LEO-to-ground optical communications link using adaptive optics correction on the OPALS downlink

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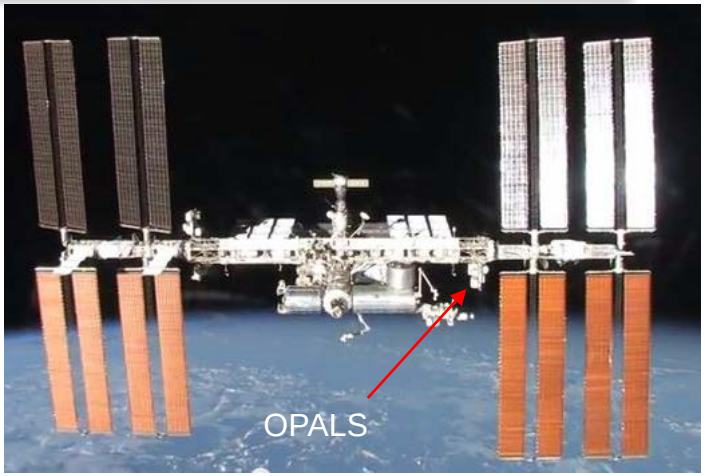
Outline

- OPALS Overview
- Flight system
- Ground system
- Previous results
- AO system integration
- Results
  - Tracking performance
  - Power in Fiber
  - Communication link
- Conclusion

OPALS Science Goals

- Optical link demonstration
  - High dynamic range (400-850km range, ~1 /s slew rate over 150 second pass)
- Received power fluctuations due to atmospheric turbulence
  - Uplink variance measured at Flight System
  - Downlink variance measured at Ground Station
- Link availability studies
  - Geometry, atmospheric, day vs. night
- Pointing performance
  - OCTL pointing and tracking
  - Flight System acquisition, tracking, stability



Installed on ISS

Optical Communications Telescope Laboratory (OCTL)

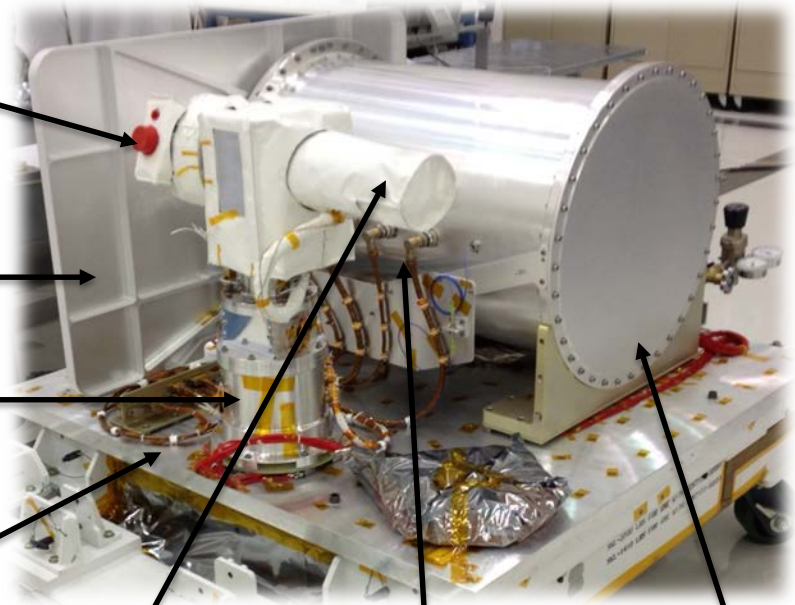
BEACON CHARACTERISTICS		
Uplink wavelength	976	nm
Average Laser power	10	W
Beam divergence	1.5	mrad
Power transmitted from OCTL	4.07	W
Mean irradiance at Flight terminal	1.33	$\mu W/m^2$

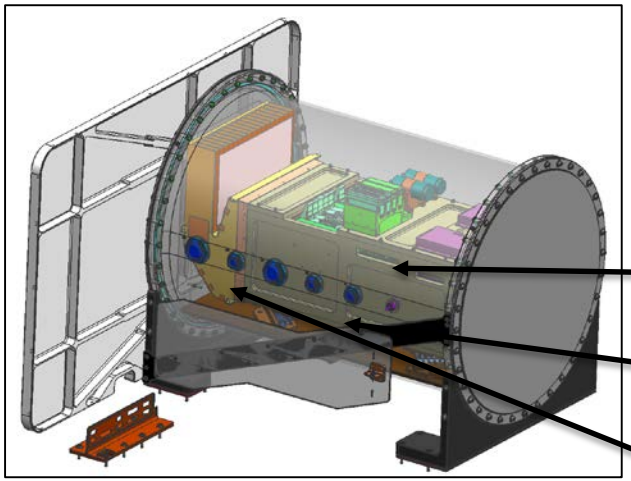
DOWNLINK CHARACTERISTICS		
SIGNALING		
Modulation	OOK	-
Uncoded BER	1.00E-04	-
ECC	Reed-Solomon	-
Modulation Rate	33-50	Mb/s
TRANSMITTER		
Downlink wavelength	1550	nm
Beam Divergence (1/e^2)	1.08	mrad
Average laser power	2.5	W
Power transmitted from FS	2.1	W
POINTING		
Mispoint Angle	< 525.0	µrad
LINK GEOMETRY		
Max Zenith Angle	65	deg
Max Range	850	km

OPALS Flight System

- Cost constrained design
- Class D Payload
- COTS electronics and laser
  - Air cooled sealed container
- Two-axis gimbal
- No independent position/ attitude determination systems on the payload
  - No star trackers/GPS/motor encoders
  - Gimbal is calibrated prior to each operation

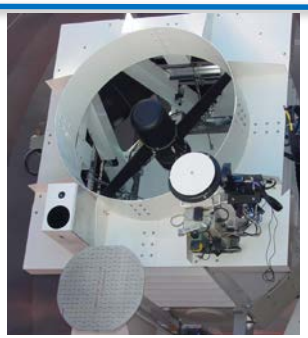
Completed Assembly

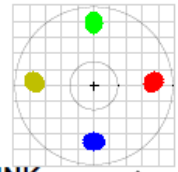


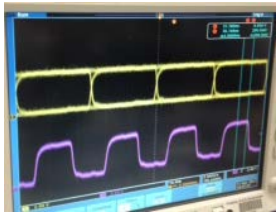


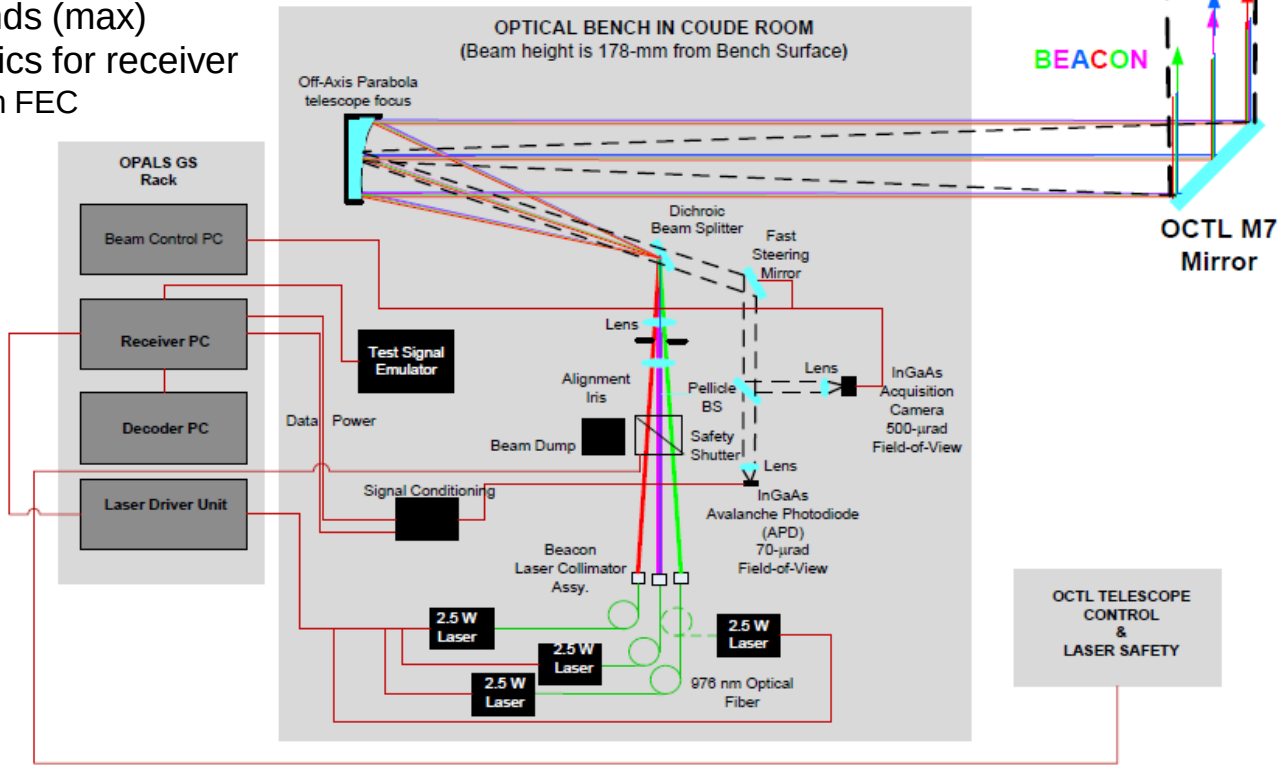
OPALS Ground System

- OCTL telescope 1-m Coudé configuration
  - F/76 near diffraction limited field-of-view (FOV) of 500-μrad
  - Fast slew rate to support LEO (~ 1 deg/s)
    - Day & Night operations, 7° from Sun
  - 4 cw beacon lasers
    - Wider beam divergences (~ 1-2 mrad)
    - Tx/Rx co-alignment relaxed
  - Contact times of 150 seconds (max)
  - COTS detectors & electronics for receiver
    - OOK with Reed-Solomon FEC
    - Post-processing receiver



