The MESSENGER Science Planning and Commanding System

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MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Ranging) is the first spacecraft to visit Mercury since the Mariner 10 flybys in 1974 and 1975 and will be the first spacecraft to orbit the innermost planet, beginning in March 2011. The science payload is designed to study all aspects of Mercury and its environment and consists of seven instruments and a radio science experiment. During the primary orbital phase of the mission, the MESSENGER team faces the challenge of scheduling science observations to meet all measurement objectives while operating in a thermally harsh environment in geometrically challenging orbits. An efficient, automated science planning and commanding system called MESSENGER SciBox has been developed to support orbital analysis and strategic planning activities prior to orbital insertion, and to schedule and command the instrument and spacecraft operation during the orbital phase. In this paper we present the architecture of MESSENGER SciBox and its application to pre-orbital simulation and in-orbit operational usage.

I. Introduction

Space missions have traditionally used manually generated command-based systems to plan and command daily operations. As missions have become ever more ambitious, the manual approach is increasingly challenged to cope with the complexity and volume of commands required. The automated command generation system[1] used by the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) Science Operations Center demonstrated that such a system significantly improves operational efficiency while optimizing science return and has enabled a small team of scientists to operate the CRISM instrument without having to deal with cryptic commanding details. In this paper we present an efficient, automated science planning and commanding system that begins from science measurement objectives and ends with command sequences ready for uplink to the spacecraft. The automated system breaks new ground by automating the planning and commanding for the entire suite of instruments, the guidance and control (G&C) system, and the radio frequency (RF) telecommunication system.

II. Background

NASA's MErcury Surface, Space ENvironment, GEochemistry, and Ranging[2] (MESSENGER) spacecraft was launched on 3 August 2004 and has twice flown by Mercury successfully, on 14 January 2008 and 6 October 2008. It will fly by Mercury a third time on 29 September 2009 before being propulsively inserted into Mercury orbit in March 2011. During the mission orbital phase[3], the spacecraft will be in a non-Sun-synchronous, highly elliptical 200 km x 15,200 km altitude orbit with an orbital inclination of approximately 80°. The orbital period will be approximately 12 hours.

The MESSENGER mission was designed to address the following six key 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 guided the development of the mission and the seven instruments and a radio science (RS) experiment carried on board the MESSENGER spacecraft. The on-board instruments[4] include a Mercury Dual-Imaging System (MDIS) with wide-angle and narrow-angle cameras for multi-spectral imaging of 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; the Mercury Laser Altimeter (MLA) to measure surface topography and planetary shape; the Mercury Atmospheric and Surface Composition Spectrometer (MASCS), which includes two sensors, the Visible Infrared Spectrograph (VIRS) and the Ultraviolet and Visible Spectrometer (UVVS) 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), which includes a Fast Imaging Plasma Spectrometer (FIPS) and an Energetic Particle Spectrometer (EPS) to characterize the charged particle and plasma environment. The science questions motivate observation objectives, which for planning purposes are most usefully organized by observational activity type, as summarized in Table 1. The fixed remote-sensing instruments, MASCS, XRS, GRNS and MLA, are mounted with a common boresight that is normal to both the direction to center of the sunshade and to the solar array axis. The MDIS camera is mounted on a pivot that provides some freedom to view sunward and anti-sunward of the common instrument boresight direction.

Table 1. Summary of MESSENGER Science Observation Activities.

Observation Activity	**Measurement requirements and relevant instrument/investigation**
Global surface mapping	• Monochrome imaging with > 90% coverage at 250-m average resolution or better for geology characterization: MDIS • Multispectral imaging with > 90% coverage at 2 km/pixel average resolution or better for mineralogy: MDIS • Stereoscopic imaging with > 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 measurement for obliquity and libration amplitude determination: MLA • Composition of polar deposits: GRNS • Polar ionized species measurement for volatile identification: EPPS • Polar exosphere measurement for volatile identification: UVVS
In-situ observations	• Mapping magnetic field to characterize the internally generated field: MAG • Determining magnetosphere structure, plasma pressure distributions, and their 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, photometry to support geology, mineralogy, and topography: MDIS
Radio science measurements	• Gravity field determination to support characterization of internal structure (in combination with topography and libration): RS

III. Orbital Operational Challenges

During MESSENGER's one-year orbital mission, the science operations team will face the challenge of planning and scheduling the set of ambitious science measurements without violating the spacecraft operational constraints. Operations in orbit at Mercury impose a number of constraints that restrict spacecraft pointing, observation opportunities, and data volume. 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 to the on-board solid-state recorder (SSR). Ensuring safe spacecraft operations while meeting mission observation goals implies that the orbital mission must be thoroughly planned well before Mercury orbit insertion and that the design and planning process must be adaptable to contingencies that may arise.

A. Spacecraft Operational Constraints

The three primary operational constraints that the MESSENGER spacecraft must obey while in-orbit are related to power, thermal control, and SSR space.

Power Allocation[5]

During certain orbits around Mercury, the Sun as seen from MESSENGER will be eclipsed as the spacecraft passes in the planet's shadow. When these eclipses last longer than 35 minutes, there will not be enough power from the batteries to power all of the instruments, and some instruments will be turned off through eclipse and remain off until the batteries are recharged. During these long-eclipse orbits, the spacecraft also passes low over the planet near local noon and the solar arrays must be protected from heat radiating from the planet so that the recharging time is also constrained. Thus, both instrument operations and spacecraft pointing are constrained to ensure that sufficient power margin is maintained to keep the spacecraft operating safely.

