Spacecraft Pointing for Science Observations for MESSENGER's Venus Flyby 2 and Mercury Flyby 1

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The MESSENGER (MErcury Surface, Space ENvironment, GEochemsitry, and Ranging) spacecraft completed its second flyby of Venus in June 2007 and its first flyby of Mercury in January 2008. A comprehensive set of science observations was obtained with the instrument suite during both of these flybys. Complex and tightly coordinated sets of spacecraft attitude and instrument commands were designed to achieve the diverse geometries required for these observations. The flyby pointing sequences exercised nearly all of the available guidance targeting options, often in combination with scan patterns. Durations and start times of each spacecraft turn and instrument observing session had to be carefully chosen based on control system capabilities. Observed areas had to be chosen to keep the sunshade pointing within the allowable zone for spacecraft thermal safety. The successful completion of both flybys has demonstrated the versatility of the MESSENGER pointing options and has provided valuable experience that will now be applied in designing observations for the remaining two Mercury flybys and for the orbital phase of the mission.

I. Introduction

THE MESSENGER (MErcury Surface, Space ENvironment, GEochemsitry, and Ranging) spacecraft was launched from Kennedy Space Center in Florida on August 3, 2004. As part of NASA's Discovery Program, MESSENGER is the first spacecraft to closely observe the planet Mercury since the Mariner 10 flybys of the mid-1970s. MESSENGER has completed one Earth flyby (2005), two flybys of Venus (2006 and 2007) and one of three planned Mercury flybys (2008). The planetary flybys are interspersed with five large deterministic deep-space maneuvers (DSMs) that target the spacecraft for its Mercury orbit insertion (MOI) maneuver in 2011. Three of the DSMs were completed in 2005, 2007, and 2008. The spacecraft will orbit the planet for one Earth-year beginning in March 2011. The Mercury flybys will assist in developing the focused science gathering of the year-long orbit phase of the mission.[1]

Figure 1 shows the MESSENGER spacecraft configuration and the locations of some of the main engineering components and science instruments. The primary factors driving the spacecraft design were the high temperatures and radiation doses to be encountered at Mercury. Protection from this environment is accomplished with a large sunshade, which shields the spacecraft components from direct exposure to the Sun. This shade must be kept between the main body and the Sun for the remainder of the mission now that the spacecraft is within 0.85 AU of the Sun. The shade has been sized to allow small deviations from direct Sun pointing when needed for science observations or engineering activities. The region of allowable deviation from direct Sun pointing is called the Sun keep-in (SKI) zone. Science observations must be designed such that spacecraft attitude remains within this zone at all times. Power generation is handled with solar panels mounted on small booms that extend beyond the sunshade and are capable of rotating to track the Sun. The solar panels are supplemented with a battery to provide power during eclipse periods. The battery was used during short eclipses as the spacecraft passed behind the planet for both Venus flyby 2 and Mercury flyby 1. The spacecraft carries high-, medium-, and low-gain antenna sets for X-band communication with Earth.[2,3]

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MESSENGER carries a diverse suite of miniaturized science instruments to globally characterize the planet.[1] Four of the science instruments are co-boresighted and mounted inside the launch vehicle adapter ring: two imaging cameras (Mercury Dual Imaging System – MDIS), a laser altimeter (Mercury Laser Altimeter – MLA), ultraviolet to near-infrared spectrometers (Mercury Atmospheric and Surface Composition Spectrometer - MASCS), and an X-Ray Spectrometer (XRS). MDIS consists of a narrow-angle camera (NAC) and a wide-angle camera (WAC) that are both mounted on a pivoted platform that extends their observing range for flybys and in orbit. Other instruments located outside the adapter ring are a Gamma-Ray and Neutron Spectrometer (GRNS), an Energetic Particle and Plasma Spectrometer (EPPS), and a Magnetometer (MAG). The antennas are also used for radio science.

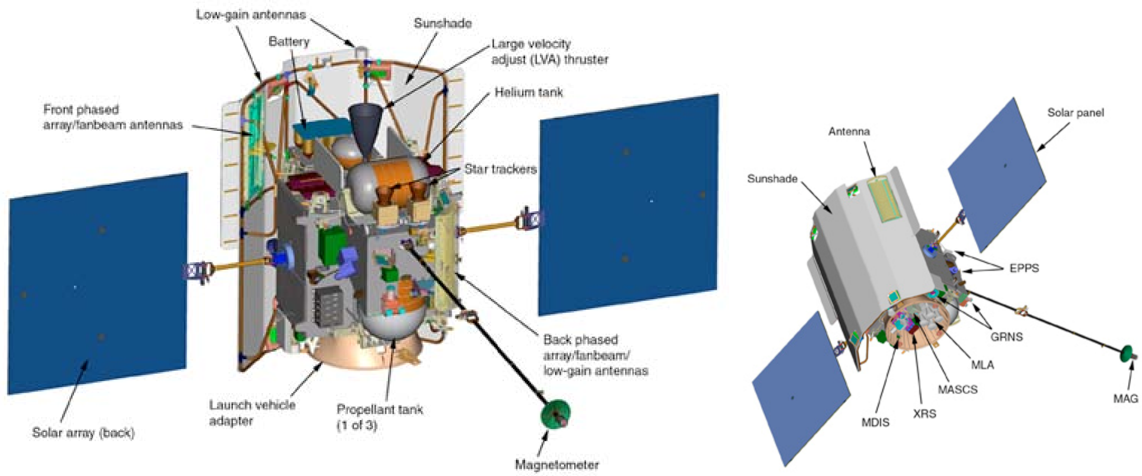


Figure 1. MESSENGER Spacecraft Components and Science Instruments.

A. Guidance and Control System Overview

The primary functions of the MESSENGER guidance and control (G&C) system are to maintain spacecraft attitude and to execute propulsive maneuvers for spacecraft trajectory control.[4] The G&C system maintains a 3-axis-stabilized spacecraft using reaction wheels as the primary actuators for attitude control. MESSENGER also carries 16 mono-propellant thrusters and one large bi-propellant main engine for trajectory corrections, attitude control (nominally during burns only), and momentum offloads. Star trackers and an inertial measurement unit containing four gyros provide knowledge of inertial attitude and rotation rates. Sun sensors are used to provide Sun-relative attitude knowledge as a backup to the inertial sensors for spacecraft safety. Software algorithms run in the main processor to coordinate data processing and commanding of sensors and actuators. The software also controls the orientation of the two solar panels, electronic steering for the two high-gain phased-array antennas, and, optionally, pivot positioning for the MDIS cameras. An additional interface with the MLA provides range and slant angle to the planet's surface used to configure the instrument but does not involve any active mechanical or electronic steering.

The desired attitude and rotation rate for each science or engineering activity is specified by setting a basic pointing command and, optionally, superimposing a scan pattern command. These two commands specify the unconstrained pointing, while an additional command determines whether or not to apply the SKI constraints. The SKI constraints are always applied during flybys including during the short eclipse periods. The guidance block in the flight software computes the desired (or commanded) spacecraft attitude and rate based on the parameter settings for the pointing option and scan pattern. Ten pointing options are available to point antennas at the Earth, point instruments at or near various celestial bodies, or align thrusters with a target direction for velocity change (ΔV).[5] Pointing targets include directions in the EME2000 inertial frame specified as vectors or right ascension and declination angles; directions from the spacecraft to the Sun, Earth, or a target planet; directions in the target planet body-fixed frame specified as vectors or as latitudes, longitudes, and heights; directions in a local vertical, local horizontal (LVLH) frame given as azimuth and elevation angles; or points on the target planet that optimize illumination geometry. Scan patterns combining periods of fixed-rate rotations about specified axes with pauses can be added to the base pointing option. These are used to design mosaics or continuous scans that enable target motion in an instrument field of view (FOV). Motions can be rotations about axes in the spacecraft body frame, the inertial frame, or the LVLH frame or translations along inertial axes. Each axis may have a different combination of rates, pauses, and motion reversals. The guidance system enforces certain compatibility restrictions between the scan frame and the base pointing option.

Ephemeris models and models for the shape, size, and rotation of a target planet are available to the guidance system when needed to formulate the commanded attitude. The guidance block continuously interpolates on-board ephemeris models to obtain the position and velocity of the Sun, the Earth, a target planet, and the spacecraft, all referenced to the solar system barycenter. The target planet had been set to Earth and Venus for those flybys and is now set to Mercury for the rest of the mission. Each body has both precise and coarse ephemeris models. The precise models are used under normal spacecraft science gathering operations and are necessary to meet the pointing requirements of the science team. The coarse models are lower precision models used as a contingency for spacecraft safing operations. They are valid over long time spans and require only occasional updates by ground controllers. The precise models use Chebyshev polynomials and a simple linear conversion of spacecraft time to terrestrial dynamic time (TDT) to extract the necessary positions and velocities for the spacecraft or the celestial body. The precise ephemeris spans are valid over shorter durations (hours or days) and must be updated by the operations team at regular intervals as the mission progresses. The precise ephemeris models used for flyby science are specially fit to provide the greatest possible accuracy during the critical time around closest approach when the geometry is changing most rapidly. The timing of the last ephemeris update is coordinated with the navigation team to use the most recent information as described in a later section. Additional G&C parameters are loaded to the flight software for the standard International Astronomical Union (IAU) model giving the target planet body-fixed frame orientation relative to the inertial frame and for the triaxial ellipsoid approximation of the planet's shape and size. The values for these parameters are specified by the science team.

1. Coordinate Systems and Angle Conventions

Any discussion of spacecraft attitude and instrument pointing must be prefaced with definitions of coordinate systems and other positioning conventions. The MESSENGER spacecraft (S/C) body frame is defined in Fig. 2. The –Y axis points out away from the sunshade and is the center of the SKI zone. Spacecraft attitude is specified as the orientation of this frame relative to the EME2000 inertial reference frame. Azimuth and elevation angles are defined relative to the body frame axes as shown in Fig. 2 and can be used to define directions to celestial objects as seen from the spacecraft. The SKI bounds are given as minimum and maximum azimuth and elevation angles. The default bounds used by the guidance software are ±10º in azimuth and ±12º in elevation. This is called the "inner" SKI zone and is the zone enforced when computing commanded attitude. The G&C flight software also has a constraint monitor function that checks whether the estimated attitude is within a "middle" SKI zone whose bounds are 1-2º outside those of the inner zone. A third "outer" SKI zone with bounds at ±15º in azimuth and elevation is used by spacecraft autonomy software. If the spacecraft attitude places the direction to the Sun outside the middle or outer SKI zones longer than specified durations, safing actions are taken and the current sequence command load is terminated. For convenience, the inner SKI zone will be referred to simply as the SKI zone in the remainder of the paper. Science observations must be designed such that spacecraft attitude remains within this zone at all times.

