On-orbit Measurement of ISS Vibrations during OPALS Extended Mission Operations

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Outline

OPALS Operations on ISS

OPALS Flight System Overview

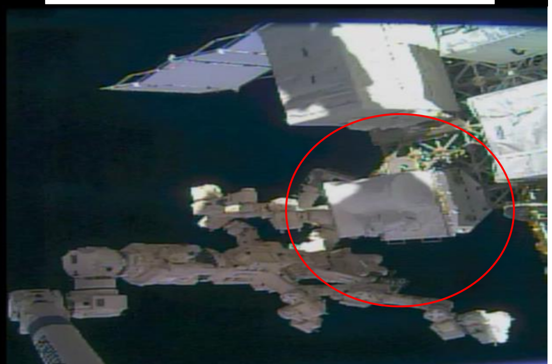
Experiment Motivation & Design

Data Processing Approach

Results Summary

OPALS Operations on ISS

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)

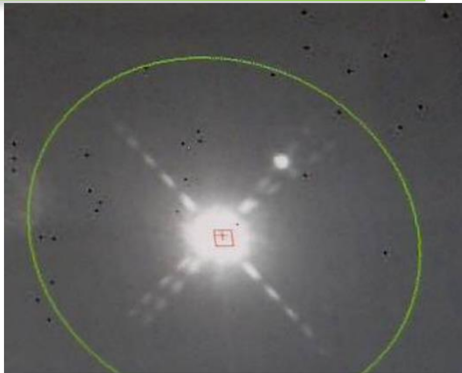
- ✓ Launched to ISS (April ’14)
- ✓ Commissioning Phase (May ‘14)
- ✓ First Official Video Downlink (6/5/14)
- ✓ First Daytime Video Downlink (6/12/14)
- ✓ Low Elevation Transmissions (June ‘14)
- ✓ Geometry/Pointing Sensitivity Tests (Jul-Aug‘14)
- ✓ PN8 and Engineering Data Downlinks (Sep ‘14)
- ✓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

Extended Mission Milestones:

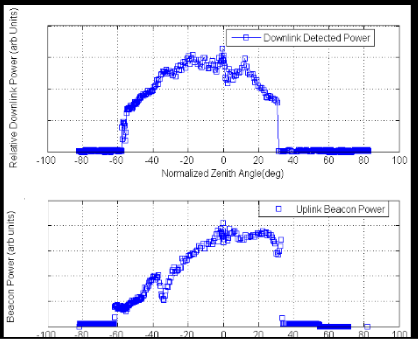
- ✓ Adaptive Optics Tests with Boeing (Jan-May ‘15)
- ✓ **ISS Platform Vibration Experiment (Aug ‘15-Apr ‘16)**
- ✓ Transmissions to DLR (Oct-Dec ‘15)
- ✓ Transmissions to ESA (Jan-Feb ‘16)
- ✓ Transmissions to CNES (Mar ‘16-Jan ‘17)

Decommissioning:

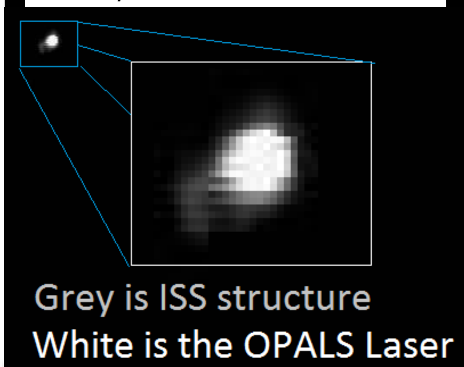
- SpaceX CRS-10 (Mar ‘17)



