On-Orbit Operations and Lasercom Experiment Results for the CLICK-A Mission

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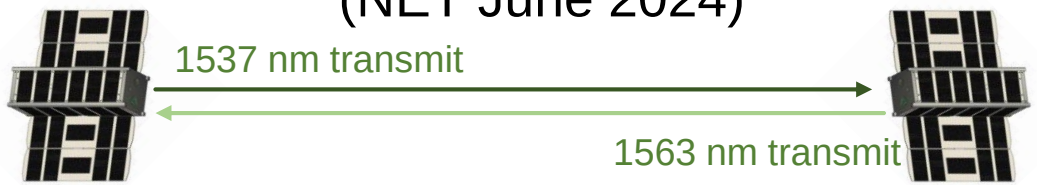
CLICK Mission

- CubeSat Laser Infrared CrosslinK (CLICK) is a two-phase mission, involving three 3U CubeSats
- Bus system provided by Blue Canyon Technologies (BCT)
- MIT Portable Telescope for Lasercom (PorTeL) Optical Ground Station (OGS) located at MIT Wallace Astrophysical Observatory in Westford, MA*

CLICK-A
(9/6/2022 - 3/30/2023)

- Single 1.2U payload
  - Downlink capability
- Mission objectives
  - Validate fine pointing system
  - Validate PorTeL OGS
  - ≥10 Mbps downlink

CLICK-B/C
(NET June 2024)



- Pair of 1.5U payloads
  - Downlink and crosslink capability
- Mission objectives
  - ≥20 Mbps full-duplex crosslink
  - <0.5 m ranging
  - Demonstration over range 25 km – 580 km

*Note: Only experiment results gathered for experiments with the MIT OGS are presented here. Results with OGS partners are not presented here.

CLICK-A Mission Concept of Operations

Downlink Experiment

Deployment & Initialization
- ISS Deployment (09/06/2022)

Prior to OGS Pass
- Initiate body pointing to OGS using ephemeris

Beacon Acquisition
- Acquire uplink beacon
- Start closed-loop tracking

Closed-loop tracking
- Activate downlink laser
- Start fine stage tracking

Communications
- While performing fine stage tracking

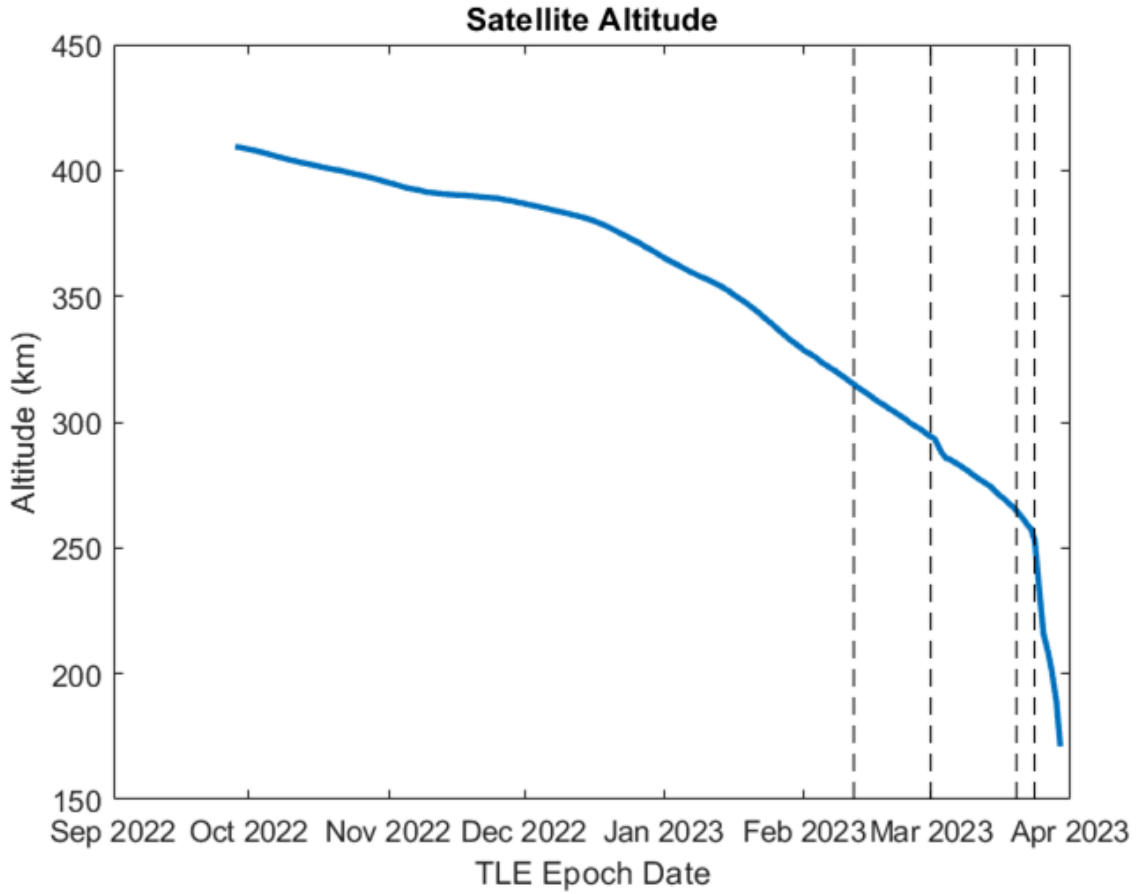
Extended Operations
- Downlink Tests
- Performance Tests

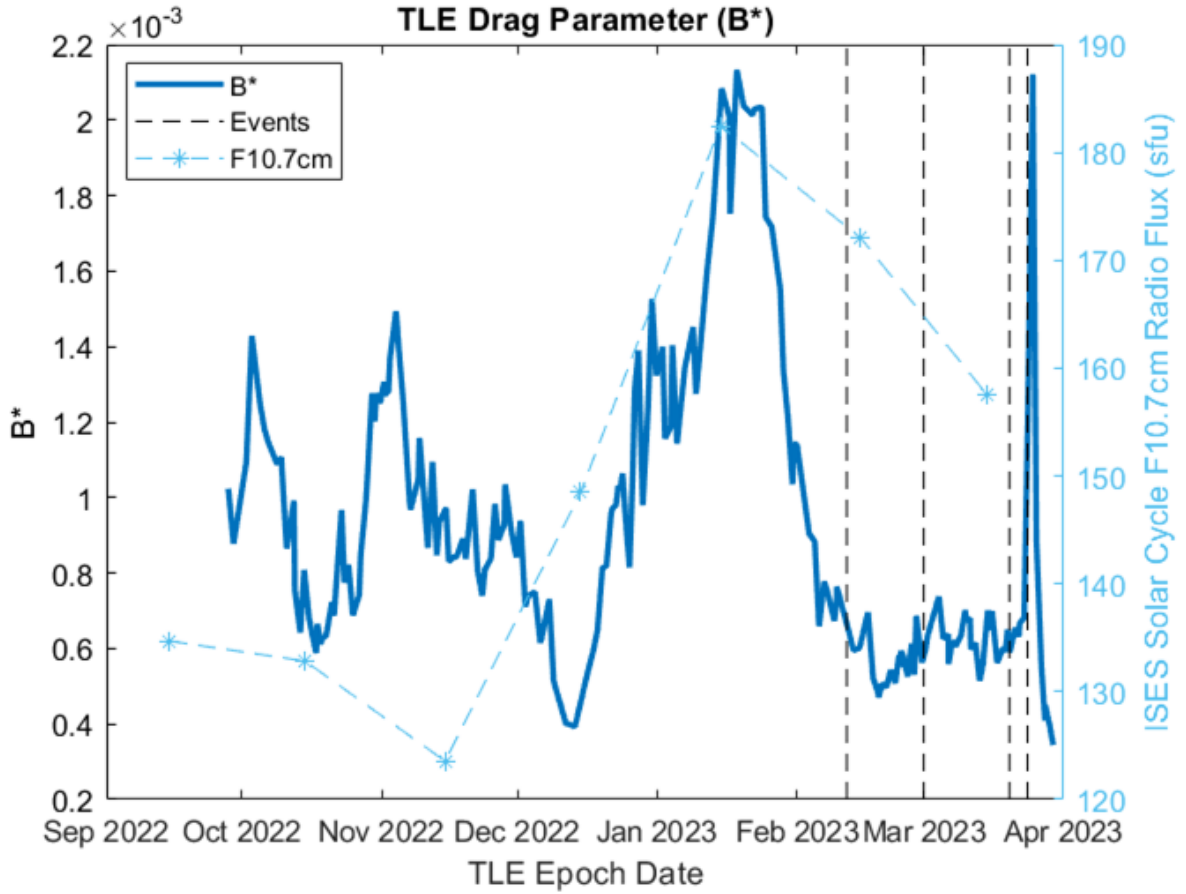
End of Life Operations
- De-Orbit 3/30/2023

CLICK-A Mission Summary

- Deployment from International Space Station via Nanoracks: 09/06/2022
- Initial Altitude: 415 km
- S/C Bus Commissioning Completed: 09/15/2022
- P/L Commissioning Completed: 10/20/2022
- Start of Lasercom Experiments with MIT OGS: 10/28/2022
- Start of Lasercom Experiments with Partner OGS's: 03/02/2023
- De-Orbit: 03/30/2023
- Mission Duration: 206 days (appx. 7 months)
- Number of Lasercom Experiments: 18 scheduled; 10 completed; 4 partial successes.
- Number of Radio Contacts: 348 scheduled; 321 successful.
- Number of radiation-related events: 14

CLICK-A Mission Summary

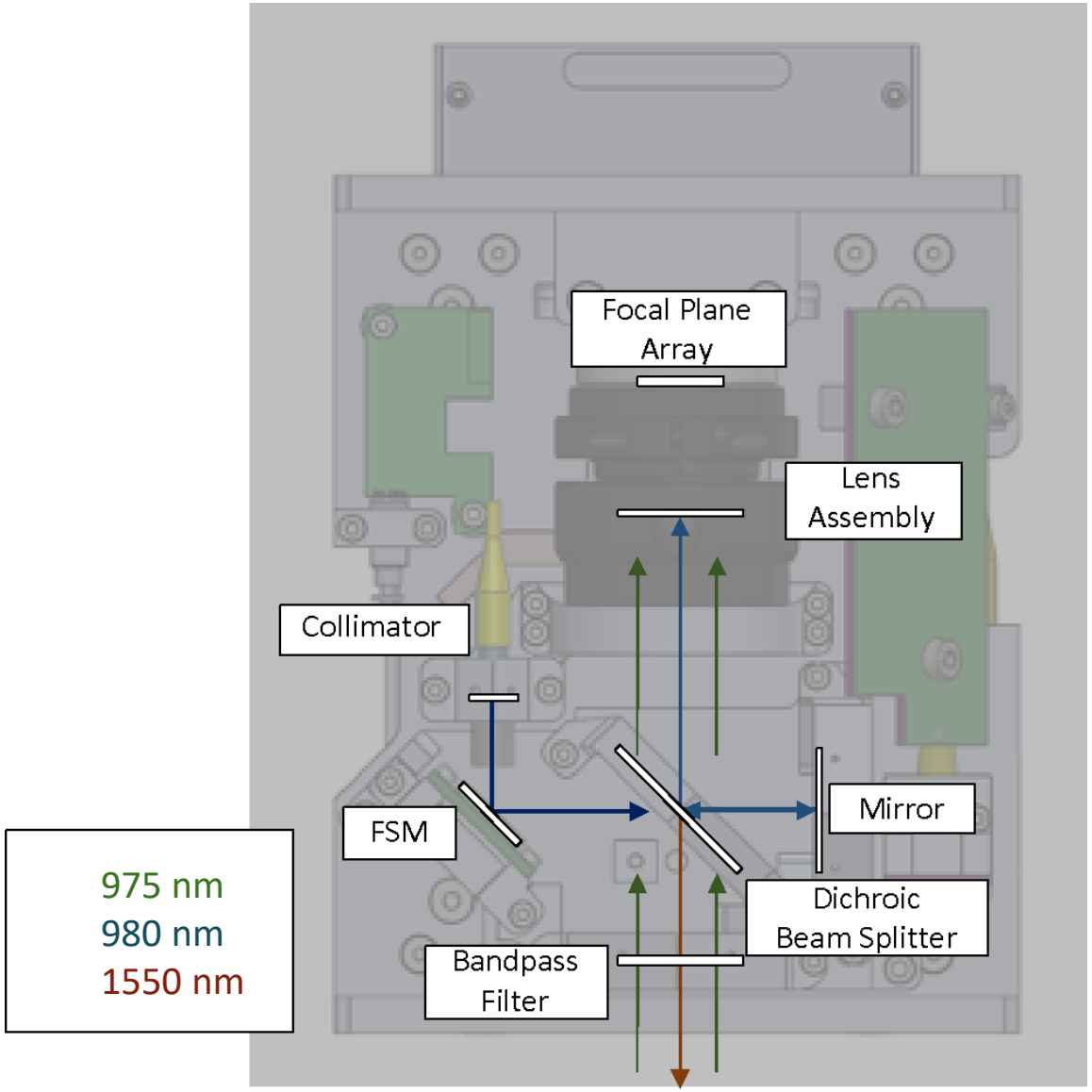




- Transitioned to off-nominal, 24-hr low drag attitude on February 12th, which extended the mission lifetime by about 1 month.
- Automatic safe-mode transitions on March 1st and March 24th hastened de-orbit.
- Radiation-related event on March 20th caused payload C&DH to become inoperable for the remainder of the mission.

