Beam Me Down, Scotty!

The cradle-to-grave story of JPL's first lasercomm system

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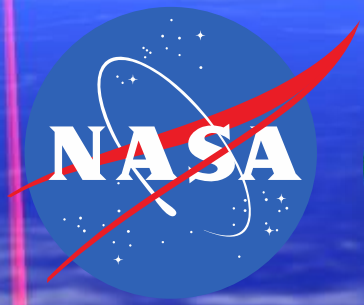
(With many contributions from others)

8 December 2017
University of Michigan
Aero 285 Seminar



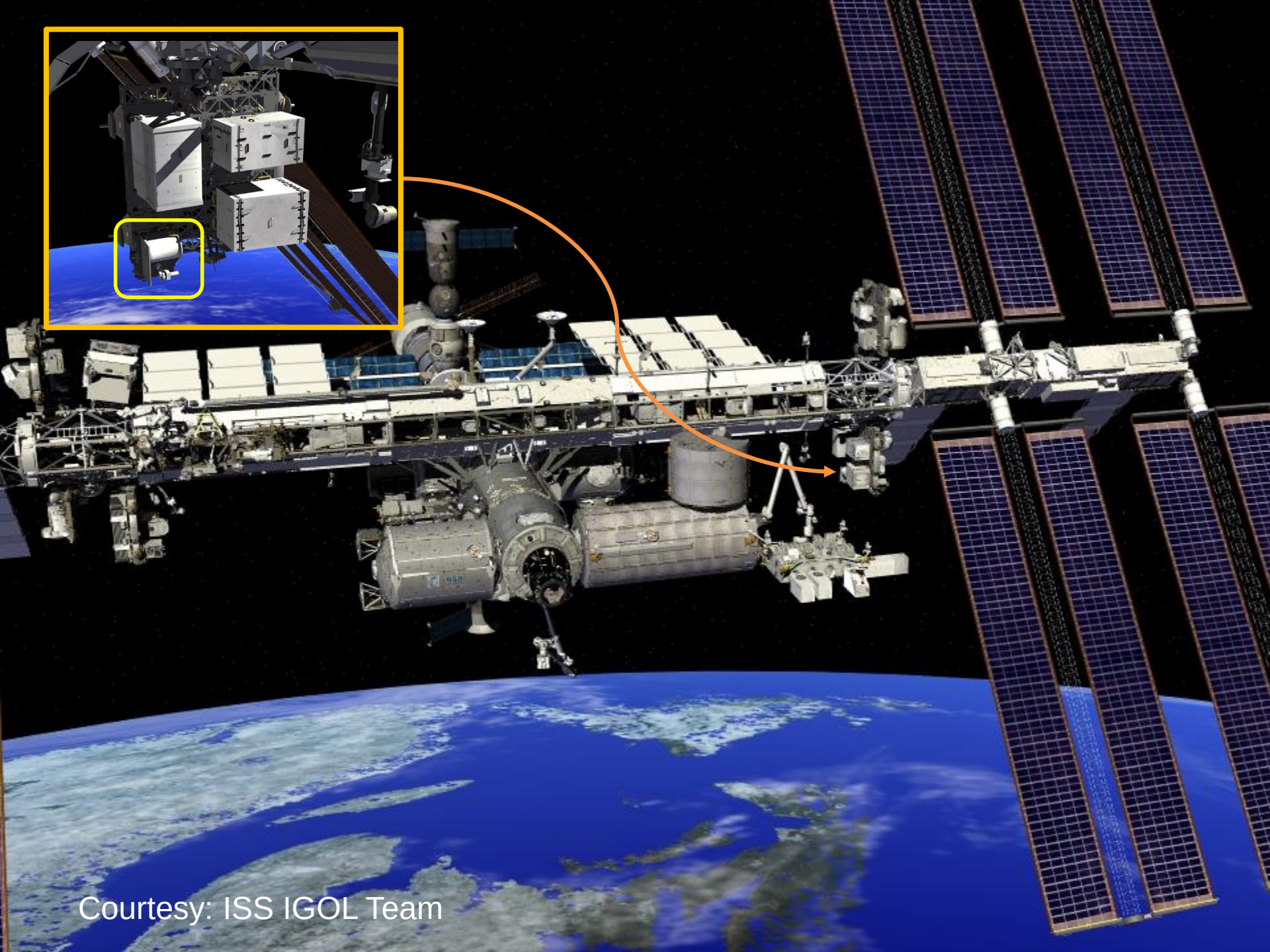
OPALS on ELC 1 – FRAM 8

May 2014 – March 2017

Courtesy of NASA JSC: https://io.jsc.nasa.gov/

OPALS in the Trunk of SpaceX CRS3

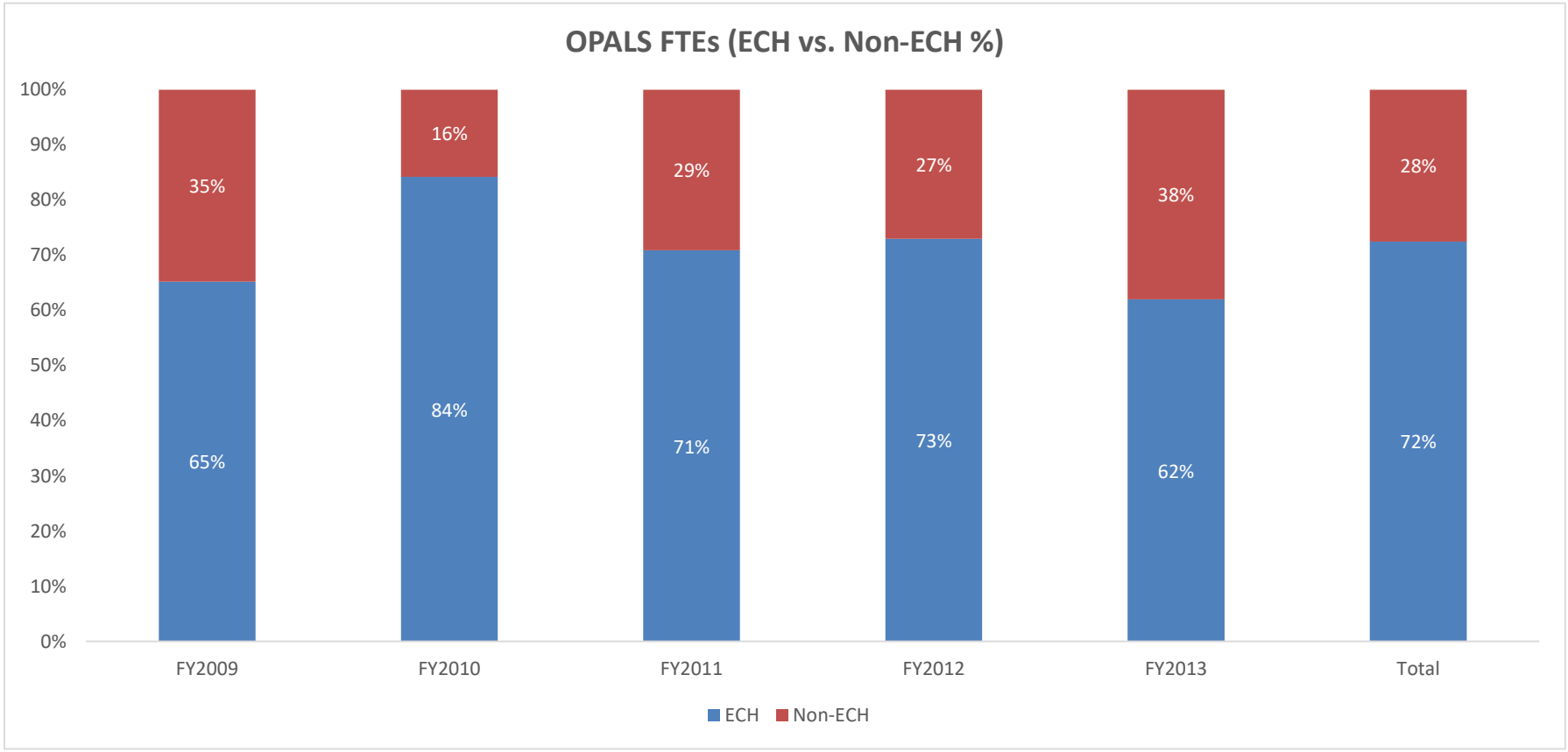
Courtesy of SpaceX


Courtesy: ISS IGOL Team

DEVELOPMENT

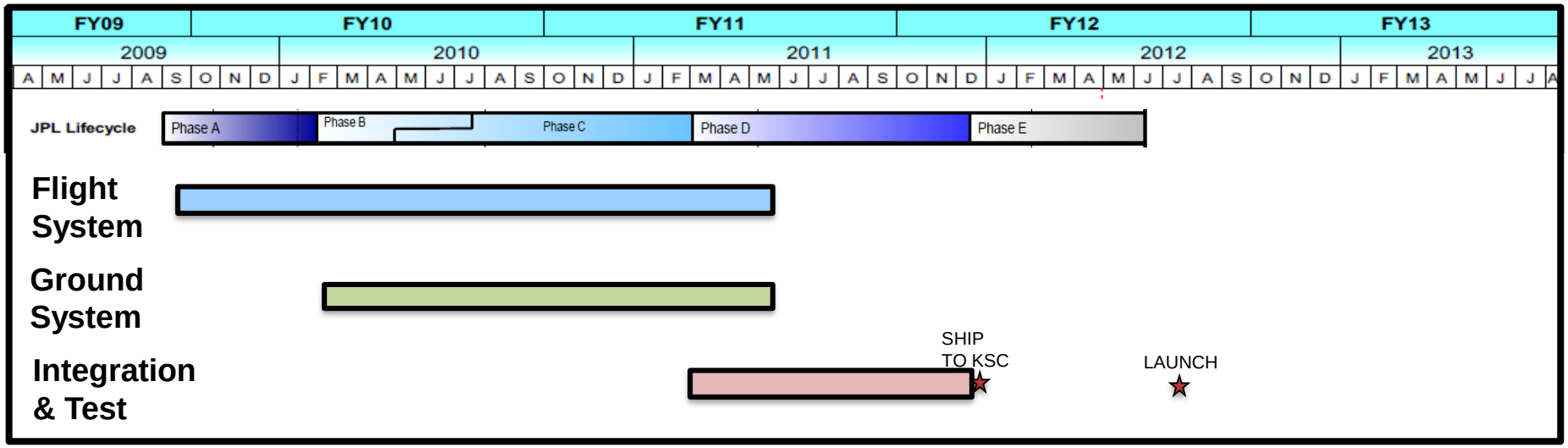
The Premise

- Build a spaceborne optical comm terminal to transmit a DVD-quality video to the ground
- Project membership must be primarily Early Career Hires (ECHs)
  - A total of 34 ECHs participated over the project lifecycle

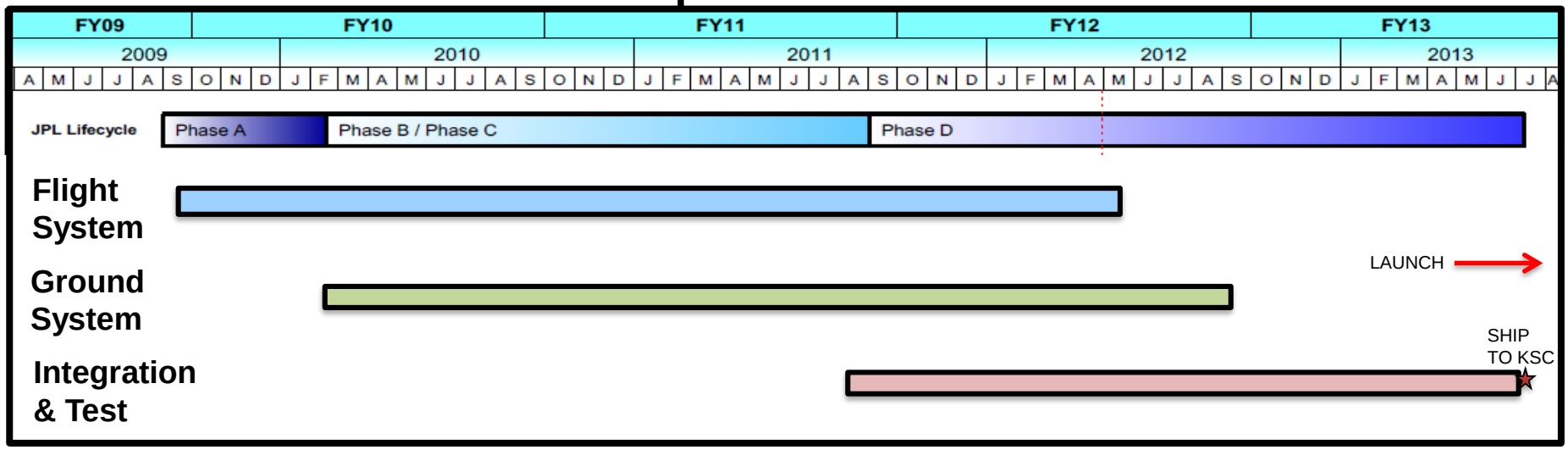


Pre-Shipment Schedule

Schedule at SRR



As-Implemented Schedule



Capability (d)evolution 2009-2012

Capability descoped due to major cost/schedule risk

Capability descoped due to major cost/schedule risk

Replan for additional time

Launch slip

Descope of V&V and replan for additional time

August, 2009 (MCR)

