Lessons Learned from International Space Station Crew Autonomous Scheduling Test

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Abstract

In 2017, our team investigated and evaluated the novel concept of operations of astronaut self-scheduling (rescheduling their own timeline without creating planning violations) onboard the International Space Station (ISS). Five test sessions were completed for this technology demonstration called Crew Autonomous Scheduling Test (CAST). For the first time in a spaceflight operational environment, an ISS astronaut planned, rescheduled, and executed their activities. The crewmember used a mobile device to perform self-scheduling while abiding by flight and scheduling constraints. This paper discusses the lessons learned from deployment to execution.

Introduction

As NASA considers long-duration exploration missions (LDEMs), it is envisioned that crews will behave more autonomously as compared to low-Earth orbit missions. As missions operate further from Earth, the communication latency between the spacecraft and Mission Control Center (MCC) will increase requiring the crew to take a more active role in reacting to daily tactical planning. In this space environment, the crewmembers themselves will have better insight as how to best manage their own schedule, minimize idle time as they wait for MCC to respond, or react to a delay in activity execution. Moreover, the crew must have the ability to self-schedule: rescheduling their own timeline without creating planning violations. A violation-free plan is essential not only as a measure of a feasible plan but also so that astronauts can react effectively in a contingency situation. This is a very different concept of operations as compared to current International Space Station (ISS) operations.

In 2017, our team investigated and evaluated a novel concept of operations onboard ISS: allowing astronauts to manage and schedule their own timeline. This self-scheduling concept of operations explores crew autonomy as a method for effective and efficient scheduling and execution of astronauts' day. The Crew Autonomous Scheduling Test (CAST) aimed to investigate the feasibility of the concept of operations in a spaceflight environment as well as to learn about the impacts to mission planning and crew satisfaction.

Overview of ISS Planning

Within the domain of human spaceflight, crew scheduling for ISS remains a human-driven planning task by large teams of flight controllers, called Ops Planners, who go through a detailed timeline

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development process to help the crew and ground support personnel get ready for execution days (ESA, 1998). These timelines, which identify all the activities the crew needs to do onboard ISS, schedule the crew to an accuracy of 5 minutes, and the Ops Planners ensure that the necessary resources are available throughout the activity's duration. Furthermore, the Ops Planners make sure that all required activities for the day are scheduled and that constraints placed on crew-time are not exceeded or violated. The result is a balanced timeline that is achievable given the complexities of spaceflight operations, which the crew follows daily.

In particular, the Ops Planners have to integrate a large set of operational constraints and objectives set forth by the ISS program for scheduling crew activity. In a timeline, one can find temporal constraints (one activity needs to occur before another within a specific timeframe), resource constraints (an activity needing communications or ground support), spatial constraints (two activities performed in the same location at the same time), crew preferences, among others. There are simple constraints such as: an activity cannot occur without communication coverage, or a particular activity can only be completed by one crewmember at a time. Other activities are more complex; for example, activities where crewmembers need to coordinate among themselves, activities that require multiple resources such as communication and equipment availability, and activities that have specific flight rules that need to be satisfied. Further complexity to crew planning and scheduling is added when major ISS events are rescheduled, like a slip in a Soyuz launch or a resupply ship docking delay. ISS operations levy much more complex operations constraints, which are highly interrelated with resources (e.g., power and/or communications) and international agreements (e.g., number of hours devoted to science experiments). These constraints are not all completely modeled in the planning tool; in other words, a plan is not deterministic. Every single plan change has to be approved by stakeholders (be it other NASA centers or an International Partner's Space Agency) before it even reaches the crew's schedule.

During the preparation of the timeline, a Task List is also used. The Task List is a collection of activities that the Flight Control Team makes available for the crew, in addition to their scheduled activities. This provides a set of unconstrained tasks that can be worked at any time. Since they are unconstrained, they tend to be lower priority and cannot support other constrained activities. The verifications and modifications for the Task List go through the same checks and process as a regular scheduled activity.