Thermal Control[5]

During the orbital mission when Mercury is at perihelion, the MESSENGER spacecraft will experience a solar flux that is 11 times higher than it is at Earth. The primary thermal control on MESSENGER is a 2.5 m x 2 m ceramic-fabric sunshade that covers one side of the spacecraft body and shields the instruments and spacecraft systems other than the solar panels from the intense insolation. The sunshade must face sunward as MESSENGER orbits Mercury, and the guidance and control system[6] includes strict rules to keep the spacecraft attitude within Sun-keep-in (SKI) limits such that the sub-solar point must remain at all times within a 6^o x 5^o angular boundary relative to the center of the sunshade. The SKI limits ensure that spacecraft components and instruments are never directly illuminated by the Sun.

In addition to solar radiation, the rear side of spacecraft will be exposed to the hot Mercury surface when the spacecraft orbit passes over the dayside of Mercury. At these times, the spacecraft must be oriented to prevent the battery from exposure to the thermal radiation from the planet and the star cameras from the bright planetary surface. As mentioned above, the rear sides of the solar arrays must also be protected from the most intense thermal planetary radiation that occurs during long-eclipse orbits.

Solid-State Recorder Space

Data taken by the instruments are compressed and stored on the on-board SSR, and are then downlinked to the Deep Space Network (DSN) using eight-hour DSN passes every other MESSENGER orbit, that is, once per day. The SSR is an 8-Gbit synchronous dynamic random access memory (SDRAM). Because of the tight pointing constraints on the spacecraft, MESSENGER is equipped with a steerable phased-array, dual high-gain antenna system that enables radio communication with DSN over the full range of Earth-Sun-Mercury angles. The available downlink bandwidth varies with the Mercury-Earth distance, the Sun-Earth-MESSENGER angle, and DSN station. To maximize the science data returned, all instruments make extensive use of data compression, and MDIS also uses image binning and sub-framing to keep the volume of extraneous data to a minimum. Even so, the instruments can readily generate more compressed data than can be downlinked, so the observations must be carefully orchestrated to take full advantage of observing opportunities while operating within SSR constraints to avoid loss of critical data.

B. Planning and Scheduling Science Observations

Scheduling the observations to meet the measurement objectives in this highly constrained environment is the most challenging task for the science operations team. Due to the complex observing geometry, competing operational requirements, short in-orbit planning cycle, and finite DSN resources this planning task requires a complete orbital mission simulation tool that accurately represents the spacecraft operations constraints, mission operations activities, instrument data generation, and data storage and downlink.

Complex Observing Geometry

MESSENGER's elliptical orbit about Mercury is illustrated in Figure 1. The altitude and velocity relative to the surface vary widely. At periapsis the altitude will be as low as 200 km with a surface-track speed of 3.7 km/s, while at apoapsis the altitude will be 15,000 km with a surface-track speed of 0.6 km/s. Many of the instruments change settings depending on altitude and velocity. For example, MDIS changes its maximum auto-exposure time according to the altitude and surface-track velocity so that the image pixels are not excessively smeared. MLA begins data collection when the distance to the surface is within the laser range and is in standby otherwise.

Mercury is in a 3:2 spin-orbit resonance, its rotation period is long, 56 days, and it completes one and a half rotations in inertial space every 88-day orbit about the Sun, resulting in a 176 day solar day. Since the MESSENGER orbit plane is approximately fixed in inertial space, comparable illumination conditions for a given location on the surface recur only twice during the year-long MESSENGER orbital mission phase. Even for arbitrary illumination conditions, opportunities to observe a specific location on the surface are limited to a handful of cases.

The SKI limits further compound the complexity of science observing geometry. The SKI rules limit the range of spacecraft attitude and nadir observing geometry. For this reason, the MDIS camera is mounted on a pivot that allows it to view the planet over a much wider range of geometries. Even so, there are large fractions of most orbits during which even MDIS cannot observe the nadir surface.

