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# S2Ops, an Autonomous CubeSat Ground System

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## ABSTRACT

The Johns Hopkins University Applied Physics Laboratory (JHU/APL) has developed an easy to use and automated, intelligent satellite command and control ground system for the United States Government. The satellite ground system, S2Ops (SmallSat Space Operations) enables the user to task the spacecraft without detailed knowledge of the spacecraft and ground system. S2Ops presents the user with available tasking opportunities. After the user has selected the tasking opportunities, no further manual intervention is required. S2Ops will integrate the tasks with other spacecraft and payload activities, execute them, and will generate the commands for upload to the spacecraft and payload. The system controls the ground antenna in real-time and tracks the spacecraft for uplink and downlink activities. When the gateway receives downlinked data, an automated SMS message and email is sent with a synopsis of the data downloaded, and the state of the health of the spacecraft. S2Ops updates the latest ephemeris data, generates reports for archiving, and manages housekeeping activities. The software application based on the SciBox uplink pipeline used on the NASA MESSENGER mission to Mercury allows for the autonomous operation for two 3U CubeSats (ORS TECH 1 and ORS TECH 2) developed by JHU/APL, launched in November 2013, for the United States Government. Except for occasions of spacecraft anomaly resolution and special experiments, the ground system has been running 24x7.

## INTRODUCTION

The use of small nanosatellites, CubeSats, for a diverse array of mission applications has increased within the global space community since their conceptual start in the late 1990's. The standardized mechanical spacecraft specification and associated launch mechanism (i.e., the Poly-Picosat Orbital Deployer, or P-POD) has made CubeSat-based missions affordable to develop and launch. While diminutive in size, with advances in more reliable commercial electronic and miniaturization techniques, these small platforms are now able to incorporate both sophisticated subsystem designs and more capable payloads. With the success of initial pathfinder missions, CubeSat constellations will provide high temporal and spatial solutions that are not realizable with monolithic systems.

Yet, satellite ground operation cost continues to be high even for a small satellite. Tasking a satellite requires coordination of many subsystem leads. The team may include system engineers, orbit analysts, command sequencers, mission operators, payload engineers, and ground station operators. The operational process can be laborious and time consuming because it requires many iterations to design the operation sequence, resolve schedule conflicts, and review and verify for system health and safety compliance. The complexity of the planning and commanding process is agnostic to the cost of the satellite and is only related to the complexity of the complete system and criticality of the mission. For a constellation of CubeSats with distributed ground stations, planning and commanding these satellites are even more challenging.

In this paper, we describe S2Ops (SmallSat Space Operations), an end-to-end real-time automated planning and commanding system that provides a path forward for operating a constellation of CubeSats. The purpose of S2Ops was to provide an easy to use ground system to support the ORS TECH 1 and ORS 2[1] spacecraft. These 3U CubeSats, carrying a single payload, were developed for the United States Government. S2Ops is a custom application built using the SciBox library[2] and SciBox's approach to planning and commanding system[3] , which is composed of an easy to use user tasking interface, and an autonomous real-time operational system. The user-tasking interface enables the user to task the satellite without detailed knowledge of the intricacy of the operation of the spacecraft and associated ground system. The real-time planning system autonomously plans all satellites activities based on user tasking, and schedules health and safety activities based on specifications provided by spacecraft and payload engineers. The real-time system runs 24x7 unattended and generates commands to drive the spacecraft and payload, and to control the ground antennas in real-time. It also performs routine self-maintaining activities by clearing its internal computation resources and updating the latest spacecraft ephemeris.

## TRADITIONAL SYSTEM

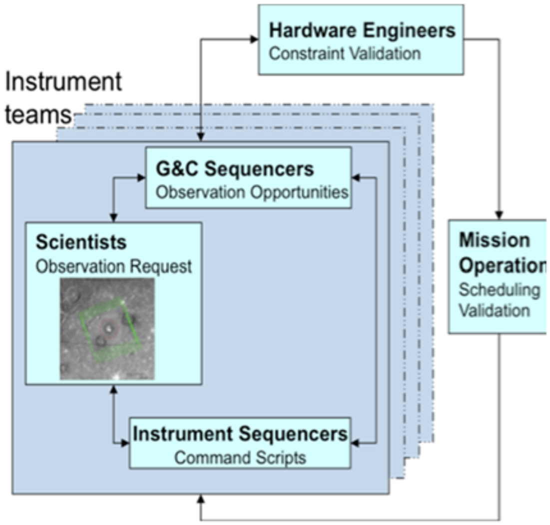

**Figure 1**: Traditional operation planning process

Spacecraft mission planning, including payload and bus operations, is a complex and iterative process which starts with a user making a request for data collection such as imaging a surface or sampling an atmosphere or magnetosphere at specified geometrics. A team of planners work with the payload engineers and guidance and control analysts to search for data collection opportunities and design the spacecraft operation sequence. The planners also work with skilled command sequencers to construct matching payload and bus 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 spacecraft and to drive the payloads has been constructed, engineers need to confirm that the sequence is within operational constraints. If there is no violation, the command sequence is then forwarded to mission operators for integration with the master mission schedule. This process is illustrated in Fig. 1

