Science Planning, Data Acquisition, Analysis, and Distribution for the MESSENGER Mission

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ABSTRACT

Data acquisition, analysis, and distribution for the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission were highly successful because of the introduction of a new orbital concept of operations for the payload and approach for science planning, powerful and innovative spacecraft and ground tools, and the dedicated and skilled teams that supported these activities. This article focuses on these key science operations activities for the more than 4 years of MESSENGER orbital operations around Mercury (from 18 March 2011 to 30 April 2015) and the final post-orbit-operations period of data analysis and archiving (through 31 May 2017). Also highlighted are MESSENGER SciBox; Planetary Information Processing Environment, Rapid Environmental Assessment Composition Tools, and QuickMap; and other tools that were critical to those activities. The success of these operations resulted in a wealth of data that will continue to support scientific investigation of the planet Mercury for decades to come.

INTRODUCTION

Substantial innovations in the approaches and tools for MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) science operations greatly enhanced the quantity and quality of the science data captured from orbit about Mercury, the ease and agility of the operations to capture those data, the serving of data products to and support for the analysis of those products by the MESSENGER team, and the delivery of data archives to the Planetary Data System (PDS). Figure 1 summarizes the key MESSENGER science operations activities, tools, and interfaces. This article discusses the major contributions of science operations to the MESSENGER mission and innovations in those operations with the following breakdown: science planning, including the payload concept of operations (ConOps); APL's MESSENGER SciBox tool that supported planning and spacecraft commanding, payload data collection and storage on the spacecraft, and the strategy and protocol for transmission of the data to the ground; the science data pipeline and the Planetary Information Processing Environment (PIPE), Rapid Environmental Assessment Composition Tools (REACT), and QuickMap tools provided by Applied Coherent Technology Corporation (ACT) that were central to that pipeline; and science data archiving to the PDS. Further details on mission operations support for these activities are provided in the article by Calloway et al. in this issue. Additional information on the design and implementation of the MESSENGER Science Operations Center (SOC) that supported these activities are provided by Winters et al.[1]

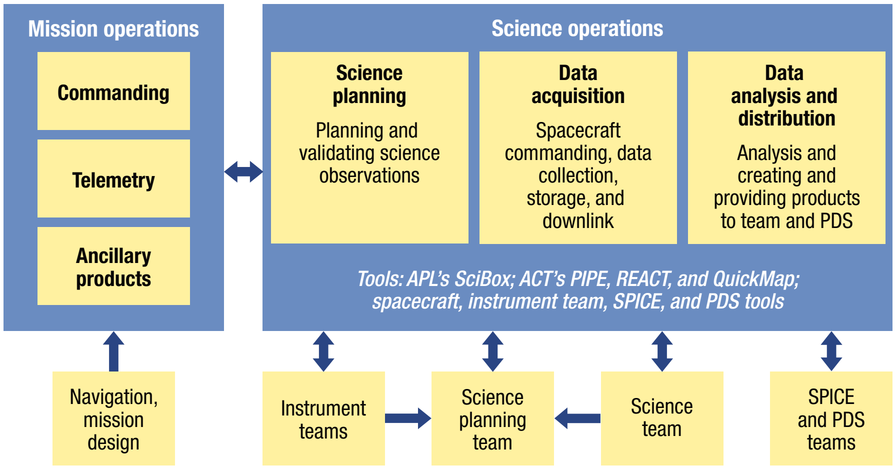


Figure 1. Science operations activities, tools, and interfaces.

SCIENCE PLANNING PIPELINE

The innovative orbital ConOps used by the science and mission operations teams[2] for the MESSENGER payload supported the automated creation of both a full-mission science observation strategy as well as weekly command loads during the orbital mission. This new ConOps ensured full mission success by (*i*) utilizing a large and complex payload effectively and efficiently, (*ii*) minimizing operational risks, and (*iii*) supporting smooth observation strategy refinement and replanning when needed. By the end of the primary and extended orbital missions, the MESSENGER spacecraft had successfully collected more than 277,000 images, millions of spectra and laser altimetry measurements, and other data, meeting or exceeding all of the baseline science requirements for the mission.

Background and Heritage

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

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

The MESSENGER orbital ConOps was developed by building on lessons learned from these missions and also applying several new technical and process innovations responsive to the unique challenges faced by the MESSENGER mission.

For example, the NEAR mission (with five science instruments plus a radio science investigation) first defined distinct 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 and constraints.[3] The NEAR mission delegated responsibility for instrument command sequence generation to each of the instrument teams. Furthermore, a single person managed the merging of the combined instrument command sequences to ensure that they were comprehensive and conflict-free before delivery to mission operations.

On the MESSENGER project, this management role was expanded and formalized as the payload operations manager (POM). The POM led the instrument team command generation effort and reported directly to the mission operations manager. As a liaison between mission and science operations, the POM also worked in close collaboration with the project scientists, the instrument teams, and the software development team for the SciBox planning tool to ensure that the operation of the science payload met the science objectives of the MESSENGER mission and that any commanding priority or spacecraft-pointing conflicts among instruments were resolved before the construction of the command loads.

During MESSENGER's nearly 7-year interplanetary cruise phase [from launch on 3 August 2004 until Mercury orbit insertion (MOI) on 18 March 2011], the level of instrument command activity was low (except for planetary flybys); instrument teams, under the leadership of the POM, manually created their own command sequences. Even the instrument commands for planetary flybys (one of Earth, two of Venus, and three of Mercury) were sequenced manually because the period of time for which commands had to be generated to support a flyby was typically only a few days before and after planetary closest approach. Therefore, there was ample time before each flyby to plan, build command sequences, and perform software and hardware simulations to validate those sequences before the actual flyby took place. However, after MOI, with the spacecraft in orbit around Mercury, instead of having months to plan for the next flyby, the team needed to plan for the equivalent of two Mercury flybys each Earth day (or 14 flybys per week), and the time to generate command sequences shrank markedly (from months to 3 weeks). With this realization, the science team determined early in the cruise phase that the traditional manual cruise planning process and tools would not be able to maintain the overall observation strategy and develop an optimized and timely command sequence for the spacecraft each week.

The development of a more automated planning approach centered on the use of the MESSENGER SciBox software tool (described in the section below). MESSENGER SciBox allowed the team to deal effectively with the increased intensity of payload operations during the orbital phase and facilitated the coordinated and automated creation of the mission-long observation strategy and the weekly instrument command sequences.

MESSENGER SciBox has strong heritage from the use of earlier versions of SciBox on the successful NASA missions MRO (for which SciBox was used to plan CRISM instrument operations) and Cassini (for which SciBox was used to plan MIMI operations). In addition, SciBox was used to support worldwide ground station coordination with the Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) spacecraft and monitoring telemetry for the Solar TErrestrial RElations Observatory (STEREO). Use of the term *SciBox* in this article refers to the mission-specific implementation of the SciBox tool, MESSENGER SciBox, except where noted otherwise.

By leveraging previously proven processes and software to develop an innovative approach for MESSENGER operational practices, risk was significantly reduced for the orbital mission. The MESSENGER mission thus had a solid process and technical foundation on which to build a new orbital payload ConOps.

Operational Challenges of a Mercury Orbiter

Mercury orbital conditions and other operational constraints set important limits on MESSENGER science planning. MESSENGER was the first spacecraft to orbit the planet closest to the Sun, and temperatures in orbit range between –300°F and 800°F. An orbit-insertion maneuver placed the MESSENGER spacecraft in a highly eccentric orbit about Mercury with a periapsis of ~200 km and an apoapsis of ~15,100 km. The initial orbital inclination was ~82°. The orbital phase of the mission posed operational challenges that were substantially different from those of the cruise phase.

Thermal Constraints

MESSENGER was required to keep its ceramic-fabric sunshade pointed within ±12° of the direction to the Sun at all times in order to protect the science instruments and spacecraft electronics. This constraint complicated observing geometry and, therefore, added complexity to scheduling science observations (by greatly limiting available viewing opportunities). In addition, when orbit periapsis was near the subsolar point, thermally sensitive parts of the spacecraft had to be protected from exposure to thermal radiation from the planet.

