SciBox, An End-to-End Automated Science Planning and Commanding System

Teck H. Choo, Scott L. Murchie, Peter D. Bedini, R. Josh Steele, Joseph P. Skura, Lillian Nguyen, Hari Nair, Michael Lucks, Alice J. Berman, James A. McGovern, F. Scott Turner

Johns Hopkins University Applied Physics Laboratory, Laure, MD

Abstract. SciBox is a new technology for planning and commanding science operations for Earth-orbital and planetary space missions. It has been incrementally developed since 2001 and demonstrated on several spaceflight projects. The technology has matured to the point that it is now being used to plan and command all orbital science operations for the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission to Mercury. SciBox encompasses the derivation of observing sequences from science objectives, the scheduling of those sequences, the generation of spacecraft and instrument commands, and the validation of those commands prior to uploading to the spacecraft. Although the process is automated, science and observing requirements are incorporated at each step by a series of rules and parameters to optimize observing opportunities, which are tested and validated through simulation and review. Except for limited special operations and tests, there is no manual scheduling of observations or construction of command sequences. SciBox reduces the lead time for operations planning by shortening the time-consuming coordination process, reduces cost by automating the labor-intensive processes of human-in-the-loop adjudication of observing priorities, reduces operations risk by systematically checking constraints, and maximizes science return by fully evaluating the trade space of observing opportunities to meet MESSENGER science priorities within spacecraft recorder, downlink, scheduling, and orbital-geometry constraints.

Keywords: Science Operation, Automated, Planning, Commanding, MESSENGER, Intelligent.

1. Introduction

Science operations planning requires coordination of many spacecraft and instrument teams (including sub-system engineers, orbit and pointing analysts, command sequencers, mission operators, and instrument scientists) and commonly calls for multiple iterations to coordinate, de-conflict, review, and test an operational command sequence. The process is iterative, time-consuming, and labor intensive. When a project schedule is tight, limited iterations can be performed, and spacecraft resources are frequently not optimally utilized. Missions tend to invest considerable time and effort in the development of mission-specific planning processes, adding to the mission development budget and schedule.

In this paper we describe SciBox, an end-to-end automated science planning and commanding system. The system begins with science objectives, derives the required observing sequences, schedules those observations, and finally generates and validates uploadable commands to drive the spacecraft and instruments. The process is automated, and there is no manual scheduling of science operations or construction of command sequences. SciBox has been developed and demonstrated incrementally over the last 10 years on several spaceflight missions. The current state of SciBox and its usage on MESSENGER are the focus of this paper.

2. Traditional Science Operation Planning

Traditional science operations planning is a complicated, iterative process. It normally begins with scientists requesting observations from various elements of a suite of instrument subsystems, to cover a planetary surface or sample an atmosphere or magnetosphere at specified geometries. A team of planners works closely with instrument scientists and guidance and control

(G&C) analysts to search for appropriate observation opportunities and design the spacecraft pointing operations, and with highly skilled instrument sequencers to construct matching instrument command sequences. If there is a scheduling conflict between subsystems, the command sequence is further iterated, often with human-in-the-loop adjudication. When an acceptable command sequence to control the G&C pointing and drive instruments is constructed and tested, it is forwarded to engineers to validate that the sequence is within operational constraints. If there is no violation, the command sequence is then forwarded to mission operators for integration with an overall schedule. This process is illustrated in Figure 1.

