OPALS: Mission System Operations Architecture for an Optical Communications Demonstration on the ISS

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In spring 2014, the Optical PAyload for Lasercomm Science (OPALS) will launch to the International Space Station (ISS) to demonstrate space-to-ground optical communications. During a 90-day baseline mission, OPALS will downlink high quality, short duration videos to the Optical Communications Telescope Laboratory (OCTL) in Wrightwood, California. To achieve mission success, interfaces to the ISS payload operations infrastructure are established. For OPALS, the interfaces facilitate activity planning, hazardous laser operations, commanding, and telemetry transmission. In addition, internal processes such as pointing prediction and data processing satisfy the technical requirements of the mission. The OPALS operations team participates in Operational Readiness Tests (ORTs) with external partners to exercise coordination processes and train for the overall mission. The tests have provided valuable insight into operational considerations on the ISS.

I. Introduction

THE Optical PAyload for Lasercomm Science (OPALS)—a NASA JPL technology demonstration mission—will showcase a space-to-ground optical communications link, via a spaceborn laser, from the International Space Station. OPALS will be launched to the ISS in April 2014 aboard a SpaceX Dragon commercial resupply capsule. The payload will be mounted externally to the ISS, in a nadir position, on the ExPrESS Logistics Carrier-1 (ELC-1) module, ensuring line of sight to an optical receiver on the ground[1].

Over the course of a nominal 90-day mission—using a 1550 nm, 2.5 W laser—the OPALS instrument will demonstrate the downlink of high quality, short duration videos to the Optical Communications Telescope Laboratory (OCTL) in Wrightwood, California[2]. To achieve this, in addition to designing and building the ISS-bound instrument, the OPALS team has developed interfaces to the existing ISS Program infrastructure (ground and in-flight) that will allow mission operators to command and monitor the payload. The operations architecture includes one mission support area (MSA) at JPL for payload command and monitor activities and an additional mission support area at OCTL for ground telescope and signal decoding activities.

Execution of the OPALS optical downlink activity requires close coordination between teams at the JPL MSA, OCTL ground station, and the Huntsville Operations Support Center (HOSC) to ensure time-critical line of sight opportunities are planned and executed to success. For example, operational restraints for the OPALS laser are enforced via coordination with the HOSC to ensure safe laser operation in the presence of ISS extra-vehicular activities. In addition, several processes, such as activity planning and pointing prediction, require information exchange between various teams. The teams jointly executed a series of Operational Readiness Tests (ORTs) to gain familiarity with on-orbit processes and test contingency responses to off-nominal activities. Several processes, tools, and personnel were inherited from the OPALS Integration & Test campaign to ensure continuity, familiarity, and to minimize development costs. Where possible, multimission and commercially available tools were also utilized. As one of the first external payloads on the ISS, the OPALS project—including the mission operations architecture and lessons learned—has paved the way for future external ISS payloads.

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II. OPALS Mission Overview

The objective of the OPALS experiment is to demonstrate the space-to-ground optical downlink of a 10-second enhanced-definition video. Beyond this primary objective, the OPALS experiment serves as an excellent opportunity to gain operational experience with a space-to-ground optical link. The ISS location in low Earth orbit provides a great platform for measuring optical link performance statistics in the presence of varying geometric and atmospheric conditions[2]. Specifically, over a single 2-3 minute pass, the space-to-ground range varies hundreds of kilometers, the space-to-ground pointing slew rate varies between 0.5°/s and 1.2°/s, and the optical signal cuts through a wide swath of atmosphere spanning horizon-to-horizon above the ground station. As such, over multiple passes, optical link performance can be correlated with atmospheric weather conditions, time of day, season, and elevation above the horizon. For this reason, the OPALS mission seeks to exercise as many optical downlinks as possible over the operational lifetime.

A. Concept of Operations

The OPALS mission operations concept is shown in Figure 1. The optical downlink experiment occurs during a

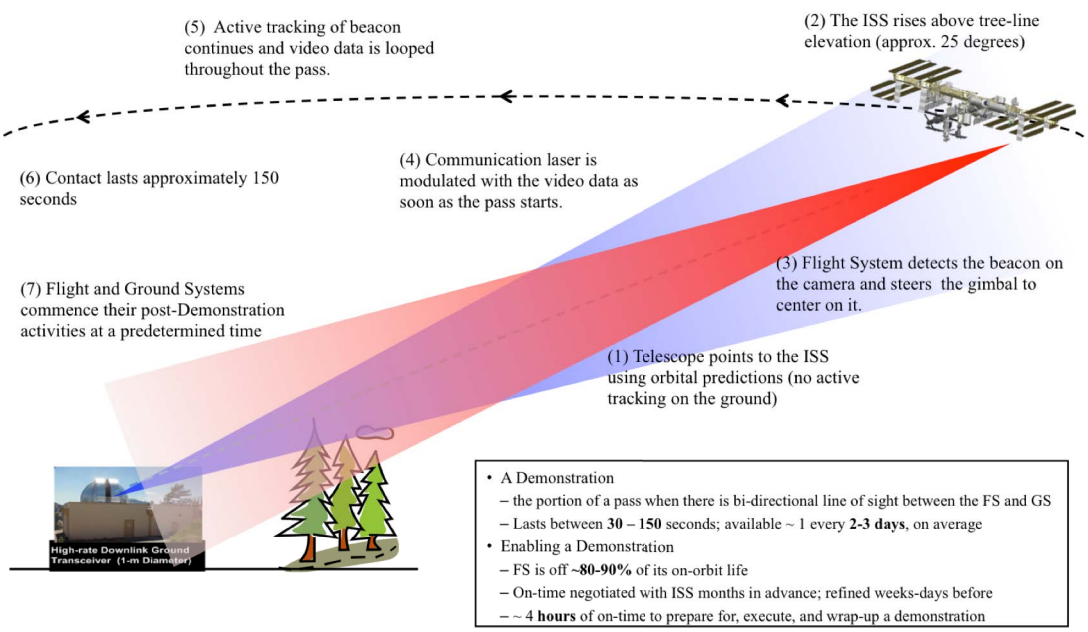


Figure 1. OPALS Mission Concept of Operations

Demonstration, defined as the period of time when bi-directional line of sight exists between the OPALS payload and OCTL. A Demonstration period typically lasts a maximum of 150 seconds due to OCTL's 25° minimum elevation constraint and pointing constraints imposed on the OPALS payload. If the OCTL minimum elevation constraint is loosened for extended operations, this duration can increase to as long as 300 seconds. A Demonstration period initiates with OCTL irradiating a 976 nm beacon laser towards the ISS using a ground-to-space pointing prediction profile. Meanwhile, the OPALS payload is commanded to point its optical transceiver toward OCTL using a space-to-ground pointing prediction profile, all the while modulating the laser transmission signal. The payload camera CCD detects the beacon signal and an onboard feedback control system steers the gimbal to center it. Since the receive and transmit optical trains are co-aligned, the downlink beam will illuminate the OCTL receiver while the feedback control system is engaged. At the end of the Demonstration period, the OPALS payload executes a graceful optical transceiver shutdown and gimbal stowage sequence, while OCTL shutters the ground beacon and ceases motion. Nominally, OPALS plans to transmit at a data rate of 50 Mbps[2].

B. Mission Architecture

The OPALS element conducting the operations phase is referred to as the Mission Operations System (MOS) within the OPALS mission architecture. The purpose of the MOS is to operate the Flight System (FS), defined as the payload mounted on the ISS, and the Ground System (GS), defined as the receiver optics and decoder software housed within the OCTL telescope. Figure 2 provides an MOS-centric view of the major components of the OPALS mission architecture The Flight MOS, located at the JPL MSA, plans and executes activities on the FS through interfaces with the HOSC. All uplink and downlink products flow through the HOSC and the Tracking Data and

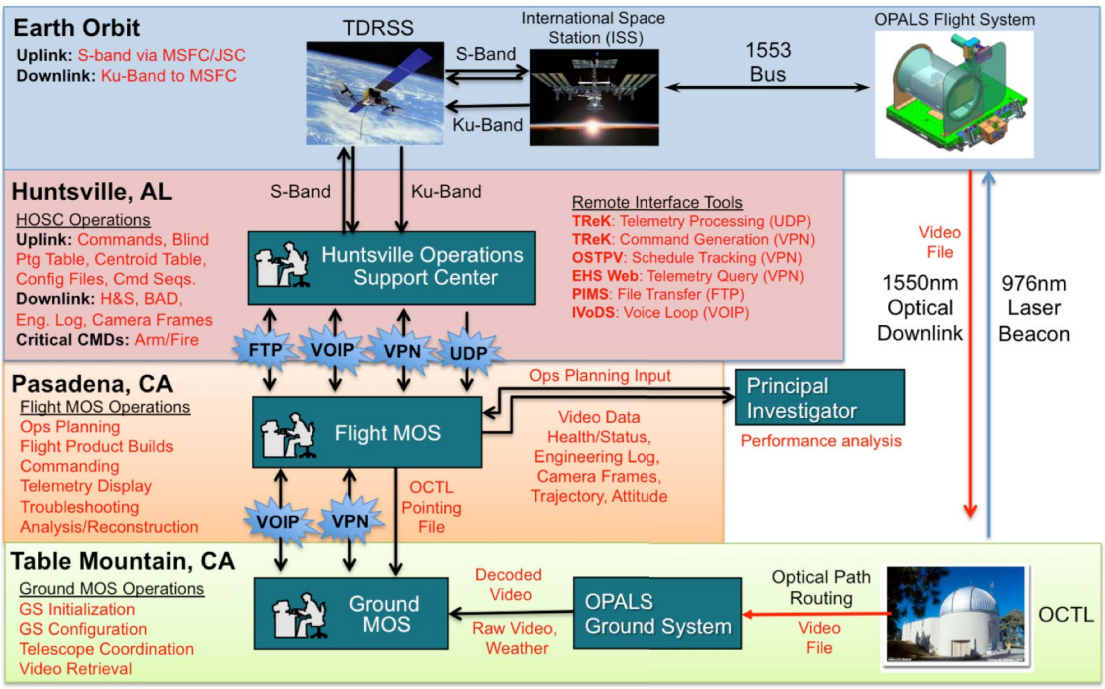


Figure 2. OPALS Mission Architecture

Relay Services System (TDRSS) to reach the FS. The Ground MOS is stationed at OCTL and responsible for coordination of the OCTL telescope, laser beacon, and GS receiver optics. The Ground MOS decodes the optical transmission and transmits all data to the Flight MOS for processing and archival[2]. The principal investigator is responsible for analyzing the optical link performance and providing recommendations for upcoming future downlink experiments.

