Two-Stage Control for CubeSat Optical Communications

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CalPoly CubeSat Developers Workshop
April 24, 2014

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

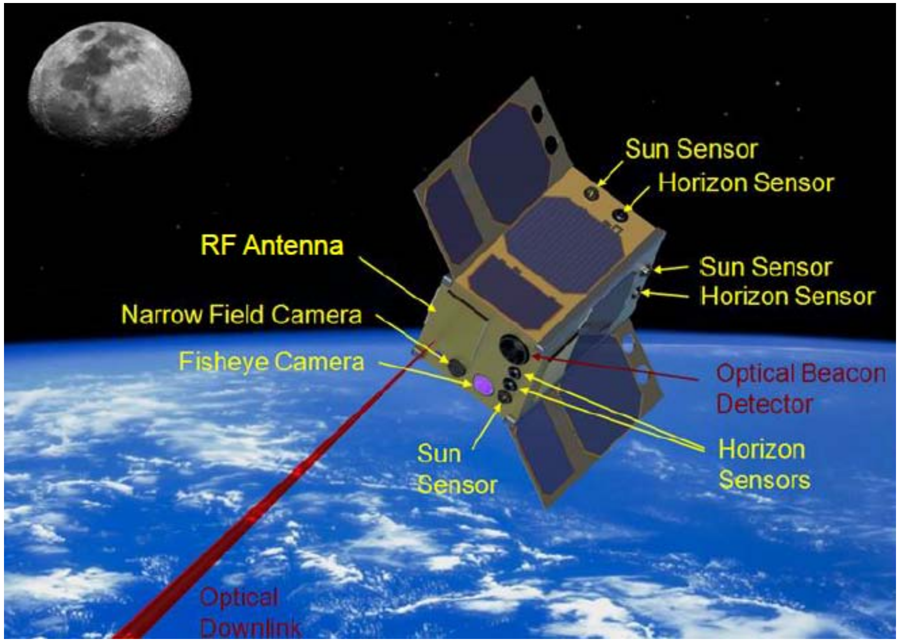
- **LUCE:** Laser-Utilizing Communications Experiment on OICETS spacecraft
- Successful LEO-to-ground FSO demo (2005-2009)
- Bidirectional
  - Closed-loop tracking w/beacon
- Multi-stage control
  - Range/resolution limits from actuators
  - Coarse: 0.1 deg @ 10 Hz (gimbal)
  - Fine: 1 urad @ 200 Hz (piezo FSM)

