Two-Stage Control for CubeSat Optical Communications

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Outline

- Problem Statement
- Prior Art:
  - Free-space Optical Communications at LEO
  - CubeSat-scale FSO
- FSO System Architecture & Requirements
- Pointing, Acquisition and Tracking (PAT)
- Future Work

Problem Statement

Design and optimize a CubeSat-scale free-space optical communication system utilizing *staged pointing control*.

- Free-space optical (FSO) communications
  - Improve size, weight and power (SWaP) over RF
  - Reduced regulatory burden
- **High-gain** apertures → *stringent pointing requirements*
- Current FSO realizations are for larger spacecraft
  - 10's of kg, 10's of Watts
  - Microradian (~arcsecond) pointing

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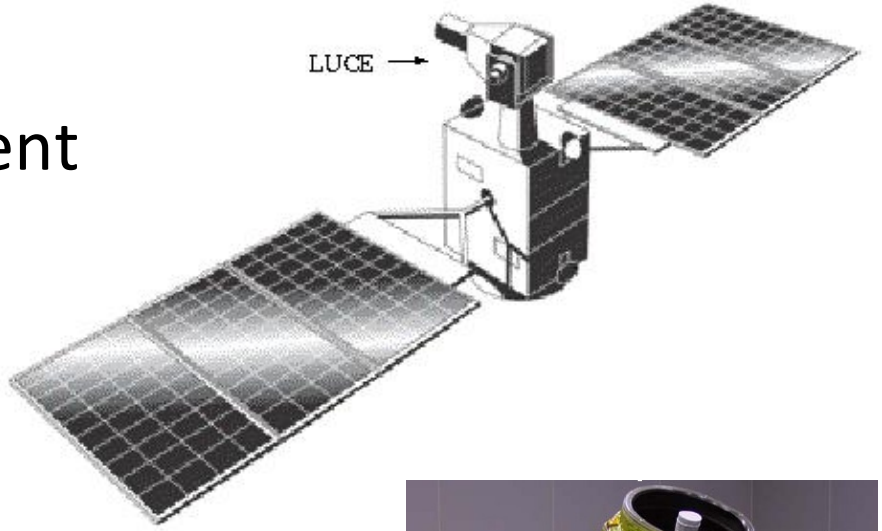
OICETS / LUCE

- **LUCE:** Laser-Utilizing Communications Experiment
- Successful LEO-to-ground FSO demo (2005-2009)
- Bidirectional capability
- Closed-loop tracking using beacon signal
- Multi-stage control
  - Range/resolution limits that are inherent to all actuators
  - Coarse: 0.1 deg @ 10 Hz (gimbal)
  - Fine: 1 urad @ 200 Hz (piezo FSM)