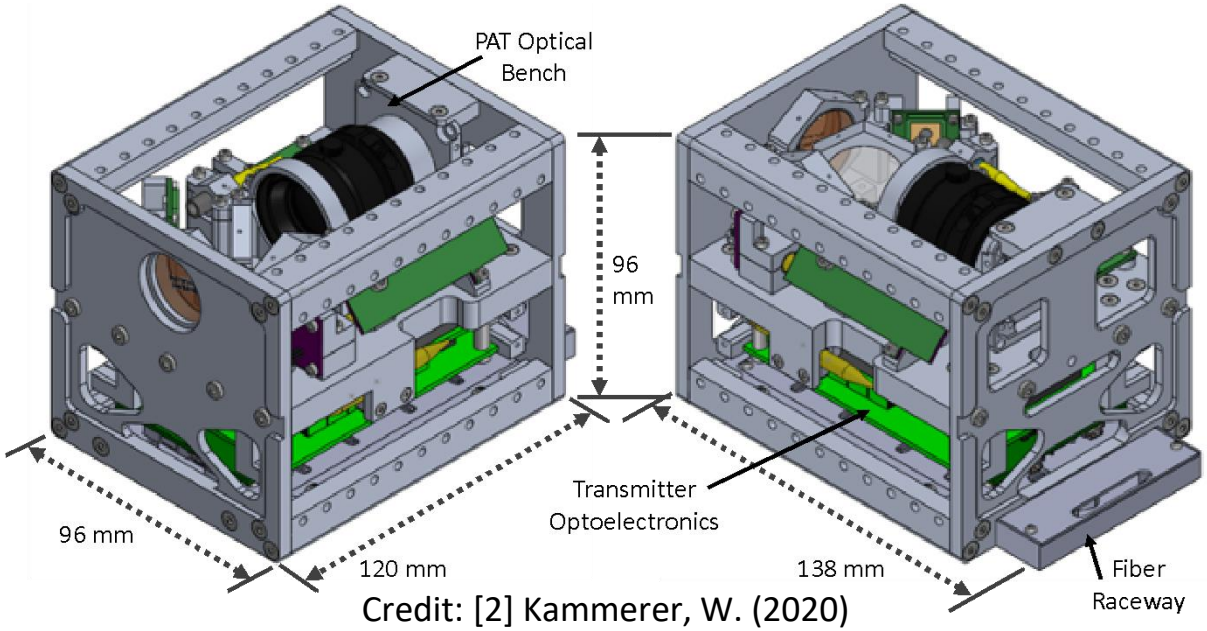
*ISES Solar Cycle F10.7cm Data Retrieved from SWPC NOAA [1]

CLICK A Payload Overview



Credit: [3] Tomio et al. (2022)

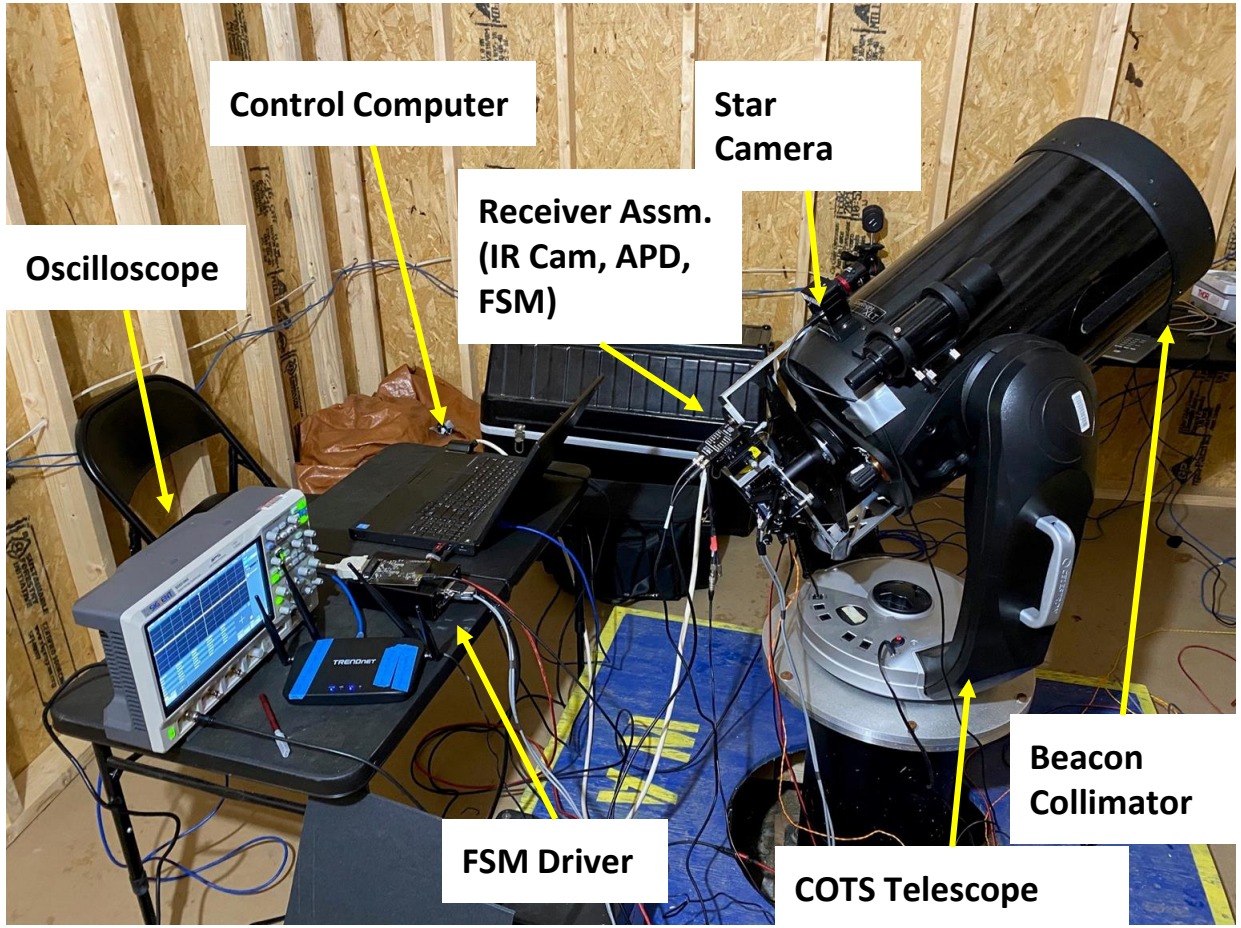
- SWaP: 1.2U, 1.17 kg, <15 W
- Camera FOV 10.6°
- Calibration Laser – 980 nm
- Downlink Transmitter Laser – 1550 nm
  - 200 mW avg.; M-ary PPM Orders 4 to 128
  - 1.15 mrad FWHM (1.96 mrad $1/e^2$)
- OGS Uplink Beacon Laser – 975 nm
  - 5 W CW
  - 4.96 mrad FWHM (8.43 mrad $1/e^2$)



Credit: [2] Kammerer, W. (2020)

Optical Ground Station (OGS) Overview

- Primary OGS: MIT's PorTeL at Wallace Astrophysical Observatory (Westford, MA)
- OGS Partners: DLR (Oberpfaffenhofen, Germany), NICT (Koganei, Japan), EOS (Mt. Stromlo, Australia)*



*Note: Only experiment results gathered for experiments with the MIT OGS are presented here. Results with OGS partners are not presented here.

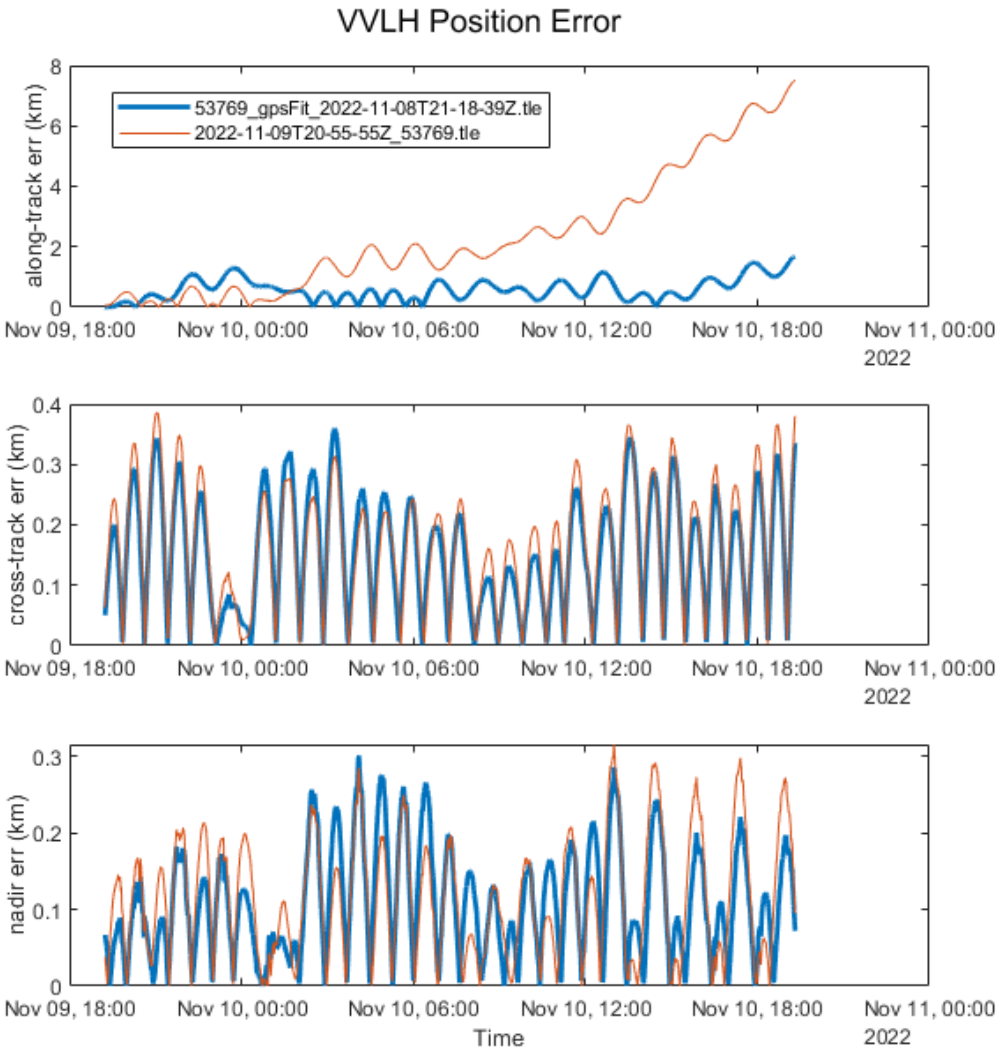
Experiment Attempts

Date	Station	AOS-LOS Duration (min)	Max El (deg)	Min Range (km)	3D Tracking Error (km)	Uplink	Downlink: IR Cam	Downlink: APD
2022-10-28 08:21:54 UTC	Wallace	0.5	43.5	565.7	4.29	No	No	N/A
2022-11-02 05:25:14 UTC	Wallace	2.27	56.6	469.2	2.88	Yes	No	N/A
2022-11-10 02:47:58 UTC	Wallace	2.77	70.3	414.9	0.73	Yes	Yes	N/A
2022-11-29 00:32:39 UTC	Wallace	1.90	59.6	441.4	1.13	Yes	Yes	No
2023-02-16 10:18:08 UTC	Wallace	1.25	43.0	451.2	9.4	No	No	No
2023-02-25 07:13:28 UTC	Wallace	2.18	71.4	321.2	0.49	No	No	No
2023-03-08 11:09:00 UTC	NICT	3.20	35.44	466.48	3.39	No	No	N/A
2023-03-09 21:49:28 UTC	DLR	4.83	54.59	342.93	1.63	No	No	N/A
2023-03-10 11:14:25 UTC	NICT	2.97	29.76	530.50	5.39	No	No	N/A
2023-03-15 16:02:32 UTC	NICT	3.47	64.07	300.11	1.71	Yes	Yes	N/A

- 18 total lasercom experiments were scheduled with the spacecraft. Of these, 8 were unable to be completed due to either ground system technical issues or rapidly changing weather. The 10 completed attempts are shown. Primary limitation on lasercom downlink opportunities is clear weather.
- Attempt on 10/28 had poor geometry. Attempts on 2/16 and 3/10 had poor TLE tracking .
- Attempts on 2/16, 3/8, 3/9, & 3/10 failed due to P/L acquisition of stray light. Attempt on 2/25 affected by thermoelastic shift of OGS beacon at low-temp.