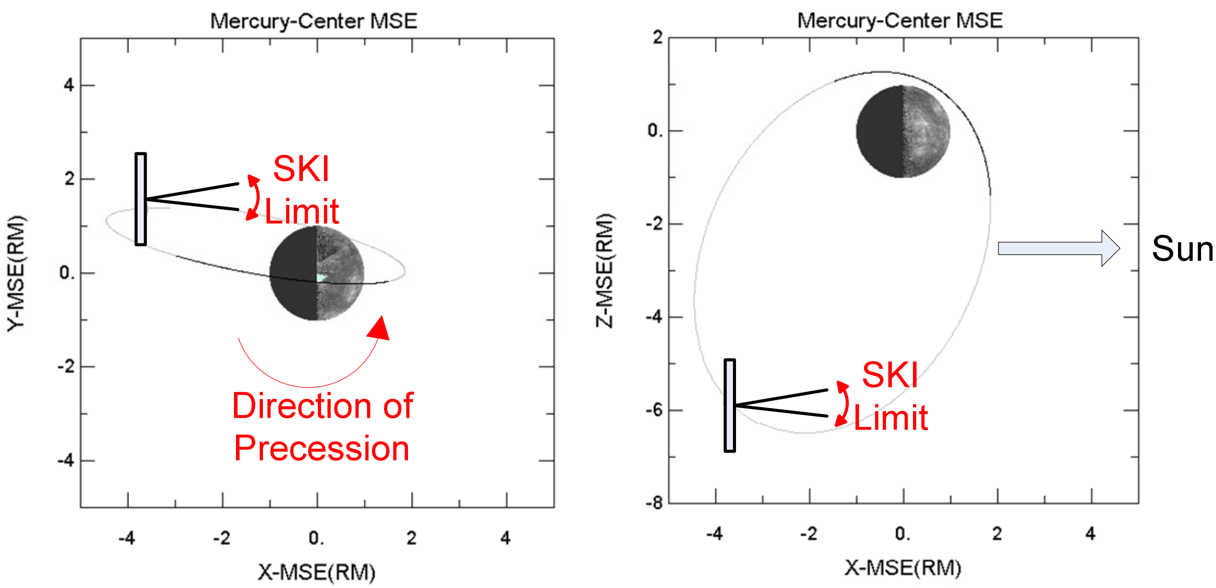

Figure 1. Sample MESSENGER orbit. *The left-hand plot shows a sample of MESSENGER's orbit about Mercury viewed from above the northern pole, and the right-hand plot shows the same orbit viewed from the side. In both projections, the Sun is to the right. The spacecraft attitude must keep the sunshade oriented such that the direction of the Sun is within SKI limits. The ascending node is farthest from the planet. This orbit is an example of a long-eclipse orbit in which the spacecraft is in the shadow of the planet for an extended period of time.*

Competing Operational Requirements

The observational activities listed in Table 1 are scientifically ambitious, operationally challenging, and in some cases mutually exclusive in the spacecraft pointing they require. MDIS stereo observations cannot occur at the same time as MLA nadir ranging. When the spacecraft is on the night side of Mercury, MLA and GRNS benefit from pointing close to nadir to minimize the slant angle for polar northern hemisphere coverage while the photon-counting instruments benefit from pointing the instrument off-nadir to the illuminated surface of Mercury, while UVVS requires pointing above the planet limb for exosphere observations. Scheduling of pointing control also requires precise timing as well as mission-long coordination. The high-resolution targeted observations must be scheduled to within a few seconds to avoid missing the target. Global mapping is a mission-long objective that requires considering the entire orbital mission plan to ensure coverage within the limited observational viewing geometry, downlink bandwidth, and SSR space. Adding to the competition for pointing control are instrument calibration activities that require pointing the instruments to other celestial objects or the interplanetary background, and engineering activities during which science pointing cannot occur, such as data downlink, orbit-correction maneuvers, and Mercury orbit insertion.

C. Short In-Orbit Planning Cycle

The intricate scheduling requirements imply that science observation scheduling can only take place after the DSN track schedule is known. During the orbital mission phase, the DSN station schedule will be available eight weeks in advance. The current MESSENGER baseline is to update the orbit prediction weekly and along-track uncertainties are expected to be significant. Thus, eight weeks out, the long-term orbit prediction is not accurate enough to ensure that a specific target can be achieved in a single observation. The planning strategy must therefore be automated and sufficiently flexible to re-arrange science observations around the DSN track schedule. In addition, the observation strategy must be robust to along-track errors in the orbit position knowledge.

IV. Approach

To address these challenges, the MESSENGER science operations team has developed a concept of operations consisting of a detailed baseline of the entire orbital science observations schedule together with a mission simulation tool that can re-schedule observations automatically. Because of the complexity of the observations, limited observation opportunities, and multiple factors constraining the observations, the baseline development proceeded iteratively. A partial set of the most basic observations, e.g., monochrome imaging and in-situ observations, was identified, and then the full mission was then simulated to identify resource and scheduling conflicts, which were then resolved. The cycle was then repeated by adding additional science observations followed by another cycle of simulation and analysis.

This process started with the design of draft science operations concepts. These were prepared by the science investigation teams and converted to simulation code by the baseline developers. The simulations were used to impose realistic operational, pointing, and resource constraints and assess the proposed operations concept as achieved in the simulation against the measurement objectives. The full mission simulation allowed detailed analysis of the strengths and weaknesses of each investigation's operations concept as well as identification of conflicts between investigations. Analysis of adjustments to the operations concepts provided quantitative direction for revisions and trades among different scenarios. Due to the complexity of the orbital mission and multiple observation objectives, the baseline development team worked closely with the science investigators to refine the operations concepts.

The baseline observation plan was refined using an iterative approach. Iterations consisted of an operations concept delivery/revision, implementation of the revised concepts in the simulation, and finally analysis and assessment. In addition, the simulation was upgraded to provide greater fidelity to mission operations activities as well as instrument and spacecraft performance based on results of cruise testing and the Mercury encounters. The results of the iterative development were captured in an incremental orbital-baseline schedule and corresponding simulation software package. Each major baseline schedule improvement was used for several analyses: the instrument science teams evaluated the science coverage against the requirements and recommended improvements or revised their concepts of operations; the engineering and operations teams analyzed critical resource usage and recommended operational risk mitigation strategies[7]; and management used it to monitor orbital phase planning progress and recommend science/technical trades and establish operational strategies and procedures.