26cm aperture

Image credit: JAXA

AeroCube-OCSD

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



- Pointing accuracy from 0.6 deg and 0.1 deg (mode 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, no 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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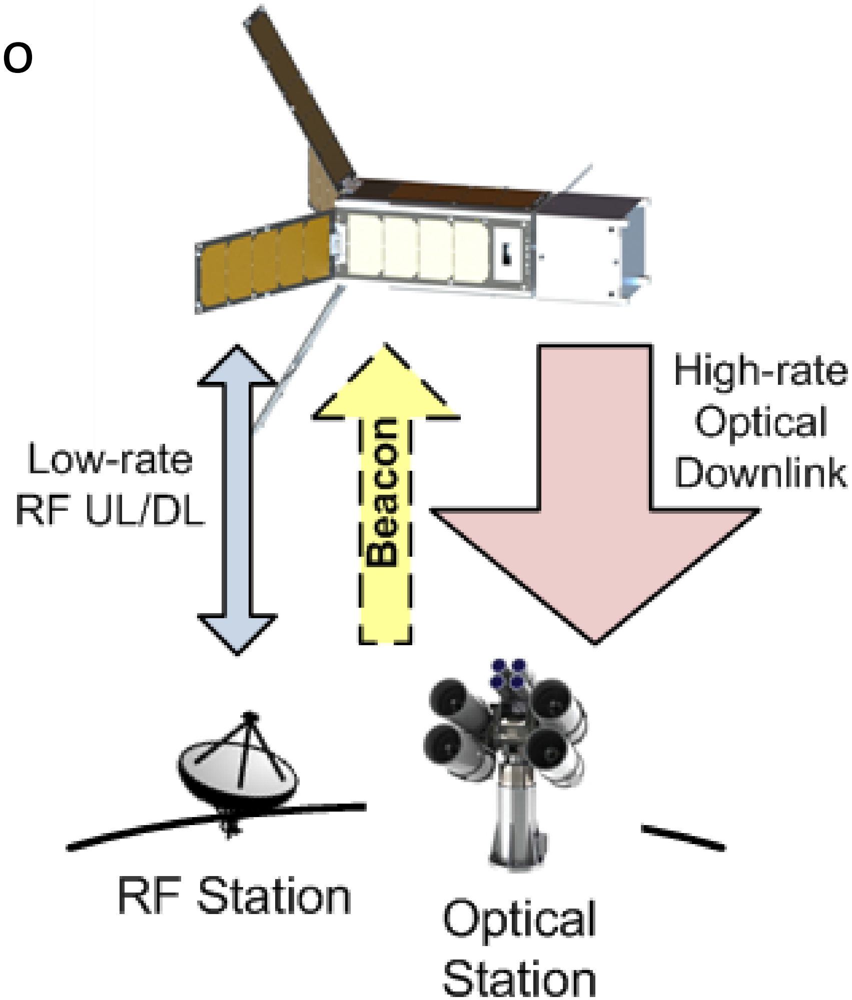
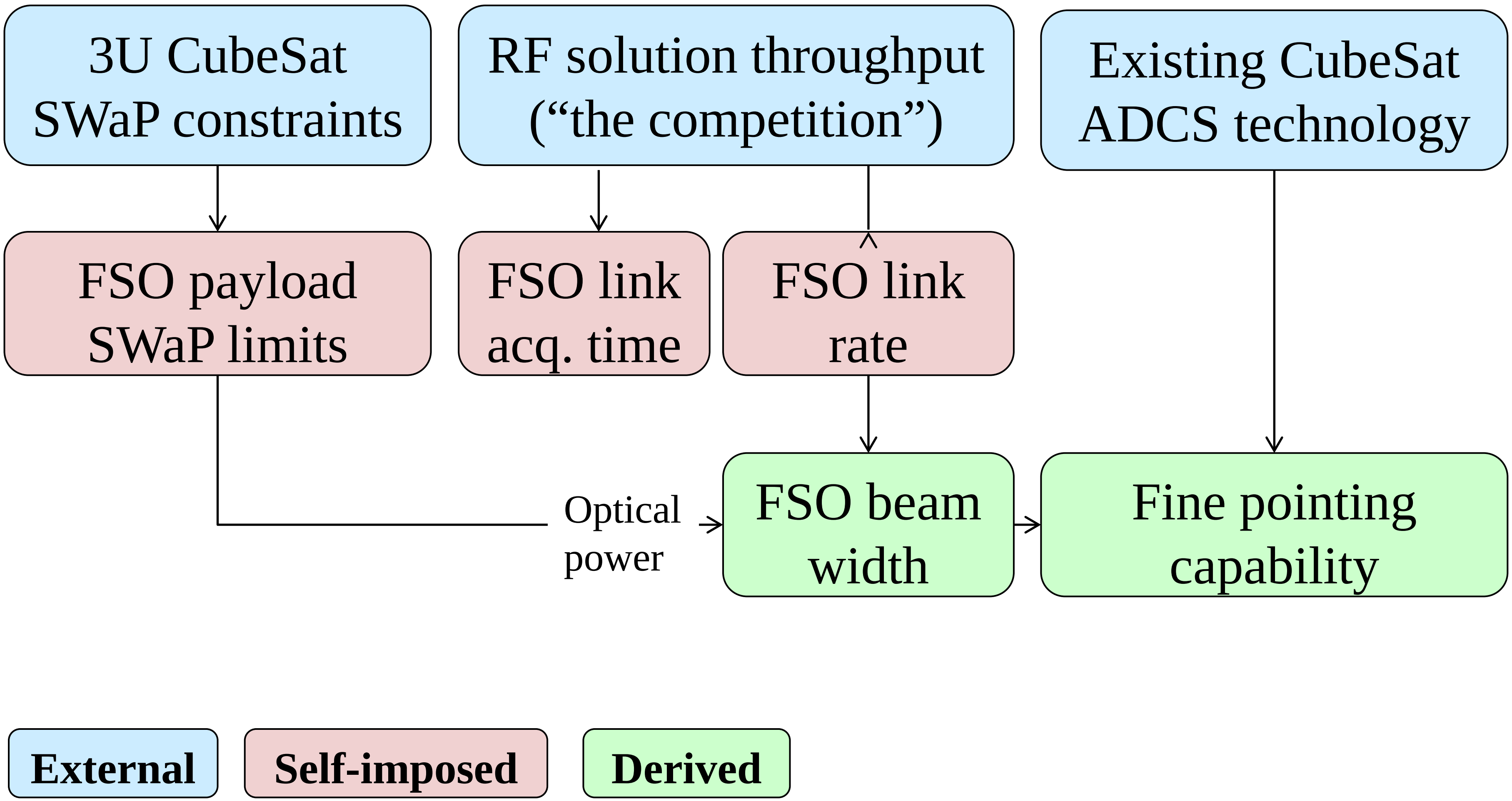
FSO System Configuration

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



Requirements Flow-down



FSO System Requirements

- Link Parameters
  - Rate: 10 Mbps
  - Range: 1000 km
    - 400 km LEO orbit
- 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 (optical)
- 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 capability 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
AeroCube OCSD	The Aerospace Corporation	~2015	0.1 deg

- Pointing accuracy to 2.0° RMS 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?

