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

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05 May 2014
SpaceOps 2014 Conference
Pasadena, CA

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Yesterday’s Activities
Agenda

- Introduction
- Mission Overview
- Mission System Architecture
- Operations Interfaces
- Pass Planning and Pointing
- Training and Status
INTRODUCTION
Why Laser Communication?

- Ever-growing demand for data rate and data volume in space exploration
  - Increase in science return from interplanetary missions
  - HD video streaming for public access
- OPALS is the first step towards JPL’s lasercomm goals
  - OPALS is JPL’s first space instrument to do lasercomm (JPL has built ground terminals)
  - OPALS will demonstrate capability to acquire and track the uplink beacon, and help to characterize the LEO to ground link
  - At 50 Mb/s, OPALS goals are far from state-of-the-art (>10Gb/s), but has allowed for a relatively inexpensive development

**Graph:**
-时间轴显示了从1960年到2010年的数据传输速率，显示了数据传输速率的显著增长。
- 图表中包括了 Pioneer IV, Mariner 69, Mariner 10, Galileo, Voyager, Cassini, 和 Kepler。

**Diagram:**
- 显示了地面站、天空站和空间站之间的连接关系。
- 地面站通过空中链路连接到空间站，形成了一个完整的激光通信网络。

**Legend:**
- GEO: Geostationary Earth Orbit
- LEO: Low Earth Orbit
- Mobile ground stations
- Fixed ground stations

**Source:**
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Optical Communications Facet of OPALS

- Optical link performance characterization & validation
  - High dynamic range (400-700km range, 0.5°/s to 1.2°/s slew rate over 150 second pass)
- Atmospheric turbulence characterization
  - Obtain downlink aperture-averaged fading statistics by recording received power
  - Obtain uplink scintillation statistics by recording beacon power on flight system
- Link availability studies
  - Geometry, atmospheric & environmental, day vs. night
- Pointing performance
  - OCTL Open loop tracking
  - Flight System acquisition, tracking, stability

### DOWNLINK CHARACTERISTICS

<table>
<thead>
<tr>
<th>SIGNALING</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation</td>
<td>OOK</td>
<td>-</td>
</tr>
<tr>
<td>Uncoded BER</td>
<td>1.00E-04</td>
<td>-</td>
</tr>
<tr>
<td>ECC</td>
<td>Reed-Solomon</td>
<td>-</td>
</tr>
<tr>
<td>Modulation Rate</td>
<td>30-50</td>
<td>Mb/s</td>
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</table>

<table>
<thead>
<tr>
<th>TRANSMITTER</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Downlink wavelength</td>
<td>1550</td>
<td>nm</td>
</tr>
<tr>
<td>Beam Divergence (1/e^2)</td>
<td>1.1</td>
<td>mrad</td>
</tr>
<tr>
<td>Average laser power</td>
<td>2.5</td>
<td>W</td>
</tr>
<tr>
<td>Power transmitted from FS</td>
<td>&gt;0.833</td>
<td>W</td>
</tr>
</tbody>
</table>

### POINTING

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Pointing Bias</td>
<td>150.0</td>
<td>μrad</td>
</tr>
<tr>
<td>Pointing Jitter (RMS)</td>
<td>125.0</td>
<td>μrad</td>
</tr>
</tbody>
</table>

### LINK GEOMETRY

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Max Zenith Angle</td>
<td>65</td>
<td>deg</td>
</tr>
<tr>
<td>Max Range</td>
<td>700</td>
<td>km</td>
</tr>
</tbody>
</table>

### BEACON CHARACTERISTICS

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Uplink wavelength</td>
<td>976</td>
<td>nm</td>
</tr>
<tr>
<td>Average Laser power</td>
<td>5</td>
<td>W</td>
</tr>
<tr>
<td>Beam divergence</td>
<td>1.7</td>
<td>mrad</td>
</tr>
<tr>
<td>Power transmitted from OCTL</td>
<td>1.26</td>
<td>W</td>
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</tbody>
</table>
OPALS Overview

Mission Success Criteria (MSC): Deliver enhanced-definition video from the ISS to an optical ground terminal via an optical communications link

