Design of a Free–Space Optical Communication Module for Small Satellites

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Outline

- Problem Statement
- Related work: AeroCube-OCSD
- System architecture
  - Design parameters & physical layout
  - Optical transmitter
  - Beacon-assisted pointing, acquisition & tracking
- Current Focus & Expected Results

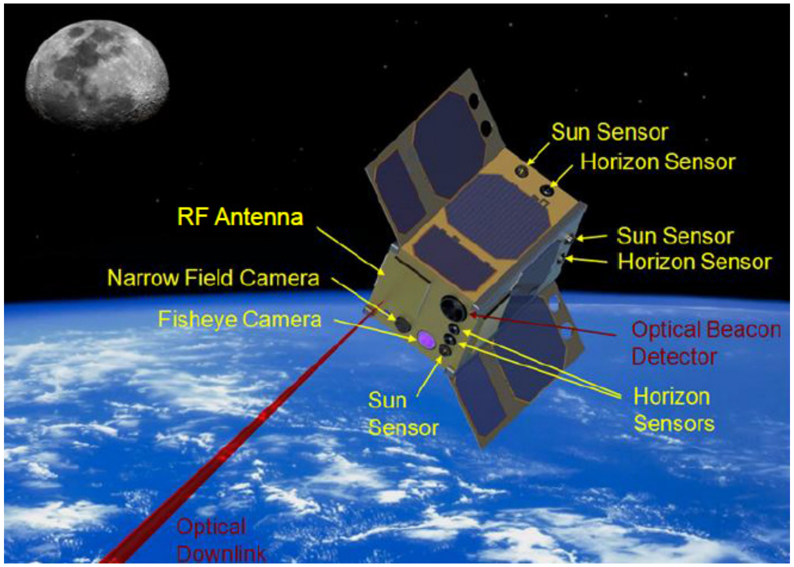
Problem Statement

- CubeSats are performing great science but the downlink bottleneck is common problem amongst operators
  - RF solutions limited by antenna gain
  - Difficult / risky regulatory process
- Optical transmitters offer narrow beamwidths & higher gain
  - Price: pointing becomes more difficult
- Recent advances in CubeSat ADCS → key enabler for lasercom
  - Reaction wheels, horizon sensors, star trackers

Our work addresses "implementation gaps" that hinder scalability of CubeSat-scale lasercom systems:
1) staged pointing control, 2) compact high-rate transmitter

