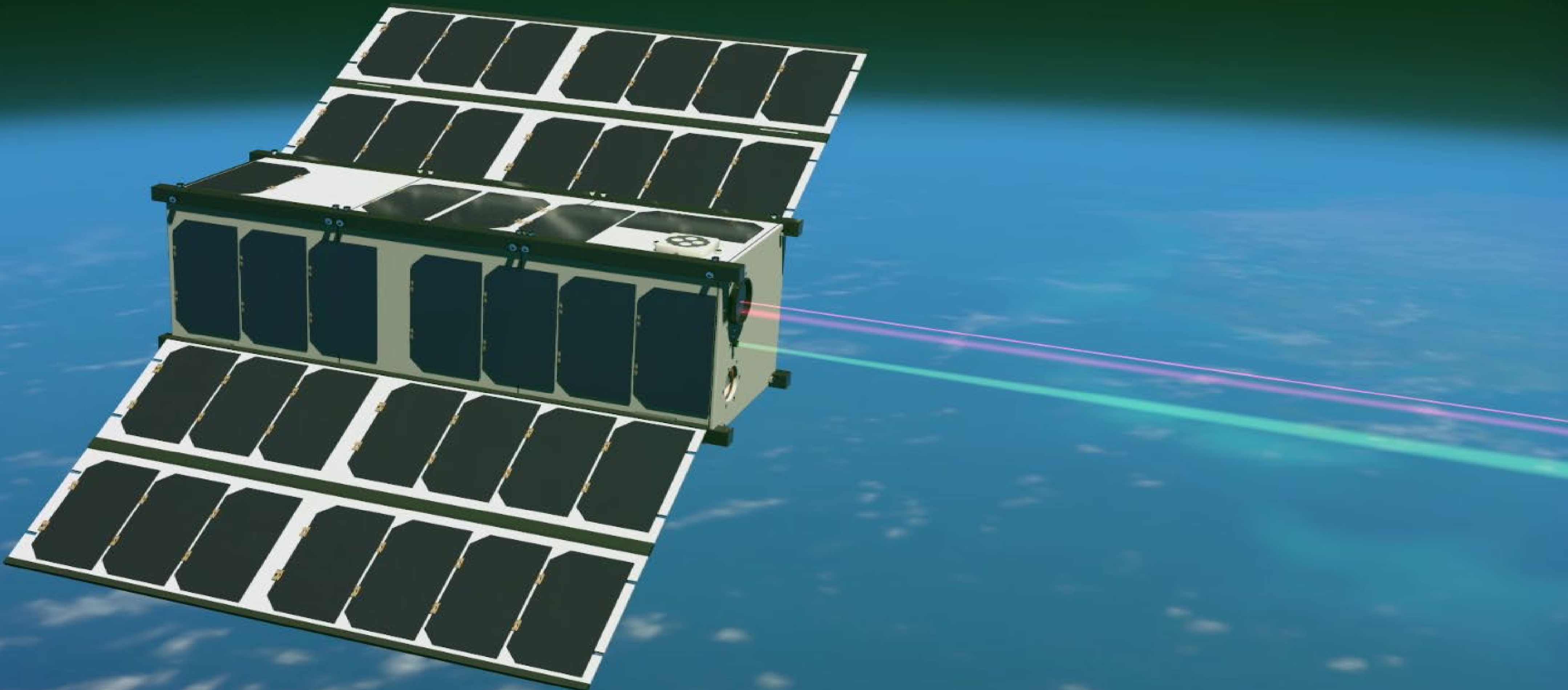
Design and Prototyping of a Nanosatellite Laser Communications Terminal for the Cubesat Laser Infrared CrosslinK (CLICK) B/C Mission



P. Grenfell, P. Serra, O. Cierny, W. Kammerer, G. Gunnison, J. Kusters, C. Payne, K. Cahoy (MIT STAR Lab).
M. Clark, T. Ritz, D. Coogan, J. Conklin (UF PSSL). D. Mayer, J. Stupl (NASA ARC). J. Hanson (CrossTrac).

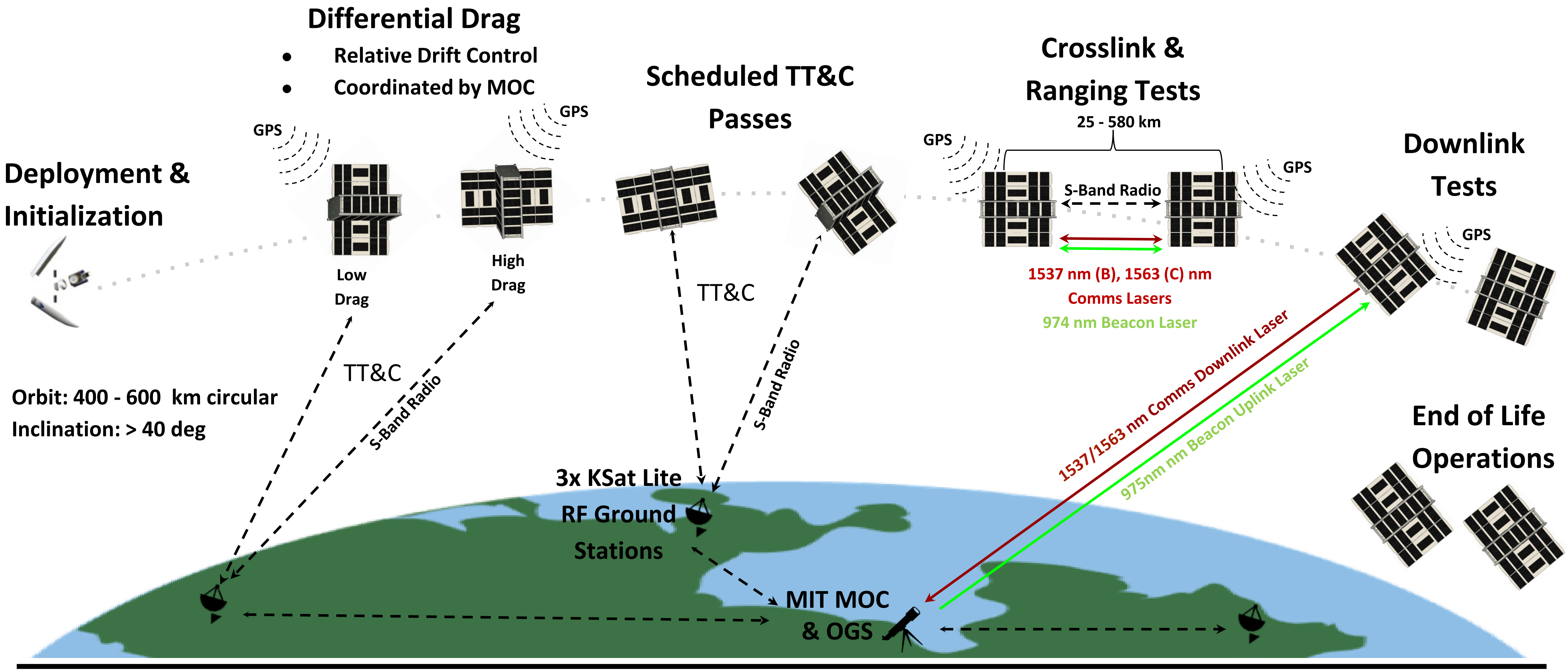
Overview

1. **Introduction**
2. Link Analysis: Crosslink Experiments
3. Link Analysis: Downlink Experiments
4. Payload Optomechanical Design & Prototyping
5. Payload Thermal Design
6. Conclusions

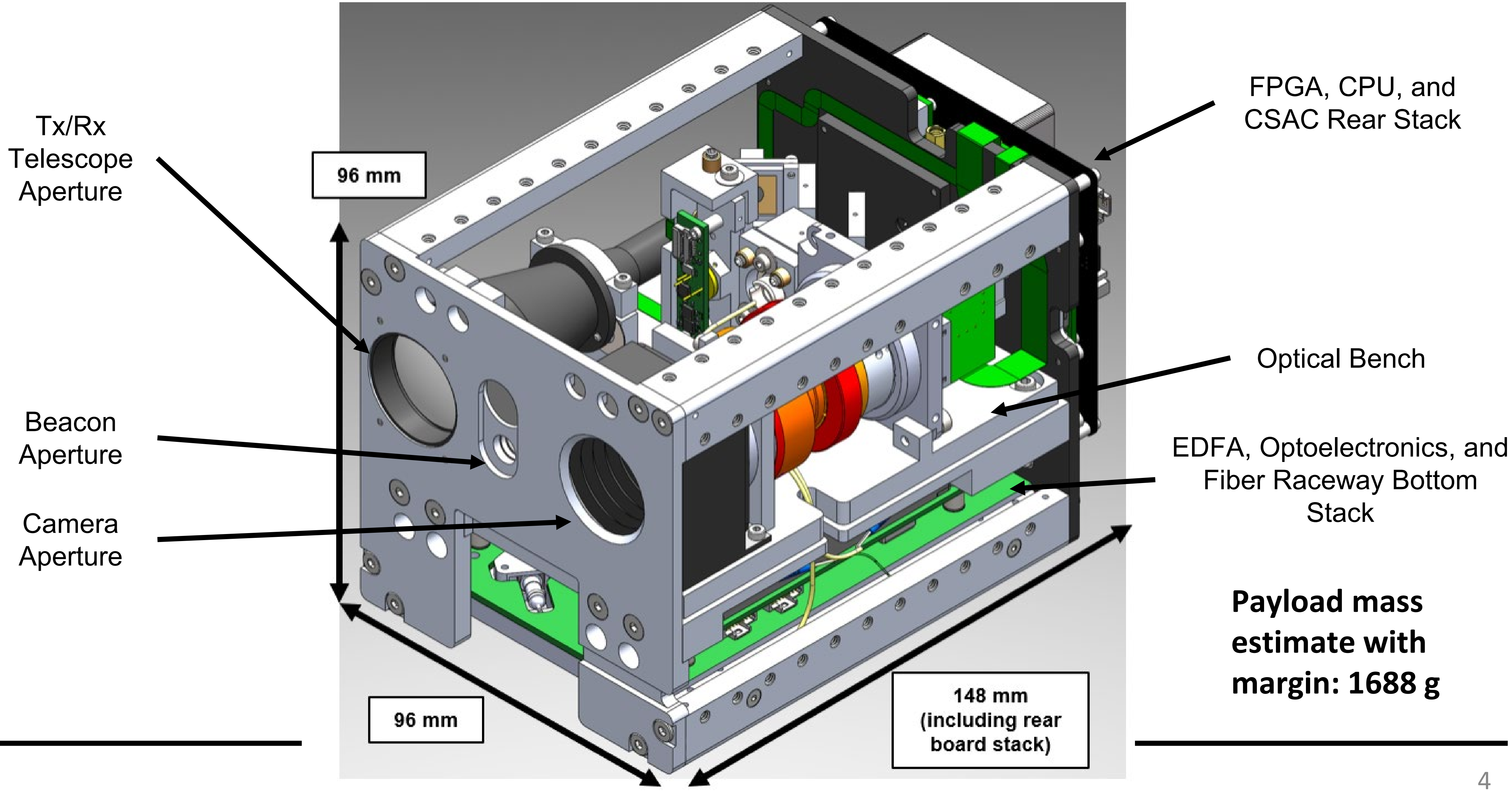
CLICK Mission Objective
Advance the state of the art in free space optical communications by demonstrating the feasibility of lasercom crosslinks and downlinks with nanosatellites using miniaturized optical transceivers.