C. Optical Downlink Timeline

A characteristic feature of OPALS operations is the fact that the payload will remain unpowered for the majority (80-90%) of its on-orbit life. This serves to minimize avionics exposure to space radiation, as well as minimize operations staffing costs. Due to payload pointing restrictions, a Demonstration period occurs once every 2-3 days on average. For each Demonstration opportunity, the OPALS operations team will be staffed on console for 10 hours to prepare for, execute, and conclude an optical downlink, with the OPALS payload powered for a total of 7 hours of that time. Figure 3 illustrates a typical optical downlink timeline, with all activities scheduled relative to the Demonstration period. The main activities are as follows:

- Build Blind Pointing Table (BPT): generate a set of space-to-ground pointing predicts spanning the Demonstration period and uplink to the FS via HOSC.
- Complete Health Checkout: verify payload health via real-time telemetry.
- Command Parameter Load: set FS parameters configuring downlink file, modulation rate, control loop gains, camera exposure times, etc.
- Coordinate Critical Commands: disable safety restraints on the gimbal and laser subsystems with HOSC support.
- Command Gimbal Calibration Sequence: calibrate gimbal step locations to gimbal coordinate frame.
- Build OCTL Pointing File: generate a set of ground-to-space pointing predicts spanning the Demonstration period.
- Command Camera On/Laser On: initiate processing of camera images and power the laser to 2.5W.

- Command Demonstration Commencement: schedule the Demonstration sequence with a Commence Demonstration command and a Blind Pointing Table.
- Transmit Optical Downlink: transmit the optical signal to OCTL.
- Command Gimbal Stow/Laser Off: ramp down the laser power, stow the gimbal at the edge of travel, and reenable safety restraints for the gimbal and laser subsystems.
- Downlink Elog / Image Files: downlink engineering log data and image snapshots from the Demonstration via HOSC.

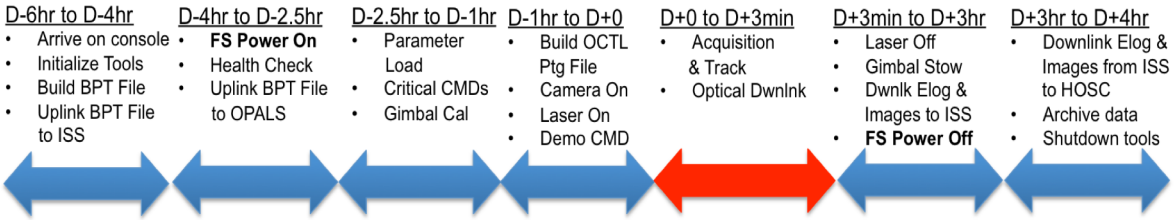


Figure 3. OPALS Optical Downlink Activity Timeline

D. Mission Phases

The OPALS 90-day mission begins once the payload is installed on the ELC-1 module on ISS. Figure 4 depicts the phases of the OPALS prime mission. Installation is completed by the Special Purpose Dextrous Manipulator (SPDM) located on the ISS robotic arm (SSRMS) via commands from the ISS robotics team at Johnson Space Center. For OPALS, the installation spans three phases: 1) extraction from the SpaceX Dragon trunk, 2) transport to the ELC vicinity , and 3) installation on ELC-1.

Once installed on ELC-1, OPALS will transition into Mission Phase I. This phase consists of commissioning activites to verify the payload's health and performance in orbit. The first activity is the initial power on of the OPALS avionics. The OPALS operations team performs a detailed health checkout by inspecting telemetry for alarm flags, temperature violations, power relay status indicators, and avionics health. Once the team verifies nominal health, it commands the gimbal from its launch position to a safe stow position at the edge of travel. The next activity is the file transfer checkout activity. In this activity, the team verifies the ability of OPALS to push and pull files from the ISS onboard file storage system. The team verifies gimbal health via a gimbal calibration routine. It commands each gimbal axis through a full range of motion, using the ISS onboard camera imagery for independent verification. Lastly, the team checks out the camera and laser units for hardware aliveness and healthy data flow. All of the above checkout activities can be scheduled at arbitrary times since they are not dependent on line of sight to the OCTL groundsite.

The first checkout activity requiring OCTL coordination is the Open Loop Characterization Test. This test measures the signal-to-noise ratio (SNR) of the laser beacon signal and assesses the pointing prediction performance of the Blind Pointing Table (BPT). It is desirable to perform this test both during daytime and nighttime conditions, as defined at OCTL, to measure variability in the SNR. The activity is similar to an optical downlink activity, except the feedback control loop is disabled and the flight laser is not powered. Using this activity's results, the operations team will set threshold levels on the camera and adjust BPT search strategies, if necessary.

The final checkout activity is the Tracking Characterization Test. It is similar to the Open Loop Characterization Test, except that the feedback control system is activated for tracking. This test measures the tracking performance of the feedback control system in angular jitter from the center of the camera CCD. Using this activity's results, the operations team will adjust the feedback control system gain values, if necessary, to improve tracking performance.

Transfer Phase: Launch to ELC-1	Mission Phase I: Checkout	Mission Phase II: Optics Calibration	Mission Phase III: Optical Downlink
3-7 days	**14-21 days**	**7-14 days**	**55-70 days**

SpX-3 Launch	Visual Inspection	• Determine misalignment between transmit and receive optics.
		• While transmitting, command offsets to gimbal pointing and measure power spikes at ground receiver
			• Transmit video via optical link:
			  • 10 sec duration
			  • Enhanced-definition
			• Decode and display within 10 minutes
			• Additional downlinks classified as extended mission

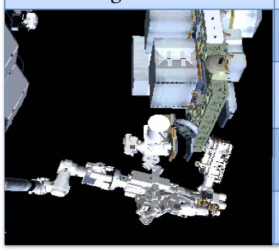
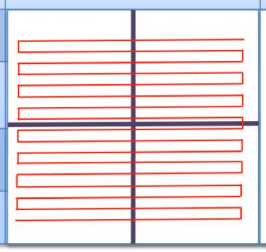
SpX-3 Trunk Extraction	Initial Power On		
Transport to ELC-1	File Transfer Checkout		
ELC-1 EXPA-1 Install	Gimbal Motion & Calibration Test		
Real-time Video Monitoring	Camera Checkout Test		
	Laser Checkout Test		
	Open Loop Characterization Test		
	Tracking Characterization Test		
	Thermal Monitoring		

Figure 4. OPALS Mission Phases

Mission Phase II will determine any misalignments between the transmit (laser) and receive (camera) optics due to thermal cycling or launch vibrations. To achieve this, the operations team configures the feedback control system to use a time-varying target profile similar to a raster scan. During tracking of the ground beacon, the control system moves the beacon along this profile, effectively pointing the optical signal in various offset directions. By looping this scan several times during a single pass and measuring the OCTL receiver's power peaks, angular misalignments in azimuth and elevation can be determined and calibrated out for future Demonstrations.

For the remainder of the 90-day mission, Mission Phase III will attempt as many optical downlinks as feasible. Mission success will be met when one 10-second enhanced definition video is successfully downlinked from space-to-ground and decoded into a viewable format[2]. The remainder of Mission Phase III offers an opportunity to test increased data rates, additional ground stations, low elevation transmissions, additional data formats, and gather important statistics on optical link performance and robustness.

III. OPALS Payload Overview

A. Payload Implementation

The OPALS flight hardware is a combination of in-house developed hardware and purchased Commercial Off-The-Shelf (COTS) hardware. The Flight System's primary elements are the sealed container, the gimbaled optical transceiver, and the ExPA-based Flight Releasable Attachment Mechanism (FRAM). The sealed container houses all electronics (avionics, power, laser) and also maintains 1 atmosphere of pressure to provide forced air cooling of the electronics (similar to convection-cooled fan using a large radiator as a heat dump). The gimbaled optical transceiver is comprised of a two-axis gimbal that holds the optical components essential to establishing the communication link[1]. The ExPA-based FRAM is a standardized and modular platform used for varied purposes on the ISS, one of which is to provide a platform for experiments like OPALS.

A critical payload feature is the ability to point the laser transmission signal toward the ground receiver. Due to laser safety considerations, the laser transmission cannot radiate the ISS structure. In addition, the OPALS payload is designed to avoid all volumes containing docked vehicles or rotating solar arrays in an effort to reduce dependency on ISS configuration for operations[1]. The resulting implementation is a reduced Field of Regard (FOR), defined as the locus of unit vectors where the gimbal can be pointed. The FOR is approximately 106° wide in azimuth by 36° wide in elevation, with each gimbal axis capped by hard stops and electromechanical limit switches at the travel edges. Figure 5 depicts the alignment of the FOR with the ISS structure. The ISS orientation is typically

aligned with the nadir and ram (velocity direction) as shown in the figure[3]. Therefore, the gimbal azimuth axis is generally aligned with the ISS direction of motion, defining the duration of Demonstration periods, while the gimbal elevation axis points starboard, defining the frequency of Demonstration opportunities. The asymmetry of the elevation axis has a pronounced effect in that it limits Demonstration opportunities to ISS passes north of the OCTL site, assuming nominal ISS attitudes.