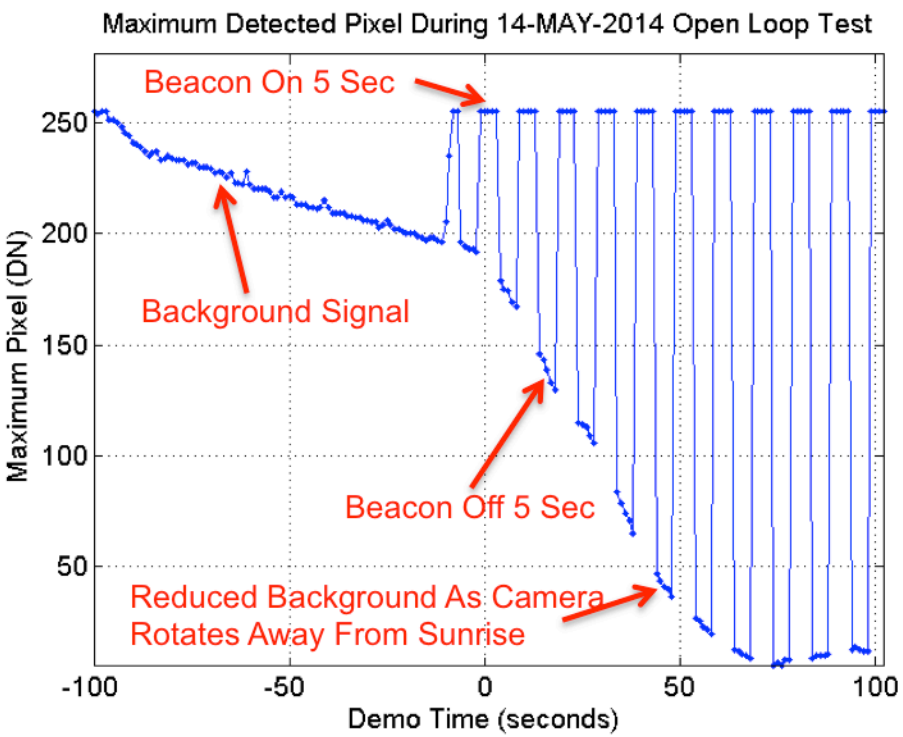


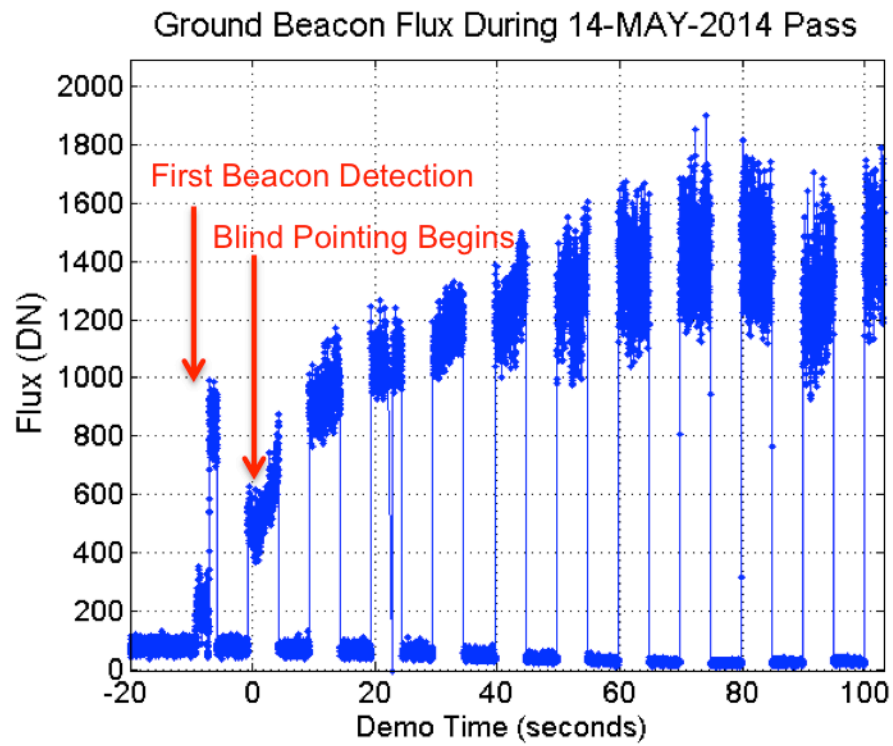




Open Loop Commissioning - Uplink

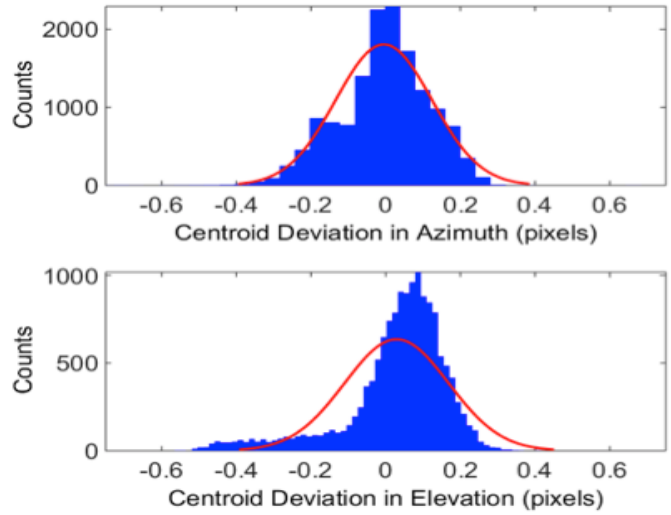
- Objective: Demonstrate beacon detection and bi-directional open loop pointing (active tracking disabled)
- Beacon toggled on/off at 5 second intervals
  - Beacon clearly detected above background
  - Beacon remained in camera FOV for entire 105 second pass using open loop predictions
  - Nominal threshold set to 100 DN based on results

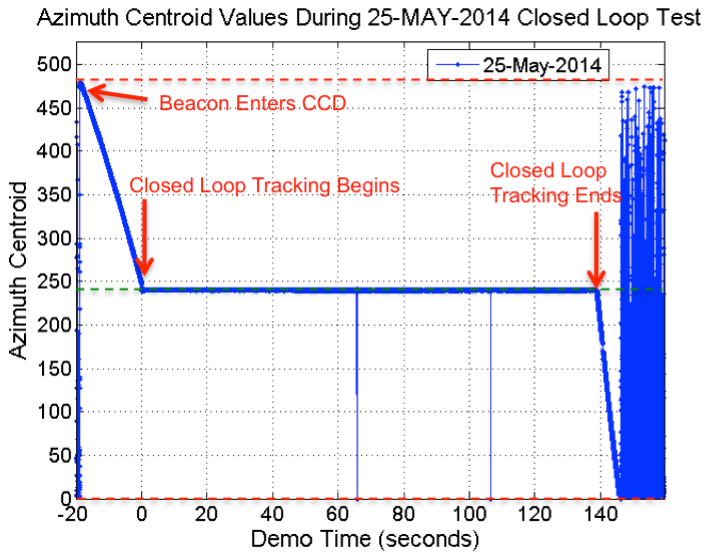


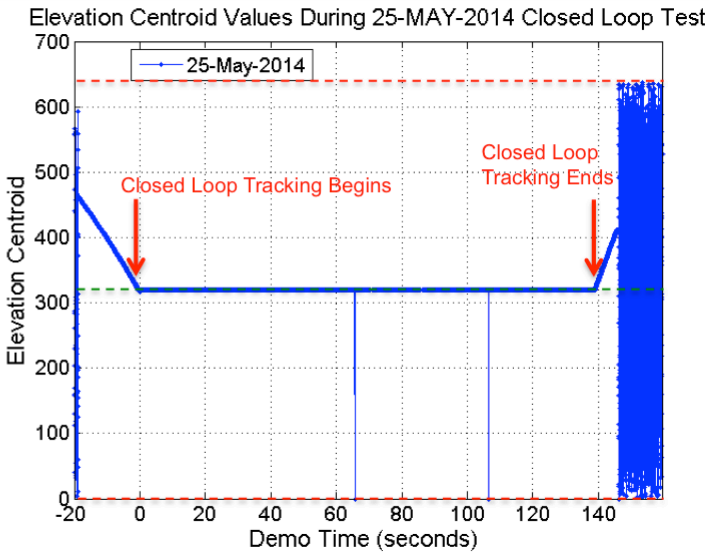


Closed Loop Commissioning-Tracking

- Objective: Demonstrate closed loop tracking within half beamwidth of downlink beam (540 µrad, 3σ)
- Beacon tracked for entire 136-second test
  - Beacon observed prior to tracking start due to wide FOV camera
  - Beacon within 10 pixels of CCD center at tracking start
  - Beacon tracked to 140 µrad, 3σ

