Laser Communications Downlink and Crosslink Designs for Cubesats

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CalPoly CubeSat Workshop 2016

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Outline

- The Need for CubeSat Lasercom
  - Motivation
  - Key design trades
- Approach and Enabling Technologies
- Ongoing MIT Programs:
  - Nanosatellite Optical Downlink Experiment (NODE)
  - Freespace Lasercom And Radiation Experiment (FLARE)
  - KitCube
- The Future of CubeSat Lasercom

The Need for CubeSat Lasercom

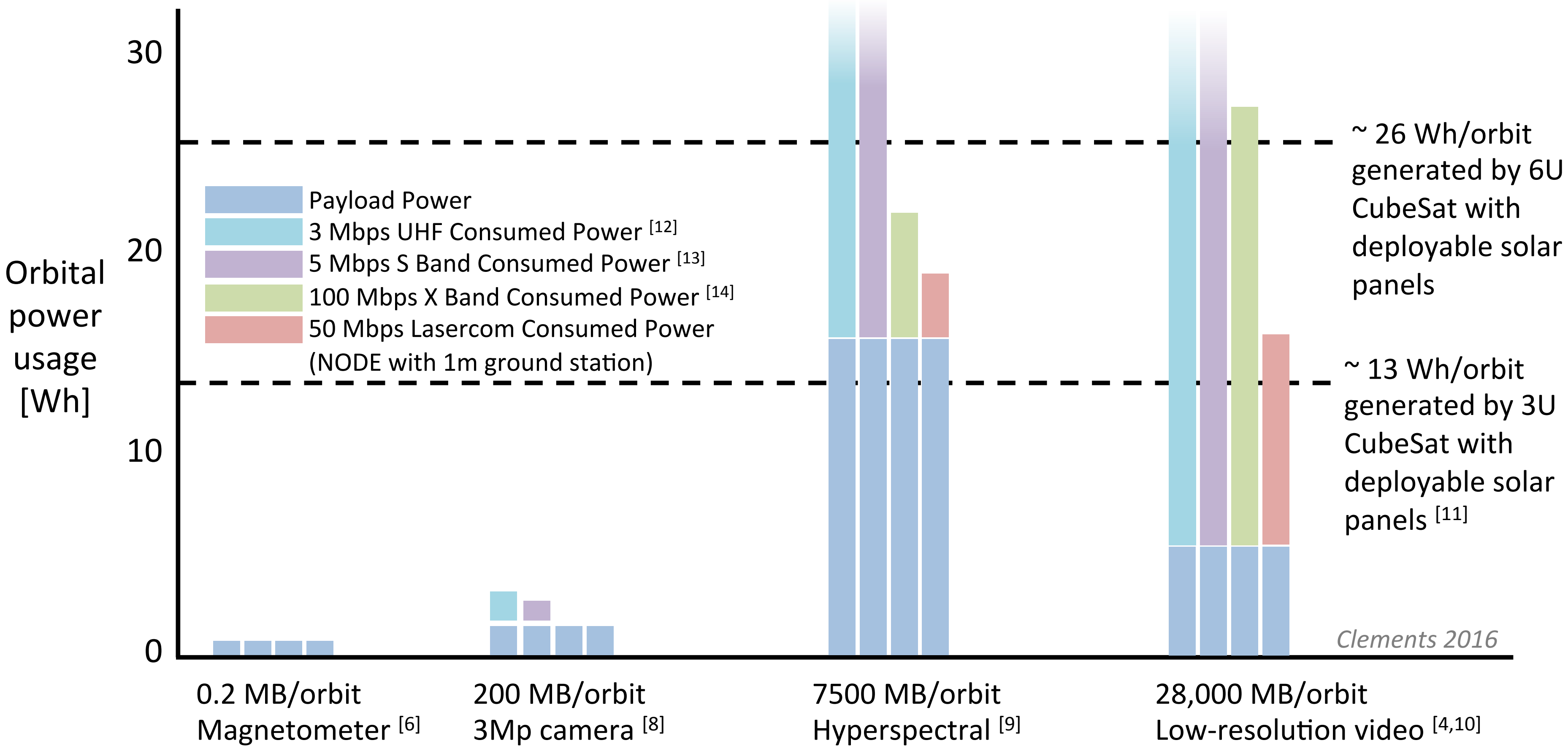
- Transitioning to more advanced payloads requires higher data rates than UHF with tapespring antenna can provide [4]
- Transmit power and cost/accessibility of high-gain ground stations are usually the limiting factors in CubeSat RF data rate [5]
- Laser communication is more power-efficient than RF:
  - **Channel capacity C scales with wavelength λ:**

$$\frac{C_{Opt.}}{C_{RF}} \propto \left(\frac{\lambda_{RF}}{\lambda_{opt.}}\right)^2$$

