Testing and validation of orbital operations plans for the MESSENGER mission

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ABSTRACT

Launched in 2004, the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft continues on its journey to become, in 2011, the first spacecraft to orbit the planet Mercury. The goal of MESSENGER's one-year orbital mission is to answer several key questions about the structure and history of Mercury and its environment. The science and mission operations teams are testing a concept of operations to use the instrument payload most efficiently and to achieve full mission success. To ensure that all essential observations are obtained and to allow for contingencies, an advance science planning (ASP) effort will develop the full yearlong mission baseline plan prior to orbit insertion. To ensure that the plan can be adapted in response to unexpected events over time, an adjusted baseline plan will be regenerated in the ASP process every five weeks during the actual orbital mission. The near-term science planning (NTSP) activity converts weeklong portions of the baseline plan into executable commands to conduct the orchestrated observations. A feedback process from NTSP to ASP will be used to ensure that the baseline observing plan accounts for and reschedules any unsuccessful observations. A testing and validation plan has been developed for the processes and software that underlie both advance and near-term science planning.

Keywords: MESSENGER, Mercury, mission planning, orbital operations, testing, validation

1. INTRODUCTION

The MESSENGER spacecraft was launched on 3 August 2004 on a Boeing Delta II rocket from Cape Canaveral Air Force Station, Florida. MESSENGER was the seventh mission selected in the NASA Discovery program for solar system exploration (Solomon et al., 2001, 2007). On 14 January 2008, MESSENGER became the first spacecraft to visit the planet Mercury since the Mariner 10 spacecraft flew by this enigmatic world three times in 1974 and 1975 (Solomon et al., 2001, 2007). MESSENGER subsequently flew by Mercury again on 6 October 2008 and 29 September 2009. The spacecraft will enter into orbit about the planet on 18 March 2011, where it will remain for one year (two Mercury solar days) studying Mercury and its solar environment.

The MESSENGER mission was designed to address six key scientific questions concerning Mercury and the formation and evolution of the terrestrial planets (Solomon et al., 2001, 2007). These are:

1. What planetary formational processes led to the high metal/silicate ratio in Mercury?
2. What is the geologic history of Mercury?
3. What are the nature and origin of Mercury's magnetic field?
4. What are the structure and state of Mercury's core?
5. What are the radar-reflective materials at Mercury's poles?
6. What are the important volatile species and their sources and sinks on and near Mercury?

In order to address these questions, a set of observations and measurements are required. These include:

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1. Mapping the elemental and mineralogical composition of Mercury's surface
2. Globally imaging Mercury's surface at a resolution of hundreds of meters
3. Determining the structure of the planet's magnetic field
4. Measuring Mercury's physical libration amplitude and gravitational field structure
5. Determining the composition of the radar-reflective materials at Mercury's poles
6. Characterizing the planet's exosphere neutrals and accelerated magnetosphere ions

These questions and the corresponding set of measurements dictated the scientific payload on board MESSENGER.

The instrument payload consists of seven instruments plus the radio science (RS) experiment, which utilizes the on-board radio frequency (RF) communications system. The on-board instruments include: a dual-imaging system with wide-angle and narrow-angle cameras for multi-spectral imaging of Mercury's surface; gamma-ray, neutron, and X-ray spectrometers for remote geochemical mapping; a magnetometer to measure the planetary magnetic field; a laser altimeter to measure Mercury's surface topography and planetary shape; an ultraviolet, visible, and near-infrared spectrometer to obtain high-resolution spectral measurements of the surface and to survey the structure and composition of Mercury's tenuous neutral exosphere; and energetic particle and plasma spectrometers to characterize the charged particle and plasma environment around Mercury (Gold et al., 2003).

Several key components and subsystems for successful payload operations include the guidance and control (G&C) system, the RF communications system, and the utilization and management of a solid-state recorder (SSR). Figure 1 is a depiction of the spacecraft, its subsystems, and the instrument payload.

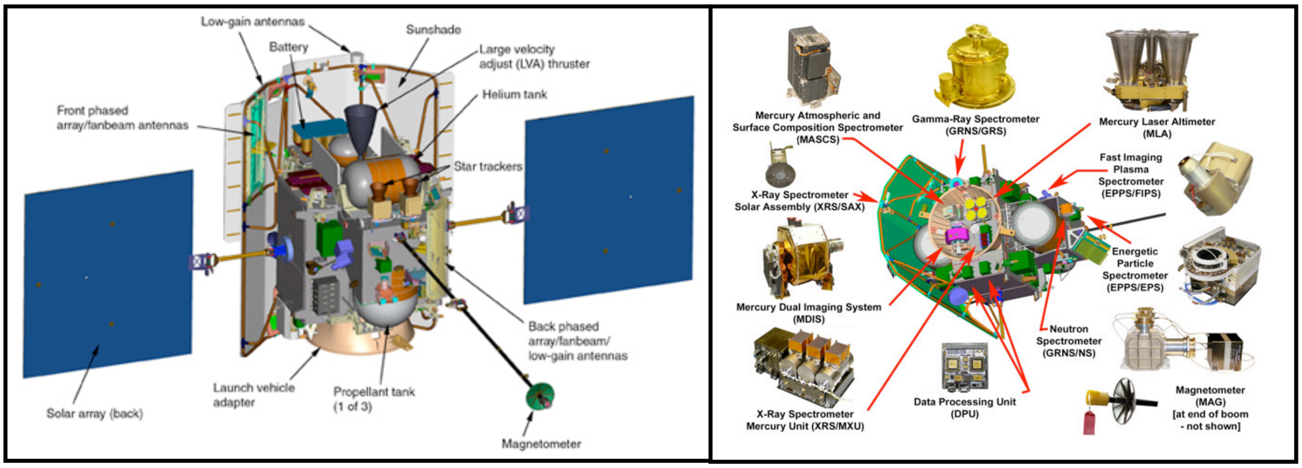


Figure 1. The MESSENGER spacecraft and its major subsystems (left) and the spacecraft's accommodation of the instrument payload (right).

