CLICK: CubeSat Laser Infrared CrosslinK

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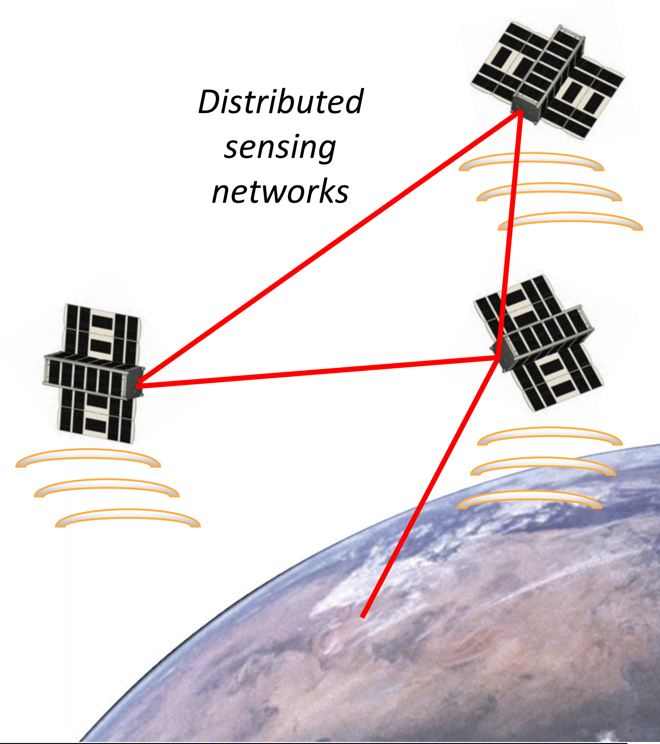
CubeSat Developers Workshop
Tuesday April 23, 2019
Presented by: Ondrej Čierny

Motivation

- To enable new **distributed & coordinated sensing missions**
- There is a need for:
  - **Mbps-rate** full-duplex crosslinks
  - **Precision ranging** and timing
- **Goal**: Development of miniaturized optical transceivers based on COTS components & compatible with CubeSat SWaP constraints

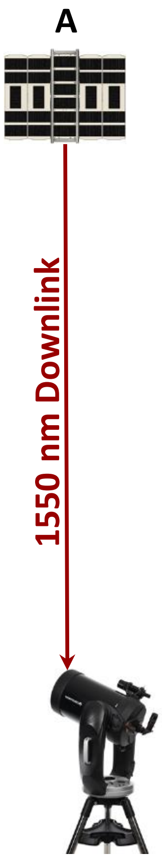


CLICK Payloads

CLICK-A

- Single **1.2 U, 800 g, <15 W** payload
- **200 mW** avg. Tx, **1.3 mrad** beam
- Uplink beacon at 976 nm and MEMS Fast Steering Mirror (**FSM**) for PAT
  - Up to ±3° bus pointing error rejection capability
- Rate-scalable M-ary **PPM downlink**
  - **43 Mbps**, 16-PPM, 1 m Rx
  - **10 Mbps**, 128-PPM, 0.3 m Rx

- Primary success criteria:
  - Validate laser transmitter
  - Validate fine-pointing stage
  - Validate optical GS
  - Successful >10 Mbps downlink



CLICK-B/C

- Pair of **1.5 U, ~1700 g, <25 W** payloads
- **200 mW** avg. Tx, **70 µrad** divergence
- **2.5 cm** receive aperture
- **500 mW** beacon at 976 nm for PAT
- Full-duplex **PPM** crosslinks 1537/1565 nm
  - **50 Mbps**, 4-PPM, <450 km
  - **25 Mbps**, 16-PPM, <920 km
- **200** ps timing accuracy & time transfer

- Primary success criteria:
  - >20 Mbps full-duplex @ 580 km
  - <0.5 m ranging w/o GPS @ 580 km

