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MESSENGER SciBox, An Automated Closed-Loop Science Planning and Commanding System

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MESSENGER SciBox is an automated closed-loop planning and commanding system used to optimize orbital science operations for the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission. The system plans all science observations for the seven science instruments on the spacecraft and also automatically generates the command sequences that drive the instruments, the guidance and control system, the solid-state recorder, the solar panels, and the radio-frequency communication system. MESSENGER SciBox interacts with the instrument scientists, mission operations team, downlink processing system, and mission design engineers to form a closed-loop system. In orbital operation, the systems employ a feedback loop, with a one-week time step, to improve the system performance. Feedback inputs are used to predict observational performance, to track all science observations, to avoid planning redundant tasks, and to recover from operational anomalies. The software tool is automated because the entire process, from ingesting the feedback inputs to creating the spacecraft and instruments commands, can function without manual interaction.

I. Introduction

Science operation centers for most space missions generally consist of two components: the uplink system and the downlink system. The uplink system deals with planning and scheduling of science observations, whereas the downlink system deals with the processing of observations returned from the spacecraft. Traditionally, the planning and scheduling of science observations, and the creation of associated spacecraft and instrument commands for science operation, are so time-consuming and labor-intensive that little time is left for the planning team to have close interactions with the data processing team. Any such interactions tend to be ad hoc and informal. On some missions, the two subsystems are so decoupled that they are even housed in different institutions and on separate networks. The lack of tightly coupled interaction frequently results in inefficient use of resources and a less-than-optimum operational schedule.

In this paper we describe an automated planning and commanding system that uses a closed-loop iterative process to continuously refine the science operation schedule and to generate spacecraft and instrument commands for uploading to a spacecraft. The planning system iteratively interacts with the instrument scientists, mission operations center personnel, mission design team, and downlink processing system to produce a science-observation-packed operational schedule and to improve the precision of planned operations. The process of ingesting feedback information from the downlink system to the generation of spacecraft and instrument commands for uplink is completely automated. This closed-loop architecture has been implemented as part of science operations for the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft now in orbit about Mercury, and it has allowed the MESSENGER team to maximize scientific return for the community with a relatively small operational staff. The closed-loop architecture and its application to MESSENGER orbital operations are the focus of this paper.

II. The MESSENGER Mission

NASA's MESSENGER[1,2] spacecraft was launched on 3 August 2004. On 18 March 2011, MESSENGER entered into a non-Sun-synchronous, highly eccentric 200- × 15,200-km-altitude orbit with an inclination of 82.5° and a period of approximately 12 hours. MESSENGER's mission is to address the following scientific questions:

1. What planetary formational processes led to the high ratio of metal to silicate in Mercury?
2. What is the geological 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 govern the measurement objectives shown in Table 1, which are addressed by a payload consisting of seven instruments plus a radio science investigation. The seven instruments[3] are the Mercury Dual Imaging System (MDIS), with wide-angle and narrow-angle cameras for imaging Mercury's surface; a Gamma-Ray and Neutron Spectrometer (GRNS) and an X-Ray Spectrometer (XRS) for remote geochemical mapping; a Magnetometer (MAG) to measure the planetary magnetic field; a Mercury Laser Altimeter (MLA) to measure surface topography and planetary shape; the Mercury Atmospheric and Surface Composition Spectrometer (MASCS), combining an Ultraviolet and Visible Spectrometer (UVVS) with a Visible and Infrared Spectrograph (VIRS) to make high-resolution spectral measurements of the surface and to survey the structure and composition of Mercury's tenuous neutral exosphere; and an Energetic Particle and Plasma Spectrometer (EPPS) to characterize the charged particle and plasma environment of Mercury.

These instruments are mounted behind a sunshade that protects the spacecraft from intense insolation. As MESSENGER orbits Mercury, the Guidance and Control (G&C) system must keep the spacecraft attitude within Sun keep-in (SKI) and hot pole keep-out (HPKO) limits, an attitude range which ensures that spacecraft components and instruments are never directly illuminated by the Sun, and that sensitive components are not exposed to thermal radiation from the hottest part of the planet.

