Pointing, Acquisition, and Tracking for Small Satellite Laser Communications

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Overview

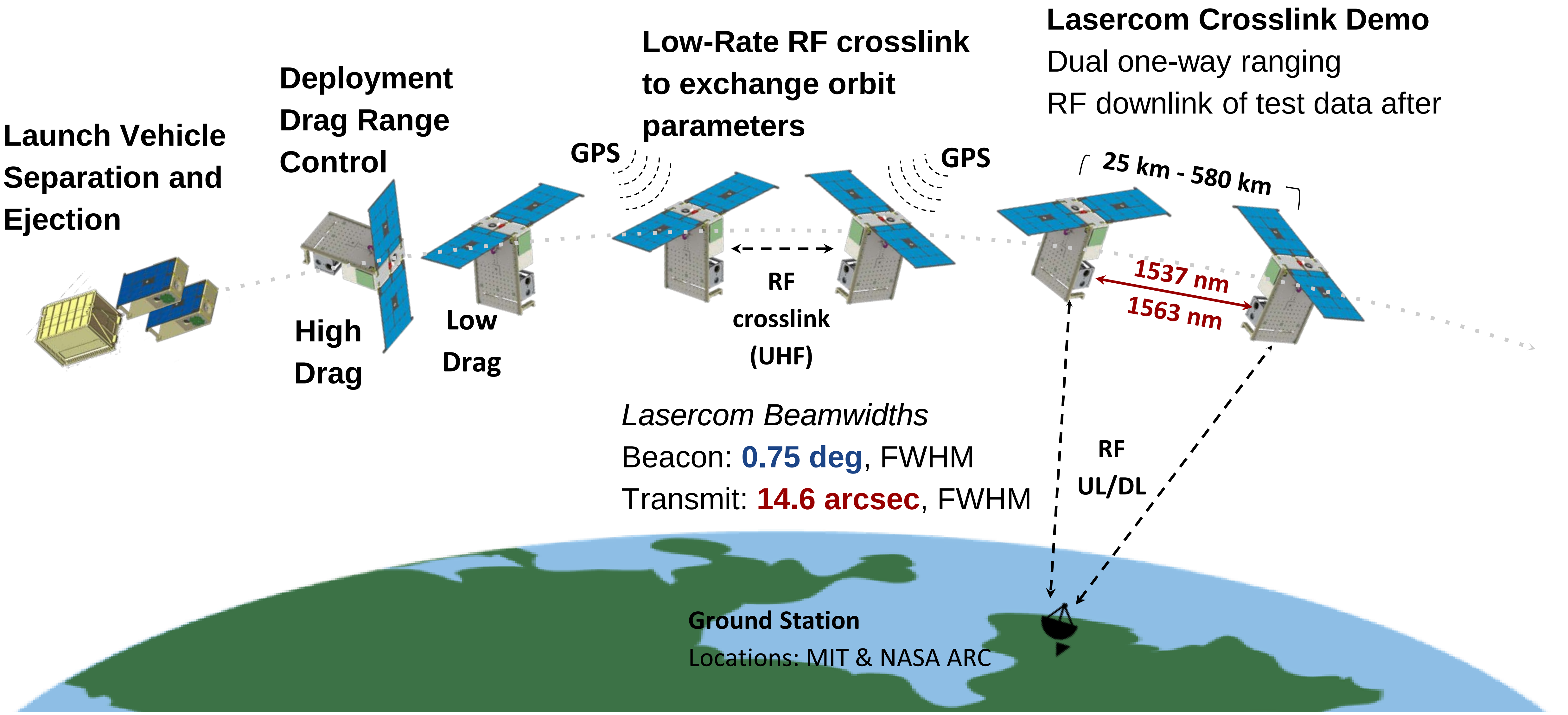
- Crosslink Mission Baseline Requirements
- Crosslink Mission Concept of Operations
- Pointing, Acquisition, and Tracking (PAT) Design
  - Coarse Pointing System (CPS)
  - Fine Pointing System (FPS)
  - Optical Layout
- PAT System Modeling & Verification
- Summary

CLICK Baseline Requirements

- CubeSat Laser Infrared CrosslinK (CLICK) Mission
  - Low cost, compact, low complexity lasercom (MIT, UF, NASA)
- < 2U, < 3 kg terminals, 200 mW transmitter
  - Full-duplex, > 20 Mbps from 25 km to 580 km, BER < 10^-4
  - Precision ranging < 50 cm
- The narrow **14.6 arcsec data beam** requires precision PAT system
  - Coarse Pointing System (CPS) with **beacon**
  - Fine Pointing System (FPS)

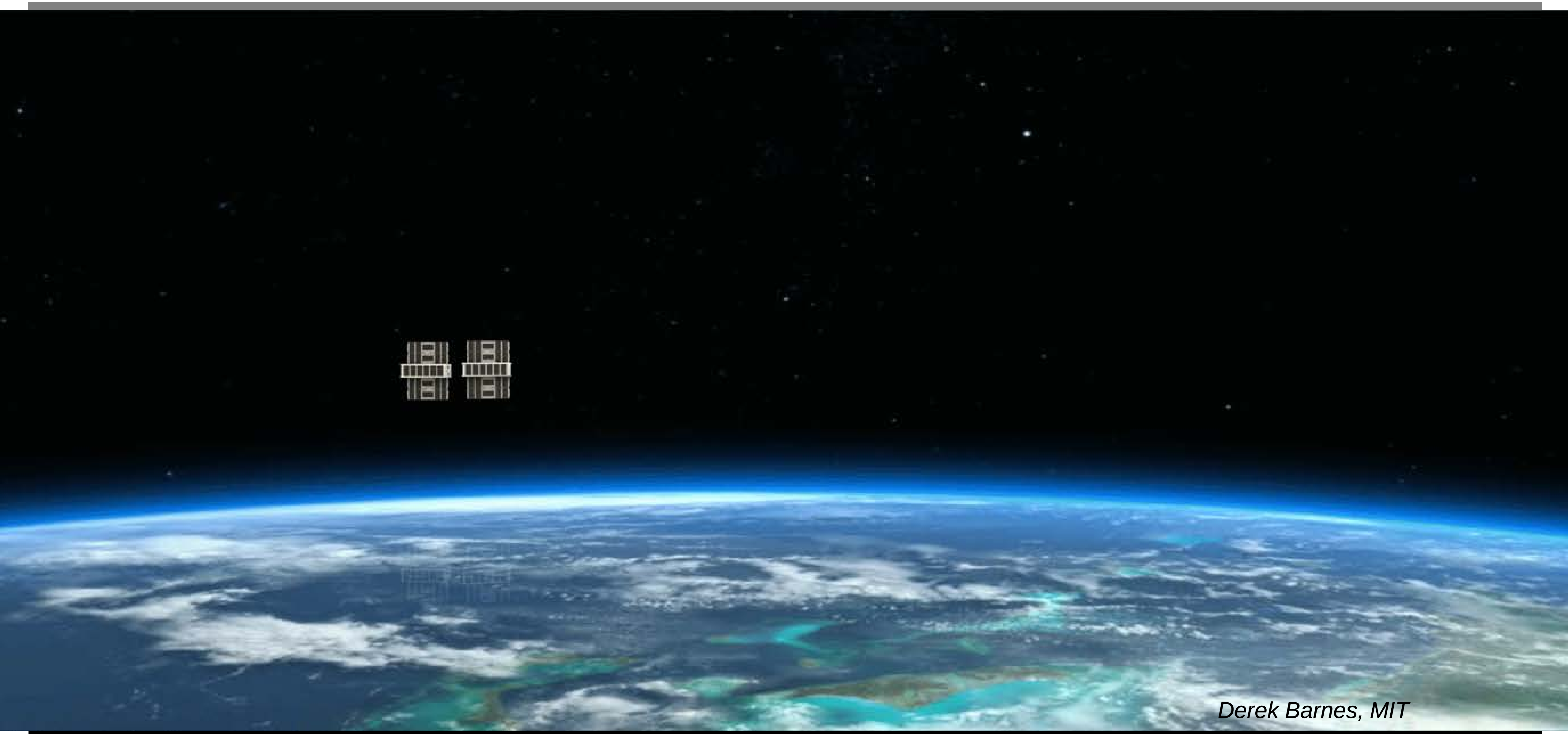
Mission	Beam Divergence Angle	Link Type
Aerocube – OCSD [1]	540 arcsec (2.6 mrad)	LEO to Ground
OSIRIS [2]	41.2 arcsec (200 urad)	LEO to Ground
CLICK	**14.6 arcsec**	**LEO to LEO**
NFIRE [3]	10.3 arcsec (50 urad)	LEO to LEO or Ground
LLCD [4]	0.515 arcsec (2.5 urad)	Lunar to Ground