Payload Design

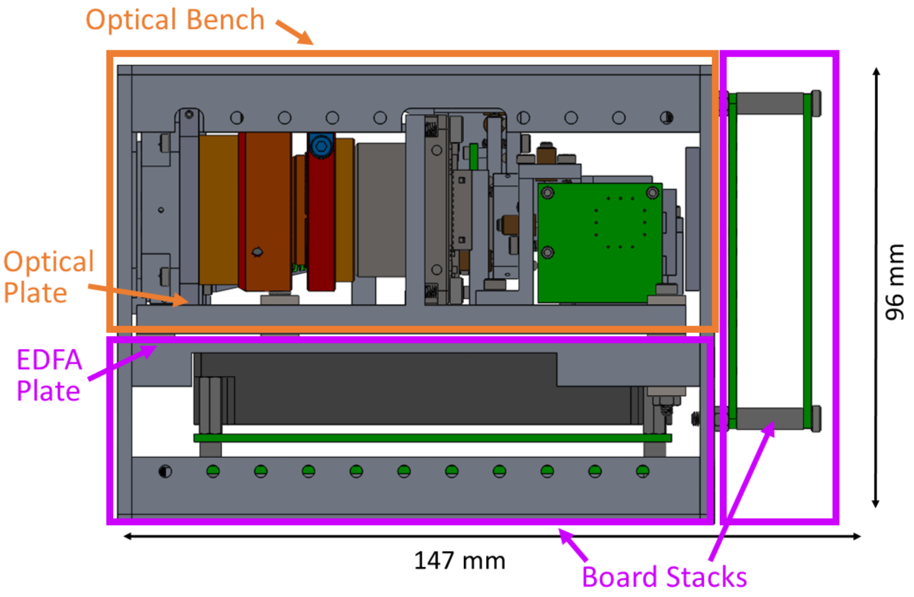


Image: L. Yenchesky

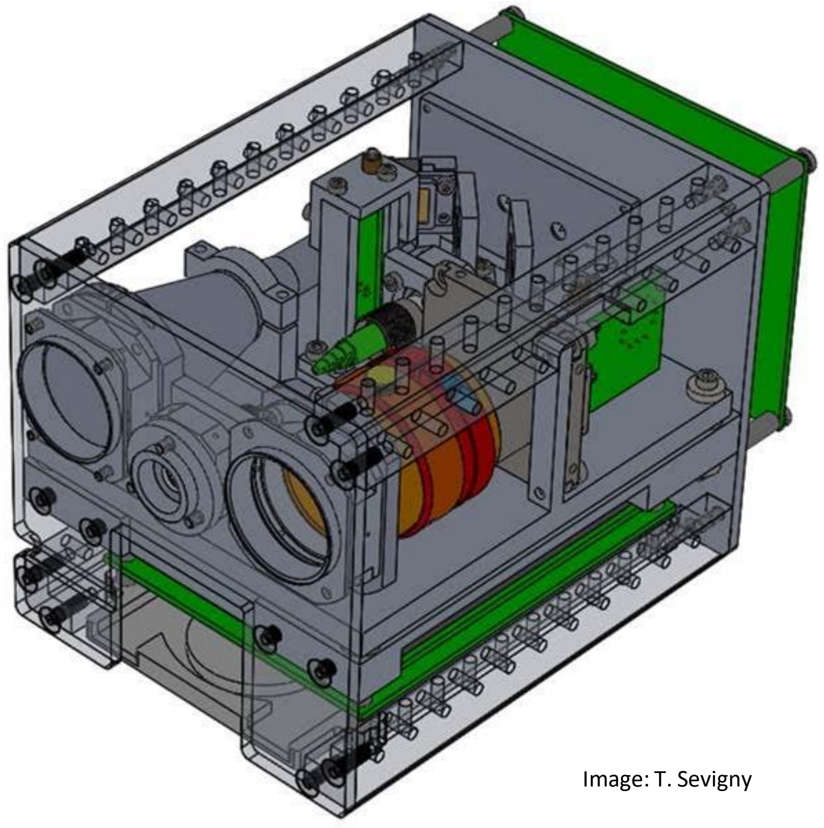


Image: T. Sevigny

Optical Paths

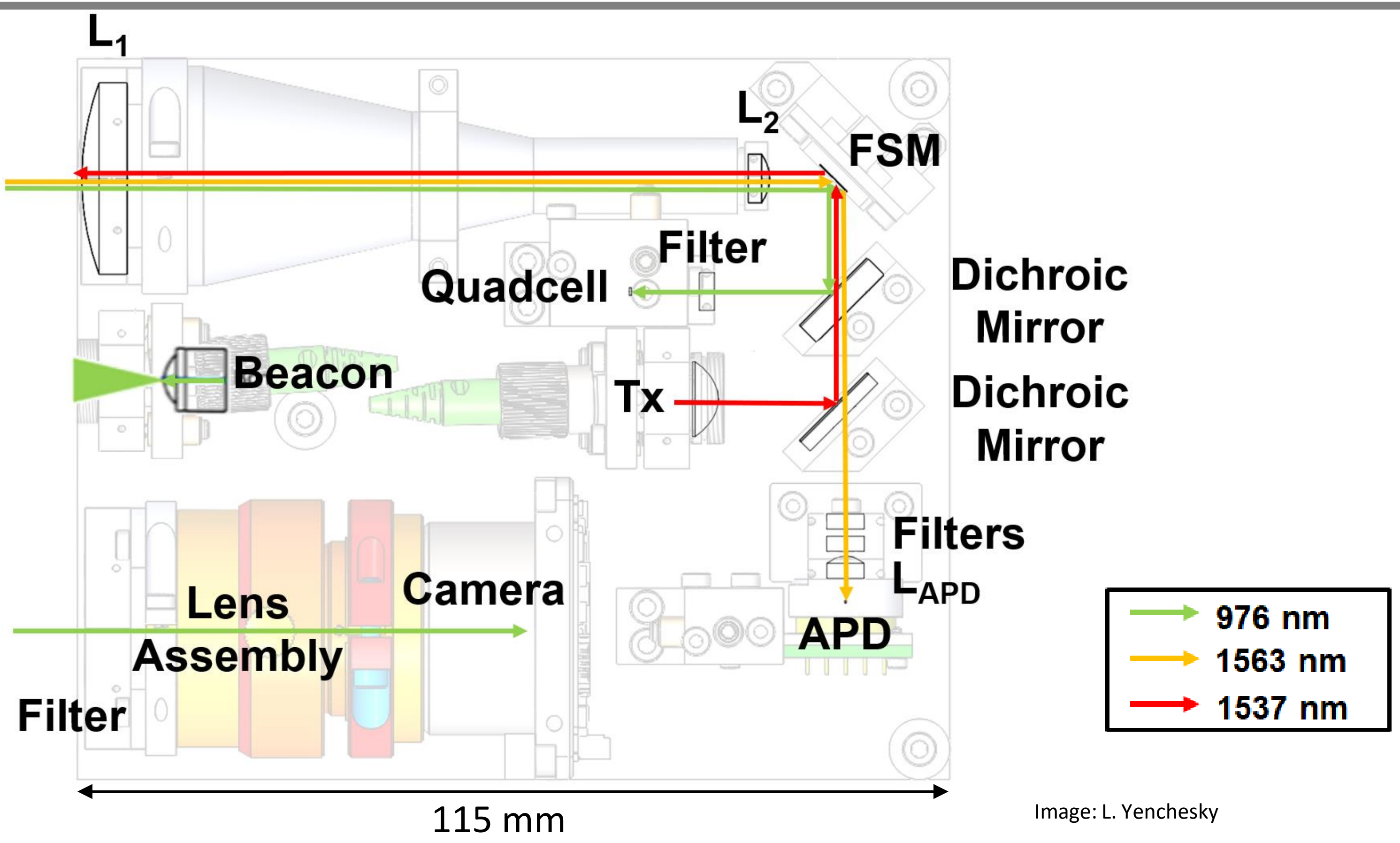


Image: L. Yenchesky

PAT Staging & Budgets

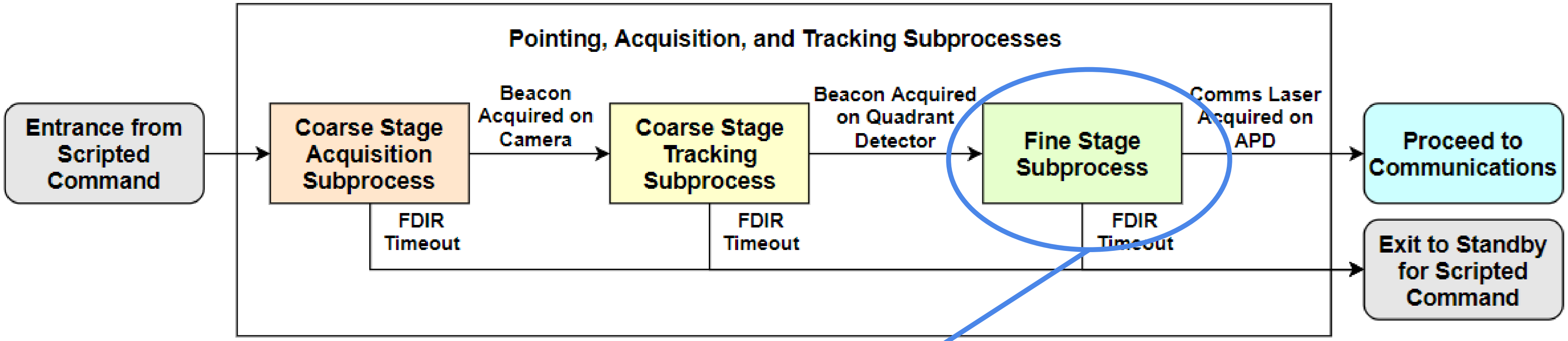
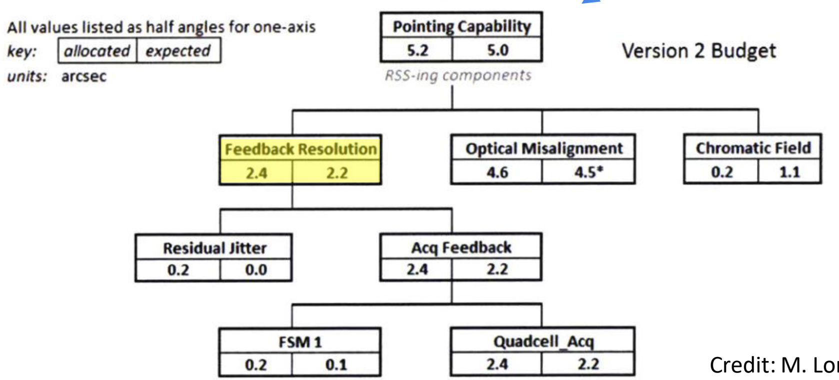


Image: P. Grenfell

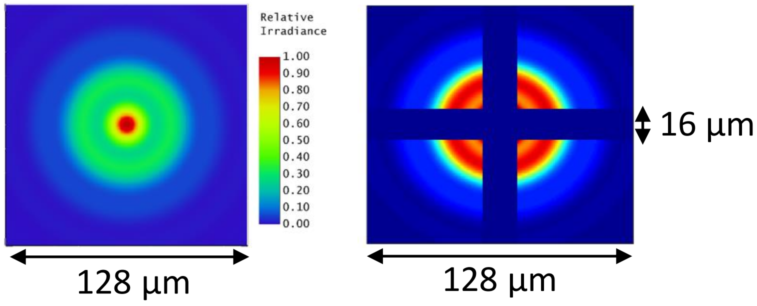


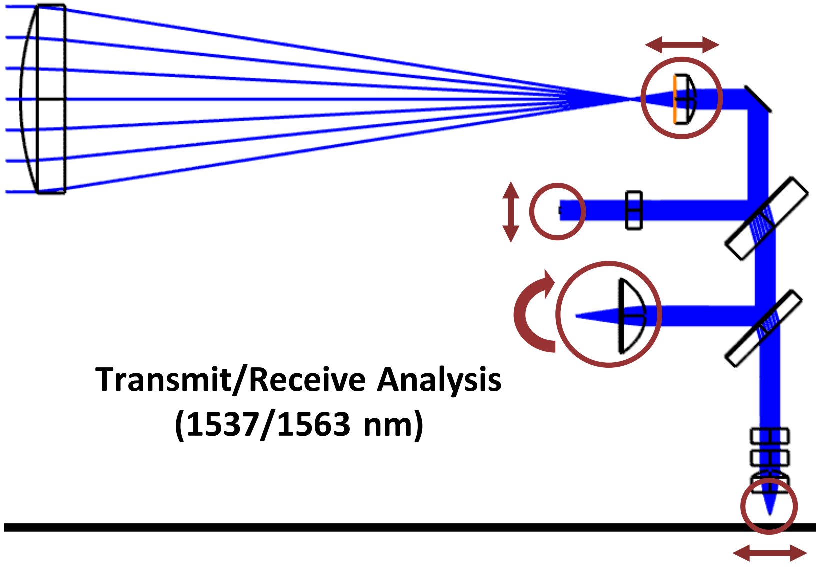
Credit: M. Long

Optical Analysis

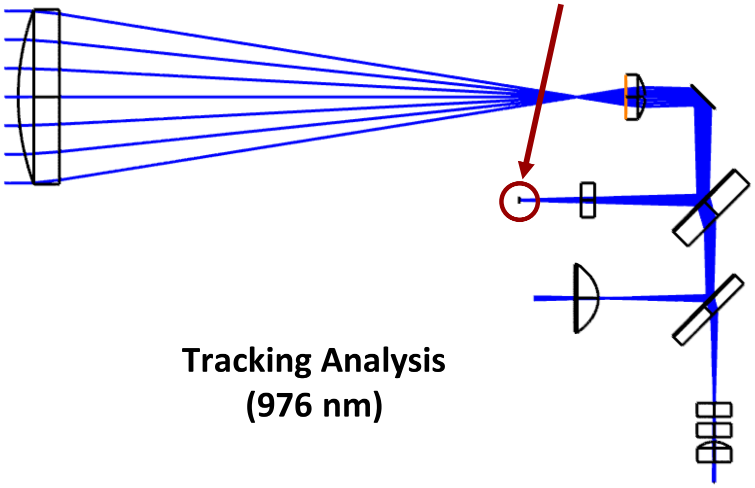
- Optimization of optics in Zemax → MATLAB
  - Beacon PSF sizing on quadcell to determine optimal tracking resolution
  - Meets allocated **2.4 arcsec**
- Tolerancing analysis to determine machining precision & identify **kinematic mounts**

Beacon PSF on Quadcell (zoom-in)





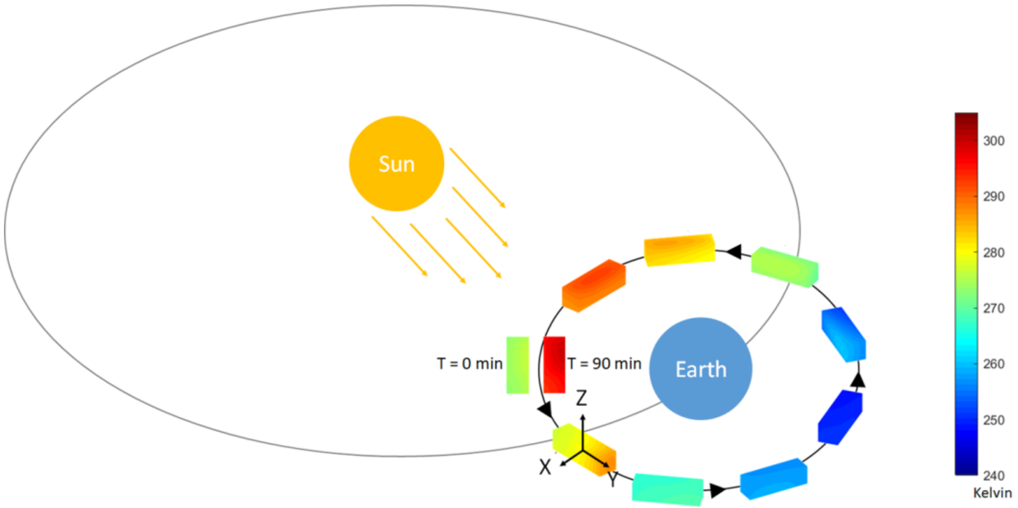
Transmit/Receive Analysis (1537/1563 nm)

