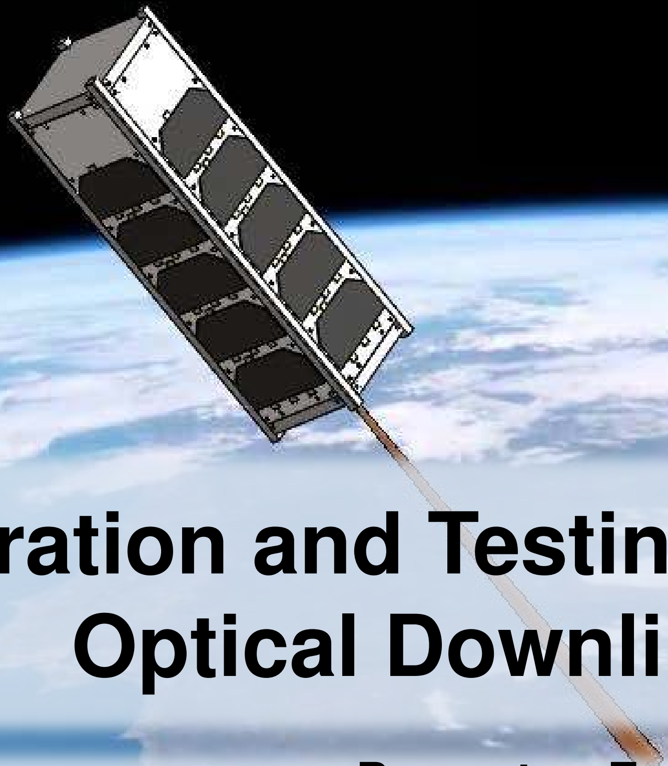


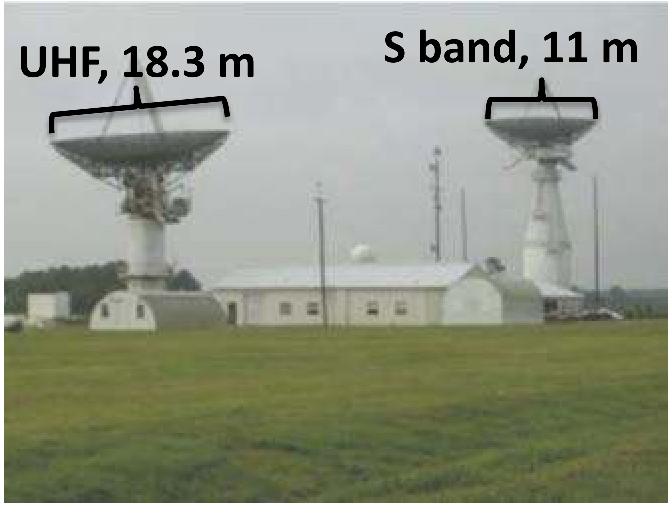
Integration and Testing of the Nanosatellite Optical Downlink Experiment

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, Olek Peraire-Bueno, Jan Heyns, Mia LaRocca, Ethan Munden, Santiago Munoz, Robert Silvestri, Marek Subernat, Alyanna Villapando, Aaron Wubshet, Alex Forsey

Motivation

- What if there were a **low cost** way for a CubeSat to downlink 100 Gb/day?
  - Most CubeSats downlink << 10 Gb/day (UHF or S-band systems) [1]
- Radio frequency (RF) downlinks challenged by resource constraints
  - E.g., ground station size, transmitter power, or spectrum
- **Lasercom is less resource constrained and could scale to Gbps[3]**
  - More power-efficient for given size, weight, and power (SWaP)
  - More bandwidth available
  - Many groups working on it: MIT, Aerospace Corporation, Sinclair, UF, DLR, JAXA, …

