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Operating a Crewed Spacecraft in the Age of Commercial Space Using Private/Government Partnership

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Abstract

Fifty years after humans completed a large-scale United States government-funded and government-engineered effort of landing humans on the moon, human spaceflight has entered a new paradigm. Private companies are now investing their own money and taking on an ever-increasing role in human spaceflight, in partnership with the U.S. government. This paper will describe the development of one of these partnerships through the lens of its mission operations team. As part of the Commercial Crew Program (CCP), NASA selected Boeing's CST-100 *Starliner* as one of the next generation of crewed vehicles. Boeing opted to partner with the US Government for their *Starliner* operations by contracting with NASA's Mission Control teams in the Flight Operations Directorate (FOD) at the Johnson Space Center to create its own Mission Operations (MO) flight controllers.

Partnering with FOD provided benefits to both Boeing and NASA while also creating new challenges. MO brought over 60 years of crewed spaceflight experience and infrastructure to Boeing's new program. Within certain legal constraints, MO was able to work closely and efficiently with their FOD counterparts who were performing both integration duties and, under the auspices of the CCP, insight of the contractors, in this case Boeing. Involvement of NASA as the Boeing operations agent did lead to what management deemed a 'healthy tension' within FOD, challenging old processes and often creating better, more robust teamwork. Successful development of the framework and boundaries of both the legal aspects and the oversight tensions has been one of the keys to developing a successful corporate/government partnership.

Due to the highly automated nature of the *Starliner*, the MO organization was designed to be much smaller than previous NASA's flight control teams for past programs. NASA has learned through the decades that spacecraft design and operations need to be as flexible and forgiving as possible. NASA's Commercial Crew Program was established to sponsor corporate development of economical vehicles that could get humans to and from low Earth orbit. These companies, of course, need to meet contractual obligations in providing a safe means of transporting astronauts to the International Space Station (ISS), but also need to do so in a manner that leads to the venture resulting in a profit at the same time. Through MO's involvement in the development of this spaceflight paradigm shift, there are ample lessons to be conveyed to future teams and programs working to develop similar missions.

Keywords:

Human Spaceflight, Government Partnerships, Commercial Spaceflight, Flight Operations

Acronyms/Abbreviations:

Apollo Soyuz Test Project (ASTP), Commercial Crew Development (CCDev), Commercial Crew Program (CCP), Commercial Orbital Transportation Services (COTS), Commercial Resupply Services (CRS), Flight Operations Directorate (FOD), International Space Station (ISS), Johnson Space Center (JSC), Manual Delta Velocity (MDV), Mission Operations (MO), NASA Docking System (NDS), Orbit Insertion (OI), Orbital Flight Test (OFT), Operations Nomenclature (Ops Nom), Public-Private Partnerships (PPP), Reimbursable Space Act Agreement (RSAA), Revolutionize ISS for Science and Exploration (RISE), Subject Matter Expert (SME)

1. Introduction

Over the course of its history, the U.S. Government has funded many high-risk endeavors with a public interest, ranging from building canals or roads to air mail postal service to the moon landing. Some sectors such as airport operations or prisons have been completely privatized, turning part or all operations over to a commercial entity.

Public-Private Partnerships (PPP) are not new to the U.S. [1], [2] with the most famous case probably being the building of the Transcontinental Railroad. During the 1860s the federal government provided funding and incentives to two private companies to build a railroad across the U.S.

Until recently, private companies looking to earn a small sum of money in space exploration would need to start with a large sum of money or significant governmental financial support. There was minimal financial return on investment. Starting as early as the Communications Satellite Act of 1962, private companies could operate satellites launched on government operated vehicles while the Commercial Space Launch Act of 1984 began to open up launch services. The commercial industry has since become quite successful in commercially exploiting the uncrewed satellite market.