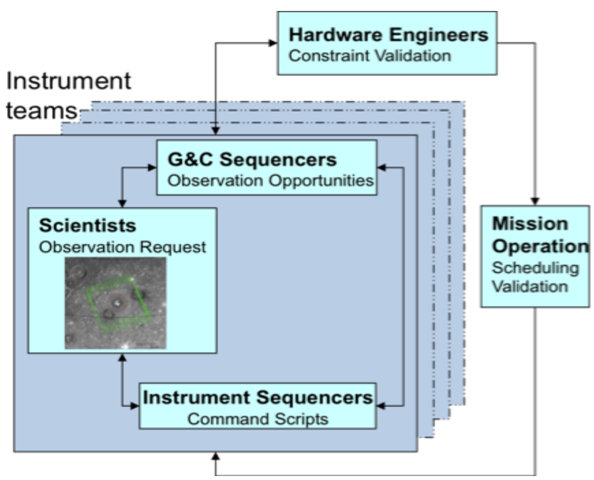

Figure 1: Traditional science operation planning process

Usually there is more than one instrument team involved in a space mission. Collaboration between teams requires a more complex planning process to coordinate observations and avoid conflicts. Such cooperation can involve multiple iterations of planning[1-3], staggered to support continuous daily or weekly operation. The entire process can be labor intensive and require multiple shifts of planning teams to manage the staggered phases. Multiple reviews and tests are conducted to ensure that science objectives are met and that operations sequences comply with all mission health and safety rules. The iterative coordination, review, and testing are time consuming, resulting in sequence development times of weeks or months. In cases where the sequence of operations is determined manually, it may not simultaneously achieve high data quality with minimized usage of key resources such as observing time, space on the solid-state recorder (SSR), or downlink bandwidth. When short-term changes in operating conditions occur, observations can be dropped, underutilizing available resources.

3. SciBox's Streamlined Planning Process

SciBox's approach to improving planning efficiency is to treat the process as a series of streamlined steps, each with the objective of achieving the highest value science possible with available resources by optimizing the operations sequence using an integrated software system. The rearranged processes are illustrated in Figure 2. They begin with science-observation *opportunity analyzers* customized to each type of science measurement. Instead of searching for single observing opportunities, the opportunity analyzers search all available opportunities, for example, to image a particular region at a defined observing geometry, or to acquire a spectrum at a given latitude and longitude. Opportunities are ranked by metrics that represent measures of data quality such as resolution or illumination. Through simulations, time- or altitude-phased thresholds are defined for instrument configurations (e.g., spatial pixel binning, allowable ranges of data-quality metrics) to accomplish measurement objectives within resource constraints. To minimize conflicts, periods are defined during which different instruments are given priority, although comparison of data-quality metrics between instruments allows interleaving of data acquisition to prevent "exclusion" of any instrument from key observing opportunities.

For each potential observing opportunity that is selected, an automated, rules-based *constraint checker* systematically validates the observing operation to ensure that it complies with all operational constraints. The validated observing opportunities are then sorted according to priority and by their data-quality metrics (weighted by the number of available observing opportunities). With the list of sorted, weighted observing opportunities, a software *scheduler* selects the best combination of observations, first placing the highest-ranked and then successively lower-ranked observations into a timeline until available resources are used up. An automated *command generator* then ingests the conflict-free schedule and generates spacecraft and instrument commands for uploading to the spacecraft. Through iterative simulations that are reviewed by instrument scientists and subsystem leads, metrics, priorities, and instrument pointing and configuration rules are refined to improve the overall outcome.

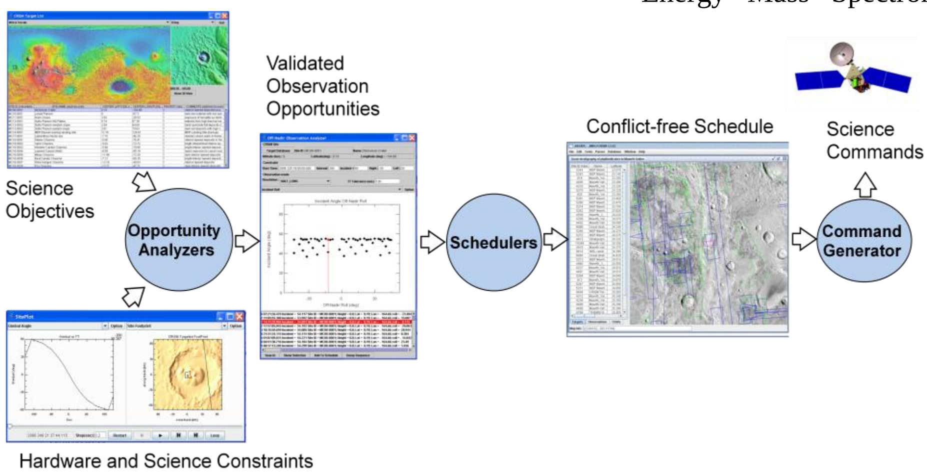

Figure2: Streamlined planning process with SciBox.

