GUIDANCE AND CONTROL OF THE MESSENGER SPACECRAFT IN THE MERCURY ORBITAL ENVIRONMENT

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The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft faces a demanding environment while in orbit about Mercury. During the one-year-long primary orbital mission phase, the guidance and control subsystem faces challenging constraints, most of which were not encountered during the cruise phase, and must incorporate the planning and approval of each weeklong command sequence within only a three-week period. This paper details the analyses that were performed to develop a streamlined and effective methodology for adhering to orbital constraints. The methodology, which has proven effective in ensuring spacecraft health and safety while in orbit about Mercury, is detailed.

INTRODUCTION

As part of NASA's Discovery Program, the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft is the first to orbit the planet Mercury, entering into orbit on 18 March 2011, after an orbit insertion maneuver that imparted 852 m/s ΔV, expended 185 kg of propellant, and lasted approximately 962 s. During an orbital phase of one Earth year, the MESSENGER mission seeks to increase understanding of Mercury as a planet, a key to understanding the formation and evolution of our inner solar system. The mission's 6.6 years of interplanetary cruise included one Earth flyby, two Venus flybys, and three Mercury flybys. Although the Mercury flybys during cruise provided a preview of orbital operations constraints, orbital operations are intrinsically different from flyby operations. The guidance and control (G&C) team is responsible for maintaining spacecraft health and safety. To achieve success during the challenging orbital phase, the G&C team developed a methodology to maintain spacecraft health and safety while successfully executing the hundreds of thousands of planned science observations.

The MESSENGER spacecraft is a 3-axis stabilized spacecraft that uses reaction wheels, and when needed, thrusters, for attitude control. The sensor suite consists of star trackers, digital Sun sensors, and an inertial measurement unit, which contains four accelerometers and four gyroscopes. During nominal operations, attitude determination and control are achieved through

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the combination of four reaction wheels, one star tracker, and four gyroscopes. Solar panels provide electric power to the spacecraft, and a heat-resistant and reflective sunshade protects the spacecraft from the extreme thermal conditions encountered close to the Sun. The spacecraft body axes and selected component locations are shown in Figure 1.

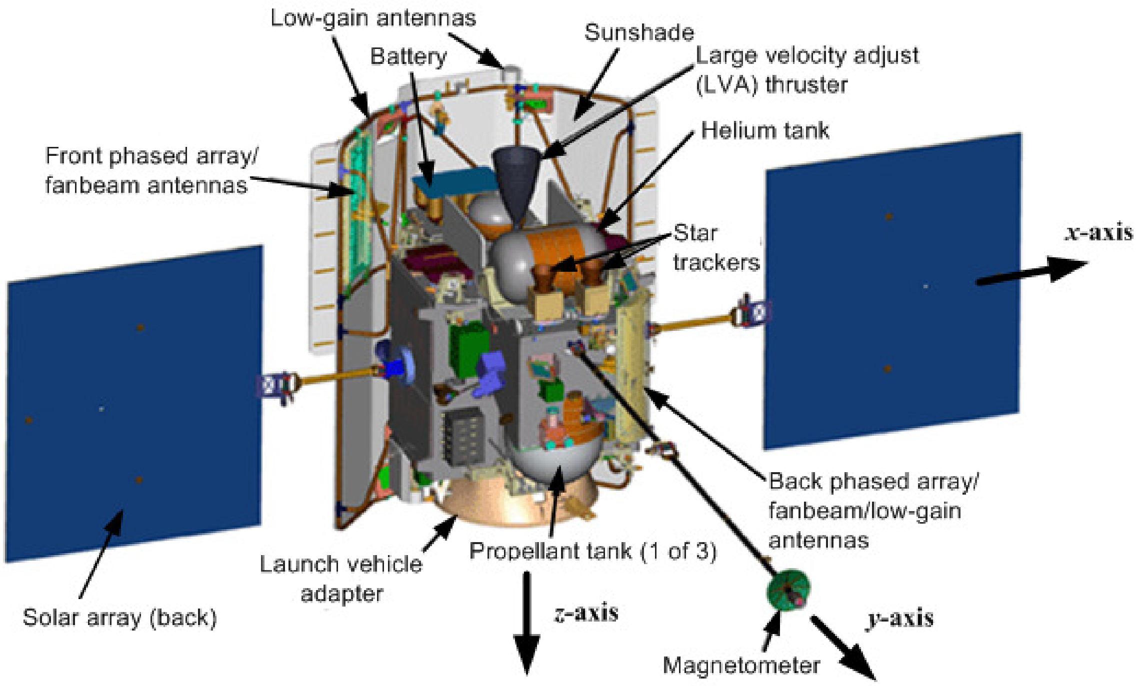

Figure 1. MESSENGER Spacecraft Components and Body-Axis Convention.

When MESSENGER is within 0.85 AU of the Sun, the sunshade must be kept between the Sun and the main body of the spacecraft to protect it from the high temperatures in the near-Sun environment. This constraint has been active since 21 June 2006 and will remain so for the remainder of the orbital phase, because the distance from MESSENGER to the Sun varies only between 0.307 and 0.467 AU. Maintaining the sunshade between the Sun and the main body of the spacecraft for the entire orbital mission poses a substantial constraint to spacecraft attitude.

The Sun keep-in (SKI) constraint ensures that the spacecraft's sunshade sufficiently shields the spacecraft and science instruments from the Sun. The SKI zone allows for deviations of ±10° from direct Sun pointing in rotations around the spacecraft z-axis, and ±12° in rotations around the x-axis. In the MESSENGER body-frame azimuth- and elevation-angle convention, shown in Figure 2, the aforementioned rotations correspond to spacecraft-to-Sun vectors of ±10° azimuth and ±12° elevation, respectively, and are known as the SKI guidance boundaries. When the spacecraft-to-Sun vector reaches one of these four boundaries, and the ground-commanded input to the flight code indicates that the SKI zone constraint is active, the G&C system limits the commanded pointing to remain inside the SKI guidance boundaries. A second tier of SKI boundaries corresponding to a spacecraft-to-Sun vector of ±12° azimuth and ±14° elevation provides additional thermal protection for the spacecraft and science instruments. In the event that the spacecraft-to-Sun vector exceeds the second-tier SKI boundaries for five consecutive 1-Hz cycles, the G&C system will initiate a "SKI-safing" turn and will request a safe-hold demotion from the spacecraft's autonomy system.

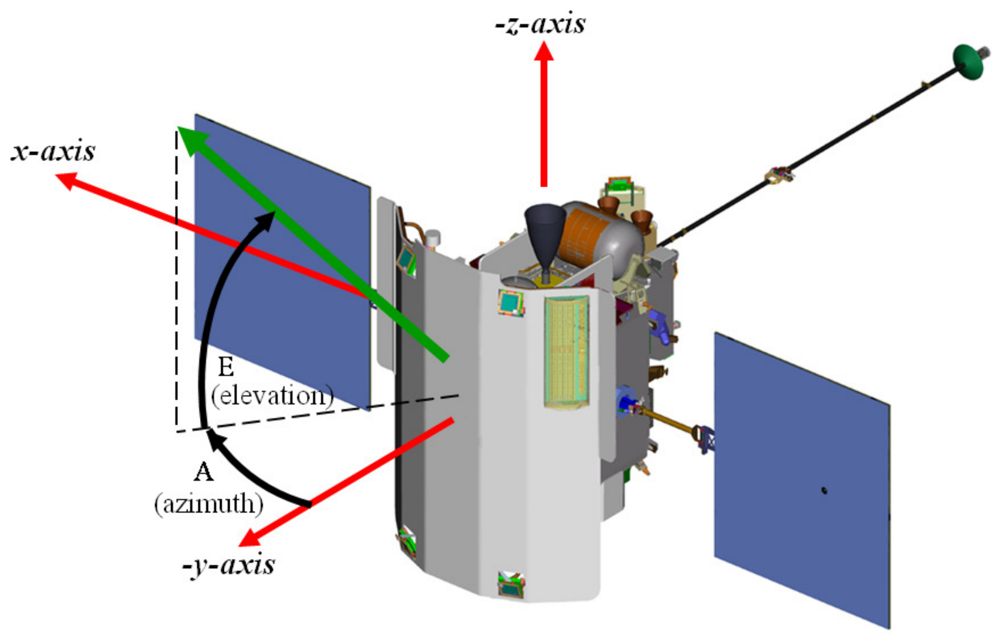

Figure 2. Azimuth and Elevation Angles in the MESSENGER Spacecraft Body Frame.

