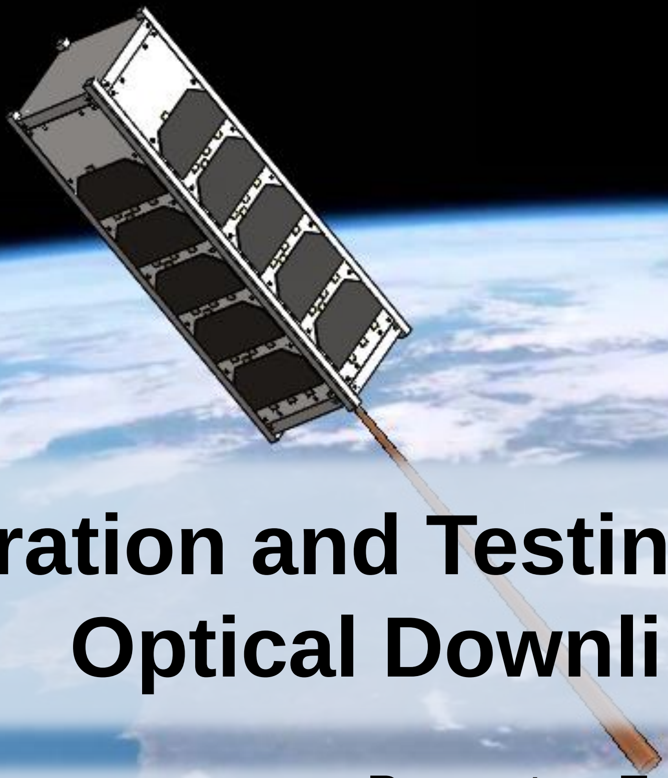


Integration and Testing of the Nanosatellite Optical Downlink Experiment

Presenter: Emily Clements
PI: Professor Kerri Cahoy

The NODE Team: Christian Haughwout, Hyosang Yoon, Kathleen Riesing, Maxim Khatsenko, Caleb Ziegler, Raichelle Aniceto, Rachel Morgan, Chloe Sackier, Jeremy Stroming, Joseph Figura, Derek Barnes, Myron Lee, Rodrigo Diez, Joe Kusters, Jim Clark, Michael Long, Tam Nguyen

Motivation

What if your small satellite could downlink 100 Gb/day?

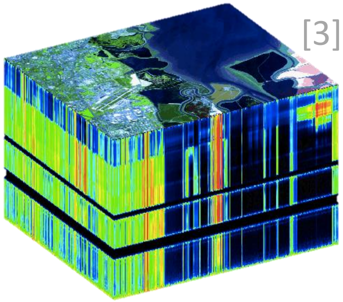
100 Gb =


[1]

80,000 images
~ 1 every second for a day


[2]

2 hours of GoPro video


[3]

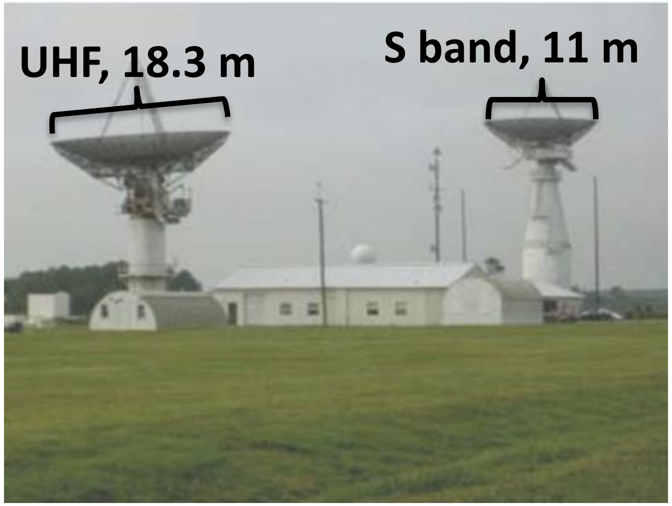
120 Hyperspectral Image Cubes

What would essentially unlimited data downlink enable?

Pushing Toward Higher Data Rates

- Radio frequency (RF) downlinks challenged by resource constraints
  - Downlink capability of existing UHF and S-band systems << 10 Gb/day [4]
  - Higher data rates possible w/ large ground stations, more power, or more spectrum
    - X-band, ex. Syrlinks,[6] Planet[7]
    - Ka-band, ex. Astro Digital[8]

- **Lasercom is more power-efficient for given size, weight, and power (SWAP) & has no spectrum constraints**
  - CubeSat lasercom could scale to Gbps,[12] but **tech. development still required**
    - Many groups working on it: MIT,[9] The Aerospace Corporation,[10] Sinclair,[11] UF,[13] DLR,[14,15] JAXA,[16] compact UAV lasercom from Google[17] and Facebook[18]…



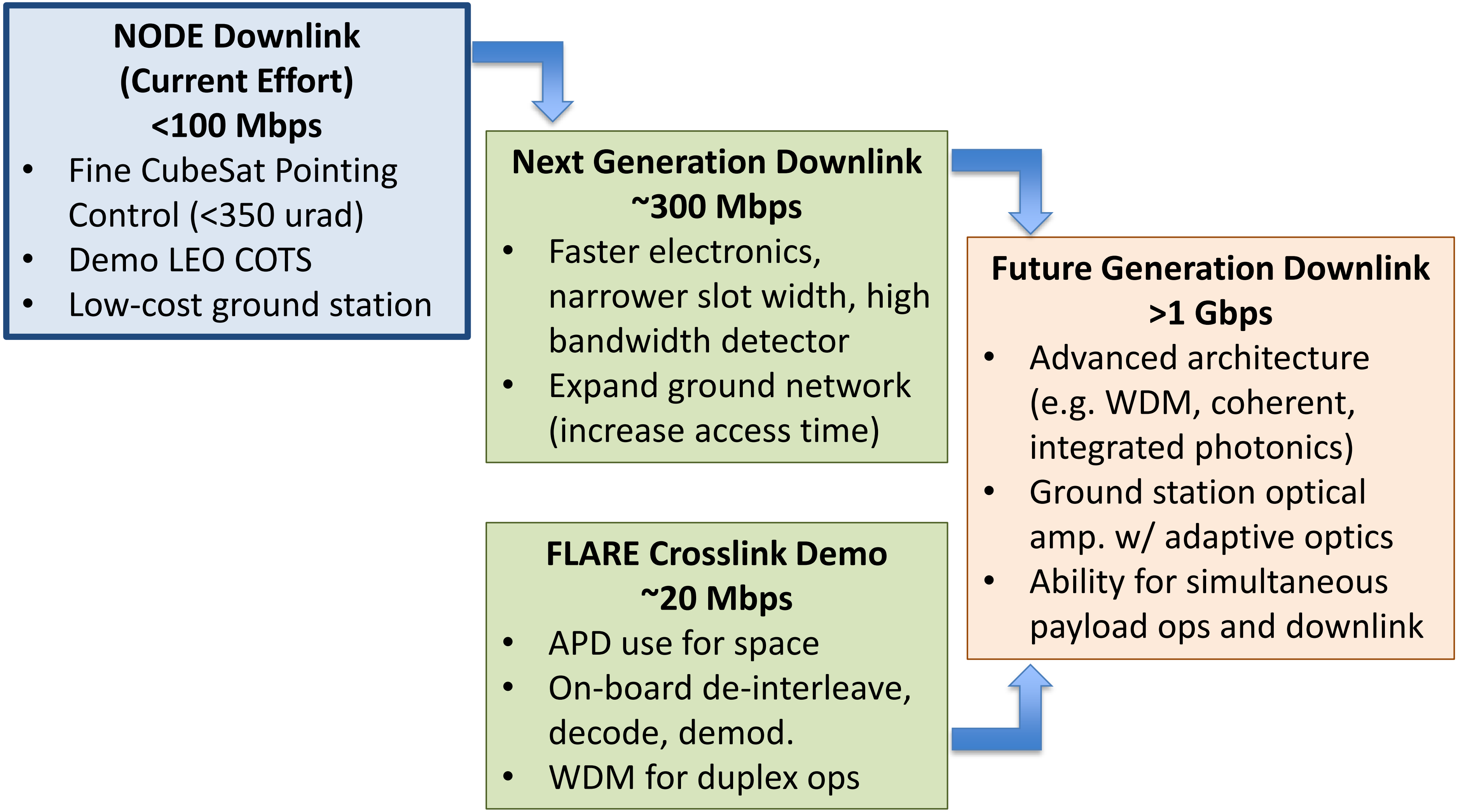
Wallops CubeSat Comm. Antennas

Image from Schaire (2013) [5]

MIT Lasercom Ground Station

Image credit: Clements

MIT* CubeSat Lasercom Roadmap



NODE Downlink
(Current Effort)
<100 Mbps

- Fine CubeSat Pointing Control (<350 urad)
- Demo LEO COTS
- Low-cost ground station

Next Generation Downlink
~300 Mbps

- Faster electronics, narrower slot width, high bandwidth detector
- Expand ground network (increase access time)

FLARE Crosslink Demo
~20 Mbps

- APD use for space
- On-board de-interleave, decode, demod.
- WDM for duplex ops

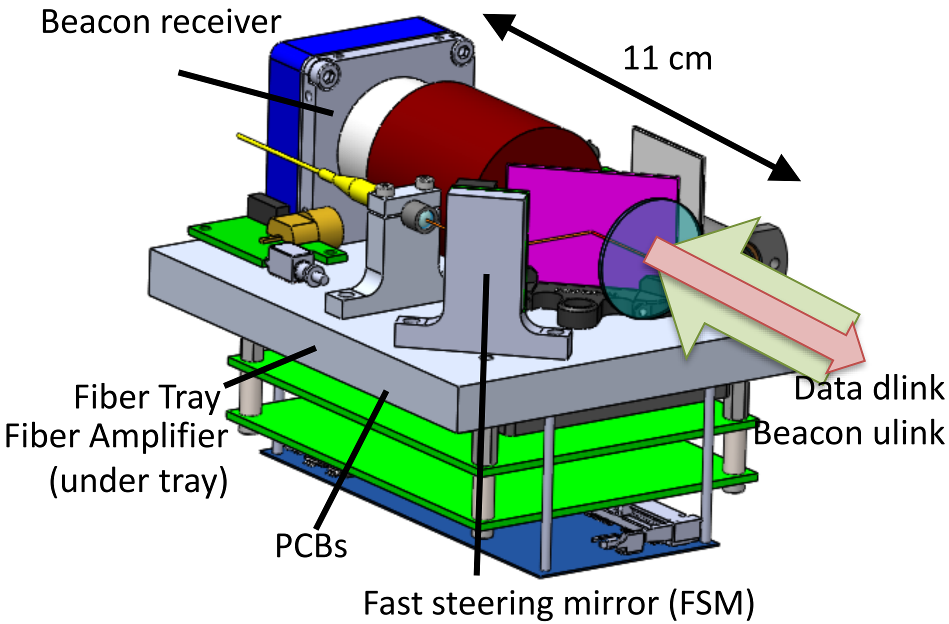
Future Generation Downlink
>1 Gbps

- Advanced architecture (e.g. WDM, coherent, integrated photonics)
- Ground station optical amp. w/ adaptive optics
- Ability for simultaneous payload ops and downlink