CLICK Mission Phases: A | B/C |

Mission Concept of Operations (ConOps)



Payload



Payload mass estimate with margin: 1688 g

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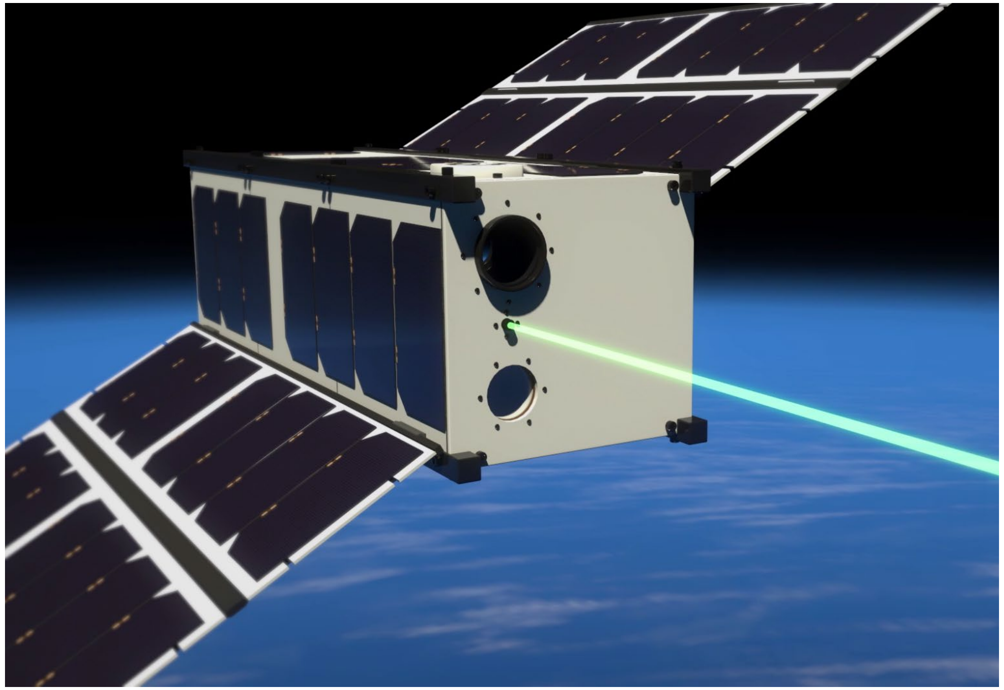
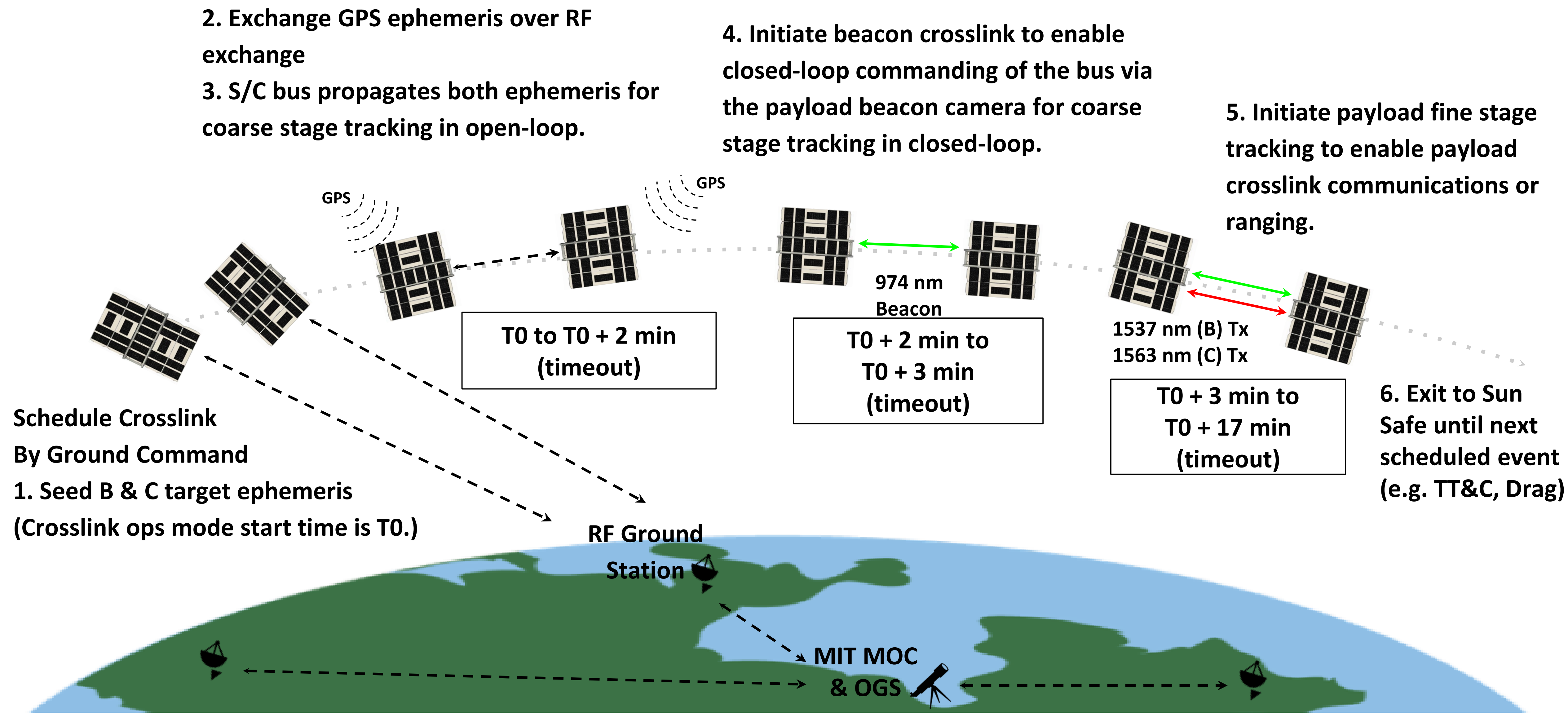
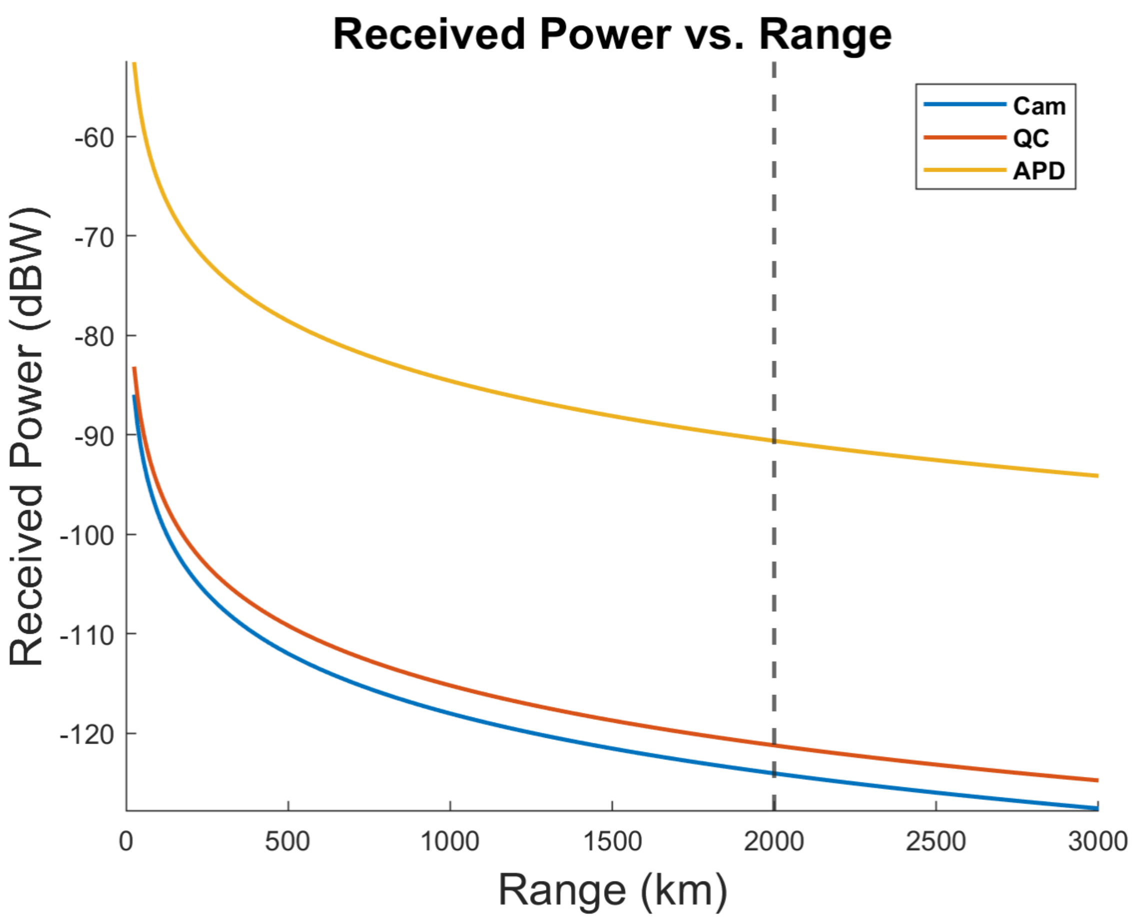
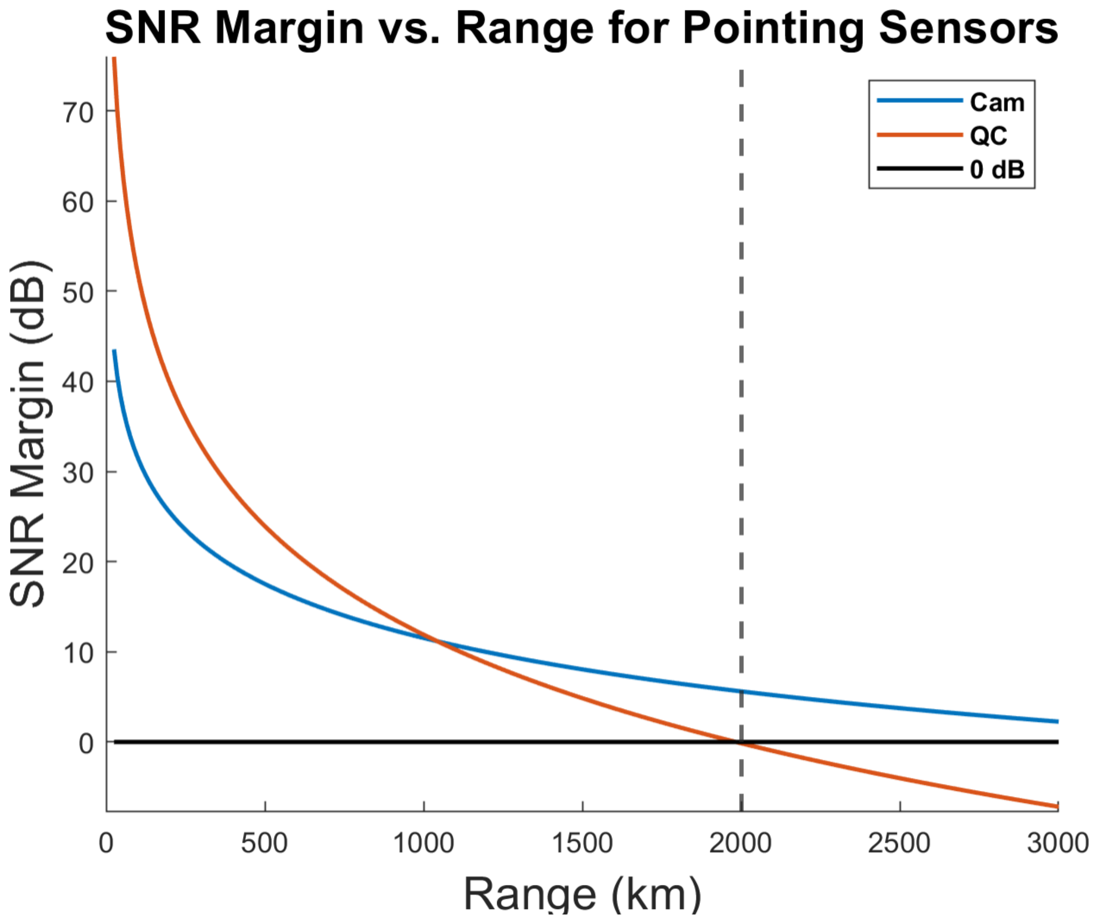