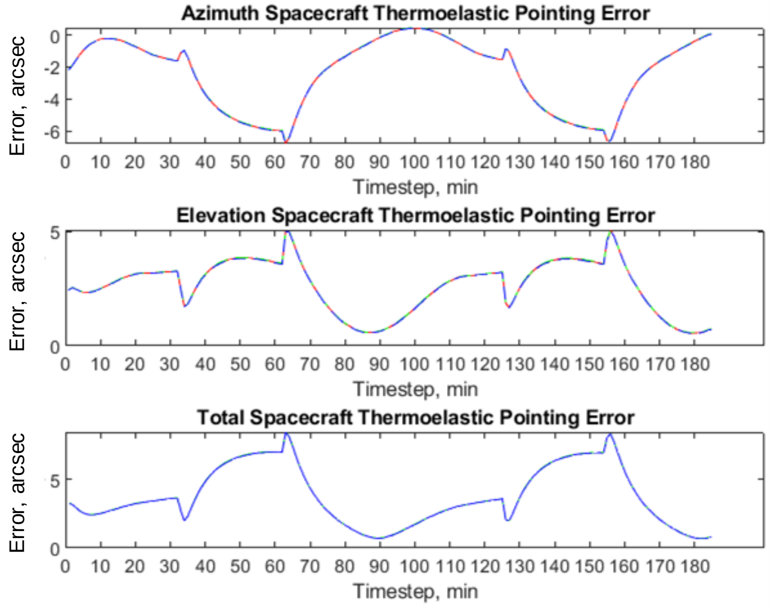


Tracking Analysis (976 nm)

Thermoelastic Analysis

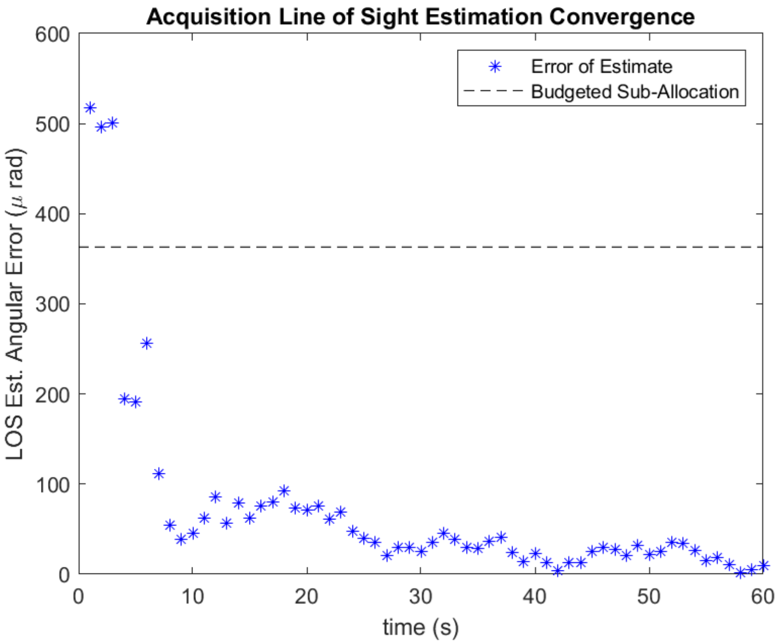
- Assessment of pointing error due to thermoelastic expansion of S/C body
- Relative alignment between S/C **star tracker** and CLICK **apertures**
- Thermal Desktop → FEMAP → MATLAB
- Initial results show significant margin on the conservatively allocated **300 arcsec**

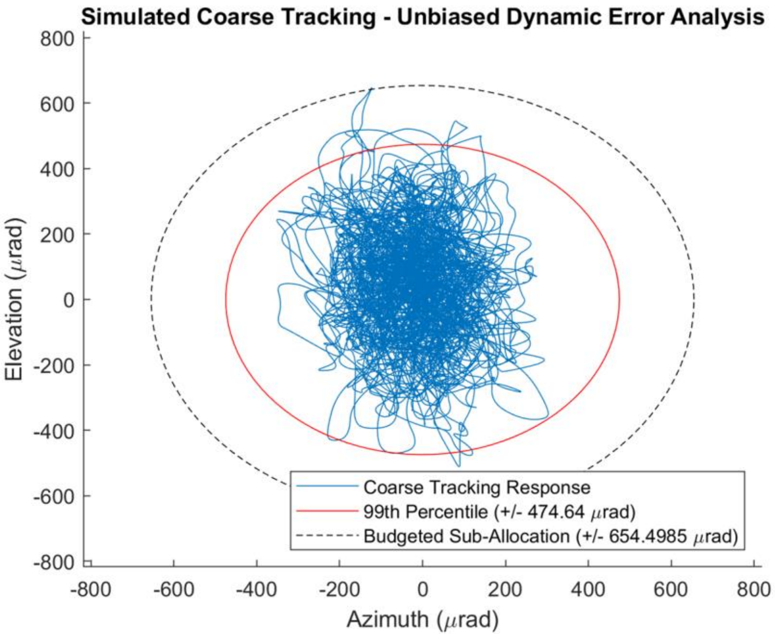




Images: L. Yenchesky

PAT Controller Analysis: CPS



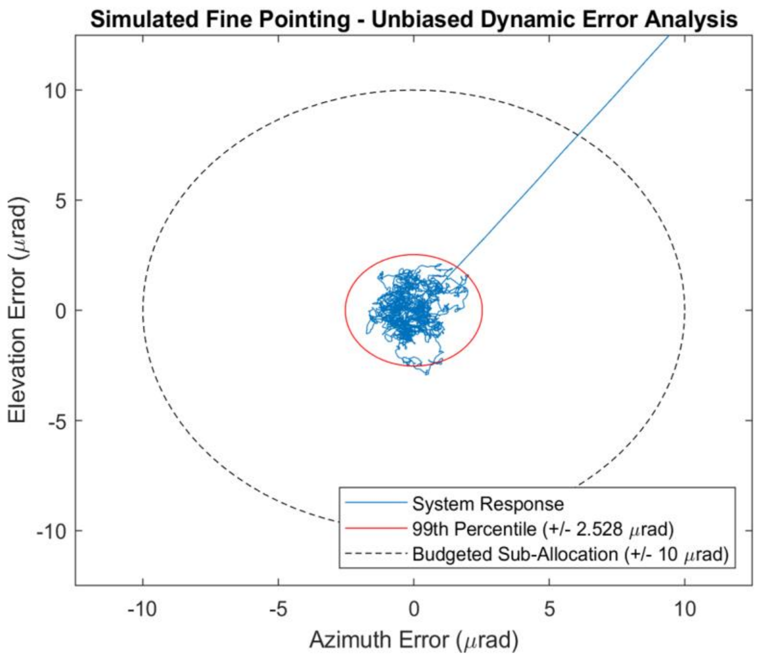


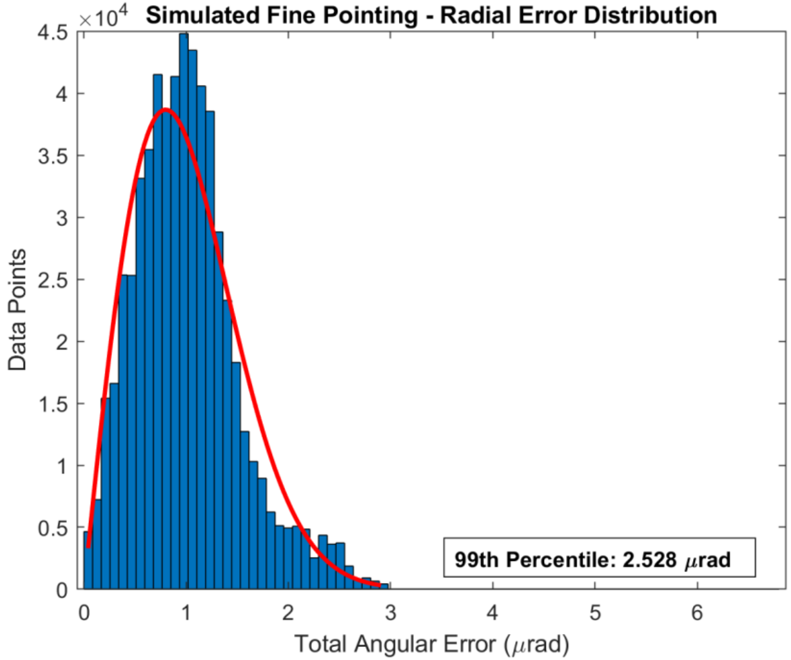
- Simulated acquisition process
- Uses GPS measurements with up to 10 sec communications delays.
- Converges in less than 30 sec.

- Simulated coarse tracking process
- Uses a 1 Hz command signal from the payload
- Converges to within sub-allocation for unbiased tracking error

Images: P. Grenfell

PAT Controller Analysis: FPS





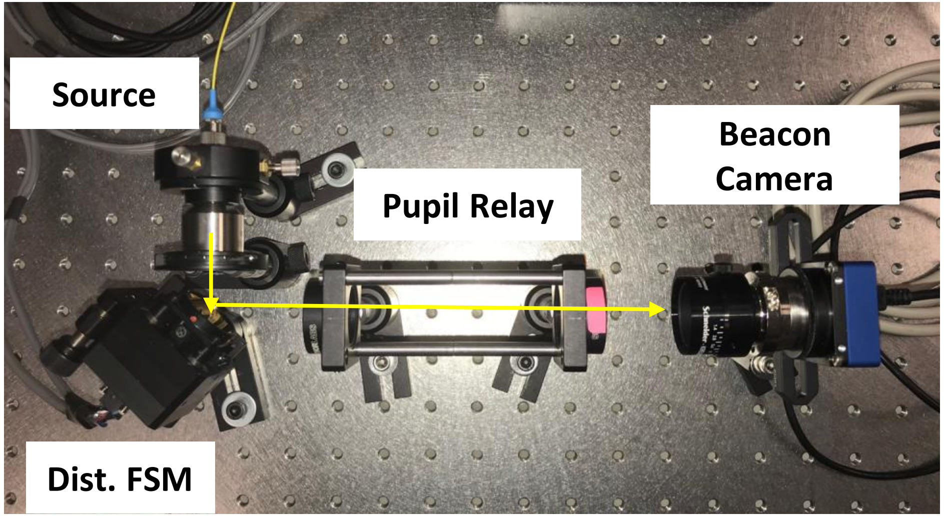
- Simulated fine pointing process.
- Response settles in 46.1 msec for this run.
- Converges to within sub-allocation for unbiased dynamics.

- Distribution from simulated fine pointing process.
- Follows a Rician model as expected, with shape parameter 0.0025 in this instance.