CLICK Concept of Operations



Pointing, Acquisition, and Tracking (PAT) Design

PAT Approach: Coarse and Fine



PAT Staged Control Steps

Begin Demo →

1. Initialization

Establish baseline acquisition state

→

2. Acquisition

Establish duplex **laser beacon** crosslink

→

3. Coarse Pointing

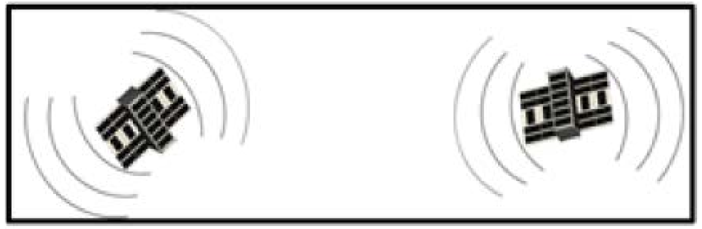
Maintain beacon inertial pointing

→

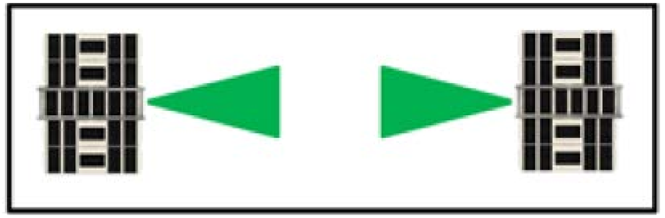
4. Fine Pointing

Establish and maintain lasercom data crosslink

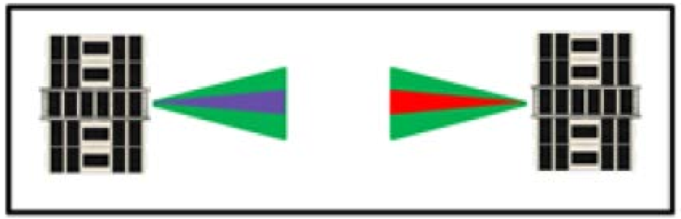
→ Lasercom Crosslink



RF Crosslink

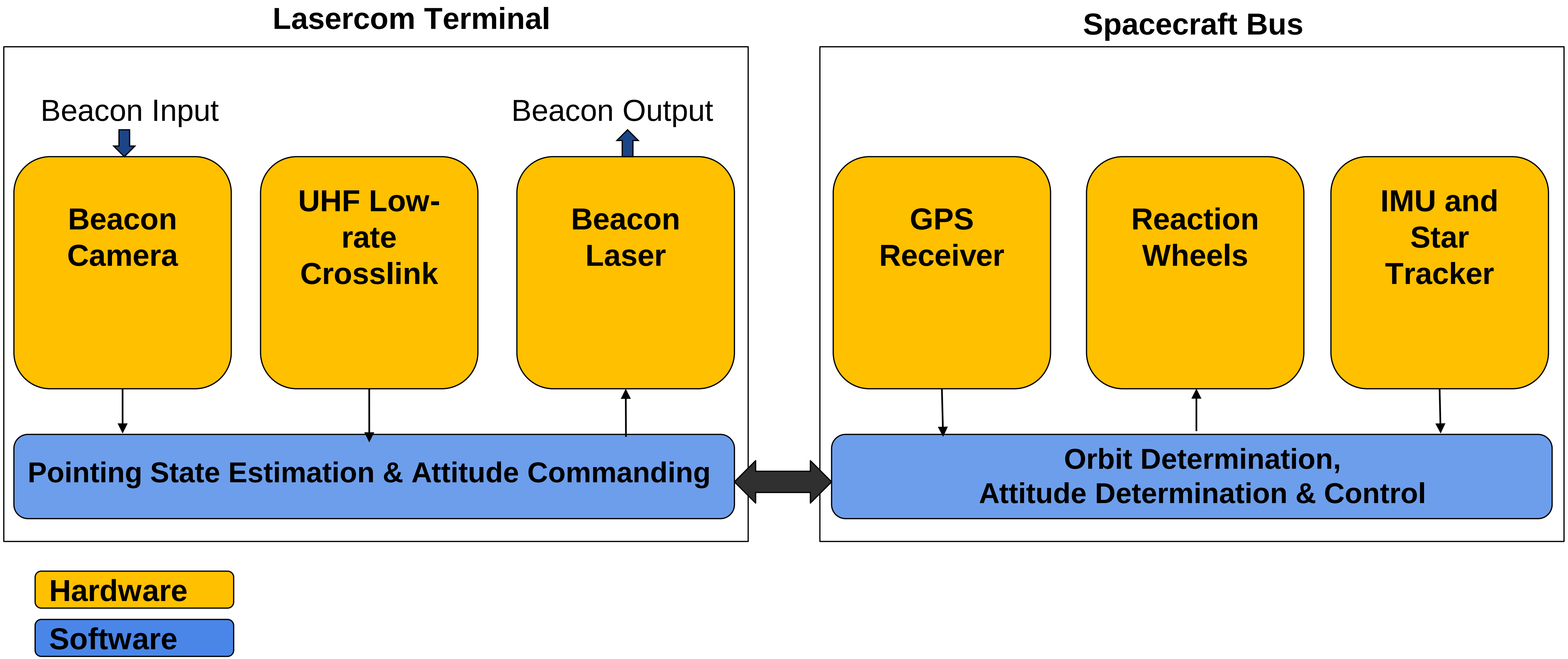


Beacon Crosslink

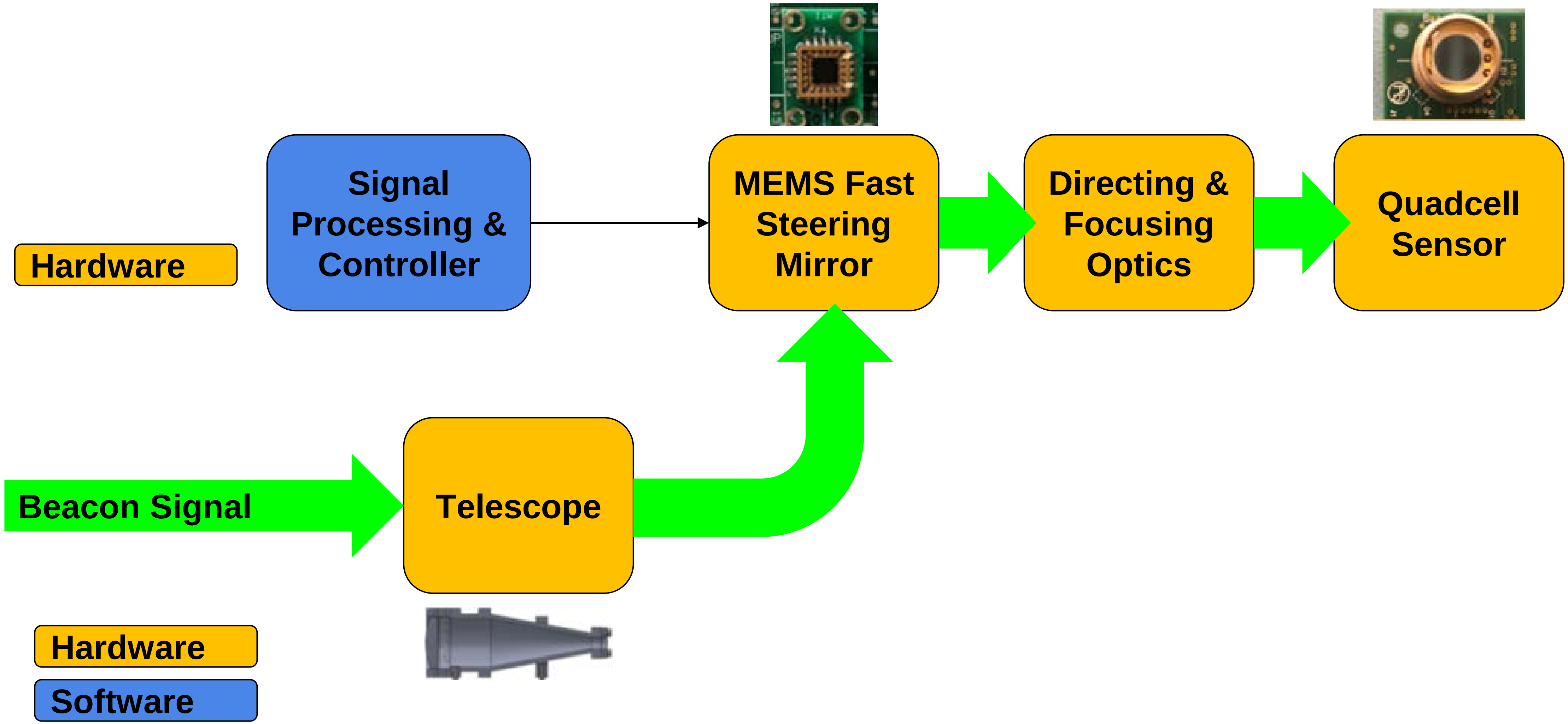


Both Beacon and Data Crosslink

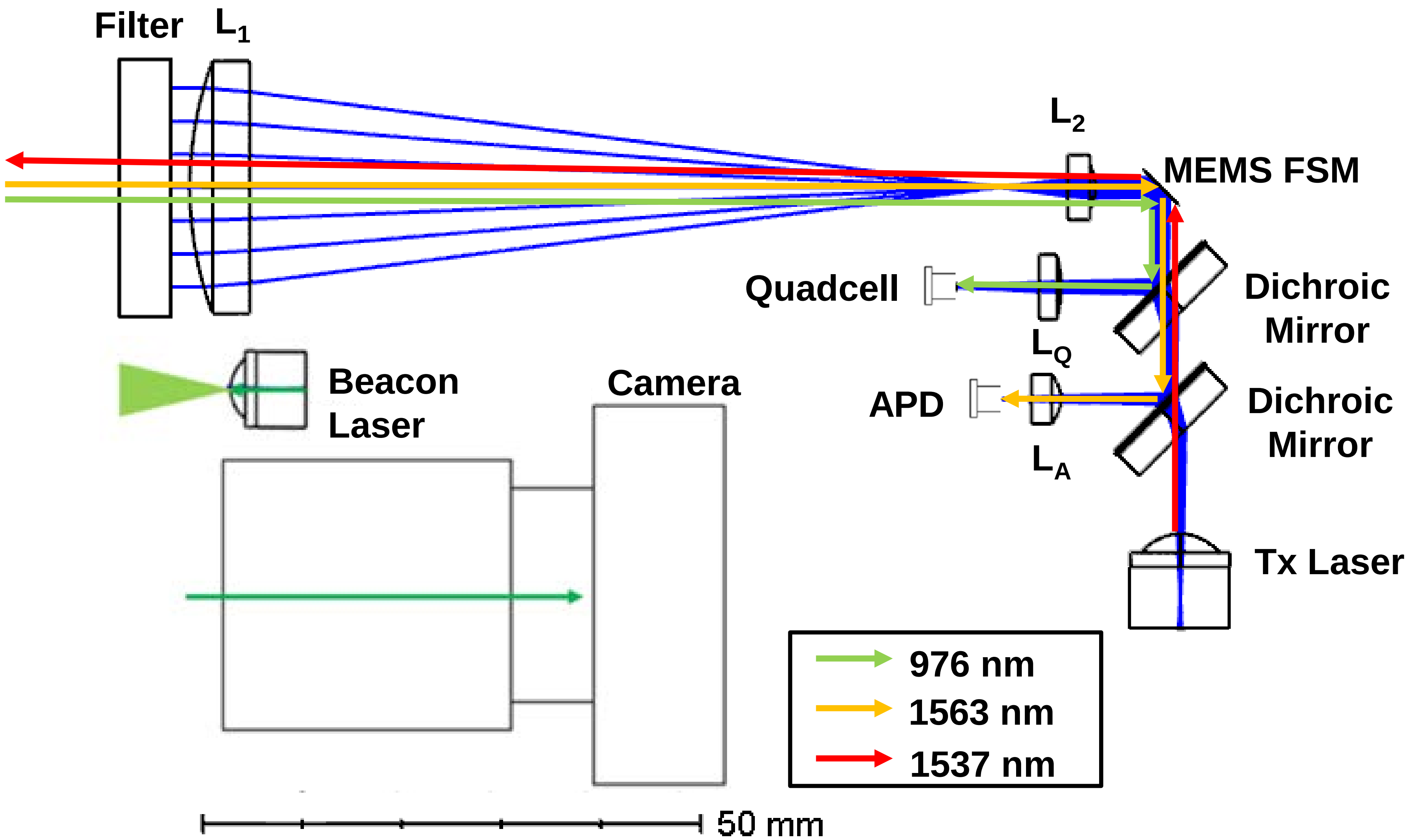
Coarse Pointing Approach



Fine Pointing Approach



Fine Pointing Optical Layout



PAT System Modeling & Verification