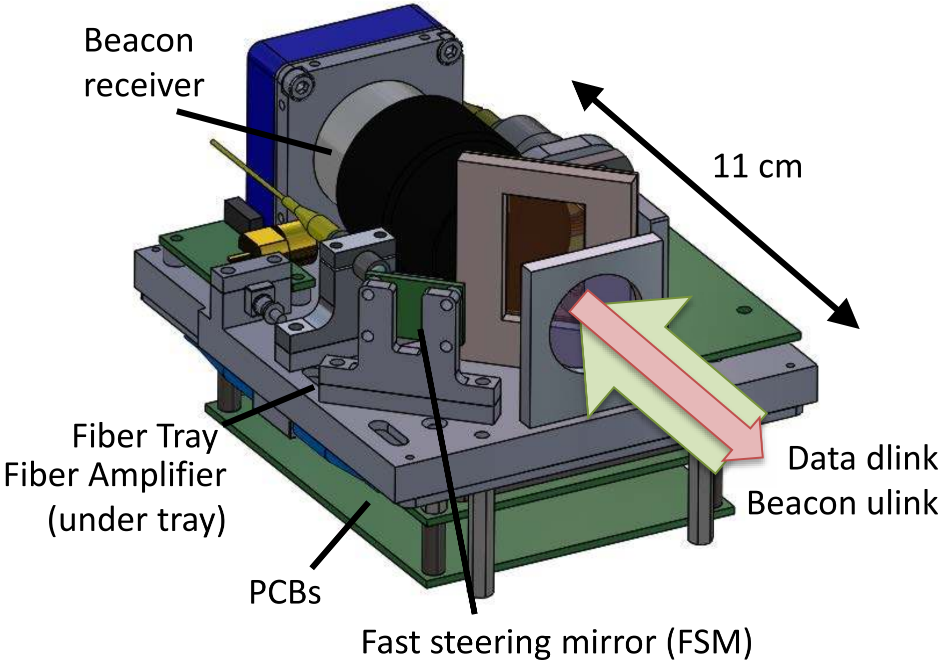


Wallops CubeSat Comm. Antennas[2]

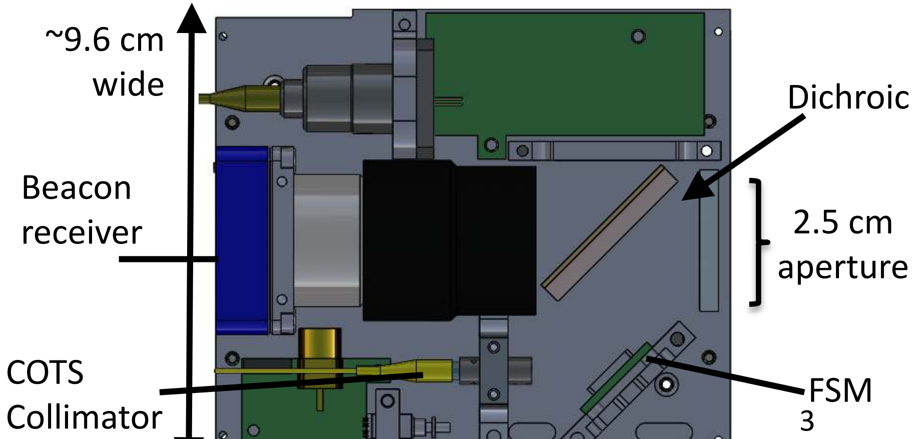
MIT Lasercom Ground Station

NODE Space Terminal Overview

Scope	CubeSat **Low-Cost** Payload (<$15k parts)
Architecture	Direct detection MOPA COTS telecom parts (1550 nm)
Downlink data rates	10 Mbps (30 cm amateur telescope) 100 Mbps (1 m OCTL)
Power	0.2 W (transmit power), 15 W (consumed power)
Beamwidth	1.3 mrad half power (initial demo)
Modulation	PPM
Coding	RS(255,239)
Mass, Vol.	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)
Current Status	• Pointing control testing • Component-level environmental tests • Functional testing • End-to-end over the air demo



M. Khatsenko, J. Heyns



D. Barnes

NODE Ground Terminal Overview

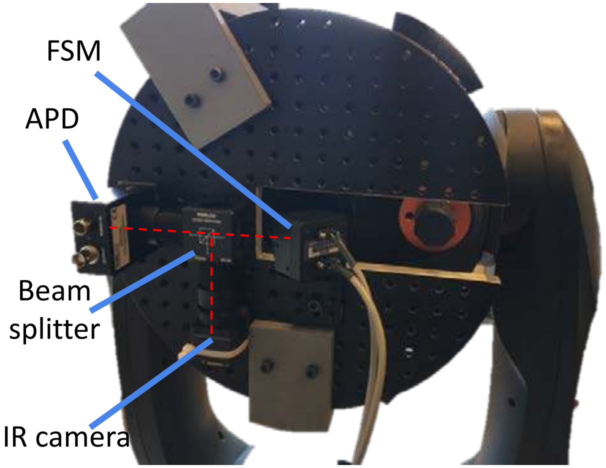
Downlink with NODE amateur telescope:

Data rate	10 - 50 Mbps
Receiver Diameter	30 cm
Detector	Direct detection w/ Voxtel APD
Receiver electronics	NODE electronics (APD & custom electronics)
Pointing	IR camera and star tracker [19] FSM to keep spot on APD (no AO)
Uplink beacon	OCTL beacon[14] (976 nm, 10 W tx power, 1 mrad beam)
Current Status	Satellite tracking, over the air data transfer

E. Clements

Downlink with JPL OCTL telescope:

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

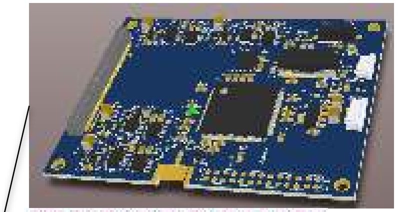
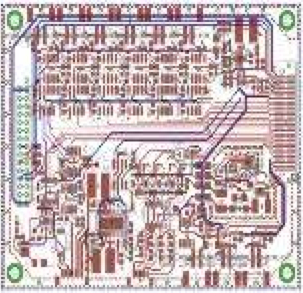
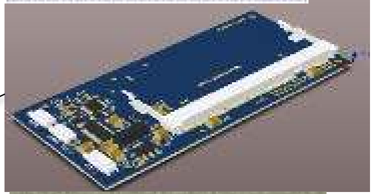


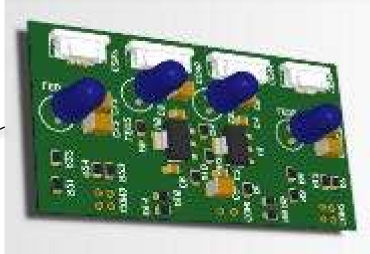
K. Riesing, H. Yoon [13]

Transmitter Electronics Boards

- On track for full engineering unit by September

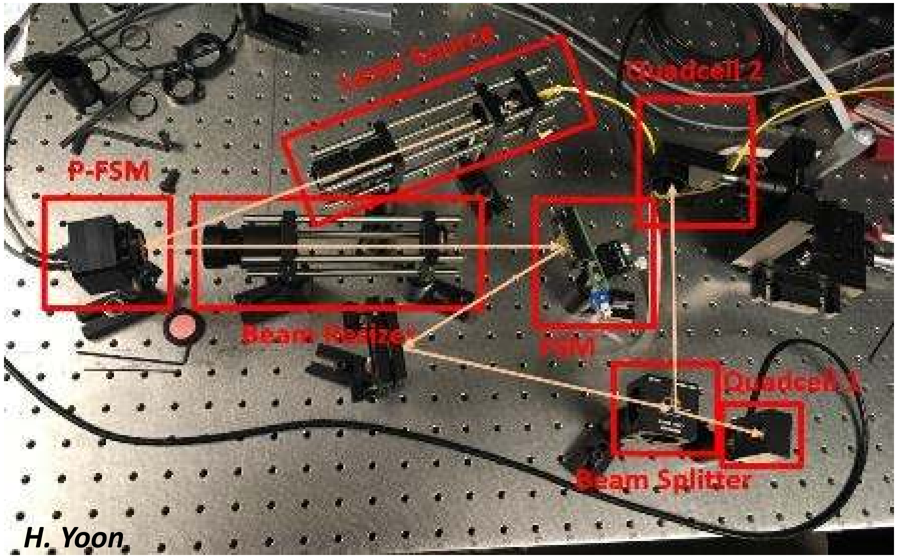
Name	Function	Status
FPGA Board	Modulation, built-in-self-test	Design finished
Daughter Board	TOSA temp and current control, sensor readouts, FSM driver	Fabricated
RPI baseboard CPU	Attitude control computation, encoding / decoding, interleaving / deinterleaving	Fabricated
Photodiode Board	APDs for built-in-self-test	Under design
TOSA Board	Breaks out TOSA	Fabricated
Feedback Laser Board	Breaks out calibration laser diode	Under design
Breakout board	Breaks out CPU	Design finished