The development of the orbital planning process also addressed the need to rapidly reschedule the science operations. By using automated opportunity analyzers to schedule science and spacecraft pointing operations while meeting operational constraints, staying within spacecraft and scheduling resources, and meeting the science observation requirements, the tools used to develop the baseline schedule also support an operations process that can respond within the 8-week scheduling constraints of deep space missions described above. To do this, the MESSENGER science operations team developed a two-phase orbital planning process: a 5-week Advance Science Planning (ASP) phase, and a 3-week Near-Term Science Planning (NTSP) phase. The 5-week planning cycle is used to coordinate all instrument operations that require pointing control, within available power and data volume based on the earliest available DSN antenna schedule. The 3-week planning cycle is used to provide timing adjustments to all science observations based on the latest orbit prediction, and to adjust SSR resource usage based on the latest data compression prediction, transmission prediction, and updated DSN station schedule. Because the ASP uses the same software tools that are used to develop the conflict-free observation schedule within all operational and resource constraints, the NTSP focus is on conversion from the observation schedule to the command load and final error checking using independent mission operations tools.

To support the baseline development and ASP process, the MESSENGER science operations team has chosen an integrated software planning system that can be used for pre-orbit phase strategic analysis as well as in-orbit tactical planning. This integrated system, MESSENGER SciBox, is based on a goal-based[8] planning system using the SciBox[9,10] software library. Goal-based planning systems have been successfully employed for the CRISM instrument on the Mars Reconnaissance Orbiter (MRO) and the MiniRF[11] instruments onboard Chandrayaan-1 and the Lunar Reconnaissance Orbiter (LRO). SciBox is a generic science-planning software library that has been used to support several space missions operated by the Johns Hopkins University Applied Physics Laboratory (JHU/APL). It contains a suite of packages for modeling and visualizing spacecraft operations.

V. The MESSENGER SciBox Architecture

Prior to orbital operation, the function of MESSENGER SciBox is to support the development of the baseline observation schedule just described by providing simulation and visualization of spacecraft and instrument operations. The tool supports the formulation of operations strategies by providing rapid simulation of operations under a variety of conditions. It also facilitates risk management by providing analysis of critical resource use. During orbital operations, it will be an integral part of the Science Operations Center and will be the primary tool used in the five-week ASP cycle to generate conflict-free operations schedules in response to mission performance to date and the latest DSN schedule. It will be used in the NTSP cycle for the science team to refine the observation timing and instrument sampling rates and generate the instrument and science pointing command sequences. It will also output reports of the planned observations and instrument state for autonomous tracking and anomaly detection by the downlink processing pipeline. The outputs of MESSENGER SciBox are uplink reports for the science team review and command sequences that include instrument commands, G&C commands, antenna commands, and the predicted observation and instrument state for use in autonomous downlink processing.

The inputs to MESSENGER SciBox are the DSN schedule, the predicted trajectory, tunable spacecraft operational constraints, science measurement objective parameters, downlink observations status, and a targeting database. The predicted trajectories are in the form of SPICE kernels. The spacecraft operational constraints are parameters that may change over time due to changes in hardware performance and are used by MESSENGER SciBox to model hardware behavior. The science measurement objective parameters are tunable, specify measurement objectives and scheduling priorities, and are used by the MESSENGER SciBox optimization and scheduling algorithms. The downlink observation status data are quality flags for observations that have been downlinked and processed and are used by MESSENGER SciBox to avoid planning duplicate observations and to reschedule failed observations. The targeting database is a list of regions of high scientific interest developed by the science team prior to the orbital mission. The targeting database can also be modified during the orbital phase. The targeting database is used by MESSENGER SciBox to schedule focused high-resolution targeted observations.

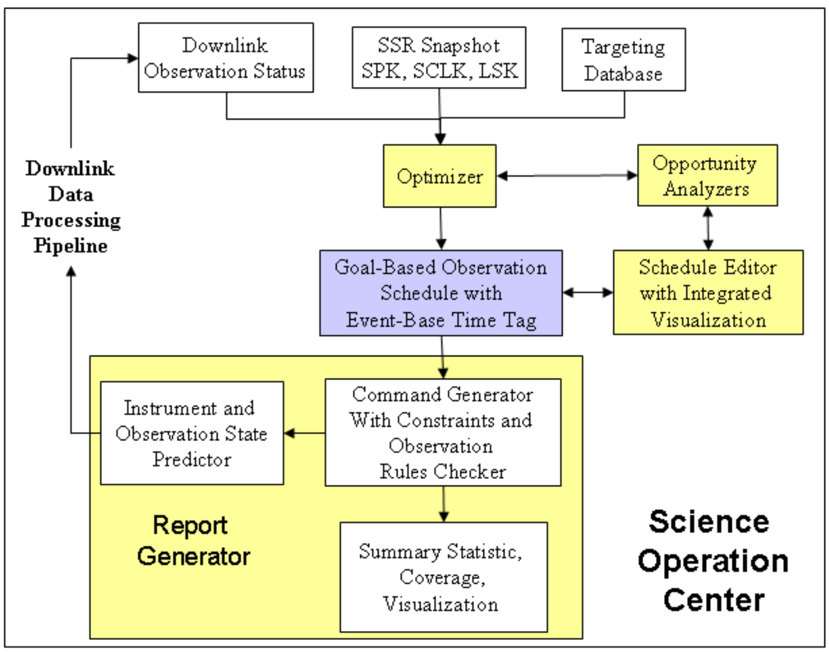

Figure 2. High-level MESSENGER SciBox system diagram. *Yellow boxes are MESSENGER SciBox subsystems, and blue boxes are goal-based schedules generated by the optimizer.*

The MESSENGER SciBox consists of four major subsystems: the opportunity analyzers, the optimizers, the goal-based schedule editors, and the report generators.