Science data are first stored on an 8-gigabit solid-state recorder (SSR) before being downloaded to the Science Operations Center (SOC) at the Johns Hopkins University Applied Physics Laboratory through NASA's Deep Space Network (DSN), using either of two electronically steerable, high-gain, phased-array antennas (PAAs). The two PAAs are mounted on opposite sides of the spacecraft and can be steered electronically by ±60°. Using both the PAAs and the G&C system, MESSENGER's antenna beam can be oriented to downlink data to DSN throughout the year except during superior solar conjunction, during which the MESSENGER-DSN link is blocked by the Sun.

Table 1. MESSENGER Science Observation Activities

Observation	Measurement requirements and relevant instrument/investigation
Global surface mapping	Monochrome imaging, ≥90% coverage, ≤250-m average resolution for morphology: MDIS Multispectral imaging, ≥90% coverage, ≤2 km/pixel average resolution for mineralogy: MDIS Stereoscopic imaging, ≥80% coverage for global topography: MDIS Elemental abundance determination: GRNS, XRS High-resolution spectral measurements of geological units for mineralogy: VIRS
Northern hemisphere and polar region observations	Northern hemisphere topography, obliquity, and libration amplitude measurements: MLA Composition of polar deposits: GRNS Polar ionized species measurement for volatile identification: EPPS Polar exosphere measurement for volatile identification: UVVS
Magnetosphere observations	Mapping magnetic field to characterize the internally generated field: MAG Determining magnetospheric structure, plasma pressure distributions, dynamics: MAG, EPPS Solar wind pick-up ions to understand volatiles: EPPS
Exosphere survey	Neutral species in exosphere to understand volatiles: UVVS
Region-of-interest targeting	High-resolution imaging, spectroscopy, and stereo of key regions: MDIS, VIRS, UVVS Photometric measurements to determine surface texture, process color images: MDIS
Radio science measurements	Gravity field determination to characterize internal structure (in combination with topography and libration): RS

III. The Orbital Operational Challenges

During MESSENGER's one-year orbital mission phase, the science operations team faces several challenges in planning and scheduling MESSENGER science observations. MESSENGER's science measurement objectives are ambitious and frequently compete with each other for resources such as power, pointing, and available SSR space. All of these measurements must be scheduled without violating spacecraft operational constraints. Specific constraints include spacecraft pointing restrictions to ensure thermal safety of the spacecraft, correspondingly limited opportunities to view the planetary surface, variable available downlink volume due to Earth-Mercury distance variations and solar conjunctions, and a consequently varying load on the SSR.

Beyond the challenge of operating with limited resources in a highly constrained environment, the global mapping measurement objectives and the regions of interest for high-resolution targeted observations require a large number of highly coordinated observations. The planning team faces the daunting task of tracking and coordinating more than 70,000 imaging observations and more than 2,700 high-resolution targeted observations during the one-year orbital phase.

IV. Approach

The MESSENGER team's approach to solving the orbital challenge was to develop MESSENGER SciBox, an automated, integrated planning and commanding system[4,5]. MESSENGER SciBox is a goal-based planning system that uses the SciBox library[6], a generic science-planning software library that contains a suite of packages for modeling the space environment and visualizing spacecraft operations. Goal-based planning and commanding systems using SciBox have been successfully employed for the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM)[7] instrument on the Mars Reconnaissance Orbiter (MRO) and the Miniature Radio Frequency (MiniRF)[8] instruments onboard Chandrayaan-1 and the Lunar Reconnaissance Orbiter (LRO). Goal-based planning systems decouple science planning from command generation and allow scientists to focus on science-observation opportunity analysis instead of commanding details.

MESSENGER SciBox was designed to represent accurately the spacecraft operational constraints, mission operations activities, instrument data generation, and data storage and downlink. It can be used to simulate all orbital-phase observations. MESSENGER SciBox was designed to support two functions. Prior to the mission orbital phase, it was used to develop an optimized observation strategy that would meet the science measurement objectives. Hundreds of MESSENGER SciBox simulations were performed to analyze observation strategy trade-offs. During the orbital mission phase, MESSENGER SciBox is being used as the operational science planning and commanding tool. It schedules the science observations and generates the commands for all the instruments, the G&C system, and the radio-frequency (RF) system.

