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Getting the Message to MESSENGER: Overview of the Weekly Planning and Sequencing of MESSENGER Orbital Activities

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For over three years, the MESSENGER spacecraft has been in orbit about the planet Mercury. Because of the thermal and radiation constraints imposed by MESSENGER's proximity to the Sun, assembling weekly command loads for the payload requires tight coordination across all operational subsystems and engineering teams. In addition to close team interaction, science planning requires a thorough understanding of mission constraints, accomplished with detailed models of recorder usage, communication uplink and downlink, orbit ephemeris and spacecraft attitude. Because of the many complexities in the orbital phase of the MESSENGER mission, such as the demanding thermal environment and changes in lighting conditions, the overlapping process of these weekly command-load builds must start approximately three weeks prior to onboard execution. The mission's planning and scheduling process is mature, having been originally designed and successfully implemented to assemble the command-load sequences for the Near Earth Asteroid Rendezvous (NEAR) orbital mission. This planning system architecture is also used on the New Horizons mission to Pluto. Refinements were periodically made during the interplanetary cruise and early orbital phases of the MESSENGER mission, and the process and code now constitute a resilient operational system as demonstrated by three very successful and productive years of Mercury orbital science operations (12+ Mercury years), with over 200,000 images captured and over 2,800 orbits completed to date.

MESSENGER's command loads are assembled through a structured process that includes guidelines for load content and data recorder management. Weekly instrument command sequences are generated to fulfill the science objectives without violating instrument and spacecraft operational constraints. The SciBox science planning software serves as a coordination tool that allows the instrument teams to plan their observations, and it uses their plans to produce a consolidated payload command load that is packaged by the mission operations team for upload to the spacecraft. Given the complex set of constraints required to safely operate MESSENGER in orbit about the planet closest to the Sun, this integrated approach ensures that potential command conflicts are resolved in a timely manner, and that the chance is minimized that an erroneous or anomalous command sequence that jeopardizes health and safety or results in data loss could ever make it through all the gates of the three-week process and then to the spacecraft.

Nomenclature

AU = Astronomical Unit
C&DH = Command and Data Handling
CMD = Commanded Momentum Dump
DSN = Deep Space Network
G&C = Guidance and Control
MDIS = Mercury Dual Imaging System
MESSENGER = MErcury Surface, Space ENvironment, GEochemistry, and Ranging
MOM = Mission Operations Manager
MOps = Mission Operations
MP = Main Processor
NEAR = Near Earth Asteroid Rendezvous
NTSP = Near-Term Science Planning
OCM = Orbit-Correction Maneuver

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.prc = Proc or Procedure file
POM = Payload Operations Manager
RF = Radio Frequency
SAF = Station Allocation File
SASF = Spacecraft Activity Sequence File
SEP = Sun-Earth-Probe
SKI = Sun Keep-In
SPE = Sun-Probe-Earth
.spo = SeqPost Output File
SSR = Solid-State Recorder
STOL = Spacecraft Test and Operations Language
XRS = X-Ray Spectrometer

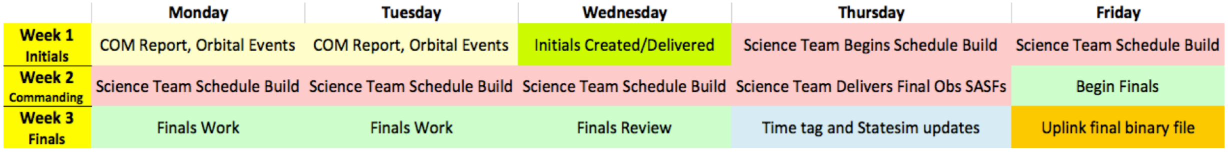
I. Introduction

THE MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft is the first probe to visit the planet Mercury since Mariner 10 performed three flybys of the planet in 1973-1974, and in March 2011 MESSENGER became the first spacecraft to go into orbit around Mercury[1]. The mission was designed for the spacecraft to operate for six and a half years in a cruise phase before entering orbit about Mercury, where it would study Mercury and the solar environment for one full Earth year (equivalent to about two Mercury solar days). Afterward, NASA granted extended mission phases to allow orbital operations to continue until the end of spacecraft life in March 2015. At that point the fuel will be depleted and MESSENGER's orbital periapsis will have decreased to a point where the spacecraft will impact onto the surface of Mercury.

In general, operating an interplanetary spacecraft is a highly complex process that involves a number of different spacecraft-level and instrument-level teams (e.g., subsystem and ground system engineers, orbit and pointing analysts, command load sequencers, flight operations personnel, Deep Space Network (DSN) support, and instrument scientists) to coordinate on a weekly basis to ensure a conflict-free schedule that integrates science and engineering activities[2]. From the cruise phase to the orbital phase, MESSENGER's highly coupled spacecraft and instrument operations commanding makes liberal use of the advanced planning schedules generated by SciBox[3-6]. The focus of this paper is on the process of building the weekly command loads that are ultimately sent to the spacecraft for execution.

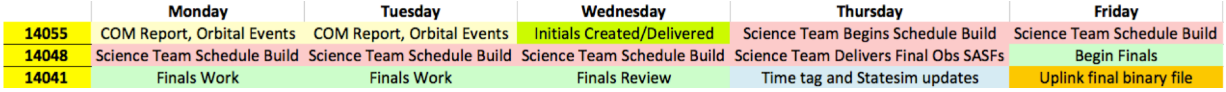
Command sequences are uplinked to the spacecraft for a week's worth of operations at a time, except in special circumstances such as near solar conjunctions, during which command uplink opportunities are limited. Execution of a command load begins each Monday – a cadence chosen so that transitions between command loads on the spacecraft occur during the work week, when the most ground support personnel are available in case there are any problems with the transition, and so the loads' mid-break transitions (discussed in further detail in section V) also occur during the work week and have immediate available ground support for any issues that might arise. Additionally, having command loads begin on Mondays drives the delivery schedule for other input products to the command builds, and drives the uplink schedule of the loads to the spacecraft.