To facilitate the coordination necessary to build a fully integrated ISS plan, processes are in place to create timeline stability within six days of execution (NASA, 2018). The rigid process is strongly motivated because operations are supported from multiple locations throughout the globe. A stable timeline allows all parties to coordinate the usage of space station resources and gives the technical experts, whose support varies by time zone, an opportunity to review and validate the timeline prior to execution. Changes within six days of execution require a Planning Product Change Request (PPCR) (McCormick, 2007). Like any change request system, there is an approval process utilizing representatives from each ISS control center who approve on behalf of their entire organization. Approval guarantees that the requisite coordination has occurred and each control center is prepared to support the proposed timeline alteration; full approval is required before the timeline is changed. Most PPCRs are simple alterations, but they can be used to make wholesale timeline changes if needed; for instance, when an expected cargo vehicle launch is aborted within six days of its expected arrival at the space station. Regardless of the number of reschedules, the intent of the PPCR system it to ensure that no changes are made to the timeline that have not been fully vetted.

ISS Ops Planners use custom-built software tools to appropriately plan and create a crew schedule that meets all required ISS program and operational constraints. Currently, the software tool that Ops Planners use is Score, originally developed by NASA Ames and now managed by NASA Johnson Space Center, which is part of a suite of tools called OPTIMIS (Smith et al., 2014). After completing a plan, they send the plan from the Score tool to the rest of the mission operations team, which views the plan using OPTIMIS Viewer. Once PPCRs are approved, the changes are implemented by the Ops Planners after a thorough review by the entire Flight Control Team in Houston and all International Partners. The Ops Plan team can then put the plan onboard the station for the crew to execute. No changes occur in the schedule on execution day.

Enabling Self-Scheduling

Previously, ISS Mission Operations Directorate had tried to evaluate crew self-scheduling with two other software tools: Score and On-board Short-Term Plan Viewer (OSTPV, the previous software aid before OPTIMIS Viewer). Based on crew feedback during self-scheduling exercises, both experiences showed that neither option was viable for meeting the objective to study crew autonomy with crewmembers on ISS due to limitations in the design of current mission planning tools (Rosenbaum, 2014). Score is designed to build plans but not execute. OSTPV is designed to execute plans as scheduled but cannot easily modify or reschedule plans. A need was identified for a highly usable (including low training time) tool that enables efficient self-scheduling and execution within a single package. The ISS Program identified Playbook as a potential option (Marquez et al., 2013; Hashemi and Hillenius, 2013).

Playbook (Figure 1) had high crew acceptance as a plan viewer from previous Earth analogs missions, had simple schedule editing capabilities, and supported ISS plans (since the same team developed Score and Playbook). At the time, Playbook was being developed to support light-weight editing and field tested in various Earth analog missions (Marquez et al., 2017). As such, the software tool met the minimum requirements to conduct self-scheduling evaluations. Playbook (version 5, which was deployed to ISS) supported:

- ISS plans from Score,
- Visualization of ISS communication band profiles (e.g., S-Band),
- Collaborative self-scheduling of activities,
- Ability to execute from timeline (e.g., status activities, access to ISS procedures),
- Ability to add activities from a Task List,
- Violation checking of constrained, scheduled activities,
    - Types of constraints: equality requirements, claimable, and temporal constraints.
- Two-server configuration (one onboard ISS, one on the ground).

In 2016, an ISS program-led technology demonstration opportunity allowed CAST to investigate the feasibility of crew autonomy through self-scheduling as a concept of operations in a spaceflight environment (Hillenius et al., 2016).