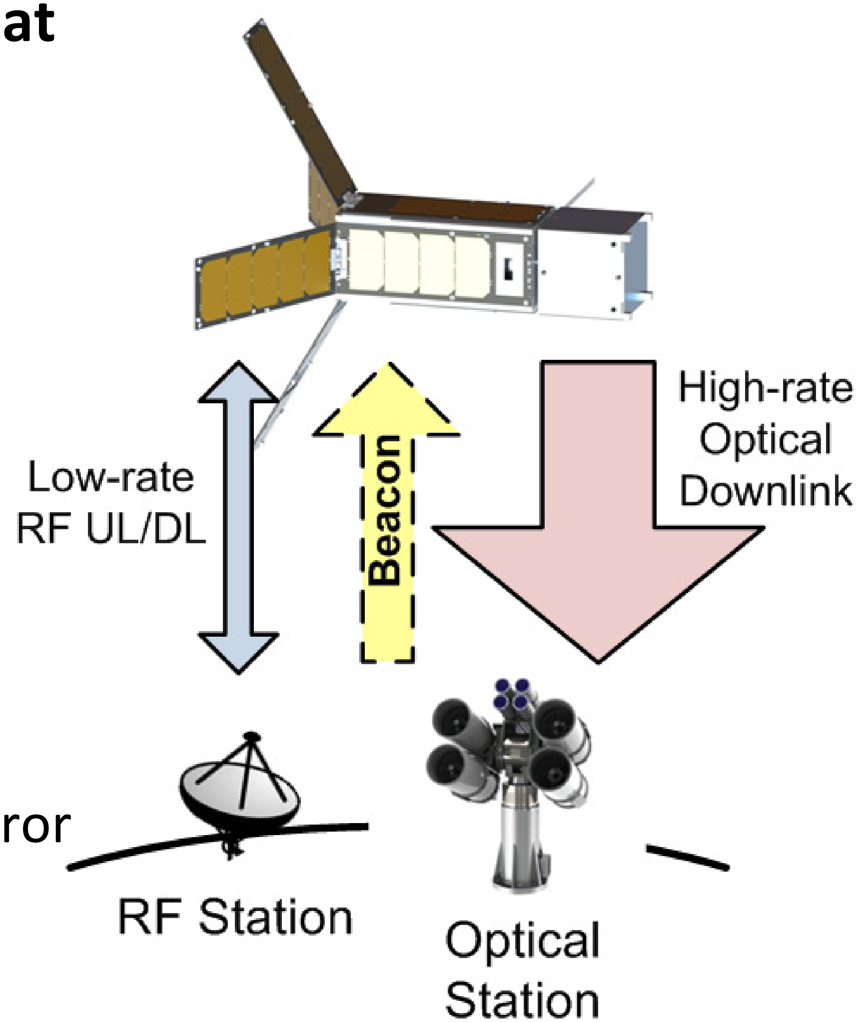
Aerospace AeroCube-OCSD

- Pair of 1.5U CubeSats
- **5 Mbps downlink**
  - Stretch goal: 50 Mbps
  - **Body-pointing only**
  - 1065 nm, 0.35° FWHM
  - **10 W average optical power**
    - Fiber amp (YDFA)
    - Custom power solution
  - GPS for precision orbit determination
- Ground station (Mt. Wilson)
  - 30 cm aperture
  - COTS APD detector operating
- Pointing accuracy from 0.7° and 0.1° (mode dependent)
- **Project status: Launch in Summer 2015**



Our System Architecture

- **Design targets "typical" 3U CubeSat**
  - SWaP, ADCS, nominal orbits
- **Most need high-rate downlink**
  - Asymmetric link design
  - Low-rate RF link (UL/DL)
  - Optical beacon for acquisition and tracking
- **Two-stage pointing system**
  - Coarse: host ADCS
  - Fine: integrated fast-steering mirror
- **Daytime or nighttime operation**