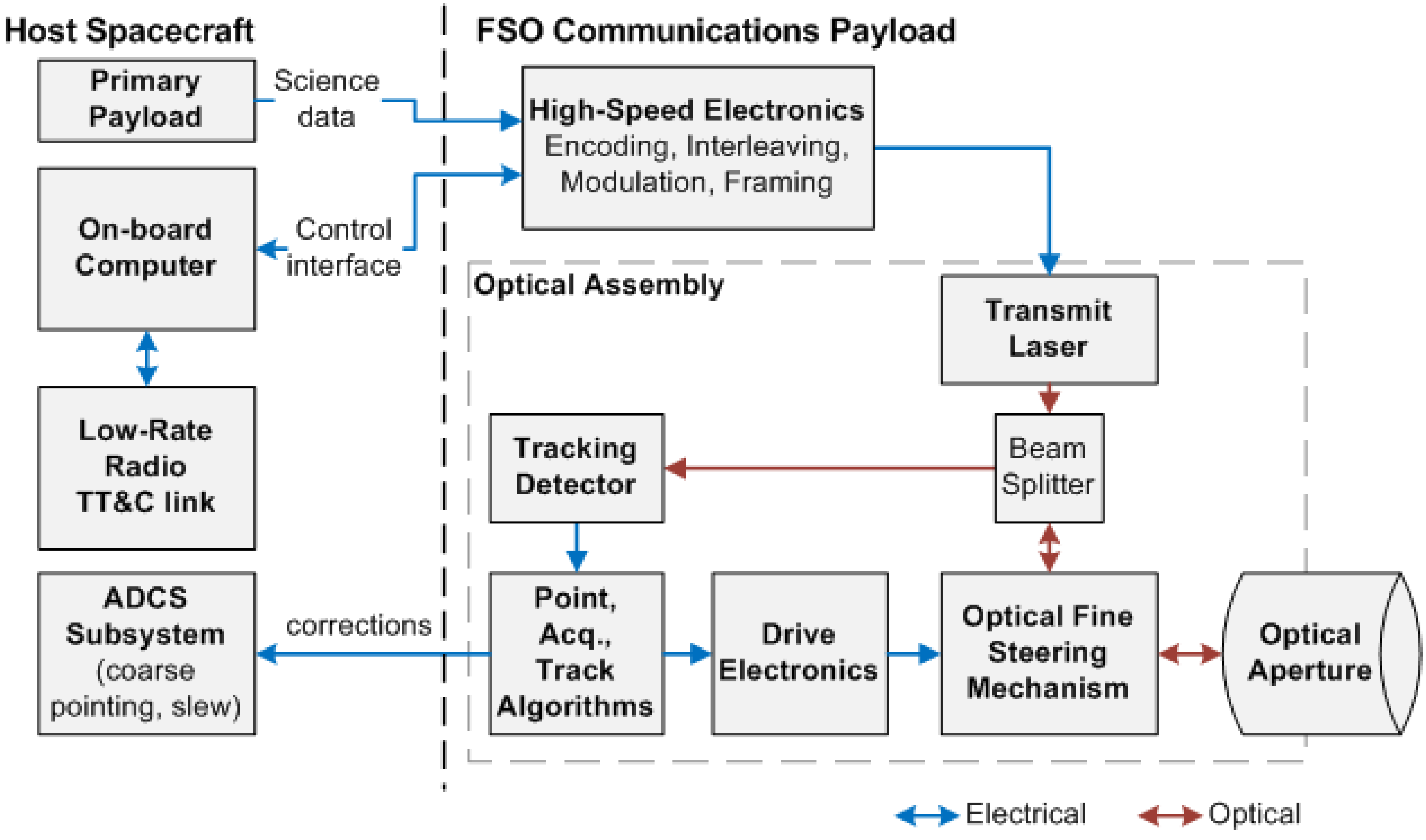
Large gap between current CubeSat ADCS solutions and pointing needs of high-rate low-power FSO comm.

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	2 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
- Mirrorcle Tech. S1630DB
  - Two-axis, 4.2 mm mirror
  - Electrostatic actuation
  - Steering range: 100 mrad
  - Bandwidth: up to 1 kHz
  - Small chip-scale package

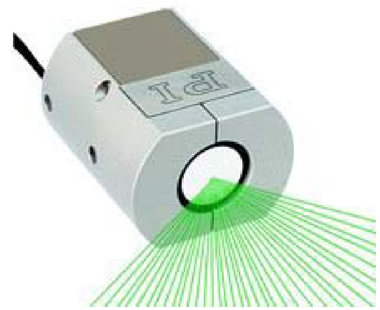


Image: Physik Instrumente

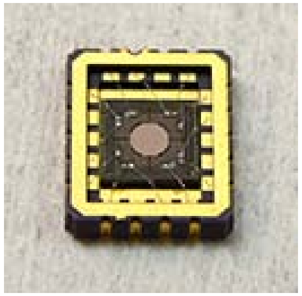
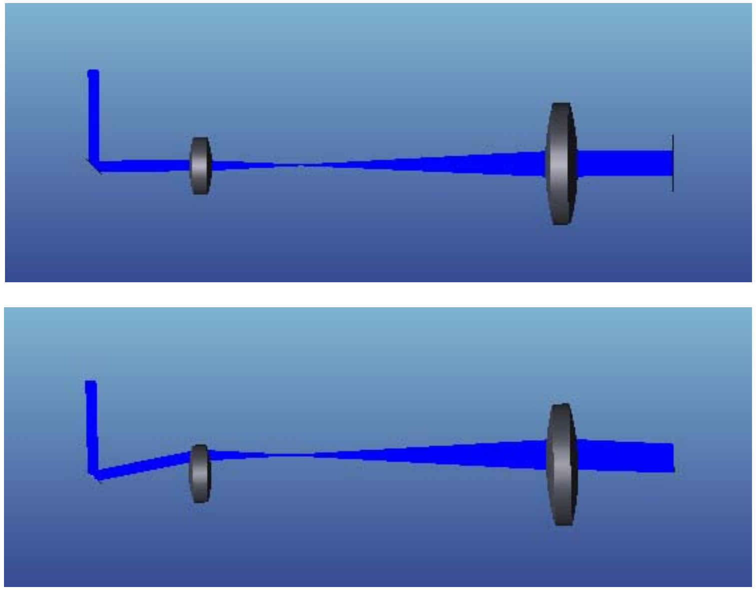


Image: Mirrorcle Tech.



