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MESSENGER MERCURY ORBIT TRAJECTORY DESIGN

James V. McAdams*

MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Ranging) will be the first spacecraft to orbit the planet Mercury when this NASA Discovery Program mission begins its one-year Mercury orbit phase in April 2009. Science goals, the spacecraft's thruster locations, sunshade orientation constraints, and a requirement that all maneuvers be observable from Earth are a few of the many design considerations for Mercury orbit-insertion and all subsequent orbit-correction maneuvers. In addition to providing details of each planned trajectory-altering maneuver, this paper will summarize trajectory perturbation effects of solar radiation pressure on both fixed and variable Sun-relative spacecraft attitude. A brief overview of recovery options for delayed implementation of Mercury orbit insertion demonstrates the spacecraft trajectory's resiliency in the event of major anomalies.

INTRODUCTION

After nearly three decades of Mercury orbiter spacecraft mission studies, recent improvements in ballistic trajectory design and spacecraft technology opened the door to low-cost mission options. These mission studies lowered Mercury orbit-insertion propellant requirements by utilizing Venus gravity assists in the 1970s[1, 2, 3, 4] and by adding a reverse ΔV-gravity assist using Mercury flybys in the 1980s[5,6,7]. The most recent improvements in ballistic trajectory optimization, using up to five Mercury flybys[8] and improving Venus-to-Venus phasing to enhance the benefit from Venus gravity assists[9], offered significant reduction in onboard propellant requirements. MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Ranging) is the first ballistic Mercury orbiter mission to combine the newest of these trajectory improvements[10,11], thereby enabling a robust scenario for orbit insertion into an orbit consistent with Mercury science goals.

The MESSENGER spacecraft, currently planned for launch during a 20-day window beginning 10 March 2004, utilizes two Venus flybys and two Mercury flybys during its 5.1-year journey along a ballistic trajectory (Figure 1) to the planet Mercury. MESSENGER, NASA's seventh Discovery Program mission, draws leadership from the Carnegie Institution of Washington and The Johns Hopkins University Applied Physics Laboratory (JHU/APL). A consortium including various NASA centers, numerous industry partners, and many educational and research institutions completes the MESSENGER Team. Launch from Florida's Cape Canaveral Air Force Station requires use of a Delta II 7925H expendable launch vehicle, which offers the heaviest mass-to-orbit capability allowed for Discovery missions. With a capable science payload, a design that keeps much of the spacecraft near room temperature despite an extreme thermal environment, and an initial 55% propellant mass fraction, the spacecraft needs this maximum lift capability. At its first flyby of Mercury in July 2007, MESSENGER will be the first active spacecraft to visit Mercury in more than 30 years. In April 2009 MESSENGER will become the first spacecraft to orbit Mercury. The nominal mission plan includes one-year of orbital operations at Mercury.

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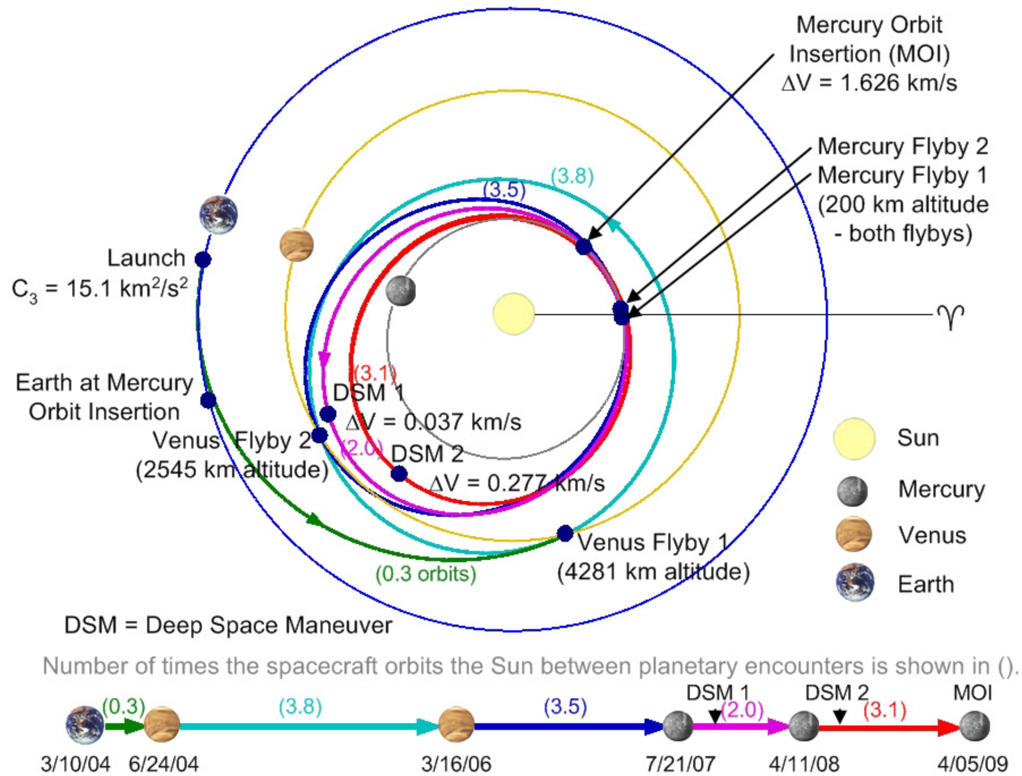

Figure 1 North Ecliptic Pole View of MESSENGER's Heliocentric Trajectory

Science objectives play a major role in establishing the trajectory and orbit maneuver design for the Mercury orbit phase. The spacecraft's orbit and the one-year Mercury orbit duration were chosen to address six scientific questions, and to minimize risk in completing the spacecraft operations necessary to achieve all science objectives. The two Mercury flybys prior to Mercury orbit insertion provide the opportunity for imaging portions of Mercury's surface under desired lighting conditions not present during the Mercury orbit phase. Brief descriptions of the function and location of each science instrument, together with sample spacecraft science-mode pointing for various orbit geometries, are summarized later in this paper.

The spacecraft's design and operational limitations further influence the selection and maintenance of the primary science orbit at Mercury. Only those aspects of the physical spacecraft that directly affect the size and orientation of the orbit or propulsive maneuvers will be discussed. The MESSENGER spacecraft combines carefully selected advanced technologies, minimal moving parts, and a design philosophy that values simple, proven techniques. Key aspects are a ceramic-cloth sunshade, a dual-mode (bipropellant-monopropellant) propulsion system, two rotating solar arrays, three-axis stabilization, and a versatile telecommunications system. In addition, a 23-Ah NiH_2 battery will provide power during eclipses of up to an hour.

Key aspects of mission design during Mercury orbit phase include designing Mercury orbit insertion, all orbit correction maneuvers, and accurately predicting the orbit's evolution. Since the spacecraft will likely perform all deterministic maneuvers using thrusters mounted on a single deck of the spacecraft bus, timing and orientation of each maneuver are most critical. The sunshade must protect the spacecraft from direct sunlight, while the solar arrays tilt away from the Sun to provide sufficient power without solar cells overheating, and one of the omni-directional antennas will provide acceptable downlink margin for monitoring the maneuver from Earth. Representation of the spacecraft with a number of flat plates (each with appropriate surface reflectance and orientation), including attitude articulation for solar array tilt, Mercury science observations, and daily data downlink all provide the ingredients for a high-precision propagator to generate a reliable record of predicted spacecraft attitude. The effect of major trajectory perturbations on key trajectory parameters will be briefly summarized.

SCIENCE REQUIREMENTS

Except for Mercury, all the inner planets have been explored by more than one spacecraft. In our solar system, only Pluto has been studied less than Mercury. During its three flybys of Mercury in 1974 and 1975, Mariner 10 imaged about 45% of the surface at an average resolution of about 1 km and < 1% of the surface at better than 500-m resolution[12,13]. As our solar system's innermost planet, Mercury has the highest known metal-to-silicate ratio of any planet or satellite in the solar system. This observation, coupled with the determination of surface composition from analysis of MESSENGER science data, may provide a unique window on the processes by which planetesimals in the primitive solar nebula accreted to form planets.

The MESSENGER mission was designed to address six important scientific questions[14]. The answers to these questions, which will offer insights far beyond the expansion of our knowledge of the planet Mercury, are the basis for the following science objectives.

1. Map the elemental and mineralogical composition of Mercury's surface.
2. Image globally the surface at a resolution of hundreds of meters or better.
3. Determine the structure of the planet's magnetic field.
4. Measure the libration amplitude and gravitational field structure.
5. Determine the composition of radar-reflective materials[15] at Mercury's poles.
6. Characterize exosphere neutrals and accelerated magnetosphere ions.