From its initial concept, MESSENGER SciBox was envisioned as an integrated part of the MESSENGER Science Operations Center (SOC) during orbital operations. It was designed to be used by scientists iteratively to plan the science observations and also to interface with the Planetary Information Processing Environment (PIPE), the downlink data-processing software, to form an automated closed-loop system to track the large number of observations. During orbital operations exercises prior to Mercury orbit insertion, it was observed that some of the outputs produced by MESSENGER SciBox helped the mission design engineers improve the modeling of the spacecraft orbit and helped mission operations engineers in coordinating with DSN stations. The closed-loop architecture was therefore extended to include the mission design team and the Mission Operations Center (MOC).

V. Closed-Loop Architecture

The closed-loop interactions between MESSENGER SciBox and the scientists, PIPE, the MOC, and mission design engineers are illustrated in Figure 1. The process begins with the scientists, who frequently use the full mission simulation capability of MESSENGER SciBox to analyze the effect of changing simulation parameters on the overall science objectives. Examples of such analyses include the impact of changing image resolution parameters on global coverage gaps and SSR space usage, the frequency of off-nadir pointing, and MLA northern polar coverage density. During the orbital phase of the mission, these parameters are tightly configured and managed, but they can be refined to take advantage of new understanding from the observations or in response to unexpected orbital events.

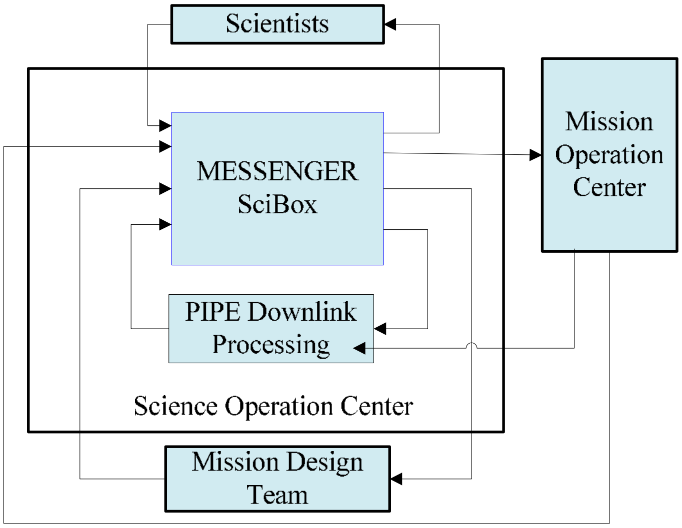

Figure 1: MESSENGER SciBox closed-loop architecture

With these observing parameters, MESSENGER SciBox creates the long-term spacecraft and instrument operations schedule as well as the desired DSN contact schedule.

Over the one-Earth-year orbital mission, the available downlink bandwidth from DSN stations located at Madrid, Canberra, and Goldstone is different and changes over time. MESSENGER SciBox finds time windows that minimize conflict with MESSEGER critical science observing times, that comply with spacecraft operational constraints, and that coincide with the DSN station having the highest available communication bandwidth to create the desired DSN contact schedule. This desired schedule becomes the request that is then sent to the MOC to be passed to the DSN planning team. The DSN planning team uses the requested schedule to allocate DSN contacts for MESSENGER for the subsequent eight weeks. The allocation usually matches the requested time windows, but occasionally the DSN planning team allocates a different time window. Such a difference is then fed back to MESSENGER SciBox in the following planning cycle to configure the RF system, to re-compute future desired DSN station contacts, and to plan observations around the new set of downlink opportunities. This closed-loop iteration repeats every week within an 8-week sliding window.

The science operation schedule produced in each planning cycle is also used to create the observation state file. The observation state file contains the predicted scheduled time and location of an observation; the predicted instrument state at the time when the observation is taken, such as the MDIS exposure setting or binning setting; the predicted observation condition such as the observing angle; and the purpose of the observation. The observation state file is placed in a network location where it can be automatically ingested by the PIPE downlink processing system. PIPE uses the information to validate the actual observations when they are received. The validation includes detecting whether or not an observation is lost in transmission and assessing the consistency of the instrument state. Differences or large deviations in the instrument state might indicate an instrument anomaly or the early sign of hardware degradation. Finally, if a downlinked observation matches the predicted observation state, it is then cataloged according to the purpose set out in the observation state file. Failed observations, observations of poor quality, and successfully calibrated observations are cataloged in a downlink observation status table. In the next planning cycle, SciBox automatically retrieves the downlink observation status table and calibrated data such as spacecraft attitude for use in fine-tuning future science operations.

