# Orbital Operations Planning and Scheduling for the MESSENGER Mission

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### Abstract

Launched in August 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 prime one-year orbital mission is to answer several key questions about the structure and history of Mercury and its surrounding environment. The science and mission operations teams have developed (and are testing) a concept of operations to use the instrument payload (seven instruments plus radio science) most efficiently and to ensure full mission success. The extreme temperatures and solar radiation at Mercury require that the spacecraft and its payload be protected by a sunshade, which must face the Sun at all times. Spacecraft pointing is therefore narrowly constrained. Furthermore, the science investigations have competing pointing requirements. To ensure that all essential observations are obtained and to allow for contingencies, an advance science planning (ASP) effort is used to develop a full yearlong mission baseline plan far in advance. The ASP maps out the entire orbital observing plan for all instruments including calibration activities. To ensure that the plan can be adapted in response to unexpected events and spacecraft and instrument performance 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 observations that were not successful. In addition, targets of opportunity can be inserted into the baseline plan when appropriate. In this paper we describe the MESSENGER payload orbital concept of operations, the approach used to develop it, and how it will be executed by the science and mission operations teams. We describe the software and processes to be used for both advance science planning and near-term science planning. We also describe the testing and validation plans for both the processes and tools.

## Overview of the MESSENGER Mission

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (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. It will fly by a third time on 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.

MESSENGER is a collaboration among many institutions, led by the Carnegie Institution of Washington (home of the mission's principal investigator) and the Johns Hopkins University Applied Physics Laboratory (APL), where the spacecraft and several of the science instruments were designed and built. In addition, APL is responsible for the operation of the mission. Team members at the Goddard Space Flight Center, the University of Michigan, and the University of Colorado supplied science instruments. Other commercial and academic institutions also partnered in providing spacecraft sub-systems and science team members.

### Science Objectives

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?

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

## The Spacecraft and Payload

Because of the harsh space environment near Mercury, one critical component of the spacecraft (Figure 1) is its 2.5 m x 2 m ceramic-fabric sunshade, which protects the electronics and science instruments. Behind this sunshade, the instruments and electronics operate near room temperature.

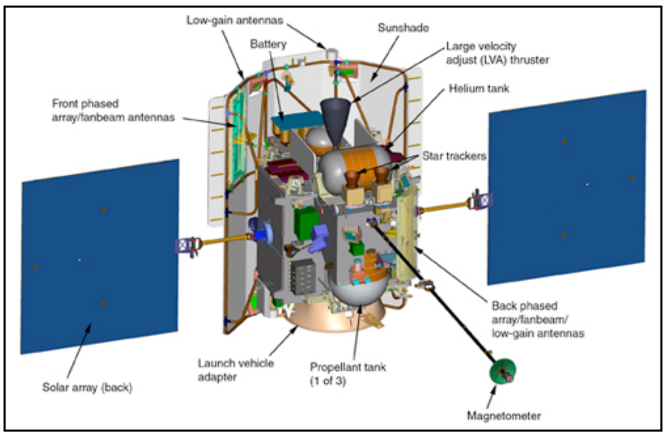


**Figure 1**: The MESSENGER spacecraft and major components

MESSENGER's propulsion system contains a large velocity adjust (LVA) thruster for large spacecraft maneuvers and several smaller thrusters for small course corrections and momentum management. The spacecraft will use nearly 30% of its fuel (a combination of hydrazine and nitrogen tetroxide) for insertion into Mercury orbit.

MESSENGER is equipped with two high-gain phased-array antennas (HGAs), two medium-gain fanbeam antennas, and four low-gain antennas (LGAs), which provide X-band coherent communications via NASA's Deep Space Network (DSN) of ground antennas. The HGAs are primarily used for the downlink of science data, and the LGAs are primarily used for lower-rate transmissions such as status data and operating commands.

Powering the spacecraft and its systems are two single-sided solar array panels, which are two-thirds mirrors and one-third solar cells. Because of the proximity of the Sun, the solar array panels could produce more than 2 kilowatts of power in Mercury orbit. However, the solar array processors are designed to take in only the energy necessary to run the spacecraft sub-systems and charge its battery.

The instrument payload consists of seven instruments plus the radio science 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).

The relevant sub-systems 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).

## MESSENGER Science, Operations, and Engineering Teams

The operation of the scientific payload is accomplished through the collaboration of three distinct groups: science operations, mission operations, and engineering. Each group is comprised of individuals from a variety of institutions.