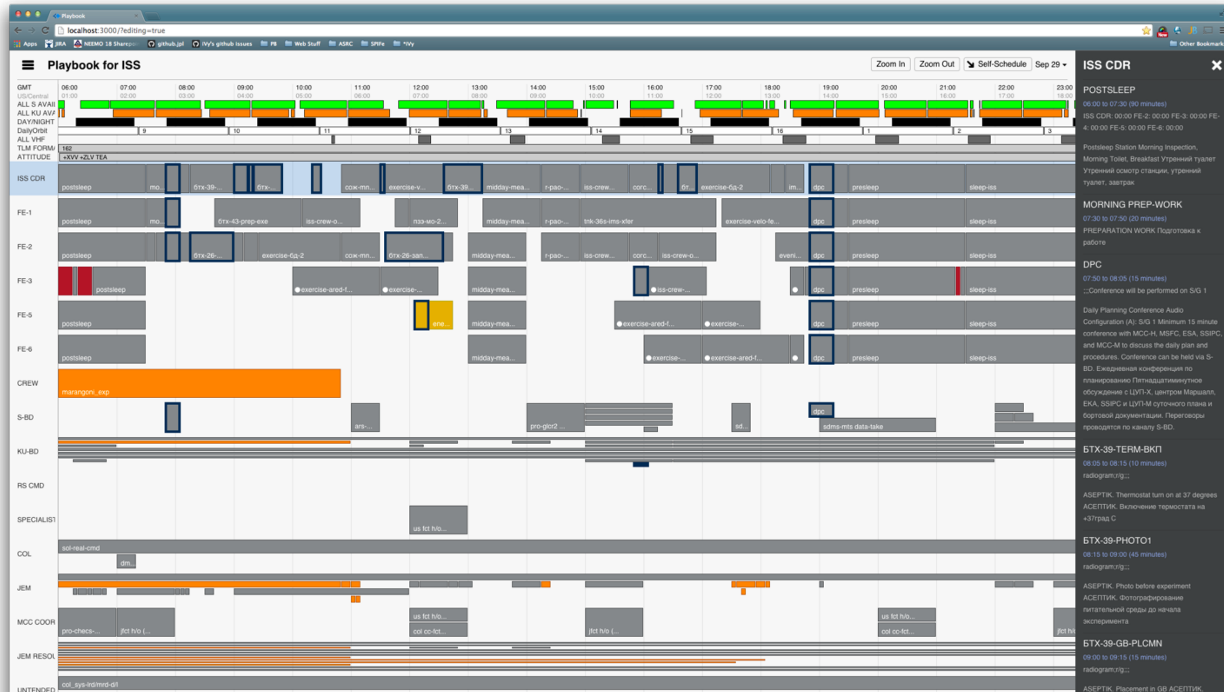

Figure 1: Playbook with ISS plan.

CAST Tech Demo

Between December 2016 and July 2017, five different CAST sessions were completed onboard of ISS by a single crewmember (Marquez, Hillenius, & Healy, 2018). All scheduling onboard was completed using Playbook. The first two exercise sessions were intended to reacquaint the crewmember with Playbook. The third exercise was practice, while the fourth and fifth were the main self-scheduling sessions. Each exercise session was meant to progressively increase crew's autonomy through self-scheduling. The CAST sessions were as follows:

- Exercise 1: Familiarization with Playbook and scheduling. Astronaut scheduled activities on a notional ISS day. Exercise did not impact any actual crew scheduling.
- Exercise 2: Execute day from Playbook based on ground-planned schedule. If desired, astronaut could reschedule flexible activities and schedule activities from the Task List.
- Exercise 3: Execute day from Playbook where the afternoon schedule was composed entirely by crew scheduled Task List activities.
- Exercise 4 & 5: Astronaut planned their entire day's schedule, which was reviewed by ground planners. Once approved, crew executed day from Playbook.

In order to accomplish these different sessions, the ISS Ops Planners had to select a feasible day for each session, composed the initial plan inputs (i.e., identify all the required activities and constraints), set up the Task List activities along with priorities, prepare Playbook for crew self-scheduling, verify plan in Playbook, and then duplicate and incorporate crew's schedule into OPTIMIS.

The crewmember was allowed to only self-schedule their own timeline. They were given guidance (through procedures) as to the priorities of the activities to be scheduled, ranging from high to low (Figure 2). They were given more activities than they could schedule. All the activities that could be added were available to the crew through Playbook's Task List. Some activities had constraints, which were modeled by the Ops Planners to the greatest extent possible.