Three of the four remote sensing instruments mounted inside the adapter ring – MLA, MASCS, and XRS - have fixed boresights that are nearly aligned with the spacecraft +Z axis. Pointing for these instruments is driven by when the angle between the target object and the Sun is between 78º and 102º. This is the angular range where +Z can be pointed at the target with the Sun elevation within the SKI bounds. The MDIS NAC and WAC boresights are nearly aligned with the spacecraft +Z axis when the pivot is at its 0º position. The pivot rotates nominally about the spacecraft X axis so that the camera boresights stay in the YZ plane. The operational range of pivot angles varies from 50º towards the +Y axis to 40º towards the –Y axis as shown in Fig. 3. The guidance software can provide pivot angle commands to MDIS along with spacecraft attitude commands to point the cameras at desired targets or to point the +Z instruments at one target while pointing the cameras as close as possible to a separate target. The software will constrain the pivot angle to remain in the operational range in addition to keeping the commanded attitude with the SKI bounds. The pivot increases the range of angles between a target object and the Sun to between 38º and 152º where the MDIS boresight can be pointed while remaining within the SKI bounds. Alignment solutions for offsets of the actual boresights from the +Z axis are available from in-flight calibration observations for MLA, for the different spectrometers in MASCS, and for the MDIS NAC and WAC cameras including orientation of the pivot plane. These are substituted for the +Z axis when necessary to optimize science return for an observation.

The two solar panels rotate about the spacecraft X axis such that the vector normal to the panel pointing outward from the solar cells moves through a total angle of 228º as shown in Fig. 4. Panel position is specified as the angle of the normal vector relative to the spacecraft +Z axis and increases counterclockwise about the +X axis. The panel control mode is normally set to automatically maintain a fixed angular offset between the normal vector and the direction to the Sun. A manual mode is also available that will put the panels at fixed angular positions and allow the Sun offset to change as spacecraft attitude changes. Rotation of the panels causes small perturbations in the spacecraft attitude that are undesirable during some science observations. Panel positions had to be carefully managed during the flybys to maintain the desired pointing stability for science observations while still providing adequate power and acceptable panel temperatures.

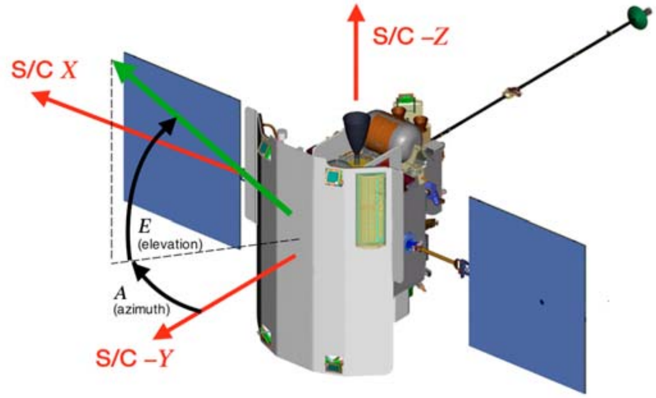


Figure 2. MESSENGER Spacecraft Body Frame and Azimuth and Elevation Angle Conventions.

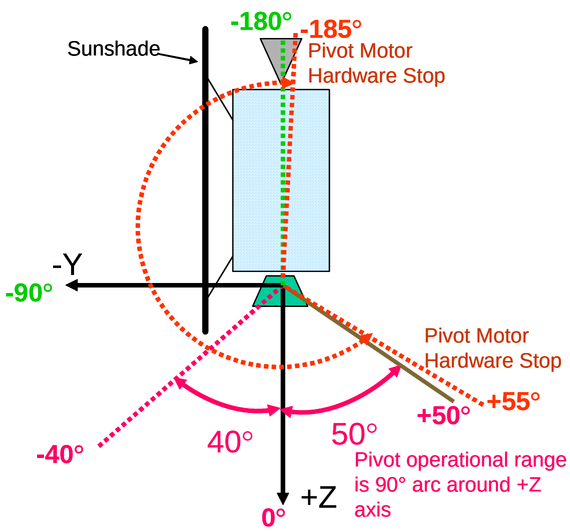


Figure 3. MDIS Pivot Angle Convention.

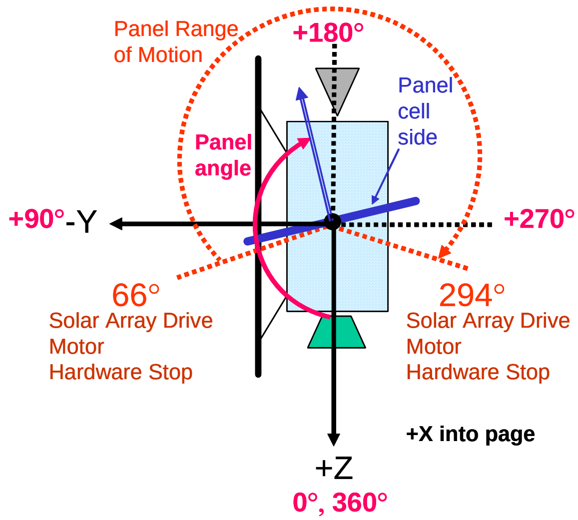


Figure 4. Solar Panel Angle Convention.

II. MDIS "Single Target" Pointing

The simplest pointing designs used for both flybys point a specified boresight in the spacecraft body frame at a single specified target (or aimpoint) for some fixed time duration without superimposing any additional spacecraft motion around this base target using a scan pattern. This simple strategy was used for several MDIS observations including approach and departure color images of the planet, color photometry imaging of a fixed surface location at different viewing angles, flat field calibration images of Venus, and approach and departure movies of the planet. The base pointing option for all of these observations was MDIS pointing or option 4. The MDIS boresight is aligned as closely as possible to a specified target while keeping the spacecraft –Y axis as close as possible to the Sun line and within the SKI zone. Spacecraft base body attitude and an MDIS pivot angle are computed by the guidance software and appropriate wheel and pivot position commands are passed to the attitude control and MDIS control software. The logic in the guidance software for MDIS pointing will move the MDIS pivot in preference to moving the spacecraft attitude away from the center of the SKI zone. It will attempt to put the MDIS boresight on the target by first changing only the pivot angle and keeping the –Y axis directly on the Sun line and then will move the –Y axis towards the appropriate limit of the SKI zone. The software stops trying to reach the target when the spacecraft attitude is at the SKI boundary and the pivot angle is at its operational limit. All of these possibilities were realized for Venus flyby 2. Mercury flyby 1 had more favorable Sun-planet geometry so that the MDIS targets could be attained by pivot motion only without moving the –Y axis off the Sun line.

The guidance software provides a comprehensive set of targets (or aimpoint options) for any selected boresight. The targets for the MDIS "single target" observations are listed in Table 1. Setting the aimpoint to nadir means that the boresight is aligned with the vector from the spacecraft to the center of the planet. Setting the aimpoint to "specular" means that the boresight is directed towards the point on the planet surface that brings the instrument boresight close to the subsolar point without creating excessively oblique viewing conditions. Mathematically this is expressed as a function of the instrument incidence angle (I) and the instrument emission angle (E). The incidence angle is defined as the angle between the target planet surface normal and the Sun direction, in the spacecraft-target

Table 1. MDIS Single Target Pointing

Activity	Flyby	Target (Aimpoint Selection)	Pivot Angle Range (º)	Sun Elevation Range (º)
Approach Movie (WAC)	Mercury 1	Specular	-28.55 to -30	Always at 0 (along –Y axis)
Departure Movie WAC	Venus 2	Specular	Start at -40 (at limit) Move to -34 by end	Start at -6; move to 0 (along –Y axis) by end
NAC	Mercury 1	Specular	37 to 41.04	Always at 0 (along –Y axis)
WAC Approach Color Image	Venus 2	Nadir	+50 (at limit)	+12 (at SKI limit)
	Mercury 1	Specular	-31.76 to -31.86	Always at 0 (along –Y axis)
WAC Departure Color Image	Mercury 1	Nadir	37.24 to 37.29	Always at 0 (along –Y axis)
Flatfield Calibration Images (NAC & WAC)	Venus 2	Nadir	+50 (at limit)	9.63 to 8.76 (off –Y axis, but within SKI zone)
Color Photometry (WAC)	Venus 2	0º latitude, 225º E longitude, 0 km height	+50 (at limit), then between +24 and -14	3.22 to 0.41 (off –Y axis, but within SKI zone), then at 0 (along –Y axis)
	Mercury 1	0º latitude, 125º E longitude, 0 km height	#1 -31.36 to -29.61 #2 -20.54 to -18.11 #3 -10.46 to -8.53 #4 -2.93 to -1.40 #5 23.63 to 23.96	-2.66 to -1.40 Always at 0 (along –Y axis)

planet-Sun plane. The emission angle is the angle between the surface normal and the spacecraft-to-surface point vector. The desired "specular" viewing conditions are achieved by finding the surface point that maximizes the product of the cosines of the incidence and emission angles (max[cos(E) cos(I)]). The final choice of aimpoint for MDIS single-target imaging was a surface latitude, longitude, and height. For both flybys, the target location was chosen on the equator at about 30º away from the terminator on the lit portion of the planet.

The primary considerations for these designs are determining the time required to turn from the previous attitude to the target attitude, the time required to move the MDIS pivot from its previous position to the new position, and selecting the duration for that pointing option so that the desired duration for science instrument data collection is achieved. The MDIS pivot rotation rate is ~1.1º/s, while the maximum spacecraft turn rate is ~0.8º/s. The pivot almost always can complete its required motion before the spacecraft finishes a large turn and settles at the target attitude. The MDIS software permits direct commanding of a pivot position in addition to responding to the pivot angles output by the G&C software when certain pointing options are in effect. A command must be sent to direct MDIS to listen to the G&C angle once the pointing option has been changed to the MDIS option. The MDIS software suppresses any pivot motion while an image is being shuttered. The typical commanding sequence for one of the single target observations first loads parameters for the pointing option that specify the desired aimpoint, issues the command to switch to pointing option 4, and then issues the command to MDIS to use the G&C pivot angle. After sufficient time to turn and settle at the target attitude, commands are issued to shutter the desired NAC and/or WAC images. The pivot angle can and will change during the observation period so the imaging commands are spaced to allow for any required pivot motion between them. For the Venus departure movie, images were taken every 20 minutes at the start and transitioned to every 60 minutes at the end. For the Mercury approach movie WAC images were taken every 20 minutes and NAC images were taken every 4 minutes for the departure movie. The other observations typically consisted of up to 11 images taken in rapid succession with very little pivot motion between them.

