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

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Yesterday's Activities

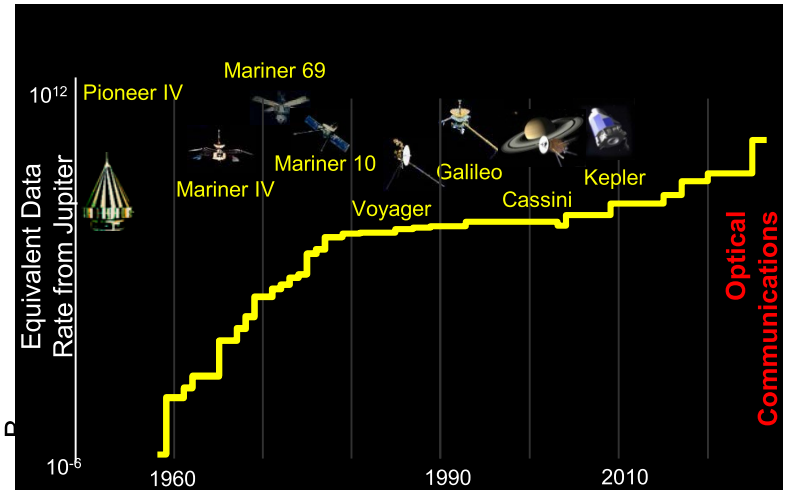
Agenda

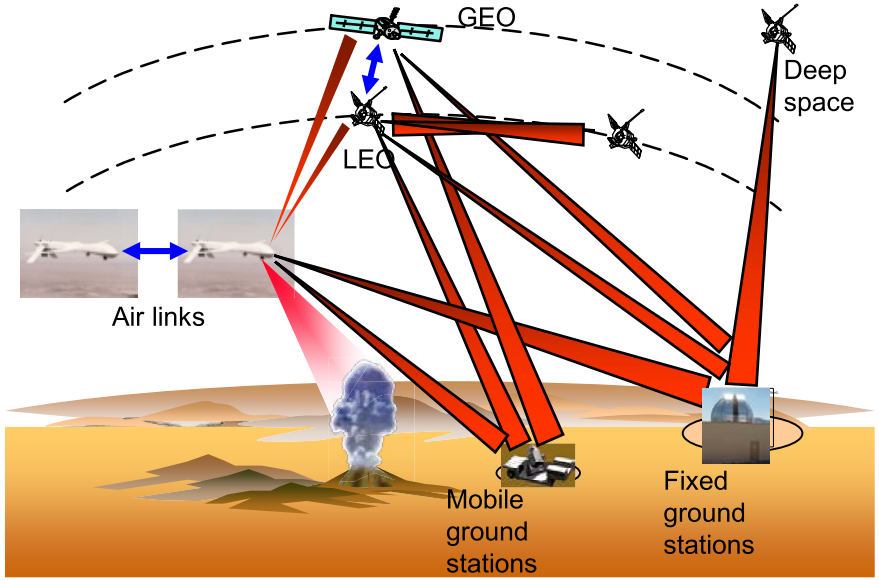
- Introduction
- Mission Overview
- Mission System Architecture
- Operations Interfaces
- Pass Planning and Pointing
- Training and Status

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



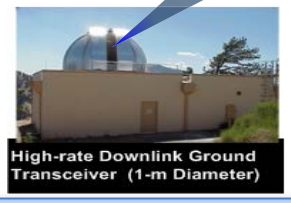


Optical Communications Facet of OPALS

- 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		
SIGNALING		
Modulation	OOK	-
Uncoded BER	1.00E-04	-
ECC	Reed-Solomon	-
Modulation Rate	30-50	Mb/s
TRANSMITTER		
Downlink wavelength	1550	nm
Beam Divergence (1/e^2)	1.1	mrad
Average laser power	2.5	W
Power transmitted from FS	>0.833	W
POINTING		
Pointing Bias	150.0	µrad
Pointing Jitter (RMS)	125.0	µrad
LINK GEOMETRY		
Max Zenith Angle	65	deg
Max Range	700	km

Optical Communications Telescope Laboratory (OCTL)



BEACON CHARACTERISTICS		
Uplink wavelength	976	nm
Average Laser power	5	W
Beam divergence	1.7	mrad
Power transmitted from OCTL	1.26	W

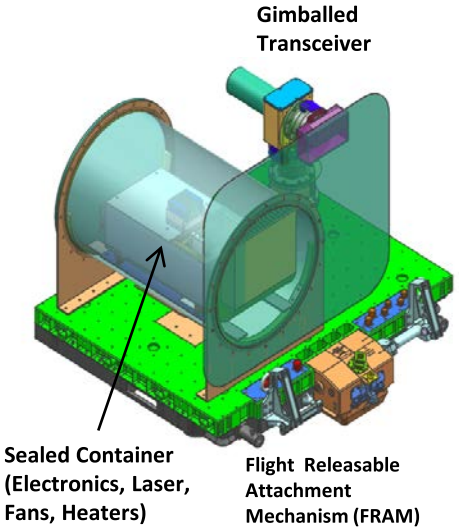
OPALS Overview

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)

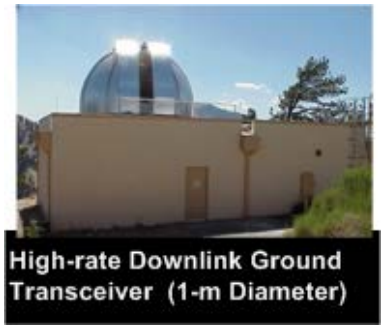
- Gimbaled Optical Tranceiver
  - Beacon Acquisition Camera
  - Downlink Transmitter
  - 2-axis Gimbal
- Sealed Container
  - Laser
  - Avionics
  - Power distribution
  - Digital I/O board
- Flight System mounted to ISS
  - Attached externally on ELC-1, EVA SITE-8



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



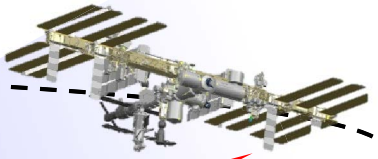
Launch: April 18, 2014
Vehicle: SpaceX Dragon CRS3
ISS Increment: 39
Operational Lifetime: 90 days

MISSION OVERVIEW

Operations Concept

(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)



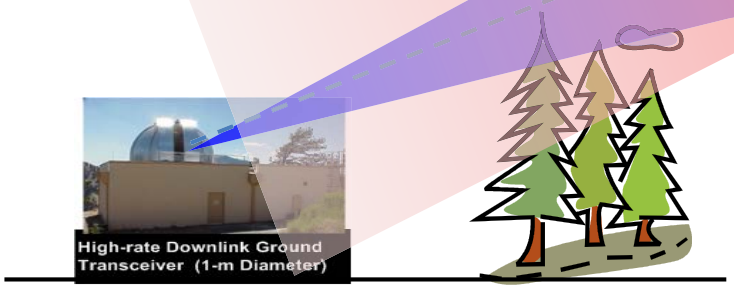
(6) Contact lasts approximately 150 seconds

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

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

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

(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

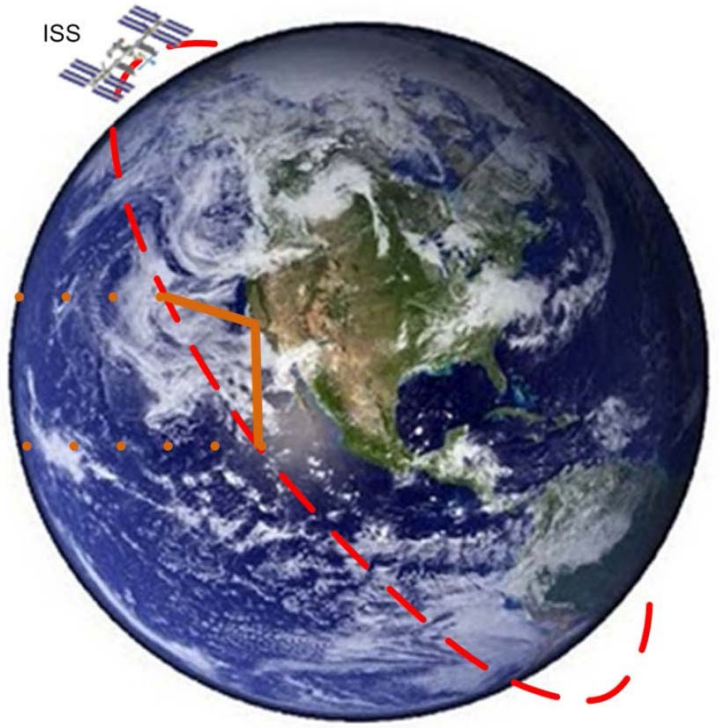
- Ephemeris Processing for open-loop pointing
  - Blind Pointing Table (space-to-ground)
  - OCTL Pointing File (ground-to-space)
- FS power-on
- System configuration activities (gimbal, camera, laser)
- Sequence uploads