* See slide 3 for other organizations in this area, e.g. the Aerospace Corporation & Sinclair

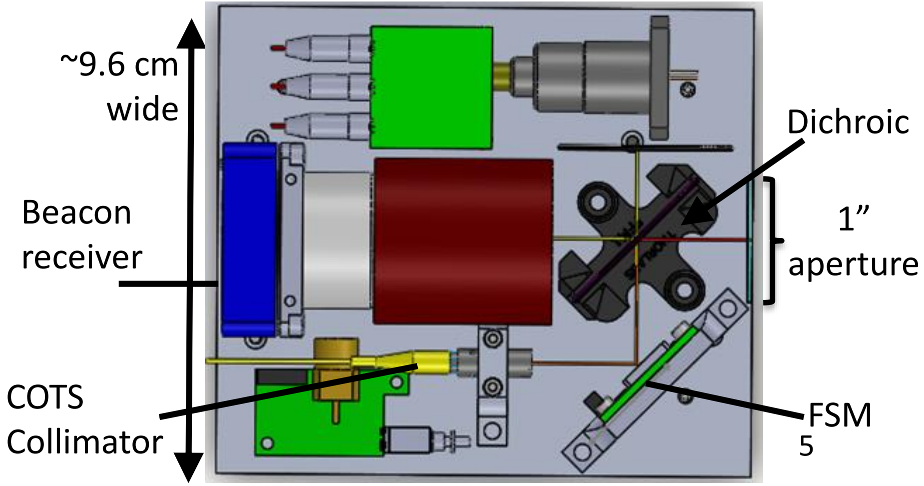
NODE Space Terminal Overview

Scope	CubeSat **Low-Cost** Payload
Architecture	Direct detection MOPA COTS telecom parts (1550 nm)
Downlink data rates	10 Mbps (amateur telescope) 100 Mbps (OCTL)
Power	0.2 W (transmit power), 15 W (consumed power)
Beamwidth	1.3 mrad (half power)
Modulation	PPM
Coding	RS(255,239)
Mass, volume	1.0 kg, 1 U
Control architecture	• Bus coarse pointing (<0.5°) • FSM fine steering (+/- 2.5°) • Beacon receiver (976 nm) for pointing knowledge (20 arcsec)



CAD Credit: Max Khatsenko

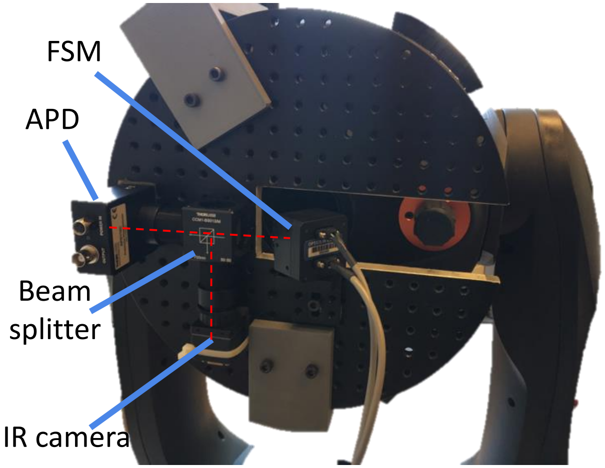
Optical Layout: Derek Barnes



NODE Ground Terminal Overview

Downlink with NODE amateur telescope:

Data rate	10 - 50 Mbps
Rx Diameter	30 cm
Detector	Direct detection w/ COTS Voxtel APD
Receiver electronics	Custom data acquisition system
Pointing	COTS IR camera and star tracker [19] FSM to keep spot on APD (no AO)
Uplink beacon	OCTL beacon[20]



Downlink with JPL OCTL telescope:

Data rate	50 - 100 Mbps
Rx Diameter	1 m
Rx electronics	NODE electronics (APD & custom electronics)
Uplink beacon	976 nm, 10 W tx power, 1 mrad beam

[19] Yoon, Hyosang, Kathleen Riesing, and Kerri Cahoy. "Satellite Tracking System using Amateur Telescope and Star Camera for Portable Optical Ground Station." (2016).

Image credits: Clements (above), Riesing (below)

NODE Test Plan

Test	Component-level	Payload Eng. Model	Payload Flight Model
Functional and Over the Air testing	limited, e.g. board-level functional tests and pointing control tests	In progress, May completion	NODE Tx to NODE OGS (Jul.) NODE OGS: Dlink from DLR* (date TBD)
Radiation Testing	EDFA (complete)		
Vibration and Shock Testing		Yes, with Host Mass Mockup (June)	Yes, with Host Mass Mockup (August)
Thermal Testing	FSM (complete) FBG & seed laser (April)	Yes (with Host Mass Mockup) (June)	
TVAC Testing	EDFA (complete)		Yes (with Host Mass Mockup) (August)

Combination of Component-level Qualification Testing, Engineering model testing, and Flight Testing to reduce risk

🟩 Complete
🟨 In Progress
🟥 Next Steps

*DLR's BiROS OSIRIS & Flying Laptop OSIRIS[13,14]

Pointing Control Testing

- Verified beacon receiver + laser beam control using FSM
  - Demo w/ Quadcell: **10 arcsec (~50 urad)** pointing control
  - NODE will implement the same closed-loop feedback control

Figure Credit: Hyosang Yoon

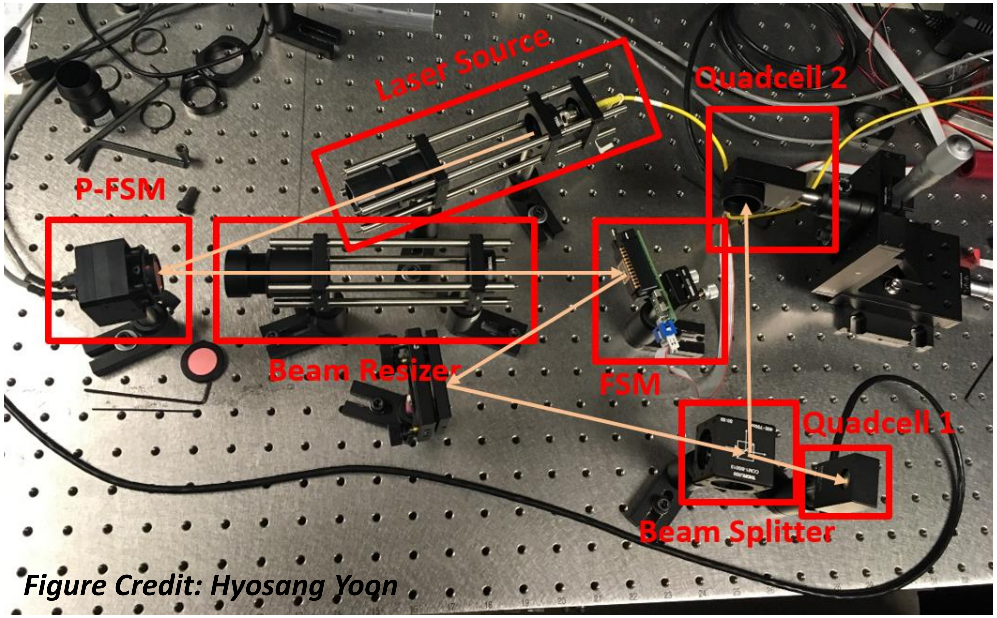


Figure Credit: Hyosang Yoon

Component Qualification: TVAC

- Objective: qualify 200 mW NuPhoton EDFA for vacuum operation

- Test Conditions:
  - Worst case mechanical setup
  - Hot case: initial temp. 30° C
  - Simulated 3 downlink passes for each of several power levels
    - 15 minute CW operations
    - Tested 20 - 24 dBm output power (23 dBm expected on-orbit)

- **Results confirmed EDFA can operate in vacuum**
  - No performance degradation from pre-test to post-test or during testing

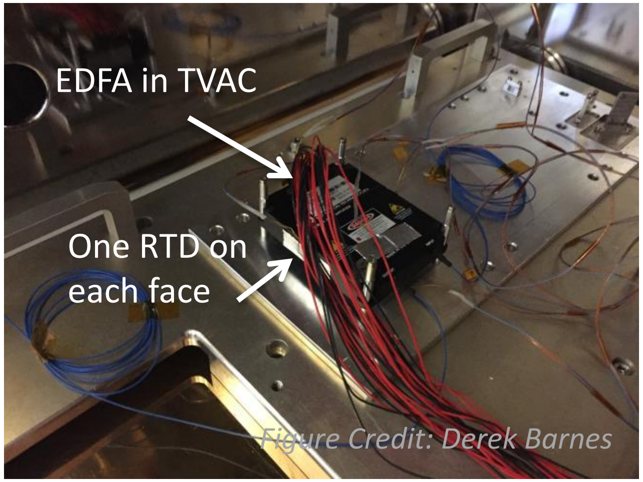


Figure Credit: Derek Barnes

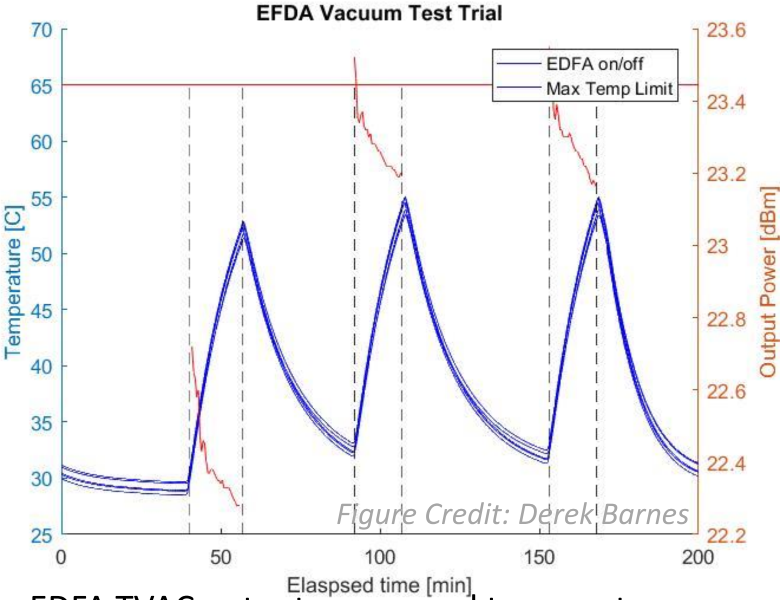


Figure Credit: Derek Barnes

EDFA TVAC output power and temperature vs test duration. EDFA powered to 23 dBm, 24 dBm, 24 dBm for trials shown.