The MESSENGER mission, its spacecraft and spacecraft subsystems, instrument payload, scientific objectives, and operations are described in higher detail in a collection of articles dedicated to MESSENGER (Domingue and Russell, 2007). Because of Mercury's proximity to the Sun, MESSENGER must operate in an extreme environment, which requires strict operational constraints. These constraints require a well-orchestrated and well-planned mode of operation for the complex payload, which has its own set of constraints and requirements for operational health and safety and for meeting the mission science objectives. A description of the personnel, and their interfaces, that are key to mission operations has been provided by Berman et al. (2009). To ensure efficient and robust operations of the MESSENGER payload, a systematic approach has been applied to the testing and validation of the orbital operations plan, which is the focus of this paper.

2. ORBITAL CONCEPT OF OPERATIONS

MESSENGER's concept of operations (ConOps) for operating the science payload and relevant subsystems for the orbital mission (March 2011 – March 2012) is derived from a strong heritage of mission operations, coupled with innovations for meeting the unique challenges of operating within Mercury's environment. Berman et al. (2009) described the roles and responsibilities of the science, operations, and engineering teams, which are derived from the successful operational experience from such missions and science instruments as the Near-Earth Asteroid Rendezvous (NEAR) mission, the Magnetosphere IMaging Instrument (MIMI) on the Cassini spacecraft, and the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) instrument on the Mars Reconnaissance Orbiter (MRO).

MESSENGER draws from the heritage of these mission and science instruments to provide many of the tools and processes that are used to execute the ConOps. A detailed description of this heritage has been given by Berman et al. (2009).

The challenges of operating a spacecraft in Mercury's environment include adapting for heating by the Sun, operating a complex instrument payload with competing pointing requirements, managing variable data acquisition and downlink rates, planning measurements within orbital characteristics that change with time, and planning observations around spacecraft operations such as propulsive events or orbit-correction maneuvers (OCMs). These challenges, described in more detail by Berman et al. (2009), require that the MESSENGER team develop efficient operations processes, scheduling strategies, and software so that MESSENGER will not miss limited observation opportunities and can react quickly to changing orbital conditions and uncertainties. These challenges have led to innovations in planning and scheduling processes, development of a baseline operations plan, and the development of tools to support the updated processes. Testing and validation of the processes and tools developed to meet these challenges have been ongoing tasks during the cruise phase of this mission.

The core feature of MESSENGER's orbital ConOps is the application of two interconnected and repeating processes: a full-mission (or long-range) planning cycle, and a short-term (i.e., one-week) scheduling process. The full-mission planning is termed advance science planning (ASP), and the short-term scheduling process is termed near-term science planning (NTSP).

While MESSENGER is in cruise phase, the mission operations, engineering, and science teams have been testing and refining the conceived plan for operating the science payload and relevant subsystems in orbit about the planet. Before reaching Mercury, the concept of operations will be fully tested to ensure that the mission's full mission success criteria can be met within the spacecraft's operational constraints and resource allocations.

3. ADVANCE SCIENCE PLANNING

The purpose of advance science planning is to formulate an efficient and effective long-range strategy of scientific observations for the entire orbital phase of the nominal mission, which lasts from 18 March 2011 to 17 March 2012. The formulation of this strategy integrates the various instrument operational requirements, spacecraft operational constraints, and scientific measurement requirements to ensure a path for achieving the mission success criteria. The process and tools for designing and constructing this long-range strategy incorporate flexibility to the mission-long plan to accommodate updates to instrument and spacecraft operational constraints and mission contingencies.

3.1 The baseline

The output product of the ASP process is the baseline operations plan, or simply, the baseline. The baseline is the long-range plan of all instrument and associated spacecraft G&C activities that span the entirety of the nominal one-year orbital mission. The baseline is constrained by the concept of operations for each instrument, the health and safety rules for the operation of the spacecraft (especially the G&C subsystem), and a prioritization of the G&C operations relative to each instrument's measurement requirements.

Each instrument has a defined set of measurement requirements to provide the dataset that will address the mission science goals. These requirements in turn place constraints on the pointing and orientation of the spacecraft. Many times the pointing and orientation constraints of one instrument will conflict with those of another. The baseline development tools examine all opportunities for each instrument to acquire their needed observations over the entire mission, thus providing a method for resolving conflicts among instrument constraints. This process provides each instrument with a strategy for meeting its measurement requirements.

3.2 ASP process

The ASP process is iterative and collaborative within the MESSENGER science and mission operations teams. During the orbital phase, the ASP lead will routinely coordinate the assessment of the baseline. This assessment incorporates an analysis of the actual science returned to date, changes in the instrument payload configuration or spacecraft performance, and updates to the mission design (e.g., trajectory and ephemeris refinements). The ASP lead must also ensure that any new spacecraft, instrument, or subsystem constraints are also incorporated into the next baseline. The product of the baseline assessment is the generation of a modified baseline for instrument payload operations for the remainder of the mission. If necessary, science conflicts and trades will be negotiated among the science team members and the principal investigator.

Once the orbital mission phase has begun, the baseline assessment will be performed every five weeks, each time producing an updated baseline for the remainder of the mission. The primary tool for review, revision, and construction of the baseline is SciBox, which is described in Section 6.1. While SciBox has a heritage for individual instrument operations, this is the first time it will be used to coordinate the operations of an entire payload and to monitor payload-related resources, such as SSR utilization. This new functionality requires robust testing and validation. The new baseline will be delivered to the payload operations manager, who is responsible for its execution through the near-term science planning process.