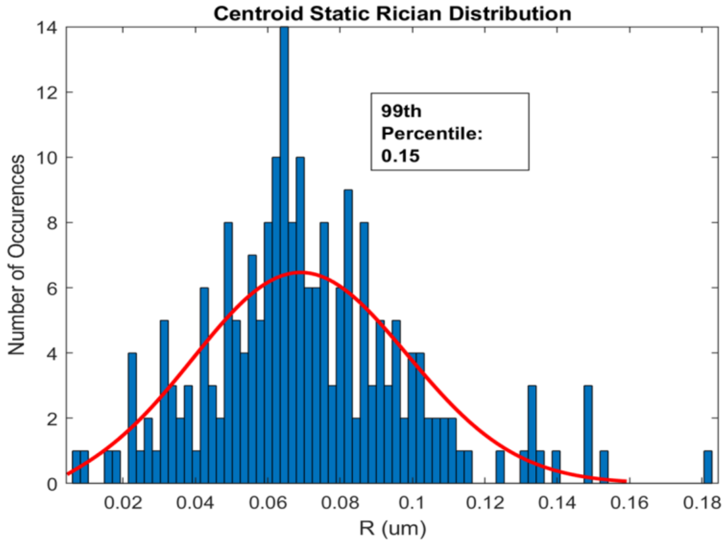
Images: P. Grenfell

CPS Hardware Testbed

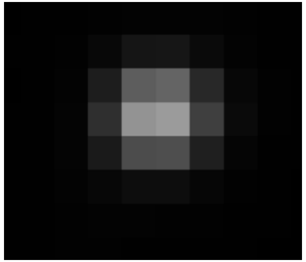
CPS Camera Hardware-In-The-Loop Testbed



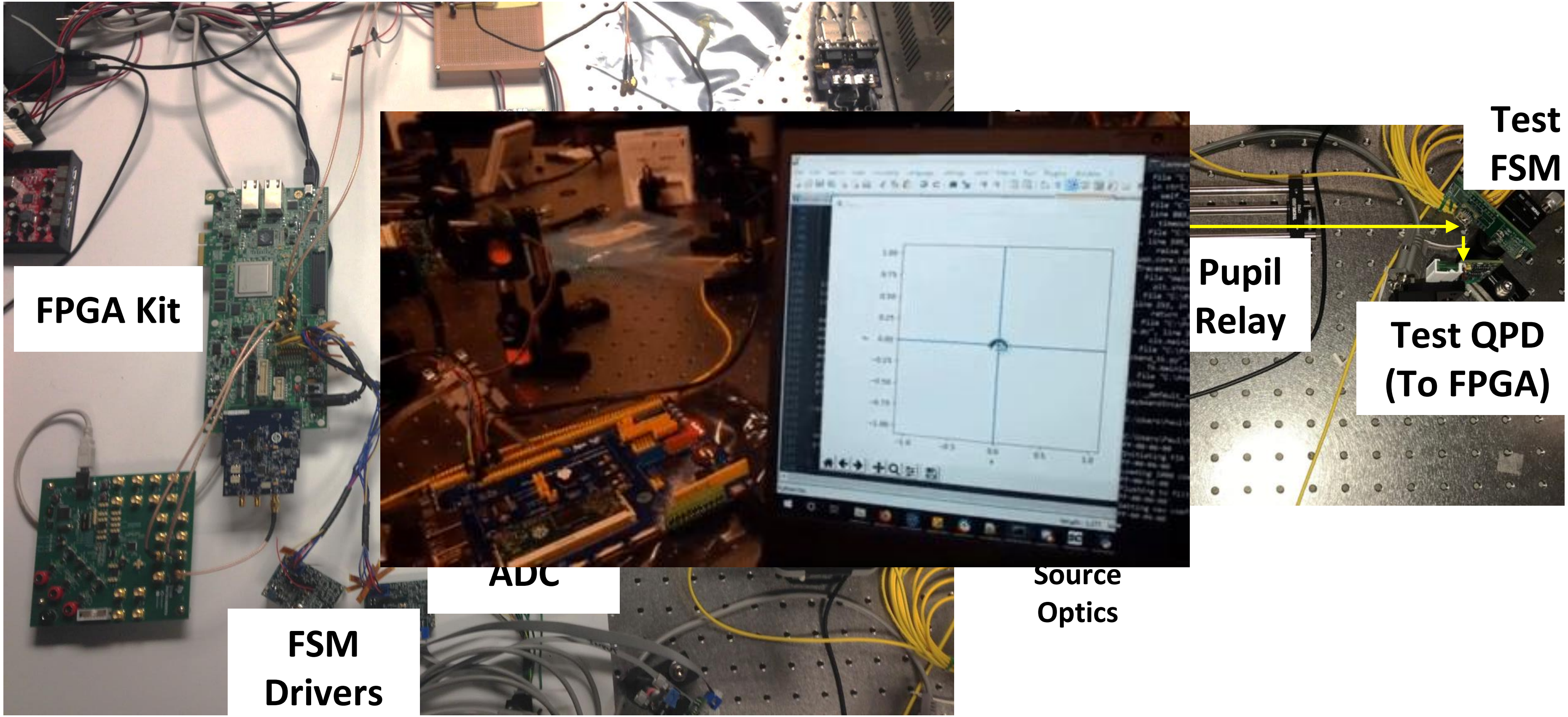
- Test setup for hardware-in-the-loop acquisition and tracking estimator and control development (in-progress).



- Measurements from static centroiding test of image processing software.
- CMOS 2542 x 1944 pixel readout, 2.2 um pixel width.



FPGA & FPS Testbed



CLICK: Next Steps

CLICK-A

- Payload design frozen
- Interface adaptation for new spacecraft bus completed
- Delta-CDR in May, TRR shortly afterward
- EDU being assembled
- Environmental testing
- Launch **2020**!

CLICK-B/C

- Payload design being finalized
- Final design and hardware analyses ongoing
- CDR split between sessions May - Oct
- EDU later this year
- Lessons learned from CLICK-A
- Integration and testing in 2020
- Launch **2021**!

Thank you for your attention!

Questions?

References

[1] Grenfell, Peter, et al. "Pointing, Acquisition, and Tracking for Small Satellite Laser Communications." Proceedings of the AIAA/USU Conference on Small Satellites, Advanced Concepts I, SSC18-WKI-01. 2018.

[2] Riesing, Kathleen Michelle. "Portable optical ground stations for satellite communication." PhD diss., Massachusetts Institute of Technology, 2018.

[3] Riesing, K. M., Yoon, H., & Cahoy, K. L. (2018). Rapid telescope pointing calibration: a quaternion-based solution using low-cost hardware. Journal of Astronomical Telescopes, Instruments, and Systems, 4(3), 034002.

[4] Čierny, Ondrej, and Kerri L. Cahoy. "On-orbit beam pointing calibration for nanosatellite laser communications." Optical Engineering 58.4 (2018): 041605.

Acknowledgements

The CLICK mission is managed and funded by the Small Spacecraft Technology (SST) program within the Space Technology Mission Directorate.

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Animation by Benjamin Schweighart, Millennium Engineering and Integration Services Company, NASA Ames Research Center.

Backup Slides

Advantage of Lasercom Crosslinks

- **High-rate, power-efficient** data links
  - Laser not regulated yet; spectrum available

- Standalone **precision timing and ranging**
  - Improvement over GPS, better than 30 cm (1 ns)
  - < 100 mm/s range rate error at 1Hz bandwidth

- **Crosslinks enable coordinated observations**
  - Near real-time onboard processing for object tracking
  - Rapid data transfer through constellation, reduced latency
  - Data fusion from different bands or sensors
  - Supports autonomous operations

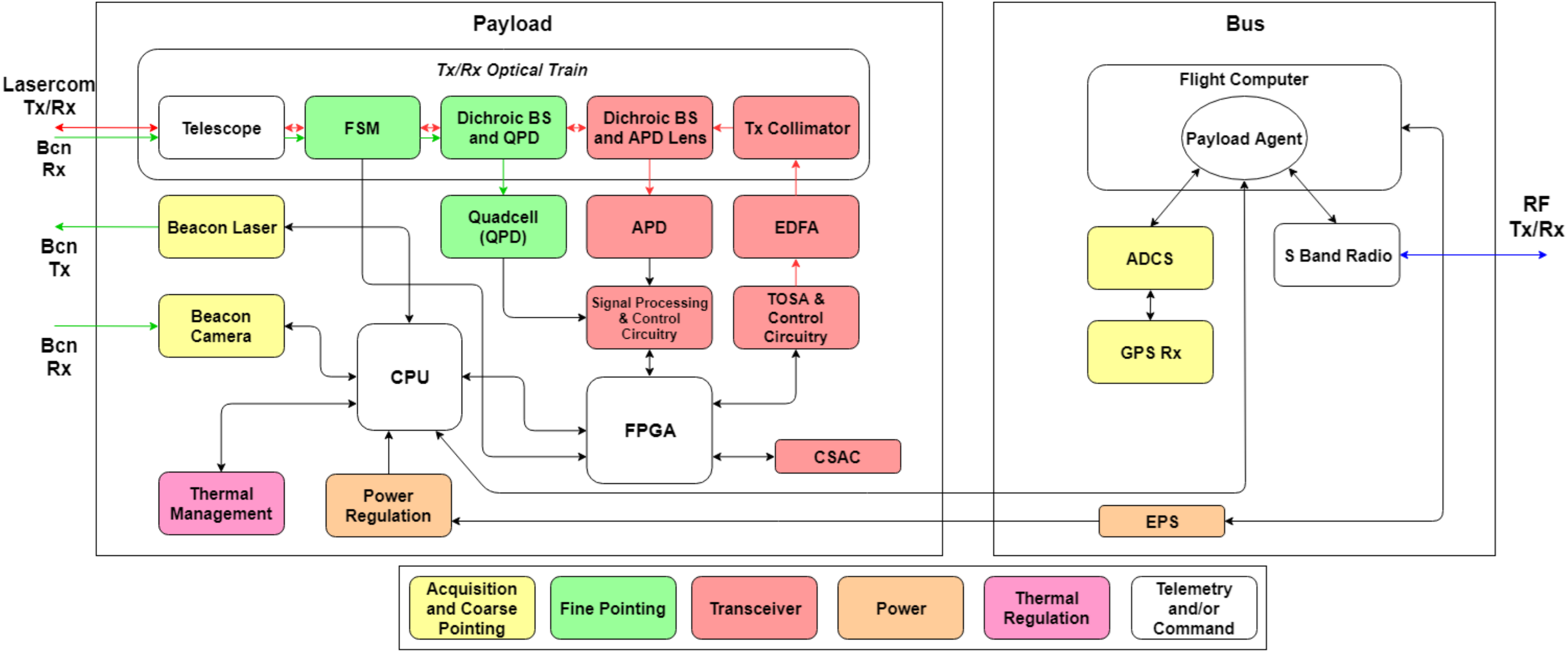
- **Fine pointing** enables power efficiency and longer range crosslink capability
  - Demonstrate ***new*** COTS MEMS fine pointing technology on-orbit with MIT
  - OCSD CubeSat just demonstrated 100 Mbps downlink *without* fine pointing stage

