SciBox: An Autonomous Constellation Management System

Teck H. Choo, Alice F. Berman, Hari Nair, Lillian Nguyen, Joseph P. Skura, and R. Joshua Steele

ABSTRACT

Planning and commanding a space operation is inherently a very complex task. It requires highly skilled operators from various disciplines to coordinate in a timely manner to ensure smooth and successful operation. The process involves 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. Resolving conflicts manually is an intensive iterative process that underuses a space system's resources and renders it less responsive to sudden schedule changes. As space missions become ever more ambitious, this manual approach is challenged to cope with the increasing complexities of space systems. Responding to this challenge is SciBox, an autonomous planning and commanding system and a technology enabler for space operations. The Johns Hopkins University Applied Physics Laboratory (APL) has been investing in SciBox since 2001. Continual improvement to SciBox and to the SciBox development process enabled the creation of more efficient space operational systems packed with more capabilities. This article describes the architecture of SciBox, the approach to its development, how its capabilities were incrementally developed, and how its use has grown over several space missions.

INTRODUCTION

A planning and commanding (or execution) system for space operations is responsible for processing user requests into commands to drive ground stations, spacecraft, and payloads. The process of turning user requests into executable commands requires coordination of technical experts from a variety of disciplines. The team may include systems engineers, orbit analysts, command sequencers, mission operators, payload engineers, and ground station operators. The high cost of space missions requires the team to use sophisticated processes to ensure that commands perform as intended without compromising the spacecraft's health or safety. The more capable a space system is, the more complex the planning and commanding system is. For some space missions, the planning process is so complex and time consuming that the system is unable to quickly respond to short-term change. As a result, the system drops critical user requests and underuses resources. The cost of developing a traditional planning system grows as system complexity increases, and in extreme cases, spacecraft capabilities or even mission objectives must be scaled back to contain cost. Even worse, proposals for worthwhile space missions could be dismissed because the ground operational cost is perceived to be too high or operational planning is perceived to be too challenging.

If the planning system is much more efficient, more responsive, and less costly to operate and develop, then perhaps more user requests could be fulfilled, program managers would be willing to take on more challenging missions, and more proposals for promising but operationally challenged missions could be put forward.

This article presents SciBox, an autonomous planning and command system that is highly efficient, highly responsive, and a technology enabler. It describes the system's architecture, its incremental development and validation since 2001, and its impact on several space missions.

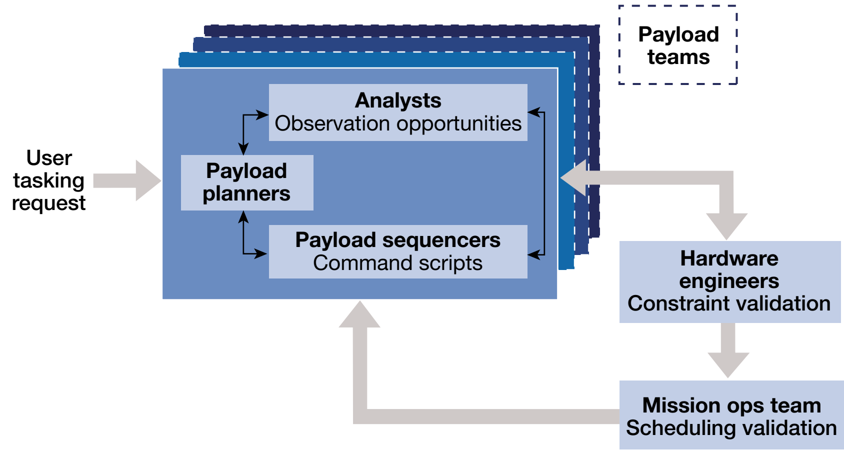

Figure 1. Traditional operation-planning process.