- 2 ground systems
- Bi-directional link
- Emulation of Mars-like link with rover ground system
- Launch September '11, Total cost $7M

October, 2009 (Delta-MCR)

- 1 ground system - No Mars rover-like ground system
- Downlink video generated by astronauts
- Launch summer '12, Total cost $7M

June, 2010 (DR1)

- Descope of all Technology (L1.5) requirements
- Specified Mission Success Criteria to be a downlink of a 10second video
- No laser uplink
- Video pre-encoded and saved on flight system prior to launch rather than generated by astronauts
- Launch summer '12, Total cost $7M

April, 2011 (Technical Status Review)

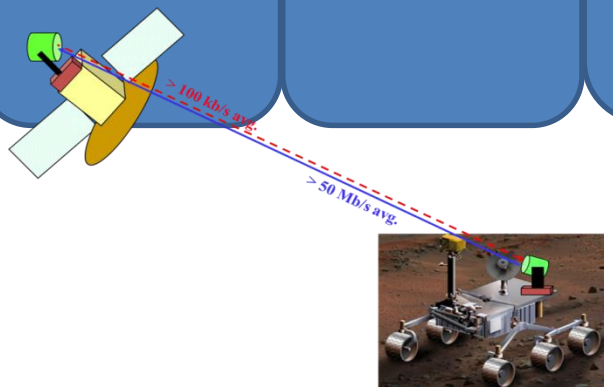
- Extended schedule due to major schedule slips
- Changed from HTV launch vehicle to SpaceX
- Launch fall '12, Total cost $9M

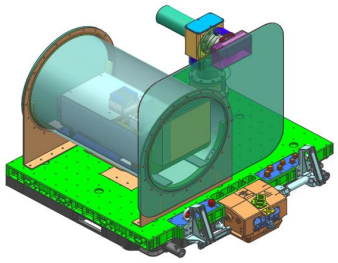
August, 2011 (DR2)

- SpaceX launch slip
- Assessed that we couldn't meet schedule and budget constraints
- Significant descope of V&V
- Launch winter '13, Total cost $9M

May 2012 (TRR)

- SpaceX launch slip allowing extension of schedule
- Subsystem delivery slips predicate need for replan
- Launch summer '13, Total cost $10M





Rock Meets Hard Place

The OPALS plan encountered challenges because:

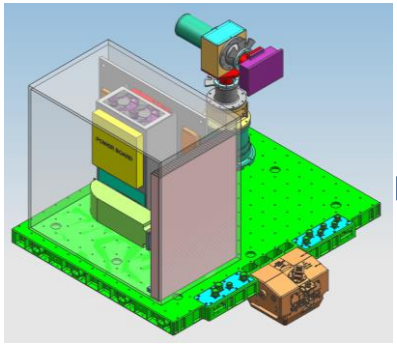
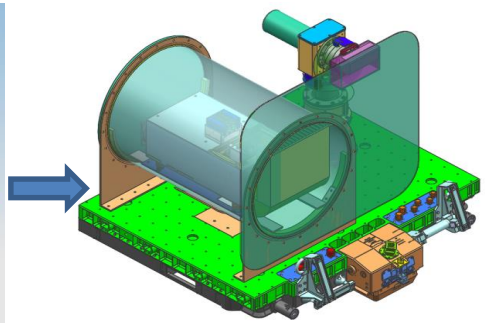
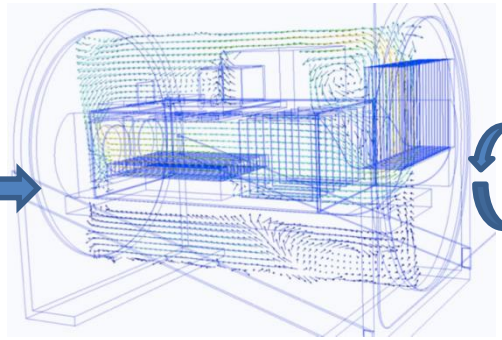
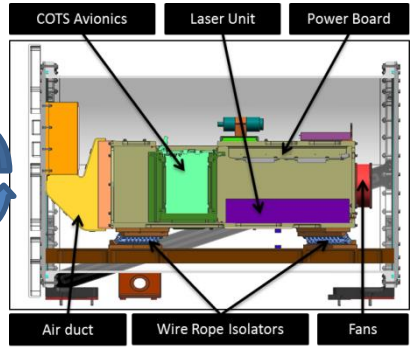
- Technical complexity of project much greater than initially expected
  - Optical components required precise mounting & alignment
  - ISS interface required extensive V&V and review board approvals
- Assumed Class D implementation could be better leveraged
  - Institution was not yet seasoned with Class D processes
- Training/learning curve not figured into plan
  - 100% efficiency assumed due to inexperience of ECH planning
- ISS safety compliance required more work than expected
- Lack of consensus among mentors on the implementation plan
- Project scope and resources were mismatched
  - A ~$10M optical communications terminal is unprecedented
  - Original plan assumed greater heritage from aircraft-to-ground R&TD

Forced Into Hard Choices

- Decisions primarily driven by cost
  - Accepted higher mission risk of latent failure to reduce implementation cost
  - ***Turned an ambitious optical comm experiment into a non-optical comm engineering challenge.***

- Severe cost cap led to poor choice of avionics architecture
  - COTS parts → forced convection cooling → significant structural and thermal design complications

- Funding profile in FY '10 forced project to split development
  - DR1 & DR2 vs typical PDR and CDR
    → difficulty obtaining institutional buy in
  - Procure gimbal early before requirements fully developed
    → Oversized gimbal
  - Delay FSW start until after DR1
    → Two years later put FSW on critical path → delayed start of system I&T

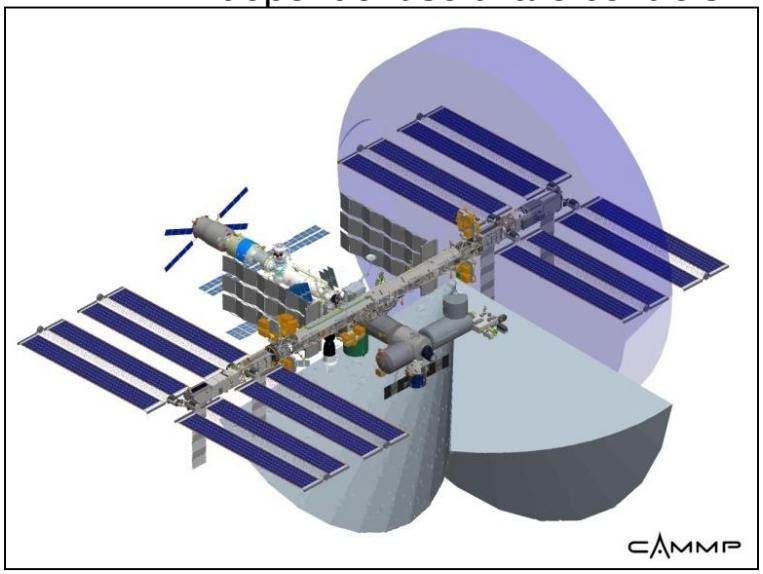





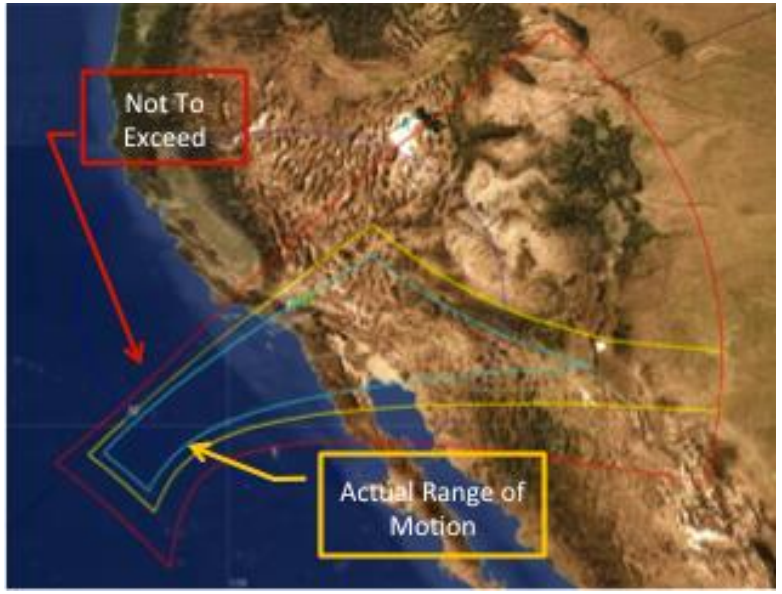
ISS Interface Challenges

- Class D Payload with Class A interface
  - → ~450 applicable ISS requirements composed >50% of OPALS requirements
  - → 37% of requirements revised by the start of OPALS I&T
  - → Two-fault tolerant design required for hazardous laser
  - Mechanical Hard Stops
  - Electrical Limit Switches
  - Independent software controls

- Range of Motion (wrt to nadir) limited to:
  - 75˚ to -35˚ in AZ (~ along track)
  - 40˚ to -1˚ in EL (~ cross track)

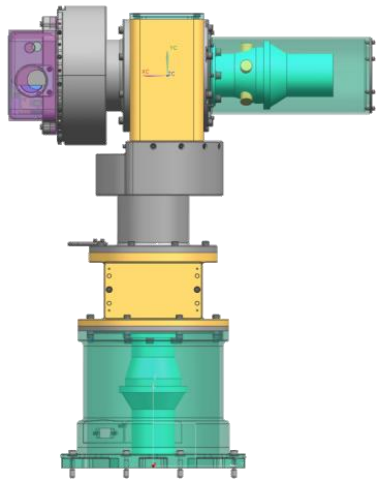
- Example of how mission safety trumps mission success
  - AZ range → pass duration
  - EL range → pass frequency