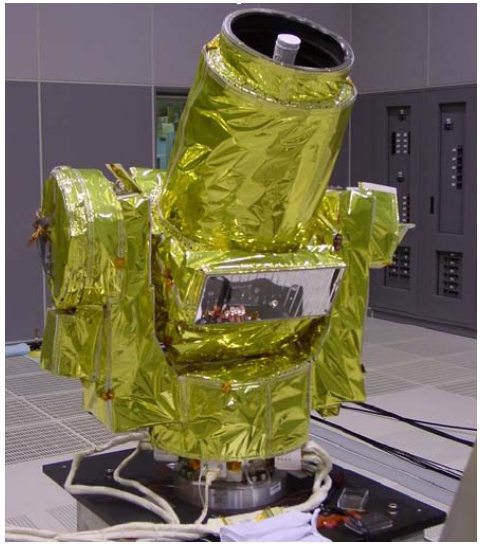
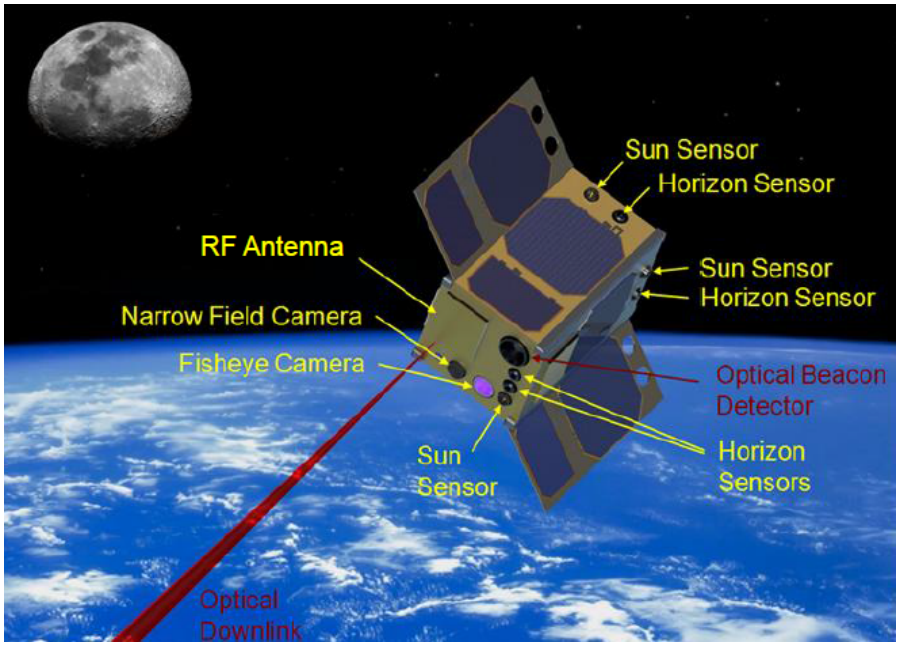


Image credit: JAXA

AeroCube-OCSD

- 1.5U CubeSat (x2)
- 5 Mbps downlink
  - **Body-pointing only**
  - 1065 nm, 1.4 deg. HPBW
  - **14W optical power out**
- Ground station (Mt. Wilson)
  - 30 cm aperture
  - COTS APD detector



- Pointing accuracy from 0.6 deg to 0.1 deg (sensor dependent)
- Project status: Launch in late 2014, early 2015

AeroCube-OCSD vs. Our Project

- AeroCube-OCSD is an **important first step**, however…
  - Single stage control design
    - Body pointing only, lacks steerable optics
  - Difficult to scale to higher data rates due to TX power limits

- Our design philosophy:
  - FSO payload should be self-sufficient, applicable to a multitude of missions
  - Partitioned control scheme makes use of host's ADCS, while providing fine steering mechanism for FSO