A. Opportunity Analyzers

The process of generating a new observation schedule using MESSENGER SciBox begins with the opportunity analyzers, the purpose of which is to find observation opportunities that satisfy the measurement objectives and comply with the operational constraints. There are two types of opportunity analyzers. The first is a generic interactive-manual analyzer, which has an interactive graphical user interface (GUI) for science team members to explore the opportunity space, and was used to derive the initial concept of operations. The second type of opportunity analyzer uses efficient opportunity-search algorithms in automated search engines. The efficient algorithms were developed only after the concept of operations was well analyzed and had been approved.

B. Optimizers

Observation opportunities returned by the automated opportunity search engines are compliant with the operational constraints but involve no assumption about schedule conflicts. Rather they generate the available opportunity space, which the optimizers then use to generate a conflict-free combined schedule of the best opportunities from all of the investigations. When a scheduled observation satisfies multiple science measurement objectives, it is tracked as a multi-use observation in order to avoid redundant observations. The optimizer maximizes the number of scheduled observations using scheduling priorities established by the MESSENGER science team. Figure 3 shows a snapshot of baseline scheduling priority. There are two different scheduling priority orders, one for each of the two solar days. The scheduling priority for the first solar day is biased toward mapping observations, while the scheduling priority for the second solar day is tailored toward gap coverage, high-resolution targeting, and other specific campaigns.

1st Solar Day	2nd Solar Day
Eclipse	Eclipse
Orbit Correction Maneuver	Orbit Correction Maneuver
Mercury Orbit Insertion	Downlink - High Gain Antenna
Downlink - High Gain Antenna	Priority-1 Targeted Observation
Post MOI	UVVS Polar Exosphere Scan
Priority-1 Targeted Observation	MDIS Stereo Mapping
UVVS Polar Exopshere Scan	MLA North Polar Off-Nadir Coverage
MLA Northern Hemisphere Nadir Coverage	MLA Northern Hemisphere Nadir Coverage
Priority-2 Targeted Observation	Priority-2 Targeted Observation
MDIS-WAC South Pole Monitoring	MDIS NAC 3x2 South
UVVS Star Calibration	UVVS Star Calibration
XRS Star Calibration	XRS Star Calibration
UVVS Limb Scan	UVVS Limb Scan
Priority-3 Targeted Observation	Priority-3 Targeted Observation
XRS/VIRS Global Mapping	XRS/VIRS Mapping
MDIS Global Color Mapping	Priority-4 Targeted Observation
MDIS Global Monochrome Mapping	UVVS Exosphere Scan
Priority-4 Targeted Observation	MDIS North Polar Ride-Along
UVVS Exosphere Scan	MAG Observation
MAG Observation	GRS Northern Hemisphere Coverage
GRS Northern Hemisphere Coverage	NS Northern Hemisphere Coverage
NS Northern Hemisphere Coverage	EPS Observation
EPS Observation	FIPS Observation
FIPS Observation	RS - Low Gain Antenna
RS -Low Gain Antenna	Priority-5 Ride-Along Targeted Observations
Priority-5 Ride-Along Targeted Observations	Priority-6 Ride-Along Targeted Observations
Priority-6 Ride-Along Targeted Observations	Priority-7 Ride-Along Targeted Observations
Priority-7 Ride-Along Targeted Observations	

Figure 3. Priority order of science measurement objectives for the first and second solar days.

The output of the optimizers consists of the operational schedules for the seven instruments, G&C, and the RF antenna system. These schedules are saved as goal-based operations with event-based time tags. The goal-based schedule is a departure from a traditional command-based schedule and offers a number of key advantages that were essential for MESSENGER. Traditional operations scheduling stores the actual command sequences that are going to be used with absolute time tags. Constructing the command sequences in this traditional method is usually a laborious manual process that is also prone to scheduler/operator error. The manually generated command sequences must therefore be reviewed, which is also tedious and requires involvement of command sequencers, G&C control engineers, instrument engineers, and instrument scientists to ensure that all appropriate constraints are obeyed. With absolute time-tagged commands, the command timing uncertainty becomes proportional to the uncertainty of the orbit prediction used at the time when the schedule is created. Either sufficient padding must therefore be included to account for the uncertainty in long-term orbit predictions, or last-minute time adjustments must be made. For an observations plan as complex as MESSENGER's and in the challenging resource-constrained environment of Mercury orbit, this traditional approach was deemed unwieldy and risky.

The goal-based scheduling approach was chosen because it offers advantages of flexibility while also ensuring that the observations as planned are within safe operational limits and within available resources. Goal-based scheduling stores the intent of the observations and contains the algorithms to produce science commands rather than the actual structure of the command sequences. With the event-based time-tag, time is specified relative to an orbital event such as periapsis, apoapsis, or closest approach to a surface target. The command sequence and the absolute timing are generated when the latest and most accurate orbit prediction is available. Algorithms for converting goal-based operations to command sequences can be validated with review by the engineer and subjected to extensive testing on a hardware simulator prior to orbital operations. When converted to commands, the tools also generate reports of key resources, metrics relative to constraints, and planned instrument operations to facilitate ease and reliability of engineering and science team reviews. During the orbital mission, at the start of the ASP cycle, the optimizer will be used to generate the corresponding five weeks of operations schedule, and because these schedules are event-based rather than time-based, it is only in the Near-Term Science Planning phase, when commands are about to be sent to the mission operations team for uplink to the spacecraft, that the schedules are converted to time-based command sequences using the latest orbit prediction.