The human spaceflight side of space exploration remained largely fully governmentally funded well into the 21st century. As the ISS was being developed and assembled, financial support was coming from governmental space programs such as NASA, Roscosmos, the European Space Agency, Canadian Space Agency, and the Japan Aerospace Exploration Agency. While commercial companies were certainly utilized by the governments to manufacture the space hardware, this was primarily under a direct contract to the government without the companies having much role in the development of requirements or design. In the NASA Authorization Act of 2005, the U.S. Congress began directing NASA to start collaborating with commercial partners but there was minimal guidance on how to do this, therefore little motion was made. More specific direction was provided in the NASA Authorization Act of 2010, which included the designation of the ISS as a National Laboratory. After ISS assembly was completed in 2011, focus of the ISS Program shifted further towards commercial involvement through its Revolutionize ISS for Science and Exploration (RISE) initiative [3].

Several additional legislative initiatives were passed in the 1980s and 1990s. Then the Commercial Space Launch Amendments Act of 2004 and the Spurring Private Aerospace Competitiveness and Entrepreneurship Act of 2015 codified government regulation of private space exploration while providing indemnity protection. This began to create specific ways and places that commercial companies could get a foothold in human spaceflight with a better means to envision financial return on investment. Several companies such as Rocketplane Kistler and XCOR attempted to capitalize on these opportunities but failed to achieve their goals. More recently companies such as Virgin Galactic, Bigelow Aerospace and Blue Origin appear on the verge of success.

Perhaps the greatest success to date has been NASA's Commercial Orbital Transportation Services (COTS) and Commercial Resupply Services (CRS) programs, where Space Exploration Technologies Corporation's (SpaceX) cargo *Dragon* and Northrup Grumman's *Cygnus* routinely conduct cargo resupply missions to the ISS. Through a combined government investment of $5.9 billion for 31 flights to both companies on the CRS-1 contract, NASA spurred a revitalization of the American commercial launch industry [4]. Low cost and frequent launch capability resulting from the innovations and competition of these companies has benefitted not only NASA but other government satellite operators and commercial launch customers as well.

With these legislative changes helping to create a path, NASA's Commercial Crew Program (CCP) was created in 2010 with the sole purpose of developing a replacement to the Space Shuttle's capability to ferry astronauts from the United State to and from the ISS. Based on the successful COTS program, NASA supported two development phases, Commercial Crew Development (CCDev) 1 and 2, where multiple private companies would develop key technologies for a crewed spacecraft. A key requirement was that NASA was not providing sole source funding but was partnering with companies who were expected to invest some of their own capital into the program. Instead of the final vehicle being U.S. property run by a contractor, the integrated system would be owned by the company and essentially leased to NASA. This unique relationship also meant that the private company retained intellectual property rights while NASA would be granted limited rights use. NASA down selected to three companies – SpaceX, Boeing and Sierra Nevada Corporation – in August 2012 to further develop fully integrated space transportation systems. On 16 September 2014, NASA selected SpaceX's *Dragon* and Boeing's CST-100 *Starliner* to demonstrate key capabilities including ascent abort, an uncrewed space flight and a crewed test flight.

Since SpaceX was already operating uncrewed cargo transport vehicles to the ISS, the crewed version would use the same infrastructure – control centers, launch pad and ground operators. Early in the development of *Starliner*, Boeing entered into a Reimbursable Space Act Agreement (RSAA) with the Flight Operations Directorate (FOD) at the Johnson Space Center to provide mission operations for the program. The RSAA was a new mechanism for NASA to provide services or capability to a non-governmental agency. With this agreement, NASA FOD personnel essentially became a sub-contractor to a private company. This allowed Boeing to quickly acquire access to a great deal of infrastructure – NASA's mission control in Houston, Texas, key interfaces to launch services at the Kennedy

Space Center and personnel steeped in over 60 years of experience in operating crewed vehicles. NASA benefitted by sharing unused capacity on existing infrastructure instead of indirectly funding duplicate contractor capability for a vehicle with a limited flight rate.