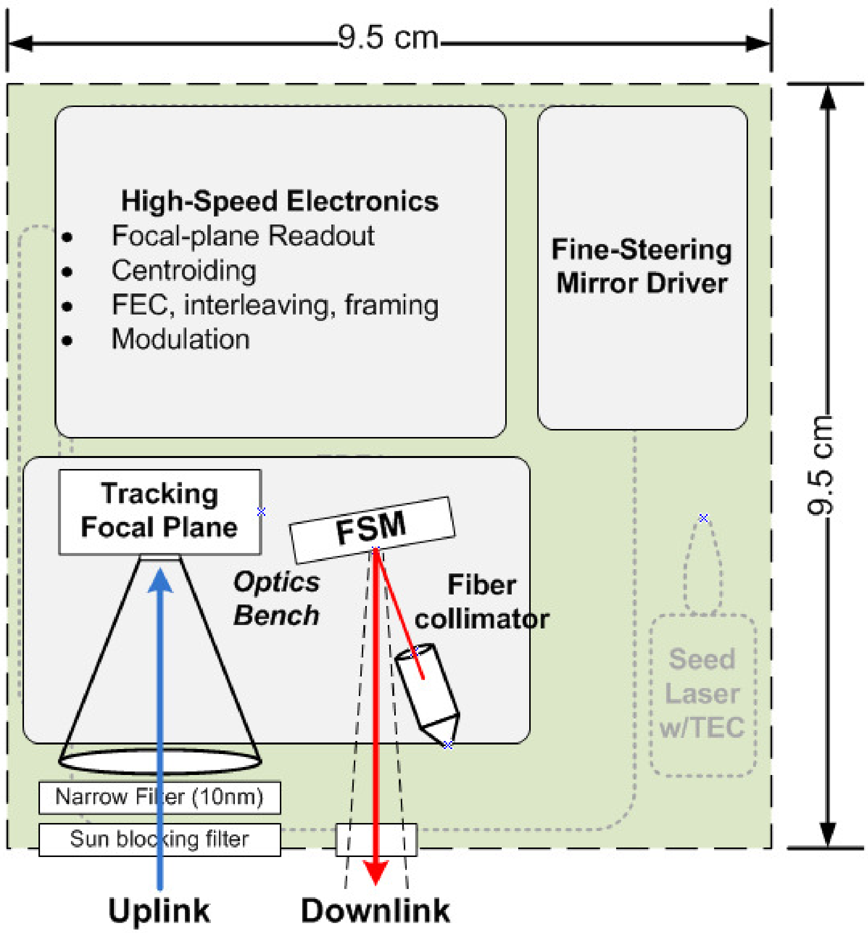


Top-Level Design Parameters

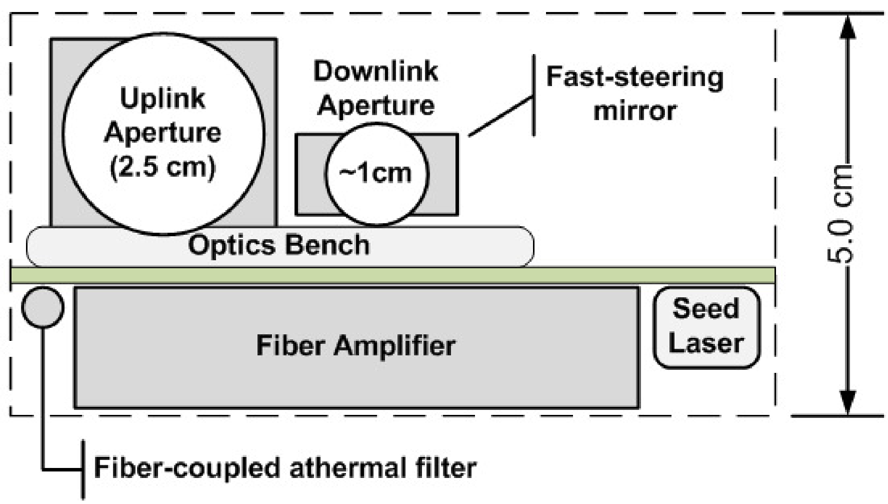
Link Parameters		
Link rate	**10 Mbps (goal), 50 Mbps (stretch)**	Uncoded channel rate
Bit error rate	10^-4, assumes code will be used	Conservative baseline for FEC
Range	1000 km	~20 deg elev @ 400 km LEO
Space Segment Parameters		
Size, Weight	**10 x 10 x 5 cm, 600 g**	"0.5 U" CubeSat mid-stack payload
Power	**10 W (transmit), 1 W (idle)**	Excludes host ADCS
Coarse Pointing	+/-5° (3-sigma), 1°/sec slew	Host CubeSat ADCS
Fine Pointing	+/-0.006° (3-sigma)	Lasercom payload fast-steering mirror
Downlink Beam	1550 nm, **0.12° FWHM**	Radiometric constraint for 10 Mbps
Beacon Receiver	Uncooled Si focal-plane array	850 nm (TBR)
Ground Segment Parameters		
Apertures	**RX: 30 cm**, beacon: TBD	Mount capable of tracking LEO object
Acq. Detector	InGaAs Camera	Informs tip/tilt FSM
Comm. Detector	COTS APD/TIA Module	Cooled module
Pointing	Coarse: TLE, Fine: tip/tilt FSM	Detector size demands fine stage