Demonstration

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

Post-Demonstration Activities

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



D-6hr to D-4hr
- Arrive on console
- Initialize Tools
- Build BPT File
- Uplink BPT File to ISS

D-4hr to D-2.5hr
- **FS Power On**
- Health Check
- Uplink BPT File to OPALS

D-2.5hr to D-1hr
- Parameter Load
- Critical CMDs
- Gimbal Cal

D-1hr to D+0
- Build OCTL Ptg File
- Camera On
- Laser On
- Demo CMD

D+0 to D+3min
- Acquisition & Track
- Optical Dwnlnk

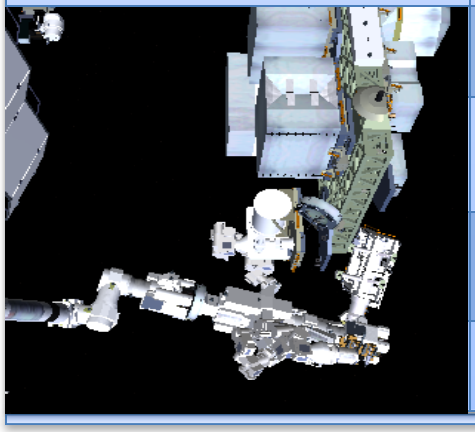
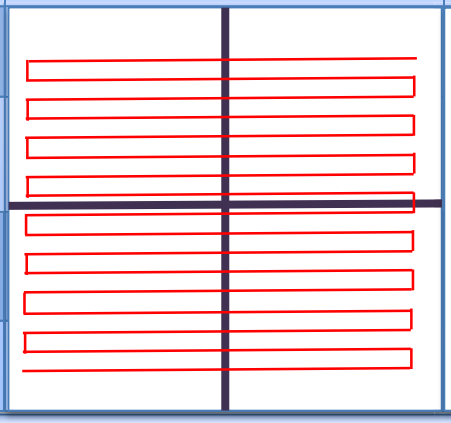
D+3min to D+3hr
- Laser Off
- Gimbal Stow
- Dwnlk Elog & Images to ISS
- **FS Power Off**

D+3hr to D+4hr
- Downlink Elog & Images from ISS to HOSC
- Archive data
- Shutdown tools

Mission Timeline

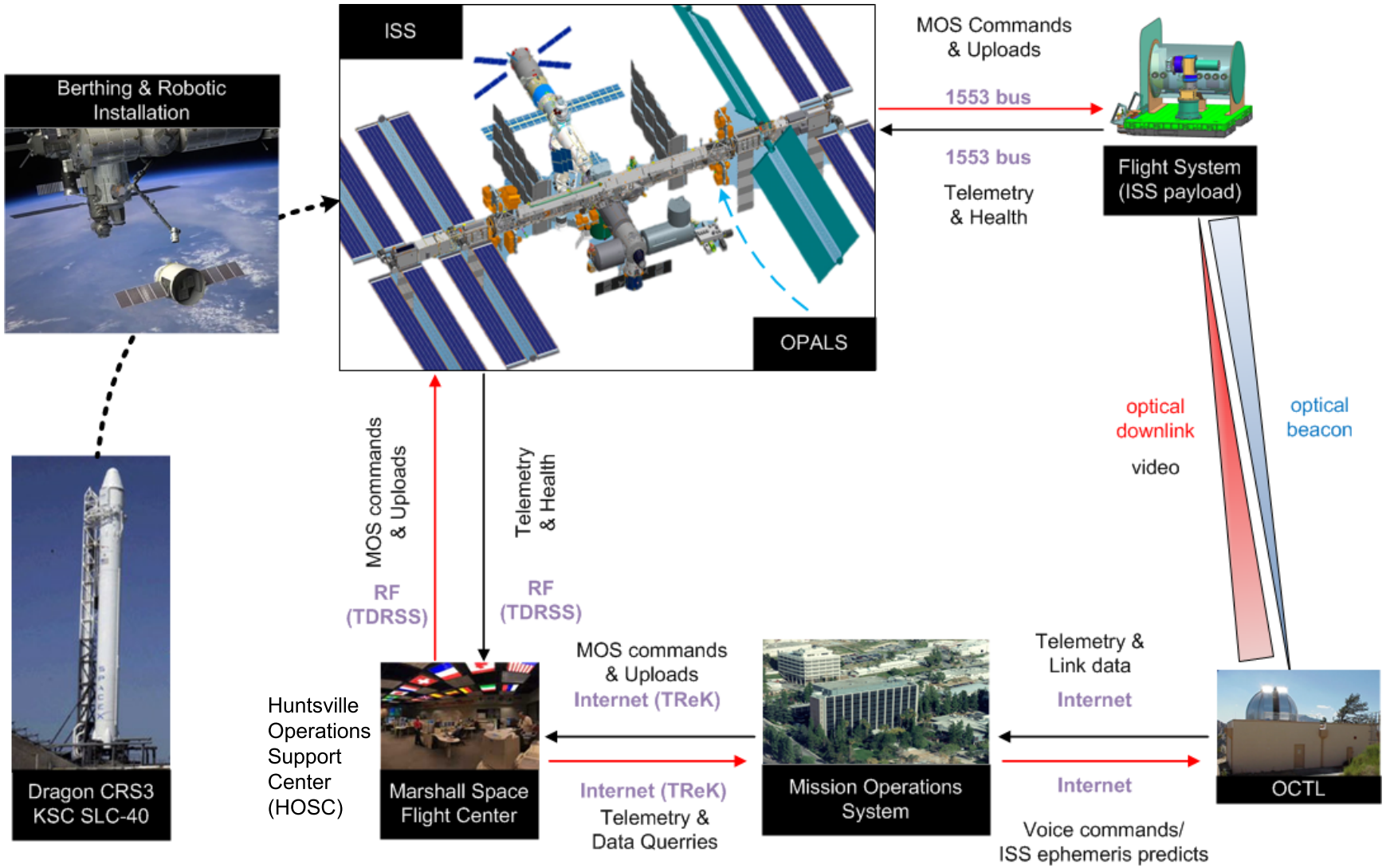
Transfer Phase: Launch to ELC-1	Mission Phase I: Checkout	Mission Phase II: Optics Calibration	Mission Phase III: Optical Downlink
3-7 days	**14-21 days**	**7-14 days**	**55-70 days**