The process is laborious and non-responsive because it requires many planning iterations to derive the commands for uplink to the spacecraft and payloads. Even though every space mission is wary of the cost of this iterative process, it is necessary to ensure safe operation of the space system. Every mission designs its custom operational planning process[4,5,6] to trade acceptable mission operational risk, system performance, and available resources.

## SCIBOX UPLINK PIPELINE

SciBox's approach to operational planning and commanding efficiency is to streamline the planning process and to integrate each step with an integrated software system.

Figure 2 illustrates the rearranged processes. They begin with observation opportunity analyzers customized to each type of data collection. Instead of searching for single data collection opportunities, the opportunity analyzers search all available opportunities to, for example, image a particular region at a defined observing geometry, or to capture a spectrum at a given latitude and longitude.

For each potential collection opportunity selected, an automated, rules-based constraint checker systematically validates the data collection operation to ensure that it complies with all operational constraints. The validated collection 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 all available resources are used. An automated command generator then ingests the conflict-free schedule and generates spacecraft and instrument commands for uploading to the spacecraft.

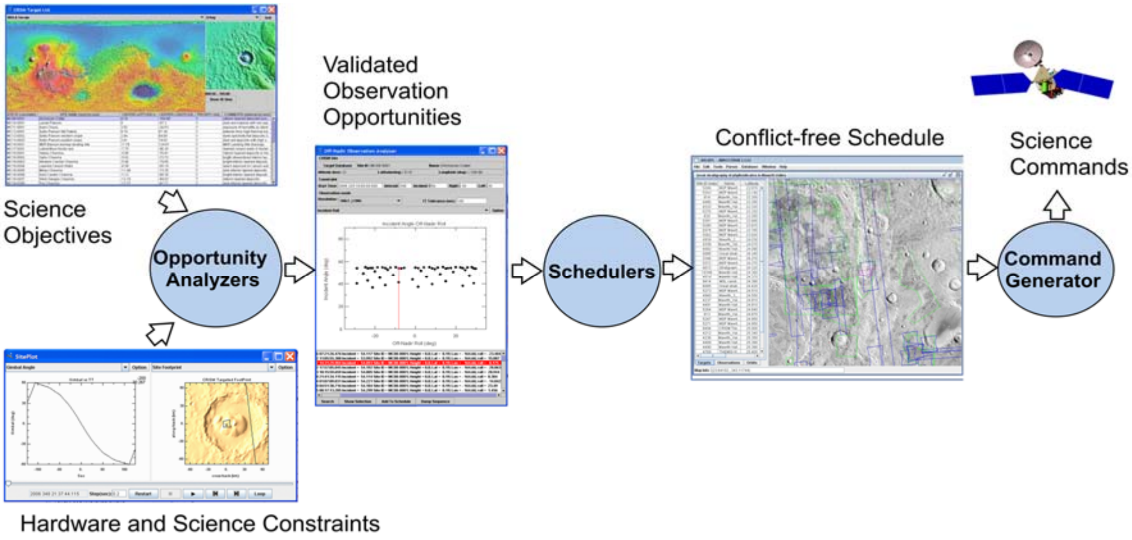

**Figure 2**: SciBox streamlined uplink process

## SCIBOX HISTORY

Development of the SciBox planning and commanding architecture was proposed in 2001. 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, 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. The CRISM planning tool[7], 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 since 2005 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.

In 2011, we scaled the system to a mission level system where we have used SciBox to plan the entire MESSENGER (Mercury Surface, Space Environment, Geochemistry and Ranging) orbital operation[8]. MESSENGER is a NASA discovery mission to study Mercury environment, and was launched in 2004 and entered into Mercury orbit in April 2011, and SciBox has been used to plan all science operation activities and command the spacecraft and all its 10 payloads. Since then SciBox has been used to plan and collect more than 200,000 images.