BACKGROUND

Planning for space operations typically begins with users requesting observations or other measurements from various elements of a suite of payload subsystems on a satellite or a constellation of satellites; for example, a user might request that a system image a target or sample an atmosphere or magnetosphere at specified geometries. A team of planners works closely with analysts to search for appropriate observation opportunities to fulfill these requests. The planners develop the flight and ground operations schedules and work with highly skilled payload and spacecraft command sequencers to construct matching command sequences. If there is a scheduling conflict between subsystems, the team further iterates on the command sequence, often with human-in-the-loop adjudication. When an acceptable command sequence is constructed and tested, it is forwarded to subsystem engineers who validate that the sequence is within operational constraints. If there is no violation, the command sequence is then forwarded to mission operators for integration with an overall schedule of spacecraft activities. This process is illustrated in Fig. 1. Usually there is more than one payload team involved in a space mission. Collaboration among teams requires a more complex planning process to coordinate observations, manage resources, and avoid conflicts. Such cooperation can involve multiple iterations of planning[1–3] that are staggered to support continuous daily or weekly operation. The entire process can be labor intensive, with multiple shifts of planning teams required to manage the staggered phases. Multiple reviews and tests are conducted to ensure that the objectives of user requests are met and that operations sequences comply with all mission health and safety rules. The iterative coordination, review, and testing are time consuming, resulting in sequence development times of weeks or months. When short-term changes in operating conditions occur, commands for observations can be dropped and, thus, available resources are underused.

The more complex the system is, the larger the team is. On some DoD and NASA space missions, the systems were so complex that many years were required to develop the planning system and coordination process. Even after a system is fully developed, the operational process can be laborious and time consuming because multiple iterations are required to design the operational sequence, resolve schedule conflicts, review the sequence, and verify the system's health and safety. It may take weeks or even months to generate even a short command sequence.

SciBox streamlines the planning and commanding process into a series of steps and then automates those steps with an integrated software system. The streamlined process is illustrated in Fig. 2.

SciBox ARCHITECTURE

The uplink pipeline begins with opportunity analyzers customized to each type of operational objective. Examples of objectives are to image a particular region at a defined observing geometry, to acquire a spectrum at a given latitude and longitude, or to collect a particular signal of interest. Instead of searching for a single operational opportunity, the opportunity analyzers search all

SPECIAL FEATURE

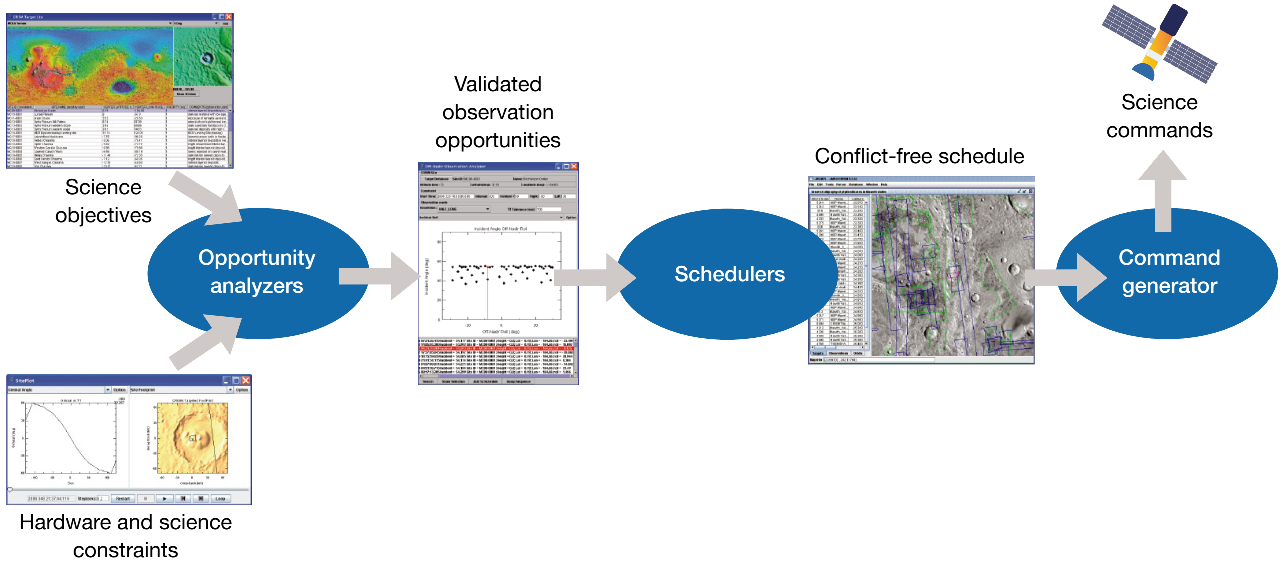

Figure 2. SciBox streamlined uplink process.

available opportunities. Opportunities are then ranked by metrics that represent measures of data quality such as resolution, illumination, or signal strength.

