

NASA Mission Operations Directorate Preparations for the COTS Visiting Vehicles

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With the retirement of the Space Shuttle looming, a series of new spacecraft is under development to assist in providing for the growing logistical needs of the International Space Station (ISS). Two of these vehicles are being built under a NASA initiative known as the Commercial Orbital Transportation Services (COTS) program. These ‘visiting vehicles’; Space X’s ‘Dragon’ and Orbital Science Corporation’s ‘Cygnus’, are to be domestically produced in the United States and designed to add to the capabilities of the Russian Progress and Soyuz workhorses, the European Automated Transfer Vehicle (ATV) and the Japanese H-2 Transfer Vehicle (HTV).

Most of what is known about the COTS program has focused on the work of Orbital and SpaceX in designing, building, and testing their respective launch and cargo vehicles. However, there is also a team within the Mission Operations Directorate (MOD) at NASA’s Johnson Space Center working with their operational counterparts in these companies to provide operational safety oversight and mission assurance via the development of operational scenarios and products needed for these missions.

Ensuring that the operational aspect is addressed for the initial ‘demonstration flights’ of these vehicles is the topic of this paper. Integrating Dragon and Cygnus into the ISS operational environment has posed a unique challenge to NASA and their partner companies. This is due in part to the short time span of the COTS program, as measured from initial contract award until first launch, as well as other factors that will be explored in the text.

Operational scenarios and products developed for each COTS vehicle will be discussed based on the following categories: timelines, on-orbit checkout, ground documentation, crew procedures, software updates and training materials. Also addressed is an outline of the commonalities associated with the operations for each vehicle. It is the intent of the authors to provide their audience with a better understanding of the mission assurance that MOD brings to commercial ventures to the ISS.

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Most of what is known about NASA's Commercial Orbital Transportation Services (COTS) program has focused on the work of Orbital Sciences and SpaceX in designing, building, and testing their respective launch and cargo vehicles. However, there is also a team within the Mission Operations Directorate (MOD) at NASA's Johnson Space Center working with their counterparts in these companies to provide operational safety oversight and mission assurance via the development of operational scenarios and products needed for these missions. The work done by NASA in ensuring that the operational aspect is addressed for the initial 'demonstration flights' of these vehicles is the topic of this paper.

I. Introduction

NASA Johnson Space Center (JSC) Mission Operations Directorate (MOD) personnel, including both civil servants and contractors, have been working with SpaceX and Orbital Sciences behind the scenes over the last few years to integrate their Commercial Orbital Transportation System (COTS) vehicles operations into those of the overall International Space Station (ISS) system.

Flight operations, especially those involving new vehicles and related systems, have to be meticulously planned and rehearsed prior to each mission. NASA and its international partners involved in the ISS (and by extension the countries they represent) have invested heavily in the hardware of the station, with crew safety being paramount. Before new vehicles can rendezvous and berth with ISS, they will have to demonstrate their operability and safety requirements have been met through extensive ground testing and demonstration missions.

The pre-mission planning lead by NASA MOD involves tasks such as developing Flight Rules, crew procedures, integrated ground procedures between entities, flight techniques, command protocols, simulation plans and a whole host of other operational items as will be described in the following pages. The mission operations personnel at JSC follow the "plan-train-fly" methodology, built upon over 45 years of human spaceflight experience; with that in mind the work described in this paper is grouped in these three categories.

II. Plan: Pre-Flight Integration

Shortly after the Space Act Agreements (SAA) were signed between NASA and the two COTS partners, NASA MOD personnel began work on long lead-time items required for these cargo vehicles to be able to rendezvous with and attach to the ISS. Work of this nature included ISS software updates, the creation of new crew computer displays for vehicle monitoring, and mission control center (MCC) integration.