First Optical Downlink

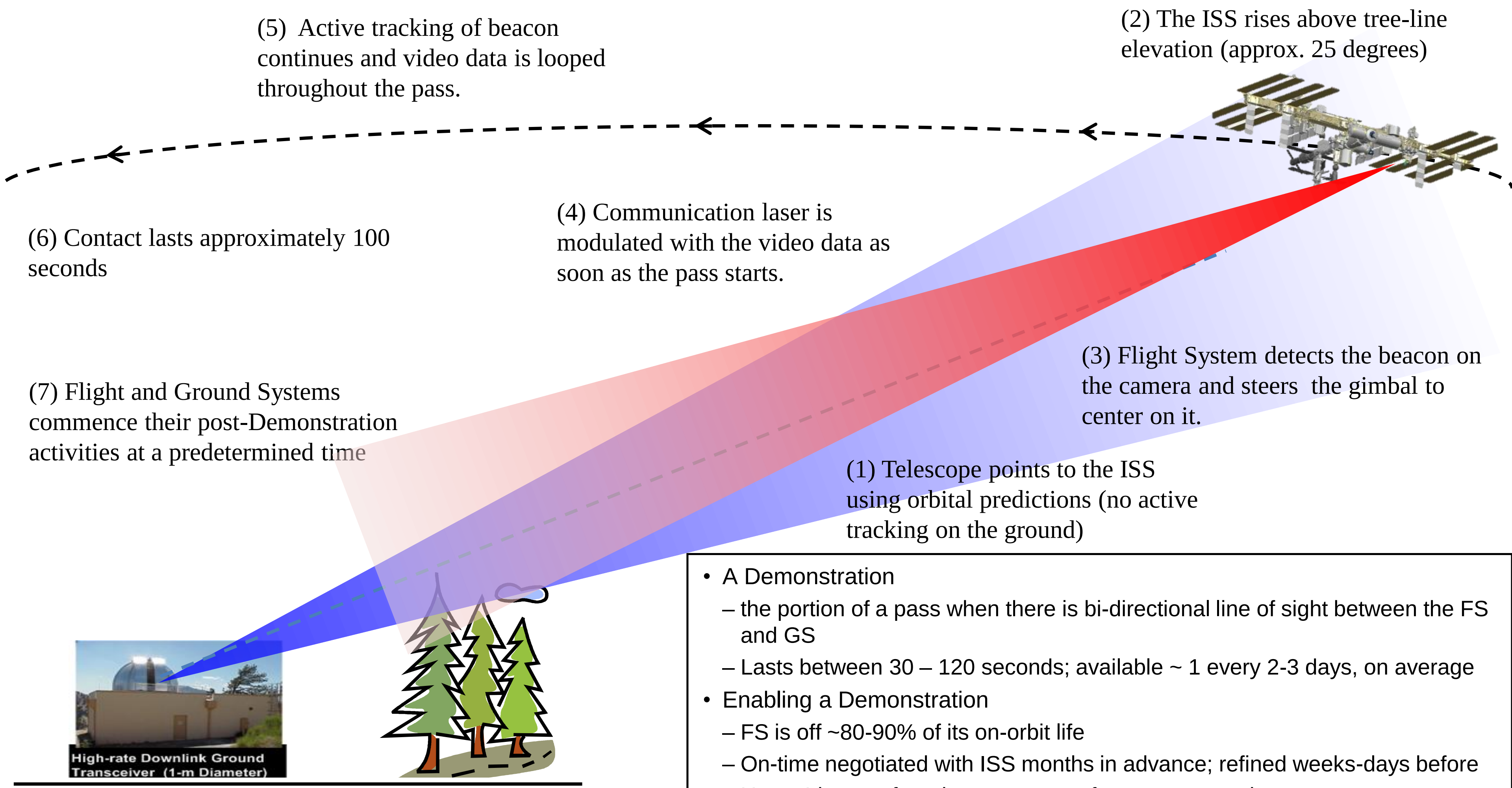


Optical Link Validation



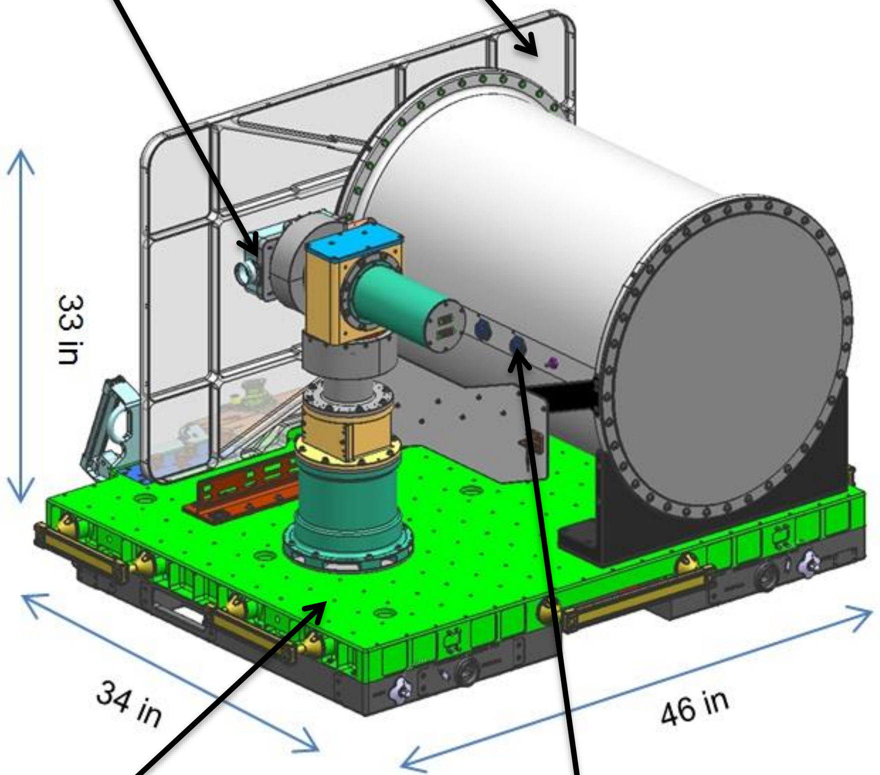
ESA Signal Acquisition at Tenerife

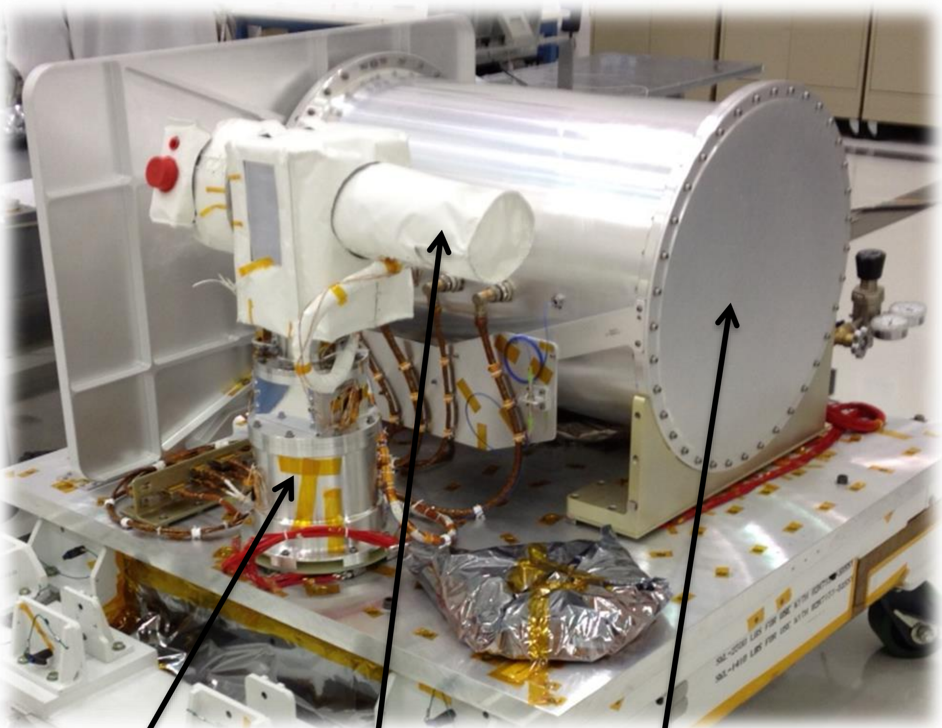
Typical Downlink Scenario



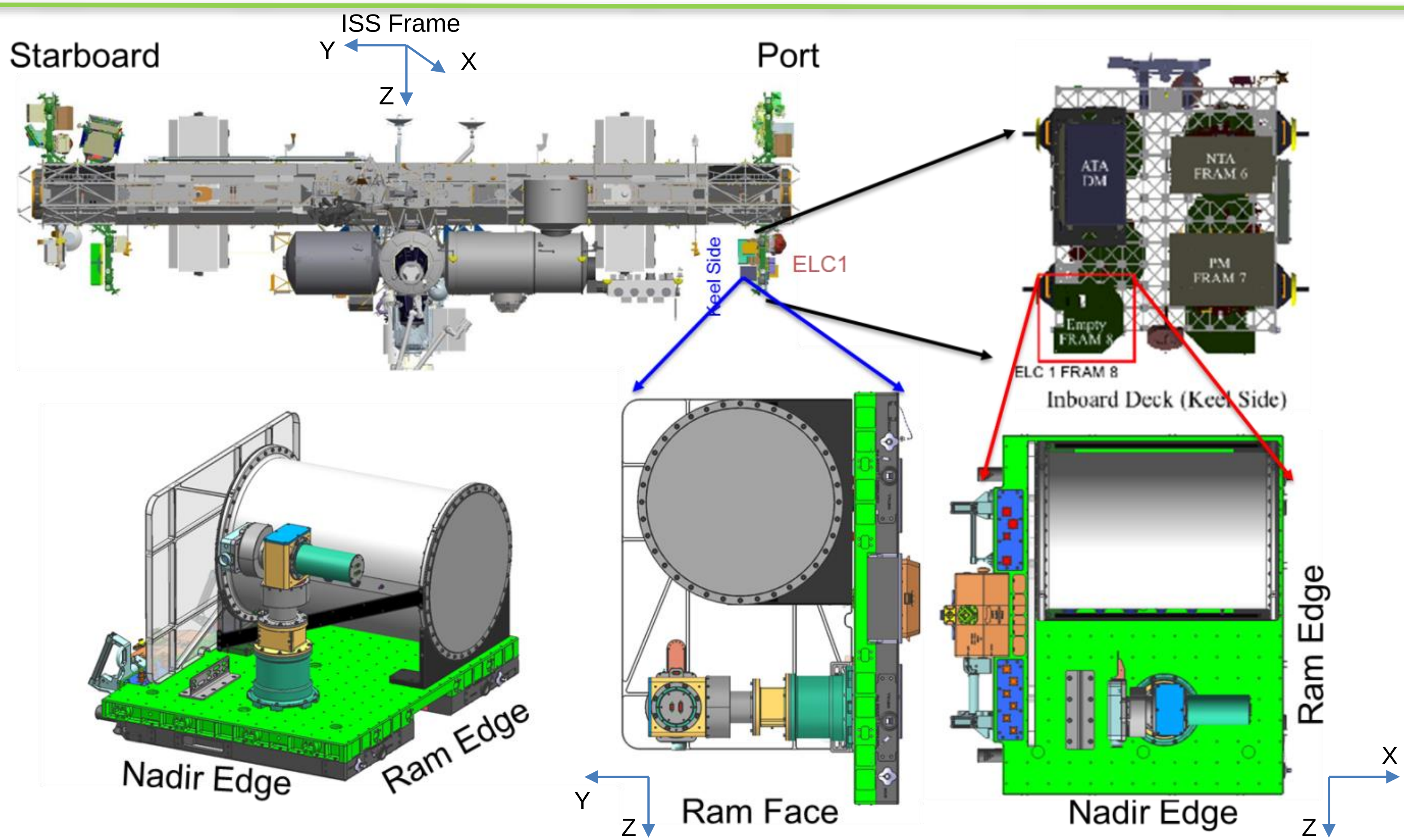
- A Demonstration
  - the portion of a pass when there is bi-directional line of sight between the FS and GS
  - Lasts between 30 – 120 seconds; available ~ 1 every 2-3 days, on average
- Enabling a Demonstration
  - FS is off ~80-90% of its on-orbit life
  - On-time negotiated with ISS months in advance; refined weeks-days before
  - Up to 4 hours of on-time to prepare for, execute, and wrap-up a demonstration

Flight System Highlights





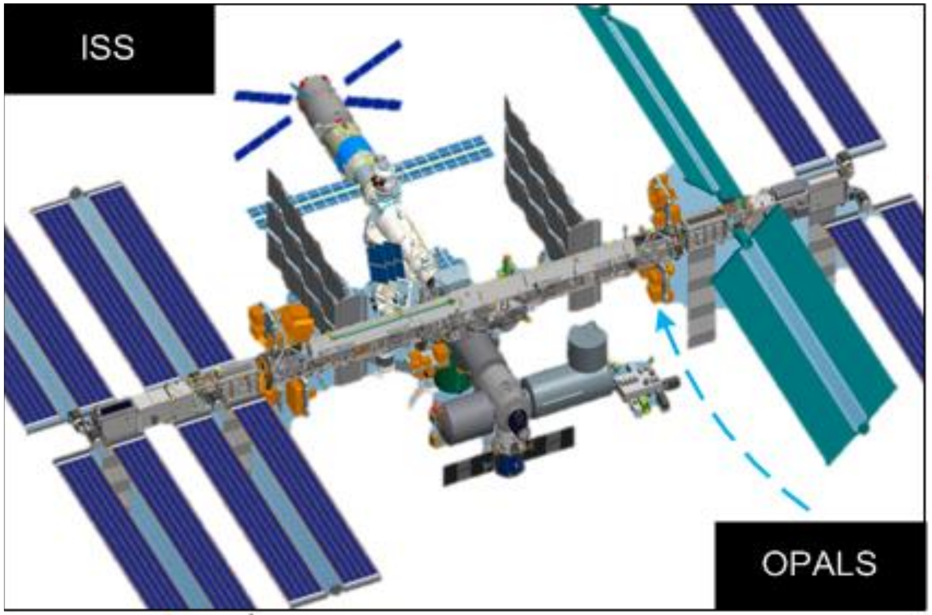
OPALS on ISS



OPALS gimbal actuation in Azimuth ~maps to pitch about ISS +Y
OPALS gimbal actuation in Elevation ~maps to roll about ISS +X

Vibration Experiment Overview

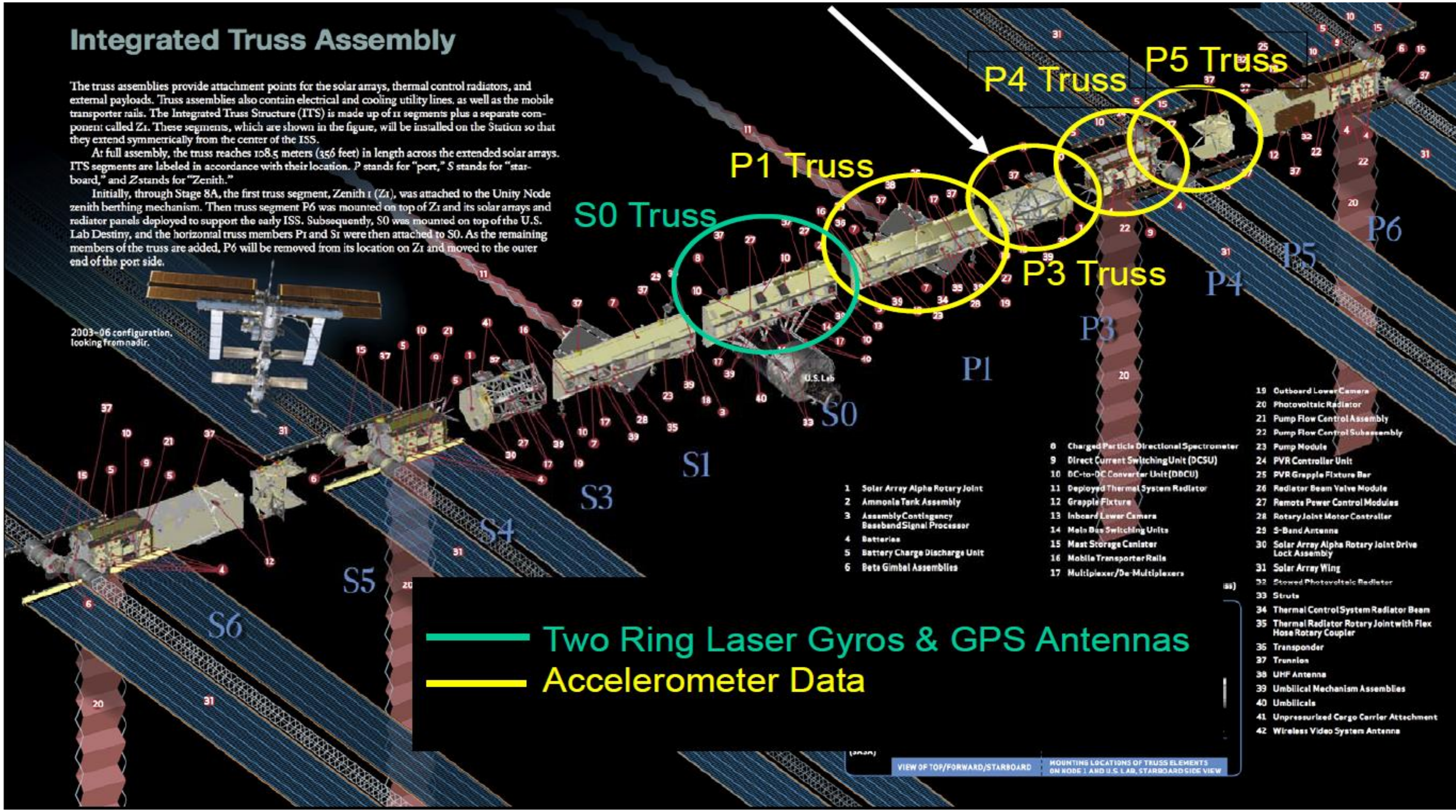
- Can OPALS be repurposed to measure vibration properties from an external payload site (ELC1 FRAM8)?