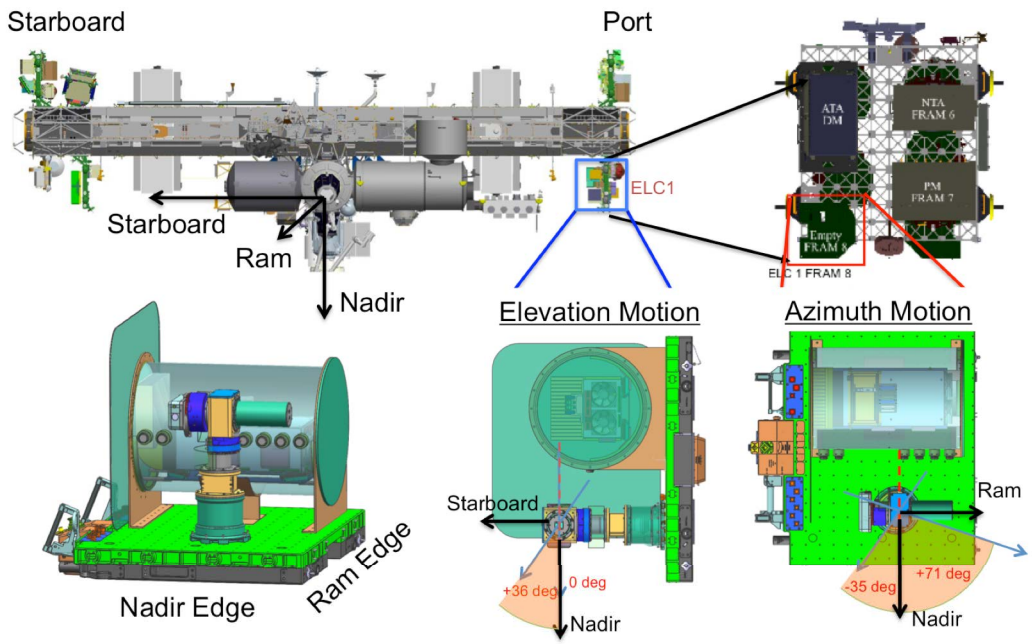


Figure 5. OPALS Pointing Field of Regard

B. Payload Operational Interfaces

The OPALS payload features command, telemetry, and file transfer interfaces for operations. The sole interface over which packetized data flows to and from the payload is a 1553 bus data connection via the FRAM. OPALS is a command driven payload (with automated and autonomous behavior during a Demonstration) that transmits its health and status (H&S) in telemetry at 1Hz, and is capable of bi-directional file transfers between itself and the ISS on command. The payload features a command handler that interprets both real-time commands and sequenced commands. Real-time commands originate from the JPL MSA or the HOSC, while sequenced commands are stored in onboard files. The payload also features autonomous behavior during the Demonstration period when the flight software transitions between a Blind Pointing Table profile and closed loop control depending on beacon detection. For further control during closed loop tracking, a Centroid Deviation Table applies pixel offsets to the centroid target when the beacon is detected.

1. Commanding

Commanding the payload can occur from the ground or through a set of commands defined in a file located on the payload. *Real-time commands* are commands that are sent directly from the ground to the payload. A real-time command contains an execution time, which will dictate whether the command is to be executed immediately or at a scheduled time in the future. A *command sequence* is a set of commands defined in an onboard file that is executed sequentially when activated by a real-time command. All commands in the sequence are scheduled relative to the real-time activation command time. Once received, commands and associated fields are validated for proper syntax by the command handler. When a command has been validated successfully, it is placed in the Command Queue for execution as shown in Figure 6.

The Command Queue, a first-in, first-out buffer, holds all commands waiting to be executed. When a command is popped off the Command Queue, its execution time is evaluated against the payload computer's system time. If a command is scheduled for a future time, all commands residing in the command queue must wait until the wait time

has expired. Only commands to enter safe mode or clear the command queue can pre-empt the execution wait period and clear all commands residing in the Command Queue.

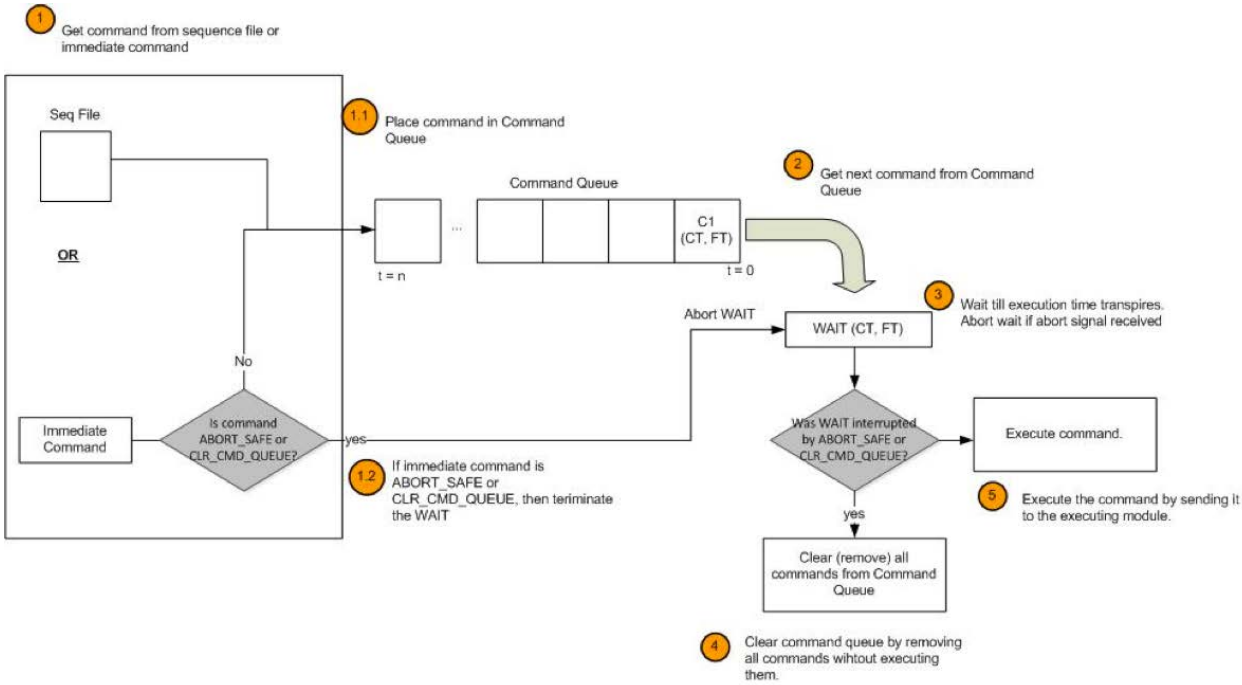


Figure 6. Flow of Commands To and From the Command Queue

2. Autonomous Commanding: Blind Pointing Table and Centroid Deviation Table

The OPALS payload can perform autonomous commanding when performing a Demonstration. When the command to commence a Demonstration is sent, the payload will enter into autonomous behavior by initially entering into open loop search for the beacon, followed by closed loop tracking of the beacon when it has been detected on the camera CCD. A Blind Pointing Table (BPT) is a ground-generated set of azimuth and elevation coordinate positions with an associated relative time at which the gimbal is commanded to point to these positions, relative to the start of a Demonstration. The BPT is used for the open loop beacon search and must reside on the payload with a specific file name. Upon command to load the BPT, the file is validated and loaded into memory. Once it has been validated, the BPT profile is interpolated and sampled at the frequency of the feedback control loop. When a Demonstration starts, the gimbal follows the profile specified by the BPT. Once the beacon is detected by the camera, the FSW will enter into closed loop tracking, no longer being commanded by the BPT but instead being commanded by the closed loop controller.

During closed loop tracking, a loaded Centroid Deviation Table (CDT) is used to apply offsets to the centroid error produced during closed loop tracking. This allows the FSW to lock on to a pixel location offset from the nominal closed loop target on the camera CCD. Since the CDT is sampled at the control loop frequency, it provides the capability to command a time-varying offset profile relative to the nominal closed loop target.

3. Health and Status (H&S) Telemetry

Health and Status of the OPALS payload is sent to the ground at a frequency of 1 Hz. The H&S telemetry contains critical data regarding the health of the payload as well as the status of safety restraints, command handler status, gimbal pointing angles, laser power, and camera centroid calculations. The FSW sends 750 bytes of H&S data per second to the ISS via the 1553 bus to the ISS. The ISS transmits this telemetry to the HOSC (via TDRS), where it is then forwarded to the OPALS MSA and OCTL. The H&S packet provides the only real-time insight into payload operations, since the detailed onboard engineering log cannot be downlinked until the end of the activity.

IV. Operational Interfaces

The OPALS operations team maintains operational interfaces with the HOSC organization at Marshall Space Flight Center (MSFC) and the Mission Operations Directorate (MOD) organization at Johnson Space Center (JSC). Figure 7 outlines the services offered by each organization and the interfaces agreements with OPALS. MOD is responsible for the overall ISS platform operations, as it relates to maintaining the ISS vehicle as a whole. This includes astronaut and robotic operations, visiting vehicle rendezvous and docking activities, and trajectory and attitude maintenance of the ISS platform. For OPALS, the interface with MOD is defined in a set of Flight Rules that dictate restrictions for OPALS operations under certain ISS platform configurations. Within the Flight Rules, notification responsibilities and communication paths are outlined so that a direct OPALS-MOD real-time operational interface is not required.