III. MLA Nadir Tracking and “Double Target” Pointing

Laser altimetry is optimized when the MLA boresight is pointed as close as possible to the center of the planet or “nadir.” MLA can sense the return signal when its laser hits the planet surface at altitudes below approximately 1500 km. The spacecraft is below this altitude for a few minutes near closest approach for each flyby. MLA measurements are given the highest priority during these periods, dictating that the spacecraft +Z axis should be pointed as close as possible to nadir within the SKI constraints. MDIS images of the surface were also desired during the nadir tracking periods. The “double target” pointing option (option 6) was used to point each instrument at their respective targets. This pointing option uses the +Z axis to the aimpoint target as the primary reference and –Y to the Sun as the secondary reference to determine spacecraft attitude. It also computes the MDIS pivot angle that puts the MDIS boresight as close as possible to a second designated aimpoint. +Z will be aligned with its target if possible within SKI bounds. +Z is offset from its target when the spacecraft attitude reaches the edge of the SKI region. MDIS will be commanded to a pivot angle as close as possible to its target, but spacecraft attitude will not be adjusted to move the pivot plane to a more favorable geometry. For Venus flyby 2, MDIS was attempting to image the surface of Venus using filters that might “see through” the heavy atmosphere. The aimpoint for MDIS was set to nadir – the same target used for MLA. For the brief period when +Z could be pointed directly at nadir within the SKI zone, the MDIS pivot angle was set to zero which put the MDIS boresight along the +Z axis. For the remainder of the nadir-tracking period, the MDIS pivot angle was set to a non-zero value that moved its boresight closer to nadir while the +Z axis was offset from nadir to keep the spacecraft attitude at the bound of the SKI zone. The MDIS boresight was able to track nadir for part of this time until the pivot angle reached its operational pivot limit of -40º. After that point, both the MDIS and MLA boresights were offset from nadir. For Mercury flyby 1, MDIS used the last seconds of the nadir tracking period to obtain its first color photometry images. The aimpoint for MDIS was set to the latitude, longitude, and height selected for the dedicated color photometry periods. In this case, the MDIS pivot angle was always offset from alignment with the +Z axis since the surface target point never coincided with nadir (the spacecraft ground track). For the Venus flyby, the spacecraft attitude began with +Z aligned with nadir and Sun elevation moving from the positive to negative SKI elevation bounds and ended with the Sun fixed at the -12º bound and +Z offset from nadir. This was reversed at the Mercury flyby where the spacecraft attitude started with the Sun at the -12 º elevation bound of the SKI zone and +Z offset from nadir. At the end of the Mercury nadir-tracking period, the Sun elevation moved from -12º towards the +12º bound with +Z aligned with nadir. Dwelling at one extreme of the SKI bound and then moving between these bounds to track nadir is typical of flyby geometry and will likely be repeated for the remaining two Mercury flybys.

The commanding sequence for nadir tracking with a secondary MDIS target first loads parameters that define the true MLA boresight in the spacecraft body frame and for the pointing option that specify the desired aimpoints for the MLA and MDIS boresights. Then the command to switch to pointing option 6 is issued. MDIS must be commanded to use the G&C pivot angle; this can be in effect as a result of a previous MDIS observation or a specific command can be added just before nadir tracking begins. After sufficient time to turn and settle at the target attitude, commands are issued to shutter the desired NAC and/or WAC images. The pivot angle can and will change during the observation period. The MLA instrument must also be commanded to use the G&C-provided range and slant angle values. This command is issued several minutes prior to the turn to nadir-tracking attitude as part of the MLA warm up (in preparation for science data collection).

IV. MASCS Sweeps

In contrast to the MDIS single-target observations and MLA observations that focus on the planet itself, one type of MASCS observation is intended to cover large areas of space ahead of or behind the planet to sense the planet’s atmosphere (Venus) or exosphere and neutral sodium tail (Mercury). These “sweeps” are designed to scan across the interior of a tube extending out from the spherical planet whose axis is the direction from the planet to the Sun (planet-Sun line). The size of the tube is set at 1 planet diameter on either side of the planet limb; the tube radius is thus 1.5 planet diameters. The time period when sweeps are performed begins when the spacecraft is close enough for the expected elemental signatures to be detectable by the Ultraviolet and Visible Spectrometer (UVVS) in MASCS and ideally continues until the spacecraft is close enough to the planet that the +Z axis begins to intersect the planet itself when pointing into the tube. Because the UVVS FOV is a small rectangle – 1º x 0.4º - and the instrument is fixed to the spacecraft, the spacecraft must be rotated to move the FOV over the much larger sweep area. The spacecraft is first oriented with the –Y axis aligned with the planet-Sun line (which is nearly coincident with the spacecraft-Sun line during the flybys) and the +Z axis in a plane normal to this line pointing up into the tube extending out from the planet. The +Z axis is rotated in this plane by the appropriate angle to move from one edge of the tube to the other. The angular arc to be traversed depends on distance of the spacecraft from the planet and increases with decreasing spacecraft distance from the planet as shown in Fig. 5. A scan pattern is used to rotate the spacecraft about the Y axis through an angle that causes the +Z axis to move through the tube. The rotation rate is chosen to allow sufficient time to collect between four and seven UVVS scans of the target area where each UVVS scan takes 30 s. Because the locations of the tube edges and the angular extent of the tube changes over time, the base pointing target for the +Z axis and the scan pattern parameters have to be adjusted periodically during the sweep periods. The attitude stays in the center of the SKI zone during the sweeps.

In the absence of any other instrument observations that require pointing during sweep periods, sweeps can be commanded with a single pointing option and superimposed scan patterns. The commanding is somewhat more complex when other observations are interleaved with the sweeps. For both flybys, the sweep periods overlapped with times when MDIS had requested images of the planet for its approach or departure movies. Table 2 lists the times, sweep angle sizes, and rates for both flybys. Sweeps were performed before closest approach at Mercury flyby 1 and after closest approach at Venus flyby 2. Sweeps continued much closer to the planet for Mercury 1 so that the maximum sweep angles were much larger than those done at Venus. The scan rate had to be adjusted to remain at a level within the control authority of the wheels for these later sweeps. For all sweep periods, the MASCS instrument was set to continuously acquire UVVS internal scans from the start to the end of the period. The instrument configuration through each sweep period was not changed in response to any of the attitude adjustments.

Table 2. MASCS Sweeps

Activity	Flyby	Start and Duration of Sweep Period	Sweep Angle and Rotation Rate Ranges	Comments
Stand-Alone Sweeps #1	Venus 2	20 minutes starting ~1.5 hours after closest approach	54.5º to 50º 0.005 to 0.00425 rad/s	
Departure Movie - Sweep Interleave	Venus 2	100 minutes, starting 1 hour, 50 minutes after closest approach	47º to 24º 0.006 to 0.0034 rad/s	Movie images taken every 20 minutes
Approach Movie – Sweep Interleave	Mercury 1	75 minutes, starting 2 hours, 40 minutes before closest approach	16º to 30º 0.00135 to 0.0022 rad/s	Movie images taken every 20 minutes
Stand-Alone Sweeps #1	Mercury 1	19 minutes, starting 1 hour, 20 minutes before closest approach	32º to 41º 0.0026 to 0.00325 rad/s	
Stand-Alone Sweeps #2	Mercury 1	22 minutes, starting 54 minutes before closest approach	47º to 133º 0.0033 to 0.0087 rad/s	

A. Stand-Alone Sweeps

When there are no concurrent MDIS observations, sweeps are implemented using the +Z pointing option (option 2) and superimposed scan patterns. Inertial directions to the center and both outer edges of the sweep tube are computed at specified times using the latest available spacecraft trajectory solution. The sweeps are broken up into either half or full arcs where the spacecraft rotates either from the center to one of the outer edges or from one edge to the other. The angles between the inertial directions to the sweep center and edges define the angular extent of the full and half arcs. The different tube edges are denoted “left” and “right” to distinguish between them. The direction of travel over a full or half arc depends on the starting and ending locations. Center to right and left to right arcs are -Y rotations, while center to left and right to left arcs are +Y rotations. The rate of rotation is set by the number of UVVS scans to be performed and the angle to be traversed. With seven UVVS scans at 30 s each, 210 s is allocated for the rotation across a full arc. The rotation rate is capped at the control system maximum of 0.015 rad/s if the sweep angle divided by the duration for 7 scans exceeds this limit.

A typical command sequence first sets parameters for pointing option 2 to point +Z at the center of the tube. A scan pattern is set to rotate about –Y so that the +Z axis moves out to the right edge. Once the scan rotation is complete, parameters for pointing option 2 are adjusted for the location of the right edge at the new current time. The next scan pattern is set to rotate about +Y so that the +Z axis moves through a full arc from the right to left edges of the tube. When the scan rotation to the left edge is complete, parameters for pointing option 2 are adjusted for the location of the left edge at the current time. The next scan pattern is set to rotate about –Y to move through a full arc back to the right the tube. A series of full arcs is built up with continuous adjustment to the sweep edge locations and rotation rates adjusted to the changing sizes of the sweep angles. The sequence typically ends with a half arc moving back to the center of the tube that is closer to the planet-pointing attitude used for the next observations by other instruments. An example stand-alone sweep sequence is shown in Fig. 6(a). The aimpoint vectors for pointing option 2 are specified as directions in the inertial frame. These are not adjusted by the flight software when the sweeps are executed. They are updated as necessary in the design cycle prior to finalizing the command sequence as the spacecraft trajectory solution is refined on the ground.

B. Interleaving Sweeps with MDIS Movies

When sweeps are interleaved with MDIS imaging, the double target pointing option (option 6) is used for the sweeps and the MDIS pointing option (option 4) is used for the imaging periods. The +Z targeting with pointing option 6 is identical to that using pointing option 2 for stand-alone sweeps. The secondary targeting for MDIS is set to the same targeting used for pointing option 4 which points the MDIS boresight at the specular point on the planet for the movie images. Movie images are positioned between sweep segments that end and start at the center of a sweep arc as shown in Fig. 6(b). At the end of a sweep segment with +Z at the center position, the pointing option is switched from 6 to 4 with the new target being the specular point on the planet. After waiting sufficient time for the spacecraft to settle after this small turn to put the specular point in the YZ plane, a set of movie images is acquired. The pointing option is then set back to 2 with +Z targeted to the sweep center at the current time. The sweeps then continue with a scan pattern rotating out towards one of the sweep edges. Adjustments to pointing option 2 parameters and new scan patterns proceed as for stand-alone sweeps to move over full and half arcs between movie images. The number of full and half arcs covered between consecutive movie images depends on the time spacing of these images requested by the MDIS team. Early in the design cycle for Venus flyby 2, the movie images were to be taken every 5 minutes and sweeps were to be performed concurrently for 24 hours after closest approach. This tight spacing permitted only two half-arcs – from center to one edge and back from that edge to the center – to be sequenced between movie images and also limited the time allowed for settling at the movie attitude before taking the images. The spacing between images was later changed to once every 20 minutes and the total duration of the sweep period was reduced to just 2 hours to decrease the number of commands needed to interleave the sweeps and movie images. For Mercury flyby 1, there was only a brief period of 1.5 hours when the sweeps were interleaved with approach movie images. With images taken every 20 minutes, three full sweeps were acquired between images; the full sweeps were bracketed by sweeps from the center to an edge after the preceding movie image and from an edge back to the center before the next movie image. Three periods of stand-alone sweeps were sandwiched between other approach MDIS observations but MDIS images were not acquired within these sweep periods.

The G&C software outputs an MDIS pivot angle when using pointing option 4 and 6, but not when using pointing option 2. The geometry at Venus 2 dictated that MDIS would be at its -40º operational pivot angle limit during the period when the movie images would be interleaved with sweeps. This meant that MDIS could be set to move to the G&C pivot angle and left in that configuration for the entire interleave period. There would be no additional pivot motion when switching between pointing options 6 and 4. This was not the case at Mercury flyby 1. Because the pivot angles required to keep MDIS as close as possible to the specular target point as the attitude changed over each sweep were within the operational limits, the G&C pivot angle did vary during the sweeps and MDIS would have been moving unnecessarily when no images were being taken if set to follow the G&C angle for the entire period. Manual commands were inserted into the sequence to move MDIS to a pivot position close to that expected for the next movie image at the end of each image taken while interleaving with sweeps and to set MDIS to respond to the G&C pivot angle just before that next movie image. These commands prevented MDIS from responding to the G&C pivot angle during the sweeps. For future flybys with similar geometry, the sweeps may be commanded using pointing option 2, as there is no need to use pointing option 6 when MDIS is not responding to the G&C pivot angle.