Beam Divergence Comparison

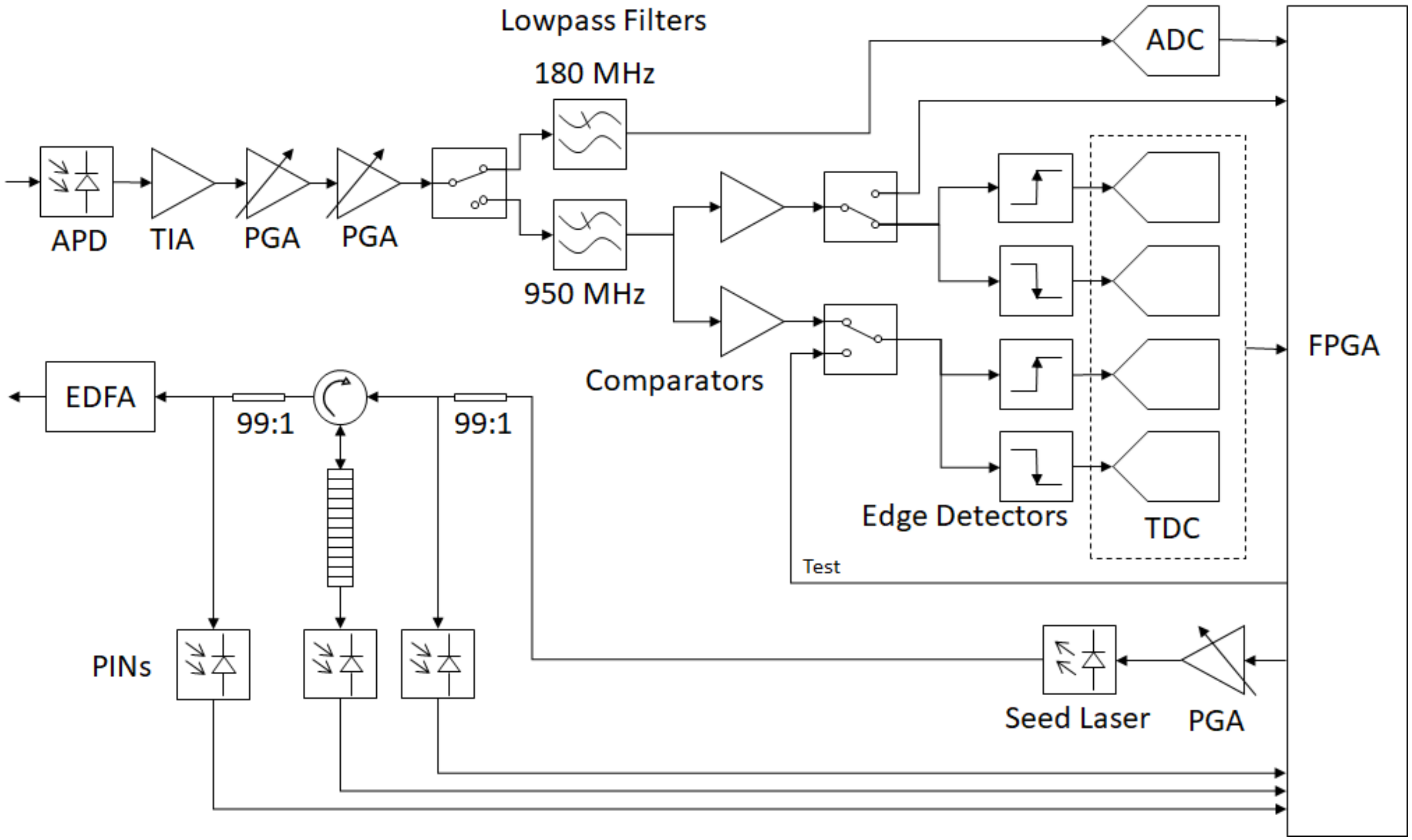
Mission	Beam Divergence Angle	Link Type
AeroCube 7 A, B, C	A: 1260 arcsec (6.11 mrad) B: 180 arcsec (0.87 mrad) C: 540 arcsec (2.61 mrad)	LEO to Ground
CLICK-A	**268 arcsec (1.3 mrad)**	**LEO to Ground**
OSIRIS	41.2 arcsec (200 µrad)	LEO to Ground
NFIRE	14.8 arcsec (71.8 µrad)	LEO to LEO
CLICK-B/C	**14.6 arcsec (70.8 µrad)**	**LEO to LEO or Ground**
Alphasat (EDRS)	1.22 arcsec (5.9 µrad)	GEO to LEO
LLCD	0.52 arcsec (2.5 µrad)	Lunar to Ground

Table ref: P. Grenfell [1]

Payload Architecture



Transceiver Architecture



ADC

- Better link margin with Matched filters
- High flexibility

TDC

- High timing accuracy
- Direct ranging readout

Image: P. Serra

Optical Ground Terminal

- MIT-developed Portable Telescope for Lasercom (PorTeL)
- Based on ⌀28 cm Celestron CPC1100
- Fitted with a custom backend & star camera
- Rapid setup and pointing calibration based on star camera quaternion solution (<15 min)

Credit: K. Riesing [2,3]

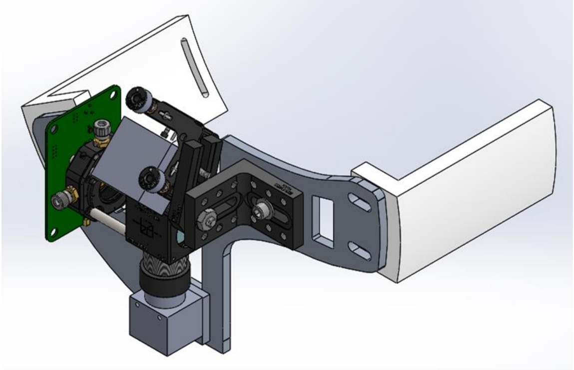


Image: T. Sevigny

Drag Control

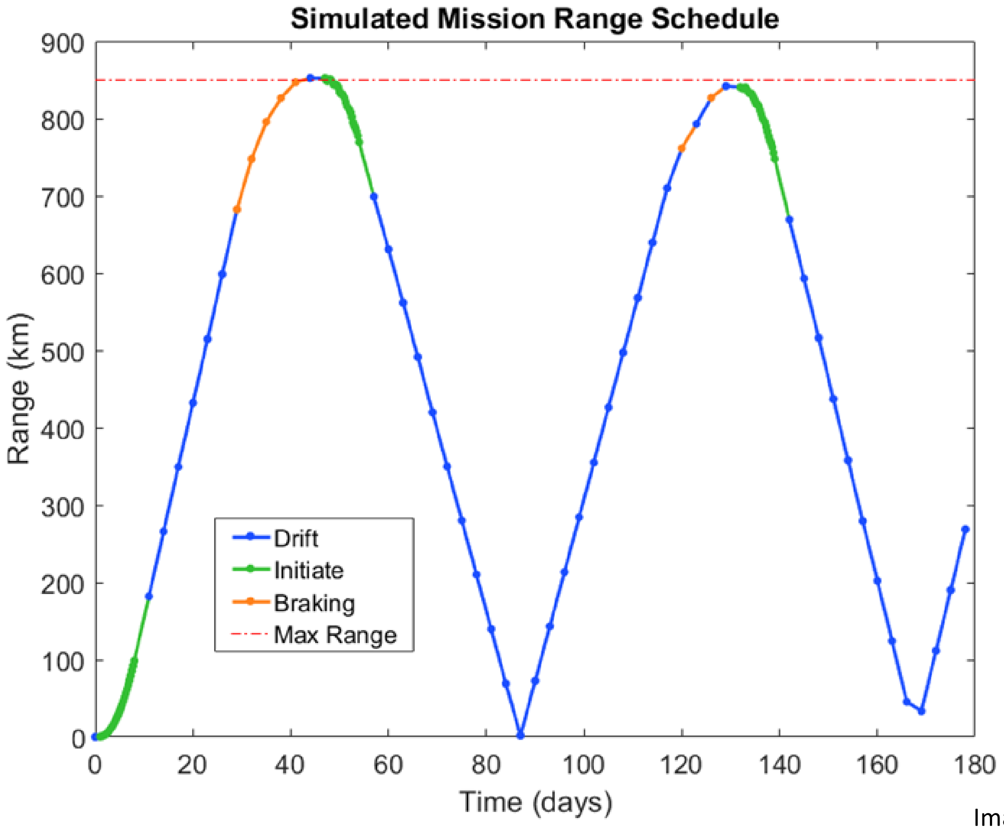
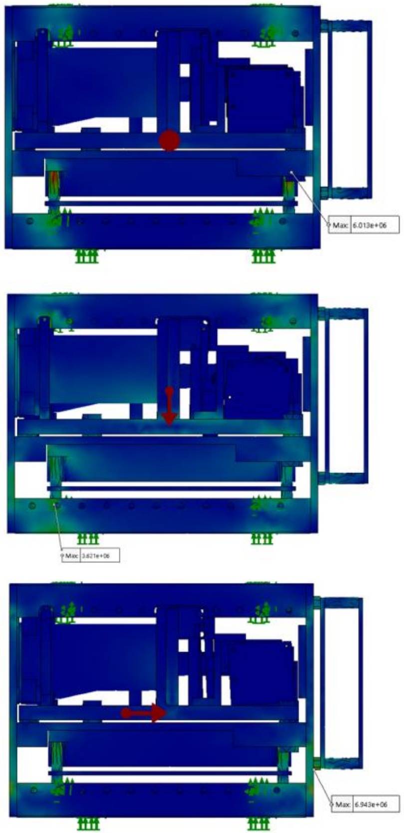