Non-repeating Orbital Operations

The spacecraft's ground speeds varied from 0.6 km/s at apoapsis to 3.8 km/s at periapsis. In addition, MESSENGER's orbit was not Sun synchronous. Instead, the orbital illumination geometry and spacecraft constraints (e.g., spacecraft pointing, thermal, and data downlink) changed from orbit to orbit in the course of a Mercury solar day (two Mercury years).

Competing Instrument-Pointing Requirements

The seven science instruments (with 12 sensors) all had demanding observation schedules as well as competing requirements for orienting the spacecraft in order to be able to obtain their observations. For example, some instruments needed to point to nadir (i.e., the point on Mercury's surface directly below the spacecraft), whereas others needed to point off-nadir or even away from Mercury (e.g., to observe Mercury's exosphere).

Complicated Instrument Data-Rate Profile and Downlink Profile

As MESSENGER's illumination geometry changed from orbit to orbit, the available viewing geometry also changed. These changes created observing "seasons" for the science instruments, as well as nonuniform data collection and downlink rates. Additionally, as Mercury orbited the Sun, the Mercury–Earth distance changed substantially, which affected the daily downlink rate. With limited spacecraft solid-state recorder (SSR) space, the onboard data storage had to be managed carefully and efficiently. Communications with MESSENGER were handled through NASA's Deep Space Network (DSN), which is a worldwide network of antennas that support interplanetary spacecraft.

Orbit-Correction Maneuvers

Approximately every 88 days during the first year of orbital operations, orbit-correction maneuvers were needed to adjust MESSENGER's orbit back to its original parameters because of the effect of solar torques on the orbit. Science operations were suspended during these orbit-correction maneuvers, but it was necessary to return to science operations as quickly as possible so that critical observations would not be missed.

These orbital challenges had to be factored into the operations processes, scheduling strategies, and software tools so that MESSENGER would not miss key, limited observation opportunities and could react quickly to changing orbital conditions.

The main areas of innovation for science planning were a new planning and scheduling process, the development of a baseline payload operations plan, and advanced new tools to support the new processes.

The core feature of the new MESSENGER orbital payload ConOps consists of two interconnected and repeating processes: (*i*) a full mission (or long-range) planning cycle called advance science planning (ASP) and (*ii*) a short-term (i.e., 1-week) scheduling process called near-term science planning (NTSP), shown in Fig. 2.

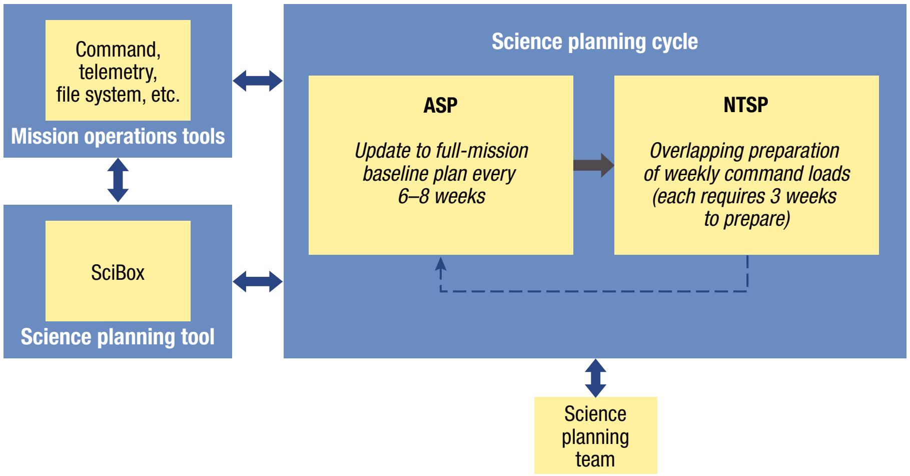


Figure 2. Science planning cycle.

Advance Science Planning

The purpose of ASP was to formulate an efficient and effective long-range strategy for scientific observations for the entire orbital mission [18 March 2011 through 17 March 2012 for the primary mission and through 30 April 2015 for the second extended mission (XM2)]. In collaboration with the MESSENGER principal investigator and science team, the ASP lead reassessed and updated the plan as needed every 6–8 weeks for the duration of the primary and extended orbital missions.

The Baseline

The output product of the ASP process was the baseline payload operations plan, or simply, the baseline. The baseline was the plan for all instrument, radio science, and instrument-related spacecraft guidance and control (G&C) activities that spanned the entirety of the remaining orbital mission. The baseline was created consistent with the ConOps 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 requirements.

The ASP lead, in collaboration with the science and instrument team leads, formulated the baseline using SciBox. The initial baseline for the primary mission was fully tested and approved before MOI to ensure a predetermined path for fully achieving the mission's science objectives. The approved baseline was delivered to the POM and instrument and science teams for implementation (i.e., creation of weekly NTSP command sequences, described below). The creation and maintenance of a baseline operations plan was an innovation in payload operations planning that ensured a path for meeting the mission's science success criteria over the orbital mission.

The ASP Process

Once the orbital phase of the mission began, the ASP process was performed every 6–8 weeks, producing an updated baseline for the remainder of the mission. The schedule of ASP activities was driven largely by the DSN scheduling time frame, because ASP inputs were used by the DSN in creating downlink schedules approximately every 8 weeks. The baseline generation optimized science operations and return across the instruments per instrument ConOps and spacecraft health and safety constraints. With each ASP cycle, results of the following assessments were incorporated into the new baseline as appropriate:

1. *Flight-systems assessment*. Any changes to the spacecraft or subsystem performance or capabilities could be incorporated in SciBox and reflected in the next baseline. Special attention was given to the downlink rate and SSR performance, because these typically had the greatest impact on the overall baseline.
2. *Mission design/navigation assessment*. Any updates to planned orbit-correction maneuvers were incorporated.
3. *Instrument operations and performance assessment*. Any changes or updates to the payload's performance and capabilities were incorporated.
4. *Data validation*. The instrument teams verified that the data received to date were complete and of sufficient quality. Any images needing to be retaken were reincorporated into the plan in a highly automated fashion.
5. *Science optimization*. The science team continued to improve the strategy for optimizing science return over the course of the entire orbital mission.
6. *Ensuring mission success and evaluating new opportunities*. The principal investigator, working with the science team, could evaluate mission objectives and consider the investigation of new findings. Large-scale changes would require NASA approval, but this planning process and the SciBox analysis results provided an efficient and effective means with which to perform these studies.

After these assessments were completed, the ASP lead approved the appropriate modifications to the long-term scheduling algorithms in SciBox, and a new baseline was generated by the payload operations team and reviewed and approved by the instrument teams. Transitioning from 12-h to 8-h orbits after the end of the primary mission and the low-altitude campaign near the end of orbital operations required major changes to the operational strategy that would have been quite challenging with a less automated approach. However, the use of SciBox made these changes feasible and straightforward. Outside of these types of significant shifts in operations, most ASP cycles required very few changes to the baseline.

Near-Term Science Planning

NTSP was the short-term scheduling aspect of the optimized orbital ConOps. Led by the POM, NTSP consisted of the processes, procedures, and tools necessary to convert 1-week portions of the science baseline into a set of executable instrument command sequences (one sequence per instrument, plus radio science and G&C). Ultimately, the mission operations team converted the SciBox-generated instrument command sequence files into the format required by the spacecraft, merged all the instrument commands with the appropriate spacecraft subsystem commands, and uplinked the integrated command load to the MESSENGER spacecraft.

The NTSP process developed for MESSENGER used the same MESSENGER SciBox software tool as that by which ASP generated the NTSP weekly instrument command sequences. MESSENGER payload operations were supported by the highly automated capabilities of SciBox rather than by the extremely time-consuming and manual process that was used for operations on the NEAR mission. The new process allowed a larger instrument complement to be operated with much less effort and iteration, keeping costs in check and reducing risk and required resources.