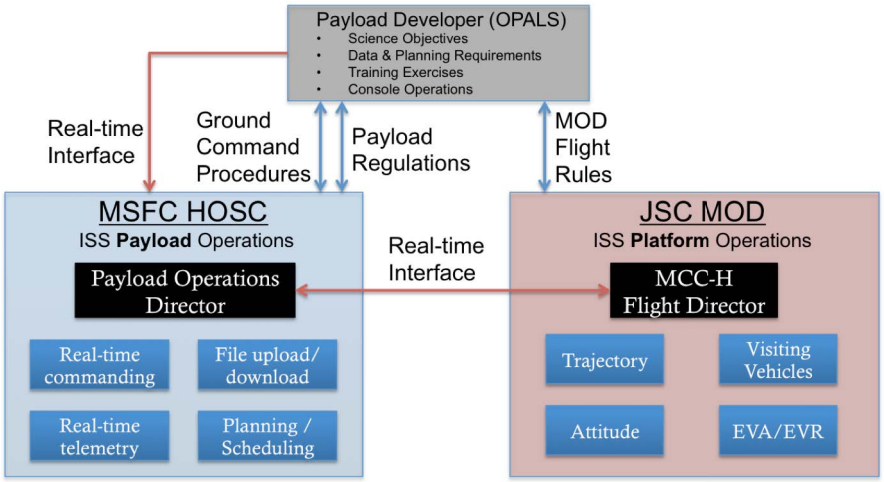


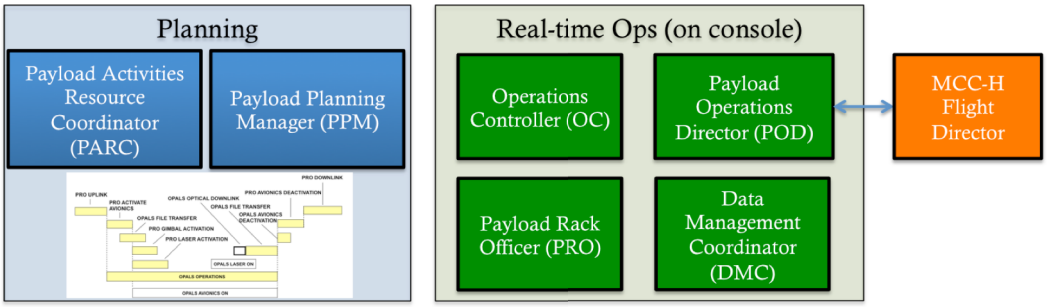
Figure 7. Operational Interfaces to HOSC and MOD

The HOSC is responsible for all internal and external ISS payload operations. For OPALS, the HOSC provides planning services to schedule OPALS activities and resource use on the ISS, file uplink and downlink services, telemetry storage services, and real-time command and telemetry services. Unlike the MOD interface, the HOSC interface with OPALS requires real-time interactions. Real-time commanding, telemetry streaming, file transfer, and voice communications all flow through the HOSC. If OPALS operations require any real-time coordination with MOD, the HOSC Payload Operations Director (POD) provides that interface to the MOD Flight Director. The HOSC-OPALS operational interface is defined in Payload Regulations that dictate HOSC services to be provided to OPALS and Ground Command Procedures (GCPs) that dictate coordination for critical payload commands.

A. OPALS-HOSC Interface

The HOSC provides support to the OPALS operations team both in planning and real-time roles. Figure 8 depicts the various support roles provided by the HOSC. In real-time operations, the primary interface to OPALS is the Payload Rack Officer (PRO) since this position sends critical commands to the payload. Coordination with the PRO is defined in GCPs the outline commands to be sent by the PRO, telemetry to be verified, and voice notifications to be issued. The OPALS GCPs cover OPALS avionics activation, OPALS gimbal activation, OPALS laser activation, and OPALS avionics deactivation. The avionics activation supplies 28V power to the payload, which automatically initializes the flight software into safe state. The gimbal and laser activation steps are required to remove safety restraints preventing inadvertent firing of the flight laser. These activities require the PRO to send critical commands that must originate from the HOSC. In addition to safety restraint removal, independent laser power commands must be sent from the JPL MSA and the HOSC to decentralize the laser powering process. This additional coordination is documented in the laser activation GCP. The avionics deactivation removes 28V power from the payload, ending FS operations for the activity.

The other members of the real-time HOSC support staff have less interaction with OPALS. The Payload Operations Director (POD) oversees the HOSC team, makes decisions regarding deviations to plan, and serves as the prime interface to the MCC-H Flight Director. The Operations Coordinator (OC) monitors the ISS activities timeline and notifies relevant parties of any dynamic events and potential impacts. Lastly, the Data Management Coordinator (DMC) responds to any issues with the command and telemetry data paths.



- **Payload Activities Resource Coordinator (PARC):** Build Payload Planning Outline detailing payload command windows and resource requirements
- **Payload Planning Manager (PPM):** Schedule payload command windows
- **Payload Ops Director (POD):** Supervises HOSC payload ops team; official point-of-authority to MCC-H Flight Director and International Partners; Enforces compliance with flight rules, safety reqs, etc.
- **Payload Rack Officer (PRO):** Power on/off commanding, critical commanding, enables/disables payload commanding (Primary payload interface)
- **Operations Controller (OC)**: Monitors real-time payload activities schedule; Notifies payload of dynamic events and impacts; Supports payload responses for anomaly resolution
- **Data Management Coordinator (DMC):** Configuration, management, and distribution of telemetry / video data to payloads

Figure 8. HOSC Payload Support Roles

For planning purposes, the OPALS team interacts with the Payload Activities Resource Coordinator (PARC) and the Payload Planning Manager (PPM). The PARC interfaces with the OPALS operations team several months prior to operations to define activity templates in a Payload Planning Outline (PPO). Each template outlines the activity flow of all events requiring coordination with the HOSC. Each coordination event is assigned a command window that allocates all resources required for the activity. These resources can include electrical power, file transfer bandwidth, or HOSC personnel. All activities are scheduled relative to the OPALS Optical Downlink Window that is aligned with the Demonstration period. A generic OPALS operations command window overlays the entire period of OPALS commanding, while more specialized windows describing coordination activites occur in the following order:

- PRO Uplink Window: PRO to uplink files from HOSC to the ISS
- PRO Avionics Activation Window: PRO to power on the OPALS payload
- OPALS File Transfer Window: OPALS payload commanded to uplink files from the ISS
- PRO Gimbal Activation Window: PRO to remove safety restraints on the OPALS gimbal
- PRO Laser Activation Window: PRO to remove safety restraints on the OPALS laser
- OPALS Laser On Window: OPALS laser is fully powered to 2.5 W
- OPALS Optical Downlink Window: OPALS Demonstration period
- OPALS File Transfer Window: OPALS payload commanded to downlink files to the ISS
- OPALS Avionics Deactivation Window: OPALS payload commanded to shutdown flight software
- PRO Avionics Deactivation Window: PRO to power off the OPALS payload
- PRO Downlink Window: PRO to downlink file from the ISS to HOSC

The Payload Planning Manager (PPM) provides the service for scheduling command windows in the ISS master schedule. This process will be elaborated in OPALS Planning Process.

B. OPALS-MOD Interface

The MOD Flight Rules for OPALS cover three categories: 1) laser safety rules, 2) payload power interruption constraints, and 3) payload communications interruption rules.

The flight rules governing laser safety are enforced to prevent inadvertent laser irradiation of ISS crew, interference with visiting vehicle navigation systems, or hardware damage to the robotic arm. These must be met before any operations of OPALS can begin. These laser safety related flight rules dicate the following operational rules:

- OPALS operations will be prohibited during EVA or Visiting Vehicle periods. EVA restrictions are in place for all times when the astronauts are outside of the airlock. Visiting vehicle restrictions vary by vehicle, but are bounded by the 4 hour period prior to docking and the 4 hour period following undocking. The exception is for the Soyuz vehicle, which restricts OPALS operations for all periods while the Soyuz is traveling to and from the ISS, since this vehicle is manned. This rule is enforced via constraint notifications during the activity scheduling process at the HOSC.

- OPALS operations will be prohibited during SSRMS (ISS Robotic Manipulator System) usage which violates the Field of Regard (FOR). This rule is enforced by routine Keep Out Zone (KOZ) incursion notifications from the MOD Robotics team.

- After the flight rules are met and permission is granted for operation, the FOR constraints are sufficient keep the laser from creating a hazard.

The flight rule for payload power interruptions inform MOD personnel of OPALS constraints given a planned or unplanned power outage on the ISS and recommend actions in each scenario. Given OPALS allowable flight temperatures, the payload can tolerate a 2.25 hour unplanned power outage or a 4.25 hour planned power outage if the payload is preconditioned prior to power loss. This information assists MOD personnel in determining priority in the event of a partial power restoration.

The communications interruption flight rule considers a prolonged telemetry outage scenario. It instructs MOD personnel to command the OPALS instrument to safe mode in the blind and terminate flight software in the event of a telemetry outage greater than one hour. This is to reduce the risk of encountering payload anomalies without telemetry insight.