52-0169: CAST Session #5 Priority List

[1] "Total Selected Crew Time" includes your pre-scheduled activities. Note that SPRINT-GUIDE-DON-OPR activity is hard-scheduled with FE-2 SPRINT.

[2] RUN1 and RUN2 of ADC activities are a continuation from earlier in the week and run into next week.

[3] No activities that cause vibration should be scheduled in the LAB during both ADC-MICROSCOPE-OPS activities (i.e. ADC MICROSCOPE-OPS cannot occur during CEVIS).

[4] Scott Tingle will be working with you from the ground on your IMS-STOWAGE-CONF activity.

[5] P/TV ADD CAM VIEW TD must be completed before the P/TV CAM PWR STOW on Friday GMT 202.

Total Selected Crew Time: 0:15

Priority	Activity Name	Duration
Highest Priority	***Exercise***	(00:00)
	EXERCISE-CEVIS	01:00
	EXERCISE-ARED	01:30
	Antibody Conjugates Inoculation Run 1 [2]	(00:00)
	ADC-GLACIER-RMV-RUN1	00:05
	ADC-MEDIA-INJECTION-RUN1	01:15
	ADC-MICROSCOPE-OPS-RUN1 [3]	01:00
	Antibody Conjugates Inoculation Run 2 [2]	(00:00)
	ADC-GLACIER-RMV-RUN2	00:05
	ADC-MEDIA-INJECTION-RUN2	01:15
	ADC-MICROSCOPE-OPS-RUN2 [3]	01:00
	IMS-STOWAGE-CONF [4]	00:15
	P/TV ADD CAM VIEW TD [5]	00:05
	CMS-ARED-CAR-FLIP	01:10
	MELFI-DEWAR-INV	00:10
	WANTED-BUMP-SHIELD	00:30
	J-RSU SENSOR-CORRECT	00:40
	MD-LAUGH-PRINT-VID	00:15
	CHeCS RACK-AUDIT-PT2	01:00
	XFER-RS-ITEMS	00:20
	BEAM-IMV-INSPCT&CLN	00:50
	CHRCL FIL-BAG-VERIFY	00:20

Figure 2: Priority List example.

Lessons Learned

The CAST sessions were successfully completed onboard ISS. Below we summarize the various lessons learned from the technology demonstration, ranging from deploying the planning and scheduling tool onboard, to the impacts on real spaceflight operations, to actual astronaut's self-scheduling task.

Playbook Deployment on ISS

The deployment of Playbook on ISS for the crew self-scheduling technology demonstration involved a number of logistical challenges. Since the demonstration involved the crewmember's actual ISS timeline (as opposed to a "contrived example" plan) the onboard Playbook server had to stay up to date with all timeline changes. In order to support this, a ground and onboard server was set up with periodic communication to synchronize information between the two servers. Plan changes, status information, and procedure updates would be communicated between the servers in order to maintain synchronization. Because of ISS limitations, a constant network connection is not possible and instead this information was exchanged using flat files periodically synchronized between the servers at 15 min intervals, depending on satellite connectivity. If there was a conflict between ground or crew synchronization plan changes, the crew changes would win; however, mission control could override a crew change if needed.

Setting up the onboard server involved other challenges. Because of the lack of internet connectivity to the server onboard and the differences in form factor from a traditional server, we needed to prototype a special deployment virtual machine that was self-contained without being able to prototype on the hardware itself. Since troubleshooting a configuration onboard involved working with a flight controller (known as PLUTO) and scheduling troubleshooting time on ISS, it was essential to get this configuration as correct as possible prior to deployment.