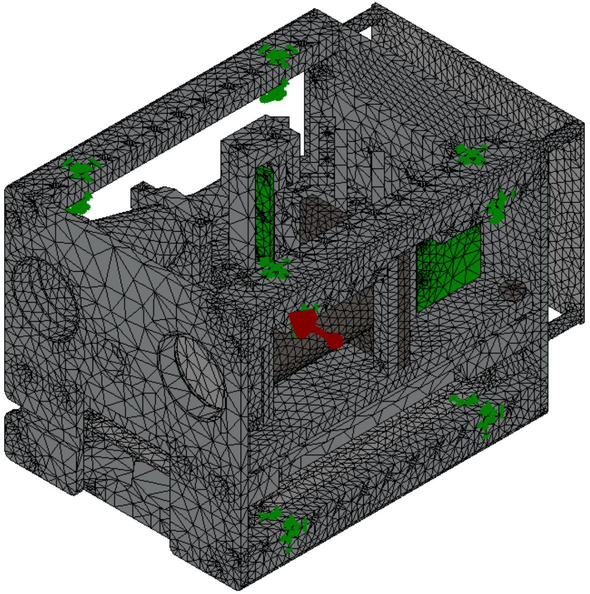
Image: R. Fitzgerald

Structural Analysis

Static Analysis	
Static Direction	**Margin of Safety**
X	26
Y	44
X	22
Resonant Freq Analysis	
Mode	**Freq (Hz)**
in progress	

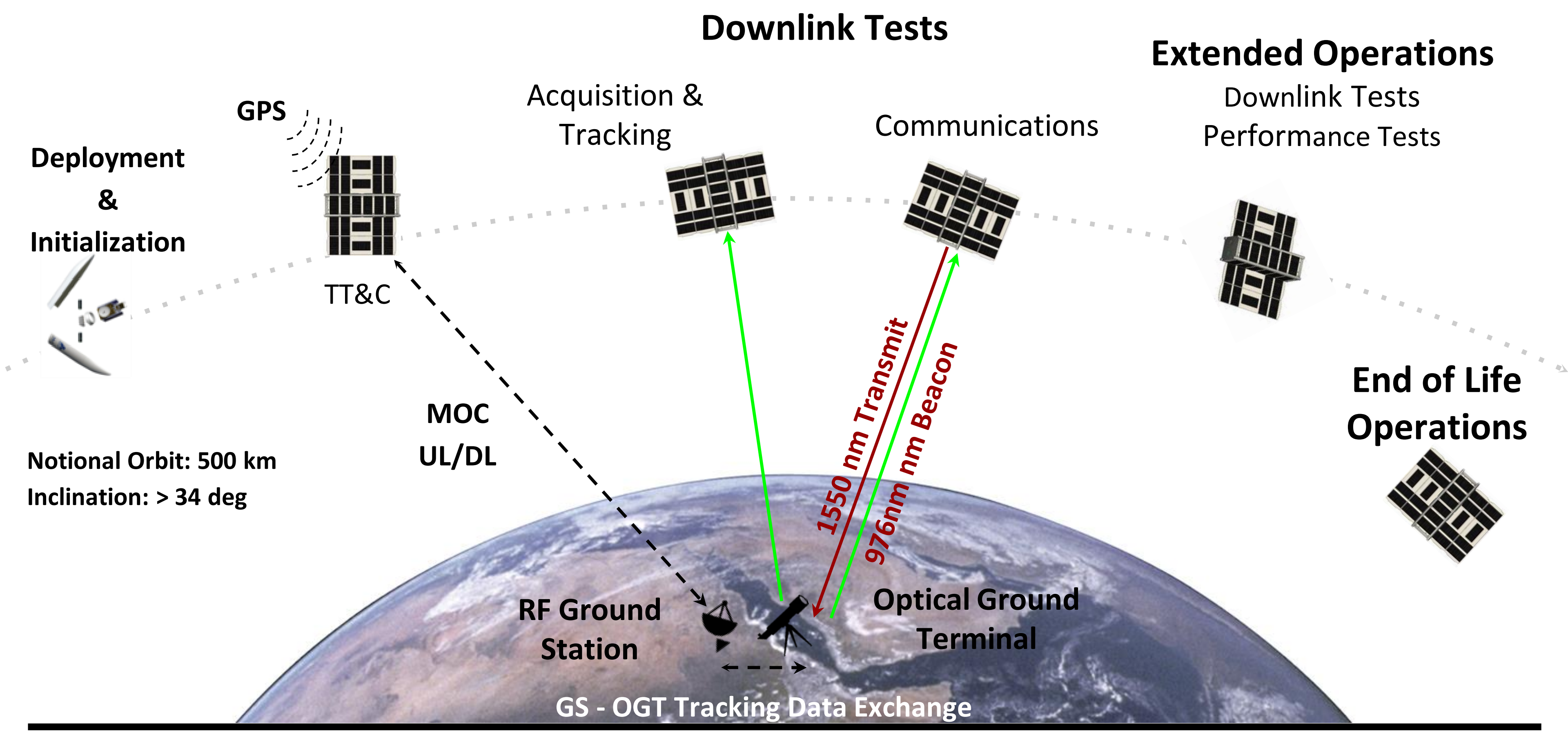
Achieved goal: MOS > 0



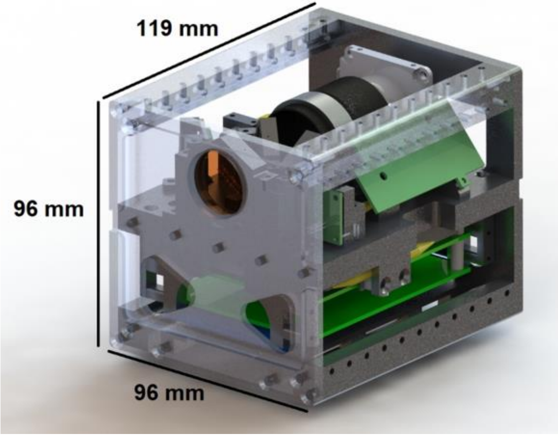


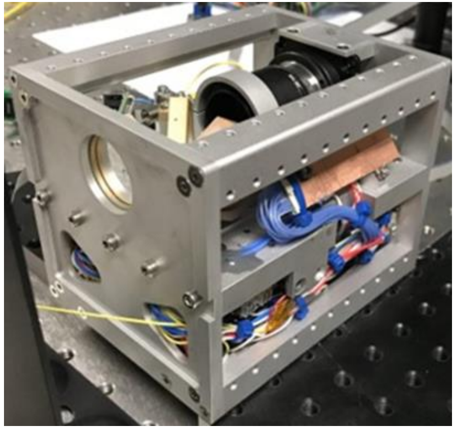
Images: L. Yenchesky

CLICK-A Concept of Operations



CLICK-A Design & PAT





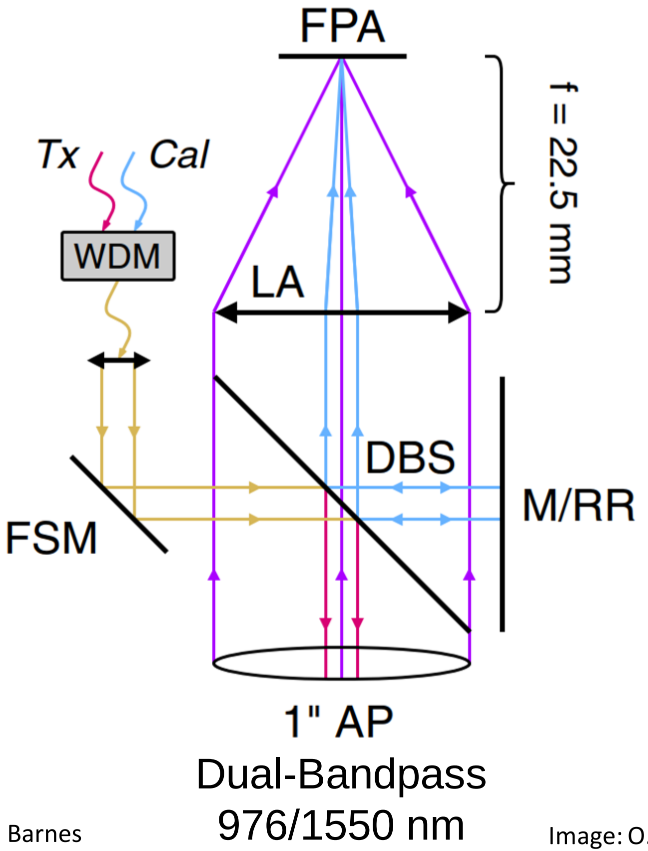


Image: D. Barnes

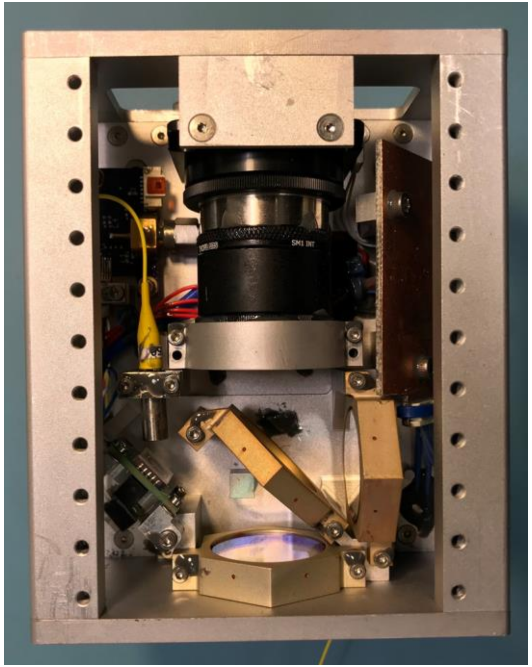
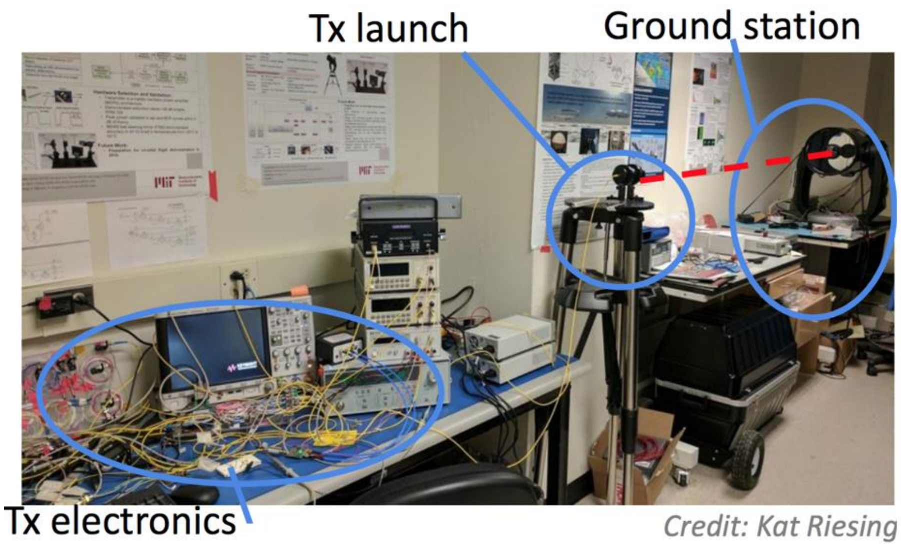