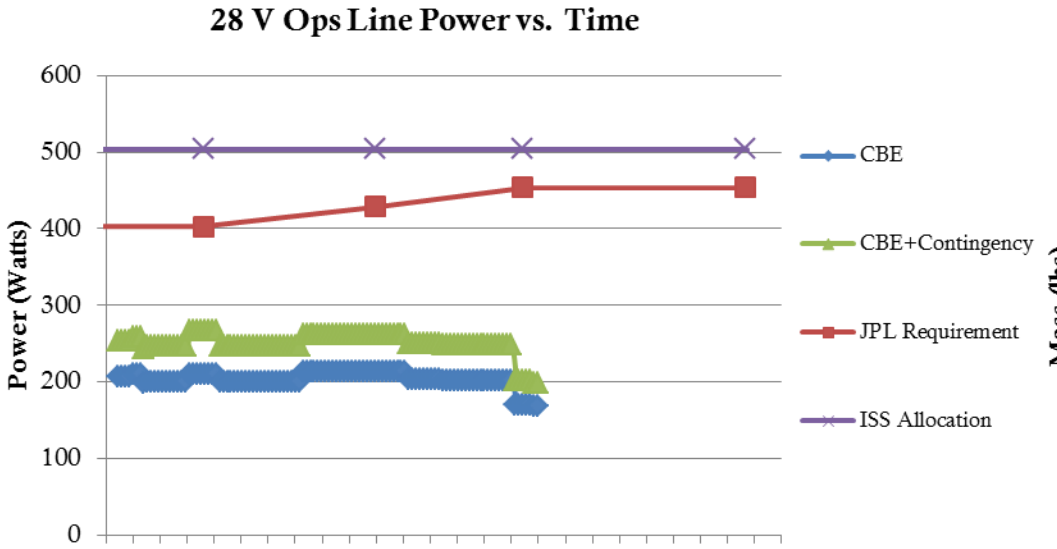
(Some of) The Good Parts

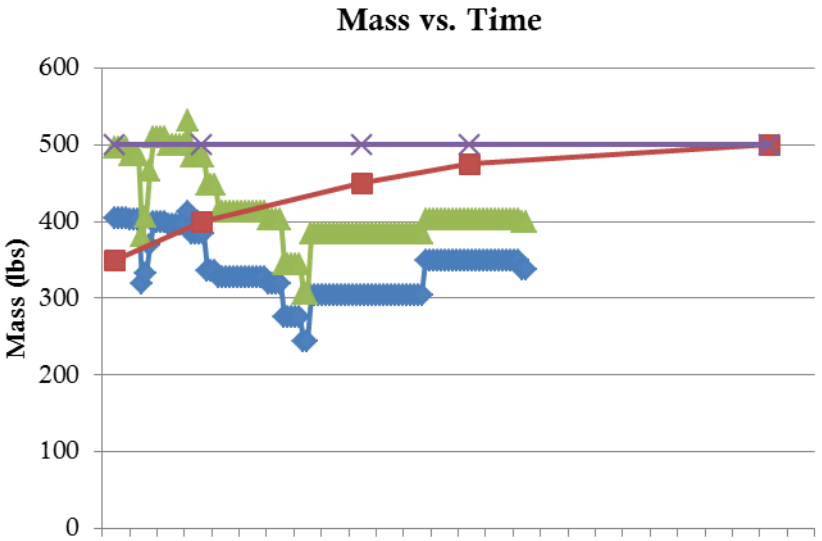
- Generous flight resource allocations
  - → No need for mass/power optimization
  - → Use mass/power to solve problems
  - → Lax margin management
- Consequences
  - Oversized gimbal (62lbs) for optical head (3lbs)
  - Fly-away instrumentation: test accelerometers, TCs, pressure transducer
  - No in-flight active power management



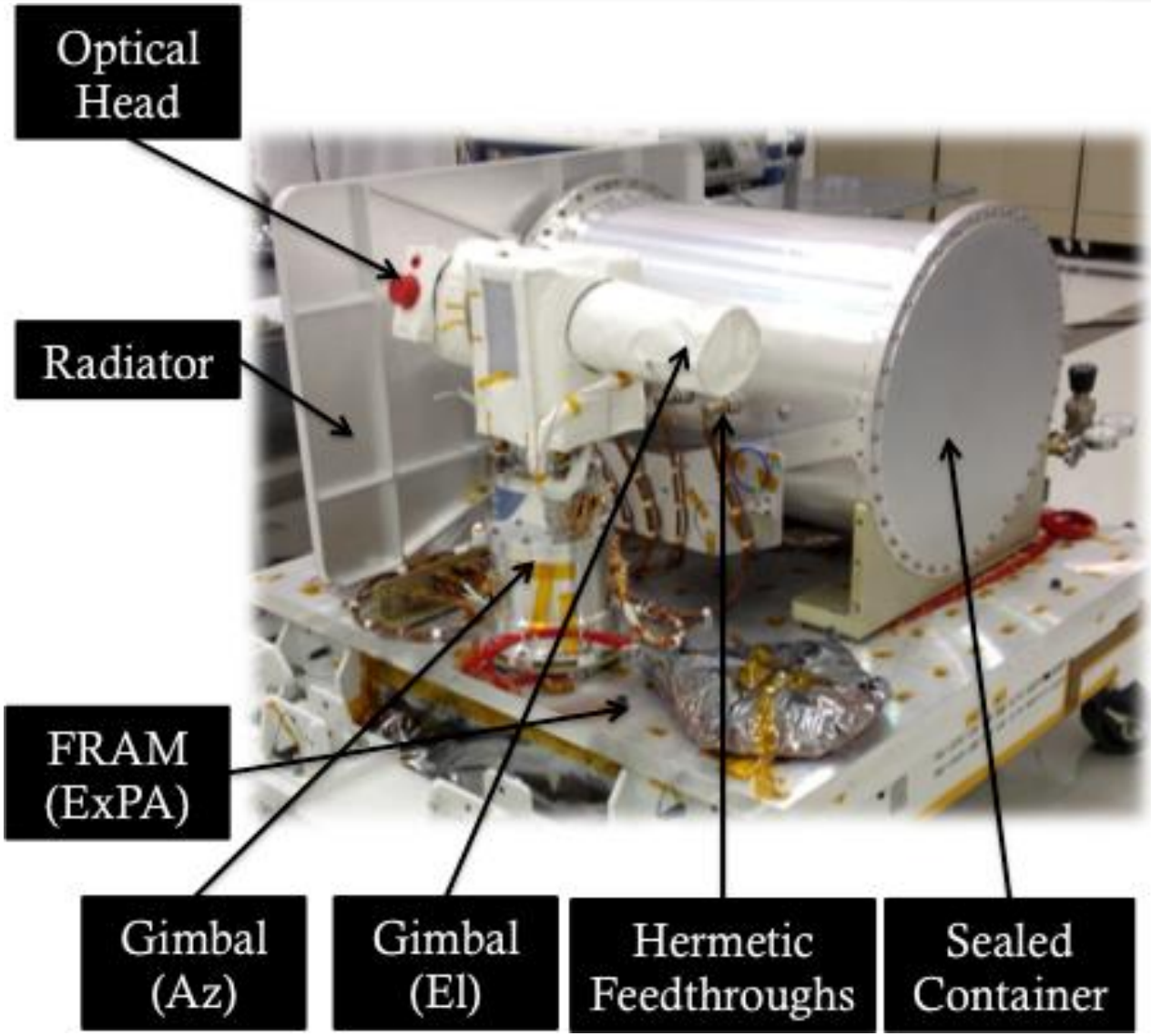
Resource	Allocation	Margin*
Mass	490 Lbs	30%
28V Ops	504 W	60%
120V Ops	750 W	60%
120V Heater	300 W	70%