Component Qualification: EDFA Radiation Testing

- Objective: Evaluate the effects of radiation on 200 mW NuPhoton EDFA w/ COTS electronics

- Test Setup:[1]
  - Total Ionizing Dose: 1 & 3 krad, 5 krad/min
    - 1 yr ISS orbit = 0.5 krad
  - Passive Test: EDFA not powered

- Results:
  - After 1 krad (~2 year dose): nominal operation
  - After 3 krad: no optical output power immediately after irradiation; normal operation after 24 hrs
- Next Step: active radiation testing, compare with other, space-rated NuPhoton EDFAs

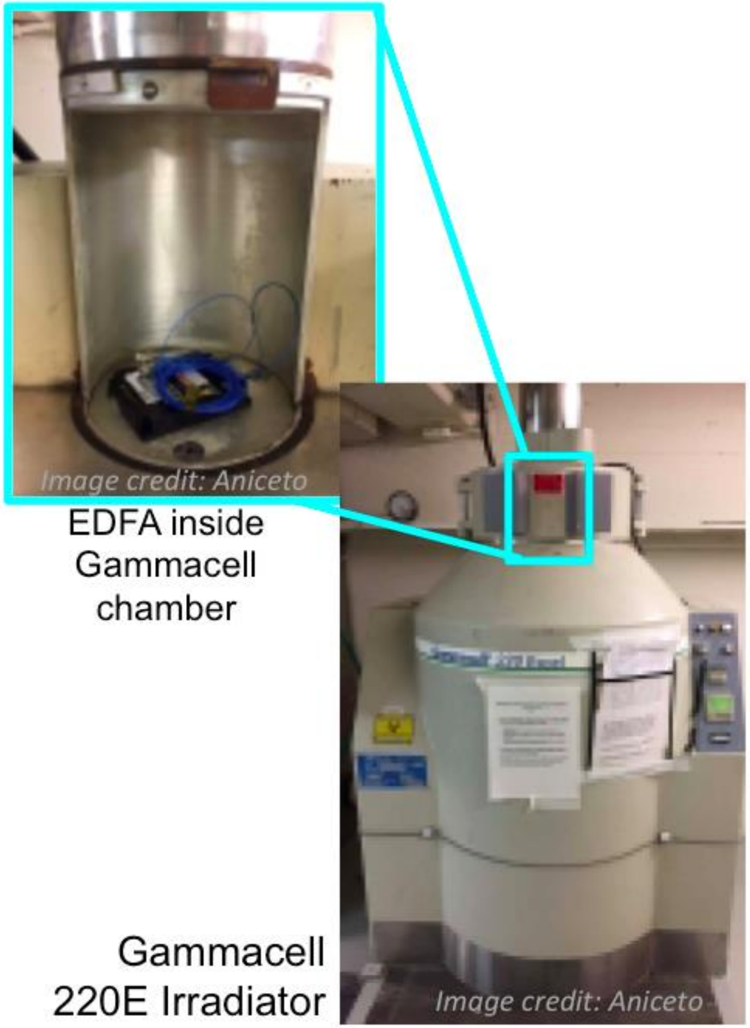


Image credit: Aniceto

EDFA inside Gammacell chamber

Gammacell 220E Irradiator

Image credit: Aniceto

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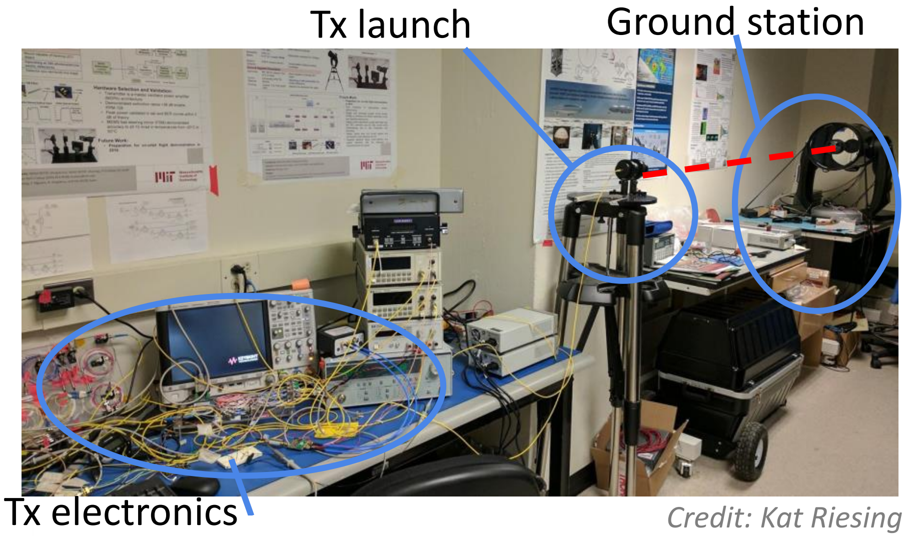
[1] Test performed by R. Aniceto with MIT Bioengineering Dept. Gammacell 220E Chamber, Cobalt-60 Source

Over-the-Air Testing

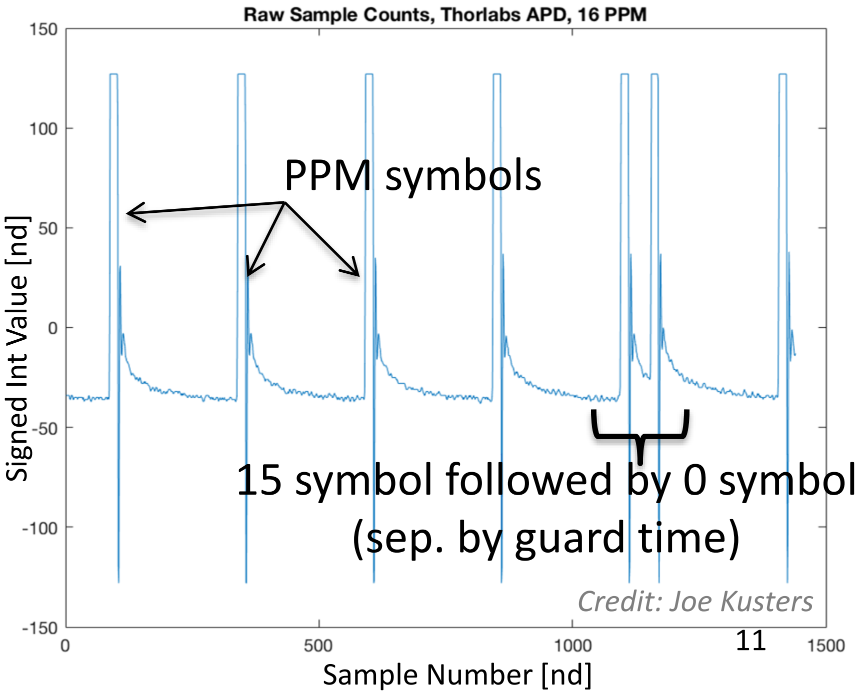
- Back-end optics assembled and successfully tracking an input signal
- Initial over-the-air tests conducted in the lab with waveform successfully recorded on the Pentek
  - ThorLabs APD (APD110C) for ease of initial testing
  - 16-PPM
  - 12 samples per slot, 8 bits per sample
  - No coding, no interleaving
- Next steps: improve mounting, integrate Voxtel APD receiver


Tx launch

Ground station

Tx electronics

Credit: Kat Riesing



PPM symbols

15 symbol followed by 0 symbol (sep. by guard time)

Credit: Joe Kusters

Conclusion & Next Steps

- Advancing CubeSat capability requires tech development for high-data rate communications
- Progress being made in many areas
  - Space Terminal: power consumption, pointing control, space use of COTS parts towards higher data rate architectures
  - Ground Terminal: low-cost ground terminals to enable large optical comm. ground network
- NODE goal is to advance technology maturity of low-cost lasercom for CubeSats
- Next Steps:
  - Complete engineering unit (June 2017)
  - Build and test flight unit (Summer 2017)

Backup / from old talks

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[2] http://www.businessinsider.com/long-lost-gopro-footage-from-the-edge-of-space-2015-9

[3] https://aviris.jpl.nasa.gov/data/image_cube.html, https://www.nasa.gov/centers/dryden/research/AirSci/ER-2/aviris.html

[4] https://www.klofas.com/comm-table/table.pdf 10 Gb/day for S band upper bound comes from: per the latest Klofas table, Lemur-2 achieved 1 Mbps with S band. If they had all the access time of the SFN (~180 min per day for SSO) they would hit 10 Gb/day.

[5] http://mstl.atl.calpoly.edu/~bklofas/Presentations/DevelopersWorkshop2013/GroundStation_Workshop_Schaire_Wallops_Standardization.pdf

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[9] Clements, Emily, et al. "Nanosatellite optical downlink experiment: design, simulation, and prototyping." Optical Engineering 55.11 (2016): 111610-111610.

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[15] Walz, S., M. Lengowski, and Mv Schoenermark. "Payload and Scientific Investigation of the Flying Laptop." *International Symposium on Small Satellite for Earth Observation Selected Proceedings*. 2005.

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[18] D. Gershgorn, “Facebook will use these lasers to beam internet from the sky,” http://www.popsci.com/facebook-will-use-these-lasers-beaminternet-sky (2 July 2015).

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[20] Biswas, Abhijit, et al. "Optical PAyload for Lasercomm Science (OPALS) link validation during operations from the ISS." *SPIE LASE*. International Society for Optics and Photonics, 2015.