→ **Lasercom is an attractive solution for future programs**

- **Ongoing compact lasercom work: Aerospace OCSD [15], Facebook [16], DLR [17], BridgeSat/Surrey, RUAG, MIT programs, & others**
  - **Related technology: CHOMPTT [20]**

Comm for Advanced LEO CubeSats



~ 26 Wh/orbit generated by 6U CubeSat with deployable solar panels

~ 13 Wh/orbit generated by 3U CubeSat with deployable solar panels [11]

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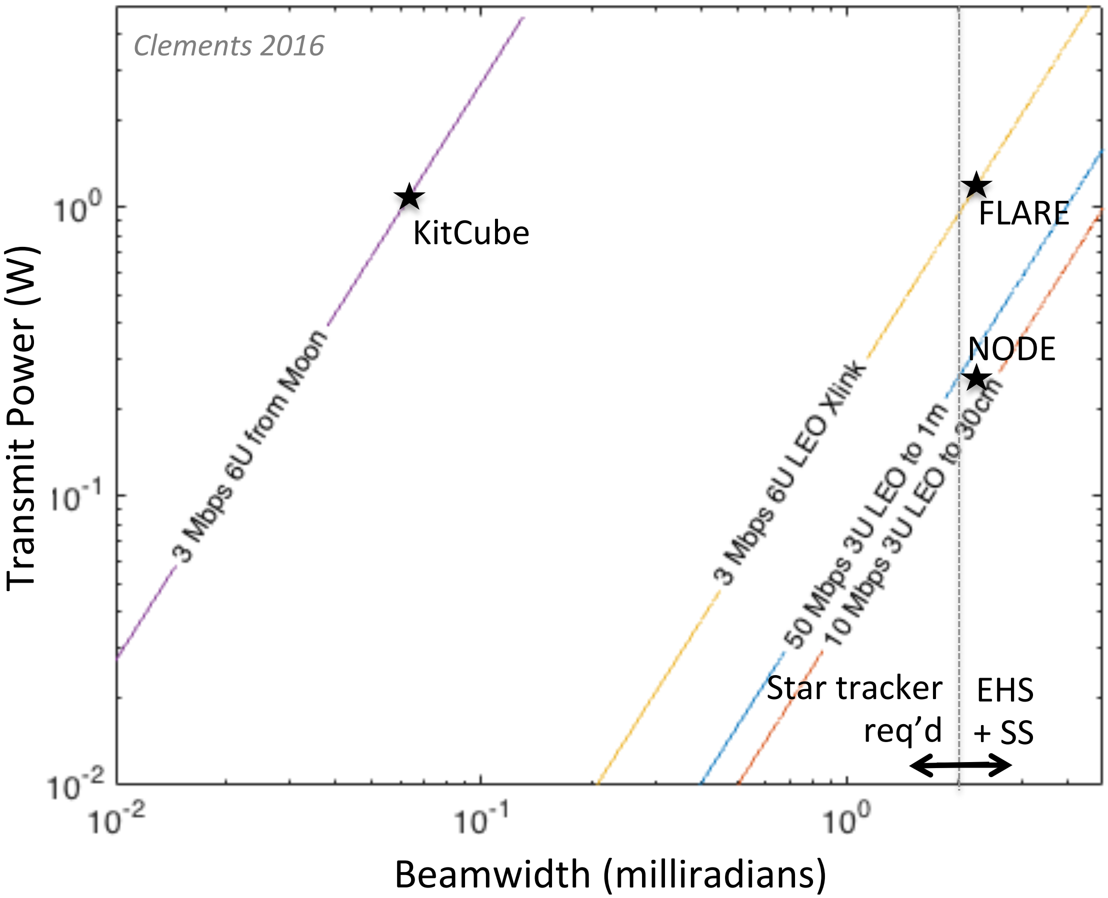
- Figure assumes payloads are running continuously & downlink is not limited by number or duration of passes
- High-power, high-data payloads drive need for CubeSat Lasercom

Lasercom Pointing Challenges

- Key challenge: **pointing control**
  - Lasercom beamwidths test limits of CubeSat attitude control with Earth Horizon Sensors (EHS) & Sun Sensors (SS)
- We will discuss solutions MIT CubeSat lasercom programs:
  - NODE: LEO downlink [2]
  - FLARE: Crosslinks in LEO
  - KitCube: Downlink from lunar orbit [18]