*Calculated as (Allocation-CBE)/Allocation

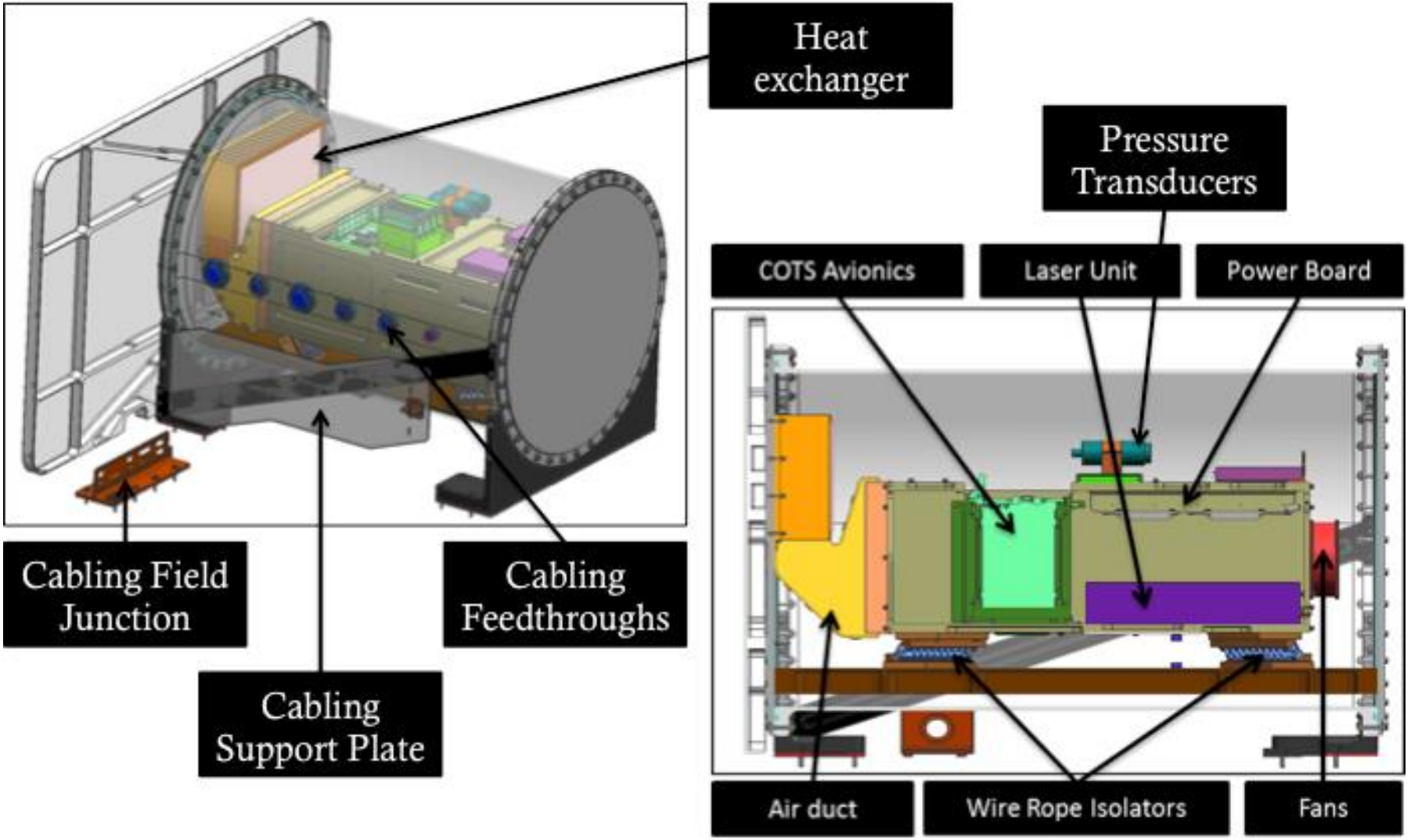




The End Result



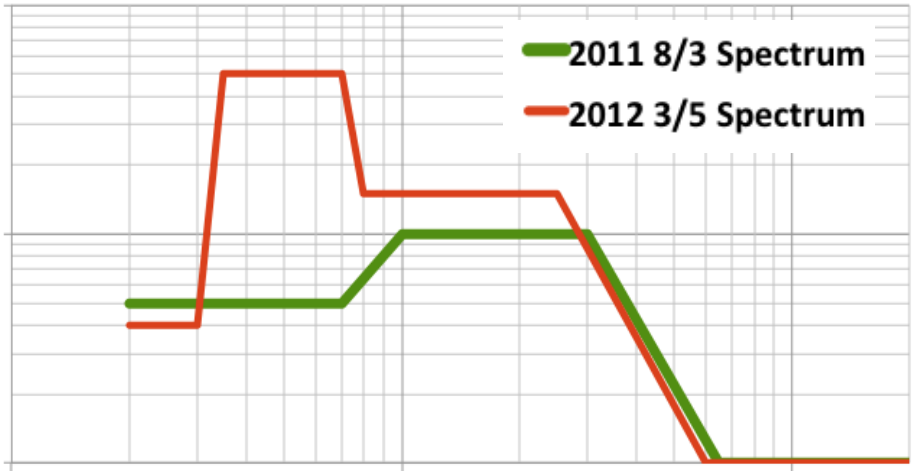
Sealed Container Design

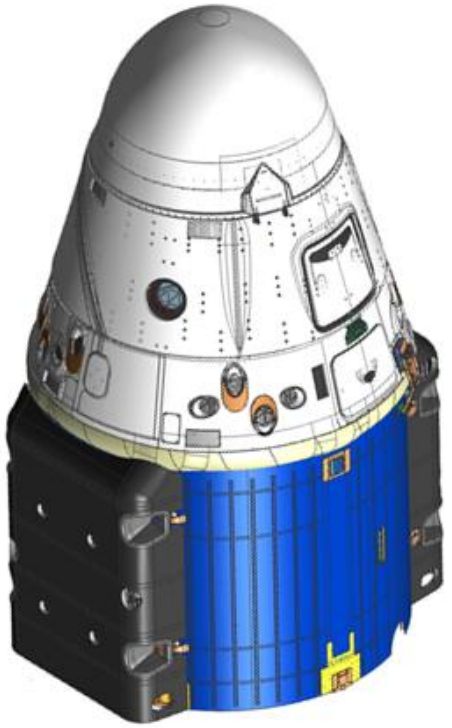


LAUNCH VEHICLE BLUES

Growing Pains

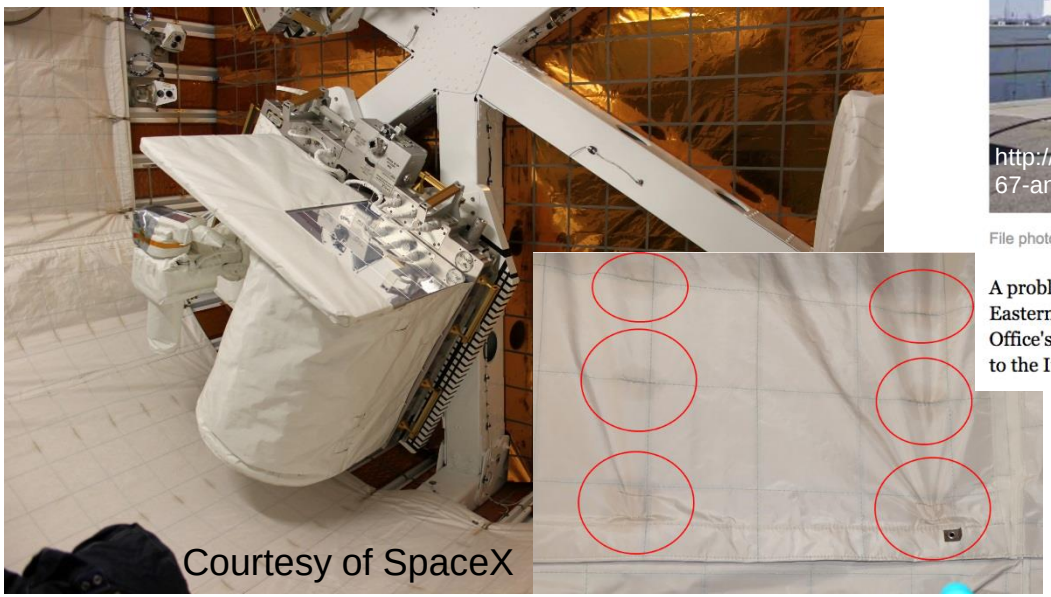
- Main challenge came from lack of Dragon design maturity at the time OPALS committed to its design
  - Original ICD had ~ dozen requirements, most containing TBDs
  - Switch to Falcon v1.1 and Dragon block upgrade between CRS-2 and CRS-3
  - Unstable vibration environment requirements
    - Received updated the morning of the first vibe test
  - Power interface mismatch
    - Addition of the “OPALS option” to the Dragon cargo I/F
  - Trunk contamination issue





Late Fires, Literally and Figuratively

- At L-2 days, contamination was found inside the trunk, delaying launch by 2 weeks
- Second launch attempt was scrubbed due to tracking radar fire



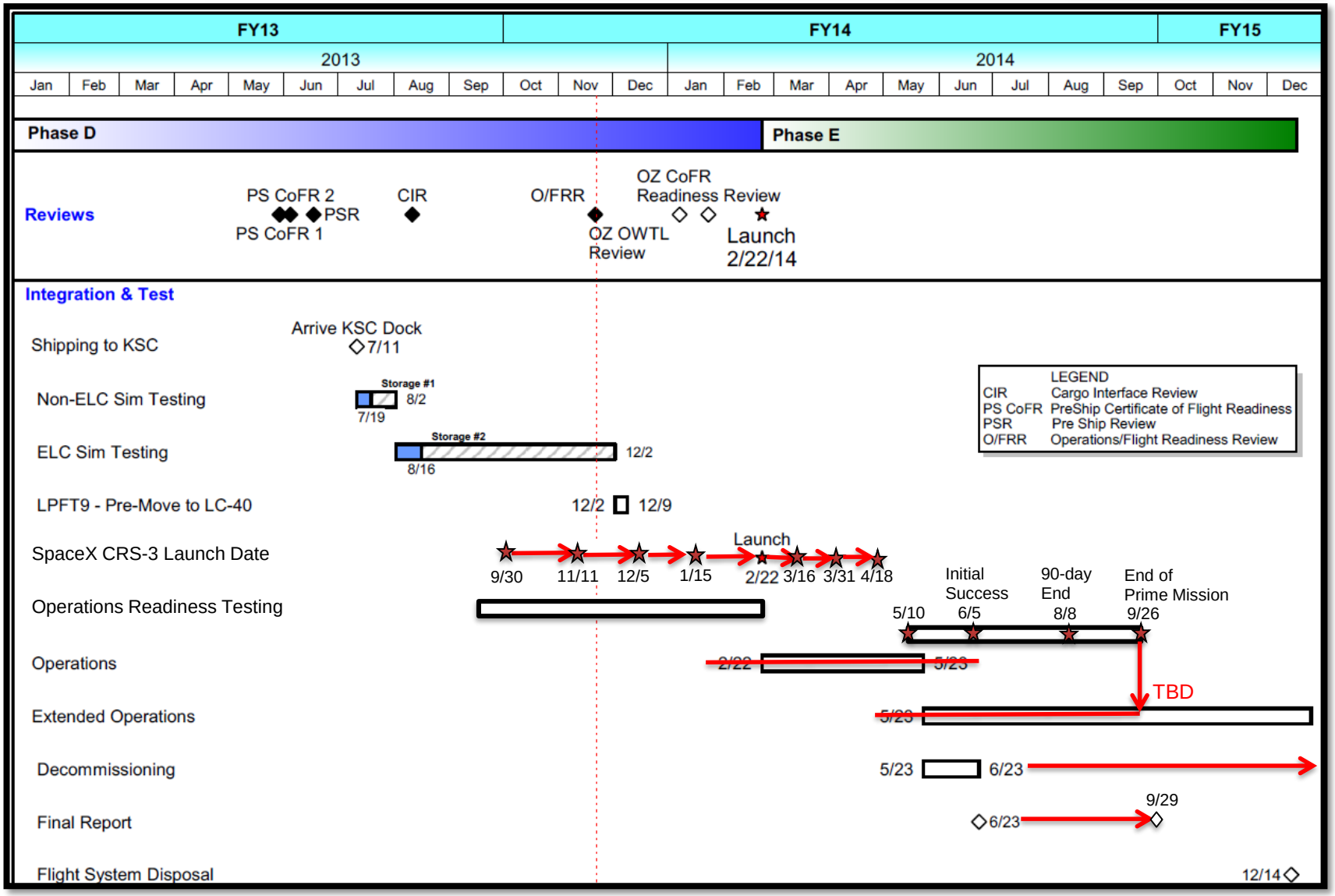
U.S. Air Force Radar Problem Delays NROL-67 and SpaceX CRS-3 Launches

Source: Marc Boucher, SpaceRef Posted March 27, 2014 11:10 AM 1 Comments

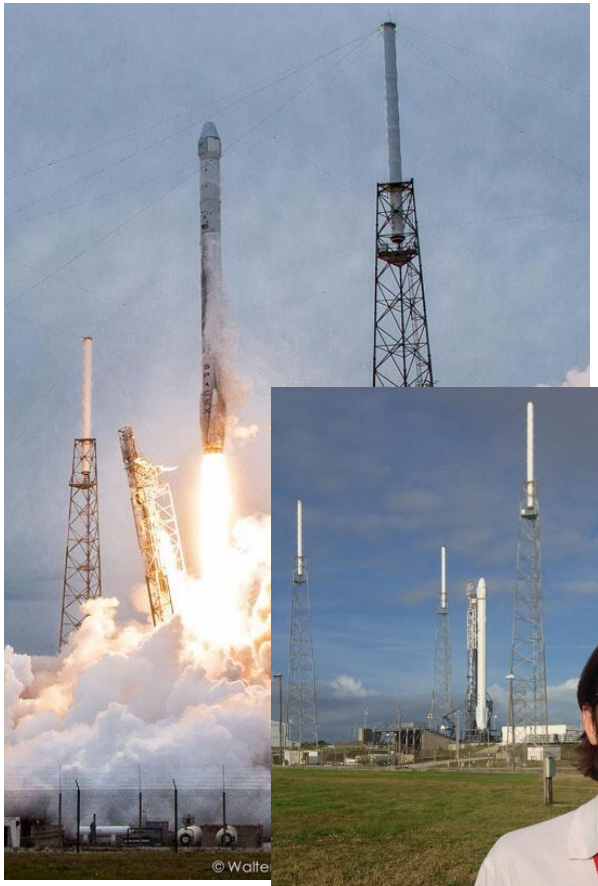
File photo of MOTR radar at White Sands. ©U.S. ARMY

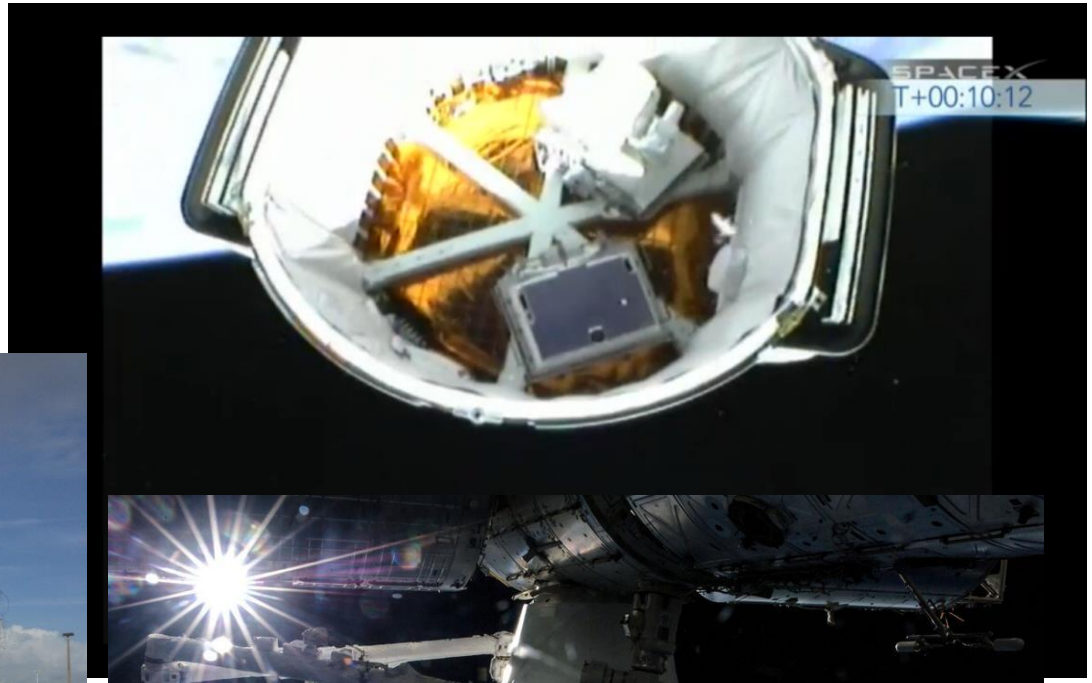
A problem with the U.S. Air Force AN/MPS-39 Multiple Object Tracking Radar (MOTR) at the Eastern Range, reportedly a fire, has delayed the launch of the National Reconnaissance Office's NROL-67 launch and now unofficially SpaceX's launch of the CRS-3 resupply mission to the International Space Station.