[21] Caplan, “Introduction to Laser Communications.” MIT IAP Lasercom Course, January 2016

Abstract

Title: Integration and Testing of the Nanosatellite Optical Downlink Experiment

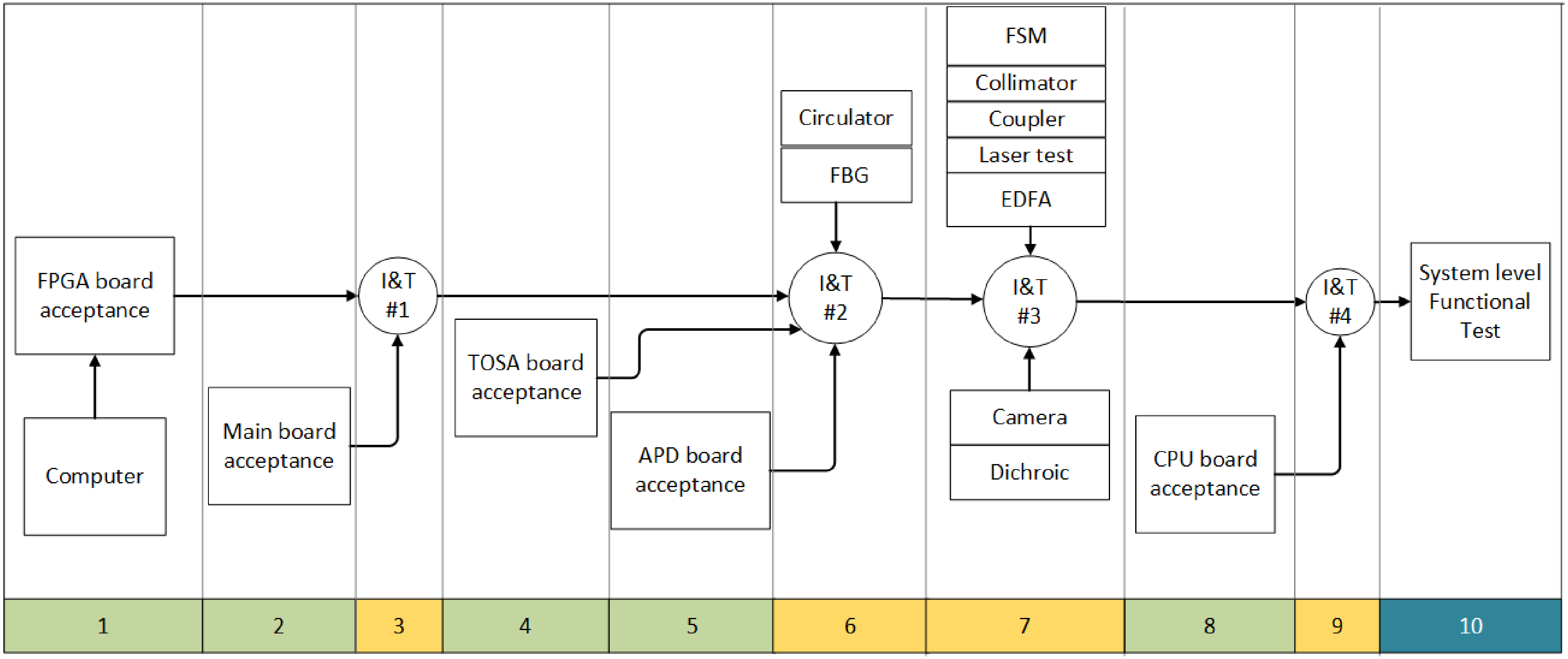
Authors: Emily Clements, Kerri Cahoy, Christian Haughwout, Hyosang Yoon, Kathleen Riesing, Maxim Khatsenko, Caleb Ziegler, Raichelle Aniceto, Rachel Morgan, Chloe Sackier, Jeremy Stroming, Joseph Figura, Derek Barnes, Myron Lee, Rodrigo Diez, Jim Clark, Michael Long, Tam Nguyen, Massachusetts Institute of Technology, Department of Aeronautics and Astronautics, 77 Massachusetts Avenue, Cambridge, MA 02139, eclements@mit.edu

As CubeSat sensor performance continues to improve despite the limited size, weight, and power (SWaP) available on the platform and as missions evolve into sensor constellations, the need for power-efficient high rate data downlink becomes more urgent. With the SWaP constraints onboard nanosatellites, it is not easy to accommodate large high gain antennas. With the growing size of scientific, defense, and commercial constellations, it is also difficult to place the high-gain burden solely on the ground stations, as it is costly to continuously schedule and operate facilities with dish diameters from 5 meters to 20 meters. In addition to the onboard and ground station challenges, it is also challenging and sometimes not possible to obtain radio frequency licenses that use significant bandwidth for nanosatellite constellation downlink operations.

Free space optical communications (lasercom) offers the potential for data rates higher than 10 Mbps for similar space terminal SWaP as current RF solutions and at reasonable cost, by leveraging components available for terrestrial fiber optic communication systems, and by using commercial amateur-astronomy telescope ground stations. In this talk, we give a progress update on the flight unit development of the Nanosatellite Optical Downlink Experiment (NODE) space terminal and ground station, scheduled for completion by summer of 2017. The NODE objective is to demonstrate an end-to-end solution based on commercial telecommunications components and amateur telescope hardware that can initially compete with RF solutions at >10 Mbps and ultimately scale to Gbps. The 1550 nm NODE transmitter is designed to accommodate platform pointing errors < 5 degrees, and uses an uplink beacon and an onboard MEMS fine steering mirror to precisely point the 0.12 degree (2.1 mrad) transmit laser beam toward the ground telescope. The mission design plans to use both the Jet Propulsion Laboratory (JPL) Optical Communications Telescope Laboratory (OCTL) ground station as well as the new low-cost 30 cm amateur telescope ground station design to reduce overall mission risk. The >10 Mbps link budget prediction is for the 30 cm amateur astronomy telescopes, and OCTL should support >50 Mbps data rates from the 200 mW NODE transmitter.

Moving beyond our initial laboratory prototyping most recently captured in Clements et al. 2016, in this talk we will discuss recent progress developing and testing the flight electronics, opto-mechanical structures, and controls algorithms that support the transmit and receive systems. We will discuss results of over-the-air testing of the NODE system, as we advance from benchtop to hallway to rooftop demonstrations. We will present thermal and environmental test approaches and experimental as well as expected results.

Functional Testing



I&T1: Interface test, PC – FPGA – Main board
I&T2: Test using Photo diodes (BIST)
I&T3: Test using Power meters and Dartboard
I&T4: Same as I&T3, PC replaced by CPU board

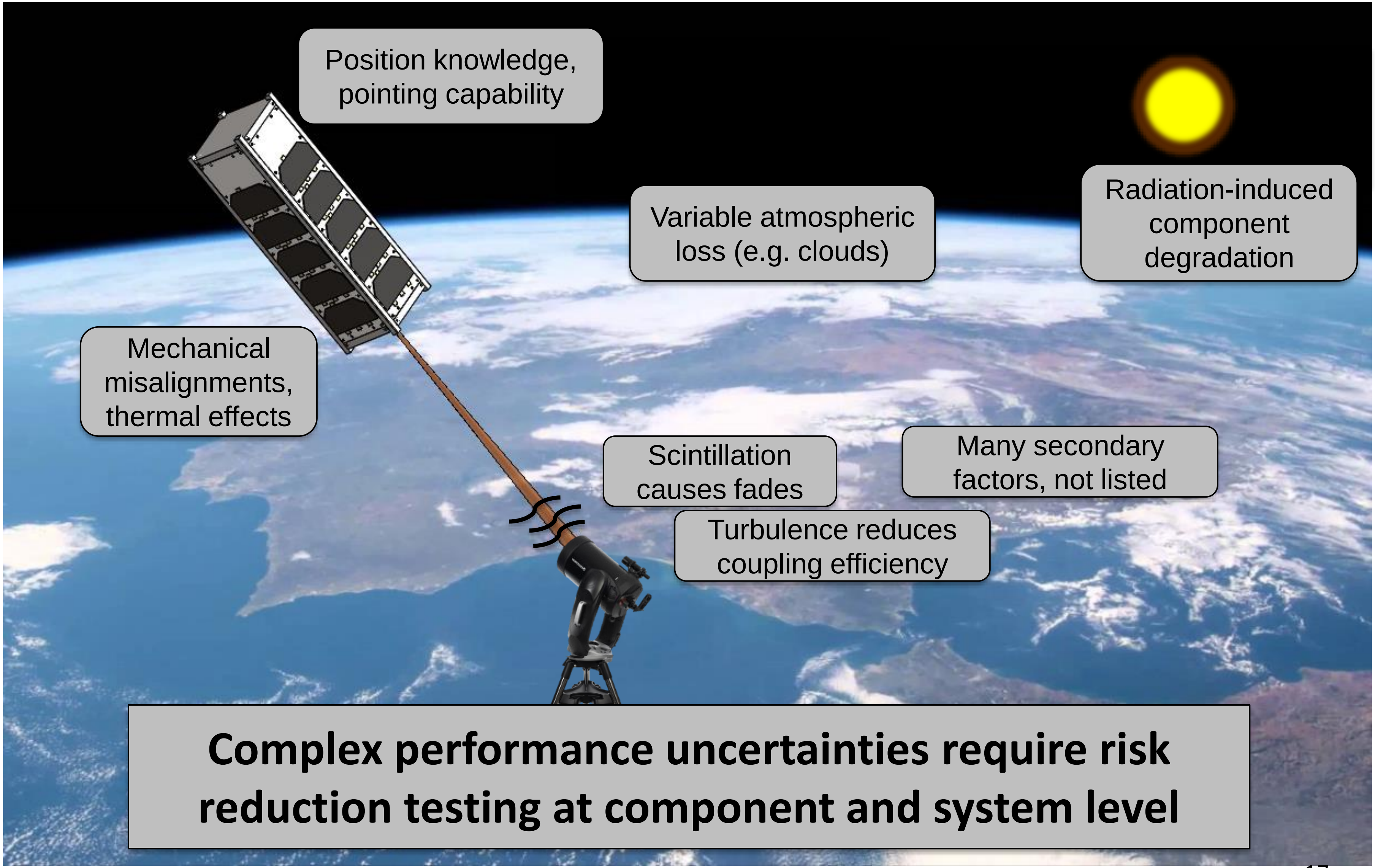
Legends

Acceptance test	Integration	Funcional test

○ I&T Integration and test

Figure credit: Diez

CubeSat Lasercom Tech. Development



Position knowledge, pointing capability

Variable atmospheric loss (e.g. clouds)