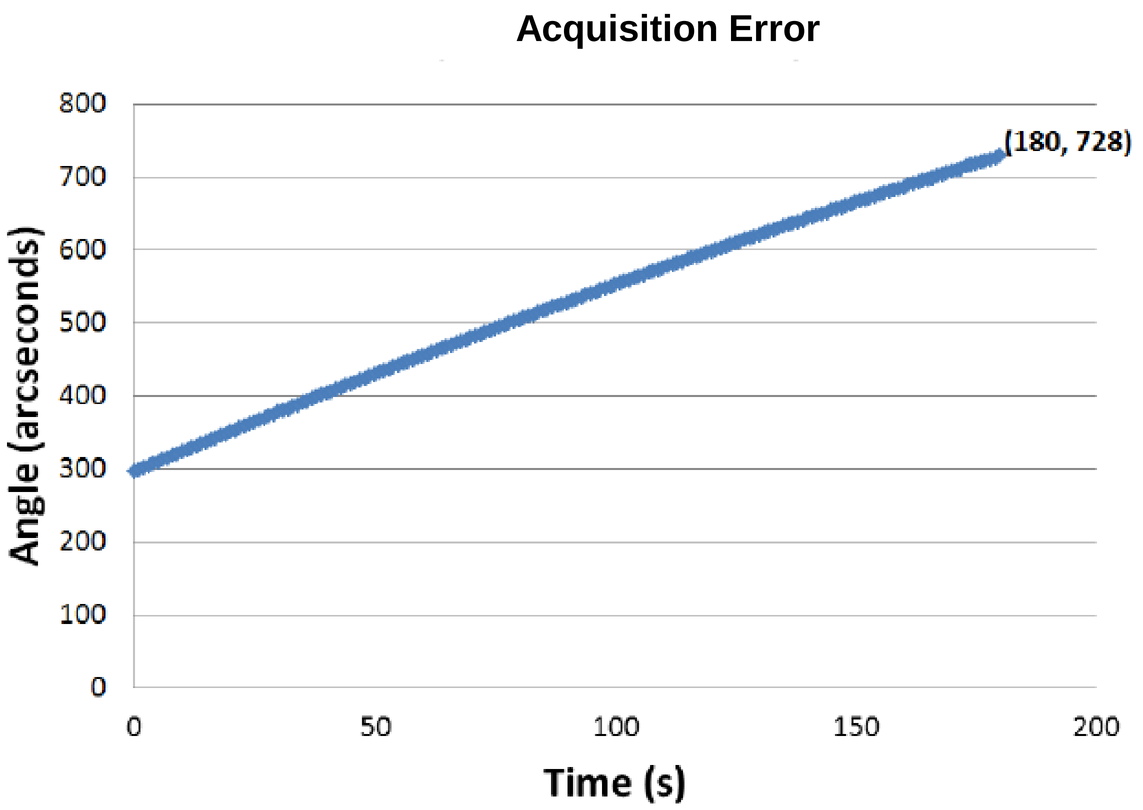
Acquisition

Initialization State:
- Altitudes: 500 km
- Range: 580 km
- Allocated delay: 180 sec

Satellite Orbit Propagator: J2
- Data source GPS receiver

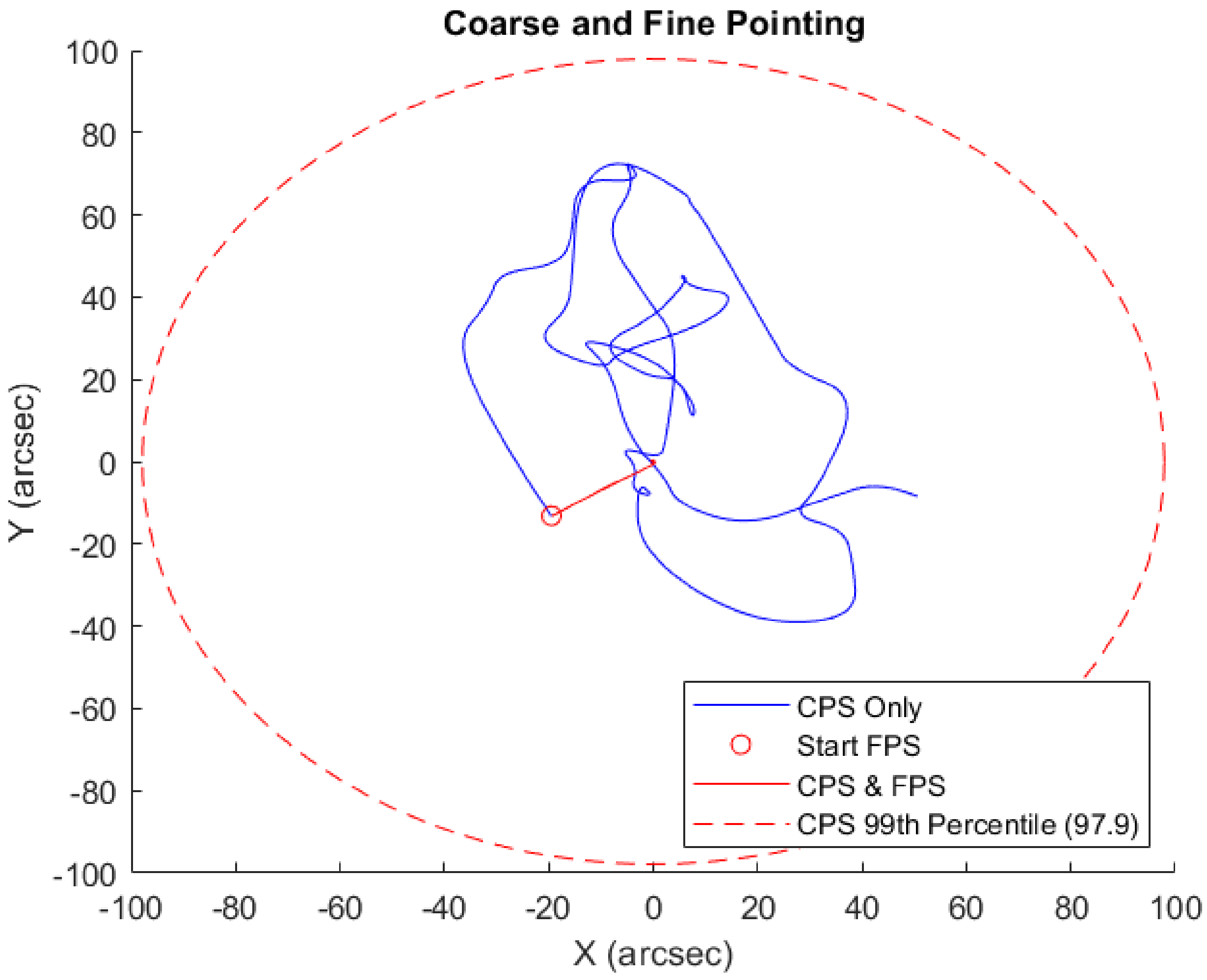
Reference Model: High Precision Orbit Propagator
- High order gravity model
- Atmospheric drag model
- Solar radiation pressure model

Error Source	Single Axis Uncertainty (arcsec)
Acquisition Error	728
Opto-Mechanical Allocation	400
RMS Total Error	831
Beacon Allocation	954
Margin	13%
Beacon Divergence	**2700 arcsec (0.75 deg)**



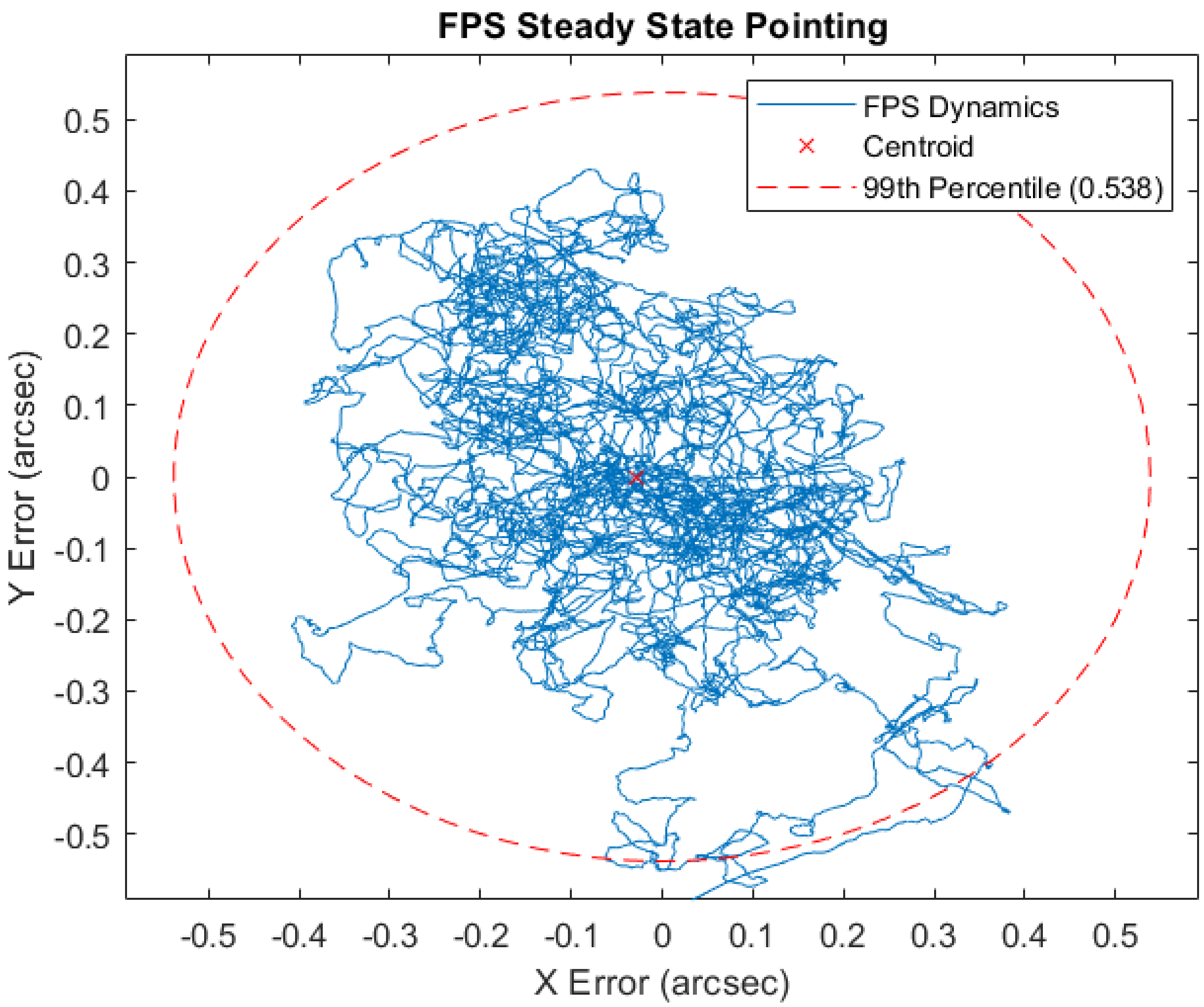
Coarse to Fine Pointing

- Coarse pointing simulation dynamics is sampled for input.
- 99th Percentile of CPS simulation: **97.9 arcsec** (half-angle)
- Pre-FPS Time Shown: 60 sec
- FPS 99% Settling Time: **62 msec**