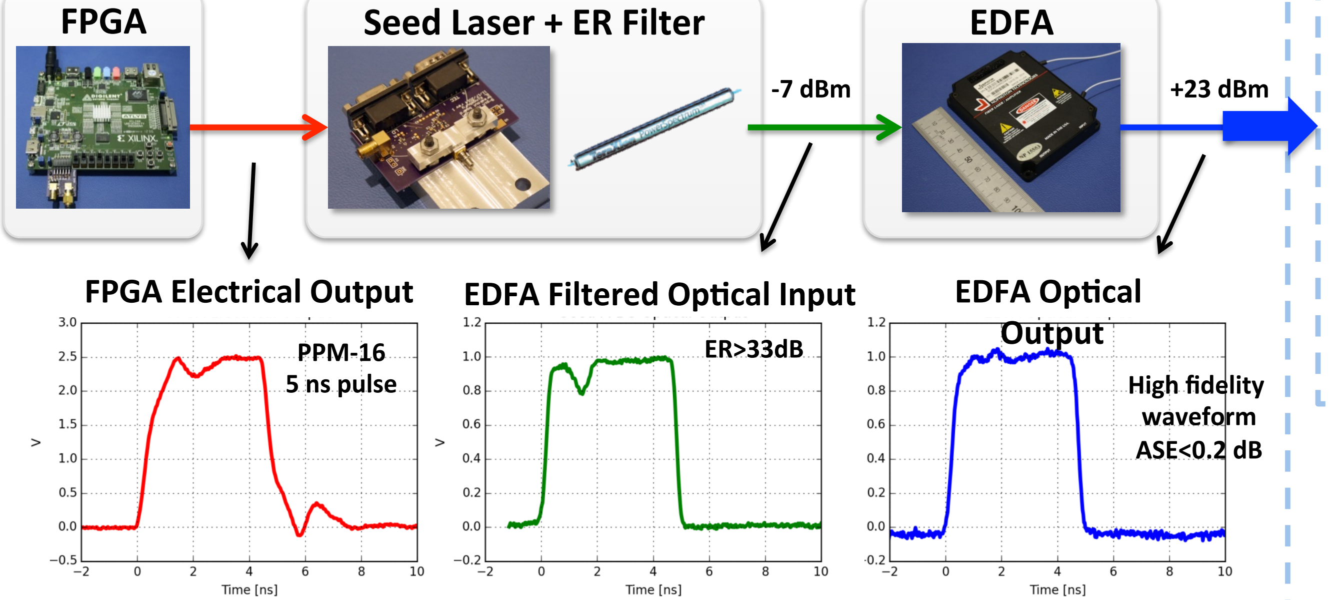
Lasercom Power & Beamwidth Trade



COTS for CubeSat Lasercom

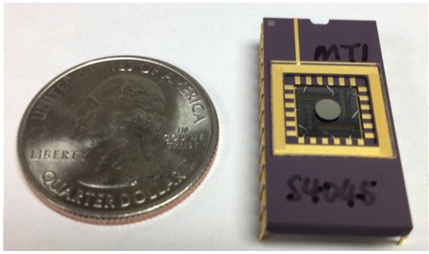
Transmitter electronics leverages telecom technology

Credit: Ryan Kingsbury [2]



Space terminal pointing control enabled by COTS Fast Steering Mirror (FSM)

Credit: Kathleen Riesing



Selected COTS tech architecture with amplification using EDFA to enable low cost (<$20k in parts cost) system scalable to 100 Mbps

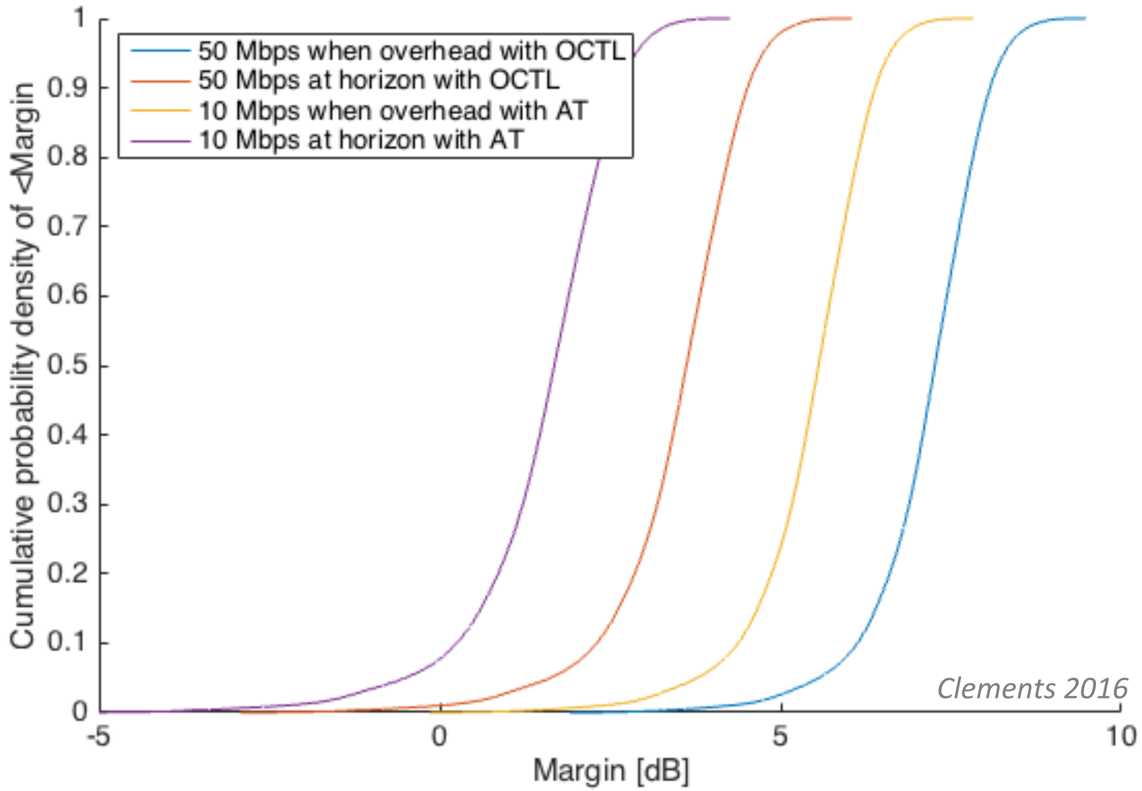
MIT Ground station uses Amateur Telescope and laptop

