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

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In April of 2014, the Optical PAyload for Lasercomm Science (OPALS) Flight System (FS) launched to the International Space Station (ISS) to demonstrate space-to-ground optical communications. During a planned 90-day baseline mission, the OPALS FS will downlink high quality, short duration videos to the Optical Communications Telescope Laboratory (OCTL) ground station in Wrightwood, California. Interfaces to the ISS payload operations infrastructure have been established to 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 ORTs have provided valuable insight into operational considerations for the instrument 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 spaceborne laser, from the International Space Station. OPALS was launched in April of 2014 aboard a SpaceX Dragon commercial resupply capsule. The payload will be mounted externally, in a nadir position, on the International Space Station's (ISS) ExPrESS Logistics Carrier-1 (ELC-1) module, ensuring line of sight to an optical receiver on the ground[1].

Over the course of a planned nominal 90-day mission—using a 1550 nm, 2.5 W laser—the OPALS Flight System (FS) will demonstrate the downlink of high quality, short duration videos to the Optical Communications Telescope Laboratory (OCTL) ground station in Wrightwood, California[2]. To achieve this, in addition to designing and building the ISS-bound instrument, the OPALS project team has developed interfaces to the existing ISS Program infrastructure (ground and in-flight) that will allow mission operators to command and monitor the OPALS payload. The operations architecture includes one mission support area (MSA) at JPL for payload commanding and monitoring 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 several operations teams to ensure time-critical line of sight opportunities are planned and executed to success. These include teams located at the JPL MSA, OCTL ground station, and the Huntsville Operations Support Center (HOSC), a Marshall Space Flight Center (MSFC) facility that supports ISS-based payload and experiment activities. 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 operations teams. To prepare for on-orbit operations, the JPL and MSFC teams have jointly executed a series of Operational Readiness Tests (ORTs) to gain familiarity with on-orbit processes and test contingency responses to off-nominal activities. For ORTs and future operations, many processes, tools, and personnel were inherited from the OPALS Integration and Test campaign to ensure continuity, familiarity, and to minimize development costs. Where possible, multimission and commercially available tools

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were also utilized. This paper demonstrates, including lessons learned, a mission architecture implementation for an optical communications terminal on the ISS.

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. As a technology demonstration, the OPALS experiment provides an excellent opportunity to gain operational experience with a space-to-ground optical link under various operational and environmental conditions. The ISS location, in low Earth orbit, provides an ideal 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 perform 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

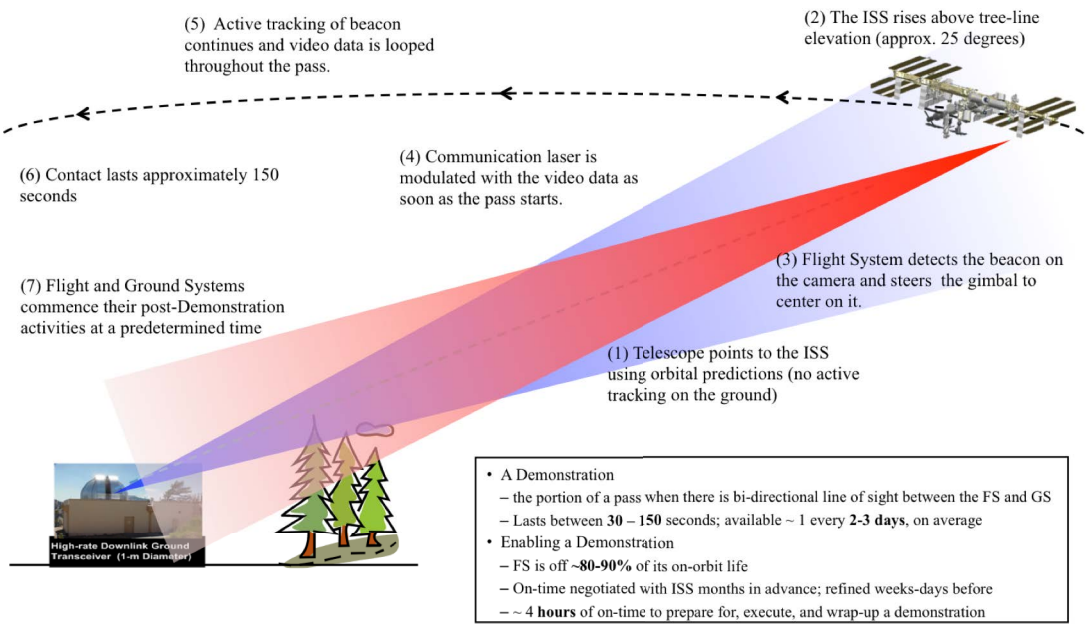


Figure 1. OPALS Mission Concept of Operations

Demonstration, defined as the period of time when bi-directional line of sight exists between the OPALS FS and OCTL. A Demonstration period typically lasts a maximum of 150 seconds due to pointing restrictions on the ground and flight lasers. The activity begins with the ISS illuminated by a 976 nm OCTL-based beacon laser using a ground-to-space pointing prediction profile. Meanwhile, the OPALS FS 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 at a nominal rate of 50 Mbps. Once the FS camera CCD detects the ground beacon signal, 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 its motion.