These load sequences provide the commands necessary to conduct science observations, communicate with Earth-based ground stations, download the recorded science data, perform correction maneuvers, enforce Sun keep-in (SKI) and hot-planet pointing constraints, and position the solar panels to maximize power while protecting them from the thermal effects of the Sun. Because of the interleaved nature of the spacecraft and instrument commanding, it takes three weeks to prepare each one-week command load[3-7]. This three-week period is broken into the "initials" phase, the science commanding phase, and the "finals" phase (Figure 1). Furthermore, as each command load requires three weeks to build, the command-sequence team is working on three overlapping command loads at any given time (Figure 2). The command loads follow a YYDDD nomenclature, which is noted in Figure 2. The "YY" indicates the last two digits of the year in which a command load will execute. The "DDD" is the day of year on which the command load begins. Thus command load 14055 would begin on day 55 (24 February) of the year 2014.



	Monday	Tuesday	Wednesday	Thursday	Friday
Week 1 Initials	COM Report, Orbital Events	COM Report, Orbital Events	Initials Created/Delivered	Science Team Begins Schedule Build	Science Team Schedule Build
Week 2 Commanding	Science Team Schedule Build	Science Team Schedule Build	Science Team Schedule Build	Science Team Delivers Final Obs SASFs	Begin Finals
Week 3 Finals	Finals Work	Finals Work	Finals Review	Time tag and Statesim updates	Uplink final binary file

Figure 1. A three-week overview of activities for one command load, from the initials phase through the finals phase and uplinking of the command load to the spacecraft.



	Monday	Tuesday	Wednesday	Thursday	Friday
14055	COM Report, Orbital Events	COM Report, Orbital Events	Initials Created/Delivered	Science Team Begins Schedule Build	Science Team Schedule Build
14048	Science Team Schedule Build	Science Team Schedule Build	Science Team Schedule Build	Science Team Delivers Final Obs SASFs	Begin Finals
14041	Finals Work	Finals Work	Finals Review	Time tag and Statesim updates	Uplink final binary file

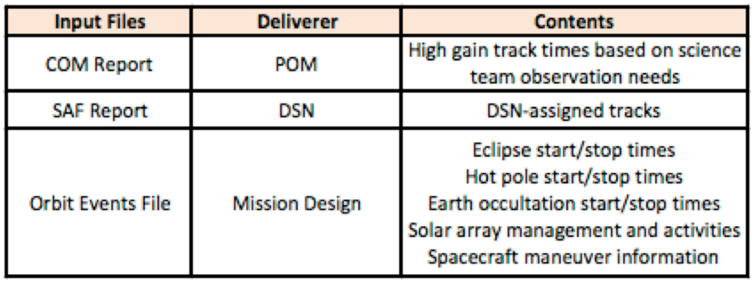
Figure 2. Three successive and overlapping command loads and their respective steps in a given week.

II. Input to the Initials

Before the command-sequence team begins building each load, they require weekly deliveries from the DSN schedulers, the mission design team, and SciBox, on set days of the week. Months before each load build, the mission operations (MOps) team and the DSN schedulers lay in idealized tracks based on a SciBox track request summary report that works around the science activities. The tracks are later negotiated and solidified 8–10 weeks in advance, and the information is delivered to the MOps team as a Station Allocation text File (SAF) with an additional week of tracks added to the bottom each week. The SAF includes the ground antenna selections and times, and this information drives the specific weekly boundary conditions (beginning and ending date/times) for each command load[4]. Although the SAF report information is available several weeks before the initials are built, it cannot be utilized by the MOps team until the Payload Operations Manager (POM) engages SciBox to perform a weekly optimization run. These runs keep track of previously executed observations (especially for targeted observations), identify opportunities for additional commanding (whether special or targeted observations may be safely performed in that command load period), and analyze the DSN tracks to identify low-gain versus high-gain Earth pointing times. SciBox also accounts for blackout periods – tracks set aside to perform spacecraft activities, such as commanded momentum dumps (CMDs) and orbit-correction maneuvers (OCMs), when science data collection is precluded. Once the POM has completed the initial SciBox optimizer run each week, the high-gain antenna/low-gain antenna allocation communication (COM) report, along with specific instrument activities not already scheduled by SciBox (such as seasonal power cycling of some instruments), is furnished to the command-load build team. Finally, the mission design team delivers a weekly "orbit events" file, which is also required to build initials. This file includes up-to-date eclipse and occultation entry and exit times, solar array position information, spacecraft maneuver information, and other pertinent orbit parameter information.

