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Efficient SmallSat Operation using SciBox

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ABSTRACT

Planning and commanding a space operation is inherently a very complex task requiring highly skilled operators from various disciplines coordinating in a timely manner to ensure both smooth and successful operation. This process can be performed manually, however, resolving conflicts quickly becomes an intensive iterative process that underuses a space system's resources and renders it less responsive to sudden schedule changes. Increasingly complex space missions combined with the desire to maximize efficiency require a different approach. Responding to these challenges is SciBox, an autonomous planning and commanding system and a technology enabler for space operations, developed by the Johns Hopkins University Applied Physics Laboratory (APL). Since its development in 2001, SciBox has automated the processes of translating user requests into a series of satellite operations, searching for observation and data collection opportunities, scheduling required resources and contact with ground stations, generating command sequences to drive payloads and spacecraft, and validating the generated command sequences against operational health and safety constraints. Continual improvements to SciBox and to the SciBox development process through its application on a number of APL small sat missions will be discussed in this paper.

The initial use of SciBox for small sat operations was on the ORS Tech 1 and ORS Tech 2 Multi-mission Bus Demonstration (MBD) program. This program required an easy-to-use, operational management system for use by a non-APL operations team. This instantiation of the SciBox was named S2Ops. With a user-friendly, graphics interface built, this version of SciBox was an ideal solution for the government operations team.

For the CubeSat Signal Preprocessor Assessment and Test (CAT) mission, APL operates two 3U satellites, each hosting an industry-provided RF instrument, in low Earth orbit (LEO). APL operates the satellites using SciBox, which provides key features to autonomously manage satellite constellations. Given the limited operational resources and the desire to maximize the number of experiments performed, SciBox is an ideal solution for the CAT mission. SciBox reduces the lead time for operations planning by shortening the time-consuming coordination process, reduces cost by automating the labor-intensive processes of human-in-the-loop adjudication of operational priorities, reduces operations risk by systematically checking mission constraints, and maximizes data return by fully evaluating the trade space of experimental opportunities versus spacecraft recorder, downlink, scheduling, and orbital-geometry constraints. SciBox is also used on CAT to generate a command schedule that executes the following operations: South Atlantic Anomaly (SAA) constraints, experiment configuration schedule, ground station contacts, delta-differential drag maneuvers, and flight safety constraints.

Finally, the latest application of SciBox is to the Electrojet Zeeman Imaging Explorer (EZIE) mission, which studies the electric currents that play a crucial role in the interactions between Earth and the surrounding magnetosphere. EZIE consists of three 6U CubeSats flying in a pearls-on-a-string orbit configuration, each carrying a Microwave Electrojet Magnetogram (MEM) instrument. This mission will utilize the SciBox capabilities demonstrated on CAT, but also include enhanced features such as early spacecraft recovery by using the observed carrier frequency (or Doppler shift), and support the systems integration phase prior to launch.

INTRODUCTION

SciBox is an autonomous planning and scheduling system developed by JHU/APL which streamlines the command process pipeline and then automates those steps with an integrated software system. This suite of tools has been used on various missions, both large and small and shown to add to the efficiency and responsiveness during mission operations while also serving as a technology enabler.

Planning and commanding a space operation is inherently a very complex task and requires highly skilled operators from various disciplines to coordinate in a timely manner to ensure successful operation. This process can, and often is, performed manually. However, resolving conflicts quickly becomes an intensive, iterative process resulting in under utilization of a system's resources, rendering it less responsive to sudden schedule changes. SciBox was developed to address these issues by translating user requests into a series of satellite operations, searching for observation and data collection opportunities, scheduling required resources and contact with ground stations, generating command sequences to drive payloads and spacecraft, and validating the generated command sequences against operational health and safety constraints.

BACKGROUND

SciBox was originally built to meet the needs of several programs in the APL Space Exploration Sector (SES). It is a software library designed specifically for space operation simulation, planning, and commanding. The SciBox library has an extensible architecture, allowing capabilities to be continually developed and integrated into it. Therefore, it is not a ready to use application but rather a toolbox for rapid development of customized, focused software applications. SciBox enables rapid development of high-fidelity operation simulation tools for use at the earliest stages of mission development, reduces the cost of developing operation simulation tools for use in spacecraft testing, instrument testing, and science operation planning and commanding.