Beam width reductions are key to improving FSO systems

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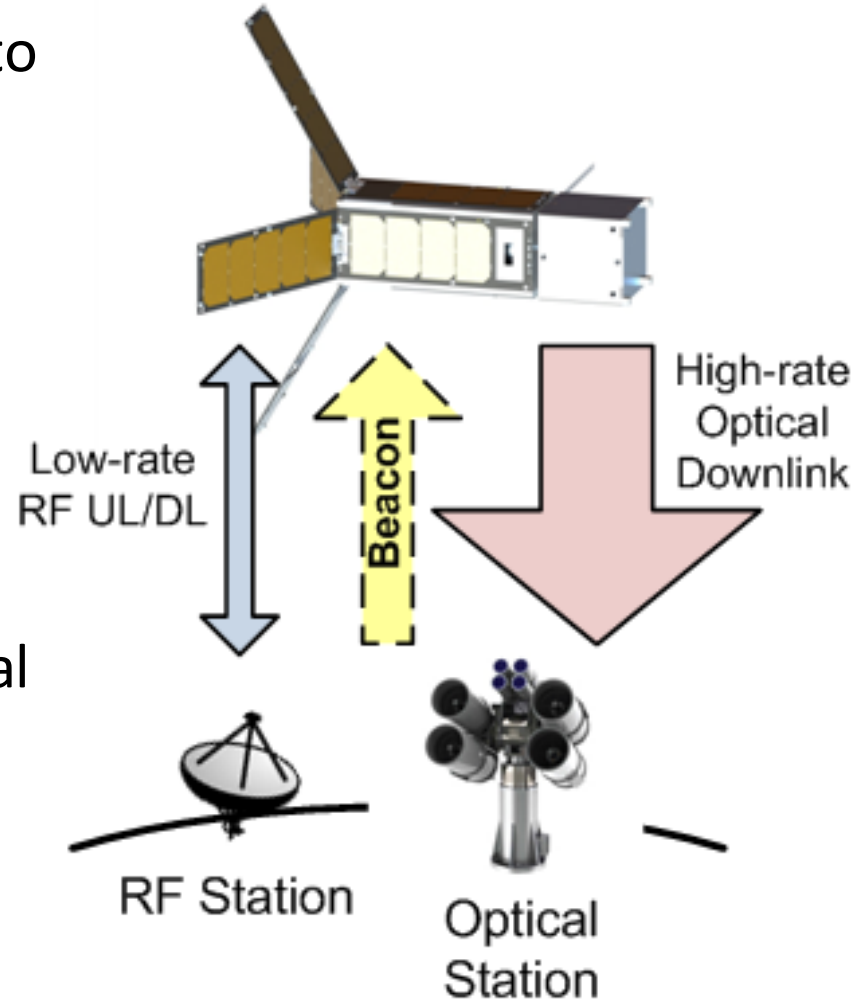
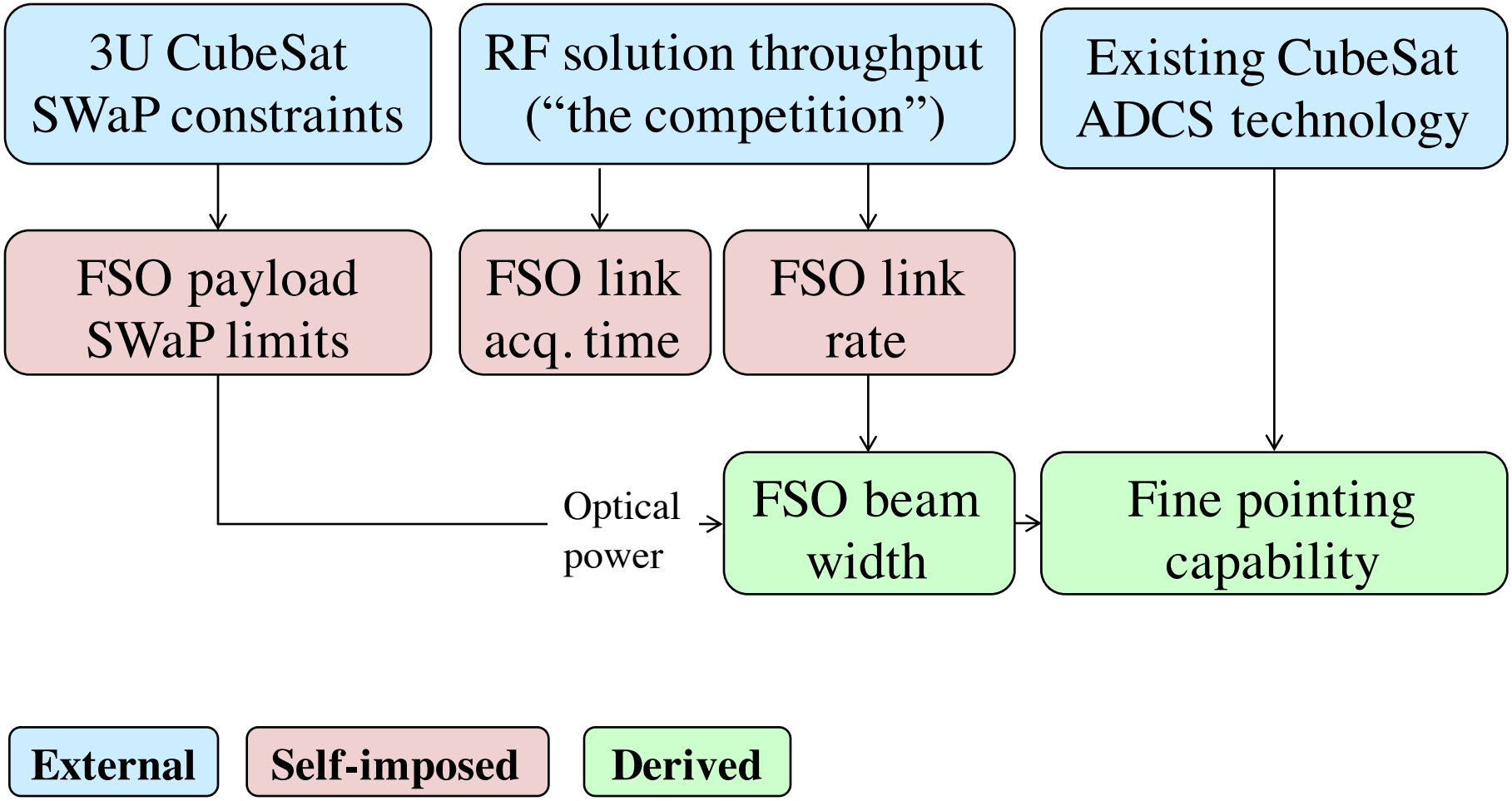
FSO System Configuration