B. Mission Architecture

The OPALS element conducting the operations phase is referred to as the Mission Operations System (MOS). It consists of ground-based facilities, infrastructure, processes, and operations personnel. The purpose of the MOS is to operate the OPALS Flight System 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

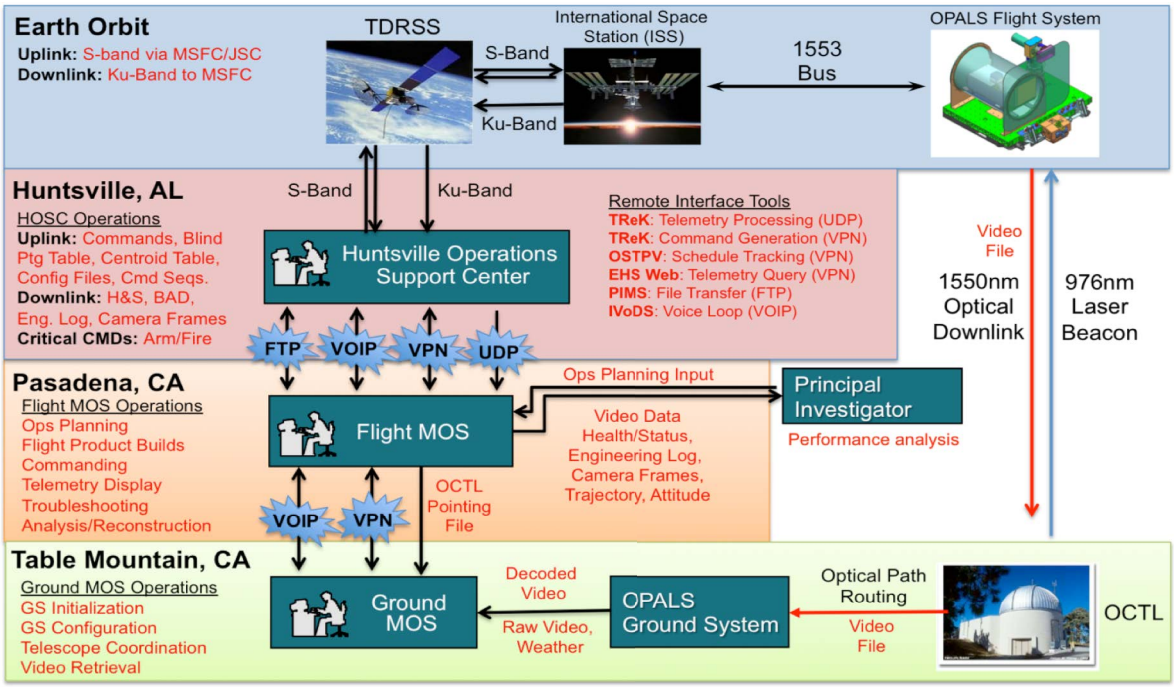


Figure 2. OPALS Mission Architecture

Relay Services System (TDRSS) to reach the FS on the ISS. 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 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 is expected to occur 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 nominal 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 predictions spanning the Demonstration period and uplink to the FS via HOSC.
- FS Power On: power avionics systems and boot flight software.
- 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 via coordination with the HOSC.
- Command Gimbal Calibration Sequence: calibrate gimbal step locations to the gimbal coordinate frame.

- Build OCTL Pointing File: generate a set of ground-to-space pointing predictions spanning the Demonstration period.
- Command Camera and Laser On: initiate processing of camera images and power the laser to 2.5 Watts.
- Send Demonstration Command: schedule the commencement of Demonstration activities on the FS.
- Transmit Optical Downlink: transmit the optical signal to OCTL as the beacon is tracked.
- Command Gimbal Stow/Laser Off: ramp down the laser power, stow the gimbal at the edge of travel, and re-enable safety restraints for the gimbal and laser subsystems.
- Downlink Elog and Image Files: downlink payload engineering log data and camera image snapshots from the Demonstration via HOSC.

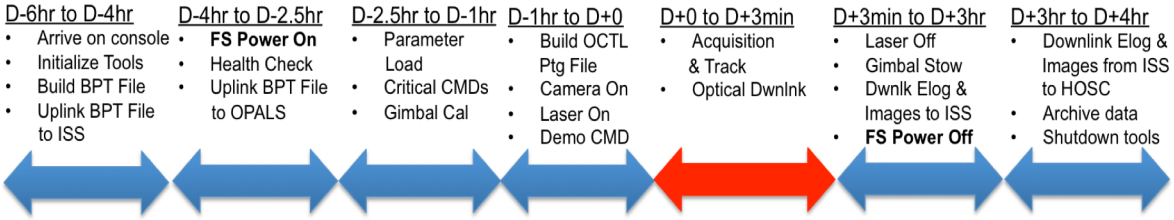


Figure 3. OPALS Nominal Optical Downlink Activity Timeline

D. Mission Phases

The OPALS 90-day mission begins once the payload is installed on the ISS's ELC-1 module. Figure 4 depicts the phases of the OPALS prime mission. Installation is completed by the Special Purpose Dexterous 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 activities 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 checkout activity is the file transfer. In this activity, the team verifies the ability of OPALS to push and pull files from the ISS onboard file storage system. The team then 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.