- Downlink at ~50Mb/s

Flight System (FS)
- Gimbaled Optical Transceiver
  - Beacon Acquisition Camera
  - Downlink Transmitter
  - 2-axis Gimbal
- Sealed Container
  - Laser
  - Avionics
  - Power distribution
  - Digital I/O board
- Flight System mounted to ISS
  - Attached externally on ELC-1, EVA SITE-8

Ground System (GS)
- Ground Station - Optical Communications Telescope Laboratory (OCTL) at Table Mountain Facility, Table Mountain, CA

- Ground System – Defined as set of receiver optics and algorithms assembled at OCTL telescope to capture and reconstruct the transmitted video

OCTL

Launch: April 18, 2014
Vehicle: SpaceX Dragon CRS3
ISS Increment: 39
Operational Lifetime: 90 days
MISSION OVERVIEW
(5) Active tracking of beacon continues and video data is looped throughout the pass.

(2) The ISS rises above tree-line elevation (approx. 25 degrees)

(6) Contact lasts approximately 150 seconds

(4) Communication laser is modulated with the video data as soon as the pass starts.

(3) Flight System detects the beacon on the camera and steers the gimbal to center on it.

(7) Flight and Ground Systems commence their post-Demonstration activities at a predetermined time

(1) Telescope points to the ISS using orbital predictions (no active tracking on the ground)

- A Demonstration
  - the portion of a pass when there is bi-directional line of sight between the FS and GS
  - Lasts between 30 – 150 seconds; available ~ 1 every 2-3 days, on average
- Enabling a Demonstration
  - FS is off ~80-90% of its on-orbit life
  - On-time negotiated with ISS months in advance; refined weeks-days before
  - ~ 7 hours of on-time to prepare for, execute, and wrap-up a demonstration
Nominal Operations Flow

Pre-Demonstration Activities
- Ephemeris Processing for open-loop pointing
  - Blind Pointing Table (space-to-ground)
  - OCTL Pointing File (ground-to-space)
- FS power-on
- System configuration activities (gimbal, camera, laser)
- Sequence uploads

Demonstration
- Hands-off, sequence-driven, semi-autonomous operations

Post-Demonstration Activities
- Subsystem power-down (except avionics)
- Engineering Log downlink
- Data Processing and video display

<table>
<thead>
<tr>
<th>D-6hr to D-4hr</th>
<th>D-4hr to D-2.5hr</th>
<th>D-2.5hr to D-1hr</th>
<th>D-1hr to D+0</th>
<th>D+0 to D+3min</th>
<th>D+3min to D+3hr</th>
<th>D+3hr to D+4hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrive on console</td>
<td>FS Power On</td>
<td>Parameter Load</td>
<td>Build OCTL</td>
<td>Acquisition &amp; Track</td>
<td>Laser Off</td>
<td>Downlink Elog &amp; Images from ISS</td>
</tr>
<tr>
<td>Initialize Tools</td>
<td>Health Check</td>
<td>Critical CMDs</td>
<td>Ptg File</td>
<td>Optical Dwnlnk</td>
<td>Gimbal Stow</td>
<td>Archive data</td>
</tr>
<tr>
<td>Build BPT File</td>
<td>Uplink BPT File</td>
<td>Gimbal Cal</td>
<td>Camera On</td>
<td>FS Power Off</td>
<td>Dwnlnk Elog &amp; Images to ISS</td>
<td>Shutdown tools</td>
</tr>
<tr>
<td>Uplink BPT File to ISS</td>
<td>to OPALS</td>
<td>Laser On</td>
<td>Laser On</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Demo CMD</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Mission Timeline