Physical Layout

Top View



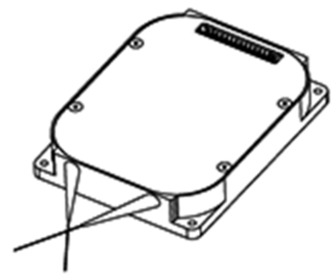
Side View

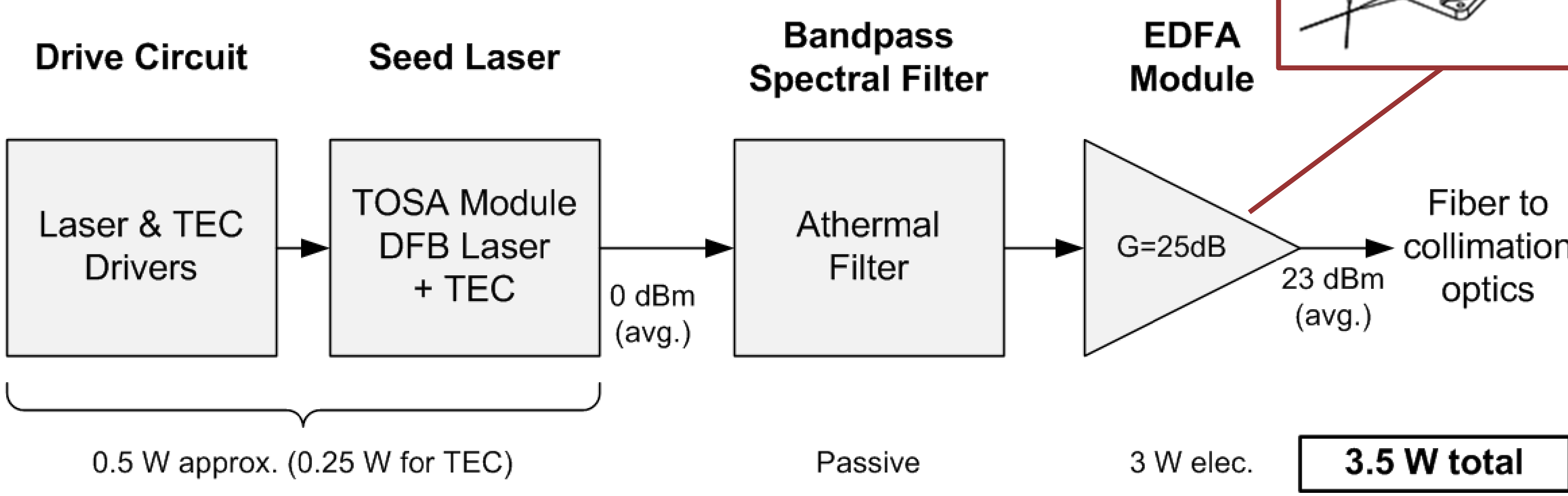


Optical Transmitter Design

- Master-Oscillator Power Amplifier (MOPA) architecture
  - COTS Erbium-doped **fiber amplifier** (EDFA), space heritage
  - High modulation bandwidths (GHz), **high peak-to-average power**
  - Expected output: 200 mW (average) at 1550 nm
- Design challenges:
  - Thermal stabilization of seed laser
  - Extinction ratio (27 dB needed for PPM-16)