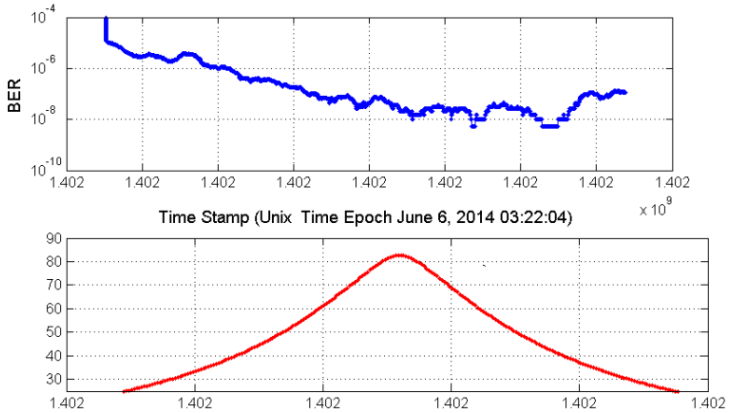




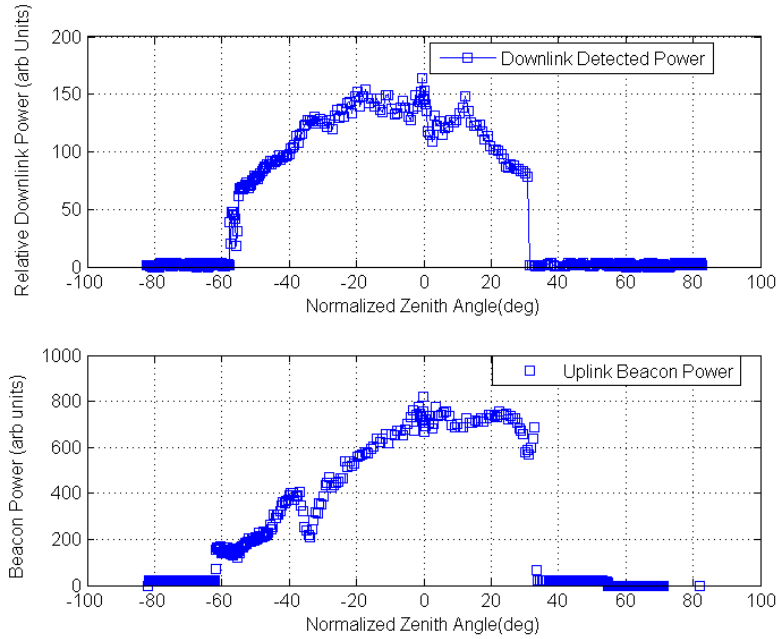


Mission Success - Downlink

- Mission success achieved on June 5, 2014
- Results shown from this pass are typical of most passes
  - Acquisition pointing and tracking performance at both ends of link exceeded requirements
  - Pass duration was ~ 148 seconds
  - Bit Error Rate < 10^{-5}, all errors corrected in post processing
  - Peak power received on APD ~ 160 nW



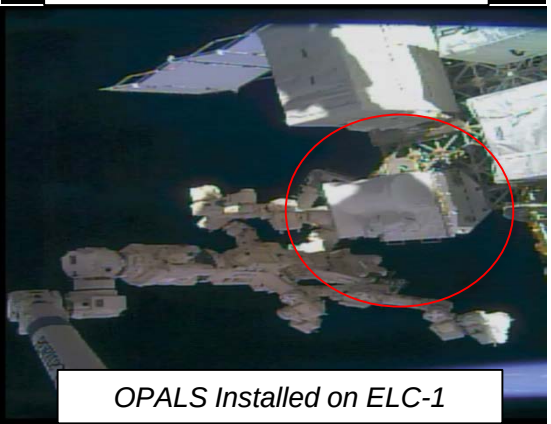
Link Validation



OPALS Mission Timeline

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

OPALS Trunk Extraction



OPALS Installed on ELC-1

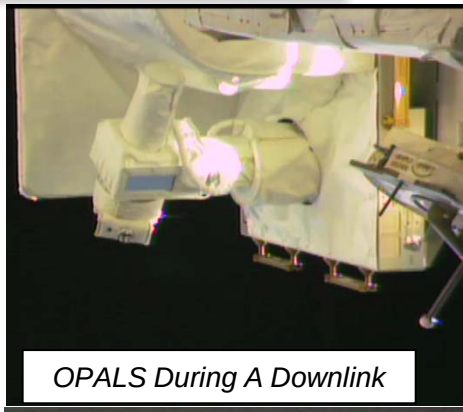
Installation Milestones:

- ✓ SpaceX CRS-3 Launch (4/18/2014)
- ✓ Dragon Docked with ISS (4/20)
- ✓ OPALS Transfer and Installation (5/5-5/7)
- ✓ OPALS Initial Power On and Checkout (5/10)

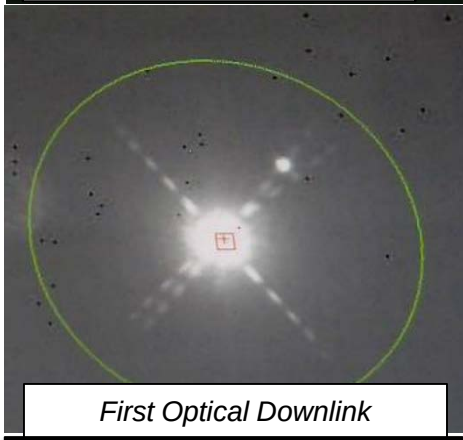
Nominal Mission:

(Dependent on ISS schedule and TMF Visibility)

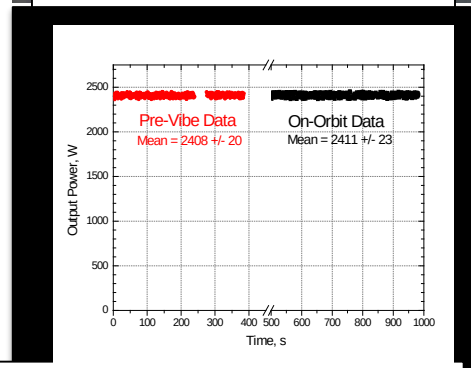
- ✓ Commissioning Phase (5/14-5/31)
- ✓ First Official Video Downlink (6/5)
- ✓ First Daytime Video Downlink (6/12)
- ✓ Low Elevation Transmissions (6/11-6/30)
- ✓ Power & Geometry Variation Testing (7/1-7/31)
- ✓ Pointing Sensitivity Tests (8/1-8/31)
- ✓ PN8 and Engineering Data Downlinks (9/1-9/30)
- ✓ Foreign Ground Station Collaborations (8/15-9/30)
- ✓ Flight Software v1.4 Checkout With DLR (10/13-10/14)
- ✓ Extended AO operations (11/2015-6/2016)



OPALS During A Downlink



First Optical Downlink



Stable laser power on orbit after ~1.5yr

OPALS AO Extended Operations

- Motivation:
  - OPALS demonstrated moderate data rate downlink to free space receiver
  - Higher data rates (> Gbps) possible but requires high speed receivers (smaller active area)
  - Single mode fiber (SMF) required for interfacing to terrestrial fiber network
  - Atmospheric effects limit focused received spot

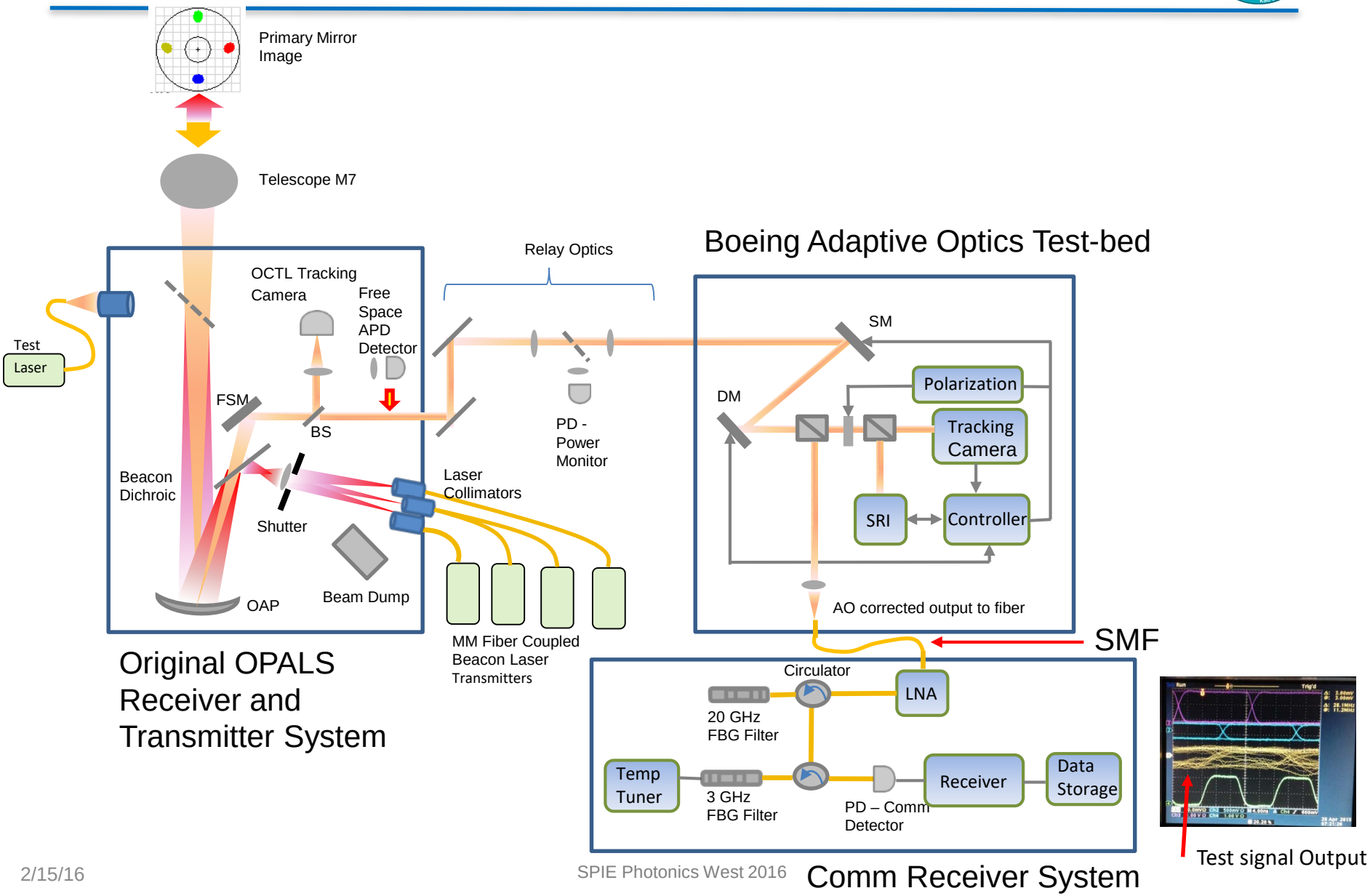
- Approach:
  - Modify the OPALS ground receiver to mitigate atmospheric effects with Adaptive Optics
  - Measure power in fiber (SMF) using optical downlink from OPALS overflight with AO correction
  - Demonstrate communication link with OPALS downlink through AO testbed