4. NEAR-TERM SCIENCE PLANNING

Near-term science planning is the short-term scheduling of the optimized orbital ConOps. Command sequences are sent to the spacecraft for the operation of its subsystems (including the payload) in one-week increments. During orbital operations, it is expected that command loads will be seven days long, due to uplink and command storage constraints. NTSP consists of the processes, procedures, and tools necessary to convert one-week portions of the baseline into a set of executable instrument command sequences (one sequence per instrument, plus G&C and RS) for upload to the spacecraft. The preparation of each one-week command sequence takes three weeks. The payload operations manager leads the NTSP process and that ensures all instrument inputs are delivered correctly (without conflicts between instruments and between the payload and spacecraft operations) and on schedule to the mission operations team. Figure 2 is a schematic of the three-week NTSP process schedule with the relevant tasks and responsible teams identified.

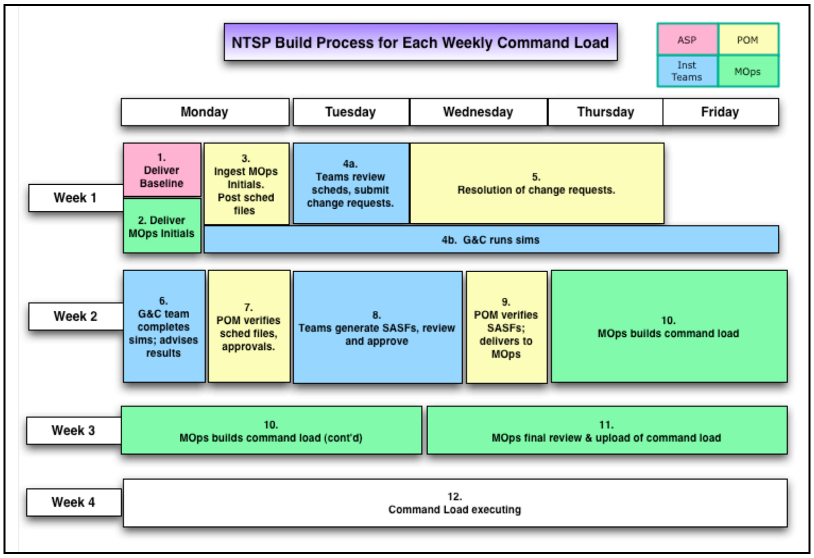


Figure 2. NTSP three-week process schedule. ASP inputs are shown in pink. Mission operations team tasks and deliveries are shown in green, instrument team activities are shown in blue, and payload operations manager responsibilities are shown in yellow.

4.1 NTSP process

The starting point of the near-term science planning process is constrained in absolute time by the receipt of a confirmed track schedule from the Deep Space Network (DSN), which is nominally available eight weeks in advance. The NTSP process begins when the mission operations team (MOps) receives the negotiated DSN track schedule and determines the boundary conditions for the next command load. These initial boundary conditions delivered by MOps contain information about orbital events such as eclipses, occultations, spacecraft maneuvers, and other instrument commanding exclusion zones. Upon receiving them, the payload operations manager uses these “MOps Initials” to generate updated instrument, G&C, and RS schedules (from the baseline) for the payload team (see Section 6.1). The generation of updated schedules is performed using the SciBox science planning tool.

Upon notification by the payload operations manager, the payload teams review the weekly instrument activities. Some minor (e.g., instrument parameter) changes can be made to their activities, but no spacecraft pointing changes can be accommodated due to the complexity of the G&C subsystem command sequence (which impacts other instrument observations) and the short timeframe of the NTSP process. Requests for changes to the spacecraft pointing are referred to the ASP process, where they may be incorporated for future operations. Before the completion of the first week, the payload operations manager will review and resolve all change requests submitted by the payload team.

Instrument change requests are reviewed to quantify their impact on SSR and downlink resources (or potential impact on other instruments’ observing plans). It is an operational constraint that the data acquired to meet the mission’s science objectives must be received prior to the end of the nominal mission and that no data remain on the SSR. The change review and analysis of potential impact on payload resources is conducted with the use of the ASP tool, SciBox.

In the first week of the NTSP process the G&C team begins its review and comprehensive simulations of the G&C command sequence. All spacecraft slews and pointing scenarios are tested to ensure there are no health and safety violations. This task is completed early in the second week of the NTSP schedule with tools used on previous missions and during MESSENGER’s cruise phase. Once the G&C commands have been successfully validated and the payload team has negotiated any other minor changes, the payload team prepares and delivers the set of actual commands to the payload operations manager. During the second week, the baseline schedules are converted to science activity sequence files (SASFs), which are in the required format for input into the mission operations software. Before delivery, each SASF is approved by the instrument scientist and instrument engineer and the G&C and RS teams. The conversion from SciBox schedules to SASF is performed within SciBox, an expanded capability of this tool that provides a key interface between science and mission operations. Because this functionality is new, a substantial effort has been focused on testing and validating this interface.

After the payload operations manager reviews the SASF inputs from all teams, the SASFs are delivered to MOps, which is responsible for developing and testing the actual command loads. These command sequences merge instrument commands (provided by the payload team) with other commanding elements, including RF communications, SSR operations, and orbital maneuvers. The mission operations team also manages the resources available for spacecraft and housekeeping operations, including power, on-board command memory space, and SSR memory. These tasks are initiated at the end of the second week of the NTSP schedule and are completed in the third or final week. MOps builds and reviews the spacecraft command load and uploads it to the spacecraft approximately 2-3 days before the start of execution. At least two upload opportunities are budgeted for each sequence to ensure a contingency opportunity.