Tam Nguyen, MIT AeroAstro

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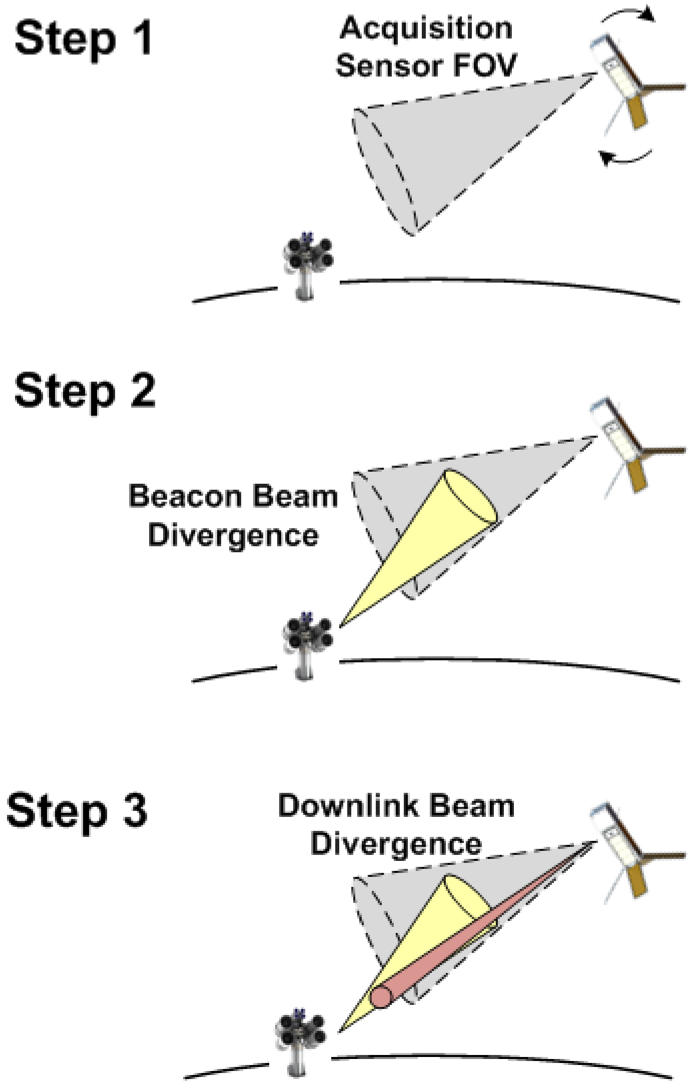
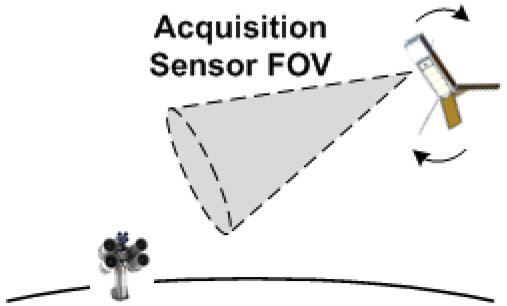
PAT Overview

- Acquisition range: 1000 km
  - 400 km LEO orbit → approx. 20 degrees above horizon
- Point-ahead ignored due to beamwidth and orbit geometry
  - 10 arcsec (51 urad)
- PAT Procedure
  1. Coarse point based on TLEs
  2. Search for beacon
  3. Steer downlink to beacon boresight offset

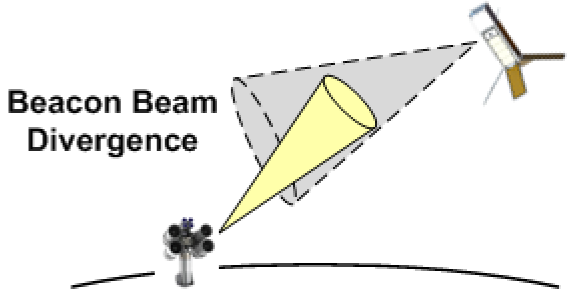


PAT Design Drivers

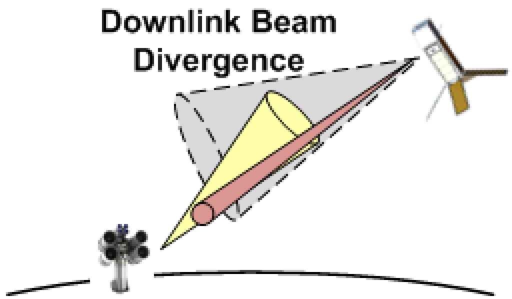
- Acquisition Sensor FOV: 5x5 deg
  - **Coarse ADCS accuracy (2 deg)**
    - Attitude knowledge
    - Position knowledge
  - Background noise (filtered)