Radiation-induced component degradation

Mechanical misalignments, thermal effects

Scintillation causes fades

Many secondary factors, not listed

Turbulence reduces coupling efficiency

Complex performance uncertainties require risk reduction testing at component and system level

Figure credit: Ziegler, Clements;
Adapted from slide 48, Caplan, "Introduction to Laser Communications"

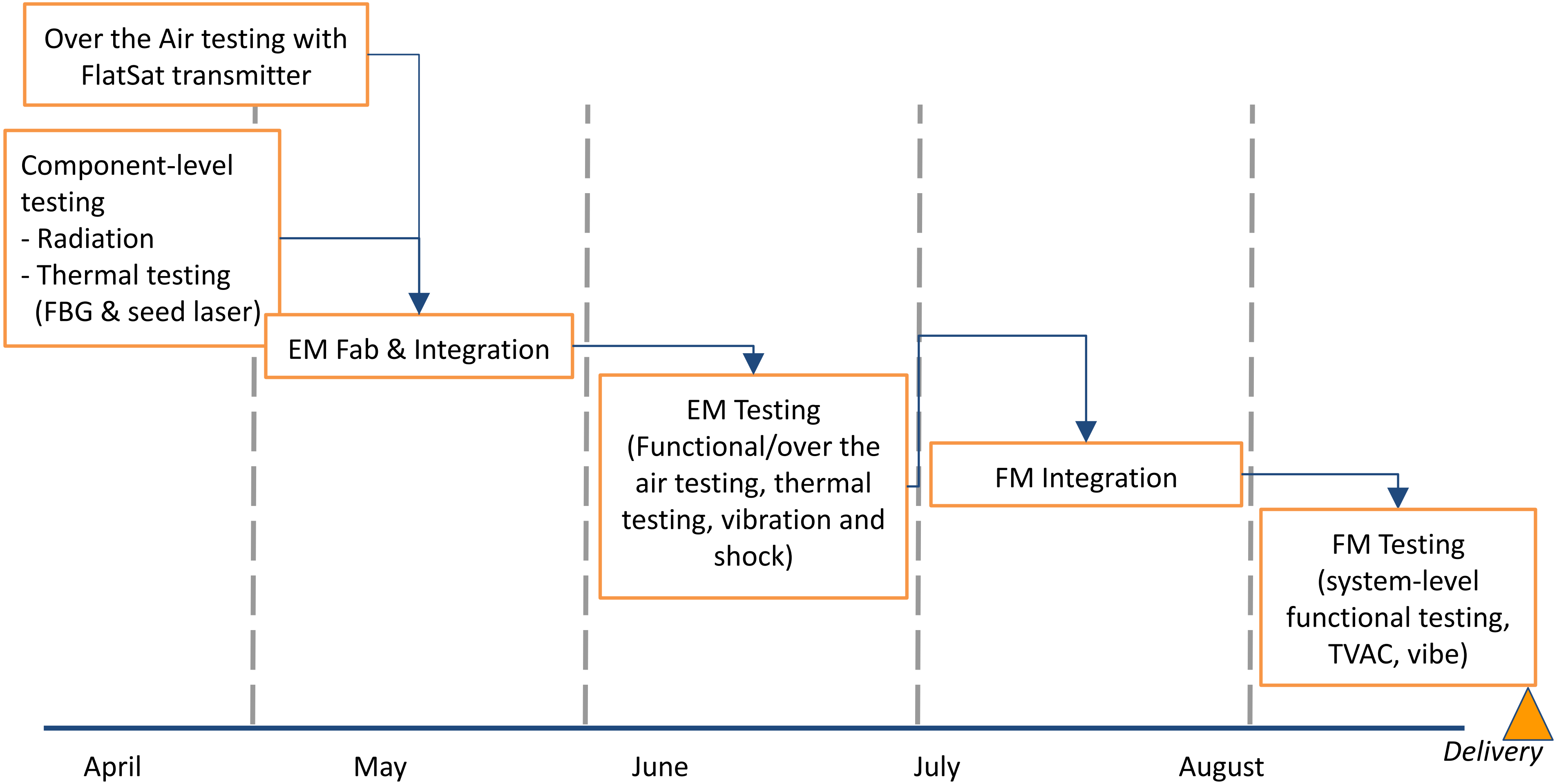
RF and Lasercom Advantages & Challenges

Objective/Metric	Radio Frequency	Lasercom
Data volume, **V**	Large transmit power and aperture size [8](Selva, 2012)	**Higher downlink rates and lower SWAP (highly scalable for future needs)**
	Spectrum availability, large aperture ground station availability	**Cloud cover** hinders access; Addressed by diversity techniques but large networks not available yet
Age of Information, **AoI (latency)**	Depends on data volume	Depends on ability to crosslink, depends on clear line of sight (e.g., cloud cover for downlinking, and ground-station diversity)
Variance data vol. & AoI, **σ^2(V)** and **σ^2(AoI)**	**Link losses are more predictable**	Dependent on atmospheric conditions, variable cloud cover, communication architecture (e.g., diversity techniques, crosslinks, etc.)

- Lasercom could scale to many Gbps, but further prototyping is needed to address challenges

→ **Nanosatellite Optical Downlink Experiment (NODE) goal is to advance technology maturity of low-cost lasercom for CubeSats**

I&T High Level Overview



Over the Air testing with FlatSat transmitter

Component-level testing
- Radiation
- Thermal testing (FBG & seed laser)

EM Fab & Integration

EM Testing (Functional/over the air testing, thermal testing, vibration and shock)

FM Integration

FM Testing (system-level functional testing, TVAC, vibe)

April

May

June

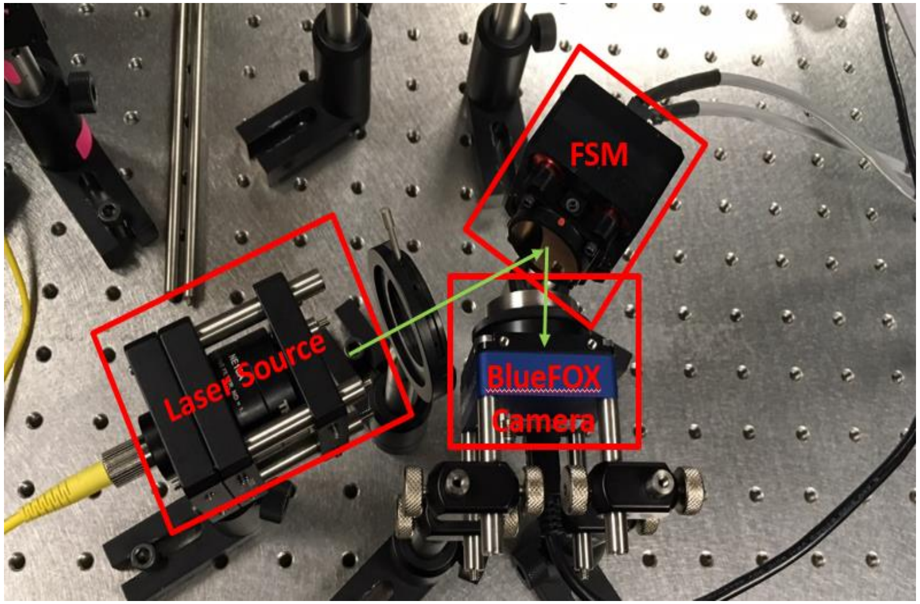
July

August

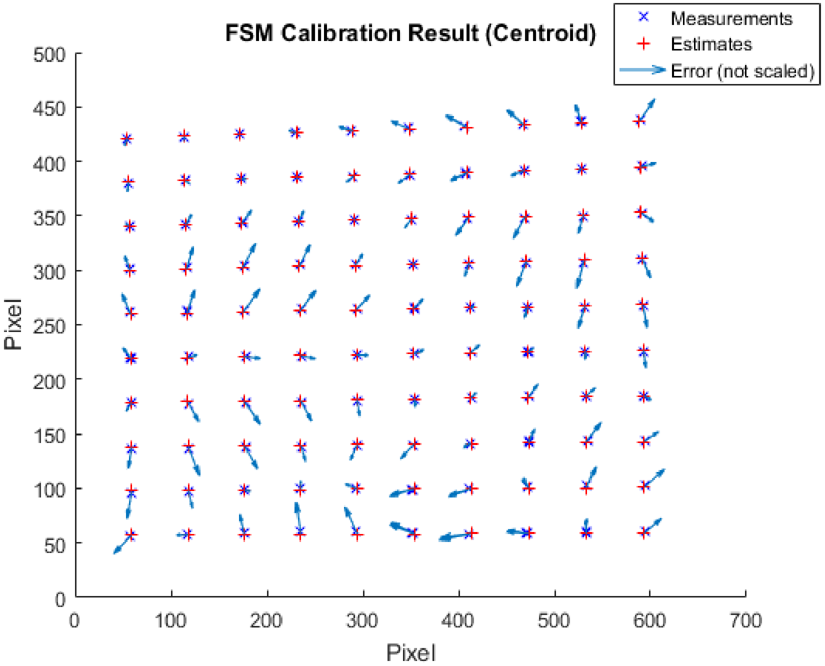
Delivery

Beacon Receiver - Software/Control

- FSM steering angle calibration (lab test)
  - The calibration is done using a grid pattern measurements



Credit: Hyosang Yoon



- RMS error: 0.0189 deg
- This calibration will be done for actual NODE hardware.

