secondary Back Phased-Array Antenna Heater	Off	Off	Off
Reaction Wheels	On	On	On
Star Tracker 1	Off	***On***	On
Star Tracker 2	Off	Off	Off
Inertial Measurement Unit	On	On	On
Instrument Data Processing Unit A	Off	Off	***On***
Instrument Data Processing Unit B	Off	Off	Off
Gamma-Ray Spectrometer	Off	Off	***On***
All Other Instruments	Off	Off	Off
Primary Instrument Survival Heaters	On	On	On
Secondary Instrument Survival Heaters	On	On	On
Magnetometer Survival Heater	On	On	On
Primary Line and Valve Heaters	On	On	On
Secondary Line and Valve Heaters	On	On	On

Table 1. Continued

Primary Battery Heater	On	On	On
Primary Spacecraft Heater	On	On	On
Secondary Spacecraft Heater	On	On	On
Auxiliary Spacecraft Heater 1	Off	Off	Off
Auxiliary Spacecraft Heater 2	Off	Off	Off
Main Propulsion Tank Heaters	On	On	On
Helium Tank Heater	On	On	On
Auxiliary Tank Heater	On	On	On
Secondary Propulsion Tank Heaters	Off	Off	***On***
Pressure Transducers	Off	Off	***On***

Note: Changes from the previous state are in bold italics.

Even though the propulsion main tank heaters are listed as on in all three phases, their set points were adjusted for phase A and B so that they would not come on. Figure 5 shows the three phases and the expected battery discharge.

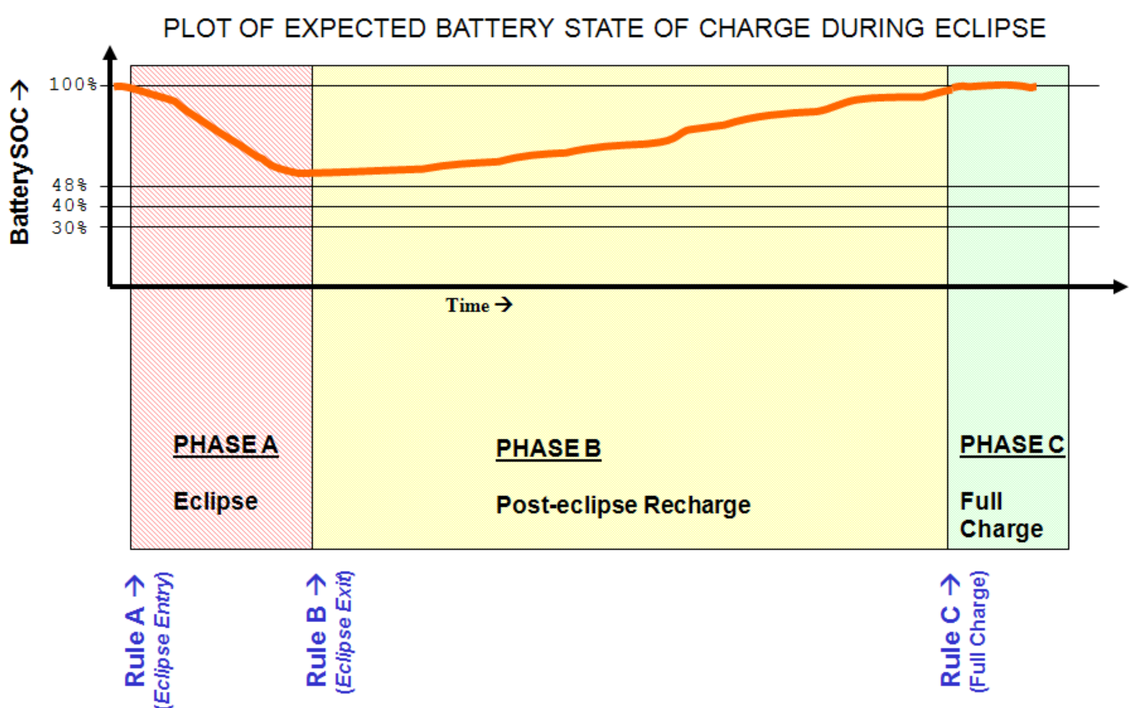

Figure 5. MESSENGER Predicted Battery State of Charge during the Second Venus Flyby

In order to test the power-down, a flight test was performed on 11 August 2006. In this test, the eclipse was simulated by commanding the solar arrays to be pointed 100° from the Sun. During the test, the power-downs and recovery performed as expected and the total spacecraft load was lower than predicted, so the minimum battery state-of-charge was only 57%.