A SKI-safing turn places the spacecraft in downlink attitude with the spacecraft-to-Sun vector at 0° azimuth and elevation. Downlink attitude is the default attitude for communications with the ground (via the NASA Deep Space Network) and is defined by two sets of vectors. The primary vectors for downlink attitude are a spacecraft-body vector (in this case the –*y*-axis) aligned to the spacecraft-to-Sun vector. The secondary vectors are a spacecraft-body vector that is chosen such that the spacecraft-to-Earth line falls in one of the quadrants of the spacecraft *x*–*y* plane covered by one of the phased-array antennas, and the spacecraft-to-Earth vector. When the Sun–MESSENGER–Earth angle is less than 90°, the –*x* body-axis aligns as close as possible to the spacecraft-to-Earth vector to use the front phased-array antenna (FPAA), and when the Sun–MESSENGER–Earth angle is greater than 90°, the +*x* body-axis aligns as close as possible to the spacecraft-to-Earth vector to use the back phased-array antenna. The G&C request for safe-hold demotion sets off a chain of reactions within the spacecraft's autonomy system, one of which is to stop execution of the command sequence. The autonomy system's main goal in this situation is to protect the spacecraft and provide communications with the ground in order to elicit a safe return to an operational state after faults have been diagnosed and addressed. The G&C team works tirelessly to prevent safe-hold demotions because when a command sequence that contains science commanding stops executing, scientific observations are missed.

ORBITAL CONSTRAINTS

The G&C system must adhere to additional constraints while the spacecraft is in orbit about Mercury, in addition to the SKI constraint, which remains the most significant constraint on spacecraft attitude. The additional constraints are specific to the orbital environment, in particular the intense thermal environment due to Mercury's proximity to the Sun and the spacecraft's orbital trajectory about the planet.

After the Mercury orbit insertion maneuver on 18 March 2011, MESSENGER entered its primary science orbit with a 207.77-km periapsis altitude, 59.976°N sub-spacecraft periapsis latitude, 12.07-hour orbit period, 350.17° right ascension of ascending node, and 82.52° initial orbit inclination. Because of small forces, such as solar gravity, the orbit slowly changes, including a drift upward of the periapsis altitude. Orbit-correction maneuvers (OCMs) are performed to keep the periapsis altitude below 500 km, which is the minimum altitude for satisfactory completion of several science goals, and to re-adjust the orbital period to 12 hours.

Hot-Pole Keep-Out Constraint

MESSENGER's orbit is such that the orbit periapsis occurs in the northern hemisphere of Mercury. When the northern hemisphere of Mercury is illuminated by the Sun and the spacecraft is 200–500 km from Mercury's surface (the orbit's periapsis altitude range), radiation from the planet can damage the –*z*-axis of the spacecraft if it is placed within 90° of Mercury nadir. The –*z*-axis of the spacecraft is the deck opposite most science instruments; thus, it is termed the top deck of the spacecraft. When ground-commanded input to the flight code indicates that the hot-pole keep-out (HPKO) constraint is active, the HPKO constraint ensures that the top deck of the spacecraft is limited to safe regions where it is not exposed to radiation from the sunlit side of the planet. For the entire Mercury orbit about the Sun, i.e., Mercury true anomaly 0°–360°, the HPKO constraint is nominally active. For critical events such as OCMs, an operational decision can be made to disable the HPKO constraint if the event cannot be completed without an HPKO constraint violation. If spacecraft pointing exceeds the HPKO constraint for 30 consecutive 1-Hz cycles while the constraint is active, an "HPKO-safing" turn will place the spacecraft in a SKI-safe and HPKO-safe downlink attitude, and the G&C system will request a safe-hold demotion from the autonomy system.

FPAA Thermal-Mitigation

Thermal trending during the first two months of MESSENGER's orbital phase predicted that the signal feeds for the FPAA assembly could near their qualification temperatures during times of highest thermal input, around 310° Mercury true anomaly. There are no electronics in the FPAA, but the feed assembly is soldered with Sn63 solder alloy, which has a melting temperature of approximately 180°C. Without mitigation, the worst-case scenario could be loss of high-gain uplink for parts of the mission when the Sun–MESSENGER–Earth angle is less than 90°, which is when the FPAA is used for high-gain uplink. To mitigate potential damage to the FPAA at times of highest thermal input, the +*z*-axis of the spacecraft must not view the planet during spacecraft orbit true anomalies from 320° to 60°. Reducing the view factor to the planet during periapsis passage prevents radiation from Mercury's surface from heating the FPAA components between the sunshade and spacecraft bus past 180°C. This attitude also allows the radiators to point out into empty space, enabling greater thermal load shedding.

Unlike the SKI and HPKO constraints, which are included in the G&C flight software, the +*z*-axis off-pointing for FPAA thermal-mitigation must be developed on the ground. Once the FPAA off-pointing attitude commands are uploaded to the spacecraft, there is no autonomous action that the G&C system can take to protect the FPAA from unsafe attitudes. Adding to the challenge of adhering to this constraint is the fact that the spacecraft true anomaly range of 320°–60° includes times when the HPKO constraint is active, which means that the off-pointing attitude must simultaneously satisfy three constraints at once: SKI, HPKO, and +*z* not viewing the planet.

The simplest solution to satisfying all three constraints at once is to align the –*y*-axis to the spacecraft-to-Sun vector at a positive elevation within the SKI zone (to avoid violating the HPKO constraint) and to command a spacecraft body vector to track Mercury nadir such that the minimum +*z*-axis to Mercury nadir angle is larger than the spacecraft Mercury limb angle. Although this method works for the majority of the high thermal input times, it cannot be used for times when the Sun–MESSENGER–Mercury angle is nearly zero because of slew rate limitations to the G&C system.

When orbit geometry allows, there is a second option that can be used to keep the $+z$-axis from viewing Mercury. The second option is referred to as pseudo-inertial pointing. Pseudo-inertial pointing aligns the $+z$-axis with a fixed inertial direction that is offset from the spacecraft orbit's angular momentum vector and aligns the Sun vector to a specified elevation angle within the SKI zone, all selected to satisfy the SKI and HPKO constraints over the time period in question (spacecraft orbit true anomaly 320°–60°). The word "pseudo" in the name refers to the fact that the spacecraft-to-Sun vector in the inertial frame is approximately constant over the time period, resulting in near-zero spacecraft body angular rates of change.

The left graphic of Figure 3 shows a representative MESSENGER noon–midnight orbit with the beginning and ending spacecraft orbit true anomalies for the FPAA thermal-mitigation $+z$-axis off-pointing marked as f_1 and f_2, respectively. The angle θ_r is the Mercury angular radius as seen from the spacecraft. The right graphic of Figure 3 shows the inertial vectors associated with the left graphic. The spacecraft to Mercury center at f_1 in the inertial frame is i^I_{Merc1}; the spacecraft to Mercury center at f_2 in the inertial frame is i^I_{Merc2}; the spacecraft-to-Sun vector in the inertial frame, which is approximately constant over the time period, is i^I_{Sun}; and the unit vector along the spacecraft orbit angular momentum vector in the inertial frame is i^I_H. The spacecraft to Mercury center vectors, i^I_{Merc1} and i^I_{Merc2}, bound the nadir vector over the time period and are in the spacecraft orbit plane.