Space Terminal Pointing Control

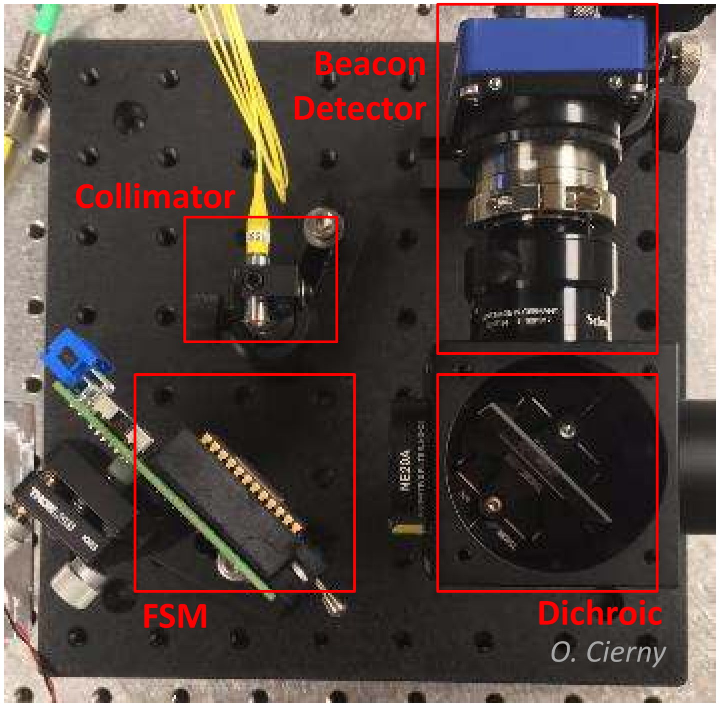
- Hardware demo of realistic spacecraft disturbances
  - The ones you see on the screen have (**18.687** mean, **41.839** 1-σ) **arcseconds** error which is realistic for a **star tracker-only CubeSat** system.
  - Once the fine pointing control is activated, we have shown in hardware (**0.7398** mean, **0.4606** 1-σ) arcseconds error.
  - **Quadcell detector** is the limiting factor of system performance



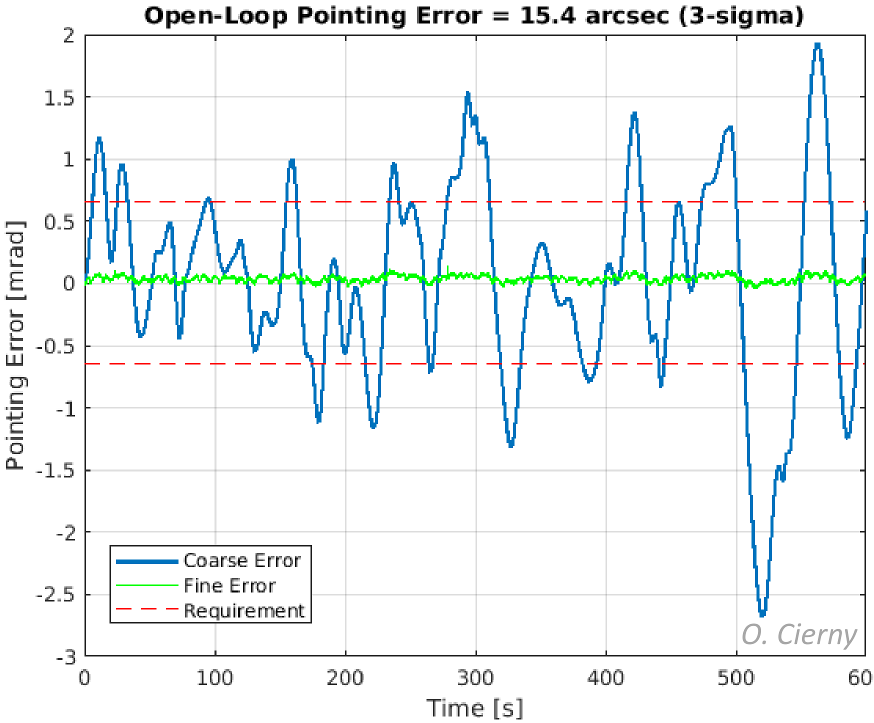
H. Yoon

Pointing Control w/ Feedback Laser

- CubeSat slewing in LEO w/ bus control of 0.1 deg accuracy (2-σ), 0.015 deg/s stability (2-σ), and 1 deg misalignment
- Fine pointing demonstrated to **15.4 arcsec (75 µrad, 0.004 deg) 3-σ**, well within our 130 arcsec (630 µrad, 0.036 deg) requirement.