MESSENGER experienced a main processor swap the day before the first Venus flyby. Fortunately, the onboard autonomy protection rules are in a different processor and still operated as designed through the eclipse. The minimum battery state of charge was 64%.

2. *Second Mercury Flyby*

The second Mercury flyby is a good example of the operational planning required for a planetary flyby with an eclipse at a low solar distance. The MESSENGER solar distance for the second Mercury flyby was ~0.34 AU. At this solar distance, the solar arrays needed to remain pointed at least 58° away from the Sun in order to keep the panels below their nominal operating temperature of 150°C. However, if the panels were positioned more than 77° away from the Sun, not enough power would be generated to carry the entire spacecraft load and the battery would begin to discharge. Short-term battery discharge in itself is not a problem, but in this case, there was also a 17-minute solar eclipse encompassing the closest approach to the planet. Since the battery discharge current is operationally limited to 14.5 A, it was desired to remain on solar array power as much as possible to allow all of the instruments to be on and functioning as desired to achieve all of the flyby science objectives.

Normally, the solar arrays would be allowed to operate in the Sun-offset mode with a commanded offset angle between 58° and 77°. However, around the closest approach time of the flyby it was desired to move the arrays as little as possible so that the array motion would not interfere with images being taken. The concern was that the array motion would cause jitter in the images. Due to the dynamic changes of the Sun elevation with respect to the spacecraft -Y-axis because of spacecraft pointing for science observations, one angle could not be chosen that would always keep the arrays within the required Sun-offset range. The time frame just after the eclipse was particularly dynamic. Various options using multiple solar array positions were discussed. It was decided to minimize the number of array motions and allow two small periods where the arrays would be too off-pointed due to the attitude required for science observations to carry the entire spacecraft load. The first was three minutes after eclipse exit. This effectively extended the eclipse to 20 minutes total. The second was a 4 minute 30 second period about 13 minutes later. Figure 6 shows the two body-fixed array positions chosen, the solar panel Sun-offset, and the Sun elevation from the -Y-axis due to spacecraft attitude excursions for science observations.

