MESSENGER Operational Influences and Environment

G. Allan Holtzman, Andrew B. Calloway, Stephen E. Jaskulek, and Daniel T. Gallagher

ABSTRACT

After a busy 6.6-year interplanetary trajectory through the inner solar system, the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft was inserted into a highly eccentric, near-polar orbit about Mercury on 18 March 2011 UTC. It conducted uninterrupted operations until, after depleting its propellant, it impacted Mercury's surface on 30 April 2015. The spacecraft faced a number of operational, power-related, and thermal challenges throughout its mission, including the extreme and highly variable thermal environment at Mercury, the collection of a wide variety of science observations, frequent orbit-correction maneuvers, radio occultations, solar conjunctions, and power and thermal constraints on the spacecraft and its instruments. The MESSENGER team met these challenges over the course of the mission's orbital phase, which lasted more than 17 Mercury years. With the team's constant vigilance and analysis, the spacecraft safely and productively completed its primary and two extended missions. The tools and talents of the entire team contributed to the successful accomplishment of that goal without a single safing event during the entire orbital phase, enabling the return of unprecedented data from the innermost planet of the solar system.

INTRODUCTION

This article provides an overview of the environmental challenges and resulting engineering solutions that kept the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft operating nominally throughout the orbital phase of the mission. The spacecraft was challenged by the constantly changing operational seasons relating to orbit geometry, the harsh radiation environment close to the Sun, the severe thermal environment around Mercury, and the increasingly difficult power management constraints as the mission neared its end. Specific power and thermal analysis was required in advance of each Mercury year to enable definition and dissemination of the details resulting from changing orbital conditions over time. The engineering teams not only met all these challenges to keep the MESSENGER spacecraft operating nominally during the increasingly difficult operational seasons in the mission, but they also implemented key innovations in the engineering process that increased the mission's science return while protecting the spacecraft through the final orbit.

OPERATIONAL SEASONS OF THE ORBITAL MISSION PHASE

The engineering strategies put in place for safe and scientifically productive orbital operations can be categorized into five recurring operational seasons. The first two, designated solar eclipse seasons and thermal mitigation seasons, were driven by the phasing between MESSENGER's orbit, Mercury's slow spin rate, and Mercury's high orbital eccentricity. These seasons repeated twice during each 88-day Mercury year in low and high ranges of Mercury true anomaly (MTA), presenting different challenges depending on which anomaly was the more severe. The other three operational seasons, designated RF occultation seasons, uplink-rate seasons, and solar conjunction seasons, were defined by the constantly changing distance and phase angle between Earth and Mercury. These seasons were therefore asymmetric, with variable overlap between combinations of them, and decoupled from the Mercury orbital period. This article summarizes the operational strategies employed over the 17 Mercury years of the orbital mission phase in the context of these five operational seasons. It also demonstrates that the strategies, such as unit power cycling, spacecraft orientation and certain science observation blackouts, solar array positioning, Deep Space Network (DSN) antenna resource scheduling, command load splitting decisions, recorder management, and even staffing, were all selected and implemented in response to the requirement to safely navigate these five challenging and recurring seasons.

Solar Eclipse Seasons

Twice each Mercury year, for ranges of consecutive orbits the MESSENGER spacecraft passed behind the planet into shadow from the perspective of the Sun (e.g., Fig. 1). These orbits were known as solar eclipse seasons. The solar panels were in shadow, and the spacecraft battery was required to power all components during portions of these orbits. As a result, the battery underwent discharge/charge cycles that required long-term trend analysis and thermal management. The eclipse seasons' date ranges and ingress/egress orbit timing were known well in advance and deviated from the predictions only slightly because of orbit drift and perturbing events, namely orbital-correction maneuver errors. Therefore, the mission operations team could carefully plan for solar eclipse seasons in coordination with the science planning team and the power, thermal, and guidance and control (G&C) teams. Command timing had sufficient margins to account for ephemeris and time-tagged command biasing uncertainty since the eclipse-related commands were placed in the sequences 4 weeks before they were executed. Eclipses occurred twice per calendar day in the first 13 months of the orbital phase with the 12-h orbits, and then three times per day after the transition in April 2012 to 8-h orbits. The length of the solar eclipses varied from just seconds on the seasonal edges to as much as 50 min at the seasonal peaks.

Figure 1. Last MESSENGER orbit as viewed from the Sun.

As the periapsis latitude progressed northward during the orbital phase and then southward again after crossing 90°, the low-MTA and high-MTA eclipse seasons flipped: high-MTA seasons originally included the more demanding combination of thermal mitigation solar array off-pointing and long eclipses, but the low-MTA seasons eventually contained the more demanding combination. The selected actions in response to low- versus high-MTA seasons differed and depended on the corresponding predicted battery depth of discharge and other factors. Whenever eclipse durations fell below an agreed-upon threshold, the operations team did not need to take any action. For orbits with longer-duration eclipses (and orbits with shorter eclipses but in combination with solar array off-pointing), certain spacecraft components were sequenced to power off in order to limit the battery depth of discharge. Examples of components that could be temporarily turned off to conserve power included secondary spacecraft heaters, the spacecraft's back antenna heater, and tank heaters with their long thermal constants. During the most demanding eclipse seasons, it was necessary to power off the secondary transponder for those orbits, which in turn required coordination with the RF communications team, the radio science team, and even the science planning team, which managed long-term data return predictions. By managing the spacecraft resources for each individual solar eclipse season, the team was able to keep the entire payload powered on and collecting data throughout the orbital phase, although for thermal reasons the Mercury Atmospheric and Surface Composition Spectrometer

(MASCS) and the X-Ray Spectrometer (XRS) Solar Assembly for X-rays (SAX) were powered off during each orbit in some seasons. The one exception was the very first eclipse season, when the team was formulating the early models and chose to be especially conservative and methodical in its approach, by identifying and powering off a subset of the payload.

Thermal Mitigation Seasons

Twice each Mercury year, the team assessed thermal model predictions and historical performance trends to determine the mitigation responses to employ over each range of MTA dates and orbit true anomaly (OTA) times. These results were in turn translated into specific commands in each weekly command load, with sufficient timing margin to account for the drift over time. This information was defined and communicated in close coordination among the mission operations, science planning, and power, thermal, and G&C subsystem teams. As with the eclipse seasons, the low-MTA and high-MTA seasons flipped in terms of those that were more challenging to address each Mercury year, and the spacecraft orbit periapsis altitude was changing with time. Ultimately, a balance was struck between the thermal season commands that the mission operations team would incorporate and those placed into the delivered blocks of commands to be merged by mission operations into the one final constraint-checked load.

Examples of thermal mitigation commanding included spacecraft off-pointing to protect against overheating of the front phased-array antenna (FPAA) and power cycling of the most susceptible payload components, namely the MASCS instrument and the XRS SAX solar monitor. In addition, the solar arrays were offset during each orbit at predetermined angles to keep their peak temperatures below defined thresholds, which were revisited each year. For the later years of the mission, additional measures were identified and employed, such as offsetting the solar arrays before the spacecraft passed over the hot planet, a technique known as pre-cooling the arrays. The durations and timing of solar array commands had to be carefully chosen in close coordination with power system analyses to ensure an acceptable overall discharge from the battery for the combination of off-pointing and actual solar eclipses. The mission operations team received updated orbit events tables from the mission design team with predefined contents and formats (which were modified periodically when appropriate to improve automated operations) and used them to ensure that all thermal mitigation commands were properly placed within the command sequences. Detailed constraint checking and load review reports and tools were used to ensure that all seasonal requirements were properly addressed. Had the sequences been generated with the wrong commands or incorrect timing, spacecraft