For each potential opportunity selected, an automated rules-based constraint checker systematically validates the observational operation to ensure that it complies with all operational constraints. The validated opportunities are then sorted according to priority and by statistically weighted data-quality metrics. Using the list of sorted, weighted opportunities for observation, an optimization 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. An automated command generator then ingests the conflict-free schedule and generates spacecraft and instrument commands for uploading to the spacecraft.

DEVELOPMENTAL HISTORY

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.

First Opportunity Analyzer

In 2001, the opportunity analyzer concept was demonstrated on Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED), an Earth polar orbiter designed to take 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 was then used by ground station operators all over the world to plan co-observations of Earth's MLTI region with TIMED instruments.

Integrated Opportunity Analyzer and Constraint Analyzer

In 2002, the next key milestone was achieved with the delivery of a science planning tool for the Magnetospheric IMaging Instrument (MIMI) on board Cassini on its mission to Saturn. Contributing to one of 12 Cassini investigations, MIMI is part of an instrument suite that includes the Low Energetic Magnetospheric Measurement System, the charge energy mass spectrometer, and the ion and neutral camera. On Saturn, sunlight is a thermal hazard for the spacecraft radiator as well as a source of instrument noise for MIMI. Saturn's orbital 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.

First End-to-End Uplink Pipeline System

Another milestone was achieved in 2005, when the first end-to-end semiautomated planning tool was delivered for the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM)[4] on board the Mars Reconnaissance Orbiter. The CRISM planning tool, JMRO,[5] 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 preplanned observations manually to manage unexpected changes to downlink or solid-state recorder space. JMRO has been used since 2005 to successfully plan CRISM's 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.

Scaling the Uplink Pipeline to Mission Level

In 2011, we scaled SciBox to a mission-level system used to plan the entire MESSENGER (MErcury Surface, Space ENvironment, Geochemistry, and Ranging)[6] orbital science operations campaign. Launched in 2004, MESSENGER was a NASA Discovery Program mission to study Mercury and its environment. It entered into orbit about Mercury in March 2011 and began a 1-year orbital science campaign. During this orbital phase of the primary mission, the spacecraft was in a non-Sun-synchronous and highly elliptical 200 km × 15,200 km orbit with an initial orbital inclination of about 82°. The orbital period was approximately 12 h. MESSENGER acquired scientific observations with seven payload instruments, as well as radio science. The onboard instruments included a dual-imaging system with wide-angle and narrow-angle cameras for multispectral imaging of Mercury's surface; gamma-ray, neutron, and X-ray spectrometers for remote geochemical mapping; a magnetometer to measure the planetary magnetic field; a laser altimeter to measure surface topography and planetary shape; a UV, visible, and near-IR spectrometer to take high-resolution spectral measurements of the surface and to survey the structure and composition of Mercury's tenuous neutral exosphere; and energetic particle and plasma spectrometers to characterize the charged particle and plasma environment of Mercury. These instruments and spacecraft systems (other than solar panels) were mounted on an instrument deck behind the sunshade that protected the spacecraft from the intense insolation. As MESSENGER orbited Mercury, the guidance and control system kept the spacecraft attitude within a range that prevented spacecraft components and instruments from being directly illuminated by the Sun. In addition, thermally sensitive parts of the spacecraft were not exposed to thermal radiation from the planet when the spacecraft was near Mercury.

After 1 year of successful operation in its primary mission, extended missions allowed MESSENGER to continue its orbital phase for an additional 3 years. During the extended mission, MESSENGER orbit design was changed from a 12-h period to an 8-h period. The orbit slowly degraded over time until the spacecraft finally exhausted all of its propellant, and the Sun's gravity caused it to impact the planet on 30 April 2015.

For the entire 4 years of MESSENGER orbital operations, SciBox[7] was used to plan and command all orbital science observations and operation of the guidance and control system. SciBox was used to accurately model all operational and attitude-control constraints, spacecraft and instrument pointing capabilities, instrument data generation, and data downlink opportunities. By means of priority-based scheduling algorithms, MESSENGER SciBox scheduled the science measurements required for the mission to meet an ambitious set of objectives and automatically generated the commands to implement those measurements.

