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AN AUTOMATED SCIENCE OBSERVATION SCHEDULING SYSTEM FOR MESSENGER

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I. Abstract

Launched in August 2004, the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft will be the first to orbit Mercury, beginning in March 2011. The spacecraft carries seven science instruments and a radio experiment designed to study all aspects of Mercury and its environment. Scheduling science observations to meet all measurement objectives during the primary orbital phase of the mission is a considerable challenge due to the thermally harsh environment and restricted viewing opportunities. The MESSENGER team therefore developed an integrated planning and commanding system, MESSENGER SciBox, to simulate the entire orbital-phase observation plan, evaluate a variety of scheduling strategies, anticipate foreseeable contingencies, analyze their impacts, and develop mitigation strategies, all before orbit insertion. In this paper we describe the architecture of the automated scheduling system, which is the core of the MESSENGER SciBox.

II. Introduction

Space science missions often use a labor-intensive approach to science observation scheduling and instrument commanding in which scientists or engineers generate and review instrument and spacecraft commands manually. For example, the Cassini mission uses multiple working groups, distributed planning tools, and a multi-level science planning and review process to achieve a conflict-free science observation schedule[1,2]. An initial departure from this methodology was made by the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) instrument team on the Mars Reconnaissance Orbiter (MRO) mission. The CRISM team developed SciBox, a fully automated science observation scheduling software system, for their instrument.[3] The CRISM SciBox tool demonstrated that a well-designed software system significantly simplifies the planning and commanding process, improves operational safety and efficiency and optimizes science return. It enabled a small team of scientists to schedule an average of 500 science observations per week achieved with approximately 50,000 instrument commands[3]. The MESSENGER mission extends CRISM SciBox from a single-instrument concept to a system capable of scheduling all observations from the array of MESSENGER investigations and providing an automated approach to generate an integrated, conflict-free observing schedule for the entire orbital mission phase.

MESSENGER SciBox is an automated science planning and commanding system that simulates the entire orbital mission and schedules science observations within operational constraints using models for each instrument and key spacecraft resources.[4] The orbital operational challenges, the approach adopted by the MESSENGER science operations team, and the general architecture of the MESSENGER SciBox have been described previously.[4] In this paper we focus on the Opportunity Search Engine and the Schedule Optimizer, which are at the core of the automated science observation scheduling capability of MESSENGER SciBox. The key new features of the MESSENGER SciBox scheduling system are the automated scheduling for the entire suite of instruments, the guidance and control (G&C) system, and the radio frequency (RF) telecommunication system. A background summary of the MESSENGER mission is given in Section III. Section IV presents an overview of MESSENGER SciBox. Section V covers the automated scheduling system. Section VI reviews sample outputs generated by the scheduling system, and section VII concludes with a summary and future plans.

III. Background

NASA's MESSENGER[5] spacecraft was launched on 3 August 2004 from Cape Canaveral Air Force Station, Florida. To lower the spacecraft orbital energy relative to Mercury, three flyby encounters with Mercury have been preformed: on 14 January

2008, 6 October 2008, and 29 September 2009. The one-year primary orbital mission phase will begin when MESSENGER enters into orbit about Mercury in March 2011.[6] The orbit will be non-Sun-synchronous and highly elliptical at 200 km x 15,200 km altitude, with an orbital inclination of approximately 82.5° and an orbital period of approximately 12 hours.

The 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, the seven instruments[7], and a radio science (RS) experiment. The seven instruments, illustrated in Figure 1, include the Mercury Dual Imaging System (MDIS) with wide-angle and narrow-angle cameras; a Gamma-Ray and Neutron Spectrometer (GRNS); an X-Ray Spectrometer (XRS); a Magnetometer (MAG); the Mercury Laser Altimeter (MLA); the Mercury Atmospheric and Surface Composition Spectrometer (MASCS), which includes two sensors, the Visible and Infrared Spectrograph (VIRS) and the Ultraviolet and Visible Spectrometer (UVVS); and an Energetic Particle and Plasma Spectrometer (EPPS), which includes a Fast Imaging Plasma Spectrometer (FIPS) and an Energetic Particle Spectrometer (EPS). The fixed remote-sensing instruments, MASCS, XRS, GRNS, and MLA, are mounted with a common boresight that is normal to both the direction to the 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 boresight direction.