- Most CubeSat developers want to downlink science data
  - Asymmetric link design
- Hybrid RF/ optical system:
  - Low-rate RF link (UL/DL)
  - High-rate optical DL
- Closed-loop tracking using optical beacon signal



Requirements Flow-down



Requirements

- Link Parameters
  - Rate: 10 Mbps
  - Range: 1000 km
- Space Segment
  - Size/mass: 0.5U, 1 kg
  - Power: 10W (TX), 1W (idle)
- Ground Segment
  - Transportable telescope & mount (e.g. 30 cm)
  - COTS detector technology (e.g. APD, PMT)

Example Downlink Radiometry

- Transmitter:
  - 1550 nm at 1 W
- Receiver:
  - Aperture: 30 cm
  - Sensitivity: 1000 photons/bit
- Atmospheric losses: 6 dB

To achieve 10 Mbps, half-power beamwidth needs to be 0.12 deg.

FSO pointing requirement typically needs to be 1/10th beam width.
(0.72 arcmin or 0.21 mrad)

CubeSat ADCS Today

Mission	Organization	Year	Pointing Accuracy
AeroCube 4	The Aerospace Corporation	2012	3.0 deg
Aeneas	USC SERC	2012	2.0 deg
QbX-1/QbX-2	NRL	2010	5.0 deg
CanX-2	University of Toronto SFL	2008	2.0 deg
OCSD	The Aerospace Corporation	~2015	0.1 deg

- Pointing accuracy to 2.0° has been demonstrated
- Sub-degree accuracy missions are under development
- Also need simultaneous high-rate slew (~ 1 deg/sec)
  - Open question: how is accuracy degraded by slew maneuver?