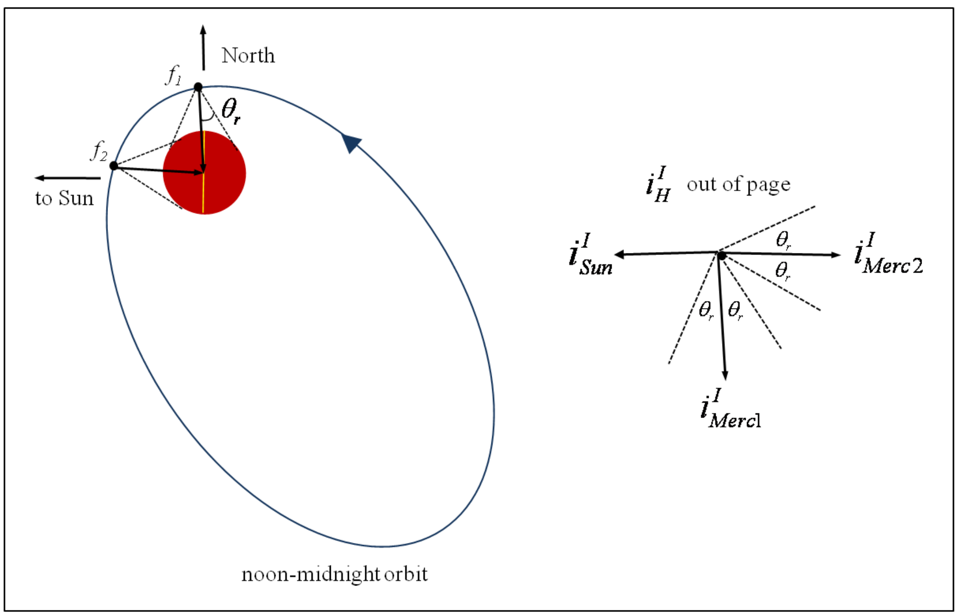

Figure 3. Inertial Vectors Used in FPAA Thermal-Mitigation +*z*-Axis Off-Pointing Attitudes, Shown for a Representative Noon–Midnight Orbit.

To point the $+z$-axis off Mercury, the angle between nadir and the $+z$-axis must be greater than the maximum Mercury angular radius over the time period, , and the $+z$-axis cannot be greater than 90° from nadir over the time period to stay within the HPKO-safe region. Over the time period defined by spacecraft orbit true anomalies f_1 and f_2, the cones around the nadir vectors with half-angle $\theta_{r\max}$ form another cone around $\pm i_H^I$ with half-angle $90° - \theta_{r\max} = \beta_r$, as seen in the left graphic of Figure 4. Because the +z-axis must stay on the i_{Merc}^I side of the $\pm i_H^I$ plane in order to satisfy the HPKO constraint, the planes bounding the HPKO region for f_1 and f_2 intersect the two cones around $\pm i_H^I$ to form two partial cones where the +z-axis can point to be off of Mercury and within HPKO, as seen in the shaded area in right graphic of Figure 4. Within the partial cones, the closer the +z-axis is to $\pm i_H^I$, the farther the +z-axis is away from the planet limb, but the closer the –z-axis is to violating the HPKO constraint.

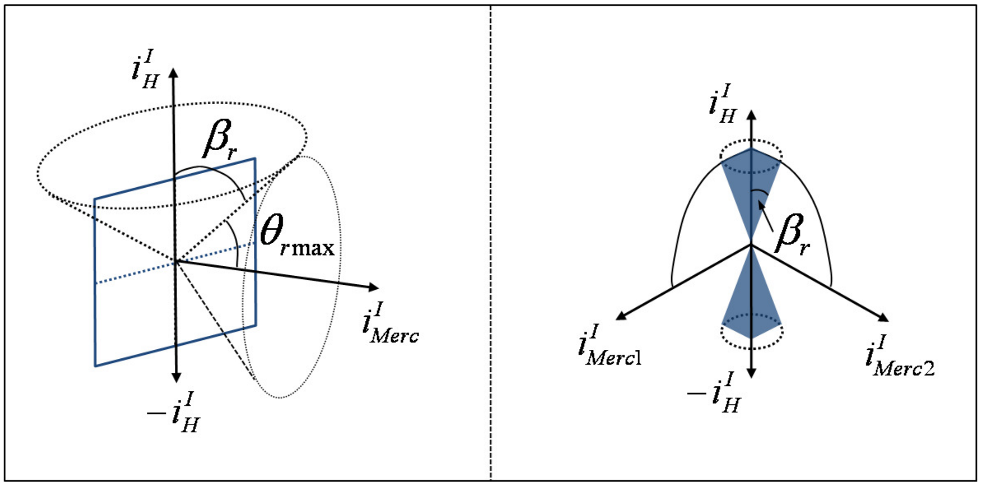

Figure 4. Solution Space for the Placement of the +*z*-Axis for FPAA Thermal-Mitigation Attitudes.

Within the partial cones that define the solution space for placement of the +z-axis over the time period, an attitude must be chosen to satisfy both the HPKO and SKI constraints for the entire time period. The left graphic of Figure 5 shows the space within the partial cone that satisfies HPKO for the full time range. The right graphic of Figure 5 shows the region for SKI compliance under the assumption that the +z-axis in the inertial frame is aligned with i_H^I or $-i_H^I$. The Sun direction will be in either the i_H^I or $-i_H^I$ halfspace, i.e., on one side or other of the spacecraft orbit plane (in the case of a noon–midnight orbit, i_{Sun}^I is aligned with the orbit plane). For SKI compliance, the angle between i_{Sun}^I and the +z-axis in the inertial frame must be between 78° and 102° because the SKI guidance boundary allows only up to ±12° spacecraft-to-Sun vector elevation angles (and the –y-axis is 90° from the +z-axis). If the angle between i_{Sun}^I and i_H^I or $-i_H^I$ is γ, and if moving the +z-axis off $\pm i_H^I$ as far as possible within the partial cone is such that $\beta_r + \gamma < 78°$, then a fixed +z-axis direction in inertial space cannot be found that will keep the +z-axis from viewing the planet while also satisfying the SKI constraint. When pseudo-inertial pointing is not possible, a changing attitude must be used to prevent the +z-axis from seeing Mercury. If the spacecraft body angular rates required for nadir-relative pointing are within the limits of the reaction wheels, nadir-relative pointing is used. If neither pseudo-inertial pointing nor nadir-relative pointing can be used, a derivative of nadir-relative pointing with rate-controlled segments must be used and must be designed for each specific case.