Image: O. Cierny

CLICK-A Hardware Testbeds

Modulator OTA test



Credit: Kat Riesing

PAT Testbed

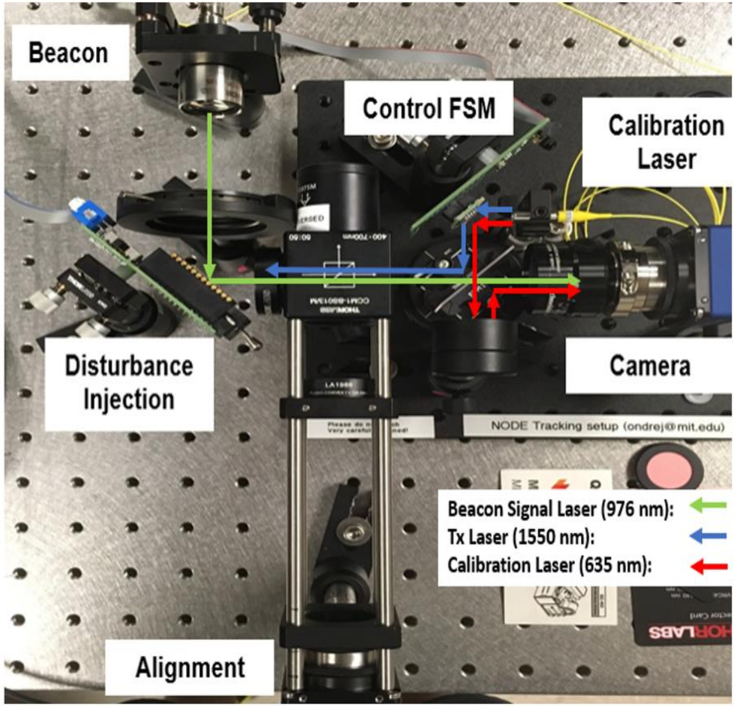
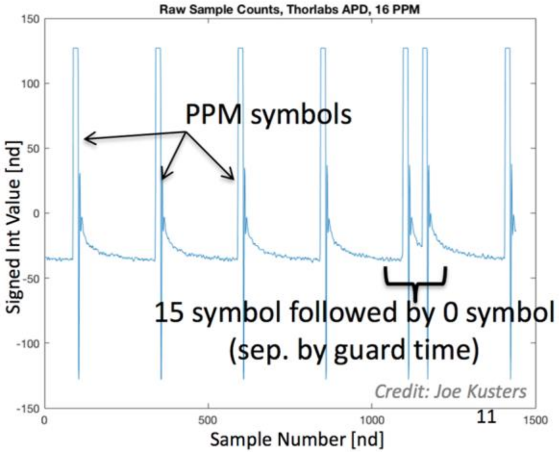


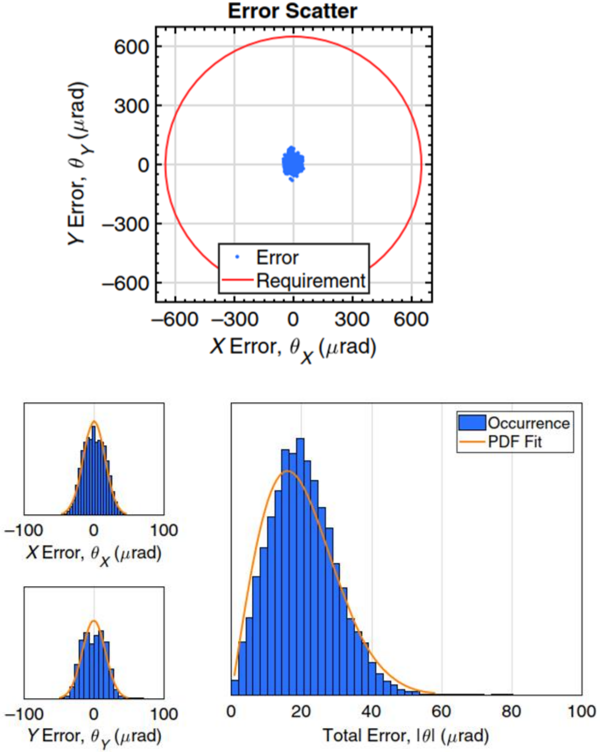
Image: O. Cierny

CLICK-A Hardware Verification

Modulator OTA Test

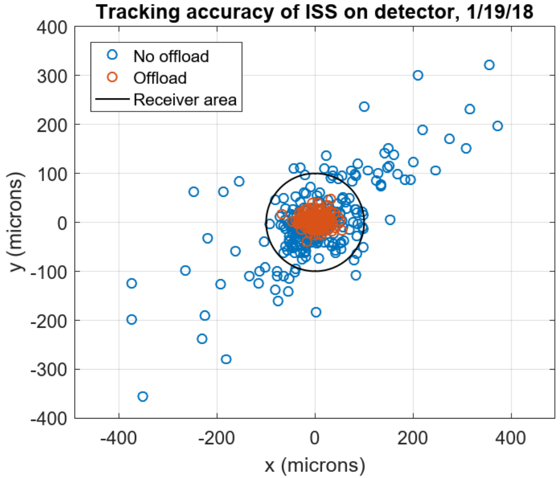


PAT Performance Test



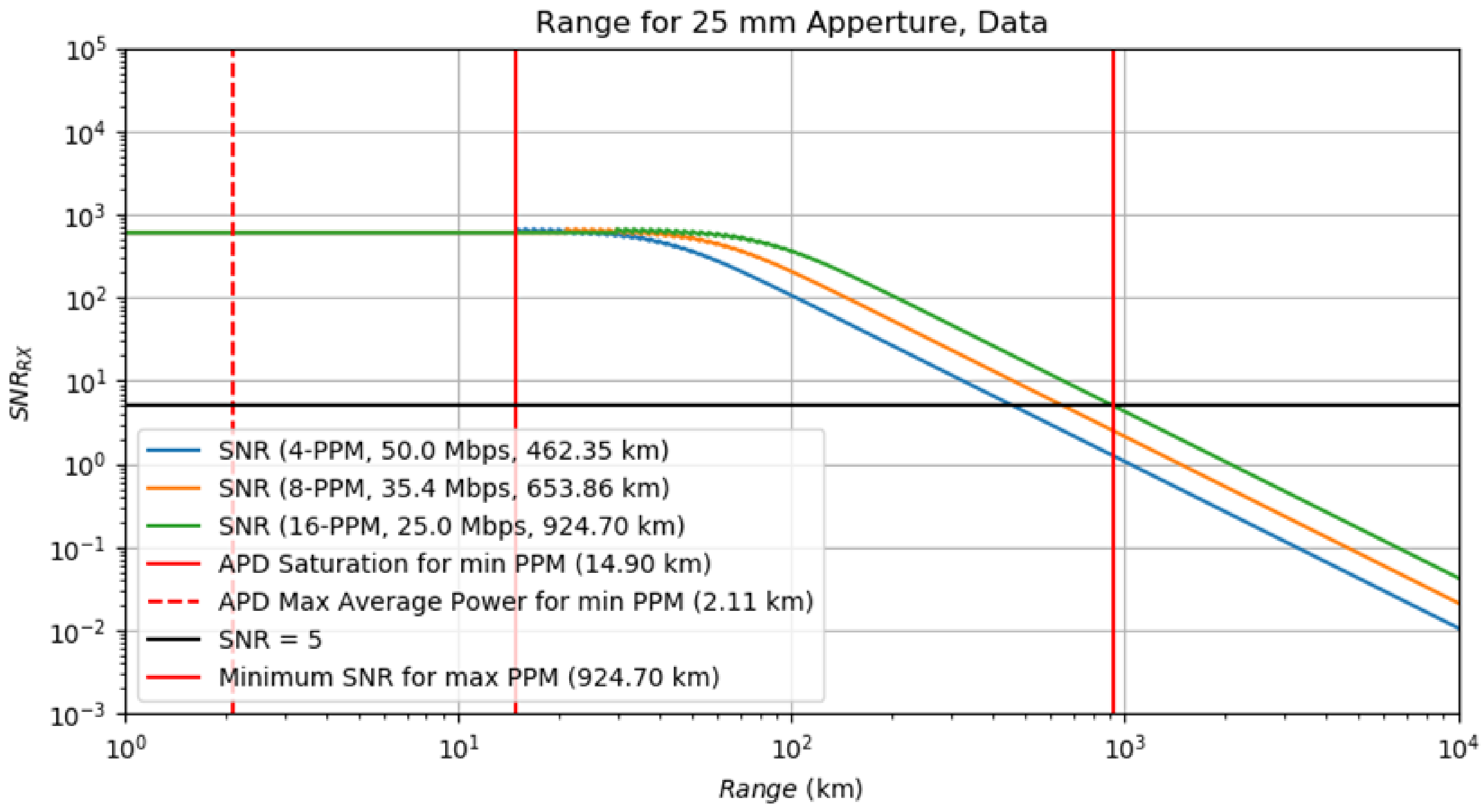
Credit: O. Cierny [4]