The science operations group includes the individual instrument teams for each of the seven payload instruments, plus the G&C and radio science teams. Each team is led by an instrument scientist, who ensures that his or her instrument is commanded to acquire the measurements needed to address the key science questions. Each instrument team also includes an instrument engineer and instrument sequencer. The instrument engineer reviews all instrument commands to ensure the safe and healthy operation of the instrument. The engineer also monitors and analyzes the health and safety data taken during operations and trouble-shoots any anomalous behavior indicated from his or her analysis of engineering or science data.

The instrument sequencer works closely with the instrument scientist to generate the actual instrument command sequences. In addition, there is a dedicated sequencer for all G&C commanding relevant to payload operations. The G&C sequencer is part of the payload operations team and works closely with each instrument sequencer to ensure that the correct G&C commanding is incorporated into the science-payload command sequences.

Because the science payload is considered a sub-system of the spacecraft, its operation is directed by the mission operations group. In addition to real-time spacecraft command and control, the mission operations group is responsible for planning and scheduling (including building the command loads) and spacecraft performance assessment. The payload operations manager (POM) leads the instrument command generation effort and reports directly to the mission operations manager (MOM). The POM also works in close collaboration with the deputy project scientists to ensure that the operation of the science payload meets the science objectives of the MESSENGER mission.

In addition to the MOM, the mission operations team is comprised of mission analysts, flight controllers, and mission planners and sequencers. The mission analysts are responsible for planning and testing spacecraft subsystem operations including communications and data handling, power, guidance and control, and autonomy. The analysts also perform routine trending and assessment of flight-system health and support any contingency response operations. The flight control team is responsible for conducting all real-time flight operations including DSN interfacing, spacecraft commanding, and real-time assessment functions. The mission planners are responsible for developing and testing spacecraft command loads that merge elements provided by the payload team with other commanding elements required, including RF communications, SSR operations, and orbital maneuvers. The planners also manage the resources available for spacecraft and the housekeeping operations including power, on-board command memory space, and SSR memory. In addition, the mission planners are responsible for enforcing flight constraints on the system and serve as the final "gate keeper" to ensure the health and safety of the flight and ground systems.

Each spacecraft subsystem is assigned a team of engineers who are responsible for the design, testing, and operation of their subsystem. Led by the mission systems engineer, the MESSENGER engineering teams oversee mission and navigation, power, thermal, fault protection and autonomy, guidance and control, communications, propulsion, integrated electronics, and flight software.

## Orbital Concept of Operations

While MESSENGER is in its cruise phase, the team is developing and testing the plan for operating the science payload and relevant subsystems for the orbital portion of the mission (March 2011 - March 2012). Before reaching Mercury, this concept of operations (ConOps) will be thoroughly tested and reviewed to ensure that the mission's full science success criteria can be met within the spacecraft's operational constraints and resource allocations.

The MESSENGER team is developing the orbital ConOps by building on the lessons learned from previous missions operated by APL and by applying several technical and process innovations.

### Building on Past Missions: Heritage

Many of MESSENGER's payload operations (i.e., processes and software) draw on the successful operational experience with the following mission and science instruments:

- The Near-Earth Asteroid Rendezvous (NEAR) mission, 1996 to 2001. NEAR, NASA's first Discovery-class mission, was managed and operated by APL.
- The Magnetosphere IMaging Instrument (MIMI) on the Cassini spacecraft, 1997 to present.
- The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) instrument on the Mars Reconnaissance Orbiter (MRO), 2005 to present.

The current MESSENGER cruise operations (launch to present) are a direct adaptation of the successful processes and tools used during the NEAR mission, which required highly coupled spacecraft and instrument operations. For example, the NEAR mission first defined the respective science and mission operations roles in order to form a highly efficient workflow (at minimal cost), while ensuring proper rigor and enforcement of flight rules (Holdridge, 2001). Rather than have the mission operations team prepare all of the spacecraft and instrument command sequences, the NEAR mission delegated instrument sequencing to the individual instrument teams. In addition, a single person managed the NEAR instrument command-sequence generation to ensure the combined instrument sequences were comprehensive and conflict free prior to delivery to mission operations. Because this team organization and workflow proved to be effective and efficient (and because some NEAR team members transitioned to the MESSENGER mission), it was logical to form the MESSENGER teams in a similar manner.