The first checkout activity requiring coordination with the OCTL ground station is the Open Loop Characterization Test. This test measures the signal-to-noise ratio (SNR) of the ground laser beacon signal in the flight camera CCD and assesses the pointing prediction performance of the BPT. It is desirable to repeat 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. This activity's results feed forward to decisions on camera threshold levels and BPT search strategies.

The final scheduled checkout activity is the Tracking Characterization Test. This builds upon the Open Loop Characterization Test by activating the onboard feedback control system for tracking of the ground beacon. This test measures the tracking performance in angular jitter from the center of the camera CCD. Using this activity's results, the operations team will adjust the FS's 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

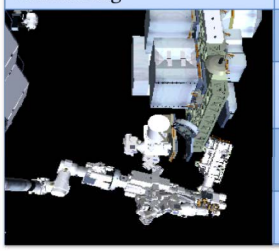
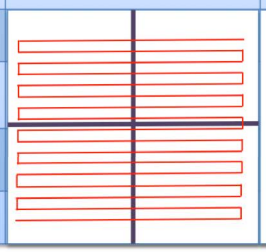
SpX-3 Trunk Extraction	Initial Power On		
Transport to ELC-1	File Transfer Checkout		
ELC-1 EXPA-1 Install	Gimbal Motion & Calibration Test		
Real-time Video Monitoring	Camera Checkout Test		
	Laser Checkout Test		
	Open Loop Characterization Test		
	Tracking Characterization Test		
	Thermal Monitoring		

Figure 4. OPALS Mission Phases

Mission Phase II will determine any misalignments between the onboard transmit (laser) and receive (camera) optics due to thermal cycling and/or launch vibrations. To accomplish this task, the operations team commands a time-varying target profile for the feedback control system, 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, the OPALS team will execute Mission Phase III, attempting as many optical downlinks to OCTL as feasible, under various operational and environmental conditions. If time and resources are available, Mission Phase III also 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 FS hardware is a combination of in-house JPL-developed and Commercial Off-The-Shelf (COTS) hardware. The 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 except for the camera (i.e., avionics, power, laser) and also maintains 1 atmosphere of pressure to provide convective forced air cooling of the electronics 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 the OPALS FS.

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 (orbit 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.

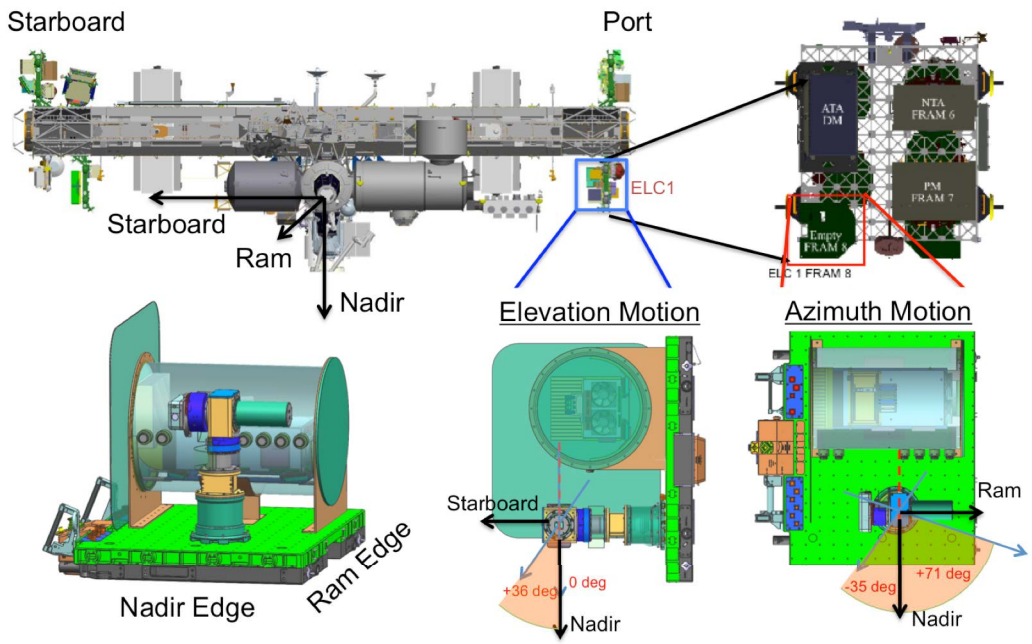


Figure 5. OPALS Placement and Pointing Field of Regard (FoR).
(In the upper left image, Ram is directed out of the page)

B. Payload Operational Interfaces

The OPALS FS features command, telemetry, and file transfer interfaces for operations. The sole interface over which packetized data flows to and from the payload is an ISS-defined 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 in telemetry at 1 Hz, and is capable of bi-directional file transfers between itself and the ISS file storage 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 uplinked and 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 in the onboard camera's image frames.

1. Commanding

Commanding of the OPALS 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. As designed, 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, the command handler validates commands and associated fields for proper syntax. When a command has been validated successfully, it is placed in the Command Queue for execution.