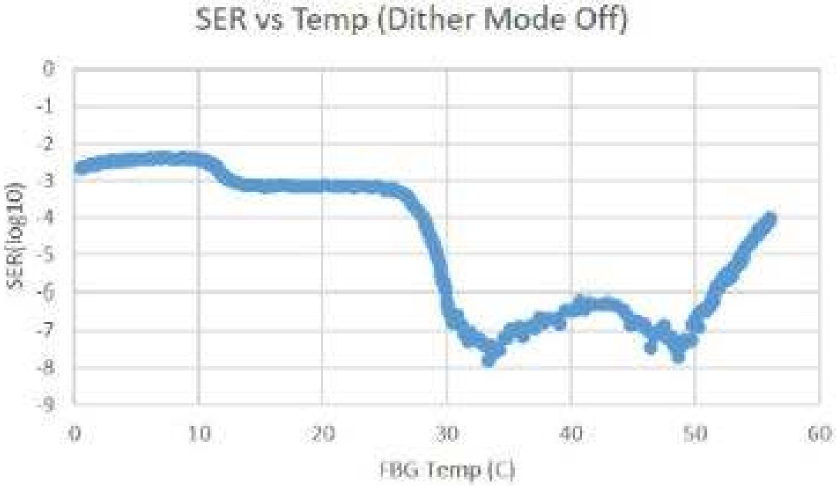
Hardware-in-the-loop Test Setup

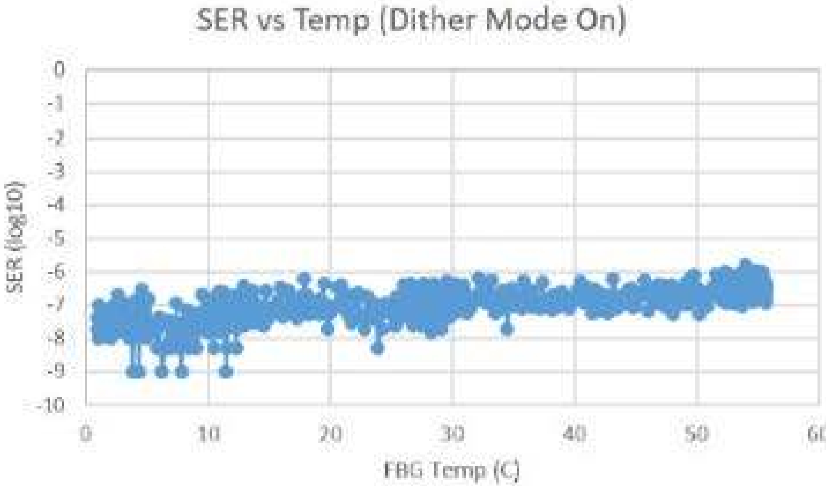


Hardware-in-the-loop Test Results

Wavelength Alignment

- Seed laser wavelength varies with temperature, current
- Slot Error Rate (SER) worsens with wavelength variation
- Active control improves SER
- Improvement w/ feedback control
  - Use photodiodes for built in self test
  - SER goes from (10^{-7}, 10^{-2}) to (10^{-8}, 10^{-6})