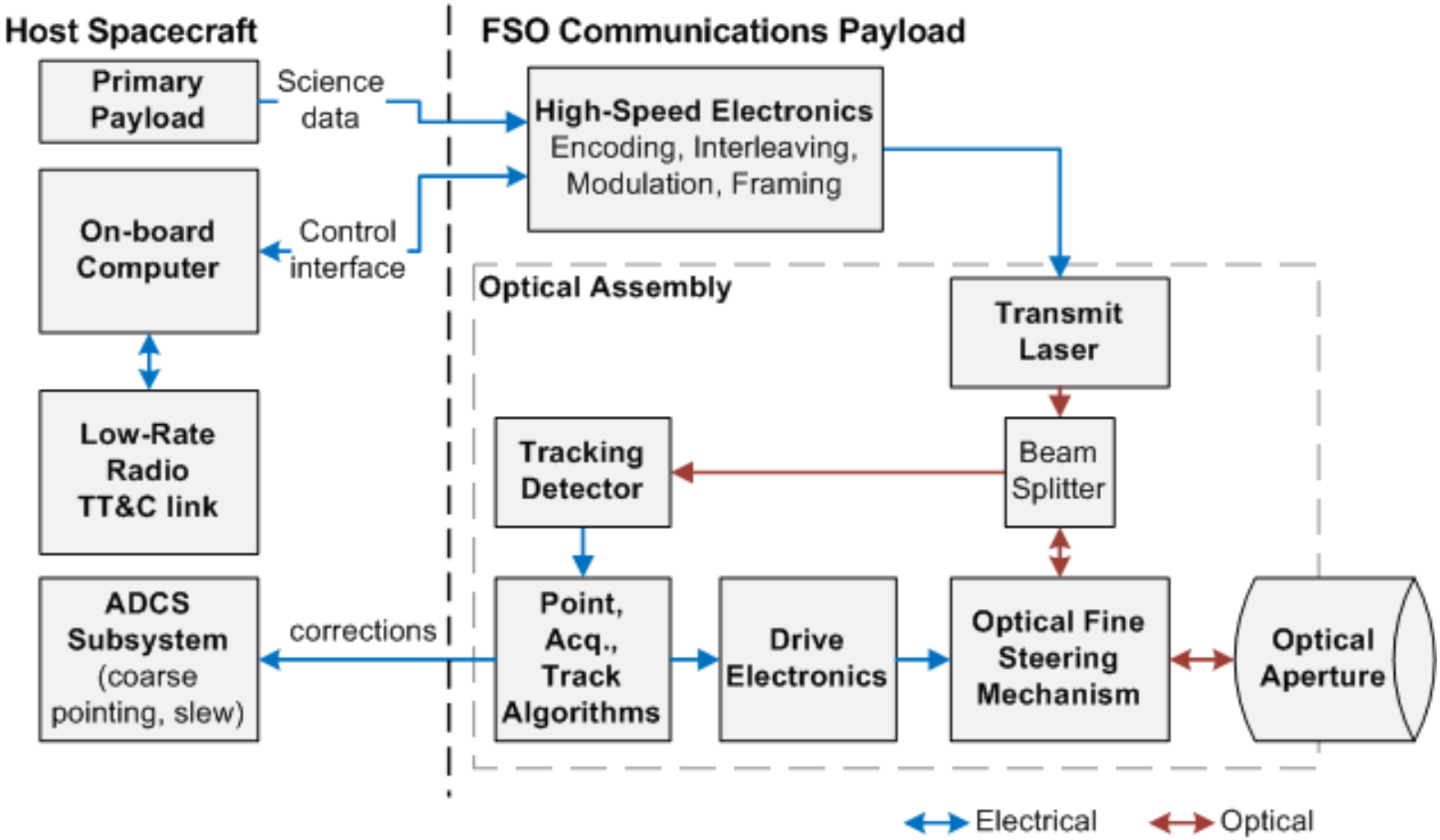
Large gap between current CubeSat ADCS solutions and pointing needs of high-rate low-power FSO comm.

Staged Control Approach

- Range/resolution/bandwidth limitations are inherent to *all* actuators and sensors
- Multi-stage solutions can alleviate these limitations
- Initial assumptions for stage partitioning (TBR):

	Coarse Stage (host CubeSat)	Fine Stage (FSO payload)
Type	Body-pointing/slew	Optical steering
Range	Full sphere	5 degrees
Accuracy/ Resolution	5 degrees (3σ)	0.01 degrees (3σ) (Based on beam width)
Bandwidth	< 1 Hz	> 1 Hz

Space Segment Diagram



Optical Steering Solutions

- PI S-334 Tip/Tilt Mirror
  - Two-axis, 12.5 mm mirror
  - Piezo-electric actuation
  - Steering range: 50 mrad
  - Bandwidth: up to 200 Hz
  - Size: 4 x 2 x 3 cm

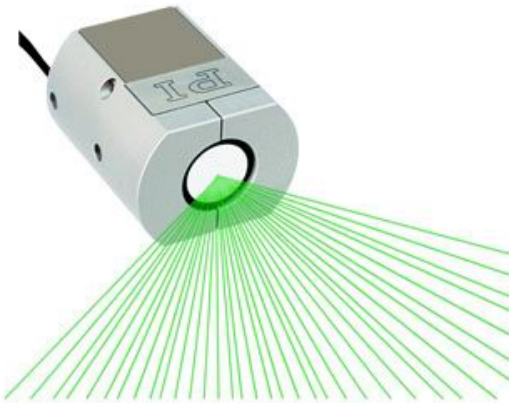


Image: Physik Instrumente L.P.