Crosslink ConOps



Link Analysis: Crosslink





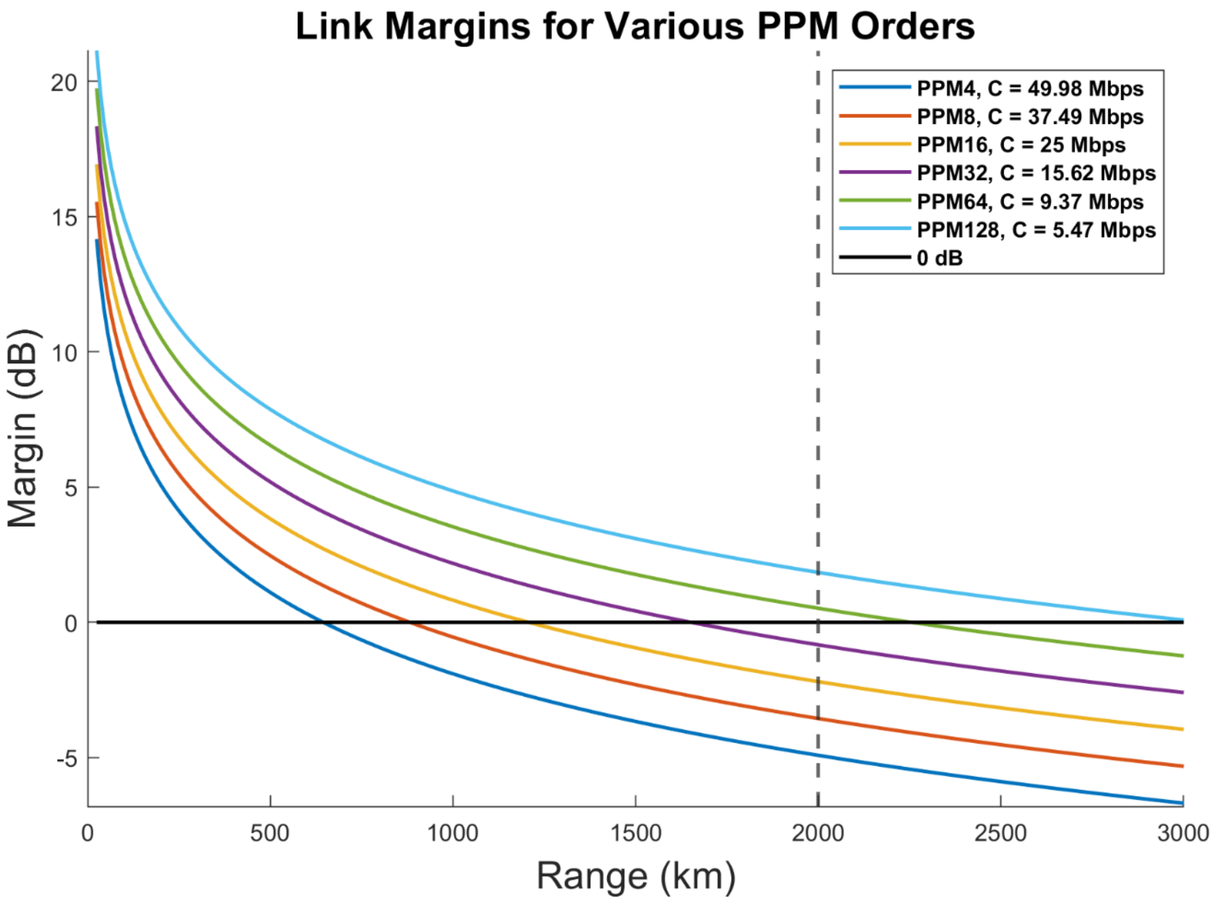
- Variation in received power is dominated by path loss.
- From 25 km to 580 km, the path loss changes by 27.3 dB.
- Limiting sensor is the quadcell, with a maximum range of 2000 km for a positive SNR.
- More than sufficient for 580 km maximum range requirement.

Link Analysis: Crosslink

- Using PPM order 16, a channel capacity* of 25 Mbps can be maintained out to 1200 km.
- Sufficient for mission requirement of 20 Mbps out to 580 km.
- Up to 21 Gb (2.6 GB) of data transfer capacity using PPM 16.

PPM	Channel Capacity (Mbps)	Max Range (km)	Data Transfer (Gb)
4	49.98	645.1	14.99 - 41.99
8	37.49	882.0	11.25 - 31.49
16	25.00	1206.9	7.50 - 21.00
32	15.62	1651.1	4.69 - 13.12
64	9.37	2253.7	2.81 - 7.87
128	5.47	3057.4	1.64 - 4.59

Transfer amounts are for link durations of 5 - 14 min.



* See Xie & Moison [2] for reference.

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Prototype of PorTeL Optical Ground Station (OGS) Credit: Riesing et al. [3]

OGS Pad at MIT Wallace Astrophysical Observatory

Downlink ConOps

1. Periodically gather S/C GPS telemetry prior to the experiment for orbit determination for initial open-loop tracking during the overpass.

2. Schedule Downlink by Ground Command. Initiate bus pointing at T_0 - 2 min.

3. Acquire uplink beacon on quadcell detector to initiate payload fine tracking. Maintain CSTOL-S/C throughout pass.

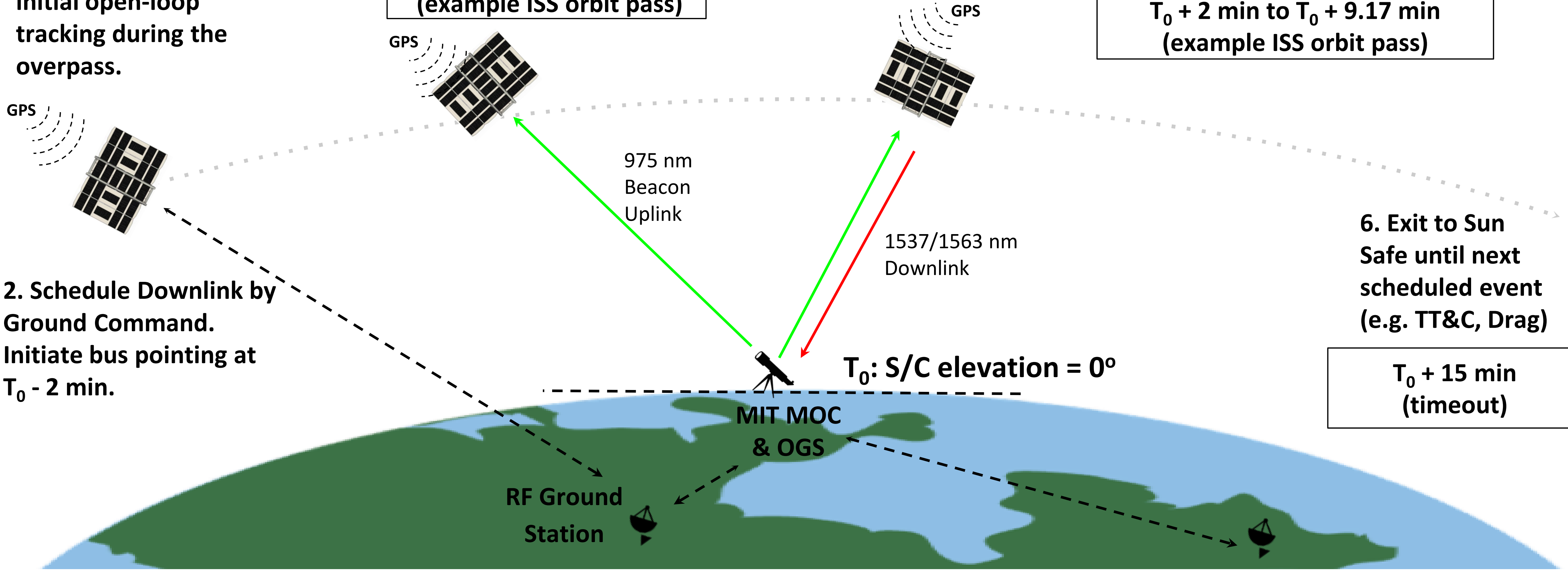
T_0 + 2 min
(example ISS orbit pass)

4. Activate downlink laser to enable closed-loop ground tracking.
5. Activate fine stage ground tracking to begin sampling downlink signal for communications data.

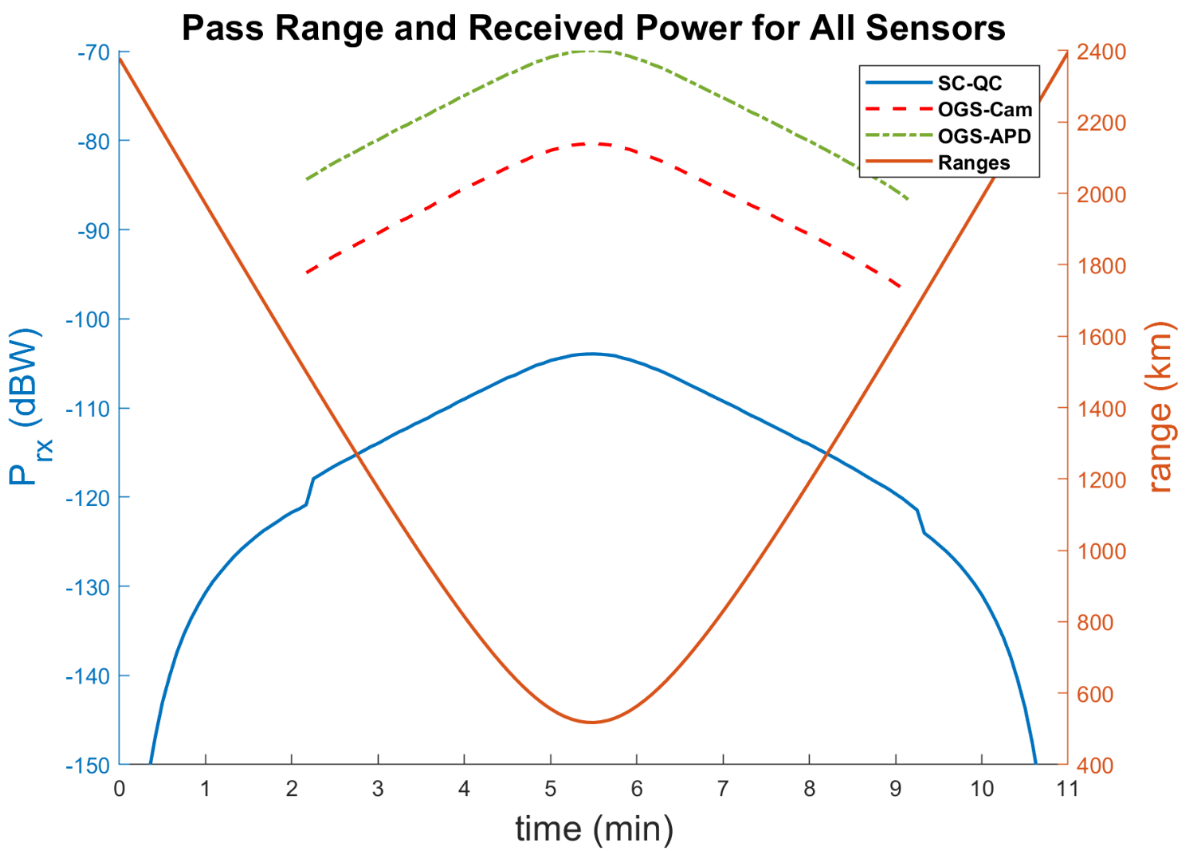
T_0 + 2 min to T_0 + 9.17 min
(example ISS orbit pass)