Orbit Determination

- Used Space-Track TLEs for radio passes, supplemented with GPS data when needed.
- For lasercom experiments, used GPS data to correct Space-Track TLEs via a SGP4 batch least squares orbit fit.
- Tracking 3D Position Error Statistics for All Experiments:
  - Min: 0.49 km; Max: 9.4 km
  - Mean: 3.1 km; Median: 2.3 km
- Uplink Beacon Divergence Designed for 3 km error (3-sigma).
- Tracking position errors are dominated by along-track dimension
- Tracking velocity errors are dominated by radial dimension
- Tracking errors are highly sensitive to drag parameter (B*) errors
- Maintaining consistent attitude patterns in lead-up to lasercom experiments helps to reduce tracking errors.
- Fitting using a high fidelity numerical orbit model could also improve tracking errors.



11/02/2022 Experiment

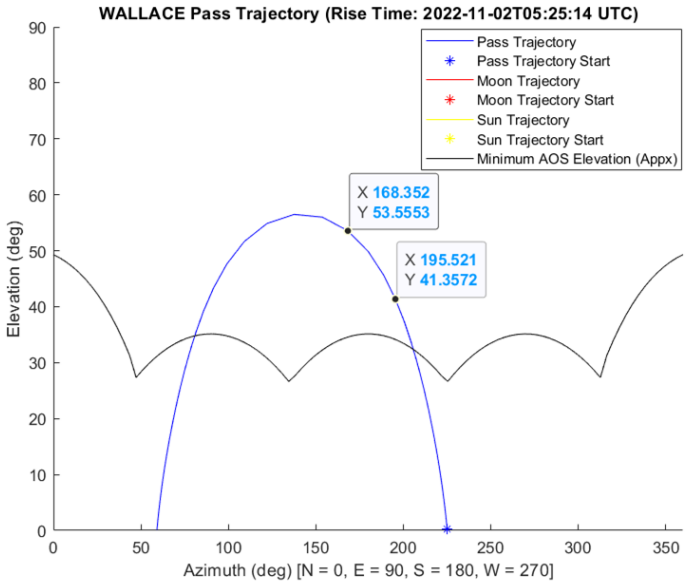
Pass Summary:

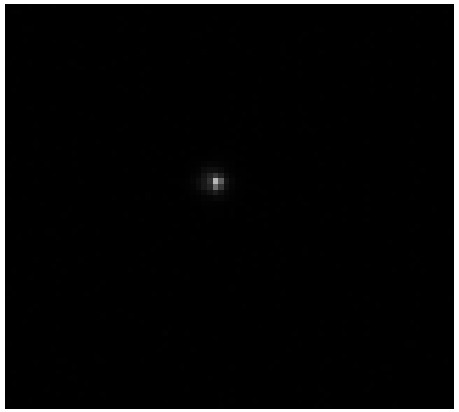
- Max Visible Duration: 2.27 min
- Max El: 56.6°
- Min Range: 469.2 km

Beacon Uplink Summary:

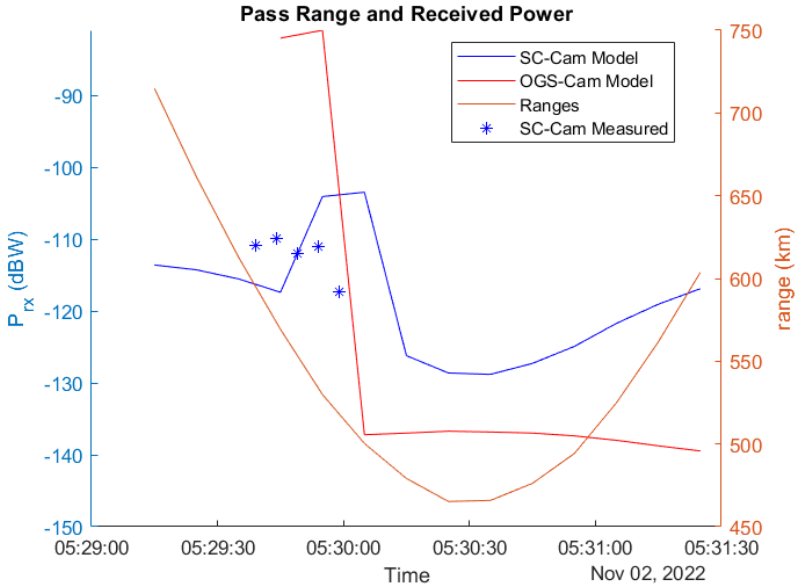
- First light for beacon uplink to S/C camera.
- AOS: (Az, El) ~ (196°, 41°); Range = 603.2 km
- LOS: (Az, El) ~ (168°, 54°); Range = 506.8 km
- AOS-LOS Duration (sec): 25.8
- Acq. Spot Gaussian Fit: (0.70, 0.70) pxl 1-σ
- S/C Cam. Exp. Times: 8.98 to 79.95 ms
- Meas. Power: -117.3 to -109.9 dBW
- Link Model Error: -7.3 to 13.5 dB; 0.14 dB avg.

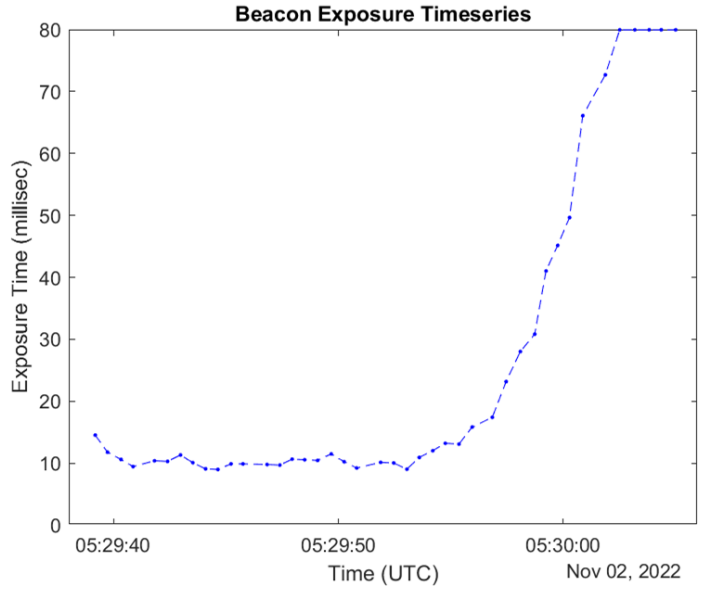
No downlink signal received.





Beacon Acquisition 2022-11-02T05-29-37 UTC
Exp 14.532 ms

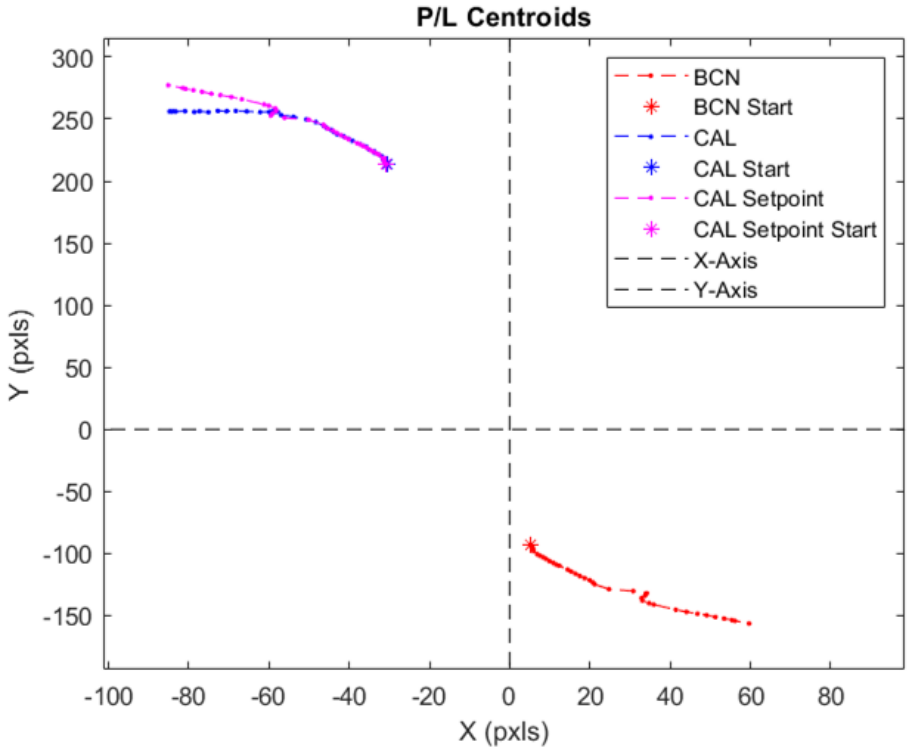


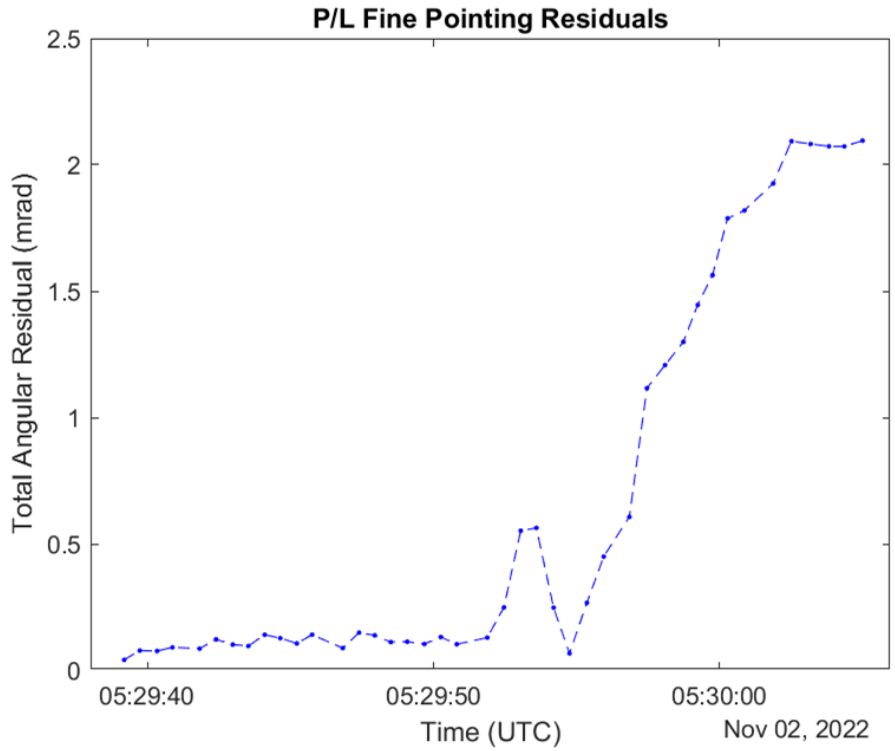


11/02/2022 Experiment

- Median pointing residual **0.145 mrad** (consistent with ground testing)
- Steady-state pointing from acquisition for **13 seconds**
- S/C attitude roll manuever starts at 05:29:52 UTC (roll angle set by secondary sun pointing objective). This causes fine pointing error to increase rapidly due to alignment bias between payload and S/C frame.
- Note that payload pointing setpoint is mirrored and biased relative to the beacon signal by design

P/L Fine Pointing Residuals Statistics (mrad)				
Min	**25%**	**50%**	**75%**	**Max**
0.041	0.104	0.145	1.299	2.096