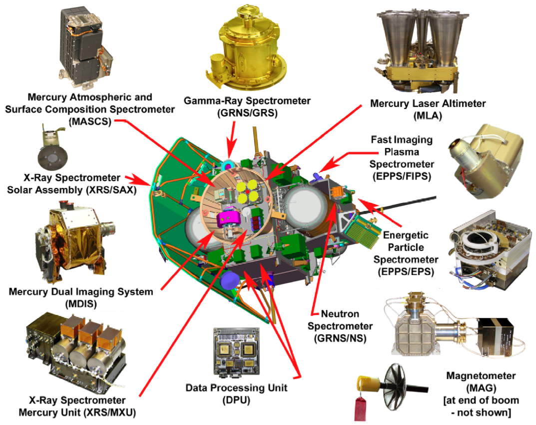


Figure 1: MESSENGER Science Payload. *This view shows the MESSENGER spacecraft from the +Z side of the main body together with detailed views of the payload sub-systems. The remote sensing instruments are mounted so as to view in the +Z direction (out of the page). The spacecraft sunshade is on the left in green, and the solar panels and Magnetometer boom are not shown in this close-up.*

The science questions motivate observation objectives and measurement requirements. For planning purposes, the measurement requirements are organized by observational activity type and are summarized in Table 1.

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 geological 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 measurements for volatile identification: EPPS • Polar exosphere measurements 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

IV. Orbital Operational Challenges

Shortly after MESSENGER is inserted into orbit about Mercury in March 2011, the one-year orbital primary science phase begins. The MESSENGER science operations team will face the challenge of planning and scheduling the set of ambitious science measurements without violating the operational constraints, which include limited spacecraft pointing control, available solid-state recorder (SSR) space, complex observation geometry, power allocation, and operational activities for orbit control and data downlink. The impact of these challenges on science observation planning is described in more detail elsewhere[4] and summarized here.

Spacecraft Attitude Limit

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[9] such that the sub-solar point remains at all times within a 12° x 10° angular boundary relative to the center of the sunshade. This in turn limits the available science observation opportunities, a situation that is partially mitigated for MDIS by its pivot, which provides a much-increased field of regard for imaging.

Solid-State Recorder Space

The SSR is an 8-Gbit synchronous dynamic random access memory (SDRAM) used to store spacecraft health and safety information as well as science data. Science data taken by the instruments are compressed prior to storage on the SSR. Once a day, for eight hours, the compressed data are downlinked to the Deep Space Network (DSN). The available downlink bandwidth varies with the Mercury-Earth distance, the Sun-Earth-MESSENGER angle, and the DSN station viewing geometry. During solar conjunctions there is no downlink activity. Due to the highly variable downlink capability, science observations must be carefully scheduled not to overflow the SSR.

Complex Observing Geometry

During the orbital science phase, because of the highly elliptical orbit, the surface-track speed peaks at 3.7 km/s at periapsis and drops to 0.6 km/s at apoapsis. Scheduled observations must account for both the orbital distance and velocity.

Observation opportunities are limited by Mercury's orbit and rotation. 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. The MESSENGER orbit plane is approximately fixed in inertial space, and this implies that comparable viewing geometries for a given location on the surface repeat only once every 176 days.

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 the fixed-mount remote sensing instruments, the majority of the observing opportunities are for off-nadir pointing.

Power Allocation

During certain orbits about 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, some instruments have to be turned off to conserve power and remain off until the power system has recharged the batteries.[8]

Competing Operational Requirements

Many of the observational activities listed in Table 1 have different spacecraft pointing requirements and compete for precious spacecraft pointing time. Scheduling the entire suite of observations must be done with great care. For example, MDIS stereo observations cannot occur at the same time as MLA nadir ranging. On the other hand, when there is an overlapping pointing requirement, observations must be carefully coordinated so as to maximize scheduling efficiency. Some observations, especially the high-resolution targeted observations, require precise timing control and must be scheduled within a few seconds in order to avoid missing the target. The global mapping measurement objectives require scheduling of more than one observation in a tightly coordinated plan. To achieve all of the observation objectives therefore requires considering the entire orbital mission plan at once as a coherent unity.

V. Approach

Scheduling the observations to meet the measurement objectives in this highly constrained environment is the most challenging task for the science operations team. It 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. The MESSENGER team is developing MESSENGER SciBox, an integrated planning and commanding system,[9] to simulate all orbital-phase observations well before orbital operations. During the orbital phase, MESSENGER SciBox will be used as the operational science planning and commanding tool to generate command requests for testing, verification, and assembly by the mission operations team in command loads. It will be used to schedule the science observations and to generate the commands for all the instruments, G&C, and the RF system.