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

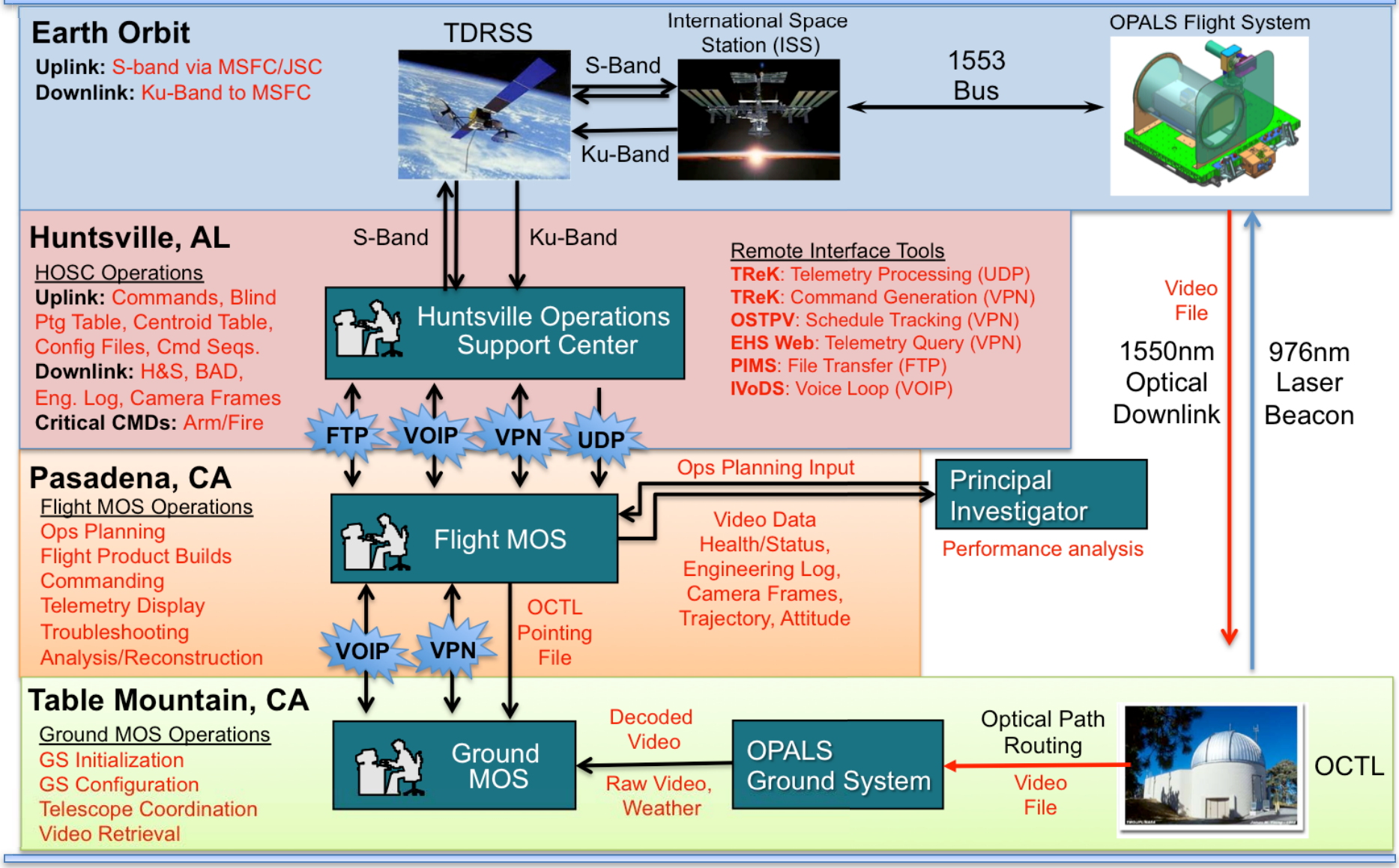
SpX-3 Trunk Extraction	Initial Power On		
EOTP Staging	File Transfer Checkout		
ELC-1 EXPA-1 Install	Gimbal Motion & Calibration Test		
Real-time Video Monitoring	Camera Checkout Test		
	Laser Checkout Test		
	Open Loop Characterization Test		
	Tracking Characterization Test		
	Thermal Monitoring		

MISSION SYSTEM ARCHITECTURE

OPALS Communications Architecture



Mission System Design



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

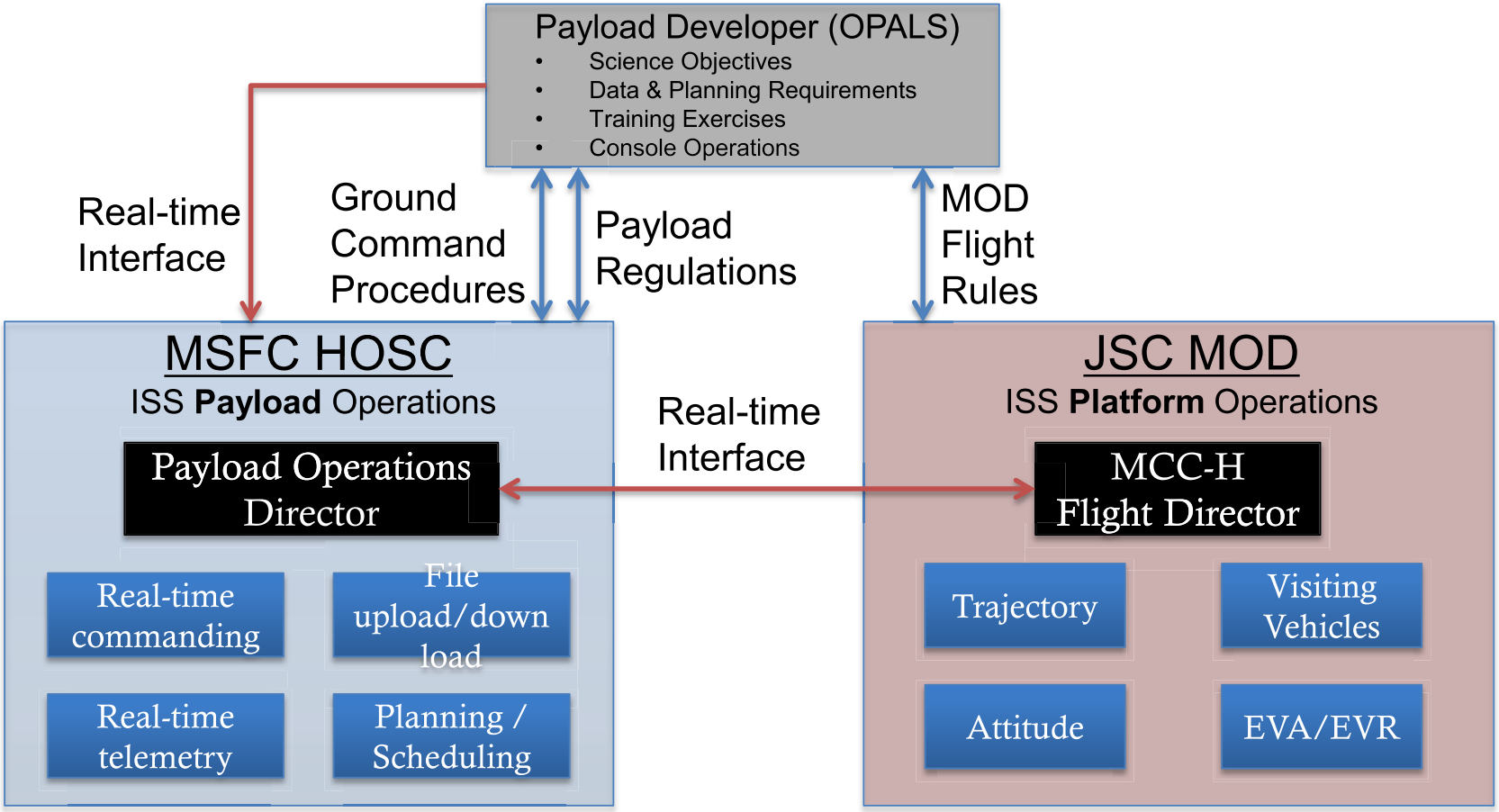
Flight Team Roles	
Activity Lead	Oversee coordination of operations activity; Execute Procedure
Command Engineer	Send real-time commands to OPALS via TReK
Telemetry Engineer	Monitor OPALS Health & Status telemetry; Confirm payload responses to commands; Detect any anomalies
Voice Operator	Communicate with Ground Team / HOSC operations team; Coordinate critical commanding activities
Ground Team Roles	
Activity Lead	Oversee Ground System activities
Telescope Operator / Voice Operator	Load OCTL Pointing File from Flight Team; Monitor Telescope; Communicate with Flight Team
Optical Train Operator	Cognizant over optical train configuration and ground laser safety operations