Because MESSENGER SciBox plans and schedules all G&C operations, it also produces predicted spacecraft attitudes that can be used for independent review of planned operations. An unintended benefit is that the mission design engineers have been able to use the predicted attitudes to improve the modeling of solar radiation forces impinging on the spacecraft in order to derive a more accurate predicted spacecraft ephemeris. The refinement of this ephemeris is performed in a two-step process. First, the mission design team produces a preliminary spacecraft ephemeris under the assumption of a given spacecraft attitude. This ephemeris is then used by SciBox to predict spacecraft attitude. The mission design team then uses the predicted attitude to derive the final mission design baseline, which is used by MESSENGER SciBox for the final science operation derivation.

VI. Orbital Operation

In orbital operations, SciBox is executed once per week in order to use the latest weekly orbit prediction from the mission design engineers. The output of MESSENGER SciBox spans from the start time of a planning cycle to the end of the mission, but only the first week of commands is used for uplink to the spacecraft. The current MESSENGER planning process uses MESSENGER SciBox to plan the science observations and to generate the science operations commands three weeks in advance of the actual command execution onboard the spacecraft. This process allows three weeks of review and validation by the scientists, engineers, and the MOC.

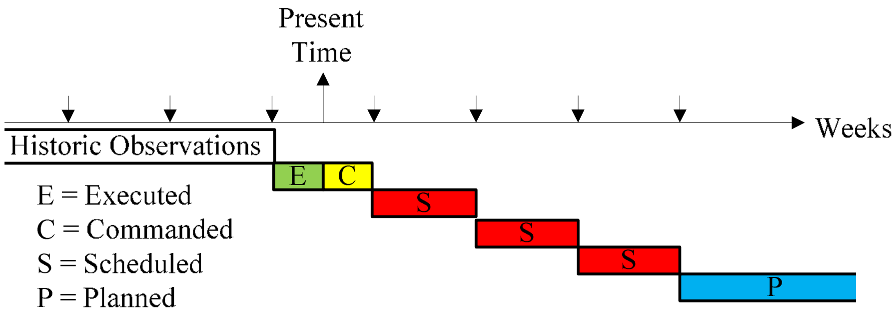

Figure 2: MESSENGER 3-week Near-term Science Planning Process.

The current planning process adopted by the MESSENGER team is illustrated in Figure 2. Each tick mark represents an increment of one week. As indicated by the blue cell, when MESSENGER SciBox is run, it plans the entire remainder of the science operations, beginning slightly more than three weeks from the present. It takes a few hours for MESSENGER SciBox to plan the entire mission. Once the science operations schedules and reports are generated, they are sent to the science team on the following day for validation and review, and the scientists have up to one week to complete that review. The scientists not only validate the commands for the first week of operations, but they also actively monitor the observing plan for future operations. If the observing strategy needs to be changed because of a change in hardware performance or from new understanding gained through recently acquired data, changes are made in the following week.

Once the scientists approve the science operations schedule, the spacecraft and instrument commands, along with the request for future DSN stations, are made available to the MOC. It takes two weeks for mission operators to integrate the science operations commands with the spacecraft health and safety commands and to perform further validation. Three weeks later, SciBox-generated commands are uploaded to the spacecraft for execution.

In parallel, after the science operations schedule is approved by the scientists, the DSN station request is passed along to the DSN scheduler, the long-term predicted spacecraft attitude is sent to mission design engineers, and the predicted observation state file is sent to the downlink processing system. The entire process from executing MESSENGER SciBox to command upload is three weeks in duration, and it is repeated every week in s staggered manner. At the start of MESSENGER SciBox execution, the latest 8-week DSN schedule from the mission operations center, the latest MESSENGER orbit prediction from mission design engineers, and the latest downlink observation status from PIPE are automatically retrieved from a network location.

Since there is more than three weeks of delay before observations are downlinked, previously scheduled observations planned by SciBox must be tracked. These include observations that have been scheduled in the previous week but have not been uplinked to the spacecraft, observations for which commands have been uploaded to the spacecraft but have yet to be executed, and observations that have been taken and saved on the onboard SSR, but have not been downlinked to the data processing system. These scheduled observations represent valuable internal SciBox feedback and must be accurately tracked in order to avoid planning redundant observations.