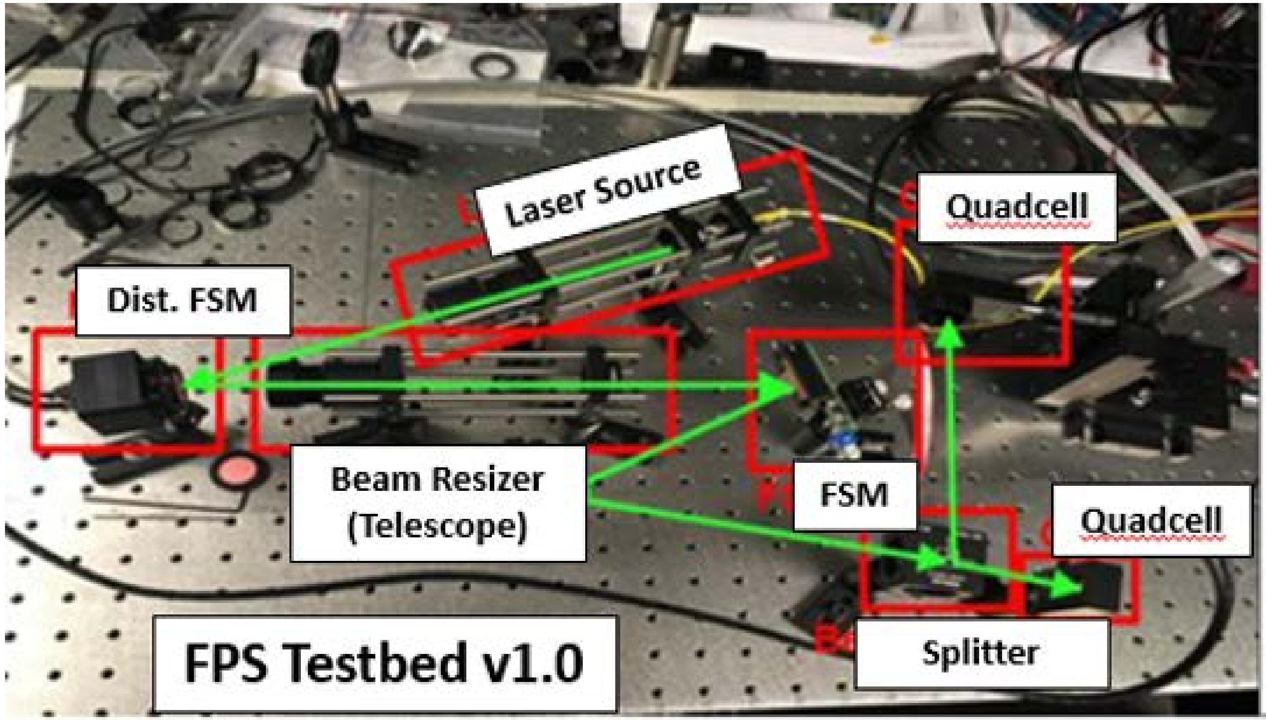


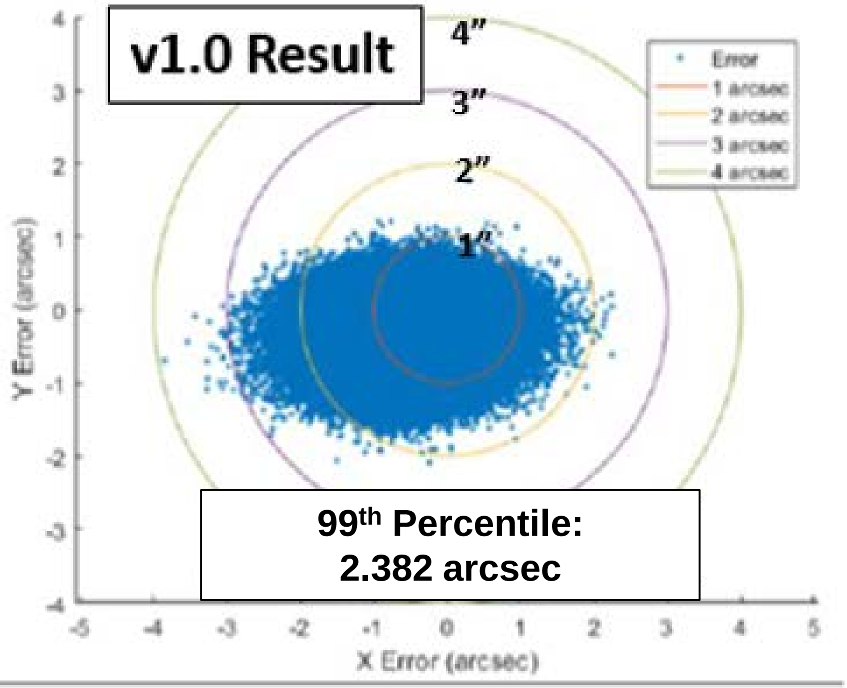
Fine Pointing

- Simulation time period shown: approx. 60 sec following settling.
- Simulation gives 99% pointing estimate of **0.538 arcsec** (half-angle)



Hardware Testing





Hardware-in-the-loop setup (v1.0) using COTS hardware gives 99% pointing estimate of **2.382 arcsec** (half-angle) [5].

Pointing Summary

Laser Divergences:

- Lasercom crosslink divergence angle: 14.6 arcsec (7.3 arcsec HWHM)
- Beacon crosslink divergence angle: 0.75 degrees

PAT Analysis & Test Results:

- Coarse Pointing & Tracking Capability (Simulation): 97.8 arcsec (half-angle)
- Fine Pointing Capability (Simulation): 0.538 arcsec (half-angle)
- Fine Pointing Capability (Hardware): 2.382 arcsec (half-angle)
- Improvement over Coarse Pointing: 41 to 181 times
- Significant margin (67% to 93%) for opto-mechanical errors

Questions

References

[1] Darren Rowen et. all. Ocsd-a / aerocube-7a status update. http://mstl.atl.calpoly.edu/bklofas/Presentations/DevelopersWorkshop2016/, April 2016. Accessed: 2018-2-7.

[2] Christopher Schmidt, Martin Brechtelsbauer, Fabian Rein, and Christian Fuchs. OSIRIS Payload for DLR's BiROS Satellite. In International Conference on Space Optical Systems and Applications, January 2014.

[3] Don M. Boroson, Joseph J. Scozzafava, Daniel V. Murphy, Bryan S. Robinson, and M.I.T. Lincoln. The Lunar Laser Communications Demonstration (LLCD). In Third IEEE International Conference on Space Mission Challenges for Information Technology, SMC-IT 2009., pages 23–28. IEEE, 2009.

[4] M. Guelman *et al.*, "Acquisition and pointing control for inter-satellite laser communications," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 40, no. 4, pp. 1239–1248, Oct. 2004.

[5] Yoon, H., "Pointing System Performance Analysis for Optical Inter-satellite Communication on CubeSats," *Ph.D Thesis*, Massachusetts Institute of Technology, 2017. http://hdl.handle.net/1721.1/113743