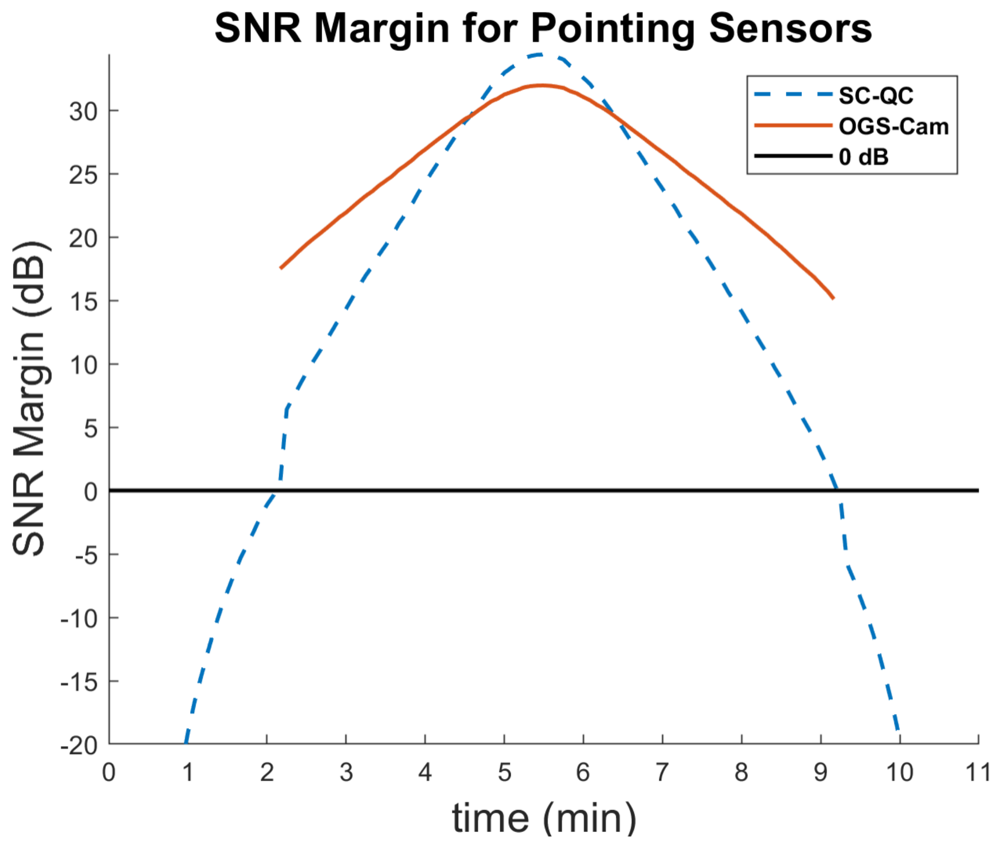
6. Exit to Sun Safe until next scheduled event (e.g. TT&C, Drag)

T_0 + 15 min
(timeout)



Link Analysis: Downlink





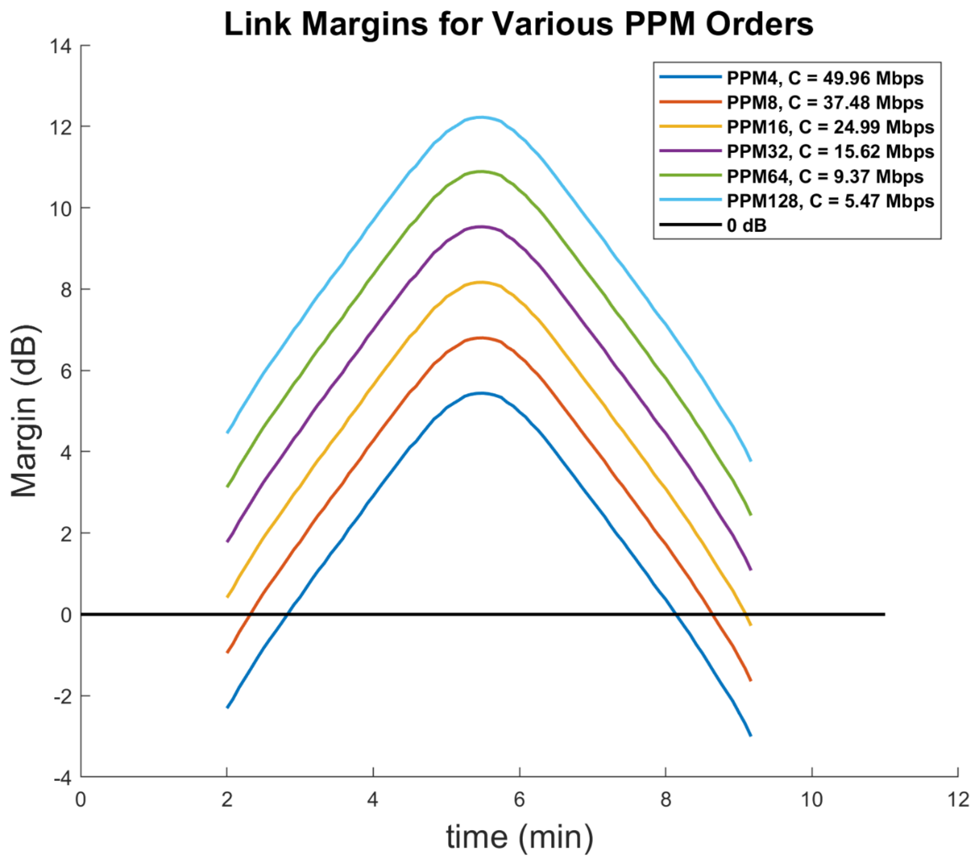
- OGS beacon uplink to payload quadcell closes at 1500 km.
- Downlink duration is restricted by the beacon uplink duration, which is 7.17 minutes for the selected overpass.
- OGS beacon uplink closure to the quadcell is defined by 0 dB SNR margin* points at 2 minutes and 9.17 minutes.

*Reference Yura [4].

Link Analysis: Downlink

- With Pulse-Position Modulation (PPM) order 32 or less, a channel capacity* of 15.62 Mbps or more can be achieved during the pass.
- Sufficient for mission requirement of >10 Mbps.
- Using PPM 16 or lower yields at least 10 gigabits of data transfer capacity for the reference overpass.

PPM	Channel Capacity (Mbps)	Duration (s)	Data Transfer (Gb)
4	49.96	315	15.74
8	37.48	375	14.06
16	24.99	425	10.62
32	15.62	430	6.72
64	9.37	430	4.03
128	5.47	430	2.35



* See Xie & Moison [2] for reference.

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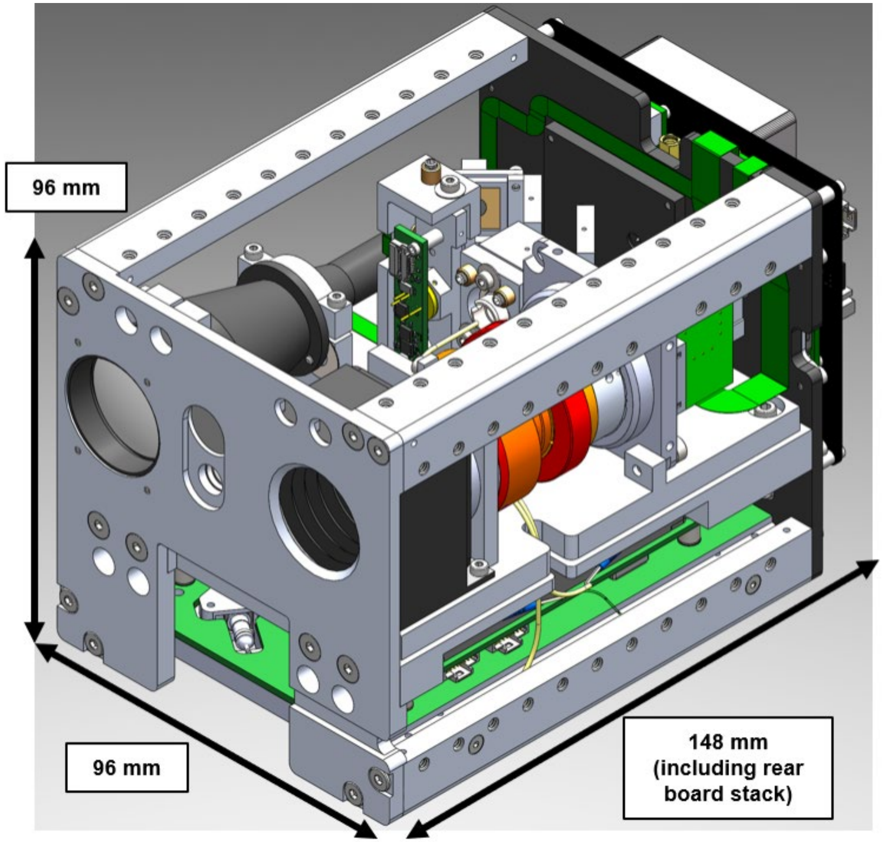


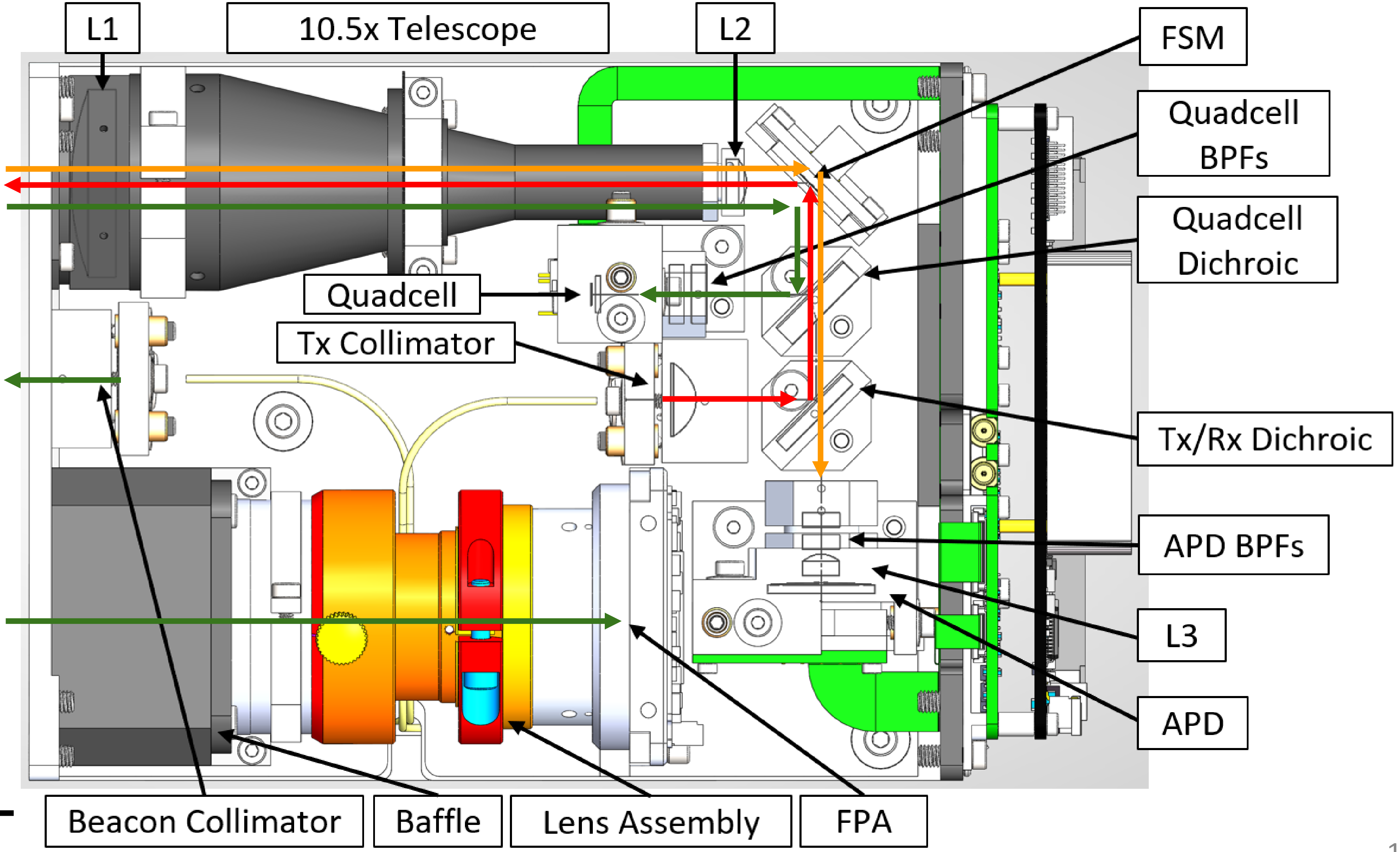
Payload Optomechanical Design

Transmit
200 mW, 1537 nm
(CLICK B)
121 µrad 1/e^2 Div.