Flight control teams having to work and integrate with outside organizations was not a new thing for the Flight Operations Directorate. While human spaceflight started out as a national competition between the United States and the Soviet Union in 1961, the two countries were already starting early talks of working together as early as 1962 [5]. Even while the Space Race was underway to get to the Moon first, mission planners on both sides of the Atlantic were looking for ways to collaborate and cooperate in space. For human spaceflight, this started with the Apollo Soyuz Test Project (ASTP). In 1970, both US and Soviet mission operations personnel were meeting to discuss the parameters of the ASTP flight and possible Soyuz dockings to the US Skylab space station once it was flown.

From these early beginnings, NASA's and Flight Operations teams have expanded its successful collaborations to include International Partners in programs such as the Shuttle SpaceLab payload, Shuttle/MIR, and the International Space Station. They have also successfully developed successful relationships with a wide array of corporate partners through commercial payload flights on Space Shuttle and the ISS, commercial cargo service providers to the ISS, and now with the Agency's Commercial Crew Program and its service providers. Partnerships involving infrastructure have occurred as is the case of a private companying using NASA's Neutral Buoyancy Laboratory to conduct oil rig survival and fire training [6]. The relationship between MO and Boeing along with benefits and challenges, is discussed in detail below.

2. Boeing CST-100 *Starliner* and Mission Operations (MO)

One reason Boeing selected FOD as its operations team was NASA already had extensive infrastructure and processes in place to operate a crewed vehicle. In this RSAA, Boeing inherited FOD's methods for developing flight rules [7], procedures, and crew training. In addition, major readiness reviews such as the Certification of Flight Readiness and the agency level Flight Readiness Reviews were already a part of FOD culture with existing detailed documents that defined the process and configuration management of it. Crew and flight control operator training were also already in place. This enabled Boeing to save a great deal of time and money so as to not have to develop all of this capability to meet NASA requirements. To demonstrate requirement compliance in these areas, Boeing pointed NASA at the existing FOD documentation of these processes.

Prior to its entering into a RSAA with NASA, the Boeing Company already had a long history of experience working with FOD. As a NASA contractor, through its heritage companies, going as far back as the first U.S. human spaceflights, Boeing had decades of experience working with the flight controllers at Johnson Space Center (JSC) and knew well the capabilities that their RSAA would be able to bring into the CST-100 *Starliner* program. Similarly, FOD had worked closely with Boeing in testing the major ISS components and modules prior to their launch. The FOD was thus familiar to Boeing's approach to hardware and software development and testing.

An interesting and unanticipated benefit of this partnership with FOD was that Boeing had quick and easy access to a work force that they could add or subtract quickly as need and budget allowed. For example, MO was leveraged by Boeing to help significantly in the design and development of the vehicle and software, something not anticipate when the RSAA was signed. The MO team even provided testing of some aspects of the integrated automated software [8]. This level of involvement in design and development was something that the FOD team had never previously done, which expanded the FOD experience base and also allowed Boeing to quickly add "contractors" without having to put a separate provider on contract. This synergy also allowed the MO team to reduce their training since a significant amount of experience would be gained from direct participation in the spacecraft design.

This design and development involvement raised some interesting challenges within NASA and FOD. While any bidding company could have entered into an RSAA with NASA, only Boeing elected to do so. This added a significant challenge to NASA to ensure that proprietary data was not leaked, from other companies either to Boeing or vice versa. NASA personnel routinely have access to proprietary data of many companies due to the nature of NASA's requirements development, implementation, and verification oversight roles. Extensive training was conducted within NASA and FOD personnel (including the contractor personnel that work within FOD) to ensure proper practices were followed. Likewise, considerable effort was made to segregate proprietary data. For example, Boeing inherited many of the tools that FOD was already using such as SharePoint web pages or in-house tools like the Mission Control "Flight Note System". Generically, the Flight Note System is a tool that allows the exchange of information between flight controllers, engineers, and other programs or partners (e.g., the ISS). To ensure segregation of proprietary data, a separate instance of this tool was created on an isolated server with controlled access to ensure access was only provided to those with the appropriate need to know.