During orbital operations, SciBox was executed once per week to use the latest weekly orbit prediction from the navigation and mission design engineers and the latest Deep Space Network ground station contact schedule. Other inputs included historical observation status and new requests submitted by users. Each time MESSENGER SciBox ran, its output spanned from the start time of a planning cycle to the end of the mission, but only the first week's output commands were uplinked to the spacecraft.

Using this operation approach, SciBox scheduled 293,983 images, more than 5 million surface IR spectra, more than 6 million UV surface and exosphere spectra, and more than 41 million laser altimeter shots. The amount of data gathered far exceeded the requirements specified in the original proposal. More importantly, there were no commanding anomalies, and MESSENGER never entered into safe mode (although there were several critical constraints that, if violated, would have demoted the state of the spacecraft).

Building an Autonomous Operation

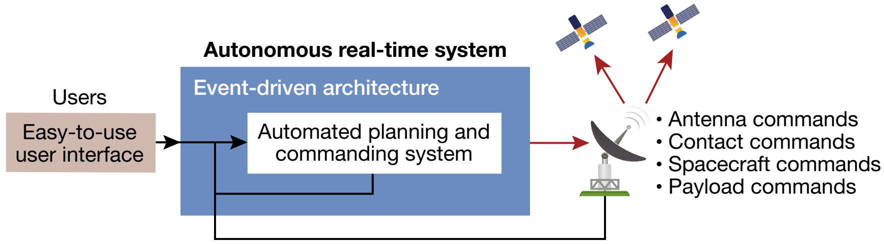

Figure 3. S2Ops system architecture.

After MESSENGER, the weekly manual execution of the SciBox uplink pipeline was enhanced to be autonomously and continuously executed. This technology was successfully demonstrated and validated on a pair of CubeSat missions, Operationally Responsive Space Technology 1 and 2 (ORS Tech 1 and ORS Tech 2).[8]

ORS Tech 1 and ORS Tech 2 were developed for the U.S. government as part of Multi-mission Bus Demonstration (MBD) program. These two CubeSats were small and cost less to develop than other NASA and DoD spacecraft that APL had previously developed. Operationally, however, the planning and commanding faced the same challenges as did bigger space missions. As part of the ground system delivery requirements, ORS Tech 1 and ORS Tech 2 required an operational management system that was easy to use. It needed to be operated by the end user without APL involvement in the day-to-day operations. In addition, the system required minimal operator involvement.

The approach to the MBD operational management challenge was to build an autonomous planning and commanding system, named S2Ops,[9] for the U.S. government. S2Ops was built by wrapping the SciBox uplink pipeline in an event-driven-based architecture, shown in Fig. 3, to create an autonomous real-time system. Then 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 user-friendly graphical user interface is designed to insulate the end user from the intricately 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 mission opportunity analysis, mission sequence derivation, and mission constraint validation, and then presents the user a list of validated collection opportunities. When the user selects one of the validated opportunities, the S2Ops real-time system reoptimizes the mission schedule and generates a new set of commands for uplink to the spacecraft.

The S2Ops real-time system ran 24 h a day, 7 days a week, and was temporarily paused only when a user was making a tasking order. Otherwise, it ran continuously to monitor the health of the spacecraft and ground systems. When there was scheduled contact between the ground station and satellite, S2Ops sent commands to, 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.

If there was a planned downlink, S2Ops compared the actual data downlink with what was planned. The system then summarized the results and sent them in an SMS message to users' cell phones, freeing the users from constant presence at the console.

As part of the delivery of S2Ops, APL trained users on the system for about an hour. All trained users were able to task the system in minutes without any help from an experienced operator. On the day of delivery, the U.S. 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 operations, S2Ops had been running without any major issues. However, as CubeSats are still a technology in progress, the spacecraft suffered several unexpected anomalies. To facilitate these anomaly investigations, APL developed a manual commanding tool that was used in conjunction with S2Ops. The tool was used to construct the diagnostic command sequence, and S2Ops scheduled the contact with spacecraft, controlled the ground antenna, and sent the commands to the spacecraft.

Scaling Autonomous Operation to a Constellation System

With continued research and development in SciBox, advancement has enabled the building of an autonomous planning and commanding system for a constellation of articulating sensors. The sensors, built for the U.S. government, will be hosted on commercial satellites and used to observe upper atmospheric cloud phenomenology.