Table 1. Thermal mitigation seasons in MESSENGER's late-mission orbital phases

Season	Start DOY	Start Date	End DOY	End Date
MY16S1 (outgoing/low MTA)	301	28 Oct 2014	332	28 Nov 2014
SA pre-cooling only	301	28 Oct 2014	302	29 Oct 2014
SA pre-cooling and SA off-pointing	303	30 Oct 2014	308	4 Nov 2014
SA pre-cooling, SA off-pointing, and eclipses	309	5 Nov 2014	321	17 Nov 2014
SA pre-cooling and SA off-pointing	321	17 Nov 2014	327	23 Nov 2014
SA pre-cooling only	327	23 Nov 2014	332	28 Nov 2014
MY16S2 (incoming/high MTA)	354	20 Dec 2014	20	20 Jan 2015
Eclipses only	354	20 Dec 2014	361	27 Dec 2014
SA pre-cooling and eclipses	361	27 Dec 2014	16	16 Jan 2015
Eclipses only	16	16 Jan 2015	20	20 Jan 2015
MY17S1 (outgoing/low MTA)	23	23 Jan 2015	56	25 Feb 2015
SA pre-cooling only	23	23 Jan 2015	24	24 Jan 2014
SA pre-cooling and SA off-pointing	24	24 Jan 2015	31	31 Jan 2015
SA pre-cooling, SA off-pointing, and eclipses	32	1 Feb 2015	43	12 Feb 2015
SA pre-cooling and SA off-pointing	43	12 Feb 2015	55	24 Feb 2015
SA pre-cooling only	55	24 Feb 2015	56	25 Feb 2015
MY17S2 (incoming/high MTA)	72	13 Mar 2015	109	19 Apr 2015
Eclipses only	72	13 Mar 2015	84	25 Mar 2015
SA pre-cooling and eclipses	84	25 Mar 2015	104	14 Apr 2014
Eclipses only	105	15 Apr 2015	109	19 Apr 2015
MY18S1 (outgoing/low MTA)	111	21 Apr 2015	120	30 Apr 2015
SA pre-cooling only	111	21 Apr 2015	112	22 Apr 2015
SA pre-cooling and SA off-pointing	112	22 Apr 2015	119	29 Apr 2015
SA pre-cooling, SA off-pointing, and eclipses	120	30 Apr 2015	120	30 Apr 2015

DOY, Day of year; SA, solar array.

health and safety would likely have been put at great risk from the Mercury thermal environment. Even with all the careful analysis, predictions were off by a few orbits in some instances. For example, on a small number of occasions, a few orbits before predictions called for proactive commanding to power cycle the SAX intentionally, internal logic autonomously powered the unit off because it reached high-temperature thresholds. However, models were fine-tuned throughout the mission, reducing and ultimately eliminating such occurrences. Examples of several successive thermal mitigation seasons during MESSENGER's second extended mission are given in Table 1.

RF Signal Occultation Seasons

One of the major scientific investigations of the mission's orbital phase was that of radio science. During certain windows of time occurring asymmetrically through the 4 Earth years of the orbital phase, the spacecraft's highly eccentric orbit took it behind the planet and then back out again as seen from the perspective of the Earth-based DSN antennas (Fig. 2). The radio science team, in coordination with the science planning team, used the SciBox tools to provide the mission operations team routinely with the predicted times of these Earth-viewed occultation ingresses and egresses, updated periodically as new ephemeris products were generated and ingested into the planning system. Since the mission operations team was aware of these times well in advance, DSN time was acquired to cover these windows, with predefined agreement on how many windows to cover on average for any given calendar week. The original 12-h orbits and the later 8-h orbits provided ample opportunities to schedule these DSN supports, although some seasons provided much more valuable data to the radio science team than others did, depending on the Earth viewing geometry and the latitude and longitude at Mercury's surface of the occultation points. A typical radio science week included DSN coverage for 14 occultation ingresses. To accommodate the desired frequency and to have a realistic chance for acquiring the support given competition with other missions, these tracks were often scheduled as stand-alone supports rather than added to the front end or back end of longer telemetry and command tracks. For this reason, the mission operations team worked with the DSN scheduling team and the engineering support team to define new configuration codes that included a shorter 45-min pre-calibration time rather than the standard 60-min calibration time. This effort resulted in less overall impact to other missions, earning the MESSENGER operations team a reputation as a conscientious steward of the DSN resources as well as providing more opportunities for conflict-free support requests. This enhancement became especially important during one 12-week campaign in 2014 during which the radio science team requested coverage over every single ingress opportunity (i.e., 21 of 21 orbits per week). The spacecraft was configured as carrier only (i.e., beacon only with no telemetry modulation on the carrier signal) for all of these orbits, and, with agreement from the mission operations team, members of the DSN support staff made their best efforts to troubleshoot responses during off-hours, given the large quantity and frequency of these supports in the orbital phase.

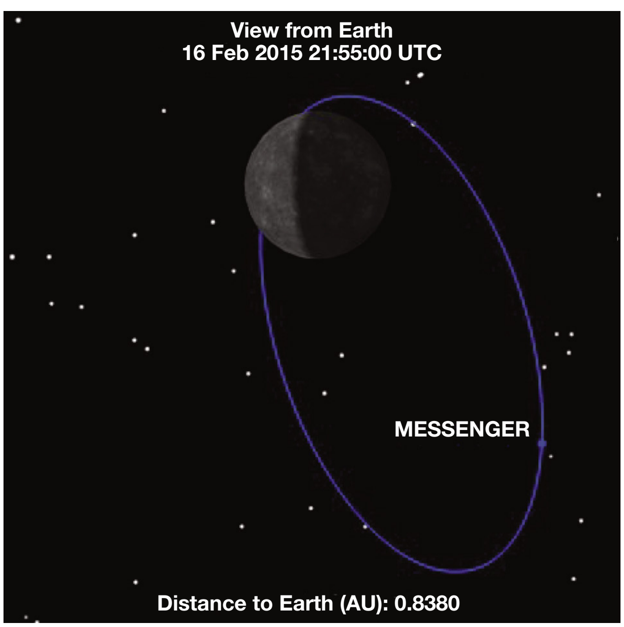

Figure 2. A typical MESSENGER orbit as seen from Earth.

From a mission operations perspective, RF occultation seasons were considerably more cumbersome and complex than the seasons in which the spacecraft orbit was in full view of the Earth at all times. This was the case not just in terms of DSN scheduling but also in terms of command sequence complexity and command volume from the additional commands. The command loads during occultation seasons had to include the sequences that transitioned to the appropriate low-gain antenna configuration at the appropriate times to overlap the DSN coverage. The DSN keyword files (DKFs) were also much more complex and voluminous, because they included all the extra transitions and equipment reconfigurations for high-gain antenna to low-gain antenna and back again at the correct times of the signal loss and acquisition. This situation was further complicated because many of the DKF directives are in ground time, but spacecraft commands are in spacecraft time, which shifted each week because of orbit drift compensation time-tag biasing. The DKFs had to be modified late in the planning cycle to resynchronize with the new spacecraft times, and the more voluminous DKF files in occultation seasons were much more cumbersome. One bonus of all this occultation coverage, however, was that DSN time typically also spanned the orbit periapsis crossings.

Table 2. Earth occultation seasons during MESSENGER's orbital phase

Season No.	Earth Occultation Season Start	Earth Occultation Season End	Peak Duration (Minutes)
1	18 Mar 2011 11:49	9 May 2011 07:41	44.97
2	9 July 2011 04:24	20 Oct 2011 00:51	33.32
3	14 Feb 2012 02:57	7 May 2012 22:46	46.65
4	24 Aug 2012 23:49	4 Oct 2012 16:05	38.82
5	30 Jan 2013 15:38	1 May 2013 16:13	38.47
6	19 Aug 2013 17:28	21 Sept 2013 17:46	46.23
7	15 Jan 2014 17:33	1 May 2014 02:27	32.82
8	11 Aug 2014 17:06	10 Sept 2014 20:25	56.23
9	27 Dec 2014 14:40	1 May 2015 12:12	28.79

The Doppler signal change as the spacecraft crossed periapsis during each orbit (speeding up and then slowing down slightly) was also very useful information to the radio science team as long as a DSN station was configured to listen. A list of all Earth occultation seasons during the mission orbital phase is given in Table 2.

Seasons with 125-bps Uplink Rates

The DSN hardware and software architecture is engineered to support spacecraft uplink rates that are even divisors of 4000 bps. Before MESSENGER was launched, the engineering team decided to balance the number of defined rates against testing complexity and cost and chose to incorporate four rates: 500 bps, 125 bps, 31.25 bps, and 7.8125 bps. The rates that could be used on any given day during the orbital phase were dictated primarily by Earth distance. The two highest rates could be used during the entire orbital phase, toggled on a seasonal basis within the planning system. Since Earth travels once around the Sun every 365 days and Mercury travels once every 88 days, the amount of time that could be supported with the highest 500-bps uplink rate was about half that of the 125-bps dates, averaging about 38 days compared with 76 days, and it varied asymmetrically over the course of the 1504 Earth days of MESSENGER's orbital phase. Link margin calculations showed that operations could comfortably select the preferred 500-bps uplink and maintain the minimum 6-dB command margin with the primary 34-m-aperture DSN antennas given the default 20-kW transmitter power whenever the Earth–Mercury distance dropped below a distance threshold. The 500-bps seasons could be extended by several additional days whenever the operations team was fortunate enough to obtain 70-m DSN antenna support on those dates, due to the 6-dB improvement from the higher gain of the larger antenna, again given the default 20-kW transmitter power. Table 3 shows the date ranges for which the spacecraft and the DSN were configured to support the 125-bps and 500-bps uplink rates during the orbital phase.