In order to decrease mission cost significantly with the goal of maximizing science return, the MESSENGER study team chose a mission scenario with only one Mercury orbiter spacecraft in a low-maintenance orbit and no surface landers. During the last 15 years, space agencies around the world have invested heavily in studies of "comprehensive" Mercury orbiter missions that often require advanced propulsion, two orbiting spacecraft, and sometimes a lander or surface penetrator. Such Mercury orbiter mission studies[7,16,17], while eloquent, encountered numerous obstacles that prevented either selection or full funding from space agencies.

This intent on maximizing science return using a single spacecraft with a maximum amount of proven technologies formed the basis for the development of the seven-instrument MESSENGER science payload[18]. Complementary to the 50-kg, 84-W, seven-science-instrument payload is the X-band transponder, the key spacecraft component for radio science. Table 1 lists the name and acronym of each science instrument, as well as their primary purpose(s) or measurement objective. Figure 2 shows the location on the spacecraft (not shown in true color) of most of these science instruments, in or near the payload adapter ring. Table 2 shows how science objectives map into mission design requirements for MESSENGER's primary science orbit. Figure 3 depicts the resulting primary science orbit in the context of both science requirements and Sun-spacecraft geometry effect on science acquisition.

Table 1

SCIENCE PAYLOAD INSTRUMENTS AND OBJECTIVES

Science Instrument Name	Acronym	Primary Measurement Objectives
Mercury Dual Imaging System	MDIS	map Mercury's surface in visible wavelengths
Gamma-Ray and Neutron Spectrometer - Gamma-Ray Spectrometer - Neutron Spectrometer	GRNS GRS NS	measure surface elemental abundances; detect polar water ice deposits
X-Ray Spectrometer	XRS	determine element composition of Mercury's surface by solar-induced X-ray fluorescence
Magnetometer	MAG	measure magnetic field of Mercury
Mercury Laser Altimeter	MLA	measure libration of Mercury and topography of northern hemisphere
Mercury Atmospheric and Surface Composition Spectrometer - Ultraviolet-Visible Spectrometer - Visible-Infrared Spectrograph	MASCS UVVS VIRS	measure surface reflectance and exospheric particle emissions during Mercury limb scans
Energetic Particle and Plasma Spectrometer - Fast Imaging Plasma Spectrometer - Energetic Particle Spectrometer	EPPS FIPS EPS	examine volatile ion species in and around Mercury's magnetosphere

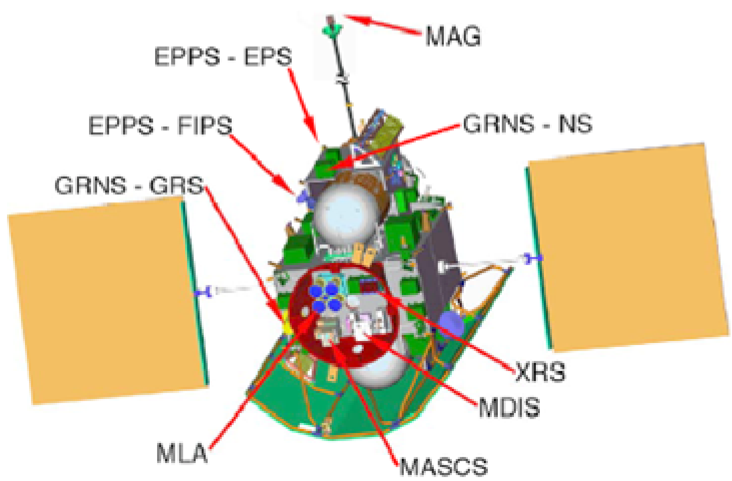

Figure 2 Science Instrument Locations on the MESSENGER Spacecraft

Additional details for MESSENGER's imagers[19] (MDIS) directly influence primary science orbit definition. The 10.5º wide angle (WA) field-of-view (FOV) imager and the 1.5º narrow angle (NA) FOV imager are mounted on opposite sides of a pivoting platform. MDIS is MESSENGER's only moveable instrument. MDIS can point from 50º toward the Sun to nadir, where it is coaligned with the other instruments, to 40º anti-sunward. The NA imager pixel field ranges from 5.2 m to 390 m at periherm and apoherm of the 200-km altitude by 12-hour period primary science orbit. The corresponding WA imager pixel field range is 72 m to 5.4 km.

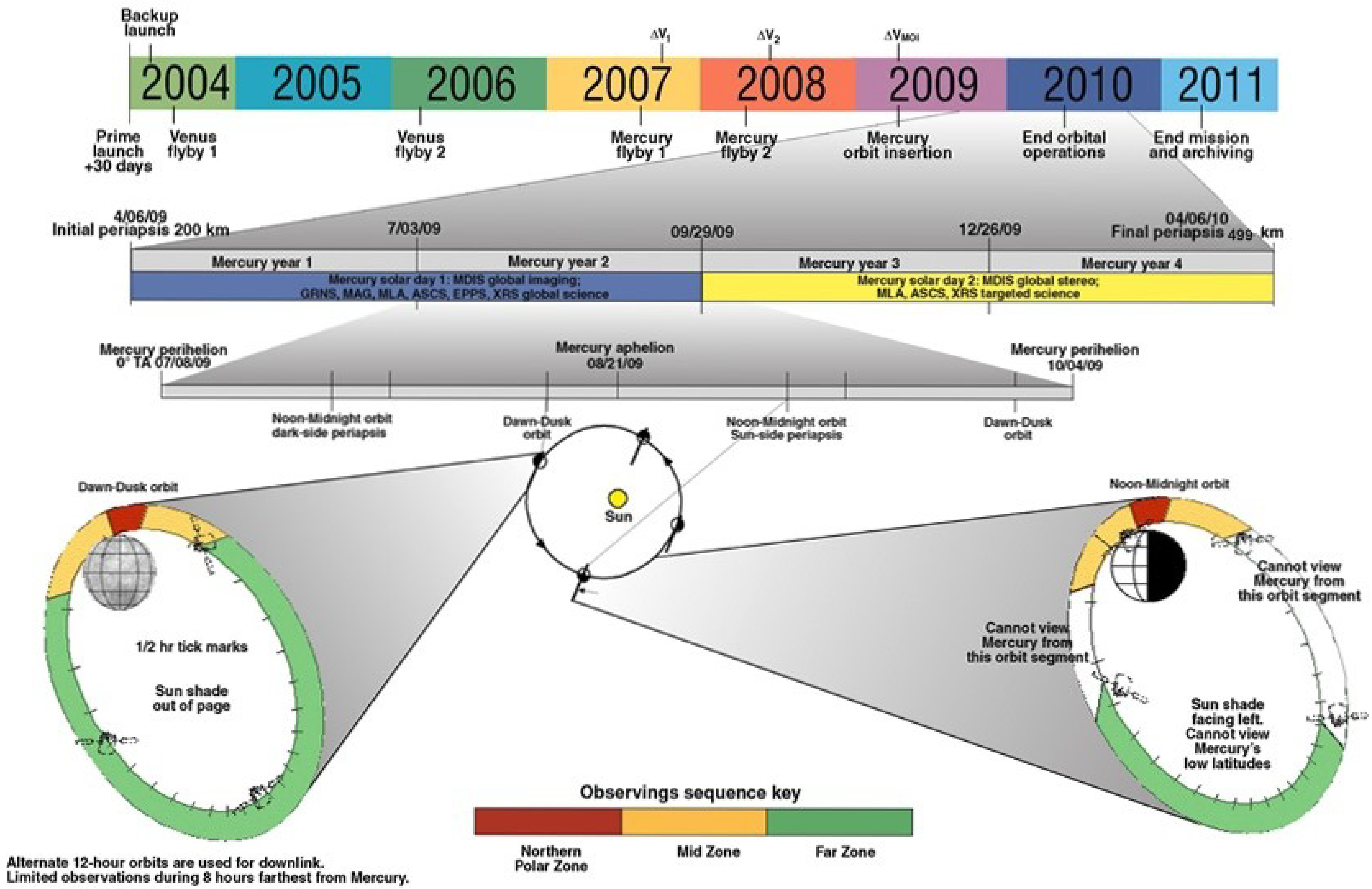

Figure 3 MESSENGER Timeline Shows Mission Implementation

Table 2

EFFECT OF SCIENCE OBJECTIVES ON MERCURY ORBIT DESIGN

Science Measurement Objectives	Mission Design Requirements	Mission Design Features
Globally image surface at 250-m resolution	Provide two Mercury solar days at two geometries for stereo image of entire surface; near-polar orbit for full coverage (MDIS)	Orbital phase duration at one Earth year with periapsis altitude controlled to 200-500 km; 80° - inclination orbit
Determine the structure of Mercury's magnetic field	Minimize periapsis altitude; maximize altitude-range coverage (MAG)	Mercury orbit periapsis altitude from 200-500 km, apoapsis altitude near 15,200 km for 12-hour orbital period
Simplify orbital mission operations to minimize cost and complexity	Choose orbit with period of 8, 12, or 24 hours	
Map the elemental and mineralogical composition of Mercury's surface	Maximize time at low altitudes (GRNS, XRS)	
Measure the libration amplitude and gravitational field structure	Minimize orbital-phase thrusting events (RS, MLA)	Orbital inclination 80°; periapsis latitude drifts from 60°N to 69°N; primarily passive momentum management; two orbit-correction ΔVs (18 hours apart) every 88 days
	Orbital inclination 80°; latitude of periapsis near 60°N (MLA, RS)	
Determine the composition of radar-reflective materials at Mercury's poles	Orbital inclination 80°; latitude of periapsis maintained near 60°N (GRNS, MLA, ASCS, EPPS)	
Characterize exosphere neutrals and accelerated magnetosphere ions	Wide altitude range coverage; visibility of atmosphere at all lighting conditions	Extensive coverage of magnetosphere; orbit cuts bow shock, magnetopause, and upstream solar wind