Another challenge with this arrangement was that NASA needed to ensure that no company had any unfair advantage. This meant taking steps such as firewalling the MO personnel off from other NASA teams. For example, while NASA personnel were developing the CCP requirements, the MO team was prevented from participating in in the review or decision process. In this regard, NASA adopted a very conservative approach. When SpaceX CEO Elon Musk visited the JSC those working for MO were not invited to attend a general discussion session.

Using NASA's infrastructure created other challenges. Flight controllers in Mission Control have a large number of voice loops to talk to each other and to other control centers. The NASA culture has been to generally grant access to anyone at NASA unless there was a rare specific reason not to, since as a civilian government agency open access was encouraged or even required. Initially, ISS and CCP personnel requested the same sort of access to all of the Boeing and MO voice loops that resided on the same voice systems, which supported Space Station and Artemis. Besides concerns that Boeing's proprietary data could be compromised, this actually created a significant asymmetry between partners. Therefore, loop access was made nearly identical between the CCP partners and reflected the more limited access that SpaceX had provided to similar personnel in Houston because their infrastructure was not integrated into the NASA voice systems.

Civil servants often have access to data from multiple providers and are covered by a blanket set of non-disclosure agreements and proprietary protection training. This means that Subject Matter Experts (SMEs) have to be extremely careful to make generic any results from testing or flight experience before it could even conceivably be shared with another company. The NASA Docking System (NDS) was designed by NASA and built by the Boeing Defense, Space & Security division of Boeing. Some of the SMEs that worked the project were also on the MO team requiring significant firewalling between the SME and other companies. Generic testing that NASA performed could be shared with any company; however, if a provider experienced something of note it could not be shared with another partner. Note that the Commercial Crew division of Boeing was similarly firewalled off from Boeing Defense, Space & Security which created problems for Boeing when the NDS was integrated into the *Starliner* and designs had to be modified.

Leveraging lessons learned through years of human spaceflight successes and failures, the Flight Operations Directorate has developed a successful, methodical approach to human spaceflight operations. This approach has been relied upon in the development of space programs to help engineers and program managers locate potential weak areas of requirements or design, and then provide options for resolving the issues. With *Starliner* and the Commercial Crew Program, FOD was going to have to learn something new – spacecraft automation. The requirements from NASA to the crew vehicle providers was that all of the new spacecraft were to be highly automated. Neither the crews nor the ground should need to be providing much input to the spacecraft; the automation would know how to fly the mission and how to work through a number of problems that might develop [8]. Experience had taught MO that even with the best-designed hardware or software, failures can come in completely unanticipated ways. One way MO applied this experience was to develop key backup capabilities. For example, MO developed a way to essentially step outside of the automated sequences and perform Manual Delta Velocity (MDV) burn. If the software were to incorrectly calculate an orbital adjustment maneuver or if an unplanned burn needed to be inserted (for example in the case to perform a debris avoidance maneuver) the flight control team could uplink a new burn. See also [8]. Procedures and flight rules were also developed to cover many likely "what if" scenarios the MO team could imagine or had previously experienced. See Fig. 1.

With the intended automation of the spacecraft, the RSSA for the MO team provided a relatively small sized flight control team compared to the number of people utilized for previous spaceflight programs. This smaller team size would appeal to a commercial company as it would be fewer human resources that needed to be covered. It also appealed to FOD because it meant that the broader FOD workforce could remain engaged in other spaceflight programs such as the ISS and beyond Earth exploration programs. To be even more appealing to Boeing's need to be budget conscious, the MO team was architected such that its size would reduce in number of people after the initial test flights. FOD personnel could be trained to operate multiple spacecraft. There did not need to be as many people assigned 100% to Boeing MO because more flight controllers could be cross trained to operate *Starliner*, the ISS, Orion, or some other spacecraft, moving between vehicles as missions came close to launching.