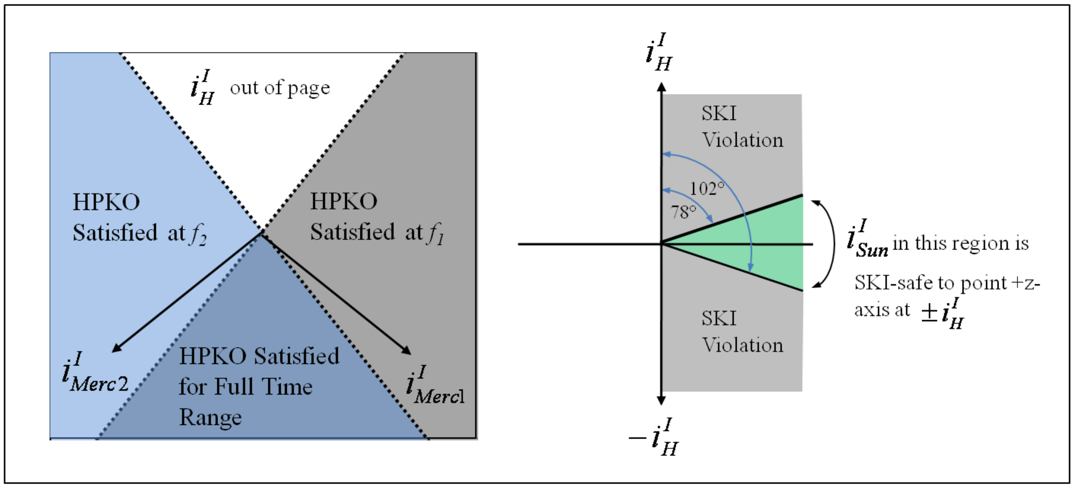

Figure 5. HPKO-Safe and SKI-Safe Regions for FPAA Thermal-Mitigation Attitudes.

Star Tracker Exclusion Zone

While in orbit about Mercury, which has a radius of 2440 km, MESSENGER's altitude above the planet varies between 200 and 15,200 km. As such, the visual magnitude of Mercury as seen from the spacecraft varies between approximately –20 and –26. During MESSENGER's cruise phase, performance issues were experienced when bright objects approximately –3 visual magnitude relative to the spacecraft and brighter entered the star tracker field of view. For reference, a visual magnitude of –20 is approximately 6.3 million times brighter than –3 visual magnitude. In addition, while in orbit about Mercury, Mercury's size on the star tracker charge-coupled device (CCD) (if the planet is viewed by the star tracker) is at least 500 pixels in length. MESSENGER's star trackers have a CCD image size that is 512 × 512 pixels; therefore, when Mercury enters the star tracker field of view, the planet substantially blocks or eliminates the star tracker's view of the stars, making the computation of an attitude solution impossible. Because of the extreme brightness of Mercury relative to the spacecraft, stray light from the planet can also markedly degrade the star tracker's ability to output valid attitude solutions. As such, for every weeklong command sequence, the G&C team checks the star tracker boresight-to-Mercury angles, submits commanding to power off the active star tracker before the star tracker boresight-to-Mercury angle reaches 30°, and powers the primary star tracker back on once the star tracker boresight-to-Mercury angle exceeds 30°. During these times, the star trackers will not be able to produce valid attitude solutions, so they are powered off until the condition clears, allowing the star tracker to reacquire an attitude solution after a hard (power) reset, which eliminates the chance of errors persisting across internal mode promotions.

The star trackers have an 8.2° half-angle field of view, and 30° is the "exclusion zone" angle limit used to protect against Mercury stray light. Mercury typically enters the star tracker exclusion zone while at downlink attitude, and it is a seasonal occurrence. It is uncommon to place Mercury within 30° of the star tracker boresight while science observations are being taken because the star trackers are mounted on the –*z*-axis of the spacecraft, which is the deck opposite that of most science instruments. When the star trackers are powered off during times when Mercury enters the star tracker exclusion zone, the G&C system propagates the attitude solution using the gyroscopes.

Momentum Management

Because the MESSENGER spacecraft uses reaction wheels for attitude control, spacecraft angular momentum must be managed. Momentum can be managed passively by changing the spacecraft's attitude and solar panel orientation or by using thrusters to actively offload momentum. The G&C system will perform an autonomous momentum dump (firing of attitude control thrusters to dump body angular momentum by spinning down the reaction wheels) if body angular momentum reaches the "red dump limit," which is nominally set to 5.5 Nms, and is a ground-commanded input to the flight code. Autonomous momentum dumps trigger the autonomy system to perform a safe-hold demotion, so significant effort is made to avoid their occurrence.

During the cruise phase, more commanding time was allotted to G&C for passive momentum management attitudes, compared with the orbital phase, for which the frequency and duration of science observations results in significantly less time for passive momentum management attitudes. Additionally, these windows occur only when the spacecraft is in contact with the Deep Space Network. As such, the passive momentum management attitudes that are allowed are confined to variations of downlink attitude within the SKI zone so that contact with the ground is not interrupted. When passive momentum management is not sufficient, a commanded momentum dump (CMD) is scheduled to avoid saturating the reaction wheels and triggering a safe-hold demotion due to an autonomous momentum dump.

There are two CMD placeholders during each week of the orbital phase. If passive momentum management is not sufficient, the G&C team instructs the mission operations team to activate one or both CMD placeholders. Passive momentum management is pursued first before activating CMDs in an effort to conserve propellant and minimize trajectory perturbations.

Solar Panel Constraints

The G&C team follows guidelines set by the power and thermal teams to manage MESSENGER's solar panels. The solar panels are placed at Sun offset angles that are a function of solar distance and satisfy temperature and power limits. Within these limits, an offset between the two solar panels is determined to passively manage momentum. Additional solar panel commanding is submitted for hot-pole flyovers and long-eclipse exit transitions. Both orbit geometries can damage the spacecraft through exposure to high temperatures if the solar panels are not pointed away from facing the Sun. During hot-pole flyovers for Mercury true anomalies from 220° to 360°, the solar arrays are positioned at 95° Sun offset for the duration that the spacecraft is over the sunlit northern hemisphere. For eclipses greater than 55 minutes, the solar panels are positioned at 80° Sun offset during the eclipse and remain at that position for 2 minutes after eclipse exit.

NEAR-TERM SCIENCE PLANNING PROCESS

Every week while in orbit about Mercury, a command sequence that spans one week is sent to the spacecraft for the operation of its subsystems, including operation of the payload. Near-term science planning (NTSP) is the short-term scheduling of the optimized orbital concept of operations.[1] The NTSP build process spans four weeks for each weeklong command sequence. The G&C team has a substantial role in NTSP because it is responsible for ensuring spacecraft health and safety. Every weeklong command sequence that is sent to the spacecraft must be simulated through a high-fidelity model to ensure that spacecraft pointing does not violate the SKI and HPKO constraints and to ensure adherence to all other orbital constraints.

SciBox

The MESSENGER SciBox automated science scheduling system is at the heart of the NTSP process. The SciBox software identifies observation opportunities and selects observations to schedule in agreement with priorities driven by observation objectives.[2] At the beginning of each week, the SciBox software is run to determine the scheduling of science observations and operational activity windows for the next command sequence to be compiled. Each payload team, including G&C, receives a schedule from SciBox that is converted into a science activity sequence file (SASF). The SASF file type is the format required for input into the mission operations software, SeqGen, which compiles each command sequence that is uploaded to the spacecraft. NTSP for each command sequence begins with the receipt of the G&C SASF from SciBox.

G&C NTSP Steps

The steps performed by the G&C team in the NTSP process for each weeklong command sequence are summarized in Figure 6. As shown in Figure 6, NTSP for each command sequence begins when the latest SciBox software is released to the payload teams on Wednesday of week 1. At this point, each payload team downloads the latest SciBox software and uses SciBox to generate payload SASFs for the command sequence in question. Step 1 for the G&C team, which is the review and modification of the SciBox G&C SASF, is the most important and time-consuming part of the G&C NTSP process.