- Application:
  - Low cost demonstration of AO correction on fast slewing LEO platform optical downlink

OPALS AO System

- Install Adaptive Optics test bed to OCTL ground receiver
  - Developed by SAIC for Boeing under previous programs
    - multi-Gbps optical links in ground-ground demonstration
  - Self referencing interferometer (SRI) design
  - Fast frame rate wave-front sensor (19 kHz InGaAs camera)
  - Boston Micromachines MEMS 1000-actuator deformable mirror (DM)
  - Polarization loop control on input to balance power splitting in SRI
  - 90% split ratio for input to AO system/comm output
  - SMF output
- Designed to correct high levels of turbulence at fast frame rates
- Relay OCTL pupil image to AO testbed input
- Fiber coupled communication receiver
  - Added communication receiver for full communication link
    - LNA to boost receive signal > 100 nW
    - 2-stage temperature tuned FBG filter (track doppler shifted signal)
      - 3 and 20 GHz for ASE suppression and background rejection
    - OC1 receiver

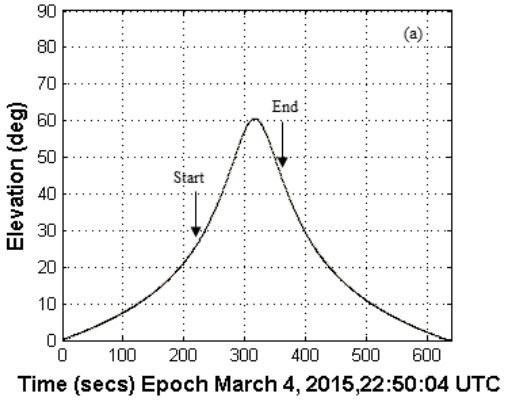
OPALS AO Receiver Test-bed

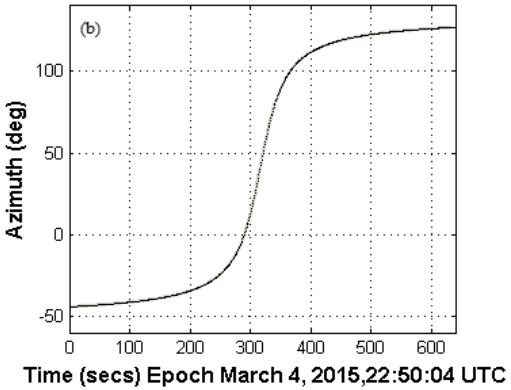


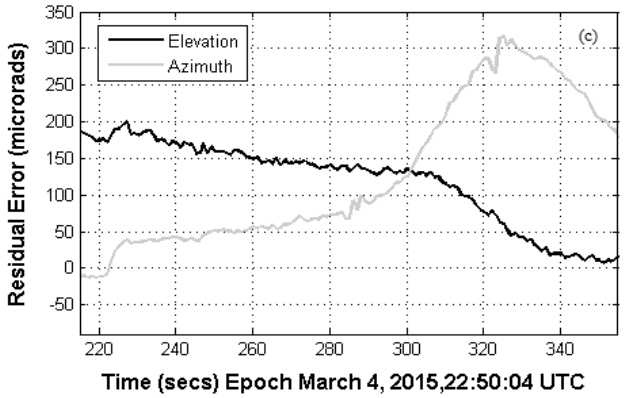
OCTL Tracking Results

Question: was tracking an issue during passes with AO correction?

OCTL telescope Elevation and Azimuth pointing during AO passes



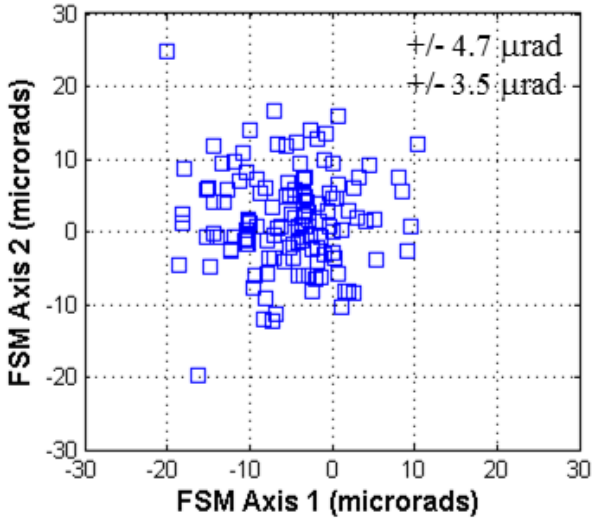


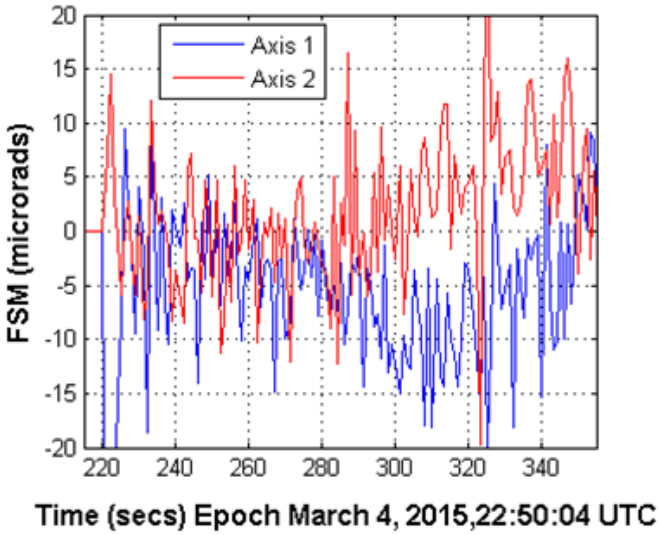


- Residual error between BPT and actual telescope pointing over pass
  - Elevation < 200 µrad
  - Azimuth < 300 µrad

OCTL Tracking Results – FSM

FSM correction of downlink on OCTL acquisition camera



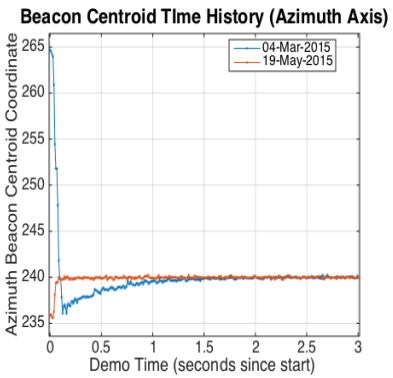


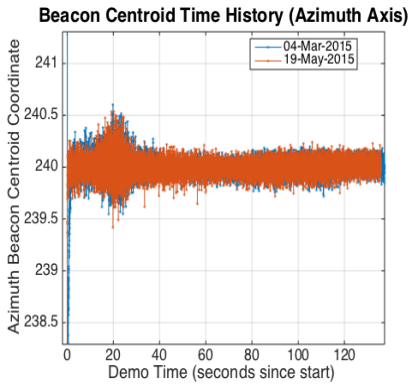
- FSM corrects downlink spot on acquisition camera to center of fov
- 1-sigma error < 5 µrad over pass
- Negligible telescope tracking error to correct over pass

OPALS Tracking Results

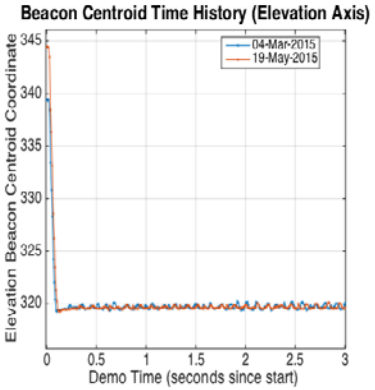
OPALS Flight System tracking (Mar 4 and May 19):