C. OPALS-OCTL Interface

During the congruent execution of the MOS at MSA and GS at OCTL operational procedures, the operators of the OPALS flight and ground systems will collaborate to prepare and execute bidirectional optical communications during the ISS pass over OCTL. This collaboration will includes voice loop communications for:

- MOS and GS status updates for situational awareness during preparation, execution, and post-demonstration activities,
- confirmation of the expected optical downlink modulate rate (determines the effective downlink rate) and selection of the downlink video file (from a preloaded menu of files onboard the FS),
- confirmation of the GS telescope configuration and beacon operation plan, including planned OCTL beacon power profile (i.e., beacon power level) and beacon toggling plan (i.e., on-off cadence), and
- go/no-go checks based on MOS and GS operational readiness for the pass, including whether the local weather is still favorable for optical demonstration.

Additionally, the MOS Pointing (Ptg) operator will provide GS operators with the OCTL pointing file within 15 minutes of the demonstration. The GS operators will stream the OCTL telemetry to the MSA for real-time situational awareness of telescope performance and recording for post-mission correlation of the joint FS and GS performance.

In post-demonstration, GS operators will use a secure connection to JPL to archive the raw and decoded video files from the downlink, optical power timelines, and beacon telemetry in the same repository as the one used by the MOS operators for that activity.

V. OPALS Planning Process

The OPALS operations team utilizes a three-week planning horizon for integrating OPALS activities into the master ISS schedule. The initial planning inputs are incorporated into a Weekly Lookahead Plan (WLP) by the HOSC. This product offers a preview of ISS activities in the upcoming two weeks and provides all parties an

opportunity to identify activity conflicts. In order to determine OPALS inputs to this process, a Demonstration forecasting capability is required. Since the occurrence of Demonstration periods is inherently tied to bi-directional line of sight opportunities between OPALS and OCTL, the forecasting capability is dependent on the ISS trajectory and attitude predictions relative to the OCTL groundsite. To facilitate this process, the MOD Pointing organization provides a forecasting service to OPALS, with content and delivery cadence defined in an Operations Interface Procedure (OIP)..

The OIP specifies that a forecast of Demonstration opportunities is delivered to the OPALS team weekly to coincide with the delivery of updated ISS ephemeral predictions. The three-week forecast includes a list of all time intervals satisfying all of the following criteria:

- ISS rise above 25° elevation, as seen by OCTL
- OCTL within OPALS Field of Regard
- Minimum Demonstration duration of 20 seconds

The purpose of the Demonstration forecast is to identify feasible time windows for optical downlink. A secondary function of the forecast is to provide information, such as pass duration, gimbal pointing profile, maximum OCTL telescope elevation, and time of day, for prioritization of Demonstration opportunities. To that end, the OIP specifies that each forecasted Demonstration pass shall contain the following information:

- Time of first bi-directional line of sight event (Demonstration time)
- Time of last bi-directional line of sight event.
- Time of closest approach between OCTL and OPALS.
- OCTL azimuth/elevation pointing at the times of ISS rise and set (25° elevation relative to OCTL) and closest approach.
- OPALS gimbal azimuth/elevation pointing at the times of ISS rise and set (25° elevation relative to OCTL)

From this information, the OPALS team prioritizes Demonstration opportunities based on longest duration, maximum margin relative to gimbal/OCTL pointing limits, and minimum Sun interference (e.g. night passes). For each pass, the forecast provides the first definition of the Demonstration time (start of the Demonstration period) around which the entire PPO template is built. A listing of all selected Demonstration times is sent to the PPM at the HOSC for incorporation into the WLP using the PPO template.

For Demonstration (D) opportunities scheduled at D-3 weeks, additional opportunities exists at D-2 weeks and D-1 week to adjust or cancel command windows based on updated forecast deliveries. The most likely change is a slight correction to the Demonstration time, due to an ISS trajectory dispersion in the along-track direction. Following the D-1 week update, the WLP schedule is integrated into the Short Term Plan (STP) schedule and considered final. The Demonstration time can shift again prior to the Demonstration, but final adjustments to the command windows are not necessary since the shift should be on the order of a few seconds and within the margins of the command windows.

VI. OPALS Pointing Prediction Strategy

The most critical aspect of OPALS operations is determination of pointing predictions for the bi-directional pointing strategy. The pointing predictions are generated at the JPL MSA and delivered to OCTL and the FS for use. The ground-to-space pointing predictions are delivered to OCTL in the OCTL Pointing File, while the space-to-ground pointing predictions are uplinked to the FS in the Blind Pointing Table. In order to maintain the accuracies required for the bi-directional pointing strategy, real-time trajectory and attitude telemetry data is obtained and extrapolated to the Demonstration time.

A. OCTL Pointing File

The OCTL Pointing File is required for pointing the OCTL telescope toward the ISS for alignment of the ground beacon and optical receiver with the optical link pathway. Unlike the FS, the OCTL telescope tracks the ISS completely open loop and thus requires highly accurate predictions to maintain pointing of the beacon and receiver. Since the receiver at OCTL is 500 μrad wide, the pointing predictions must be accurate to ±250 μrad through the Demonstration pass. Initial attempts to track the ISS using publicly available Two-Line Element (TLE) ephemerides and MOD published ephemerides resulted in pointing errors on the order of milliradians. A new approach was

required to obtain fresh predictions without real-time reliance on an external team for delivery, given the time-critical nature of the OPALS experiment.

The approach adopted by the OPALS operations team is a state query and propagate approach. It involves obtaining a near real-time, time-correlated GPS state vector from the ISS broadcast data and propagating it forward to the Demonstration period using JPL navigation software. The process involves the following steps:

- Query a recent GPS state vector and time from the HOSC database at D-30 minutes
- Correct state vector with latest International Earth Rotation and Reference System (IERS) Earth orientation data
- Propagate trajectory through the Demonstration period using gravity, atmospheric drag, and solar pressure force models
- Sample trajectory at 10Hz during the Demonstration period and calculate OCTL topographic pointing angles
- Print out OCTL topographic pointing angles to the OCTL Pointing File

Two methods were used to verify the accuracy of the predictions. For the first method, a playback of GPS state vectors spanning the Demonstration is queried from the HOSC database following the Demonstration pass. These states, directly from the ISS GPS receiver, are differenced with the propagated trajectory used for the OCTL Pointing File build. At the nominal ISS altitude of 400 km, a ±250 µrad pointing error translates to approximately ±100 meters of trajectory prediction error. To date, the OCTL telescope has successfully tracked the ISS on eight attempts, with trajectory errors no greater than 40 meters and pointing errors no greater than 100 µrad. Figure 9 illustrates the pointing performance verification during an April 3, 2013 ISS pass over the OCTL site, with ISS trajectory dispersions no greater than 20 meters and OCTL topographic pointing errors no greater than 80 µrad.

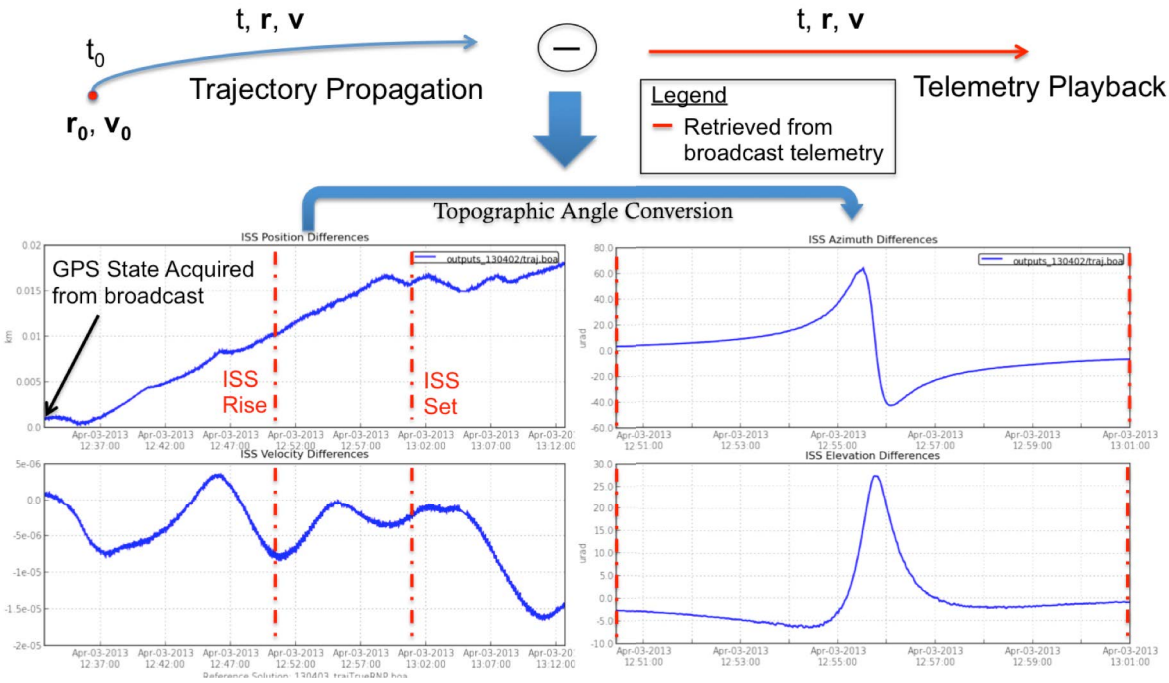


Figure 9. Example of Space-to-Ground Pointing Prediction Performance for April 3, 2013 Pass

The second verification for pointing accuracy is to observe the ISS image within the OCTL telescope camera during a tracking pass. For all successful tracks, the ISS was observed within the OCTL telescope view for the duration of the pass. Figure 10 shows ISS images obtained during approach to (left) and departure from (right) the OCTL telescope.