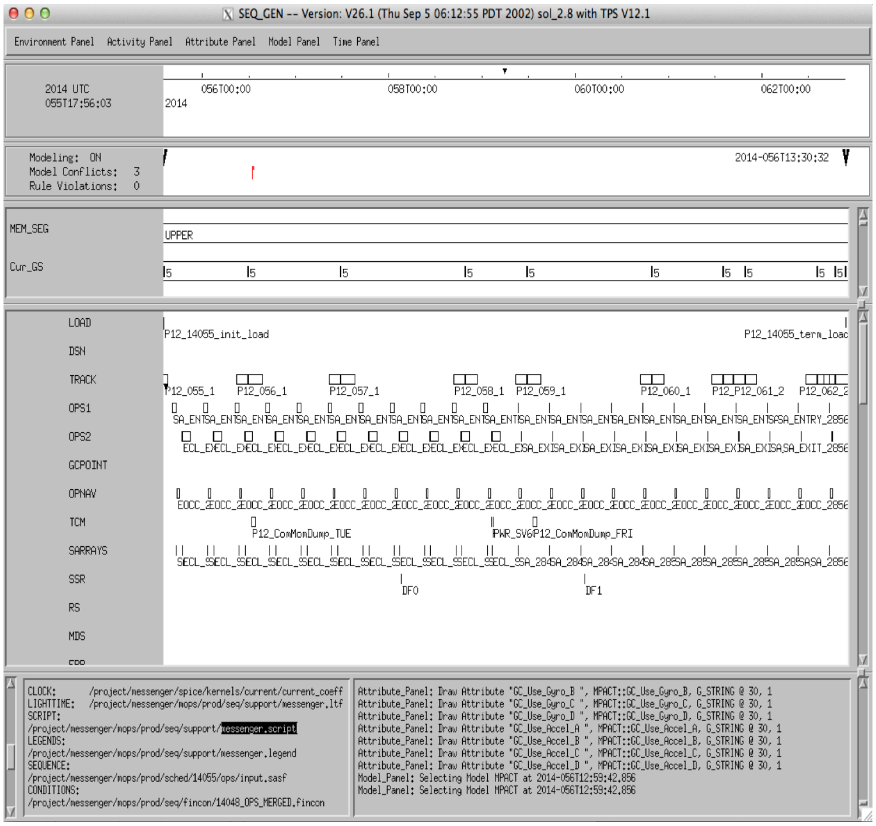
III. Initials Phase

Once the SciBox COM report, the DSN SAF, and the mission design team's orbital events file (Table 1) are delivered to the command sequencers each week, the initials file is generated, and this in turn is used by the instrument teams to build and deliver their respective observation schedules each week. The command sequencer runs a software tool called SeqGen[8] to generate the initial Spacecraft Activity Sequence File (SASF). This SASF is a time-ordered, human-readable text file containing only the activity requests for the spacecraft subsystems for that week. The SeqGen graphical user interface (GUI) (Figure 3) allows the command sequencer to verify the contents of the SASF by manual inspection of the layout of the orbital events and DSN inputs. The command sequencer notes all track entries and compares them with the COM report listing to ensure that all DSN tracks are accurately laid out in the GUI and thus will be reflected in the SASF output. The command sequencer will also examine the tracks to verify that the uplink rates are set correctly. The default setting for the uplink rate is 125 bits per second (bps), but during high-rate uplink seasons, when Mercury is within 0.9 Astronomical Units (AU) of the Earth (Figure 4), the Sun-probe-Earth (SPE) angle is greater than 90°, and the Sun-Earth-probe (SEP) angle is not less than 2° (which occurs at inferior conjunction), the rates climb to 500 bps. The command sequencer has to manually edit the uplink rates to 500 bps during the seasons in which it is applicable.



Input Files	Deliverer	Contents
COM Report	POM	High gain track times based on science team observation needs
SAF Report	DSN	DSN-assigned tracks
Orbit Events File	Mission Design	Eclipse start/stop times Hot pole start/stop times Earth occultation start/stop times Solar array management and activities Spacecraft maneuver information

Table 1. List of Input Files for Building of the Initials.



SEQ_GEN -- Version: V26.1 (Thu Sep 5 06:12:55 PDT 2002) sol_2.8 with TPS V12.1

2014 UTC
055T17:56:03

Modeling: ON
Model Conflicts: 3
Rule Violations: 0

2014-056T13:30:32

```
CLOCK:      /project/messenger/spice/kernels/current/current_coeff
LIGHTTIME:  /project/messenger/mops/prod/seq/support/messenger.ltf
SCRIPT:
/project/messenger/mops/prod/seq/support/messenger.script
LEGENDS:
/project/messenger/mops/prod/seq/support/messenger.legend
SEQUENCE:
/project/messenger/mops/prod/sched/14055/ops/input.sasf
CONDITIONS:
/project/messenger/mops/prod/seq/fincon/14048_OPS_MERGED.fincon
```

```
Attribute_Panel: Draw Attribute "GC_Use_Gyro_B ", MPACT::GC_Use_Gyro_B, G_STRING @ 30, 1
Attribute_Panel: Draw Attribute "GC_Use_Gyro_C ", MPACT::GC_Use_Gyro_C, G_STRING @ 30, 1
Attribute_Panel: Draw Attribute "GC_Use_Gyro_D ", MPACT::GC_Use_Gyro_D, G_STRING @ 30, 1
Attribute_Panel: Draw Attribute "GC_Use_Accel_A ", MPACT::GC_Use_Accel_A, G_STRING @ 30, 1
Attribute_Panel: Draw Attribute "GC_Use_Accel_B ", MPACT::GC_Use_Accel_B, G_STRING @ 30, 1
Attribute_Panel: Draw Attribute "GC_Use_Accel_C ", MPACT::GC_Use_Accel_C, G_STRING @ 30, 1
Attribute_Panel: Draw Attribute "GC_Use_Accel_D ", MPACT::GC_Use_Accel_D, G_STRING @ 30, 1
Model_Panel: Selecting Model MPACT at 2014-056T12:59:42.856
Model_Panel: Selecting Model MPACT at 2014-056T12:59:42.856
```

Figure 3. The SeqGen GUI showing a visual layout of tracks and other non-science activities of the spacecraft. Note the red flag near the top indicating that there is an issue that requires the command-load build team to intervene.

During hot-pole seasons, when the orbit of the spacecraft passes between the Sun and Mercury, the Mercury Atmospheric and Surface Composition Spectrometer (MASCS) and X-Ray Spectrometer (XRS) instruments may require power cycling (for thermal mitigation) that is not laid out in SciBox ahead of time[9]. These power cycling requests are manually input to the SASF by the command sequencer via text editor. The instrument teams identify these periods in advance, and the command sequencers are alerted by the POM[3] to the specific on/off times coincident with the COM report deliveries.

The command sequencer also takes note of any red error or blue warning flags that may appear in the GUI (see Figure 3). These flags indicate a variety of potential issues. Red flags indicate problems or issues that must be corrected by the command sequencer, such as timing collisions between two macro calls or science activity commanding during CMD blackout periods. Blue flags merely note a state of a subsystem, such as star trackers powered off for a period of time. The command sequencer does not typically take intervening action in response to the blue flag notifications unless specifically directed to do so by the subsystem team.

Mercury's thermal environment is highly dynamic, and during the hot-pole and eclipse seasons, additional tweaks may be necessary to manage the peak temperatures on the solar arrays and ensure that the arrays produce sufficient power for the spacecraft. Solar array thermal and power models are produced by the subsystem teams, and these models drive routine array-pointing guidelines. Minor adjustments to solar-array management strategies may be provided by the power and thermal teams on the basis of changes in the orbit or flight performance of the arrays.

The final step in building initials is CMD timing placement. Although SciBox accounts for the blackout CMD tracks, it does not model the CMDs. It is, therefore, the responsibility of the command-load sequencer to place these requests into the appropriate tracks consistent with the COM report notes.