The small size of the MO team, with the intention to become even smaller, caused some unique challenges for the team. When the CST-100 program was in development and preparing for its first flights, the Space Shuttle had recently retired after 30 years of flight and the assembly of the ISS was complete. Flight controllers in MO had worked one or both of those programs and were well versed in the products, processes, and procedures that had been honed and refined over the years. Sometimes those processes did not work as intended in the *Starliner* program. Sometimes, the processes were not nimble enough or took too long to complete. Newer, simpler, and more efficient approaches were required. For example, a software tool called Workflow had been developed over many years to perform change control of flight rules and procedures. While an effective tool to manage inputs from many organizations and international partners, it was not designed to protect proprietary data. A simpler, but access controlled SharePoint© site was created for *Starliner* operational products. What worked "back then" no longer worked with the short turnaround times and smaller team sizes that the Boeing program demanded. While development of the alternate techniques took time (in some cases months or years), the result has been computational and analytical tools and processes that will benefit both CST-100 and other FOD-supported programs well into the future.

There were naturally some downsides and drawbacks to having the Mission Operations team come from within FOD, beyond the logistics already mentioned regarding proprietary data. Two significant areas of tension developed. One such area dealt with the oversight role that NASA provides to ensure that requirements were being met. The other area dealt with the pace and depth with which MO was involved in vehicle design and development, where the rest of FOD was not.

With respect to requirements verification, in prior Programs the "NASA side of the house," which would include all of FOD, would work together to confirm adherence to all NASA requirements. This work was largely based on assessment of data provided by the contracting company and determining whether sufficient evidence existed to confirm that the requirement has been met. In some cases, requirements could only be confirmed by actually flying the mission. In those situations, NASA would ensure that the vehicle or mission was safely postured to be successful in performing that verification without excessive risk to the crew or vehicle. These assessments routinely involved NASA asking for additional data, analysis, and/or testing to provide enough data to satisfy the requirements verification.

With CST-100, MO was tasked to provide some of Boeing's data to NASA for this verification work. MO, of course, was largely providing data related to CST-100 operations and that data was reviewed and assessed by the FOD. A healthy tension developed given that different components of the same FOD organization that were providing and assessing the same data. There were benefits of this arrangement in that the MO team knew what the FOD team would be looking for in their assessment and would ensure in the best way possible that the first data submission contained everything that was needed. When disagreements arose, it was possible for personnel on both teams to gather and work through questions and disagreements with relative ease.

Frustrations arose when FOD, ISS or CCP personnel requested additional data that Boeing was not on contract to provide. Over many years of crewed spaceflight these NASA organizations were used to having access to an incredible wealth of data developed by NASA contractors or within the FOD, data products that were typically funded and openly provided. MO, on a fixed budget, was in the position of having to decline the request and have the personnel (in offices just down the hall) take their requests up to the NASA CCP and then down into Boeing to get the requested data. It was frustrating to NASA that MO personnel seemed to have "gone over to the Dark Side" and resisted sharing data that was important to performing the requirements verification work. The instances of these types of requests reduced over time as MO and FOD continued to learn how to best work together to accomplish the tasks put in front of them while also maintaining the integrity of agreements with both Boeing and with NASA. This included developing various working groups where joint teams of MO and FOD personnel could work through draft data deliveries before they were officially submitted.

With 60 years of human flight experience including operations that resulted in the loss of 3 crews, FOD tended to be a bit conservative in its approach. This would sometimes frustrate Boeing when MO appeared to "gold plate" the design or operations when they felt what they had was "good enough". However, the personnel assigned to the *Starliner* program were able to operate with an open mind and both sides would give and take, bringing the best of both viewpoints together. Other elements in NASA, in particular within FOD and the CCP, would ensure that such debates did not compromise crew safety.

Perhaps one of the more visible instances FOD's varied roles in the commercial crew vehicle era came in the Flight Readiness Review process for the inaugural Orbital Flight Test (OFT) mission. Given that portions of FOD are flying the CST-100 for Boeing (Boeing MO), portions are verifying ISS readiness for approach and docking of CST-100 (NASA FOD), and portions are verifying CST-100 requirements are being met for the CCP (NASA FOD), readiness reviews for three different programs needed to be supported. FOD, as an organization, needed to certify that it was ready to fly CST-100 (for Boeing), certify that ISS was ready to receive CST-100 (for the ISS Program), and certify that FOD-related requirements for CST-100 were met (for the CCP). The output of this single Readiness Review would then split off to the readiness reviews of the three programs being supported - Boeing (as the vehicle provider), ISS, and CCP.