Another successful NEAR process was the generation of an initial, skeleton command load (by mission operations) reserving the times required for DSN operations, spacecraft maneuvers, and other housekeeping operations. This set-up file, called "MOps (for Mission Operations) Initials" was delivered to the instrument teams at the start of the weekly command-load build process to block out times when their instruments could not control spacecraft pointing or perform certain activities. After receiving the "MOps Initials," the NEAR instrument teams constructed their sequence files, including their instrument-specific attitude-control commanding within the timeframes allowed in the "MOps Initials." The usage of "MOps Initials" greatly alleviated major downstream conflicts in flight systems usage between the mission and science operations teams.

As on NEAR, it is the responsibility of the MESSENGER science operations (not mission operations) group to resolve any scheduling (or pointing) conflicts between instruments. After resolving the conflicts, the individual instrument sequences are safety checked by instrument engineers and forwarded to the mission operations team planners, who are responsible for merging the instrument sequences with the spacecraft housekeeping commands. The planners are also responsible for managing the combined resource usage and final testing and review of the command load.

During the NEAR mission, the weekly command generation process was two-tiered, with phase A and phase B instrument-sequence deliveries. Because of the one-time flyby opportunities, it was imperative to allow for two complete sequence building and test iterations to fully validate the instrument sequences and full spacecraft command loads.

Phase A was an initial test delivery of instrument inputs and generation of the command load. This step allowed for initial error checking and conflict resolution. Phase B was the final generation of the instrument command load, incorporating any changes needed to resolve the conflicts identified in phase A. MESSENGER's Venus and Mercury flybys employed this same strategy.

The MESSENGER command-generation software has a strong legacy. The ground software, scheduling (or sequencing), and command generation and validation tools are the next generation set of tools first used by the NEAR mission. These include SeqAdapt and SeqGen (provided by the Jet Propulsion Laboratory), SeqPost (provided by APL), StateSim (provided by Dewitt & Associates for APL), and various scripts that run these tools (provided by APL). Many of the scripts have been modified, and others have been added to the library, to provide reports unique to the MESSENGER mission.

As on NEAR, MESSENGER's instrument payload is commanded using fully tested, reusable command blocks. These command blocks were built from canned activity sequences (CASs) and the fragment protocols (frags) on which the CASs are built. During the cruise-phase flyby operations, the instrument teams have been testing the CASs and frags that have been built for instrument operation in the orbital phase of this mission. Therefore, prior to orbital insertion, all instrument commands will have been tested both with ground software and hardware, and also onboard the spacecraft. This validation will ensure reliable, safe commanding and acquisition of all critical science data.

The instrument teams will use the science planning software, SciBox (described below), to construct their orbital instrument command sequences. SciBox has heritage from previous successful NASA missions, such as MRO (used to plan the CRISM instrument operations) and Cassini (used to plan the MIMI instrument operations), in addition to supporting worldwide ground station coordination with the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) spacecraft and monitoring telemetry for the Solar TErrestrial RElations Observatory (STEREO).

The data-validation tools being used by MESSENGER include Planetary Information Processing Environment (PIPE) and Rapid Environmental Assessment Composition Tools (REACT), developed by Applied Coherent Technology Corporation (ACT), which have a heritage from such previous NASA missions as NEAR, Mars Global Surveyor (MGS), and MRO. Some modifications have been made for MESSENGER-specific needs, but these tools build on a strong heritage of supporting space exploration. PIPE is a network-centric data processing, management, and analysis server that has been optimized for solar system exploration missions. It provides telemetry data ingestion, data search engines, and archive generation, in addition to data processing (converting telemetry data to raw data and raw data into calibrated data). REACT is an analytic and data fusion workbench for analysis and decision support. REACT provides access to multiple varieties of data sets (correlating imaging and spectral observations), cartographic and data coverage knowledge and displays (for data validation and planning), and output of data to multiple formats (facilitates reporting and publishing). In addition, REACT is integrated with PIPE and SciBox, the main science operations tools.

By basing MESSENGER operational practices on previously proven processes, significant risk is reduced for the orbital mission. Furthermore, most of the same software tools are being adapted for the mission operations and science operations teams. The MESSENGER mission thus has a solid process and technical foundation on which to build the new orbital concept of operations.

## Operational Challenges of a Mercury Orbiter

MESSENGER will be the first spacecraft to orbit the planet closest to the Sun (where temperatures range between 800° F and -300° F).

A set of two Mercury orbit-insertion (MOI) maneuvers will place MESSENGER in a highly elliptical orbit about Mercury with a periapsis of ~200 km and an apoapsis of ~15,100 km. The orbital inclination will be approximately 80°. The orbital mission poses significantly different challenges from those of the cruise phase.