SciBox converted instrument activity schedules into the instrument commanding syntax required by mission operations, using the same mission operations command building libraries tested and validated during the cruise phase. Unlike NEAR, which used a two-phase command sequence delivery process, there was only a single delivery of payload command sequences to mission operations for MESSENGER because of the automation, constraint checking, and error checking in SciBox. This single-step process afforded greater efficiency during orbit, where the time to produce command loads for delivery to mission operations was much shorter than during the cruise phase.

As with ASP, flexibility was also critical in the NTSP process. The MESSENGER payload provided unique scientific data from the Mercury flybys during cruise, and the team anticipated that more discoveries would be made during the orbital phase of the mission. It was critical that the NTSP process allowed for late changes in NTSP as a result of contingencies or discoveries.

The NTSP Process

The NTSP process used the baseline from the ASP, the confirmed DSN track schedule, and other updated inputs (described below) to create weekly command loads. The following NTSP process steps were generally completed over a 3-week period:

1. *Delivery of "MOps Initials."* The build process for a command load began when the mission operations (MOps) team received the confirmed DSN schedule for the next command load under construction. Mission operations delivered the relevant DSN schedule and spacecraft-related constraints (e.g., power or thermal) to the POM (in a file called the MOps Initials) to block out periods when no instrument commanding was allowed.

2. *Preparation of payload schedule files.* The POM ingested the MOps Initials file into SciBox along with the latest orbit determination and ephemeris updates. The updated orbit determination and ephemerides were used to update the timing of all commanded payload activities.

3. *Delivery of weekly schedules.* The POM delivered the weekly instrument schedules to the instrument and G&C teams and provided up-to-date information on available SSR resources.

4. *Review of instrument and G&C schedules.* Using SciBox, the instrument and G&C teams reviewed their schedule files for the next command load. The instrument sequencers checked the commanding syntax, and the instrument scientists verified the scientific strategy for the week's observations.

5. *Change requests.* During the NTSP process, only a few minor changes to an instrument schedule were accommodated (e.g., temporarily increasing a data collection rate). Generally, however, no changes involving G&C were permitted at this late stage. If a change was requested, the instrument scientists submitted a web-based change request, which was reviewed and addressed quickly by the POM and deputy project scientist.

6. *Approval of instrument and G&C schedules.* If no changes were required, or after a change request was approved or rejected, the sequencers notified the POM that the schedule had been approved by both the instrument scientist and the instrument engineer.

7. *G&C team review of spacecraft pointing.* Before proceeding, the G&C team reviewed the instrument-pointing requirements and associated spacecraft G&C commands to ensure that there were no spacecraft-pointing or slew violations.

8. *Generation of science activity sequence files.* Once all instrument and G&C schedule files were properly approved and submitted, the instrument and G&C teams converted the SciBox-syntax schedule file into the required instrument command request syntax [i.e., a science activity sequence file (SASF), which is the required format for input to the mission operations software]. Both the instrument scientist and the instrument engineer reviewed and approved all instrument commands before they were uploaded to the spacecraft.

9. *SASF delivery.* The POM reviewed all payload SASF deliveries and approvals. If there were no errors or missing approvals, the POM delivered the SASFs to the mission operations team, which included them in the generation of the entire spacecraft command load.

10. *Construction of the command load.* The mission operations team built and reviewed the spacecraft command load (including the delivered instrument commands) and uploaded it to the spacecraft ~2–3 days before the start of execution. At least two upload opportunities were budgeted to ensure a contingency opportunity.

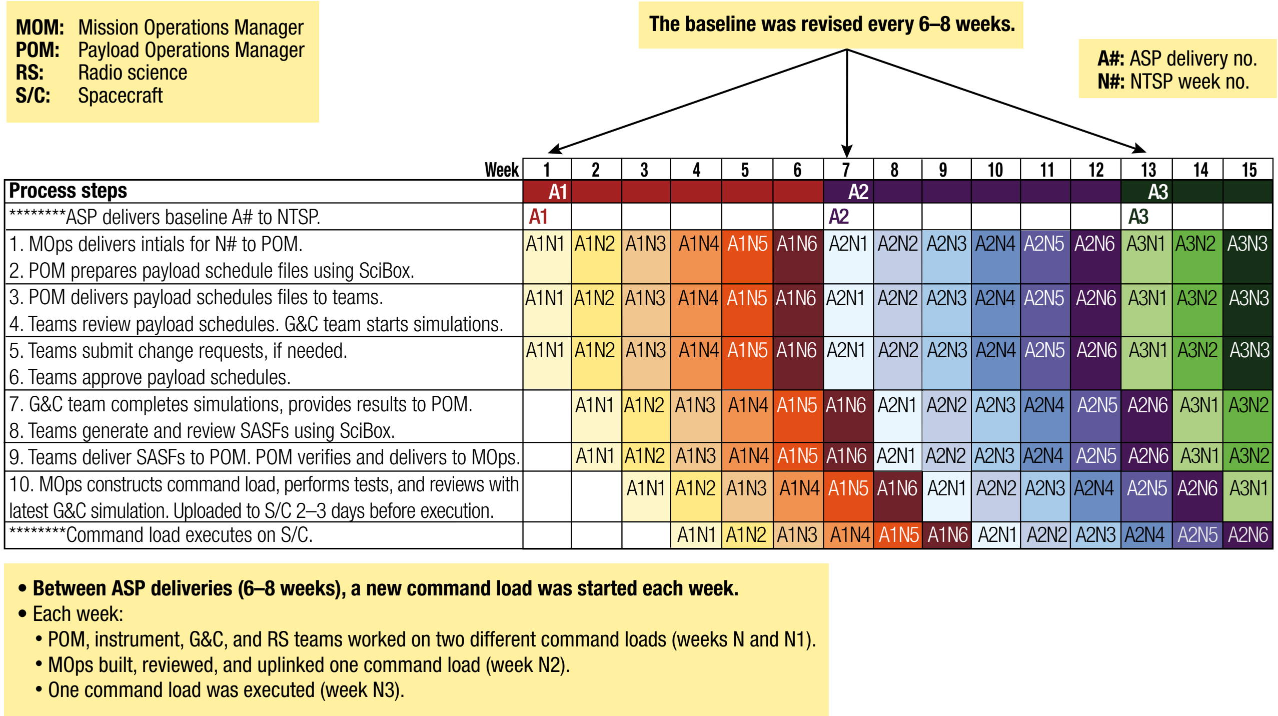
Because it generally took 3 weeks to complete the NTSP cycle for each weekly command load, the mission operations and science operations teams were, therefore, working on more than one command load at the same time (Fig. 3). For contingencies, special events, or holidays, the NTSP schedule could be compressed to ~2 weeks.

Both the ASP and NTSP activities were managed using the commercial web-based Atlassian JIRA tool. Projects were created in JIRA for both the ASP and NTSP workflows. This choice provided an easy mechanism for approvals, change requests, and configuration management of all necessary documents. JIRA also sends automated e-mails when workflow steps are completed, which ensured that all team members were kept up to date.

Refinement, Replanning, and the Acquisition Feedback Loop

A highly automated feedback process from the NTSP to the ASP ensured that the baseline plan accounted for, and automatically rescheduled, critical observations if there were any anomalies, missed observations, or new discoveries that required quick turnaround to update the baseline plan. Generally, very few manual interventions or computations were needed. SciBox, which automatically received feedback on observation status from the ACT REACT tool (described in the Science Data Pipeline section of this article), kept track of the overall planet coverage and replanned any missed or degraded images with high priority as needed (and without operator intervention).

Deviations from the baseline could also result from the loss of a DSN downlink track or an instrument anomaly (e.g., single-event upset). SciBox was used during the ASP phase to generate the baseline sched-



MOM: Mission Operations Manager
POM: Payload Operations Manager
RS: Radio science
S/C: Spacecraft

The baseline was revised every 6–8 weeks.

A#: ASP delivery no.
N#: NTSP week no.