Due to *Starliner's* design as an automated vehicle where the flight control team's main function was to act in the case of contingency (see [8]) the team was sized to be much smaller than had been the case for previous NASA programs. In the past, the flight control team consisted of main or front room controllers supported by one or more personnel in a second, or back, room (see [9]). When assembly on the ISS was completed the back-room support was reduced but not eliminated and is still present during major activities. Due to the automated nature of the CST-100 the back-room support was eliminated. In fact, the initial plans for MO called for flight controllers to work two 12-hour shifts, further keeping the flight controller footprint as small as possible. Owing to the smaller team size and the fact that they were drawn from experienced flight controllers, the training plan, especially in terms of the number of simulations, was budgeted to be much smaller than had been historically the case for other programs. An additional rationale for the smaller team was for FOD to demonstrate that contrary to the image of a "standing army", they could match the cost and quality of support needed in modern commercial space ventures. Later, MO realized that for the test flights the automation would not be fully matured, requiring more ground interaction and therefore the team was expanded to 3 shifts. Since MO had essentially a fixed price contract with Boeing a major challenge was in training this third team with the same budget. This was accomplished by again choosing very experienced flight controllers and developing an abbreviated training plan that would get controllers ready for non-critical or dynamic shifts like ascent, rendezvous or landing. The MO team also continued to leverage its involvement in hardware and software design and testing as part of its flight controller training campaign.

Fig 1: Training simulation one month before the OFT mission. It was through simulations like this one where the MO developed the MDV concept of operations. (Top left) The MO flight control team in the Mission Control CST room. (Top right) The Boeing engineering Mission Support Room personnel down the hall from the MCC-CST. (Lower Left) The CCP team monitoring the operations, as they did in flight, in a room above the MCC-CST. (Lower right): The MO training team running the event across the Johnson Space Center campus.

NASA also struggled with the smaller operations team size. Culturally, other NASA organizations were used to FOD, which has significant resources, being able to provide a great deal of analysis or review especially for "what if" scenarios. The leaner MO team however could not always provide such depth with the result that these outside organizations often saw MO as not being a team player.

There were other cultural differences between spaceflight programs. With 30 years of flight experience with the Space Shuttle program, the former shuttle flight controllers were used to a mature program focused on repeatability. The ISS story has been one of continued change and evolution (cf. [9]) with key phases marked by assembly, the COTS program, changes in research priorities and now the commercial crew program. For crewed vehicles, the CCP was the NASA interface, which was structured more like the Space Shuttle program, as they oversaw a system designed to ferry astronauts to the ISS. While SpaceX had only ever known the ISS way of doing things, Boeing was familiar with both Space Shuttle and the ISS. Boeing, similarly, also structured their systems more like the Space Shuttle processes their team was familiar with. This often meant that MO had to bridge the gap between Shuttle and Station processes and cultures. This meant "tailoring" products or processes in a way that would more clearly align with the ISS systems and yet be understandable and not completely foreign to those with Shuttle backgrounds. A basic example was the format of procedures and the development of Ops Nom, or Operations Nomenclature. Initial development could be described as "Shuttle-centric" and did not always mesh well with astronauts who now had extensive experience flying on the ISS. A reverse of this cultural phenomenon occurred in the early days of the Space Station program. Of course, both vehicles perform different functions – one has a very dynamic mode of operation while one "coasts" continually in low earth orbit – necessitating some differences. MO spent a great deal of resources developing hybrid standards that incorporated the best of both the experiences and lessons learned from both programs.