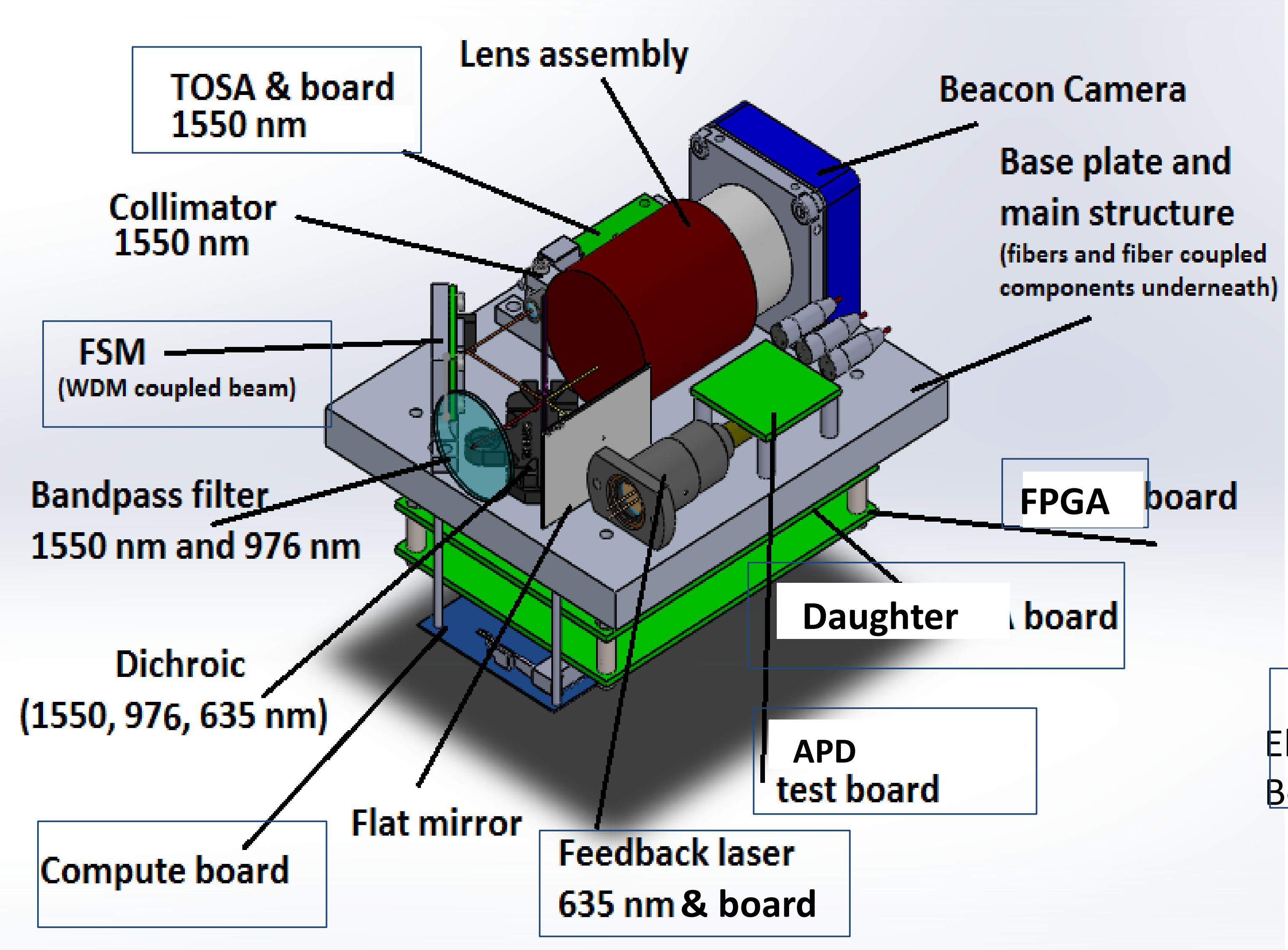
On-Orbit Experiment Objectives

- **Objective: Demonstrate low-cost lasercom downlink at rates > 10 Mbps from a 3U CubeSat to a COTS telescope toward long term goal of >100 Mbps downlinks.**

- Downlink Validation
  - COTS tx components
  - MEMS FSM for fine pointing
  - Power efficiency (built in self test points)
- On-orbit Calibration
  - 635 nm internal cal laser (FSM, misalignments)
  - Uplink beacon receiver
- Pointing Control Validation
  - Cal laser feedback control
  - Beacon receiver feedback control
  - Pointing control expected performance: 0.345 mrad
    - Goal to determine if (and by how much) beamwidth can be reduced in future versions

- Downlinks:
  - OCTL, set up NODE Rx there, use their beacon
  - COTS NODE telescope with NODE Rx and beacon
  - OGS at DLR, use their Rx and beacon
- Ground station testing:
  - BiROS OSIRIS or Flying Laptop OSIRIS to COTS NODE telescope

Payload-Host Mechanical Interface



TOSA & board
1550 nm

Lens assembly

Beacon Camera

Collimator
1550 nm

Base plate and
main structure
(fibers and fiber coupled components underneath)

FSM
(WDM coupled beam)

Bandpass filter
1550 nm and 976 nm

FPGA board

Daughter board

Dichroic
(1550, 976, 635 nm)

APD
test board

Electronic
Boards

Compute board

Flat mirror

Feedback laser
635 nm & board

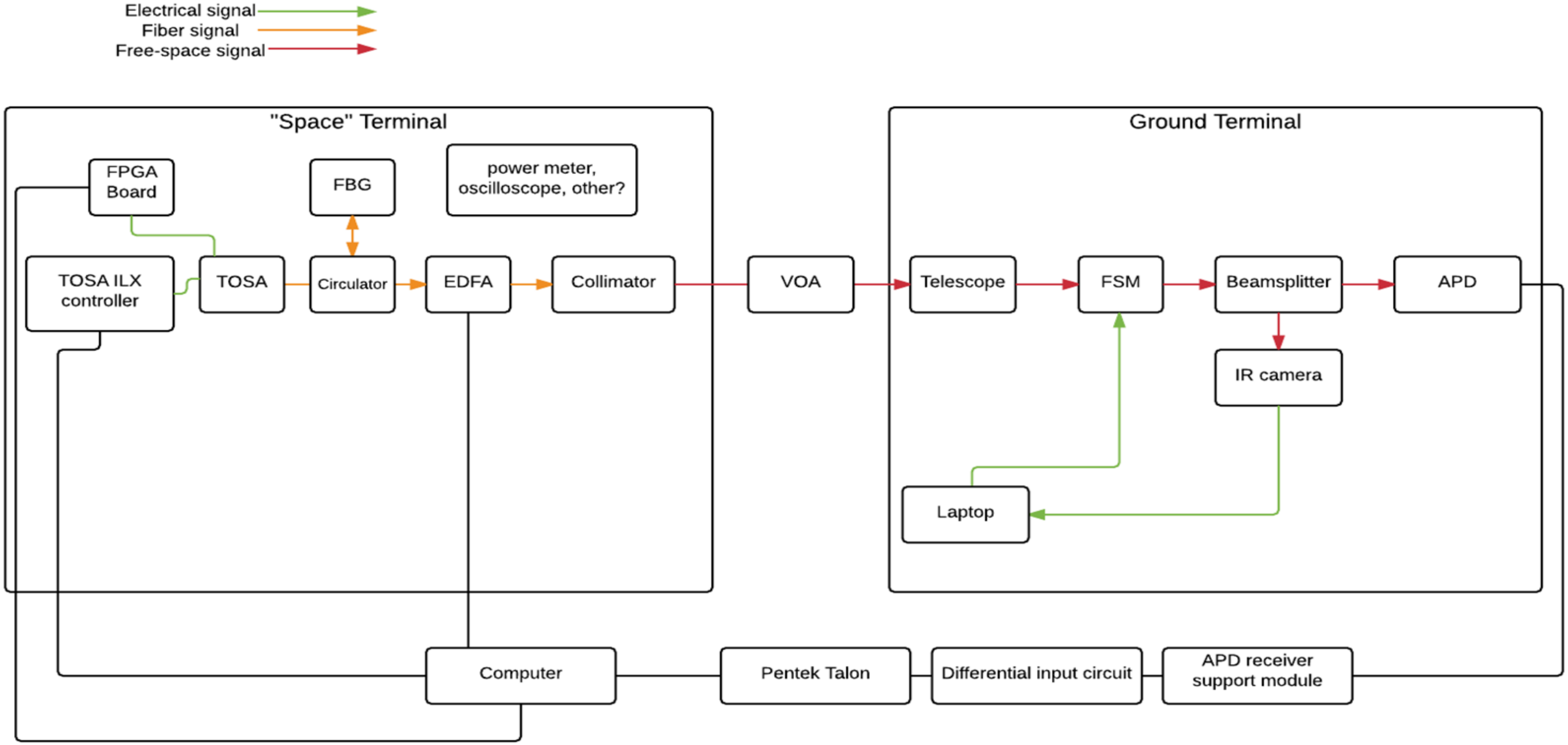
Figure Credit:
Max Khatsenko

Downlink Pointing Error Budget

Item	Specification	Note
Body Pointing Error (expected)	<0.5 deg	This is within the beam steering range of 2.5 deg.
Stability (expected)	<0.06 deg/sec	Orbital angular rate (0.065 deg/sec)
Beacon Receiver Error	20 arcsec = 0.00556 deg (1**σ**)	iFoV of the beacon receiver
FSM Angle Calibration Error (with I-contoller)	0.00189 deg (1**σ**)	Assuming the integral feedback controller reduces the error to 1/10 of the open loop calibration error or 0.0189 deg.
Time Delay Error	0.003 deg (1**σ**)	0.06 deg/sec * 50 ms (beacon camera's frame rate of 20 Hz, for two [3.6 deg x 2.7 deg] windows)
Expected Pointing Error	0.00659 deg (1**σ**) or 0.0197 deg (3**σ**)	Square root sum of the errors (with integral controller)
Pointing Requirement	0.65 mrad = 0.037 deg	A half of beamwidth

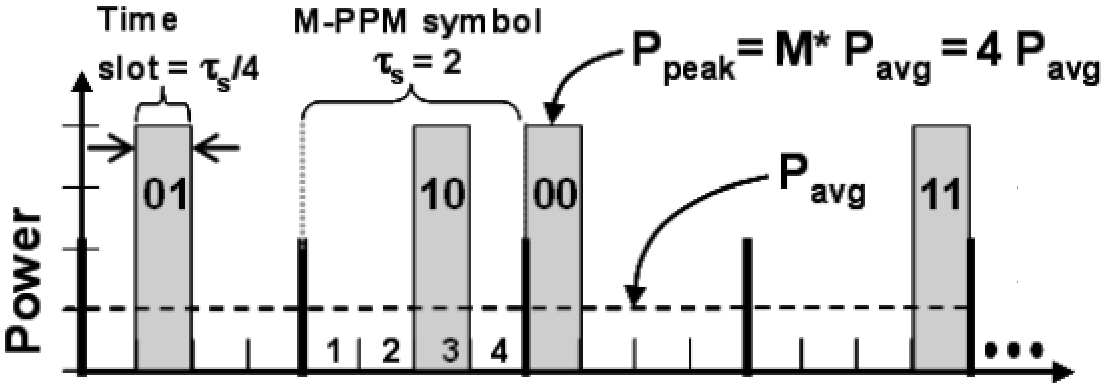
Over-the-Air Testing

- Purpose: demonstrate over-the-air testing, test ground station algorithms, and collect data for post-processing