Launch Schedule



But Eventually All is Forgiven…



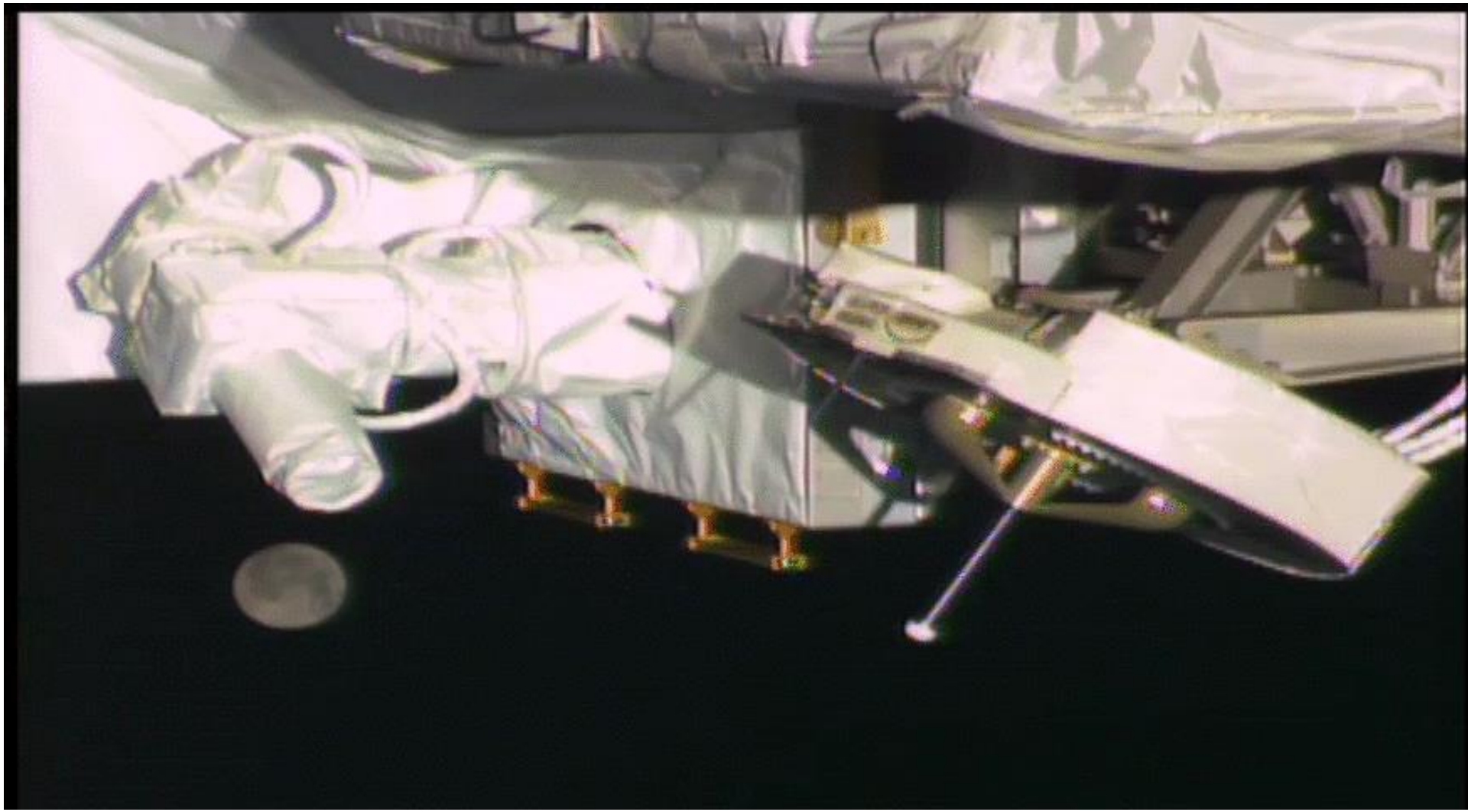


OPERATIONS

OPALS Installation On ISS

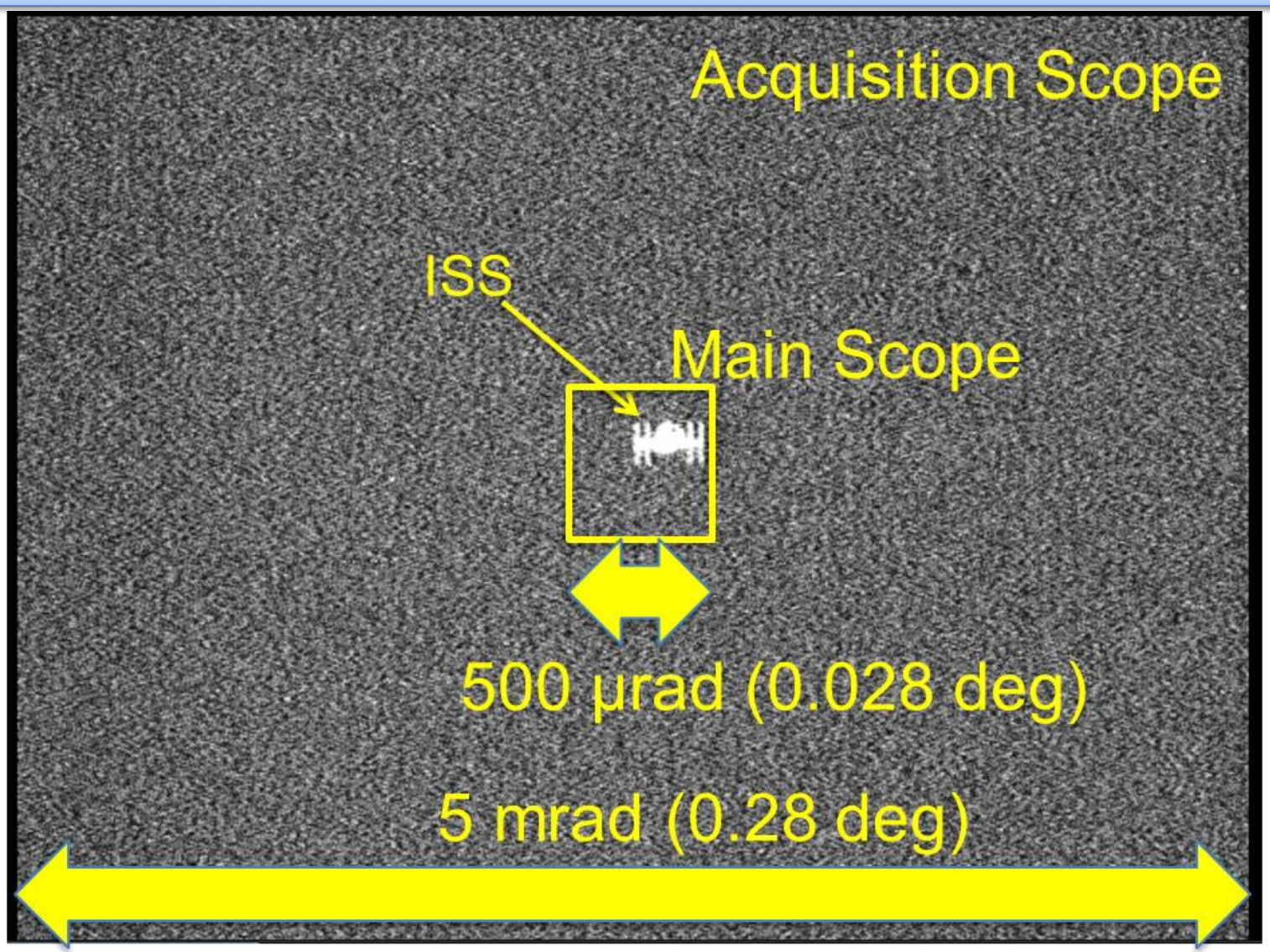
Courtesy CSA: http://www.asc-csa.gc.ca/eng/search/video/watch.asp?v=1_det4ggu5

OPALS on ISS ELC 1 – FRAM 8



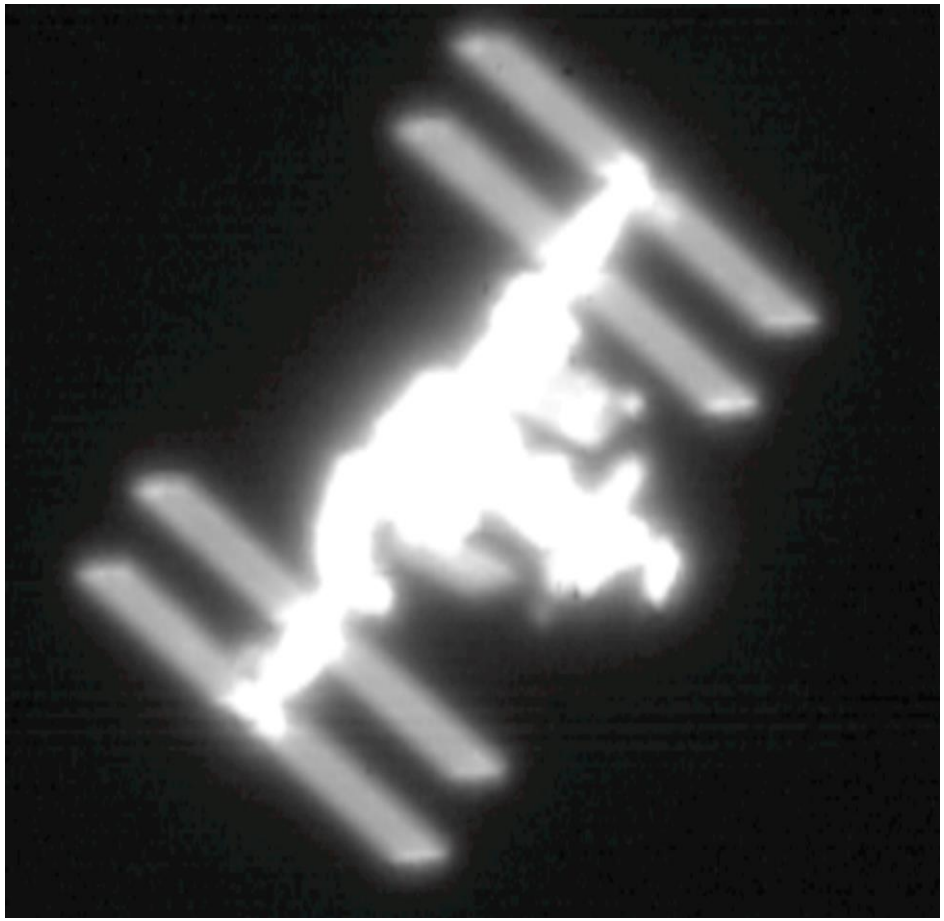
Jet Propulsion Laboratory
California Institute of Technology