SPACECRAFT OPERATIONAL CONSTRAINTS

Although science objectives play a major role in determining the desired spacecraft orbit at Mercury, spacecraft design and operation must be carefully coordinated to ensure that the final orbit choice is achievable, low risk, and maintainable. During MESSENGER's early design phase much attention focused on spacecraft orbit geometry with respect to Earth, Mercury, and the Sun during both coast and maneuver portions of the spacecraft orbit. This geometrical data affected design and operational limitations of certain spacecraft subsystem hardware. Figure 4 establishes the context for spacecraft operational constraints by depicting the location and orientation of major spacecraft components.

Since the spacecraft is 53% to 70% closer to the Sun than Earth during Mercury orbit phase, the spacecraft's thermal subsystem had the greatest number of issues directly related to spacecraft trajectory design. The difference between the Sun's radiation on the spacecraft at Earth and while at Mercury is 4.7 times at Mercury aphelion and 11.1 times at Mercury perihelion. Even though it is desirable to obtain uniform global mapping of Mercury's surface, a circular orbit around Mercury would subject the spacecraft to an unmanageable thermal environment[20]. The shape and orientation of the 200-km by 12-hour orbit are conducive to orbit stability (periherm altitude increases, but orbit period is almost constant) and thermal manageability. Thermal analysis of the spacecraft's orbit at Mercury revealed worst-case thermal conditions for the sunshade, thermal blankets, solar arrays, and science instruments[21] (Figure 5). Results of this thermal analysis helped produce the spacecraft orbit constraint on longitude of the ascending node, i.e., throughout the orbit phase longitude of ascending node must lie between 248º and 360º or between 0º and 73º. This constraint effectively places the spacecraft orbit periherm near the day/night terminator or on Mercury's night side when Mercury is closest to the Sun.

Another thermal requirement on ΔV orientation relative to the Sun direction ensures that the sunshade protects the spacecraft bus from direct sunlight exposure during propulsive maneuvers. All deterministic (those with pre-launch knowledge of spacecraft attitude requirements) ΔVs use either the large velocity adjust (LVA) bipropellant thruster and/or two to