Credit: Hyosang Yoon

Uncertainty-based Link Analysis

Developing new link analysis approach to handle system uncertainties:

- COTS parts not yet qualified for space environment
- Traditional, worst-case link analysis is too conservative for risk-tolerant CubeSats
- Probabilistic modeling approach to lasercom link budgets helps to assess risks



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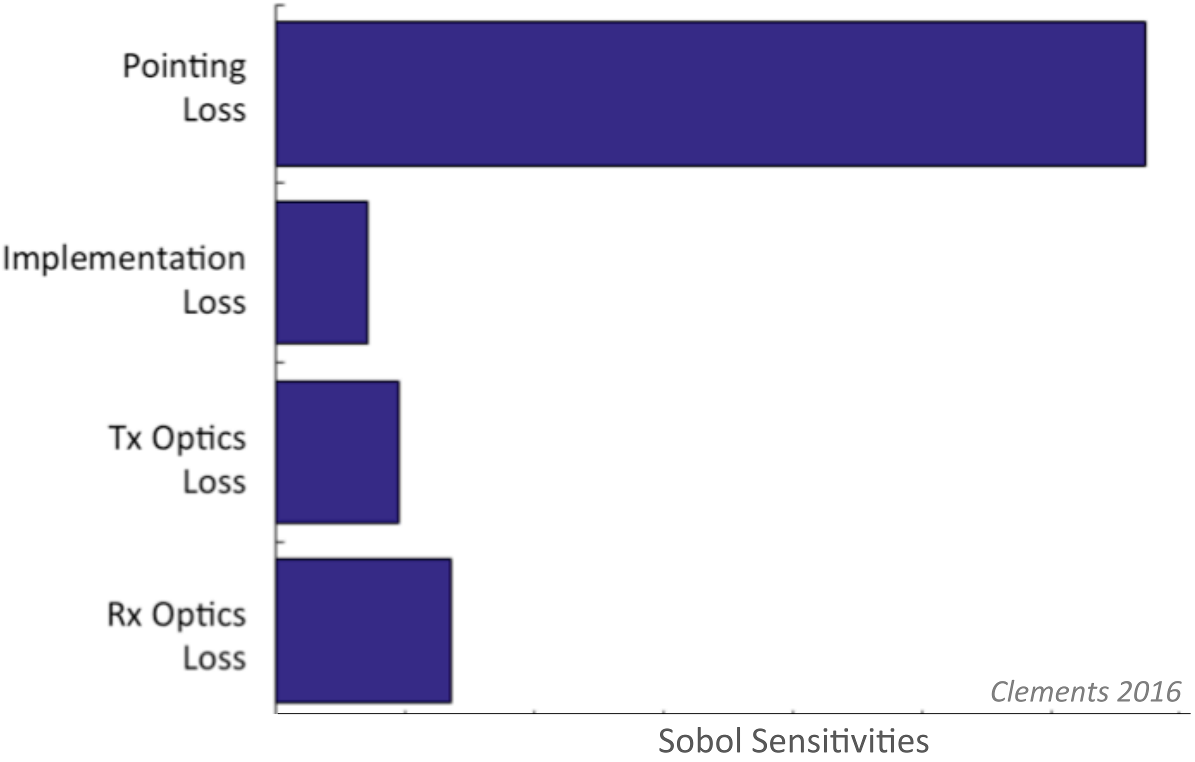
Uncertainty-based Link Analysis

→ **How to address uncertainties:** Use global sensitivity analysis to identify uncertainties with highest impact on Link Margin

- Global sensitivity analysis helps to visualize contributors to performance uncertainty