The orbital phase of the mission was very uplink intensive, which is why the seasonal toggling between the two highest rates was very important to operations, given the difference of a factor of 4. Every DSN track was either a primary or backup opportunity for a critical uplink activity, including ephemeris loads, commanded angular momentum desaturation targeting and activation, and command sequence loads. The weeklong command loads were so voluminous that they had to be split into biweekly loads (Monday through Friday and Friday through Monday), and the DSN daily track durations were typically only 3–5 h because of the orbit geometry, thermal constraints, and contentions. The half-week loads often required more than 4 h each just to radiate during the 125-bps seasons, not including the requisite momentum desaturations and varying round-trip light times. Because of this ratio, the loads often had to be spread across two or more DSN tracks requiring specifically tailored A, B, and even C segments, adding considerable risk and complexity to the operations. This issue was exacerbated after the change from 12-h orbits to 8-h orbits when thermal pointing restrictions resulted in shorter DSN real-time support tracks on average. If even one uplink frame was dropped for some reason, the entire load uplink had to be restarted from the beginning once the counters were resynchronized, which usually meant having to wait until the next day's track. This situation was precarious on a recurring weekly basis, since even

Table 3. Uplink-rate toggle dates for MESSENGER's orbital phase

Year	DOY to 125 bps	DOY to 500 bps	Days Spent at 55	Days Spent at 125
2011	076	083	0	7
2011	130	200	47	70
2011	246	324	46	78
2011/2012	355	066	31	76
2012	111	181	45	70
2012	230	310	49	80
2012/2013	335	049	25	79
2013	087	161	38	74
2013	212	290	51	78
2013/2014	318	034	28	81
2014	067	146	33	79
2014	196	273	50	77
2014/2015	303	017	30	79
2015	048	120	31	72
		Total days	**504**	**1000**

DOY, Day of year.

one DSN antenna problem, bad weather, or a transmitter glitch could push the reload to the final opportunity, which did happen on several occasions. Had an onboard orbital phase command load ever run out without the next one ready, the spacecraft would have autonomously entered a "safe" mode of operations when the combination of G&C software and fault protection would have detected incorrectly oriented flight over the hot sunlit part of the planet, risking permanent damage to the hardware. It is therefore not surprising that the mission operations team looked forward to the 500-bps seasons when the 4-h loads required only an hour to uplink.

This higher rate added considerable margin, in that a failed uplink could likely be restarted even within the same DSN track, in addition to opportunities on subsequent days. It also provided additional margin during the DSN scheduling that had occurred months beforehand. The mission operations team had much more flexibility during negotiations when other projects requested shortening of track time, or they could even forego an entire track as long as it was during a season that allowed commanding at the 500-bps rate. Acquiring and retaining DSN time for the weeks that only supported 125-bps rates required much more pointed negotiations. During those difficult negotiations, team members often pointed out the increased likelihood that the spacecraft would go into safe mode. During 500-bps seasons, real-time staffing could be reduced, with just one flight controller on hand to monitor the uplink. The rationale was that if a glitch affected the uplink, one person could handle a restart, given that pressure would be reduced because sufficient time was allotted. In hindsight, having the 250-bps option available would have been helpful to reduce risk in the orbital phase of the mission, since it could have been selected during a subset of the time when communication operated at 125 bps. Analysis of the distances over time between Earth and Mercury prior to launch could have possibly added 250 bps to the implemented rates, and that kind of trade should be considered for future planetary missions with constraints similar to those of MESSENGER.

Solar Conjunctions/Seasons with Low Downlink Rates

Solar conjunctions posed many challenges to the planning and operation of the mission. A solar conjunction occurs when the spacecraft and the Sun appear within a certain angular distance of each other in the celestial sky relative to Earth-based antennas. This range was defined as 3° within the MESSENGER project planning system (Fig. 3). A conjunction can be a superior solar conjunction, when the spacecraft is on the far side of the Sun relative to Earth, or an inferior solar conjunction, when the spacecraft is between Earth and the Sun. Inferior conjunctions had minimal impact on operations, primarily reduced downlink and uplink rates for 3 days near their peaks. These were therefore not defined to have seasons associated with them. Superior solar conjunctions, on the other hand, each had up to 3 months of modified operations and low-downlink-rate tracks centered on the peaks and were therefore considered to be operational seasons that warranted special planning.

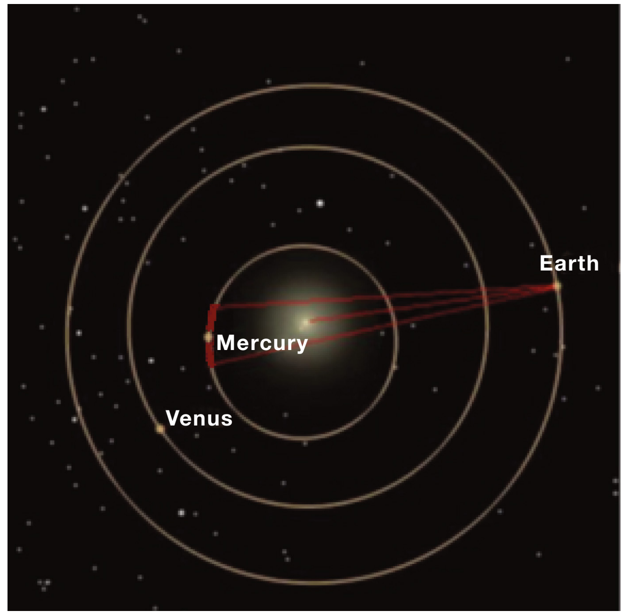

Figure 3. An example of a superior solar conjunction.

Superior conjunction durations during the orbital phase ranged from 11 days to about 4 days, depending on how fast Mercury was moving through its orbit arc relative to Earth. The shortest conjunctions therefore occurred when Mercury was near perihelion while opposite the Sun from Earth, and the longest occurred when Mercury was near aphelion and moving the slowest while opposite the Sun from Earth, and there were many in between. During superior conjunction periods, both uplink and downlink communications with the spacecraft were degraded and communications were deemed unreliable because of interference from solar plasma and scintillation effects. The MESSENGER operations team developed a flight-proven suite of activities to mitigate the impact of superior solar conjunctions. These activities included placing prudent boundaries on beginning, end, and intermediate command loading, temporarily extending command-loss countdown timers, incorporating active momentum management techniques and cadence modifications, modifying ephemeris load cadence, specially managing the solid-state recorder and command sequence volume, and modifying DSN track coverage. There were 22 superior solar conjunctions during the mission, with 13 in the orbital phase and the longest at 11 days, as shown in Table 4.

Solar conjunction seasons were typically more than 2 months in duration and approximately centered on

Table 4. MESSENGER superior solar conjunctions

Orbital Phase Superior Solar Conjunction No.	Start Date	End Date	Duration (Days)
1	10 June 2011	14 June 2011	4.5
2	25 Sept 2011	1 Oct 2011	6.5
3	4 Feb 2012	9 Feb 2012	6
4	25 May 2012	29 May 2012	5
5	7 Sept 2012	13 Sept 2012	7
6	14 Jan 2013	21 Jan 2013	8
7	9 May 2013	14 May 2013	6
8	22 Aug 2013	27 Aug 2013	6
9	24 Dec 2013	2 Jan 2014	10
10	23 Apr 2014	28 Apr 2014	6
11	6 Aug 2014	10 Aug 2014	5
12	3 Dec 2014	13 Dec 2014	11
13	7 Apr 2015	12 Apr 2015	6

the conjunctions themselves. When entering these seasons, to reduce the inevitable accumulation and backlog of data on the solid-state recorder as the downlink rates plummeted over an extended period of time, the mission operations team worked closely with the science planning team to throttle back data collection of second-tier payload data such as Energetic Particle Spectrometer scan data and Neutron Spectrometer and Gamma-Ray Spectrometer diagnostic data. A conjunction season was not considered complete until the backlog of data was finally cleared, usually weeks beyond the peaks, depending on how quickly downlink rates increased again afterward. Strategic negotiations and placement of 70-m DSN antennas on the front and back ends of these seasons also kept many of these backlogs from being much larger and lasting longer, thereby allowing more new data to be collected during and after the peaks of these conjunction periods. During MESSENGER's extended missions, margins were intentionally lowered and greater risk of saturation accepted to allow the recorder to accumulate data routinely near 80–85% capacity versus 65–70%, introducing some acceptable risk of short-term data loss should any unforeseen DSN antenna or weather issues occur during the recorder playback tracks. This situation was deemed acceptable given the team's years of experience working with the DSN and proven strategies for identifying lower-priority data that could be deleted from the recorder to salvage newer or higher-priority data under those circumstances. While the team operated at those tighter margins for more than 3 years, low-priority images were deleted only once, and the solid-state recorder reached only a brief saturation once—a miniscule amount of nonessential data loss compared with the amount of additional data that was captured and returned as a result of the decision not to artificially scale back or not to collect the data in the first place.