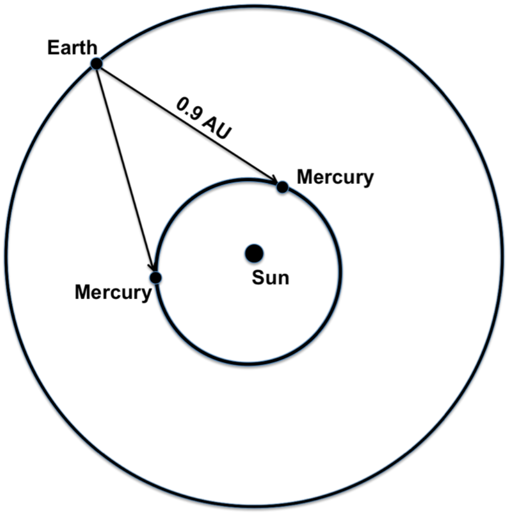


Figure 4. Illustration of Earth and Mercury when Mercury is at 0.9 AU from Earth. The 500 bps high rate season is when Mercury is along the short arc between the two orbit points indicated.

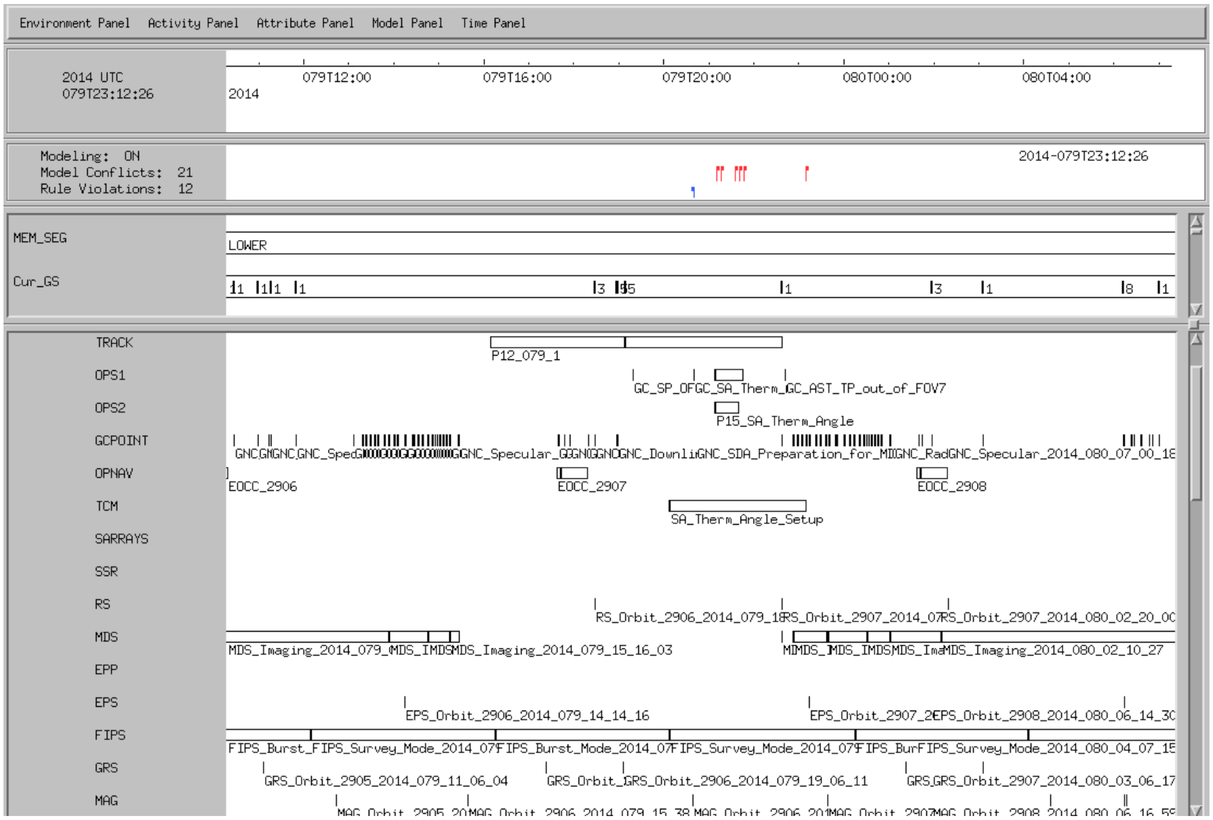
IV. Science and Subsystem Inputs Phase

Once initials have been generated, the command load sequencer utilizes the Near-Term Science Planning (NTSP) tracking tool JIRA[10] to advise the POM that the initials are ready and that the SASF is available to the instrument teams, who may then review the SciBox-generated science schedules for their respective instruments overlaid with the initials information in their SeqGen GUIs[4]. At this point, the instrument teams may manually edit their planned commands in the SASF to ensure compliance with their instrument constraints and satisfaction of their science goals. From this SciBox-created schedule, the instrument teams generate individual instrument SASFs that will later be delivered to the command-load build team for inclusion into the finals command-load merged build[3-7].

V. Finals Phase

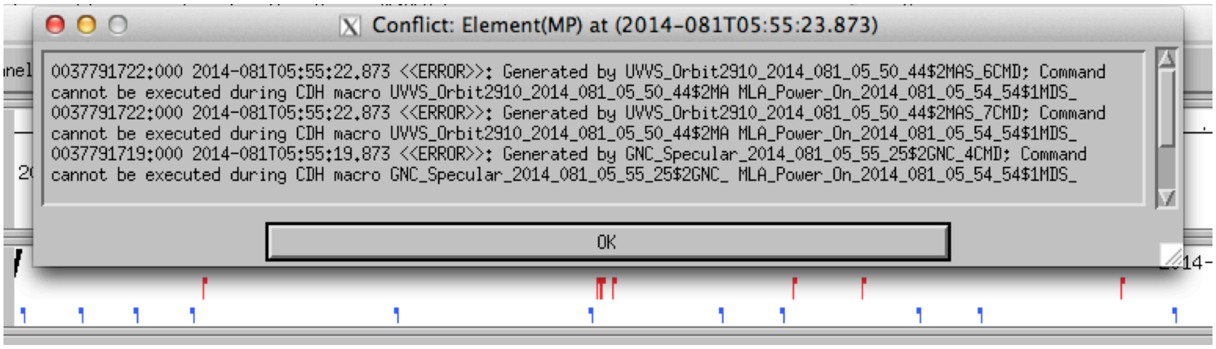
Before the final merged assembly of the command load can commence each week, the command sequencer must first update the original idealized downlink rate placeholders with actual track-specific rates and rate steps (if needed). The command sequencer works closely with the MOps radio frequency (RF) analyst to ensure that the spacecraft communications are optimized. This step can often be performed prior to the delivery of the science SASFs. Once this final step is complete, the command load sequencer may begin working on the final merged command load SASF. This process begins approximately one week before the load is to be uplinked to the spacecraft (Figure 1).