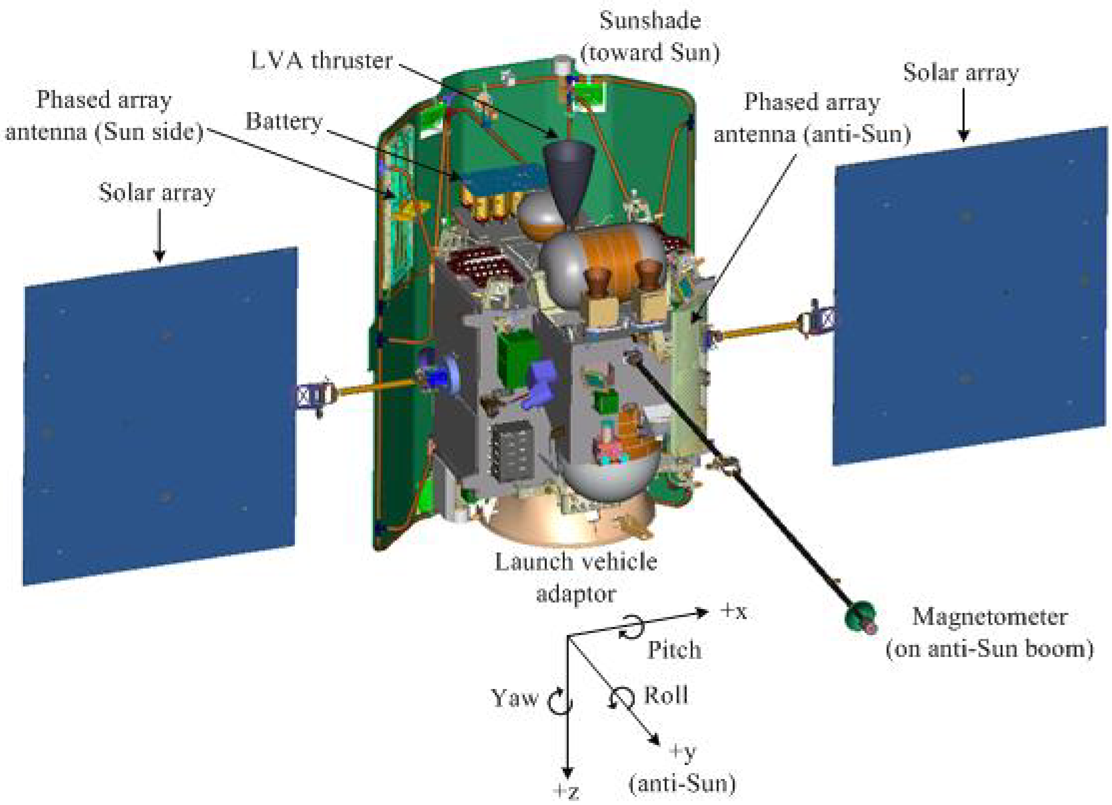

Figure 4 Deployed Configuration of the MESSENGER Spacecraft

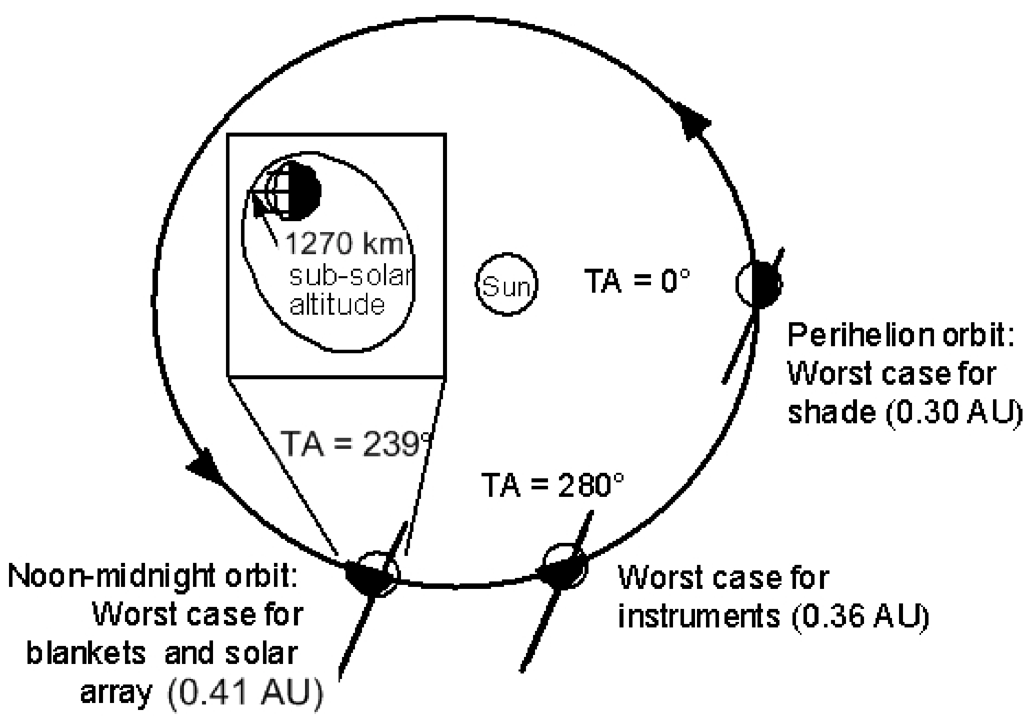

Figure 5 Orbit at Mercury showing Worst-Case Thermal Conditions

four of the thrusters mounted on the same deck as the LVA thruster. Figure 4 clearly shows a 90º orientation offset between the LVA thruster and the –y direction toward the Sun. Spacecraft rotations in yaw of ±15º and +13.5º to –12.4º in pitch define the operational zone where direct sunlight never impinges on any part of the spacecraft protected by the sunshade. A greater margin of safety during propulsive maneuvers limits these rotation angles to ±12º (a Sun-spacecraft-ΔV angle between 78º and 102º). During propulsive maneuvers in Mercury orbit the spacecraft-Sun direction will never be > 12º from the –y-axis direction. This constraint on spacecraft attitude during propulsive maneuvers limits the opportunities for performing orbit-correction maneuvers (OCMs) to twice per 88-day Mercury year. These two opportunities for performing OCMs occur when the spacecraft orbit plane (dark diagonal lines through Mercury in Figure 5) is nearly perpendicular to the Sun-Mercury line. Neglecting small solar radiation pressure perturbation effects, these OCM opportunities arise near Mercury orbit true anomaly angles of 325º (where Mercury orbit insertion occurs) and 145º. Furthermore, since science objectives require highly accurate knowledge of the spacecraft's orbit, the time between OCMs must be maximized. About one Mercury year after the spacecraft's periherm altitude is 200 km, the periherm altitude nears the 500-km upper limit expressed in Table 2. For these reasons all OCM pairs occur once every 88 days, when Mercury is near 325º true anomaly.

Another thermal requirement affecting spacecraft orbit design involves the tilt of the solar arrays with respect to the Sun direction. In order to accurately predict solar pressure perturbations on the spacecraft's orbit, the orientation of the solar arrays must be known relative to the spacecraft-Sun line. Mission design and navigation software use predicted spacecraft attitude to compute the net solar pressure force acting on the spacecraft. This reduces the uncertainty in future spacecraft position and velocity. The thermal rationale for solar array rotation (Figure 6) is to keep the solar array surface, 30% solar cells and 70% optical surface reflectors (OSRs), at or below 150ºC, a normal array temperature for Earth-orbiting spacecraft.

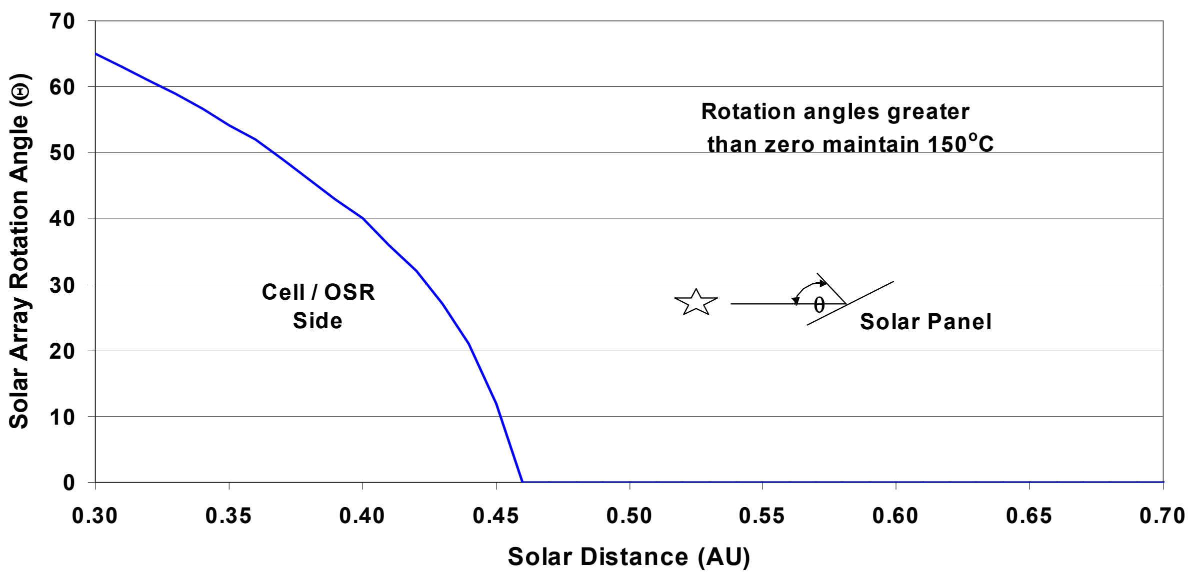

Figure 6 Solar Array Rotation Angle Temperature Constraint

The number, location, orientation, and performance of the spacecraft's thrusters directly affect the maneuver design process for each maneuver performed in Mercury orbit. The locations and orientation of the spacecraft's one 660-N LVA thruster, four 22-N thrusters, and 12 4.4-N thrusters are shown in Figure 7. The LVA thruster is rated to operate at 316 seconds specific impulse for thrust levels from 665 to 672 N. The other thrusters operate at specific impulse typical of efficient hydrazine thrusters. The dual-mode propulsion system, built by Aerojet Corporation, uses bipropellant (fuel and oxidizer) for maneuvers with ΔV > about 10 m/sec, and monopropellant (hydrazine) for smaller maneuvers. The spacecraft's five propellant tanks include two large tanks for fuel, one large tank for oxidizer, one small auxiliary tank for fuel (small ΔVs), and a helium tank for main tank pressurization. Only two burn modes of propulsion system maneuver implementation are planned for Mercury orbit maneuvers. One such burn mode, reserved for maneuvers < 10 m/s ΔV, uses two of the 22-N thrusters to perform a propellant settling burn (i.e., settle the propellant in the auxiliary tank over the inlet to that leads to the main fuel tanks), followed by all four 22-N thrusters to complete the ΔV. Both parts of the Mercury orbit insertion (MOI) maneuver and the periherm-lower maneuvers (OCMs 1, 3, and 5) utilize the bipropellant burn mode. This burn mode consists of a propellant settling burn, an auxiliary tank refill burn that also uses two 22-N thrusters, the main LVA burn, and a short trim burn that uses up to four of the 22-N thrusters to more precisely (than LVA cutoff only) complete the ΔV. The 4.4-N thrusters provide attitude control during operation of the other thrusters. For large maneuvers near periherm, when fuel efficiency requires timely impartation of ΔV, attitude control thrusters help the ΔV to follow a prescribed attitude profile. Other maneuvers use a fixed inertial spacecraft attitude.

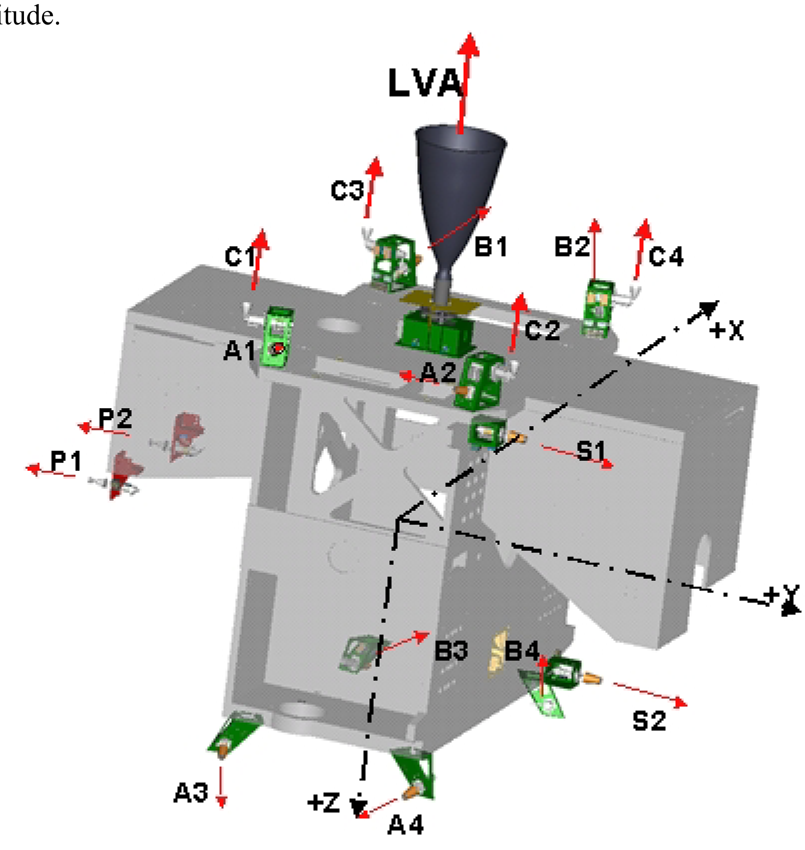

Figure 7 Thruster Locations and Directions

Trajectory selection and maneuver design are also affected by the spacecraft's power subsystem in that the battery must supply needed power during solar eclipse passage. Mass margin concerns early in the development phase restricted the battery size such that the maximum time the spacecraft could safely not receive power from the solar arrays is 65 minutes. The current orbit design includes a 61.5-minute maximum-duration eclipse in mid-June 2009. Insertion into an orbit with a periherm latitude < 60º from the equator would produce longer eclipse times since the spacecraft passes more slowly through Mercury's shadow at a higher altitude. Another rule impacting maneuver design is that no ΔV may be performed within two-hours of a solar eclipse.