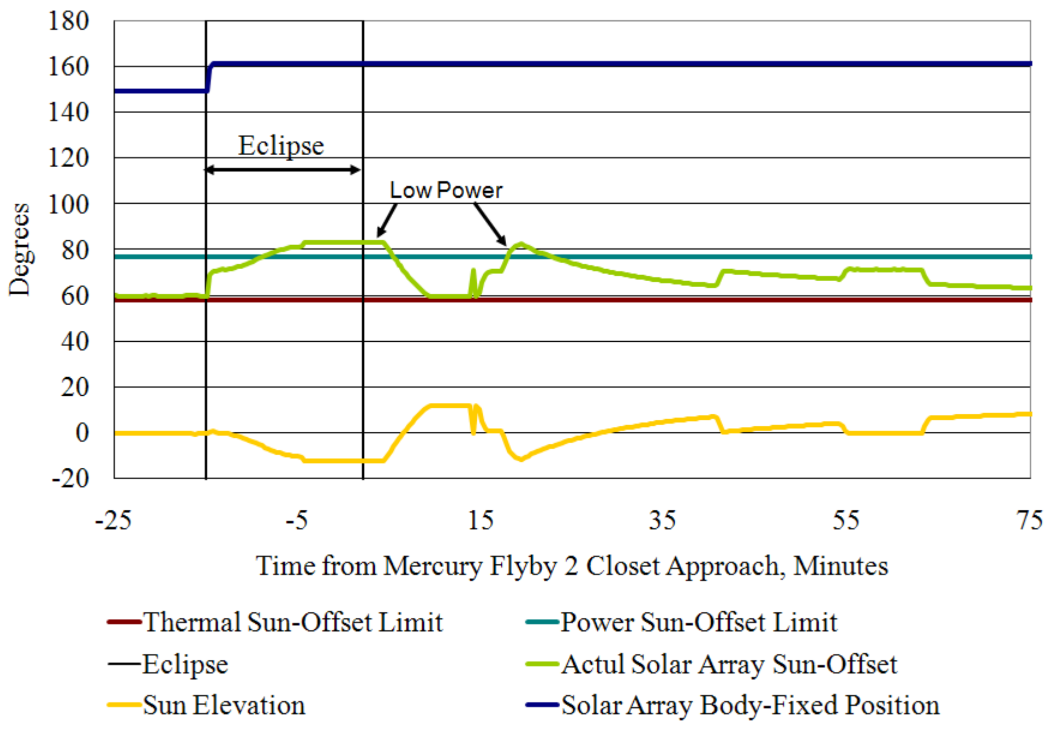

Figure 6. Actual Mercury Flyby 2 Solar Array Positions

The solar array Sun-offset angles and panel temperatures are shown in Fig 7. The plan worked as intended with the peak solar array temperature reaching 154°C.

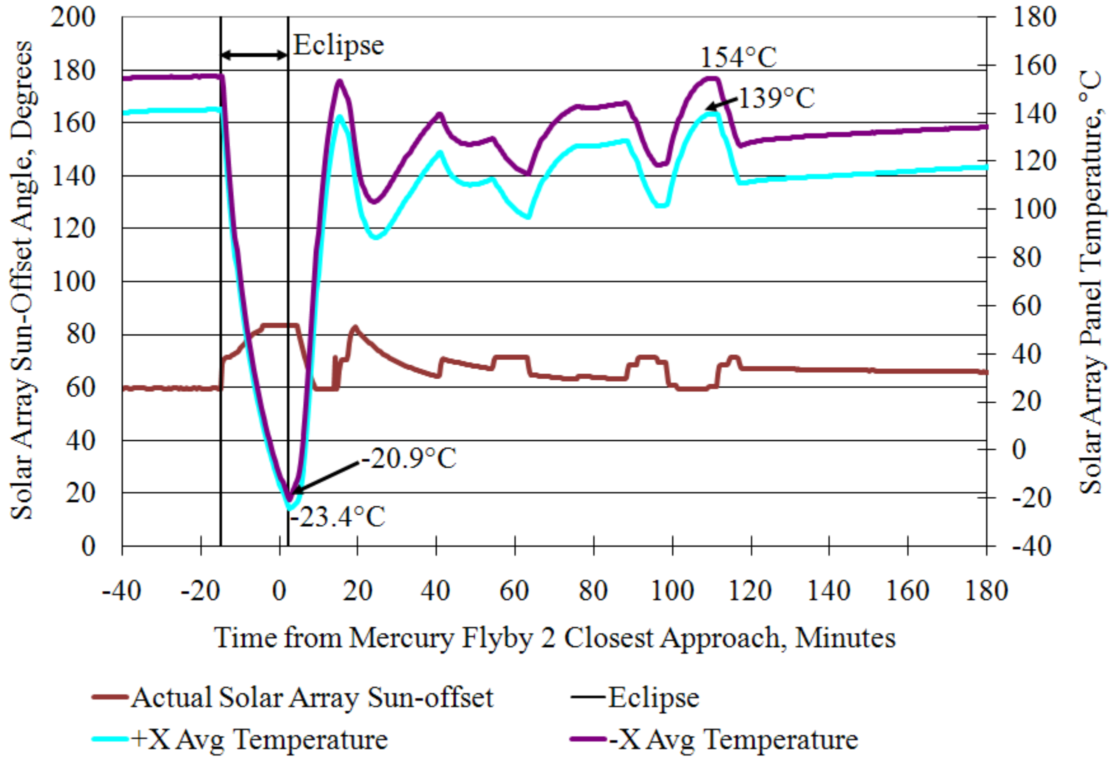

Figure 7. MESSENGER Mercury Flyby 2 Solar Array Sun-Offset Angle and Panel Temperature

For the effective 20-minute eclipse, a power-down was performed to keep the battery current below the 14.5 A limit. In this case, since the eclipse duration was short, the battery depth of discharge was not an issue; the power-down was able to be limited to various spacecraft heaters, so science operations were not affected. The battery pressure and state-of-charge are shown in Fig 8. The second low-power time due to the array body-fixed positions is seen as an extended time at 87% state of charge and as small decreases in the battery pressure.