- Mirrorcle Tech. S1630DB
  - Two-axis, 4.2 mm mirror
  - Electrostatic actuation
  - Steering range: 100 mrad
  - Bandwidth: up to 1 kHz
  - Small chip-scale package

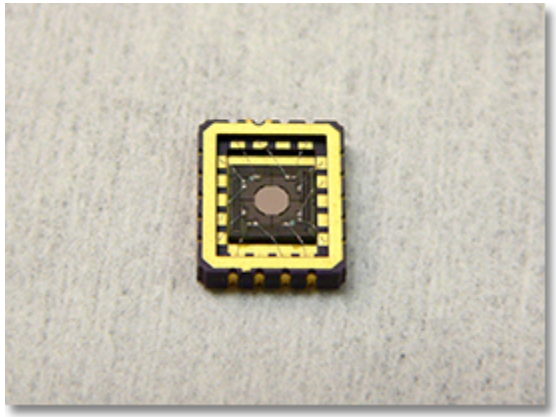
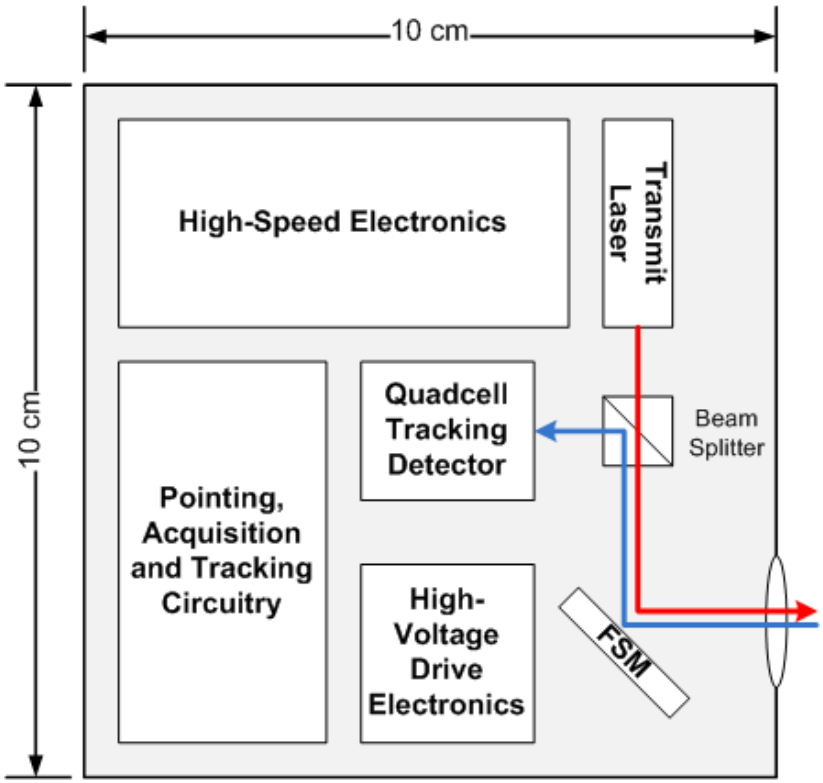