- Beacon Beam Divergence: 2 mrad
  - **Satellite pos. knowledge (1 mrad)**
  - Telescope mount (0.3 mrad)
  - Eye safety (TBD)



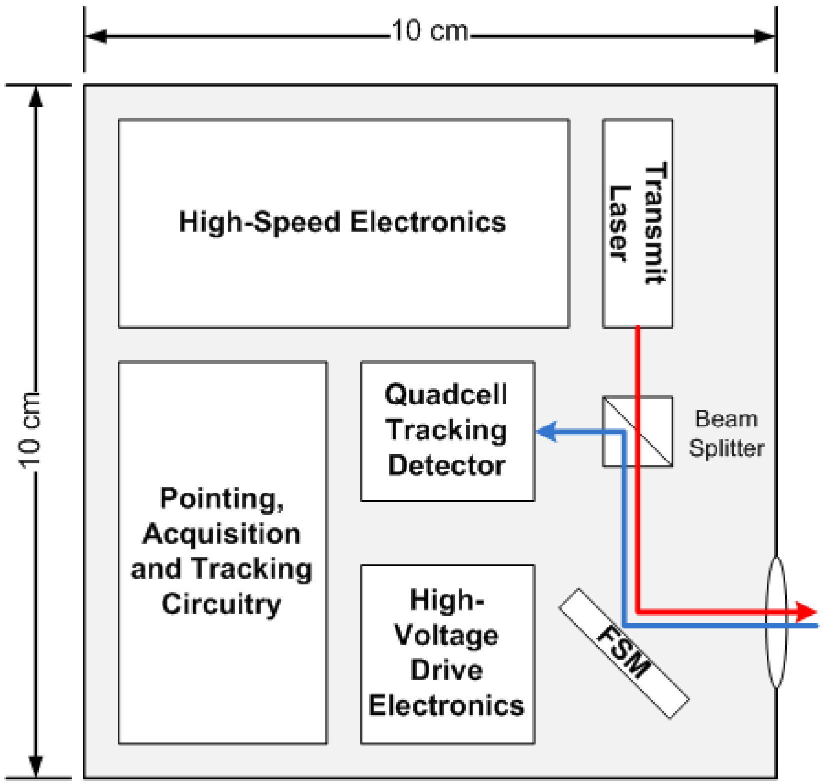
- Downlink Beam Divergence: 0.12 deg
  - **Fine pointing stage accuracy**



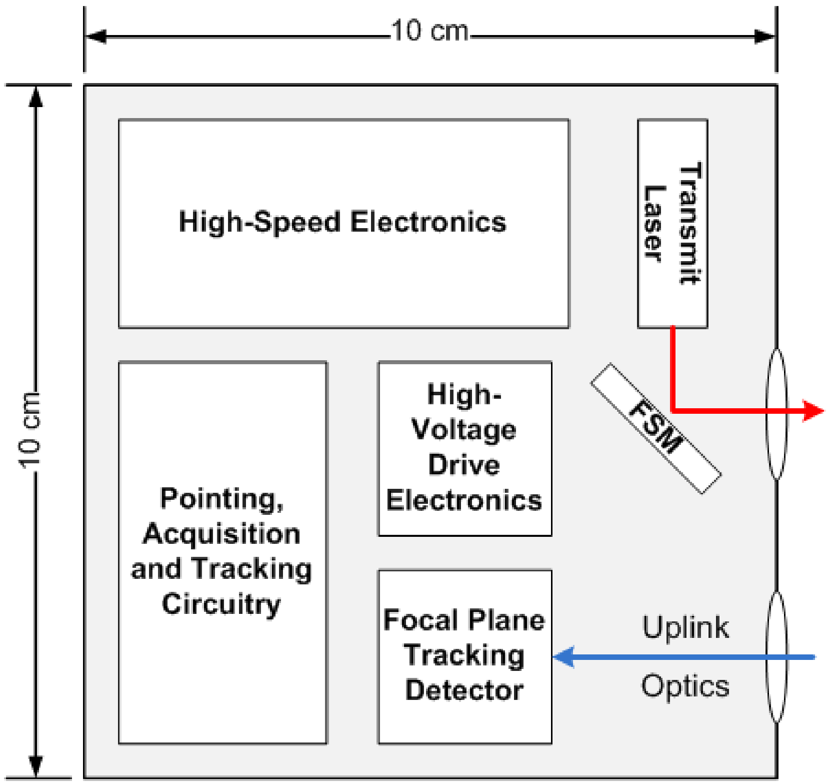
Dominant design drivers bolded

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

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 → wavelength selections!
  - Fast-steering mirror, driver integration
  - High-speed electronics: driven by FEC/interleaving needs
- End-to-end bench demonstration
  - Flight-like optical components, eval. board electronics
  - Disturbances simulated with mechanical "shaker" table