Development of the SciBox uplink pipeline architecture was proposed in 2001. However, no planners of space missions worth hundreds of millions of dollars would accept a new unproven system to solve a complex problem. To bring the proposed theoretical architecture into reality, key SciBox software modules were developed and demonstrated incrementally over 11 years on a variety of spaceflight projects at the Johns Hopkins University Applied Physics Laboratory (APL). The opportunity analyzer concept was initially demonstrated on an Earth-orbiting satellite. The constraint analyzer was then added for payload planning on a Saturn mission. Adding the scheduling and commanding system for a Mars mission resulted in the first end-to-end payload commanding system for SciBox. Finally, the end-to-end system was extended to the entire payload and guidance and control system for a Mercury mission. Continual improvement then enabled the team to build an autonomous operational system for a pair of CubeSats. Currently, the team is scaling the autonomous system for a constellation of satellite-hosted payloads. In 2017, it was used to deliver an operational intelligent autonomous system for a large constellation of payloads hosted on commercial satellites. Although SciBox has been used for large scale system, it is flexible enough to be tailored for small project, or for project where some level of manual control is required.

SCIBOX ARCHITECTURE

The SciBox architecture begins with uplink inputs customized for each type of operational objective (see Figure 1). Examples of objectives are to collect data from a particular region at a defined observing geometry, to acquire data at a given latitude and longitude, or to collect a particular signal of interest. The opportunity analyzers then search all available opportunities and rank them according to metrics that represent measures of data quality such as resolution, illumination, or signal strength.

An automated rules-based constraint checker systematically then validates each potential opportunity selected for compliance with all operational constraints. These validated opportunities are sorted according to priority and by statistically weighted data-quality metrics. Using the list of sorted, weighted opportunities, a software scheduler selects the best combination of observations, placing first the highest-ranked and then successively lower-ranked observations into a time line until available resources are exhausted. The automated command generator then ingests the conflict-free schedule and uses it to generate spacecraft and instrument commands for uplink.

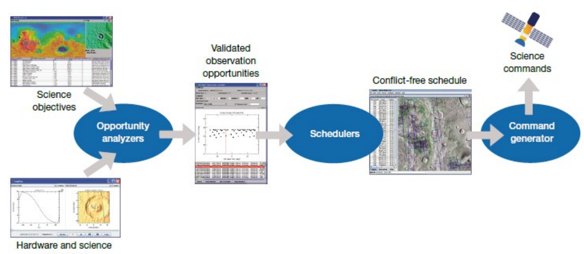

Figure 1 – SciBox Uplink Pipeline Architecture

APPLICATIONS

Since its inception in 2001, continual improvements have been made to SciBox through its application on a number of APL small sat missions. The following sections describe those missions and the impact SciBox had on operations.

MBD

ORS Tech, also known as Multi-mission Bus Demonstration (MBD), was a mission designed and built by JHU/APL. MBD demonstrated the operational military utility of a small satellite by leveraging past experience to create a flexible and modular spacecraft architecture that would allow low-cost execution of critical missions. JHU/APL designed and built two 3U Cubesats to achieve the desired combination of performance and reliability. These satellites were launched and deployed on November 19, 2013 and successfully provided payload telemetry before de-orbiting in April 2015.

At the time of MBD's development there were very few companies providing CubeSat components or spacecraft buses with space flight heritage. JHU/APL designed nearly every facet of the MBD spacecraft to maintain optimum payload mission performance at any altitude and orbit. In addition to designing and building the space vehicles, the mission operations were conducted by JHU/APL in Laurel, MD using the L3 Technologies InControl^{TM} Satellite Command and Control Software. The MBD ground station consisted of a Yagi antenna, antenna controller, ground transceiver that was almost identical to the spacecraft transceiver, and a computer to plan and execute the mission.

Often the challenges of planning, commanding, and scheduling small sat operations are similar to those of larger space missions. MBD required an operational management system that was easy to use and could be operated by the end user without APL involvement in the day-to-day operations. In addition, the system required minimal operator involvement. To meet these requirements, MBD was the first of the JHU/APL small sat missions to leverage SciBox (called S2Ops for MBD) for end-to-end automated spacecraft planning and commanding. S2Ops was built by wrapping the SciBox uplink pipeline in an event-driven-based architecture, shown in **Figure 2**, to create an autonomous real-time system. A user-friendly graphical user interface was built to provide a simple means for the user to task the spacecraft through the real-time system.