Trajectory analysis and maneuver design must factor requirements imposed on spacecraft operation by the telecommunications subsystem. These requirements include the desire (not a strict requirement since part of MOI is obscured during the backup launch opportunity) to monitor 100% of every planned propulsive maneuver, the responsibility to determine timing for daily 8-hour data transmission times, and the need to define periods when solar interference prevents reliable spacecraft communication. MESSENGER's Mercury orbit includes a maneuver schedule that avoids Earth occultation, when Mercury blocks the spacecraft-Earth line of sight. When the Sun-Earth-spacecraft angle drops below 3º and approaches 2º, the spacecraft enters solar conjunction – a region where solar interference degrades spacecraft communication with Earth ground stations. Mission analysis reports the timing of solar conjunctions in order to assist team members planning command uplink or data downlink. Spacecraft-Earth distance, which helps determine data transmission rate, is another key factor in developing the science data downlink strategy. Daily time for data downlink is scheduled from 4-hours before to 4-hours after apoherm on every other orbit. Knowledge of the spacecraft attitude during these data downlink times is useful for accurate trajectory propagation, since a significant change in the Sun-relative spacecraft attitude is often required to enable communication with Earth ground stations. Such changes in spacecraft attitude alter the spacecraft's net solar pressure acceleration direction.

Navigation requirements and the mission team maneuver design process impose additional constraints on the initial Mercury orbit orientation and the spacing between OCMs. In order to lower risk by improving Mercury approach orbit determination, the direction and timing of the incoming hyperbolic approach asymptote were altered to place a bright star in the MDIS narrow angle FOV for optical navigation images of Mercury. In addition, the planning and spacecraft upload time needed between OCMs 1 and 2, 3 and 4, and 5 and 6 may require slightly more than the currently allotted 18-hours (1.5 orbits). The maneuver design for the next even-numbered OCM would be on the spacecraft prior to the implementation of the previous odd-numbered OCM. The maneuver redesign and upload for the imminent even-numbered OCM would occur to apply early OCM performance assessment to refine the timing and burn direction of the upcoming OCM. No constraint violation would occur if this time between maneuvers were increased from 18 to 29 hours (2.5 orbits later).

MERCURY ORBIT INSERTION

The preceding science requirements and spacecraft operational constraints, when coordinated with the characteristics of the Mercury approach trajectory, determine the spacecraft trajectory and the Mercury orbit insertion maneuver requirements. The initial primary science orbit (Figure 8) for the MESSENGER spacecraft will have an 80º-orbit inclination, 200-km periherm altitude, 12-hr orbit period, 118.4º-argument of periherm (60ºN latitude), and a 248º to 73º longitude of ascending node. These angles are expressed in Mercury-centered inertial (equator and equinox of January 1.5, 2000) coordinates. The term h_a in Figure 8 denotes the apoherm altitude. For the 10 March 2004 launch date, the optimal heliocentric trajectory yields a 56ºN latitude initial periherm latitude. The MOI strategy for MESSENGER includes adjusting MOI-1 start time to achieve the required 4ºN latitude rotation of periherm.

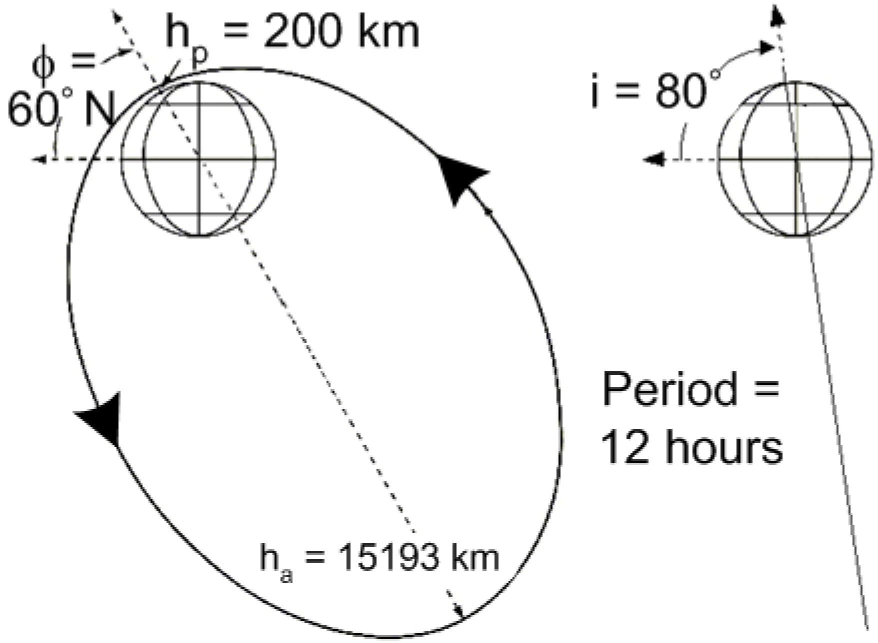

Figure 8 Shape and Orientation of the Initial Primary Science Orbit

Planning of the Mercury orbit insertion strategy incorporated many details to maximize the likelihood of success for this sequence of maneuvers that will consume nearly 70% of the propellant loaded onto the spacecraft. The current strategy utilizes two powered-turn maneuvers (MOI-1 and MOI-2) using the LVA thruster operating at 672-N thrust and 316.1-s specific impulse, such that four full orbits occur between each maneuver. Since each maneuver slows the spacecraft's Mercury-relative velocity, the direction of each maneuver's thrust vector is nearly opposite of the spacecraft velocity vector. For the 10 March 2004 launch date, the orbit period of the spacecraft with respect to Mercury between MOI-1 and MOI-2 is 14.7 hours. Although, longer orbit periods and fewer transition orbits between MOI-1 and MOI-2 would decrease ΔV consumed to counter gravity loss, decreased stability for these higher orbits would increase uncertainty in the planned start time and ΔV of the MOI-2 maneuver. This MOI-2 maneuver is supposed to provide < one-minute of orbit period variation from 12 hours. Because MOI occurs as Mercury nears its perihelion, Mercury's accelerating heliocentric angular motion will rotate the Sun-relative spacecraft orbit orientation to the point of preventing sunshade protection of part of the spacecraft. This condition can occur < four-days after MOI-1, thereby adding risk to the choice of longer transition orbits. Another feature that works well for dates early in the March 2004 20-day launch window is the initial daily data downlink timing of about 8:30 am to 4:30 pm EST. Figure 9 provides two perspectives of Mercury orbit insertion.

This Mercury orbit insertion strategy offers a fast, precise, low-risk entry into the primary science orbit. The strategy is fast in that it requires only 2.5-days of the maximum 13-days allowed to place the spacecraft into the initial primary science orbit. The 13-day requirement is the 365-day orbit phase minus two 176-day (duration of one Mercury solar day) observation periods needed for stereo imaging of Mercury's surface. The strategy is precise in that it uses a small clean-up ΔV to increase the probability of achieving a ± one-minute orbit period tolerance. Because MOI-2 imparts about 2.2% of the total ΔV needed for MOI, there is almost no possibility that an MOI-1 over burn could insert the spacecraft into an orbit with period < 12 hours. The strategy is low risk because plenty of time is allotted between MOI-1 and MOI-2 for reliable orbit determination, MOI-2 maneuver design update, upload to the spacecraft, and verification of the uploaded burn command sequence. Figure 9 clearly shows that 100% of MOI-1 and MOI-2 are visible from Earth ground stations. A Sun-Earth-spacecraft angle > 6º ensures that no solar interference will corrupt communications with the spacecraft at this time. Given the many operational constraints the spacecraft must meet in harsh thermal conditions near Mercury perihelion, it is prudent to limit MOI to only two-maneuvers with at least one contingency opportunity to complete MOI-2 one orbit after the scheduled time.