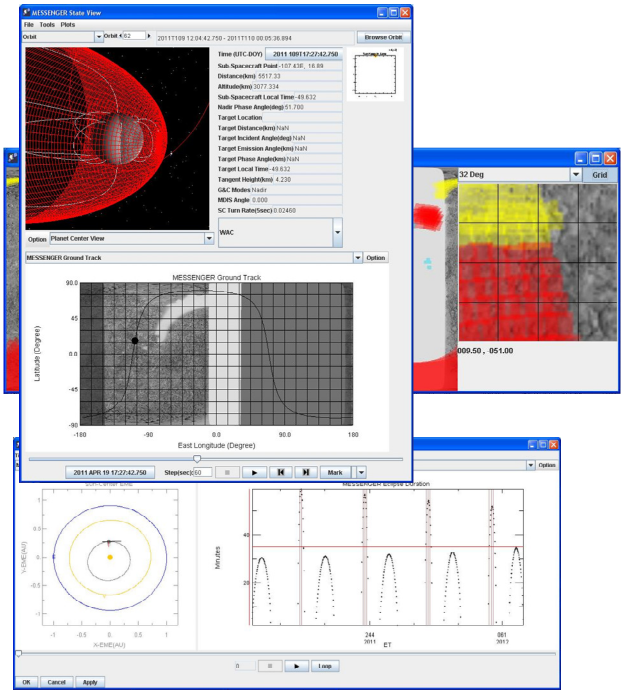

Figure 4. Sample MESSENGER SciBox interactive visualization display with VCR-like time control.

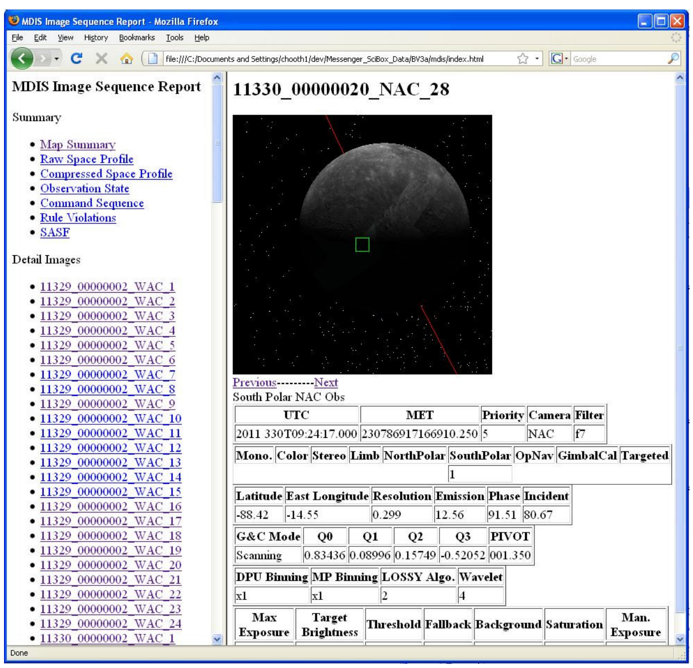

Figure 5. Outputs of MDIS report generator with hyperlinked reports. *The left panel contains indexing links to various reports, a summary plot, SSR usage, the predicted observation state, the command sequence, rule violation reports, the SASF, the actual command sequence, and an index to individual images.*

C. Goal-Based Instrument Schedule Editors

Schedule editors are provided within MESSENGER SciBox primarily for review purposes but also to allow manual editing of the schedules. The editors provide GUIs and are linked to the resource and constraint compliance checks used by the optimizers. The schedule editors are designed for final minor adjustments to the observations schedule during the ASP cycle and during NTSP to modify instrument data rates in response to near-term predictions of SSR profile available at that time. In manual editing the constraints checker is automatically invoked to provide immediate feedback to the scientists so that the final products to be sent to the mission operations team comply with operational constraints and will acquire the correct observations.

Feedback to the changes made in the editors is provided via multiple interactive graphic and text displays and reports. Scientists can use the interactive visualization to review the schedule on various time and spatial scales from mission-long periods down to sub-second time steps and from astronomical units down to meters. Visualization tools provide remote sensing instruments fields of view, footprints, and global coverage maps of various quality metrics specified by the instrument teams. The visualization tools make use of physical models of the environment from the Positions and Proper Motion (PPM) Star Catalog, the International Astronomical Union (IAU) model of planets, and a magnetosphere model adapted for Mercury's environment. Schedule changes can be validated using this interactive interface and the comprehensive output reports. The comprehensive reports can be generated interactively on the schedule-editor menu and are available for immediate review.

D. Schedule Report Generators

The schedule-report generators are the subsystems that generate the comprehensive reports. The report generators consist of three reporting systems: the command generator with built-in constraint checker; the observation and instrument state predictor; and the visualization reporter. The reports generated are hyper-linked together to aid in reviewing the outputs. The command generator with constraint checking takes less a few minutes to run even for the most complex instrument operations.