Other changes to routine operations were required during these solar conjunction seasons. For example, to preserve sufficient command margin to maintain the preferred 125-bps uplink rate, carrier power that was allocated to range modulation was reallocated to the command modulation instead. The real-time flight controllers of the mission operations team were preauthorized to coordinate with the DSN link controllers to disable command modulation and enable range modulation whenever all real-time commanding was complete on any given track during those seasons. This flexibility allowed the flight control teams to provide the navigation team at least some useful data points for their orbit determination solutions. In addition, the 1-week command loads often had to be extended to 2 or even 3 weeks during these seasons, depending on the number of days of unreliable commanding on either side of the peak days. The mission operations team had to coordinate carefully with the science planning team to choose appropriate mid-load breaks so that command volume would not swell one of the segments to the point that it could not be safely loaded in the available reliable tracks before and after the 3° Sun–Earth–probe angle that signaled the onset or end of conjunction. This situation sometimes required modifying the instrument commanding in the sequence so that it could operate a little differently with fewer commands to keep the size of the load segments on par with a typical half-week size. Ephemerides were uplinked every Friday during the orbital phase when feasible. During conjunctions, the previous week's ephemeris, which was already on hand, was often rebuilt and reloaded with a new range of dates as an extension that could be loaded on a reliable track before the newest delivery was ready. The newest ephemeris was then loaded on an off-nominal day on the first opportunity after the conjunction until the nominal cadence could be resumed the following week. The same strategy was also employed for commanded momentum desaturations, which typically occurred on either Tuesdays or Fridays and were preceded by a unique target load set of parameters.

There were 13 superior solar conjunctions and corresponding low-downlink-rate seasons during the orbital phase of the MESSENGER mission. Although the team had a range of similar strategies and options from which to choose for getting through these superior solar conjunctions, each brought a unique set of challenges depending on when it occurred relative to other seasons, the length and days of the week it encompassed, and the science being collected at the time and accumulating on the recorder. The mission operations, navigation, science planning, and spacecraft subsystem teams had to maintain careful and in-depth analyses and communications to navigate each of the conjunctions safely. Ultimately, they were all safely traversed without any significant spacecraft health and safety issues or operational mode

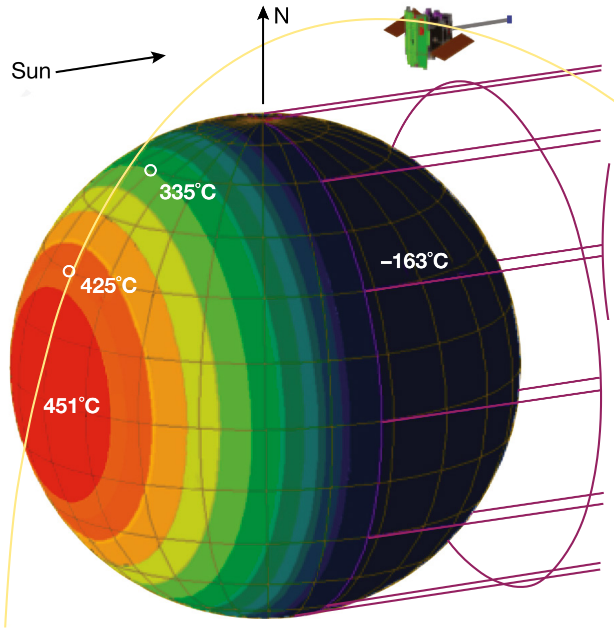

Figure 4. Mercury surface temperature.

demotions, allowing MESSENGER to return substantially more data from the innermost planet than would otherwise have been possible.

THERMAL ENVIRONMENT AND MANAGEMENT

The thermal environment at Mercury is severe and highly variable, which was challenging for some spacecraft components and instruments. After the spacecraft entered orbit about Mercury, a thermal analysis process was put in place to evaluate all spacecraft maneuvers and ensure that no planned activities jeopardized the spacecraft or its instruments. This process included thermal modeling of critical components, which provided detailed temperature profiles for each component that could be evaluated for safety and balanced with science needs. Special considerations, such as changing the orbital period, comet observations, or end-of-mission planning, were evaluated directly with these tools and

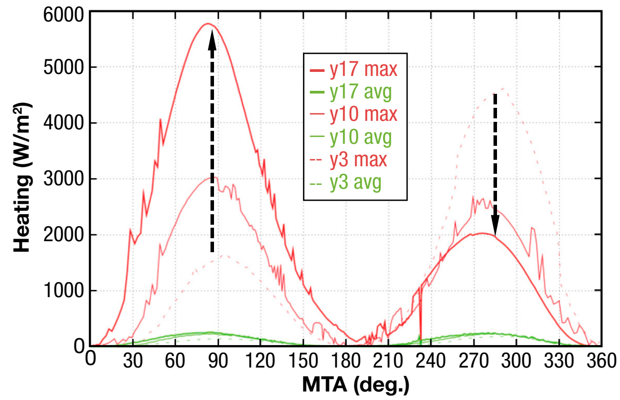

Figure 6. MESSENGER's seasonal heating rates.

gave the engineering teams a precise thermal view of what would happen on the basis of the potential trades that were considered.

MESSENGER Thermal Environment

The solar constant for Mercury's eccentric 88-day orbit varies from 4.7 Earth solar constant (ESC) (planet aphelion is 0.46 AU) to 11.1 ESC (planet perihelion is 0.30 AU). Mercury's high surface emissivity of 0.93, coupled with a 59-day rotation and virtually no atmosphere, causes the planet's surface temperatures to be very hot on the sunlit side of the planet (up to 451°C at the subsolar point near perihelion) and very cold on the nightside of the planet (–163°C). This extreme temperature distribution on the surface of Mercury at perihelion is shown in Fig. 4.

After comprehensive thermal analysis,[1] the initial orbital geometry for MESSENGER was chosen to minimize the impact of the highly varying thermal environment around Mercury. The spacecraft was injected into a dawn–dusk orbit (highly eccentric 200 × 15,200 km altitude with a period of 12 h) placing thermally challenging noon–midnight orbits, the peaks of the two hot seasons that MESSENGER initially experienced each Mercury year, around MTA 100° and 280°. These values did not change much during the mission orbital phase because the orbit plane was relatively inertial with respect to the Sun. Orbit-correction maneuvers were periodically performed to readjust the orbit (including a major adjustment to the orbital period to 8 h).

Over the course of the mission, the orbital line of apsides rotated around Mercury (because of gravitational forces from Mercury and the Sun), changing the location of the orbit periapsis relative to the subsolar point

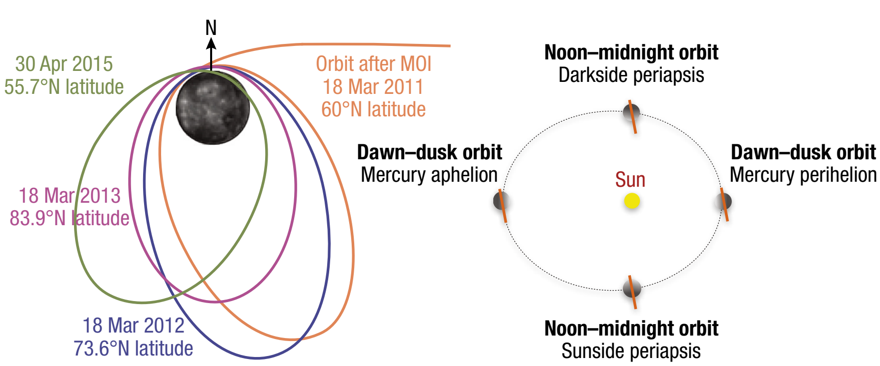

Figure 5. MESSENGER orbit progression.