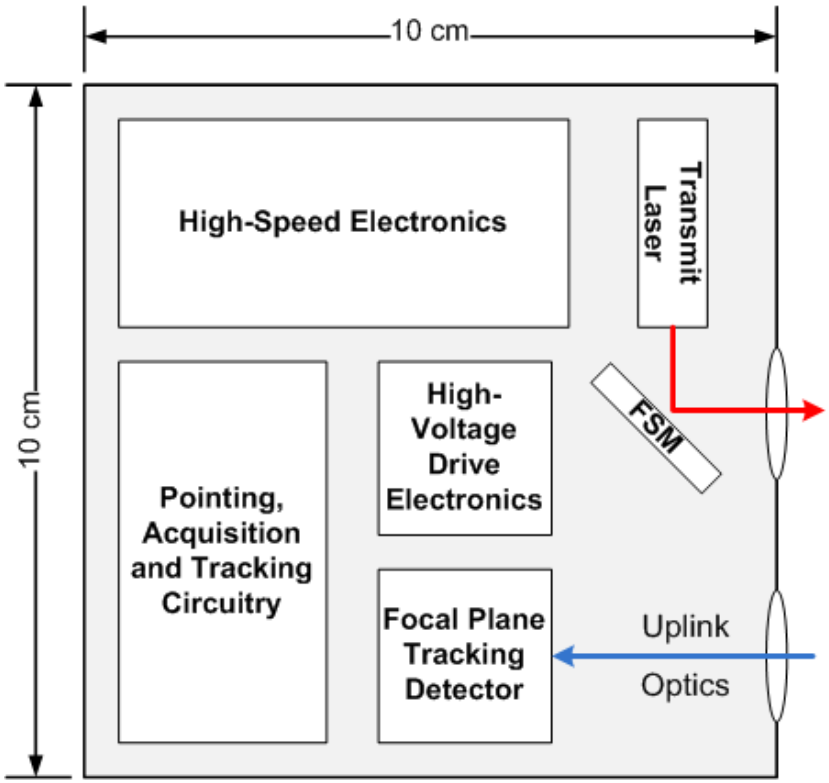
Image: Mirrorcle Tech.

Closed-Loop Tracking Options

- Exploring two acquisition/tracking detector options
  - Quadcell: limited FOV, good sensitivity, complex optics
  - Focal plane: wider FOV, but less sensitive, simpler optics



Config A: quadcell, common path



Config B: focal plane, independent

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PAT Introduction

- PAT: Pointing, acquisition and tracking
  - Start: mission-specific satellite attitude
  - End: fine-pointing alignment of optical terminal with ground station, optical link established

- Acquisition starts at 1000 km range
  - 400 km LEO orbit → approx. 20 degrees above horizon
  - Atmospherics make acquisition difficult at lower angles

- Beam point-ahead issues can be ignored due system beam width and orbital geometry.
  - 400 km LEO → 51 microradian (10 arcsec)

PAT Process Overview

	Ground Terminal	Space Terminal
Point	• Point telescope (open-loop) at predicted satellite position • Enable uplink (UL) beacon	• Host ADCS points to ground terminal; use uplinked TLEs • WFOV beacon detector looks for UL signal • Coarse pointing scan (optional)
Acq.	• Waits for downlink acquisition sequence	• Steer FSM to offset indicated by UL beacon (fine steering) • Transmit downlink acquisition sequence
Track	• Monitor link performance • Refine pointing based on arrival angle of downlink (optional)	• Switch to comm transmission • Coarse pointing errors fed to host ADCS

Beacon Design Drivers

Goal: High probability we hit the satellite with the beacon

- Sources of uncertainty
  - Satellite position knowledge: 2 mrad
  - Ground telescope pointing: 200 urad
- Ground segment implications
  - Beacon divergence must be larger than uncertainties
  - Eye safety limitations
- Space segment implications
  - Tracking detector field of regard must be larger than spacecraft coarse pointing uncertainty
  - Detector resolution must be better than desired fine pointing performance

Future Work

- Control system analysis
  - End-to-end system model: performance during slew
  - Stochastic analysis: actuator saturation, stage handoff time
- Component selection & qualification
  - Optical transmitter / amplifier
  - Fast-steering mirror, driver integration
  - High-speed electronics: driven by FEC/interleaving needs
- Beacon design: spatial diversity needs
- End-to-end bench demonstration
  - Flight-like optical components, eval. board electronics
  - Disturbances simulated with mechanical “shaker” table

Closing

- First attempts at CubeSat FSO comm motivated by:
  - Demand to downlink payload data
  - Advances in CubeSat ADCS
- Our work will address future implementation gaps:
  - Optical steering mechanism and staged control
  - High-speed electronics
- Acknowledgements
  - JPL Strategic University Research Partnership (H. Hemmati, W. Farr)
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