## ORS TECH 1 AND ORS TECH 2

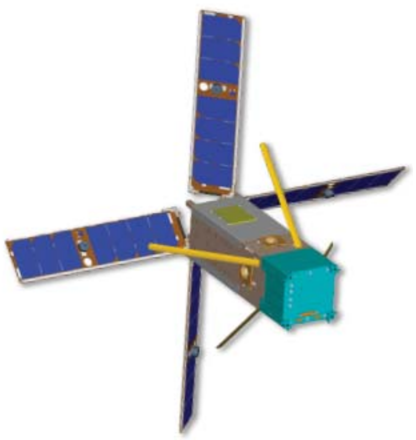

**Figure 3**: ORS TECH 1 in deployed configuration

Responding to the needs of our US Government sponsors for smaller spacecraft to more effectively utilize access lower cost opportunities into space, APL has created a flexible and modular, Multi-Mission Nanosatellite (MMN) spacecraft architecture for low-cost execution of critical missions. The MMN spacecraft architecture was created after carefully considering the requirements and their implications for a broad set of high-priority missions; the intricate technical details associated with engineering a flexible, scalable platform; and the issue of quality management to ensure successful missions. Moreover, the spacecraft platform was developed with the goal that it could become an open, nonproprietary standard broadly used by the developer community. The initial triple (3U) CubeSat hardware prototype has being designed, with two flight units, ORS TECH 1 and ORS TECH 2, launched on November 19 2013.

## OPERTIONAL CHALLENGE

ORS TECH 1 and ORS TECH 2 are small spacecraft costing less to develop compared with other NASA and DoD spacecraft that JHU/APL has previously developed. Yet, spacecraft operation planning and commanding faces the same challenges as the bigger space missions. As part of the ground system delivery requirements, the ORS TECH 1 and ORS TECH 2 must include an operational management system that is easy to use. The requirement is for the end-user to operate the complete system without APL involvement in the day-to-day operations. In addition, the system must be easy to use with minimal operator involvement.

## S2OPS ARCHITECTURE

The approach to the ORS TECH operational management challenge is to adapt the SciBox uplink pipeline to automate the operational planning and commanding process for ORS TECH 1 and ORS TECH 2. The SciBox uplink pipeline works within an event driven based system to create an autonomous real-time system, and a user-friendly graphical user interface (GUI) is then built to provide a simple means for the user to task the spacecraft through the real-time system. Figure 4 shows the S2Ops architecture.

**Figure 4**: S2Ops system architecture

The user-friendly GUI insulates the end user from the intricate detailed mission opportunity analysis, mission sequence derivation, mission constraints validation, system health and safety operation, resource scheduling, and command generation. The user enters the mission, and the system immediately uses SciBox uplink pipeline to perform the mission opportunity analysis, mission sequence derivation, and mission constraints validation, and then presents to the user a list of validated mission opportunities. When the user selects one of the validated opportunities, S2Ops real-time system re-optimizes the mission schedule, and generates a new set of commands for uplink to the spacecraft.

The S2Ops real-time system runs 24x7, and is temporarily paused only when a user is making a tasking order. Otherwise, it runs continuously to check the spacecraft state of health and ground system state of health. When there is a scheduled ground station and satellite contact, it sends commands to and receives telemetry from the spacecraft. Simultaneously, real-time commands are also generated to steer the ground antenna motor to track the spacecraft during contact.

The S2Ops real-time system is built by wrapping SciBox processing pipeline inside an event-based architecture. The event-based architecture uses external and internal inputs to provide real-time asynchronous services and processing.

Whenever the user adds new tasking or removes existing tasking from the system, a created event triggers the system to optimize the operational schedule, and to generate a new set of commands. S2Ops optimizes the schedule so that health and safety activities are among mission activities tasked by users. The S2Ops system spreads activities out over time so that the battery has enough time to recharge.

Health and safety background task are activities not related to mission activities, but are necessary to keep the spacecraft in an operational condition. For example, S2Ops must set the flight system counters to ensure smooth operation.

Besides the routine setting of spacecraft counters, the spacecraft clock drifts over time so S2Ops keeps the clock synchronized with the GPS time system by generating time synchronization commands to the onboard GPS receiver. ORS TECH 1 and ORS TECH 2 need an accurate clock to precisely activate and deactivate various onboard spacecraft subsystems and the payload at the scheduled time.

The Guidance Navigation and Control (GNC) subsystem also requires an accurate onboard clock and accurate spacecraft position to maintain attitude and orientation. The spacecraft position is derived by propagating the position-velocity vector sent from the ground. S2Ops also schedules position-velocity vector updates for the GNC subsystem.

In the absence of unforeseen anomaly such as an energetic solar flare, the spacecraft should operate without any manual intervention with all the commands sent from S2Ops.

On the ground, S2Ops operates to support unattended operation and to perform self-maintenance activities. S2Ops generates internal events to trigger the uplink pipeline to re-plan activities, and to control external system based on the optimized operational schedule.

From the operational schedule, S2Ops determines which spacecraft will be in communication with the ground station and will steer the antenna to track the spacecraft. The motor (antenna rotator) moves the ground antenna 0-450 degrees in azimuth rotation and 0-180 degrees in elevation control. The computer running S2Ops connects to the motor (antenna rotator) through the RS-232 serial port and sends commands to the motor controller at 9600 baud to ensure smooth tracking.