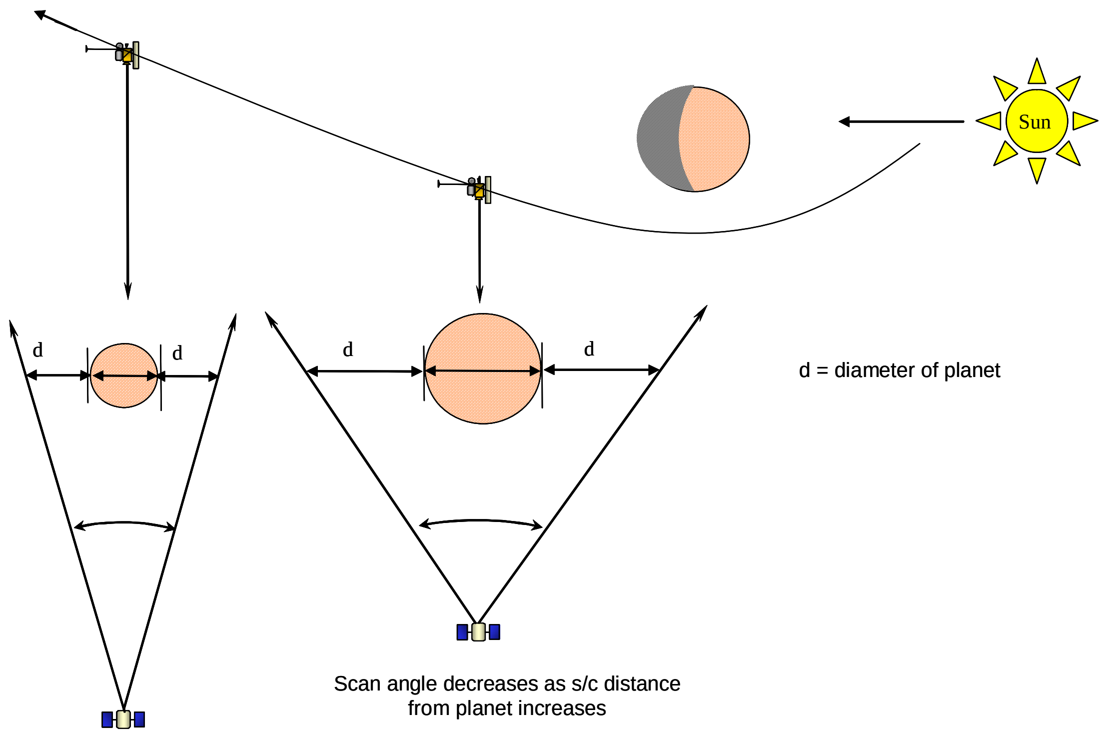
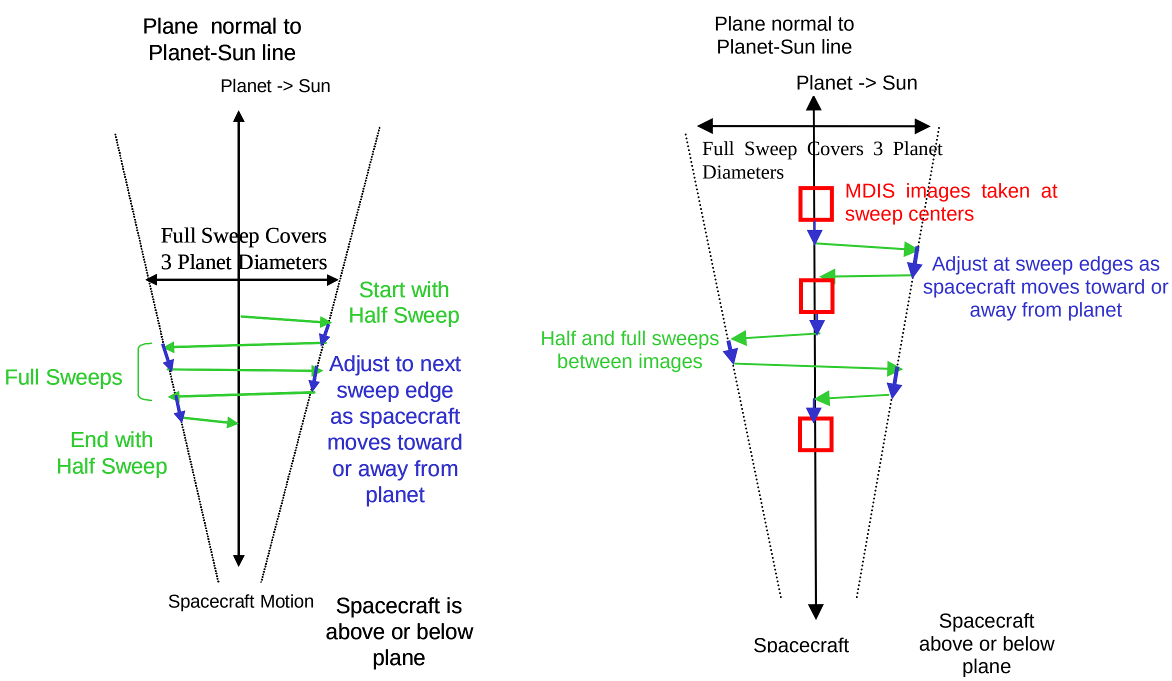


Figure 5. MASCS Sweep Geometry.

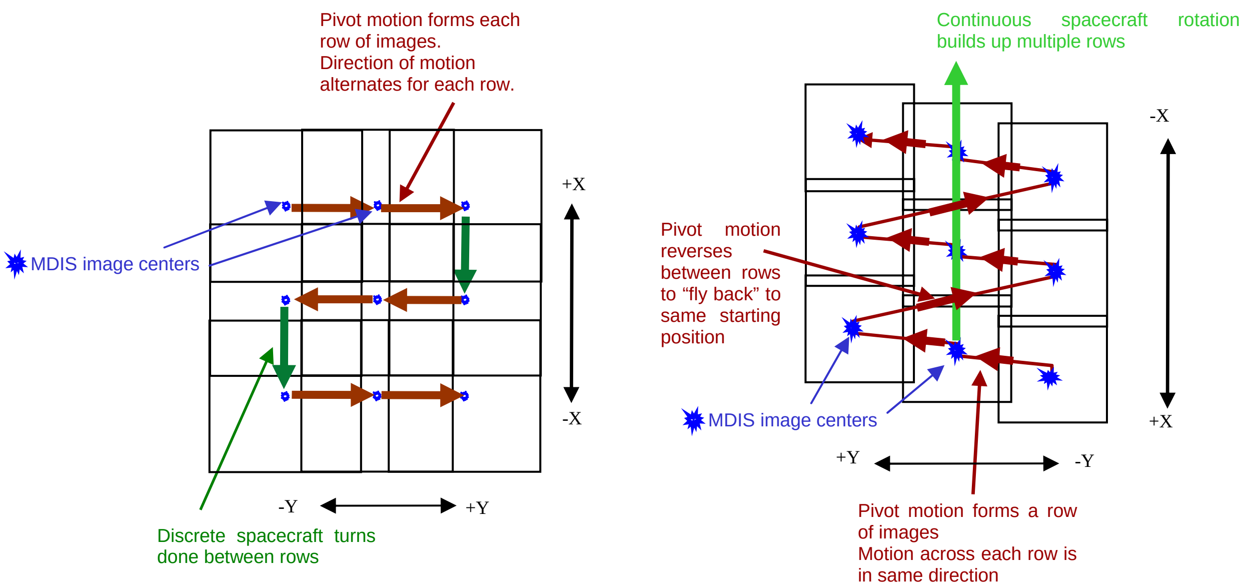


a) Stand-Alone Sweeps **b) Sweeps Interleaved with MDIS Images**

Figure 6. MASCS Sweep Implementation

V. MDIS Mosaics

Perhaps the most complex pointing designs for both flybys were the mosaics taken with the MDIS cameras. Each mosaic was to obtain images aligned in roughly a rectangular grid with a specified overlap between each imaging position; the entire grid was targeted to cover either a portion of the illuminated surface of the planet, the full visible disk, or the full illuminated portion of the visible disk of the planet. Full-color mosaics using the WAC were to capture multiple images using different filters at each mosaic position. Monochrome mosaics using the NAC were to capture only one image using a single filter at each mosaic position. There were several alternatives available for combining G&C and MDIS pivot commands to accomplish the positioning desired for the mosaics. It would have been possible to manipulate the G&C software parameters for MDIS pivot motion, spacecraft base pointing, and scan patterns to have the required pivot angle profile passed to MDIS entirely from the G&C software. MDIS can also accept "manual" commands to move the pivot directly without reference to the G&C-provided angle or to apply an offset to the G&C-provided angle. The team preferred to use the pivot offset angle commands to simplify coordination with other MDIS commands to set filters and exposures before each image was taken. The "rows" of each mosaic would be assembled by moving the MDIS pivot through a specified series of offset positions applied to the "base" pivot angle provided by the G&C software. The change in offset angle between each position was set by the desired FOV overlap for NAC or WAC frames. The total angle change over the row was set by the size of the area to be covered. The G&C base pointing was selected to place the MDIS boresight at the center of each row. Motion from one row to the next was accomplished by either commanding a small spacecraft turn between each row or by a slow, continuous rotation over the entire mosaic duration. The size of the discrete turn or the magnitude of the rotation rate was determined by the desired overlap between images. Mosaics using discrete turns between rows are called "step-and-stare" mosaics and those using a constant rotation rate are called "scanning" mosaics. These two mosaic design techniques are illustrated in Fig. 7 and compared in the following paragraphs.



a) Step-and-Stare Mosaic **b) Scanning Mosaic**

Figure 7. MDIS Mosaic Implementations

A. Step-and-Stare Mosaics

G&C commanding for a step-and-stare mosaic is fairly straightforward as this had been the expected mosaic implementation when the flight software was developed before launch. The MDIS pointing option (option 4) is used to position the MDIS boresight at the center of each row. The aimpoint for pointing option 4 is set to some location on the planet that is the desired center of the mosaic. Parameters that define the MDIS pivot plane and zero pivot angle location are initially set to make the first row of images lie at the required offset from the mosaic center. When using these "virtual" boresight and pivot plane for MDIS the software computes a spacecraft attitude that places the true boresight at the proper offset for the first row of the mosaic. Once the spacecraft settles at the first attitude, the camera shutters the desired number of images for a row with pivot offset angle commands interspersed between commands to take the images. The pivot offset angle sequence is centered at zero and has positive and negative offsets of the same magnitude around the central "zero offset" position. At the end of each row, the G&C "virtual" MDIS boresight is adjusted to cause the spacecraft to turn so that the true boresight moves to the correct position for the next row. Sufficient time is allowed between the last image in the previous row and the first image in the next row for the spacecraft to execute the small turn and stabilize at the new attitude. At the end of the mosaic, the G&C

MDIS parameters are returned to their nominal values and the pivot offset angle is set to zero. The direction of motion along each row is reversed for alternate rows by adjusting the values of the pivot offset angles.