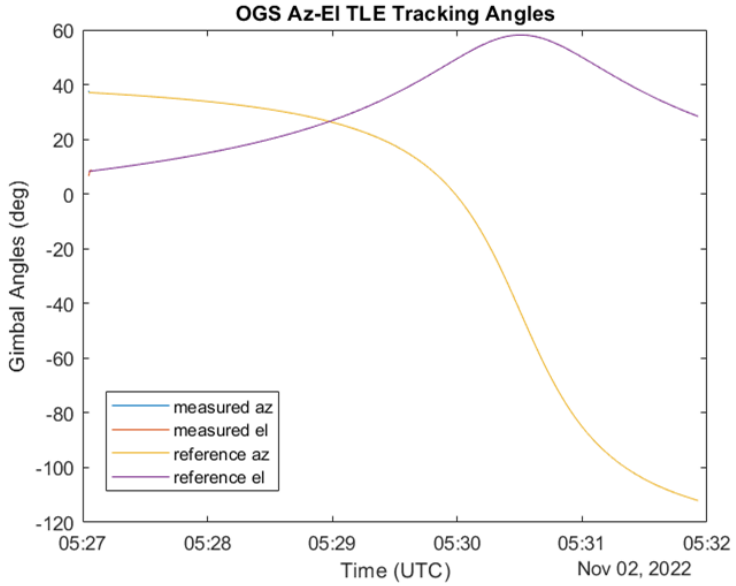


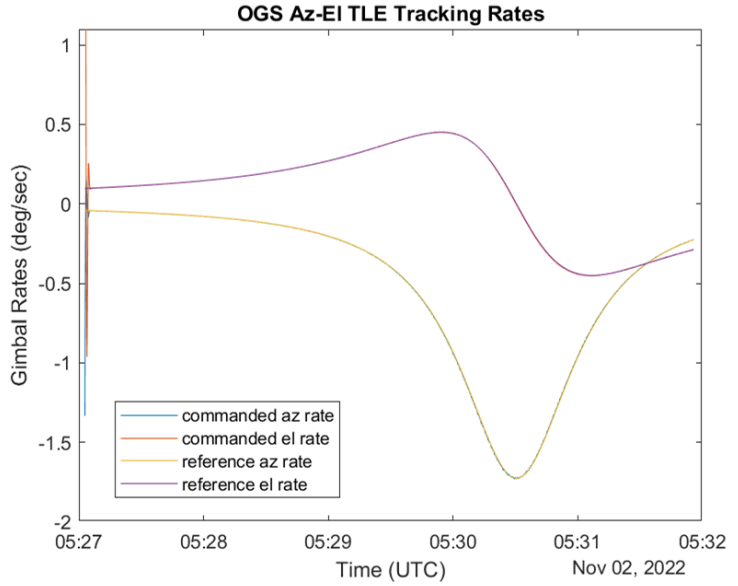


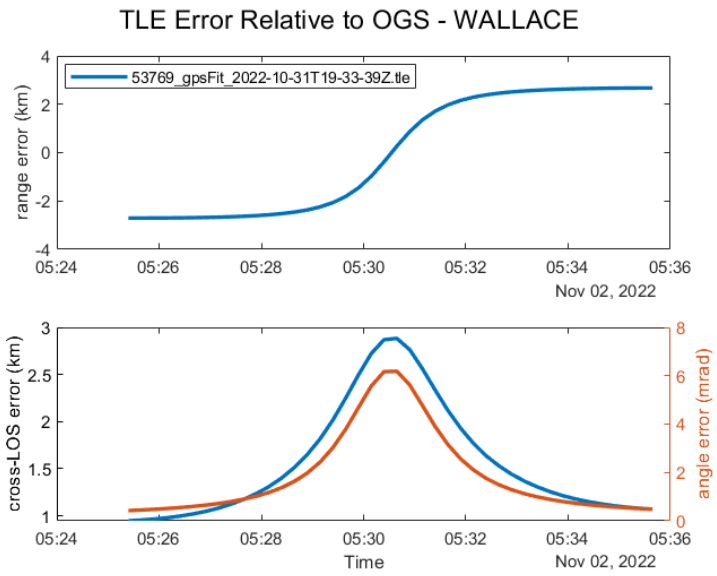
11/02/2022 Experiment

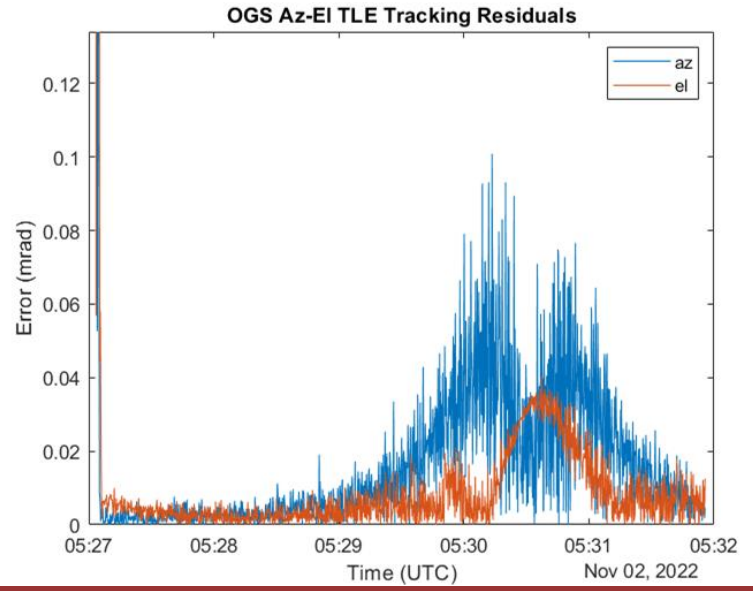
- Max El 56.6° at Az 138° (SE)
- Max El Rate: 0.45 deg/s
- Max Az Rate: -1.73 deg/s
- TLE Range Error: -2.7 to 2.7 km
- TLE Cross Line of Sight (LOS) Error: 0.95 to 2.89 km
- TLE LOS Error Angles: 0.42 mrad to 6.18 mrad
- Open-Loop TLE Tracking Residuals: Median 0.010 mrad

Take-Away: First Light for Beacon Uplink From MIT OGS to CLICK A P/L.









11/10/2022 Experiment

Pass Summary:

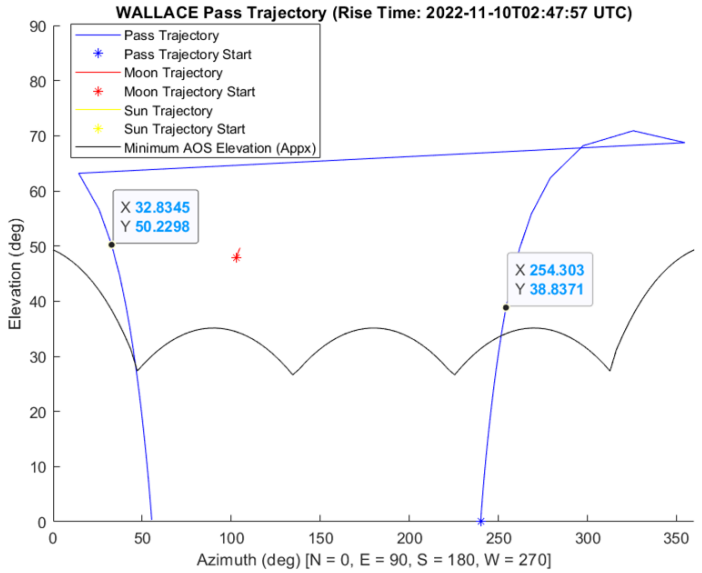
- Max Visible Duration: 2.77 min
- Max El: 70.9°
- Min Range: 416.1 km

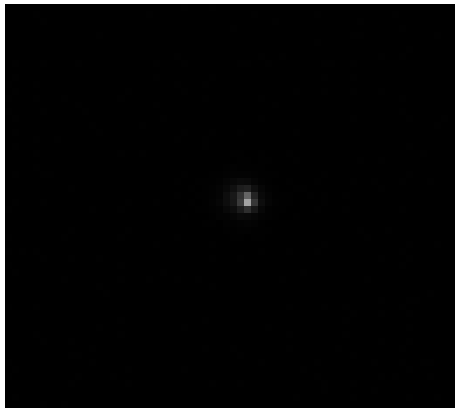
Beacon Uplink Summary:

- AOS: 2022-11-10T02-52-13 UTC
- LOS: 2022-11-10T02-53-49 UTC
- AOS-LOS Duration (sec): 96
- AOS: (Az, El) ~ (254°, 39°); Range = 602.6 km
- LOS: (Az, El) ~ (33°, 50°); Range = 481.2 km
- Acq. Spot Gaussian Fit: (0.45, 0.73) pxl 1-σ
- S/C Cam. Exp. Times: 3.95 to 13.51 ms
- Meas. Power: -112.2 to -106.0 dBW
- Link Model Error: 4.3 to 6.1 dB; 5.2 dB avg.

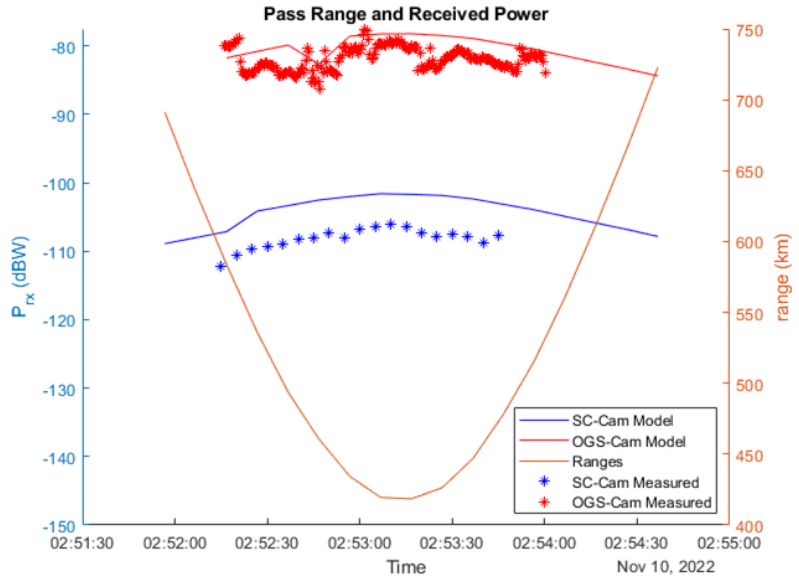
Transmit Downlink Summary:

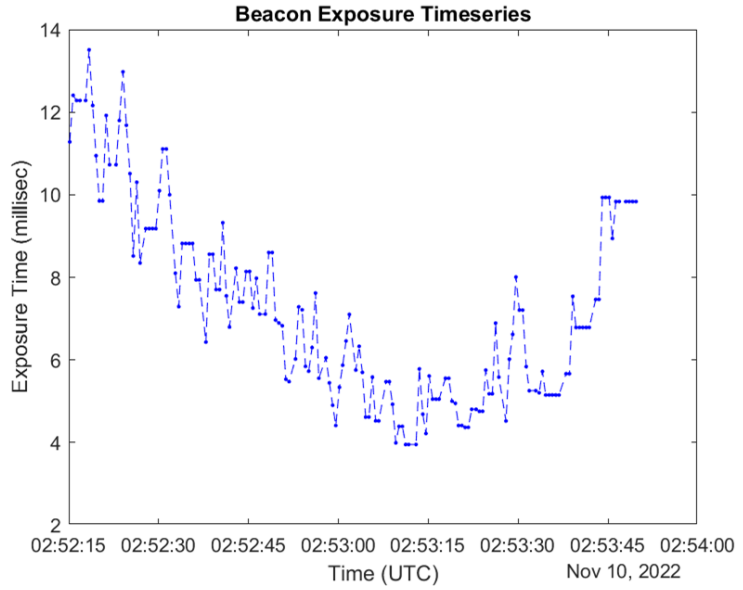
- First light for P/L downlink to OGS camera.
- AOS: 2022-11-10T02-52-21 UTC
- LOS: 2022-11-10T02-54-00 UTC
- AOS-LOS Duration (sec): 99
- OGS Cam. Meas Power: -86.4 to -77.5 dBW (high-uncertainty due to spot exposure)
- Link Model Error: -2.4 to 5.2 dB; 2.3 dB avg
- PPM order set to 16. APD not installed yet.