- OPALS can capture angular measurements using:
  - Wide FOV camera with 100 Hz frame rate
  - Two-axis gimbal with azimuth and elevation axes
  - Ground-referenced laser beacon

- **Motivation:** Detailed understanding of the International Space Station vibration environment has been of high interest to payload developers. The availability of such information, however, especially measured data, has been scarce. Existing IMUs are not located at external payload sites; OPALS measurements on ELC1 can serve as a complementary data set
- **Experiment:** OPALS captures 100 Hz camera imagery of a ground reference beacon and attempt to isolate the ISS contribution to the jitter detected by the camera

Existing ISS Sensor Data



The relatively low frequency cutoff and lack of direct angular measurements from ELC sites make it challenging to assess the ISS contribution to jitter-induced effects on optical systems.

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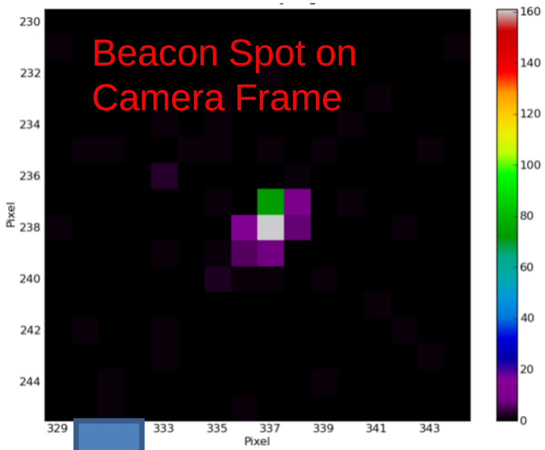
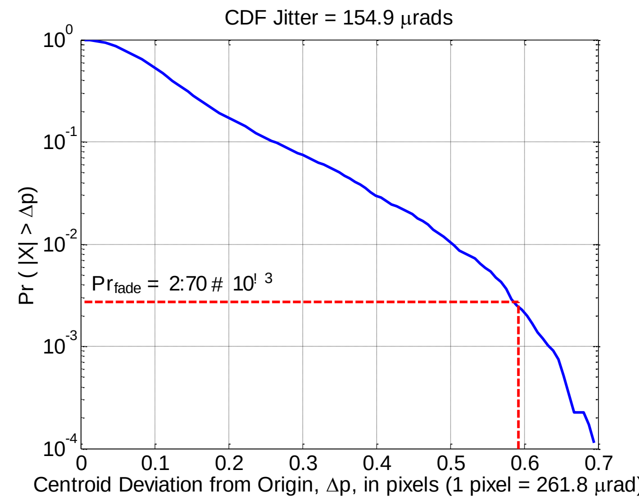
Total System Jitter

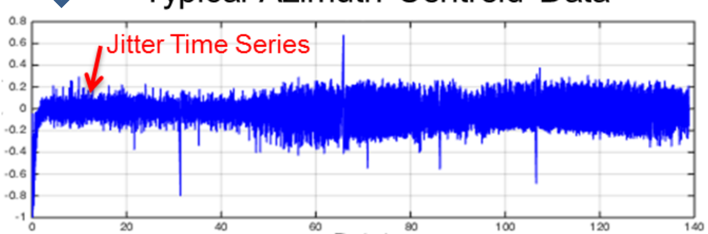


The Total System Jitter measured during a typical downlink includes:

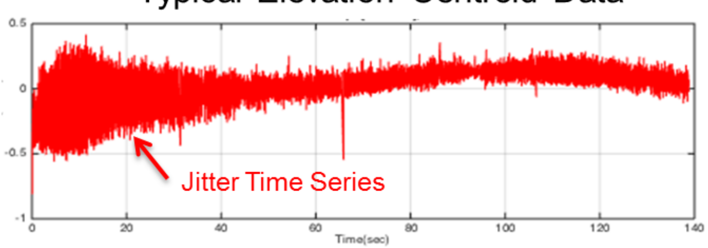
- ISS Contributions
- OPALS Contributions
  - Gimbal vibrations
  - Centroid algorithm artifacts/errors



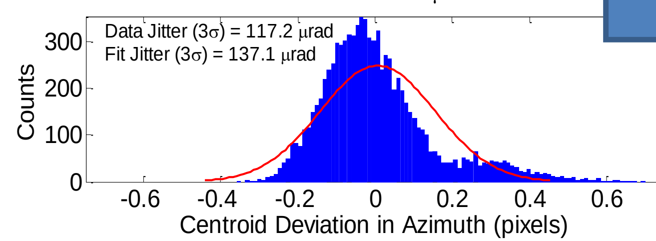
Typical Azimuth Centroid Data

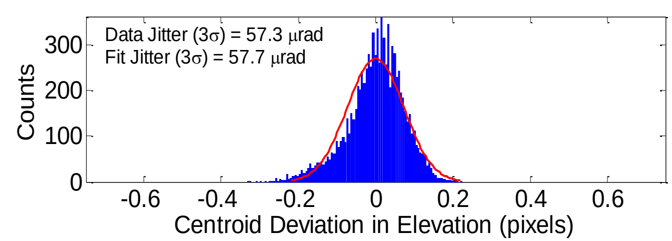


Typical Elevation Centroid Data



Data Jitter = 130.4 µrads;
Fit Jitter = 148.6 µrads

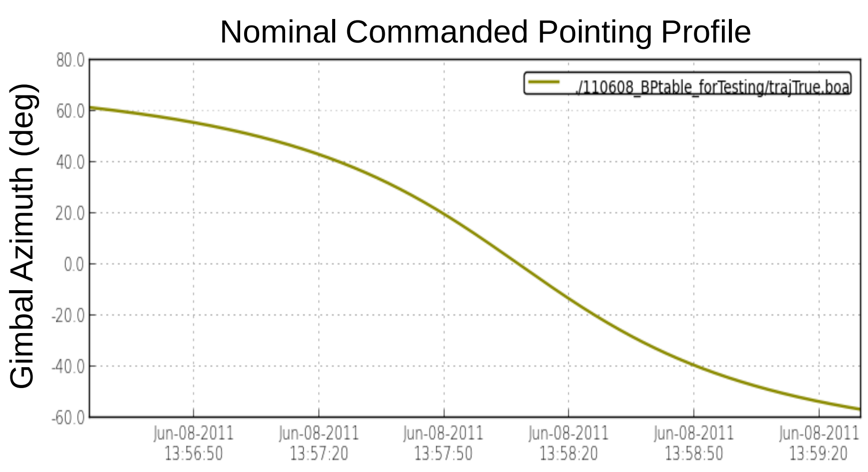


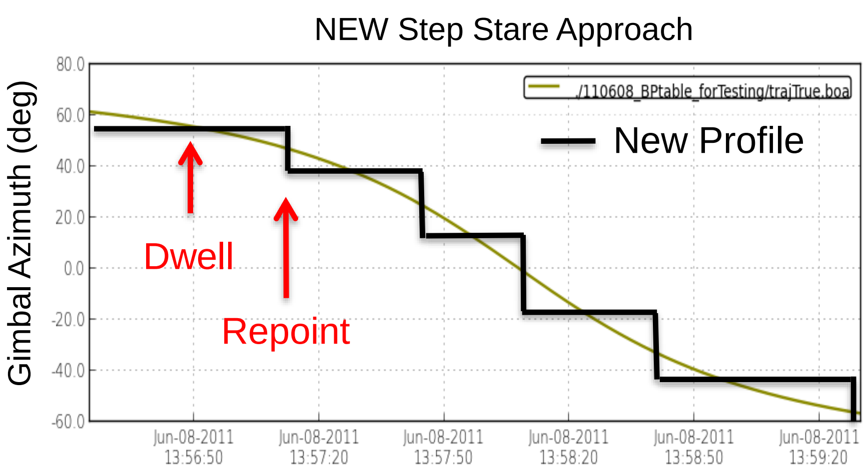


Oaida, B.V.; *et al* "Impact of pointing performance on the optical downlink for the Optical PAyload for Lasercomm Science (OPALS) system" Proc. ICSOS 2014, S3-1, Kobe, Japan, May 7-9 (2014).

Vibration Experiment Design

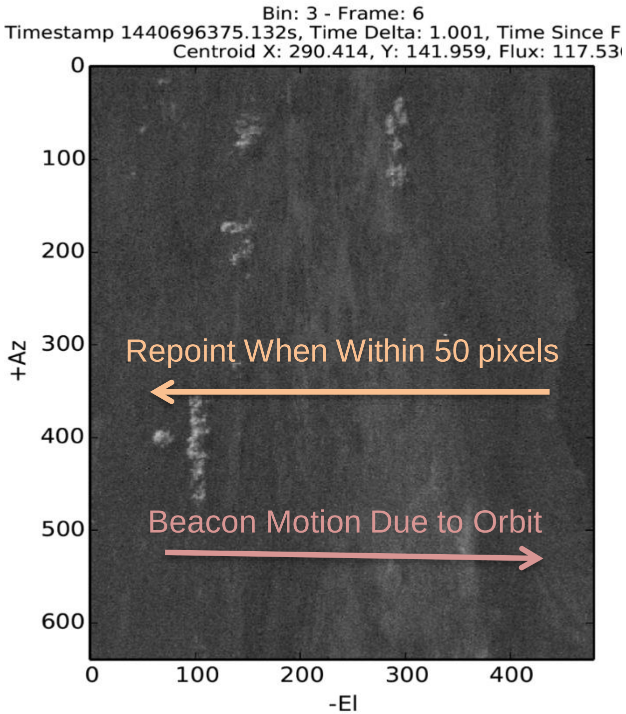
- For this experiment, the gimbal pointing must be fixed during measurement periods
  – Intended to isolate motor vibrations from platform vibrations
  – Periodic repoints must be executed to retain the beacon in the camera FOV
- To isolate the ISS contributions, the following approach is taken:
  – **Propagate** ISS state vector to over-flight segment and **compute** open loop pointing
  – **Modify** the open loop pointing to have a step-stare profile, with multiple dwell periods with no gimbal movement (beacon should move left to right across CCD)
  – **Uplink** the step-stare pointing profile to OPALS for execution
  – Following the pass, **remove** the slew periods, **de-trend** the orbital motion, **remove** systematic errors, **compute** PSDs and jitter