The command load sequencer runs the SeqGen software again in order to build the final command load. This run merges all the science SASFs into a final SASF. Since each instrument SASF is built and delivered independently with only MOps initials overlaid, there are routine instrument command interference/timing collisions with spacecraft commanding or other instrument commanding that needs to be addressed. These are observed as red flags in the SeqGen GUI (Figure 5). The user may click on the red and blue flags in the SeqGen GUI to view a dialog box that outlines these error messages (Figure 6). Often, they simply identify situations requiring that the execution time of lower-priority activity be adjusted. There are usually obvious timing gaps into which the lower-priority activity may be moved.



Modeling: ON
Model Conflicts: 21
Rule Violations: 12

Figure 5. A zoomed-in view of the SeqGen GUI during the finals phase, showing the operations that were occurring when the red flag was thrown. This view shows the spacecraft commanding, the tracks, and some of the science observation requests.



```
0037791722:000 2014-081T05:55:22.873 <<ERROR>>: Generated by UVVS_Orbit2910_2014_081_05_50_44$2MAS_6CMD: Command
cannot be executed during CDH macro UVVS_Orbit2910_2014_081_05_50_44$2MA MLA_Power_On_2014_081_05_54_54$1MDS_
0037791722:000 2014-081T05:55:22.873 <<ERROR>>: Generated by UVVS_Orbit2910_2014_081_05_50_44$2MAS_7CMD: Command
cannot be executed during CDH macro UVVS_Orbit2910_2014_081_05_50_44$2MA MLA_Power_On_2014_081_05_54_54$1MDS_
0037791719:000 2014-081T05:55:19.873 <<ERROR>>: Generated by GNC_Specular_2014_081_05_55_25$2GNC_4CMD: Command
cannot be executed during CDH macro GNC_Specular_2014_081_05_55_25$2GNC_ MLA_Power_On_2014_081_05_54_54$1MDS_
```

Figure 6. Error messages associated with the red flags in the SeqGen GUI.

Typically, a move is on the order of seconds to minutes, and they follow pre-defined allowable guidelines. If, in very rare cases, it proves necessary to move the conflicting commands farther than the defined threshold, the instrument or subsystem team leads are consulted for instrument health and safety verification before those activities may be moved. If the activity cannot be safely moved, then either the activity will be deleted or the higher-priority activity's instrument team will be consulted. However, the higher-priority-level activities are often directly linked with guidance and control (G&C) spacecraft pointing, and would require an enormous team effort to re schedule, so this option is seldom pursued.

Because the command-load data volume can be large, requiring hours to uplink to the spacecraft during the 125-bps seasons, loads are divided into two parts. This "mid-break" is manually added to the command load SASF during the finals phase at a point approximately halfway through the load period of a downlink telemetered track (Thursday afternoons or Friday mornings), so the transition can be observed and confirmed in real time.

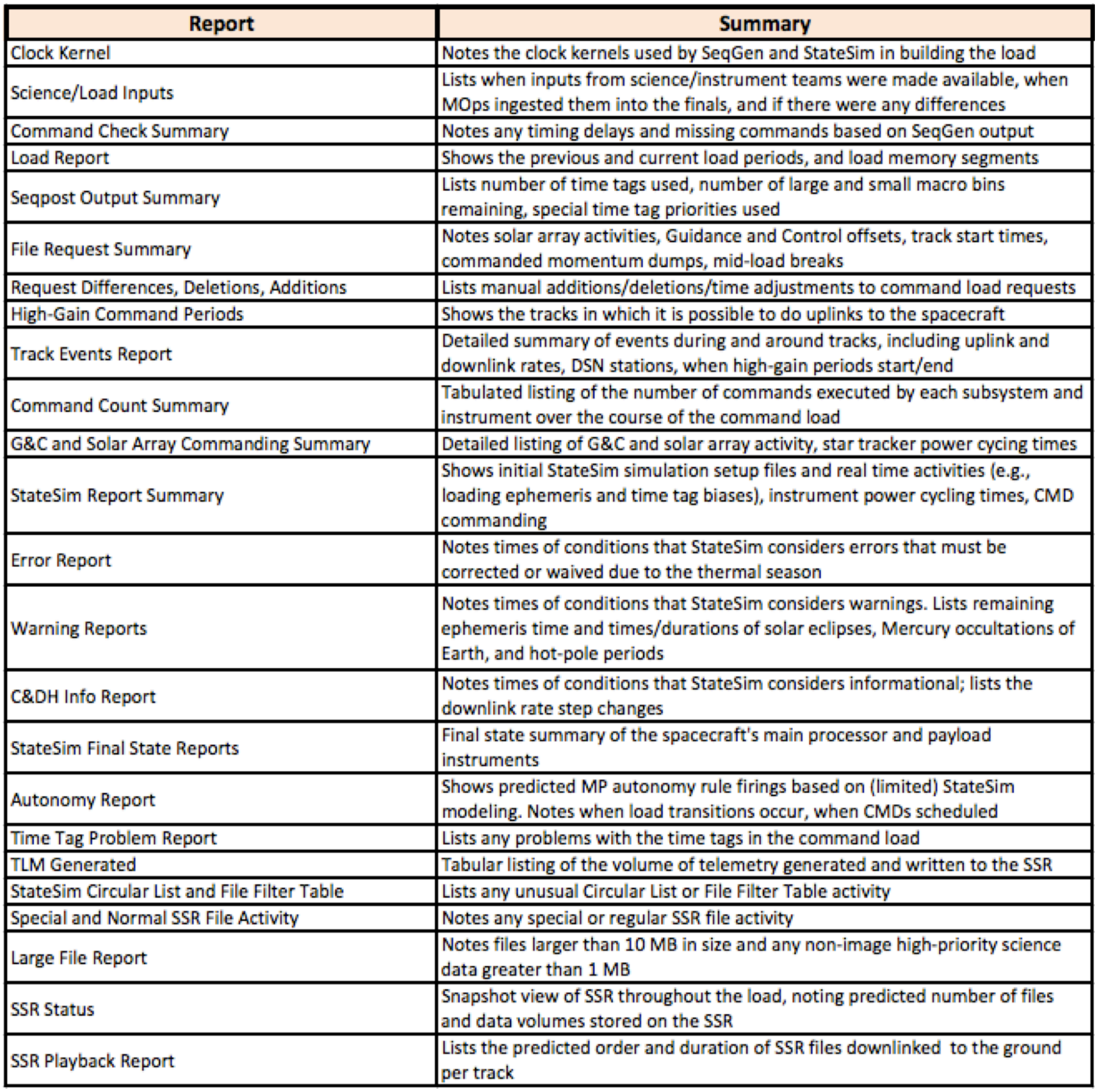
In addition to the mid-break load splitting, it is occasionally necessary to further divide each part again when there are tracks of short duration and the uplink times for the load are long. Whether or not to perform this additional load splitting is a judgment call made by the Mission Operations Manager (MOM), who reviews the track times and durations and available uplink opportunities based on load break placement, as well as the size of each load segment, and decides if additional load divisions are needed and what the corresponding ratios are to be. The MOM furnishes this information to the command sequencers, who then break up the command load segments with these additional load splits.