Technical Limitations

Like many software systems on ISS, the timeline is not a self-contained product—it links and connects to many different software systems needed for ISS operations. Two of these core systems, procedures and stowage notes, were requirements to have the crewmember use the Playbook tool for their actual mission execution. To support this, the Playbook team built a linking capability to IPV (International Procedure Viewer), which is the official software tool for crew procedures. The second system, stowage notes, likewise had a separate software interface which the Playbook team had to connect to. These systems had separate integrations for the ground and onboard system, which required that Playbook understand which mode it was running in (crew or ground). In addition to this, Playbook had to frequently poll the procedure and stowage systems to retrieve all procedures and stowage notes to display alongside an activity. A lightweight user interface was built to go back to their Playbook mission plan from procedures or stowage notes.

One key technical limitation is that Playbook and OPTIMIS Viewer could not share data between each other. This was important for MCC because if one astronaut was executing their timeline from Playbook, the rest of MCC (who were mostly following along through OPTIMIS Viewer) needed to also see that progress. In response to this limitation, mission control had both Playbook and OPTIMIS Viewer open to follow the execution progress of all crewmembers together.

Furthermore, during the technology demonstration it was difficult to see exactly what was happening on the crew server until the post-analysis of the downlinked data. To obtain an initial insight during the demonstration, manual analysis of the flat files sent between the servers were used to infer what changes were made by the crew in addition to checking on the health of the server.

Selecting Self-Scheduling Days

The selection criteria for determining what days would be best to use for the crew self-scheduling test depended on various factors. Primarily, the days could not be during high risk events or on days with minimal flexibility. High risk events include EVAs, visiting vehicles, dockings, and berthings. Days with irregular sleep schedules were also eliminated because of the uncharacteristic schedule constraints imposed. The challenging part of the process was obtaining agreement from various stakeholders, including NASA centers, principal investigators, and international partners. A lot of ground coordination is required for crew schedules and many constraints need to be accounted for. The addition of a crew altering the schedule so close to execution deviated from the regular ISS planning process. Extensive negotiation with individual stakeholders was required to build trust and understanding within teams. Ensuring a flight control team review prior to execution was critical to stakeholders.

Once a day was selected, the corresponding activities were arranged in a prioritized list (Figure 2). Using human factors principles, the Priority List tool was designed as an interactive tool in an electronic spreadsheet for the crew to use while working on scheduling the day. It provided multiple pieces of information to facilitate an overall understanding of the activities: the sequence, ground or team dependence, duration, and others items useful for scheduling. This priority list was sent to the crew with prior coordination and approval by the Flight Director and flight control team. Although this was helpful for the crew in making decisions for what activities should be prioritized while building their own schedules, the crew mentioned they wanted more insight on the constraints.

Self-Scheduling Sessions

Each of the five evaluation sessions were successfully completed as planned. For the first time in a spaceflight operational environment, an astronaut scheduled and rescheduled their own assigned activities and executed the resulting timeline. From this perspective, CAST demonstrated that the self-scheduling concept of operations is feasible in spaceflight operations (Figure 3).

The process of self-scheduling proceeded as follows: 1) the astronaut would open their procedure that showed the Priority List, 2) the astronaut would open Playbook on an iPad, and 3) schedule activities from Playbook's Task List view into the Timeline view. Scheduling was done through drag and drop. Figure 4 shows the Task List view. Figure 5 shows how one activity (EXERCISE-ARED) was moved from the Task List to the Timeline. If the activity was scheduled in a manner that did not abide to constraints, the activity would be flagged with a violation (red outline in the Timeline).

Figure 3: Playbook onboard International Space Station (Credit: NASA).

The on-orbit practice and refresher training from the first three CAST sessions plus the one hour of ground training several months before flight proved sufficient. In Session 3, the astronauts requested more activities to be "flexible" (i.e., that could be rescheduled) and they also, without any prompting from the investigators, rescheduled their day to reflect actual execution start times making the plan both an input as well as a record of the day's operations.

We infer from these observations two important lessons learned: basic timeline editing in Playbook was easy to learn and use, and the low entry barrier encouraged additional self-scheduling. Currently, Ops Planners spend significant amount of time training to become certified in their flight controller position. On the other hand, crew are already swamped with training and are not required to have the same expertise as a flight controller. Having a tool that facilitated simple rescheduling was essential to enabling crew to conduct onboard self-scheduling. Ideally, crew self-scheduling would provide the astronaut autonomy to make necessary changes in his or her timeline without violating any of the constraints that the Ops Planners diligently plan.