The Command Queue, a first-in, first-out buffer, holds all commands waiting to be executed. When a command is retrieved from 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 FS safe mode or clear the command queue can pre-empt the execution wait period and clear all commands residing in 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 camera detects the beacon, the flight software will enter into closed loop tracking, no longer being commanded by the BPT but instead being commanded by the closed loop controller using the Centroid Deviation Table developed in mission phase II.

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 flight software 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 TDRSS), where it is then forwarded to the OPALS Flight and OCTL Ground MSAs. 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. Operations Interfaces

The OPALS operations team maintains external interfaces with the HOSC organization at Marshall Space Flight Center (MSFC) and the Mission Operations Directorate (MOD) organization at Johnson Space Center (JSC), as well as internal interfaces between the Flight MOS at JPL and the Ground MOS at OCTL. Figure 6 outlines the services offered by each external 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.

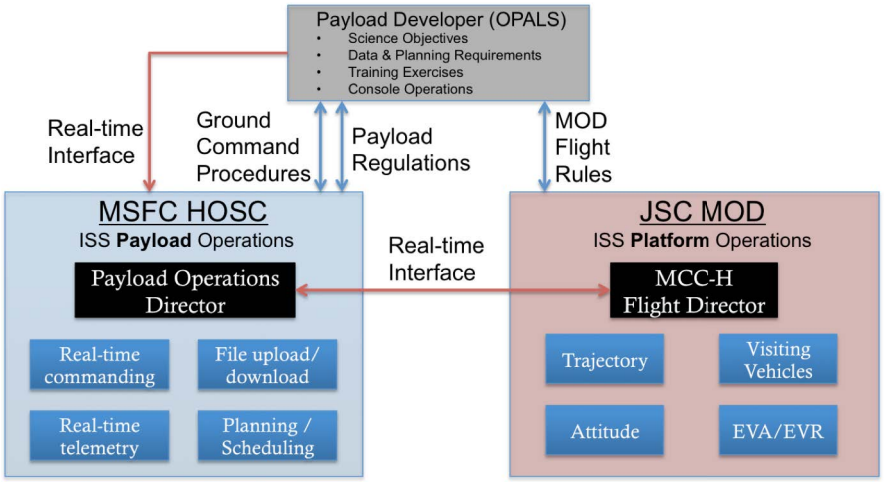


Figure 6. Operations Interfaces to HOSC and MOD

As such, during real-time operations only external interfaces between OPALS and HOSC are exercised.

The HOSC is responsible for all 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. 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 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.

The Flight MOS and Ground MOS interface is primarily implemented over a dedicated voice loop. The main function of this interface is to maintain situational awareness between the two teams, ensuring Demonstration readiness for both the FS and OCTL. Each team will also have available streaming telemetry from both the FS and OCTL to enhance situational awareness.

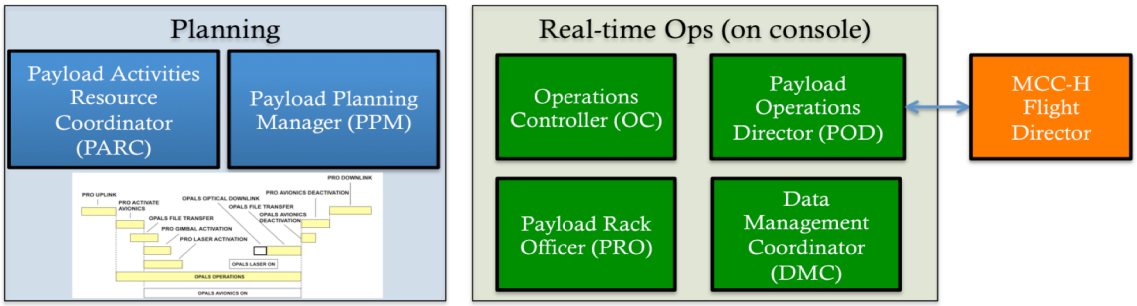
A. OPALS-HOSC Interface

The HOSC provides support to the OPALS operations team both in planning and real-time roles. Figure 7 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. The GCPs and Payload Regulations outline all coordination activities with the PRO, including critical commanding, telemetry verification, and voice notifications. For OPALS, these coordination activities include avionics activation, gimbal activation, laser activation, and avionics deactivation. The avionics activation GCP supplies 28V power to the payload, which automatically initializes the OPALS flight software into safe state. The gimbal and laser activation GCPs 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. After removal of laser safety restraints, the laser activation GCP contains laser power commands that must be sent independently by the Flight MOS and the PRO to decentralize the laser powering process. Finally, the avionics deactivation GCP removes 28V power from the payload, ending FS operations for the activity. Additionally, Payload Regulations are in place to specify event notification, telemetry monitoring, and contingency response services provided by the HOSC for the OPALS MOS team.

The other members of the real-time HOSC support staff have less interaction with OPALS. 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.