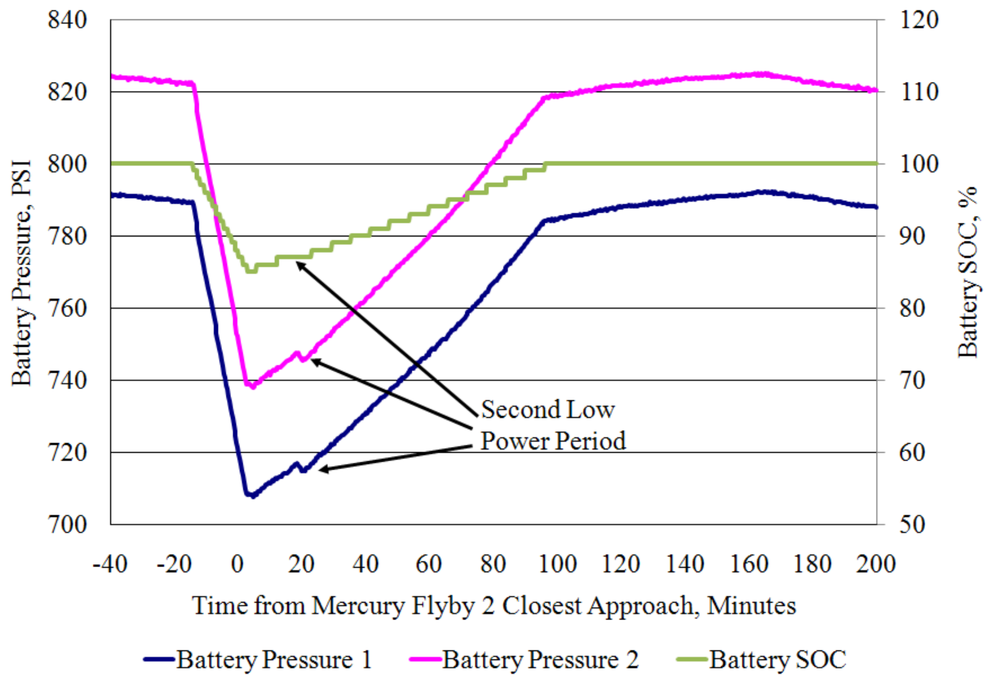

Figure 8. MESSENGER Mercury Flyby 2 Battery State-of-Charge and Pressure

3. February 2009 Vulcanoid Survey

Mission operations in a widely varying thermal environment are a constant learning experience. One of the routine science activities performed by MESSENGER is the vulcanoid survey. The survey is performed near perihelion and involves taking images with the Mercury Dual Imaging System. Blocks of images are taken on several days around perihelion. In each block, three or four sets of images are taken spaced several hours apart. During each set of images, the spacecraft is rolled about the Y-axis and pitched from zero to +12°.

The February 2009 survey occurred at a solar distance of ~0.31 AU. A previous vulcanoid survey had been performed in June 2008 with a slightly higher solar distance ranging from 0.32 – 0.36 AU. For the survey, the solar arrays were pre-positioned at a body-fixed angle prior to each of the individual groups of maneuvers to avoid possible jitter in the images. Since the solar distance was so low, the nominal operating band of the solar arrays was only ~6°. A position was chosen to prevent battery discharge when the spacecraft pitched to +12° and to keep the solar array temperatures below a steady state 160°C when the spacecraft was at 0° pitch. The 160° limit is higher than the nominal operating limit of 150°C but still below the high operating limit of 180°C.

However, during the survey, the arrays did not reach a steady-state temperature. The temperatures changed rapidly when the spacecraft maneuvered. The peak temperature was 192°C. Figure 9 shows the solar array Sun-offset angle and temperatures during the survey.