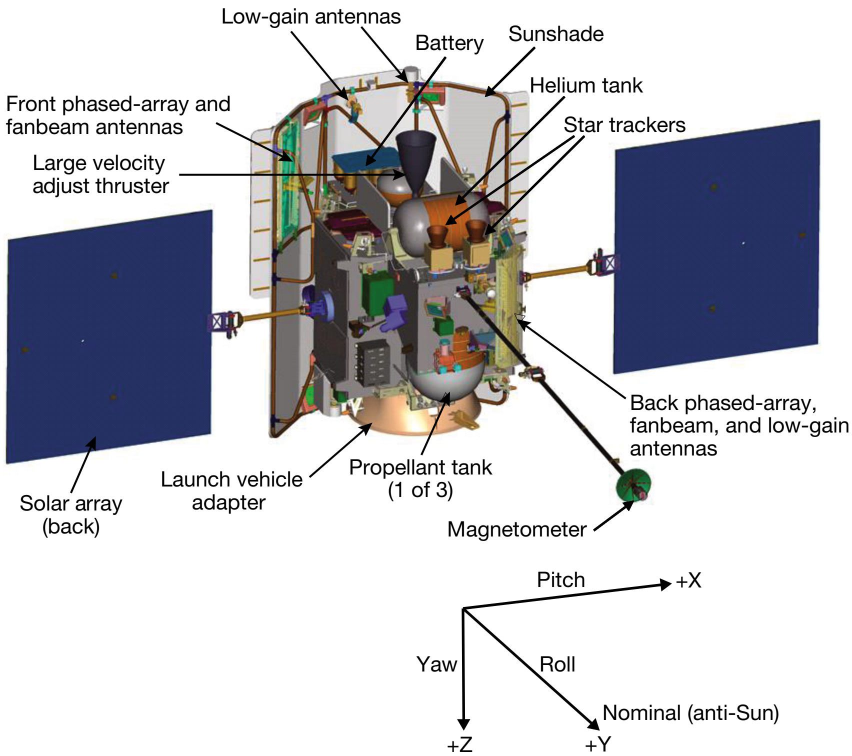

Figure 7. MESSENGER spacecraft and spacecraft coordinate system.

(Fig. 5). This drift caused the first hot season in each Mercury year gradually to become hotter, because periapsis moved northward and eventually switched to the dayside of the planet during this season, and the second hot season to become less hot. The heating of the planet-facing side of the spacecraft (a side mostly insensitive to specific spacecraft maneuvers) by (IR) radiation from the planetary surface for Mercury years 3, 10, and 17 is shown in Fig. 6, illustrating that the heating increased with time in the first season and decreased in the second, as indicated by the arrows on the figure. The orbit average heating increased slightly with successive Mercury years because of the decrease in the orbit period and general lowering of the periapsis altitude.

Spacecraft Thermal Control System

The MESSENGER thermal control system was very robust, protecting the spacecraft from the severe and changing thermal environment while in Mercury orbit. The spacecraft had a ceramic-cloth sunshade (Fig. 7), which protected most components from the intense solar heating. Other components, such as the solar arrays, were specially designed to survive high temperatures. During noon–midnight orbits, the spacecraft passed between Mercury and the Sun, which exposed components behind the sunshade to the substantial, but transient, IR heating from the planet. Figure 7 shows the heat rates on the ±X and ±Z faces of the spacecraft versus OTA during a portion of a typical orbit in Mercury year 17 near the peak of the first hot season. The default orientation of the spacecraft was to orient the adapter ring (+Z face) toward the planet so that remote sensing instruments could collect data, which resulted in higher heating on this face. The planetary heating on the top deck (–Z) is shown in Fig. 8 to be largely attenuated as a result of this orientation, which is why temperature-sensitive components such as the battery were located on the top deck. Components with dedicated radiators on the +X face were protected by the use of diode heat pipes, which effectively stopped conducting when the radiator surface became hot and resumed normal operation when the radiator cooled, thereby protecting the electronics from the transient heat pulse. In general, this thermal control approach worked extremely well; however, there were exceptions that caused deviations from the original operational plan and required attitude adjustments, additional monitoring, and modeling. Three of these components, namely the FPAA, battery, and solar arrays, are highlighted in this article.

Thermal Process for Temperature Predictions

Although extreme, variable, and coupled with the operation of the MESSENGER spacecraft, the thermal environment of MESSENGER was proven to be quite predictable if all contributions to heating were considered. Initially, commercial thermal software was used to calculate the environmental heating and make predic-

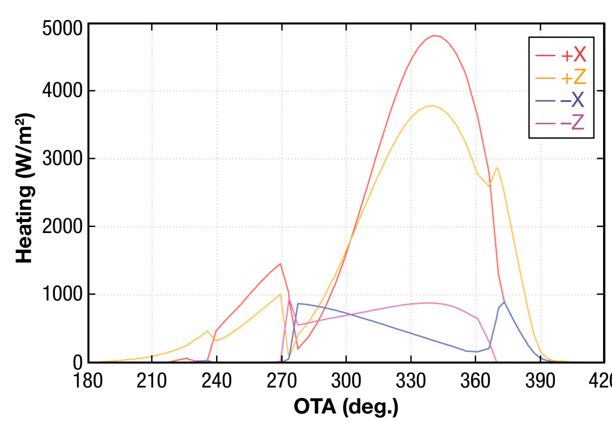

Figure 8. MESSENGER spacecraft heating rates.

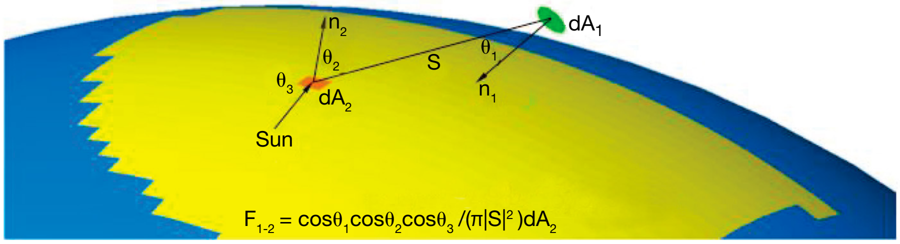

Figure 9. Planetary IR and reflected solar calculations.

For most spacecraft components, heating on the main faces of the spacecraft was sufficient to predict their thermal response. For others that were nestled somewhat inside the spacecraft structure, such as the battery and FPAA, blockage from the surrounding structure is critical to understanding their thermal response. A look-up table was created for each surface using ray-tracing techniques to determine how much radiation was blocked for each planet element in the numerical integration of the planetary IR heating. As an example, the blockage look-up table for the +Z surface of the FPAA is shown graphically in Fig. 10. Incident rays indicate directions that are not blocked by other spacecraft surfaces.

tions for the spacecraft. However, the need to include more detail from the Mercury heating environment coupled with the higher resolution and longer simulation times quickly became prohibitive to set up and execute. For this reason heating and temperature predictions for the spacecraft were transitioned to custom algorithms. All planned maneuvers and science observations were run through this thermal process to ensure the operational health and safety of the spacecraft.

The key environmental heating inputs for the MESSENGER spacecraft are the direct solar and planetary IR emissions, which depend on the solar vector and the position of the spacecraft over the planet surface. The IR heating on each spacecraft face was calculated using numerical integration of the temperature distribution, as shown in Fig. 9. Planetary surface properties, temperature, and solar heating were applied on a per-element basis, and the individual element contributions were summed to obtain the total value.

A wrapper program took a series of orbit positions, attitudes, and solar vectors (provided by Choo et al.[2]), passed it to the heating algorithm, and calculated planetary IR and direct solar heating on a number of positions and orientations of the spacecraft. Because some temperature calculations needed heating specified at fine intervals (down to ≤10 s), and simulations sometimes spanned a Mercury year or longer, the number of time steps for a given scenario might be in the millions. However, heating calculations are independent across time steps, and once implemented on a graphics processing unit, the execution time for the heating code was improved >500 times compared with the serial version of the code. This improvement proved to be crucial for MESSENGER, enabling full-Mercury-year and Monte Carlo analyses to be done in minutes, as opposed to weeks or months. It should be noted that the capital investment for this type of capability is hundreds of dollars (for a reasonable graphics processing unit, given that a computer is already available to host it). The heating calculation process itself can be tailored to the type and format of the input provided, so no additional labor was required for the interface, in contrast to the situation with commercial codes (analyses for which can take considerable time to set up, run, and post-process).