For scheduled command uplinks, S2Ops generates the commands and sends it to the ground radio for transmitting to the spacecraft. Built into the S2Ops commanding system is a command resend capability. Commands sent by S2Ops are not always received by the spacecraft. S2Ops breaks the entire set of commands in batches. After the uplink of a batch of commands, S2Ops uses the command count confirmation to decide whether it needs to resend commands. If command uplink is a success, it sends the next batch of commands. The real-time retransmission and active antenna steering without manual intervention allows for unattended uplink operation.

If the communication is a telemetry downlink, S2Ops steers the ground station antenna without sending commands through the radio. Immediately right after the telemetry downlink, S2Ops parses the downlink packet to determine the spacecraft's state of health. It uses the state of health information to flag if the spacecraft is healthy, needs attention or in trouble. An email or SMS text message sends a summary of the spacecraft state of health to the mission operators.

When there is no user tasking, no uplink, and no telemetry downlink, S2Ops takes a snapshot of the system. It creates a comprehensive report for archiving. The comprehensive report includes historical and future activities, commands sent, and log of all processing activities.

## DISCUSSION

Due to the nature of the program, S2Ops had a short development time and test time before delivery to the end-user for operational evaluation. Development of S2Ops in such a short time was workable only with the availability of a mature SciBox planning and commanding system, and the use of an agile development process. Instead of starting from scratch, SciBox planning and command pipeline provided a framework for S2Ops to build upon. The SciBox software library contained many software components that were ready for use by S2Ops. At the start of S2Ops development, requirements were only at high system level, much of the operational environment was not well known, and some of the hardware performance was still under test. In this dynamic development environment, the agile development process was ideal to the S2Ops development. From the start of S2Ops development to delivery of S2Ops to the end-user for operational evaluation was approximately six months.

The major challenge in developing S2Ops was building the real-time 24x7 system. Although SciBox can run in a real-time operation environment, the real-time system was never developed and validated. Before S2Ops, the SciBox uplink pipeline operated as a standalone analysis tool, or as a number crunching batch processing application.

In this standalone application setting, even though there is no manual planning and command scripting, SciBox processing pipeline still runs with manual intervention each time to plan the operation sequence and to generate commands for uplink to the spacecraft. Inputs to the system were manually collected and specified at each run.

For the autonomous real-time system, inputs must be collected, and S2Ops internal states updated with the new inputs without manual intervention. With the system running 24x7, any memory leak will accumulate in the system and could crash the system. S2Ops performs self-maintenance such as pruning obsolete tasking that takes up memory space. Memory leaks in a sophisticated system are hard to test. To test S2Ops, it has to run without interruption. With changing requirements and better understanding of the spacecraft, the optimization of S2Ops was ongoing, and the older version of S2Ops needed to be stopped to run the newer version. Sometimes the operating system rebooted due to other non-related S2Ops activities. All these activities interrupted the testing. For S2Ops, we have to resort to estimating memory leaks by extrapolating tests spanning a few days.

One of the S2Ops requirements is that it must be easy to use with minimal training. As part of delivery, JHU/APL provided about an hour of training on S2Ops. All trained users were able to task the system in minutes without any help from an experienced operator. On the day of delivery, the US Government was able to unpack the cargo boxes, connect all the cables, set up the ground station, task the spacecraft, uplink the commands and collect the data all in one day.

For normal operation, S2Ops has been running without any major issue. But, since the delivery of the ground segment, the spacecraft and ground hardware have suffered unexpected anomalies that required JHU/APL personnel reach back support. During anomaly investigations, the manual commanding tool was used in conjunction with S2Ops. The manual commanding tool constructed the diagnostic command sequence, and S2Ops scheduled the contact with spacecraft, controlled the ground antenna, and sent the commands to the spacecraft.

## SUMMARY

JHU/APL has developed an easy to use, intelligent satellite command and control ground system that can run 24x7 without manual intervention. S2Ops provides an easy to use tasking interface, optimizes user tasked data collection activities with spacecraft maintenance activities, generates commands for uplink to the spacecraft, monitors the spacecraft by parsing the downlink state of health packets, sends SMS or email summarizing the state of the spacecraft, controls the ground antenna to track the spacecraft, and performs maintenance activities with periodic updates. All these activities are done without any manual intervention. This new capability is extending the benefits of the space system to a wider community by enabling non-space experts to task their space asset in minutes, perform mission activities, and collect telemetry data. The system removes the need for users to bear full knowledge of the intricacy of the satellite and ground system design. The system reduces operational cost, and solves the inefficiencies that constrain traditional planning and command systems. S2Ops's automated planning and commanding approach addresses this and other critical challenges enabling the affordable, dependable operation of satellite constellations.

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