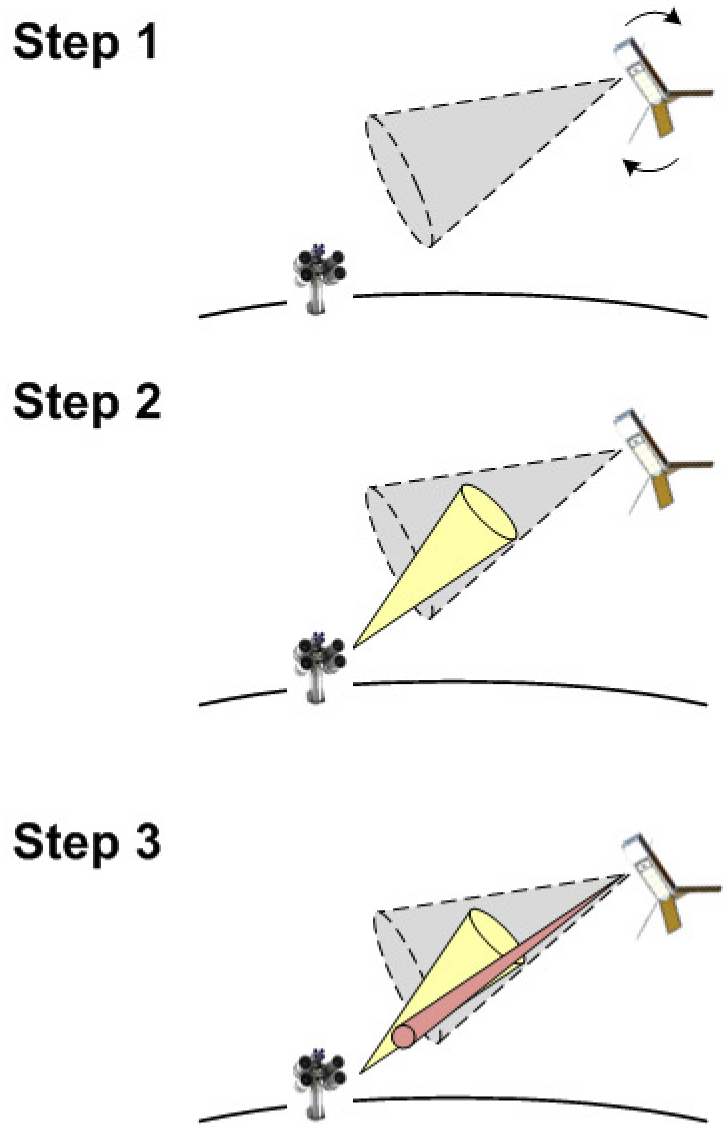
½ MSA EDFA
9 x 7 x 1.5 cm





Pointing, Acquisition & Tracking

- Satellite autonomously slews from mission-defined attitude
- Acquisition sensor stares for beacon signal
  - Centroid algorithm estimates boresight offset
  - ADCS closes loop using beacon offset
- Integrated fine-steering mechanism rejects residual error
  - Fast mirror steers downlink

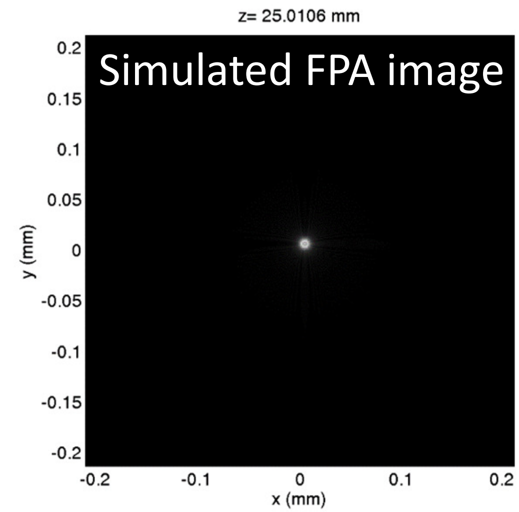


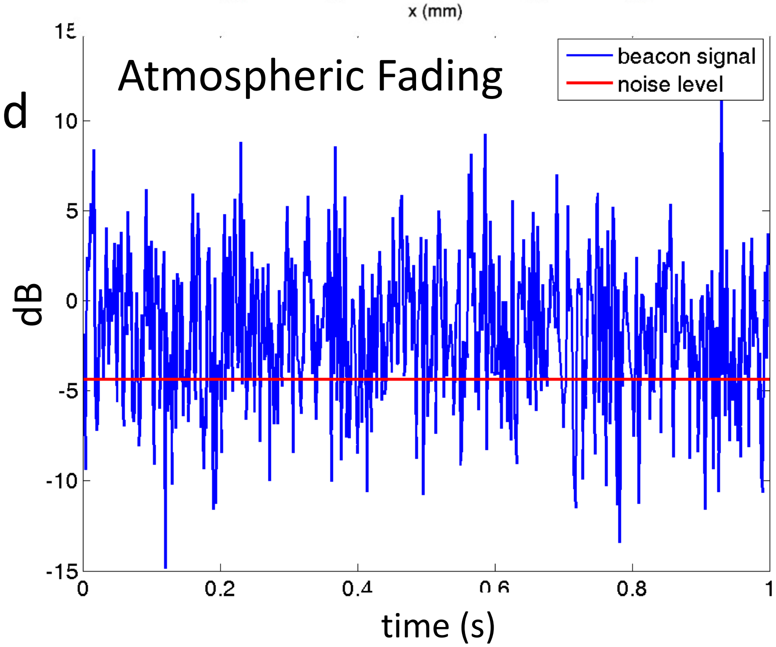
Beacon & Detector Design

- Uplink beacon at near-infrared (**850 nm**)
  - TLE & orbit propagation sufficient for orbit determination
  - High-resolution focal plane arrays