Note: Team roles may be combined for low intensity operations activities

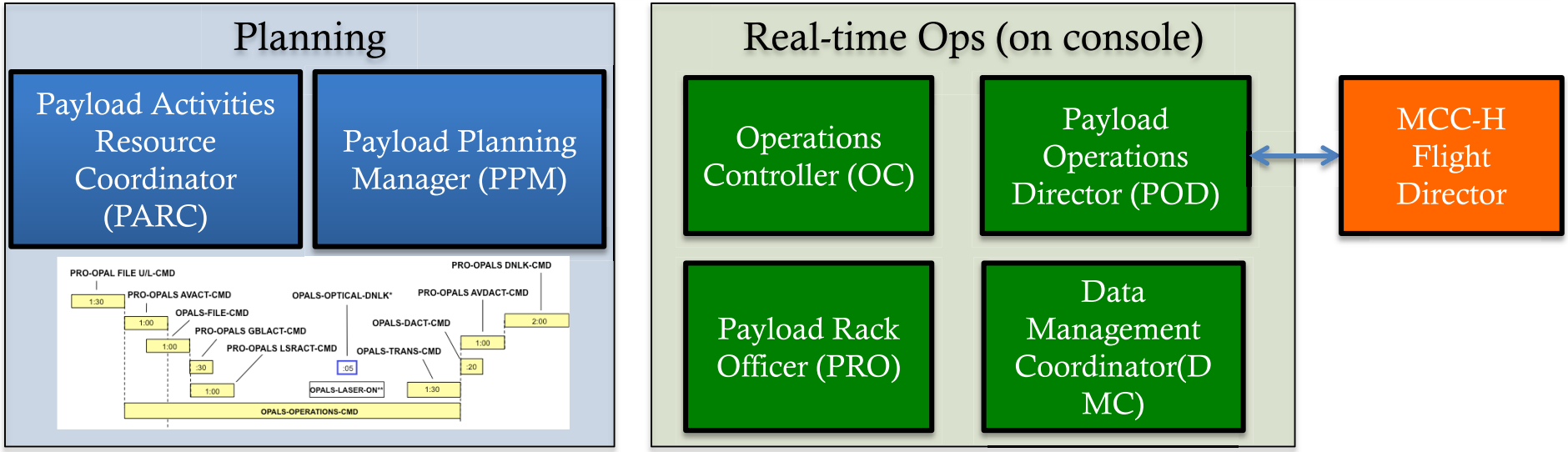
OPERATIONS INTERFACES

Cross Agency Operations Support

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



HOSC Operations Interface



- **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

Coordinated Activities

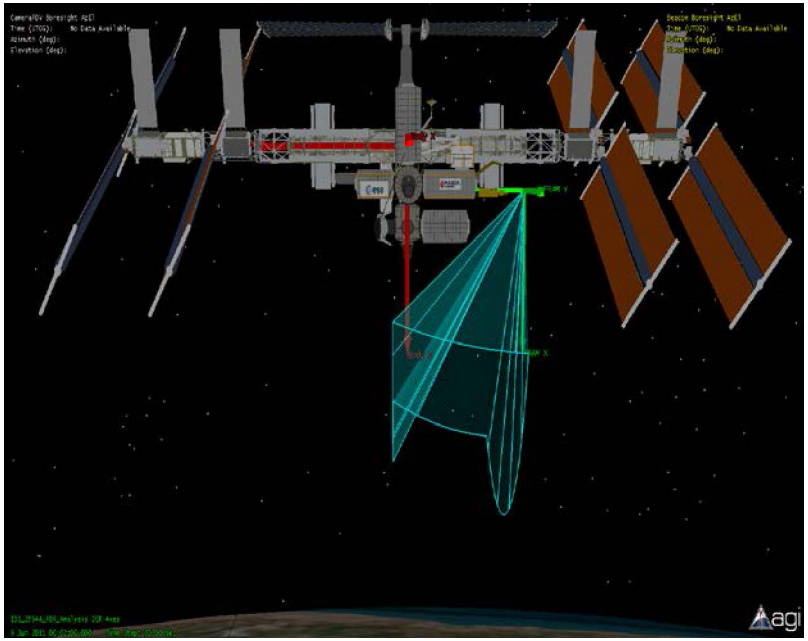
- HOSC-JPL Coordinated Activities
  - PRO Uplink Window: PRO to uplink files from HOSC to the ISS
  - PRO Avionics Activation Window: PRO to power on the OPALS payload
  - Gimbal Activation Window: PRO to remove safety restraints on the OPALS gimbal
  - PRO Laser Activation Window: PRO to remove safety 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.

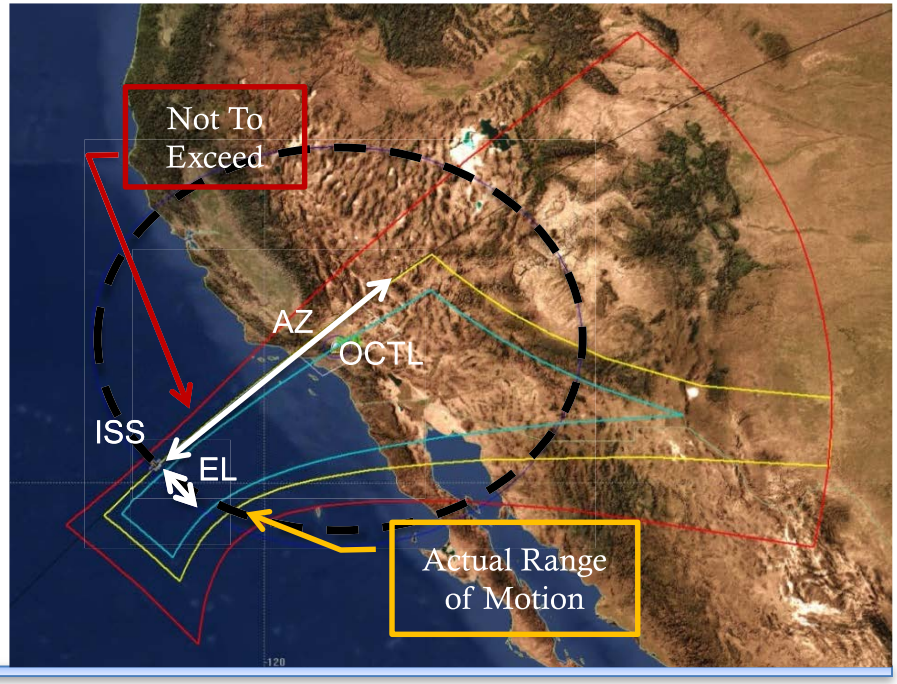
PASS PLANNING AND POINTING STRATEGY

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)

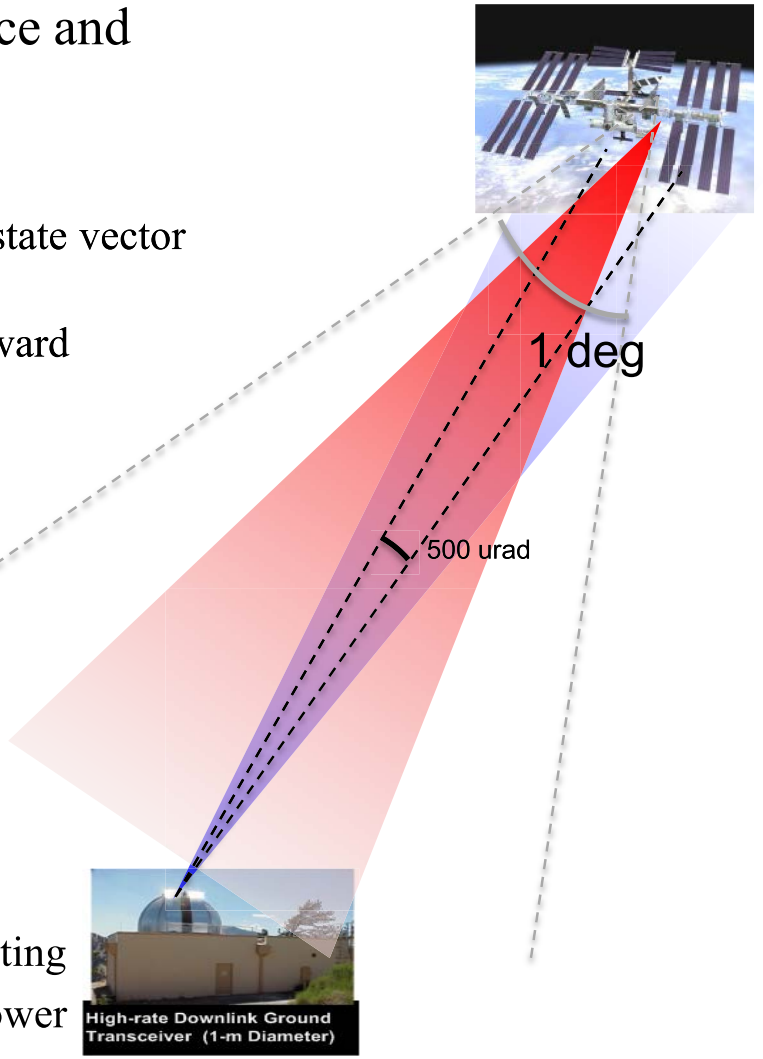
- **Field of Regard (FOR)**: Restricted pointing region for OPALS gimbal to prevent irradiation of any ISS structure with Class 4 laser
  - Limit switches at ends of gimbal travel cut laser power and provide only gimbal pointing feedback to payload