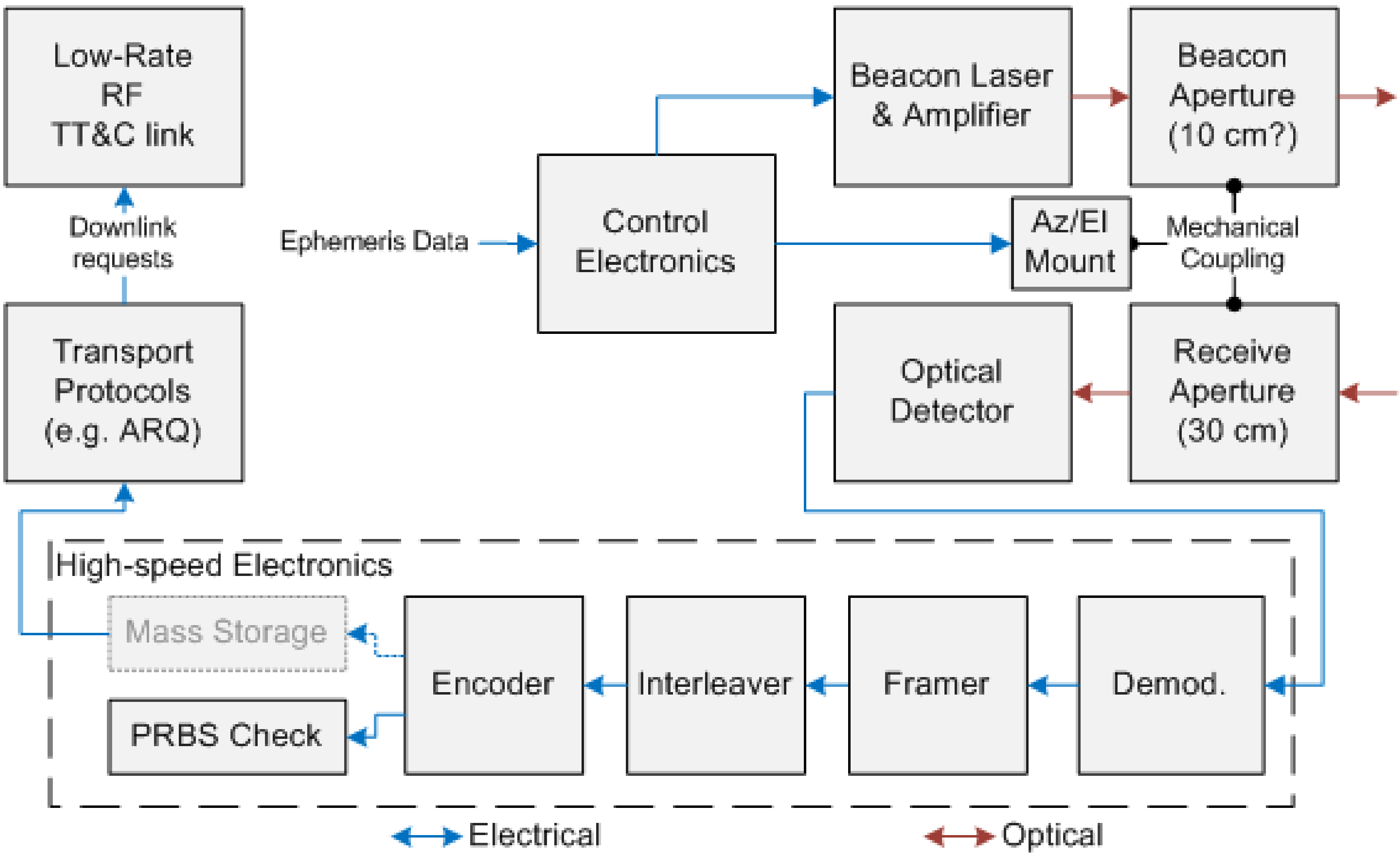
Closing

- 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)
  – NASA NSTRF Program (A. Swank)
  – Thesis Committee (D. Caplan, J. Twichell at MIT/LL)