- Detector provides largest FOV possible while maintain necessary resolution & SNR
  - 10° full-angle FOV
  - 5 Mpixel resolution → actuation-limited

- Ongoing analysis/design activities:
  - Atmospheric fading (multi beam?)
  - Detector noise modeling
  - Focal plane readout performance





Staged Control Approach

- Coarse stage patterned after **typical COTS ADCS solutions**
- Staged control alleviates range, resolution and bandwidth limitations inherent to all sensors and actuators
- Staged control **essential for scaling** to higher data rates

	Coarse Stage (host CubeSat)	**Fine Stage (lasercom payload)**
Type:	Body-pointing/slew	Optical steering
Range:	Full sphere	+/- 1.25°
Accuracy:	+/- 5° (3σ, pre-acq) +/- 1° (3σ, post-acq)	+/- 0.006° (3σ) **(1/10th our beamwidth)**
Bandwidth:	< 0.1 Hz	> 1 Hz

Fine Steering Mechanism

- Selection criteria:
  - Field of regard, accuracy, BW
  - SWaP (mirror + driver)
- MEMS Fast-Steering Mirror
  - 2-axis MEMS tip/tilt mirror
  - Steering range: +/- 1.25°
  - No integrated feedback sensors
- Qualification in progress:
  - Positioning repeatability
  - Thermal stability
  - **Goal: predictable response across environmental ranges**