Collection requests are received from an external real-time system, and SciBox immediately generates commands to task the sensors in near real time. The system also provides a manual editor for an operator to insert ad hoc activities or modify the autonomously scheduled operations. Because sensors will be launched over several years and on satellites yet to be determined, the planning system is flexible enough to accommodate any number of sensors and a wide variety of satellite orbits.

SPECIAL FEATURE

OPERATIONAL SYSTEM DISCUSSION

We have demonstrated a new planning system that is much more efficient than traditional systems in many ways. Foremost is SciBox's ability to use modern computing power and efficient algorithms to perform much more comprehensive searches for observation opportunities, as well as its ability to perform many more trade-off analyses than feasible with a manual system. The result is a much more efficient use of available resources. For MESSENGER, it took only 3 h to plan the schedule for the entire year, involving billions of opportunities for search operations as well as task deconfliction and constraints validation.

On MBD, collections were initially planned using a traditional manual system, and as a result, only a limited number of collections were scheduled. Valuable collections during low-elevation passes and other secondary modes of operation were excluded because the cost and risk of manual operation outweighed the benefits. However, with SciBox, merely a few button clicks safely scheduled those collections without incurring additional cost and risk.

The response time of the automated system is also much faster because manual typing cannot match computing speed. For example, on MESSENGER an entire year's worth of observations were scheduled and the associated commands generated in less than 3 h. On MBD, the system enabled direct tasking from the user.

A system's ability to respond to short-term changes improves its resiliency. At the beginning of MESSENGER's orbital phase, differences between some observed temperatures and those predicted by models required a change in the spacecraft orientation for safety reasons. This change invalidated all uploaded collection sequences, and the sequences had to be discarded. By simply re-running SciBox, revised sequences compatible with the new orientation were quickly generated, and the mission objectives were recovered with no noticeable decline in overall mission performance.

Although the original objective of SciBox was to maximize payload return by improving the planning efficiency, the improved efficiency also significantly reduces operational cost. With an autonomous system, the recurring operational cost is a small fraction of that associated with a traditional manual approach.

The improvement in response time, gain in efficiency, and reduction in operational cost are all realized without increasing the system's risk. In fact, because all operational sequences are systematically validated and verified, a risky operational sequence is less likely to slip through SciBox than through a manual review process. Long-term resource usage forecasting also provides an early preview of resource margins. As a result, a systems engineer has sufficient lead time to mitigate situations when resource margins are small (e.g., getting additional ground station support to improve downlink bandwidth margin).

The combination of automation and intelligent scheduling algorithms is a new enabling capability for space missions. SciBox's capability to simulate an entire year's worth of observations in just 3 h encourages planners to conduct what-if analyses to explore alternative operational approaches that they might not otherwise consider. In fact, the MESSENGER team routinely did this. One of the most profound results of such what-if analyses was the changing of MESSENGER's orbital period from a 12-h geometry to an 8-h orbit geometry.

After nearly a year of successful MESSENGER operations, the science team met in a Boston restaurant for a social gathering. A member of the team flew a paper airplane, and the person whom the plane landed on had to write a wish for MESSENGER. One of the wishes was to orbit Mercury at lower altitude to gain higher resolution. The initial reaction was that this wish was a dream; senior scientists involved in many traditional space missions believed that achieving the goal was not feasible. They assumed that there was not enough time to replan the operational schedule, that the cost of operational planning would be too high, and that it would be too risky to make so many changes. However, after the gathering, the mission systems engineer discussed the idea with the principal investigator and the project manager. A few weeks later, the team was presented with six different orbital designs, ranging from an 11-h orbital design all the way to a 7-h orbital design. With slight modifications to SciBox, all six cases were simulated unattended over a weekend, and the results were presented in comprehensive hyperlinked reports for evaluation. Included in every scenario were a fully validated detail operation sequence and a command sequence ready to be executed. This information allowed the team to understand the benefits and feasibility of the alternative orbital scenarios and to pursue a risk analysis that ultimately resulted in the decision to change the orbital period in the extended mission to 8 h.