For planning purposes, the OPALS team interacts with the Payload Activities Resource Coordinator (PARC) and



- **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 7. HOSC Payload Support Roles

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, and/or HOSC personnel. All activities are scheduled relative to the OPALS Optical Downlink Window that is aligned with the OPALS Demonstration period. A generic OPALS operations command window overlays the entire period of OPALS commanding, while more specialized windows describing coordination activities occur in the following order:

1. PRO Uplink Window: PRO to uplink files from HOSC to the ISS
2. PRO Avionics Activation Window: PRO to power on the OPALS payload
3. OPALS File Transfer Window: OPALS payload commanded to uplink files from the ISS
4. PRO Gimbal Activation Window: PRO to remove safety restraints on the OPALS gimbal
5. PRO Laser Activation Window: PRO to remove safety restraints on the OPALS laser
6. OPALS Laser On Window: OPALS laser is fully powered to 2.5 Watts
7. OPALS Optical Downlink Window: OPALS Demonstration period
8. OPALS File Transfer Window: OPALS payload commanded to downlink files to the ISS
9. OPALS Avionics Deactivation Window: OPALS payload commanded to shutdown flight software
10. PRO Avionics Deactivation Window: PRO to power off the OPALS payload
11. 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 section.

B. OPALS-MOD Interface

The OPALS interface with MOD is entirely governed by MOD Flight Rules. 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 dictate the following operational rules:

- OPALS laser 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 laser operations will be prohibited during SSRMS (ISS Robotic Manipulator System) usage that violates the OPALS Field of Regard. 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 Field of Regard constraints are sufficient to keep the laser from creating a hazard.

The flight rule for payload power interruptions informs MOD personnel of OPALS constraints given a planned or unplanned power outage on the ISS and recommends actions in each scenario. Given OPALS allowable flight temperatures, the payload can tolerate up to a 2.25-hour unplanned power outage or a 4.25-hour planned power outage if the payload is thermally 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 Flight MOS and Ground MOS Interface

During operations, the Flight MOS and Ground MOS will collaborate to prepare and execute bidirectional optical communications during the ISS pass over OCTL. This collaboration includes voice loop communications covering:

- Status updates for situational awareness during preparation, execution, and post-demonstration activities.
- Confirmation of the expected optical downlink modulation rate and selection of the downlink video file.
- Confirmation of the OCTL telescope configuration and beacon operation plan, including planned OCTL beacon power profile and beacon shuttering times.
- Go/no-go checks based on Flight and Ground MOS teams' operational readiness for the pass, including whether the local weather at OCTL is still favorable for optical demonstration.

Additionally, the Flight MOS operators will provide Ground MOS operators with the a set of ground-to-space pointing predictions within 15 minutes of the Demonstration. The Ground MOS will stream the OCTL telemetry to the Flight MOS for real-time situational awareness of telescope performance and recording for post-mission correlation of the joint OPALS FS and OCTL ground station performance.

In post-demonstration, Ground MOS 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 Flight 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 two weeks prior to any OPALS FS operations. This product offers a preview of all ISS activities in the upcoming two weeks and provides all parties an opportunity to identify activity conflicts. A Demonstration forecasting capability is used to supply inputs to this process. Since the occurrence of Demonstration periods is inherently tied to bi-directional line of sight opportunities between the OPALS FS and OCTL, the forecasting capability is dependent on the ISS trajectory and attitude predictions relative to the OCTL ground station. 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 be 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 FS.
- OCTL azimuth and elevation pointing at the times of ISS rise and set (i.e., 25° elevation relative to OCTL) and closest approach.
- OPALS gimbal azimuth and elevation pointing at the times of ISS rise and set (i.e., 25° elevation relative to OCTL).

Using this information, the OPALS team prioritizes Demonstration opportunities based on longest duration, maximum margin relative to FS gimbal and OCTL pointing limits, and minimum Sun interference (e.g., night passes). For each pass, the forecast provides the first definition of the Demonstration time (i.e., 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 ISS trajectory dispersions in the along-track direction. Following the D-1 week update, the WLP schedule is integrated into the ISS Short Term Plan (STP) 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

A 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. 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 BPT. 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 Generation

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 unacceptable pointing errors on the order of milliradians. Thus, 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:

1. Query a recent GPS state vector and time from the HOSC database at D-30 minutes.
2. Correct state vector with latest International Earth Rotation and Reference System (IERS) Earth orientation data.
3. Propagate trajectory through the Demonstration period using gravity, atmospheric drag, and solar pressure force models.
4. Sample trajectory at 10Hz during the Demonstration period and calculate OCTL topographic pointing angles.
5. 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 8 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.