**Thermal constraints**. MESSENGER must keep its ceramic-fabric sunshade pointed within ±12° of the Sun at all times in order to protect the science instruments and spacecraft electronics. This constraint complicates observing geometry and therefore adds complexity to scheduling science observations (by limiting available viewing opportunities). In addition, when orbit periapsis is near the sub-solar point, thermally sensitive parts of the spacecraft must also be kept from being exposed to thermal radiation from the planet.

**Non-repeating orbital operations**. The spacecraft's ground speeds will vary from 0.6 km/s at apoapsis to 3.8 km/s at periapsis. In addition, MESSENGER's orbit will be non-Sun synchronous. As the spacecraft's orbit precesses around Mercury, the orbital illumination geometry and spacecraft constraints will change from orbit to orbit.

**Competing instrument pointing requirements.** The seven science instruments (with 12 sensors) will have ambitious data-taking schedules as well as competing pointing requirements. For example, some instruments must point to nadir (the point on Mercury directly below the spacecraft), while others need to point off-nadir or even point away from Mercury for observing Mercury's exosphere.

**Complicated instrument data rate profile and downlink profile**. As MESSENGER's illumination geometry changes from orbit to orbit, the available viewing geometry will also change. These changes will create observing "seasons" for the science instruments, as well as a non-uniform data output rate. Additionally, throughout the orbital mission, the Mercury-Earth distance will change significantly, which will affect the daily downlink rate. With limited SSR space, the onboard storage must be managed carefully and efficiently.

**Orbital correction maneuvers**. Approximately every 88 days, a set of orbital-correction maneuvers (OCMs) will be needed to adjust MESSENGER's orbit back to its original parameters because of the effect of solar torques on the orbit. Science operations must be suspended during these operations.

## Breaking New Ground: Innovation

These new challenges require the MESSENGER team to develop efficient new operations processes, scheduling strategies, and software so that MESSENGER will not miss limited observation opportunities and will react quickly to changing orbital conditions and uncertainties.

The main areas of innovation are: a new planning and scheduling process, the development of a baseline operations plan, and new tools to support our processes.

The core feature of the new MESSENGER orbital ConOps is two interconnected and repeating processes: (1) a full mission (or long-range) planning cycle and (2) 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).

## 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 mission (18 March 2011 to 17 March 2012). Like other missions' long-range plans, the ASP process will be iterative; the advance science planning lead will reassess and update the plan regularly for the remainder of the orbital mission. The MESSENGER phase A process used for planetary flybys was adapted into this new ASP process.

**The baseline.** The output product of the ASP process is the baseline operations plan, or simply, the baseline. The baseline is the plan of all instrument and associated spacecraft G&C activities that span the entirety of the nominal orbital mission. The baseline is built on the basis of the concept of operations for each instrument, the health and safety rules for the operation of the spacecraft (especially the G&C sub-system), and a prioritization of the G&C operations relative to each instrument's requirements.

The advance science planning lead, in collaboration with the science and instrument team leads, is currently formulating the baseline. The baseline will be tested and approved before Mercury orbit-insertion (MOI) to ensure a pre-determined path for completing the mission's full science objectives. The creation and maintenance of a baseline operation plan is an innovation in payload operation planning that ensures a path for meeting the mission's science success criteria

**The advance science planning process.** Once the orbital mission phase has begun, the ASP process will be performed approximately every five weeks, producing an updated baseline for the remainder of the mission. The new baseline will be delivered to the POM, who is responsible for its execution.

Each ASP cycle begins with a review of the following areas:

1. *Flight-systems assessment*. Any changes to the spacecraft or subsystem performance or capabilities will be incorporated into the next baseline. Special attention will be given to the downlink rate and SSR performance, as these can have the greatest impact on the overall baseline.
2. *Mission design/navigation assessment*. Updates to the orbit determination and ephemeris will be incorporated.
3. *Instrument operations and performance assessment*. Any changes or updates to the payload's performance and capabilities are incorporated.
4. *Data validation*. The instrument teams will check that the data received are complete and of sufficient quality.
5. *Mission objective re-assessment*. Re-definition of the mission success criteria, if necessary, by the principal investigator. This re-assessment would be instigated by a major new scientific discovery and would require NASA approval.
6. *Science optimization*. The science team will continue to improve the strategy for optimizing science return.

After the above issues are reviewed, the appropriate modifications are made to the long-term scheduling algorithms, and a new baseline will be generated and reviewed by the instrument teams. Simulations and reports will be run to ensure that the new baseline still meets the full mission success criteria. In addition, checks will be made to verify that resource usage is still within allowable limits.