Beacon Acquisition 2022-11-10T02-52-13 UTC
Exp 11.279 ms

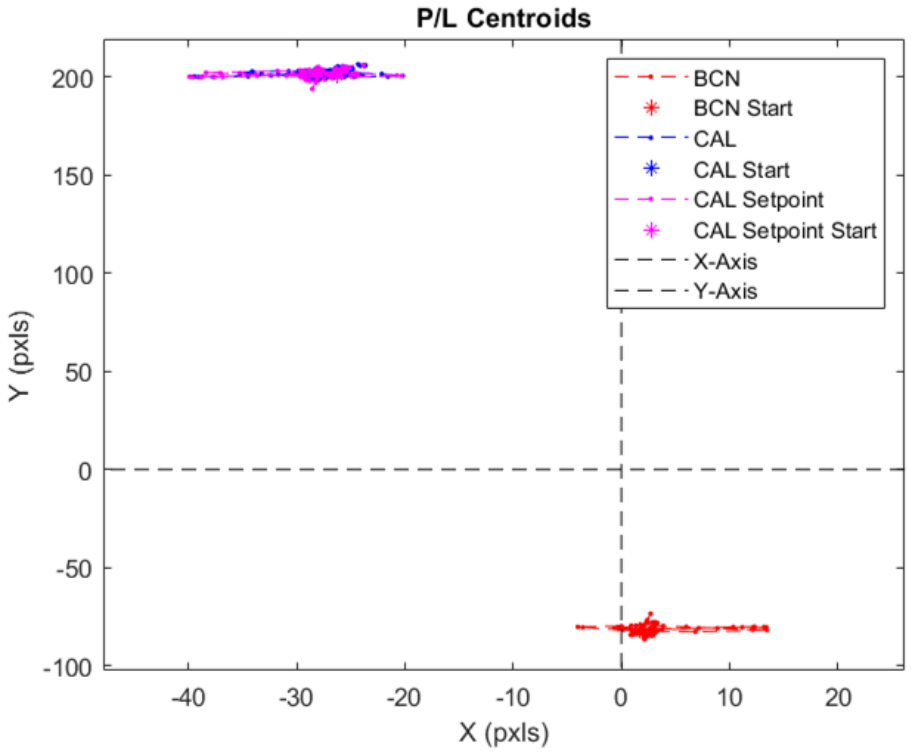


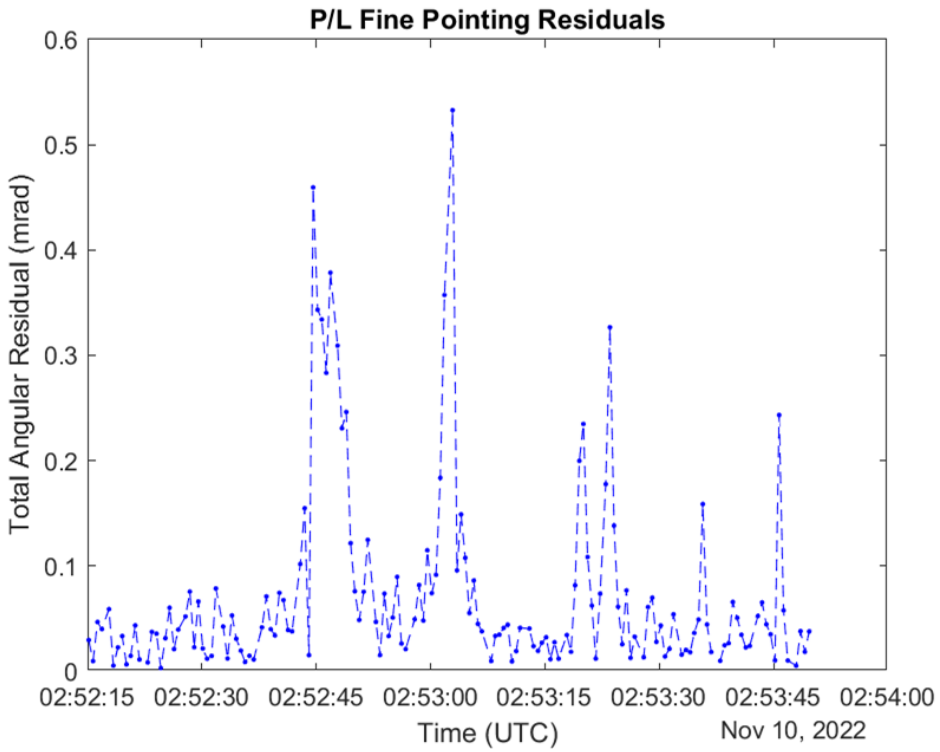


11/10/2022 Experiment

- Median pointing residual **0.041 mrad** (consistent with ground testing)
- Steady-state pointing from acquisition for **96 seconds**
- S/C attitude stable throughout, with some drift in the payload camera x-axis

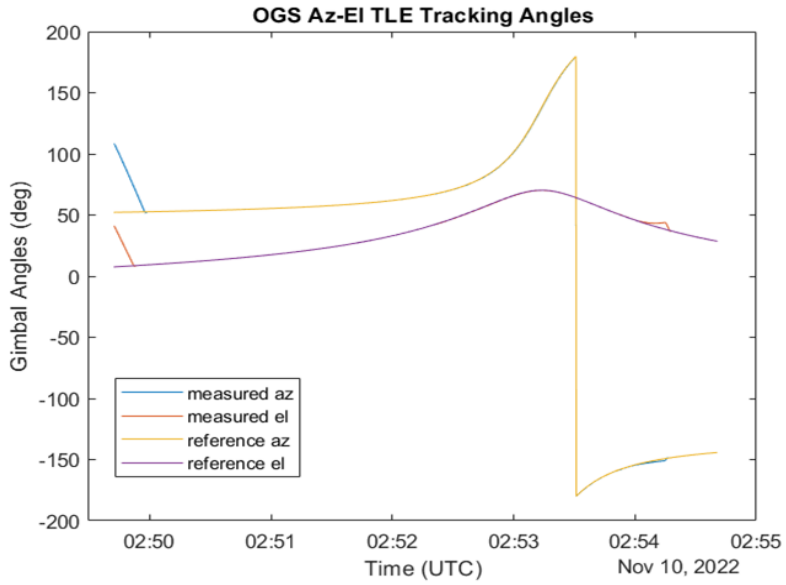
P/L Fine Pointing Residuals Statistics (mrad)				
Min	**25%**	**50%**	**75%**	**Max**
0.003	0.021	0.041	0.074	0.533

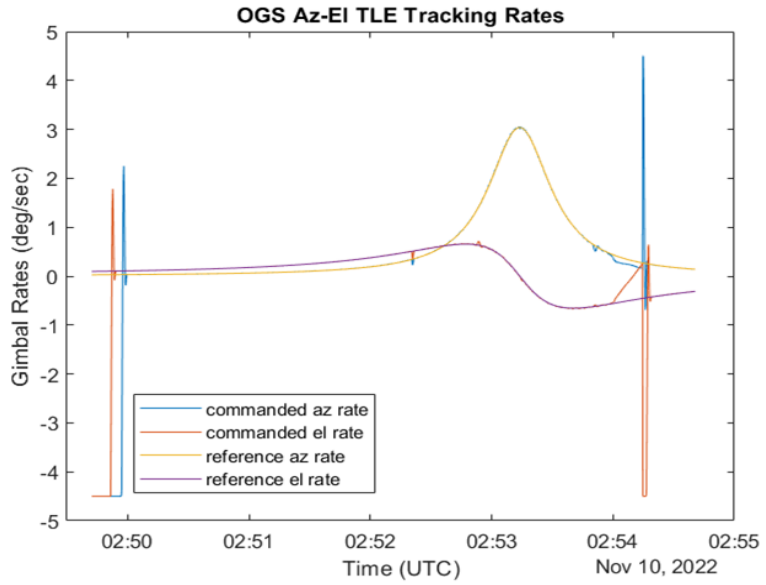


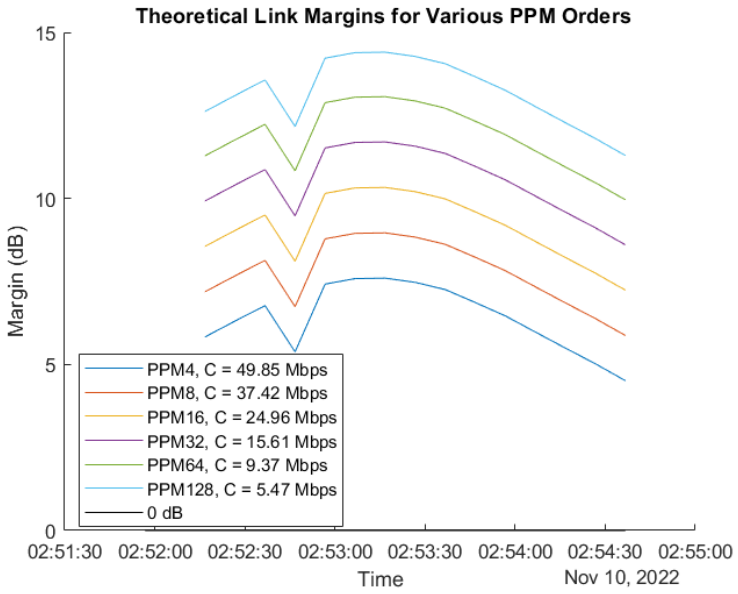


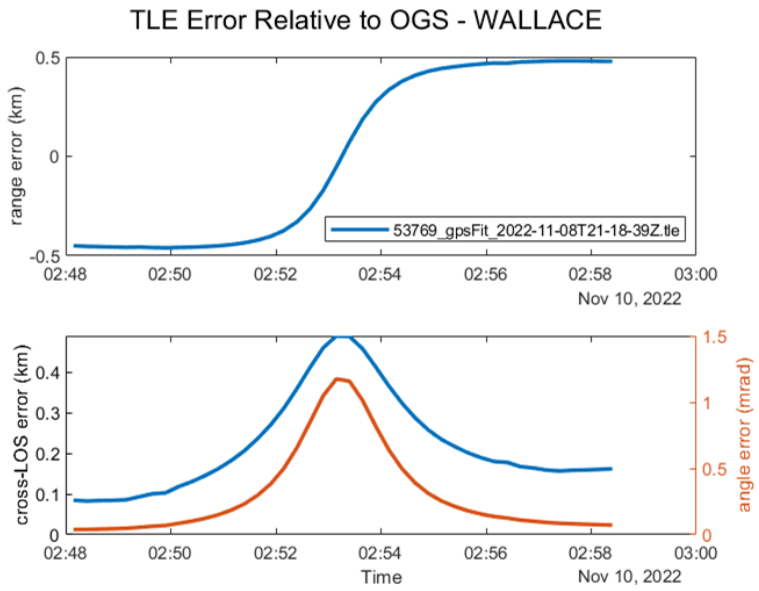
11/10/2022 Experiment

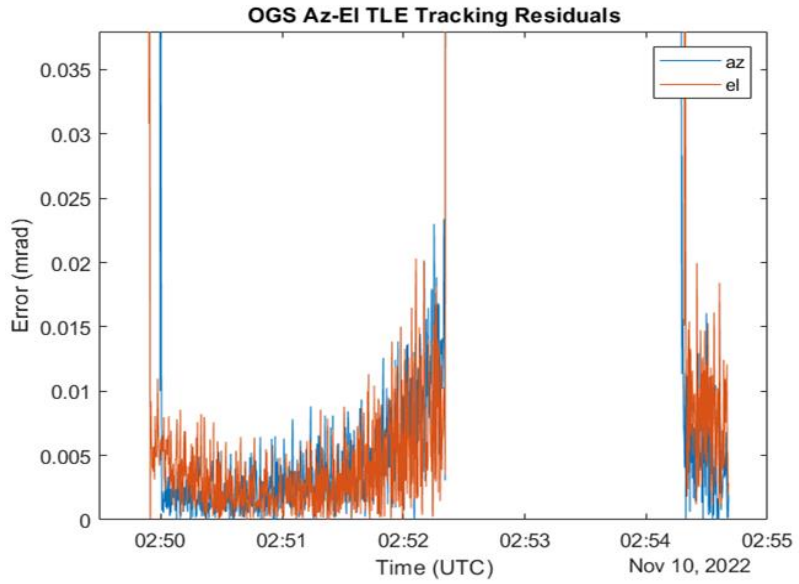
- Max El Rate: +/- 0.66 deg/s
- Max Az Rate: 3.04 deg/s
- TLE Range Error: -0.46 to 0.48 km
- TLE Cross Line of Sight (LOS) Error: 0.08 to 0.49 km
- TLE LOS Error Angles: 0.04 mrad to 1.17 mrad
- Open-Loop TLE Tracking Residuals: Median 0.006 mrad