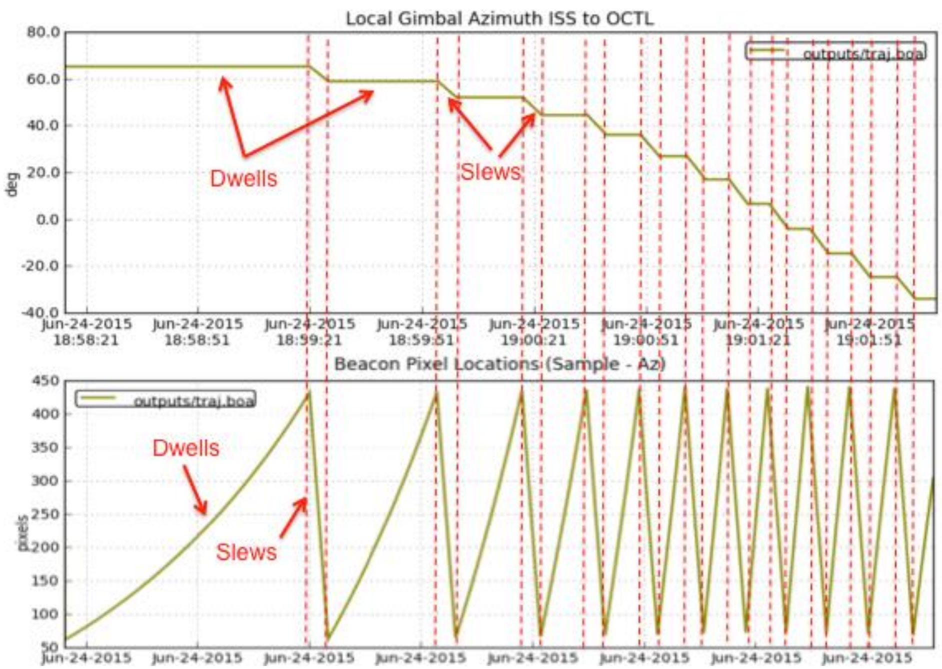


Computing the Step-Stare Profile

- Assumptions:
  - Begin observations at 10 deg rise above horizon
  - Update pointing any time beacon is within 50 pixels of camera edge (0.75 deg)
  - Look ahead in azimuth to compensate for orbital motion
  - Re-center elevation coordinate
  - Assume 5 seconds for pointing update slew
- Dwell characteristics: Longest dwell: 65 sec; shortest dwell: 5.8 sec
  - Tradeoff: Longest dwells have more content, but lower SNR due to greater slant range



Predicted Beacon Motion



Data Post-Processing

[Step 1] **Clean & Segment AZ data** (into 12 segments)

[Step 2] **Detrend data**: Fit each segment separately with a 16^{th} order polynomial and remove as trend

[Step 3] **Compute PSD** of detrended data

- Treat segments as independent and identically distributed realizations of the same stochastic process
- Pad segments with zeros to accommodate non-commensurate data lengths and ensure fine frequency sampling grid (nfft=2^14=16384)

[Step 4] **Descurve data**: Remove S-curve error from each segment using same-axis pixel period

- Reparametrize time in terms of pixel crossings (using 16^{th} order polynomial detrend), and assume S-curve has a 1 pixel-per-pixel period
- Fit single tone S-curve model to data using least squares in pixel-pixel coordinates, and then remove S-curve fit and replot on time axis (Higher harmonics are ignored)

[Step 5] **Double-Descurve data**: Repeat Step 4 by additionally removing S-curve error from each segment using cross-axis pixel period

[Step 6] **Compute PSDs of Descurved data and Double-Descurved** data (after applying a linear detrend to each segment) and compare results

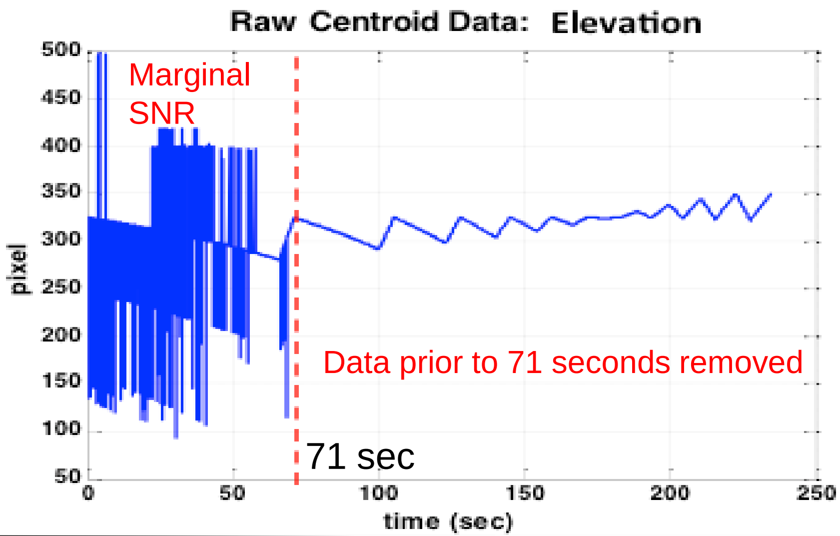
[Step 7] **Repeat for EL data**

Nomenclature

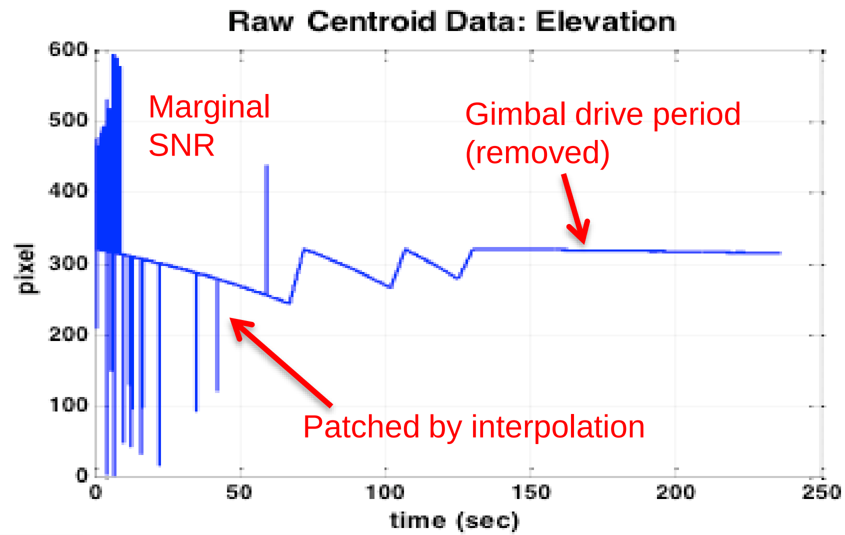
- "Descurve" (De-S-Curve) verb: remove S-curve signature from data using same-axis pixel period
- "Descurved data" = data that has had its same-axis S-curve signature removed
- "Double-Descurve"= remove both same-axis and cross-axis S-curve signatures

Raw Optical Centroid Data (EL Axis)

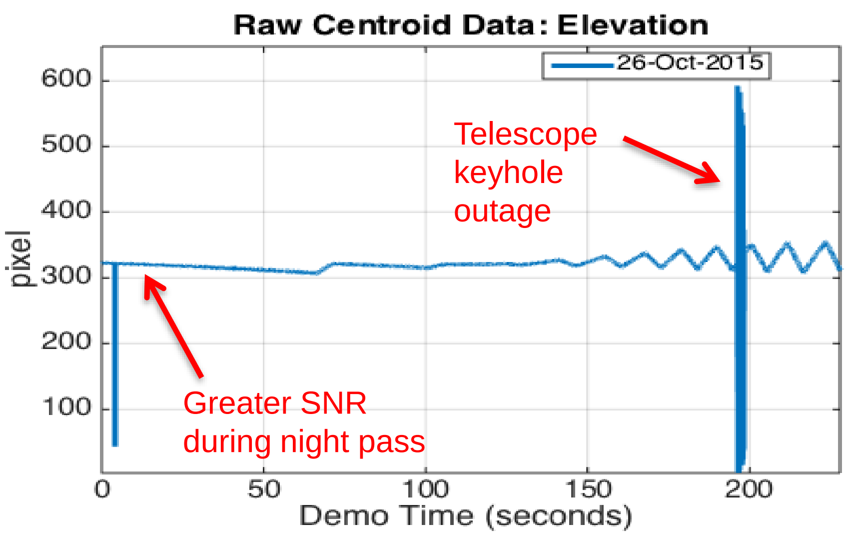
GMT 239



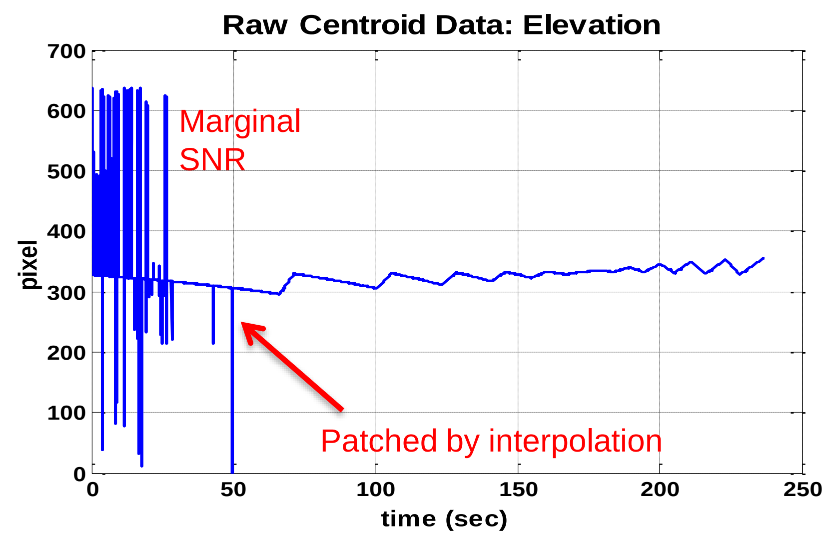
GMT 260



GMT 300



GMT 096



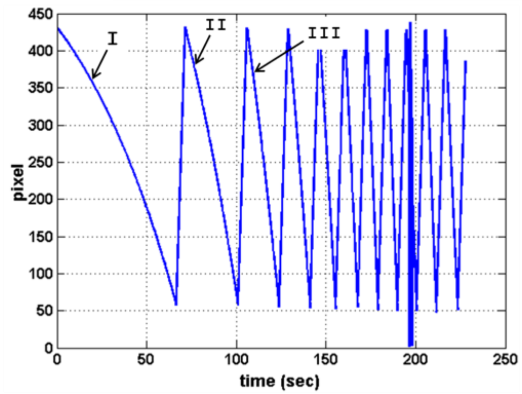
Step 1-3: Cleanup, Segmentation, Detrend & PSD

Cleanup
- Each dropped data grouping is cleaned by replacing it with a linear interpolant to its good data points on either side of the grouping.
- Because of the number of dropped data points is low (typically less than 10 out of 10,000), the cleaning has minimal impact on subsequent time series analysis.