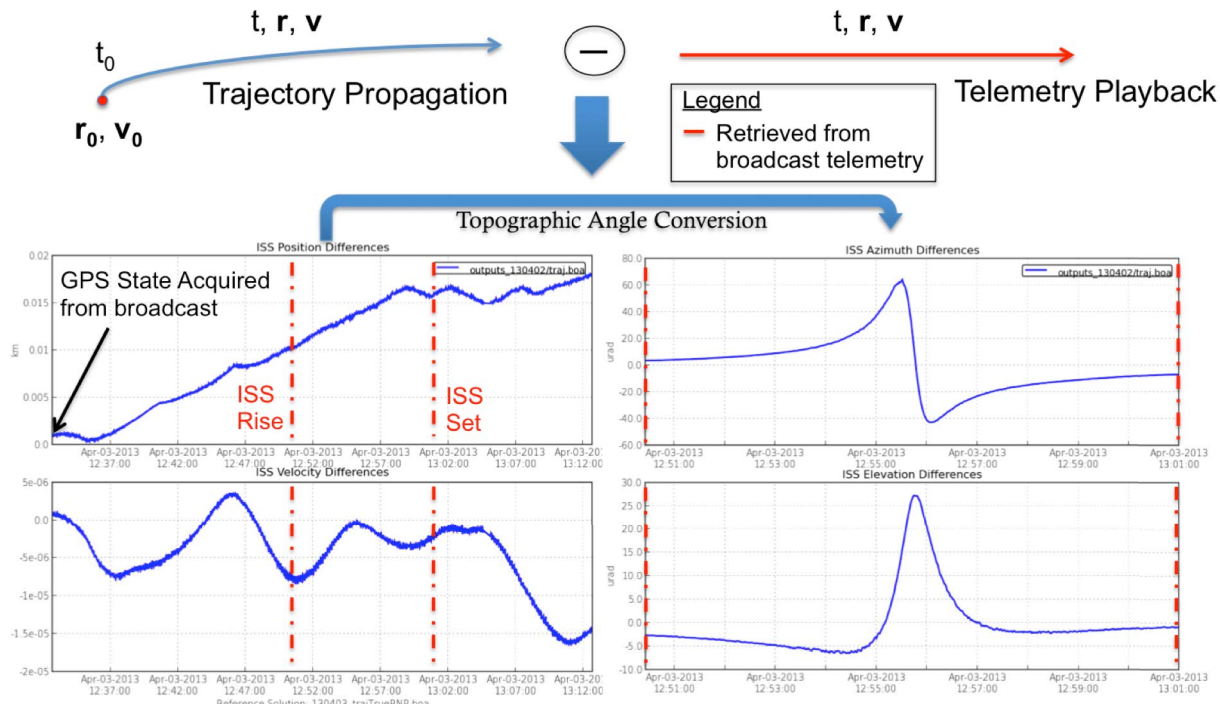


Figure 9. Example of Space-to-Ground Pointing Prediction Performance for April 3, 2013 Pass

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 9 shows ISS images obtained during approach to (left) and departure from (right) the OCTL telescope.

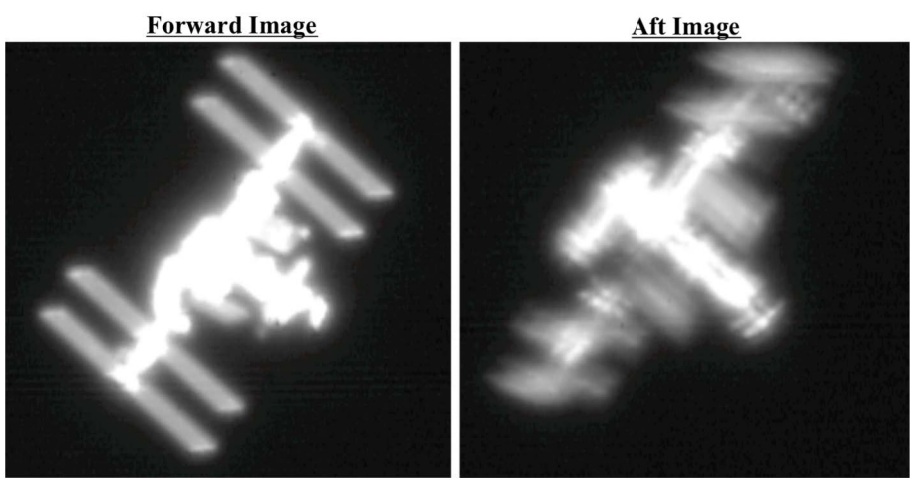


Figure 8. ISS Images Obtained in OCTL Telescope During April 3, 2013 Pass

B. Blind Pointing Table Generation

The BPT is required for pointing the FS optical transceiver towards the OCTL ground site. Since the feedback control system is responsible for fine pointing, the BPT 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 HOSC-supported 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 Demonstration. 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 for the BPT, the pointing accuracy requirements will likely be met. Additional accuracy is obtained by predicting the phase of the attitude oscillation at the Demonstration time. Figure 10 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 10, the total pointing prediction error should be less than 1 degree.