Thermal Management of FPAA, Battery, and Solar Arrays

During the MESSENGER hot seasons, the FPAA was protected by rotating the +Z axis of the spacecraft off nadir during the hottest portion of the orbit. As the orbit geometry continued to change and the spacecraft began to see conditions outside of its original design envelope, the FPAA temperatures reached up to 168°C in flight (the solder of the feed assembly would have melted around 180°C). Spacecraft attitudes favorable to the FPAA were unfavorable to the XRS SAX instru-

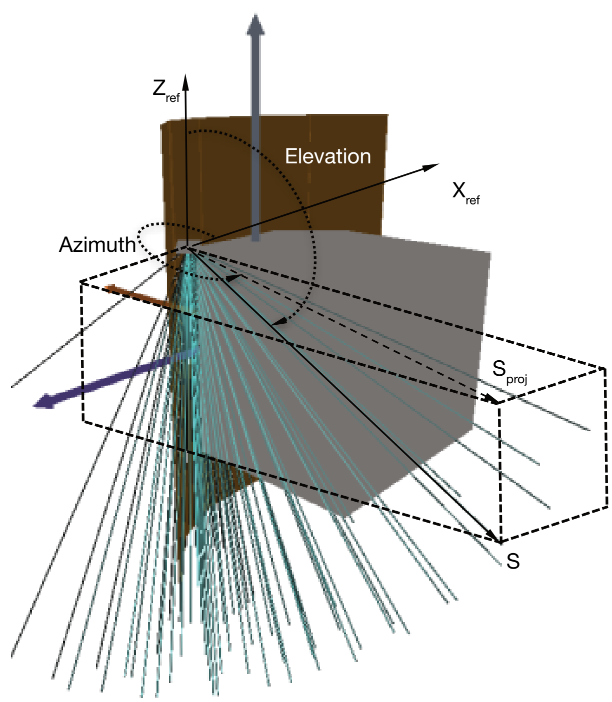

Figure 10. Blockage vectors for the FPAA.

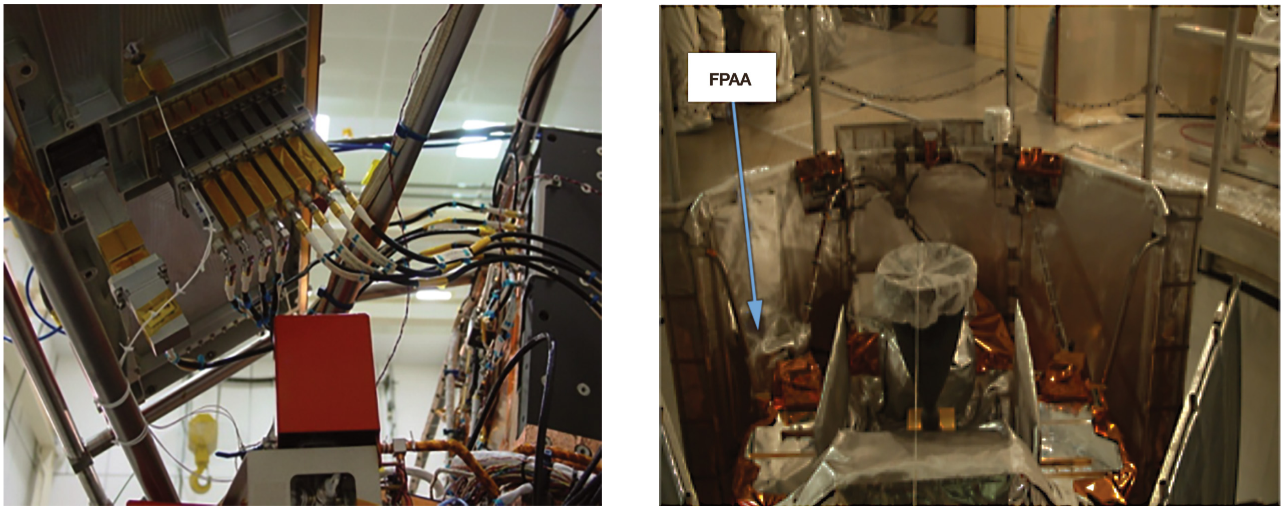

Figure 11. FPAA signal feeds (left) shown before integration with the spacecraft. The FPAA is shown integrated into the spacecraft with thermal blankets applied (right).

ment, which complicated the thermal mitigation for the FPAA, and a balance had to be struck while still maximizing science return. To solve this problem, a thermal model was created for the portion of the FPAA in question (inside of the sunshade, shown in Fig. 11), which was very lightweight and thus responded very quickly to its environment. Blockage of the spacecraft and sunshade to environmental heating on its bottom (+Z) and side (–X) surfaces was critical for making accurate temperature predictions, and was included in the thermal model process (close agreement with flight data is shown in Fig. 12).

Packaged directly behind the sunshade on the –Z deck, the MESSENGER battery consisted of 11 two-cell NiH_2 common pressure vessels (Fig. 13) attached to a space-facing radiator for heat rejection. Although the battery placement provided ideal protection from Mercury's dayside when in orbit, it actually received detectable heat input from the back of the sunshade, either from solar heating on the front side or from planetary IR heating on the back. Because the battery was critical to the mission and had relatively tight temperature constraints, a thermal model, consisting of a node each for the radiator and the cells, was created that took into account the thermal environment and electrical dissipation and correlated with flight data. Blockage from the sunshade was included in the environmental heating on the battery radiator surface, along with a thermostatic heater (sensor on the battery cells as in the actual design implementation). The internal dissipation of the battery was very active and could be exothermic or endothermic at times very close to one another, so the power team provided the internal dissipation profile as a function of time. The battery tended to get warmer for orbits that were favorable to FPAA, but because it was so heavy, it responded to its heating environment slowly and typically took multiple orbits for temperatures to ratchet up during the peak of the season.

As shown in Fig. 13, the battery temperature predictions agree fairly well with the flight data, gener-

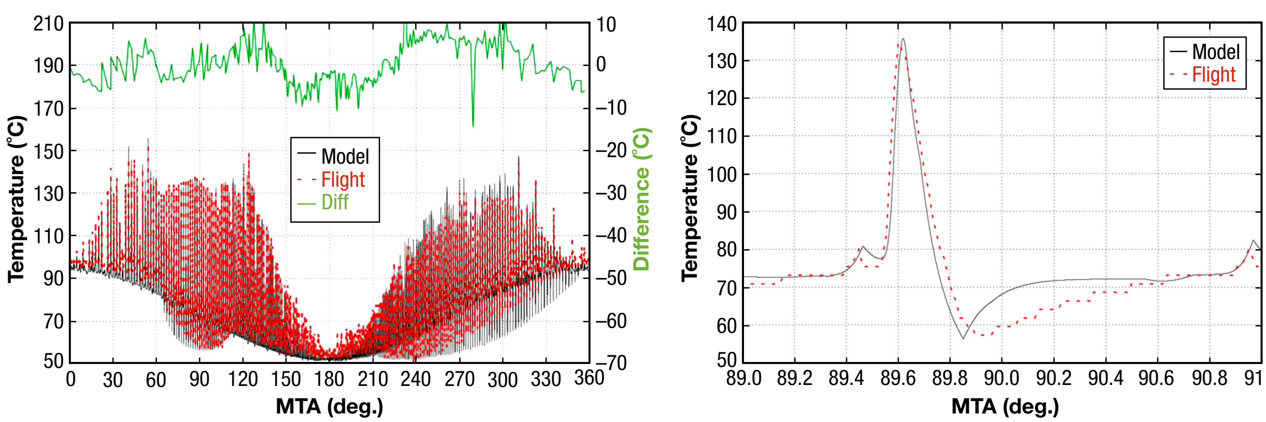

Figure 12. FPAA temperature predictions compared with flight data for Mercury year 16 (left) and for one orbit near MTA 90° in Mercury year 16 (right).