4. SciBox Development History

Development of the SciBox planning and commanding architecture was begun in 2001[4] on the MESSENGER mission. In order to bring the proposed theoretical architecture into reality, key SciBox software modules were developed and demonstrated incrementally over 10 years on a variety of spaceflight projects at the Johns Hopkins University Applied Physics Laboratory. In 2001 the opportunity analyzer concept was demonstrated on the Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) mission (http://www.timed.jhuapl.edu/), an Earth polar orbiter designed to make measurements of the mesosphere, lower thermosphere, and ionosphere (MLTI). The opportunity analyzer, called the TIMED coincidence calculator, computes co-observing opportunities between TIMED instruments and any selected ground station and provides times and required ground-station azimuth and elevation angles. The TIMED coincidence calculator has been used by ground-station operators all over the world since its delivery to plan co-observations of Earth's MLTI region with TIMED instruments.

In 2002, the next key milestone was achieved with the delivery of a science planning tool for the Magnetospheric IMaging Instrument (MIMI) onboard the Cassini mission to Saturn (http://sd-www.jhuapl.edu/CASSINI/). One of twelve Cassini investigations, MIMI is an instrument suite that includes the Low Energetic Magnetospheric Measurement System, the Charge Energy Mass Spectrometer, and the Ion and Neutral Camera. At Saturn, sunlight is a thermal hazard for the spacecraft radiator as well as a source of instrument noise for MIMI. Saturn dust particles are also hazardous to MIMI. The MIMI planning tool, JCSN, is an improved opportunity analyzer that includes position and pointing constraint visualization. Since its deployment, JCSN has been used by the MIMI science operations team to orient MIMI sensors in ways that most accurately measure and most fully sample the magnetospheric environment while keeping the instrument and spacecraft operating safely.

The next milestone was achieved in 2005, when the first end-to-end, semi-automated planning tool was delivered for the Compact Reconnaissance Imaging Spectrometer for Mars (*CRISM)* onboard the Mars Reconnaissance Orbiter (http://crism.jhuapl.edu/). The CRISM planning tool[5], JMRO, includes integrated opportunity search, constraint validation, scheduling, command generation, and reporting capabilities for one instrument. Although an automated plan is generated, sequencers routinely add and modify pre-planned observations manually to manage unexpected changes to downlink or SSR space. JMRO has been used for five years to plan CRISM weekly science operations including high-resolution targeted observations, reduced-resolution global multispectral mapping, atmospheric monitoring, limb observations, and routine calibrations matched to each observing mode. The output of the weekly plan is a CRISM instrument command sequence ready to upload to the instrument. JMRO has sufficient internal expertise to enable a relatively small operations staff of professional scientists both to operate the investigation and to help analyze the observations that they plan.

5. The MESSENGER Mission

The latest milestone was achieved in 2011 with delivery of a mission-level science planning and commanding system for MESSENGER, the first spacecraft to orbit Mercury. SciBox[6] is used to command all the instruments as well as the spacecraft G&C system, solar panels, radio frequency (RF) communication, and SSR.

On 18 March 2011, MESSENGER entered into a non-Sun-synchronous, highly eccentric 200 × 15,200 km orbit with an inclination of 82.5° and a period of about 12 hours. MESSENGER addresses 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?[7,8]. 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[9] 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.

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, NS 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

These instruments are mounted behind a sunshade that protects the spacecraft from intense insolation. As MESSENGER orbits Mercury, the 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 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 in 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 where the MESSENGER-DSN link is blocked by the Sun

6. MESSENGER Operations Challenges

The combination of the spacecraft's orbital geometry, Mercury's harsh environment, MESSENGER's ambitious measurement objectives, and limited downlink resources creates challenges for science operations.