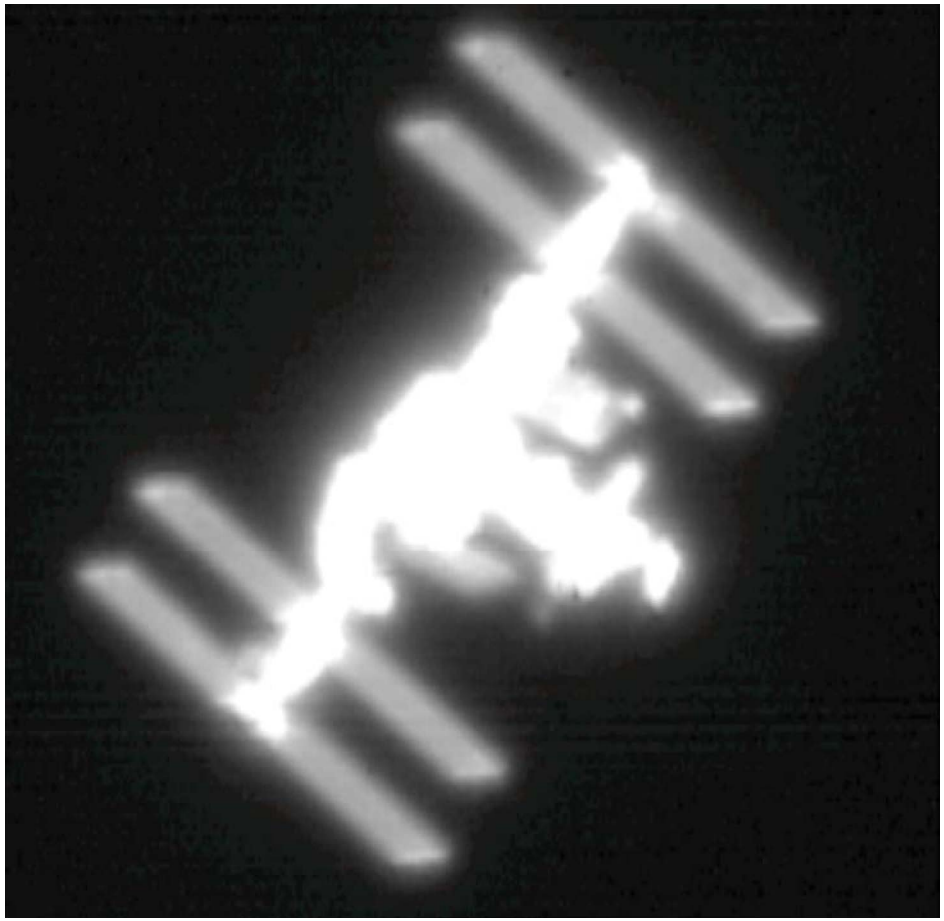
OPALS Pointing Architecture

- 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

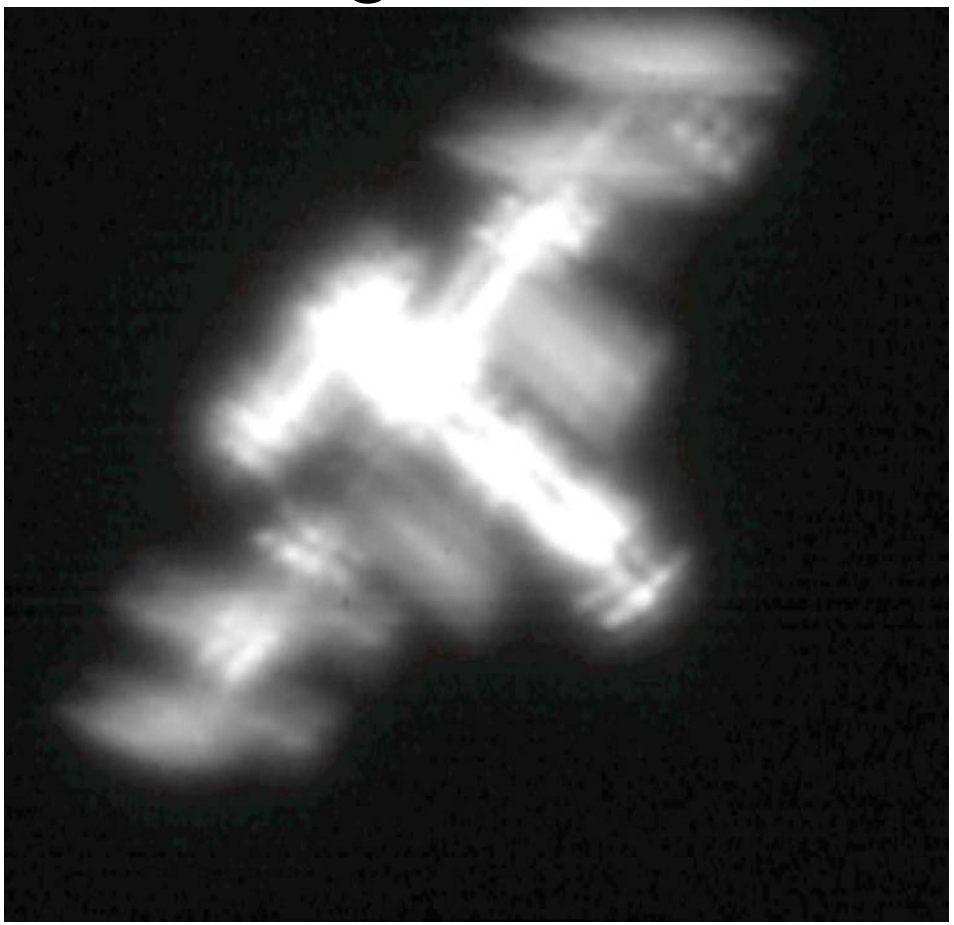


OCTL Tracking Snapshots of ISS

- 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

	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

STATUS

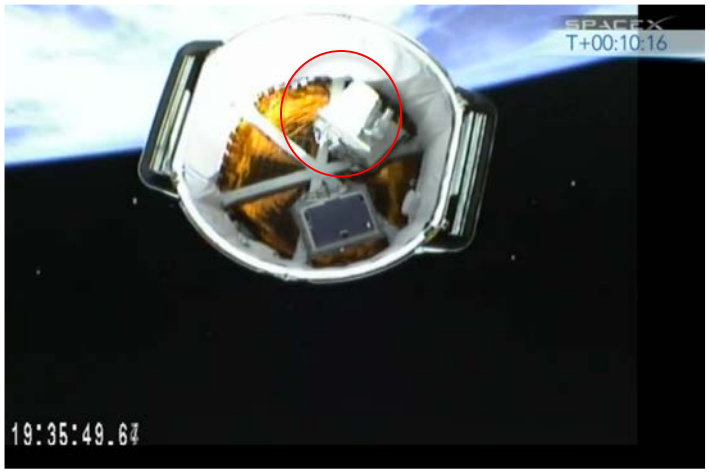
The Long Road to the ISS

- 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

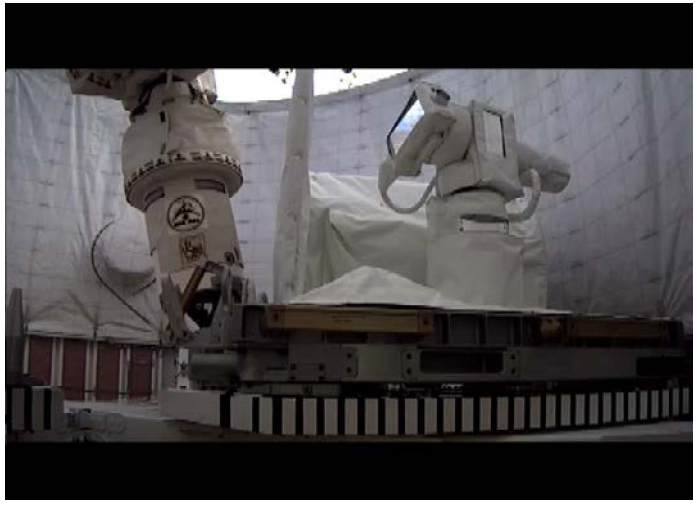