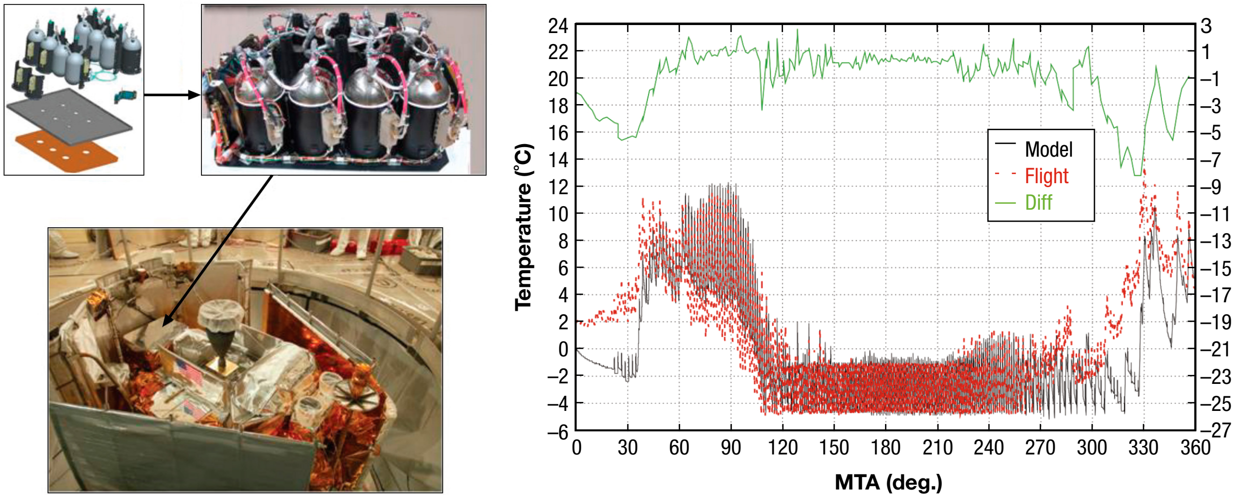

Figure 13. MESSENGER battery with predicted and observed temperatures.

ally within 5°C for the peaks of each orbit, for Mercury year 16. With this predictive capability, science operations outside of the mission objectives and nominal plan (such as observations of the comets Encke and ISON) were possible. Such observations would have otherwise been disallowed because of risks to the battery.

The solar arrays each had a 2:1 ratio of optical solar reflectors to triple-junction gallium-arsenide solar cells,[3,4] as shown in Fig. 14, and were managed throughout the Mercury year by pointing them off the Sun by a prescribed amount that increased with solar heating (because of the eccentric orbit of Mercury). The solar arrays also received planetary IR heating near Mercury, potentially on both sides, and during the peak of the hotter seasons the solar arrays were commanded to point far off the Sun for a short time to mitigate this transient heat pulse. In later Mercury years, to pre-cool the solar arrays, they were pointed more off the Sun than during normal operations for ~1 h before orbital peak heating. The solar array commanding was determined using a thermal model of the arrays for every Mercury year.

The solar array thermal model consists of a flat plate, with environmental heating calculated on both sides, rotated about the spacecraft X axis to the prescribed Sun offset for a given time step. The model can also find just-in-time offset values to keep the solar array temperatures within a specified temperature limit to enable definition of the MTA, OTA, and offset values that should be used for a given thermal season, spacecraft trajectory, and attitude plan. The offset times required to keep the arrays within limit during Mercury year 16 is shown in Fig. 14, plotted as OTA versus MTA values. The corresponding magnitude of the Sun offset values as a function of MTA values are also indicated in the figure.

Thermal Management of Instruments

MESSENGER's instruments used many unique design concepts to survive the extreme environment anticipated during the orbital phase of the mission and achieve their scientific objectives. The extremes of the initial Mercury orbit geometry and later conditions (the change to an 8-h period and the shifting argument of periapsis) challenged some instrument designs more than predicted in the design phase. The thermal analysis process was improved to address these issues, and

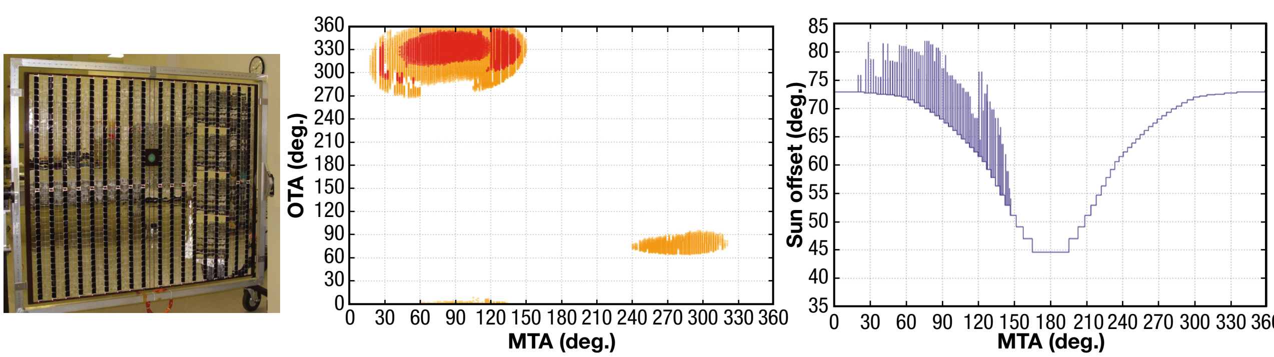

Figure 14. MESSENGER solar array and off-pointing plan.

spacecraft attitude and instrument power states were identified as a way to control temperatures.

Idealized orbits in the design phase kept the spacecraft +Z axis toward the center of the planet as a default orientation, allowing the directional instruments inside of the adapter ring to take measurements of their target, but necessary operations such as limb scans, calibrations, off-nadir pointing, and downlink attitudes resulted in variations to the thermal environments. The instruments' observed dependence on spacecraft attitude highlighted the importance of monitoring planned spacecraft maneuvers and limiting planetary exposure of sensitive surfaces. Because off-nadir pointing was unavoidable, examination of the expected heating rates in each command load became an important strategy to avoid unexpected temperature peaks while enabling necessary maneuvers.

A typical instrument orbital response to high heating rates was a sharp increase followed by an approximately exponential decay in temperature toward a steady-state level that may never be reached because of either the long instrument thermal time constant or the response of a heater. In small, light instruments (e.g., SAX), the decay was rapid, with equilibrium temperatures obtained within a short period of time (e.g., ~3 h after the peak heating event). For these instruments, no change in peak temperature was seen from the change to an 8-h orbit. Other instruments reacted more slowly, with temperatures continuously cooling until the next heating pulse caused another jump in temperature. Many of the instruments, such as MASCS, were powered off to avoid the periods of highest heat flux during the hot season, although power system limitations drove some of this instrument inactivity. The resulting decrease in internal dissipation reduced instrument temperatures and allowed passage through the extremes while maximizing science returns. The Mercury Laser Altimeter (MLA) successfully completed the primary mission but experienced laser degradation from firing at temperatures >30°C. An autonomy rule was added to prevent laser activity at greater than 30°C, which prolonged instrument life. The combination of the new limit, increasing heating rates, and the 8-h orbit would have resulted in many orbits with no MLA science, but with the improved thermal management scheme the instrument was cooled below its operating temperature so that the laser could still be fired near periapsis when peak heating occurred.

POWER MANAGEMENT

The MESSENGER orbit geometry, Mercury thermal environment, and degradation of optical properties presented increasingly difficult power management challenges for the spacecraft as the mission progressed.

Power System Topology

The MESSENGER power system implemented an unregulated topology with a battery-dominated bus and peak-power tracking capabilities. Eight parallel current-mode control buck converters delivered solar array power to the spacecraft power bus. The duty cycle of the converters, and therefore the solar array operating voltage, was established by three control loops. The first control loop was a peak-power tracking loop that adjusted the solar array voltage to operate at the maximum power point of the array. The second was a battery charge current loop that adjusted the operating point to maintain a selected battery charge current. The third was a battery voltage loop that adjusted the operating point to maintain a temperature-compensated battery voltage. All loops operated continuously, and the loop with the largest error signal dominated. Generally the system operated in the current-limit mode.

Solar Array Management

The solar array generated electricity for the spacecraft. Management in the Mercury environment required both that acceptable temperatures be maintained and that sufficient power be generated using only a single variable: the rotational position of the arrays relative to the Sun. Positions with lower rotational offsets generated more power but also resulted in higher operating temperatures.

