Weather Sensing and Laser Communications for Nanosatellites
Kerri Cahoy, MIT AeroAstro
Why Space? Above the Atmosphere

Gamma Rays, X-Rays and Ultraviolet Light blocked by the upper atmosphere (best observed from space).

Visible Light observable from Earth, with some atmospheric distortion.

Most of the Infrared spectrum absorbed by atmospheric gasses (best observed from space).

Radio Waves observable from Earth.

Long-wavelength Radio Waves blocked.

[http://www.ipac.caltech.edu/outreach/Edu/Windows/irwindows.html]
Above the Atmosphere

[http://www22.homepage.villanova.edu/rex.saffer/SESAME/radiation_files/transatmos.jpg]
Overview

• Introduction
  – CubeSats 101

• Communications
  – NODE
    • Laser communication downlink

• Laser Occultation
  – Bending angle and T,P profile recovery
    • GPS Radio Occultation for validation

NanoRacks deployment of MicroMAS from the ISS Japanese Experiment Module Remote Manipulator System (JEMRMS). Photo courtesy NASA/NanoRacks
Satellite Classification

- Small Satellite < 500 kg (all wet mass)
- Microsatellite 10 – 100 kg
- Nanosatellite 1 — 10 kg
- Picosatellite 0.1 kg – 1 kg
- Femtosatellite < 0.1 kg
- CubeSat 1U 10 cm x 10 cm x 10 cm cube
- 1U as a building block
- 1.5U, 2U, 3U, 6U, 12U...
CubeSats 101

• On the scene in 1999
  – Jordi Puig-Suari (Cal Poly SLO)
  – Bob Twiggs (Stanford)
  – “OPAL” Orbiting Picosatellite Automatic Launcher
  – Too complicated
  – “Beanie babies” vs. “Klondike bars”

• 1 standard CubeSat unit (1U)
  – Volume: 10 x 10 x 10 cm
  – Mass: < 1.33 kg
  – Common sizes: 1U, 1.5U, 2U, 3U...
  – Now 6U... 12U?

• Low cost and short development time

• Increased accessibility to space
Tall, Grande, Venti...

Pumpkin, Inc. Motherboard

http://ccar.colorado.edu/asan5050/projects/projects_2013/Naik_Siddhesh/Cubesat.JPG
Poly-Picosatellite Orbital Deployer

http://www.nasa.gov/centers/ames/images/content/152693main_genebox-015.jpg
Launch integration on Rocket

CubeSat deployment pods on top of the Bion-M1 spacecraft: BeeSat-2, BeeSat-3 and SOMP in front; OSSI-1 (1U) in a 3U-Pod back left; DOVE-2 (3U) in back right. [http://amsat-uk.org/tag/beesat-2](http://amsat-uk.org/tag/beesat-2)
Launch from Space Station

- Deliver to NanoRacks
- Get integrated into NRCSD
- Get integrated into Cargo
- Cargo integrated into Cygnus
- Cygnus shipped to launch site
- Cygnus integrated into rocket
- Antares launch
- Cygnus separation
- Cygnus rendezvous with ISS
- Cygnus unpacked
- Cargo unpacked
- NRCSD integrated to slide table
- Slide table through airlock
- NRCSD onto JEMRMS
- Deployment

Cygnus being unberthed from Harmony module
http://www.flickr.com/photos/nasa2explore/12644390754/
• Space is hard
  – Rocket acoustic/phys vibe
  – Rockets can fail/explode
  – It’s far away
  – Vacuum
  – Microgravity
  – Hot / cold temp. swings
  – Radiation / solar storms
  – Things break – *a lot*
  – Hard to find small objects
  – Lots of safety paperwork
  – Expensive to get there
  – Expensive ground staff
• Space is hard
  – Rocket acoustic/phys vibe
  – Rockets can fail/expplode
  – It’s far away
  – Vacuum
  – Microgravity
  – Hot / cold temp. swings
  – Radiation / solar storms
  – Things break – *a lot*
  – Hard to find small objects
  – Lots of safety paperwork
  – Expensive to get there
  – Expensive ground staff

• Space is also awesome
  – Helps us answer “why are we here?”
  – Incredible ability to observe Earth
• CanX-4 and CanX-5 have demonstrated relative navigation using carrier-phase differential GPS
  – *Newman et al., SmallSat 2015*
  – Separations from 1 km to 50 m
    • Sub-meter position accuracy
    – ATO: along track orbit
    – PCO: projected circular orbit