OPALS at Second Stage Sep



April 22, 2014: OPALS in Dragon

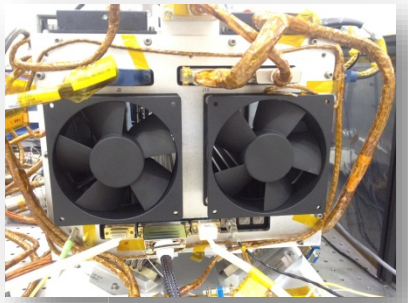
April 20, 2014: Dragon Docks

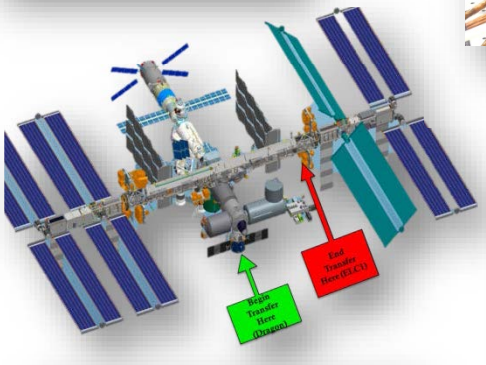
May 5, 2014: Dragon Extraction

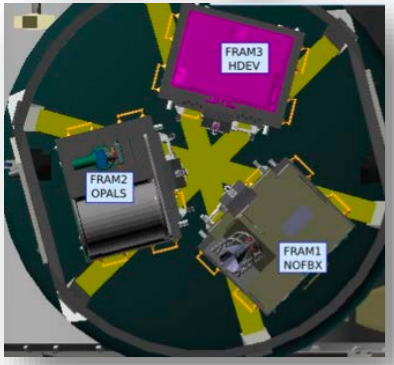


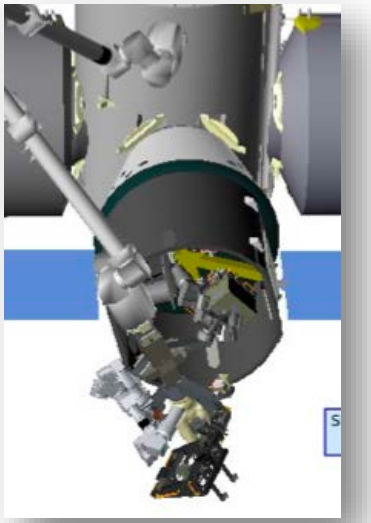
OPALS: The First of Many?

- 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)

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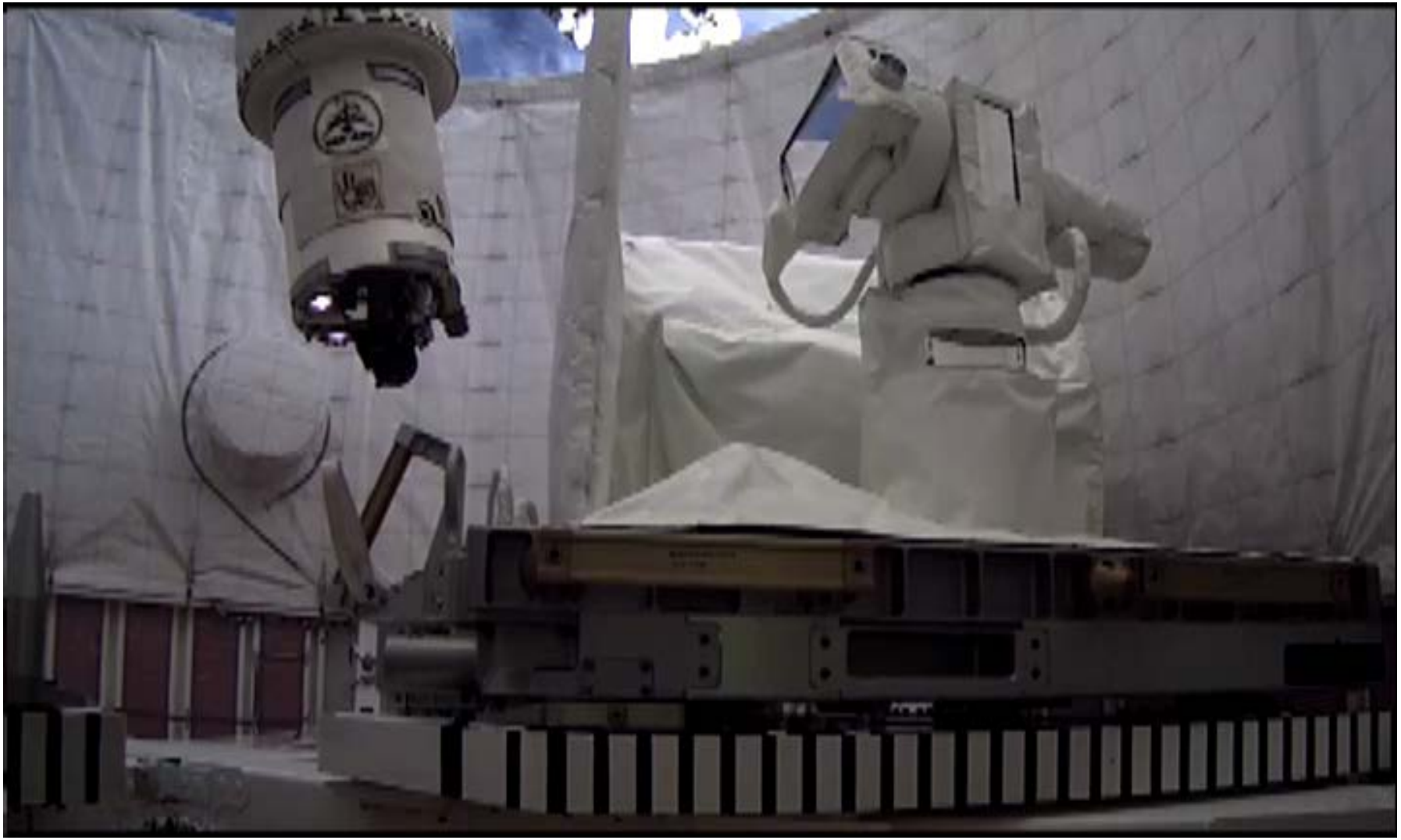
HOSC and MOD support staff