The graphical user interface was designed to separate the end user from the detailed mission opportunity analysis, mission sequence derivation, mission constraint validation, system health and safety operation, resource scheduling, and command generation. The user enters the tasking request, and the system immediately uses the SciBox uplink pipeline to perform the opportunity analysis and presents the user a list of validated collection opportunities. When the user selects one of the validated opportunities, the S2Ops real-time system re-optimizes the mission schedule and generates a new set of commands for uplink to the spacecraft.

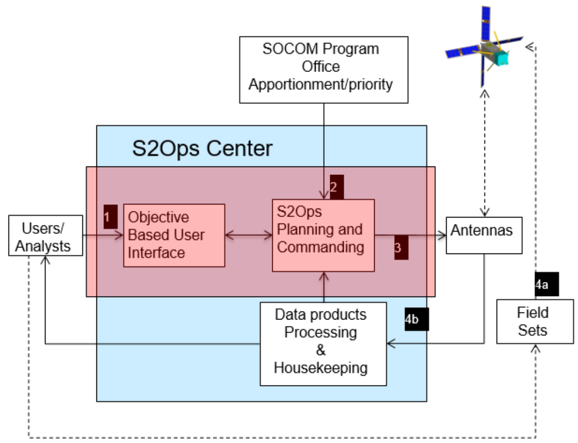

Figure 2 – S2Ops for MBD

The S2Ops real-time system ran 24 hours a day, 7 days a week (pausing only when a user was making a tasking order) to continuously to monitor the health of the spacecraft and ground systems. During scheduled contacts between the ground station and satellite, S2Ops sent commands to the spacecraft and received telemetry from the spacecraft. Simultaneously, the system generated real-time commands to actively steer the ground antenna motor to track the spacecraft during contact. For planned downlinks, S2Ops compared the actual data downlink with planned activities. The system then summarized the results and sent messages to the user, thus freeing the user from constant presence at the console. Using SciBox allowed JHU/APL to deliver a ground station to the end-user to 'fly' their spacecraft and plan their own missions with limited training.

CAT

The primary objective of the CubeSat Signal Preprocessor Assessment and Test (CAT) mission is to use two COTS 3U spacecraft to support a communications experiment. JHU/APL performed the role of mission integrator for CAT by performing a wide range of tasks including: an initial assessment of industry-supplied spacecraft buses, management and oversight of the development of the spacecraft (provided by Blue Canyon Technologies [BCT]), system integration and test of the payload and the spacecraft bus, and mission operations using an automated planning and commanding technology.

On January 31, 2019, the CubeSat Assessment and Test (CAT) mission deployed from the International Space Station (ISS). CAT completed its primary mission success objectives in two months and continued to collect mission data two years post-launch. During deployment and initial checkout of the space vehicles, the CAT mission operations (MOPs) team was involved with the day-to-day activities, with SciBox only being used to create the daily command load files (and the MOPs team performing manual checks prior to upload). After meeting mission objectives, the focus shifted to increasing data return from the payloads on the two spacecraft with the CAT team working to evolve the mission to continue to maximize its payload data return. Over time, the mission operations team moved to unattended operations with more and more reliance on SciBox.

Given the limited operational resources and the desire to maximize the number of experiments performed, SciBox is an ideal solution for the CAT mission. SciBox provides key features to autonomously manage satellite constellations such as: reducing the lead time for operations planning by shortening the time-consuming coordination process, reducing cost by automating the labor-intensive processes of human-in-the-loop adjudication of operational priorities, reducing operations risk by systematically checking mission constraints, and maximizing data return by fully evaluating the trade space of experimental opportunities versus spacecraft recorder, downlink, scheduling, and orbital-geometry constraints.

CATApp is an instantiation of SciBox, which is a larger software platform, used across other APL missions, including TIMED, MESSENGER, and MBD. For the CAT mission, CATApp generated a deconflicted command schedule for each satellite on a weekly basis. A command schedule is essentially a sequential list of timetag commands and configurations that satellites execute. **Figure 3** provides the input and output data flow for CATApp. The Mission Operations Team implemented CATApp in the following sequence during a single planning session:

1) Schedule South Atlantic Anomaly (SAA) events
   a. Calculated SAA crossings based on TLE propagation and SAA zone definition
   b. Powered off payload and GPS receiver
   c. Protected sensitive components from radiation effects
2) Schedule payload collect events
   a. Imported Payload Scheduling Requirements (PSR) provided by Payload Team
   b. Executed payload collect sequence
3) Schedule ground station contacts
   a. Imported confirmed contact schedule provided by Mission Operations Team
   b. Executed ground station contact sequence
4) Schedule eclipse maximum differential drag maneuvers
   a. Imported differential drag maneuver report provided by MDNAV Team
   b. Executed maximum differential drag maneuvers during eclipse periods
5) Schedule eclipse minimum differential drag maneuvers
   a. Calculated eclipse crossings based on TLE propagation and eclipse prediction
   b. Executed minimum differential drag maneuvers during eclipse periods

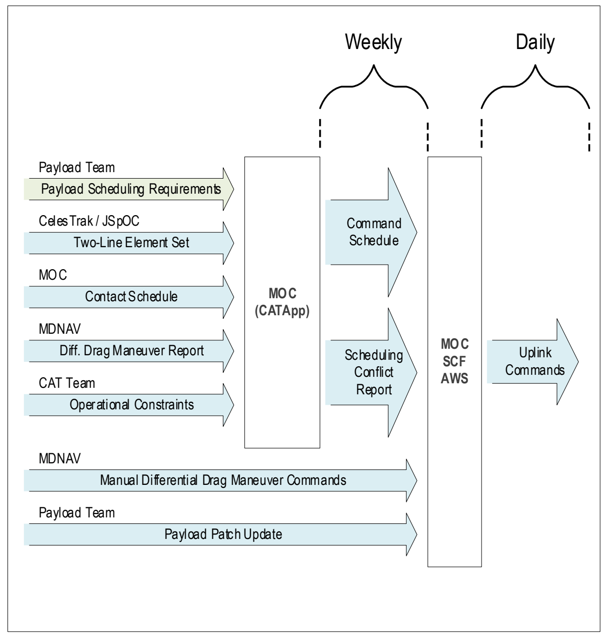

Figure 3: CATApp Data Flow

In addition to scheduling activities, CATApp also enforced operational constraints:

1) Prevent scheduling of a payload collect within 6 hours of each other (≈ 4 orbits)
   a. Allowed for power and thermal recovery
2) Prevent scheduling of a ground station contact when ISS, NOAA-20 or SNPP satellites are in view of the SCF or AWS ground stations
   a. Protected high priority assets from potential RF interference
   b. Restricted for uplink only, therefore, downlink could continue, if needed

CATApp also allowed updates to operational sequences and configurations throughout mission:

1) Adjusted timing and constraints of command sequences for payload collects, SAA crossings, differential drag maneuvers, etc.

    a. Some adjustments allowed for more collect opportunities
2) Reconfigured attitude definition for minimum differential drag maneuver
3) Added new payload command sequence to allow the packetization and transfer process to be deferred to another time after a collect whenever there is conflict with an SAA crossing
    a. Created more collect opportunities
4) Added new attitude and site definitions for payload collects
    a. Provided more scheduling flexibility for payload collects
5) Added new schedulable ground stations for AWS
6) Added new payload configuration fields for a payload collect (e.g. priority, transfer rate)
7) Added feature to offset payload collect start times by comparing the TLE used for payload collect planning and the current TLE used for generating satellite commands
    a. Implemented towards end-of-mission when JSpOC TLEs were less accurate

Over the duration of the mission, using CATApp is estimated to have reduced mission operations time by 98% for the planning and commanding task. A manual approach to mission ops took up to 2 hours per day for nominal planning and commanding tasks, resulting in 14 hours per week. Once CATApp was established and set up with the proper activities and constraints, the routine planning and commanding activities were reduced to ~15 minutes per week. This does not include command uplink activities for each satellite.

Additionally, CATApp also increased the number of payload collects the system was able to attain. With adjustments and fine-tuning of CATApp activities and constraints, the collect coverage over the areas-of-interest increased from 86% to 157%. Specifically, these changes included:

1) Changing the scheduling constraint of a payload collect within 9 hours of each other to 6 hours
2) Adding new payload command sequence to allow the packetization and transfer process to be deferred to another time after a collect whenever there is conflict with an SAA crossing
3) Adding new attitude definitions for payload collects that eliminated the need to add new sites into CATApp and MDNAV
    a. Provided the Payload Team a "port" & "starboard" attitude configuration that were defined as a "collect site", and as a result, collects were no longer dependent on a specific pre-defined site location, ground elevation angle or line-of-sight, but were still dependent on time, however, the Payload Team still occasionally used the pre-defined mission sites for convenience

Mission operations implemented CATApp on a weekly basis. Towards the last few months of the mission prior to deorbit, mission operations implemented CATApp two to three times a week to ensure accurate timetag commands. Changes to CATApp followed an informal engineering change process that was implemented by a software engineer and verified by the systems lead, along with relevant affected stakeholders, prior to flight implementation. The team also implemented a simple software configuration management process that tracked changes and allowed for reversion to a previous state.