Segmentation
- The data is segmented into Arcs I, II and III.
- For 1 Hz lowest frequency need data segments of approximately 10 sec duration.
- This gives a total of 12 data segments of approximately 10 secs each for further processing.

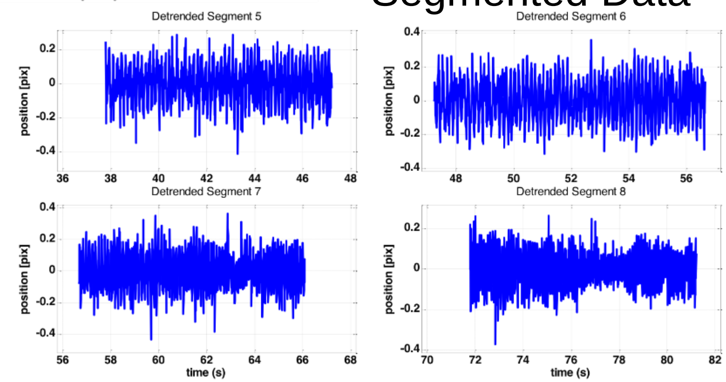
Detrending
- Data must be detrended for ISS orbital motion
  - Use a 16th order polynomial fit to remove orbital motion and attitude drift

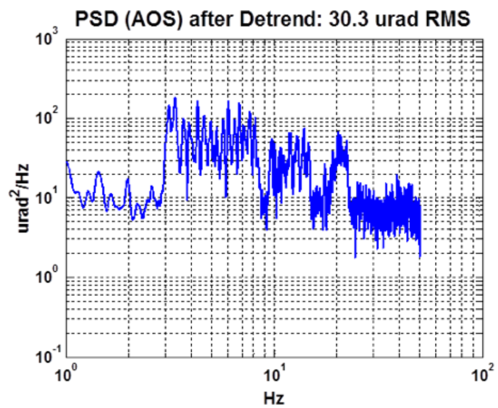
PSD Generation
- PSDs are doubled in magnitude and plotted only over positive values of frequency



Segmented Az Data

Detrended Segmented Data





Power Spectral Density of Detrended Data

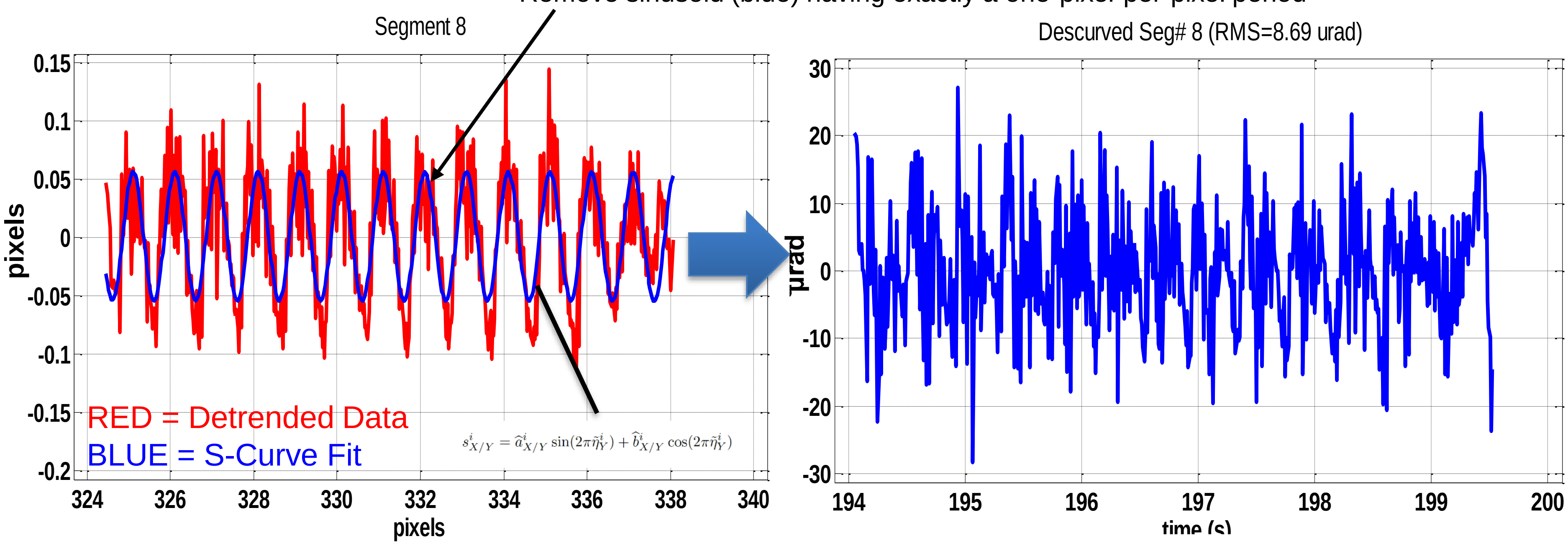
Step 4: De-S-Curve

A systematic error is present each time a pixel boundary is crossed

- S-curve error is a pixelation effect associated with centroiding that occurs as the source image is dragged over the periodic pixel boundaries of the detector.
- The “S-curve” artifact is removed by first plotting the detrended data in pixels-versus-pixels coordinates, and then fitting and subtracting out the 1-pixel-per-pixel period sinusoid

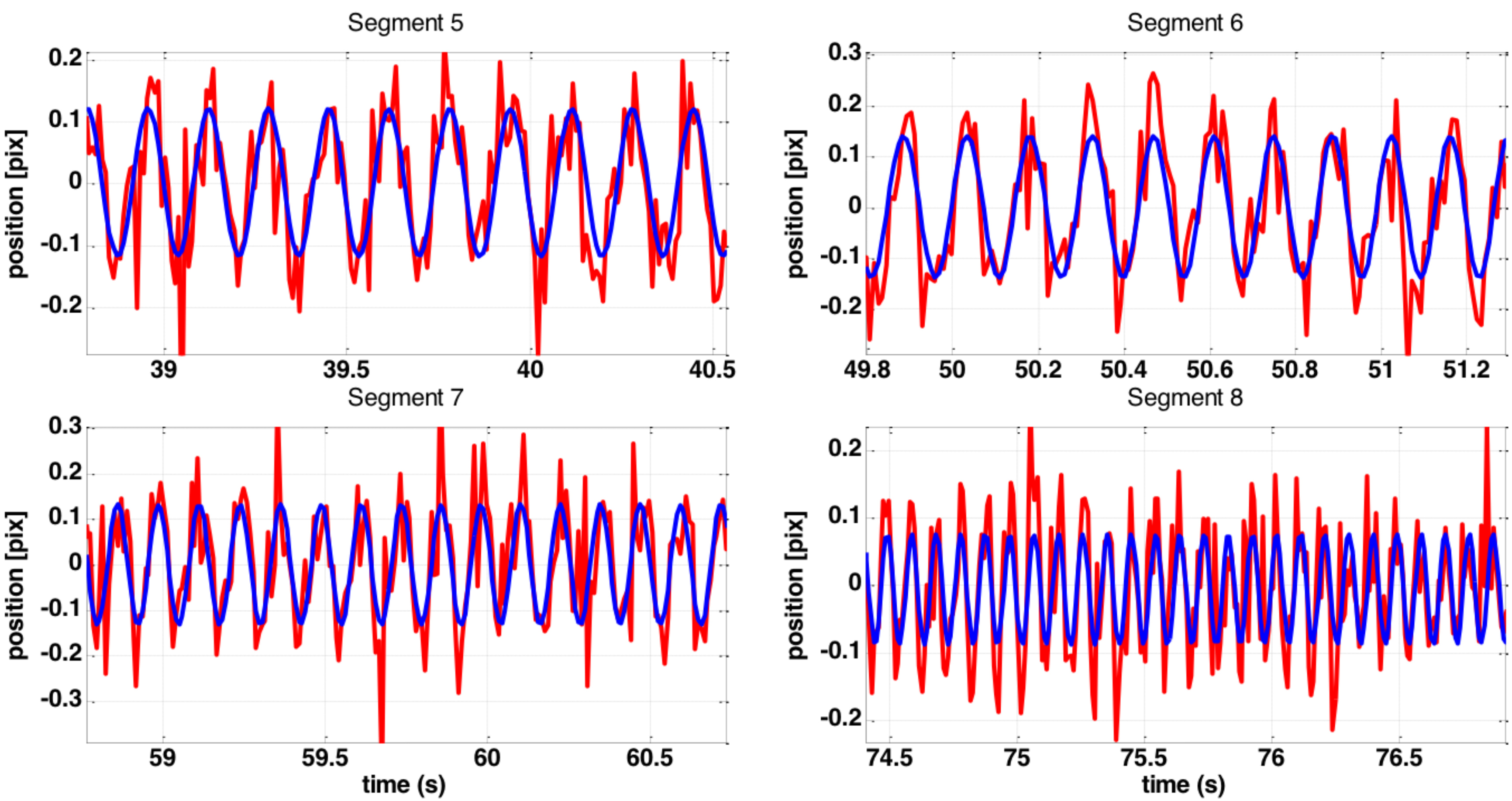
S-curve systematic error is removed for both same-axis (see below) and cross-axis pixel crossings (see Step 5)