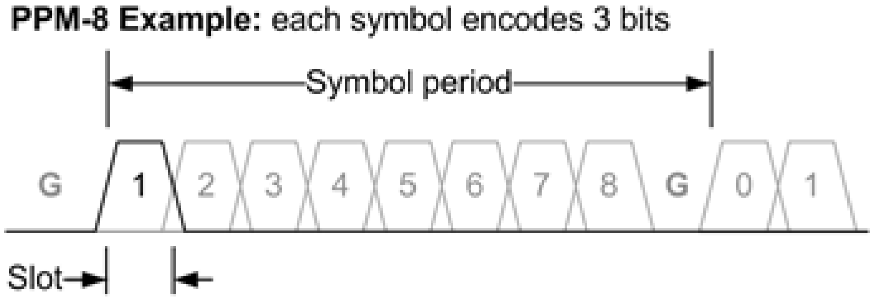


Credit: Emily Clements, Caleb Ziegler

PPM Diagrams



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



Credit: Ryan Kingsbury

Link Performance Modeling

Nominal Link Budget for NODE (LEO, CubeSat, downlink-only)

	NODE	Units
Datarate	43	Mbps
P_{tx}	-7.0	dBW
G_{tx}	69.6	dB
L_{tx}	-1.5	dB
$L_{freespace}$	-258.2	dB
L_{atm}	-1.0	dB
G_{rx}	114.7	dB
L_{rx}	-3.0	dB
P_{rx}	-78.0	dBW
P_{req}	-84.2	dBW
Margin	**6.2**	dB

Table from Clements et al. (2016)[15]

Alternative modeling approach estimates input uncertainties and creates CDFs of link margin

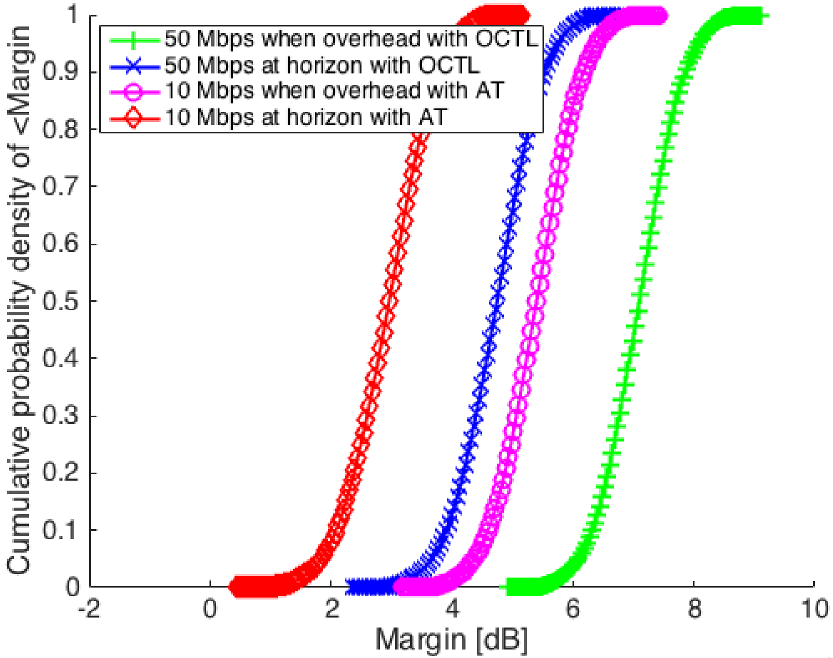


Figure from Clements, Cahoy (2017)[21]

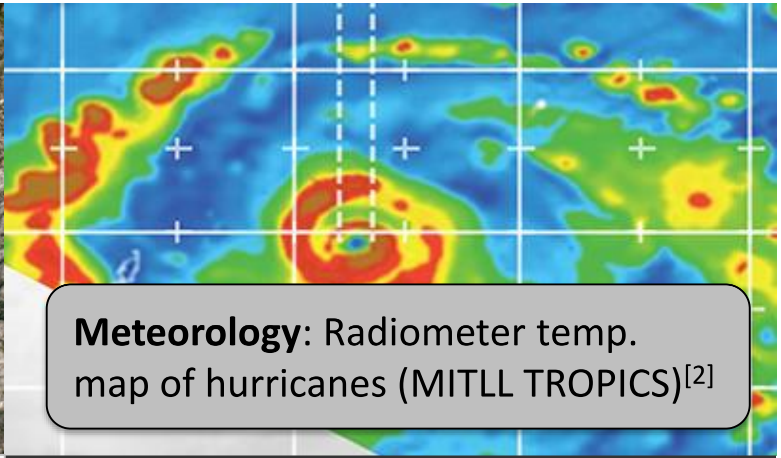
Can model deterministically or through Monte Carlo analysis

E.g., for NODE (MIT CubeSat lasercom downlink payload in development for resource-constrained systems)

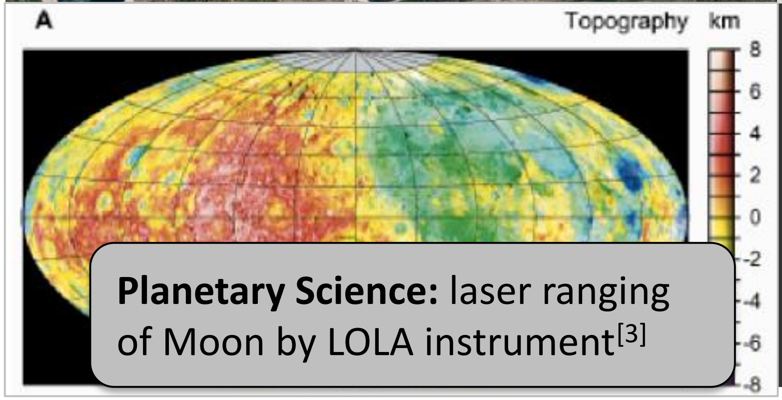
Missions can benefit from lasercom

Satellite data are used to provide insight into many problems, such as…

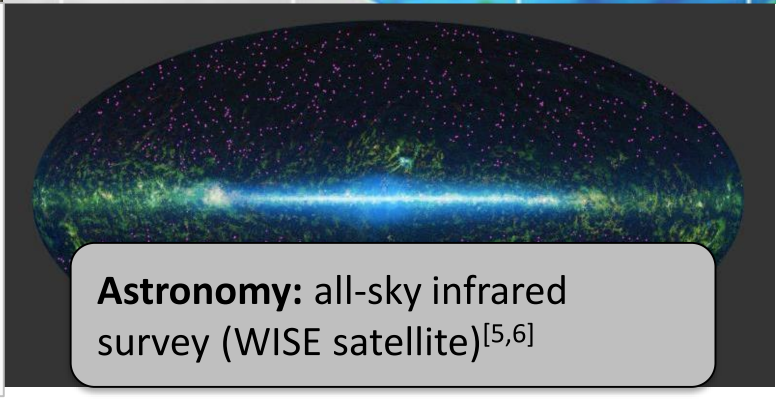
Local issues: Images of California draught (Planet Labs Inc.)[1]



Meteorology: Radiometer temp. map of hurricanes (MITLL TROPICS)[2]



Planetary Science: laser ranging of Moon by LOLA instrument[3]



Astronomy: all-sky infrared survey (WISE satellite)[5,6]

Can <u>relaxed data constraints</u> enable new capabilities?

Utility for Small Satellite Missions

- Small satellites offer a cost-effective solution to global coverage w/ improved temporal resolution
- Data need metrics are: Volume of data downlinked, Timeliness/latency