Backup Slides

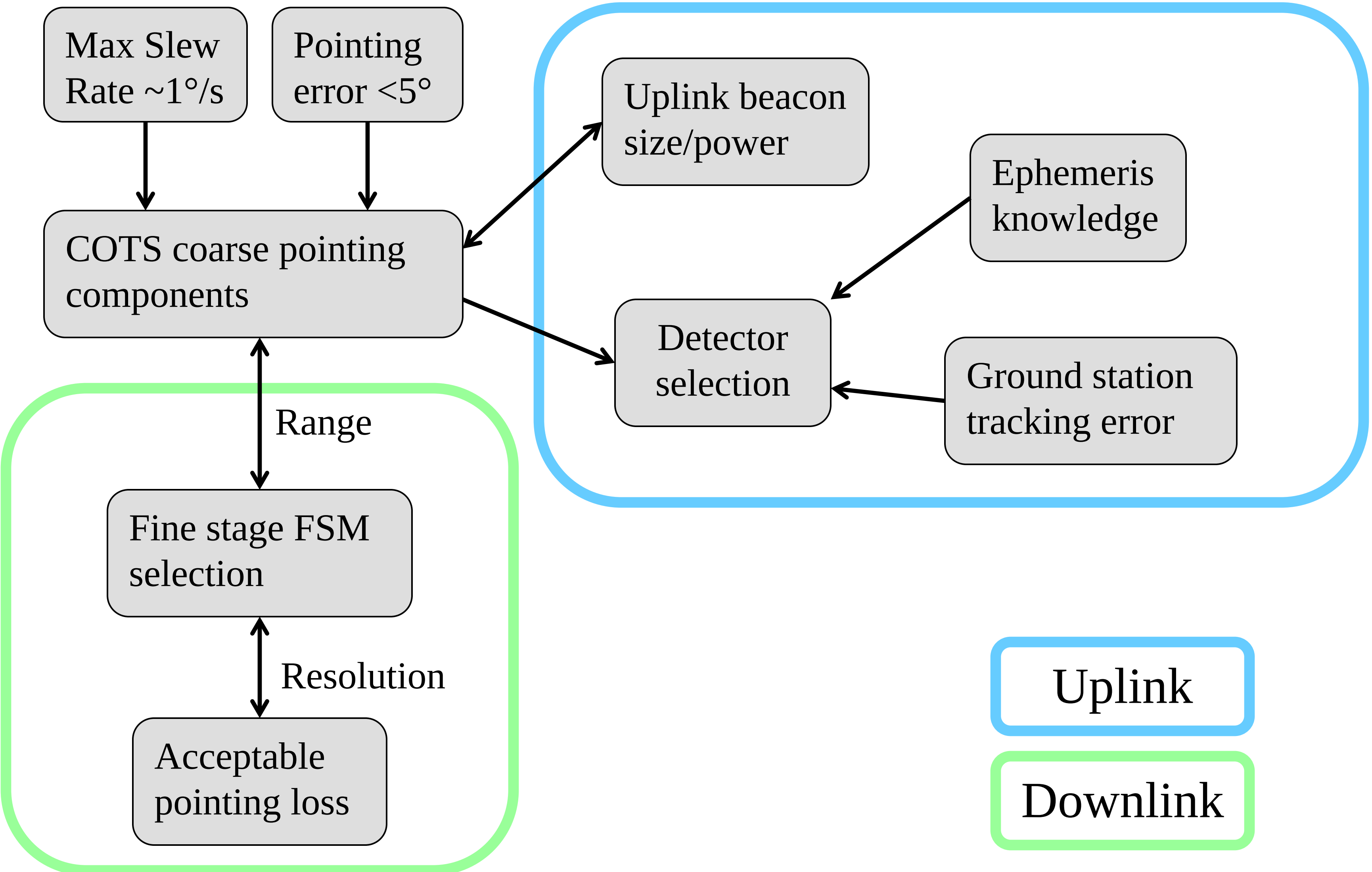
Ground Segment



Radiometric Link Budget (DL)

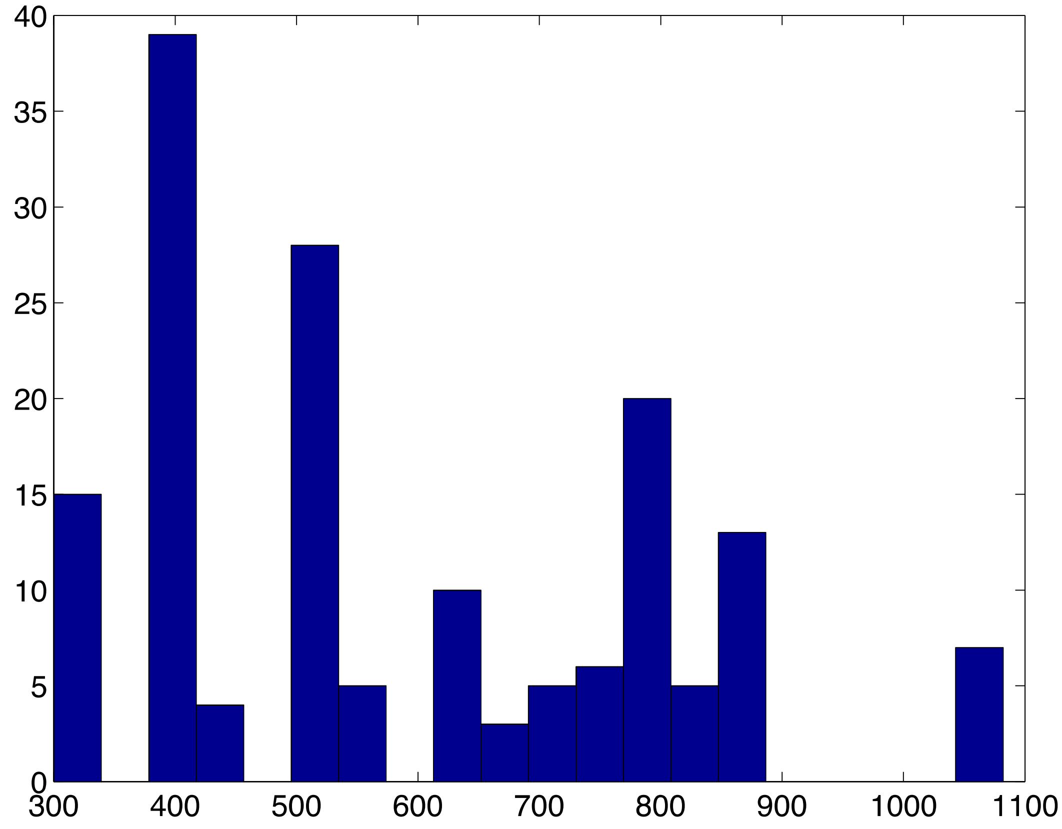
	Symbol	Value	Units	Notes
Transmitter Parameters				
Laser optical output power	PLD,elec	1	W	
Laser wavelength	λpeak	1550	nm	Peak wavelength
Modulation duty cycle		0.5		Simple RZ for now
Laser avg. optical power (dBW)	PLD,opt,avg,dB	-3.0	dBW	
Half-power beam width	θ1/2	0.120	degrees	Full cone angle where power is half of peak intensity
Transmit antenna gain (dB)	Gt,dB	65.60	dBi	Based on divergence above
Channel Parameters				
Path length	d	1000	km	LEO at 400km can be tracked down to 20 degrees above horizon
Path loss (dB)	Lpath,dB	-258.2	dB	Standard free-space path loss equation
Atmpheric loss placeholder	Latm,dB	-6.00	dB	Placeholder value for absorbtion, scattering, turbulence
Receiver Parameters				
Aperture diameter		30	cm	
Receive antenna gain (dB)	Gr,dB	115.7	dB	Diffraction limited gain
Power at detector (dB)	Prec,dB	-85.9	dBW	
Power at detector	Prec	1.28E-09	W or J/s	
Photons per second		1.00E+10	photons/sec	
Required photons/bit		1000	photons/bit	An “easy” to achieve receiver sensitivity
Predicted data rate		**10000102**	**bits/sec**	