Remove sinusoid (blue) having exactly a one-pixel-per-pixel period



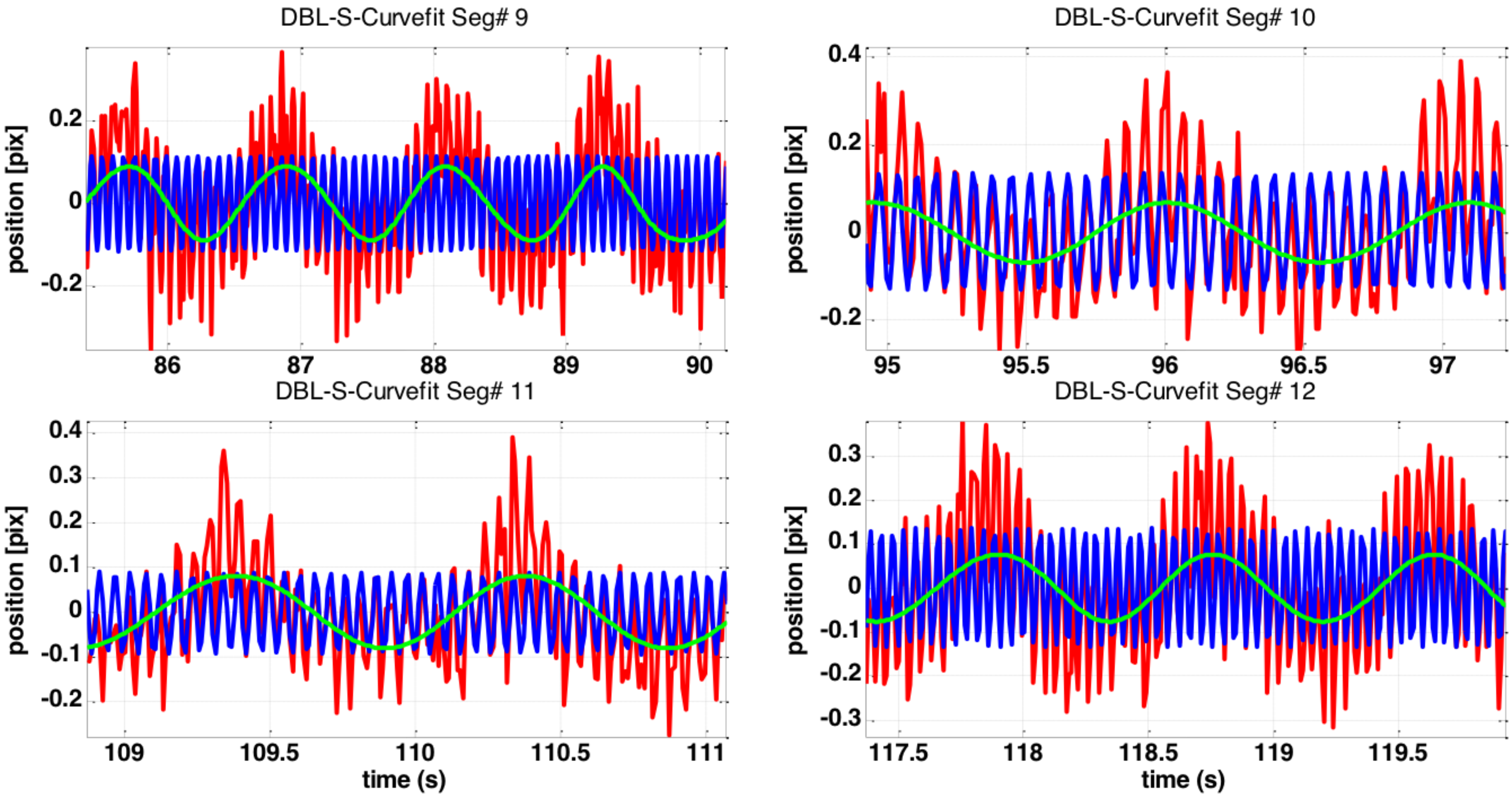
Step 4: De-S-Curve

In frequency space, this error is spread across multiple frequencies since the pixel rate is accelerating until zenith, then decelerating



Step 5: Double-DeSCurve

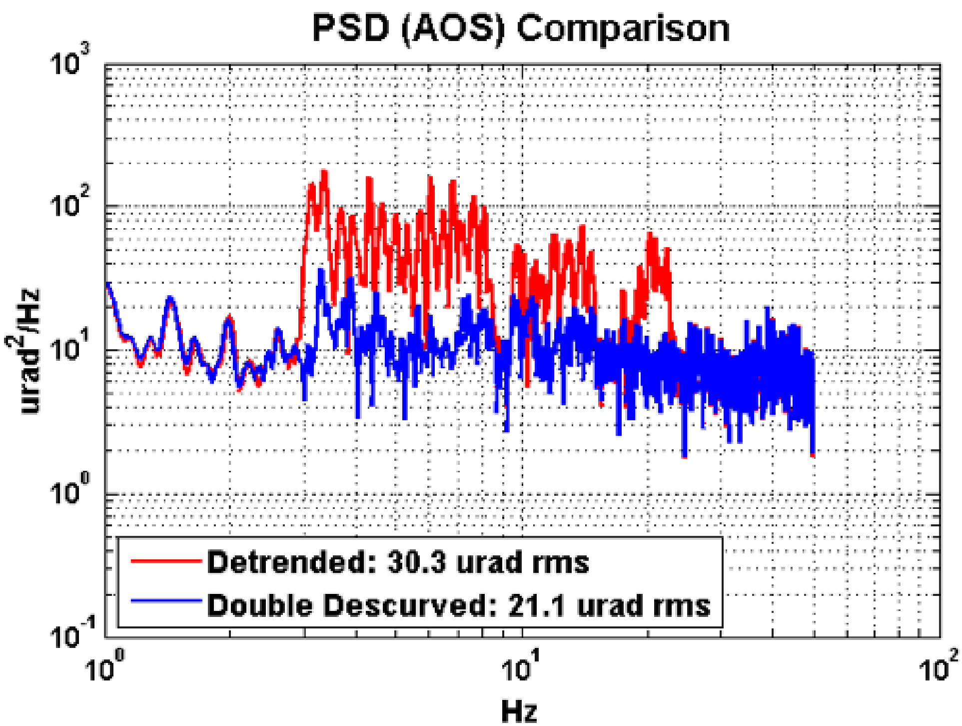
- Pixel crossings in EL axis show strong coupling in AZ axis measurements
- GMT 096 AZ data segments 9-12, (red) showing fits to two separate tones, as associated with same-axis (blue) and cross-axis (green) S-curve signatures (1 pixel equals 262 urad).



Step 6: Recompute PSD

- The corresponding estimate of RMS jitter is reduced from 30.3 to 21.1 µrad based on removing same axis and cross-axis systematic errors.
- The systematic error is removed across a wide band of frequencies (mostly 3 to 23 Hz), even though only two pure tones have been removed in the data processing.
  - the tone frequencies removed correspond to pixel-crossing rates which change as a function of time throughout the data set.
  - Hence they project over a wide range of frequencies when converted back into a time-domain analysis.

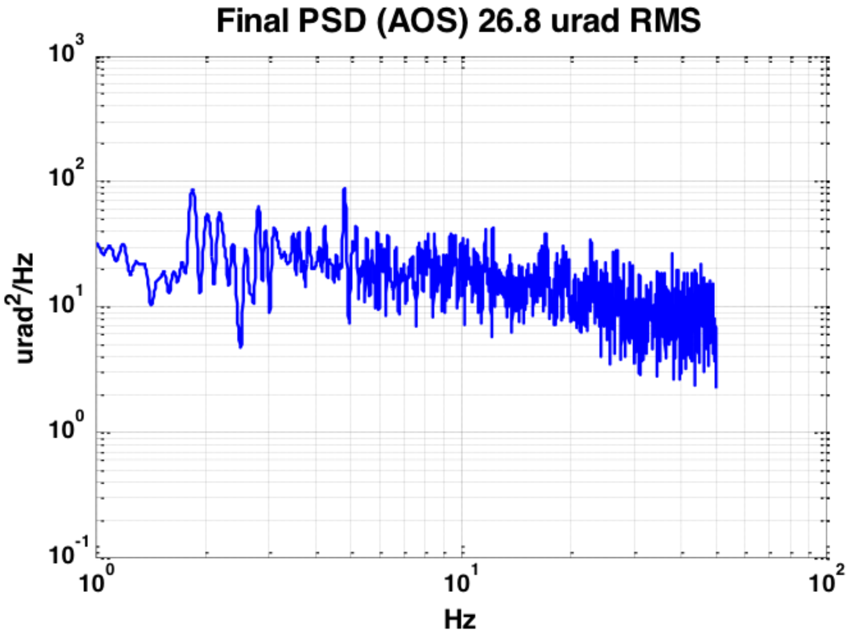
GMT 300 AZ data



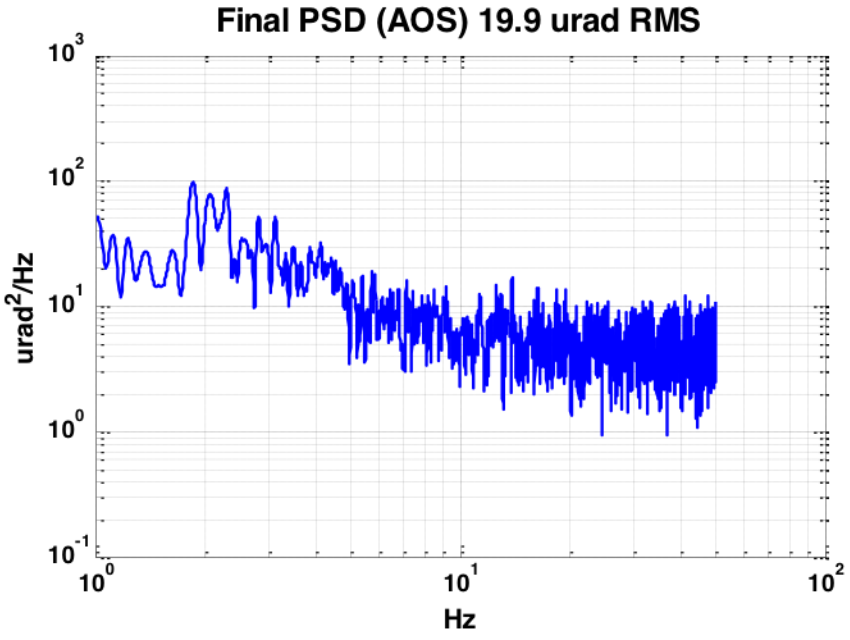
PSDs are doubled in magnitude and plotted only over positive values of frequency