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Process steps	A1						A2						A3		
********ASP delivers baseline A# to NTSP.	A1						A2						A3		
1. MOps delivers intials for N# to POM. 2. POM prepares payload schedule files using SciBox.	A1N1	A1N2	A1N3	A1N4	A1N5	A1N6	A2N1	A2N2	A2N3	A2N4	A2N5	A2N6	A3N1	A3N2	A3N3
3. POM delivers payload schedules files to teams. 4. Teams review payload schedules. G&C team starts simulations.	A1N1	A1N2	A1N3	A1N4	A1N5	A1N6	A2N1	A2N2	A2N3	A2N4	A2N5	A2N6	A3N1	A3N2	A3N3
5. Teams submit change requests, if needed. 6. Teams approve payload schedules.	A1N1	A1N2	A1N3	A1N4	A1N5	A1N6	A2N1	A2N2	A2N3	A2N4	A2N5	A2N6	A3N1	A3N2	A3N3
7. G&C team completes simulations, provides results to POM. 8. Teams generate and review SASFs using SciBox.		A1N1	A1N2	A1N3	A1N4	A1N5	A1N6	A2N1	A2N2	A2N3	A2N4	A2N5	A2N6	A3N1	A3N2
9. Teams deliver SASFs to POM. POM verifies and delivers to MOps.		A1N1	A1N2	A1N3	A1N4	A1N5	A1N6	A2N1	A2N2	A2N3	A2N4	A2N5	A2N6	A3N1	A3N2
10. MOps constructs command load, performs tests, and reviews with latest G&C simulation. Uploaded to S/C 2–3 days before execution.			A1N1	A1N2	A1N3	A1N4	A1N5	A1N6	A2N1	A2N2	A2N3	A2N4	A2N5	A2N6	A3N1
********Command load executes on S/C.				A1N1	A1N2	A1N3	A1N4	A1N5	A1N6	A2N1	A2N2	A2N3	A2N4	A2N5	A2N6

- **Between ASP deliveries (6–8 weeks), a new command load was started each week.**
- Each week:
  - POM, instrument, G&C, and RS teams worked on two different command loads (weeks N and N1).
  - MOps built, reviewed, and uplinked one command load (week N2).
  - One command load was executed (week N3).

Figure 3. Science planning pipeline.

ule as well as a set of reports and graphs on instrument coverage, SSR usage, and other information that allowed instrument team members to assess the ongoing success of their instrument's data collection. The flexibility built into SciBox allowed the POM or SciBox developers to designate certain events (e.g., loss of a downlink track) and quickly regenerate the baseline and reports so that the appropriate instrument and science team members could examine the impact of the event on mission success. A full examination of this type was performed well in advance of MOI in order to identify the most sensitive portions of the baseline plan. Early identification enabled the science and operation teams to devise contingency plans, such as arranging additional DSN support, modifying an instrument ConOps, or changing data rates (or other instrument parameters) for a certain period of time.

Contingency plans, once devised, could be incorporated into the baseline in the next ASP cycle (sometime within the next 5 weeks) or, for more pressing observations (e.g., the last optimal time to image a particular feature), immediately into the command sequence in the next NTSP cycle. In either case, the contingency plan would become part of the official new baseline. This rapid accommodation could not have been accomplished easily without the aid of an automated tool such as SciBox.

SciBox

The SciBox software library is a groundbreaking tool kit for the automated and optimized planning of operations derived on the basis of goals, priorities, and constraints. MESSENGER SciBox is a mission-specific implementation of that library[4,5] that was developed by APL early in the last decade. MESSENGER was the first mission for which SciBox was used to perform operations planning for the entire science payload, as well as pointing (G&C) and radio science (low-gain antenna selection, high-gain antenna selection, and downlink data rate). SciBox generated spacecraft commands consistent with the planning inputs provided by the team plus a full series of reports that allowed verification of the plan by mission and instrument scientists. MESSENGER SciBox also supported thermal analyses, DSN antenna selection requests, and other constraint checks to ensure the health and safety of the instruments and spacecraft, while also ensuring that the MESSENGER mission science goals were fully met. These achievements were enabled by a novel approach to mission planning that emphasized automated, quick-running analyses; treating the science mission and payload as a whole instead of focusing on individual instruments one at a time; and prioritizing health, safety, and resource maximization.

A New Approach to Mission Planning

The SciBox tool for MESSENGER incorporated scientific goals, historical data (e.g., imaging history), spacecraft location information, DSN schedule, and other relevant planning inputs. In less than 3 h, SciBox was able to generate a baseline plan for a year (or more) of spacecraft operations and a series of full reports for each instrument that described the science obtained as a result of that plan (e.g., image footprints on both sinusoidal and cylindrical projections). This significant improvement in turnaround over the manual cruise planning approach made it possible for the MESSENGER team to readily maintain the baseline plan and create weekly command sequences that encompassed the equivalent of 14 Mercury flybys.

Reflecting the dual science planning cycle (described in the Science Planning Pipeline section of this article), scientist interaction with SciBox occurred on two distinct levels. In ASP, performed every 6–8 weeks throughout the orbital phase of the mission, instrument and mission scientists would evaluate and alter science priorities and feed that information into SciBox. The SciBox capability to adjust priorities was very powerful in supporting the evolution of the planned science over the mission as new discoveries were made or goals were met (e.g., the completion of the imaging of a given target). Weekly near-term planning involved the scientists on a very minimal level compared with typical manual planning methodologies. Although some command-intensive instruments such as the imager still required review, SciBox was able to validate command sequences before the schedule reached the sequencer for that instrument. SciBox also provided support for dynamic, flexible inputs that allowed members of the SciBox planning team to respond to scientists' near-real-time requests that did not fall in the realm of ASP, allowing the specification of imaging compression parameters, orbit selection for certain instrument schedulers (which dictated when that instrument would obtain data), resolution for spectrometers, and much more.

Performing the science planning for all of the MESSENGER instruments simultaneously was very beneficial to the mission; using SciBox to investigate all of the possible opportunities for a set of science observations that adhered to the team's agreed-upon set of science priorities allowed each instrument's science to be maximized each week. This cross-payload optimization eliminated the great majority of "horse-trading" meetings that occur on most missions in order to attempt to meet all of the objectives of individual instrument teams, usually at the cost of suboptimal planning and resource usage overall. This science planning approach also allowed automated checking of both instrument and spacecraft constraints, which eliminated an entire subset of the opportunity space, allowing for a more optimized and safe instrument command sequence.

Treating the system as a whole also facilitated SciBox analysis of other "big picture" considerations such as command count (which was vital during superior solar conjunctions when uplink availability was constrained and smaller command sequences were required), SSR usage (which, in turn, dictated the desired DSN schedule as well as future imaging plans), and pointing information used in analyses by the thermal team (because SciBox was aware of all science pointing performed by the spacecraft).

How MESSENGER SciBox Enabled a Successful Mission

Three focus areas for SciBox enabled key activities during the mission that greatly facilitated mission success: automation, treating the payload as a whole, and focusing on health and safety.

Although the SciBox-generated command sequences were central and vital to enabling the spacecraft and instruments to acquire the data that were necessary to fulfill the mission requirements, team members could not easily discern from the command sequences directly how well those commands satisfied the goals of the mission. Therefore, the SciBox team developed several ways to visually represent the results of the commands in order to help the science team verify that the mission goals would be satisfied. For example, a 3-D viewer that showed the MESSENGER spacecraft and its orientation in space, as well as views from the various boresights (and the instrument fields of view), allowed developers and instrument scientists to ensure that the spacecraft was pointed as desired for a given observation. Once a baseline plan was generated, a set of reports was made available for review. A novel plotting technique was used to show the pointing control of the spacecraft (Fig. 4) and allowed for the quick review of months of orbital operations. Plots showing, for example, predicted and downlinked image footprints, planned laser altimetry tracks, and planned spectrometer footprints were among the many reports used to validate the baseline plan well in advance of execution of the corresponding commands on the spacecraft. Figure 5 shows SciBox plots of the coverage for the Mercury Dual Imaging System (MDIS) eight-color images planned and acquired during the primary orbital mission. This example illustrates the ability of the SciBox tool to track data acquisition and adjust the baseline plan accordingly. The map produced from these images (Fig. 5, bottom) is shown in ACT REACT and QuickMap.