Finding safe and scientifically valuable observing opportunities requires analysis of non-intuitive and complex observing geometries. The combination of a highly eccentric orbit and the spin of the planet results in non-repeating observing geometries. Safe observing spacecraft orientations change continually. The observing geometry repeats only every 176 Earth days or 1 Mercury solar day; MESSENGER's primary mission is only two Mercury solar days in duration. Standard pointing sequences cannot be created and reused, and every observing opportunity requires specifically tailored spacecraft and instrument configurations. All operations sequences must comply with SKI and HKPO limits, keep the spacecraft from excessive slewing, and conserve power during eclipses.

Observing opportunities derived from MESSENGER measurement objectives frequently create conflicting G&C pointing requirements. These conflicts cannot be resolved with only a simple science-objectives prioritization. Both observation quality and the number of available observing opportunities must be considered to maximize the number and quality of scheduled observations while not omitting infrequent but critical observation types. For example, rare opportunities to meet lower-priority measurement objectives may receive higher scheduling priority over higher-priority measurement objectives having many acceptable observing opportunities. In addition, the final G&C schedule must also include spacecraft maintenance operations such as orbit-correction maneuvers (OCMs), power conservation during eclipses, and orientation of

Table 2: MESSENGER Scheduling Priority

1st Solar Day	**2nd Solar Day**
Eclipse	Eclipse
Orbit-correction maneuver	Orbit-Correction maneuver
Mercury orbit insertion	G&C high rate
G&C high rate	High-gain antenna downlink
High-gain antenna downlink	Priority-1 TO
Post MOI checkout	UVVS polar scan
Priority-1 TO	MDIS stereo mapping
UVVS polar scan	MLA north polar off-nadir coverage
MLA NH nadir coverage	MLA NH nadir coverage
Priority-2 TO	Priority-2 TO
MDIS WAC south pole monitoring	MDIS NAC south pole monitoring
UVVS star calibration	UVVS star calibration
XRS star calibration	XRS star calibration
MDIS limb scan and pivot calibration	MDIS limb scan and pivot calibration
UVVS limb scan	UVVS limb scan
Priority-3 TO	Priority-3 TO
XRS/VIRS global mapping	XRS/VIRS global mapping
MDIS global color mapping	Priority-4 TO
MDIS global monochrome mapping	UVVS exosphere scan
Priority-4 TO	MDIS north polar ride-along
UVVS exosphere scan	MAG observation
MAG observation	GRS NH coverage
GRS NH coverage	MAG observation
MAG observation	GRS NH coverage
GRS NH coverage	NS NH coverage
NS NH coverage	EPS observation
EPS observation	FIPS observation
FIPS observation	RS Low-gain antenna
RS Low-gain antenna	Priority-5 ride-along TO
Priority-5 ride-along TO	Priority-6 ride-along TO
Priority-6 ride-along TO	Priority-7 ride-along TO
Priority-7 ride-along TO	
NH = Northern Hemisphere	G&C Commanding required
TO = Targeted Observation	No G&C commanding
	Pivot commanding only

the spacecraft and PAAs for downlink. Table 2 shows the current solar day 1 and solar day 2 scheduling priorities for each spacecraft subsystem and measurement objective. The scheduling priority for the first day is biased toward mapping observations, whereas the scheduling priority for the second solar day is tailored toward gap coverage, high-resolution targeting, and other specific campaigns. This ordering between activities in the two solar days allows more critical observation types to be conducted during the first solar day, with backup opportunities on the second.