GMT-2015-260 Final PSD

AZ

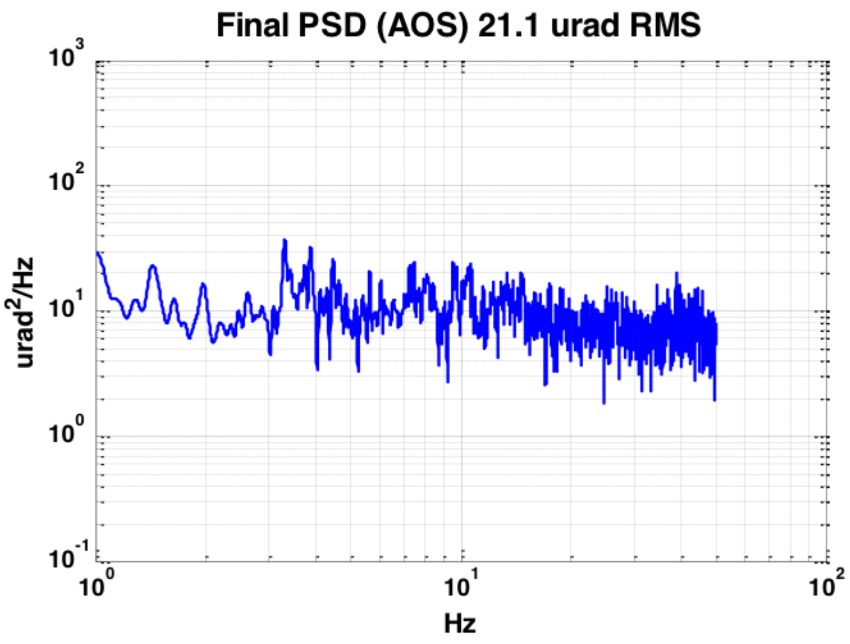


EL

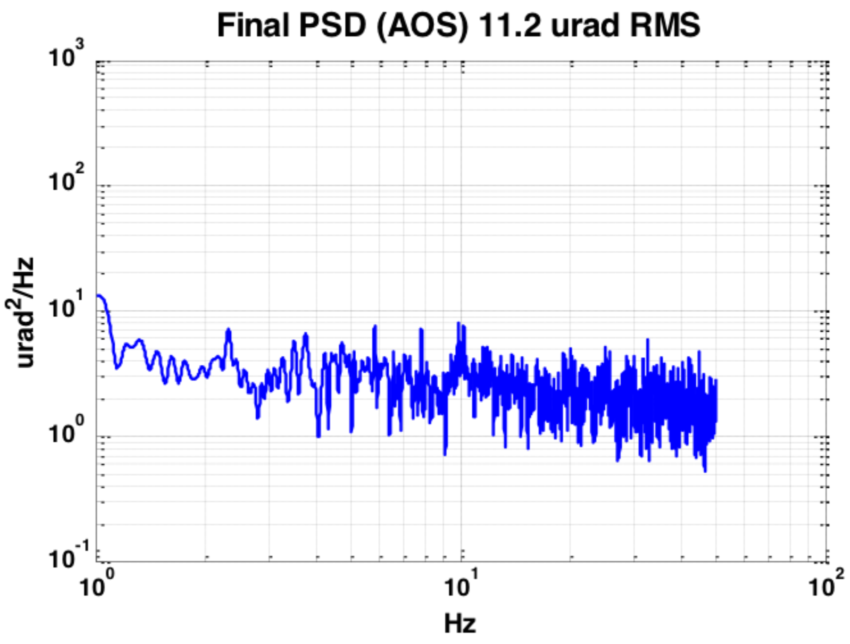


GMT-2015-300 Final PSD

AZ

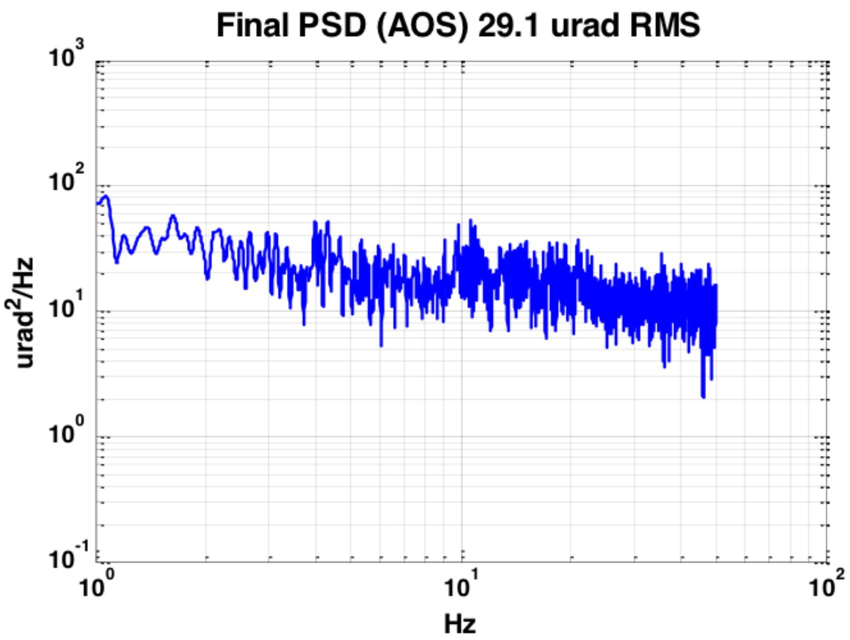


EL

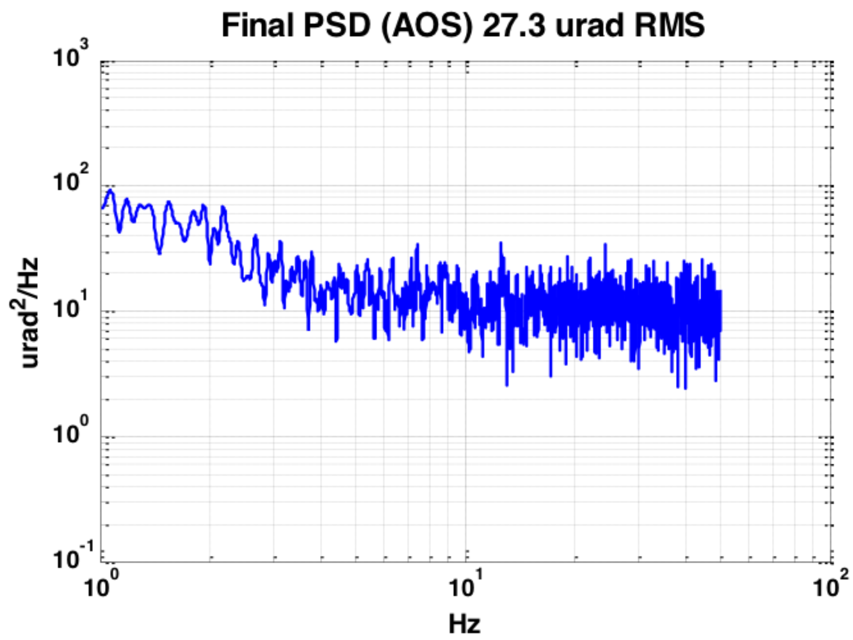


GMT-2016-096 Final PSD

AZ



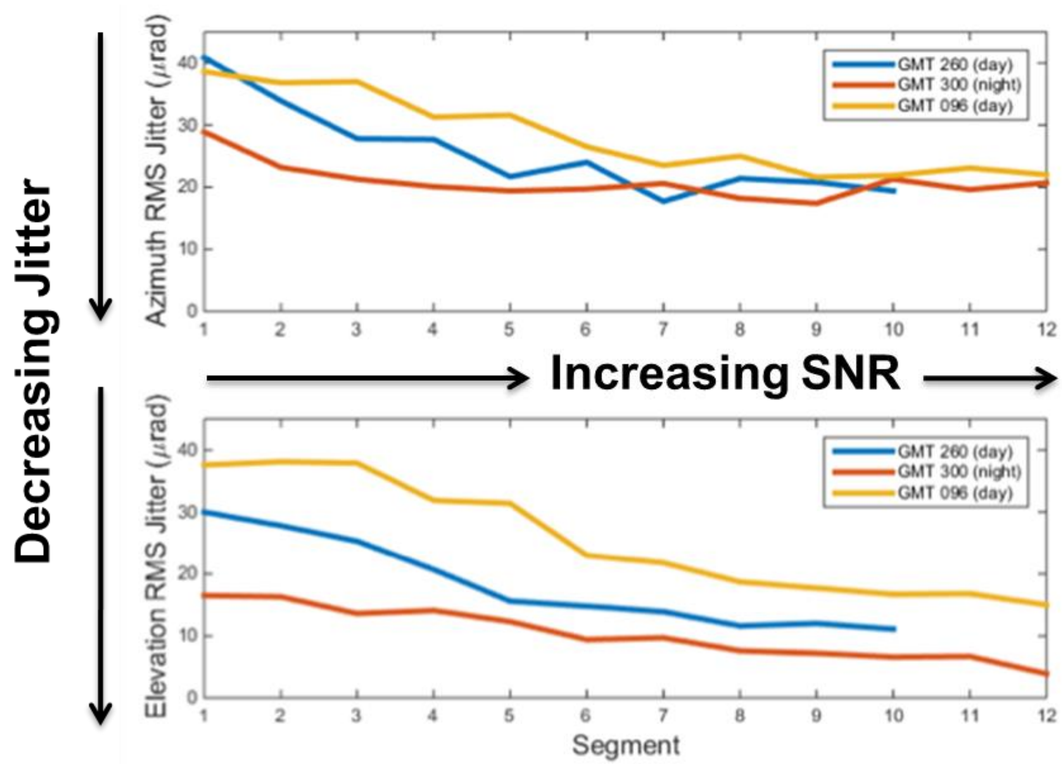
EL



CONCLUSIONS

Jitter Sensitivity to SNR

- The resulting PSDs are likely not completely free of OPALS-induced signatures
  - i.e. centroid performance is correlated to ground-beacon SNR
- There appears to be sensitivity to background lighting conditions and slant range, which affect signal SNR
  - Consistent with results obtained during ground testing (next slide)
- Early segment results may be more conservative due to low SNR → actual ISS contribution may be lower than the lowest values shown