After the mid-break is in place, the command sequencer runs the SeqGen output through an in-house-developed application called SeqPost. The SeqPost algorithm converts the commands of the SASF into macros. The command sequencer can adjust a number of input parameter "knobs" to optimize the run accounting for time tag bins and macro space usage. If the SeqPost run fails, the command sequencer can then re-adjust the input parameters and run SeqPost again. Depending on the density of commands in a given load, this step can require multiple iterations to find the settings that optimize the command load size. SeqPost produces two human-readable output files: a SeqPost output file (.spo) that contains all activity requests in a Spacecraft Test and Operations Language[11] (STOL) format, and the STOL procedure file (.prc).

After SeqPost has been run successfully, the .spo file must be converted to a binary file format that will be tested on the simulator and uplinked to the spacecraft. This file conversion is accomplished with the EPOCH[12] 2000 Command and Telemetry (C&T) software by Integral Systems, Inc. The .prc file contains the necessary binary load file directives and commands (which are created from the .spo file). Once the binary file has been created, the command sequencer runs the load through a constraint checking tool known as StateSim[13]. StateSim is a powerful in-house software tool that simulates the state of the spacecraft. StateSim runs substantially faster than real time (about 11 minutes for a 1 week command load), allowing rapid confirmation of the expected spacecraft state. Any violations that may not have been evident in earlier steps of the command-load build process are highlighted by this tool. StateSim is used by the command sequencer to model various hardware modes and parameters, solid -state recorder (SSR) levels, G&C attitude changes and pointing, available/used power, and other spacecraft activities. It is also capable of doing limited modeling of individual instrument activities. However, because of the complexity of temperature prediction, StateSim is not used for modeling or constraint checking of the thermal environment.

The output of StateSim and other post-processing software consists of a number of files, reports, and plot data that the command sequencer will further examine for errors or constraint violations. These output files include a comprehensive list/timeline of commands, the final conditions of the spacecraft (including attitude and position constraints), and solar-array and battery-power levels. Additionally, StateSim predicts metadata for all spacecraft files created, including the file directory locations, names, and sizes. StateSim also predicts the Mercury Dual Imaging System (MDIS) camera image compression times when performed in the spacecraft's main processor (MP). Furthermore, StateSim models data bandwidth for uplink and downlink and predicts the state of the onboard file system during each DSN contact.

After the StateSim modeling run has been completed, the command sequencer will then generate a suite of more than 40 reports (Table 2), including those on errors, timing conflicts or issues, and other modeling anomalies that were not detected in earlier stages of the final command load generation process. The command sequencer will also generate a dozen plots that yield a graphical display of additional information, such as the predicted percentage usage and space of the SSR over the period of the command load (Figure 7 and a confirmation that the G&C pointing positions are maintained within the SKI limits (Figure 8). These products are reviewed each week as a team, led by the mission planner, builds the finals for each load. If there are any problems at this stage, either in the reports or in the plots, the command sequencer must step back through the finals build process, correct the problems, and then repeat these steps. This stage can sometimes be an iterative process if some errors do not become evident



Report	Summary
Clock Kernel	Notes the clock kernels used by SeqGen and StateSim in building the load
Science/Load Inputs	Lists when inputs from science/instrument teams were made available, when MOps ingested them into the finals, and if there were any differences
Command Check Summary	Notes any timing delays and missing commands based on SeqGen output
Load Report	Shows the previous and current load periods, and load memory segments
Seqpost Output Summary	Lists number of time tags used, number of large and small macro bins remaining, special time tag priorities used
File Request Summary	Notes solar array activities, Guidance and Control offsets, track start times, commanded momentum dumps, mid-load breaks
Request Differences, Deletions, Additions	Lists manual additions/deletions/time adjustments to command load requests
High-Gain Command Periods	Shows the tracks in which it is possible to do uplinks to the spacecraft
Track Events Report	Detailed summary of events during and around tracks, including uplink and downlink rates, DSN stations, when high-gain periods start/end
Command Count Summary	Tabulated listing of the number of commands executed by each subsystem and instrument over the course of the command load
G&C and Solar Array Commanding Summary	Detailed listing of G&C and solar array activity, star tracker power cycing times
StateSim Report Summary	Shows initial StateSim simulation setup files and real time activities (e.g., loading ephemeris and time tag biases), instrument power cycling times, CMD commanding
Error Report	Notes times of conditions that StateSim considers errors that must be corrected or waived due to the thermal season
Warning Reports	Notes times of conditions that StateSim considers warnings. Lists remaining ephemeris time and times/durations of solar eclipses, Mercury occultations of Earth, and hot-pole periods
C&DH Info Report	Notes times of conditions that StateSim considers informational; lists the downlink rate step changes
StateSim Final State Reports	Final state summary of the spacecraft's main processor and payload instruments
Autonomy Report	Shows predicted MP autonomy rule firings based on (limited) StateSim modeling. Notes when load transitions occur, when CMDs scheduled
Time Tag Problem Report	Lists any problems with the time tags in the command load
TLM Generated	Tabular listing of the volume of telemetry generated and written to the SSR
StateSim Circular List and File Filter Table	Lists any unusual Circular List or File Filter Table activity
Special and Normal SSR File Activity	Notes any special or regular SSR file activity
Large File Report	Notes files larger than 10 MB in size and any non-image high-priority science data greater than 1 MB
SSR Status	Snapshot view of SSR throughout the load, noting predicted number of files and data volumes stored on the SSR
SSR Playback Report	Lists the predicted order and duration of SSR files downlinked to the ground per track