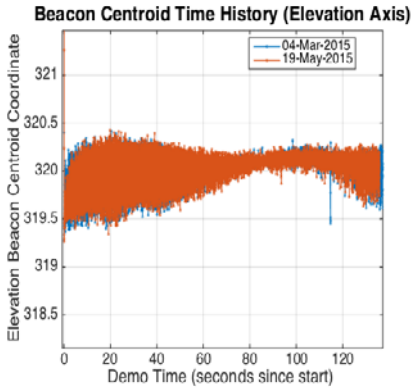
- Azimuth axis



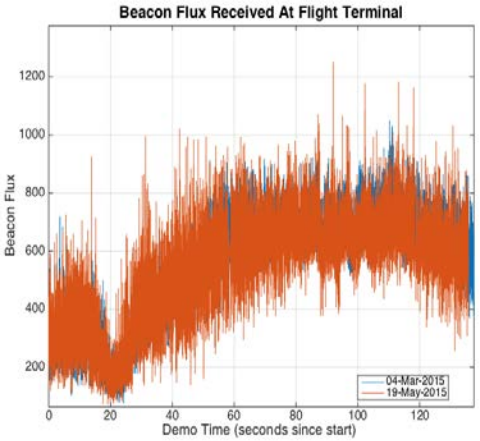


- Elevation axis





OPALS Flight System camera flux:

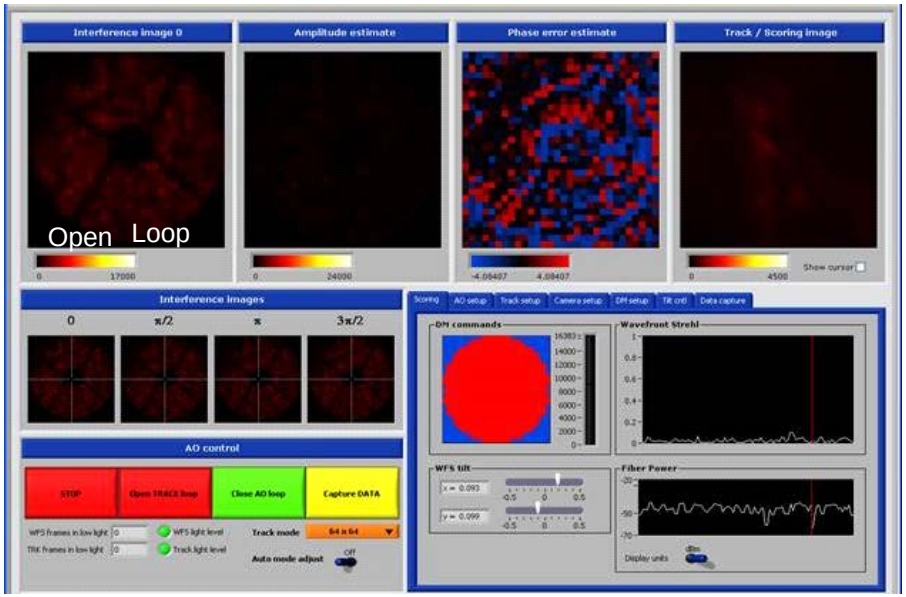


- Initial offset gives prediction error
  - 25, 19 pixels for az, el Mar 4th
  - 4, 24 pixels for az, el May 19th
- Acquisition centered within +/- 0.5 pixel in 1 sec
- Tracking error within +/- 0.5 pixel (133 µrad)
- Increased centroid error at ~ 20 s due to reduced beacon signal flux
  - Beacon geometry – telescope spider and beam walk-off
- Flux in 8x8 pixel area with background subtraction

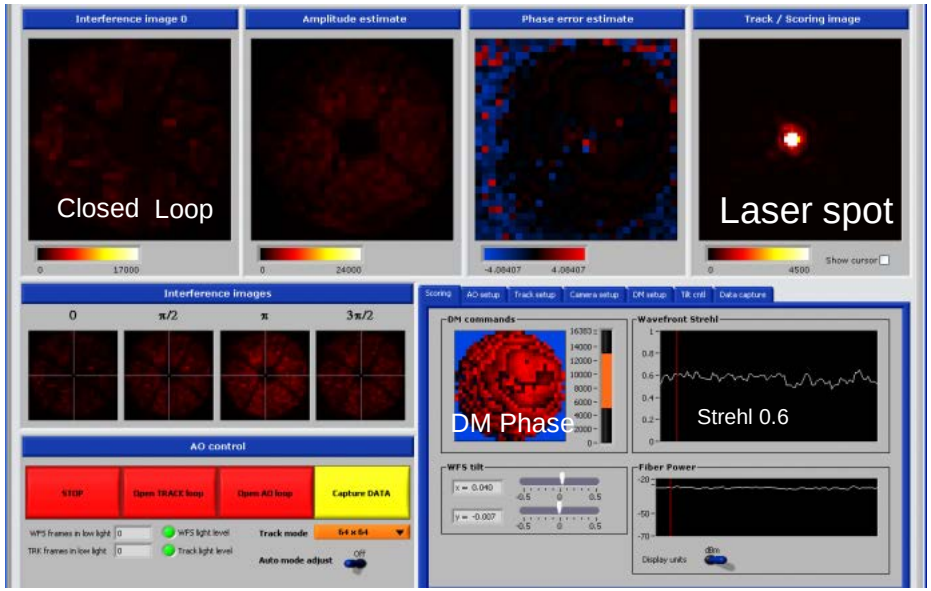
AO Ground Test

Ground – ground optical link demonstrated with AO loop closed

- Transmit and receive channels aligned
- Laser transmitter placed at remote 1.6 km range
- AO correction demonstrated on signal of comparative strength to OPALS downlink
- Power at AO aperture ~ 220 nW and AO loop remained closed as signal decreased



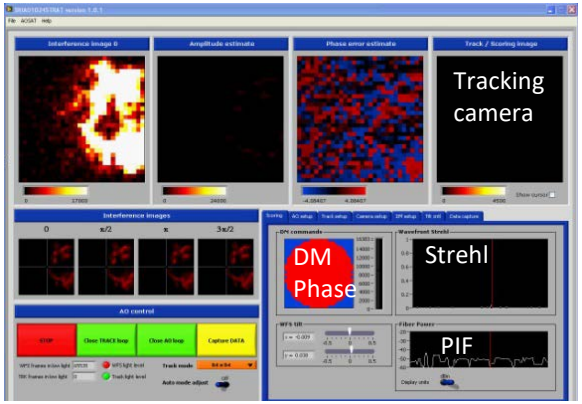
AO Open Loop



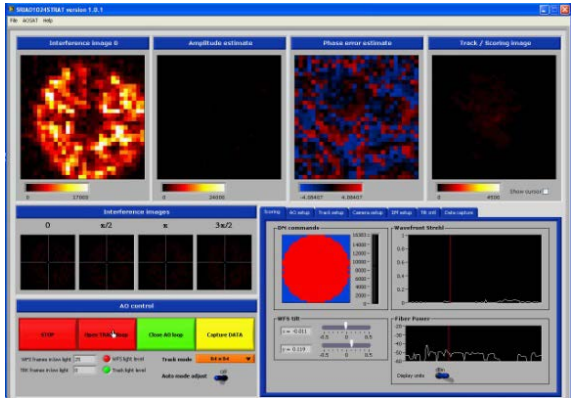
AO Loop Closed

OPALS AO Downlink

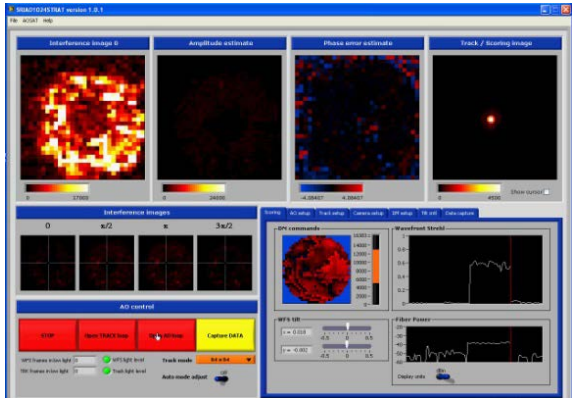
AO correction on OPALS downlink – Mar 4, 2015, 2:54 pm local, clear skies