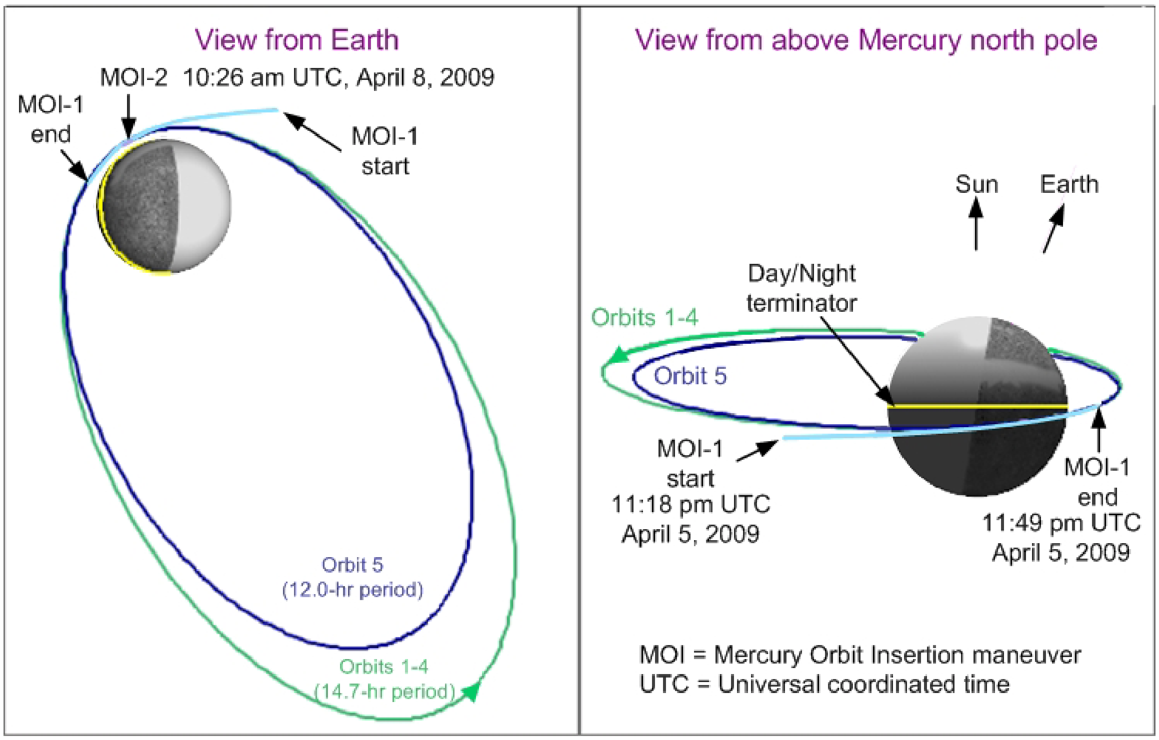

Figure 9 Shape and Orientation of the Initial Primary Science Orbit

The quantitative Mercury orbit insertion summary, shown in Table 3, shows how well MOI-1 and MOI-2 meet angular constraints. Note that the 17-m/s reduction in MOI ΔV magnitude across the 20-day launch window is due primarily to a reduction in the spacecraft Mercury-relative approach velocity. After MOI-1, the initial orbit periods are 14.7 hours and 12.8 hours, respectively, for the 10 March 2004 and 29 March 2004 launch dates. Mercury approach state vectors were obtained from integrated, optimized heliocentric trajectories created by Chen-wan Yen of NASA Jet Propulsion Laboratory. For the 29 March launch case, fewer details of MOI-2 segments are given here in order to place more emphasis on the 10 March case. Near the end of the 20-day launch window, MOI ΔV may be increased enough to ensure compliance with the Sun-spacecraft-ΔV 102º upper constraint.

Table 3

MERCURY ORBIT INSERTION MEETS ALL REQUIREMENTS

Orbit Insertion Maneuver Segment	Maneuver Date and Year Month Day	Time (UTC) hh:mm:ss	Maneuver Magnitude (m/sec)	Earth-S/C Distance (AU)	Sun-S/C Distance (AU)	Sun-S/C-ΔV Angle (deg)	Sun-Earth -S/C Angle (deg)
Requirement →						(78° to 102°)	(> 2°)
Baseline 3/10/04 Launch (Day 1 of 20)							
MOI-1 settle/refill	2009 Apr 05	23:17:31	2.0	1.292	0.317	95.8	6.3
MOI-1 LVA start	2009 Apr 05	23:18:16	1585.7	1.292	0.317	95.9	6.3
MOI-1 LVA end	2009 Apr 05	23:48:30	-	1.292	0.317	101.2	6.3
MOI-1 trim end	2009 Apr 05	23:48:45	2.2	1.292	0.317	101.2	6.3
MOI-2 settle/refill	2009 Apr 08	10:24:46	5.6	1.258	0.311	85.2	8.9
MOI-2 LVA start	2009 Apr 08	10:26:01	28.1	1.258	0.311	86.0	8.9
MOI-2 trim end	2009 Apr 08	10:26:26	2.3	1.258	0.311	86.5	8.9
	Mercury orbit insertion total ΔV =		1625.9				
Baseline 3/29/04 Launch (Day 20 of 20)							
MOI-1 settle/refill	2009 Apr 06	7:52:54	2.1	1.288	0.316	96.8	6.7
MOI-1 LVA start	2009 Apr 06	7:53:39	1592.4	1.288	0.316	96.9	6.7
MOI-1 LVA 50%	2009 Apr 06	8:08:36	-	1.288	0.316	98.9	6.7
MOI-1 trim end	2009 Apr 06	8:23:48	2.3	1.288	0.316	102.4	6.7
MOI-2 end	2009 Apr 08	11:24:44	12.0	1.256	0.311	88.3	9.0
	Mercury orbit insertion total ΔV =		1608.8				

Unlike ballistic trajectory orbit insertion scenarios for most planets, MESSENGER's robust orbit insertion strategy offers credible contingency scenarios that enable complete recovery to the designated primary science orbit. For example, one scenario would be if a decision was made months or years prior to the nominal MOI date to delay Mercury orbit insertion. A small ΔV, often < 10 m/s, could be designed to retarget the old Mercury approach trajectory into a third gravity-assist flyby that returns the spacecraft to Mercury 1.5-years later at a substantially lower Mercury approach velocity. Near the first aphelion after the third Mercury flyby, an additional 183 m/s ΔV would complete the retargeting strategy by establishing a contingency MOI date of 22 September 2010. Using the third Mercury flyby to adjust the Mercury-spacecraft resonant period from 4:3 to 6:5, would save 470 m/s ΔV compared with the ΔV plan at launch.

Another more complex contingency scenario for MOI involves an unexpected abort or cancellation of the MOI-1 maneuver on final approach to Mercury. If properly targeted for MOI, the approach trajectory would never come closer than 365 km above Mercury's surface. About 100 days after this third Mercury flyby, a 667-m/s ΔV would be performed near spacecraft perihelion. This retargeting maneuver would set up a fourth 200-km altitude Mercury flyby on 19 September 2010 at about the same Mercury heliocentric location as the third Mercury flyby. This flyby then leads to a fifth and final 200-km altitude Mercury flyby 88 days later at the same Mercury orbit position. The sixth encounter with Mercury, which would occur on 25 January 2011 prior to Mercury's perihelion, would be reserved for a much lower 808-m/s MOI ΔV. The small savings in onboard propellant using this contingency design would have to be combined with margin ΔV to change the initial post-MOI orbit inclination from 90º to the desired 80º. The timing and number of MOI maneuvers in the sequence leading to the primary science orbit must be carefully planned for this complex, yet feasible MOI contingency recovery scenario.

Studies were also performed to analyze MOI thrust-level variations, recovery from burn-start delays, and under-burn and over-burn cases. Although these results are not given in this paper, such studies are far more straightforward and easily defined than the previously mentioned MOI contingency recovery scenarios.

ORBIT CORRECTION MANEUVERS

After completion of the Mercury orbit-insertion maneuvers, an extended period of more than 12 weeks allows sufficient time to refine the Mercury gravity and perturbing force models in preparation for the first pair of orbit correction maneuvers. Each pair of OCMs are designed to return the spacecraft to as close as possible to the original size and orientation of the primary science orbit. The first OCM of the pair will impart a ΔV opposite to the spacecraft velocity direction at apoherm in order to lower periherm altitude to 200 km. Since this ΔV decreases the spacecraft orbit period by nearly 15 minutes, the next OCM will occur at periherm close to the velocity direction to return orbit period to 12 hours. This second OCM of the pair must occur 1.5 or 2.5 orbits (18 to 29 hours) after the previous OCM. A further one-orbit delay is possible without violating Sun-spacecraft-ΔV angle constraints that ensure sunshade protection of the spacecraft. Given the science and spacecraft operational requirements discussed earlier and the predicted rate of periherm altitude increase, the time between OCM pairs is close to one 88-day Mercury year. This interval marks the time when the spacecraft orbit plane is most nearly perpendicular to the spacecraft-Sun direction.