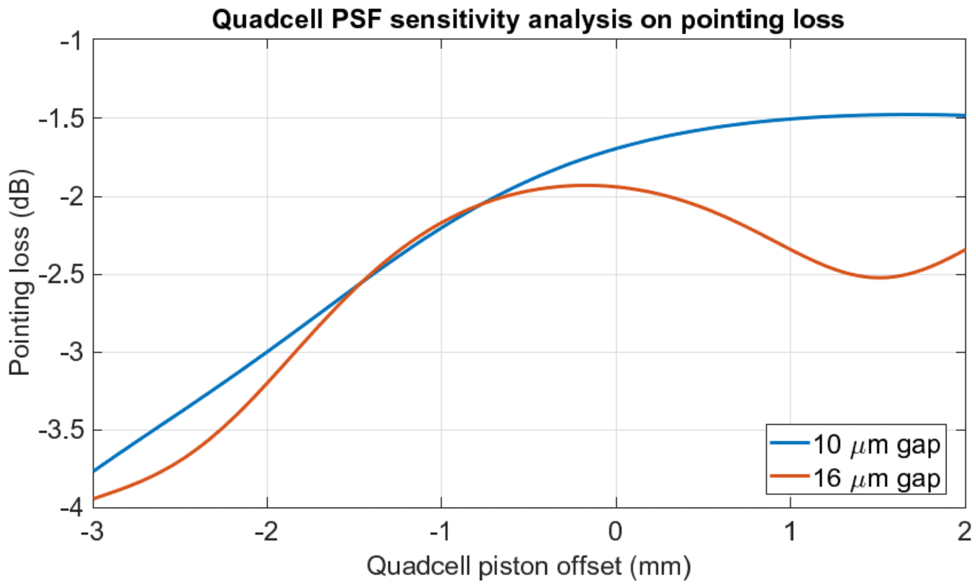
Receive
1563 nm (CLICK B)
22.86 mm aperture

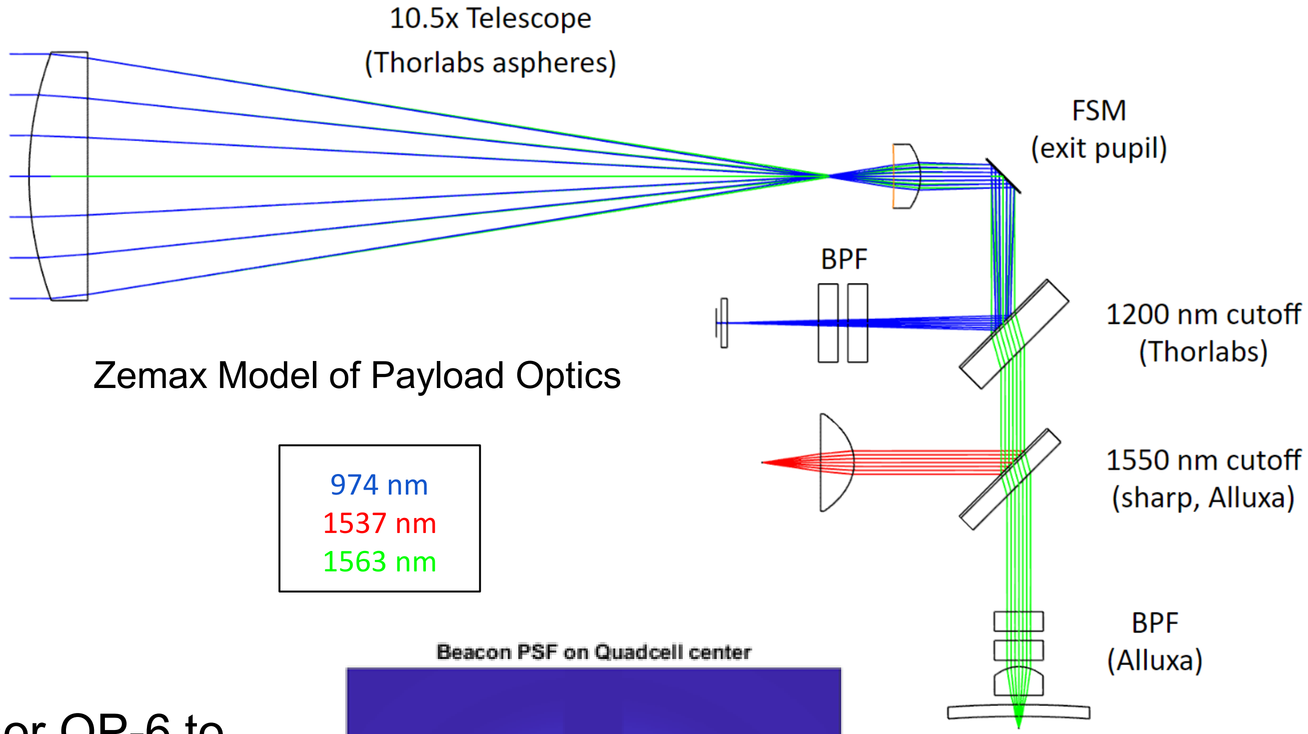
Beacon
250 mW, 3kHz,
974 nm,
7.147 mrad 1/e^2 Div.

Beacon Camera,
Silicon CMOS FPA,
16.4 mm aperture,
10.6° FOV
Camera Baffle
Sun Keep-Out Half-Angle: 46.5°

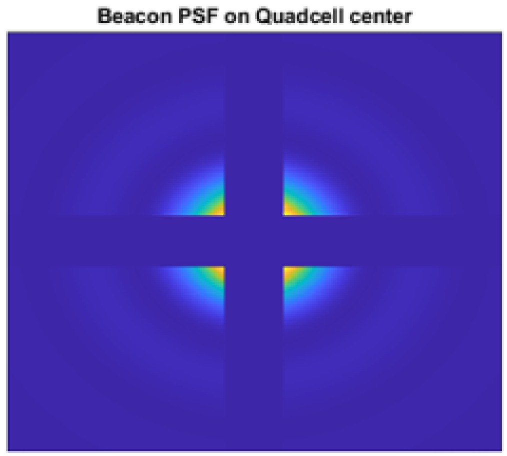


Payload Optical Design: Quadcell



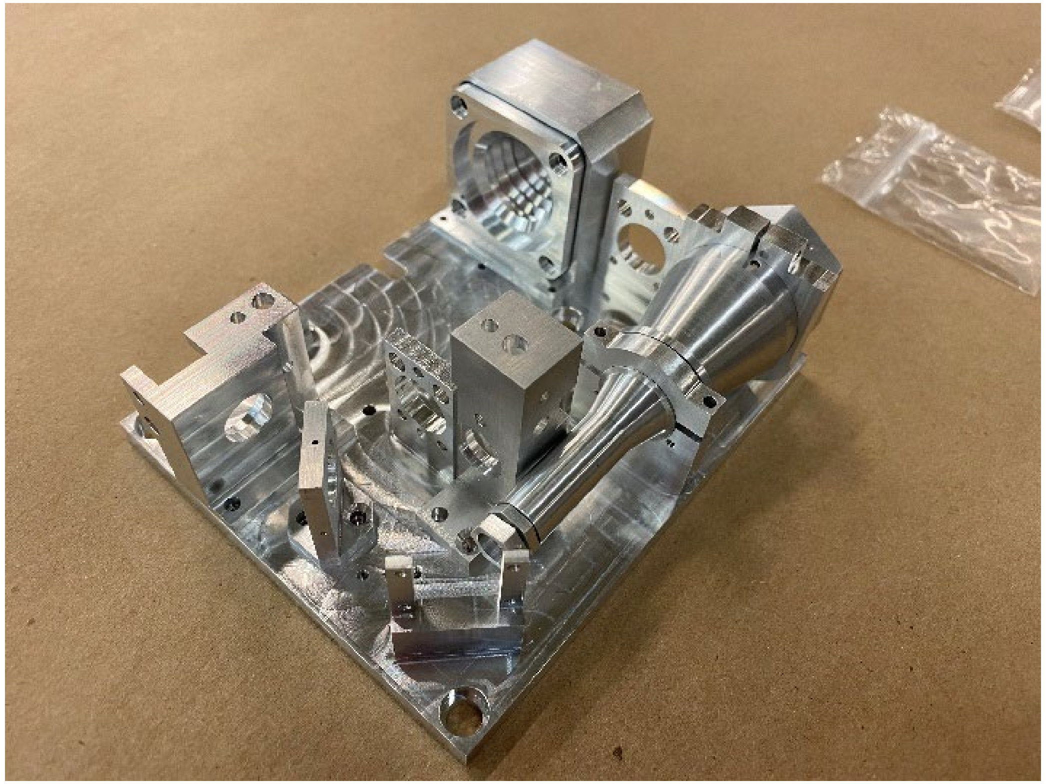


- Quadcell part number changed from First Sensor QP-6 to slightly larger Advanced Photonix SD085.
- Telescope defocus at 974 nm is used for focusing quadcell spot instead of a dedicated focusing lens.
- Quadcell piston location is set to minimize gap loss.

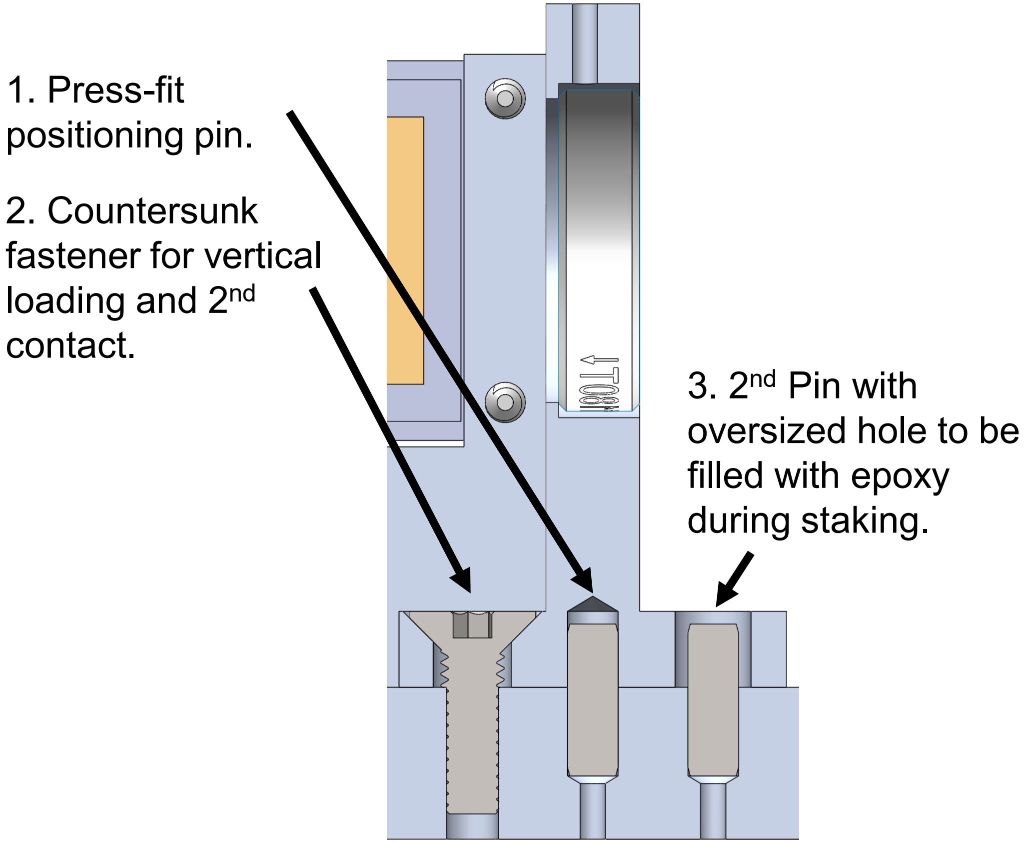


Payload Optical Bench Prototyping

- Payload Engineering Design Unit (EDU) is currently being developed.
- Nominal tolerances: 0.005" (127 um). Critical tolerances: 0.001" (25.4 um).
- The optical bench manufacturing is complete.