Sometimes the NASA cultures aligned but were at odds at the commercial model. For example, NASA has used a Flight Operations Review to conduct a deep review of operations products (i.e., flight rules, timelines, procedures). Traditionally the process takes months beginning with a release of all products in a baseline, followed by weeks of engineering review and culminating in an intensive week of dedicated meetings to conduct a final review. While effective, there is a great deal of overhead in a process that is not the most efficient. When MO proposed adopting more of a virtual review – releasing products continuously and reviewing via online tools for comments and holding only dedicated splinter meetings when needed – both the ISS and Commercial Crew programs struggled to embrace this change. *Starliner*-only products were initially reviewed the traditional way for the OFT mission and evolved to a more virtual process for the second flight. Joint products with the ISS (i.e., those applicable within a 1x2km Approach Ellipsoid around the station) were reviewed with the classic FOR approach for both of the first two missions.

3. Mission Execution – Orbital Flight Test

Starliner's OFT was largely a successful mission, despite the fact that rendezvous and docking with the International Space Station did not occur This success included completion of the primary objective of the OFT mission - to successfully land and recover the CST-100 spacecraft after a launch from Florida. A wide array of additional hardware and software capabilities were successfully demonstrated. The strength of the partnerships between MO and the rest of Boeing Engineering, between MO and its NASA FOD counterparts, and between MO and the CCP was also demonstrated.

Shortly after separation from the Atlas V launch vehicle, the CST-100's automated sequences are programmed to converge on the timing and size of a number of burns that will take it from its initial orbit up to the ISS (see also [8]). While it is computing these burns, it is also performing its first critical burn, the Orbit Insertion (OI) burn. The CST-100 must, through its OI burn, complete the final boost phase into a preliminary orbit. Due to CST-100 software issues related to the initial time of launch [8], *Starliner's* automation was unable to perform the OI burn.

The MO flight control team leveraged its experience with design, development, and testing the flight software to swiftly develop a plan to get the spacecraft into a stable orbit and then worked with Boeing Engineering and Program managers to determine which parts of the mission could still proceed. Utilizing years of history and experience as a guide, the MO team had spent a considerable amount of its preflight training time developing responses to "what if" scenarios that not only covered single failures but multiple failures as well. While none of the training cases the teams had worked through were exactly the same as what was seen shortly after OFT's launch, the team was able to use the experience and products that had been developed to generate a workable plan for the remainder of the mission. Using the MDV burn discussed above, the flight control team was able to bypass the software issue and directly command the vehicle to perform an OI burn.

While Boeing, with input from MO, had developed the mission objectives and priorities for OFT, MO led the replanning effort to determine what objectives could be completed. This plan, which was vetted by the NASA FOD and CCP teams as well as Boeing engineering and management, worked to accomplish as many on-orbit test objectives as possible while also returning the spacecraft to the New Mexico desert at the earliest possible opportunity. See Fig. 2.

Fig 2: The MCC-CST just prior to OFT launch on 20 December 2019.

The initial recovery from the missed OI burn resulted in more usage of the Service Module propulsion system, both propellant and the thrusters themselves, than planned for the nominal mission at that early part of the flight. In order to account for this additional usage, MO had to develop methods for adjusting which thrusters would be utilized and work with Boeing specialists in flight software; guidance, navigation, and control; and propulsion to generate and uplink new software parameters. MO was able to provide a 'backstop' to the engineering teams to cross check the updates being provided and tested so that as many "sets of eyes" were on the updates as possible.

Many of the OFT mission's 49 hours were flown outside of the pre-planned automation sequences due to the fact that the mission was not going to be rendezvousing with the ISS. To compensate for this, MO leveraged non-rendezvous "holding" sequences for the free flight portion of the mission prior to transitioning into the final preparations for deorbit, entry, descent, and landing.

Because of the proximity of the various teams, including the CCP, information and planning for the mission on-the-fly proceeded exceedingly quickly. This was particularly apparent during the Starliner Mission Management Team meetings, a real-time program management board consisting of Boeing and various NASA stakeholders, where Boeing, MO and CCP were well integrated. While Boeing led, agreement from the NASA CCP was still required for most aspects, which ultimately has authority to restrict or disapprove most aspects of the designs. During the shortened OFT mission, MO was able to seamlessly leverage its Public/Private Partnership and work between the large private company and the CCP. When a situation demanded quick decision making, the experience and familiarity with the personnel on Boeing's operations agent streamlined discussions between Boeing, the CCP, and MO. This greatly reduced the risk of organizational misunderstanding and mistrust that can occur with two geographically separated organizations with different work cultures and unfamiliar personnel in a stressful situation.