## Near-Term Science Planning

Near-term science planning (NTSP) is the short-term scheduling aspect of the optimized orbital ConOps. 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). Ultimately, the mission operations team merges all the instrument sequence files with the other appropriate spacecraft subsystem commands and uplinks the integrated command load to the MESSENGER spacecraft.

The motivation behind the NTSP approach was summarized by Holdridge and Calloway (2007) as follows:

> The complexity of science operations and the logistics of large round-trip light times require that science operations be conducted via an on-board command load. This situation requires a strictly scheduled planning and command load process.

This MESSENGER NTSP cycle is a modified version of the cruise operations process originally developed for NEAR. However, the MESSENGER team will use the same software (SciBox), which constructs the ASP Baseline, to generate the NTSP weekly instrument command sequences. The highly automated process contained in SciBox replaces what was a highly time consuming and manual process for NEAR operations. This new process will allow a larger instrument complement to be operated with less effort and iteration.

SciBox will convert instrument schedules into actual command sequences using the same CAS and frag libraries tested and validated during the cruise phase. Unlike NEAR, however, there will be only a single delivery of payload command sequences to mission operations. This affords greater efficiency during orbit, where the time for producing command loads for delivery to mission operations is much shorter than during the cruise phase.

As with the advance science planning, flexibility is also critical to the near-term science planning process. The MESSENGER payload is already providing unique 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.

**The NTSP process.** The starting point of the near-term science planning process is constrained in time by the receipt of a confirmed DSN track schedule, which is normally available eight weeks in advance.

The main NTSP process steps are:

1. *Delivery of "MOps Initials."* The build process for a command load begins when the mission operations team receives the confirmed DSN track schedule for the next command load under construction. Mission operations delivers the relevant track schedule and spacecraft-related constraints (e.g., power or thermal) to the POM to block out periods when no instrument commanding is allowed. The POM integrates these constraints into the baseline using SciBox and saves the new instrument schedule files.
2. *Delivery of weekly schedules.* The POM delivers the weekly instrument schedules to the instrument and G&C teams and provides up-to-date information on available SSR resources.
3. *Review of instrument and G&C schedules.* Using the SciBox software, the instrument and G&C teams review their schedule file(s) for the next command load. The instrument sequencers check the commanding syntax, and the instrument scientists verify the scientific strategy for the week's observations.
4. *Change requests.* During the NTSP process, some minor changes to an instrument schedule can be accommodated (e.g., temporarily increasing a data collection rate). Generally, however, no changes involving G&C are permitted at this late stage. If a change is requested, the instrument scientists submit a web-based change request, which is processed by the POM and deputy project scientist with fast turnaround.
5. *Approval of instrument and G&C schedules.* If no changes are required, or after a change request is approved or rejected, the sequencers notify the POM when the schedule has been approved by both the instrument scientist and the instrument engineer.
6. *G&C team review of spacecraft pointing.* Before proceeding, the G&C team reviews the instrument pointing requirements and associated spacecraft G&C commands to ensure that there are no violations.
7. *Generation of science activity sequence files (SASFs).* Once all instrument and G&C schedule files have been properly approved and submitted, the instrument and G&C teams convert the SciBox-syntax schedule file into the required instrument command request syntax (i.e., an SASF file, which is the required format for input to the mission operations software). Both the instrument scientist and the instrument engineer must review and approval all instrument commands before they are uploaded to the spacecraft.
8. *SASF delivery.* The POM reviews all SASF deliveries and approvals. If there are no errors or missing approvals, the POM delivers the SASFs to the mission operations team, who will include them in the generation of the entire spacecraft command load.
9. *Construction of the command load.* The mission operations team builds and reviews the spacecraft command load (including the delivered instrument commands) and uploads it to the spacecraft approximately one week prior to the start of execution. At least two upload opportunities are budgeted to ensure a contingency opportunity.

Currently it is anticipated that it will take approximately three weeks to complete the NTSP cycle for each weekly command load. Therefore, the mission operations and science operations teams will be working on more than one command load at one time. For example, each week the mission operations team will be responsible for building, reviewing, and uploading the next command load.

The timing of each of the NTSP steps will be tested fully during specific rehearsal tests in 2009 and 2010, with a focused effort to streamline the process steps and improve the software.

## Contingency Planning

As stated previously, the environment in Mercury orbit heavily constrains spacecraft pointing, which in turn constrains power generation, data downlink opportunities, and observation opportunities. In order to meet the mission's science goals, a complex observation plan must be used, and that plan must be optimized with respect to pointing opportunities and storage/downlink resources. The creation of an optimal plan requires a thorough examination of risk-mitigation strategies.