Table 2. Summary of StateSim Final Reports Used for the Final Command Load Review.

until a previously detected error has been corrected. Usually no more than one or two iterations are required to resolve these late-breaking issues.

Once a clean final command load has been produced, the power and RF operations analysts review the load and appropriate StateSim reports. After they approve the load, a second MOps analyst reviews the load. A JIRA hand-shaking notice is also sent to the instrument teams indicating that the command load timeline is ready for their final review[3]. After that approval, the command sequencers meet with the rest of MOps team to review the reports, identify specific events that need to be monitored or elaborated prior to the execution of the load, and review the timeline of activities in the load. Once the entire team is satisfied with the state of the final load, the command sequencer delivers it to the production directory for uplink to the spacecraft. Uplink is scheduled for the first opportunity after each load or mid-load break to ensure adequate uplink opportunities in the event of a communications dropout between the spacecraft and the DSN. Until the load or mid-load transitions, the sequence is stored in macro space memory on the spacecraft.

VI. StateSim Updates

Each StateSim cycle is first run using a weekly ephemeris given to the MOps team by the navigation team, expanded just for mission planning to cover the full seven-day period. Each week, a few days before a given command load is to begin executing, MOps produces a more current flight version of the ephemeris file. This ephemeris is loaded onto the spacecraft along with the upcoming command load and takes effect immediately. It is

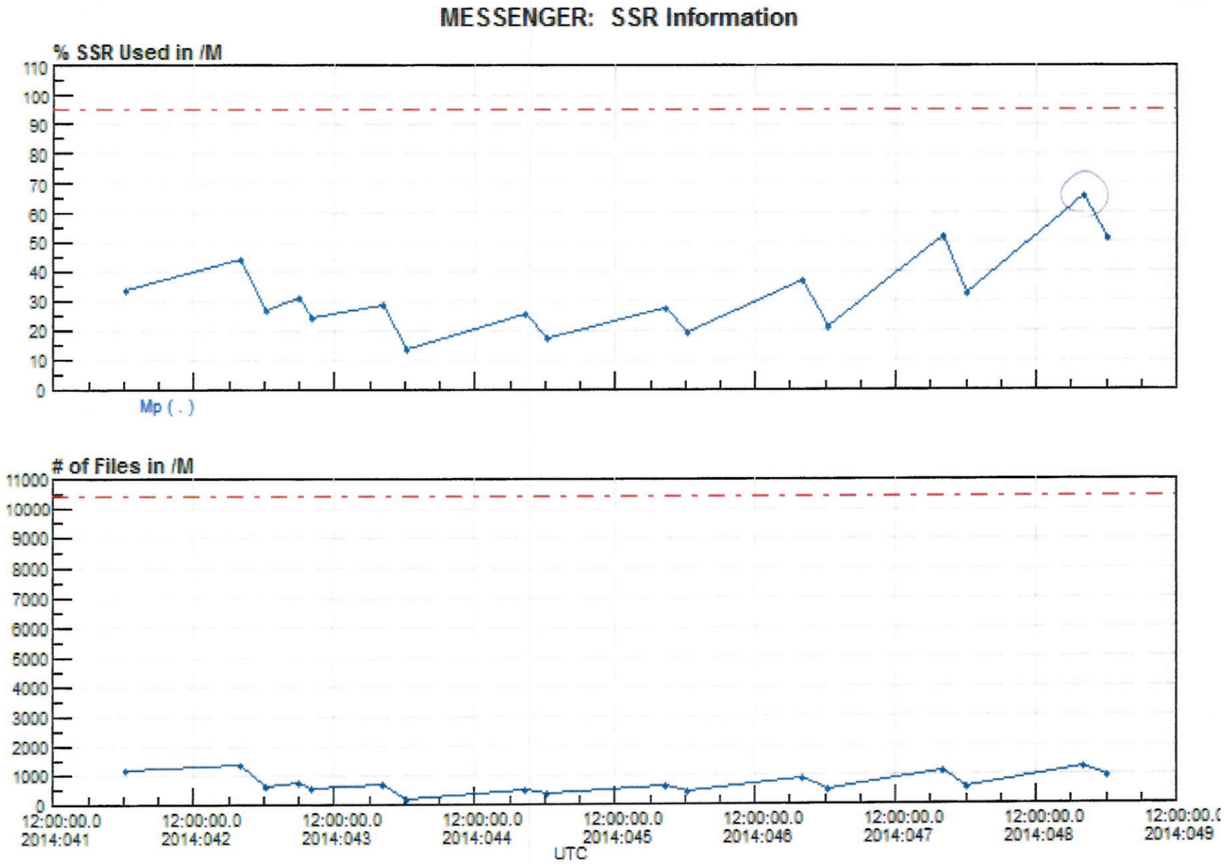


Figure 7. Graphs showing the amount of science data on MESSENGER's solid-state recorder. The upper graph illustrates the percentage of the recorder being used during a given command load. The peak is noted for the review meeting. The dashed red line at the top is a hard limit for the percentage of the recorder that may be used for all types of data. The lower graph shows the other hard limit for the recorder: the number of files that it can hold. Because of the way that the data are managed, the upper graph is more critical to track, especially during high-science-volume and low-downlink periods.

also used with the next StateSim run to reflect actual on-board conditions, and a cursory check of standard output products is made at that time. Since an on-board executing command sequence was designed four weeks earlier, a timing adjustment is necessary to synchronize the command sequence to each new ephemeris. The time tag bias values for synchronizing each new on-board ephemeris with the start of each new command sequence execution are calculated by the MOM and furnished to the command sequencers. They in turn fold that time-tag bias value into a standard macro that is uplinked days in advance and is called at the start of each command load to ensure that synchronization takes place regardless of whether that DSN support is nominal or not.