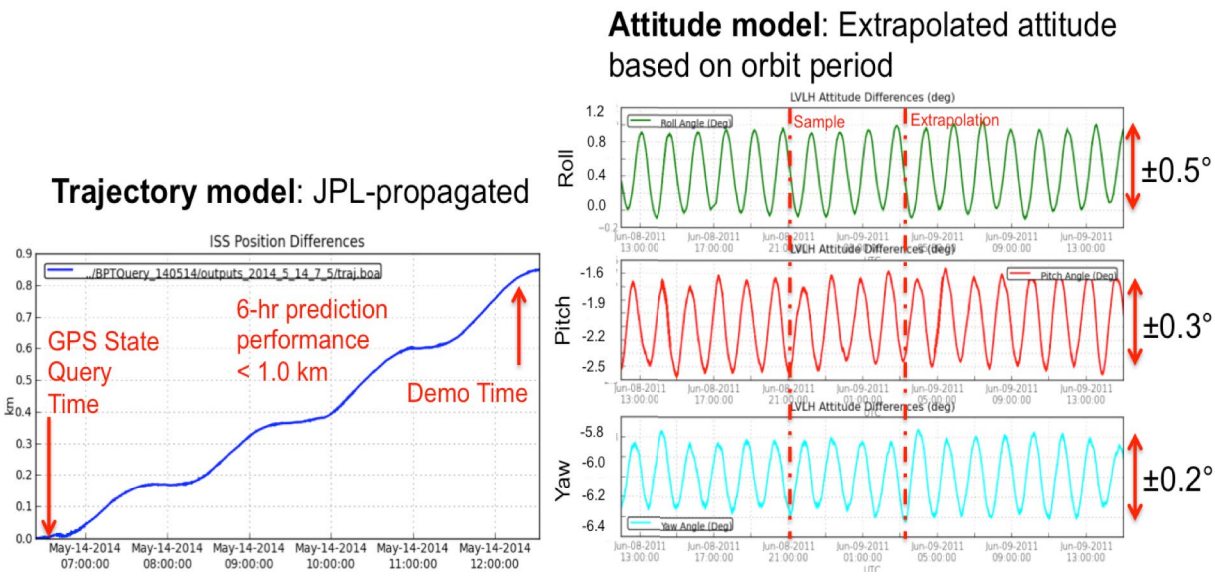


Figure 10. ISS Trajectory and Attitude Extrapolation for the Blind Pointing Table (Left plot shows the error growth between predicted and actual ISS position following BPT generation, right plot shows differences between predicted and actual attitude)

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 11 shows typical blind pointing (left) and slew (right) profiles for a Demonstration activity.

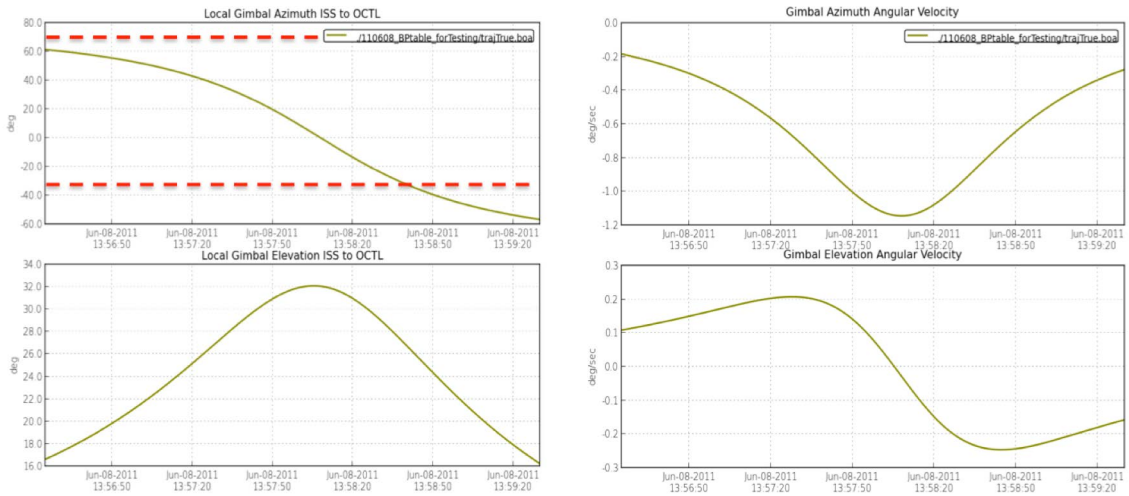


Figure 11. Blind Pointing Table Profile for a Typical Demonstration Pass

VII. OPALS Mission Operations Infrastructure

The OPALS Mission Support Area (MSA) is co-located with other Earth Science missions within the JPL Earth Science Mission Center (ESMC) facility. It includes physical workstation space, IT and security network resources, uninterrupted power supplies, and phones for the Flight MOS operators. The OPALS Engineering Model (EM) is also located in the MSA to serve as a testbed and provide a flight-like testing environment for the ORTs and training simulations.

OPALS MSA provides 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). During an operational pass, the TE is responsible for monitoring 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 coordinates all critical commanding activities with the PRO. 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. Furthermore, prior to optical communication demonstrations, the Ptg operator is responsible for generating the BPT and OCTL Pointing File. The Ptg operator can also assist in validating new OPALS files and sequences prior to uplink.

The TE, CE, and VO/PD positions complete all work on three Windows-based operations workstations. A fourth workstation with an identical configuration is stationed at the OCTL ground station for use by the Ground MOS. It provides the Ground MOS operators with situational awareness akin to that of the Flight MOS operators and facilitates real-time monitoring of the joint Flight-Ground system. The workstations utilize a combination of HOSC and MOD-provided, project-specific, and COTS software. The core HOSC provided software resources include:

- Telescience Resource Kit (TReK) for commanding and telemetry processing.
- Internet Video Distribution System (IVoDs) for voice loop communications.
- Enhanced HOSC System Web Tool (EHS Web) for file uplink and downlink to/from the ISS file storage access to HOSC telemetry and command databases, telemetry query capabilties, and operations change requests.

The operators also employ a MOD-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 several Python and 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).

The Ptg completes all pointing prediction tasks on a separate workstation using 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 other workstations cannot support operations of other MOS roles.