4. Conclusion and Future Public/Private Partnerships

While PPPs are not new, their application within NASA has been limited. This paper describes one utilization case of PPP within NASA. Successful partnerships build on the strengths of both sides while filling holes in capabilities of each partner. Using a RSAA with FOD, Boeing was able to quickly gain an experienced flight operations team that was able to contribute immediately to the design and development of the *Starliner* system. This experience was pivotal during the OFT mission which allowed it to complete a safe landing at the primary landing site, accomplish most of its objectives, and pave the way for the Crewed Flight Test targeted for 2020. In turn, FOD was able to retain experienced flight controllers between the end of the Space Shuttle program and prior to the ramp up of the Artemis project. FOD also learned a set of new, valuable skills related to the operations of automated spacecraft.

As the Artemis programs prepares to return to the moon in 2024, NASA has been directed to maximize the use of commercial partnerships. For the first time a private company, Axiom, has been granted permission to consider developing a commercial module on the ISS [10]. Local governments are also forming PPPs for space exploration as is the case with Houston's Ellington Airfield partnering with Sierra Nevada Corporation [11]. Lessons learned from the CCP in general and the Boeing-FOD partnership in particular will be important in the success of these ventures going forward.

The experiences of the OFT mission demonstrated the importance and usefulness of having the operations teams closely involved in the design, development, and testing of the CST-100. In theory, Boeing could have brought the MO team late in the development phase of the program. Boeing's investment in the RSAA with NASA was well served by being able to leverage the MO team's decades of prior spaceflight operations experience. Not only did this provide operational insight into the design, which increased mission flexibility, it also provided a mechanism for integrating vehicle systems and information across the various Boeing engineering and design groups. Given that MO would be flying the integrated spacecraft, MO's knowledge of various system developments and challenges helped inform operations and design changes to other elements of the spacecraft.

The flight of the OFT mission shows how that investment can pay significant dividends when the operations teams have considerable depth of knowledge of hardware and software systems and interdependencies. The OFT mission also showed that not all failure modes can be anticipated in advance. There needs to be the capability for flexibility and alteration of the spacecraft, especially software, should conditions warrant. The CST-100 software has considerable capability to be updated, but these updates can only be performed by ground commanding. This fact warrants re-examination for future spacecraft and space systems that are operating beyond cis-lunar space with considerable light-time delays from Earth-based mission controls. For human spacecraft and systems operating further away from Earth, for example at Mars or beyond, the crew may need the capability themselves to update the flight software. There would surely continue to be collaboration with spacecraft designers, engineers, and operators, but inserting the flexibility for in-situ updates by the crew might well one day save a mission or a life if waiting dozens of minutes for uplink from Earth is too long of a wait.

In the case discussed here, NASA's Commercial Crew Program contracted with a private company to provide integrated commercial crew services. That company (Boeing), in turn partnered with NASA for part of those services. The success of the OFT mission has provided one case study where this type of partnership was a key component of mission success. While workable, this partnership does add a layer of complexity that should not be overlooked. Since each partnership or contract also has administration overhead, there could be inefficiencies incurred in terms of extra costs or barriers to success. Further case studies and reviews on this topic are warranted as the CST-100 program completes the Crewed Flight Test and begins regular crew rotation flights to the ISS. These case studies might also focus on comparing the success of this PPP vs. potential successes or options if the same services had been procured directly as Government Furnished equipment. As the authors look forward to future successful *Starliner* missions, they also point out that the Partnership in place for CST-100 does demonstrate the Private/Public Partnerships are possible, can be successfully implemented, and can be substantial force multipliers for the success of complex missions or tasks.

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