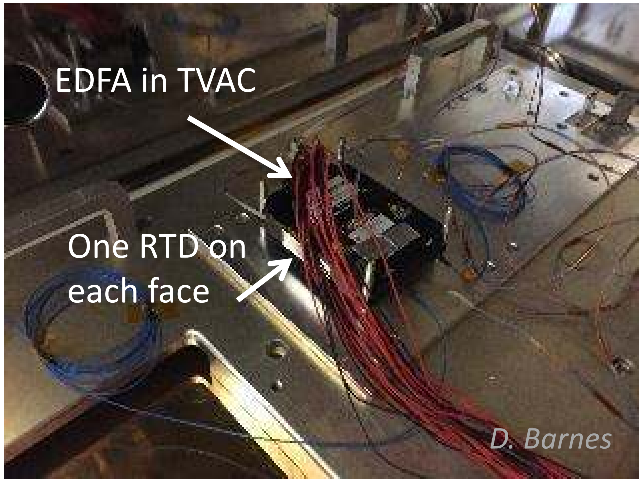


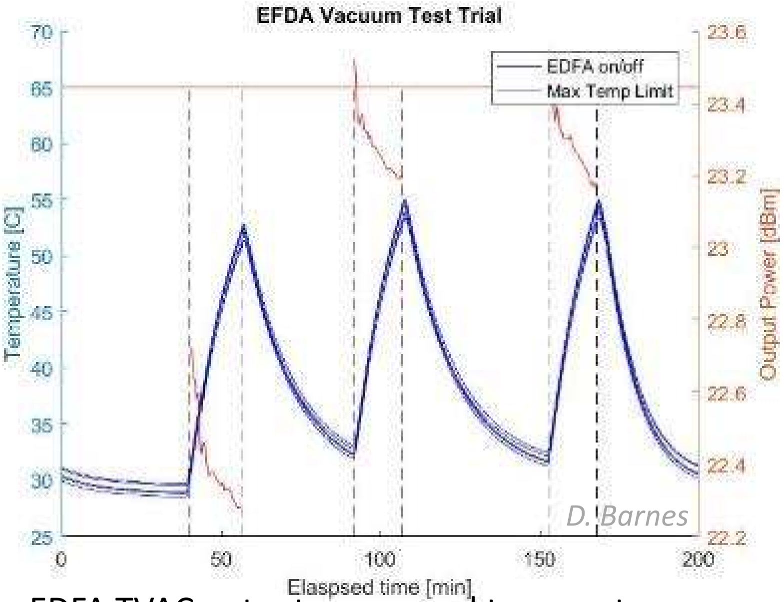


M. Lee [14]

Component Qualification: TVAC

- Qualified 200 mW NuPhoton EDFA for vacuum operation
- Tested at hot case of 30° C
- Tested for 3 downlink passes
  - 15 minute CW operations
  - 20 - 24 dBm output (23 dBm expected on-orbit)
- **COTS EDFA works fine in vacuum for 15 minute downlinks**





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

EDFA Total Ionizing Dose Radiation Testing

- 200 mW NuPhoton EDFA
- TID of 1 krad and 3 krad, dose rate of 5 krad/min
  - Passive Test: EDFA not powered
- ISS orbit for 1 year sees ~0.5 krad
- Results
  - After 1 krad (2 year dose): nominal
  - After 3 krad (6 year dose): no optical output power after irradiation, but normal after 24 hrs
- Important note: NuPhoton does have space-rated EDFAs, but these were not space-rated, just COTS