Because it will take three weeks to complete the NTSP cycle for each weekly command load, the mission operations and science operations teams will be working on multiple command loads per week. Each week, the mission operations team will be responsible for building, reviewing, and uploading the next command load.

5. CONTINGENCY PLANNING

The harsh environment in the vicinity of Mercury heavily constrains spacecraft pointing, which in turn constrains power generation, data downlink opportunities, and observation opportunities. To meet the mission’s science goals, a complex observation plan must be implemented, and that plan must be optimized with respect to pointing opportunities and storage and downlink resources. The creation of an optimal plan requires a thorough examination of risk-mitigation strategies.

Deviations from the baseline may result from such situations as a spacecraft-safing event, the loss of a downlink track with the DSN, or the failure of an instrument (or some functionality therein). In addition to the operational constraints listed above, the constraint of time also exists on the ground. If an event occurs that affects the schedule, there is insufficient time to examine the impact of such a loss on the remainder of the mission without the aid of a tool such as SciBox.

SciBox is used during ASP to generate the baseline schedule, instrument coverage reports, data properties, and SSR usage to allow science team members to assess mission success. The flexibility built into SciBox allows the user to model certain events (e.g., loss of a downlink track) and quickly regenerate instrument schedules and reports in order to examine the impact of the event. This examination must be done well in advance of the orbital phase in order to identify the most sensitive portions of the mission schedule. Early identification allows for the instrument and operation teams to devise contingency plans, such as additional DSN support, modifying an instrument concept of operations, or changing data rates (or other instrument parameters) for a given period of time.

Contingency plans, once devised, have two routes back into the planning cycle: insertion into the next ASP cycle (sometime within the next 5 weeks) or, for more pressing observations (e.g., the last optimal time we can image a high-priority feature), immediate insertion into the upcoming NTSP cycle.

As with ASP, flexibility is also critical to the NTSP process. The MESSENGER payload has already provided novel scientific data from the Mercury flybys, and it is anticipated that more discoveries will be made during the orbital mission. The NTSP process must allow for critical late changes due to contingencies or late discoveries.

6. SOFTWARE TOOLS

This section describes the primary software tools to be used during the ASP and NTSP processes. Both processes use overlapping tool sets to facilitate planning and communication. Figure 3 is a high-level system diagram of the major software components used by the science operations and mission operations teams. As can be seen in the figure, the science operations tools for orbital operations are new and need to be tested and validated in flight. However, the mission operations tools are the same as those that have been employed since launch and have a strong heritage from use on previous missions. Therefore, they have been thoroughly tested, except for the interfaces with the new science operations software.

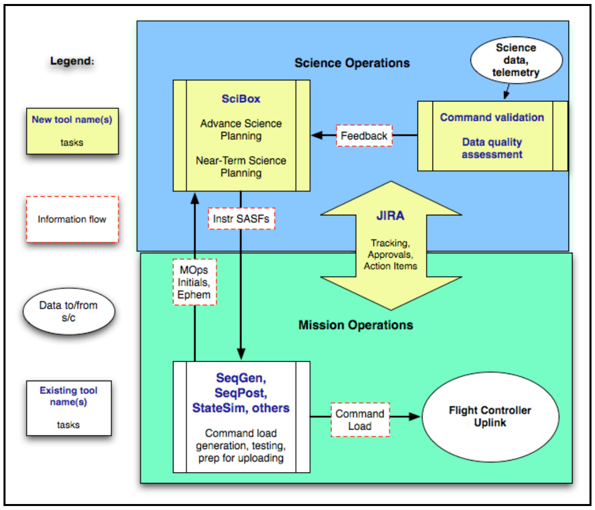


Figure 3. Science operations and mission operations system diagram. New components are shaded in yellow.

6.1 SciBox

SciBox is the automated planning and scheduling software system to be used for both ASP and NTSP. Developed at The Johns Hopkins University Applied Physics Laboratory (APL) for space operations, SciBox is a goal-based planning system that has been successfully used on previously launched missions, such as MRO (for CRISM instrument operations) and Cassini (for MIMI instrument operations).

MESSENGER SciBox will be the first implementation of this tool to perform multi-instrument scheduling and resource monitoring. To perform these tasks SciBox is required to model the orbital, spacecraft, and instrument pointing constraints, SSR usage, and DSN downlink opportunities. Details on the components and architecture of the SciBox tool have been described by Choo et al. (2009). A high-level system diagram is provided in Figure 4.

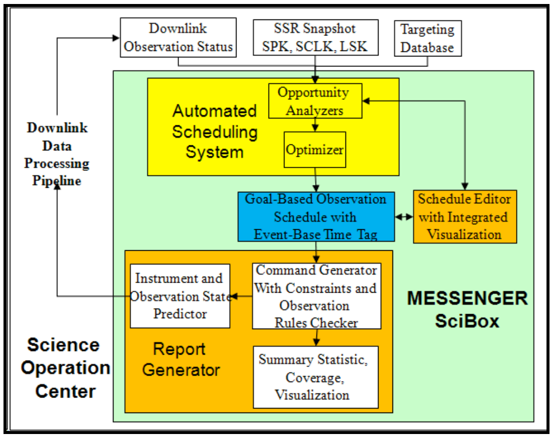


Figure 4. High-level MESSENGER SciBox system diagram.

For ASP, the inputs to SciBox include details about missed or unsuccessful observations from the data analysis results (so that they can be rescheduled), updates to spacecraft or instrument operational constraints or models, and updates to trajectory information. After running the Automated Scheduling System, SciBox produces a conflict-free updated baseline plan and associated reports for review. After each ASP run, the science team must review and approve the new baseline plan before its delivery to NTSP.