PorTeL Tracking Test

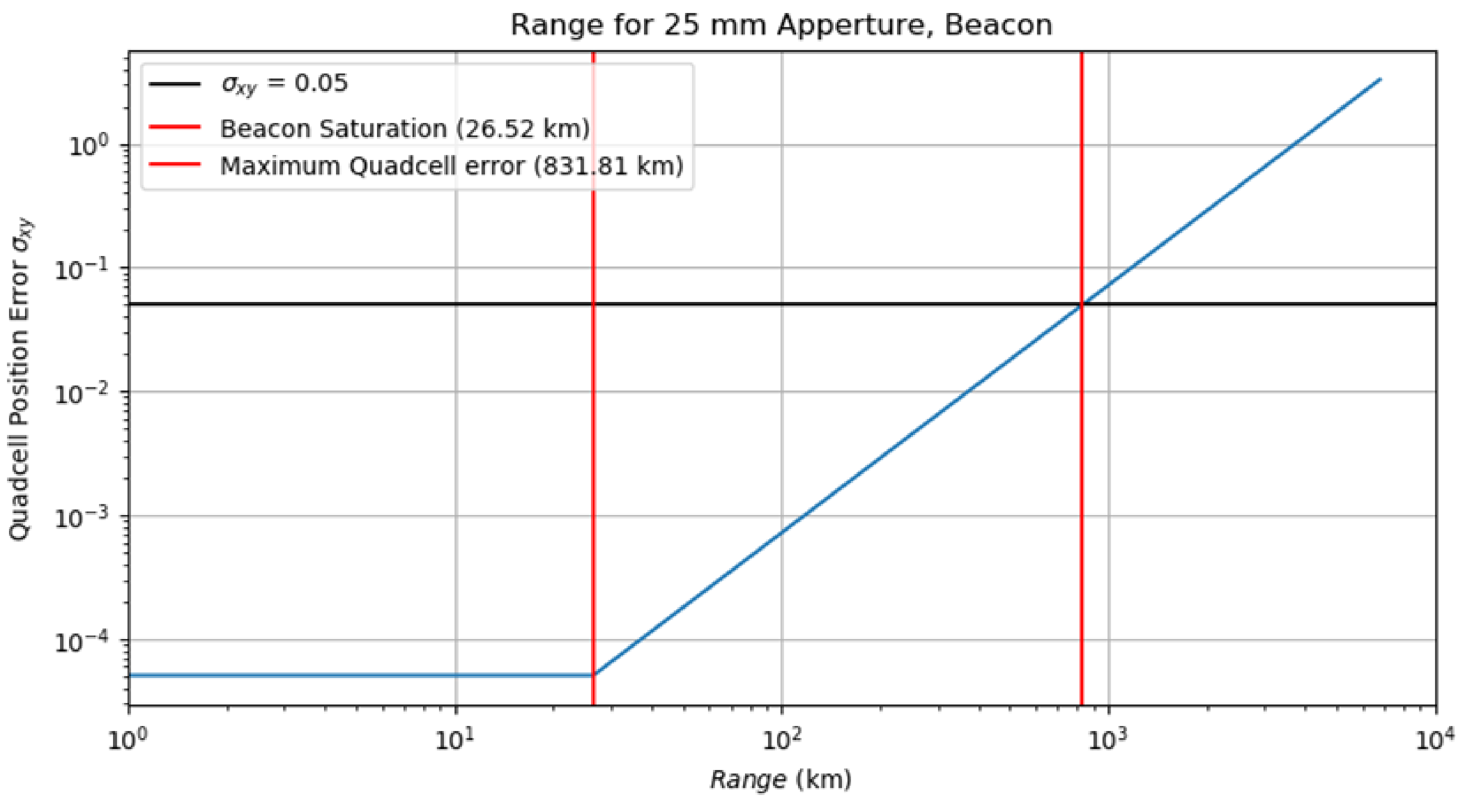


Credit: Kathleen Riesing [2]

CLICK-B/C Crosslink Budget

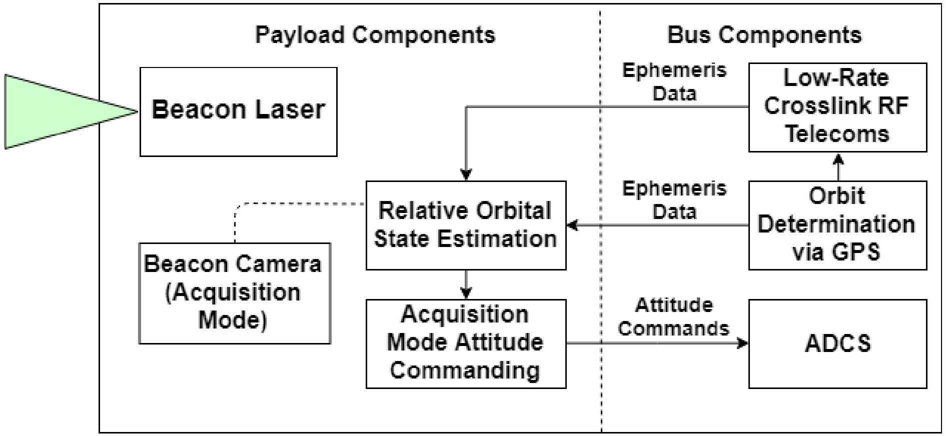


CLICK-B/C Quadcell Budget

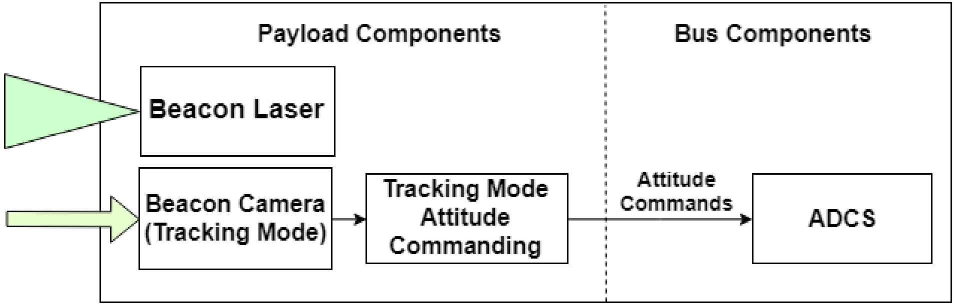


CLICK B/C Coarse PAT

Coarse Stage Acquisition Subsystems



Coarse Stage Tracking Subsystems



Images: P. Grenfell

CLICK B/C Fine Tracking Flow

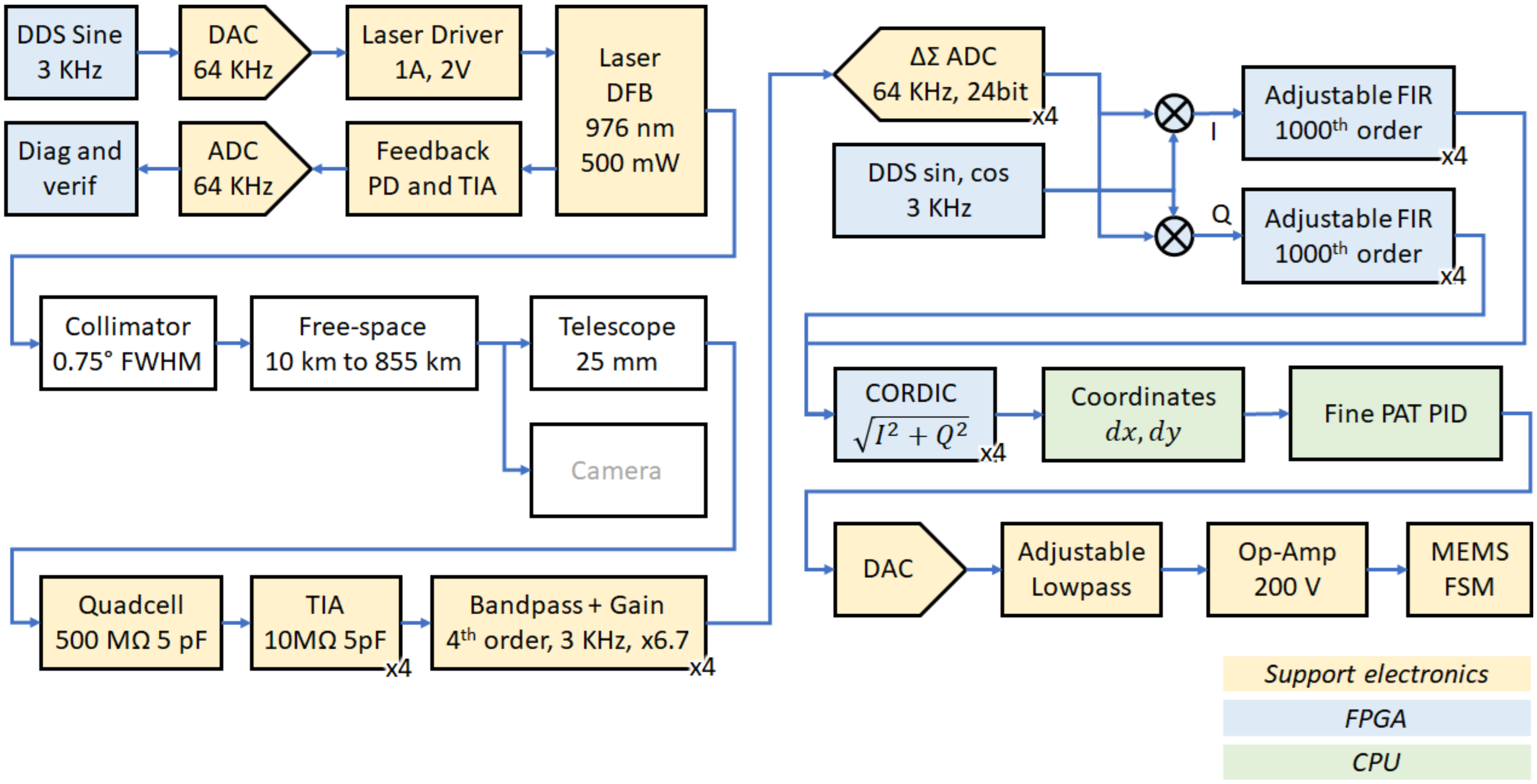


Image: P. Serra