ADCS Requirements Flow-down



Uplink PAT Requirements

- Nominal CubeSat orbits were determined by surveying previous missions
- A reference orbit of 400km is assumed for this application
  - Required max slew rate: 1.1deg/s



Eye Safety Regulations

- ANSI Z136.6, “Safe Use of Lasers Outdoors”
  - Commericial/proprietary
  - Basis for NASA and FAA policies
- NASA Use Policy for Outdoor Lasers
- FAA Regulation: Order JO 7400.2

State of CubeSat Communications

- Majority of CubeSats to be launched in 2013/2014 use low-rate UHF links. [1]
  - Amateur bands: 1200 bps
  - ISM bands: < 115 kbps
- High-rate RF options:
  - COTS products available for UHF and S-band
  - Very large ground aperture is typically required
  - Regulatory impediments

MicroMAS Comm. Configuration

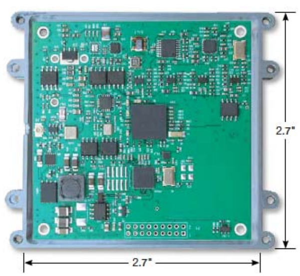
Space Segment:

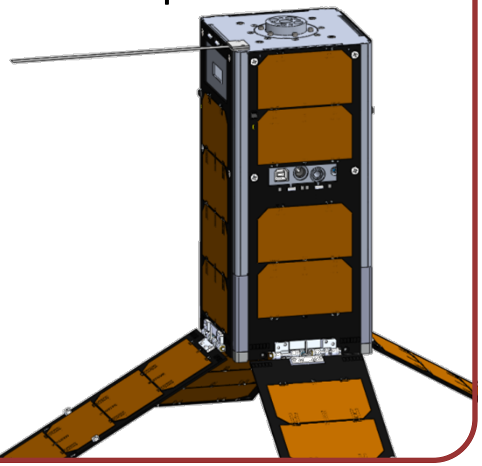
- UHF Monopole antenna
- Size/Mass: 176 g, 9 x 9 x 2.4 cm
- Power: 10 W (TX), 0.3 W (RX)

Ground Segment: 18 m dish @ Wallops

Data rate: 3 Mbps (un-coded)

- 2.3 Gbit/day → 26.6 kbps continuous





[1] Klofas, Brian. “Upcoming CubeSat Launches: The Flood Has Arrived.” AMSAT-NA Symposium, 1 Nov 2013.

FSO System Requirements

Optical Link Parameters		Notes
Optical link rate	10 Mbps (goal) 50 Mbps (stretch)	Uncoded channel rate
Bit error rate	1×10^{-6} BER	Without coding
Operational range	$\leq$ 1000 km	Appropriate for most LEO missions
Optical Space Segment Parameters		
Size	0.5 U	5 cm × 10 cm × 10 cm
Mass	2 kg	
Power	10 W (TX) 1 W (idle)	Includes FSO payload, excludes host ADCS
PAT scheme	closed-loop	Using uplink beacon
Coarse pointing	satellite body-pointing	Provided by host ADCS
	goal: 2.0° (TBR)	3σ, absolute
	stretch: 0.5° (TBR)	3σ, absolute
Coarse slew rate	3.0 deg/s (TBR)	Provided by host ADCS
Fine point/track	single two-axis MEMS	Shared by TX and RX optical paths
Fine point range	±5.0° (TBR)	Greater than coarse pointing accuracy
Fine point resolution	TBD	Beam width dependent
Ground Segment Parameters		
Receive aperture	$\leq$ 30 cm	COTS telescope
Mass	50 kg	For portability
PAT scheme	open-loop	Based on TLE/ephemeris
Detector	APD, PMT, etc.	Commodity/COTS unit is desirable
Uplink beacon	TBD eye-safe laser	Req. for closed-loop tracking