The key output of the command generator is the command sequence. The command generator reads in the goal-based schedule, generates the command sequence based on the intent of the observations, and converts the event-based time tag to absolute time from the latest orbit prediction. The command generator includes a constraint checker that checks for any operational constraint violation including SKI limits, invalid command options, invalid instrument states, and incorrect command timing. If there is an operational commanding violation, it is reported as an error. In addition to checking for operational violations, the constraint checker checks for science observation rules by comparing what has been commanded against the goal-based schedule. A warning violation is generated if the commanding is inconsistent with the schedule. A warning flag is issued instead of an error flag because there is no harm being done to the instrument except that the commanded observations might not be those desired. For example, an image marked as a star calibration is expected to have no planet in the view. If for some reason the spacecraft attitude has been altered such that the planet is blocking the instrument field of view, no operational rules are violated, but the observed images may be invalid calibration images.

The visualization report provides another independent qualitative verification. The visualization report consists of a variety of plots, from planning-cycle-long summaries, to individual detailed-observation-coverage plots, to resource-use plots. For example, the visualization shown in Figure 5 provides integrated surface coverage, shown as a hyperlinked map summary, individual image coverage shown in the right panel, and SSR resource use, shown as a hyperlinked raw-space profile and compressed-space profile.

For a more detailed and quantitative verification, the report generator produces ASCII values of predicted observation and instrument states, and the values are stored as a comma-separated value (CSV) file that can be easily imported into a spreadsheet. During orbital operation, these CSV files will also be sent to the downlink-processing pipeline where they will be used as a trigger for downlinked observations processing and anomaly detection.

VI. Development Status

At the time of this writing, the incremental orbital baseline version 3a (BV3a) has been delivered. For BV3a the optimizers and report generators were integrated to form a complete automated simulation system. From running the optimizer with an empty schedule to generating the complete mission reports by the report generators takes about 4 hours running on a dual quad-core (8 CPUs), 64-bit, 2.66-Hz server with 16 gigabytes of RAM. The simulation created 20 megabytes of operational schedules, more than 78,000 images, about 220,000 commands, and more than 1 gigabyte of summary plots and hyperlinked reports.

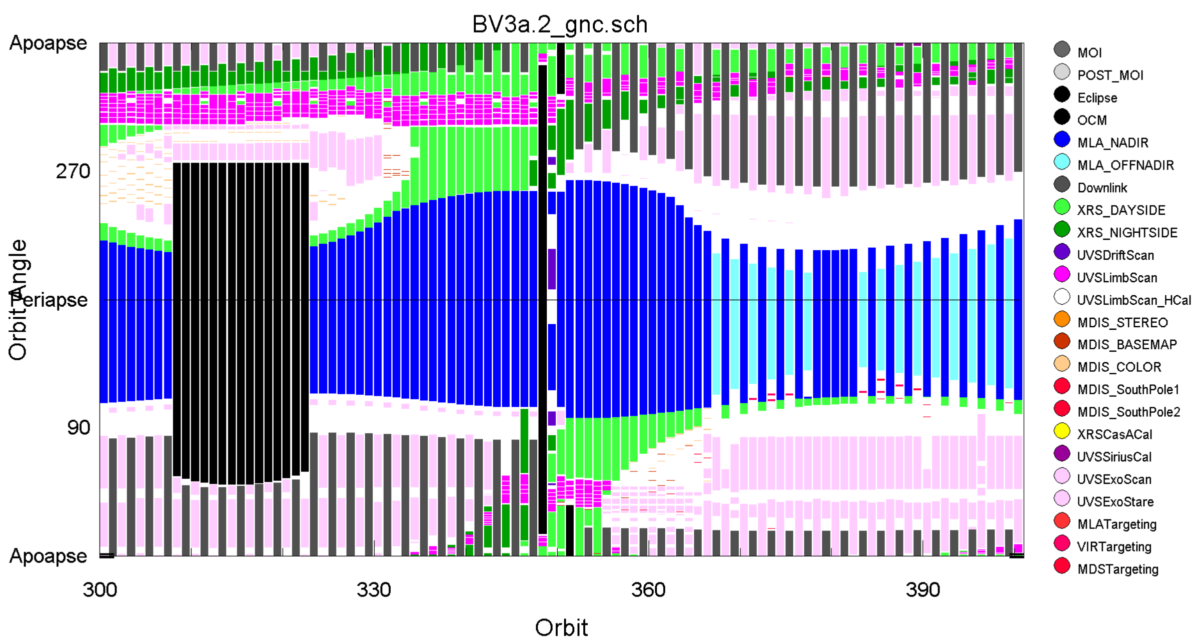

Figure 6. Sample BV3a G&C operations schedule.

Sample report plots illustrating the BV3a orbital operations strategy are given in Figures 6 and 7. Figure 6 is a plot of 100 orbits of the G&C operations schedule. Each vertical bar represents one orbit starting from apoapsis at the bottom, through periapsis in the middle, and ending at the next apoapsis at the top. The color code shows the G&C mode of operation to support the instrument driving spacecraft pointing. Even though only one instrument drives pointing at any given time, multiple instruments operate and collect science data simultaneously. For example, while MLA is controlling the spacecraft attitude, GRNS, XRS, VIRS, and MDIS also generally operate taking science data while riding along with the pointing determined by MLA. The in-situ observing instruments, MAG and EPPS, operate continuously. Because the schedules of all instruments rely on the spacecraft pointing even if it is driven by another instrument, changes to spacecraft pointing are not allowed in the NTSP cycle, since to do so would require re-execution of the opportunity analyzers and optimizers.