Steady-State Management

Limits on array rotational position were established for steady-state operation. The lower bound ensured that solar array temperatures remained below target limits. The upper bound ensured that sufficient power was generated to support spacecraft operations, including battery recharge. These limits, which varied with solar distance, were reviewed prior to each eclipse season. Arrays were

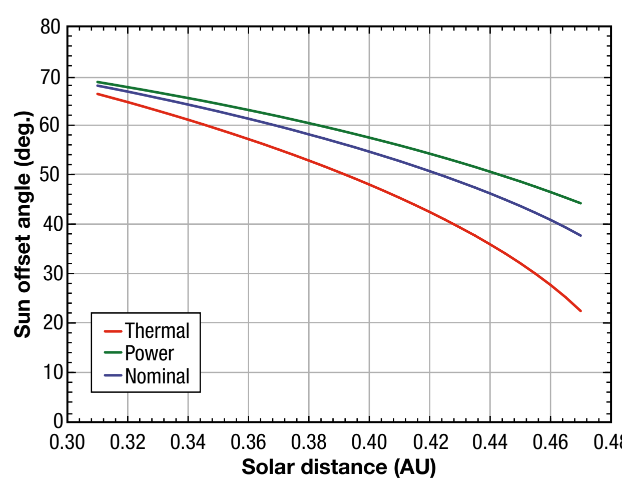

Figure 15. MESSENGER solar array offset limits vs. solar distance in April 2014.

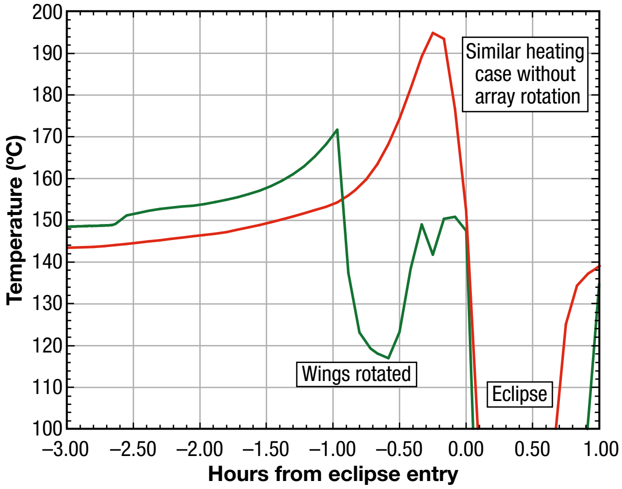

Figure 16. MESSENGER solar array temperature with and without pre-cooling.

periodically characterized (power and temperature measurements at controlled conditions) to support the limit updates. The G&C team managed the array position to the limits as part of the weekly command load activities. Figure 15 presents the limits in use in April 2014.

The solar array performance degraded during the mission. Both the optical properties and the conversion efficiency declined, resulting in increased array temperatures and reduced power generation. Over time the power and thermal limits converged at low solar distances, significantly reducing the flexibility to select array offset angles.

Transient Management

As discussed above, the solar array was routinely exposed to transient planetary heating. To limit temperature excursions during these periods, the array rotational offset was increased from the steady-state angle to reduce the solar heating. Offset angles from 75° to 90° (no illumination) were used during the mission. During the rotational periods, it was necessary to supplement solar array power production with a battery discharge. The transient rotational offset angles were selected to limit the transient temperature to 180°C, although it was necessary to raise the limit beyond 200°C during a low-periapsis-altitude campaign near the end of the mission. As with the steady-state limits, the transient offsets were reviewed in planning for each eclipse season.

As the environmental conditions became more challenging, the use of a third rotational offset was introduced. The "pre-cooling" angle implemented a rotational offset between the steady-state and planetary heating angles. The pre-cooling condition essentially established a lower-temperature steady-state power limit capable of spacecraft operations without battery recharge. The arrays were moved to the pre-cooling angle 1 h before the planetary flyover (after the battery was recharged), reducing the starting temperature for the transient heating. Figure 16 illustrates array temperatures during planetary heating events both with and without pre-cooling implemented.

Battery Management

The battery provided the energy to operate the spacecraft during periods of eclipse and solar array planetary heating described above. Management during the orbital mission focused on limiting both the depth of discharge and the temperature excursions during planetary heating. This procedure was adopted not only to maximize battery health but also to avoid tripping autonomy rules that would cause a safe hold transition ("low state of charge" and "battery over-temperature"). As noted earlier, operation of the vehicle in the safe-hold or Earth-acquisition modes would have presented a variety of challenges during the extended mission.

The deepest discharges occurred during seasons with both eclipses near apoapsis and with significant solar array planetary heating. The battery was discharged twice per orbit under such conditions, with limited recharge between the discharges, as illustrated in Fig. 17. The spacecraft payload was shut down as a precaution (to minimize depth of discharge) during the first orbital eclipse/heating periods. This practice was later terminated, as both analyses and observations showed it to be unnecessary.

A depth of discharge limit of 55% was adopted early in the mission, providing some margin to the 60% threshold at which autonomy would initiate the safe mode transition. In flight this limit was never reached; the maximum observed depth of discharge was about 45%.

Battery temperatures were driven both by internal dissipation and by external environmental heating as described above. A closed-loop analysis cycle was established that coupled battery depth of discharge analyses with thermal analyses to predict battery peak temperatures; the resulting temperature predictions are presented in the Thermal Management of FPAA, Battery, and Solar Arrays section.

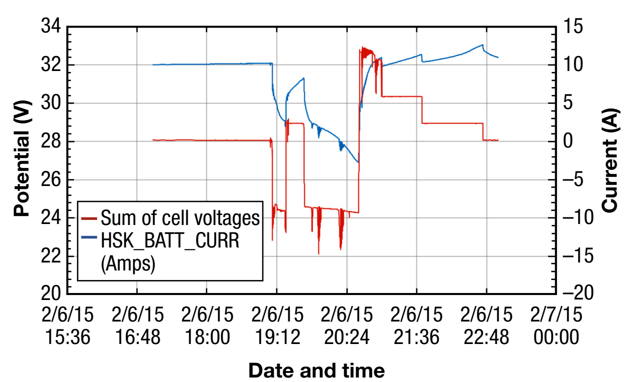

Figure 17. MESSENGER battery discharge.

CONCLUSION

Enhanced engineering support of the MESSENGER spacecraft allowed the operations team to optimize planned spacecraft maneuvers for maximized science return while mitigating risks to the spacecraft and its instruments. The thermal environment of Mercury is extreme and for the MESSENGER mission was highly coupled with the operation of the spacecraft, but the thermal design of the spacecraft was robust and continued to yield nominal results throughout the mission. This dynamic thermal situation required constant vigilance on the part of the engineering team but also created the opportunity to tie in predictions of the spacecraft with the operational plan to enhance the scientific return from this NASA-sponsored mission.

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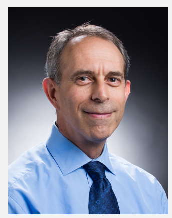
G. Allan Holtzman, Space Exploration Sector, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Allan Holtzman holds a B.S. in aerospace engineering and an M.S. in mechanical engineering from the University of Texas at Austin and is a Senior Professional Staff member at APL. He served as the Lead Spacecraft Thermal Engineer for MESSENGER from the extended mission phase to the end of orbital operations. He is currently working on the Parker Solar Probe mission. His e-mail address is allan.holtzman@jhuapl.edu.

Andrew B. Calloway, Space Exploration Sector, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Andrew B. Calloway is a member of the Principal Professional Staff in APL's Space Exploration Sector. He has 24 years of experience in space operations as of 2017, including geostationary Earth orbit, low Earth orbit, and planetary missions. He was the Mission Operations Manager for MESSENGER from 2007 through end of mission in April 2015 and a core team member of New Horizons through the Pluto flyby encounter. He continued exploring the solar system when he joined the OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer) team in April 2016, supporting the mission to return samples from asteroid Bennu as the Mission Operations Manager. His e-mail address is andrew.calloway@jhuapl.edu.



Stephen E. Jaskulek, Space Exploration Sector, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Stephen E. Jaskulek received his B.S. degree in electrical engineering from Washington University in 1979 and a M.S. in computer science from Johns Hopkins in 1986. A member of the Principal Professional Staff at APL, he has been a member of the Space Instrumentation Group of the Space Exploration Sector since 1981. Steve has extensive experience in the design, fabrication, testing, and integration of space instrumentation, and he has been the systems engineer on numerous energetic particle instruments. He was the systems engineer for instruments on the NASA Cassini mission at Saturn and for two instruments within the Particle Environment Package (PEP) suite of the European Space Agency's upcoming JUpiter ICy Moons Explorer (JUICE) mission to Jupiter's satellites. His e-mail address is steve.jaskulek@jhuapl.edu.

Daniel T. Gallagher, Space Exploration Sector, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Daniel T. Gallagher is a Principal Professional Staff member in APL's Space Exploration Sector. He has worked in spacecraft power for over 30 years, most recently on APL's MESSENGER, Van Allen Probes, and DART missions. He holds an M.S. from Princeton University and a B.S. from the University of Delaware, both in electrical engineering. His e-mail address is daniel.gallagher@jhuapl.edu.