<table>
<thead>
<tr>
<th>Transfer Phase: Launch to ELC-1</th>
<th>Mission Phase I: Checkout</th>
<th>Mission Phase II: Optics Calibration</th>
<th>Mission Phase III: Optical Downlink</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3-7 days</strong></td>
<td><strong>14-21 days</strong></td>
<td><strong>7-14 days</strong></td>
<td><strong>55-70 days</strong></td>
</tr>
<tr>
<td>SpX-3 Launch</td>
<td>Visual Inspection</td>
<td>• Determine misalignment between transmit and receive optics.</td>
<td></td>
</tr>
<tr>
<td>SpX-3 Trunk Extraction</td>
<td>Initial Power On</td>
<td>• While transmitting, command offsets to gimbal pointing and measure power spikes at ground receiver</td>
<td></td>
</tr>
<tr>
<td>EOTP Staging</td>
<td>File Transfer Checkout</td>
<td></td>
<td>• Transmit video via optical link:</td>
</tr>
<tr>
<td>ELC-1 EXPA-1 Install</td>
<td>Gimbal Motion &amp; Calibration Test</td>
<td>• 10 sec duration</td>
<td></td>
</tr>
<tr>
<td>Real-time Video Monitoring</td>
<td>Camera Checkout Test</td>
<td>• Enhanced-definition</td>
<td>• Decode and display within 10 minutes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Additional downlinks classified as extended mission</td>
<td></td>
</tr>
</tbody>
</table>

| Laser Checkout Test           | Open Loop Characterization Test |
| Tracking Characterization Test |
| Thermal Monitoring            |

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MISSION SYSTEM ARCHITECTURE
Mission System Design

Earth Orbit
Uplink: S-band via MSFC/JSC
Downlink: Ku-Band to MSFC

Huntsville, AL
HOSC Operations
Uplink: Commands, Blind Ptg Table, Centroid Table, Config Files, Cmd Seqs.
Downlink: H&S, BAD, Eng. Log, Camera Frames
Critical CMDs: Arm/Fire

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Flight MOS Operations
Ops Planning
Flight Product Builds
Commanding
Telemetry Display
Troubleshooting
Analysis/Reconstruction

Table Mountain, CA
Ground MOS Operations
GS Initialization
GS Configuration
Telescope Coordination
Video Retrieval

Remote Interface Tools
TReK: Telemetry Processing (UDP)
TReK: Command Generation (VPN)
OSTPV: Schedule Tracking (VPN)
EHS Web: Telemetry Query (VPN)
PIMS: File Transfer (FTP)
IVoDS: Voice Loop (VOIP)

Huntsville Operations Support Center
S-Band
Ku-Band
FTP
VOIP
VPN
UDP

Flight MOS
OCTL Pointing File
Video Data
Health/Status,
Engineering Log,
Camera Frames,
Trajectory, Attitude

Ground MOS
Decoded Video
Raw Video, Weather

OPALS Ground System
Video File
Optical Path Routing

Principal Investigator
Performance analysis

Video File
976nm Laser Beacon
1550nm Optical Downlink

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# Team Roles / Support Areas

## JPL Earth Science Mission Center
- Staffed by Flight Team
- Windows 7 workstations available loaded with HOSC multi-mission software
  - Receive payload telemetry from HOSC
  - Send payload commands to HOSC
  - Receive OCTL telescope telemetry
  - Voice loop communications
- Linux workstation available for generating pointing prediction files

## OCTL Mission Center
- Staffed by Ground Team
- Window 7 workstation with identical configuration to JPL workstations
  - Receive payload telemetry from HOSC
  - Voice loop communications
- Telescope tracking systems
- Laser safety systems
- Signal decoding systems

### Flight Team Roles

<table>
<thead>
<tr>
<th>Role</th>
<th>Responsibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activity Lead</td>
<td>Oversee coordination of operations activity; Execute Procedure</td>
</tr>
<tr>
<td>Command Engineer</td>
<td>Send real-time commands to OPALS via TReK</td>
</tr>
<tr>
<td>Telemetry Engineer</td>
<td>Monitor OPALS Health &amp; Status telemetry; Confirm payload responses to commands; Detect any anomalies</td>
</tr>
<tr>
<td>Voice Operator</td>
<td>Communicate with Ground Team / HOSC operations team; Coordinate critical commanding activities</td>
</tr>
</tbody>
</table>