Table 3 gives sizes and pointing targets for the three step-and-stare mosaics performed at the two flybys. The step-and-stare mosaic technique was used for WAC full-color mosaics of the entire illuminated portion of both Venus and Mercury. These mosaics consisted of 3 rows with 3 positions in each row. Eleven WAC images were taken at each position (99 total images). This technique provided a more stable spacecraft while images were being shuttered for the WAC mosaics, which facilitates ground processing that combines the images taken at each position into a single color image and assembly of the mosaic into one image. One of the NAC mosaics of Venus was also performed as a step-and-stare mosaic. Originally all three of the Venus flyby 2 NAC mosaics were designed as step-and-stare because there had been insufficient time to develop and verify a scanning mosaic technique. One viable scanning mosaic technique was finally perfected late in the design cycle for the Venus flyby, allowing two of the NAC mosaics to be switched to use that method.

B. Scanning Mosaics

G&C commanding for a scanning mosaic proved to be less straightforward than the step-and-stare technique because it had not been anticipated before launch that spacecraft motion would be desirable or allowed while the cameras were taking images. The flight software includes checks that prevent superimposing a scan pattern when the MDIS pointing option (option 4) is selected. While many of the other pointing options do permit scan patterns to be used, most of them do not compute a pivot angle to target the MDIS boresight and could not directly use the MDIS pivot geometry in determining the spacecraft attitude. There was some concern that the "base" spacecraft attitude would not properly follow the changing spacecraft-planet geometry needed when pointing MDIS if other spacecraft-fixed vectors were used to define the attitude. Also the MDIS mosaic command set had already been designed to output offset angles centered around zero instead of absolute pivot positions where the base value would have to be derived from the spacecraft trajectory geometry. A generic pointing option (option 1) is included in the guidance software that requires the user to explicitly specify the primary and secondary vectors in the body frame and the inertial frame that define the desired attitude. One of the ways that the spacecraft boresight (primary) vector can be specified is by an MDIS pivot position. When an MDIS pivot angle is set as the boresight, the software outputs that constant angle to MDIS as the G&C angle. The aimpoint associated with this boresight can be specified in the same ways as for pointing option 4 so the same planet-relative locations can be used as is done for any other MDIS observation. Specifying that the –Y axis be pointed as close as possible to the Sun as the secondary vectors is equivalent to what the software assumes for pointing option 4. The key difference when using pointing option 1 with an MDIS pivot angle is that the G&C software will not allow the MDIS pivot angle to vary whereas MDIS pivot motion takes preference over spacecraft motion for pointing option 4. The spacecraft orientation relative to the planet, and therefore relative to the Sun, must be changed to follow the selected target position when using pointing option 1. Since the MDIS pivot plane is nominally the YZ plane, this means that the Sun elevation can change during the course of the scanning mosaic. The direction of MDIS pivot rotation also means that motion along the rows set by pivot offset angles is equivalent to spacecraft rotation about the X axis. To get the desired spacing between rows in the orthogonal direction requires spacecraft rotation roughly about the Y axis so that the scan pattern would be set for rotation in the spacecraft body frame about the Y axis. Mosaic center target and size had to be chosen so that the maximum and minimum pivot positions were within the pivot operational range when the offsets are added to the base position set with pointing option 1 and also so that the spacecraft attitude variation did not exceed the SKI bounds while the mosaic was executing.

While not optimal for spacecraft thermal configuration, motion towards the bounds of the SKI zone or dwelling at the edge of the zone was not as much of a concern for Venus flyby 2 as at Mercury flyby 1 due to the larger distance of Venus from the Sun. At Venus, the solar panels could be pointed directly at the Sun and a wide range of Sun offset angles could be tolerated without inducing extreme temperature variations. At Mercury, the panels needed to be offset from the full "face on" orientation to maintain a safe temperature while still generating sufficient power. This meant that the panels might have to rotate during the mosaics as the spacecraft attitude changed the Sun direction relative to the spacecraft. It is difficult to predict precisely when motions will occur with the automatic Sun-tracking control mode for the panels. Keeping a fixed spacecraft-Sun orientation to prevent panel motion during imaging and maintaining a uniform thermal environment for the panels motivated the search for another scanning mosaic implementation. A constant spacecraft-Sun orientation during the mosaic would be possible only if the MDIS pivot could rotate over the composite range needed both to track the target motion and to apply the offsets for positions within a row. The G&C software would have to provide the underlying range of pivot angles for target tracking instead of the fixed pivot angle provided when using pointing option 1 with a scan pattern. The only other pointing option that permitted use of a scan pattern and output an MDIS pivot angle is pointing option 6. However, the MDIS pointing is a secondary goal for that pointing option. Normally pointing option 6 will try to point another boresight fixed in the body frame at the moving target within the SKI constraints. In order to get pointing option 6 to appear to give preference to the MDIS pointing it would be necessary to constrain the ability to move the primary boresight as close as it might otherwise be able to using the default SKI bounds. Setting the primary boresight to the +Z axis with the secondary boresight kept at the –Y axis forces the primary aimpoint to lie in the spacecraft YZ plane. Because this is the nominal pivot plane for MDIS, it means that the primary aimpoint is now also in the pivot plane. Setting the primary and secondary aimpoints to the identical planet-relative target means that the Sun and the target point are both in the YZ plane. Using the default guidance SKI bounds, the Sun elevation could be non-zero to move +Z as close as possible to the target aimpoint. This could mean that the MDIS pivot angle would be closer to its operational limits than it needed to be if the –Y axis were kept aligned with the Sun. But if the guidance SKI bounds are altered so that they define a very small area around the –Y axis, the software is forced to keep –Y aligned with the Sun and the +Z axis effectively switches to the secondary boresight and serves only to put the target in the YZ plane. The pivot operational range is much larger than the SKI elevation bounds, and for Mercury flyby 1 it was possible for MDIS to point directly at the target aimpoint for the mosaics when –Y was constrained to stay fixed on the Sun. Having the G&C software provide a varying pivot angle for MDIS has the advantage that the angle is derived from the on-board ephemeris models that are updated with the latest available navigation solutions for the spacecraft trajectory. This allows the actual pivot angle to vary from what might have been computed using the information available several weeks before the flyby when the final spacecraft command sequences have to be generated and tested.

G&C commanding for a scanning mosaic begins similarly to that for a step-and-stare mosaic. A base pointing option is used to position the MDIS boresight at the center of the first row. The pointing option for a fixed G&C pivot angle and varying Sun elevation during the mosaic is option 1 with boresight set to an MDIS pivot angle. The pivot angle value is chosen as the average of the values that would keep the MDIS boresight tracking the aimpoint over the duration of the mosaic if pointing option 4 were used. G&C tools are used to determine this range of angles from the navigation trajectory solutions and planetary ephemerides. The pointing option for a varying G&C pivot angle and the Sun fixed at 0º elevation (along the –Y axis) is option 6 with the primary boresight set to the +Z axis and the secondary boresight being the MDIS boresight. The primary aimpoint for either pointing option is set to some location on the planet that is the desired center of the mosaic. For pointing option 6, the secondary aimpoint (used for MDIS) is set to this same target. Parameters that define the MDIS pivot plane and zero pivot angle location are initially set to make the first row of images lie at the required offset from the mosaic center. The software is commanded to use this "virtual" boresight and pivot plane for MDIS so that the spacecraft attitude places the true boresight at the proper offset for the first row of the mosaic. When using pointing option 6, G&C parameters defining the bounds of the SKI zone are set to near-zero values that force the –Y axis to be kept aligned with the Sun. After allowing sufficient time for the spacecraft and MDIS pivot to turn to their starting locations, a scan pattern is commanded that causes the spacecraft to begin a slow rotation nominally about the Y body axis. The direction of rotation is matched with the virtual boresight setting so that the MDIS boresight traverses the desired area on the planet. Simultaneously with the beginning of spacecraft rotation, the camera is commanded to begin shuttering the desired number of images for a row with pivot offset angle commands interspersed between commands to take the images. At the end of each row, the pivot is commanded to "fly back" to the first offset angle position for the next row. Extra time is allotted to move between positions at the end of one row and the beginning of the next since the total angle traversed is larger than the change between two consecutive positions in a row. The sequence of pivot offset angles in each row is identical so that the direction that images are taken is the same in each row. Mosaic sizes and execution times relative to the closest approach to the planet are carefully chosen to ensure that the rotation rate required to get the desired spacing between rows keeps the smear during images within acceptable limits. The rate is set so that the desired angular overlap between images from row to row is traversed in the time between the first images in consecutive rows. For the varying pivot angle scanning technique, the required total pivot angle to be traversed is checked to ensure that the pivot hardware can accomplish the movement in the time allotted between each image in a row and between rows.

Table 3 lists the mosaics implemented with each of the two scanning mosaic techniques at each of the flybys. A single NAC image was taken at each position so that the total number of images is just the product of the number of row positions and number of rows. The scanning mosaic technique with a fixed pivot angle output by the G&C software was used for two of the three NAC mosaics taken at Venus flyby 2 and all but one of the NAC mosaics taken at Mercury flyby 1. Unfortunately, the technique with a varying G&C pivot angle had not been conceived at the time of Venus flyby 2. A flight test of the new technique had been performed in September 2007 using a star field as a target. While that test was successful, it did not fully emulate conditions during a planetary flyby where the aimpoint direction can change rapidly over the course of the mosaic. Ultimately it proved possible to find a fixed panel position with acceptable temperature excursions for all attitudes with the Sun elevation within the SKI bounds for Mercury flyby 1, which reduced concerns about Sun elevation changes during mosaics. All of the highest priority NAC mosaics for Mercury flyby 1 were implemented using the original scanning technique. The newer scanning mosaic technique was used for the last and lowest priority NAC mosaic at Mercury flyby 1. NAC departure mosaic #4 executed successfully, providing the final flight test needed to permit using this new technique if required at the remaining Mercury flybys

All of the scanning mosaics executed as expected during Venus flyby 2, but there was a problem with the timing of pivot commands during the NAC high-resolution mosaic #1 taken during Mercury flyby 1. MDIS commands are spaced 5 s apart for the NAC mosaics. A command to shutter an image is supposed to be issued on the same second as the command to move to the next pivot position. The MDIS software is designed to first complete the image and then act on the pivot move command. However, the sequence issues a single command to MDIS to shutter multiple images separated by a fixed interval while each pivot offset command is sent individually. All MDIS commands are passed through the flight software to the MDIS control software in the instrument data processing unit (DPU). One of the pivot offset commands was issued just 4 s after the previous command instead of the intended 5 s. The camera itself maintained the regular 5-s spacing between images so that one of the images was taken while the pivot was in motion, causing a gap at one location in the mosaic. Subsequent investigation has shown that this same timing problem had occurred in the flyby simulations run prior to uploading the sequence to the spacecraft but was overlooked in checking the simulation results. The timing of the command transmissions is usually quite regular but is sometimes affected by the way commands are packaged for execution by the sequence software. For this mosaic, the pivot commands were split across two partitions instead of all being contained in the same partition. Pivot and image command timing will be checked more closely in mosaic sequences for future flybys, and partitioning of commands may be controlled to avoid the potential for similar gaps.