Fit check of parts for EDU optical bench during manufacturing.



Optical Mount Fixturing (Example shown here is the quadcell dichroic mount.)

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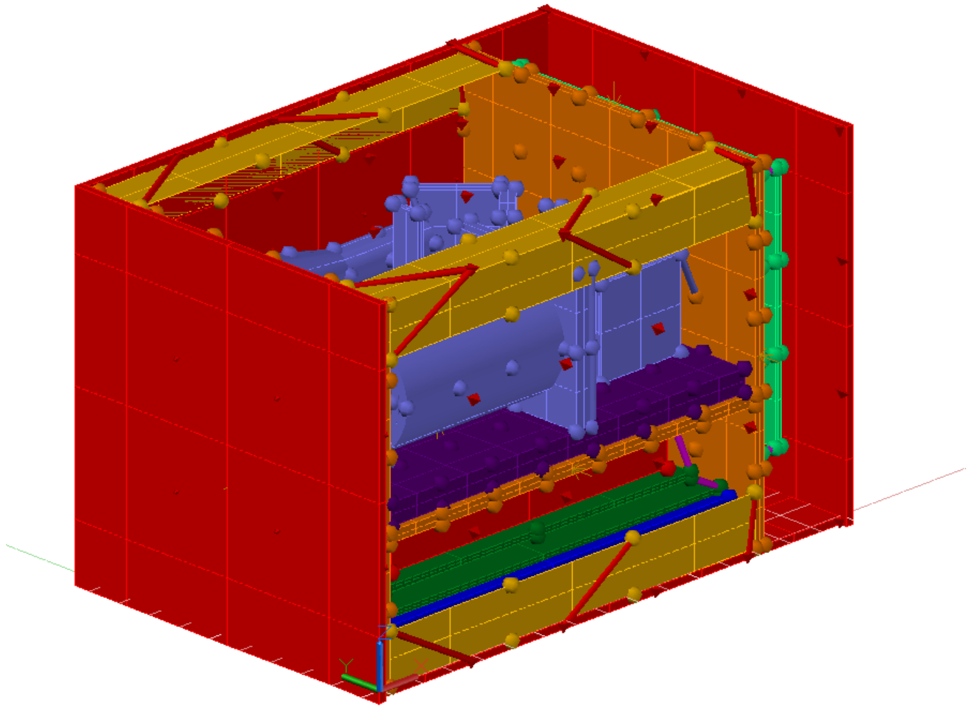


Bus/Payload Thermal Desktop Model

Payload Thermal Design

- Thermal design is primarily passive.

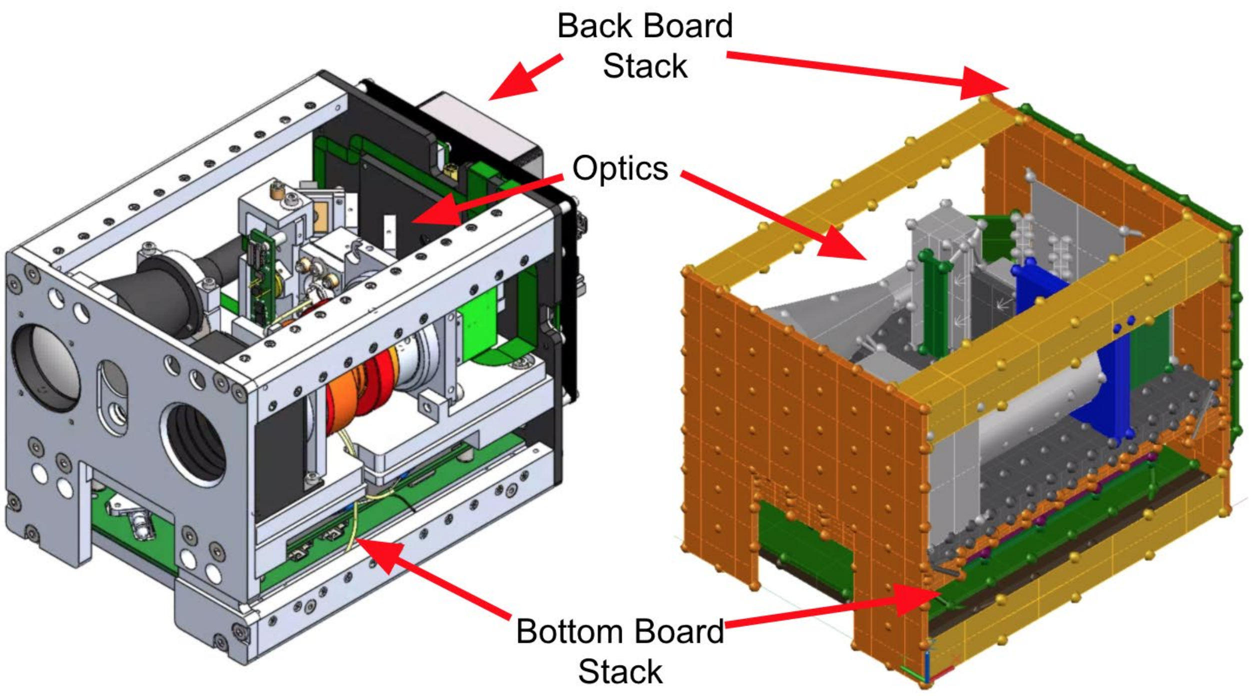
- Thermal modes are:

  1) Start up – payload power on with heaters.

  2) Transmit – sensors and lasers powered on and heaters powered off.

  3) Power down – data processing prior to shutdown without need for heaters.

- Thermal design meets operational and survival temperature requirements with margin.



Conclusions

- **Crosslink** analysis shows that the primary mission requirement of **20 Mbps** at ranges of **25 km and 580 km** is met with margin using **PPM 16 or lower**.

- **Downlink** analysis shows that the mission requirement of **>10 Mbps** is met with margin using **PPM 32 or lower**.

- The payload **Engineering Design Unit (EDU)** is being developed. Optical bench **manufacturing is complete** and is now in the process of optics mountings and assembly.

- The **thermal design** has been verified in simulation to **meet operational and survival** temperature requirements with margin.

- Important next steps include **calibration** of the payload optics, **environmental testing** of the EDU, and verification of optical communications performance via **over the air testing** of the EDU.

References

[1] Peter Grenfell. GNSS-Based Relative Navigation for LEO Nanosatellite Laser Communications. Master's Thesis. Massachusetts Institute of Technology. 2020.

[2] Bruce Moision and Hua Xie. An Approximate Link Equation for the Direct-Detected Optical PPM Link. Technical report, Jet Propulsion Laboratory, California Institute of Technology, 2014.

[3] Riesing, K., Yoon, H., & Cahoy, K. (2018). A portable optical ground station for low-earth orbit satellite communications. *2017 IEEE International Conference on Space Optical Systems and Applications, ICSOS 2017*, 108–114. https://doi.org/10.1109/ICSOS.2017.8357219

[4] H. T. Yura. Threshold detection in the presence of atmospheric turbulence. Applied Optics, 34(6):1097-1102, 1995.

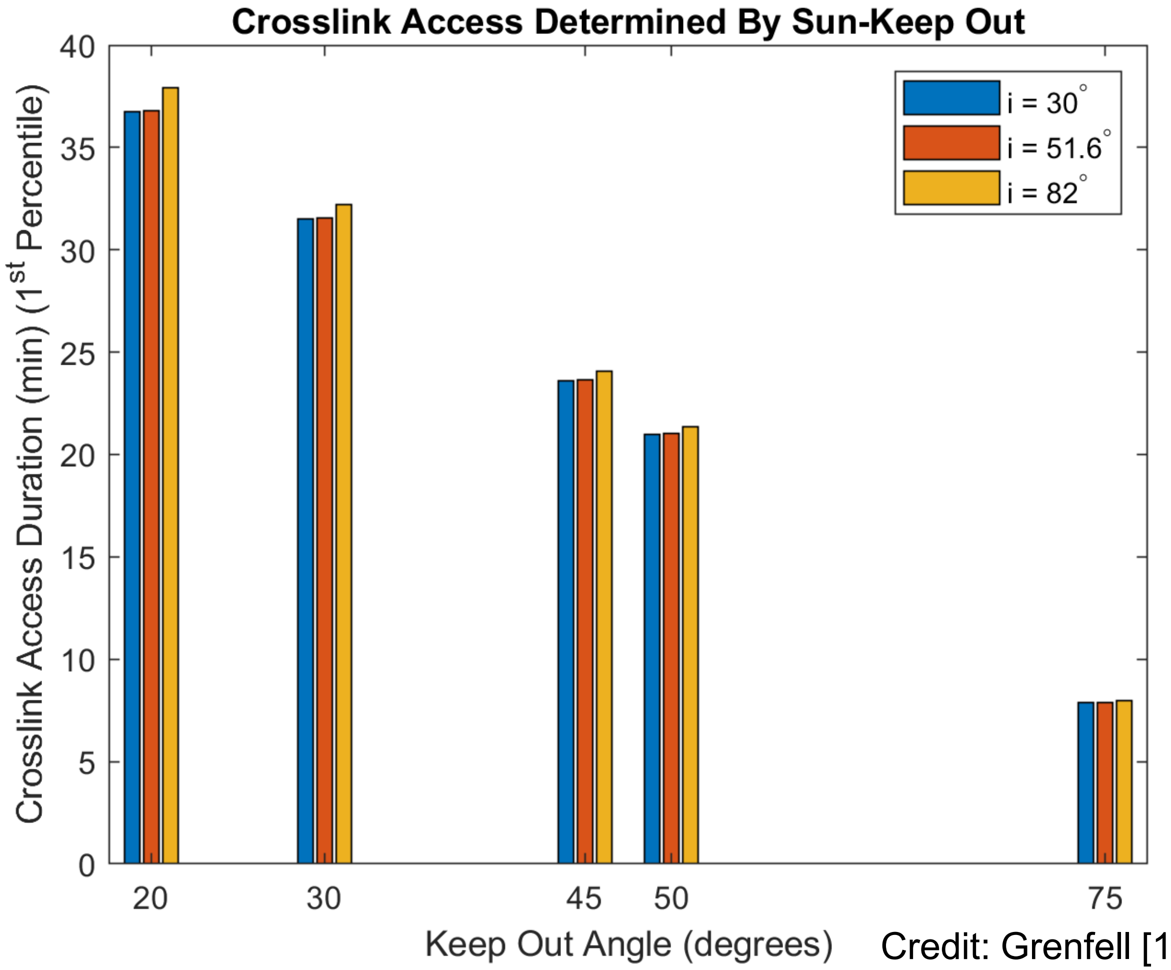
Backup

Key L1 System Requirements

Requirement
The CLICK satellites shall demonstrate an optical communications crosslink at a data rate of at least 20 Mbps at 580 km with a BER better than 10^{-4} without error correction code.
The CLICK satellites shall demonstrate a minimum crosslink range of 25 km or less.
The CLICK satellites shall demonstrate an optical downlink at a data rate of at least 10 Mbps from a LEO reference orbit to a ground station.
The CLICK satellites shall demonstrate the ability to operate a full duplex crosslink.