There are many other examples of SciBox's impacts on decisions regarding mission operations. However, its impact is not limited to the operational phase. SciBox can also guide prelaunch engineering trade-offs. One case is the selection of the solar panel mounting design for a space mission currently being studied. While working on an APL concept study to fly a spacecraft to an asteroid, the team debated about whether to use a gimbaled solar panel or a fixed solar panel. The fixed solar panel is mechanically easier to build and carries lower mass margin. However, it was hard to prove that the fixed solar panel can provide sufficient power margin when the spacecraft is oriented for payload operations. SciBox was used to prove the existence of alternative observing geometries and opportunities that can use fixed solar panel design. The systems engineer was able to make a critical design decision without conducting a prolonged study.

SYSTEM DEVELOPMENT DISCUSSION

When the SciBox end-to-end system was first proposed, the cost for development was too high and the schedule was questionable, so an alternative approach to development had to be found. Ultimately, development followed an incremental path, with the system maturing to its present state over the course of more than 14 years. During that time, continual improvements were made to the system development processes, which include requirements gathering, system design, system implementation, system validation, operational infusion, and applying lessons learned. Information on these processes is captured in the SciBox knowledge system.

Extensive details on the SciBox knowledge system are beyond the scope of this article, but the knowledge system is briefly described to provide context for how the system arrived at its current state. The knowledge system consists of a software library storing reusable code and a repository storing documentation on historical operational planning, rapid experimental ideas, and lessons learned.

Although each space mission is unique, missions may share some common challenges such as spacecraft pointing and power constraints and downlink bandwidth constraints. If the responses to these shared challenges can be captured in a software library,[10] they might be able to be reused in subsequent projects. Likewise, the repository stores documentation on the latest best practices, state-of-the-art algorithms, and experimental ideas. The stored software, documentation, and processes may not apply to development of future systems but could provide a template for starting a system's development.

When development of a new system starts, some of the challenges may have already been solved, and software code developed and validated on previous missions can readily be reused. A development template provides a system blueprint for a much more straightforward implementation for a new space mission, eliminating a redundant system analysis process. Therefore, rather than starting from scratch, system development could begin from a more mature state. Lessons learned during development of the new system are then folded back into the software library and the repository.

Lessons learned are not limited to application in space operational projects; such lessons can be applied to any space-related projects. Two examples are the Satellites Vulnerability Assessment (SVA) tool developed for the Navy and the Resilience, Intelligence, Surveillance, and Reconnaissance (RISR) studies developed for the Office of the Under Secretary of Defense for Acquisition, Technology and Logistics. Although these two projects did not include the building of any planning and command systems, they improved our understanding of what is required to build a successful autonomous constellation management system.

The most important component of SciBox is the collaborative environment within APL. Subject-matter experts with great technical depth are easily accessible within the Laboratory. Given that space mission challenges are continuously changing and growing, the close collaboration of these subject-matter experts allows the state-of-the-art algorithms and solutions used in SciBox to be kept up to date.

As shown in Fig. 4, with this incremental development approach and easy access to subject-matter experts, the SciBox team can continually extend the system's capabilities. Even with increased capabilities and sophistication, the system is now more affordable and the development schedule is manageable.