EZIE

Electrojet Zeeman Imaging Explorer (EZIE) is a recently selected NASA heliophysics mission flying three 6U CubeSats in a pearls-on-a-string orbit configuration in low Earth orbit (LEO). EZIE will study electric currents in Earth's upper atmosphere linking aurora to the Earth's magnetosphere – one piece of Earth's complicated space weather system, which responds to solar activity and other factors. Similar to CAT, EZIE will leverage differential drag maneuvers to manage the separation distance between each satellite without the use of a propulsion subsystem. Also similar to CAT, EZIE intends to use SciBox, leveraging all of the lessons-learned. **Figure 4** provides the input and output data flow concept for SciBox within the EZIE architecture. The key differences between EZIE and CAT implementation of SciBox are as follows:

1) EZIE Science Operations Center (SOC) will host and manage SciBox
2) SciBox will determine the required differential drag maneuvers for each satellite based on inputs from Mission Design & Navigation (MDNAV) and Mission Operations Center (MOC)
3) SciBox will manage instrument patch updates for each satellite
4) SciBox will leverage orbit states from multiple sources: daily orbit states based on GPS solutions provided by the MOC, TLE states provided by the Joint Space Operations Center (JSpOC) and custom ephemeris data from MDNAV
5) SciBox will automatically generate daily command schedules with at least a 4-day outlook with feature to manually generate command schedules

SciBox is capable of providing autonomous operations to enable more "hands off" operations. For EZIE and CAT, only the basic open-loop planning features were leveraged, which still provides high value to small sat operations. As program budget allows, future small sat missions, including EZIE, should consider more advanced features such as:

1) Autonomous ground station contact scheduling and cancelling
2) Satellite power and thermal predictions and constraint-checking
3) Real-time and playback telemetry processing, monitoring, analysis and trending
4) Real-time and unattended satellite commanding

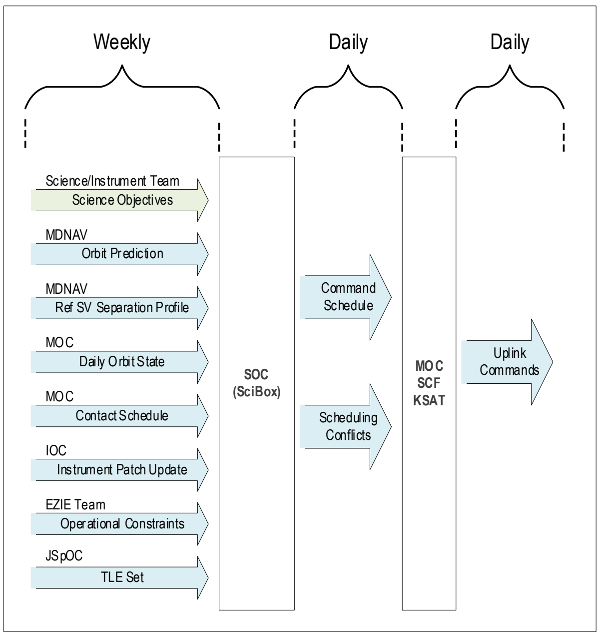

Figure 4: EZIE SciBox Data Flow

CONCLUSION

SciBox has now been demonstrated on both large and small-scale projects. However, as seen in this paper, SciBox is especially ideal for low-cost small sat constellations. The evolution of the SciBox tool for small sats has resulted in a flexible architecture that enables new and modified features or command sequences during flight with minimal software engineering support. SciBox provides a streamlined, stable, and routine approach for planning and commanding satellite operations. The benefits seen from the application of SciBox on small sat programs includes easing the process burden of the mission operations team, reducing the overall risk of operator or process errors, increasing system availability and responsiveness, and reducing mission operations labor costs. The output products are highly consistent between each planning cycle, providing high confidence in mission execution.

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