Updating the command and control software on-board the ISS is a multi (2+) year effort due to the extensive testing that must be done on the ground before software is cleared for usage on-board the ISS. Recall that when the SAA for the COTS cargo vehicles was signed the first demonstration mission of each vehicle was slated to happen within a few years so updates to the ISS software were required immediately. NASA MOD and ISS Program Office personnel thus began discussions with the COTS vendors to identify

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all changes needed to ISS software to accommodate their vehicles. These changes included the allocation of memory within the ISS command and control computers for visiting vehicle data, the sizing and defining a stream of telemetry coming from the visiting vehicle to the ground via the ISS, the creation of Caution and Warning messages triggered on-board for crew awareness of vehicle anomalies, additions to the ISS software to allow commands from the ground to be routed to the visiting vehicles via ISS and updates to the robotic workstation software to allow the crew to capture/berth/unberth/release these free flying vehicles.

Each of these changes required the NASA team to have some understanding of the architecture and inner workings of the visiting vehicles, both of which were at roughly a preliminary design review (PDR) phase at the time that these ISS software changes needed to be incorporated. NASA MOD personnel participated in PDR to gain the necessary understanding of the vehicle configuration. As one can imagine both vehicles have made changes to their vehicles post-PDR so some additional ISS software updates have been required in software cycles subsequent to the initial update. (The first missions of these vehicles have also slipped allowing these changes to be accommodated largely within existing software update schedules.)

Another long lead time item developed by MOD personnel is the creation of computer displays (graphical user interfaces, GUIs) used by the ISS crew for real-time monitoring of the visiting vehicle trajectory and limited subsystems. One of these GUIs, referred to as the 'Robotic Workstation (RWS) Overlay' places visiting vehicle data over live video of the vehicle as it approached or departs the ISS. An example of this type of overlay display is shown in Figure 1. The center of the display shows corridors for crew monitoring of vehicle position. The edges of the display show ISS and visiting vehicle data such as attitude, range, range rate, vehicle mode and communication status.



Figure 1: Example RWS Overlay for Visiting Vehicles

A handful of other crew GUIs were also developed to allow the crew insight into a small subset of visiting vehicle data (pressure, smoke detector status, etc). This information is mostly for crew situation awareness but could be reference in crew procedures executed in response to a vehicle caution and warning message being triggered.

Another multi-year effort has been the integration of the ground control centers. In order for the COTS vehicles to be commanded to via ISS assets extensive work had to be done to connect the ISS Mission Control Center in Houston (MCC-H) with the *Dragon* MCC in Hawthorne, CA (MCC-X) and the *Cygnus* MCC in Dulles, VA (MCC-D). Once completed this allows command sent from the COTS partner control centers to route through MCC-H and be uplinked to the ISS. This also allows visiting vehicle

telemetry coming down through ISS to be routed from JSC to the remote MCCs and back. Voice and video circuits are also routed between the control centers.

II. Plan: Operations Product Development

A substantial portion of the work done by the NASA MOD team in the years and months leading up to the initial flight of each of these vehicles has been in the preparation of operations products (ops products). The term ‘ops products’ encompasses all the materials needed by the flight control teams and ISS crew for real time execution of the visiting vehicle missions. This includes procedures for both the ground and crew, flight rules governing the mission, timelines for the mission, systems manuals for reference, and work instruction-type documents.

Procedures developed include all the procedures needed for a nominal vehicle approach, capture, berthing, activation, ingress, etc as well as those for probable issues/malfunctions. During launch, far-field rendezvous and reentry of the COTS vehicles, any procedures needed are developed and maintained in-house by the COTS providers. For ISS missions, there is an agreed to point in the rendezvous trajectory where the mission enters ‘integrated operations’ and subsequent procedures will have steps for MCC-H, the ISS Crew as well as the COTS MCC. Timelines and joint procedures for this phase of the mission are owned and maintained by NASA MOD.

The rendezvous portion of the mission from the start of integrated operations until capture is a heavily scripted timeframe with procedures outlining every vehicle, mission controller and crew action as well as the expected calls between the involved parties. This portion of the mission is also heavily rehearsed (as is described in a later section of this paper) to ensure that teams are well prepared for safe execution. The post-capture to install and activation phase of the mission is also carefully scripted and follows the sequence of events developed and flight proven with the two HTV missions that have already been successfully conducted at ISS.