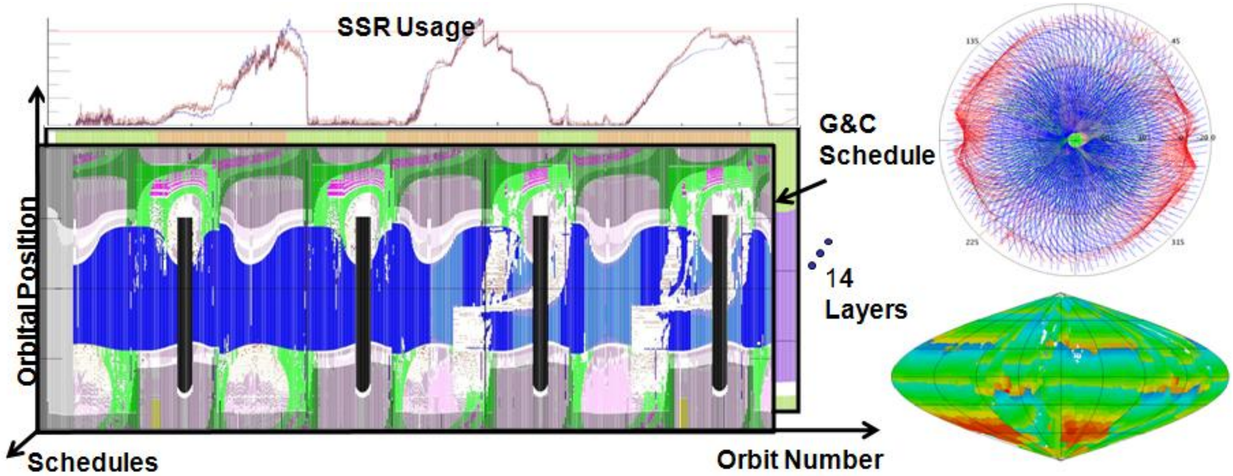

Figure 3: Sample MESSENGER operations schedules and derived reports. Figures displayed clockwise from the top left are predicted SSR usage, MLA northern polar coverage, MDIS global monochrome pixel resolution map, and the 14 layers of orbital schedules

Spacecraft pointing is not the only resource that must be carefully managed. Available SSR volume is also a resource that requires close attention. Science data must always fit within the SSR's 8-gigabit limit to avoid loss of data. All instruments employ data compression, and MDIS also uses pixel binning to manage data volume. Many full-mission detailed simulations prior to MESSENGER's orbit insertion were required to develop and test the strategy to meet science objectives while not exceeding the 8-gigabit SSR limit[10].

The end result of pre-orbital operations planning and simulation is a conflict-free schedule for the entire orbital mission for ten sensors (of MESSENGER's seven instruments, three include two sensors) and the spacecraft's G&C subsystem, the RF communication subsystem, the solar panels, and the SSR. The integrated schedule contains approximately 80,000 carefully placed images, more than 4 million spectra, and more than 360 DSN contacts. The integrated schedule is used to generate an exhaustive set of reports detailing the science observations for each investigation and the resources used. The lower-left diagram in Figure 3 illustrates the 14 layers of schedules, for the ten sensors and four spacecraft subsystems. The layer shown is the G&C schedule. Each vertical line shows the spacecraft's position within one orbit; the 750 vertical lines represent 750 orbits for the nominal mission. Different G&C operations are color-coded. At present, the G&C pointing schedule is fully utilized, and there are no unused time slots. Above the schedules in Figure 3 is the predicted SSR usage for the entire mission. The three peaks displayed are consistent with superior solar conjunction when minimal or no downlink is expected and science data will have accumulated on the SSR. To the right are the predicted northern polar coverage for the MLA instrument, and the global pixel resolution for the MDIS monochrome global map

7. Orbital Performance

MESSENGER began its primary science phase on 4 April 2011. Every week, the entire remaining part of the mission is re-planned using the latest orbit prediction, the current knowledge of success or failure of past commands, and a new DSN-station schedule. A new set of commands for the seven instruments and the four spacecraft subsystems is then generated for the following week. As part of command generation, SciBox also regenerates the mission monitoring products to track progress toward mission-long science measurement objectives. Figure 4 shows the current progress of MDIS global monochrome coverage at the time this article was written. The map shows, in color-coded form, monochrome images that have been downloaded, images that have been taken but remain on the SSR, images for which commands have been sent to the mission operations team for uplink during the previous week, and images planned for the coming weeks. The graph shows past actual and future anticipated percent-coverage as functions of time; the red line denotes the time of writing. 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.