The creation and use of SciBox as an automated baseline strategy and command sequence generation tool was vital in keeping the SciBox development team and the payload operations team small. Over the course of the mission, no more than five developers worked on MESSENGER SciBox at any given time, and some of those individuals were not full time on that effort. With guidance from the SciBox team, the POM and the assistant POM ran the command sequence generation each week. The flexibility in both the SciBox code architecture and the highly parameterized inputs allowed the system to be updated on both long-term (advanced science) and weekly (near-term) planning cycles, with a minimal but tightly integrated connection to the science team. The ability to modify planning parameters quickly and rerun a simulation for review enabled a greater level of optimization of the sequence very late in the planning process.

In November 2011, MESSENGER was awarded an extended mission (XM), and the science team wanted to investigate alternative science goals during that new phase of the mission. Among the ideas suggested was the transition of the spacecraft's trajectory from a 12-h orbit to an

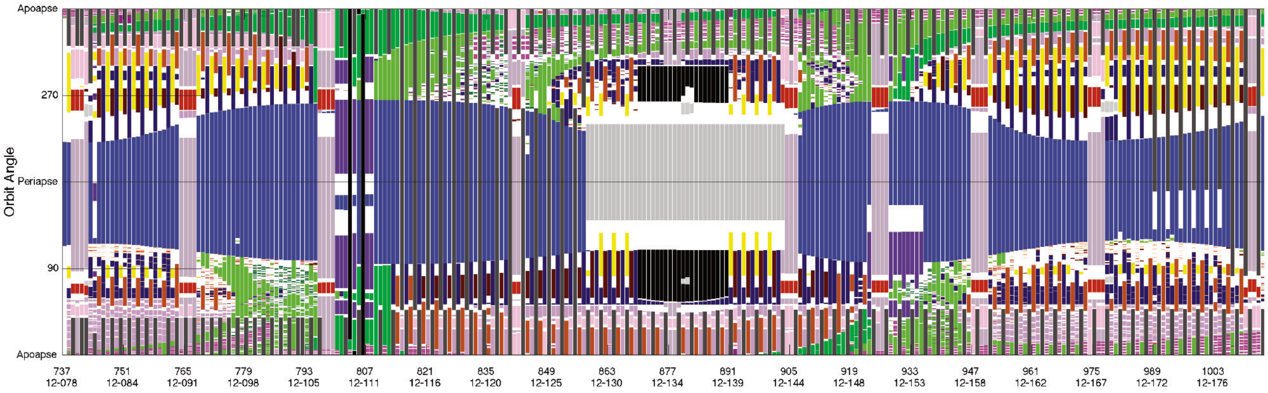
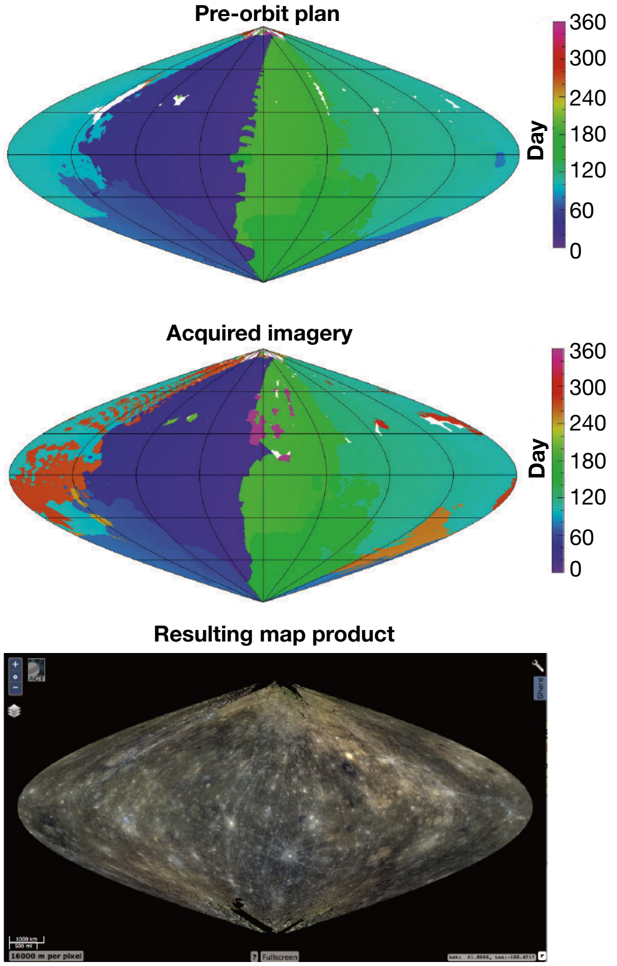


Figure 4. A G&C activity plot for approximately the first 100 days of MESSENGER's first extended mission (XM). Orbit number and day of year are on the abscissa, and the ordinate follows the path of the spacecraft from apoapsis to apoapsis on a full orbit. Because of the difference in ground speed at apoapsis versus periapsis, time is not constant along the ordinate; rather, it is stretched near periapsis and compressed near apoapsis. The colored sections within each orbit column represent activity for a particular instrument. For example, the dark blue near periapsis shows control of the pointing by the Mercury Laser Altimeter instrument, the dark gray near apoapsis signifies downlink pointing, and the various shades of pink and purple around apoapsis at the bottom of the plot show pointing by the Mercury Atmospheric and Surface Composition Spectrometer instrument. Places without color (white spaces) represent spacecraft slewing. This bird's-eye view of the G&C allowed instrument scientists to ensure that their instrument was acquiring observations for the required time not only during each orbit but also during each season as local time at periapsis evolved and Mercury completed its orbit about the Sun.

8-h orbit (see Gold et al., this issue). The SciBox team was tasked with analyzing the XM science return for a nominal 12-h orbit and comparing that return with that obtained from three different 8-h orbit trajectories. The automation and flexible input capabilities of SciBox and the ability to run the SciBox software processes on a distributed, cluster-based hardware server system allowed the SciBox team to configure and run all four scenarios over a weekend. The full reports were made available to the science team for review the following workweek. Armed with this information, the science team was able to determine that an 8-h orbit was no worse (and in some cases better) than a 12-h orbit with respect to the refined XM science goals, and the 8-h orbit was recommended to MESSENGER project management and ultimately adopted.


Pre-orbit plan

Acquired imagery

Resulting map product

Figure 5. SciBox support for data acquisition and resulting science products. Top, SciBox baseline plan for MESSENGER primary mission color imaging. Color as denoted in the key indicates the day of the 1-year primary mission that imagery at the corresponding location was expected to be acquired. Middle, SciBox plot of acquired color images at the end of the MESSENGER primary mission. SciBox supported the tracking of acquired data and adjusted when images would be acquired in the baseline plan in response to changes in operations and priorities to ensure meeting science goals. Bottom, The successful acquisition of color images for the MESSENGER mission made possible the creation of a global eight-color map, viewed here in ACT's REACT and QuickMap tools. This and other products created from the MESSENGER data supported the MESSENGER team in their investigations and have been made available to the public via the PDS.

Later, during a second extended mission (XM2), it became increasingly vital to monitor temperatures on both the spacecraft and the instruments because MESSENGER's orbit evolution and lowering periapsis altitude made the natural high-temperature seasons increasingly pronounced. SciBox's knowledge of the spacecraft and instrument pointing, which was derived during each weekly planning execution, made it a prime candidate to make a zeroth-order analysis of the thermal conditions on the spacecraft. With the aid of members of MESSENGER's thermal design team, a medium-fidelity thermal model was incorporated into the SciBox codebase that allowed a thermal analysis to be added to the set of final reports produced with each run of the software. Weekly and remainder-of-mission plots were made available for each of the primary axes of the spacecraft, and thermal limits were indicated on those plots. During early SciBox runs each week, members of the SciBox planning team were able to identify potential trouble areas in the thermal profiles and send pointing information for that time to the thermal team for further analysis. If needed, parameters could then be adjusted in time for the final weekly run in order to produce a thermally acceptable planning schedule for that week.