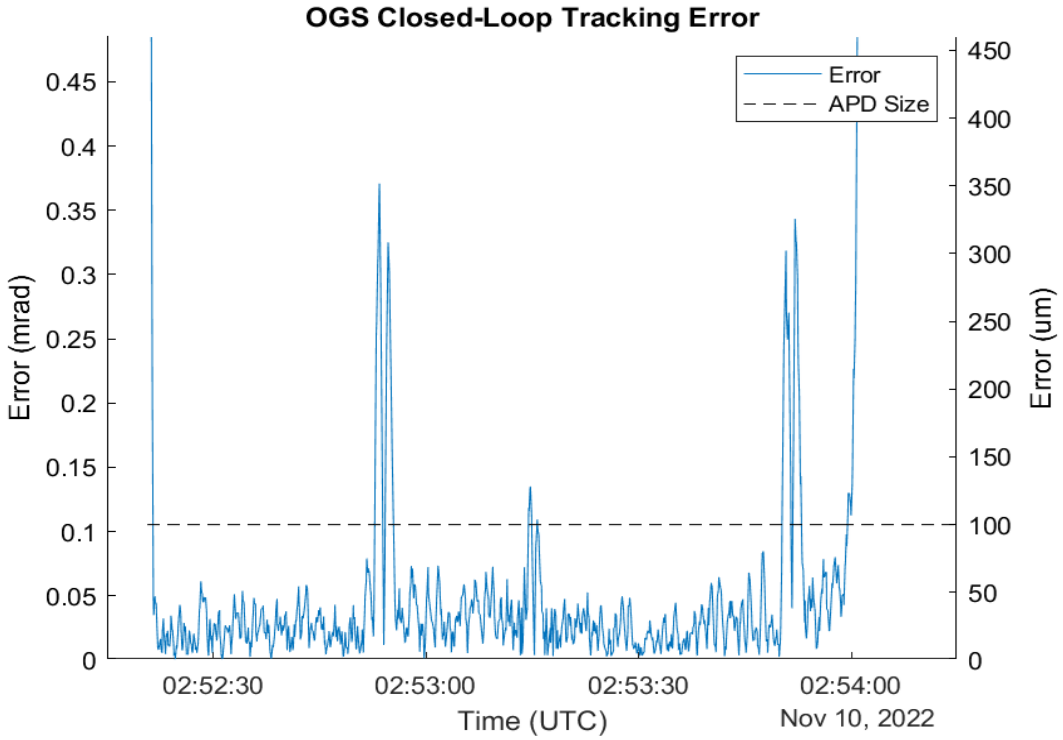






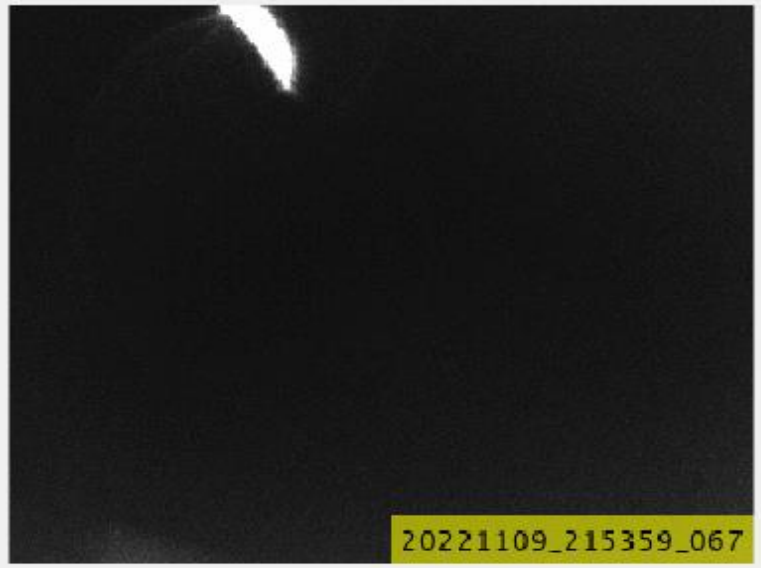
11/10/2022 Experiment

- First light at the Wallace OGS
- IR Camera Settings:
  - Exposure Time 11.67 ms
  - Gain 11 e/count
  - Spot is over-exposed.
- Closed-loop tracking meets 0.105 mrad (100 um) stability requirement on average. Closed-loop tracking maintained signal lock through maximum elevation point.



OGS Closed-Loop Tracking Error Statistics (mrad)				
Min	**25%**	**50%**	**75%**	**Max**
0.0007	0.018	0.032	0.061	1.335

IR Camera Video



Take-Away: First Light for CLICK A downlink to MIT OGS IR Camera.

11/29/2022 Experiment

Pass Summary:

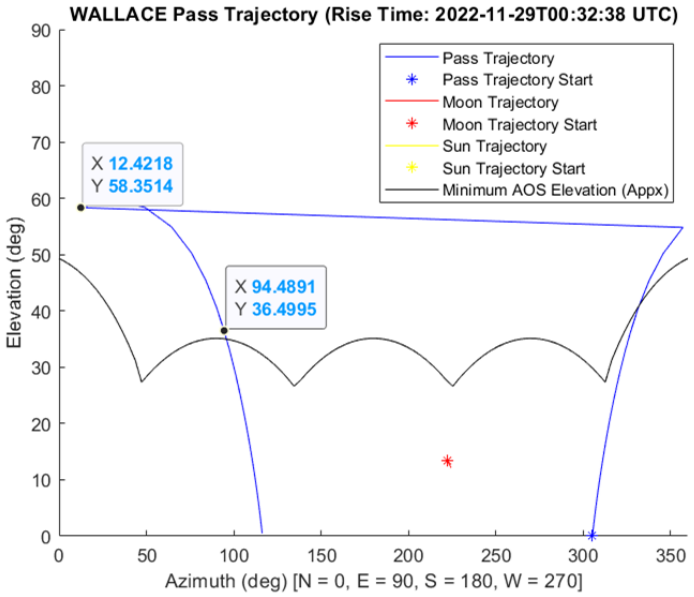
- Max Visible Duration: 1.90 min
- Max El: 59.7°
- Min Range: 429.0 km

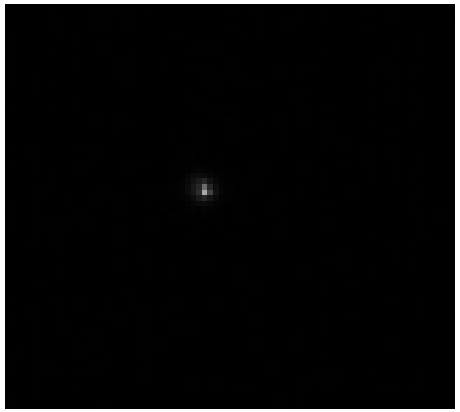
Beacon Uplink Summary:

- AOS: (Az, El) ~ (12°, 58°); Range = 437.7 km
- LOS: (Az, El) ~ (94°, 36°); Range = 575.8 km
- AOS-LOS Duration (sec): 65.8
- Acq. Spot Gaussian Fit: (0.45, 0.73) pxl 1-σ
- S/C Cam. Exp. Times: 4.85 to 10.6 ms
- Meas. Power: -109.8 to -104.0 dBW
- Link Model Error: -3.5 to 4.9 dB; -0.4 dB avg.

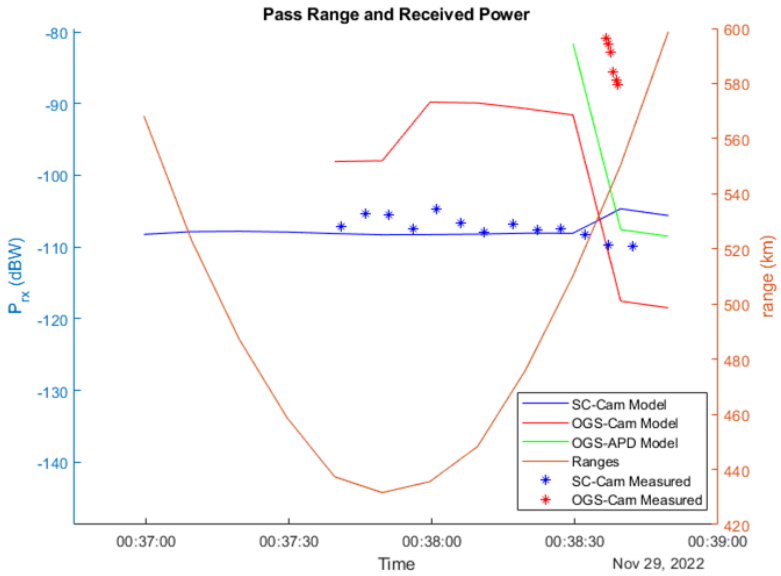
Transmit Downlink Summary:

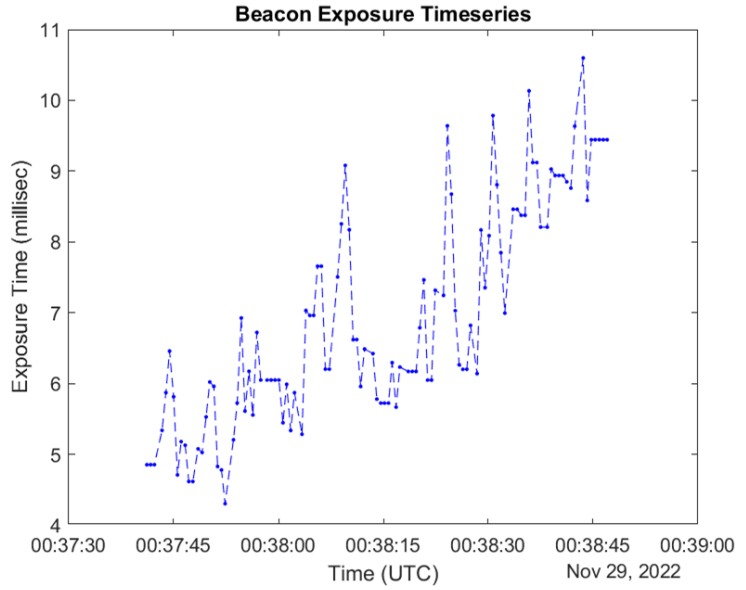
- AOS: 2022-11-29T00-38-33 UTC (El ~ 46°)
- LOS: 2022-11-29T00-38-39 UTC (El ~ 43°)
- AOS-LOS Duration (sec): 6
- OGS Cam. Meas Power: -87.4 to -80.8 dBW (high-uncertainty due to spot exposure)
- Link Model Error: -29.5 to -27.9 dB; -28.7 dB avg
- PPM order set to 16.
- APD installed, but no signal measured. Likely due to misalignment. Closed-loop signal tracking too short to activate OGS FSM.





Beacon Acquisition
2022-11-29T00-37-39 UTC
Exp 4.412 ms

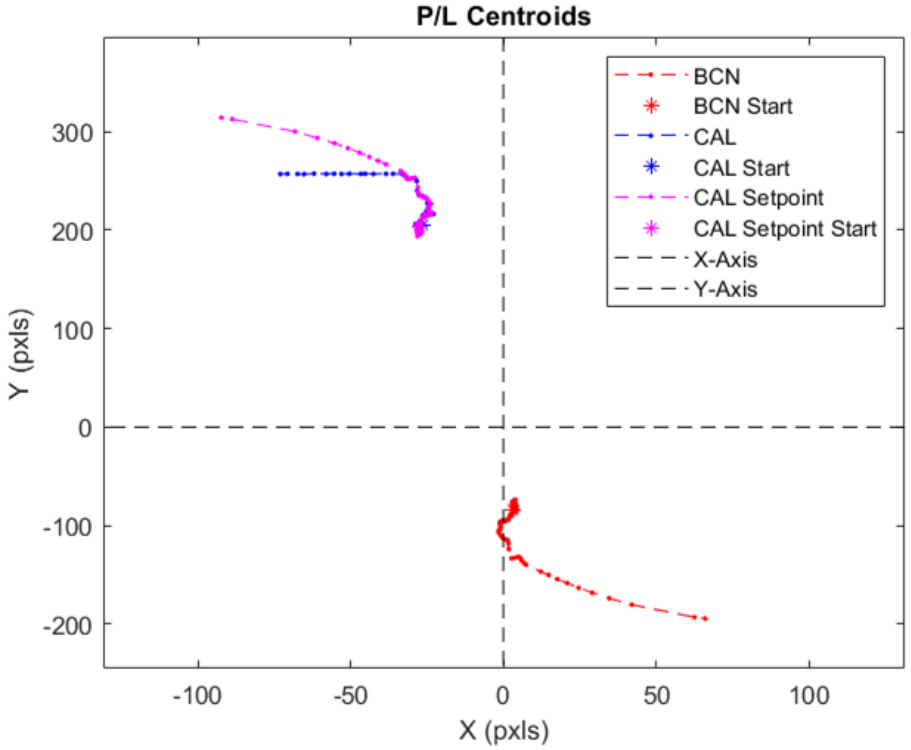


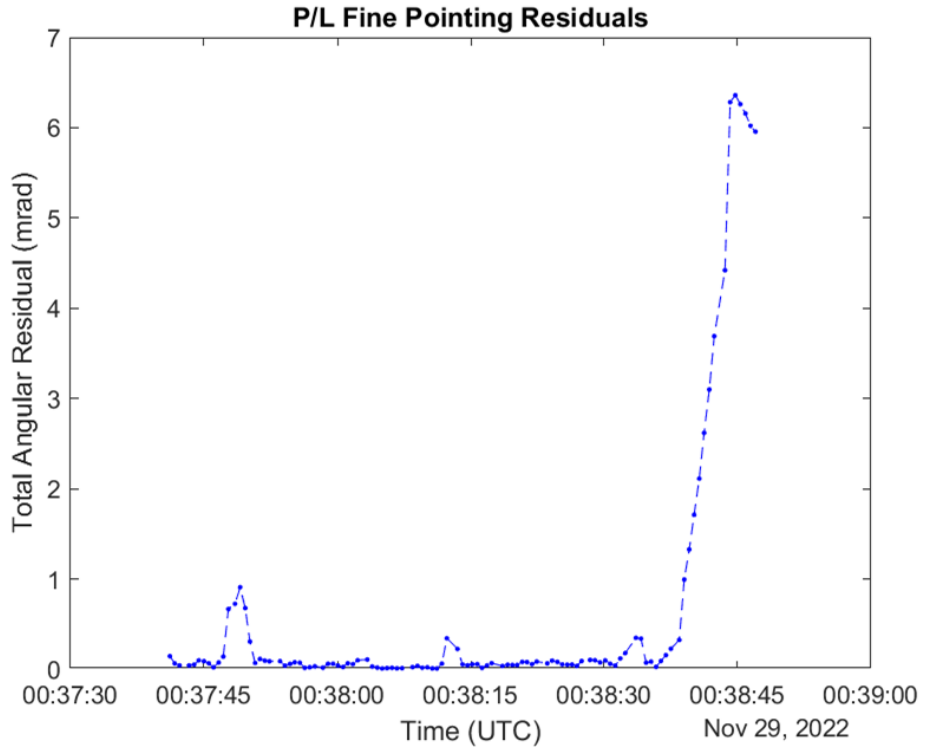


11/29/2022 Experiment

- Median pointing residual **0.072 mrad** (consistent with ground testing)
- Steady-state pointing from acquisition for **65.8 seconds**
- S/C attitude roll manuever starts at 05:38:38 UTC. This resulted in a downlink signal fade.