The baseline review and approval process includes the examination of SciBox instrument operations reports that provide summary information of the mission-long observations for each instrument. Each instrument team receives reports tailored to its instrument's observation characteristics. For example, Figure 5 shows a sample SciBox plot for the X-ray spectrometer (XRS) instrument. This plot provides the total integration time for each area on the surface of Mercury over the entire nominal orbital phase. The XRS team will use this, as well as other plots and reports, to ensure that the baseline schedule fulfills their science requirements.

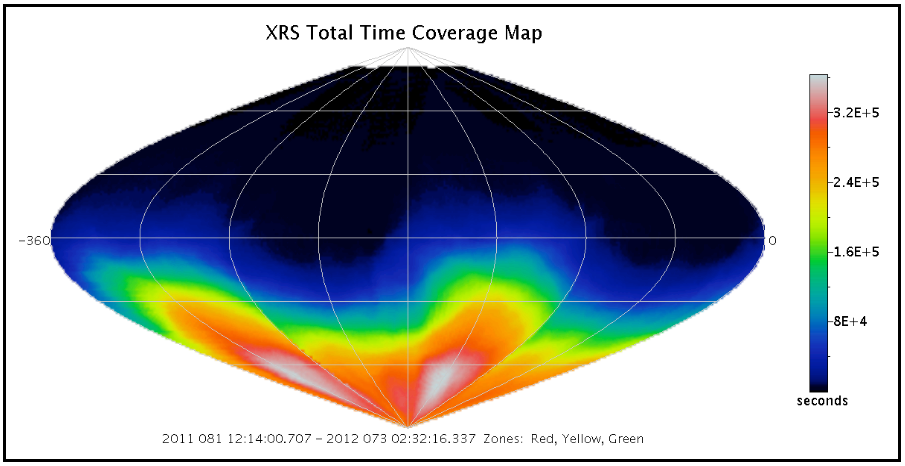
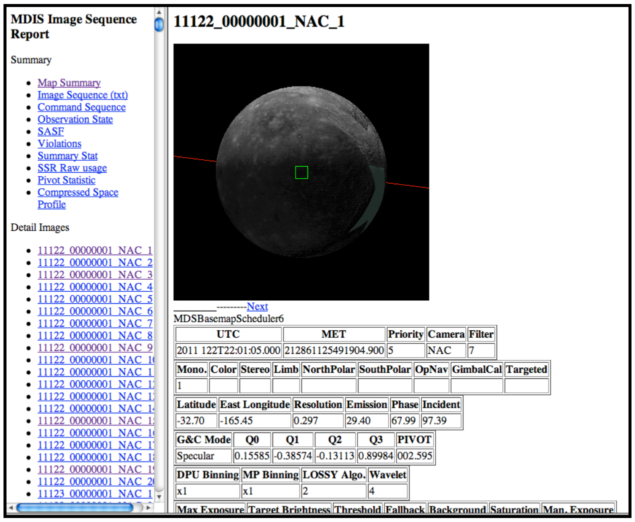


Figure 5. The XRS integrates the number of photons received from an area to calculate elemental abundances. To extract these abundances, a lower limit on integration or observing time must be met. This plot allows the XRS team to evaluate the integration time over Mercury's surface to establish the resolution with which elemental abundances can be mapped.

For NTSP, the instrument, G&C, and RS teams use SciBox to review, modify, and generate the weekly set of commands to be uplinked to the spacecraft. For this process, SciBox ingests an updated spacecraft ephemeris and the negotiated DSN track times. It then produces a set of graphs, reports, and schedules that the teams use to view their weekly activities. The Schedule Editor component is used by the teams to examine and modify their weekly activities. By selecting a particular activity within the schedule, the Schedule Editor allows instrument teams to make minor (non-pointing) modifications or updates to their weekly activities.

Figure 6 illustrates an example of a schedule report used by the Mercury Dual Imaging System (MDIS) team to examine the properties of the images to be acquired during a particular command sequence. This report provides the MDIS team with a visualization of the images their sequence will acquire during the command load. This capability greatly facilities the review of the load sequence. Similar visualization reports are generated for all instrument teams.



MDIS Image Sequence Report

Summary

- Map Summary
- Image Sequence (txt)
- Command Sequence
- Observation State
- SASF
- Violations
- Summary Stat
- SSR Raw usage
- Pivot Statistic
- Compressed Space Profile

Detail Images

- 11122_00000001_NAC_1
- 11122_00000001_NAC_2
- 11122_00000001_NAC_3
- 11122_00000001_NAC_4
- 11122_00000001_NAC_5
- 11122_00000001_NAC_6
- 11122_00000001_NAC_7
- 11122_00000001_NAC_8
- 11122_00000001_NAC_9
- 11122_00000001_NAC_1
- 11122_00000001_NAC_1
- 11122_00000001_NAC_1
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- 11123_00000001_NAC_1

11122_00000001_NAC_1

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MDSBasemapScheduler6

UTC	MET	Priority	Camera	Filter
2011 122T22:01:05.000	212861125491904.900	5	NAC	7

Mono.	Color	Stereo	Limb	NorthPolar	SouthPolar	OpNav	GimbalCal	Targeted
1								

Latitude	East Longitude	Resolution	Emission	Phase	Incident
-32.70	-165.45	0.297	29.40	67.99	97.39

G&C Mode	Q0	Q1	Q2	Q3	PIVOT
Specular	0.15585	-0.38574	-0.13113	0.89984	002.595

DPU Binning	MP Binning	LOSSY Algo.	Wavelet
x1	x1	2	4

Max Exposure	Target Brightness	Threshold	Fallback	Background	Saturation	Man. Exposure

Figure 6. SciBox report showing relevant imaging information for evaluation of an MDIS command sequence. This report shows the image footprint on Mercury's surface and provides a variety of image details, such as incidence and emission angles, binning, and exposure time.