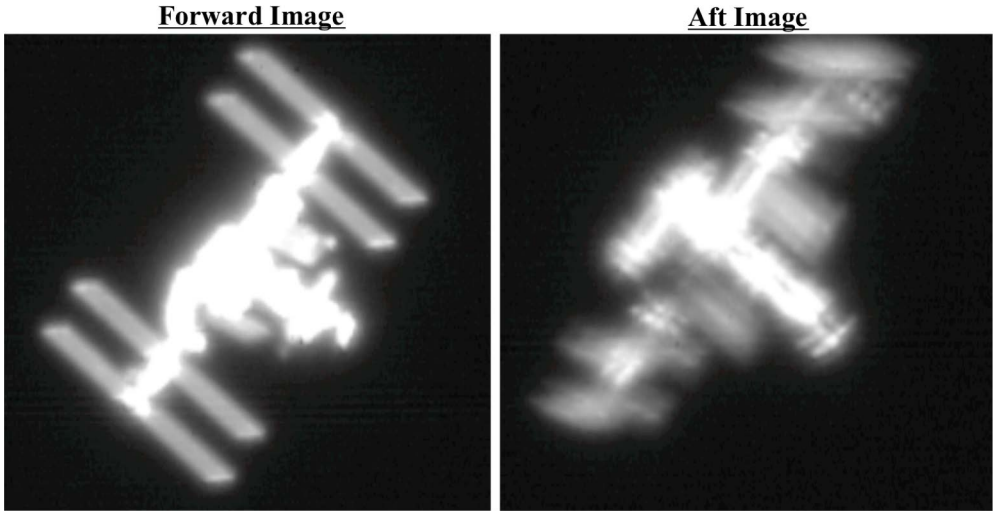


Figure 10. ISS Images Obtained in OCTL Telescope During April 3, 2013 Pass

B. Blind Pointing Table

The Blind Pointing Table is required for pointing the FS optical transceiver towards the OCTL ground site. Since the feedback control system is responsible for fine pointing, the Blind Pointing Table is only required to be accurate enough to locate the ground beacon by the flight camera. Therefore, the BPT pointing requirement is much looser than the OCTL Pointing File at ±1.0° per axis. However, unlike the OCTL Pointing File, the BPT must be generated at least six hours prior to the Demonstration to be compatible with the file uplink process. It also requires extrapolation of the ISS attitude in addition to the ISS trajectory.

The approach for ISS trajectory predictions is identical to the process noted for the OCTL Pointing File, with the exception that the GPS state must be queried and propagated six hours prior to the Demostration. The approach for ISS attitude prediction is to extrapolate the approximate attitude at Demonstration time based on the periodic motion of the ISS as-flown attitude. In nominal flight, the ISS attitude varies approximately ±0.5° per axis about the equilibrium attitude with a regular period equal to the orbital period of 90 minutes[3]. By using the equilibrium attitude attitude for the BPT, the pointing accuracy requirements will likely be met. However, extra margin is obtained by predicting the phase of the attitude oscillation at the Demonstration time. This is achieved by querying the LVLH-to-Body (Local Vertical, Local Horizontal) quaternion at a time that is an integer number of orbits prior to the Demonstration (e.g. D-6 hrs) and applying it to the LVLH frame at the Demonstration time. Figure 11 illustrates the trajectory and attitude prediction using this approach. Assuming the ISS trajectory can be predicted within 1.0 km and the attitude can be predicted within the half amplitude values observed in Figure 11, the predicted RSS error is 0.63°.

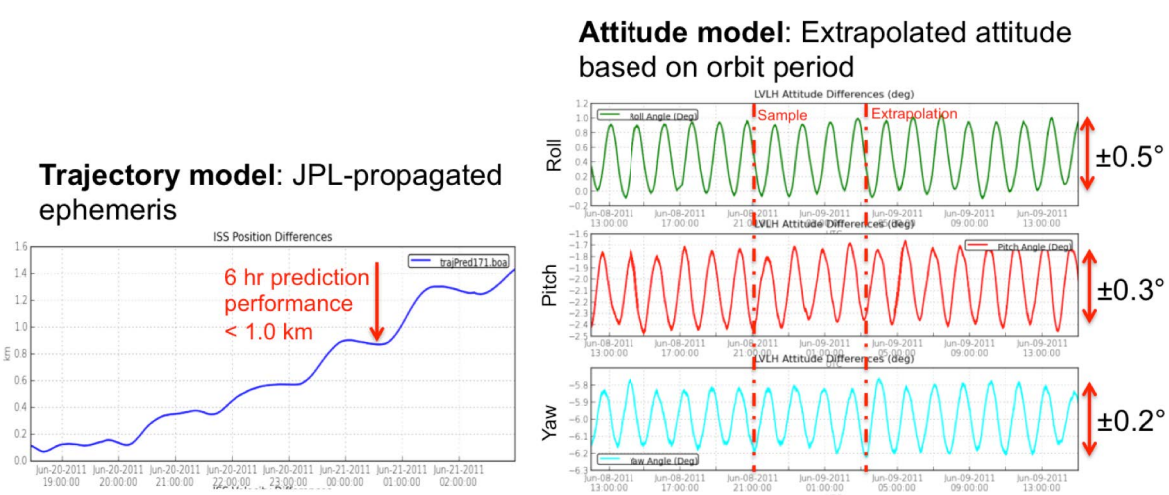


Figure 11. ISS Trajectory and Attitude Extrapolation for the Blind Pointing Table

The BPT generation process will determine the final Demonstration time to be used for commanding the FS for the optical downlink, since this time must be correlated with the angular profile in the BPT. It is expected that this time will only differ a few seconds from the Demonstration time determined by MOD Pointing in the D-1 week delivery. However, since the ISS is traveling at approximately 7 km/s, even timing errors on the order of tenths of a second will violate the BPT pointing requirements. Therefore, it is critical that this final Demonstration time is calculated and commanded to the FS with sufficient precision to meet pointing requirements. This includes correcting for any clock drifts aboard the ISS relative to GPS time. Figure 12 shows typical blind pointing and slew profiles for a Demonstration activity.

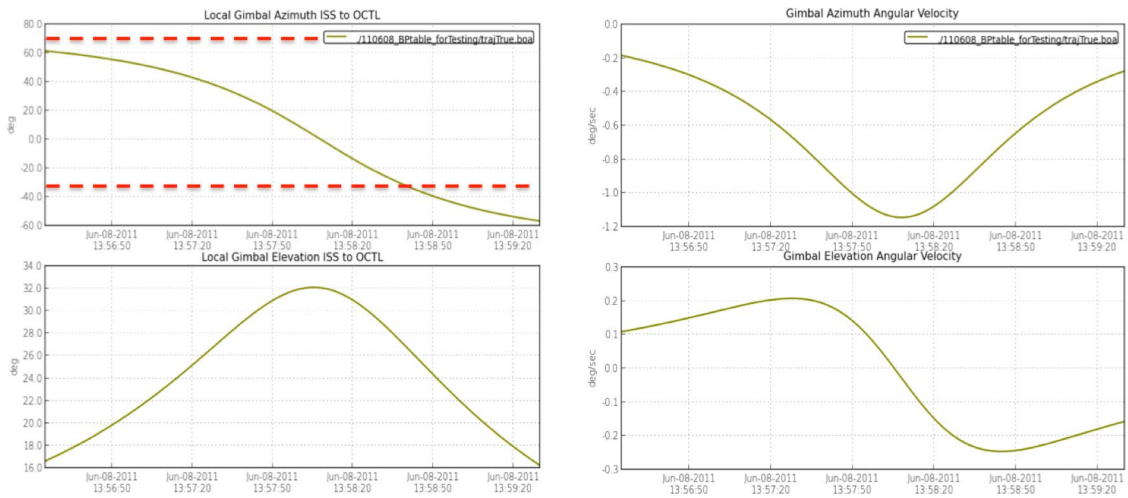


Figure 12. Blind Pointing Table Profile for a Typical Demonstration Pass

VII. OPALS Mission Operations Infrastructure

For the MOS FS operators, the OPALS Mission Support Area (MSA) was deployed within the existing Earth Science Mission Center (ESMC) facility at JPL. By leveraging a subset of the available ESMC Ground Data System (GDS) infrastructure—e.g., physical workstation space, IT and security network resources, uninterrupted power supplies, phones—within the multi-mission operational space, the OPALS MSA was ready for Operational Readiness Tests (ORTs) about a month after the final checkout of the Flight System during assembly, test, and (pre-) launch operations (ATLO) testing at KSC. The use of the MSA was broadened via colocation of the OPALS Engineering Model (EM) with the operational workstations. Amongst many benefits, this set-up provides a flight-like testing environment for the ORTs and training simulations with the EM.

OPALS MSA provides four workstations to support five operational roles: Telemetry Engineer (TE), Command Engineer (CE), Voice Operator (VO), Payload Developer (PD, i.e., the activity lead), and Pointing Engineer (Ptg).. The TE is responsible for mentoring OPALS FS real-time health and status telemetry, confirming responses to commands, and detecting any anomalies in the telemetry stream. The CE is responsible for sending real-time commands to OPALS. The VO is responsible for voice communications with HOSC and OCTL GS operators. In particular, the VO must coordinate critical commanding activities. The VO's workstation can be shared with the Payload Developer (PD), i.e., the OPALS Activity Lead. The PD is responsible for the overall coordination of OPALS operations activity, specifically the execution of the applicable Operational Procedure for the activity. It is the responsibility of the PD to ensure FS safety and work toward activity success, which includes providing the authoritative decision making. Furthermore, prior to optical communication demonstrations, the Ptg operator is responsible for generating the BPT and OCTL Pointing File. Ptg operator can also assist in validating new OPALS files and sequences prior to uplink

The TE, CE, and VO/PD positions are assigned to windows-based workstations. These Windows-based machines run HOSC and ISS provided, project specific, and COTS software. The core HOSC provide software resources include:

- Telescience Resource Kit (TReK) for commanding and telemetry streaming,
- Internet Video Distribution System (IVoDs) for voice loop communications, and

- Enhanced HOSC System Web Tool (EHS Web) for file uplink and downlink to/from the ISS Payload Multiplexer/Diplexer Data Manager (MDM), access to released telemetry and command databases, telemetry query by time, and operations change requests.