Ground Station (OCTL) Tracking Cameras

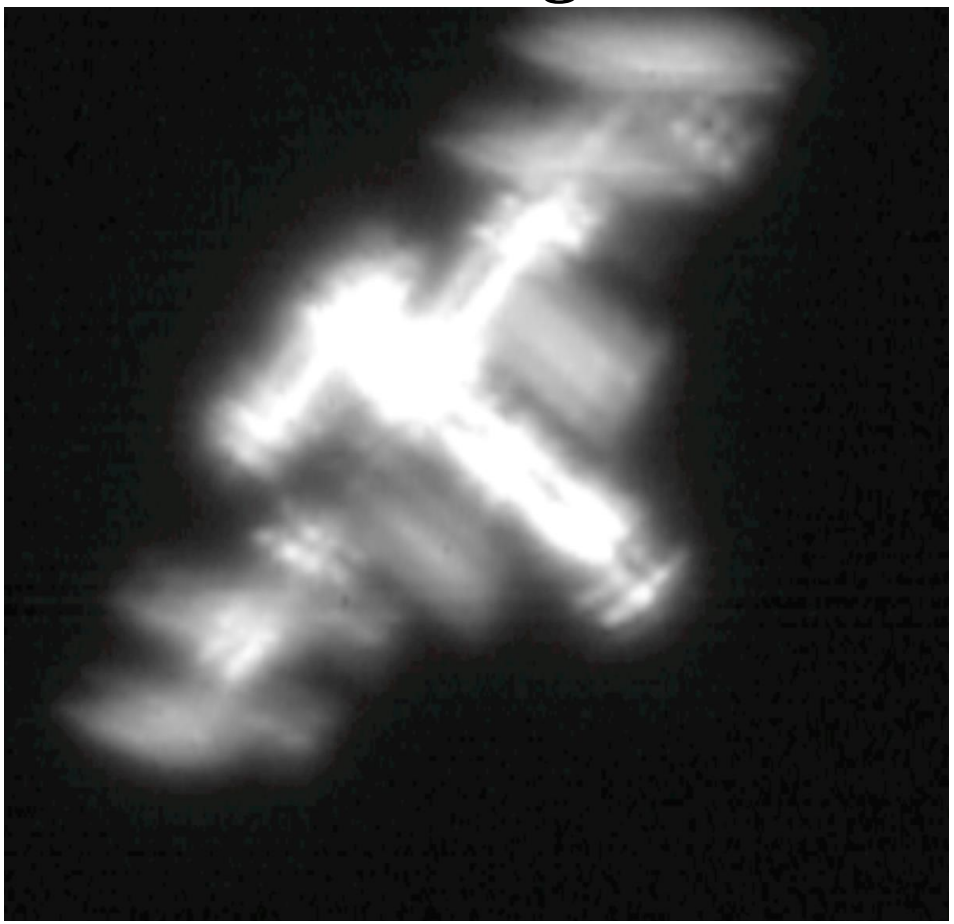


Sunlit ISS Viewed by OCTL

Forward Image

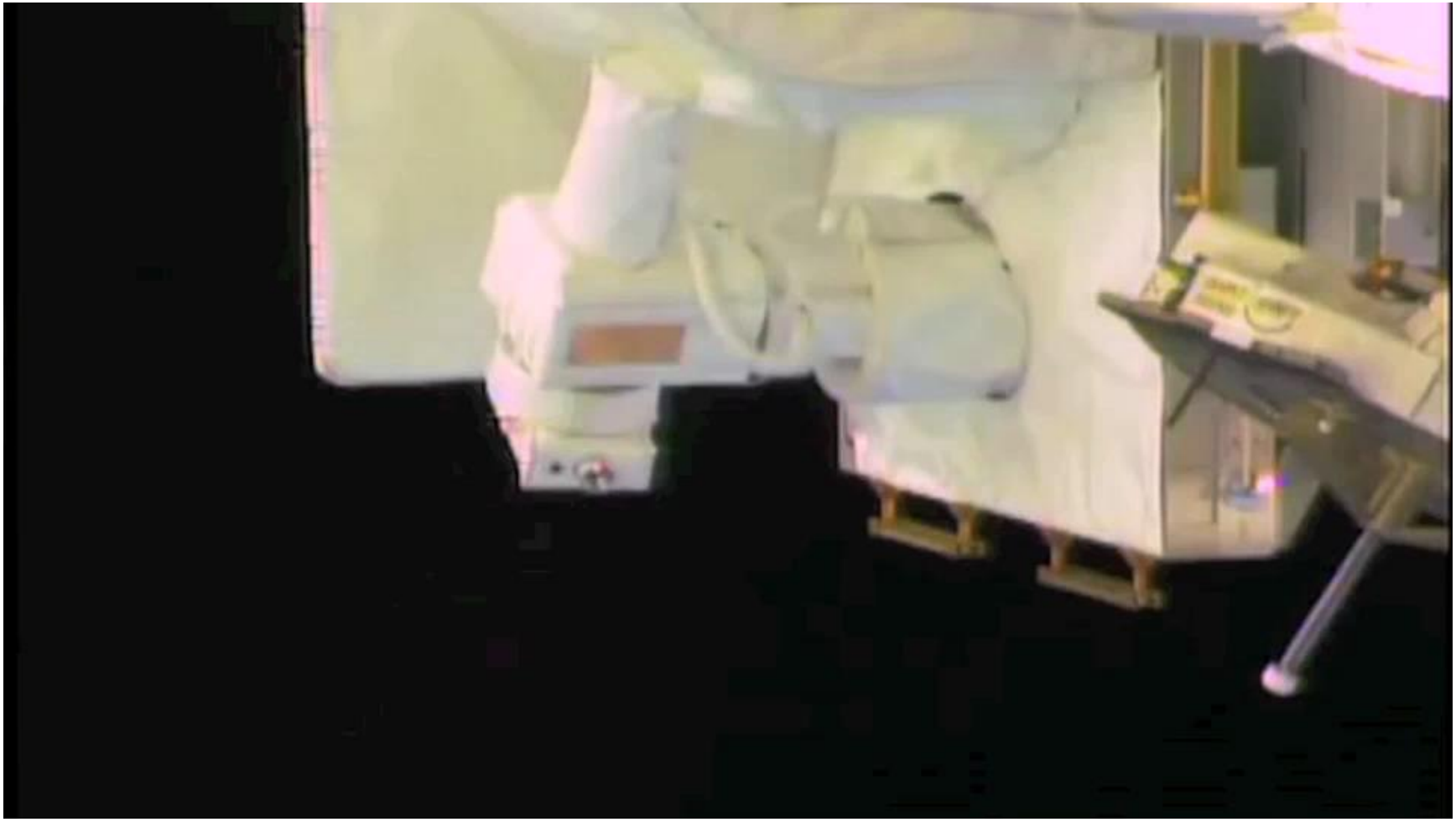


Aft Image

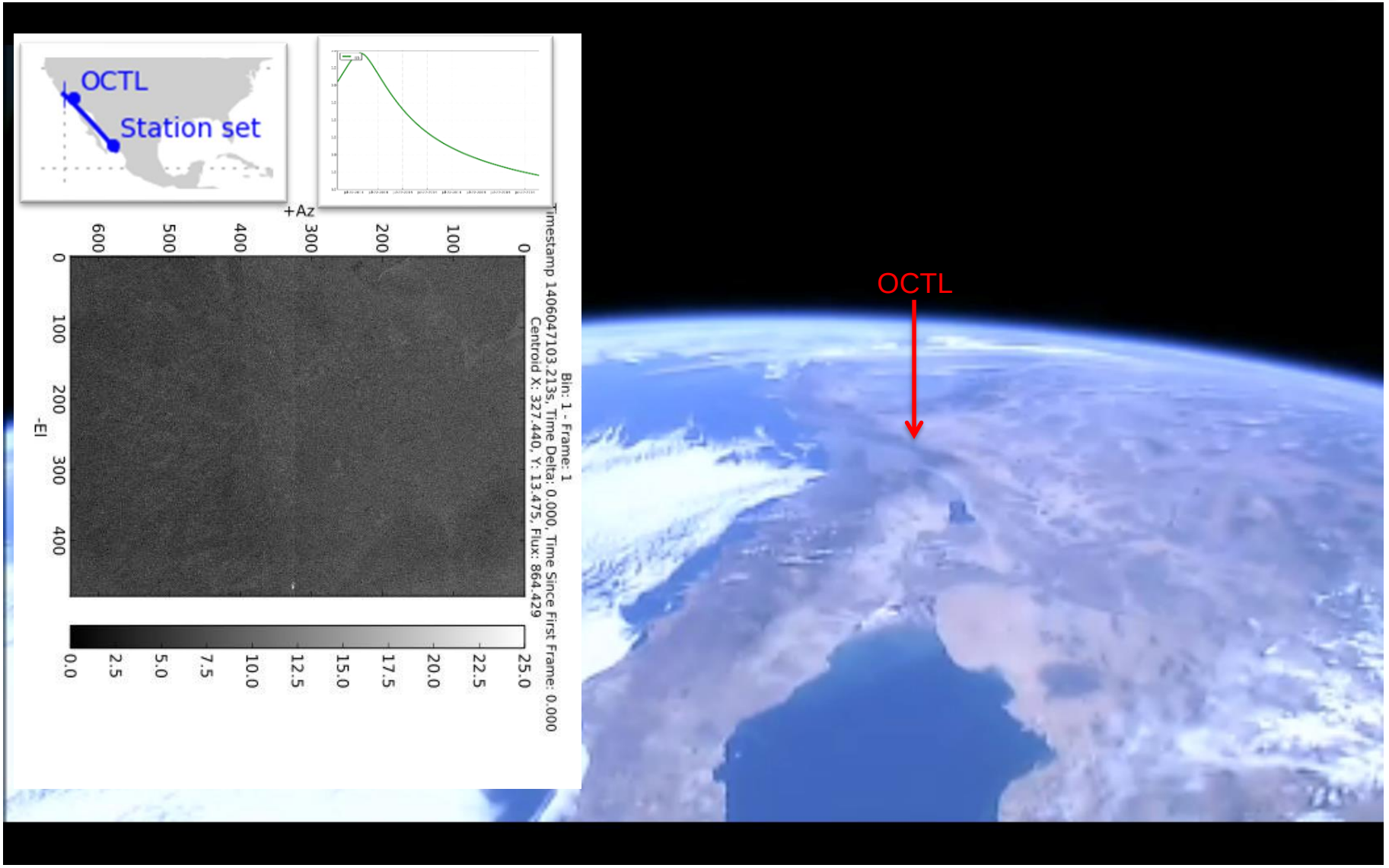


ISS in 1550 nm band

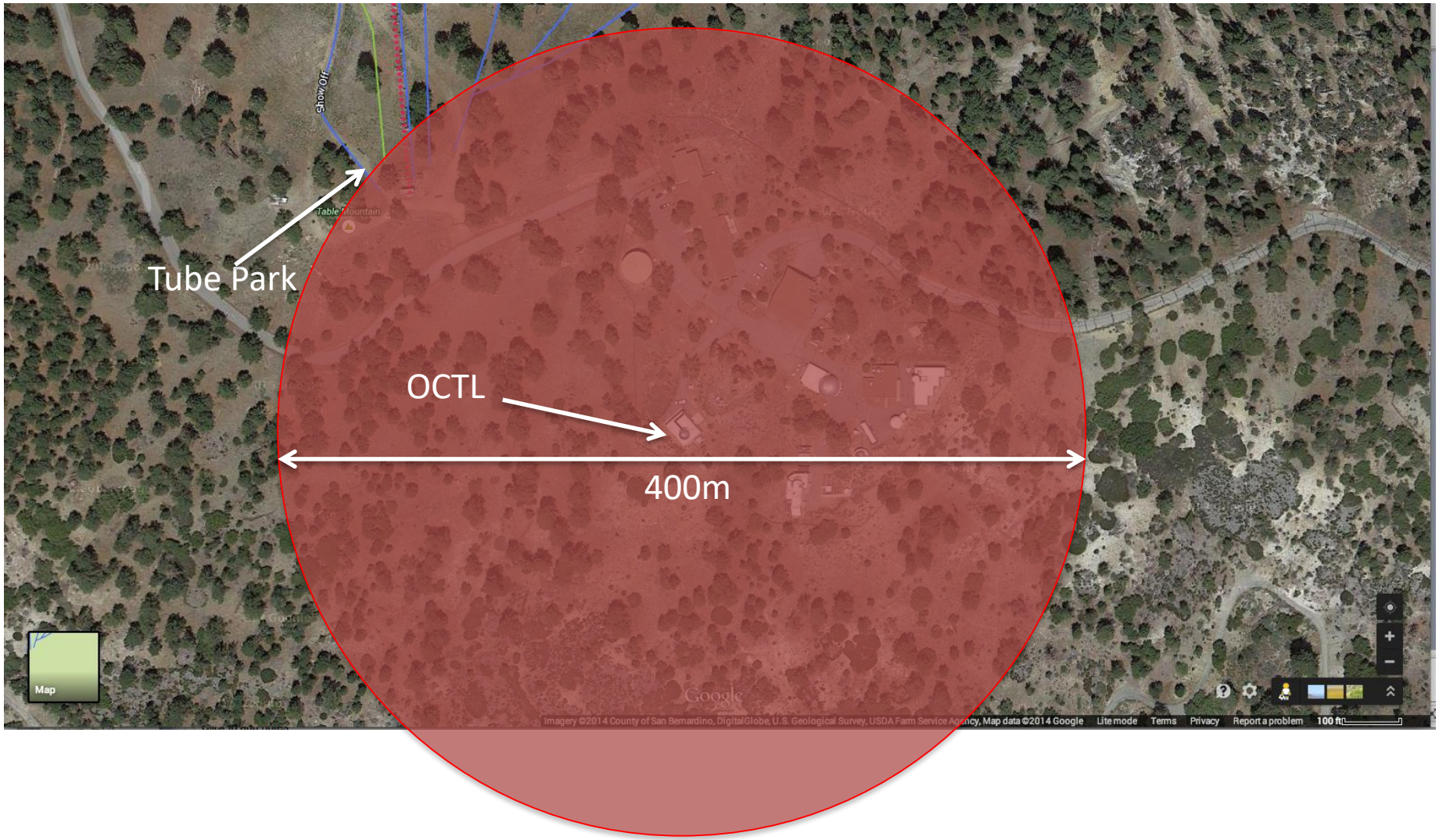
OPALS Pointing to OCTL