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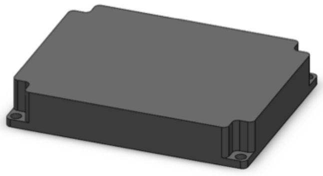
NODE Overview

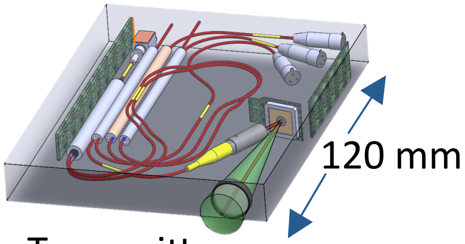
- **N**anosatellite **O**ptical **D**ownlink **E**xperiment
- 10-100 Mbps downlink from LEO CubeSat w/ 1550 nm, 2.26 mrad beam
- <10 W consumed power for 0.2 W transmit power
- Leverages COTS parts for transmitter and receiver

Transmitter

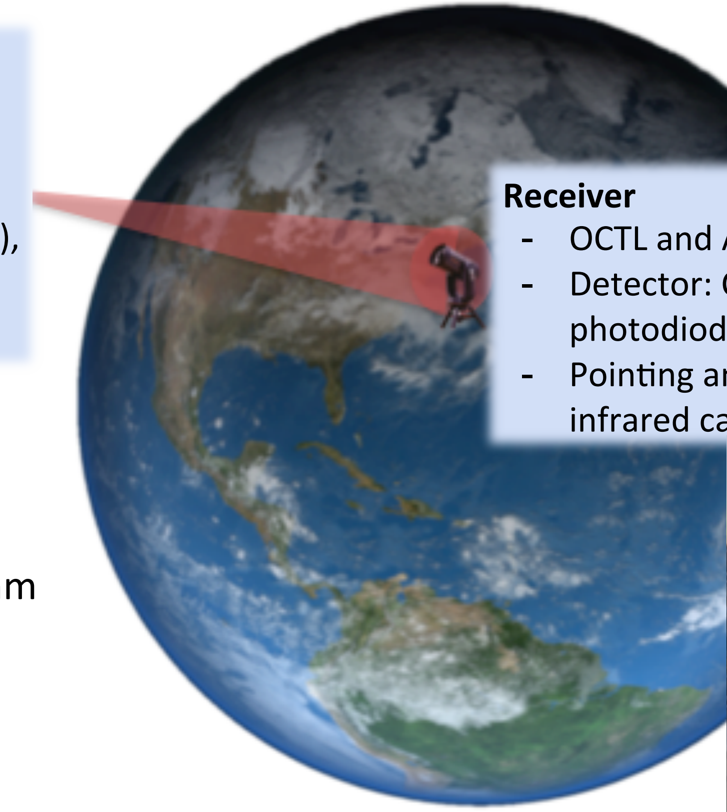
- Electronics: Commercial telecom laser components, PPM modulation
- Mechanical: 3D printed structure
- Pointing strategy: bus pointing (coarse pointing), Fast steering mirror (fine pointing)
- Components in two submodules



Transmitter EDFA submodule

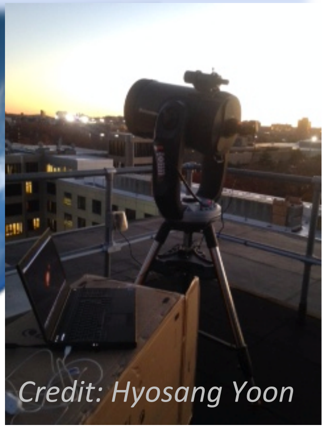


Transmitter optics submodule



Receiver

- OCTL and Amateur telescope
- Detector: COTS avalanche photodiode
- Pointing and tracking: COTS infrared camera + star tracker