Table 4

MERCURY ORBIT CORRECTION MANEUVERS MEET ALL REQUIREMENTS

Orbit Correction Maneuver Segment	Maneuver Date Year Month Day	Time in UTC (hh:mm:ss)	Maneuver Magnitude (m/sec)	Earth-S/C Distance (AU)	Sun-S/C Distance (AU)	Sun-S/C-ΔV Angle (deg)	Sun-Earth -S/C Angle (deg)
Requirement →						**(78° to 102°)**	**(> 2°)**
Baseline 3/10/04	**Launch**						
OCM-1 start	2009 Jul 03	15:51:37	26.3	1.225	0.315	85.7	12.1
OCM-1 end	2009 Jul 03	15:53:23	-	1.225	0.315	85.6	12.1
OCM-2 start	2009 Jul 04	9:28:13	4.1	1.237	0.313	89.9	11.4
OCM-2 end	2009 Jul 04	9:28:40	-	1.237	0.313	89.6	11.4
OCM-3 start	2009 Sep 29	14:51:09	25.2	0.791	0.315	87.1	15.1
OCM-3 end	2009 Sep 29	14:52:54	-	0.791	0.315	87.0	15.1
OCM-4 start	2009 Sep 30	8:28:48	3.9	0.809	0.313	91.3	15.8
OCM-4 end	2009 Sep 30	8:29:13	-	0.809	0.313	91.1	15.8
OCM-5 start	2009 Dec 26	13:50:41	23.7	0.805	0.315	88.5	16.7
OCM-5 end	2009 Dec 26	13:52:24	-	0.805	0.315	88.4	16.7
OCM-6 start	2009 Dec 27	7:29:38	3.7	0.788	0.313	92.8	10.5
OCM-6 end	2009 Dec 27	7:30:02	-	0.788	0.313	92.6	10.5

The quantitative results for OCMs (Table 4), demonstrate compliance with timing and angle constraints covered in the Spacecraft Operational Constraints section. Even though OCMs 1, 3, and 5 require moderate duration, their occurrence at apoherm minimizes change in the Sun-relative thrust orientation. Although they are near the periherm 3.8-km/s maximum spacecraft velocity, the short-duration OCMs 2, 4, and 6 experience minimal change in Sun-relative direction. Each OCM complies with mission constraints, including geometry consistent with uninterrupted communications link with Earth ground stations, regardless of the launch date. The OCM ΔV magnitude decreases over time since the periherm's northward drift causes a reduction in the rate of periherm altitude increase. A total of 86.9 m/s plus 22 m/s ΔV margin is allocated for OCMs.

ORBIT EVOLUTION

As evidenced by several significant spacecraft orbit parameter changes, Mercury orbit deviations are caused by factors other than propulsive maneuvers. For instance, solar radiation pressure acts on the spacecraft to perturb the spacecraft trajectory (except during solar eclipse). Additional sources of interruption in spacecraft solar power and communications must be defined and accounted for in science observation and spacecraft operational planning. After the nominal one-year orbit phase, orbit correction maneuvers can only delay the spacecraft's certain demise.

Solar gravity and solar pressure are the primary perturbing forces behind a number of small to moderate orbit parameter changes. Throughout these orbit changes, the Sun-relative orbit orientation, left and right, respectively varies between two extremes, the dawn-dusk terminator and noon-midnight orbits (Figure 10). The change in periherm altitude and latitude of the spacecraft orbit, depicted in Figure 11, indicate northward and upward drift in periherm altitude.

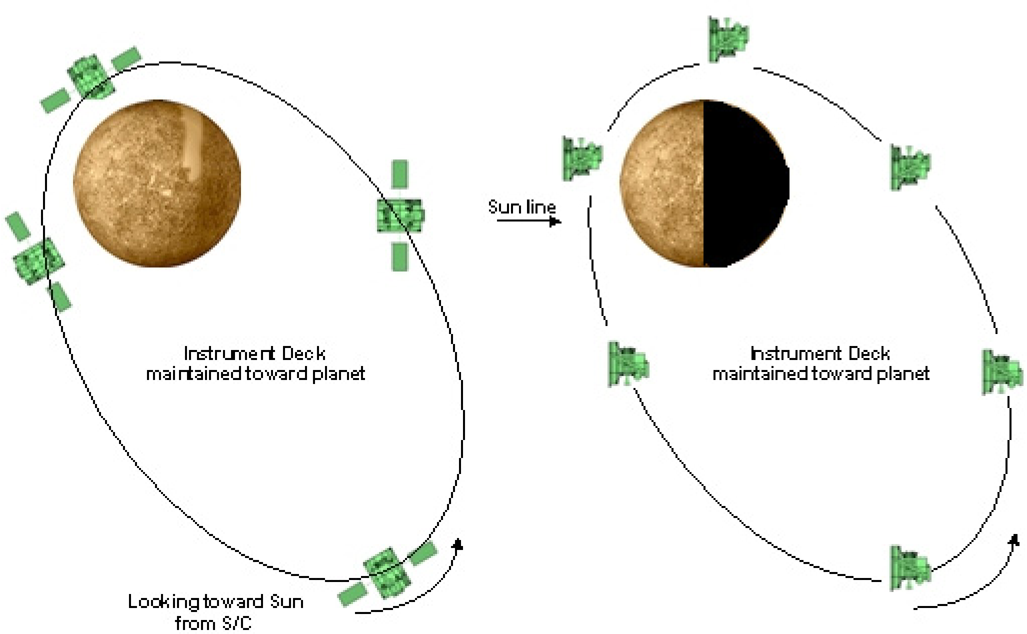

Figure 10 Normal Orbit Phase Operation (excluding Data Downlink)

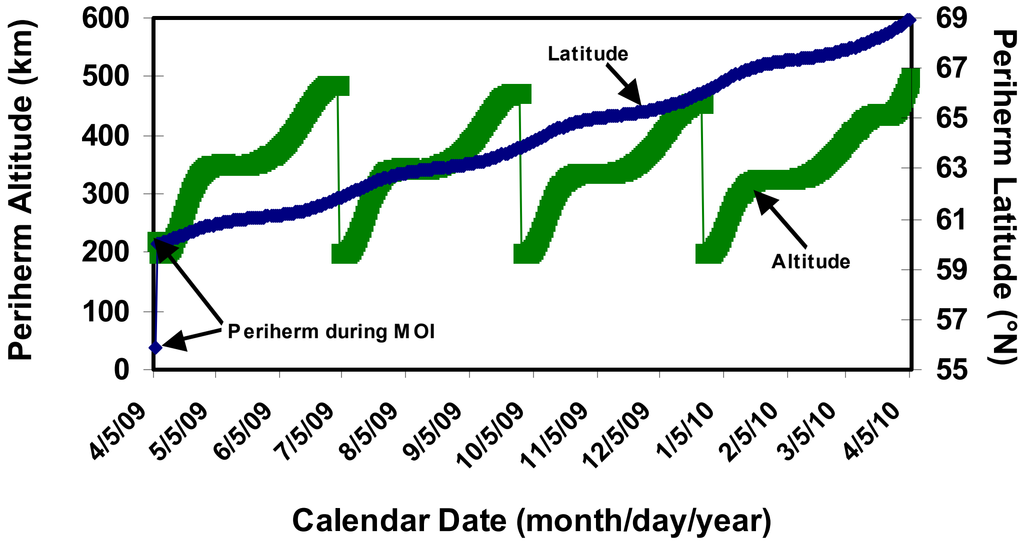

Figure 11 Spacecraft Orbit Periherm Evolution (OCMs at Altitude Drops)

The change in the orbit's Sun orientation is best measured by the longitude of the ascending node and orbit inclination. These angles (Figure 12) measure the tilt angle of the spacecraft orbit plane relative to the orbit plane and the orbit plane normal direction. Notice that orbit inclination moves in a northerly direction, one that moves closer to an orbit that would fly directly over potential north polar ice deposits. Longitude of ascending moves periherm location away from the Sun at Mercury perihelion.