Throughout the mission, modeling of resources such as SSR space and command count was paramount because the availability of or limits on those resources (or the ability to increase the availability of or limits on those resources) varied throughout the mission. SciBox's holistic approach to modeling the payload enabled reviewers to gain a snapshot of both the SSR and command-count volume each week, as well as a forecast of those resources until the end of the mission. Translation of the science goals into actionable instrument commands allowed SciBox to estimate both the SSR volume for a given command as well as the associated command volume. SSR volume could then be modeled against the expected downlink rate (a product of the DSN schedule and rate-stepping estimates) to predict the SSR volume at any given time. Command-count estimates could be compared with the estimated weekly load volume provided by the mission operations team and, if needed, adjustments to the planned science for that week could be made before schedules were released to the science team for review.

ONBOARD PAYLOAD DATA COLLECTION

Several aspects of the data collection and downlink system implemented in the MESSENGER main processor flight software on board the spacecraft were new to APL and enhanced the management and downlink of the science data. The use of a file system to store data on the MESSENGER spacecraft enabled a correspondence between the data files stored on the spacecraft and the ground and allowed the team to better organize their data. The file filter table (FFT) gave the team control over the routing of data types to files in the system. A priority system was used to ensure that the most critical data were downlinked to the ground first. In addition, the CCSDS (Consultative Committee for Space Data Systems) file delivery protocol (CFDP) was used by the software on the spacecraft and the ground to manage file downlink and automatically retransmit data that were not properly received on the ground. These approaches were significant for ensuring that the most important science data had priority for downlink and were managed efficiently. The operation of the system also lent predictability and timeliness to the data downlink and made it easier for the science teams to track their data status.

The file system on the MESSENGER spacecraft was very similar to any file system on a PC. The files were stored in specific directories organized by downlink priority (Fig. 6) to ensure that the most critical data were downlinked first. Files were closed and new files were opened nominally once per day to keep files sizes small for faster playback. Files could be promoted (moved to a higher-priority directory) or demoted (moved to a lower-priority directory or the /TRASH directory). Mission operations ground software tools supported predictions of the files created on the spacecraft to allow tracking of the downlink and receipt of those files in the SOC.

The FFT was a tabular structure with commandable entries used by the flight software to route data from the spacecraft subsystems and instruments to these onboard files. The FFT supported routing each data type to up to two files with commandable priority and a portion of the data of that type routed to each file; this procedure allowed for a small subset of data to be given high priority to support spacecraft health and safety, or data-quality concerns, while the larger data set would be given lower priority. The FFT evolved over the course of the mission, with major changes occurring at the point of transitioning to the orbital mission phase and late in orbital operations.

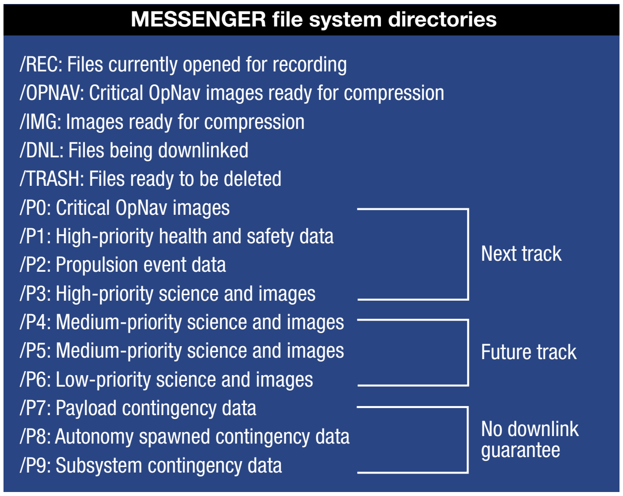


Figure 6. Spacecraft file system priorities.

The MESSENGER onboard file system and downlink flight software supported 10 priority levels from P0 (highest) to P9 (lowest). Files in the higher-priority directories were downlinked first (older files first within the same priority directory). The files were created and sized with the goal of ensuring that files with priority P0–P3 would be downlinked. Many SSR playbacks also resulted in the download of many lower-priority files as well. Priority P7–P9 files were not guaranteed to be downlinked; they were used to troubleshoot problems by being promoted to higher-priority directories as needed. Most of these lower-priority files were never downlinked and were deleted to recover SSR memory space for new data.

The flight and ground software elements of the CFDP system supported the downlink process in two ways. The first was the CFDP priority system (distinct from the MESSENGER onboard file priorities) for which there were two priority levels, 0 and 1 (0 was high priority). CFDP priority 0 was assigned to the priority P0 and P1 files as designated by the MESSENGER onboard file system. CFDP priority 1 was assigned to priority P2–P9 files as designated by the MESSENGER onboard file system. Anytime a CFDP priority 0 file became eligible for playback while downlinking a CFDP priority 1 file, the current playback would be paused. The CFDP priority 0 file would start and complete playback before resuming the playback of the CFDP priority 1 file. This hierarchy allowed important data such as critical optical navigation images and propulsive event data to be played back as soon as possible.

The second feature of the CFDP system allowed for automatic retransmission of data to the ground that had failed on the previous transmission. Handshaking communications between the flight and the ground CFDP software elements, including the use of "ACK" and "NAK" messages (to indicate successful and unsuccessful receipt of data on the ground, respectively), were used to facilitate the retransmission of portions of files with transmission errors. This automated system allowed the science teams to receive their science data more quickly and required little intervention by mission operations.

SCIENCE DATA PIPELINE

The MESSENGER science data pipeline was designed to have a flexible architecture for the timely support of the evolving and emerging needs for the following tasks:

- Downlinked data ingestion, management, access, analysis, and archiving
- Mission planning and science objectives validation
- Instrument performance monitoring

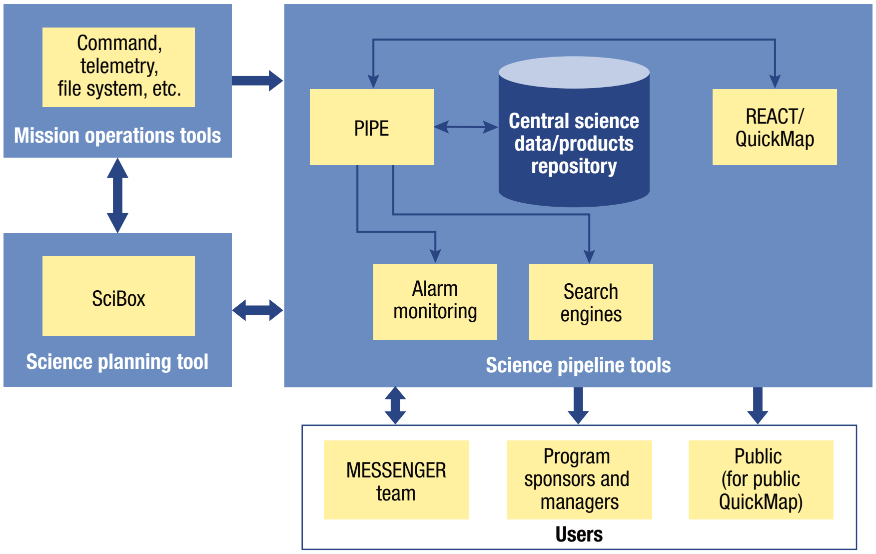


Figure 7. Science pipeline tool interfaces.

Part of the MESSENGER SOC ground facility, the pipeline was designed and built by ACT Corporation for the MESSENGER mission, based on ACT's PIPE, REACT, and QuickMap tools, in order to support science team members, analysts, program managers, and the public.