The attached/quiescent operations periods (up to 30 days in duration) for each of these vehicles involves very little operations. During this time period each vehicle is placed into a quasi-dormant state with all non critical subsystems safed and/or powered down. Any operations necessary during the attached operations period will be planned near real-time following the standard ISS planning process. Similar to the rendezvous portion, the departure phase of the mission is also heavily scripted and rehearsed. Detailed timelines and procedures govern this portion of the mission which takes the better part of two days (as is described in the Real Time Operations Section of this paper).

An example daily timeline for the ISS is shown in Figure 2. Each activity for each of the 6 crewmembers is detailed within this timeline as well as all planned ground activities involving commanding to the ISS. Timelines like this are typically developed ten days out for each day of ISS operations. Timeline development for the dynamic days of the visiting vehicle missions (rendezvous/capture, berthing/activation, unberthing/release, etc.) started more than a year before the first missions, to allow for these timelines to be used in mission simulations.

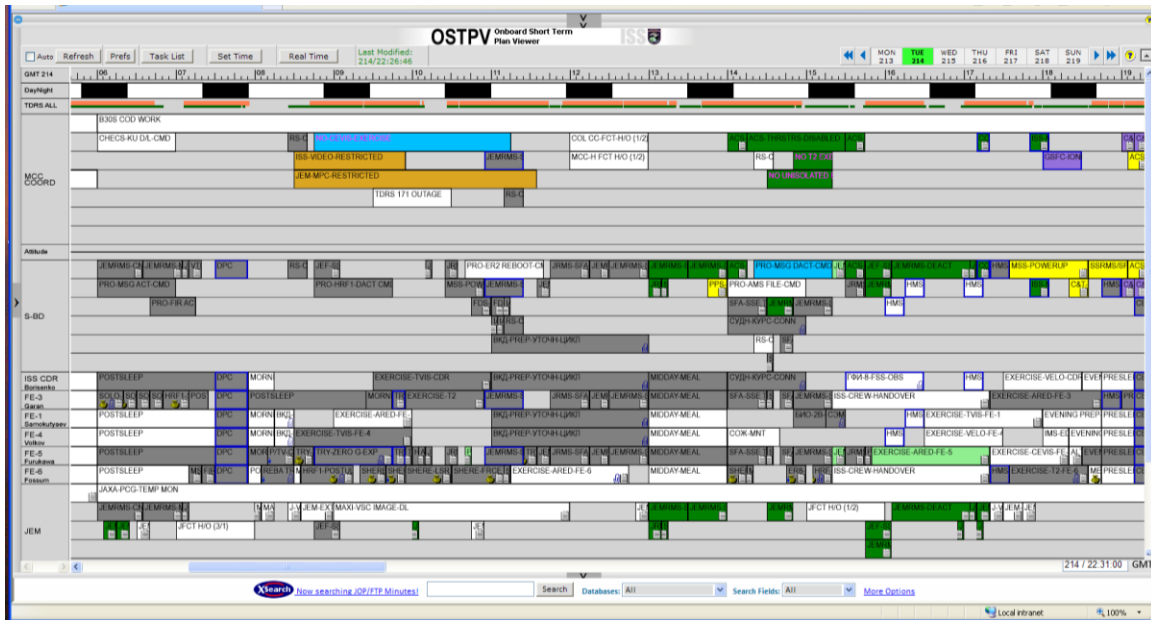


Figure 2 - ISS Onboard Short Term Plan (OSTP)

In addition to timelines and procedures, the Houston team has worked with SpaceX and Orbital Sciences to develop a systems manual for each of their vehicles. This proprietary document details the subsystems of each of the vehicles with emphasis on the subsystems that interface directly with the ISS (power, data, environmental, communications, mechanical, etc). These systems manuals are to be used by the mission control teams pre-flight for training and real-time as a reference document.

A substantial amount of time has also been spent by the operations team to develop a set of 'flight rules' governing the COTS vehicle missions. As has been done for every space shuttle mission, the ISS, HTV and ATV each COTS vehicle now has its own volume of flight rules. These rules aim to define responsibility and authority for the mission as well as to document expected configurations, operational hazard controls and responses to off-nominal situations. Developing and documenting these flight rules for the COTS missions has proven invaluable in narrowing down areas of open work and disagreement leading up to the missions and will ensure that flight controllers are well prepared to make real-time decisions, often on safety critical matters, in a timely manner.