After review (and possible modification of some allowed parameters), SciBox is then used to produce the set of instrument, G&C, and RS commands to be uplinked to the spacecraft (as described in Section 4) in the form of SASFs, the mission-operations-compliant format. During the current cruise phase of the mission, the instrument teams manually create their own SASFs. For infrequent calibration activities and flyby science, the work required to do so is not overly burdensome. However, for the full-time mode of data acquisition during orbital operations, the generation of SASFs must be automated. This need creates an additional interface between science and mission operations, which must be validated prior to full operations during orbit.

After producing the SciBox-generated SASF, each instrument team is responsible for validating their commands using mission operations software before delivery to the payload operations manager. The payload operations manager provides one last review of the integrated payload command set before delivering it to the mission operations team. Because this step is both a new and critical component of the MESSENGER sequencing system, much effort is currently being expended to ensure that SciBox produces instrument, G&C, and RS commands that are accurate, safe, and compliant with the mission operations format. See Section 7 for more details.

6.2 Near-term science planning tracking tool

Because the MESSENGER team will work concurrently on multiple command loads, it is necessary to establish an efficient tracking and communication tool that models the actual NTSP workflow (e.g., creates new command loads, notifies teams of deadlines, reviews SciBox weekly activities, and generates and delivers approved SASFs). With geographically dispersed instrument teams, two key requirements on such a tool are: availability at multiple facilities across different platforms and an automated e-mail system to alert team members when there is an action that requires their attention.

The project has chosen a highly configurable, commercial web-based application called JIRA by Atlassian Software (http://www.atlassian.com/software/jira/). JIRA is an issue and project management tool, which has been customized by

APL to fit the NTSP process. At each workflow step, the command load (JIRA "issue") and instrument (JIRA "sub-tasks") are assigned to the appropriate team member. As NTSP tasks are completed, the next action is automatically assigned to the appropriate team member, and an automated e-mail is sent. With JIRA, completed tasks are easily recorded, and actions are automatically pushed to team members via e-mail. Therefore, the payload operations manager can efficiently monitor progress and status of instrument and command load tasks.

7. TESTING AND VALIDATION

The verification and validation of the orbital ConOps processes and software has been an ongoing and iterative endeavor during MESSENGER's cruise phase. As shown in the Figure 7 timeline, an initial set of simple orbital operations tests began as early as 2006 concurrent with a full schedule of critical cruise activities such as planetary flybys and deep-space maneuvers (DSMs). These initial tests were scheduled to minimize the disruption to critical cruise activities yet still allowed an opportunity to provide timely inputs to the orbital ConOps development.

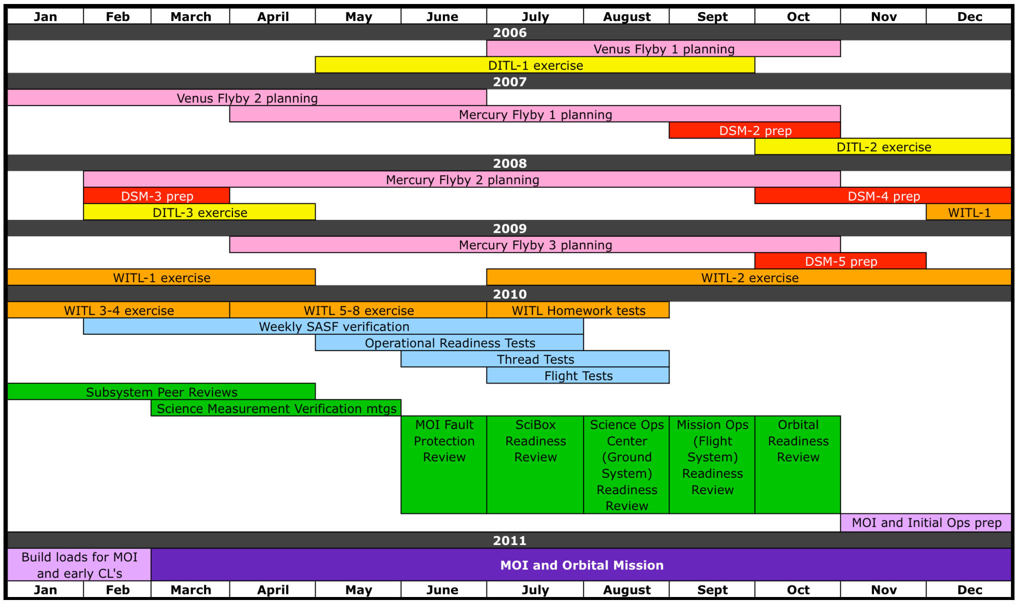


Figure 7. Timeline of major activities and milestones from 2006 leading up to Mercury orbit insertion in March 2011.