### Ground Team Roles

<table>
<thead>
<tr>
<th>Role</th>
<th>Responsibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activity Lead</td>
<td>Oversee Ground System activities</td>
</tr>
<tr>
<td>Telescope Operator / Voice Operator</td>
<td>Load OCTL Pointing File from Flight Team; Monitor Telescope; Communicate with Flight Team</td>
</tr>
<tr>
<td>Optical Train Operator</td>
<td>Cognizant over optical train configuration and ground laser safety operations</td>
</tr>
</tbody>
</table>

*Note: Team roles may be combined for low intensity operations activities*
OPERATIONS INTERFACES
Cross Agency Operations Support

- HOSC: Huntsville Operations Support Center / MSFC
- MOD: Mission Operations Directorate / JSC
**HOSC Operations Interface**

**Planning**
- **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

**Real-time Ops (on console)**
- **Operations Controller (OC)**
- **Payload Operations Director (POD)**
- **Payload Rack Officer (PRO)**
- **Data Management Coordinator (DMC)**

**MCC-H Flight Director**
Coordinated Activities

• HOSC-JPL Coordinated Activities
  – PRO Uplink Window: PRO to uplink files from HOSC to the ISS
  – PRO Avionics Activation Window: PRO to power on the OPALS payload
  – 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
  – PRO Avionics Deactivation Window: PRO to power off the OPALS payload
  – PRO Downlink Window: PRO to downlink file from the ISS to HOSC

• OCTL-JPL Coordinated Activities
  – 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 beacon illumination profile
  – Delivery and load of the OCTL Pointing File
  – 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.
PASS PLANNING AND POINTING STRATEGY
**OPALS Pass Planning**

- Optical downlink opportunities are planned when bi-directional line of sight occurs
- Limited by laser safety pointing restrictions
  - AZ range → pass duration (2-3 min)
  - EL range → pass frequency (Every other day)
- Range of Motion (wrt to nadir) limited to:
  - 71° to -35° in AZ (~ along track)
  - 36° to 0° in EL (~ cross track)

- **Field of Regard (FOR):** Restricted pointing region for OPALS gimbal to prevent irradiation of any ISS structure with Class 4 laser
  - Limit switches at ends of gimbal travel cut laser power and provide only gimbal pointing feedback to payload
OPALS Pointing Architecture

- To close the optical link, accurate ground-to-space and space-to-ground tracking is required
- OCTL Pointing File (ground-to-space)
  - Open-loop telescope pointing using a propagated GPS state vector
    - GPS vector queried within 30 minutes of Demonstration Pass
  - 500 urad accuracy required to point ground receiver toward downlink signal
- OPALS Blind Pointing Table (space-to-ground)
  - **Stage 1**: Open loop coarse pointing based on state & attitude predictions in Blind Pointing Table (BPT) File
    - 1 degree of prediction error tolerated
    - Due to ISS upload timeline, must be prepared ~6 hours prior to pass
    - Need accurate time tag for BPT interpolation
  - **Stage 2**: Acquire first centroid of OCTL laser beacon
  - **Stage 3**: Closed-loop control system provides fine pointing
    - 125 urad accuracy required to transmit required power
OCTL Tracking Snapshots of ISS

- Forward Image
- Aft Image
TEAM TRAINING
Training Activities

HOSC Scenario Activity
• OPALS-scripted scenarios with HOSC interface to exercise OPALS processes and coordination

HOSC Simulation Activity
• Full ISS operations simulation with multiple payloads
• ISS/HOSC-scripted events
• Test familiarity with ISS payload ops processes
• Test scheduling and coordination under time constraints (TDRSS comm outages)