Deviations from the baseline may result from events such as a spacecraft-safing event, the loss of a downlink track with the Deep Space Network, 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 (described more in the next section).

SciBox is used during the ASP phase to generate the baseline schedule, as well as a set of information on instrument coverage, solid-state recorder usage, and other information that allows science team members to assess the success of the mission. The flexibility built into SciBox allows the user to designate 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 on mission success. This examination must be done well in advance of MOI 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 Deep Space Network 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 feature), immediate insertion into the upcoming NTSP cycle.

## Software Tools

In this section, we describe the primary software tools to be used during orbital operations.

**SciBox.** MESSENGER's planning and scheduling software system is based on a goal-based uplink pipeline architecture (Choo et al., 2008) using the SciBox library (Choo and Skura, 2003). The goal-based planning system allows scientists to focus on science observations instead of command details. Scientists use the tool to analyze observation opportunities and schedule science observations. Instrument commands and G&C commands are automatically generated when the observation schedules are completed and converted to SASFs. The planning and scheduling system is built using SciBox (Choo and Skura, 2004), a software library developed at APL that is designed specifically for space operation simulations. It contains visualization packages to support exploratory concepts of operations, scheduling packages for saving and interacting with abstract science operations, and geometry and event analysis packages for rapid analyses of observational opportunities.

For the MESSENGER orbital mission, the planning and scheduling software system will be used for both the advance science planning and near-term science planning processes. Its primary users will be the instrument sequencers and Instrument Scientists, as well as the advance science planning lead and payload operations manager.

For the ASP process, SciBox (and its Optimizer tool) will be used to revise the baseline. Inputs from the data-validation process are transferred from the data validation tool, PIPE, to SciBox. In addition, the Optimizer algorithms must process changes in targeting priorities and/or changes in spacecraft and instrument performance. To produce a viable baseline, SciBox must model all orbital, spacecraft, and instrument pointing constraints, as well as SSR usage per instrument and DSN downlink opportunities. SciBox will produce graphs and reports to verify the new baseline. The ASP Optimizer can be run from the command line or through a graphical user interface (GUI).

For the NTSP process, the POM, instrument sequencers, and instrument scientists will be the primary users of SciBox.

The Coordinator Tool is the primary interface for the POM-related NTSP functions. The POM will use SciBox to ingest the "MOps Initials" data and produce up-to-date schedule files for review by the instrument and G&C teams. The Coordinator Tool also provides an overall view of all the instrument activities for a given time period. Figure 2 is a screenshot of a sample view of the SciBox Coordinator Tool. All the POM functionality is available via this interface. In addition, SciBox provides a high-level graphical overview of the planning period (and each instrument's activities). By clicking on an instrument activity or orbital event, additional details are provided in a pop-up box.

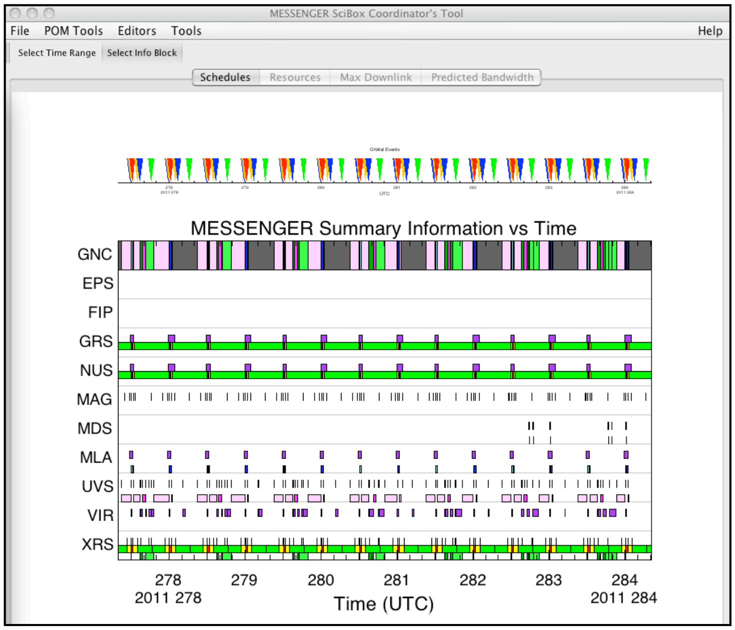


**Figure 2**: MESSENGER SciBox Coordinator Tool showing an overview of activities for a given orbitalweek.

The POM will also use SciBox to view changes to the actual DSN track schedule that could affect instrument data resources for the week. SciBox will also provide the POM with useful instrument commanding statistics, such as total number of commands and data volume per instrument. The POM must ensure that each instrument team remains within its data volume allocation per week.