Crosslink Access Analysis

- Primary constraint on access is the sun keep out constraint on the beacon camera: 46.5^{o} half-angle.
- System's Tool Kit (STK) analysis for a 500 km circular orbit predicts link access durations greater than 21 minutes with 99% probability [1].
- Sufficient for maximum experiment duration of 17 minutes.



Credit: Grenfell [1]

Link Budgets - Crosslink

Link Parameter	APD		Quadcell		Camera	
P_{Tx} (dBW)	-6.99	200 mW avg.	-6.02	2.5 W avg.	-6.02	2.5 W avg.
G_{Tx} (dB)	93.40	121 μrad $1/e^2$	57.97	7147 μrad $1/e^2$	57.97	7147 μrad $1/e^2$
G_{Rx} (dB)	93.32	22.86 mm Ap.	97.35	22.86 mm Ap.	-94.48	16.4 mm Ap.
L_{path} (dB)	-226.1, -253.4	25 km, 580 km	-230.2, -257.5	25 km, 580 km	-230.2, -257.5	25 km, 580 km
$L_{\mathrm{Tx,imp}}$ (dB)	-1.55	CBE	-1.02	CBE	-1.02	CBE
$L_{\mathrm{Rx,imp}}$ (dB)	-0.86	CBE	-1.15	CBE	-1.10	CBE
L_{ptg} (dB) (99.7%)	-3.51, -3.73	38.1 μrad, 39.3 μrad	-0.12, -0.12	417 μrad, 418 μrad	-4.34, -3.41	2527 μrad, 2238 μrad
P_{Rx} (dBW)	-52.33, -79.86		-83.16, -110.5		-90.20, -116.6	
$P_{\mathrm{Rx,bkgd}}$ (dBW)	-111.2	Tx stray light & eclipse	-217.4	eclipse	-207.1	eclipse
Metric	-52.33, -79.86	P_{Rx} (dBW)	85.82, 31.20	SNR (dB)	48.80, 22.45	SNR (dB)
Requirement (dB)	-69.38, -83.05	P_{req} - PPM16	9.83	$\mathrm{SNR}_{\mathrm{req}}$	9.48	$\mathrm{SNR}_{\mathrm{req}}$
Margin (dB)	17.06, 3.18		75.98, 21.36		39.32, 12.97	

APD ranging SNR values: 31.82 dB at 25 km, 16.08 dB at 580 km. 1537 nm or 1563 nm Tx to APD. Using 1550 nm avg. here for simplicity. BER = 10^{-5}. 974 nm Beacon to quadcell and camera.

Link Budgets – Downlink (Min. Range)

Link Parameter	OGS-APD		OGS-Camera		S/C-Quadcell	
P_{Tx} (dBW)	-6.99	200 mW avg.	-6.99	200 mW avg.	3.98	2.5 W avg.
G_{Tx} (dB)	93.40	121 μrad $1/e^2$	93.40	121 μrad $1/e^2$	55.51	9487 μrad $1/e^2$
G_{Rx} (dB)	115.1	28 cm Aper.	115.1	28 cm Aper.	97.34	22.86 mm Ap.
L_{path} (dB)	-252.5	517.60 km	-252.5	517.60 km	-256.5	517.60 km
$L_{\mathrm{Tx,imp}}$ (dB)	-1.55	CBE	-1.55	CBE	-1.02	CBE
$L_{\mathrm{Rx,imp}}$ (dB)	-0.82	CBE	-11.27	CBE	-1.15	CBE
L_{ptg} (dB) (99.7%)	-14.49	78.1 μrad	-14.49	78.1 μrad	-0.04	304.7 μrad
L_{atm} (dB)	-2.10	el = 53.99°	-2.10	el = 53.99°	-2.10	el = 53.99°
P_{Rx} (dBW)	-60.92		-80.38		-104.0	
$P_{\mathrm{Rx,bkgd}}$ (dBW)	-181.6	eclipse	-169.0	eclipse	-208.5	eclipse
Metric	-60.92	P_{Rx} (dBW)	40.20	SNR (dB)	44.22	SNR (dB)
Requirement (dB)	-79.45	P_{req} - PPM32	8.25	$\mathrm{SNR}_{\mathrm{req}}$	9.62	$\mathrm{SNR}_{\mathrm{req}}$
Margin (dB)	9.53		31.95		34.39	

1537 nm or 1563 nm Tx to OGS-APD & OGS-Camera (1537 nm used here e.g. CLICK B downlink). BER = 10^{-5}. 975 nm Beacon to S/C-Quadcell.

Pointing Analysis: Crosslink

Optimal Divergence Computation:

$$\Theta_{\text{ptg}} = \sqrt{\Theta_x^2 + \Theta_y^2} \sim \text{Rice}(\sqrt{2}\mu, \sigma)$$

$$\Theta_x \sim N(\mu, \sigma) \quad \Theta_y \sim N(\mu, \sigma)$$

$$\Theta_{\text{ptg}}^2 = \sigma^2(\Theta_x^2/\sigma^2 + \Theta_y^2/\sigma^2) \equiv \sigma^2 X$$

$$X \sim \chi_2^2(2\mu^2/\sigma^2)$$

$$J(\theta_{1/e^2}) = L_{\text{ptg,dB}}(\theta_{1/e^2}) + G_{\text{Tx,dB}}(\theta_{1/e^2}) \quad (3a)$$

$$= -80\text{Log}_{10}(e)\left(\frac{\Theta}{\theta_{1/e^2}}\right)^2 + \ldots \quad (3b)$$

$$\ldots - 20\text{Log}_{10}(\theta_{1/e^2}) + 10\text{Log}_{10}(32) \quad (3c)$$

$$\theta^*_{1/e^2} = \sqrt{8\sigma^2 F_X^{-1}(p_r; \mu, \sigma)}$$

$$L^*_{\text{ptg,dB}}(\theta^*_{1/e^2}) = -10\log_{10}(e) \approx -4.343 \text{ dB}.$$

Budget Element	25 km range		580 km range	
	μ (μrad)	σ (μrad)	μ (μrad)	σ (μrad)
Relative Navigation	13.80	343.1	0.001	20.44
Open-Loop Point Ahead	0.063	0.001	1.46	0.016
P/L Fiducial Msmt. Residual	0	484.8	0	484.8
Launch Induced Shift	0	423.3	0	423.3
Thermal Deformation	38.15	4.36	38.15	4.36
Spacecraft Body Pointing	0	122.2	0	122.2
Total	52.02	739.5	39.61	655.5
θ_{1/e^2} [μrad]	7147			
θ_{ptg} [μrad] ($p_\theta = 0.997$)	2527		2238	
$L_{\text{ptg,dB}}$ [dB] ($p_l = 0.997$)	-4.343		-3.407	

Pointing error budget for crosslink coarse stage tracking in open-loop (CSTOL) at minimum and maximum ranges.

Ref: Grenfell [1]. Ref: Ondrej Cierny, Paul Serra, William Kammerer, Peter Grenfell, Grant Gunnison, Joseph Kusters, Cadence Payne, Paula do Vale Pereira, Kerri Cahoy, Tyler Ritz, John Conklin, David Mayer, Jan Stupl, and John Hanson. Testing of the CubeSat Laser Infrared CrosslinK (CLICK-A) Payload. In Proceedings of the 34th AIAA/USU Conference on Small Satellites, 2020.

Pointing Analysis: Crosslink

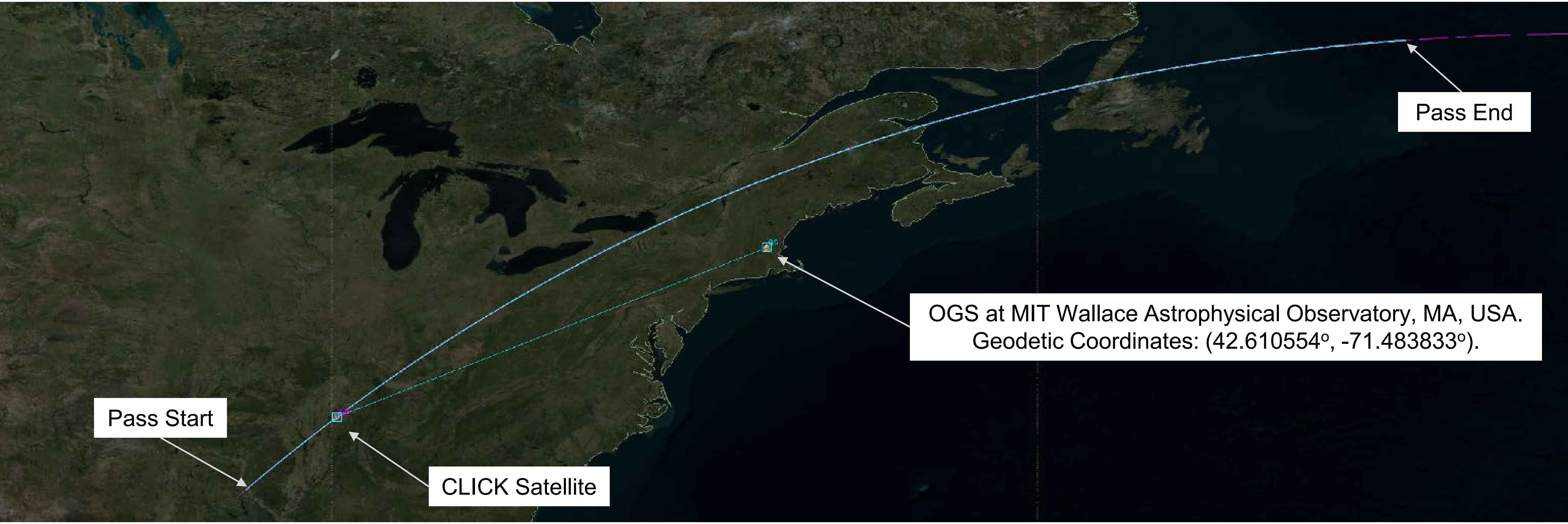
Table 4: Pointing error budget for crosslink coarse stage tracking in closed-loop at minimum & maximum ranges.

Budget Element	25 km range		580 km range	
	μ (μrad)	σ (μrad)	μ (μrad)	σ (μrad)
Camera NEA	0	0.337	0	7.00
Closed-Loop Point Ahead	0.126	0.001	2.911	0.031
Camera feed-back calibration residual	0	3.98	0	3.98
Beacon-to-Camera calibration residual	0	2.95	0	2.95
Spacecraft Body Pointing	0	122.2	0	122.2
Total	0.126	122.3	2.911	122.5
θ_{1/e^2} [μrad]	7147			
θ_{ptg} [μrad] ($p_\theta = 0.997$)	416.8		417.6	
$L_{\text{ptg,dB}}$ [dB] ($p_l = 0.997$)	-0.1181		-0.1186	

Table 5: Pointing error budget for crosslink fine stage tracking at minimum & maximum ranges.