Simulation Activities

<table>
<thead>
<tr>
<th>Activity</th>
<th>ORT #1</th>
<th>ORT #2</th>
<th>ORT #3</th>
<th>ORT #4</th>
<th>ORT #5</th>
<th>ORT #6</th>
</tr>
</thead>
<tbody>
<tr>
<td>New Elements</td>
<td>Optical Downlink</td>
<td>Optical Downlink</td>
<td>Optical Downlink</td>
<td>Optical Downlink</td>
<td>Commissioning: Initial Power On</td>
<td>Optical Downlink</td>
</tr>
<tr>
<td>Off-Nominal Activities</td>
<td>OSTPV Timeline Generation</td>
<td>1. BP Table Upload to HOSC dropbox</td>
<td>Engineering Model Telemetry</td>
<td>OCTL Operations</td>
<td>New Activity</td>
<td>None</td>
</tr>
<tr>
<td>ISS CPU Reset</td>
<td>1. PRO Command Delay</td>
<td>1. ISS CPU Reset</td>
<td>1. FSW Reset Command Timeout</td>
<td>None</td>
<td>1. HOSC Delay 2. Personnel Absence</td>
<td></td>
</tr>
<tr>
<td>Findings</td>
<td>S-band/Ku-band outages</td>
<td>Necessary to validate BP Table prior to HOSC upload</td>
<td>Additional time required for telemetry verification and recording</td>
<td>GO/NO GO criteria required following a system reset</td>
<td>Additional time required for downlink command window</td>
<td>Alignment of procedure steps to command windows needed</td>
</tr>
</tbody>
</table>
The Long Road to the ISS

- 3/13: Contamination Discovered in Dragon Trunk (3/16 launch scrubbed)
- 3/26: Fire at Eastern Range Radar (3/31 Launch scrubbed)
- 4/11: Redundant MDM fails on robotic arm (Launch still GO for 4/14)
- 4/14: Helium Leak Discovered at T-1 hour (4/14 Launch scrubbed)
- 4/18: Launch
- 5/1: Robotic Arm Unable to Grasp OPALS (5/1 Dragon Extraction Delayed)
- 5/5: Robotic Extraction Complete
OPALS Status

April 18, 2014: Launch

April 20, 2014: Dragon Docks

April 22, 2014: OPALS in Dragon

May 5, 2014: Dragon Extraction
OPALS: The First of Many?

• First JPL-built space-borne lasercomm terminal
• First US lasercomm terminal on ISS
• First JPL design using forced convection (to our knowledge)
• First JPL-built unpressurized ISS payload
• First JPL cargo to fly on SpaceX
• First FRAM-based cargo to fly on SpaceX (tie with HDEV)
• First flight of SpaceX Dragon v1.1 (tie with HDEV)
• First FRAM-based cargo to undergo robotic extraction from Dragon trunk (tie with HDEV)
Acknowledgements

OPALS Project Staff (past and current)

- Matt Abrahamson, Abi Biswas, John Choi, Jessica Bowles-Martinez, Baris Erkmen, Parker Fagrelius, Santos Fregoso, Michael Gallagher, Galen Hollins, Michael Kokorowski, Joe Kovalik, Phillip Marks, Bogdan Oaida, Jordan Padams, Oleg Sindiy, Suzana Sburlan, Dan Turner, Mike Underhill, Marcus Wilkerson, Lauren White, Thor Wilson, Rob Witooff, William Wu, Danny Zayas

HOSC and MOD support staff

Past and Current OPALS Interns
BACKUP
Robotic Approach
Robotic Approach Inside Dragon
Trunk Extraction
Trunk Hover
Trunk Departure
SPDM Reconfiguration
EOTP Mount Preparation
EOTP Mount Preparation
EOTP Mount Preparation
EOTP Mating
EOTP Mate
Robotic Arm Stow
Ground-to-Space Performance

Requirement: \( \pm 225 \mu \text{rad} \)

\( t, r, v \)

Propagation

\( r, v, q \)

Typical 30 min prediction: \(< \pm 100 \mu \text{rad} \)

\( t, r, v \)

Broadcast Playback

- Retrieved from broadcast

GPS State Acquired from broadcast

ISS Position Differences

ISS Azimuth Differences

ISS Velocity Differences

ISS Elevation Differences

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Space-to-Ground Performance

- BPT is dependent on both trajectory and attitude predictions
  - Six hour trajectory prediction performance < 1.0 km (~0.14° at 400 km altitude)
  - LVLH-relative steady-state attitude oscillates once per orbit rev with half amplitude of approximately 0.5°

**Attitude model**: Extrapolated attitude based on orbit period

**Trajectory model**: JPL-propagated ephemeris

- 6 hr prediction performance < 1.0 km

- ±0.5°
- ±0.3°
- ±0.2°