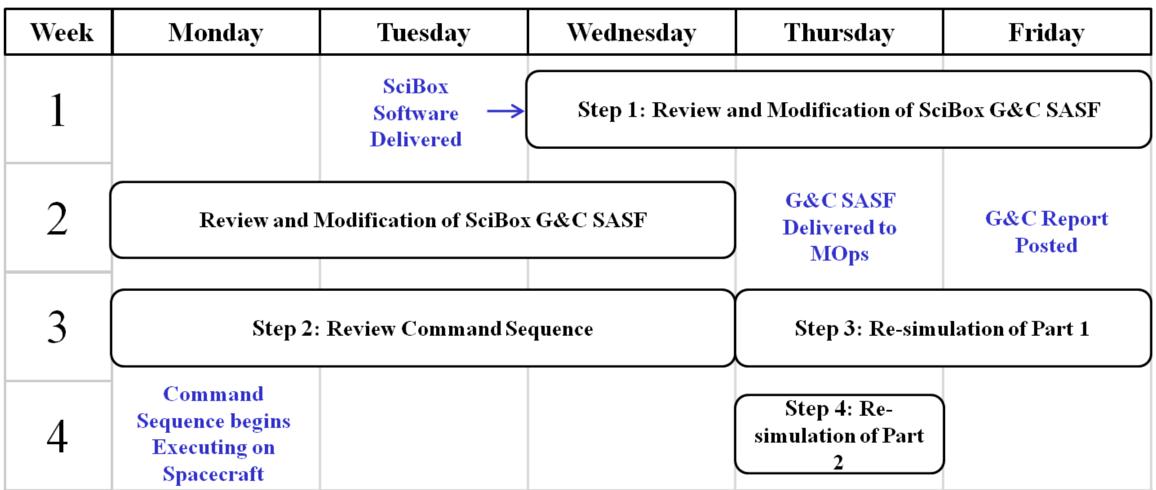

Figure 6. Nominal G&C NTSP Schedule for Each Weeklong Command Sequence. MOps Denotes Mission Operations.

The high-fidelity model of the spacecraft and G&C system is referred to as the “RTW model.” The name comes from the fact that MESSENGER’s G&C flight software was developed in MATLAB/Simulink and then converted into C code using MATLAB Real-Time Workshop. The MESSENGER G&C RTW model requires two files in order to run simulations: an initial conditions (IC) file and a file with time-ordered G&C commands called a “Trk” file. A Perl script called “SASF2TRK” converts SASF requests into a time-ordered Trk file, which can then be run through the RTW model. An RTW model simulation of G&C commands spanning one week takes 2–2.5 hours to complete.

Step 1 in the G&C NTSP schedule can be broken down into four sub-tasks, which are outlined in Figure 7. Step 1a is the initial RTW simulation of the G&C SASF generated from SciBox. This sub-task is performed in order to determine whether any pointing violations exist in the SciBox-generated attitude profile. If any pointing violations exist, the requests at fault are redesigned to eliminate violations. Also in this step, the IC file to be used for all of the simulations in step 1 is set appropriately with the initial attitude, the initial momentum state, and the orbit determination (OD) solution to be used for the spacecraft trajectory.

When all pointing in the G&C SASF has been verified to be safe, utilities are run in step 1b to generate additional commanding that must be added to the G&C SASF to adhere to orbital constraints for the solar panels, passive momentum management, and FPAA thermal-mitigation off-pointing. The utilities check to determine whether additional commanding is required on the basis of orbital geometry and user inputs. If additional commanding is required, the utilities generate the additional SASF requests in separate files. The additional commanding is then added to the G&C SASF from step 1a, creating a merged SASF. At this point, another simulation is performed using the merged SASF, and adherence to orbital constraints is verified.

Once step 1b is complete, all additional G&C commanding required has been added to the merged SASF except for star tracker power management for times when Mercury enters the star tracker exclusion zone. In step 1c, the RTW simulation results (in particular the estimated spacecraft attitude) from step 1b are used to determine whether Mercury enters the star tracker exclusion zone. When star tracker commanding is required, the necessary SASF requests are generated and added to the merged SASF from step 1b, and an additional RTW simulation is performed using the updated merged SASF. Once spacecraft health and safety and correct star tracker commanding are verified using the latest RTW simulation results, the final merged SASF is run through SeqGen in order to deliver it to mission operations. If no star tracker commanding is required, the final merged SASF is run through SeqGen and delivered to mission operations without an additional RTW simulation in step 1c.

The final sub-task in step 1, step 1d, ensures that the G&C SASF delivered to mission operations for inclusion into the command sequence includes all intended G&C commanding, i.e., that all G&C requests were read by the SeqGen software. When an SASF is run through SeqGen, the software reorders the SASF requests into a specific format and ingests the SASF into the command sequence build area. The SASF sent to the command sequence build area is used in a final simulation during step 1d to ensure that the correct G&C commanding will be included in the command sequence. Once the final SASF from SeqGen has been verified to be correct, the final SASF, final IC file, final Trk file, and final simulation results are archived. The G&C SASF must be delivered by the Thursday of week 2, and the final simulation results report must be posted by the Friday of week 2. To complete the review and modification of the SciBox G&C SASF in nominally only 6.5 business days, the methodology used to complete step 1 must be extremely efficient.

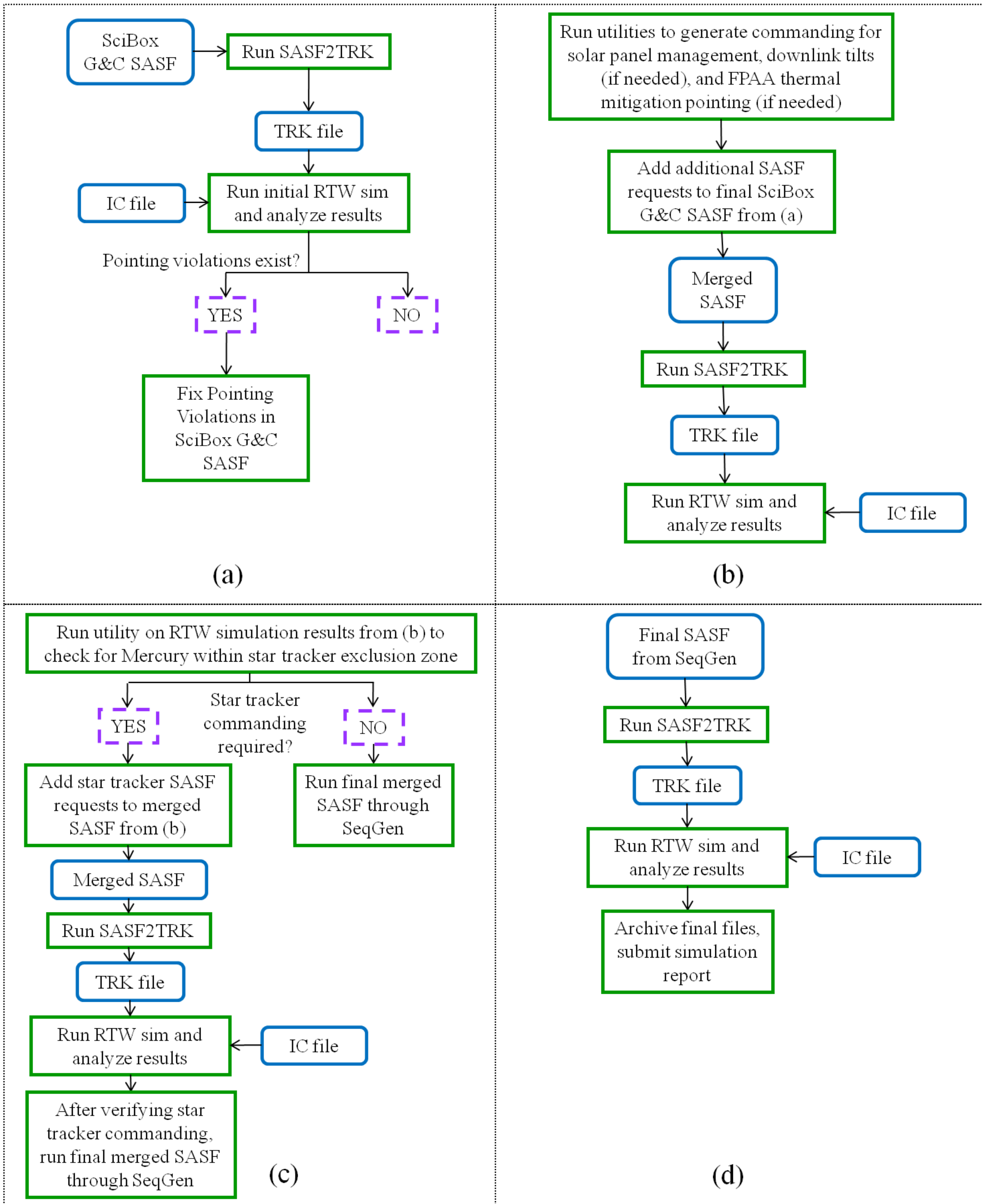

Figure 7. Nominal Sub-tasks of Step 1 of the G&C NTSP Process.