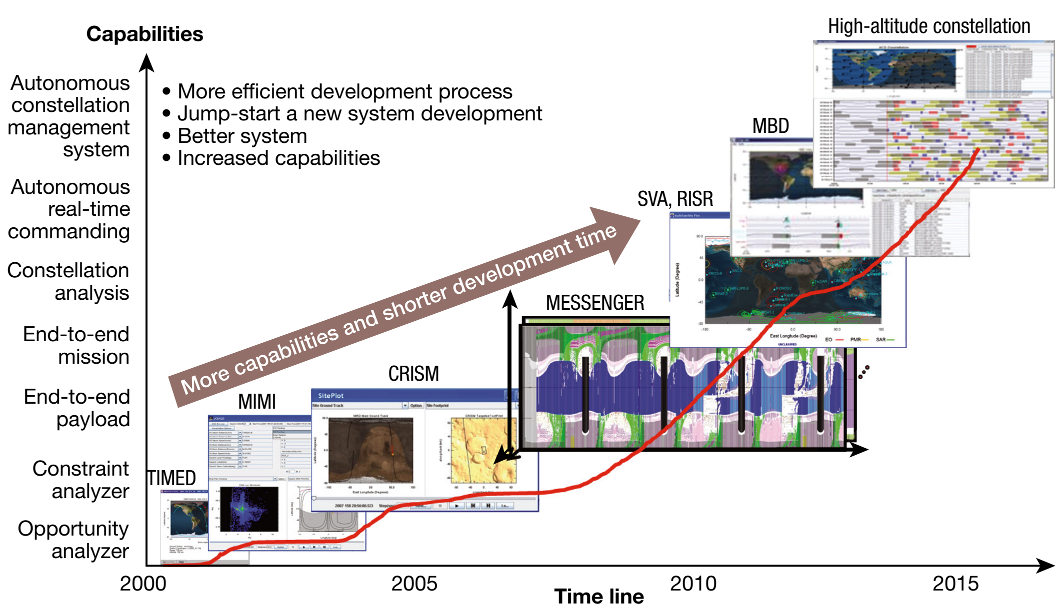

Figure 4. Key capabilities milestones.

SPECIAL FEATURE

SUMMARY

We have presented an autonomous planning and command system that is a proven technology enabler for space operations. The SciBox system is highly efficient and has enabled NASA and DoD space missions to meet challenges that would not have been feasible using traditional manual approaches. In addition, best practices and novel ideas derived from development of various operational space missions, along with mission concepts studied along the way, are continually captured in the SciBox knowledge system. Drawing on the wealth of knowledge, validated codes, and proven development processes, new systems could assume more capabilities and development could begin from a much more matured state. With the continual growth of SciBox's capabilities, mission objectives that were previously deemed too operationally challenging to achieve using traditional manual systems may be realizable, and cost-constrained missions could be developed without sacrificing mission capabilities.

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REFERENCES

[1]Holdridge, M. E., "NEAR Shoemaker Space Mission Operations," *Johns Hopkins APL Tech. Dig.* **23**(1), 58–70 (2002).

[2]Wenkert, D. D., Bridges, N. T., Eggemeyer, W. C., Hale, A. S., Kass, D. M., Matrin, T. Z., et al., "MRO's Evolving Process for Science Planning," in *Proc. AIAA Space 2007 Conf. & Exposition*, Long Beach, CA, paper AIAA-2007-6107 (2007).

[3]Paczkowski, B. G., and Ray, T. L., "Cassini Science Planning Process," in *Proc. AIAA Space Ops 2004 Conf.*, Montreal, Quebec, Canada, pp. 1–10 (2004).

[4]Murchie, S., Arvidson, R., Bedini, P., Beisser, K., Bibring, J.-P., "Compact Reconnaissance Imaging Spectrometer on Mars (CRISM) on Mars Reconnaissance Orbiter (MRO)," *J. Geophys. Res.* **112**(E5), E05S03 (2007).

[5]Choo, T. H., McGovern, J. A., Murchie, S. L., Seelos, F. P., Seelos, K. D., et al., "An Efficient Uplink Pipeline for the MRO CRISM Instrument," in *Proc. AIAA Space 2008 Conf. and Exposition*, San Diego, CA, paper AIAA-2008-7656 (2008).

[6]Solomon, S. C., McNutt, R. L. Jr., Gold, R. E., and Domingue, D. L., "MESSENGER Mission Overview," *Space Sci. Rev.* **131**(1), 3–39 (2007).

[7]Choo., T. H., Murchie, S. L., Bedini, P. D., Steele, R. J., Skura, J. P., Nguyen, L., et al., "SciBox, an End-to-End Automated Science Planning and Commanding System," *Acta Astronautica* **93**, 490–496 (2014).

[8]Rogers, A. Q., and Summers, R. A., "Creating Capable Nanosatellites for Critical Space Mission," *Johns Hopkins APL Tech. Dig.* **29**(3), 283–288 (2010).

[9]Choo, T. H., Huang, P., Wells, E., Darrin, M., Rogers, A., and Lafferty, P., "S2Ops, an Autonomous CubeSat Ground System, in *Proc. 31st Space Symp.*, Colorado Springs, CO, pp. 1–8 (2015).

[10]Choo, T. H., and Skura, J., "SciBox: A Software Library for Rapid Development of Science Operation Simulation, Planning and Command Tools," *Johns Hopkins APL Tech. Dig.* **25**(2), 154–162 (2004).