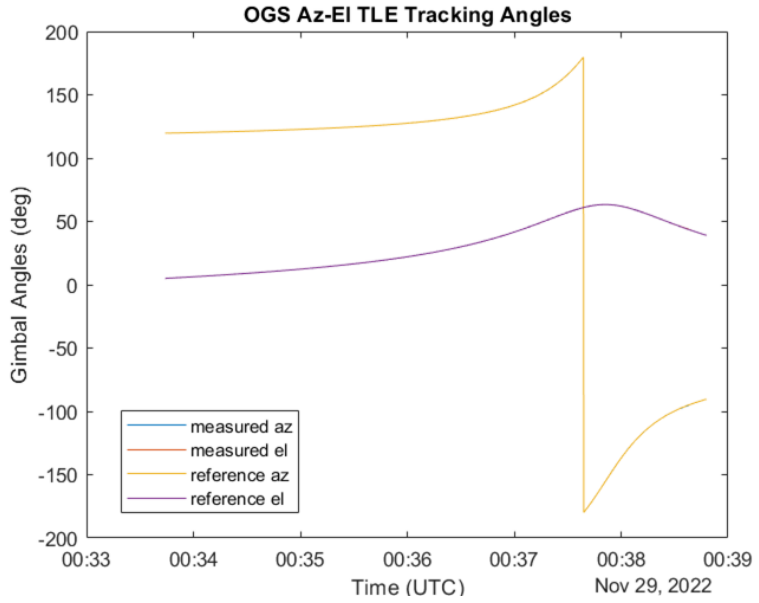
P/L Fine Pointing Residuals Statistics (mrad)				
Min	**25%**	**50%**	**75%**	**Max**
0.008	0.043	0.072	0.154	6.36

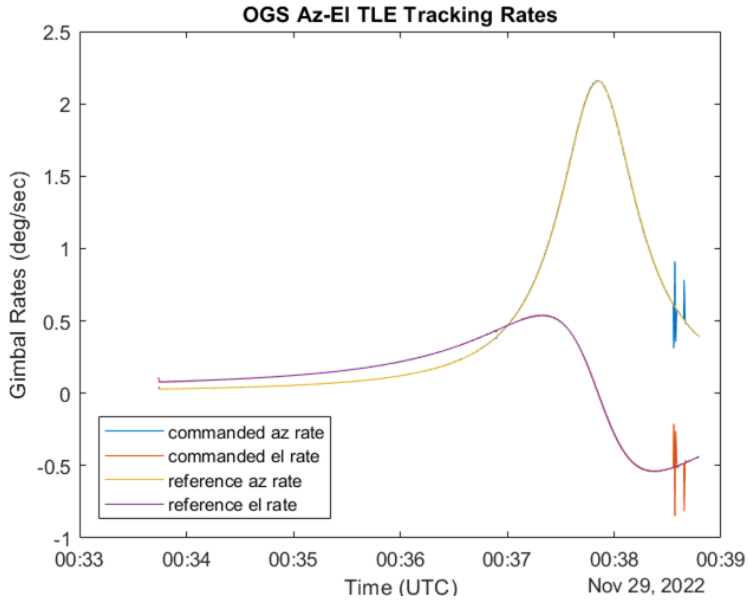


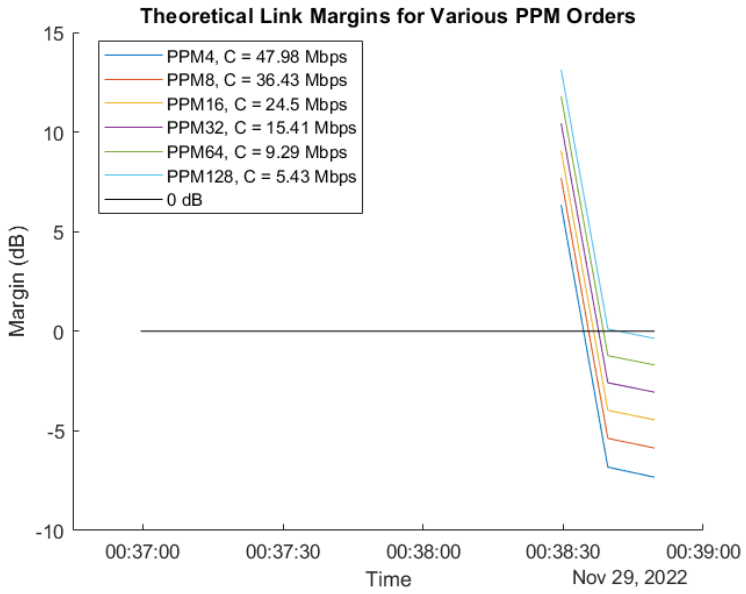


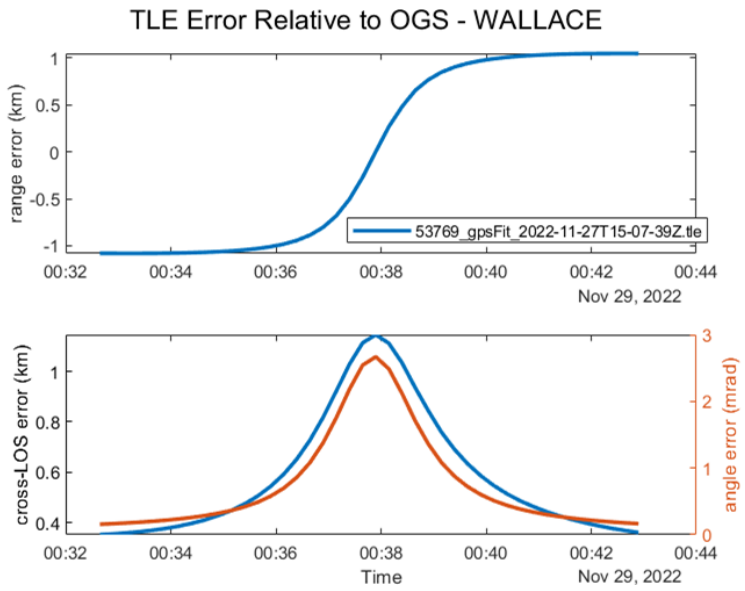
11/29/2022 Experiment

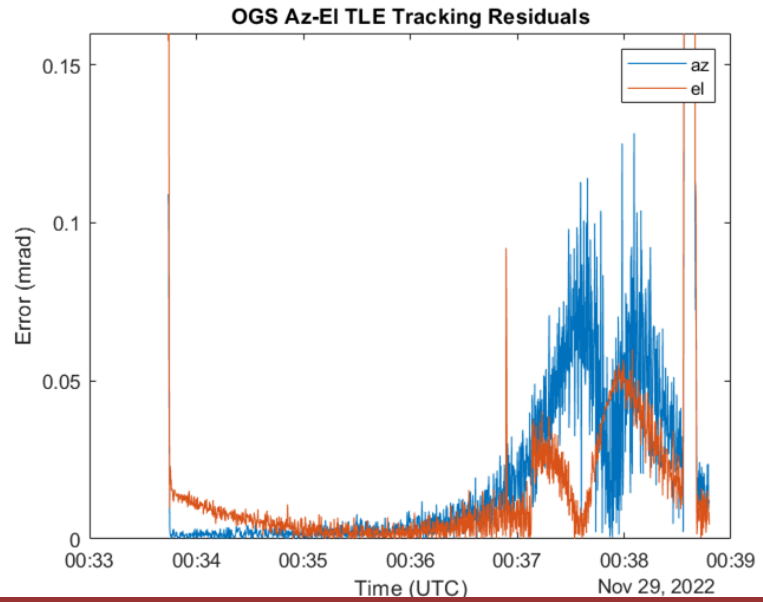
- Max El Rate: +/- 0.66 deg/s
- Max Az Rate: 3.04 deg/s
- TLE Range Error: -1.08 to 1.05 km
- TLE Cross Line of Sight (LOS) Error: 0.35 to 1.15 km
- TLE LOS Error Angles: 0.16 mrad to 2.67 mrad
- Open-Loop TLE Tracking Residuals: Median 0.010 mrad





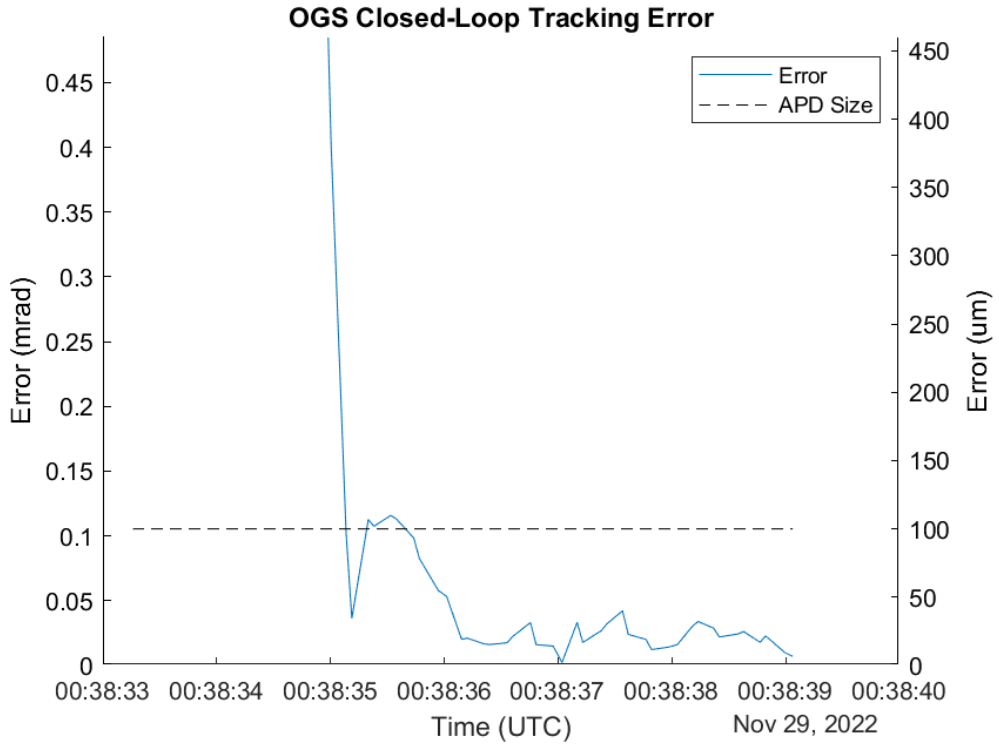






11/29/2022 Experiment

- IR Camera Settings:
  - Exposure Time 4.22 ms
  - Gain 62 e/count
  - Spot is better than 11/10, but still over-exposed.
- Downlink signal acquired at edge of FOV after max elevation point (46°). Closed-loop tracking meets 100 um requirement.
- Signal fades before LOS due to spacecraft attitude roll



OGS Closed-Loop Tracking Error Statistics (mrad)				
Min	**25%**	**50%**	**75%**	**Max**
0.002	0.020	0.034	0.707	2.572

IR Camera Video

Take-Away: Second CLICK A downlink to MIT OGS IR Camera.

Key Lessons Learned

Payload:

- P/L FSW was generally reliable.
- FSM generally performed well and withstood all loads from handling and launch.
- Payload temperatures during experiments ran on the colder side (0 to 20 C): better than expected. Also helped reduce impact of thermoelastic misalignment effects. Also, inelastic shift due to launch/handling was negligible (ISS resupply).
- Payload stray light can be mitigated by reducing max exposure time (< approx. 500 ms) and filtering spots deemed too large. Adding a baffle would also reduce stray light.

Spacecraft Bus:

- S/C ADCS & GPS hardware was essential and performed well during the mission. S/C FSW was generally reliable.
- Rolling while pointing due to secondary downlink attitude command of sun pointing caused issues due to misalignment of the payload to the S/C.
- Solar activity means that a low drag profile earlier in the mission would have extended the lifetime further.

Ground Stations:

- KSAT lite network is has more passes and more flexibility than single radio ground station .
- Multiple optical ground stations greatly increases lasercom downlink opportunities by mitigating bad weather.
- The ground beacon diode emits light and needs to be optically isolated from the rest of the receive optics on the OGS.
- Adding a power meter in the receive path at the optical ground station would improve capabilities.
- Adding a WFOV IR camera to the ground station would improve capabilities.
- Thermoelastic shifts can cause significant beacon mispointing at extreme ground temperatures.
- Using a COTS APD receiver can mitigate risk of unforeseen issues with custom solutions.
- Using motorized solution for APD alignment instead of manual kinematic mounts would increase repeatability and reduce time spent calibrating the system.