During week 3 of NTSP, the mission operations team takes the SASFs delivered by each payload team and builds the command sequence. When the command sequence is complete, the G&C team reviews it during week 3 (step 2) to ensure that all additional G&C commanding and modifications made to the SciBox G&C SASF are included in the command sequence. The readable format of a command sequence looks very similar to a typical spreadsheet. Each command to be loaded to the spacecraft is listed in a time-ordered manner, and the column length of the spreadsheet typically numbers tens of thousands of rows. Because the command sequences can be reviewed only by visual inspection, and the time allotted for command sequence review is short, the G&C team focuses only on additional G&C commanding and modifications made to the SciBox G&C SASF. The fact that visual inspection must be utilized during the last approval step before the command sequence is uploaded to the spacecraft highlights the importance of a streamlined and effective methodology for processing each weeklong command sequence.

The remaining G&C NTSP steps are re-simulations of the final G&C SASF using updated OD solutions and time-tag biases. The SciBox software determines the scheduling for each command sequence on the basis of the most recent OD solution that is available at the time that the SciBox opportunity analyzer is run. Every Thursday afternoon, the navigation team releases a new OD solution. The OD solution is processed the same afternoon by both the G&C and mission operations teams. The G&C team creates meta-kernel files that contain the navigation OD and the mission design full-mission reference trajectory (the full-mission reference trajectory from mission design includes the navigation OD). The mission operations team takes the OD solution from the navigation team and converts it into a format that can be loaded to the spacecraft. The G&C team reviews this "operations ephemerides" file against the OD file that the navigation team delivered and converts the operations ephemerides into a file that the RTW model can ingest. If the operations ephemerides are approved by the G&C team, they are uploaded to the spacecraft, typically the next day, Friday.

Because a new OD solution is released each week, and the NTSP build process takes three weeks before the command sequence begins executing on the spacecraft, the OD solution used to build the command sequence will be out of date by three weeks (or three OD solutions). Therefore, differences will exist between the trajectory that SciBox adopted while scheduling observations and the most up-to-date knowledge of what the spacecraft trajectory will be when the observations are executed. To minimize the impact of trajectory differences, along with the OD solution, the navigation team also delivers a periapsis crossing report each Thursday that compares the periapsis crossing times between the just released OD solution and the OD solution that was used to build the command sequence currently running on the spacecraft, as well as between the just released OD solution and the OD solution that was used to build the command sequence that will begin running on the spacecraft the next Monday. The average differences between the different OD solution periapsis crossing times are chosen as the time-tag biases for each respective command sequence.

In command sequences "time tags" contain groups of commands. When a time-tag bias is applied, the bias effectively causes commands to execute earlier or later in time. When a command sequence is built, science observations are placed at certain points in time and implemented a certain way, on the basis of what is known at the time about where the spacecraft is located in space in reference to Mercury (its orbit). As the navigation team acquires more tracking data, the OD solution improves, and thus knowledge of the spacecraft trajectory through space improves. By moving commands earlier or later in time (whatever the case may be), commands are lining back up with the point in space that the spacecraft was assumed to be when the command sequence was designed.

To ensure that spacecraft health and safety will be maintained when the command sequence is executed on an updated OD solution and with time-tag biases applied, two additional steps are necessary in the G&C NTSP schedule, step 3 during week 3 and step 4 during week 4. During the second half of week 3, the Monday-through-Friday portion of the command sequence is re-simulated using the OD solution to be loaded to the spacecraft on the Friday of week 3 and the time-tag bias that will be applied to the Monday-through-Friday portion of the command sequence. During week 4, the command sequence begins executing on the spacecraft. On the

Thursday of week 4, a new OD solution is released and a time-tag bias is selected for the remainder of the command sequence. Step 4 is the re-simulation of the remaining portion of the command sequence to be executed with the updated OD solution and associated time-tag bias.

ANALYSES PERFORMED PRIOR TO ORBITAL PHASE

The ability to follow the G&C NTSP schedule as laid out in Figure 6 and ensure adherence to all aforementioned orbital constraints requires an effective and streamlined approach. The most challenging aspect of the G&C NTSP schedule is the amount of time allotted for the review and modification of the SciBox G&C SASF (step 1). Each week, a new command sequence begins running on the spacecraft, and because the G&C NTSP schedule is four weeks in length, four command sequences are moving through the NTSP schedule at once. Because multiple command sequences are being built at once, the G&C NTSP steps are performed for each command sequence by a single G&C analyst. Adding to the time constraint is the amount of time that each RTW simulation takes to complete. An RTW simulation covering a duration of one week takes between 2 and 2.5 hours to complete. If no star tracker commanding is required in a command sequence, the minimum number of RTW simulations that must be run in step 1 is three, and if star tracker commanding is required, the minimum number is four, as shown in Figure 7. Therefore, assuming perfect conditions, the minimum amount of time that must be dedicated to the actual execution of RTW simulations is 6 hours, nearly one full business day, because simulations cannot be run simultaneously and the sub-tasks are serial.

Numerous analyses were performed prior to the orbital phase to ensure that while in orbit about Mercury, a weeklong command sequence adhering to all orbital constraints will begin executing each Monday and that each command sequence contains the optimal science observations and operational activities required for the MESSENGER mission to meet all mission science goals. The analyses performed were instrumental in developing an orbital concept of operations for each subsystem and payload team, improving the SciBox scheduling software, and developing the G&C NTSP process, which was detailed in the previous section.

Year-in-the-Life Testing

The role of the G&C team in Year-in-the-Life (YITL) testing was the RTW simulation of the SciBox G&C SASF for every week in the MESSENGER mission's nominal one Earth-year mission. One of the primary goals of YITL testing was to improve the SciBox scheduling software for use in the orbital phase. SciBox uses its own model of the G&C subsystem and spacecraft attitude dynamics, which is limited in comparison to the high-fidelity RTW model, in order to minimize the amount of computational time required to generate the science observation schedule for the full Earth-year in orbit about Mercury. As such, the predicted science observation schedule for the full Earth-year in orbit was simulated with the G&C team's RTW model to ensure that attitude profiles designed by SciBox do not violate the SKI and HPKO pointing constraints. Additionally, the RTW simulations of a set of sample weeklong attitude profiles that represented the many different pointing scenarios to be used during the orbital phase were analyzed to ensure that the G&C system would be capable of executing the attitude profiles designed by SciBox within the required accuracy.[3] Whenever a pointing violation occurred in an RTW simulation during YITL testing, the violation was noted and information describing the cause of the violation was distributed to the SciBox development team. In this way, the G&C team was able to provide the necessary information for SciBox to be iteratively developed.