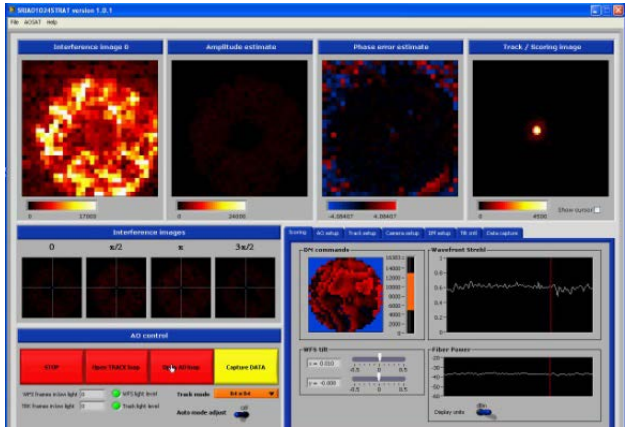
First Light Time 0 sec



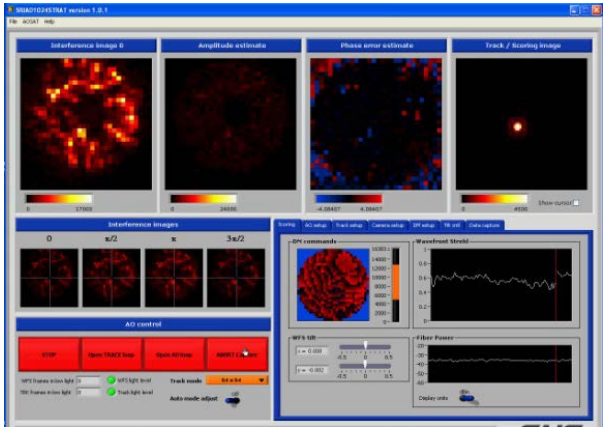
AO track enabled Time 11 sec



AO Closed Loop Time 17 sec

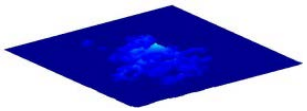


AO Closed Loop Time 68 sec

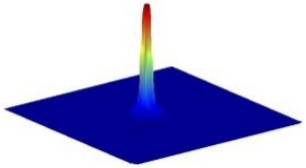


AO Closed Loop Time 134 sec

Received Signal



Open Loop -No AO Correction

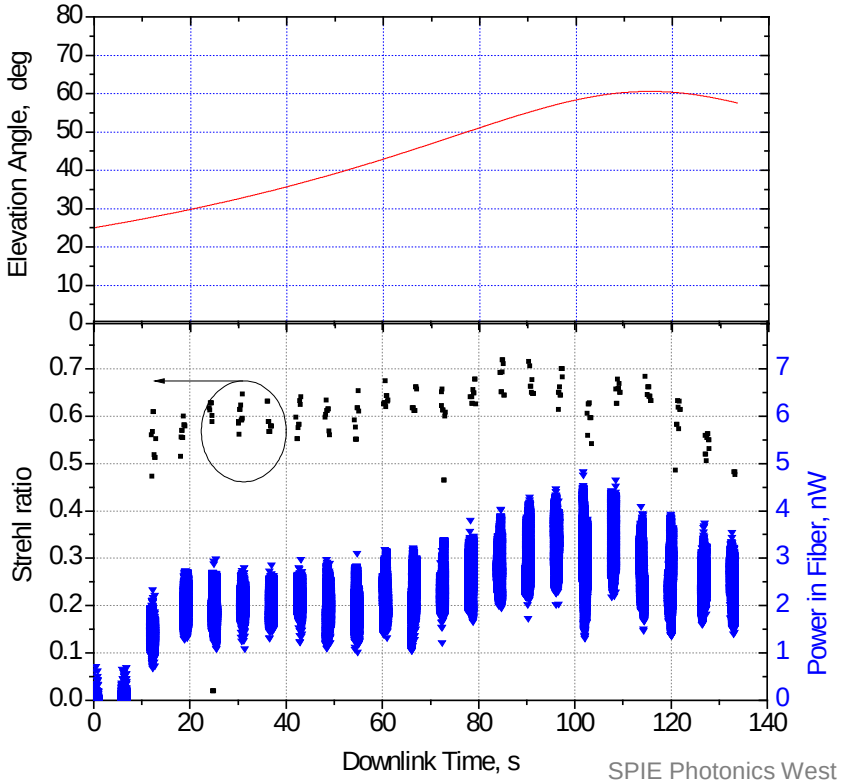


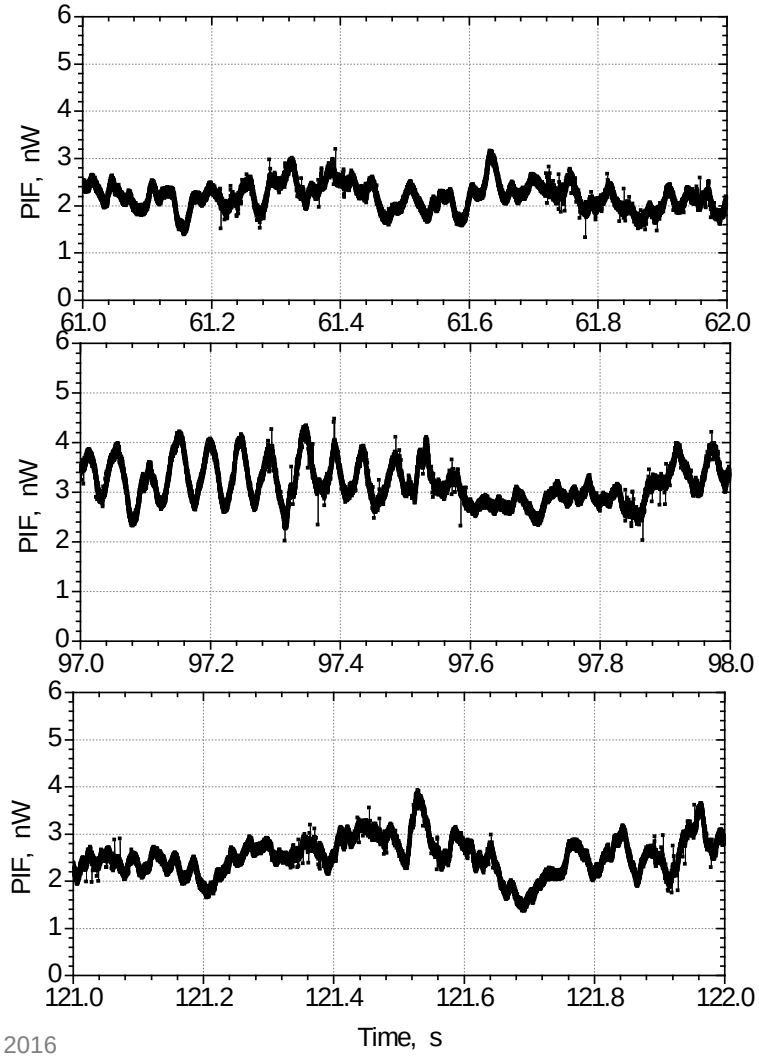
Closed Loop -With AO

OPALS AO Downlink - PIF

Strehl and PIF measured over pass duration

- Strehl computed by residual error from residual wave-front and calibration phase
- Power in SMF sampled at 18 kHz in 1 s samples
- AO tracking camera Strehl ratio
- Power variation but signal > WFS threshold so AO lock for entire pass

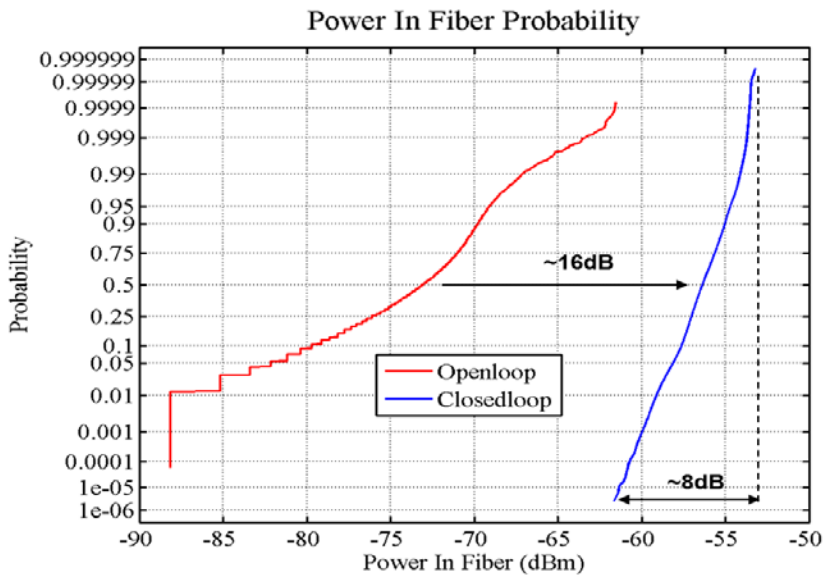


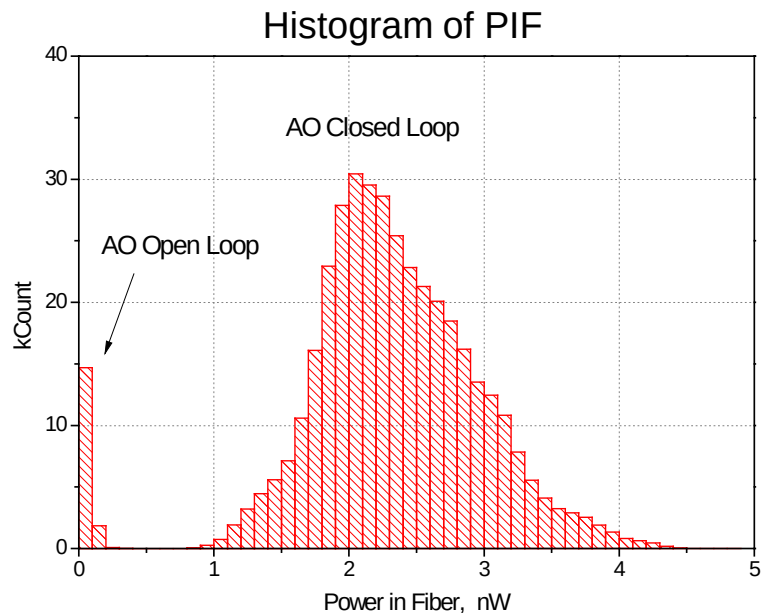


OPALS AO Downlink - PIF

Power in fiber statistics

- Power in SMF 16 dB improvement in the mean when AO loop closed
- Lower signal variation during closed loop AO operation
  - Stable communication link
- Low received power due 90% received signal to AO system