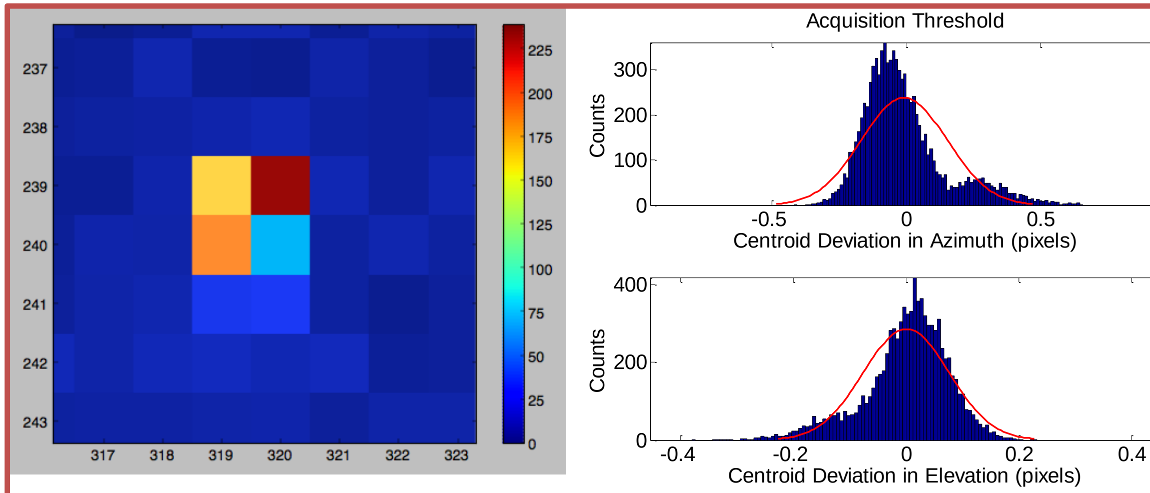


SNR contribution to Pointing Jitter*

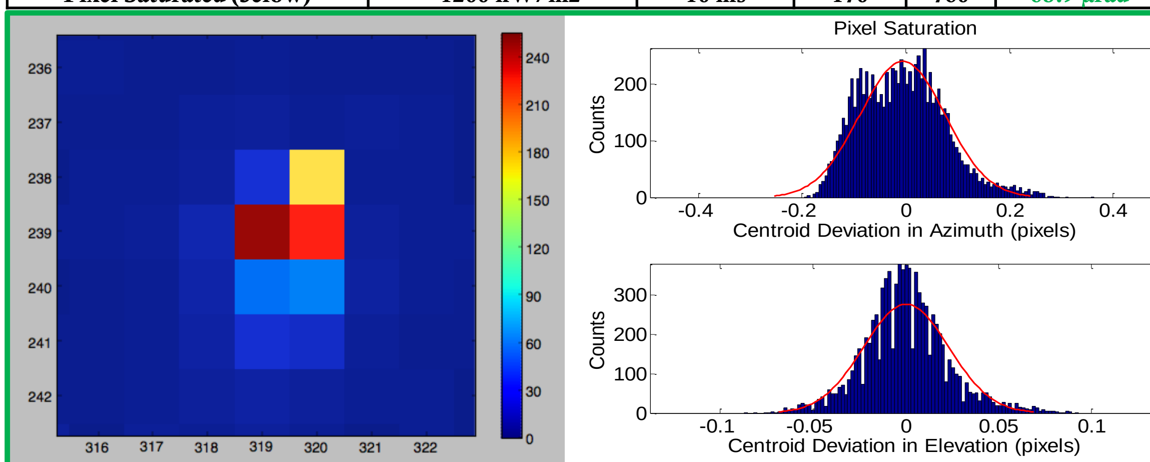
- Closed loop pointing jitter of the gimbal is sensitive to beacon intensity
  - This likely extends to open loop pointing as well
- Ground testing showed increasing beacon by 4x over acquisition threshold corresponds to 2x lower jitter

Unpublished results

Closed-loop ground testing*



Beacon Detection Level	Beacon Irradiance	Exposure	Gain	Flux	Jitter (~3σ)
Acquisition Threshold (above)	~300 nW/m2	10 ms	500	750	155.1 μrad
Pixel Saturated (below)	~1200 nW/m2	10 ms	170	760	68.9 μrad

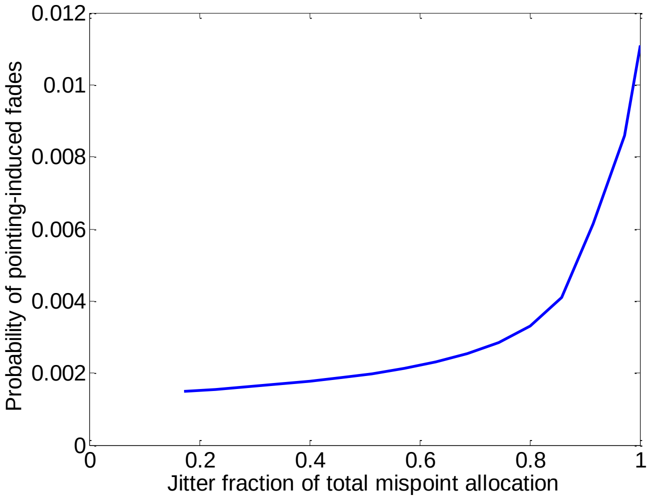


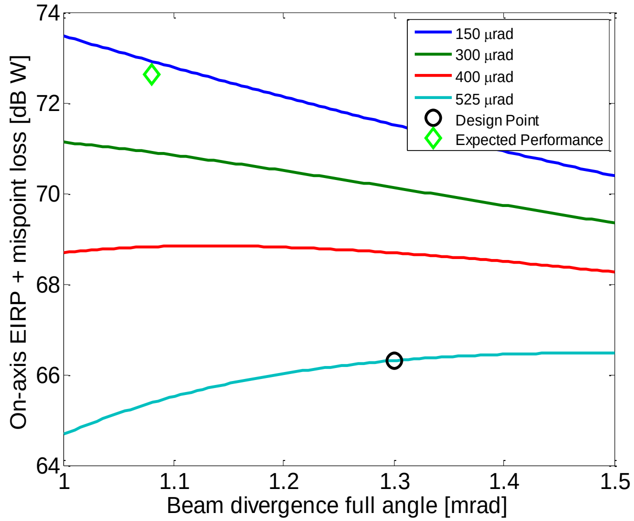
Conclusions

GMT	Date (GMT)	Ground Station Lighting	Crew Activity	AZ RMS Jitter (μrad)	EL RMS Jitter (μrad)
260	9/17/15 16:35	Day	Crew Exercise*	26.8	19.9
300	10/26/15 00:59	Night	Crew Sleep	21.1	11.2
096	4/5/16 01:15	Day	Crew Sleep	29.1	27.3

- Lacking knowledge of ISS jitter environment during design, OPALS allocated 125 μrad, 1σ, to total system jitter (and 150 μrad to bias, 3σ) for a total pointing error of 525 μrad, 3σ (see graphs to right)
  - Of the 125 μrad, 1σ:
    - ~50 μrad was bookkept for ISS contributions
    - ~40 μrad was bookkept for centroiding errors
- The lowest measured jitter during this experiment is at least a factor of 2 better than assumed during design, and as low as 10-20 μrad, 1σ.
- Could be ~10x better then initial assumption, depending on:
  - Assumptions about coupling between the various sources of jitter
  - How much of the calculated PSD contains remnants of OPALS centroiding errors

*Subsequent to manuscript submission it was learned that the level of crew exercise reported on GMT 260 is not representative of typical crew exercise periods; the environment experienced on GMT260 is more in line with the lack of crew exercise

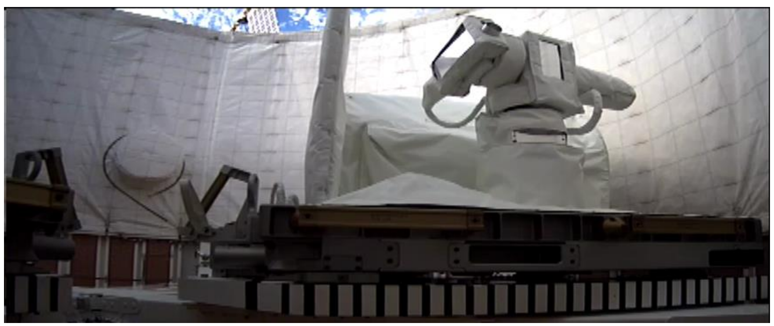


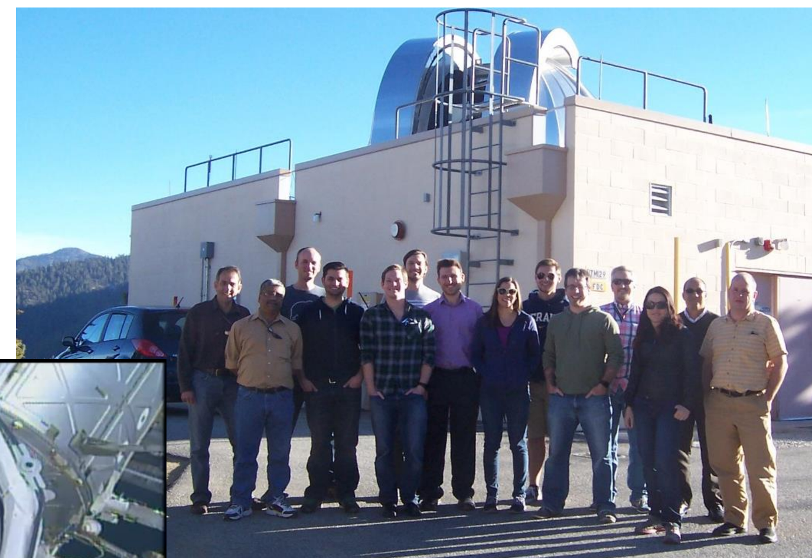


Oaida, B.V.; Kokorowski, M.; Erkmen, B.I.; Andrews, K.S.; Wu, W.; Wilkerson, M., "Impact of pointing performance on the optical downlink for the Optical PAyload for Lasercomm Science (OPALS) system" Proc. ICSOS 2014, S3-1, Kobe, Japan, May 7-9 (2014).

Acknowledgments

- Thanks for ISS TDO and HRMSO for funding this experiment
- Thanks to the OPALS team and MSFC HOSC for supporting on-orbit and ground station operations
- Thanks to the ISS Loads & Dynamics team for supporting SDMS data takes during the OPALS experiment periods

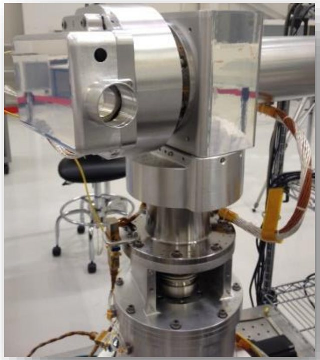


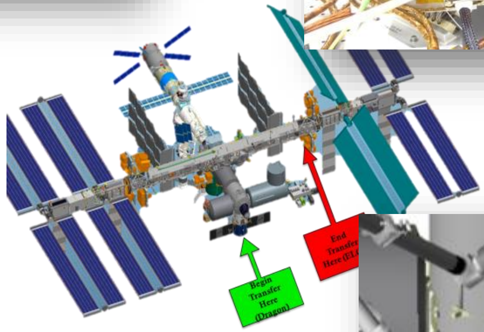


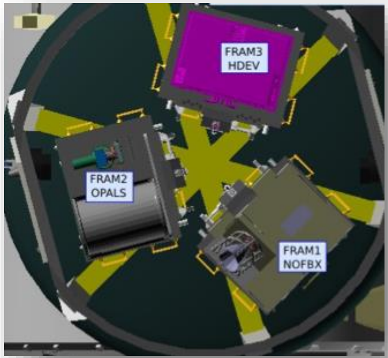
BACKUP

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)
- First space lasercomm terminal to downlink to 4 different optical ground stations
- Decommissioned on the first SpaceX launched from Pad 39A







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Downlink Animation

https://youtu.be/YOcSjDmpv_g