The SciBox G&C SASFs that were simulated through the RTW model as part of G&C YITL testing were sent through a limited step 1 of the G&C NTSP process. Each weeklong G&C SASF was simulated without additional G&C commands, SciBox pointing profiles were not modified, and the same low initial momentum state was used for each week. The limited scope of RTW simulations in YITL testing was necessary given the time required to complete and analyze 52 weeklong simulations. In addition to providing information to the SciBox development team, the RTW simulations provided an opportunity to assess and refine the G&C orbital concept of operations.

Starting each weeklong simulation with the same low initial body angular momentum state and the same passive momentum management strategy allowed the assessment of the rate of body angular momentum buildup throughout the orbital year. For each weeklong RTW simulation, the ending angular momentum state and the number of autonomous momentum dumps performed were recorded. The results of the rate of angular momentum buildup analysis showed that passive momentum management alone cannot ensure that momentum always stays below the autonomous momentum red dump limit. YITL testing concluded that a worst-case scenario of two CMDs would be required per week in combination with passive momentum management in order to avoid safe-hold demotions due to autonomous momentum dumps, and to stay below a comfortable momentum magnitude under the red dump limit for the sake of conservatism. As such, MESSENGER's orbital concept of operations includes two CMD placeholders twice per week, one on Tuesday and one on Friday.

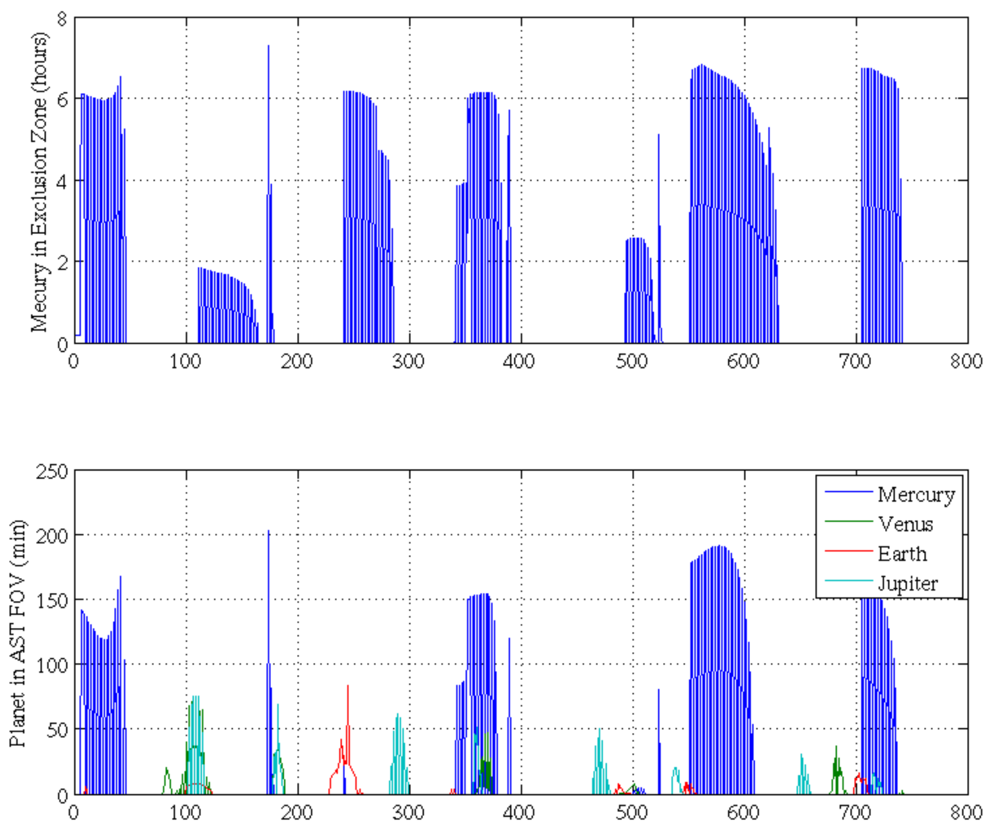

Figure 8. Frequency and Duration That Mercury Is Within the Autonomous Star Tracker (AST) Exclusion Zone and Bright Planets Are Within the AST Field of View (FOV) Using SciBox Version CCB2.0 for the Orbital Phase Attitude Profile.

In addition to providing information to develop the momentum management orbital concept of operations, YITL testing provided information on the frequency of seasonal events that would require additional G&C commanding during the orbital phase. Of particular concern was the frequency that Mercury would enter the star tracker exclusion zone, and at what attitudes. As mentioned previously, Mercury's brightness relative to MESSENGER and its size on the star tracker CCD allow no chance of valid attitude solutions when Mercury is within the star tracker field of view, and stray light presents a problem when the star tracker boresight-to-Mercury angle is within 30°. Figure 8 shows the frequency and duration that Mercury would enter the star tracker exclusion zone during the entire orbit year according to SciBox version CCB2.0. YITL testing showed that Mercury will enter the star tracker exclusion zone frequently, sometimes for nearly 7 hours in duration, and that the majority of times when Mercury will enter the star tracker exclusion zone are times when the spacecraft is in downlink attitude. Because of this analysis, power-cycling of the star tracker during downlink tracks in which Mercury enters the star tracker exclusion zone was added to the orbital concept of operations. To ensure that such a high frequency of star tracker power-cycling commanding could be generated during step 1 of the G&C NTSP process within the allotted time, utilities were developed to automate the creation of star tracker power-cycling SASF requests.

Week-in-the-Life Testing

Another type of orbital simulation testing, called Week-in-the-Life (WITL) testing, was performed prior to the orbital phase. The overall goal of WITL testing was for each subsystem and payload team involved in NTSP to practice the NTSP procedures and to test software by building orbital command sequences. WITL testing began with the production of a weeklong command sequence in non-real-time, meaning that each step of NTSP was lengthened past the nominal schedule of three weeks from the time that SciBox schedules are released to the time that the command sequence is compiled. Later WITL testing was performed using a real-time NTSP schedule, first with only one weeklong command sequence moving through NTSP at once, then two consecutive weeklong command sequences built back-to-back, and finally four consecutive weeklong command sequences built back-to-back.

WITL testing helped the G&C team to develop a streamlined and effective methodology, especially the WITL exercises that were performed under orbital phase time constraints. Without a set of procedures and utilities to automate analysis and generate SASF requests for added G&C commands, completing step 1 in Figure 6 within only 6.5 business days for back-to-back command sequences for a duration of one Earth-year would be nearly impossible and unsustainable by the team, and the risk of human error would be greatly increased. An effective orbital phase methodology had to be developed to ensure adherence to all orbital constraints and to provide the best opportunity for science collection. The G&C NTSP procedures used in the orbital phase, which are shown in Figure 7, were developed and refined during WITL testing, including the development of extensive supporting software.

Orbital Flight Test

In August 2010, approximately 7 months before Mercury orbit insertion, an orbital flight test was performed to exercise the flight system under flight conditions close to those experienced in orbit. Like WITL testing, the orbital flight test provided an opportunity to practice the NTSP procedures, but it also allowed the team to take preparations one step farther, by matching a typical week of orbital operations in flight. The orbital flight test spanned two weeks. During the first week, one CMD was performed, an orbit-like ephemeris was used for the precise spacecraft ephemeris, daily Deep Space Network contacts were scheduled, and outside of Deep Space Network contacts, standard momentum management and cruise attitude profiles were performed. The first week allowed the team to ease into orbit-like conditions and guarantee nominal operation before embarking on the second week of the orbital flight test, which was far more demanding. Before the first week of the orbital flight test, it had been nearly four Earth-years since a CMD was executed on the spacecraft, and never before had an orbit-like ephemeris been used in flight. Orbital spacecraft ephemerides usually require approximately 130 Chebyshev polynomial spans to achieve the required knowledge accuracy, whereas cruise spacecraft ephemerides typically require up to 6 spans, and cruise spacecraft ephemerides that include planetary flybys require approximately 12 Chebyshev polynomial spans.