II. Train: Pre-Flight Preparation

Starting about eight months before the first demonstration mission of each vehicle the mission control center teams (MCC-H and MCC-X or MCC-D) began participation in joint simulations (sims). Less than ten joint sims are planned for each vehicle before the first mission. (Subsequent cargo missions are slated to have 3 joint sims between each mission.) Each sim will run 6-8 hours with full teams of flight controllers participating. Three types of sims will be performed: rendezvous, installation/activation and departure.

Rendezvous sims begin at the start of integrated operations and run until the vehicle is captured with the robotic arm. Approximately half of the integrated sims rehearse this timeframe. Failures of vehicle hardware critical to rendezvous are exercised during these sims. Failures of ISS hardware that will impact capture, installation or attached operations are also exercised. Installation/Activation sims begin after the vehicle has been captured and run until the vehicle has been ingressed and fully connected to ISS utilities. Departure sims typically begin after the vehicle has been disconnected from ISS utilities, has been closed out and is ready to be unbolted. These sims end once the vehicle has exited the ISS approach ellipsoid. One of the joint sims will be a long sim, spanning multiple shifts to allow the team to exercise shift handovers.

A major challenge in running these joint sims has been the integration of the visiting vehicle simulator (running at the vendor control center) with the ISS simulator (running at JSC in Houston). Getting these sims to exchange data and stay in sync has proven to be much more difficult than initially anticipated. Differences in the programming languages and parameters used by each sim has proven challenging to both teams. Orbital's *Cygnus* spacecraft has the added complication of needing to perform sims with both MCC-H and SSIPC in Japan. *Cygnus* is using the JAXA PROX system for rendezvous ops onboard the ISS, so proper training of the rendezvous and departure portion of the mission must involve all three participants.

A non-trivial amount of work goes into the planning of each joint sim. Failures to be interjected in each sim must be "scripted" with input from both teams. Expected responses are documented, with relevant flight rules noted. The personnel involved in scripting and running the sims take pride in selecting complicated cases where flight controller skills are really put to the test. Making the sims as mission-like as possible is paramount to the training of the teams. The MOD motto is and has always been to "Sim Like You Fly", no matter what it takes, and numerous examples of the importance of this credo can be found through the past 50 years of human spaceflight.

Simulations serve not only to train the flight control teams but also to validate timelines, procedures, flight rules and displays (GUIs) for the mission. The execution of both nominal and off-nominal scenarios allow the team to verify that the vehicle operates as planned and that procedures accomplish stated objectives. Procedures that are not able to be validated in simulations must be validated through joint testing or, if that is not possible, through desktop walkthrough. All operations products are signed by both teams pre-mission during the flight operations review.

III. Fly: Real-Time Roles

Both COTS vehicles are designed with a certain degree of autonomy, the details of which will not be discussed in this paper due to company-specific proprietary sensitivities. That being said, there is much to be said about the real-time roles for the respective control centers on the ground and the ISS onboard crew.

As has been previously mentioned, SpaceX and Orbital will have mission authority for their respective vehicles until a previously agreed to point in the flight profile (aka "integrated/joint operations"). The majority of pre-launch, launch and early free-flight operations are, by design, delegated to these companies, with NASA playing a supporting role (verifying that the ISS is in the appropriate configuration to receive these logistic vehicles for example). Actual command and control for *Cygnus* and *Dragon* will reside at their respective control centers.

SpaceX operates the *Dragon* spacecraft from their new facility in Hawthorne California (near Los Angeles) designated Mission Control Center - SpaceX (MCC-X).



Figure 3: MCC-X (Image credit SpaceX)

Orbital will operate *Cygnus* from a new control room within their campus in Dulles, Virginia (near Washington DC).