Credit: Hyosang Yoon

CAD Credit: Derek Barnes

NODE I&T Progress Update

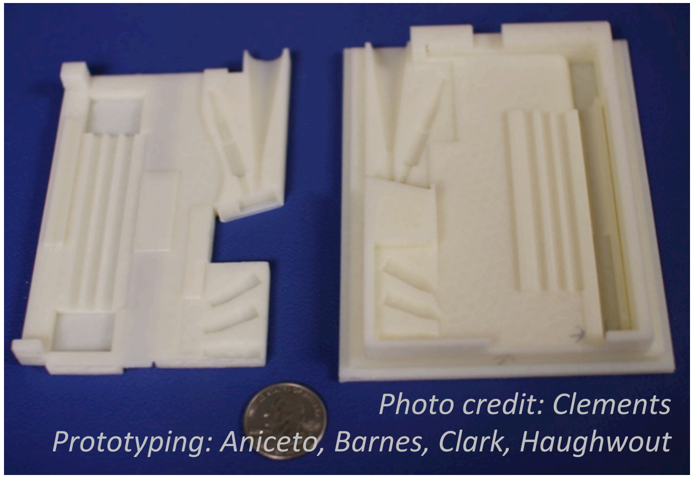


Photo credit: Clements
Prototyping: Aniceto, Barnes, Clark, Haughwout

Mechanical Prototyping

Photo Credit: Clements
GS lead: Hyosang Yoon

Ground Station Prototyping

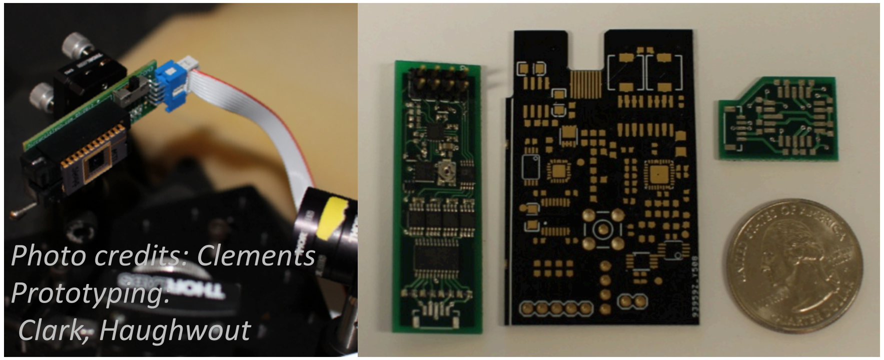


Photo credits: Clements
Prototyping:
Clark, Haughwout

FSM & Transmitter Prototyping

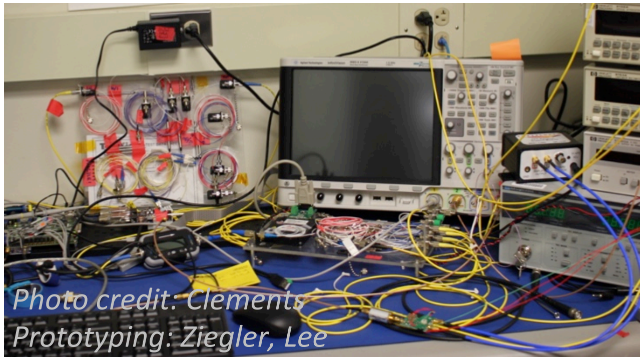


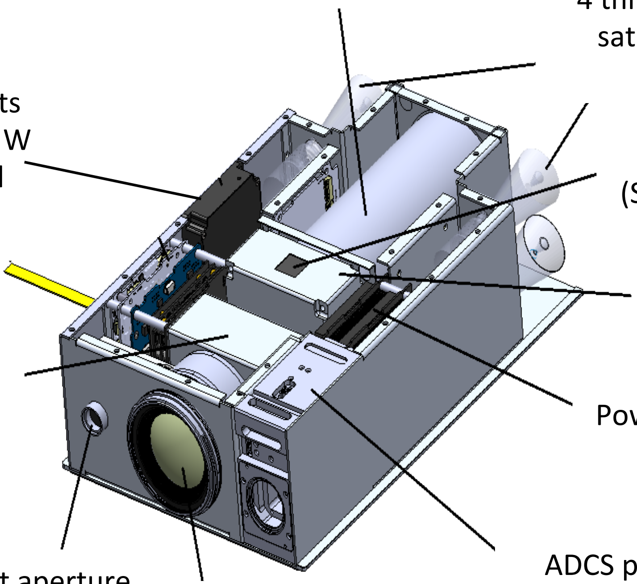
Photo credit: Clements
Prototyping: Ziegler, Lee

Functional Testing

FLARE Mission Overview

Freespace **L**asercom and **R**adiation **E**xperiment

- Intersatellite laser communications with CubeSats
- Two satellites, compact half-duplex transceiver system
- MIT's entry into the AFRL UNP-9 competition
- Pre-PDR



Fuel Tank

4 thrusters maintain satellite crosslink distance

EDFA outputs 1550 nm 1.2 W laser signal

Sparrow window (Secondary Payload)

Sparrow [19] module (Secondary Payload)