The contributions to the MESSENGER mission and the innovations of the science data pipeline, detailed below, include timely, convenient access to a large, centralized repository of the full-mission science data and products; powerful, sophisticated, science-enabling tools; the ability to accommodate large increases in data volumes and reprocessing requirements with mission extensions; the ability to exceed requirements and expectations and accommodate new requirements; and cost savings.

The MESSENGER science pipeline tools were integrated with each other and interfaced with the MESSENGER SciBox planning tool, as illustrated in Fig. 7. PIPE orchestrated science data product generation using SQL databases to manage telemetry processing and product generation and an image-processing engine. PIPE automatically created core science products and ingested other externally produced instrument-team products, thus maintaining a centralized repository for MESSENGER science data and products. During orbital operations, the alarm-monitoring tool provided timely notifications to instrument team members regarding conditions that may have needed to be addressed through instrument configurations to ensure performance and safety. Interactive search engines supported query retrieval of core instrument products from the central science data repository based on user-selectable combinations of acquisition time and other observation parameters. The sophisticated, multi-data-layer analysis and visualization REACT tool interacted with PIPE, served as a powerful analysis and data-validation tool for the MESSENGER team, supported identification of targeted observations of interest, and supplied information on the targeted observations as well as validation feedback for those targeted observations to SciBox. QuickMap is a powerful and easy-to-use web tool for the interactive visualization of map products. QuickMap accesses, combines, and creates visualizations and status views of data from PIPE and REACT to serve the MESSENGER team, upper-level management, and the public.

The highly automated science pipeline supported generation and interactive serving of more than 150 different products to the science team and project management. The high degree of automation was necessary to meet performance monitoring requirements and team expectations for the turnaround of science products from downlinked telemetry during operations and also to make possible the large-scale reprocessing of data for PDS deliveries, especially as the volumes of data grew with mission extensions. The degree of automation also made it possible for ACT to manage the science pipeline with a small team.

Incoming telemetry data were processed and products were made available to the MESSENGER team in near-real time (within 1–2 h) during the active mission, supporting the required quick turnaround for instrument performance monitoring and rapid initial science data evaluation. Pipeline processing priorities were easily configurable to promote the generation of specific instrument products as needed during incoming telemetry processing or product reprocessing. As a result of the management of data on the spacecraft, the telemetry containing the data for individual product instances would sometimes not be fully downlinked for months. The PIPE architecture was designed to accommodate that delay, providing partial products for team analysis before their full download.

Having all the science data and products available in one location greatly benefits team access, collaboration, archiving efforts, and data backup and longevity. These data and the science pipeline tool user interfaces were conveniently accessible to the team via the main MESSENGER SOC webpage. Also accessible through this webpage was an area for large file sharing that was added after the primary mission and greatly facilitated team sharing and collaboration.

QuickMap support for interactive, merged data query and visualization greatly enabled the MESSENGER science team's access to progress on the acquisition of

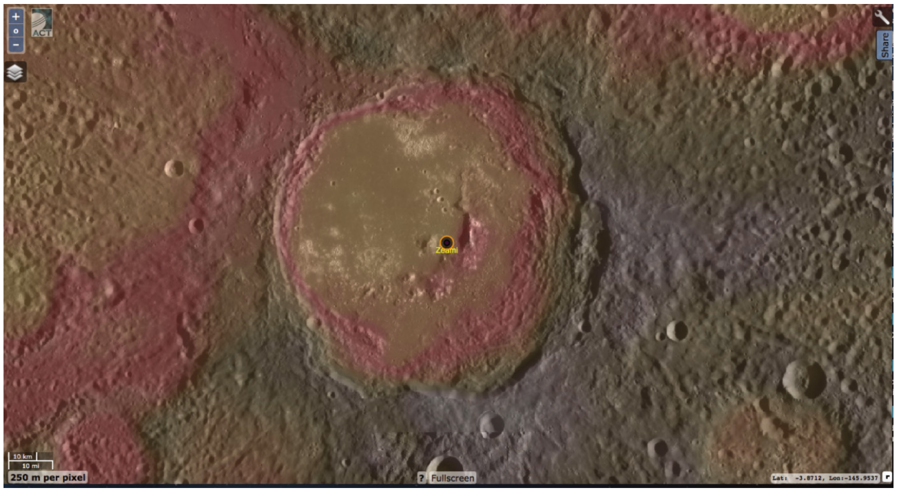


Figure 8. Using QuickMap to explore Mercury hollows in Zeami impact basin. QuickMap supports feature location, simultaneous viewing of data layers, and 3-D views.

key data products. Mapping and correlation of multi-instrument data sets that would be very difficult and labor intensive with standard tools are effortless to the user and instantaneous with QuickMap. This tool greatly increased the possibilities for exploration and discovery by the instrument teams. For the MESSENGER MDIS team, it greatly enhanced the exploration of local Mercury features, facilitating the discovery of hollows and volcanic features on Mercury. It also provided a valuable global perspective on these features and the ability to correlate MDIS data with MESSENGER spectral and altimeter data in a consistent registration. Figure 8 illustrates the power of QuickMap to explore the hollows in the Zeami impact basin, leveraging the QuickMap feature location capability, the simultaneous viewing of data layers (MDIS monochrome base map and color-coded digital elevation model data in this example), and the 3-D visualization tool.

Products and tools that are made public benefit from the validation that results from being core team products and tools. The science pipeline automatically created products in PDS-compliant formats, and team use of those as their primary analysis products provided a valuable part of their validation before their delivery to the PDS. Likewise, the team version of the ACT REACT and QuickMap tools benefited from extensive team use and was the basis for the public version.

Meeting requirements, accommodating team expectations for product turnaround and PDS delivery milestones, and increases in estimated data volumes drove the design of the science pipeline and many behind-the-scenes activities. Facilities expansion and upgrades made in preparation for the primary orbital mission and with each mission extension were important to maintaining pipeline performance and reliability. These upgrades and the scalability of the PIPE architecture allowed the science pipeline to keep up with the ever-increasing data volumes and number of products over the mission. The PIPE software was instrumented for MESSENGER to support benchmarking individual processing tasks and large-scale stress tests to gauge performance for the full suite of instruments under high operational loads and to anticipate and predict performance and turnaround for the science team. With the information from these tests, ACT was able to do targeted optimizations to the PIPE software to strategically improve performance and throughput.

The ability to accommodate new science pipeline requirements and adapt to emerging needs was key as science priorities and objectives evolved over the course of the mission. Examples of capabilities that were added after the primary mission include science objective metrics and visualizations that greatly facilitated assessment and reporting of science objective status, support for multiple versions of products for rapid team evaluation, QuickMap and related tools for the public and for education and public outreach, and the quick injection of data processing algorithms into the pipeline in three dimensions for final products.

SCIENCE DATA ARCHIVING

Archiving MESSENGER data to the PDS ensures that the scientific community, educators, and the general public have long-term access to the wealth of MESSENGER data from cruise, flybys, and more than 4 years of Mercury orbital operations. Data for the PDS were painstakingly prepared, documented, and validated by scientists and engineers with the benefit of intimate knowledge of instrument design and operation. Figure 9 shows the tools and teams supporting MESSENGER PDS deliveries.