The operators also employ a JSC provided web-based tool, Onboard Short-Term Plan Viewer (OSTPV), for tracking the ISS schedule of activities, including those assigned to OPALS. Furthermore, project specific software is employed to display thermocouple temperatures from the OPALS TLM stream, for file validation, and data products processing. OPALS workstations also employ COTS software, such as VLC media player for streaming video from the ISS, and combination of Python and/or MATLAB scripts for sequence verification, data processing of the engineering logs, image processing, and long term trending (detailed further in the OPALS Data Processing Strategy section).

These Windows-based workstations are configured identically with all of the required operational tools. Prior to each operational activities, all three of these workstations will be setup identically. Thus, if any of the workstations become unavailable, the TE, CE, VO and PD operators can perform any and all of the operator roles and functions using any one of the remaining functional workstation(s).

One of the Windows-based machines has the additional capability of an interface to the Engineering Model (EM). This connection allows MOS operators to command and control the EM, and stream flight-like OPALS H&S telemetry to the workstation, which provides an operations-like platform for testing operational procedures, flight software updates, and sequences on the EM prior to any operations with the installed FS on the ISS. This capability can be deployed outside of and during real-time activities with the OPALS FS.

The fourth workstation at the MSA is a Red Hat Linux box, running an institutional navigation and pointing propagation software, Mission analysis and Operational Navigation Toolkit Environment (MONTE). This workstation is dedicated to the Ptg MOS role and unlike the Windows-based workstations can not support operations of other MOS roles.

Last but not least, another Windows-based workstation, is also deployed at the OCTL Ground Station (GS) and is configured identically to the MSA ones, which provides the MOS GS operators with situational awareness akin to that of the MOS operators. For example, it allows GS operator(s) to communicate with MOS operators to plan, prepare, and perform optical communication demonstrations, as well as listen in other HOSC channels for situational awareness. By streaming OPALS FS telemetry to OCTL, the GS operators can track the real-time performance of the joint system—OCTL GS and OPALS FS—during the optical demonstrations. Thus, providing some initial real-time feedback on the performance of the system with respect to the mission success criteria.

VIII. OPALS Operations Processes

A. Configuration Management

As with many other aspects of OPALS, the configuration management (CM) process was also tailored to better accommodate both the smaller scope and the higher risk posture of the mission. The main principles that guided the reduced CM process were a) reduction of formal project documentation, which most often manifests itelf in the form of project-approved documents, and b) minimization of the the number of project artifacts that require managerial approval for revision. Formal project documentation was limited to only items that were both needed to document the design and incurred a high penalty if deviations from the content occured. Managerial approval was required primarily for artifacts that fell in the latter category so as to minimize the risk of discrepancies which could adversely impact development or operations.

This philosophy applied to both the implementation and operation portions of the project lifecycle. As a consequence, OPALS would not necessarily benefit from utilizing all of the CM tools provided by JPL to its flight projects, as the overhead associated with using them would outweigh their benefit for a small project with a short primary mission. Instead OPALS opted for extensive usage of wikis for capturing design or configuration, especially in situations were changes are frequenly required to reflect new knowledge, as is often the case during operations. To that end, the project has used password-protected, JPL internal wikis to capture everything from instructions on how to set up an operations console, to capturing which sequences are present at any given time on either of the two partitions of the flight software. Changes to the latter, however, along with any other made to the configuration of the file system of the spaceborn payload, are reviewed and approved a priori using JPL's Multi-mission Configuration Management system (MMCM) wich provides projects with both breath and depth towars the need to control changes and review change history. New or modified command sequences, as well as new software builds are evaluated and approved using this system. The synergy between the flexibility offered by wikis and the control offered by existing infrastructure illustrates how OPALS was able to right-size the solution by leveraging JPL's existing infrastructure while maintaining ease of use and minimizing process overhead.

B. Anomaly Response

When an anomaly is detected with the flight system during a pass and there is any question regarding the safety of the hardware or the restraints for laser safety the operations team will send an "Abort Safe" command and the flight system will put itself into a safe state with the laser restraints enabled.

All events that indicate unexpected performance of the ground system, flight system, or flight team during operations will then be documented in an anomaly report in the JPL institutional Problem Reporting System. If the issue is determined to be the result of flight system hardware, software, or operator error a corresponding Problem Failure Report (PFR) will then be generated.

Depending on the source and scope of the issue the HOSC may also choose to document the incident within their own reporting system to track issues on their ground system, ISS hardware, or other areas of concern.

C. OPALS Data Processing Strategy

Anytime the onboard flight software (FSW) is active, detailed engineering data is written to an onboard engineering log (Elog). A new Elog is created each time the avionics are turned on. Elogs from multiple activity sessions and accompanying image files from onboard camera operations are periodically downlinked to the MOS operators for post-processing and data analysis. A MATLAB-based analysis tool was developed as a centralized graphical user interface (GUI) that wraps various processing and analysis scripts written in MATLAB and Python by the OPALS development and operations team members. The tool has six modules: Elog processing, Elog(s) trending, gimbal calibration processing, image (IMG) centroid processing, thermocouple processing, and image processing. The purpose, inputs, logistics, and outputs of each one of these modules is summarized in Table 1.

Table 1. OPALS Data Processing Tool Modules

Module	Purpose	Inputs	Outputs
Elog Processing	To parse Elog files into a usable tabular format for analysis	Elog(s)	Processed data is stored in a MATLAB™ file (.mat). Users can load the file into the workspace to view the data, parameter names, file name, and file date of the processed Elogs
Elog Trending	To analyze parameter trends over multiple activities	MATLAB™ data structure from Elog Processing	Plots of parameter trends spanning all selected Elogs
Gimbal Calibration Processing	To trend the consistency of gimbal limit switch actuation points over one or more Elog sessions	Elog(s)	Histograms of gimbal switch actuation locations
Image Processing	To process compiled IMG files from the camera to individual frames with statistics	Camera binned IMG file(s).	PDF file of each processed IMG frame with headers including bin number, frame number, timestamp, centroid location, and flux information
Centroid Processing	To plot image processing trends and statistics	Camera centroid results	Centroid statistics and plots; e.g., camera flux, position, etc.
Thermocouple Processing	To parse thermocouple data for plotting and analysis	Thermocouple telemetry	Thermocouple temperature plots over time with caution and warning boundary limits

Outputs from each module can be saved in a PDF format and archived for later viewing. After processing all these modules for a given Elog, a report option is available to compile a PDF document containing all outputs, graphs, and images associated with a chosen Elog from the modules used. This data can then be used by the OPALS operators to monitor the status of the payload and ground station equipment over different time spans, allowing for more informed decisions to extend the operational life of the payload.

Furthermore, for archival of all FS, MOS, and GS generated data (raw and processed data products from all testing and operational activities), the project employs an institutional, continuously supported, repository with

unlimited space. Operator processes are instructed to place all relevant activity data to this repository from all ORTs, simulations, operational, and data processing activities.

IX. OPALS Team Training

A. Team Training Strategy

OPALS MOS and GS operator teams consist of a dozen part-time operators, nine dedicated to operations at the MOS MSA and three dedicated to operations at OCTL GS. Operator training consists of numerous types of activities: ATLO testing and integration, dedicated team and one-on-one training sessions, self-guided training, MOS team simulations, MOS, GS and HOSC operator involved ORTs, and MOS and GS operator operational training retreats.

Foremost, from the start the project benefited because most of the OPALS MOS and GS operators were involved in development and ATLO activities. However, while the experienced developers' transition to operations provides the domain knowledge and continuity, the new operators provide the fresh, inquisitive nature needed in order to collectively prepare for operations. For example, during development and ATLO many of the processes were known only by a single individual. However, for operations, the team deployed project-specific wiki pages to document instructions for these processes for the entire team, with subsequent training that refined the instructions and achieved the desired knowledge dissemination. For example, wikis were created detailing how to set up the workstations with all of the tools required for operations, how to set up and use a tablet for as-run procedure documentation, EM operations, configuration management of the EM and FS files on respective partitions, pointers to related documentation (e.g., File ID assignments, TLM & CMD dictionary, anomaly handling and reporting), etc.

Additionally, use of operational procedures from ATLO as a starting point for in-flight operational procedures (e.g., Commissioning, Optical Downlink, File Preparation and Uplink, FSW Patch, Contingency, etc.) was not only beneficial for operational procedure preparation, but the process of building these procedures was in itself a training opportunity. The authorship of the operational procedures was allocated to five MOS operators. This leveraged their expertis, but also provided an opportunity for these operators to learn the inner workings of the FS and operational interfaces that they did not have previously.

Initially many impromptu training sessions were held to familiarize the operators with the core HOSC and JSC provided tools. This was followed up by regular weekly training sessions to train the team on all things Flight System and Operations. A few operational planning sessions were effective to focus the operators' attention for planning and preparing for commissioning, and for in-depth discussions. Individual and self-guided training sessions were also provided to support the operator schedules, bring them up to speed, and provide an environment for self-paced instruction. Not only did the GS operators train alongside the MOS operators, tours were held for MOS operators at the OCTL facility, so as to familiarize them with the ground segment of OPALS operations.