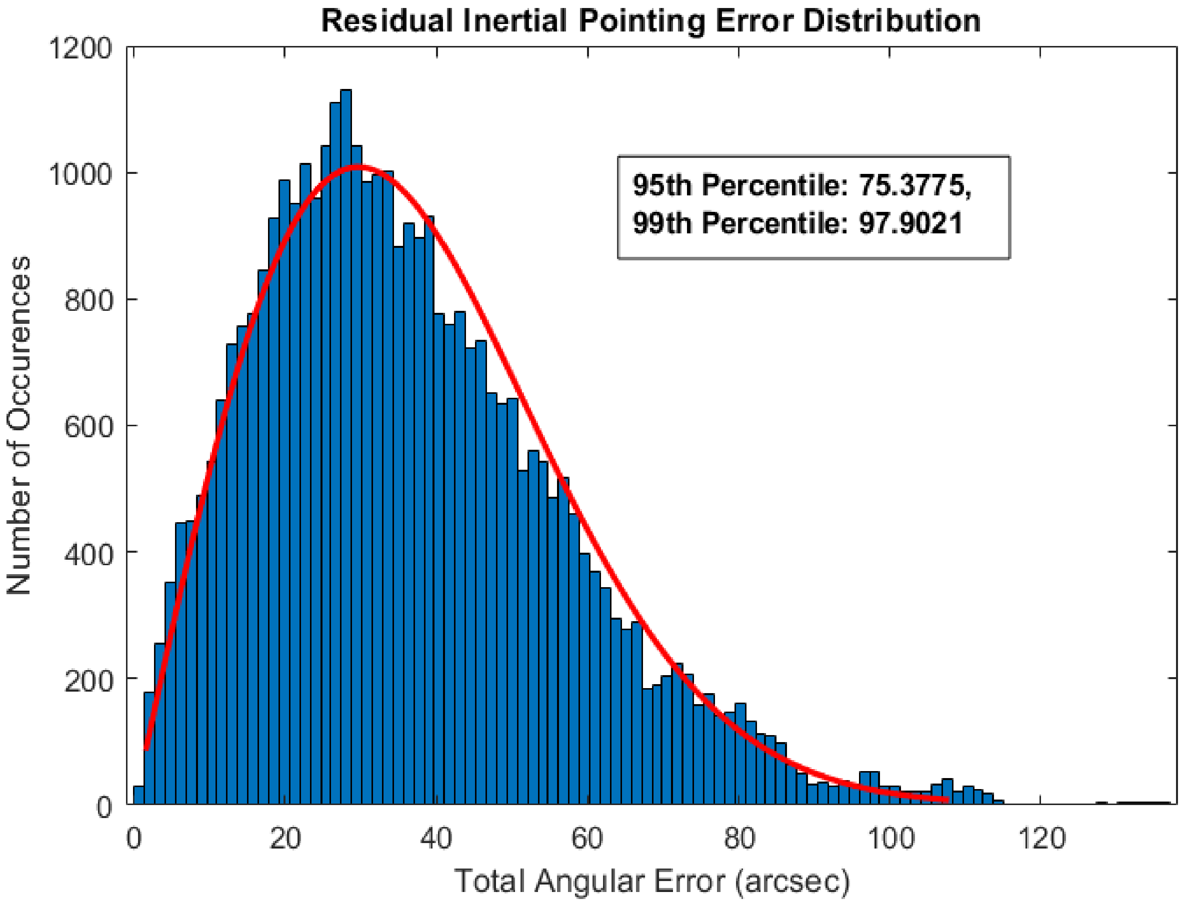
Backup

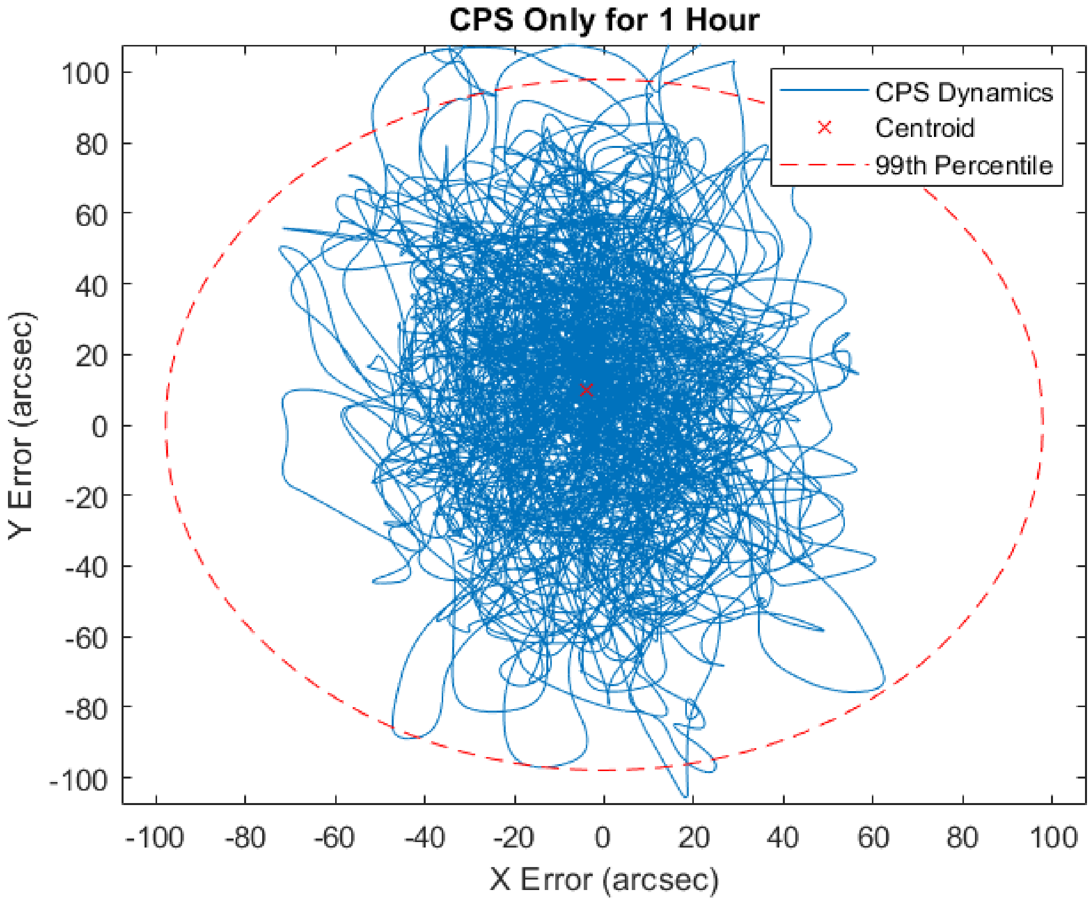
Link Budgets

Inter-satellite Crosslink Budget	
Range (km)	855.00
PPM Order	16.00
Transmit Power (dBW)	-6.99
Full Width Half Maximum (arcsec)	14.6
Transmitter Gain (dBi)	95.02
Transmitter Loss (dB)	-1.74
Receiver Gain (dBi)	92.16
Receiver Loss (dB)	-1.75
Path Loss (dB)	-257.54
Atmospheric Loss (dB)	0.00
Pointing Loss (dB)	-3.00
Photons Per Bit	768.70
Power Received (dBW)	-83.36
Power Required (dBW)	-86.44
Margin	**2.98**

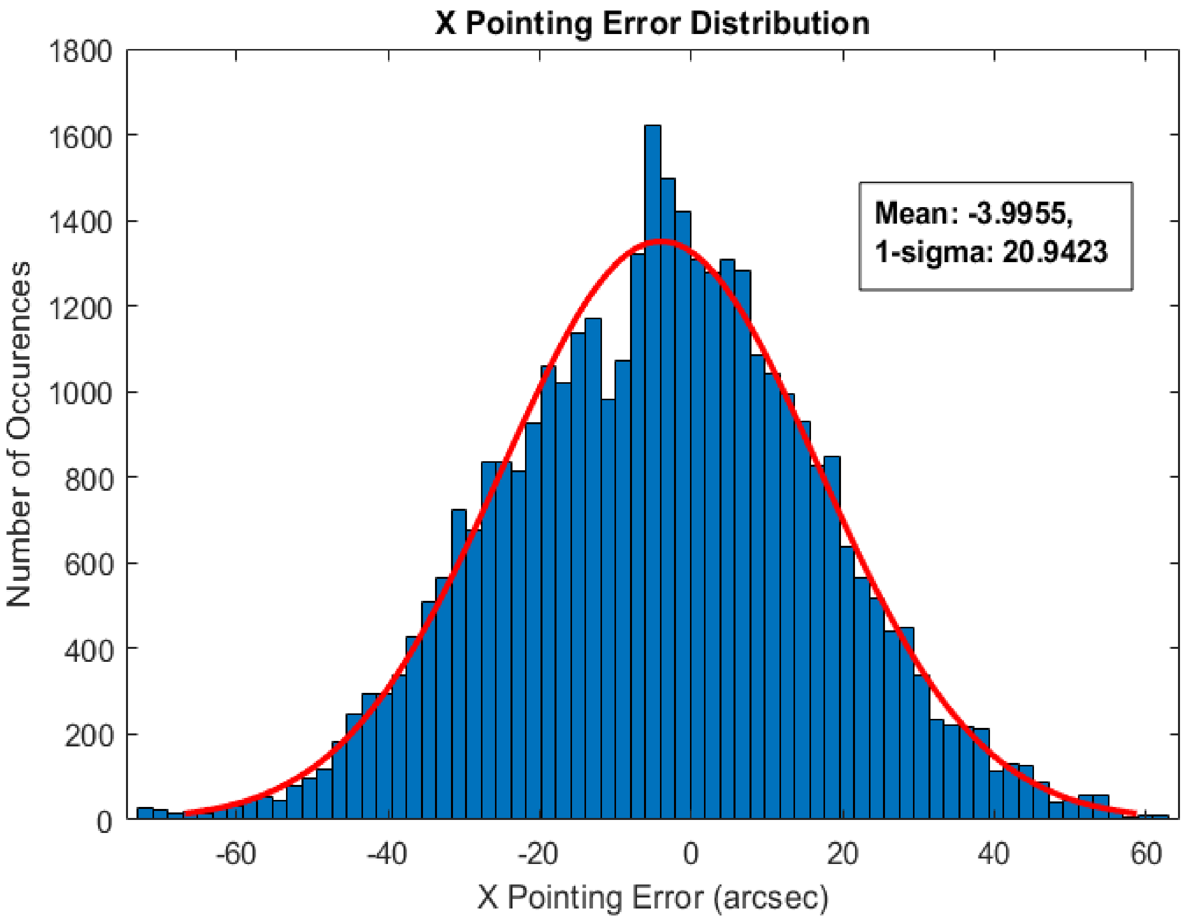
Link Range (km)	10	100	500	850	1000	1500
Beacon Optical Power (dBW)	-3.01	-3.01	-3.01	-3.01	-3.01	-3.01
Beacon Wavelength (m)	9.76E-07	9.76E-07	9.76E-07	9.76E-07	9.76E-07	9.76E-07
Pointing Loss (dB)	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50
Half Power Beamwidth (rad)	0.01	0.01	0.01	0.01	0.01	0.01
FSO Path Loss (dB)	-216.17	-242.20	-256.17	-260.78	-262.20	-265.72
Tx Optics Loss (dB)	-0.40	-0.40	-0.40	-0.40	-0.40	-0.40
Rx Optics Loss (dB)	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10
Receiver Aperture Diameter (mm)	20.00	20.00	20.00	20.00	20.00	20.00
Sensor Responsivity (A/W)	0.62	0.62	0.62	0.62	0.62	0.62
SNR (dB)	36.67	26.63	18.91	15.64	14.51	11.49