The contributions to the MESSENGER mission and the innovations in the science data archiving, detailed below, are many. The team had a track record of timely PDS deliveries of high-quality products that benefited MESSENGER, the PDS, and the public. The set of products originally promised for delivery was expanded. The delivery approach was well thought-out, coordinated, communicated, and executed. The approach contributed greatly to the success of the deliveries, was praised by PDS management, and reduced the effort required of the MESSENGER science team members to prepare the deliveries, allowing them to focus more of their time on the analysis of their data.[6]

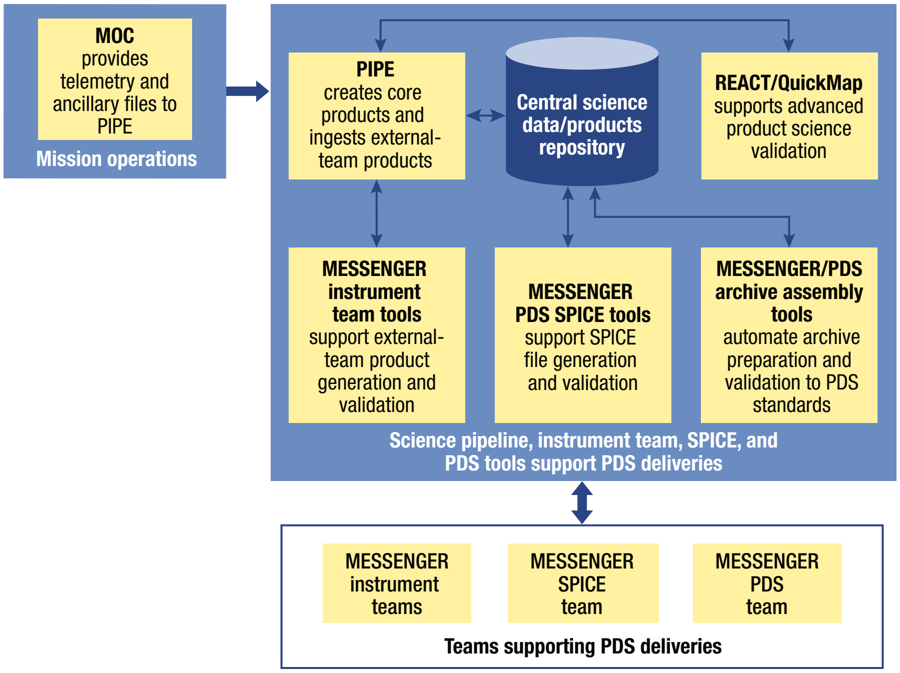


Figure 9. Tools and teams supporting MESSENGER PDS deliveries. MOC, Mission Operations Center.

With its final delivery of data products in May 2017, MESSENGER completed a total of 16 deliveries to the PDS. This delivery count expanded from an original nine deliveries planned for the primary mission and included nearly 200 product types and >10 TB of data. Before orbit insertion, PDS deliveries were timed to mission events such as planetary flybys. After orbit insertion and through XM2, deliveries were made every 6 months, and the final delivery was made at the end of the final mission extension in May 2017. Initiating the delivery of raw and calibrated products (with initial calibrations completed from data acquired during the three Mercury flybys) before the start of orbital operations gave the team a considerable advantage in completing the time-consuming product definition, documentation, and PDS peer-review process. With those activities complete for the majority of products to be delivered, mission teams were free after orbit insertion to focus more fully on the intense orbital operations period and the development of the advanced products from the primary mission. These products included global maps that required additional Mercury data and were first delivered to the PDS 1 year after the end of the primary mission. With each mission extension, additional advanced products, notably additional map and digital elevation model products, were added to the deliveries to the PDS. The final two deliveries (15 and 16) included the regeneration of previously delivered calibrated and advanced products for the mission with final calibrations and geometry. Not only do these important deliveries meet MESSENGER's contractual obligation, but their quality and timeliness were considered favorably by NASA in the evaluation of proposals for MESSENGER's mission extensions.

The resources and coordination to complete PDS deliveries are considerable and beyond the baseline efforts of the instrument teams to monitor and analyze their data. MESSENGER management support was critical to the success of the PDS deliveries. This support was shown through their messages to the team about the importance of archiving, their allocation of resources to the effort, their support for the team organization needed for the deliveries, and their prioritization of issues that arose during the effort. A single team coordinated the PDS deliveries for the seven MESSENGER instruments and the radio science experiment, and the lead for that effort reported directly to the MESSENGER project manager. This approach empowered the lead to work with all of the data producers in accomplishing the deliveries. The planning and scheduling approach established over the course of the MESSENGER PDS deliveries was key to their success. The PDS considered MESSENGER PDS deliveries a model for other missions.

The MESSENGER approach to PDS deliveries emphasized on-time deliveries of high-quality products and documentation with attention to product consistency. Contributing factors to the timeliness and quality of deliveries were planning of and early starts to required peer reviews and delivery activities, phasing deliveries and including margin in schedules, tracking of issues from previous deliveries to ensure they were addressed in later deliveries, and thorough validation at multiple levels by multiple teams (addressing scientific validity and PDS compliance) before delivery to the PDS.

Timely and clear communication with the distributed MESSENGER team and the six distributed PDS nodes supporting MESSENGER was extremely important to the success of data deliveries. To be effective, communications needed to convey plans, timelines, responsibilities, status, and changes in plans when they occurred. Communications had to occur early and regularly and needed to be reinforced.

That a centralized PDS team coordinated and assembled data products for deliveries to PDS enhanced the consistency and timeliness of the deliveries and relieved science team members from needing to have knowledge of detailed PDS requirements, allowing them to focus more of their time on science.

The quality of the navigation, orientation, and other ancillary products created by the MESSENGER team for use in science product generation directly impacted the quality of those science products. For this reason, creators of these ancillary products, including the navigation, mission design, mission operations, instrument, and geophysics teams, as well as specialists in designing, developing, and validating those products, put in substantial effort, with multiple iterations of development, test, and review. Spacecraft star calibrations were used to improve models over the course of the mission. Updates to the Mercury coordinate system were also implemented with resulting improvements to the products created with the updated coordinate system. In addition, the navigation team reduced the error in their final spacecraft ephemeris reconstruction. Use of the SPICE (Spacecraft ephemeris, Planet/satellite ephemeris, Instrument information, Camera orientation, Event information) formats for these ancillary products allowed the team and other users to leverage the PDS SPICE tool kit that supports projects in preparing and using these products.

Coordination with the mission operations and engineering teams on acquisition and interpretation of science and spacecraft data was key to timely data inclusion in deliveries and product accuracy. Adaptations needed to be made around the time of conjunctions when downlink was delayed and nominal science processing timelines were adjusted to ensure product completeness and accuracy. The planned spacecraft clock reset in January 2013 required the addition of explicit clock partition numbers to PDS products and corresponding changes to pipeline and external team processing to avoid ambiguity because of the discontinuity in clock times after the reset.

Building on the experience and success of the earlier PDS deliveries, PDS delivery 15 was the most significant for the mission because of the volume of the delivery; the reprocessing and finalization of products and documentation for the mission; the inclusion of new products, including new digital elevation model products, in the delivery; the incorporation of a global digital elevation model in the generation of key advanced products; and the longer timeline, additional effort, and greater care required to complete it successfully. Planning and efforts for delivery 15 started more than 2 years ahead of its May 2016 release to the public and included a lengthy PDS peer review of the improvements to the Mercury coordinate system and early PDS validation of final SPICE kernels used to generate the delivery products.

CONCLUSION

MESSENGER was a groundbreaking mission to a harsh, not yet fully explored environment. Meeting the mission's science success criteria, under severe operating constraints, required a focused, integrated, and flexible operating plan that spanned the full mission. Building on the proven history of successful APL mission operations, the MESSENGER team applied innovative changes to its processes and tools to ensure a flexible plan that not only met mission success criteria but also allowed for quick modifications in response to operational challenges, contingencies, and discoveries. The two-tiered planning and scheduling approach maximized science return and provided a robust review system to minimize operational risks. MESSENGER SciBox provided a novel approach to mission planning for the mission. Treating the payload, and its associated science goals, as a whole, a highly customizable and automated process optimized the overall science strategy and weekly instrument commanding while limiting resource usage and keeping instrument and spacecraft health and safety as high priorities.

The MESSENGER SOC provided centralized management for the downlinked science data with powerful, interactive tools, including ACT's REACT and QuickMap, to support the team in data analysis as well as validation of mission planning and science objectives.

Thanks to the MESSENGER planning, spacecraft, instrument, science, and ground approaches; teams; and tools, the Mercury data acquired by the MESSENGER mission far exceeded original expectations. This success led to many exciting discoveries and the completion of 16 deliveries of MESSENGER data products to the PDS, including >10 TB of data, thus ensuring long-term access to those data by the scientific community, educators, and the general public in support of future investigations of Mercury.

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