SciBox provides each team with its own Schedule Editor module to review weekly instrument commanding. The Schedule Editor will also be used to make minor changes to instrument commands and parameters and investigate available targeting opportunities (if applicable). All instrument and G&C commands are saved in a SciBox-syntax schedule file, which can be modified and read back into SciBox.

Because the instrument and G&C commands must be provided to the mission operations team in a different syntax (not used by SciBox), the SciBox software converts the SciBox schedule file into the required SASF format. During the current cruise phase, SASFs are generated manually by each instrument and G&C team. Because instrument activities are not very frequent in cruise (except for planetary flybys), it is not an arduous process. However, once in orbit, it will not be possible to generate each of these SASFs manually every week.

Radio science commanding will not be handled by SciBox; instead, a report will be generated along with the baseline that describes the expected uses of the HGA and LGA for the mission, including the choice of antenna and time windows for use. The radio science team will use this information, along with information from the MOps initials, to generate commanding in the form of an SASF file.

**NTSP Tracking Tool.** The process of building and uploading a weeklong command load by the science and mission operations teams will take more than one workweek. Therefore, the mission and science operations teams will work on more than one command load at one time. There are details pertaining to each command load that must be recorded at each process step. The MESSENGER team members will require an easy-to-use tracking tool to capture critical information and deliver automated e-mails of status and action items. While most of the same information is tracked during cruise operations, it can be handled manually with existing tools since there are far fewer science activities during cruise.

The details that need to be tracked on orbit are:

- Command loads in production and their status
- Instrument scientist and instrument engineer approvals of schedules and sequence files
- Change requests with supporting information and final disposition.
- Outstanding action items

The users of the tracking tool will be:

- Mission operations personnel (mission operations manager, schedulers, analysts)
- Instrument and G&C teams (sequencers, scientists, engineers)
- Payload operations manager, science planning group coordinator, advance science planning lead
- Mission systems engineer, other engineers

Each user (or group) will have a specialized set of functions and privileges within the tracking tool. For example, instrument scientists will have a mechanism (and the authority) to approve SciBox and SASF files and also submit change requests. The POM will have the authority to approve or reject submitted SASF files. Whenever an action is taken, automatic e-mail is sent to the next person or team in the process flow.

For MESSENGER NTSP tracking, the team has chosen the implementation of a commercial web-based product called JIRA by Atlassian Software (http://www.atlassian.com/). JIRA is an "issue tracking" software package, but it is easily modified for tracking command loads, instrument sequences, and other tasks related to orbital operations. In fact, JIRA is already being used by other APL missions with positive results. Initial set-up and testing of MESSENGER JIRA have begun. Several enhancements have been identified and will be implemented and tested before orbital operations.

Figure 3 is a screenshot of the MESSENGER JIRA implementation (with sample test data).