Bus FPGA generates signal for lasercom seed laser & interprets received signals

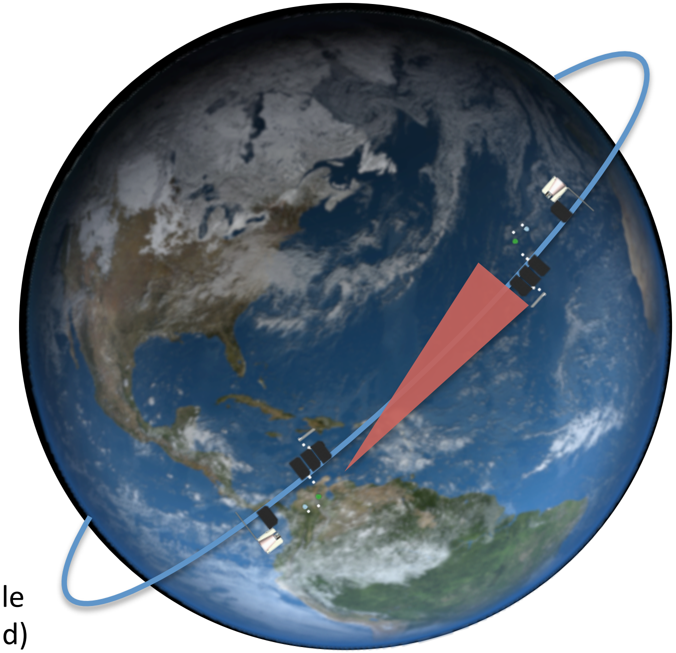
Power management & batteries

ADCS provides 3 axis attitude control

Lasercom transmit aperture (2.26 mrad beam)

8.5 cm lasercom receive aperture

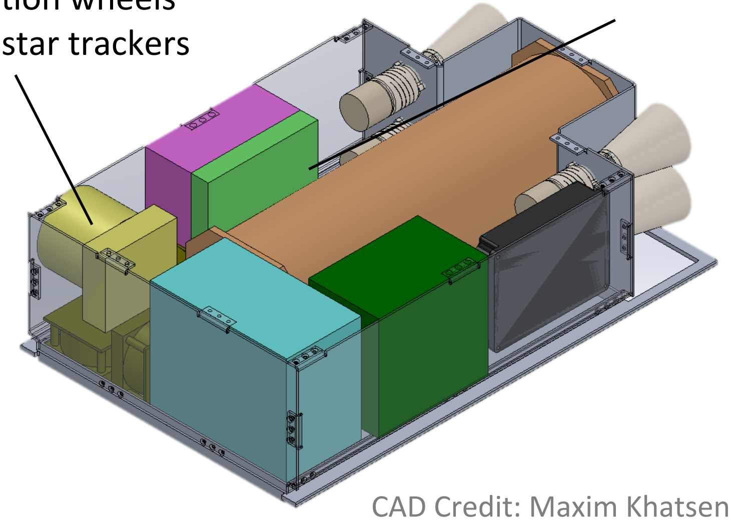
CAD Credit: Maxim Khatsenko



KitCube Mission Overview

Program Objectives

- MIT’s entry into the NASA CubeQuest Challenge
- Design and build a 6U CubeSat that wins one of the 3 remaining spots on SLS EM-1.
- Achieve lunar orbit ($1.5 M)
- Goal of winning the Best Burst Data Rate competition with a laser communications downlink transmitter.
- Also compete for largest aggregate data volume, and longevity.



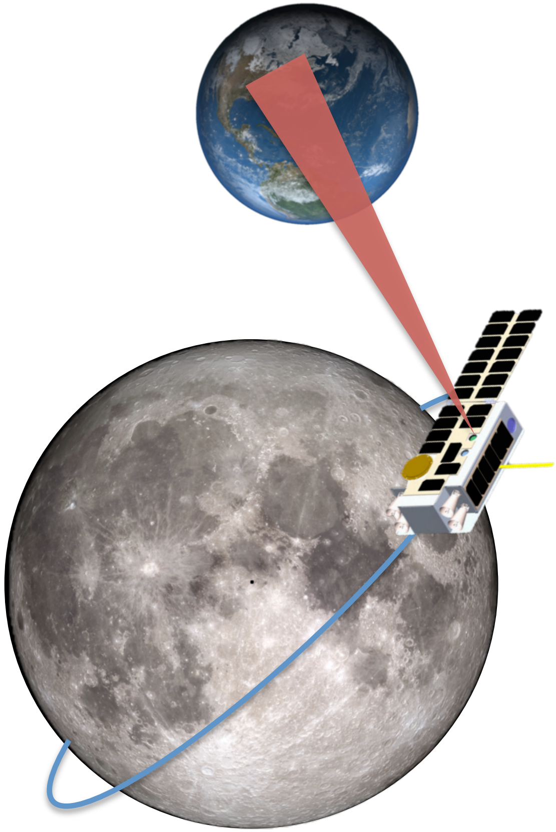
Lasercom payload:

- 1550 nm 1.2 W transmitter
- 0.1 mrad beam
- Beacon receiver

Pointing solutions:

- Reaction wheels
- Two star trackers

CAD Credit: Maxim Khatsenko



The Future of CubeSat Lasercom

Upcoming Tech Demo Missions (MIT examples; many others exist)

LEO downlink

MIT example: NODE

>50 Mbps with 0.2 W transmitter & 1 m ground station

Other examples: Aerospace OCSD, CHOMPTT

LEO crosslink

MIT example: FLARE

>10 Mbps with 1.2 W transmitter

Lunar downlink

MIT example: KitCube

>1 Mbps with 1.2 W transmitter

Future Architectures

LEO downlink

½ U payload & ground station network would enable higher duty cycles of advanced CubeSat payloads