This integrated system, MESSENGER SciBox, is based on a goal-based planning system that uses the SciBox[10,11] software library. The goal-based planning system decouples the science planning and command generation and allows scientists to focus on science observation opportunity analyses instead of commanding details. Goal-based planning systems have been successfully employed for the CRISM instrument on MRO and the MiniRF[10] instruments onboard Chandrayaan-1 and the Lunar Reconnaissance Orbiter (LRO). Underlying these planning and commanding systems is SciBox[11,12], a generic science-planning software library that contains a suite of packages for modeling the space environment and visualizing spacecraft operations.

The full simulation of the orbital operation is captured in an orbital baseline schedule. Because of the complexity of the observations, limited observation opportunities, and multiple factors constraining the observations, the baseline schedule development proceeded iteratively. This process started with the design of draft science operations concepts prepared by the science investigation teams. These concepts of operations were then converted to simulation code. A partial set of the most basic observations (e.g., monochrome imaging and in-situ observations) was identified, and then the full mission was 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.

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.

VI. The Automated Scheduling System

The architecture of MESSENGER SciBox is shown in Figure 2. During the orbital phase of the mission, it will be integrated into the MESSENGER Science Operations Center (SOC) and used by the science operations team to generate the instrument commands, G&C commands, and RF commands for all orbital observations. The core of the MESSENGER SciBox planning and commanding system is the automated scheduling system, which consists of an opportunity search engine and a schedule optimizer. Both are identified by the yellow boxes in Figure 2. It is the responsibility of the automated scheduling system to create a conflict-free science observation schedule that is then used to derive commands for submission to mission operations to test and build as command loads.

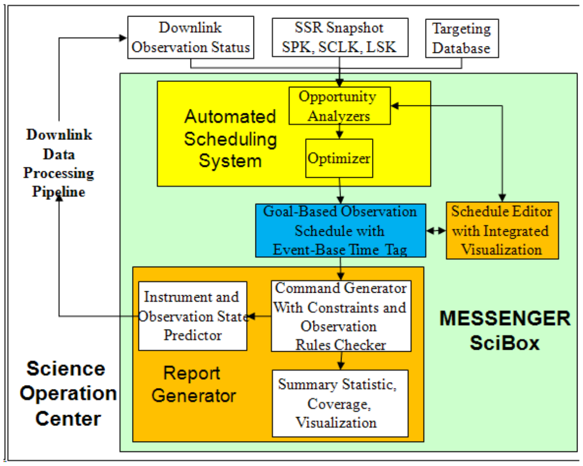


Figure 2. High-level MESSENGER SciBox system diagram. *Yellow boxes are MESSENGER automated scheduling subsystems, blue boxes are goal-based schedules generated by the optimizer, and orange boxes are the graphical user interface, for scientists to edit manually the observation schedule, and the report generator for generating coverage reports.*

Opportunity Search Engine

The scheduling processing begins with the opportunity search engine, which is a collection of many small opportunity search engines. Each small search engine is a software module for finding specific science observation opportunities that satisfy specific measurement criteria within operational constraints. The software module is coded from the concepts of operations drafted by the science investigating teams. There are small opportunity search engines associated with every science measurement objective in Table 1.

The search engines input a variety of information. These inputs include: the predicted trajectory, tunable spacecraft operational constraints, science measurement objective parameters, downlink observation 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 parameters specifying measurement objectives and acceptable observation criteria. 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 missed observations. The targeting database is a list of regions of high scientific interest developed by the science team. The targeting database can be modified during the orbital phase. The targeting database is used by the opportunity search engine to find focused, high-resolution targeted observations.

With these inputs, the opportunity search engine uses a multi-pass approach to find all operationally compliant observation opportunities. On the first pass, the opportunity search engine finds all time windows in which a surface location, a Mercury exosphere point, or a star can be observed. On the second pass, windows of opportunity that fail the operational constraints such as the SKI limit or spacecraft attitude slew rate are eliminated. Further elimination is done by filtering out windows of opportunity that fail to meet observational criteria such as the surface illumination or observing slant angle.

The final observing opportunities returned by the opportunity search engine meet the science measurement criteria and satisfy the operational constraints. Each observation opportunity completely describes the required spacecraft attitude and the required instrument operation.