Past and Current OPALS Interns

BACKUP

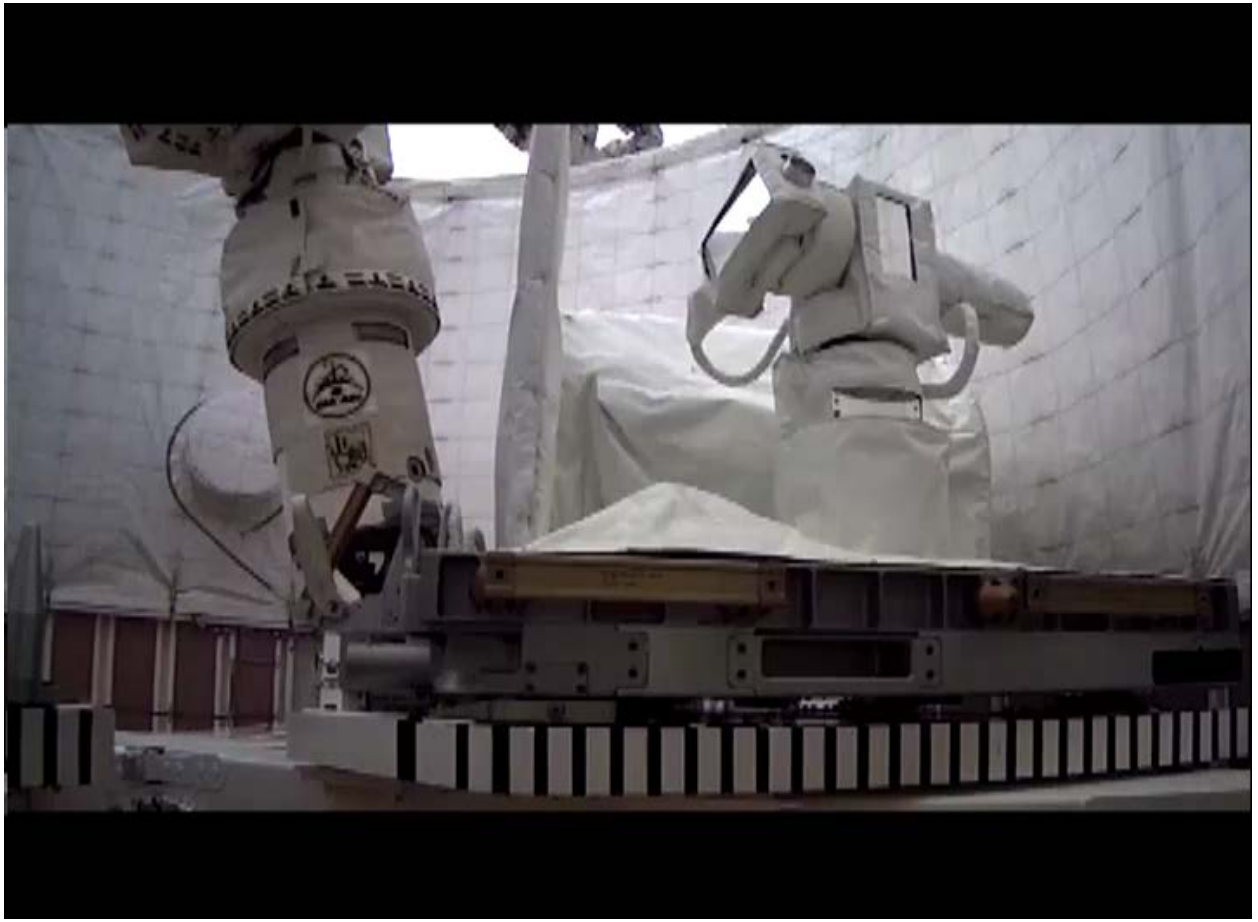
Robotic Approach

Robotic Approach Inside Dragon

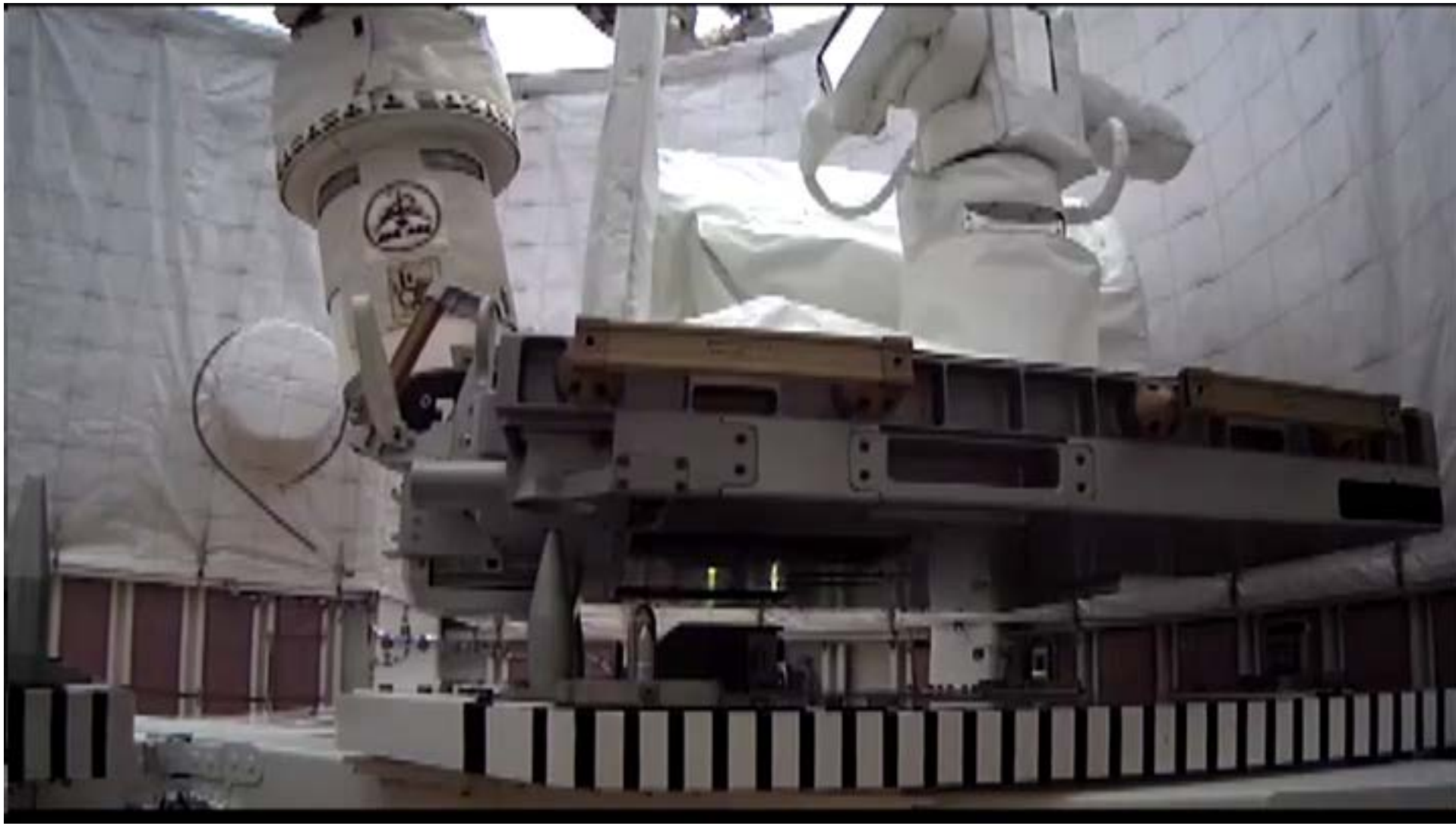


OPALS Grapple

OPALS Grapple

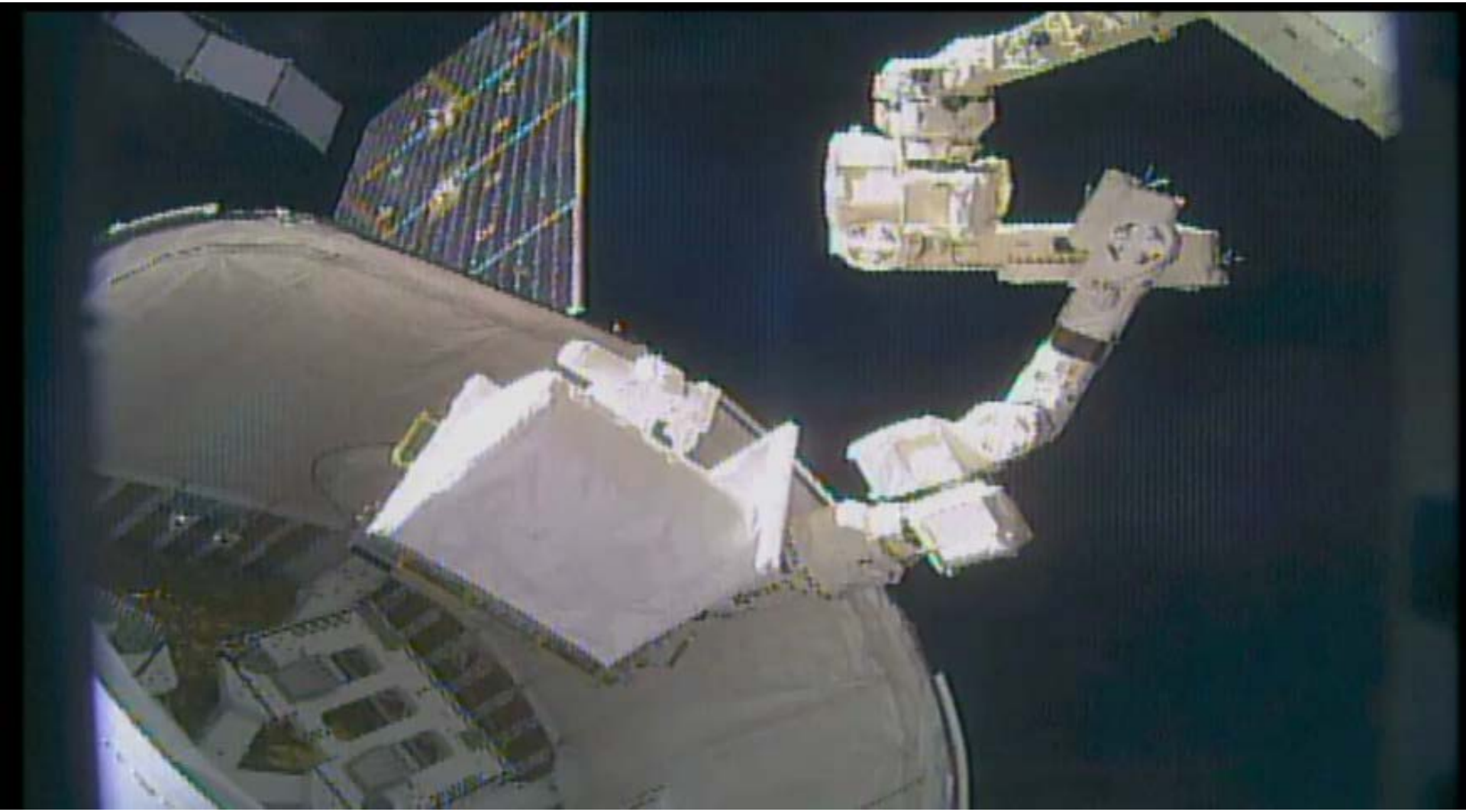


FRAM Demate



Trunk Extraction

Trunk Hover



Trunk Departure

SPDM Reconfiguration

EOTP Mount Preparation

EOTP Mount Preparation

EOTP Mount Preparation

EOTP Mount Preparation

EOTP Mount Preparation

EOTP Mating

EOTP Mate

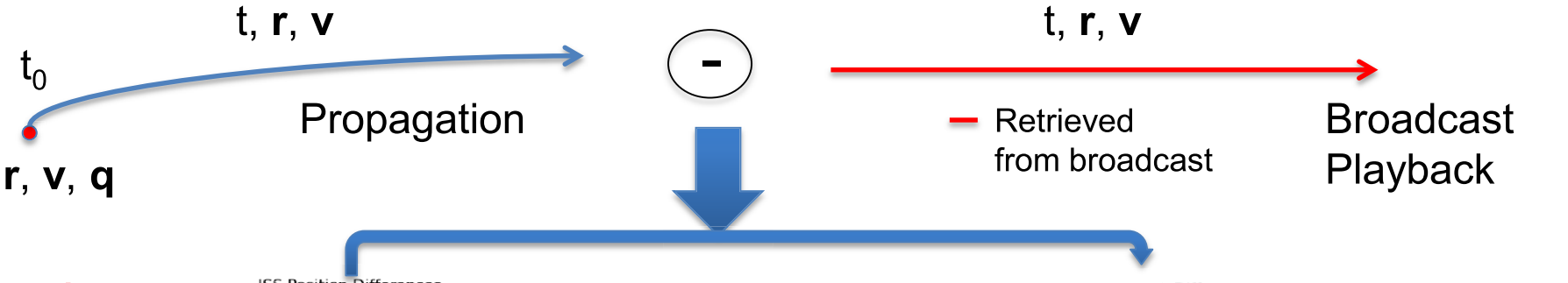