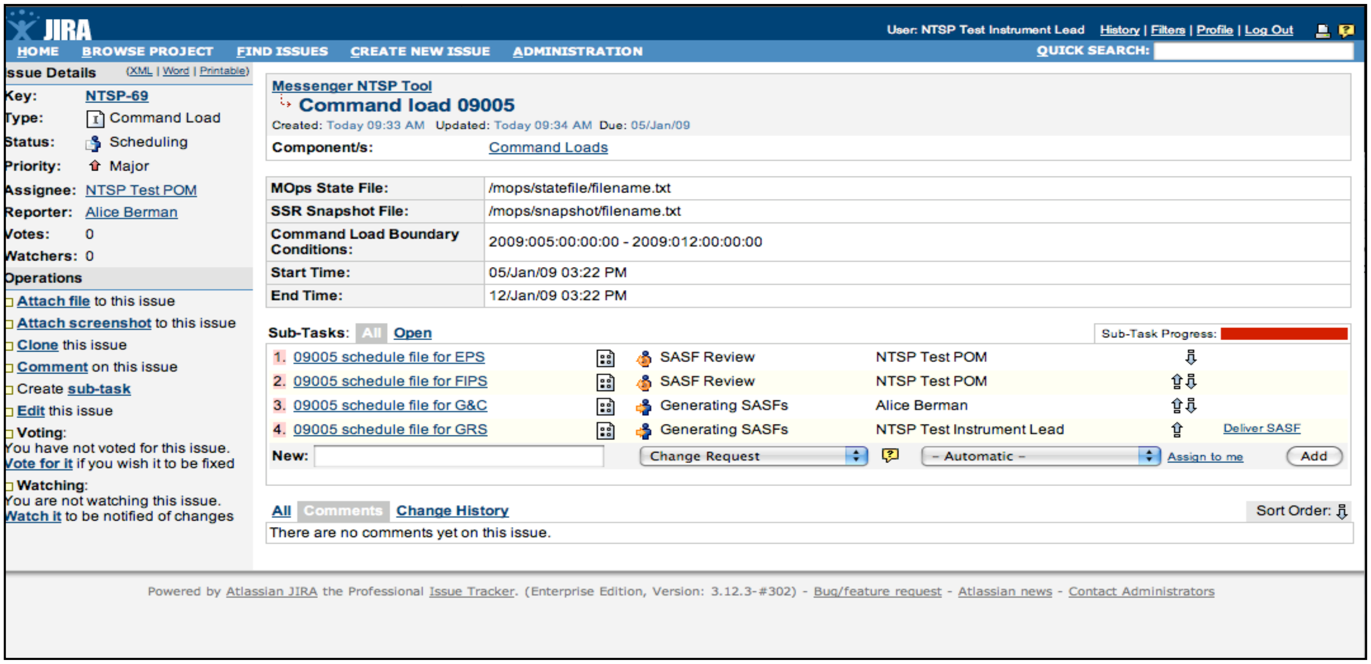


**Figure 3**: Sample data entered into the MESSENGER JIRA Tracking Tool

## Testing/Validation

The verification of the orbital ConOps processes and software is top priority to the MESSENGER team. Readiness reviews of all key mission systems must be completed in 2010. A key component of the planning system validation plan is a series of orbital planning simulations using existing ground software and mission hardware simulator (which includes fully functional versions of the science instruments and key spacecraft systems).

In 2007 and 2008, three day-in-the-life (DITL) planning exercises were performed. The main objective of these tests was to practice building sequences and command loads that were representative of one day in orbit (over a range of different orbit conditions). For these early tests, instrument SASFs were constructed manually, combined with the necessary spacecraft commanding, and then tested with ground software and hardware. While DITL testing did not exercise the actual processes planned for orbital command sequence development, it did serve to focus the entire team on the development of realistic flight timelines, a process which engaged both instrument and spacecraft teams to the common goal of planning and de-conflicting flight timelines that can accomplish mission objectives within the operation constraints. This process uncovered a number of issues that had to be resolved before longer, more automated operations could be attempted.

In 2009, the science operations, mission operations, and engineering teams began work on the first orbital week-in-the-life (WITL) test where a full seven-day command load was generated and tested with all ground software and hardware tools. SciBox was used to generate all instrument and G&C schedule files and SASFs. In addition to testing software and hardware, the objective of the first WITL test was to work through the ConOps process together so that processes and tools could be evaluated and refined. A series of six more WITL tests are planned for the 2009-2010 timeframe. Some WITLs will be run in a realistic orbital operations timeframe so that the teams can test how long it takes to accomplish each of the necessary planning steps.

There are several key operational circumstances during orbit that the WITL tests are designed to investigate, and these are tracked with a test matrix that captures system operations, science operations, and contingency scenarios. The completion of the WITLs will include a validation and optimization of the process, tools, and the test matrix to ensure orbital operations readiness.

Apart from the structured WITL exercises, all 52 weekly SciBox schedules will also be run independently through the mission operations ground software system prior to MOI to ensure there are no health or safety issues. Some key spacecraft and instrument activities will also be tested the flight hardware simulator.

Overall orbital readiness will be assessed not only with the in-the-life tests, but also with flight tests and specific readiness reviews. For example, a series of flight tests will be used to verify data validation and other critical processes. A set of focused review meetings will be used to organize the tests and define the minimum requirements for orbital readiness.

## Summary

MESSENGER is a groundbreaking mission to a harsh, new environment. Meeting the mission's science success criteria, under severe operating constraints, requires a focused, integrated operating plan that spans the entire mission's duration.

Building on a history of successful mission operations, the MESSENGER team has applied innovative changes to its processes and tools to ensure a flexible plan that not only meets its success criteria, but also allows for quick modifications in response to operational challenges, contingencies, and new discoveries. The two-tiered planning and scheduling approach maximizes science optimization and provides for a robust review system to minimize operational risks. The testing and validation program will examine all aspects of orbital operations, from process to information flow and tools before the orbital mission begins.

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