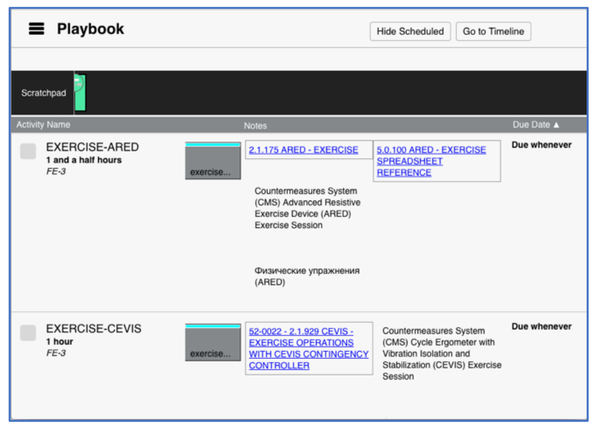

Figure 4: Playbook Task List view, list of activities from Priority List to be scheduled.

Sessions 4 and 5 were the most difficult by design, since the astronaut was asked to schedule their entire day. During session 4, the astronaut participant was unable to schedule a completely violation-free plan. The issue occurred because Playbook's constraint visualization (Go/No-Go Zone functionality, Figure 5) showed a particular activity as always creating a violation. The No-Go Zone visualization works well for simple single temporal or resource constraints such as an activity that must start within 2 hours of another activity, or a constraint against a resource such as available satellite communication coverage. However, when the solution within the constraint network involves several moves or steps to solve across multiple activities, the constraint space will appear as one continuous No-Go Zone. Since ISS plans have hundreds of constraints, a major lesson learned is that new, more novel constraint visualizations are required for the type of constraint complexity expected in human spaceflight operations. Session 5 did not have this issue and the astronaut successfully planned a violation-free plan.

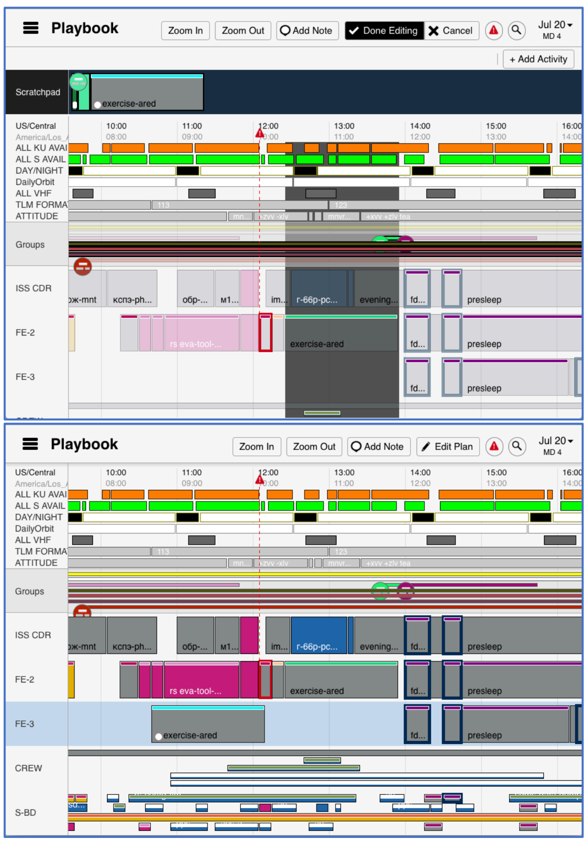

Figure 5: Playbook Timeline view, with activity EXERCISE-ARED selected and Go/No-Go Zone (top) and then scheduled (bottom).