Optimizer

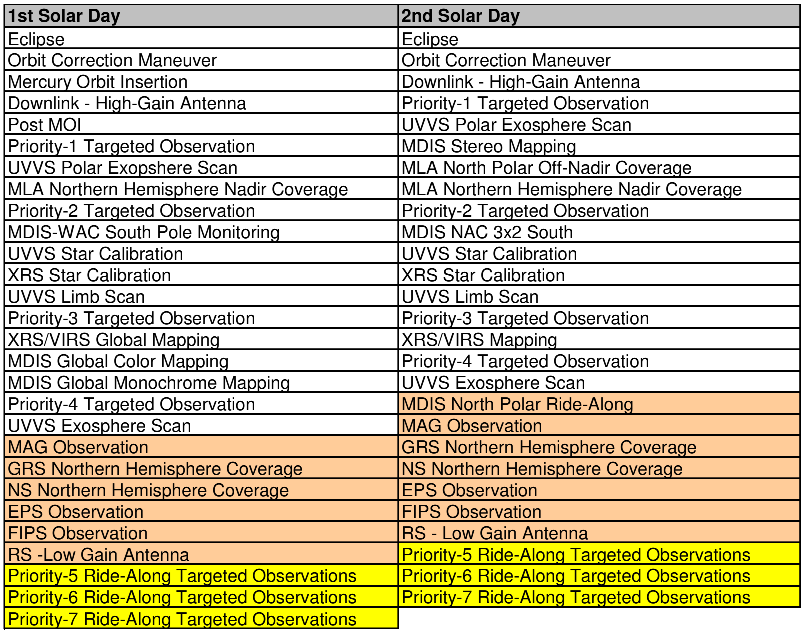
Although observation opportunities returned by the search engines are compliant with the operational constraints, they are derived without regard for schedule conflicts between different observation objectives generated by other search engines. Schedule conflicts are resolved by the optimizer after the search engines have all been run using the observation opportunity candidates as inputs. The observation opportunities can be grouped into five scheduling types, and each requires a different scheduling algorithm in the optimizer.

Stand alone Opportunity. A stand-alone opportunity is an observation or operation that has a well-defined time window and can be scheduled as a stand-alone operation. It is independent of the number of available observation opportunities and the number of times it has been scheduled. If there is no schedule conflict, the optimizer will try to schedule all of the stand-alone opportunities. A simple example of a stand-alone operation is the orbit correction maneuver (OCM), which will be performed a number of times during the orbital mission. During an orbital correction maneuver (OCM), the spacecraft will be placed in a downlink attitude, and all instruments must cease science observation activities in order not to interfere with any of the maneuver activities. The optimizer treats each OCM as a stand-alone operation, and it will schedule all of the OCM activities regardless of the number.

Single Targeted Opportunity. A single targeted observation may have many opportunities over the mission, with a variety of viewing geometries. The goal of the optimizer is to schedule the observation opportunity with the best viewing geometry. When one of the targeted observation opportunities is scheduled, the rest of the observation opportunities are dropped.

Targeted Opportunity Set. The targeted opportunity set is a variation of the single targeted opportunity. The optimizer must be able to schedule a set of matching observation opportunities. If one of the matching observation opportunities has a schedule conflict, the entire set is discarded, and the optimizer will try to schedule an alternative set. For example, a stereo imaging pair requires imaging of the same surface spot from the two different orbital positions. If either one of the imaging opportunities cannot be scheduled due to a conflict, the candidate imaging pair is dropped. The optimizer will then try to schedule the next best stereo pair. The process continues until a stereo pair is successfully scheduled or the list of stereo imaging opportunities is exhausted.

Mapping Opportunity Set. The mapping opportunity set contains a large number of observation opportunities, and the optimizer needs to select a subset to meet the global mapping objectives. For example, the number of MDIS monochrome imaging opportunities is more than one million, and the optimizer needs to schedule only a subset (less than thirty thousand imaging observations) to provide the coverage needed to meet the global monochrome mapping measurement requirement.



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.

Ride-along Opportunity. Ride-along observation opportunities are found by searching for G&C operations that have been scheduled for other measurement objectives but could be used to satisfy another science measurement objective. Examples of such ride-along opportunities are VIRS dayside ride-along observations while MLA is controlling the pointing. When MLA is performing nadir observations on the northern hemisphere, the VIRS instrument, which is co-aligned with MLA, can be scheduled to co-observe when the spacecraft is on the dayside of the planet, and return to standby when the spacecraft is on the nightside of the planet.

These five groups of observation opportunities are scheduled by the optimizer using a priority-ordered scheduling algorithm. The scheduling priority order established by the MESSENGER science team is shown in Figure 3. 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.

VII. Sample Outputs

The outputs of the optimizer are goal-based schedules for the seven instruments, plus G&C, RF, and the DSN stations. These schedules can then be immediately passed to other subsystems of MESSENGER SciBox for immediate validation and generation of visualization products.