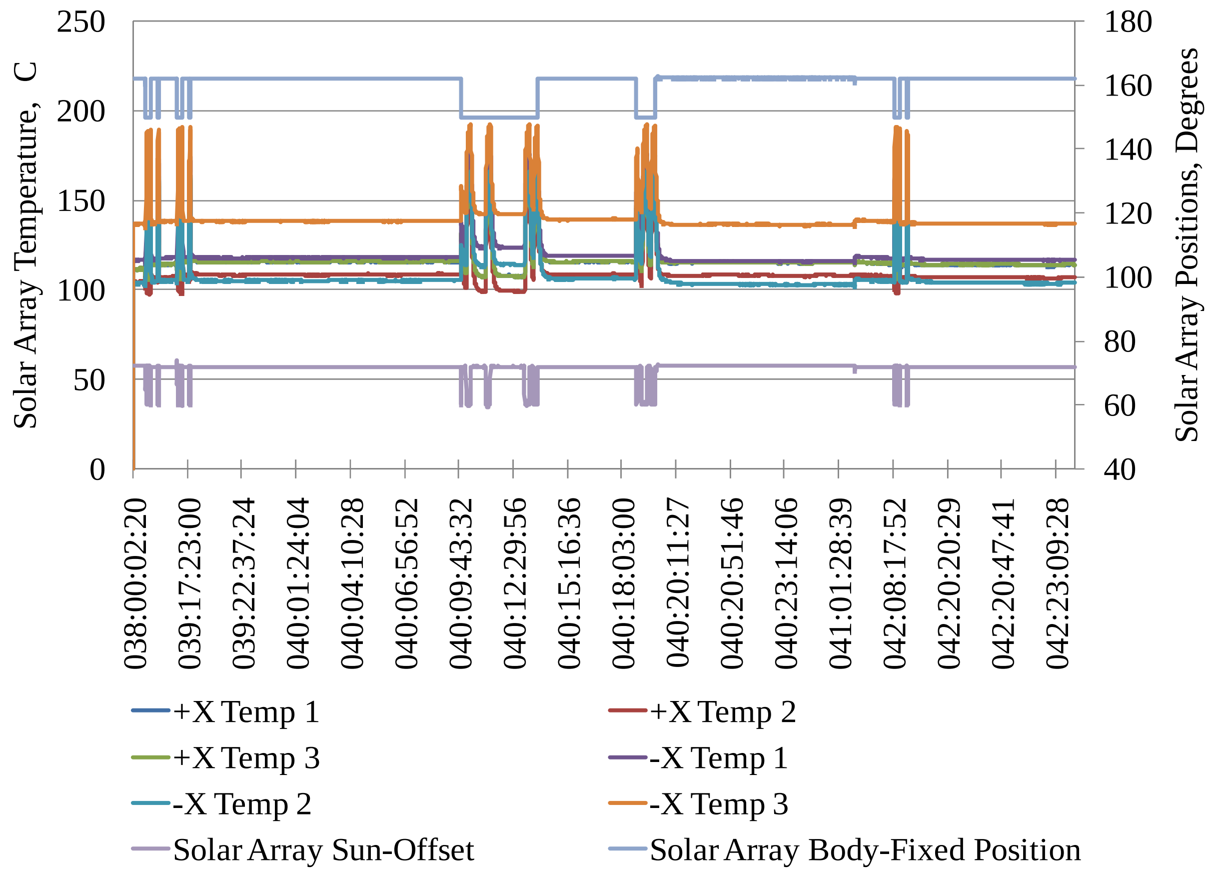

Figure 9. Solar Array Position and Temperatures during the February 2009 Vulcanoid Survey

No damage was done to the solar arrays, and the average temperatures remained below the higher 180°C threshold. Since the test, the models for the solar array temperature have been updated and the solar distance array Sun-offset thermal limits have been updated to reflect the data acquired during this test.

V. Conclusion

Operating the power and thermal systems of a spacecraft over widely varying solar distances causes unique and interesting challenges. At near-Earth distances spacecraft cooling was a major concern. Near Mercury, the challenge is to balance solar array power output with thermal protection of the solar arrays. Because of these concerns, plans for spacecraft activities such as flybys or image surveys should be adapted to suit the individual conditions created by changing environment.