Confirming Self-Scheduled Activities

ISS planning is not designed to accommodate real-time self-scheduling by resident astronauts. Astronaut self-scheduling is a timeline change, so within six days of execution a PPCR is required. Since self-scheduling alters an entire crew day, full approval of the change request is critical to limit operational risk. In a globally distributed support team, it is desirable to provide as much time as possible for coordination and approval. The desire for this time is in opposition to the goal of self-scheduling. In self-scheduling the priority is choosing and ordering activities to meet personal preferences. Therefore, for self-scheduling, it is desirable to alter the timeline as close to execution as possible. To balance the needs of the PPCR process against the desire to schedule as close to execution as possible, it was decided that astronaut self-scheduling should occur two days prior to execution. This timeframe was the minimum amount of time required for the ground to create, process, and approve a PPCR so that the proposed self-scheduled timeline became the official timeline prior to execution[2].

Despite the fact that the CAST process fit within the PPCR process, significant difficulties occurred when preparing the self-scheduled timeline. Given the short turn-around time of having the astronaut self-schedule two days prior to execution, the CAST team made contact with all other personnel supporting activities that may be selected for execution. The goal of this contact was twofold. One reason was to obtain and model ground availability in the constraints prior to self-scheduling. The second reason was to inform them of their role in self-scheduling, and convey that the exact timeline would not be known until the day prior to execution. This was a challenge for many ground support personnel who were familiar with and expected a predictable timeline. The CAST team recognized these concerns and spent considerable time to assure the affected parties that they would

[2] Analog field testing also suggested at least two days were required (Marquez et al., 2017).

receive personal contact from the CAST team as soon as the self-scheduled timeline was known. This addressed the concerns of some stakeholders and facilitated the PPCR approval process. The coordination with ground support personnel was a significant overhead and the imposed constraints reduced timeline flexibly for the astronaut when self-scheduling. A significant improvement to self-scheduling would require a ground support community that embraced timeline change or a community decoupled from the precise timeline.

Execution Challenges

Several tools and processes outside the timeline were also affected. The ISS stowage tool depended on having a known timeline. Due to the CAST experiment, the timeline was not known until the crewmember completed self-scheduling and a PPCR was processed to formalize those plan changes. This delay affected the teams needing to add stowage notes to their activities during the regular review periods. Effectively, this was a blackout period for creating new stowage information.

Another execution challenge was staffing and support. The coordination became difficult when support was not generic, meaning the specialist of a certain console position was not available at any time. Coordination requires time to prepare, console support sleep shifts, hours already worked or not being able to predict when the console needed to be covered, and adjust to the crew self-schedule in a short amount of time. An example of that difficulty was with the ISS Operations Supporter Officer (OSO) flight control position. OSO supports the crew systems and spacecraft structures. Due to the amount of hardware under their prevue, they use a model where each console operator specializes in certain equipment. OSO wants to match the specialist with the hardware being worked on. Since ISS has 24-hour operations, getting the right person, on the right shift, at the right time, is more difficult when the 'right time' is not known until a day before. This was further complicated because the OSO position goes on call while the ISS crew is not actively working. Therefore, OSO is not present for nearly 12 hours out of each 24-hour cycle, limiting their ability to react on short notice.

In general, the crew self-scheduling exercise required significant replanning of ground personnel to support crew activities. This also affected power and data resource verification. The CAST team needed to coordinate all the changes with different parties, verify payload director availability, inform impacts from late implementation of the crew plan (e.g., stowage notes, PPCRs implementation), and support timeline review for CAST activities all within a day of execution.

Future Work

This first initial evaluation onboard the ISS focused on one astronaut self-scheduling a carefully selected flight date. Our team continues to research alternate methods to facilitate crew self-scheduling: rescheduling grouped activities, including descriptive constraint explanations, and leveraging plan fragments for complex scheduling problems. These strategies are being evaluated in Earth analog missions. Additionally, our team is working on identifying and developing new constraint visualizations, as well as exploring collaborative automated planning. Discussions for a follow-up CAST demo include evaluating these new self-scheduling aids and expanding session to include multiple crewmembers in planning sessions.

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