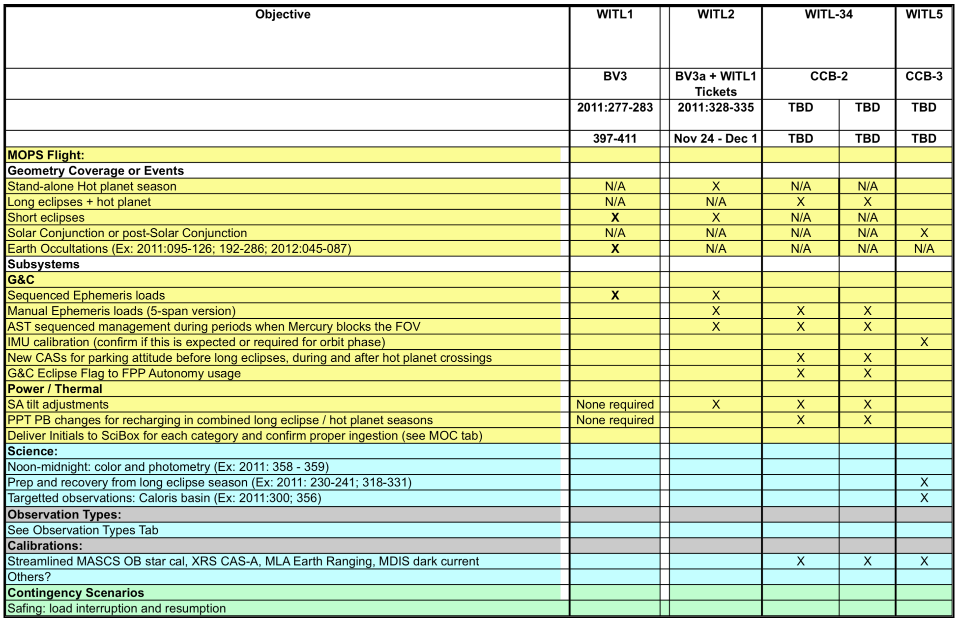
From 2007 to 2009, four planetary flybys and four propulsive maneuvers were the primary focus for the mission operations and science operations teams. The three Mercury flybys provided invaluable scientific data that led to finalization of the instrument teams' data collection strategy. Successful execution of the maneuvers (including the flybys) was critical to ensure that MESSENGER's trajectory would lead to successful orbit insertion in 2011. In 2009, however, the testing of weeklong orbital command loads became a priority, alongside the final Mercury flyby. The teams worked on two extended exercises (described below) while completing the preparations for the final Mercury flyby.

A comprehensive testing strategy was developed and is currently in implementation to examine the flow of information and the robustness of interfaces through a series of rehearsal tests, operational thread tests, flight tests, and final reviews. All of these elements are tracked through a test matrix, where the outcome of each test informs the testing level of subsequent tests.

Using the well-known principle "test what you fly; fly what you test," the MESSENGER team will test all new spacecraft activities and observing scenarios, either on the hardware-in-the loop flight simulator, on the actual spacecraft and instruments, or in some cases both.

7.1 Test matrix and schedule

In order to organize and prioritize the activities, interfaces, and processes that require testing and validation, the mission systems engineer and mission operations manager derived and maintain an overall testing matrix. A small, abridged portion of the matrix is depicted in Figure 8.



Objective	WITL1	WITL2	WITL-34		WITL5
	BV3	BV3a + WITL1 Tickets	CCB-2		CCB-3
	2011:277-283	2011:328-335	TBD	TBD	TBD
	397-411	Nov 24 - Dec 1	TBD	TBD	TBD
MOPS Flight:					
Geometry Coverage or Events					
Stand-alone Hot planet season	N/A	X	N/A	N/A	
Long eclipses + hot planet	N/A	N/A	X	X	
Short eclipses	**X**	X	N/A	N/A	
Solar Conjunction or post-Solar Conjunction	N/A	N/A	N/A	N/A	X
Earth Occultations (Ex: 2011:095-126; 192-286; 2012:045-087)	**X**	N/A	N/A	N/A	N/A
Subsystems					
G&C					
Sequenced Ephemeris loads	**X**	X			
Manual Ephemeris loads (5-span version)		X	X	X	
AST sequenced management during periods when Mercury blocks the FOV		X	X	X	
IMU calibration (confirm if this is expected or required for orbit phase)					X
New CASs for parking attitude before long eclipses, during and after hot planet crossings			X	X	
G&C Eclipse Flag to FPP Autonomy usage			X	X	
Power / Thermal					
SA tilt adjustments	None required	X	X	X	
PPT PB changes for recharging in combined long eclipse / hot planet seasons	None required		X	X	
Deliver Initials to SciBox for each category and confirm proper ingestion (see MOC tab)					
Science:					
Noon-midnight: color and photometry (Ex: 2011: 358 - 359)					
Prep and recovery from long eclipse season (Ex: 2011: 230-241; 318-331)					X
Targetted observations: Caloris basin (Ex: 2011:300; 356)					X
Observation Types:					
See Observation Types Tab					
Calibrations:					
Streamlined MASCS OB star cal, XRS CAS-A, MLA Earth Ranging, MDIS dark current			X	X	X
Others?					
Contingency Scenarios					
Safing: load interruption and resumption					

Figure 8. Sample portion of the orbital testing and validation matrix.

This matrix tracks the different components from both mission and science operations that are to be tested and validated. For example, there are multiple orbit profiles that contain their own constraints on spacecraft subsystems and data acquisition strategies. The test matrix tracks those orbital profiles that have been examined in each test to ensure that all profiles are tested. It tracks the software version under which the test was conducted and any action items resulting from the test results. These actions direct those matrix items that can be tested at the next test level, and they inform the development of the software until it is placed under configuration management. Testing prior to placing software under configuration management allows for positive feedback early in the development process, permits more rapid development, and does not delay the validation process until late in the schedule.

7.2 Rehearsals

With new procedures and tools on the science operations side, it is critical to practice the new ASP and NTSP processes with the teams in a realistic environment to ensure that the processes are robust. This testing allows the teams to examine the degree to which operational constraints (both instrument and spacecraft) have been captured, as well as the quality of the interfaces and efficiency of the information flow. This aim has been achieved using in-the-life (ITL) tests.

The purpose of the ITL tests is to: (1) familiarize the teams with the NTSP process and refine the process to be most efficient, (2) familiarize the teams with the software and ensure that it accurately captures operational constraints, and (3) test the software interfaces and information flow. Items within each of these operational areas are captured in the test matrix described above. Each ITL has been designed to examine specific items within an area. Although each ITL is not designed to test all areas, the full suite of ITL tests together will test all items within the matrix.