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: 1) reduction of formal project documentation, which most often manifests itself in the form of project-approved documents, and 2) minimization of 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 occurred. Managerial approval was required primarily for artifacts that fell in the latter category so as to minimize the risk of discrepancies that could adversely impact development or operations.

The OPALS team made extensive usage of wikis for capturing design and configuration, especially in situations where changes are frequently required to reflect new knowledge, as is often the case during operations. Changes that directly affect the Flight System are reviewed and approved a priori using JPL's Multi-mission Configuration Management system (MMCM) which provides projects with both breadth and depth towards the need to control changes and review change history. New or modified command sequences, as well as new FSW 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 leveraged JPL's existing infrastructure while maintaining ease of use and minimizing process overhead.

B. Anomaly Response

When an anomaly is detected with the FS during a pass and there is any question regarding the safety of the hardware or the laser safety restraints, the operations team will send an "Abort Safe" command. The FS response will terminate laser power, stow the gimbal, and enter into a safe state with all laser restraints enabled. All events that indicate unexpected performance of the OCTL ground station, FS, or MOS team during operations will then be documented in an anomaly report in the JPL institutional Problem Reporting System. Furthermore, 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 is active, detailed engineering data is written to an onboard engineering log. A new Elog is automatically 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. An analysis tool was developed as a centralized graphical user interface (GUI) that wraps various processing and analysis scripts written in MATLAB and Python. The tool has six modules that are 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	Elog(s)	Histograms of gimbal switch actuation locations

	sessions		
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

After all modules have been processed for a given Elog, a report option is available to compile a standard report containing all outputs, graphs, and images associated with a chosen Elog from the modules used. This data can then be used by the OPALS MOS operators to monitor the status of the FS and OCTL ground station equipment over different time spans, allowing for more informed decisions to extend the operational life of the payload.

IX. OPALS Team Training

A. Team Training Strategy

OPALS Flight MOS and Ground MOS operator teams consist of a dozen part-time operators, nine dedicated to operations at the MOS MSA and three dedicated to operations at OCTL ground station. Operator training consists of four types of activities: software tool training sessions, procedure training sessions, HOSC scenario sessions, and HOSC simulation sessions.

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 all MOS operators on various Flight System processes and procedures. Next, the Flight MOS team participated in scenario activities facilited by the HOSC to practice real-time coordinated activities. These sessions did not include a simulated timeline, nor interfaces to other operating ISS payloads, therefore offering a chance to train without distractions or time pressure. Following the scenarios, the Flight MOS team participated in HOSC simulation sessions. These activities included detailed timelines of simulated TDRSS coverage, onboard activities, and additional payloads competing for resources with OPALS. The simulation activities were used to execute all formal Operational Readiness Tests (ORTs) of the Flight MOS and Ground MOS teams. 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 Ground MOS operators have the added benefit of prior successful deployment of the OCTL ground station 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.

Lastly, some of the newer operators brought on to the OPALS Flight 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 Development and Operations Team 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 strategically used as much as possible and as early as possible during the assembly, integration, and test phases.

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 FS throughout development, they had a clear understanding of the functionality and idiosyncrasies as operations preparations began. A consequence of this approach is that the development and then operations preparations 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 also 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 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 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 develop both test and operations interface tools because they are one in the same. Whenever the OPALS team was testing functionality with the operational 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 operators because of the extensive testing experience.

C. Operational Readiness Testing

The MOS team was readied for operations through a series of Operational Readiness Tests (ORTs) coordinated with the HOSC. The ORTs were primarily intended to place the MOS team in realistic, full-scale simulations of various operational activities such as commissioning, a regular day-in-the-life, and off-nominal scenarios. The complexity of the ORTs was increased gradually; each ORT added additional flight-like conditions. For example, inclusion of pointing prediction generation and file upload processes, inclusion of EM for real-time telemetry streaming, and inclusion of the Ground MOS 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.

Members of the team participated in commissioning and 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. Some off-nominal events were introduced by the HOSC, such as the ISS computer system reset, while others were introduced on the OPALS side of the interface, such as the BPT values exceeding valid ranges. In each case, the Flight MOS team assessed the impact on the FS functionality. In each assessment, the team considered the time needed to resolve the issue against the time remaining until the Demonstration to make a final recommendation on proceeding.

Table 2. OPALS Operational Readiness Testing Overview

	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 Voice Loop	1. BP Table Generation 2. File Upload to HOSC dropbox	Engineering Model Telemetry	OCTL Operations	New Activity	None
Off-Nominal Activities	ISS CPU Reset	1. PRO Command Delay 2. BPT Out of Spec	1. ISS CPU Reset 2. Ground Software Issues	1. FSW Reset 2. HOSC Command Timeout	None	1. HOSC Delay 2. Personnel Absence
Findings	S-band/Ku-band outages affect activity flow	Necessary to validate BP Table prior to HOSC upload	Additional 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 ORT 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 a significant 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 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 which the test conductors 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 uninterrupted 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 coverage 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 pose 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 lessons learned, however, is deferred to a future publication that can cover those from the operations as well.

XI. Conclusion

A comprehensive mission operations 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
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 Dexterous Manipulator
SSRMS	=	Space Station Robotic Manipulator System