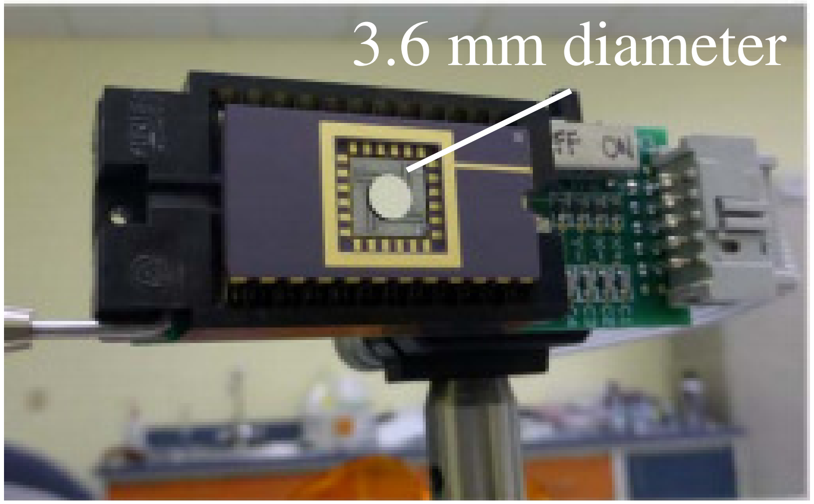
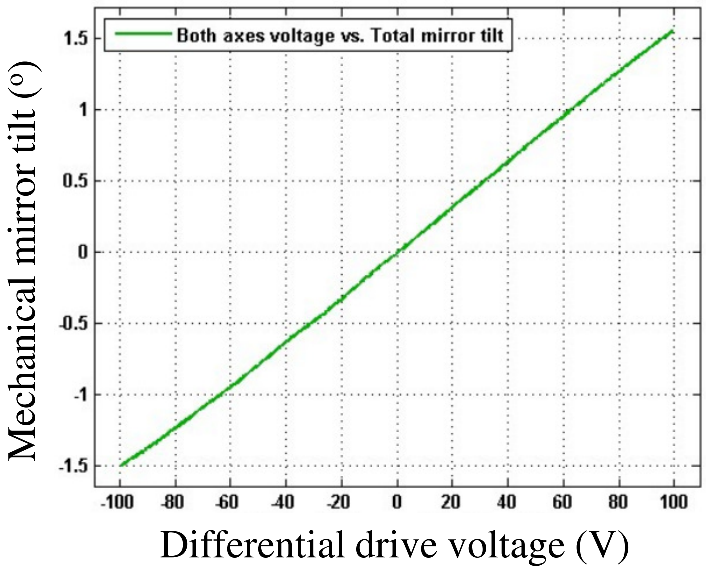
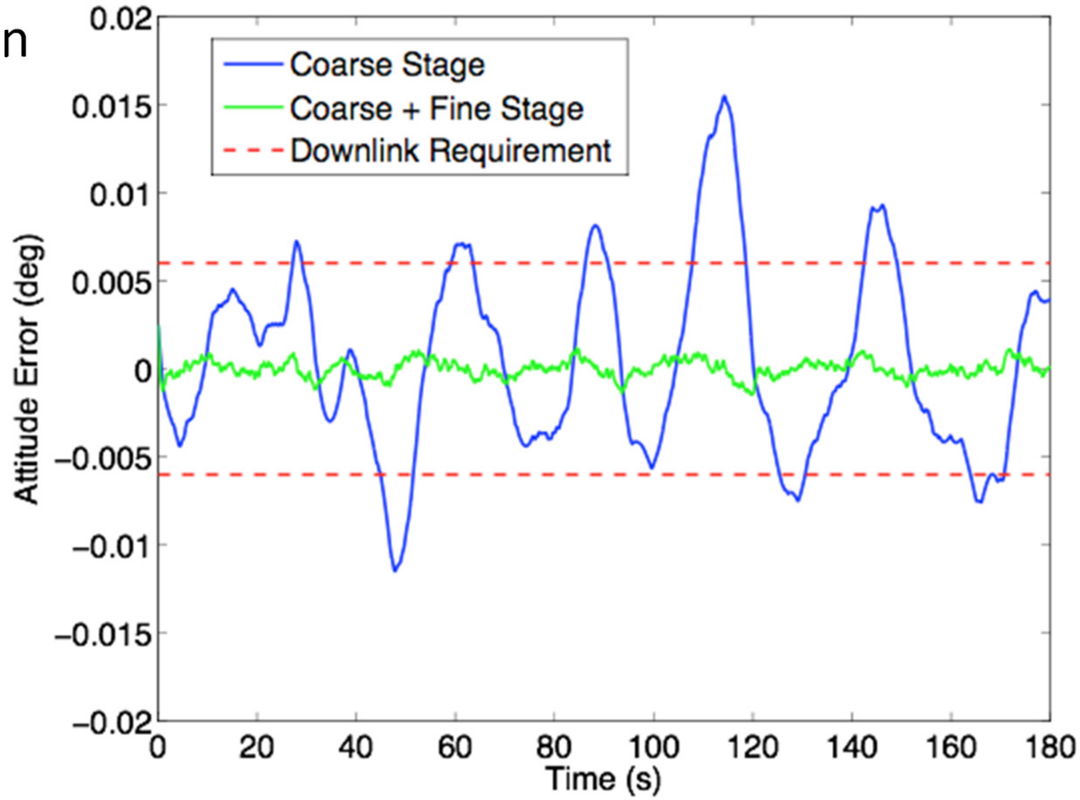


Image: Mirrorcle Technology Inc.



PAT Analysis

- Single-axis tracking simulation
  - 400 km altitude
  - Post-acquisition
- Modeled disturbances:
  - Solar radiation
  - Magnetic
  - Gravity gradient
  - Aerodynamic drag
  - Reaction wheels
- Future work:
  - Expand to 6 DOF
  - Time to acquire



Single Axis Simulation Results	
Coarse Pointing Accuracy	±0.02° (3-σ)
Fine Pointing Accuracy	±0.001° (3-σ)

Closing Remarks

- First attempts at CubeSat lasercom motivated by:
  - Demand to downlink payload data
  - Advances in CubeSat ADCS

- Our work will address future implementation gaps:
  - Optical steering mechanism and staged control
  - Compact, scalable optical transmitter

- Expected results in next 12 months
  - Hardware-in-the-loop PAT demonstration
  - Bench-top end-to-end link demonstration

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