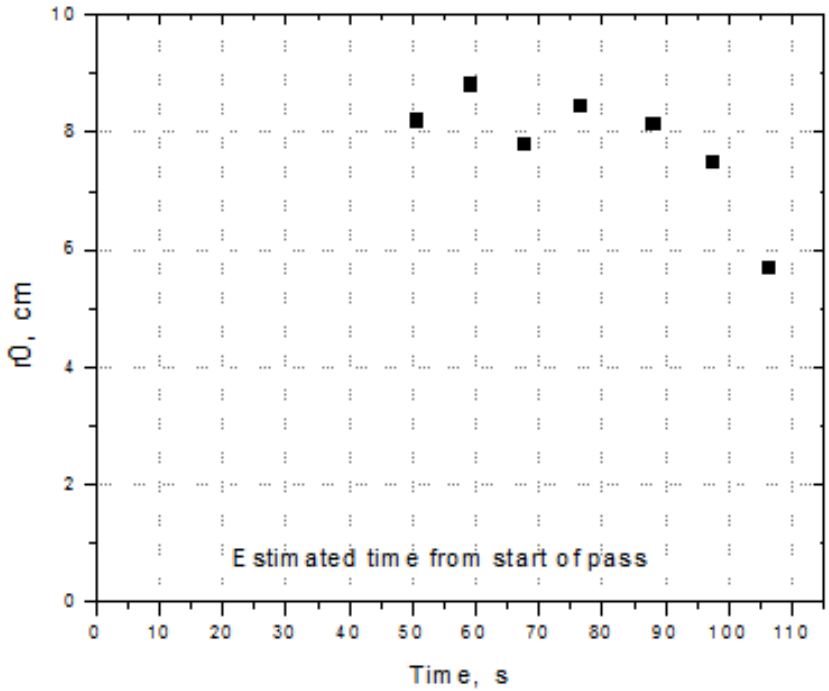


AO correction over the entire pass with stable power in the fiber (SMF)

OPALS AO Downlink – r_0

Atmospheric characterization using Fried parameter, r_0

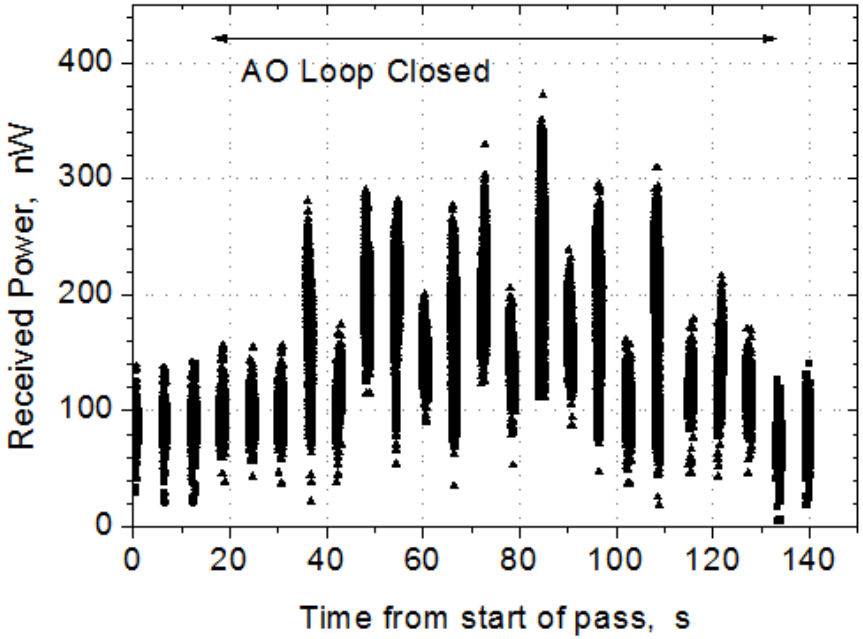
- At 1550 nm
- Using modulation transfer function method validated against calibrated phase screen
- Total input disturbance includes DM commands and residual wave-front measured error
- Each value is from 1000 frames at 18 kHz (55 ms)
- Slew rate increases as air mass is reduced so not a static r_0 measurement

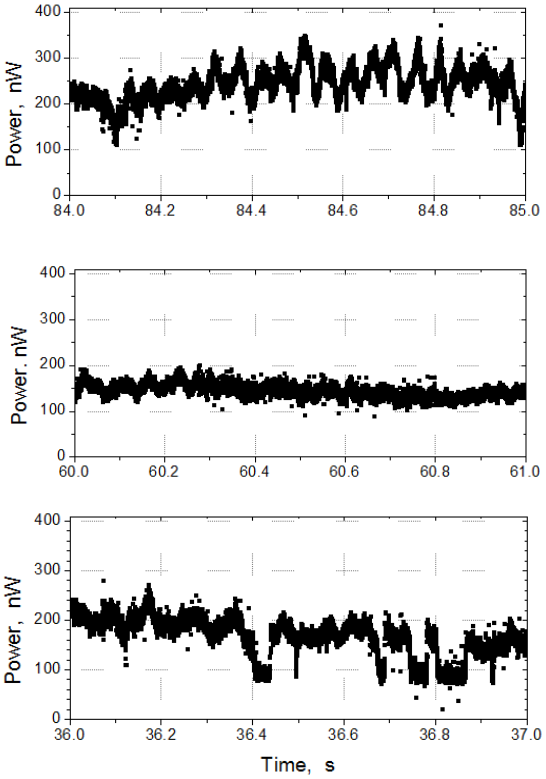


OPALS AO Downlink – Comm Link

AO correction on OPALS downlink – May 19, 2015, 9:41 am, clear skies

- Communication receiver added following SMF output with LNA
- PIF measured from tap after LNA
- Dropouts due to weak signal on WFS