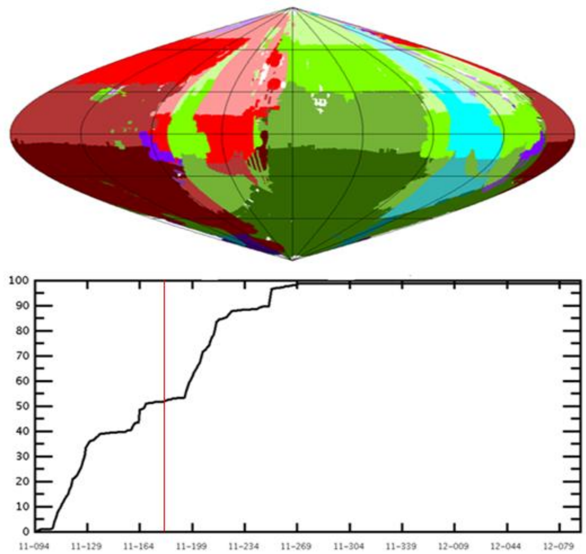

Figure 4: MDIS Global monochrome imaging progress report. Figures displayed from the top are the surface coverage status and the percentage surface area covered.

At the time of writing, SciBox has generated more than 45,000 spacecraft and instrument commands for the first eight weeks of science operations, and the commands have been successfully executed on the spacecraft. More than 19,000 images and 360,000 spectra have been downloaded to the SOC. All were executed as predicted by SciBox to within expected uncertainties, with only three small exceptions: images taken during the instrument commissioning phase were off-target by a larger than usual amount due to initially high uncertainties in orbit determination; some images were mis-pointed when higher-than-expected spacecraft deck temperature led to temporary pointing restrictions; and one set of imager pointing calibrations was blurred due to an error in a G&C command.

8. Discussion

Early MESSENGER orbital operations have demonstrated that SciBox's automated approach to science operations planning works as intended. Data are being acquired as planned, by a staff that is small for a planetary mission, with only minimal performance issues, all of which have been corrected. SciBox thus improves operations efficiency, maximizes the science return from available resources, reduces cost, and controls operations risk. Each of the 750 elliptical science orbits is not unlike a planetary flyby; instead of weeks or months of labor-intensive coordination to derive each week's command load, MESSENGER's science operations team can, in two hours, generate the entire year of mission plan; of which the first week of commands are used for upload to the spacecraft.

This ability to re-plan science operations rapidly was tested within the first three weeks of operations. Although Mercury orbit insertion executed within all specifications, the orbital period achieved on 18 March was more than 4 minutes longer than the pre-insertion predicted period. Two weeks later, the accumulated difference resulted in more than two hours of misalignment between optimal time for downlink and the pre-arranged DSN station schedule. Continued used of the pre-planned DSN schedule would have required orienting the spacecraft non-optimally or removing science observations to enable downlink. Instead, the MESSENGER science operations team was able to re-plan the entire schedule without degradation to the science return. SciBox automatically found new observing opportunities and rescheduled all observations around the existing DSN schedule using the new orbit prediction. The RF antenna was reconfigured to utilize fully the available bandwidth.

Equally importantly, SciBox reduces risk from tactical operations. Traditional mission operations use multiple automated and human-in-the-loop reviews to validate commands and constraints. The human-in-the-loop component depends on the experience of the reviewers and their alertness at the time of a review. SciBox contains several strategically placed validation tools that examine constraints that reflect instrument mechanical and software limitations, safeguard instrument health, and verify compliance with data quality standards (e.g., matching image exposures with spacecraft altitude to limit smear). These validation tools automatically and systematically validate all science operations scenarios.

Finally, SciBox also reduces science implementation risk that is not obvious during weekly operations. Over the course of MESSENGER's one-year orbital mission, there are three superior solar conjunctions during which downlink is sharply curtailed. Observing opportunities are limited by the mission's two-solar-day length so, unavoidably, observations must be taken during and around conjunction, and they accumulate on the SSR. The risk of SSR overflow is not obvious from any single week of operations, but it becomes obvious when the full year is scheduled. SciBox's ability to simulate the entire mission allows development and testing of strategies to accomplish mission science objectives without SSR overflow. Prior to orbit insertion, hundreds of full mission simulations were analyzed to identify data acquisition and compression strategies that maximize science return within the 8-gigabit SSR limit. In addition, SciBox simulated a variety of contingency scenarios[10] to identify first-order risk mitigation strategies.