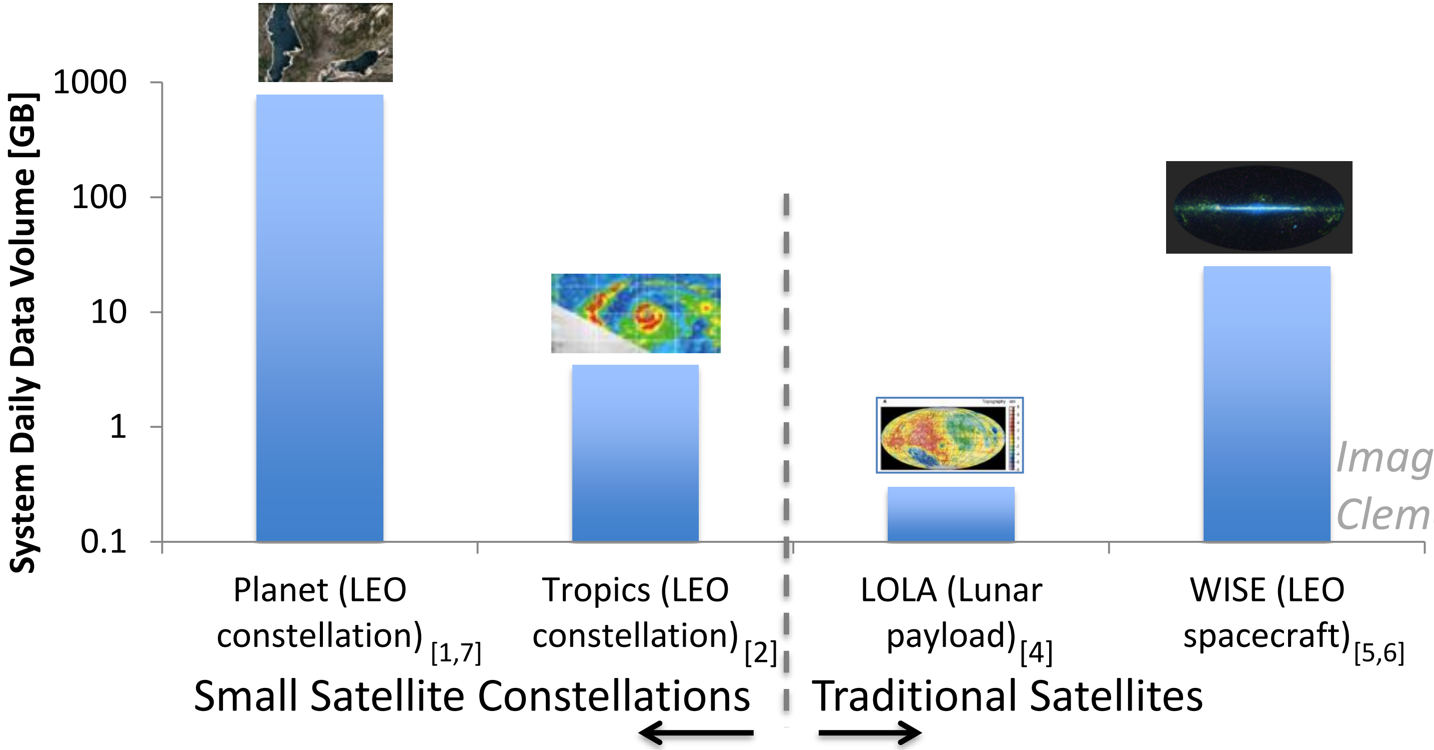


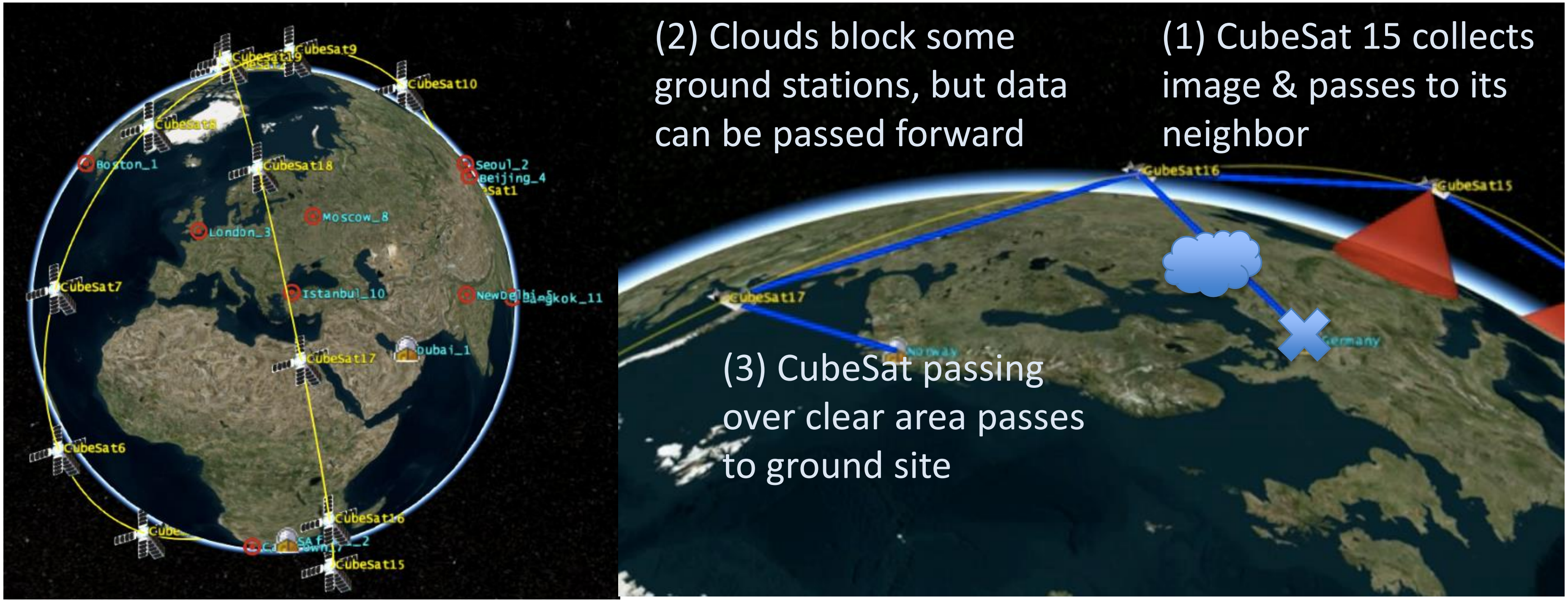
Image credit: Clements (2017)

Systems of small satellites can produce as much data as traditional satellites

Constellation Opportunities

Problem: capacity saturation of ground stations for constellations of satellites with high datarate downlink needs

Solutions: (i) Many inexpensive ground terminals, (ii) Crosslinks



(2) Clouds block some ground stations, but data can be passed forward

(1) CubeSat 15 collects image & passes to its neighbor

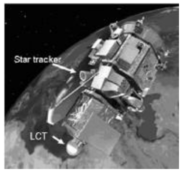
(3) CubeSat passing over clear area passes to ground site

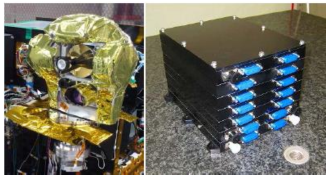
Visualization of Earth-observing small satellite mission using laser communication

Figure credit: A. Kennedy

SmallSat* Lasercom Missions

SmallSat Lasercom Tech. Demos





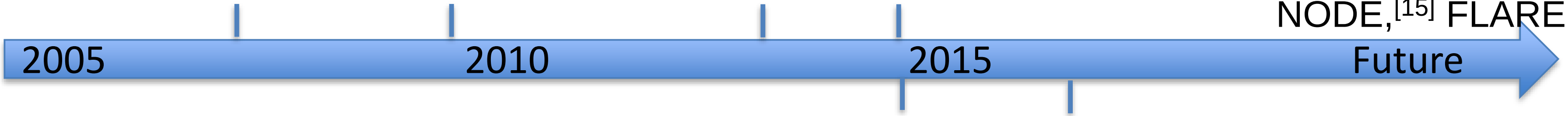
NFIRE-TerraSAR-X[9]
5.6 Gbps,
LEO crosslink

NFIRE LCT[10]
5.625 Gbps,
LEO downlink

LLCD[11]
622 Mbps
Lunar downlink

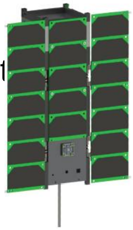
SOTA[12]
10 Mbps,
LEO downlink

OCSD[15]
NODE,[15] FLARE



BRITE[13]
0.0115°

MINXSS[14]
0.002° pointing, first
flight of Blue Canyon
rxn wheels



Missions that Advance Supporting Tech.

Related: UAV lasercom:

Facebook Aquila[17]
Optical crosslinks between aircraft

Google Loon[18]
155 Mbps crosslink,
balloon lasercom system

*Defined SmallSat as <500 kg[19]

Link Performance Modeling

- Received power is a function of gains and losses throughout the system:

Data → **Transmitter** → **Optics** → **Channel** → **Optics** → **Receiver** → $\widehat{\textbf{Data}}$

$$P_{\text{Tx}}\underset{\underset{\left(\frac{\pi D_{tx}}{\lambda}\right)^2}{\uparrow}}{G_{Tx}}L_{\text{Tx}}L_{\text{Tx.point.}}\underset{\underset{\left(\frac{\lambda}{4\pi R}\right)^2}{\uparrow}}{L_{FS}}L_{\text{atm}}\underset{\underset{\left(\frac{\pi D_{\text{rx}}}{\lambda}\right)^2}{\uparrow}}{G_{Rx}}L_{\text{Rx}}L_{\text{Rx.point.}}\eta = P_{\text{rx}}$$

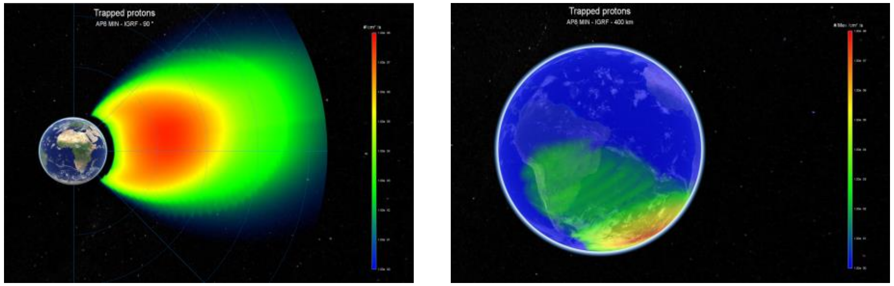
Aside: equations same as RF! →

Data rate is proportional to P_{Rx}

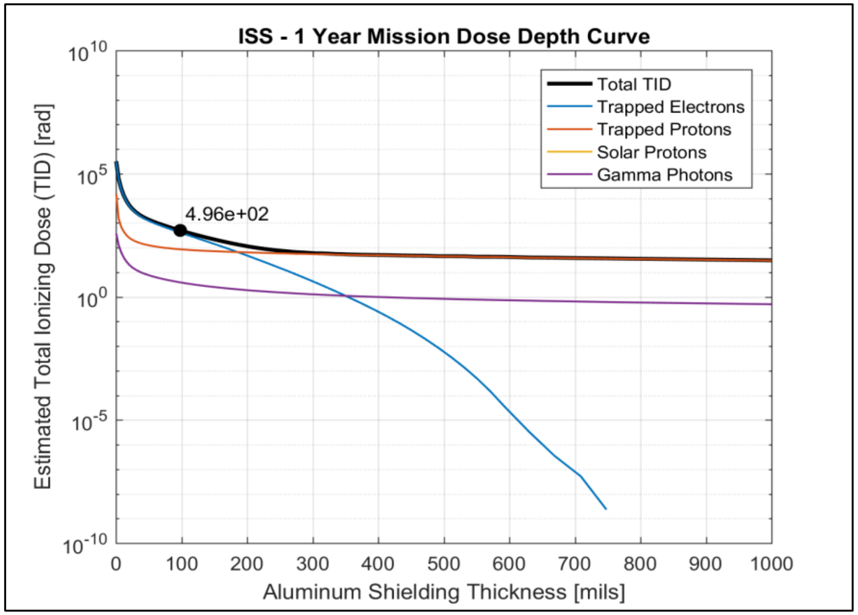
Figure adapted from Figure 2, Caplan, David O. "Laser communication transmitter and receiver design." Journal of Optical and Fiber Communications Reports 4.4-5 (2007): 225-362.

Component-level Qualification - Radiation Environment

- OMERE radiation software used to simulate the space radiation environment for 1-year ISS orbit mission
- Radiation Sources
  - Trapped protons & electrons in inner radiation belt
  - Heavy ions & protons from Galatic Cosmic Rays (GCRs)
  - Solar ions & protons
- Mission Radiation Requirement:
  - Expected Total Ionizing Dose (TID) for 100 mils Al shielding: ~0.50 krad.
  - **2x Margin TID Requirement: ~ 1 krad for 100 mils Al shielding**



1 MeV Trapped Protons. Left - Trapped protons along radiation belts. Right - Concentration of trapped protons in South Atlantic Anomaly



Mission Dose Depth Curve