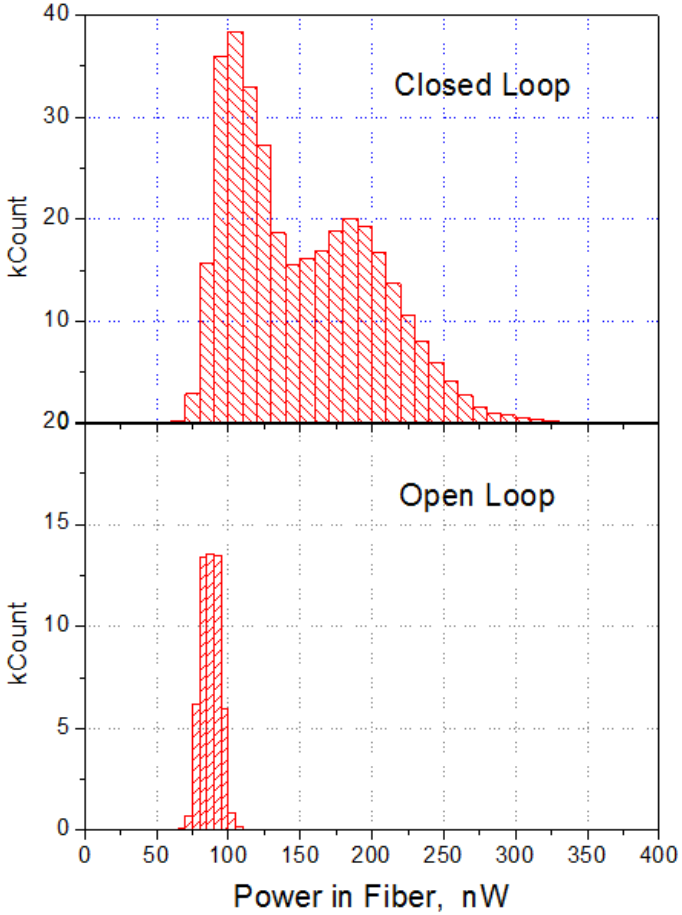


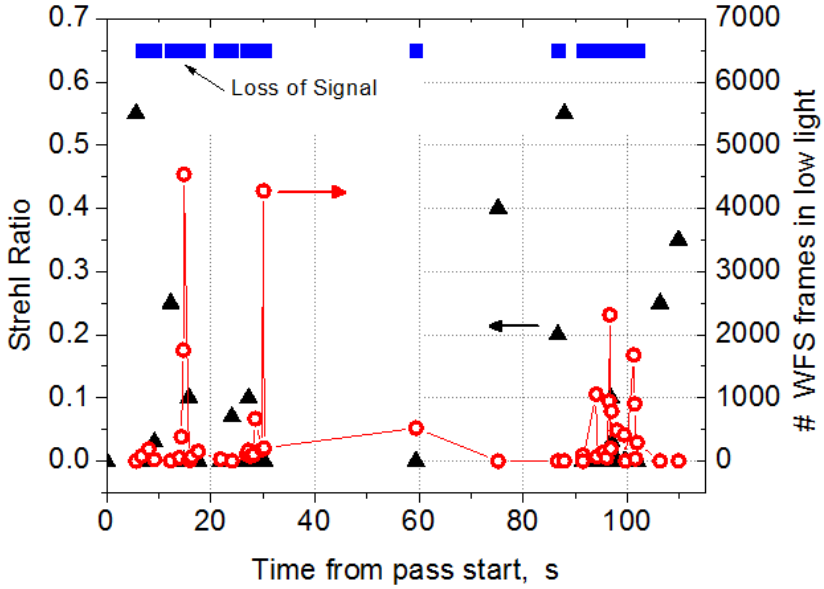


OPALS AO Downlink – Comm Link

AO correction on OPALS downlink with communication link

- Intermittent link
- Loss of signal on WFS



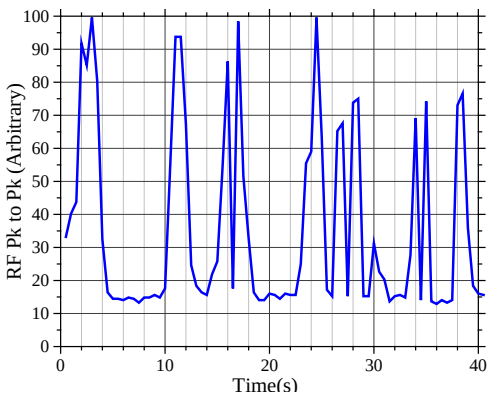


OPALS AO Downlink – Comm Link

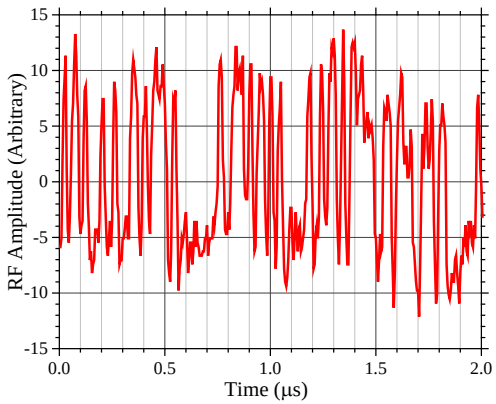
Communication signal during AO correction

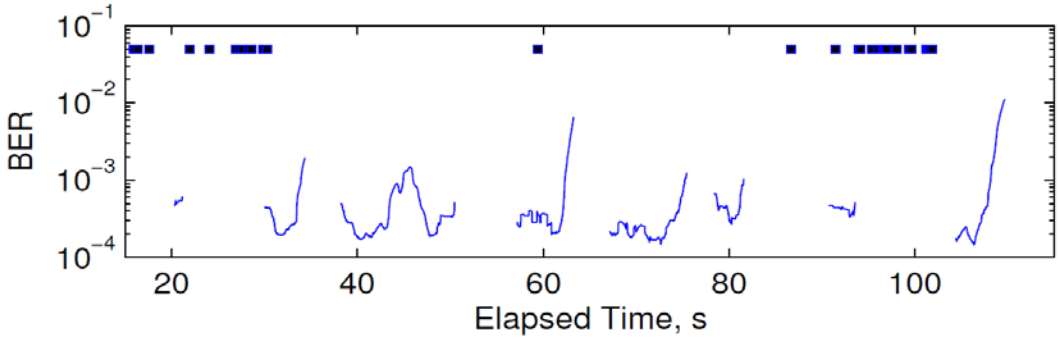
– Signal captured intermittently

Data Signal RF Amplitude



Snapshot of PD output





- Full downlink video recovered in post-processing
- OPALS video looped on downlink (~ 3.5 s)
- s/w RS decoder
- BER from error counts:
  - Gaps when no code word synchronization or too many errors.
- Intermittency sources:
  - Received power dropouts
  - Temp tuning of receive filter
  - Clock recovery in CDR

First LEO-Ground optical communication link into SMF demonstrated with AO correction on the downlink signal through 1-m receive aperture

Conclusion

- OPALS ground station upgraded with AO testbed
- Successively demonstrated full AO correction on optical downlink from fast slewing LEO platform
- Stable power in the fiber of AO corrected signal possible during entire pass
- Established successful communication link during AO correction with intermittent received signal

- Future plans:
  - High rate ground – ground demonstrations with AO correction
  - Airborne tests of high rate optical communications with multi-Gbps

Acknowledgements

We gratefully acknowledge the support of:

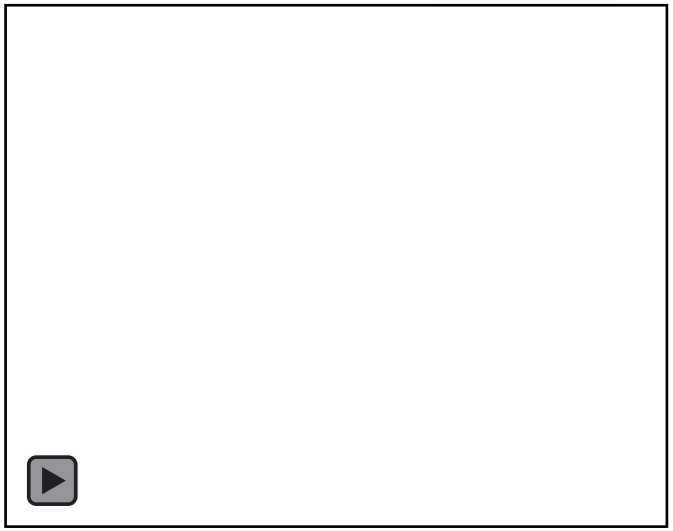
- **NASA, HQ -** Don Cornwell, SCaN Program Office
- **The Boeing Company** - Peter Chu, Advanced Technologies, Network and Space Systems

Backup

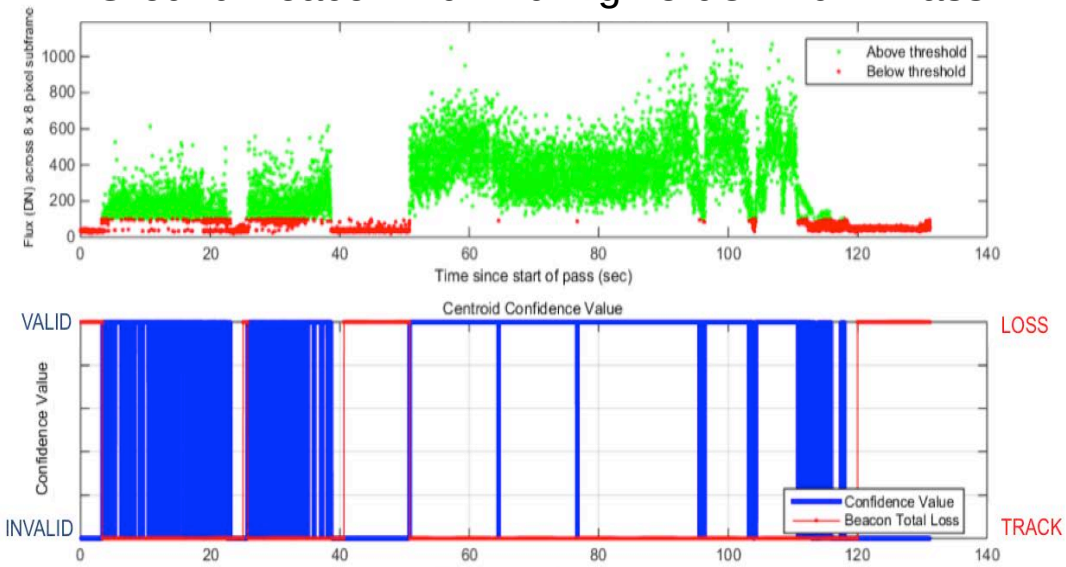
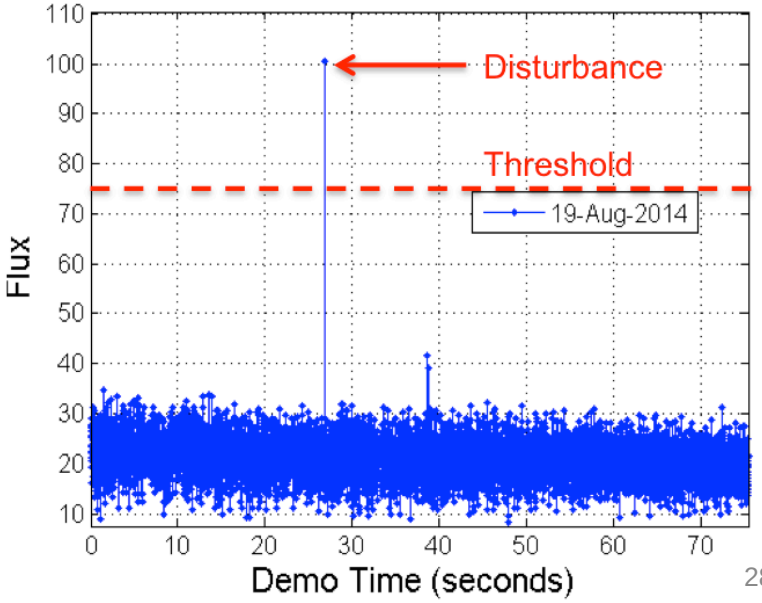
2014 6 6
3:21:55

Partly Cloudy Acquisitions

- Clouds often complicate the acquisition process
- On July 15, four cloud interruptions occurred
  - Resulted in late initial acquisition followed by two successful reacquisitions
- On August 19, a single disturbance sent OPALS into tracking mode prior to first beacon detection
  - The resulting loss of pointing calibration (from sudden accelerations) prevented beacon reacquisition
- Reacquisitions are successful if optical disturbances are not present



Ground Beacon Flux During 15-JUL-2014 Pass



Ground Beacon Flux During 19-AUG-2014 Pass