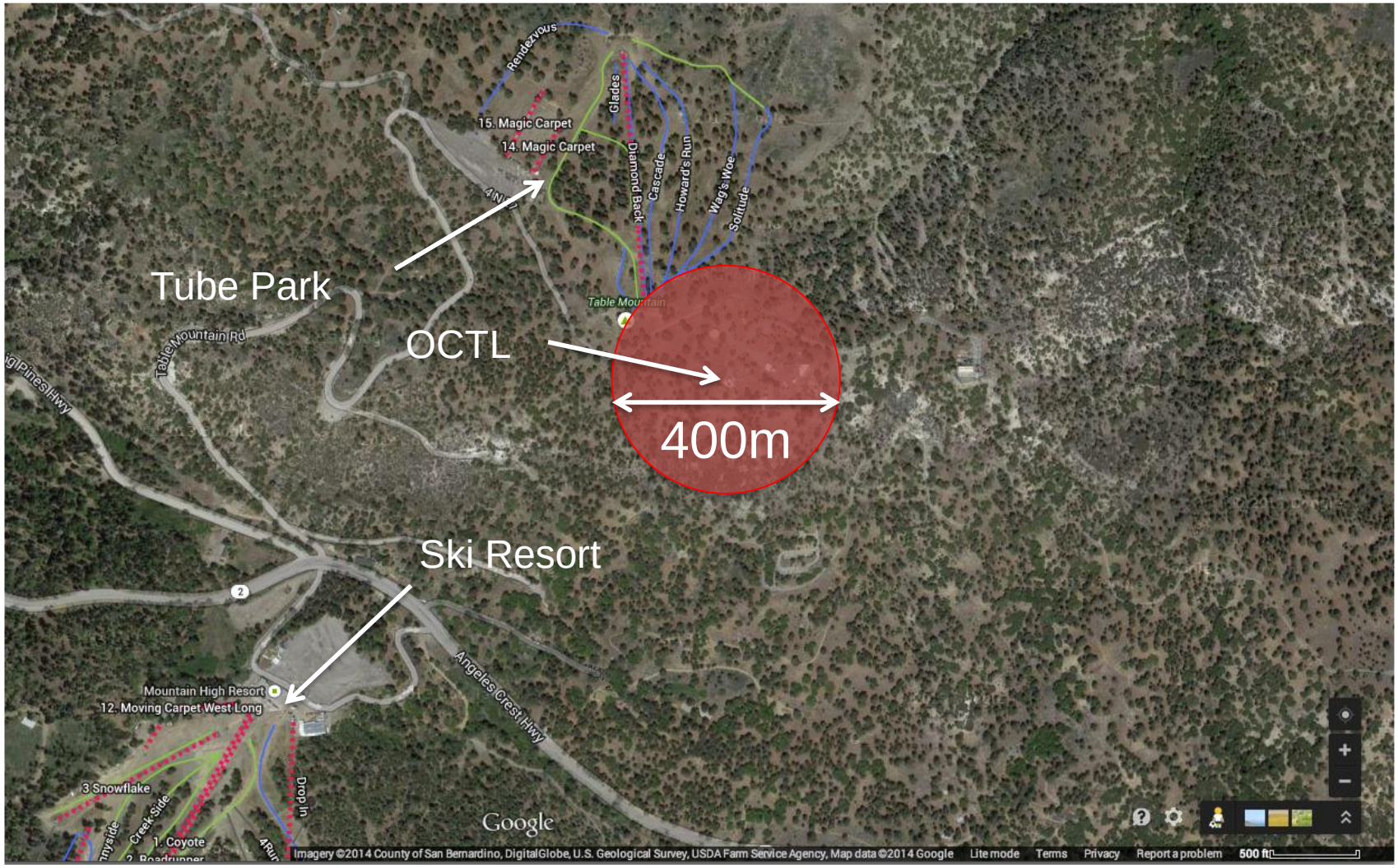
View From ISS during OPALS Pass



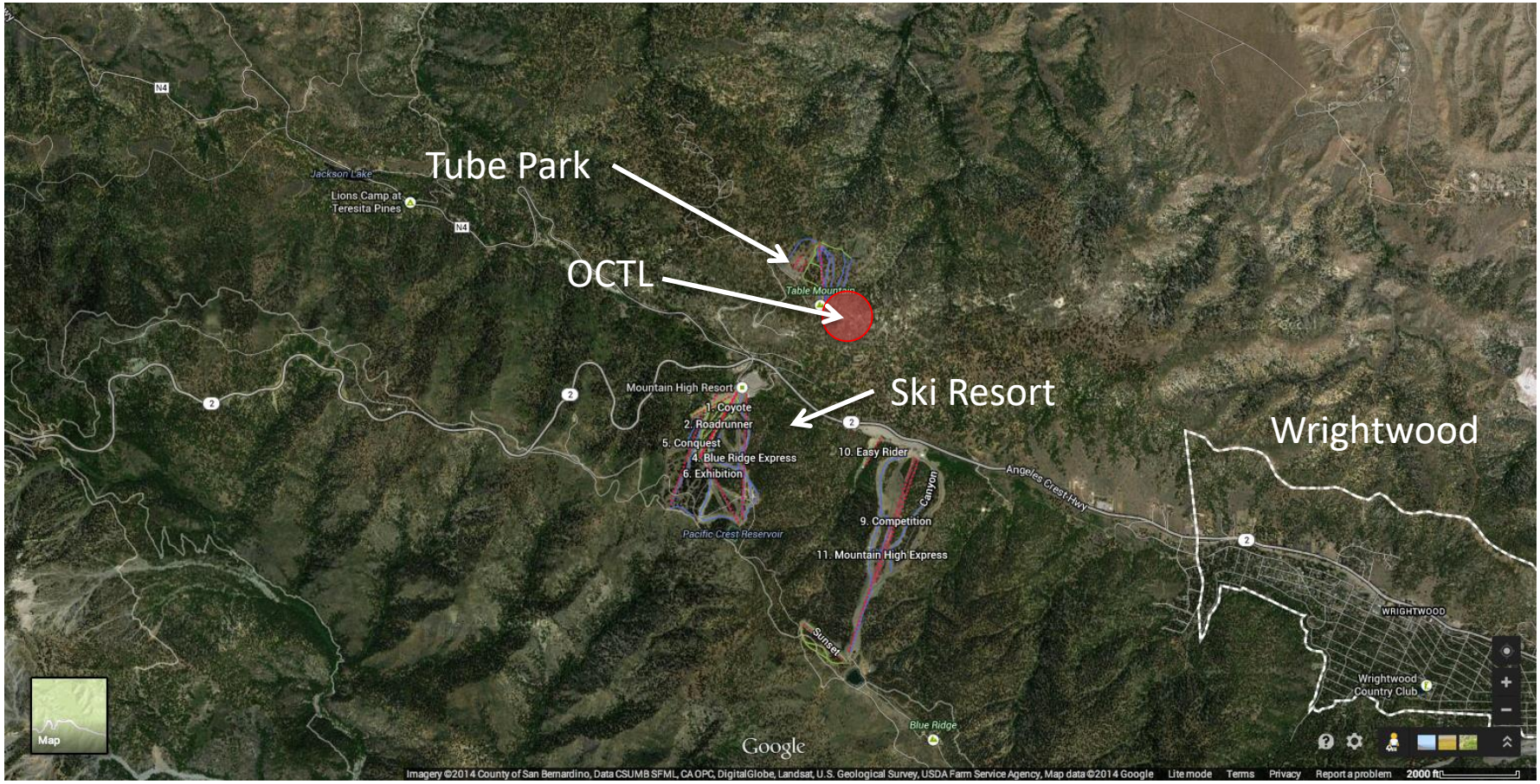
It's like aiming a laser pointer..



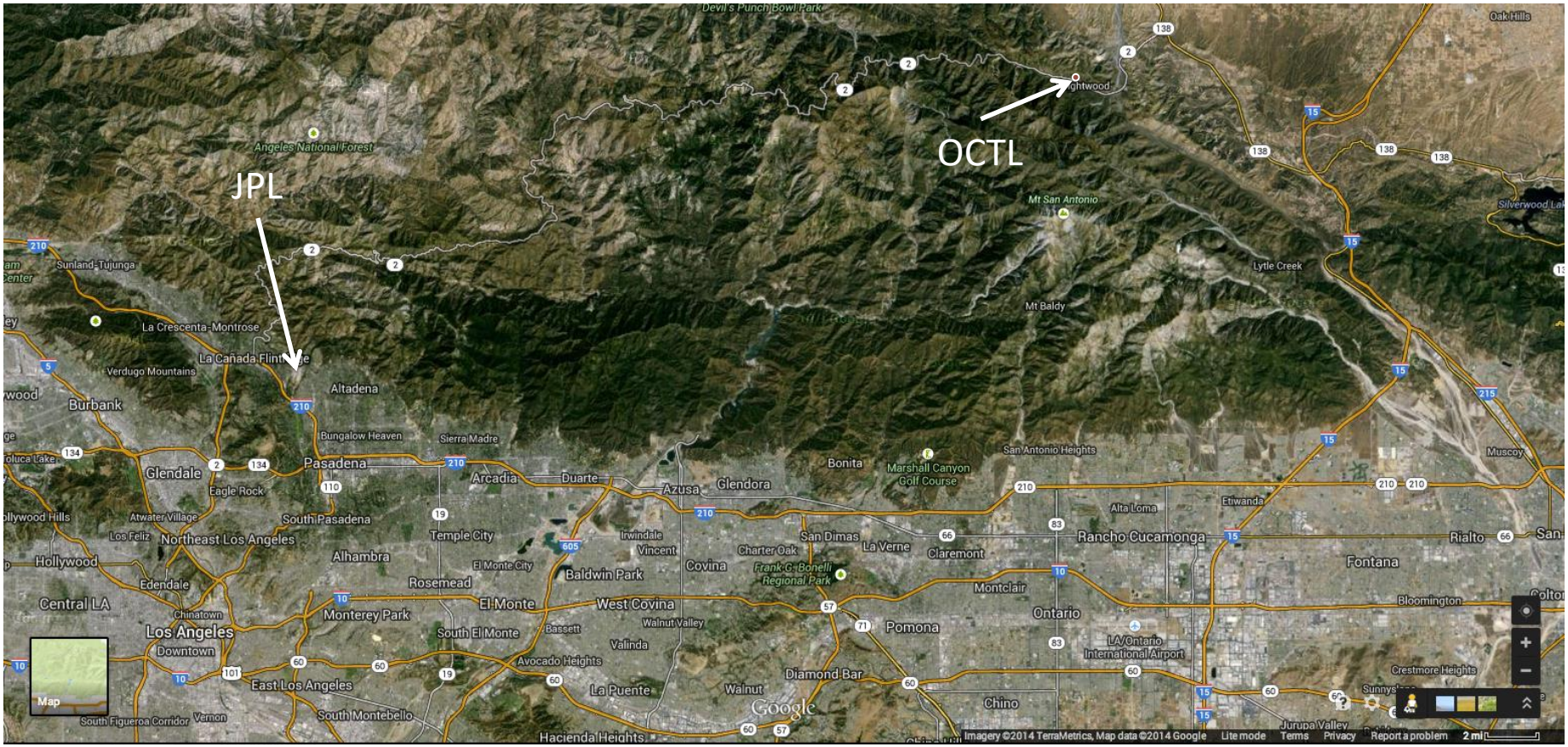
… at an area the diameter of a human hair …



… from 30 feet away…



… while you're walking!