To following the "test-as-you-fly" principle, the team used ORTs to cross train all of the MOS operators, including some of the GS operators, on all the MOS roles. The complexity of the ORTs was increased gradually; each ORT added additional flight-like conditions. For example, inclusion of HOSC operations, TDRS LOS (loss of signal) and AOS (acquisition of signal) communication windows, inclusion of EM for real-time TLM streaming, including of GS operators were added gradually. The purpose of this approach was to progressively train the team to operate in flight-like conditions, but without overwhelming initially with all of the flight-like conditions. Furthermore, additional non-ORT simulations are employed to allow various operators to train in roles they would like additional experience in, as well as authors of various commissioning and nominal operations procedures to walk through their respective procedures for completeness and effectiveness checks.

The GS operators have the added benefit of the recent successful deployment of OCTL GS for LADEE (Lunar Atmosphere and Dust Environment Explorer) lunar laser communication demonstrations, allowing for feed forward of some of the core hardware, software, operational processes, and lessons learned to the OPALS project. With that said, OPALS mission operations are different than LADEE's because of different optical frequencies, pointing requirements, and tracking conditions—e.g., OPALS's short and fast moving operations from ISS orbit versus LADEE's long, slow moving optical passes at the moon.

The most difficult component of preparing for operations was user access to all of the required JPL, HOSC, and ISS resources. It is very time consuming to obtain, track, and maintain all of the access for all of the operators. A related time-consuming process was working with various IT specialists at various sites for opening up firewalls for sharing information between HOSC, JPL MSA, and OCTL GS.

Last but not least, some of the new operators brought on to the OPALS MOS team are also on the development teams for future JPL payloads to the ISS, thus providing operational knowledge and process retention for ISS payload operations by JPL operators beyond the OPALS project.

B. Benefits of ATLO/Operations Overlap

OPALS is a relatively small project with limited resources. Therefore it is imperative that the team performs work as efficiently as possible. In preparation for Mission Operations, OPALS chose two approaches to smooth the transition from development to operations. First, OPALS maintained the same core team for design, development, testing, and mission operations phases. Second, the operations interface tools (i.e. TReK) were used as much as possible and as early as possible during the assembly and test phases of ATLO.

OPALS chose to keep the same small core team through all phases of the project in order to keep project knowledge and expertise close at hand. Since the same individuals maintained cognizance over portions of the flight system throughout development, they had a clear understanding of the functionality and idiosyncracies as operations preparations began. A consequence of this approach is that the development and then operations preperations tasks were completed serially. In a larger project, or one on a faster development schedule, the need for parallelizing tasks would have eliminated this efficiency. OPALS was able to eliminate the imperfect knowledge transfer between the hardware developers and the mission operators. Not only did this save time and money because no effort was required for knowledge transfer, but it also ensured that all developmental knowledge, however subtle, remained with the team. Aside from being able to serialize the work, another prerequisite for this approach is that the individuals on the team have to be interested in multiple project phases. The small OPALS core team self-identified as enthusiastic and eager to remain involved throughout the project lifecycle. In order to reap the benefits of this approach in Mission Operations, the assembly and test team are the most crucial members to hold on to because of their intimate knowledge of the fully-assembled systems.

The second prong in the approach that the OPALS team used to efficiently prepare for Mission Operations was to use the operations interface tools in assembly and test as early on in the process as possible. This approach goes hand in hand with maintaining the same individuals within the workforce. It allows for early practice for the team with the operations tools as well as eliminates the need to develp both test and operations interface tools because they are one in the same. Whenever the OPALS team was testing functionality with the mission operation interface, then we were also testing operations capability by default. Additionally, when making late-phase trades that include an operational element, the team has a better understanding of the effects on mission operators because of the extensive testing experience.

The OPALS project was able to capitalize on two important efficiencies in preparation for Mission Operations, namely, keeping the same core team and using the same testing/operations interface tools. Not every project will be able to take advantage of these effeciences because of time or workforce constraints. A workforce that is motivated to participate in multiple project phases and a relatively small project size with the ability to serialize many of the tasks are the most important prerequisites for the success of these approaches.

C. Operation Readiness Testing

Following standard JPL practice, the flight team was readied for operations through a series of Operational Readiness Tests (ORTs) and Thread Tests. While ORTs were primarily intended to place the flight team in realistic, full scale simulations of various operational activities such as commissioning, a regular day-in-the-life, and off-nominal scenarios, Thread Tests focused on execution of a sub-set of activities occurring during operations that required end-to-end involvement of the team. Members of the team participated in one commisioning, and five optical downlink ORTs, all of which involved real-time participation of the HOSC in high-fidelity operational scenarios. Table 2 lists the ORTs elements incorporated and any off-nominal events introduced. The team also executed several Thread Tests focused on generation of pointing predicts which are used by both the ground station and the Flight System and are unique to each pass.

Table 2. OPALS Simulation Training Events

	ORT #1	ORT #2	ORT #3	ORT #4	ORT #5	ORT #6
Activity	Optical Downlink	Optical Downlink	Optical Downlink	Optical Downlink	Commissioning: Initial Power On	Optical Downlink
New Elements	OSTPV Timeline Sim Voice Loop	1. BP Table Generation 2. File Upload to HOSC dropbox	Engineering Model Telemetry	OCTL Operations	New Activity	None
Off-Nominal	PLMDM Reset	1. PRO Command	1. PLMDM Reset	1. FSW Reset	None	1. HOSC Delay

Activities		Delay 2. BP Table Out of Spec	2. Ground S/W Issues	2. HOSC Command Timeout		2. Personnel Absence
Findings	S-band/Ku-band outages affect activity flow	Necessary to validate BP Table prior to HOSC upload	Add'l time required for telemetry verification and recording	GO/NO GO criteria required following a system reset	Additional time required for downlink command window	Alignment of procedure steps to command windows needed

X. Design Considerations Based on Simulation Experience

The ORTs and Thread Tests have afforded the team a wealth of lessons learned and the opportunity to make adjustments prior to commencement of operations. The experience gained during the simulations was especially important to the OPALS team for two interdependent reasons: 1) the flight team membership draws heavily from the team that designed, integrated, and tested the flight payload, and 2) because of this, the team's experience was largely shaped by operating the flight hardware in an "interface vacuum," meaning that the majority of the testing occurred in the absence of an external interface. While having the development and test team transition into an operations role certainly brings an unquantifiable benefit, it can come with various degrees of tunnel vision. This became evident in early simulations during which the flight team exhibited difficulty in adjusting its mode of operations to accommodate and fit into the larger ISS operations, as well as those of the ground station operators, both of which were not geographically collocated with the OPALS team.

Interfacing with the the ISS operations, both from an infrastructure and a cadence standpoint provided a constant challenge for the OPALS operators during ORTs. During laboratory testing at JPL, the cadence of any given test was dictated by the speed with wich the test conducturs could safely operate the flight hardware and supporting equipment. This pace turned out to be approximately 20%-30% faster than what was experienced during the simulations with the HOSC. The main reason for this was two fold. For one, OPALS is one of many payloads, both internal and external to the ISS, that are in operations at any given time, and thus cannot command the uninterupted attention of the ISS operators for extended periods of time during one session. Furthermore, the ISS does not benefit from continuous Ku- and S-band covereage needed for uplink and downlink, respectively, and thus necessarily slows down the pace. This aspect is further compounded by the a priori defined, and well adhered-to, structure and timing of command windows made available to payloads. The additional timing restrictions self-imposed by the project for certain commands poses an additional constraint on the process. While all these factors were well known and understood prior to partaking in the simulations, their effect was not fully appreciated until the team underwent the training provided by the ORTs. The consensus within the flight team is that the outcome of early development flight-ground capability trades may have had a different outcome had these factors been appreciated more fully at that time. Discussion of such leasons learned, however, is deferred to a future publication that can cover those from the operations as well.

XI. Conclusion

A comprehensive mission system has been developed for OPALS that enables regular space-to-ground optical communications experiments on the ISS. Key components include an automated Demonstration forecasting service, activity planning templates, laser safety agreements, and pointing prediction capabilities. Given the complexity of operational interfaces, all OPALS team members are trained using thread tests and HOSC-participating ORTs. Findings from the ORTs suggest that a high level of situational awareness is required with respect to the Demonstration time, HOSC coordination timeline, TDRSS outage periods, and voice loop notifications. Leveraging these results, the OPALS team continues to improve its processes as it prepares for the operations phase and future optical link experiments.

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Abbreviations

BPT	=	Blind Pointing Table
CDT	=	Centroid Deviation Table
ELC	=	ExPrESS Logistics Carrier
FOR	=	Field of Regard
FRAM	=	Flight Releasable Attachment Mechanism
FS	=	Flight System
GCP	=	Ground Command Procedure
GS	=	Ground System
HOSC	=	Huntsville Operations Support Center
ISS	=	International Space Station
JPL	=	Jet Propulsion Laboratory
JSC	=	Johnson Space Center
MCC-H	=	Mission Control Center Houston
MOD	=	Mission Operations Directorate
MOS	=	Mission Operations System
MSA	=	Mission Support Area
MSFC	=	Marshall Space Flight Center
OC	=	Operations Coordinator
OCTL	=	Optical Communications Telescope Laboratory
OPALS	=	Optical PAyload for Lasercomm Science
ORT	=	Operational Readiness Test
POD	=	Payload Operations Director
PPM	=	Payload Planning Manager
PRO	=	Payload Rack Officer
SPDM	=	Special Purpose Dextrous Manipulator
SSRMS	=	Space Station Robotic Manipulator System