Figure 4: MCC-D (Image Credit Orbital Sciences Corp)

On rendezvous day, overall mission authority shifts to Mission Control Center -Houston (MCC-H). Specific 'gates' will be coordinated by MCC-H as *Cygnus* or *Dragon* approach the ISS. Prior to each major burn or event being executed, sync points between the control centers will be met. These include demonstration objectives to validate how the spacecraft will respond to onboard, ground, and crew

commands in-flight (vehicle propulsive burns, ‘holds’, retreats, etc.) Some of these events occur earlier in the mission for both vehicles as well. Once both entities agree these gates have been met, a ‘GO’ will be given by MCC-H to proceed to the next objective. This will occur at specific points throughout the rendezvous up to vehicle capture. All of the demonstration objectives and ‘GO’ calls will be agreed to pre-flight between NASA and SpaceX or Orbital, and documented in the Flight Rules.

The Houston control team will also be involved in coordinating and configuring the ISS for the visiting vehicle, which is typical for any visiting spacecraft. This includes maneuvering the ISS, orientating the solar arrays and radiators in the correct configuration, coordinating with the other international partners to ensure they are in the correct configuration for rendezvous, and a host of other preparatory activities.

The ISS crew has the ultimate say during final approach and capture. They will be able to monitor the vehicles and related safety-critical parameters in the final phases. They do not manually ‘fly’ the spacecraft, but have a subset of commands they can send, including an abort command, if the vehicles do not operate as expected. They are prime to capture and berth *Dragon* and *Cygnus* with the ISS robotic arm (SSRMS).

At the end of the rendezvous approach, both vehicles are placed in free drift. The crew then utilizes the SSRMS to capture the vehicles. Once capture is complete, the crew maneuvers the spacecraft to the berthing position on Node 2 nadir (note: later missions may also berth to the Node 2 zenith port on ISS). The crew and MCC-H will perform Common Berthing Mechanism (CBM) ops to complete the berthing process. A sequence of events then follows, including leak checks in the vestibule between the two entities, Node 2 hatch opening, vestibule outfitting (installing vestibule jumpers for power, data, and air sampling, removing components of the ISS Common Berthing Mechanism (CBM) for access, etc.). Once this is complete, the crew is go to ingress the vehicle.

The majority of time spent for either vehicle on-orbit is expected to be berthed to ISS. In this quiescent state, monitoring of the vehicles health and status will be the primary role of the respective control centers (MCC-D or MCC-X) with oversight from Houston.

Cargo transfer is expected to occur over days or weeks, depending on the specific vehicle, overall NASA manifesting plan, and competing ISS crew priorities. Cargo operations will be directed from MCC-H with input from the vendor’s flight control team. Similar to other vehicles that service the ISS, new cargo is transferred to the station while trash is restowed within *Dragon* and *Cygnus*.

For *Cygnus*, the cargo launched will include both passive cargo and ‘active’ payloads, the latter being powered. Those are similar to payloads that were launched on the Space Shuttle middeck. *Cygnus* cargo is all internal and *Cygnus* has no return capability; the vehicle performs a controlled destructive reentry similar to HTV, ATV or *Progress*.

Dragon contains both internal and external cargo. Internal cargo is pressurized and includes traditional passive cargo and active payloads as described above. External cargo is unpressurized and envisioned to be spares, orbital replacement units, etc. Unlike ATV, HTV or *Cygnus*, *Dragon* reenters the Earth’s atmosphere and splashes down in the Pacific Ocean so *Dragon* can provide return capability for internal (pressurized) cargo. The unpressurized section of *Dragon* does not reenter.

As the berthed portion of the missions come to an end, attention turns to preparing the vehicles for departure. The ISS crew closes out the vehicles. Both spacecraft have requirements to secure internal cargo for return (*Dragon*) or disposal (*Cygnus*). Specific center of gravity (CG) numbers have to be adhered to, as one doesn’t want cargo shifting around one of these vehicles as it departs ISS, impacting how the departing vehicle operates.

Next, the crew deconfigures the vestibule between Node 2 and *Cygnus* or *Dragon*. This includes removing vestibule jumpers for power, data, ventilation and air sampling, reinstalling internal components of the ISS Common Berthing Mechanism (CBM), closing hatches and performing leak checks. The removal of ISS power and data services is choreographed between the crew and the control centers. The RF command/telemetry path needed for departure has to be verified operational before removing the ISS 1553B vestibule jumpers. Powered connectors have to be verified safe to handle before the crew demates them.