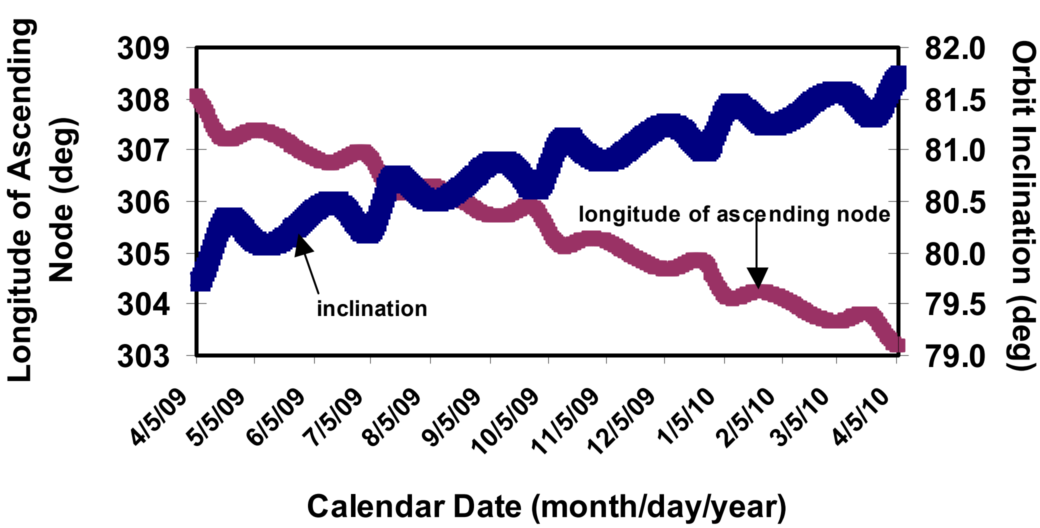

Figure 12 Spacecraft Orbit Plane Orientation Relative to the Sun Direction

Operational sequence details specifying predicted spacecraft attitude will help predict the spacecraft's net solar radiation pressure magnitude and direction. The current software model uses 23 flat plates to model the spacecraft's Sun-facing side and 23 additional flat plates to model the spacecraft's anti-Sun side. The surface reflectance and orientation of each plate are specified along with ephemerides for the Sun, Earth, and Mercury. Spacecraft orientation can be specified in several different ways – by attitude quaternions, by direction cosines of spacecraft axes, or by following simple rules that closely approximate spacecraft and solar array attitude during science acquisition and communication modes. A comprehensive science-planning tool generates reliable attitude quaternions for the entire Mercury orbit phase. The effect of Mercury albedo (solar radiation reflected off the surface of Mercury and onto the spacecraft) and time-varying surface reflectance will be specified later. The solar radiation pressure[22]

$$d\boldsymbol{F} = - \Theta_{Sun}/c \, [(1-\rho)\boldsymbol{S} + 2\,(\delta/3 + \rho \cos\beta)\, \boldsymbol{n}]\, dA\, |\cos\beta| \qquad (1)$$

where, for each spacecraft Sun-exposed surface plate:
$d\boldsymbol{F}$ is the elementary force on the area dA,
Θ_{Sun} is the solar flux,
c is the velocity of light,
ρ is the specular reflectivity,
δ is the diffuse reflectivity,
$\boldsymbol{S}$ is the unit vector from the surface to the Sun,
$\boldsymbol{n}$ is the unit vector normal to the surface, and
β is the angle between $\boldsymbol{n}$ and $\boldsymbol{S}$.

is used along with the solar array rotation angle (Figure 5) to generate the net solar pressure perturbation force acting on the spacecraft. Application of the rules approximating spacecraft attitude were applied to the latest MOI-1 to OCM-1 trajectory for the Mercury orbit phase. At the end of this 3-month trajectory, orbit period increased by about 10 s. This delayed OCM-1 by just over 15 minutes. Less than a 1-km increase was noted for periherm altitude.

Events that interrupt or alter the routine of science observation sequences and spacecraft-Earth communications include solar eclipses, Earth occultations, and solar conjunctions. The 61.5-minute maximum-duration eclipse that the spacecraft will encounter will occur in mid-June of 2009 (Figure 13). Monitoring eclipse times and duration provides important power management information for mission planners. Some instruments must be turned off to ensure sufficient battery power during eclipses longer than 35 minutes. Longer eclipses, which occur when the spacecraft is farther from Mercury, decrease in duration as periherm drifts northward and as the orbit line of nodes rotates slowly. Shorter eclipses, which occur when the spacecraft is at lower altitudes, increase throughout the orbit phase. Earth occultation occurs when Mercury blocks the spacecraft-Earth line-of-sight. Although no propulsive maneuvers are scheduled during an Earth occultation, OCMs 4 and 6 come within minutes of short Earth occultation periods. The phasing of Earth and Mercury prevents Earth occultation from occurring for the first three-months in Mercury orbit. When they occur, Earth occultations are usually < 45 minutes. Table 5 lists every solar conjunction predicted during MESSENGER's year at Mercury. All solar conjunctions are more than one week from planned OCMs. However, depending on whether 2º or 3º Sun-Earth-spacecraft angle is used as the entry and exit condition, MOI-1 occurs only 4 or 3 days after solar conjunction exit. This condition will affect how spacecraft operators design the Mercury approach trajectory. Only one solar conjunction is longer than six-days during the Mercury orbit phase.

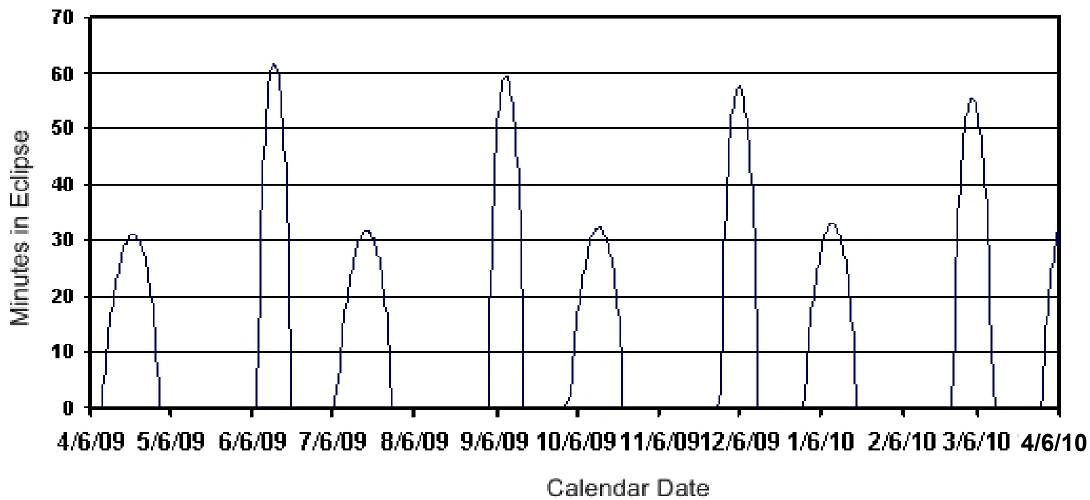

Figure 13 Solar Eclipses Occur Twice per Mercury Year in Mercury Orbit

Table 5

SOLAR CONJUNCTIONS DO NOT INTERFERE WITH PLANNED MANEUVERS

Solar Conjunction Date, Time year/month/day UTC hour:minute:second				**Conjunction Duration (days)**		**Distance to Earth (AU)**		**Distance to Sun (AU)**	
Enter		Exit		SEP < 2°	SEP < 3°	Enter	Exit	Enter	Exit
2009/03/29	00:41:43	2009/04/03	02:23:47	3.03	5.07	1.3610	1.3252	0.3677	0.3309
Mercury Orbit Insertion		**2009/04/05**	**23:17:31**						
2009/05/16	11:28:40	2009/05/20	02:51:53	2.26	3.64	0.5576	0.5510	0.4552	0.4626
2009/07/11	19:35:50	2009/07/16	05:01:24	2.28	4.39	1.3214	1.3355	0.3108	0.3249
2009/09/20	10:30:52	2009/09/20	18:00:31	0.00	0.31	0.6486	0.6503	0.3582	0.3564
2009/10/31	17:34:31	2009/11/10	06:52:52	6.35	9.55	1.4167	1.4455	0.4286	0.4595
2010/01/04	02:39:47	2010/01/05	06:04:10	0.00	1.10	0.6746	0.6717	0.3116	0.3145
2010/03/11	22:34:36	2010/03/17	08:58:19	2.72	5.43	1.3666	1.3366	0.3780	0.3469

Enter and exit times correspond to Sun-Earth-spacecraft (SEP) angle = 3°.
Mission-critical events within 5 days of solar conjunction are shown in **bold-face type**.

At the end of the nominal one-year Mercury orbit phase, the number and scope of options for the spacecraft trajectory depends upon extended mission status, cost, ground station schedule, and amount of excess propellant. Given the potential amount of propellant remaining, many extended mission options will be studied and debated among MESSENGER team members. If nothing is done to alter the end-of-nominal mission trajectory, the spacecraft will impact Mercury's surface within a few years.

CONCLUSION

With a successful launch in March 2004, the MESSENGER mission will become the first spacecraft to orbit Mercury in April 2009. During its one-year orbital mission at Mercury, the spacecraft will use its miniaturized science payload to accomplish a lengthy list of science goals. In the extreme thermal and radiation environment of space near the planet Mercury, and in the face of numerous spacecraft operational constraints, the spacecraft will follow a robust trajectory and maneuver design strategy. Recovery is possible from a variety of temporary spacecraft subsystem failures that affect the timing and orientation of propulsive maneuvers.

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