VI. Special Considerations and Pointing Constraints

The observations described in the preceding sections were for the most part achievable within system constraints such as SKI bounds and reaction wheel capabilities. For each flyby, there were a few observations that required special commanding to work within these constraints or to avoid possible violation of them. At Venus flyby 2, the SKI bounds did constrain observations desired on first approaching the planet. The MDIS team wanted to obtain pictures starting about 4 hours before closest approach with the planet disk just outside the edges of the NAC and WAC fields of view to calibrate their sensitivity to scattered light. The trajectory was such that the planet still entirely filled the camera FOV with the pivot at its +50º operational limit and the spacecraft tilted to the +12º SKI elevation bound of the SKI zone prior to 2 hours before closest approach. The scattered light images could not be moved later in time without sacrificing other imaging activities with higher priority. A full scattered light assessment required obtaining images with the lit planet at distances of 100, 250, 500, and 1000 pixels from each of the 4 edges of the NAC or WAC FOV. The SKI and pivot angle bounds prevented obtaining images with the planet off the "top" edge corresponding to pivot rotation towards the +Y axis. The images with the planet off the opposite or "bottom" edge were easily obtained by rotating the pivot back from its limit towards the +Z axis while holding the spacecraft attitude fixed. Rotation about the MDIS boresight at its 50º pivot position to move the planet off the two remaining edges would have put the spacecraft attitude outside of the SKI bounds. But moving the Sun line out of the YZ plane through a series of non-zero azimuth angles while holding the elevation fixed at the +12º bound would allow the planet to move outward roughly along each edge. Larger azimuth excursions were needed for the WAC imaging due to its larger FOV as compared to the NAC. The resulting series of images approximated a "T" with the planet at the intersection of the two lines and images strung along the three directions outward from the intersection. Pointing option 1 was used for the scattered light observations with the aimpoint set to the center of the planet. The boresight in the spacecraft body frame was set with an elevation corresponding to the MDIS pivot at 50º and azimuth varying in positive and negative increments from zero corresponding to the desired pixel offsets between the planet limb and the edge of the NAC or WAC FOV. The MDIS pivot was manually commanded to the 50º position. Images were acquired along the "left" edge of the T, then along the "right" edge. The parameters for pointing option 1 were adjusted to rotate the spacecraft to the each consecutive position along the T. The final attitude returned to the intersection point of the T. The MDIS pivot was then manually commanded to move to pivot positions smaller than 50º that provided the desired offsets from the bottom edge of the FOV. The attitude changes at Venus flyby 2 began with the WAC scattered light imaging at 4 hours before closest approach. The NAC scattered light imaging followed at about 2 hours before closest approach.

The commanded attitudes for the flybys were always within or at the edge of the SKI zone. The spacecraft cannot instantaneously move from one attitude to another, and the control logic determines the path taken to move between two consecutive commanded attitudes. It is often the case that the actual attitude temporarily moves outside the inner SKI bounds while turning to a new attitude that is at or near the SKI limits. In extreme cases, the attitude can move outside the larger “middle” SKI bounds, causing a safing turn to be performed to align the Sun with the –Y axis and a safe mode demotion. If this were to happen during any of the flyby turns all remaining science observations would be lost. Simulations showed that excursions due to controller overshoot could be large enough to induce a safe mode demotion for the first turn of Venus flyby 2 for the WAC scattered light imaging. The original design put the starting attitude at a corner of the inner SKI zone with maximum offsets in both azimuth and elevation. The designs were changed to have the extreme attitude stay 2º within the inner SKI zone with the Sun at ±8º azimuth and elevation at +10º. In addition, the first turn from downlink attitude was broken up into three separate turns. The first and largest segment of the turn moved from the downlink attitude to put the planet in the YZ plane with –Y aligned with the Sun (Sun at 0º azimuth and elevation). The second segment of the turn applied the first azimuth offset ending with the Sun at -8º azimuth and elevation still 0º. The third segment applied the elevation offset ending with the Sun at the extreme location at -8º azimuth and +10º elevation. The decrease in Sun azimuth and elevation extremes for the WAC scattered-light imaging meant that the maximum offset of the planet from the edge of the FOV was decreased from the desired 1000 pixels.

Table 3. MDIS Mosaics.

Activity	Flyby	Base Target (Aimpoint Selection)	Mosaic Type	Mosaic Size (# of Positions per Row x # of Rows)	Pivot Angle Range (º)	Sun Elevation Range (º)
NAC Approach Mosaic	Venus 2	Nadir	Step-and-stare	11 x 3	49.71 to 36.28	+12 (at SKI limit)
NAC Hi-Res Photometry Mosaic	Venus 2	Latitude/longitude/height	Scanning Fixed G&C pivot angle	5 x 10	42.68 to 37.31	7.59 to -2.66
WAC Approach Color Mosaic	Venus 2	Nadir	Step-and-stare	3 x 3	30.51 to 49.48	12 to 9.72
WAC Departure Color Mosaic	Mercury 1	Nadir	Step-and-stare	3 x 3	26.85 to 39.84	0 (on –Y axis)
NAC Departure Mosaic	Venus 2	Specular	Scanning Fixed G&C pivot angle	6 x 12	-32.24 to -38.96	-12 (at SKI limit)
NAC Approach Mosaic	Mercury 1	Specular	Scanning Fixed G&C pivot angle	5 x 11	-36.98 to -31.62	+0.55 to -0.55
NAC Hi-Res Mosaics	Mercury 1	Latitude,longitude,height	Scanning Fixed G&C pivot angle	#1 17 x 4 #2 11 x 9	3.64 to 22.75 33.69 to 20.25	-4.76 to 5.93 -2.57 to +3.01
NAC Departure Mosaics	Mercury 1	#1 Specular #2 Specular	Scanning Fixed G&C pivot angle	#1 9 x 11 #2 8 x 10	39.7 to 29.23 40.77 to 31.38	-0.904 to +0.899 -0.645 to 0.414

		#3 Specular		#3 6 x 8	41.14 to 34.44	-0.304 to 0.018
		#4 Latitude/longitude/height	Scanning Varying G&C pivot angle	#4 6 x 7	41.77 to 34.80	0 (on –Y axis)

The possibility of SKI violations from controller overshoot was also discovered for the turn from MDIS color photometry imaging to nadir tracking for MLA at Venus flyby 2. The nadir tracking period began with the time when +Z could be pointed directly at nadir by moving the Sun elevation from +12º to -12º and ended with the Sun fixed at the -12º bound. The original single turn to start nadir tracking would move from the center of the SKI zone to put the Sun at the maximum bound of +12º elevation. This turn was also segmented so that the initial transition would only result in Sun elevation of about +8.5º. The next segment changed the targeting to put +Z as close as possible to nadir and was timed so that the required Sun elevation was well inside the SKI zone.

The Sun-planet geometry was more favorable at Mercury flyby 1 and there were fewer observations that required attitudes offset from the center of the SKI zone. However, there was one period near closest approach when the rate of change of the nadir direction as seen from the spacecraft was larger than the maximum turn rate achievable with the reaction wheels. Special turns had to be added to the sequence to accomplish the required large spacecraft rotation between the last MASCS sweeps and the start of nadir tracking. Simulations using aimpoint targets derived from the ephemeris models always resulted in SKI violations because the controller could not follow the commanded rate. An automatic turn driven by ephemeris-based targeting was replaced by aimpoints using inertial vectors and a scan pattern to perform the required rotation at a reasonable rate. At the end of the last sweep, the attitude was commanded to put the Sun on the –Y axis and keep the +Z axis as close as possible to the inertial direction to the center of Mercury at that time. A scan pattern was used to rotate by 158º about the Y axis at a rate of 0.008 rad/s three minutes after this turn. Immediately after the scan was disabled, the secondary reference for the base pointing was changed to a new inertial vector that corresponded to the nadir direction at that time. The transition to nadir tracking at this point was another turn from the center of the SKI zone out to the maximum allowed Sun elevation. SKI violations due to controller overshoot were possible as had been the case at Venus flyby 2. To avoid this, the pointing at the end of the forced rotation was changed so that the resulting Sun elevation would be -10º instead of 0º. This reduced the attitude change required when nadir tracking was commanded to a smaller turn moving from -10º to -12º Sun elevation.

One other turn had to be segmented to avoid possible SKI violations for Mercury flyby 1. This was the transition between the color photometry attitude and the starting attitude for the first NAC high-resolution mosaic. Because that mosaic was using the original scanning mosaic technique with a fixed G&C pivot angle, the spacecraft was turning to keep the MDIS boresight correctly following the desired mosaic target. The attitude was in the center of the SKI zone for the preceding photometry imaging and needed to move to a Sun elevation near the -12º limit to start the mosaic. In this case, the segmenting of the turn was accomplished by changing the MDIS pivot angle used as the boresight. A smaller pivot angle of 2º was used for the first turn; this was replaced by a pivot angle of 13º for the actual mosaic. This had the effect of keeping the attitude closer to the center of the SKI bound until the geometry had changed enough that the mosaic target could be reached at a Sun elevation a few degrees inside the lower SKI limit. The potential for a SKI violation when performing similar mosaics at future flybys may be avoided by using the newer technique that keeps the –Y axis aligned with the Sun and varies the MDIS pivot angle commanded by the G&C software.

A final constraint that has been mentioned only briefly in the previous sections is solar panel motion. The control system acts to counteract the torque imparted to drive the panels to new positions, causing a small deviation from the commanded attitude. These deviations can be detrimental to certain types of imaging observations and to the MLA laser altimetry. The impact on altimetry arises not so much from the attitude change itself as from the temporary degradation in the accuracy of the attitude estimate during the change. In the early planning stages for both flybys, options were considered for inserting deliberate commands to move the panels at opportune times between science observations. Eventually power and thermal analyses showed that the panels could be left at fixed positions for the key hours around closest approach with the greatest number of attitude changes. For Venus flyby 2, the panels were placed at their 90º positions 4 hours before closest approach at the start of the MDIS WAC scattered light imaging. They remained in this position until 28 hours after closest approach at the end of the MDIS departure movie. The attitude changes over this period caused the Sun angle relative to the panel normals to vary between 0º and 12º. For Mercury flyby 1, the panels were placed at the 160º position 2 hours and 40 minutes before closest approach just before the start of the MASCS sweeps. They remained in this position until 1 hour and 37 minutes after closest approach when the MDIS departure movie started. There was no need to fix the panel positions during the MDIS movies because the Sun always remained aligned with the –Y axis. The attitude changes while the panels were fixed at 160 º resulted in the Sun offset angle varying between 62.5º and 82º. Commands were added to the sequence to manage the power load before and after eclipse to accommodate these changes in panel-Sun orientation.

VII. Pointing Robustness

As is evident from the discussion in preceding sections, the attitude commanding for most of the science observations depends heavily on the flyby geometry. Changes to the shape of the spacecraft trajectory arc around the planet or to the time at which it passes closest to the planet will change the optimal viewing geometry. The differences are magnified the nearer in time an observation is to the closest approach. Allowing the G&C software to use the on-board ephemeris models to compute the required attitude can mitigate some of the differences between the trajectory used to design the observations and the actual trajectory followed during the flyby. There is always some remaining uncertainty in trajectory knowledge even for the latest solutions generated a few days before closest approach, so attitudes computed on-board may still be slightly different from the intended geometry. The path taken by the reaction wheel control law to turn between any two attitudes and the time to complete the turn is highly correlated with the system momentum at the time the turns are executed. Where possible, the designs should be made insensitive to trajectory and momentum deviations within an expected reasonable range of variations. For MESSENGER, adding robustness to the pointing designs is an iterative process that uses a combination of simulations and knowledge updates performed throughout the design cycle and management of the final spacecraft configuration going into the flyby.