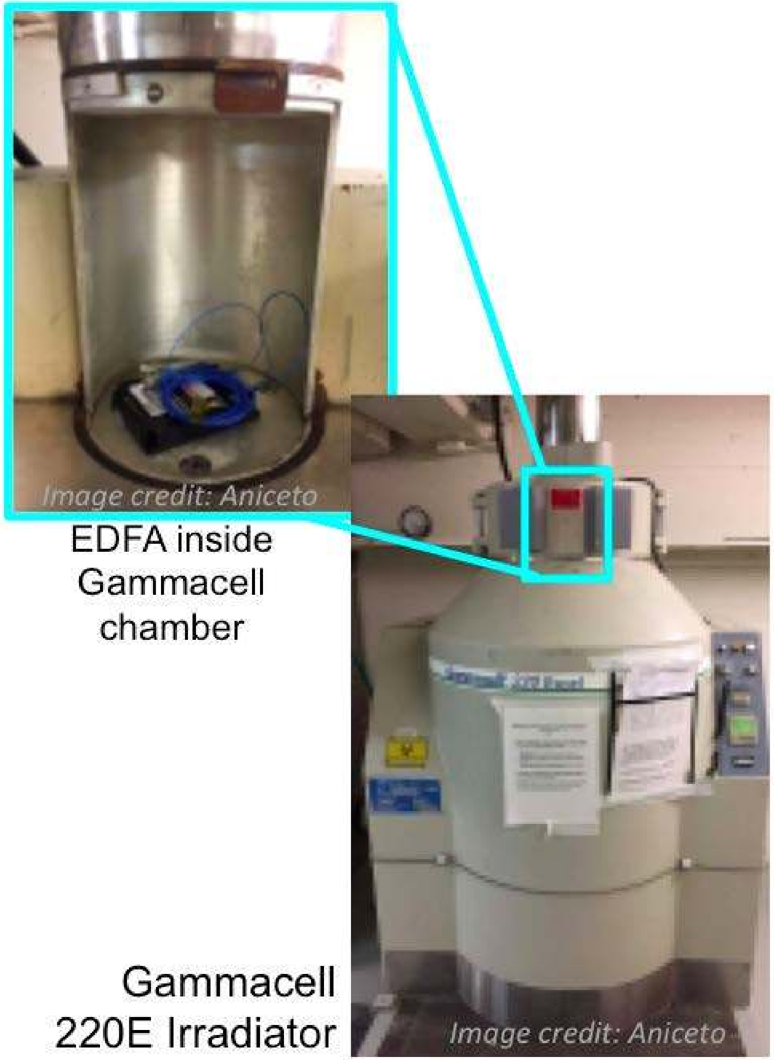


Image credit: Aniceto

EDFA inside Gammacell chamber

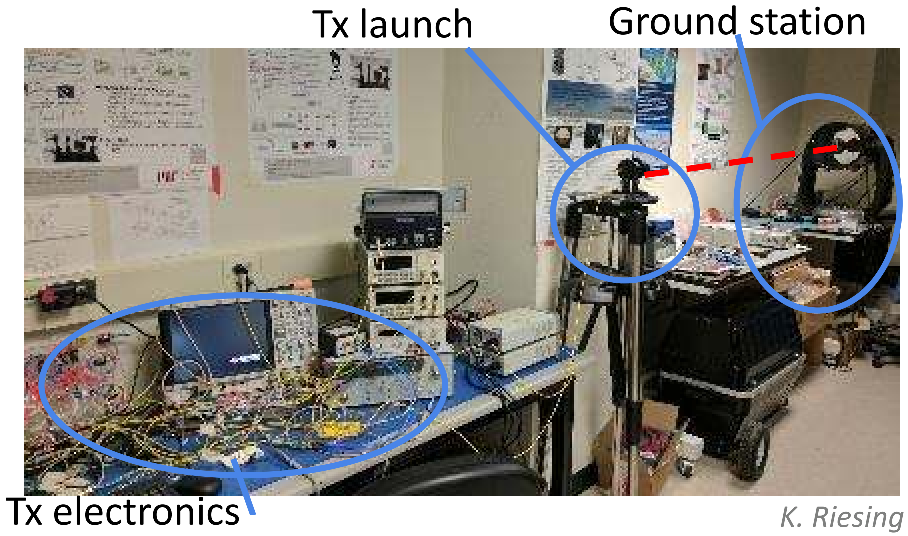
Gammacell 220E Irradiator

Image credit: Aniceto

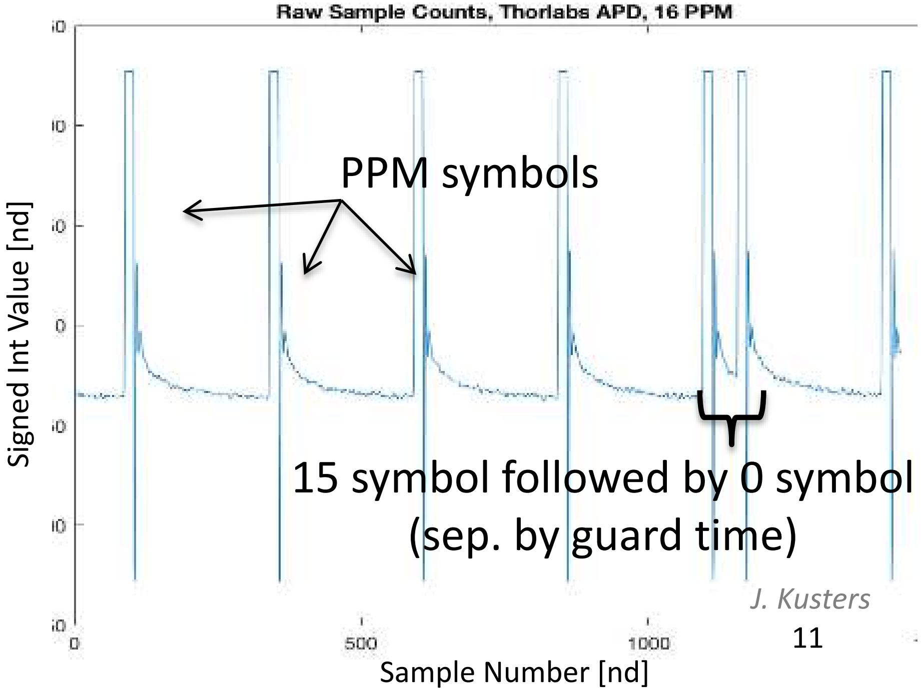
Test performed by R. Aniceto with MIT Bioengineering Dept. Gammacell 220E Chamber, Cobalt-60

Over-the-Air Testing

- Successfully transmitted data from NODE transmitter electronics to ground station over the air
- Initial tests conducted in lab
  - ThorLabs APD (APD110C)
  - 16-PPM
  - 12 samples per slot, 8 bits per sample
  - No coding, no interleaving
- Next steps: improve mounting, integrate Voxtel APD receiver



K. Riesing



PPM symbols

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

J. Kusters

Conclusion & Next Steps

- NODE goal is to advance technology maturity of low-cost, low-complexity lasercom for CubeSats

- Progress summary
  - Space Terminal: pointing control, environmental testing of COTS telecom parts
  - Ground Terminal: satellite tracking and over-the-air testing

- Next Steps
  - Complete engineering unit (September 2017)
  - Build and test flight unit (October 2017)

Learn more about MIT lasercom at Rachel Morgan's student presentation on crosslinks, 10:45 am Wednesday!