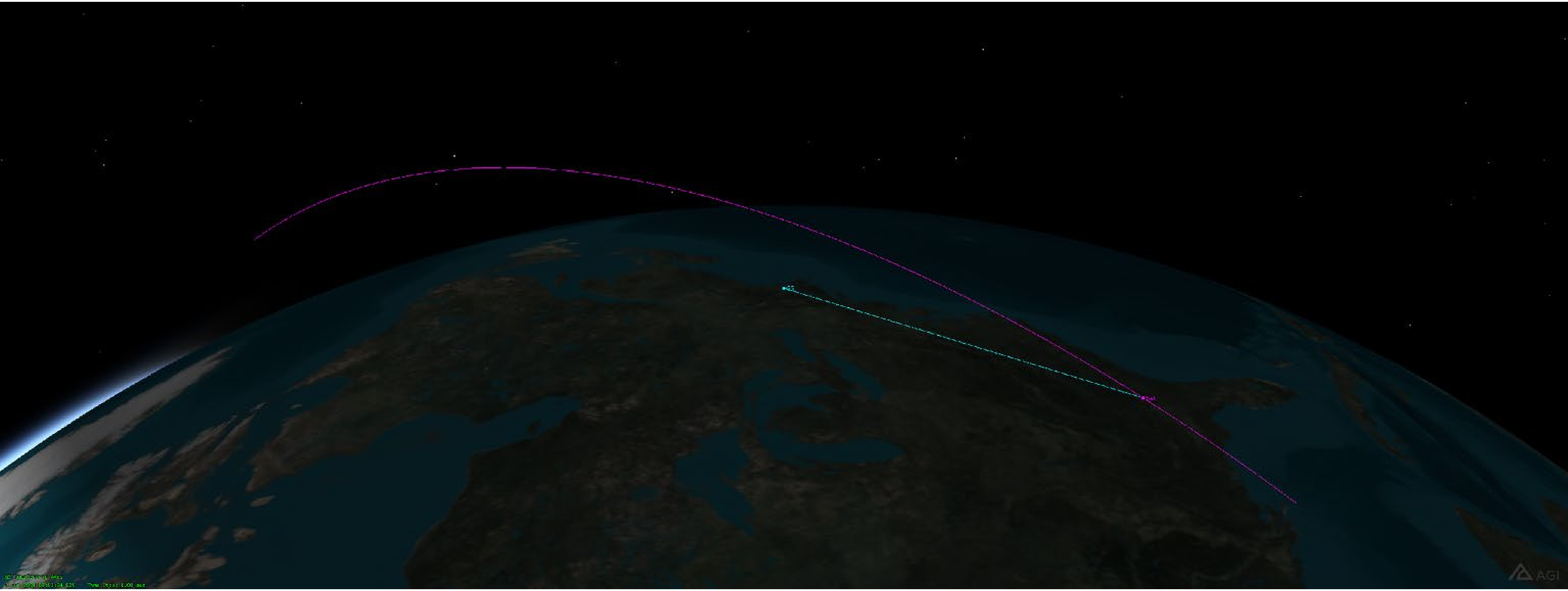
Budget Element	25 km range		580 km range	
	μ (μrad)	σ (μrad)	μ (μrad)	σ (μrad)
Quadcell NEA	0	1.826	0	1.826
FSM Control Residual	0.062	3.077	0.062	3.077
Closed-Loop Point Ahead	0.126	0.001	2.911	0.031
Tx-to-Quadcell alignment residual	0	9.178	0	9.178
Thermal Deformation	0	5.396	0	5.396
S/C Reaction Wheel Jitter	0	1.454	0	1.454
Total	0.188	11.27	2.973	11.27
θ_{1/e^2} [μrad]	121.0			
θ_{ptg} [μrad] ($p_\theta = 0.997$)	38.42		39.66	
$L_{\text{ptg,dB}}$ [dB] ($p_l = 0.997$)	-3.506		-3.734	

Downlink Overpass Analysis



- Used STK to survey ISS orbit overpasses for a 3 year duration starting from June 07, 2020 12:56:15.000.
- Out of 7435 overpasses, 1746 (23.5%) satisfy desired characteristics: 1) 1 minute minimum pass duration. 2) Maximum pass elevation angle between 20º and 80º. 3) Minimum pass range less than 1000 km. 4) Pass time is during eclipse.
- 1.59 desirable passes per day on average. Average waiting time between desirable passes is 15.03 hours.
- Chose a reference overpass for further analysis with Keplerian elements at the pass time of: $(a = 6791.3\text{km},\ e = 6.084{*}10^{-4},\ i = 51.483^\circ,\ \Omega = 221.52^\circ,\ \omega_p = 181.99^\circ,\ M = 220.44^\circ)$
- Reference pass: Range varies from a maximum range of 2400 km at 0º elevation to 517.6 km. 10.6 minute duration. 53.99º max. elevation.

Overpass Analysis: Downlink



Pointing Analysis: Downlink

Table 8: Pointing error budget for OGS beacon coarse stage tracking in open-loop (CSTOL) at time of uplink/downlink closure (1.67 min, 1699.8 km).

Budget Element	μ (μrad)	σ (μrad)
Satellite Ephemeris	0	517.5
OGS Star Tracker Calibration	0	315.1
Gimbal Pointing Jitter	0	85.11
Open-Loop Point Ahead	12.24	4.93
Beacon Alignment Residual	0	6.39
Total	12.24	611.9
θ_{1/e^2} (μrad)	9487	
θ_{ptg} (μrad, $p_\theta = 0.997$)	2086	
$L_{ptg,dB}$ (dB, $p_l = 0.997$)	-1.680	

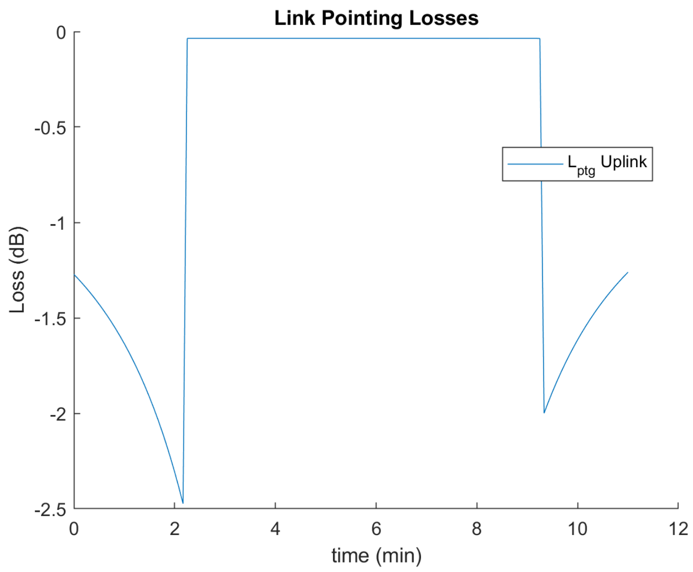


Table 9: Pointing error budget for OGS beacon coarse stage tracking in closed-loop (CSTCL) at time of uplink/downlink closure.

Budget Element	μ (μrad)	σ (μrad)
OGS Camera NEA	0	5.429
Gimbal Pointing Jitter	0	85.11
Closed-Loop Point Ahead	24.48	9.859
Beacon Alignment Residual	0	6.39
Total	12.24	86.09
θ_{1/e^2} (μrad)	9487	
θ_{ptg} (μrad, $p_\theta = 0.997$)	304.3	
$L_{ptg,dB}$ (dB, $p_l = 0.997$)	-0.036	

Table 10: Pointing error budget for payload fine stage tracking at time of uplink/downlink closure.

Budget Element	μ (μrad)	σ (μrad)
S/C Quadcell NEA	0	1.826
FSM Control Residual	0.062	3.077
Closed-Loop Point Ahead	24.48	9.859
Tx-to-Quadcell alignment residual	0	9.178
Thermal Deformation	0	5.396
Bus Reaction Wheel Jitter	0	1.45
Total	24.54	15.02
θ_{1/e^2} (μrad)	121.0	
θ_{ptg} (μrad, $p_\theta = 0.997$)	78.10	
$L_{ptg,dB}$ (dB, $p_l = 0.997$)	-14.49	

Quadcell Change

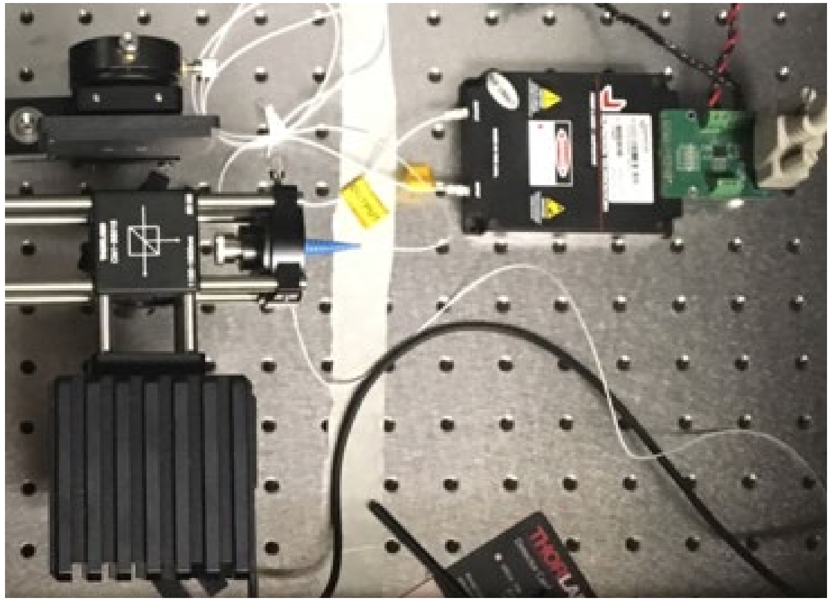
	Old design	New design
Quadcell	FirstSensor QP-6	Advanced Photonix SD085
Quadrant gap	16 μm	10 μm
Noise equiv. angle (3σ)	19.5 μrad	5.5 μrad
Active area	1 mm^2	9 mm^2
Field of view	±0.135 deg	±0.18 deg

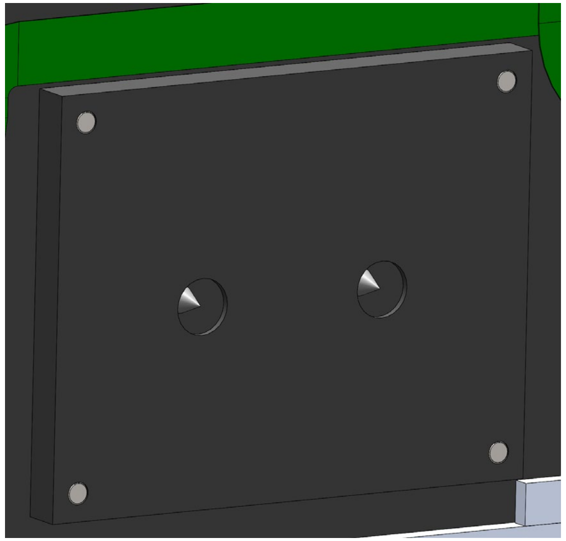
Beam Dump

- Tx/Rx isolation
  - L1 and L2 are C-coated but 1% Tx backreflection would still blind APD
  - Combination of a -30 dB beam dump and 2x -30 dB BPFs results in sufficient attenuation for APD isolation

3D printed beam dump test:

- Measured -31 dB loss in BD
- Meets isolation budget requirement
- Expected better performance with real machined part





Payload Thermal Design

Component:	Temperature Limits of Each Component (°C)			
	Survival		Operational	
	Min	Max	Min	Max
Daughter Board	-55	125	-40	85
FPGA Board	-55	125	-40	85
APD Board	-55	125	-40	85
CPU Board	-55	85	-10	70
Optoelectronics Board	-55	125	-40	85
Quadcell Board	-55	125	-40	85
EDFA	-20	65	0	65
Camera	-40	60	-40	45

Temperature limits of each component.

Component:	Power Draws (W) for Each Mode		
	Start Up (10 Minutes)	Transmit (15 Minutes)	Power Down (5 Minutes)
Daughter Board	1	5	1
FPGA Board	0	5.45	0
APD Board	0	2	0
CPU Board	2.53	2.84	2.53
Optoelectronics Board	0	6.39	0
EDFA	0	5.2	0
Camera	0	1	0
Heaters	10	0	0
Total	**13.53**	**27.88**	**3.53**

Heat loads for crosslink experiment.