The operations and engineering teams perform a number of activities prior to the flyby that assist in setting up the proper geometry and spacecraft configuration at the flyby itself. A set of trajectory correction maneuvers is scheduled to keep the trajectory following the nominal baseline. After each maneuver is performed, new trajectory solutions are generated that estimate the effect of the maneuver. In addition to simply propagating the effect of the last maneuver to the time of the flyby, the remaining portion of the MESSENGER trajectory may be reoptimized after the maneuver. This can sometimes result in large changes to the time or altitude at closest approach for a flyby since the optimization attempts to minimize the required ΔV over the entire mission. After the final targeting maneuver is executed, the navigation team continues to generate trajectory solutions that incorporate the latest radiometric tracking data and optical navigation images. The operations team can update the on-board spacecraft ephemeris model and command execution times a few days before the flyby using the latest navigation solution. A single command is available that can adjust the times of the commands in the flyby sequence after the command load has been uplinked to the spacecraft. This can be used to move the entire block of commands to preserve the timing relative to closest approach when the predicted closest approach time shifts in the navigation solution. The flight team also manages system momentum through a combination of thruster dumps and changing the orientation of the sunshade and solar panels to use torques resulting from solar pressure. Thruster dumps can be combined with some of the flyby targeting maneuvers and changes can be made to the sunshade and panel "tilts" to drive the system momentum magnitude to a low level leading into the flyby science observations. All of these options were exercised at the Venus and Mercury flybys.

Turn times are part of the allocated duration for each science observation from the start of the design cycle. An initial estimate of turn times is available from the results of generic Monte Carlo simulations, in which all of the key G&C parameters are varied for a wide range of turn sizes and directions. Extra margin is deliberately added to accommodate any changes that may arise as the design cycle proceeds. All of the turns are run through the G&C high-fidelity simulation to confirm that they complete in the allotted time (and also that the desired targets are achieved). This is done repeatedly throughout the design cycle using the latest available trajectory solutions and estimates or actual values for all of the G&C flight and dynamic model parameters. Observations can be run singly, or the entire flyby sequence can be run as a single case. The entire sequence is always run through this simulation whenever the designs are changed, the trajectory solution changes, or any of the G&C parameters changes. The core science period for the flybys is typically several hours. The computer time required to run the full sequence through a Monte Carlo simulation with 500-1000 individual runs is prohibitive. Instead, the most sensitive turns are isolated and Monte Carlo cases are run for them where the initial starting momentum is varied along with all of the other G&C parameters such as sensor biases and alignments and spacecraft inertia properties. The trajectory itself is not varied in the Monte Carlo runs, but the runs are repeated for selected trajectory updates or potential perturbations from the baseline. Monte Carlo runs were done for all of the SKI-sensitive turns for Venus flyby 2 and Mercury flyby 1. These runs helped verify that changes to the designs that segmented what had initially been single turns greatly reduced the probability of a SKI violation when the turns were executed in flight. The operations team also runs the entire sequence through their hardware simulator using the trajectory solution and G&C parameters adopted for the single-case runs of the G&C high-fidelity simulation.

The design cycle for the flybys has two phases. A baseline trajectory is designated by the navigation and mission design teams for each phase. The baseline trajectory used in the second phase of the flyby design cycle can be significantly different if a reoptimization is adapted in the middle of the design cycle. There are often interim trajectory solutions available in addition to the planned releases of the baseline trajectories for each phase. The G&C simulations are repeated each time the official trajectory is changed and for many of the interim solutions. Changes are made to the designs based on the results of these simulations. One of the purposes of the two phases is to allow for changes needed to accommodate trajectory updates. It is possible, though discouraged, to make changes to the designs during the second phase as trajectory knowledge and targeting for the maneuvers performed on approach to the flyby are refined. In both phases, the navigation and mission design team provide a set of "perturbed" trajectories that are representative of 3-σ excursions in spacecraft altitude and time at closest approach to the planet. A number of variations are run with the G&C simulation using these perturbed trajectories. One variation sets the flight code to execute the existing commands at times measured relative to the baseline closest approach and with the baseline ephemeris while using one of the perturbed ephemerides with a different closest approach time in the dynamic model. These runs highlight differences in the observing geometry if the final sequence timing and on-board ephemeris are not changed going into the flyby. A second variation uses one of the perturbed trajectories as the source for both the on-board and dynamic model ephemerides and moves the absolute times of the commands to execute them at the same time relative to the new closest approach time. This tests the expected performance if both the execution time and ephemerides are updated on the spacecraft prior to the flyby. The other variations where only command execution times or on-board ephemerides are updated without changing the other are also run if time permits even though they are not considered representative of the actual configuration for the flyby. If any serious problems are discovered early enough, changes are made to the designs and the runs are repeated. Once the designs pass through these variations with no serious threats to spacecraft safety, no further changes are made to the flyby sequence. A final set of simulations are run using a navigation solution generated just a few days before closest approach. The results of these runs determine whether or not the on-board command timing or spacecraft ephemeris is updated prior to the flyby. The on-board spacecraft ephemeris was updated prior to both Venus flyby 2 and Mercury flyby 1. A time shift of +88 s was applied to the Venus flyby 2 sequence but none was applied for Mercury flyby 1. The navigation solution predicted a change of only 3 s in the time of closest approach to Mercury and simulations had shown there was no significant change in the observation geometry with this small time shift.

VIII. Optical Navigation Imaging

Optical navigation (OpNav) uses images acquired with the spacecraft camera to measure the location of the spacecraft relative to the target planet. It supplements the radiometric tracking data which measures the spacecraft location relative to Earth. The optical navigation images are not part of the flyby science observations, but they are important in improving the spacecraft trajectory solution and determining if additional trajectory correction maneuvers will have to be performed in the final days leading up to the flyby. Characteristics of the MDIS camera make optical navigation imaging for MESSENGER different from that done for other missions such as Cassini. The traditional optical navigation image captures the planet against a background star field. The exposure time is set to make the stars detectable while not saturating the bright planet. Given the dynamic range of the MDIS cameras and the distribution of brighter stars it is rarely possible to capture both stars and the planet in a single image. For MESSENGER, images of a nearby star are taken separately from images of the planet. The spacecraft attitude changes over several degrees between the star images and the planet images. It is important that nothing disturb the boresight of the camera while the images are being taken. For this reason, the pivot angle is fixed and the solar panels are prevented from moving during each optical navigation session. The planet position is specified as a location in the inertial frame instead of allowing the software to compute it from on-board ephemeris models.

The SKI elevation bounds and the pivot operational limits determine the time prior to the flyby when optical navigation imaging can begin. For Mercury flyby 1, nine optical navigation image sets were taken starting 5 days before closest approach and ending about 1.5 days before closest approach. The pivot angle was at the -40º operational limit for the first three of these sets, and the Sun elevation angle started at -6º when pointing at the planet. As the spacecraft moved closer to the planet the pivot angle moved in towards 0º, and the Sun elevation moved toward 0º. The last OpNav image set had the pivot angle at -29.8º and Sun elevation at 0.160º when pointing at the planet. The stars imaged in the OpNav sessions were chosen such that the Sun elevation would remain within the SKI bounds with the pivot set at the angle needed to image the planet.

The optical navigation imaging sessions performed at the Venus flyby were included as practice for the Mercury flyby. The Venus atmosphere makes it difficult to determine accurately the planet position in the images so these were not used in the navigation solutions. In fact, the Venus flyby 2 OpNav images were taken after closest approach when illumination conditions made the planet disk appear closer to the way Mercury would appear before the flyby. Eight optical navigation image sets were taken starting 15 hours after closest approach and ending about 9 days after closest approach. The pivot angle varied between -34.48º and -24.79º from the first to last Venus flyby 2 OpNav as the spacecraft moved away from the planet. The Sun elevation angle was always 0º when pointing at the planet.

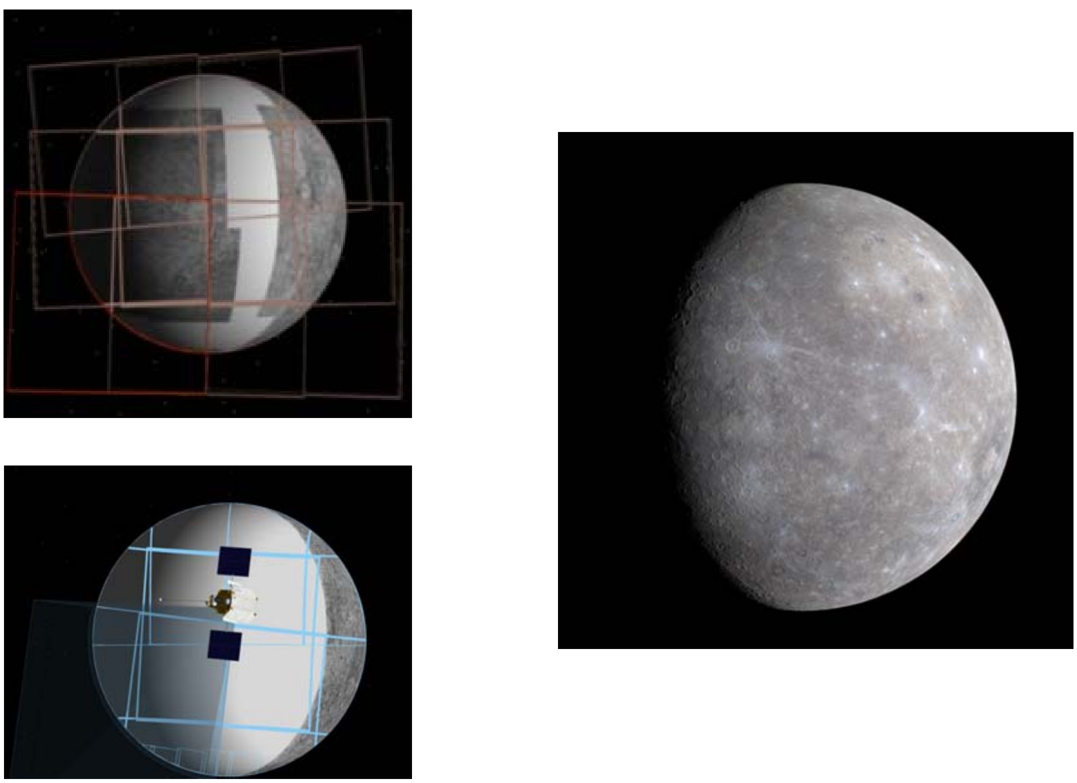
The basic command sequence for optical navigation imaging sessions is identical for Venus flyby 2 and Mercury flyby 1. The first commands put the solar panels in a fixed position and set the control mode to prevent motion while the images are being taken. Pointing option 1 is used to change the attitude for three different image sets. The boresight is set to the same MDIS pivot angle for each of these three turns. The aimpoint for the first turn is a target star specified by right ascension and declination angles in the inertial frame. After allowing the spacecraft to stabilize at this attitude, two NAC images are taken where the star should appear in the center of the frames. Next, the pointing option 1 aimpoint parameters are adjusted by a very small amount to cause the star image to move a few pixels from the center of the frame. A single NAC image is taken at this slightly different attitude. This small tweak assists in distinguishing the star images from noise sources when the images are processed on the ground. The third change to the pointing option 1 aimpoint parameters moves to an inertial direction that is the predicted location of the planet as seen from the spacecraft. This is a much larger attitude change than the small tweak between the star images. A larger time is allocated for the spacecraft to stabilize at the planet-pointing attitude. Two NAC and three WAC images are taken of the planet. For Mercury flyby 1, the science team added a set of NAC and WAC images at this final attitude with exposures optimized for imaging science instead of navigation.