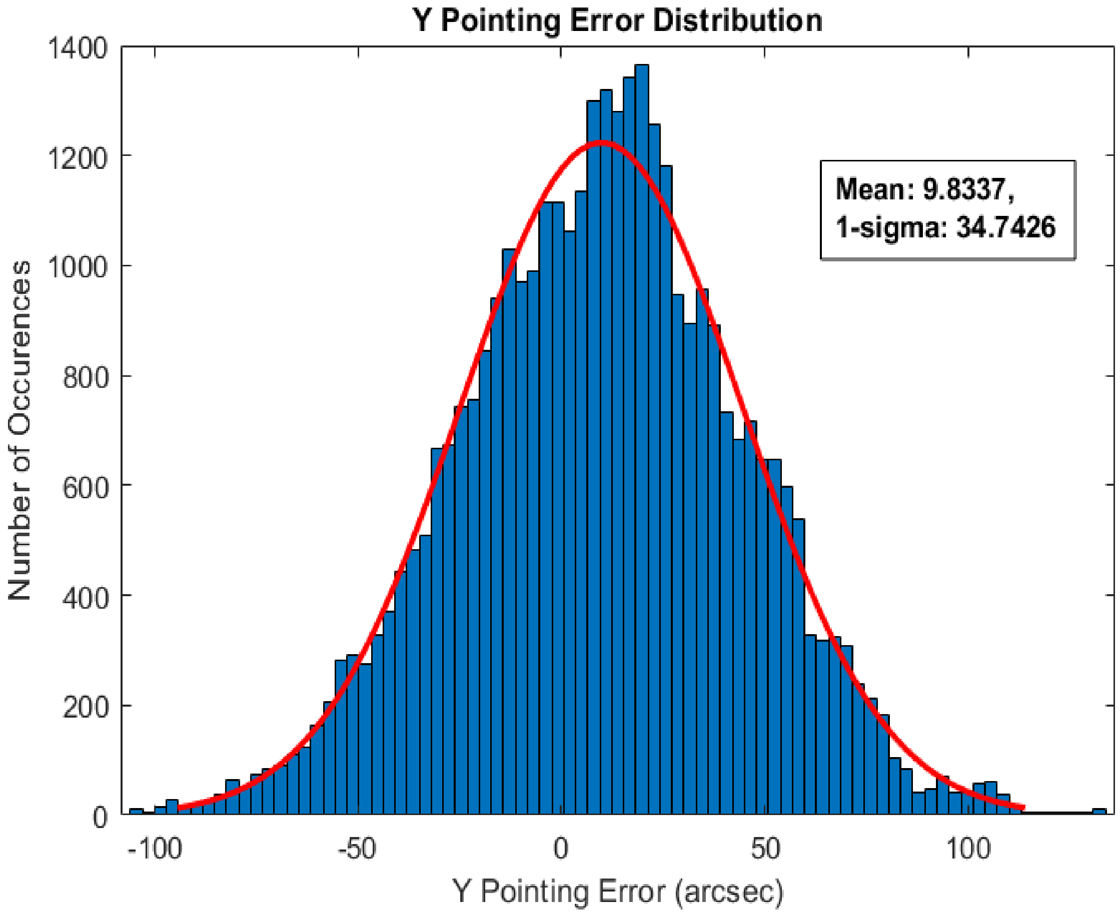
CPS Simulation Results



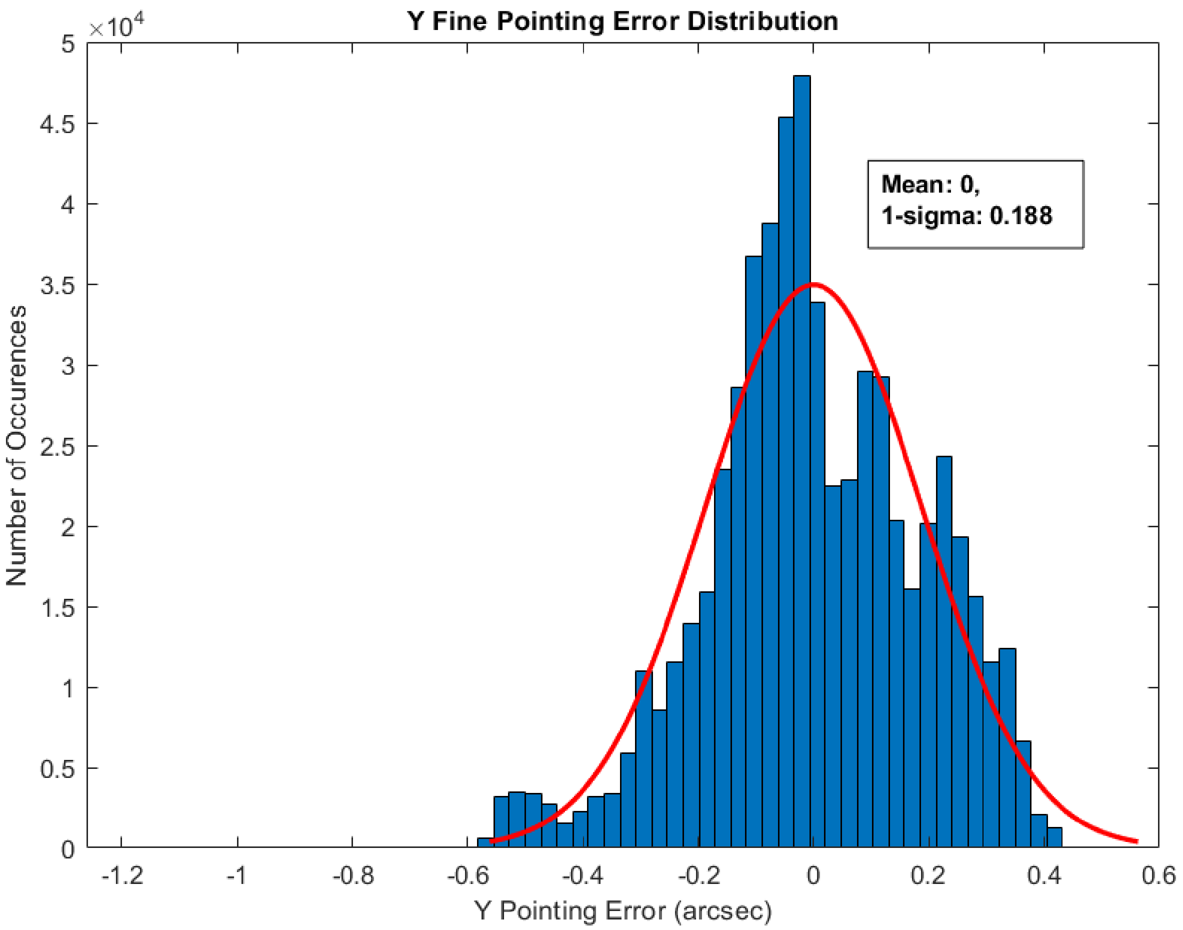


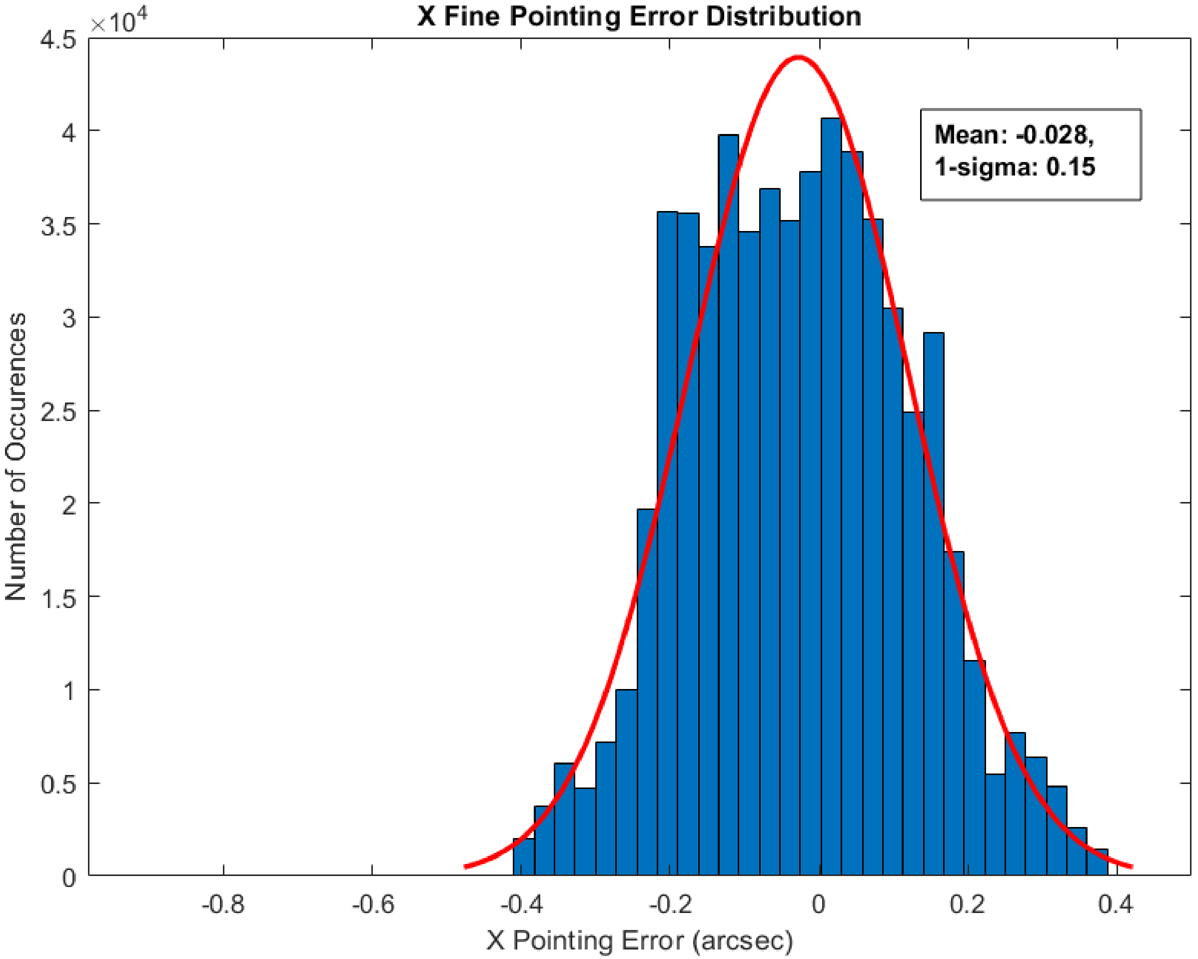
CPS Simulation Results



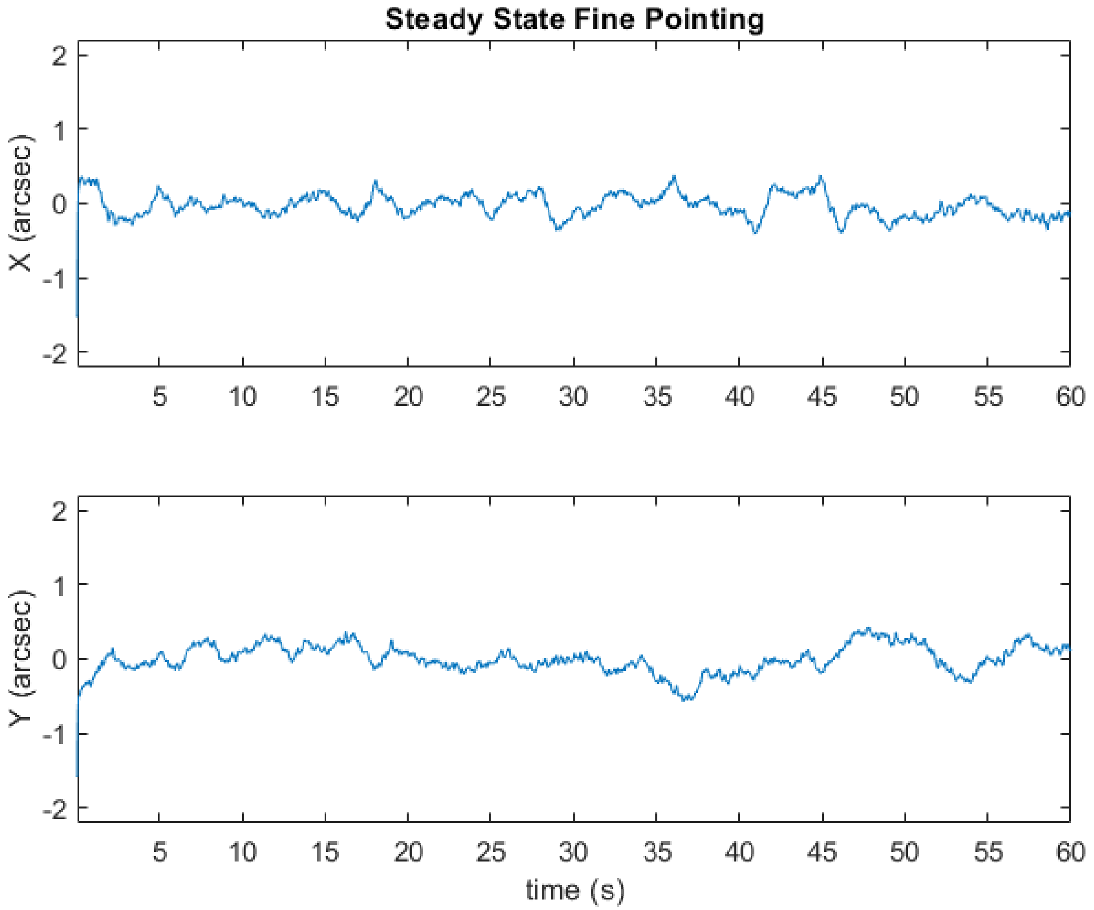


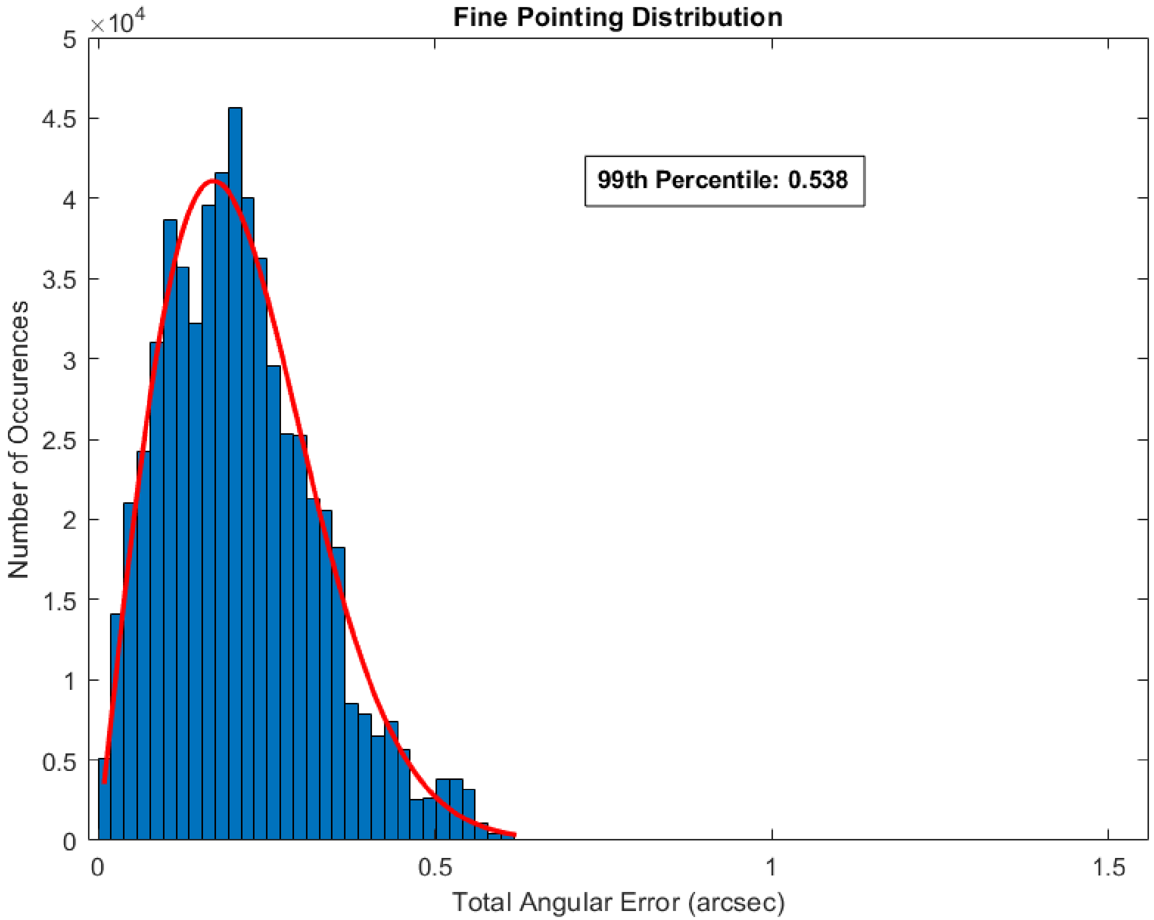
FPS Simulation Results



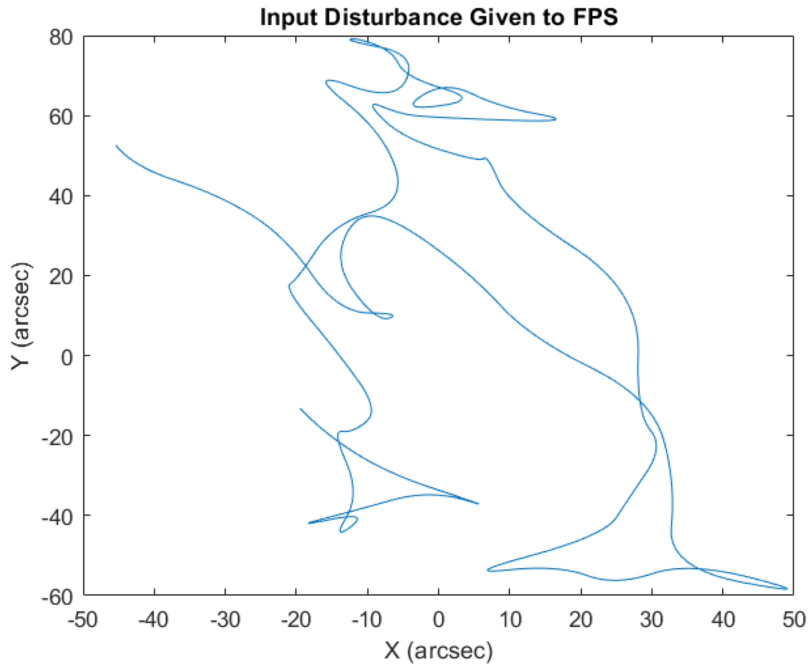


FPS Simulation Results



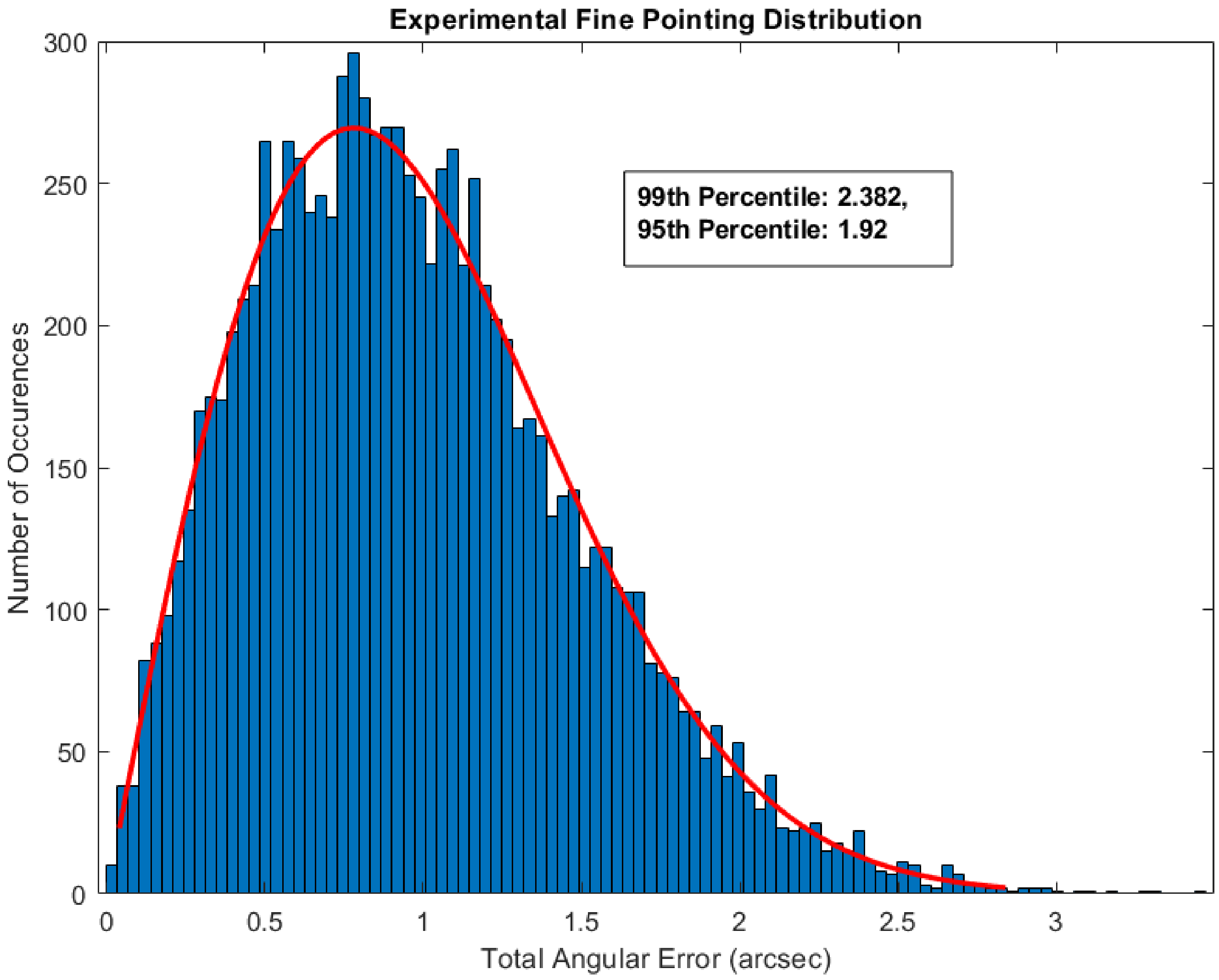


Simulation Results

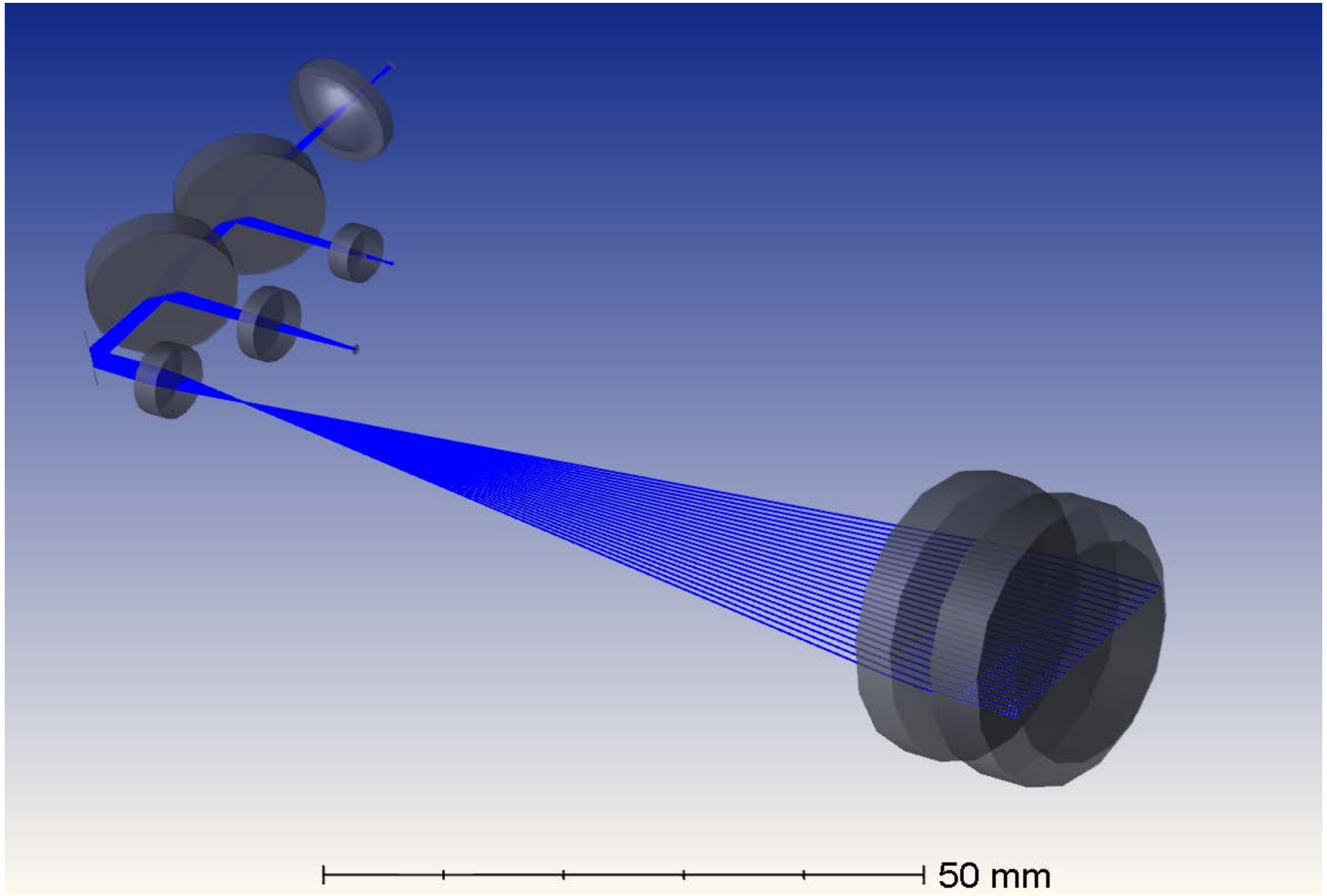


Error Source	Simulation (v1)	Convergence Estimate (v2)	Hardware (v1)
Fine Pointing Control	0.54	1.46	2.38
Opto-Mechanical Allocation	4.00	4.00	4.00
Total RMS	4.04	4.26	4.66
Total Pointing Allocation	5.18	5.18	5.18
Margin	22%	18%	10%