Another StateSim update task of the command sequencer is to ensure that StateSim agrees with the spacecraft with respect to the number of files that are on board MESSENGER. This task is typically performed once a week, or more often if the situation warrants, such as following a significant DSN station outage. While StateSim accurately predicts file downlink bandwidth, it models that all files downlinked are received by the ground station without any problems and that downlinked files are immediately deleted from the simulated SSR. StateSim estimates the size of the files, but image sizes in particular can be difficult to predict, as the compression ratios are inherently unknown, resulting in a gradual divergence between the true SSR volume and the StateSim prediction. It is incumbent upon the command sequencers to "re-align" StateSim to match the spacecraft so that an accurate accounting of the SSR volume may be maintained, particularly during periods of low downlink bandwidth when recorder volume can reach saturation levels. The command sequencers do this by comparing the files received on the ground with files StateSim still predicts to be on the SSR. The command sequencer can synchronize StateSim after the fact by artificially stopping an SSR playback early (StateSim is ahead of the spacecraft) or by inserting an artificial playback (StateSim is behind the spacecraft).

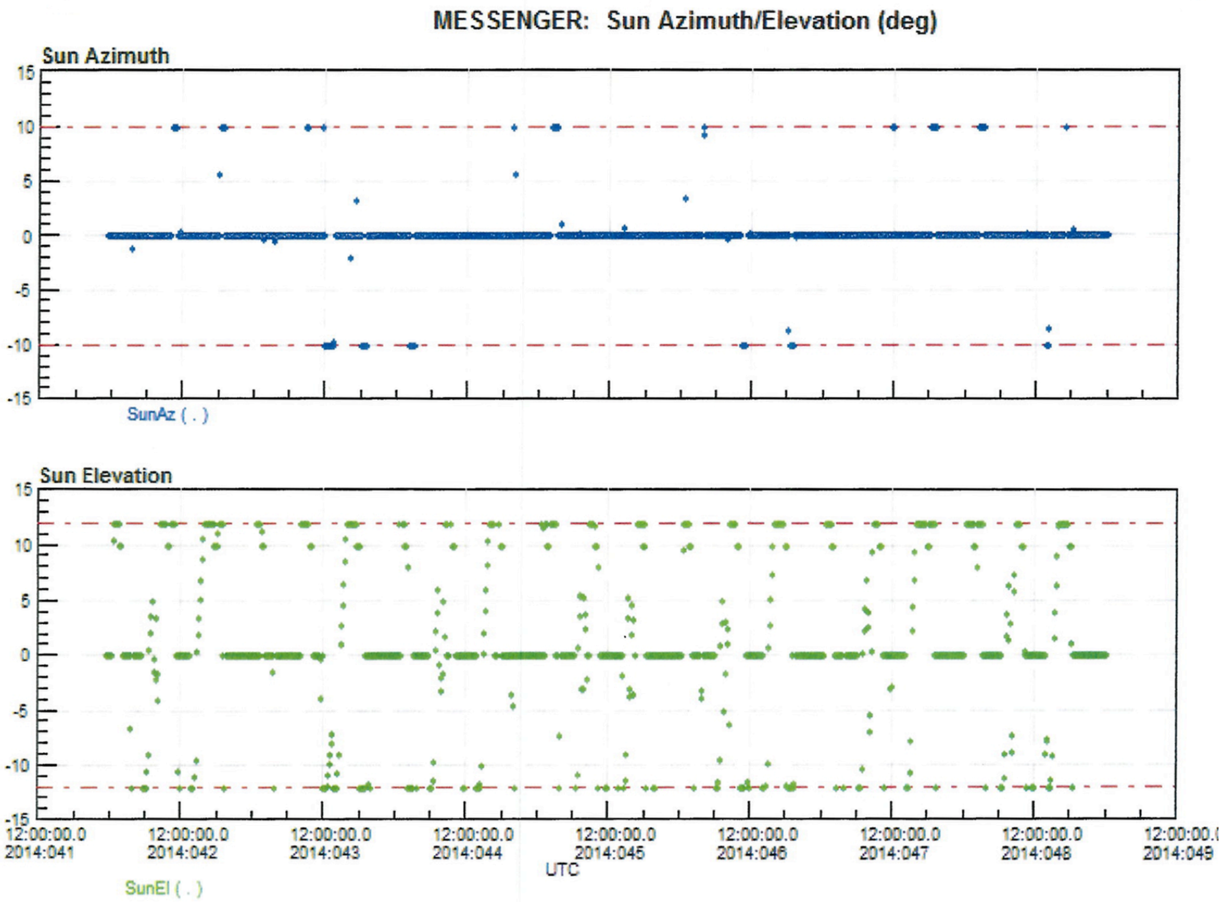


Figure 8. The Sun keep-in plot, showing the guidance and control pointing for observations during the command load, and the red-dashed hard limit lines beyond which the spacecraft is not allowed to move the Z-axis, along which many of the science instruments are positioned and point.

VII. Summary

There is a substantial amount of input and coordination that goes into assembling a command load for MESSENGER. It is crucial that these steps be accomplished in a timely manner given the weekly cadence necessary for orbital operations. In addition, the command loads cover finite durations between the load breaks and mid-breaks. If a command load is not uplinked to the spacecraft and activated before the previous load finishes executing, the spacecraft will enter a "safe" mode on the first orbit for which there would be no commands in effect to maintain spacecraft position and orientation within flight thermal and pointing constraints. And until return to a full operational mode, such a demotion would also cost scientific observing time. Therefore, in order to ensure the success of the mission, the planning process has been continuously streamlined and fine tuned to keep the spacecraft operating safely and efficiently in arguably the most demanding thermal environment in the Solar System. This planning process has kept the spacecraft operating safely without interruption for the entirety of the three years of MESSENGER orbital operations, helping to maximize the scientific return of the mission.

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