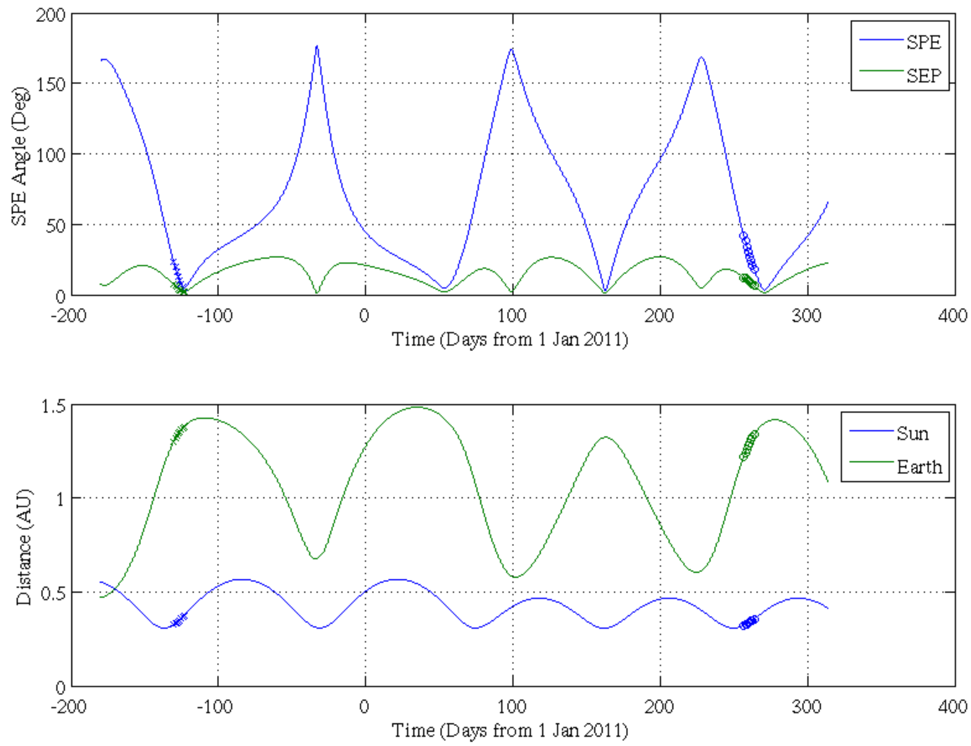

Figure 9. Planetary Geometry Comparison Relative to MESSENGER, with DOY 235, 2010 – DOY 242, 2010, and DOY 257, 2011 – DOY 264, 2011, Highlighted. SPE = Sun–MESSENGER–Earth Angle, SEP = Sun–Earth–MESSENGER Angle.

During the second week of the orbital flight test, operations activities included two CMDs plus approximately seven days of SciBox version CCB4.0-generated instrument and G&C commanding. The two CMDs were executed during the Tuesday and Friday Deep Space Network contacts, respectively, which mimicked the orbital phase placement of CMD placeholders. The orbital week that was selected had similar planetary geometry to the time of the second week of the flight test. To keep the flight test as realistic as possible, planetary geometry had to be similar in order to the get the spacecraft attitude motion to approximate orbital phase conditions. In particular, the spacecraft-to-Sun distance, spacecraft-to-Earth distance, Sun–MESSENGER–Earth angle, and Sun–Earth–MESSENGER angle had to be similar. Figure 9 shows these values for the spacecraft's trajectory during the second week of the orbital flight test (Day-of-Year (DOY) 235, 2010 – DOY 242, 2010) and the time in MESSENGER's predicted orbital trajectory that most closely matched (DOY 2011, 257 – DOY 264, 2011). The optimal orbital phase time frame was actually a Wednesday-to-Wednesday time period. Because the orbital flight test was intended to be a full operations dress rehearsal, the time frame was shifted to the nearest Monday-to-Monday time period (DOY 255, 2011 – DOY 261, 2011); orbital phase command sequences span one week, Monday-to-Monday. Although the time period used was less optimal in terms of similar planetary geometry, by choosing a Monday-to-Monday period, the operations, instrument, and subsystem teams were able to follow the NTSP process under more orbit-like conditions to produce the command sequence.

To force the spacecraft to exercise attitude motions similar to the orbital phase, the ephemerides used by the flight software had to be modified, essentially tricking the spacecraft into thinking that it was in orbit about Mercury. The target planet ephemeris was replaced with the true heliocentric spacecraft ephemeris, and the precise spacecraft ephemeris was replaced with the predicted Mercury-centered orbital phase ephemeris for the orbital week that was executed on the spacecraft (DOY 255, 2011 – DOY 261, 2011). Because of the similarity of planetary geometry, the Sun and Earth ephemerides were not changed. This introduced small errors in the spacecraft's knowledge of its heliocentric position (maximum of approximately 16,000 km) but was not enough to impact Earth and Sun pointing.

The commanding for the second week of the orbital flight test was generated using the same NTSP procedures that are used in orbit. Therefore, preparations for the second week of the orbital flight test were much like a WITL test, but with a flight test at the end to confirm the validity of the team's procedures and software. The orbital flight test was completed nominally in all regards, ensuring that the spacecraft and flight team were prepared for MESSENGER's orbital phase.

CONCLUSION

The constraints that the MESSENGER spacecraft faces while in orbit about Mercury are more demanding and copious than the constraints experienced during the cruise phase. In addition, the G&C team faces a constant stream of weeklong command sequences that must be built within a short period of time, and in each command sequence, spacecraft health and safety must be assured. Although the demands of the orbital phase are greater than what was experienced prior to Mercury orbit insertion, the methodology used by the G&C team to produce each command sequence has been proven effective. As of the writing of this paper, the spacecraft has successfully executed tens of thousands of science observations without a single spacecraft safe-hold demotion or any other off-nominal extended interruption to planned science observations. The analyses performed prior to the orbital phase, in particular, the YITL testing, the WITL testing, and the August 2010 orbital flight test, were instrumental in developing the streamlined and effective methodology used by the G&C team to ensure spacecraft health and safety throughout MESSENGER's orbital phase. The methodology continues to be improved, ensuring the best chance for the successful completion of all of MESSENGER's science goals.

REFERENCES

[1] A. F. Berman, D. L. Domingue, M. E. Holdridge, T. H. Choo, R. J. Steele, and R. G. Shelton, "Testing and Validation of Orbital Operations Plans for the MESSENGER Mission." *Observatory Operations: Strategies, Processes, and Systems III*, *SPIE Astronomical Telescopes and Instrumentation 2010*, Conference 7737, paper 7737-13, 13 pp., San Diego, CA, June 30–July 2, 2010.

[2] T. H. Choo, B. J. Anderson, R. J. Steele, J. P. Skura, and P. D. Bedini, "An Automated Science Observation Scheduling System for MESSENGER." *60th International Astronautical Congress*, paper IAC-02-C1.3.8, 8 pp., Daejeon, Republic of Korea, October 12-16, 2009.

[3] R. M. Vaughan, D. J. O'Shaughnessy, and S. H. Flanigan, "MESSENGER Spacecraft Pointing Performance during the Mission's Mercury Orbital Phase." *American Astronautical Society/American Institute of Aeronautics and Astronautics Astrodynamics Specialist Conference*, paper AAS 11-551, 20 pp., Girdwood, AK, July 31-August 4, 2011.