Teck H. Choo, Space Exploration Sector, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Teck H. Choo is a member of the Principal Professional Staff in the Space Exploration Sector's Analysis and Applications Group. He has a B.S. and an M.S. in electrical engineering from the University of Kansas. Before coming to APL, he worked as a software engineer at the Space Telescope Science Institute, where he developed the data processing pipeline for the Hubble Space Telescope. Since joining APL, he has developed software tools for data analysis and visualization and simulation tools for Galileo, ACE, Ulysses, New Horizons, Cassini, TIMED, CRISM, MESSENGER, and numerous DoD projects. His primary research is in automated intelligent planning systems. He is the creator of SciBox and is the recipient of 2015 American Astronautical Society Space Entrepreneurship Award. His e-mail address is teck.choo@jhuapl.edu.

Alice F. Berman, Space Exploration Sector, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Alice F. Berman is the Assistant Group Supervisor in the Space Exploration Sector's Ground Applications Group and a member of the Senior Professional Staff at APL. Alice joined APL in 2006 as the MESSENGER Payload Operations Manager. Alice has a B.S. in physics and mathematics from Montclair State University and M.S. degrees in astronomy and IT systems from SUNY Stony Brook and Johns Hopkins University Carey Business School, respectively. Alice has an extensive background in spacecraft and payload operations, including planning and scheduling systems. Before joining APL, Alice was the Head of Mission Planning for the FUSE spacecraft (Johns Hopkins University Homewood) and Program Coordinator at the Space Telescope Science Institute. Her e-mail address is alice.berman@jhuapl.edu.

Hari Nair, Space Exploration Sector, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Hari Nair is a member of the Senior Professional Staff in the Space Systems and Analysis Branch of the Space Exploration Sector. Before coming to APL, he was a member of the Technical Staff at JPL, where he developed ground software for the AURA/TES and OCO missions. He joined APL in 2007 and has been a system developer and analyst for several major NASA missions such as CASSINI, TIMED, TWINS, IMAGE, MRO/CRISM, MESSENGER, and OSIRIS-REx. His e-mail address is hari.nair@jhuapl.edu.

Lillian Nguyen, Space Exploration Sector, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Lillian Nguyen is a member of the APL Senior Professional Staff in the Space Exploration Sector's Analysis and Applications Group. She holds an M.A. in mathematics from Johns Hopkins University. Prior to joining APL she worked at AAI Corporation as a signal processing specialist. Since joining APL, she has worked as a software engineer on a variety of civilian space programs and has contributed to the development of SciBox planning and commanding tools. She holds a patent in real-time compression of serial data streams. Currently, she is the lead developer for OSIRIS-REx laser altimeter planning and commanding system. Her e-mail address is lillian.nguyen@jhuapl.edu.

Joseph P. Skura, Space Exploration Sector, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Joseph P. Skura is a member of the Senior Professional Staff at APL. After joining APL, he became active in nonacoustic anti-submarine research, radar propagation, and biomedical research and has several patents in biomedical engineering. He is now in the Space Exploration Sector where he develops software tools for scientific analysis, visualization, simulation, and mission planning. He has developed applications for Galileo, TIMED, SSUSI, New Horizons, MESSENGER, and LRO. Presently, he is leading the development of a SciBox vulnerability assessment tool for the OPNAV program office. His e-mail address is joe.skura@jhuapl.edu.

R. Joshua Steele, Space Exploration Sector, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

R. Joshua Steele is a scientific and mobile applications developer in the Space Exploration Sector's Science Applications and Analysis Group and a member of the Senior Professional Staff at APL. Josh joined APL in 2002 after receiving a B.S. in physics from Virginia Tech, an M.S. in physics from the University of North Carolina at Chapel Hill, and an M.S. in computer science from Virginia Tech. Shortly after joining APL, Josh started working on tasks related to the SciBox planning system, eventually joining the MESSENGER team in 2004 as a SciBox developer, where he helped design the software to schedule the science activities for several instruments on the spacecraft; aided the development of models to track resources on board the spacecraft, such as the solid state recorder; and coordinated tasking between the SciBox team and other teams on the project. Josh later served as the Deputy MESSENGER SciBox Lead Developer and eventually as the MESSENGER SciBox Lead Developer in the later phases of the mission. Since the MESSENGER project ended, Josh has been working on developing scientific and mobile applications for sponsors in the healthcare business area and serving as an instructor at the Johns Hopkins Whiting School of Engineering, where he teaches iOS mobile development. His e-mail address is josh.steele@jhuapl.edu.

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