Backup

NODE Test Plan

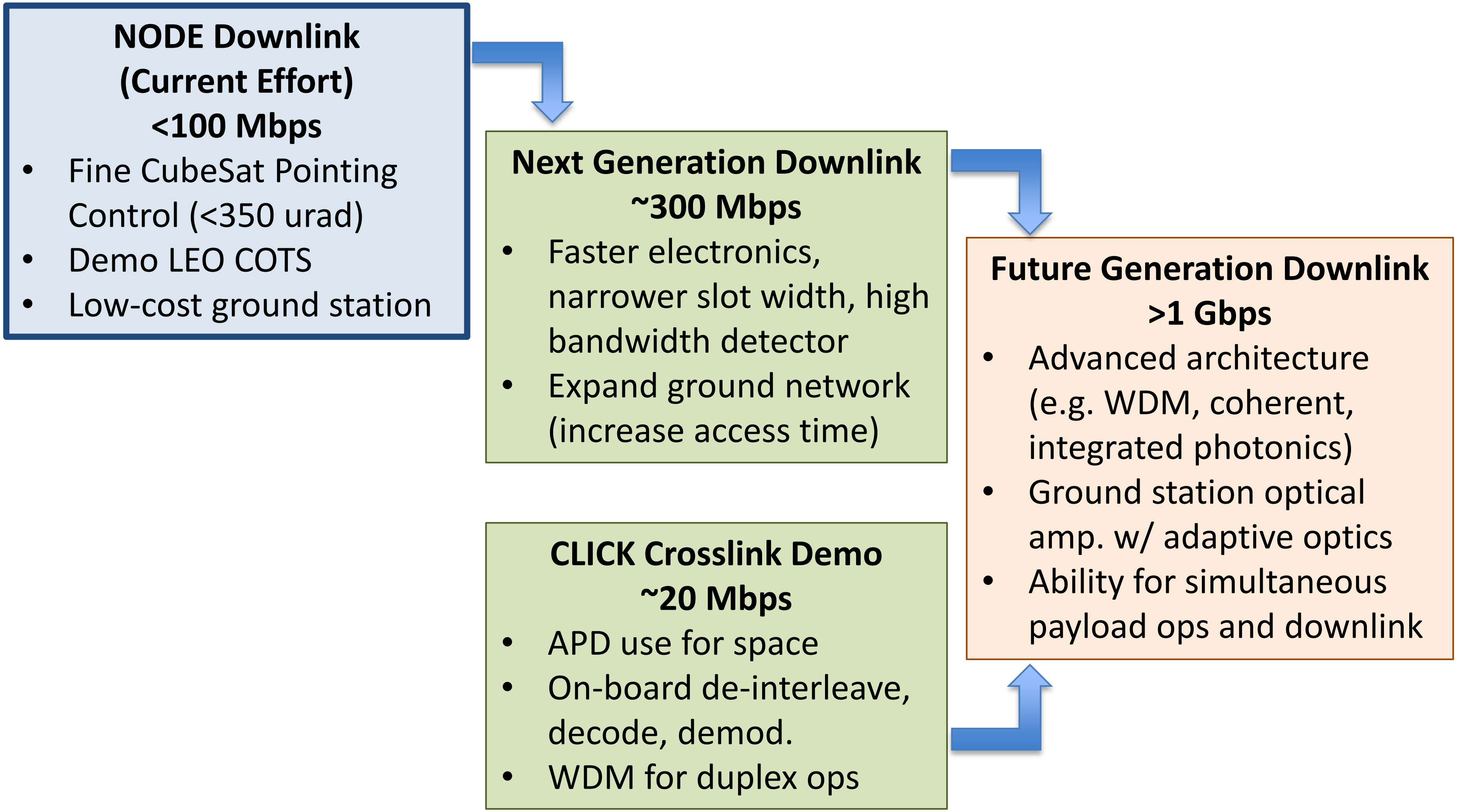
Test	Component-level	Payload Eng. Model	Payload Flight Model
Functional and Over the Air testing	limited, e.g. board-level functional tests and pointing control tests	In progress, Sept. completion	NODE Tx to NODE OGS (Oct.) NODE OGS: Dlink from DLR* (date TBD)
Radiation Testing	EDFA (complete)		
Vibration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

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]

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)

CLICK 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

Bibliography

[1] 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.

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

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[6] http://www.sinclairinterplanetary.com/opticalcomms

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