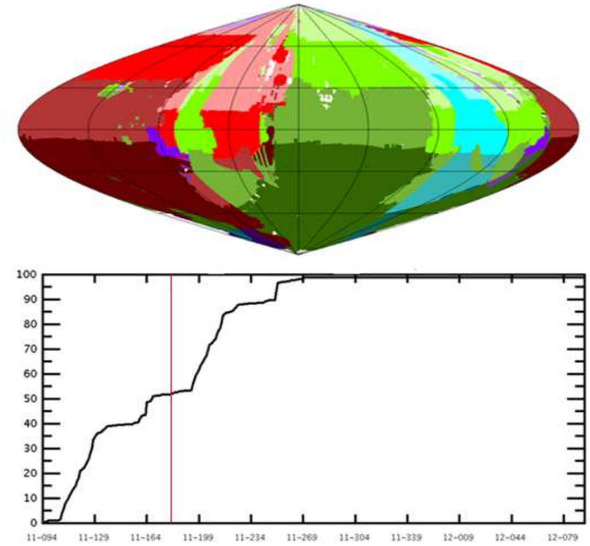

Figure 3: MDIS global monochrome imaging progress report. Figures displayed from the top are the surface coverage status and the percentage surface area covered.

An example of how SciBox tracks MDIS global monochrome mapping is shown in Figure 3. The map shows, in color-coded form, monochrome images that have been downloaded (in dark red), images that have been taken but remain on the SSR (in light red), images for which commands have been sent to the mission operations team for uplink during the previous week (in blue), and images planned for the coming weeks (in green). The graph below shows past, actual, and future anticipated percent coverage as functions of time, with the red line denoting the start time of the planning window. On the graph, regions of steep slope represent times of year when observing geometries from MESSENGER are most suitable for acquisition of this measurement type.

In addition to tracking the previously scheduled observations, SciBox also applies the latest correction to these observations with the latest available calibrated data. For example, when the latest orbit prediction is made available, time and location of scheduled observations are updated to reflect the most probable observation footprints. During low downlink bandwidth season, observations taken are stored onboard the SSR for weeks, whereas the spacecraft attitude is immediately available as part of the spacecraft health and safety engineering data. SciBox uses the latest spacecraft attitude and the latest reconstructed MESSENGER trajectory to re-compute the observation geometry and the global coverage. This level of fine correction is critical, particularly in reducing imaging gaps in the global mosaic map that are caused by orbit and spacecraft attitude uncertainties.

Closed-loop tracking is critical not only in coordinating global mapping observations, but also in enabling rapid recovery of the observation plan from unexpected orbital events. Since orbit insertion, MESSENGER has encountered a number of unexpected operational events that might have threatened meeting measurement objectives, had it not been for the capability to re-plan quickly. One such event was associated with the initial orbit into which the spacecraft was placed. Although the orbit insertion maneuver was highly successful, the relatively small difference in orbital period attained from what was planned (a deviation of approximately four minutes) resulted in images being taken at incorrect locations. The feedback mechanism allowed MESSENGER SciBox rapidly to salvage observations that were taken at the wrong location but were still usable, and re-plan others that had not met the observational requirement. Another unexpected event occurred during the first MESSENGER hot-planet season, during which the periapsis of the MESSENGER orbit is near the subsolar point of Mercury. As this first hot-planet season approached, it became clear that the temperature of a critical spacecraft component would likely increase to an unacceptable level during the season. A prudent decision was made to alter the science operations plan generated by MESSENGER SciBox and immediately move the spacecraft to a safer attitude. The last-minute change resulted in hundreds of images being taken in the wrong configuration, but the MESSENGER science operations team was able to use SciBox to react rapidly to this unexpected event by salvaging usable images and re-planning a new set of observations during the following week. This action resulted in minimal impact to the overall science observation plan.

VII. Conclusion

The use of MESSENGER SciBox, an efficient planning and commanding system with a feedback loop, has enabled MESSENGER to meet the challenges of an ambitious orbital operations phase. The system has allowed MESSENGER to efficiently coordinate and plan tens of thousands of science observations, and more than 365 DSN contacts to meet its science objectives. It improves system response time and operational robustness. It has already been used to recover observations from several unexpected orbital events. At the time of this writing, MESSENGER has completed 17 weeks of orbital operations, and as predicted in the pre-orbital-phase simulation, SciBox has enabled MESSENGER to achieve its Program Level Requirement minimum success criteria.

VIII. Acknowledgements

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