Early ITL tests were constrained to cover a single day-in-the-life (DITL) during orbit. These were conducted between 2006 and 2008, and their main objective was to practice building sequences and command loads that were representative of one day in Mercury orbit over a range of different orbital conditions. They addressed such issues as the capture of operational constraints and the translation of SciBox schedules into SASFs. For these early tests, SASFs were constructed manually (this functionality was not yet in SciBox) and then tested with ground software and hardware. The DITLs focused on the development of realistic flight timelines, a process that engaged both instrument and spacecraft teams in the common goal of planning timelines and resolving conflicts to accomplish mission objectives within operational constraints. This process uncovered a number of issues to be addressed before longer, more automated operations could be attempted. For example, the testing revealed that SciBox schedules included multiple instrument power on/off commands simultaneously, which cannot be accommodated onboard the spacecraft. Therefore, a new power on/off strategy was devised and incorporated into the baseline development effort.

In 2009, the science operations, mission operations, and engineering teams participated in two single week-in-the-life (WITL) tests, in which one-week command loads were generated and tested with the complete suite of orbital ground software and hardware tools. SciBox was used to generate all instrument and G&C schedule files and to convert them to SASF deliverables to the mission operations team. The objective of these first WITL tests was to work through the ConOps so that both processes and tools could be evaluated and optimized. No attempt was made to practice the NTSP steps in a realistic timeframe; rather the focus was on familiarizing all team members with the new processes and software tools. These initial WITL tests facilitated communication and dialogue between both mission and science operations and the SciBox development team. It provided feedback on the requirements for SciBox interfaces and the conversion of operational constraints into executable algorithms. For example, the generated schedules for the Ultraviolet and Visible Spectrometer on the Mercury Atmospheric and Surface Spectrometer instrument accented the need for a more detailed concept of operations from that instrument team. Another key result from these early WITL tests was the optimization of the NTSP timeframe into the current three-week schedule.

During the remainder of the cruise phase, the WITL tests will be conducted in accordance with the three-week timeframe. The first test conducted in 2010 examined the construction of two consecutive command loads built in accordance with the NTSP schedule (Figure 2). Both instrument and mission operations teams successfully demonstrated that they can perform all tasks and meet all required deadlines. Additional WITL exercises are scheduled for the summer of 2010.

There are several key operational circumstances during orbit about Mercury that the WITL tests are designed to investigate, and these are tracked with the test matrix described above. The completion of the WITL tests will include validation and optimization of the process, tools, and the test matrix to ensure orbital operations readiness.

7.3 Operational thread tests

The purpose of operational thread tests is to exercise the data flow paths, processes, and timing for expected nominal operations (i.e., they are system end-to-end tests). This effort has included running the DITL and early WITL command loads through the hardware-simulation test bed. In addition to the structured WITL exercises, all 52 weekly SciBox schedules are to be run independently through the mission operations ground software system and the G&C software simulators before Mercury orbit insertion (MOI) to ensure that there are no health or safety issues. As of this writing, ~20 weeks have been run through the mission operations and G&C software, and several commanding issues have been discovered that are being remedied. For example, the algorithms used to define the instrument commanding around orbital correction maneuvers are currently under revision.

The thread tests are being designed to include the weekly navigation update process, applying time-tag bias, nominal and contingency OCM planning, and DSN contact period changes. Simulations with SciBox, as part of the ASP planning process, will examine the impact of several contingency situations on the data acquisition and instrument operation plans.

Operational readiness tests (ORTs) are dedicated testing sequences designed to exercise the team in the real-time execution of unique operations for the orbital phases. ORTs will be run for nominal operations and anomalous situations (e.g., safehold demotion recovery, Earth-acquisition demotion recovery, initial commissioning, and OCMs) and are to be completed by July 2010.

7.4 Flight tests

The purpose of a flight test is to exercise operations with the actual flight system in order to ensure that no modeling assumptions have affected the planning system. The current plan is to perform flight tests in August 2010 covering a nominal week of operations, as well as other critical spacecraft activities (e.g., commanded momentum dump and battery discharge/charge test).

7.5 Orbital readiness reviews

As shown in Figure 7, a series of peer and readiness reviews are underway in 2010. The purpose of these meetings is to review the testing and verification efforts to confirm that the teams are ready for orbital operations.

To demonstrate readiness of the orbital baseline plan, each instrument scientist presented to the appropriate science team discipline group(s) a summary of the plan detailing the specific science measurements to be made by the instrument in orbit and how the measurements will meet the Program Level-1 Requirements. The adequacy of SciBox reports to assess the baseline plan was addressed, as well as the ability of the user interfaces to assist in verifying the weekly command sequences. The payload-related meetings were completed in May, and any remaining open issues are being worked in the same manner.

In addition to these discipline group discussions, a readiness review dedicated solely to the SciBox planning tool is scheduled for July 2010. The purpose of this review is to ensure that SciBox planning, verification, user interfaces, and data interfaces are ready for orbital operations. By completing these reviews well in advance of MOI, sufficient margin remains for any necessary re-testing and additional verification activities required before the start of the orbital phase of the mission.

8. SUMMARY

Building on a history of successful mission operations, the MESSENGER team devised a new set of processes and tools to perform science planning for the Mercury orbital mission phase, beginning in March 2011. Because new tools and processes are to be used, the team developed an extensive strategy of exercises, tests, and reviews to verify fully and validate the new concept of operations and associated software. The MESSENGER team is now completing the final preparations for the orbital phase of the mission. A set of operational readiness tests and reviews will be completed by October 2010, so that actual orbital operations work can commence before MOI.

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