9. Summary

SciBox is a generic framework with a supporting SciBox software library[11] tailored specifically for a specific mission science planning and commanding system. The generic framework describes streamlined automated processes and a strategically placed validation system and is part of SciBox's uplink operation system. SciBox's uplink operation system represents a substantial advancement in ground technology. It allows a project to improve operations efficiency while shortening the lead time for planning, reduce costs by automating many labor-intensive steps of scheduling and commanding, maximize overall science return by efficiently analyzing the trade space of available resources, and reduce risk by systematically validating all science operations and providing mission-long resource and margin evaluation. SciBox is no longer a theoretical system, but a tested approach to operating a planetary science spaceflight mission.

References

[1] M. E. Holdridge, "NEAR Shoemaker Space Mission Operation." Johns Hopkins University Applied Physics Laboratory Technical Digest, Vol. 23, Issue 1, pp. 58–70, 2002.

[2] B. G. Paczkowski and T. L. Ray, "Cassini Science Planning Process." AIAA SpaceOps 2004 Conference, 10 pp, Montreal, Quebec, Canada, 17-21 May 2004.

[3] D. D. Wenkert et al., "Science Planning for the NASA Mars Reconnaissance Orbiter Mission." AIAA Space 2007 Conference & Exposition, 9 pp., Long Beach, Calif., 18-20 September 2007.

[4] T. H. Choo, S. L. Murchie, and J. S. Jen, "The MESSENGER Science Planning Tool," Workshop on Mercury: Space Environment, Surface, and Interior, pp. 11-12, Lunar and Planetary Institute, Houston, Tex., 2001.

[5] T. H. Choo, J. McGovern, and S. L. Murchie, "An Efficient Uplink Pipeline for the MRO CRISM." AIAA Space 2008 Conference and Exposition, AIAA-2008-7656, 8 pp., San Diego, Calif., 9-11 September 2008.

[6] T. H. Choo, B. J. Anderson, P. D. Bedini, E. J. Finnegan, J. P. Skura, and R. J. Steele, "The MESSENGER Science Planning and Commanding System." *AIAA Space 2009 Conference and Exposition*, paper AIAA-2009-6462, 11 pp., Pasadena, Calif., 14-17 September 2009.

[7] S. C. Solomon, R. L. McNutt, Jr., R. E. Gold, and D. L. Domingue, "MESSENGER Mission Overview." Space Science Reviews, Vol. 131, Issues 1-4, pp. 3-39, 2007.

[8] S. C. Solomon et al., "The MESSENGER Mission to Mercury: Scientific Objectives and Implementation." Planetary and Space Science, Vol. 49, Issues 14-15, pp. 1445-1465, 2001.

[9] R. E. Gold, R. L. McNutt, Jr., S. C. Solomon, and the MESSENGER Team, "The MESSENGER Science Payload." Proceedings of the 5th International Academy of Astronautics International Conference on Low-Cost Planetary Missions, Special Publication SP-542, edited by R. A. Harris, European Space Agency, Noordwijk, The Netherlands, pp. 399-405, 2003.

[10] R. J. Steele, T. H. Choo, J. P. Skura, B. J. Anderson, and E. J. Finnegan, "Comprehensive Mission Simulation Contingency Analyses: Achieving Science Observation Plan Resiliency by Design." AIAA Space 2009 Conference and Exposition, paper AIAA-2009-6464, 9 pp., Pasadena, Calif., 14-17 September 2009

[11] T. H. Choo, and J. Skura, "SciBox: A Software Library for Rapid Development of Science Operation Simulation, Planning and Commanding Tools." Johns Hopkins University Applied Physics Laboratory Technical Digest, Vol. 25, Issue 2, pp. 154-162, 2004.