For Venus flyby 2 the default "ideal" alignment parameters were used when pointing at the stars for OpNav images. For Mercury flyby 1, the navigation team requested that the estimated MDIS alignment be used when pointing the optical navigation images. The MDIS alignment model was formulated such that the G&C parameters had to be changed for each pivot angle to match the resulting boresight direction. Test images of Sirius and the Pleiades were taken in September 2007 using the ideal and estimated boresights for the NAC and WAC at different pivot angles to verify the G&C interpretation of the alignment model. The stars were located closer to the center of the frames when the estimated alignment parameters were used. For Mercury flyby 1, commands were added at the start of each OpNav session to set the G&C parameters to the estimated alignment of the NAC at the selected pivot angle. The alignment parameters were not changed for the WAC images since its FOV is much larger. The ideal alignment parameters were used for the MDIS science observations because the pivot angle varied so much over short time periods that too many commands would have been needed to change the alignment for each pivot angle. The general goal for MDIS planet imaging is to capture some desired area in the image FOV rather than to put a specific location exactly at the center of an image. The small differences in pointing are of less importance when imaging an extended area since they are not large enough to move images significantly off the specified target.

IX. Design Tools

Venus flyby 2 was the first time during the mission when focused observations of the same target by the entire instrument suite were to be packed into just a few hours. It provided a unique opportunity to prepare for the Mercury flybys that were to follow where the observations would contribute to the overall science goals of the mission. While most of the G&C pointing options had been tested with previous calibration and engineering activities, they had been performed in isolated periods of one or two observations separated by weeks or months. There was ample time to generate the pointing designs, and fairly simple tools were able to convert files used for the G&C simulations to the format needed for spacecraft sequence generation. This process would have been awkward to use for the flyby designs since the G&C tools were unfamiliar to other team members involved in generating and checking the sequence and were not automated enough to handle the volume of commands. There was a desire to supplement the existing sequence design tools used by the operations team with software that could rapidly simulate spacecraft motion (faster than real-time) and provide visualization of the coverage obtained with the different instruments. Visualization was particularly important for the MDIS observations. The scientists wanted to see footprints of the FOV projected on the planet's surface to verify that the appropriate regions were being imaged and appropriate overlap was maintained between images in the mosaics. A design tool with these capabilities is under development for the orbital phase of the mission, but it was not available for use at the flybys. The G&C team had already developed to capability to use the Analytic Graphics STK© software to visualize spacecraft motion and instrument viewing geometry from results of its high-fidelity simulation. The G&C simulation was developed prior to launch using Matlab Simulink© software and contains both the flight software and a truth model that includes spacecraft rotational dynamics and G&C hardware emulators. A planning team assessed the capabilities of the sequence development and G&C tools and determined that a few simple routines could be developed that would allow the team to simulate and visualize easily the pointing designs in a more automated process. The necessary routines converted the design inputs used for the sequence software to equivalent time-ordered lists of G&C parameter changes and pointing commands in the format used by the G&C simulation, extracted MDIS pivot commands and times when individual images were to be taken, merged the manual pivot positions and pivot offsets with the pivot angles output from the G&C software, and generated files used by STK to drive the animation. The STK files specified spacecraft attitude, MDIS pivot angle, solar panel angles, MDIS NAC and WAC boresight pointing directions as functions of time, and times when NAC or WAC images are shuttered. STK can show FOV footprints for MDIS and for instruments such as MASCS and MLA whose boresights are fixed to the spacecraft; no special files are needed to specify the pointing of the fixed-boresight instruments.

A pointing design usually begins with a rough idea of the time and values for the pointing parameters specified in a sequence input file. One of the new tools is then used to generate a corresponding file to drive the G&C simulation. Next, the G&C simulation is run and its outputs are used to generate the input files needed for STK. Both the results of the G&C simulation and the STK animation are used to verify that the design is correct. On the basis of the results of the first simulation, adjustments may be made to the design by editing the original sequence input file and rerunning the G&C simulation and STK animation. Iterations continue until the design meets the science objectives for the observation. This process and the supporting tools have been used extensively for the two flybys. MDIS images of Venus and Mercury have verified that the STK footprint visualization is accurate. Figures 8 and 9 show STK animations and the resulting mosaics constructed from actual MDIS images for the WAC color mosaic and the NAC approach mosaic from Mercury flyby 1. In addition to supporting the remaining flybys, these new tools will assist in testing the software tool that will replace this process for orbital operations. The orbital design tool also outputs files in the format that can now be automatically converted to files that drive the G&C simulation.

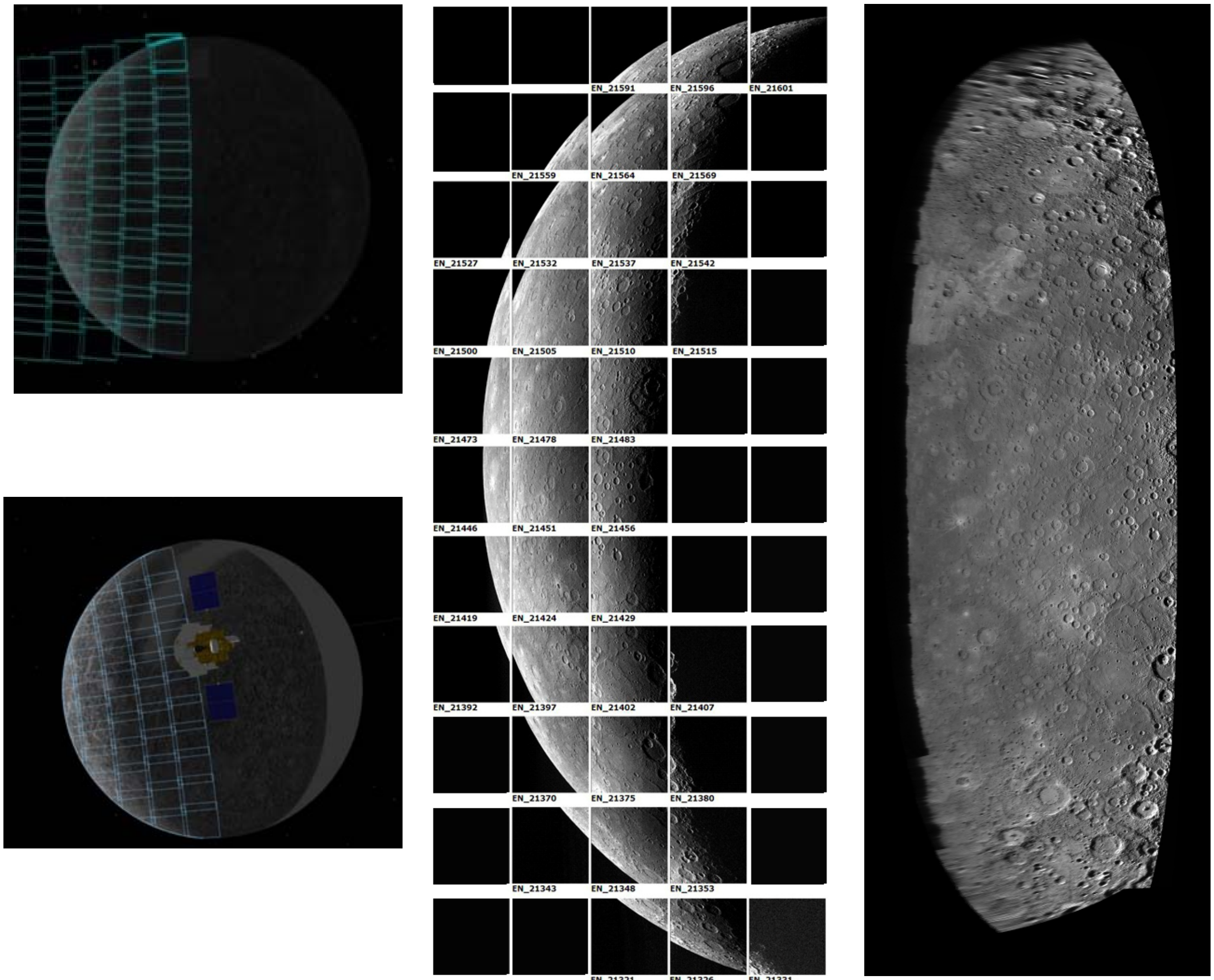


a) STK animations showing MDIS WAC FOV footprints

b) Mosaic assembled from WAC images taken during Mercury flyby 1

Figure 8. Design Visualization and Actual Images for MDIS WAC Color Mosaic for Mercury Flyby 1 (Step-

and-Stare Mosaic)



a) STK animations showing MDIS NAC FOV footprints

b) Mosaic assembled from NAC images taken during Mercury flyby 1

Figure 9. Design Visualization and Actual Images for MDIS NAC Approach Mosaic for Mercury Flyby 1 (Scanning Mosaic)

X. Conclusion

Like many other aspects of the MESSENGER mission, sequencing the science observations for planetary flybys has challenged the capabilities of both the spacecraft and its supporting flight team. The Venus and Mercury flybys represent comprehensive tests of the capabilities of the spacecraft's guidance and control flight system and of the science instrument operation. The successful execution of all turns for science observations during these flybys has demonstrated that the spacecraft is ready for its final two Mercury flybys. The flight team has created and validated tools and procedures and gained valuable experience that will be applied at these flybys. The flyby pointing designs also serve as guidelines that will assist in coordinating instrument and spacecraft activities during the orbital phase of the mission.

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References

[1]Solomon, S. C., McNutt, R. L., Jr., Gold, R. E., and Domingue, D. L., "MESSENGER Mission Overview," *Space Science Reviews*, Vol. 131, Nos. 1-4, August 2007, pp 3-39.

[2]Leary, J. C., et al., "The MESSENGER Spacecraft," *Space Science Reviews*, Vol. 131, Nos. 1-4, August 2007, pp 187-217.

[3]Vaughan, R. M., et al., "Return to Mercury: The MESSENGER Spacecraft and Mission," *IEEE Aerospace* Conference [CD-ROM], IEEEAC paper 1562, 4-11 March 2006.

[4]Vaughan, R. M., O'Shaughnessy, D. J., Shapiro, H. S., and Haley, D. R., "The MESSENGER Spacecraft Guidance and Control System," NASA 2005 Flight Mechanics Symposium, Goddard Space Flight Center, Greenbelt, MD, October 18-20, 2005.

[5]O'Shaughnessy, D. J. and Vaughan, R. M., "MESSENGER Spacecraft Pointing Options," *Spaceflight Mechanics 2003, Advanced in the Astronautical Sciences, Vol. 114, Part II*, pp. 747-766.