Summary

- First light for beacon uplink to S/C camera on 11/02/2022.
- First light for P/L downlink to OGS camera on 11/10/2022.
- P/L fine pointing median residual 0.041 to 0.145 mrad for 11/2, 11/10, & 11/29 experiments. Consistent with ground testing.
- P/L fine pointing is sensitive to rapid changes in S/C attitude, including roll maneuvers due to alignment bias between P/L and S/C star tracker. S/C rolling should be minimized during experiments.
- Error in the TLE drag parameter (B*) typically dominates, causing an increasing along-track error.
- Mean 3D position error using GPS-corrected TLEs over all experiments was 3.1 km (OGS beacon was designed for 3 km 3-σ)
- OGS closed-loop tracking median residual 0.032-0.034 mrad for 11/10 & 11/29 experiments (0.105 mrad requirement).
- OGS closed-loop tracking maintained signal lock through maximum elevation point.
- Estimated received uplink beacon power in P/L camera -117.3 to -104.0 dBW (1.86 to 39.8 pW) for 11/2, 11/10, & 11/29.
- Estimated received downlink power in OGS camera -87.4 to -77.5 dBW (1.81 to 17.8 nW) for 11/10 & 11/29.
- Significant increase in solar activity in January & February 2023 limited mission lifetime to 7 months. Using low-drag attitude profile earlier in the mission may have extended operations further.
- Primary limitation on lasercom downlink opportunities is clear weather. Adding partner OGS sites enabled downlink experiments to continue in March at an increased cadence.
- Stray light from the moon acquired by the P/L was an issue for some passes. This can be mitigated in software by limiting maximum exposure and spot size.
- CLICK B/C planned launch NET June 2024. CLICK A mission successfully reduced risk for B/C by testing many critical elements such as the ground support systems (KSAT, OGS's, MOC), transferable payload hardware & software (e.g. FSM & camera), and spacecraft bus hardware & software.

Thank you for your attention!

References

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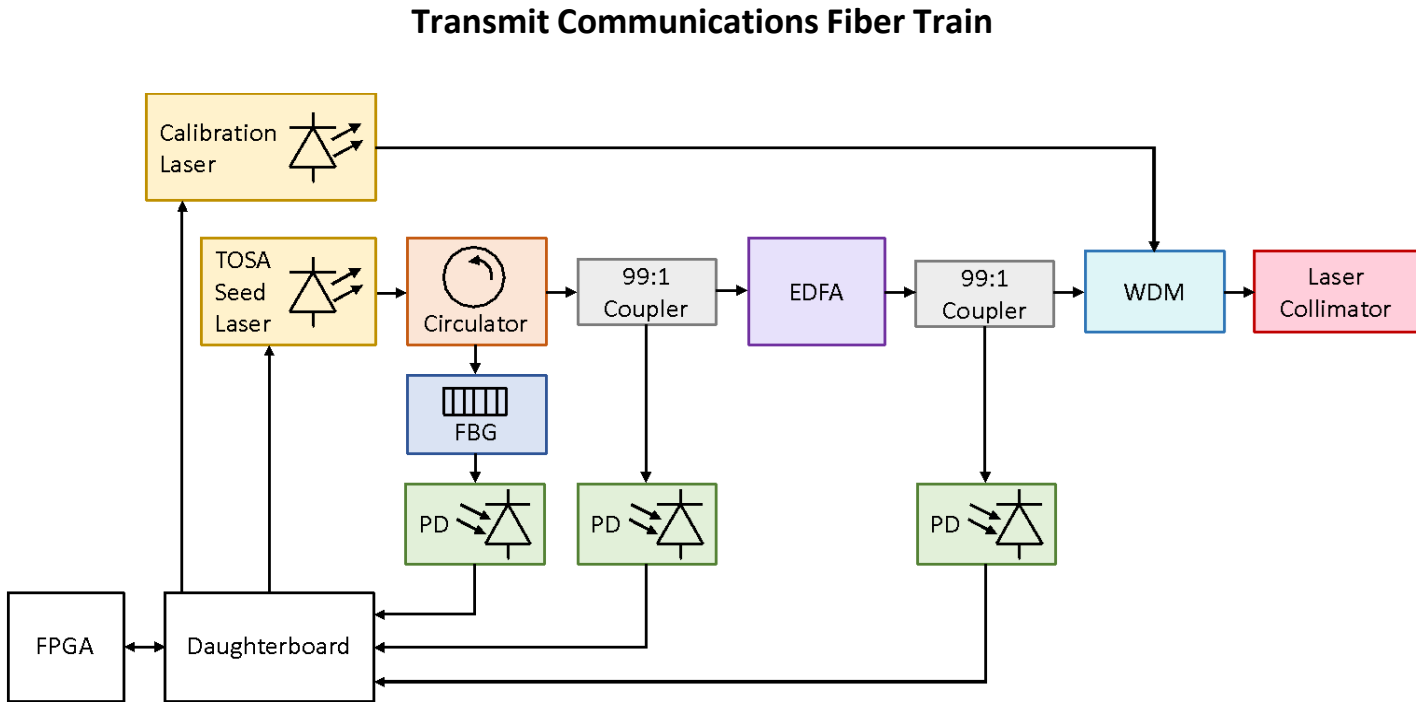
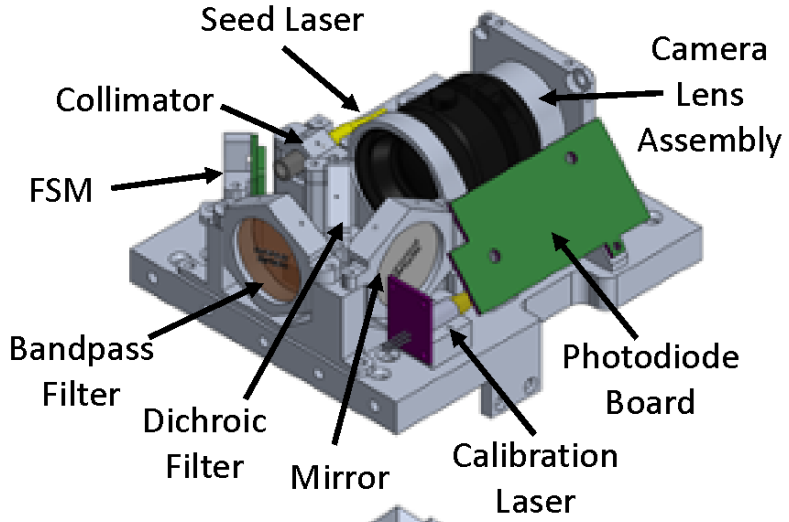
Backup Slides

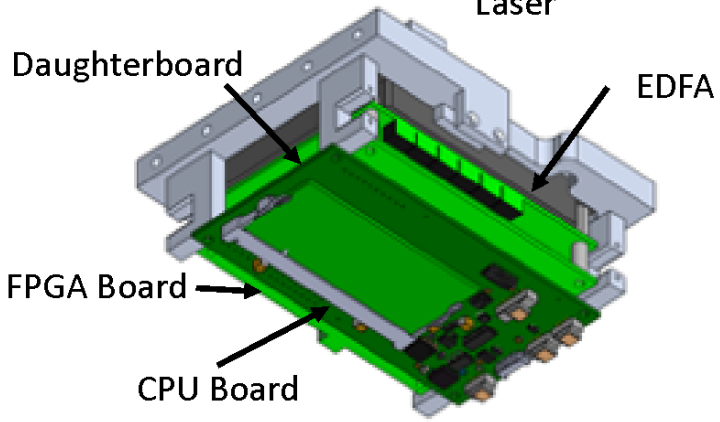
CLICK A Radio Ground Network

CLICK A Payload



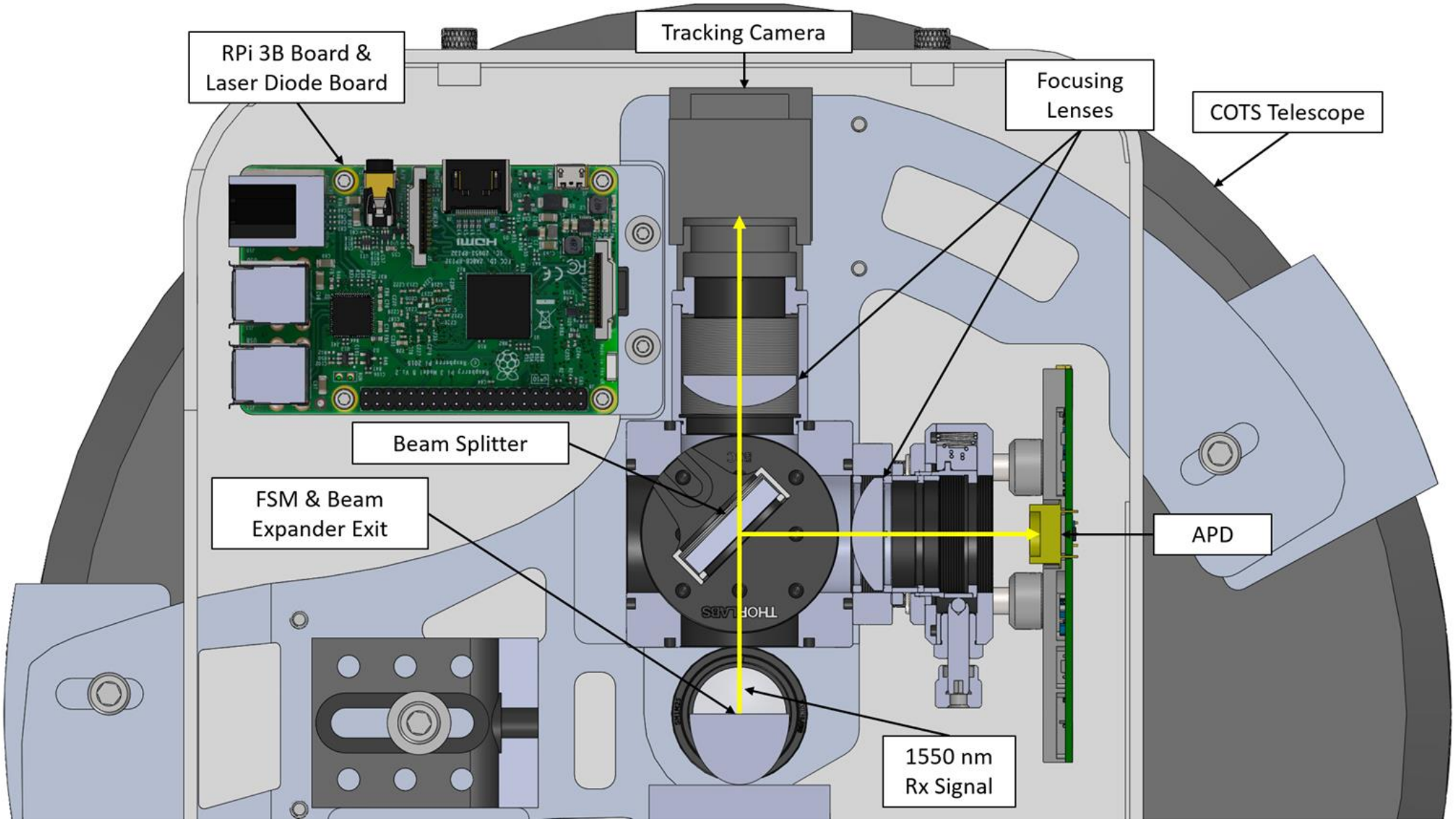
Credit: [3] Tomio et al. (2022)





Credit: [2] Kammerer, W. (2020)

PorTeL OGS Optomechanical Design



Credit: [4] Cierny et al. (2020)

PorTeL OGS APD Issues

- Original PorTeL design used legacy APD board from University of Florida's CHOMPTT mission. This was used in GSE for CLICK A ground testing.
- August 2022: Legacy CHOMPTT APD board failed. Backups also failed. Did not have resources to fix the board.
- Sept-Oct 2022: Tested CLICK B/C APD board for potential use in PorTeL. Board issues discovered: required more development before being ready to use.
- Oct-Nov 2022: Procured COTS Thorlabs APD device. Installed in PorTeL at end of November.
- 11/29/2022: Wallace experiment downlink to IR cam was successful, but too short to activate FSM for APD. Further alignment testing also showed that APD was likely misaligned. Refined alignment procedure over next couple months, but did not have another successful downlink at Wallace prior to end of mission.
- Partner OGS did not have time to get APD sensors set up prior to end of mission.

Orbit Determination

- Downloaded S/C GPS data daily (24 hour span of saved data sampled once per minute)
- Used batch least squares estimation technique initialized with most recent available Space-Track TLE to process GPS data and generate an updated TLE for lasercom experiment satellite tracking
- Orbit model: SGP4
- Tested Various Fitting Approaches On-Orbit:
  - Data span: 24 hrs, 48 hrs, 72 hrs
  - Data sampling: 1 min, 5 min, 15 min
  - Data weighting: uniform, linearly increasing, quadratically increasing
  - Including B* as a parameter to fit or not
- Best approach: 24 hr data span, 15 min sampling, quadratically increasing weighting, including B*