Robotic Arm Stow

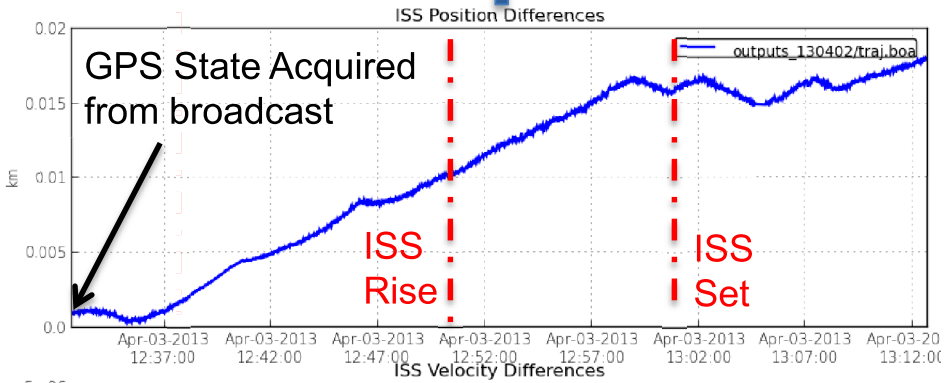
Robotic Arm Stow

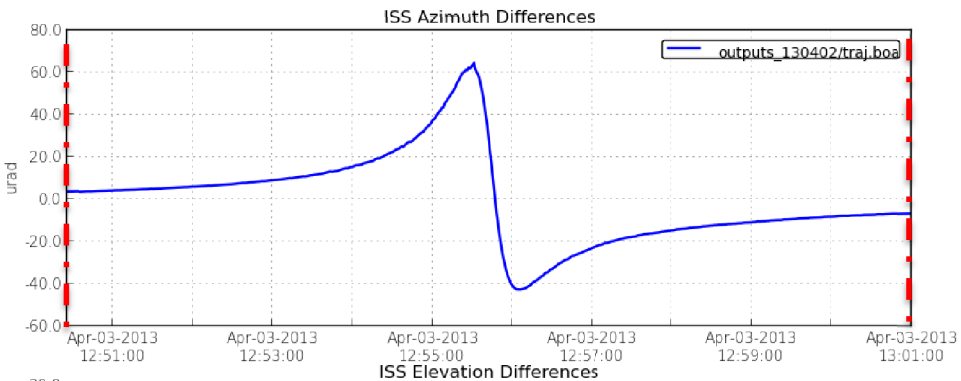
Ground-to-Space Performance

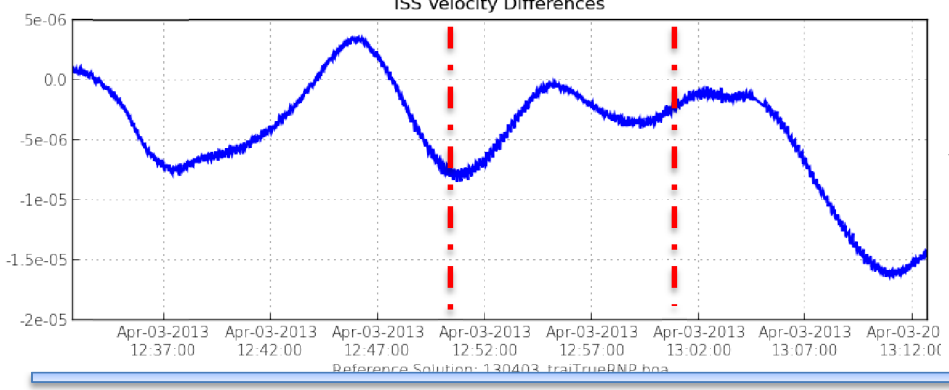
Requirement: ±225 μrad

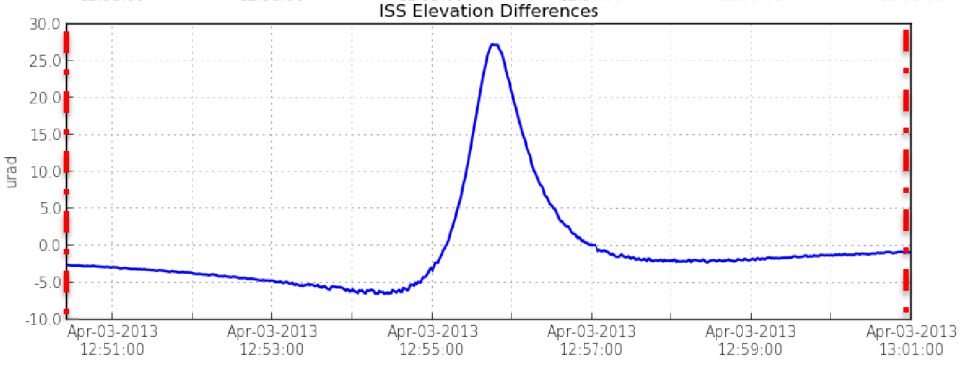
Typical 30 min prediction : < ±100μrad







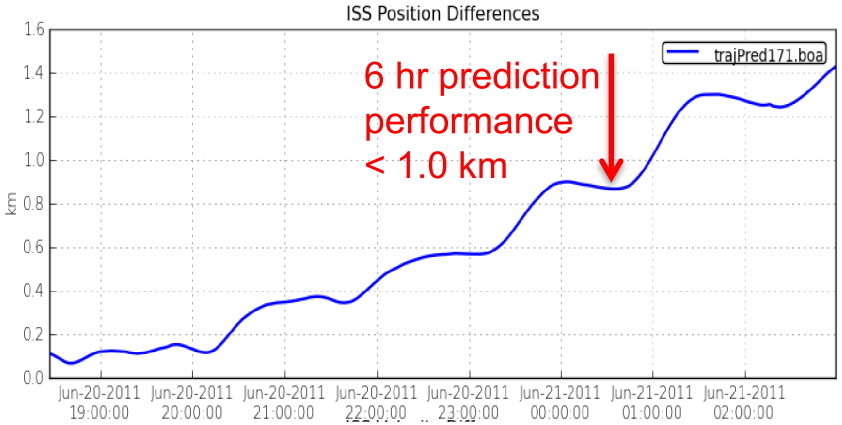




Space-to-Ground Performance

- 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˚

Trajectory model: JPL-propagated ephemeris



Attitude model: Extrapolated attitude based on orbit period