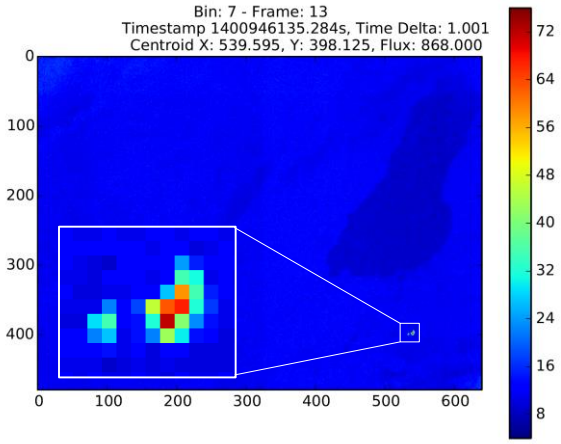


But When You Get it Right…

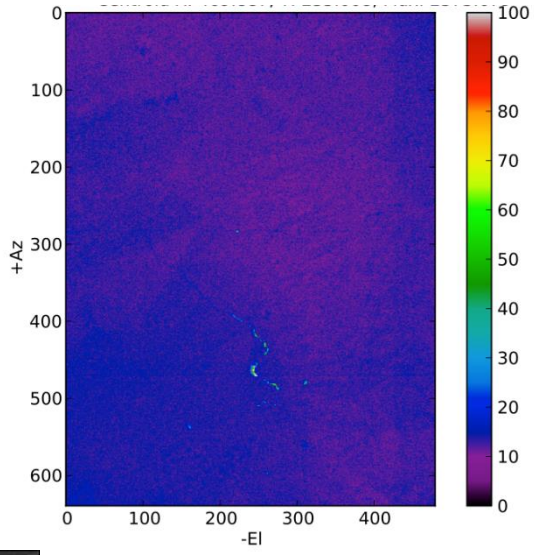
- **First successful downlink on June 5, 2014**
  - **Total duration of lock: ~145 seconds**
  - **Bit Error Rate several orders of magnitude better than required**

No Shortage of Surprises

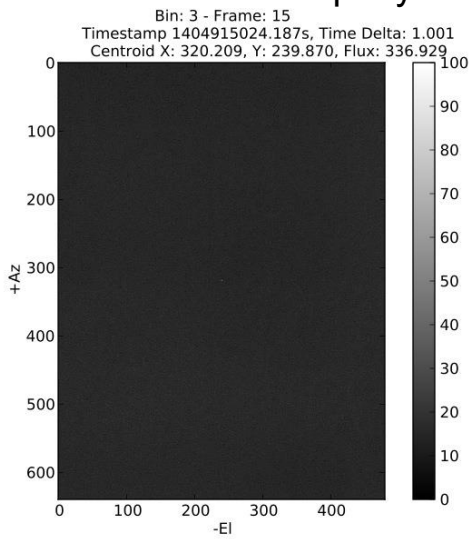
5/24 – Salton Sea



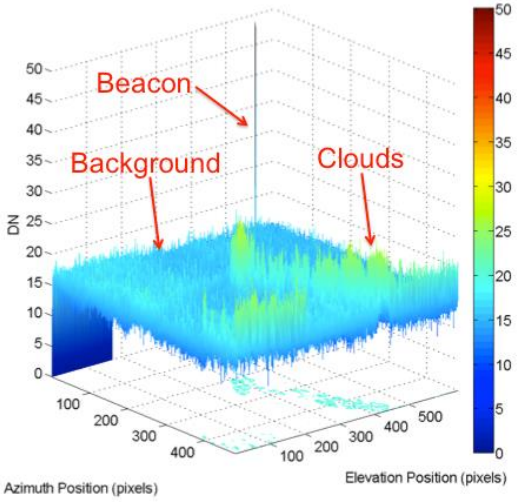
7/1 – Silver Snake



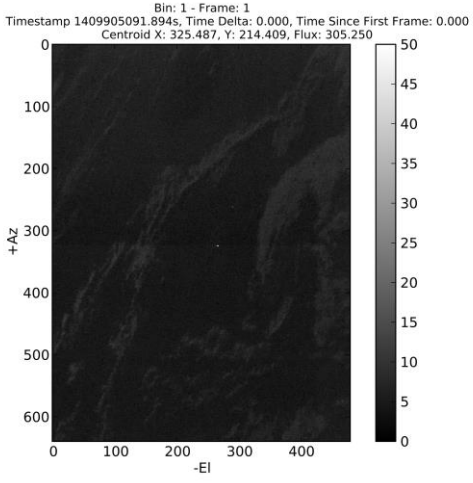
7/9 – Three's Company



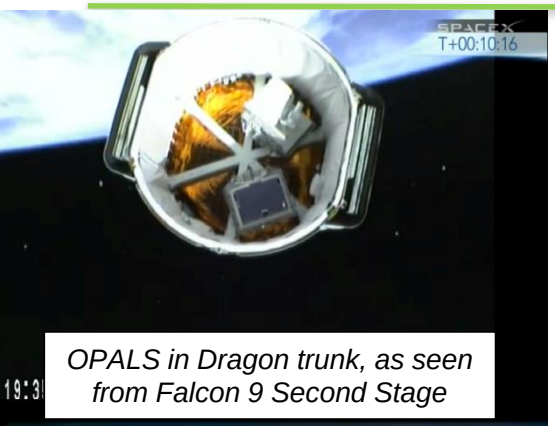
Cloud disruptions



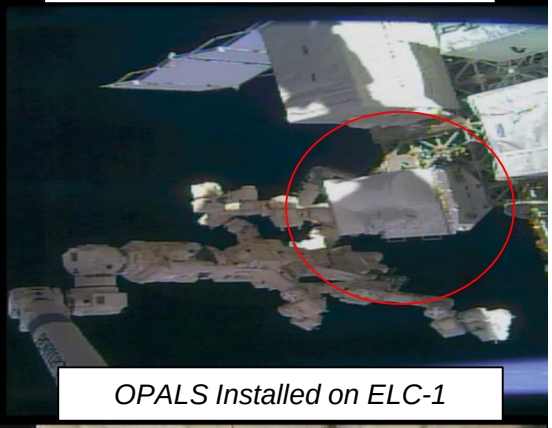
9/5 – Tenerife (ESA) Downlink



In A Nutshell



OPALS in Dragon trunk, as seen from Falcon 9 Second Stage



OPALS Installed on ELC-1

OPALS During A Downlink

OPALS Mission:

Demonstrate the feasibility of space-to-ground laser communications transmissions from ISS

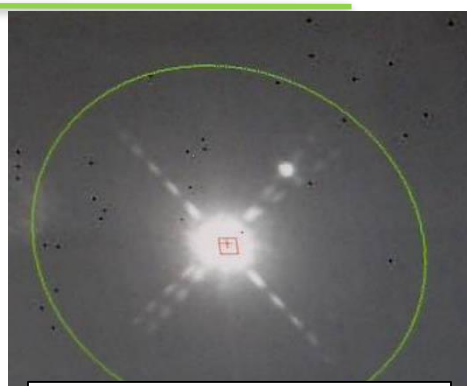
Prime Mission Milestones:

(Dependent on ISS schedule and TMF Visibility)

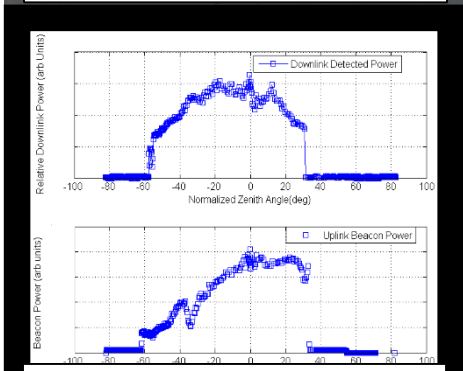
- ✓ Launched to ISS (April ’14)
- ✓ Commissioning Phase (May ‘14)
- ✓ First Official Video Downlink (6/5/14)
- ✓ First Daytime Video Downlink (6/12/14)
- ✓ Low Elevation Transmissions (June ‘14)
- ✓ Geometry/Pointing Sensitivity Tests (Jul-Aug‘14)
- ✓ PN8 and Engineering Data Downlinks (Sep ‘14)
- ✓ Foreign Ground Station Collaborations (Oct ‘14)

Extended Mission Milestones:

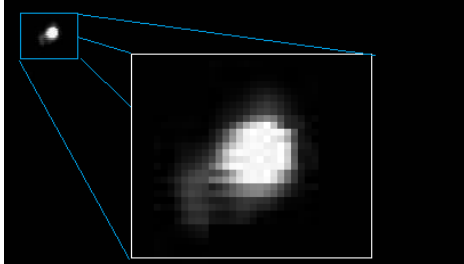
- ✓ Adaptive Optics Tests with Boeing (Jan-May ‘15)
- ✓ ISS Platform Vibration Experiment (Aug ‘15-Apr ‘16)
- ✓ Transmissions to DLR (Oct-Dec ‘15)
- ✓ Transmissions to ESA (Jan-Feb ‘16)
- ✓ Transmissions to CNES (Mar ‘16-Dec ‘16)
- ✓ Decommissioning (Feb ‘17)



First Optical Downlink



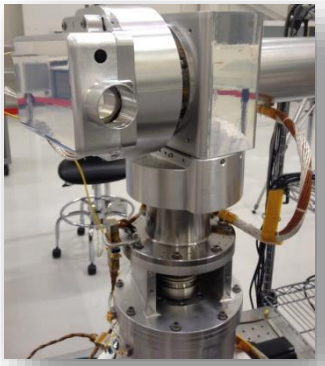
Optical Link Validation

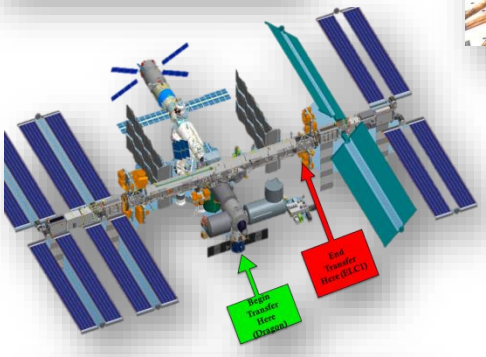


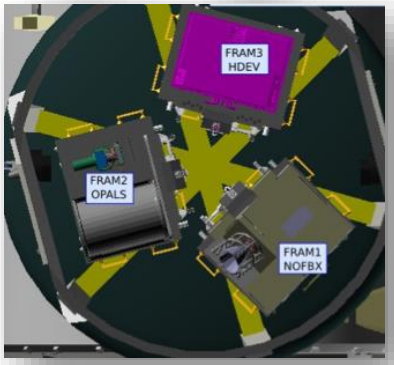
ESA Signal Acquisition at Tenerife

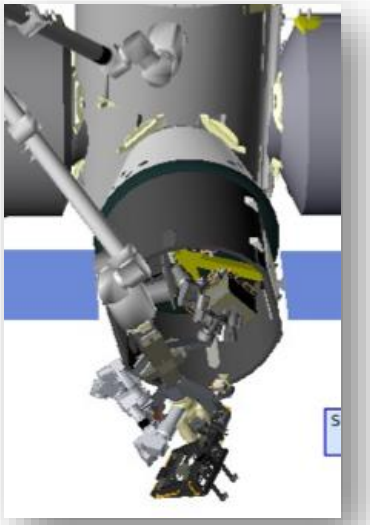
OPALS Firsts

- 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 launch 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)









BACKUP

OPALS Publications

Oaida, B., Abrahamson, M., Witoff, J., Bowles-Martinez, J., and Zayas, D., "OPALS: An Optical Communications Technology Demonstration from the International Space Station," Aerospace Conference, IEEE, Big Sky, MT, 2-9 March 2013.

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Abrahamson, M., Sindiy, O., Oaida, B., Fregoso, S., Bowles-Martinez, J., Kokorowski, M., Wilkerson, W., and Konyha, A., "OPALS: Mission System Operations Architecture for an Optical Communications Demonstration on the ISS," SpaceOps 2014 13th International Conference on Space Operations, Pasadena, CA, 5-9 May 2014. AIAA-2014-1627."

Biswas, A., Kovalik, J., Wright, M., and Roberts, W., "Optical Communications Telescope Laboratory (OCTL) Support of Space to Ground Link Demonstrations," SpaceOps 2014 Conference, Pasadena, CA, 5 - 9 May 2014.

Oaida, B.V.; Kokorowski, M.; Erkmen, B.I.; Andrews, K.S.; Wu, W.; Wilkerson, M., "Impact of pointing performance on the optical downlink for the Optical PAyload for Lasercomm Science (OPALS) system" Proc. ICSOS 2014, S3-1, Kobe, Japan, May 7-9 (2014).

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Biswas, A., Oaida, B., Andrews, K., Kovalik, J., Abrahamson, M., and Wright, M., "Optical Payload for Lasercomm Science (OPALS) Link Validation During Operations from the ISS," SPIE Proceedings, Vol. 9354: Free-Space Laser Communication and Atmospheric Propagation XXVII, San Francisco, CA, 16 March 2015.

Sindiy, O., Abrahamson, M., Biswas, A., Wright, M., Padams, J., and Konyha, A., "Lessons Learned from Optical Payload for Lasercomm Science (OPALS) Mission Operations," AIAA SPACE 2015 Conference and Exposition, Pasadena, CA, 31 August - 2 Sept. 2015.

Wright, M., Morris, J., Kovalik, J., Andrews, K., Abrahamson M., Biswas, A., "LEO to Ground OPALS Optical Communication Link Using Adaptive Optics Correction into SMF," Optics Express, vol. 23, no.26, 22 Dec. 2015.

Oaida, B.V., Bayard, D.S., Abrahamson, M.J., (2016) "On-orbit Measurement of ISS Vibrations during OPALS Extended Mission Operations," Aerospace Conference, IEEE, Big Sky, MT, 6-11 March 2017.

Courtesy of NASA JSC: https://io.jsc.nasa.gov/


On SPDM after ELC Demate

Trunk Install for Deorbit