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, …

[1]Reference 1
[2]Reference 2
[3]Reference 3
## NODE Space Terminal Overview

<table>
<thead>
<tr>
<th>Scope</th>
<th>CubeSat <strong>Low-Cost</strong> Payload (&lt;$15k parts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Architecture</td>
<td>Direct detection MOPA</td>
</tr>
<tr>
<td></td>
<td>COTS telecom parts (1550 nm)</td>
</tr>
<tr>
<td>Downlink data rates</td>
<td>10 Mbps (30 cm amateur telescope)</td>
</tr>
<tr>
<td></td>
<td>100 Mbps (1 m OCTL)</td>
</tr>
<tr>
<td>Power</td>
<td>0.2 W (transmit power), 15 W (consumed power)</td>
</tr>
<tr>
<td>Beamwidth</td>
<td>1.3 mrad half power (initial demo)</td>
</tr>
<tr>
<td>Modulation</td>
<td>PPM</td>
</tr>
<tr>
<td>Coding</td>
<td>RS(255,239)</td>
</tr>
<tr>
<td>Mass, Vol.</td>
<td>1.0 kg, 1 U</td>
</tr>
<tr>
<td>Control architecture</td>
<td>• Bus coarse pointing (&lt;0.5°)</td>
</tr>
<tr>
<td></td>
<td>• FSM fine steering (+/- 2.5°)</td>
</tr>
<tr>
<td></td>
<td>• Beacon receiver (976 nm) for pointing</td>
</tr>
<tr>
<td></td>
<td>knowledge (20 arcsec)</td>
</tr>
<tr>
<td>Current Status</td>
<td>• Pointing control testing</td>
</tr>
<tr>
<td></td>
<td>• Component-level environmental tests</td>
</tr>
<tr>
<td></td>
<td>• Functional testing</td>
</tr>
<tr>
<td></td>
<td>• End-to-end over the air demo</td>
</tr>
</tbody>
</table>

- **Beacon receiver**
- **Fast steering mirror (FSM)**
- **Fiber Tray**
- **Fiber Amplifier** (under tray)
- **PCBs**
- **Dichroic**
- **COTS Collimator**
- **Data dlink**
- **Beacon ulink**
- **2.5 cm aperture**
- **11 cm**
- **~9.6 cm wide**
- **M. Khatsenko, J. Heyns**
## NODE Ground Terminal Overview

### Downlink with NODE amateur telescope:

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

[^14]: E. Clements
[^19]: K. Riesing, H. Yoon

### Downlink with JPL OCTL telescope:

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data rate</strong></td>
<td>50 - 100 Mbps</td>
</tr>
<tr>
<td><strong>Receiver Diameter</strong></td>
<td>1 m</td>
</tr>
<tr>
<td><strong>Receiver electronics</strong></td>
<td>NODE electronics (APD &amp; custom electronics)</td>
</tr>
<tr>
<td><strong>Uplink beacon</strong></td>
<td>976 nm, 10 W tx power, 1 mrad beam</td>
</tr>
</tbody>
</table>
Transmitter Electronics Boards

- On track for full engineering unit by September

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

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

```
<table>
<thead>
<tr>
<th>Sample Number [nd]</th>
<th>Signed Int Value [nd]</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>124</td>
</tr>
</tbody>
</table>
```

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

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

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

*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.