Once this is complete, the crew proceeds with Robotic and CBM ops. Similar to the Japanese HTV vehicle, the SSRMS is grappled to the departing vehicle by the crew. CBM ops commence to unberth the vehicle. The crew then maneuvers the grappled vehicle to the release point. Once given a final go by MCC-H (which coordinates with the vendor control centers), the crew releases the departing spacecraft. The crew and ground teams then monitor the spacecraft as it departs ISS. Once outside a certain range of

the station, MCC-D or MCC-X become prime for the final stages of flight: re-entry and splashdown for *Dragon* or a targeted destructive reentry for *Cygnus*.

IV: Anticipated Post-Flight Roles

The yearly flight rate for *Dragon* and *Cygnus* after the initial demonstration missions of each is an evolving process, but NASA/MOD is expecting multiple missions per year for both vehicles. That being said, there will be down-time between flights. During these periods, MOD expects to coordinate mission debriefs with their respective Orbital and Space X counterparts, and incorporate new changes in procedures and flight techniques based on lessons-learned from operating the spacecraft. This will be similar to debriefs for other spacecraft servicing the ISS. Station crew and flight controller input is vital for these meetings. New and refined flight techniques will be created from experienced gained in operating the new spacecraft in orbit. Operational efficiencies will be gained on later missions, once the vehicles have proven themselves on orbit. Demonstration objectives planned for the first missions of *Cygnus* and *Dragon* will not need to be repeated for subsequent flights. The teams also expect to perform simulations between missions to maintain the teams' proficiency and to practice techniques and procedures. The number of sims will most likely fluctuate between flights.

Of interest for *Dragon*, work is ongoing between NASA and SpaceX to coordinate the recovery of ISS scientific samples and hardware post-landing. But that is outside of the scope of this paper.

V. Conclusion

America's Human Spaceflight program is evolving with the end of the Space Shuttle program and the maturity of the International Space Station (ISS). Part of that change includes the integration of NASA's new commercial partners into supporting the station and commercializing Low Earth Orbit. NASA's Mission Operations Directorate is in the forefront of that plan, working with Orbital Sciences and SpaceX for the past few years in preparation for their COTS missions. Following the NASA MOD "plan-train-fly" model, extensive work has been done between the teams in the areas of preflight planning, mission simulations, flight techniques, and operational product development...all leading up to working together in the real-time environment. The innovation of SpaceX and Orbital, combined with the diligence and experience of NASA's Mission Operations Directorate (MOD) and related entities strives to ensure safe and successful *Dragon* and *Cygnus* missions to the ISS.

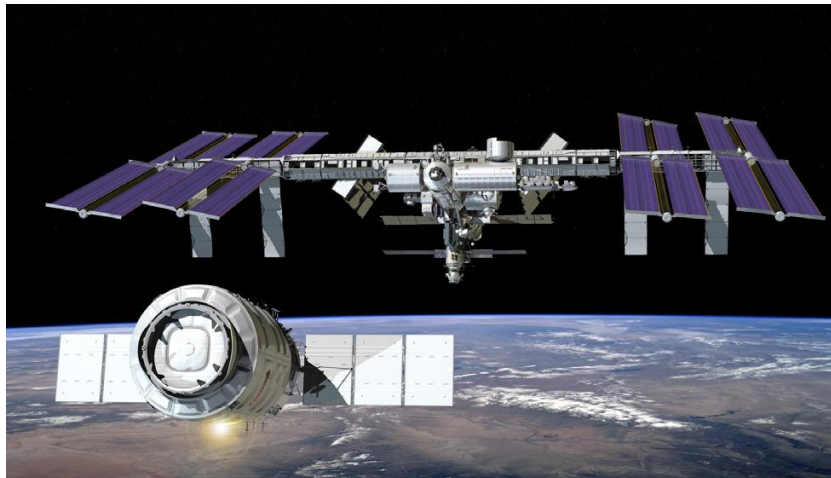


Figure 5 - *Cygnus* Departure from ISS - artist rendition
(Image credit Orbital Sciences Corp)



Figure 6 - *Dragon* Approach to ISS - artist rendition
(Image Credit NASA)