LEO crosslink

Low-power crosslinks reduce latency of downlinking payload data

Deep space

CubeSats could be used as probes on interplanetary missions (ex. Starshot), with the communication ability to relay findings back to Earth

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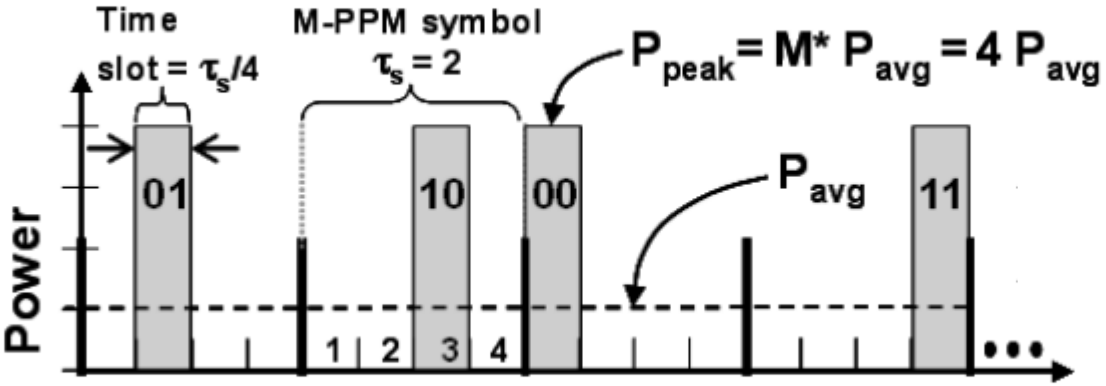
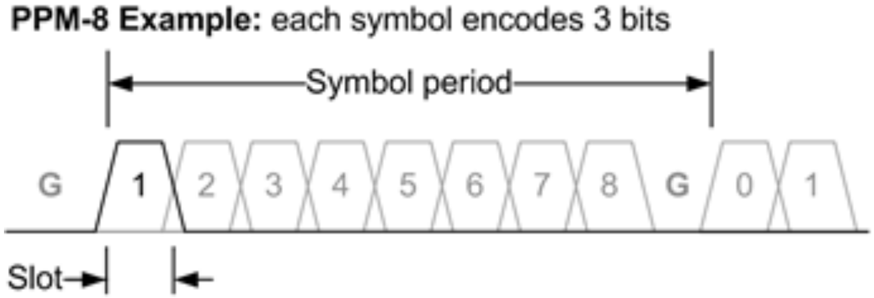
Backup Slides

PPM Diagrams



Credit: *Laser Communication Transmitter and Receiver Design* by Dave Caplan



Credit: Ryan Kingsbury

Abstract

"Laser Communications Downlink and Crosslink Designs for CubeSats”

Optical communication, or lasercom, can provide much higher link rates than an RF system with comparable energy consumption. This is because optical signals can be directed more effectively towards the ground station. The main engineering costs associated with these systems are the stringent pointing requirements that are levied on the laser transmitter. Recent advances in CubeSat attitude determination and control systems (ADCS) are addressing these needs, and there have been several missions that have demonstrated three-axis stabilization – a key enabler for lasercom.

We discuss developments in laser communications capabilities for downlink and crosslink on 3U and 6U nanosatellite platforms and ground stations based largely on commercially available components. We present predicted and prototyped capabilities of spacecraft transmitters and receivers for a power-constrained 1550 nm direct-detection system with average output power ranging from 200 mW to 1.2 W for three case studies: low-Earth orbit downlink, low-Earth orbit crosslink, and deep space downlink. We describe expected performance for a representative orbital configurations, including consideration of propulsion and pointing capability, as well as ground station geometries for these case studies. Passive and active beacon approaches are also considered. The case studies capture ongoing work at MIT on the Nanosatellite Optical Downlink Experiment (NODE), the MIT KitCube entry in the NASA CubeQuest Lunar Derby Challenge, and the Free-space Lasercom and Radiation Experiment (FLARE) in the University Nanosatellite Program 9.

Lasercom has the potential to unlock large amounts of bandwidth at optical wavelengths even for resource-constrained CubeSat platforms. The highly directed nature of the optical links make them extremely difficult to intercept and jam resistant. These same link parameters also support extensive spatial reuse of carrier frequencies. We use onboard memory storage to address weather/availability concerns for using optical transceivers for ground uplink and downlink. Many missions do not have “real-time” downlink latency requirements, so data can be stored onboard until a ground station is available. Applications with more stringent latency requirements can field additional geographically diverse ground stations, particularly if the ground stations are compact and low-cost.