Hardware Testing



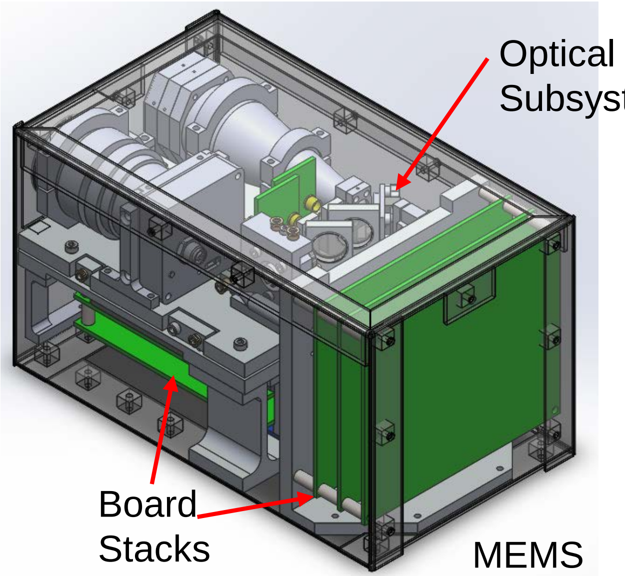
Optical Modeling

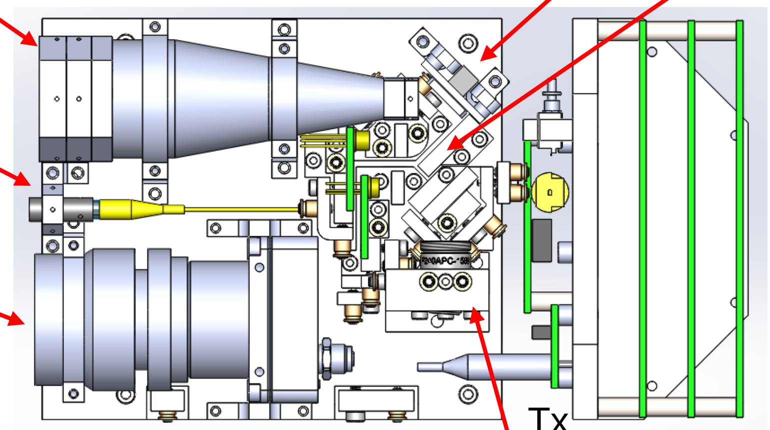


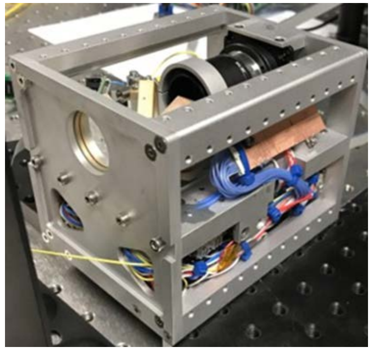
Zemax® Optical Raytracing

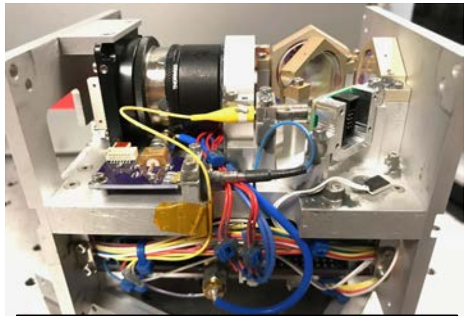
CLICK Instrument Overview

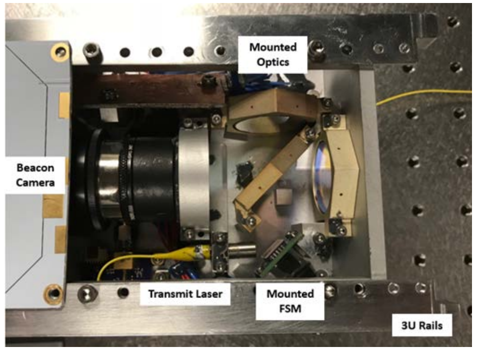
Technical Summary*	
Application	Compact lasercom transceiver suitable for small-satellite constellations and swarms
Communications	20 Mbps, Full-Duplex, PPM, 1537 / 1565 nm, 14.6” divergence, 200 mW
Crosslink Ranges	10 km - 855 km (extended)
Downlink	LEO to 30 cm Ground Station
Size, Weight, and Power	Volume <2U, Mass <2 kg, Peak power <40W
Beacon	976 nm, 0.75^{o} divergence, 500 mW 10^{o} FOV 5 Mpx CMOS Camera