The spatial-resolution distribution for MDIS monochrome global mapping in displayed in a sinusoidal map projection in Figure 7. The spatial resolution is variable, but the average is 210 m/pixel. Four longitude zones in resolution are evident and correspond to four monochrome imaging seasons. They result from the combined effects

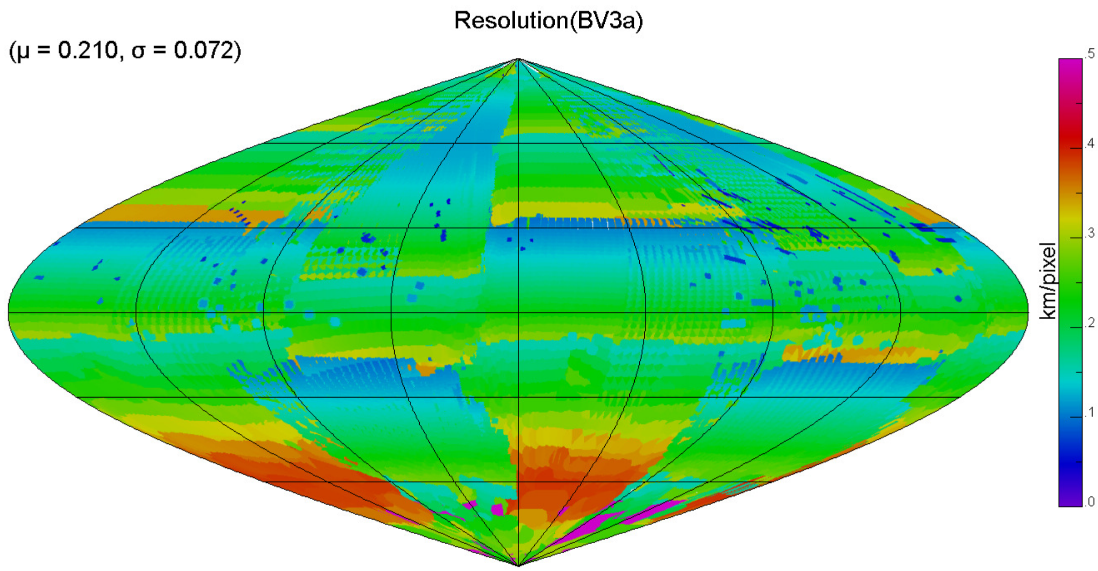

Figure 7. Spatial resolution distribution for MDIS global monochrome coverage in projected sinusoidal projection.

of Mercury's rotation and orbital motion under the nearly inertially fixed MESSENGER orbit. Within each longitude zone, four latitudinal zones in image resolution are apparent. The latitudinal zones are due to selection of camera setting according to the spacecraft altitude and velocity. Localized areas of high-resolution imaging correspond to areas of high-resolution targeted observations.

VII. Summary

The orbital phase of the MESSENGER mission presents unique planning and scheduling challenges resulting from the operational constraints imposed by the severe environment at Mercury together with the broad range of science observations objectives. To address these challenges the project has developed a mission-long simulation capability using the MESSENGER SciBox software package to simulate in-orbit operations. This package captures each science investigation's concept of operations in goal-based schedule generators, which are constrained by operational and resource limitations to match mission engineering restrictions, and generates command sequences ready for testing by the mission operations suite of tools and hardware spacecraft simulator. The package is integrated in operations planning in two distinct cycles, Advance Science Planning (ASP), which adjusts the plan to account for observations acquired to date and in response to contingencies that may arise, and Near Term Science Planning (NTSP), which converts the event-based schedule to operations-ready commands from which the spacecraft command loads are built. The tool also supports regression analyses to identify risk scenarios and develop mitigation strategies.

By means of an incremental development process, a baseline observation schedule has been derived that meets all of the science requirements and also includes resiliency to contingencies. The automated scheduling capability of MESSENGER SciBox enabled mission-long trade-off analyses that resulted in an improved orbital baseline schedule, better understanding of resource use, sharpened orbital operations strategy, and reduced risk by identifying key resource constraints, developing strategies for their mitigation, and pinpointing key capability enhancements implemented in mission flight software.

MESSENGER SciBox is an efficient and robust simulation and science observation command-generation system that can reduce operational cost and maximize scientific return. It models all science measurement objectives and is to rapidly plan and generate operations schedules for all instruments, G&C, and the RF system. The built-in constraints checker automatically validates the command sequence generated against the operational safety rules as well as science observation rules. MESSENGER SciBox has intuitive, integrated visualization displays for the scientists to modify the operations schedules interactively and provides instantaneous constraint checks and feedback. MESSENGER SciBox is an integrated part of the Science Operations Center both for command generation and for support of tracking and monitoring of downlink observations by generating planning reports and ingesting observation status and quality as feedback to the next planning cycle. MESSENGER SciBox will be a key tool that will ensure optimal science return while minimizing mission risk.

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