Figure 4 shows snapshots of the G&C schedule at three different scheduling stages. All three panels show 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. The first panel shows a snapshot of the G&C schedule after the eclipse, Mercury Orbit Insertion (MOI), and OCM operations, all of which are high-priority activities, have been successfully scheduled. The black bars spanning several orbits represent MESSENGER operations during eclipse; the two vertical gray bars are the OCM or MOI activities. (MOI, which occurs prior to the first orbit, is not shown on the plot.) The second panel shows the partially filled G&C schedule in the middle of priority scheduling stages, and the last panel shows the completely filled G&C schedule when the optimizer completes the scheduling. The white space is time reserved for the spacecraft to transition from one pointing control to another pointing control.

The G&C schedule shows only the driving instrument schedule. 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. When a scheduled observation satisfies multiple science measurement objectives, it is tracked as a multi-use observation in order to avoid redundant observations.

At the time of this writing, a full-mission scheduling simulation takes about 3 hours running on

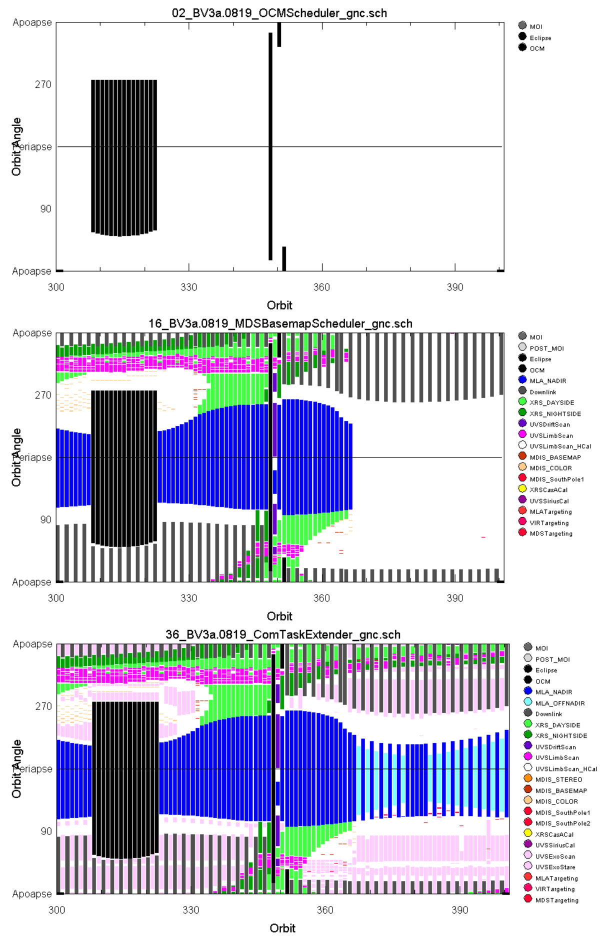


Figure 4. Snapshot of the G&C operations schedule at scheduling round 3, round 16, and round 36.

a dual quad-core (eight-CPU), 64-bit, 2.66-Hz server with 16 gigabytes of RAM. The simulation created 20 megabytes of operational schedules, and scheduled more than 78,000 MDIS images. The commands, reports, and coverage plots for all instruments, G&C, and the RF system require another hour of run time.

VIII. Summary

To address the challenge of scheduling an ambitious suite of science observations given the limited number of observation opportunities while in orbit at Mercury, the MESSENGER team is developing an automated science observation scheduling system to simulate all orbital-phase science operations, identify observation opportunities, and select observations to schedule in consonance with priorities driven by the observation objectives. We have presented the architecture of the MESSENGER SciBox automated science scheduling system that encompasses the entire suite of instruments, G&C, and the RF system science objectives. The system has been used to simulate science-observation coverage under a variety of operational strategies, to simulate foreseeable contingencies[13], and design mitigations, well before orbital operations. The results of the simulations have been captured in a mission-long baseline schedule. A command sequence derived from the observation schedule has been tested with the mission operations suite of tools and hardware spacecraft simulator. For the MESSENGER mission, integrating this automated scheduling system with the Mission Operations and Science Operations Centers will allow the science and operations teams to focus on achieving the mission objectives without becoming overwhelmed by the minutiae of manual command editing and review. Moreover, the simulation and automated opportunity search capability enables science planning to take the fullest possible advantage of the observational opportunities to maximize the science return and likelihood of mission success.

Acknowledgments

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