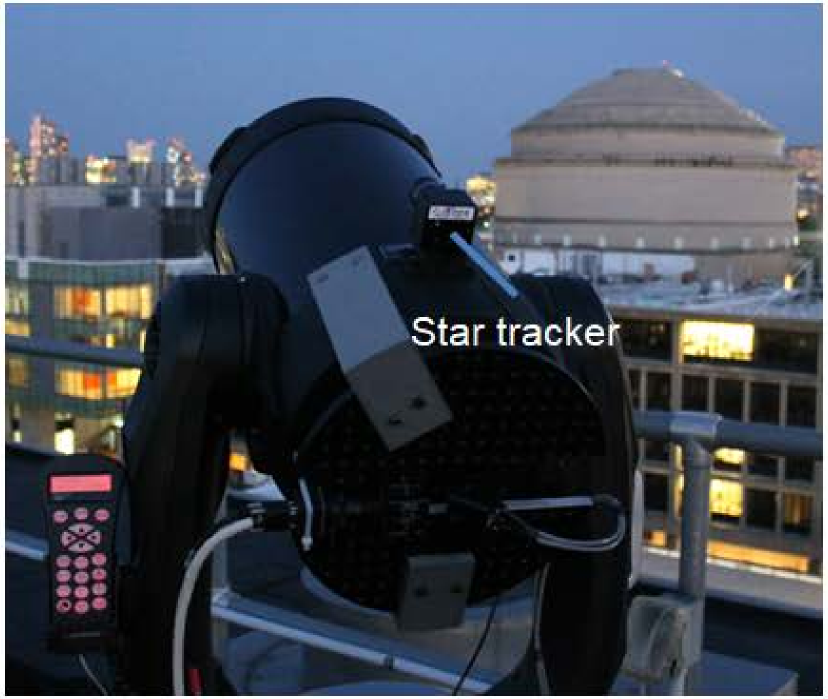
NODE Heritage

*Exact Values Subject to Revision

Images Courtesy D. Barnes, M. LaRocca, L. Yenchesky

Optical Ground Station Equipment

Tracking Assembly (Coarse Stage)



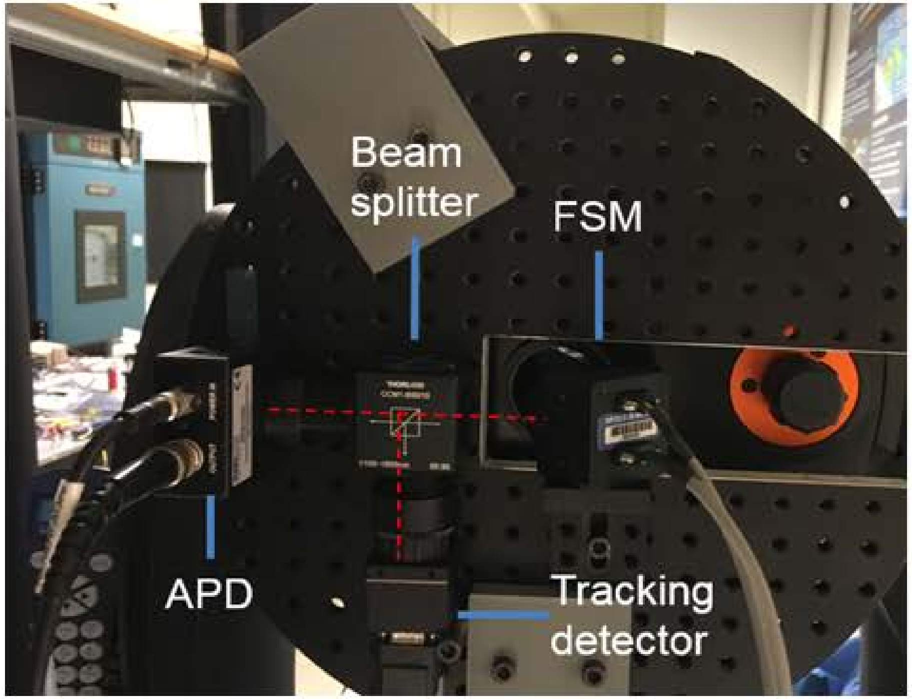
Telescope
Celestron CPC1100

- Ø11" (28 cm)
- f/10
- 0.6 deg FOV

Star tracker
iNova PLB-Mx2

- f = 35 mm lens
- 7.8×5.9 deg FOV

Receiver Assembly (Fine Stage)



Fast steering mirror
Optics in Motion 1"

- Voice-coil actuated
- >850 Hz bandwidth

Tracking detector
Sensors Unlimited SWIR 320CSX

- 320×256 pixels
- 12.5 micron pitch
- 60 Hz full-frame rate

Receiver
Voxtel RDC1-NJAF APD

- 300 MHz
- 200 microns

K. Reising