Table 5: Summary of formation control results

<table>
<thead>
<tr>
<th>Formation</th>
<th>$\Delta v_{\text{expected}}$ [cm/s/orbit]</th>
<th>$\Delta v_{\text{actual}}$ [cm/s/orbit]</th>
<th>3D-RMS [m]</th>
<th>3D-RMS [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATO 1000</td>
<td>3.65</td>
<td>5.55</td>
<td>0.590</td>
<td>0.453</td>
</tr>
<tr>
<td>ATO 500</td>
<td>1.71</td>
<td>1.62</td>
<td>0.345</td>
<td>0.513</td>
</tr>
<tr>
<td>PCO 100</td>
<td>0.99</td>
<td>1.63</td>
<td>0.517</td>
<td>0.602</td>
</tr>
<tr>
<td>PCO 50</td>
<td>3.07</td>
<td>1.27</td>
<td>0.554</td>
<td>0.594</td>
</tr>
</tbody>
</table>
CubeSat Inertial Pointing Capability

- A study of variability of massive, luminous stars and supernova
- BRITE (BRIght Target Explorer) Constellation
  - 7 kg, 20 cm cube nanosatellites
  - University of Toronto and collaborators
- Multiple satellites help with continuous viewing
- Different filters on satellites
- Demonstrated **up to 12 arcsec** RMS pointing over 15 min

http://utias-sfl.net/?page_id=407

11/4/2015
Fighting the “but, the tiny aperture” issue

- Utah State University Space Dynamics Laboratory “Petal”
  - Deployable Petal Telescope

Autonomous Assembly of a Reconfigurable Space Telescope (AAReST)

- Autonomous rendezvous and docking for telescope re-configuration
- Low-cost active deformable mirrors
Improved optical quality of apertures

- AAReST deformable mirrors for on deployables
Overview

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NanoRacks deployment of MicroMAS from the ISS Japanese Experiment Module Remote Manipulator System (JEMRMS). Photo courtesy NASA/NanoRacks

11/4/2015
# Optical vs. RF

<table>
<thead>
<tr>
<th></th>
<th>Radio</th>
<th>Optical “Lasercom”</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Space Segment</strong></td>
<td>Radio modem, patch antenna</td>
<td>Laser transmitter, steering system</td>
</tr>
<tr>
<td><strong>Spectrum / License</strong></td>
<td>~Megahertz  Heavily regulated</td>
<td>Terahertz available Unregulated</td>
</tr>
<tr>
<td><strong>Ground Segment</strong></td>
<td>Large dish (20+ ft) and facility $1M and up</td>
<td>1 ft amateur astronomy telescope $100k</td>
</tr>
</tbody>
</table>

Lasercom offers **superior link efficiency** (less power per bit) due to its ability to better direct signal to receiver.
Comparison of RF and Optical

- TX aperture is 30 cm
- RX aperture is 30 cm
- Link range is 700 km (LEO)
- Receiver sensitivities typical for 1 Gbps link

<table>
<thead>
<tr>
<th></th>
<th>Optical λ = 1000 nm</th>
<th>RF (10 GHz) λ = 3 cm</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX Power (P_t)</td>
<td>0</td>
<td>0</td>
<td>dBW</td>
</tr>
<tr>
<td>TX Losses (L_t)</td>
<td>-2</td>
<td>0</td>
<td>dB</td>
</tr>
<tr>
<td>TX Aperture (G_t)</td>
<td>119</td>
<td>30</td>
<td>dB</td>
</tr>
<tr>
<td>Path Loss (L_path)</td>
<td>-259</td>
<td>-169</td>
<td>dB</td>
</tr>
<tr>
<td>RX Aperture (G_r)</td>
<td>119</td>
<td>30</td>
<td>dB</td>
</tr>
<tr>
<td>RX Power (P_r)</td>
<td>-23</td>
<td>-109</td>
<td>dBW</td>
</tr>
<tr>
<td>RX Sensitivity</td>
<td>-97</td>
<td>-114</td>
<td>dBW</td>
</tr>
<tr>
<td>Margin</td>
<td>74</td>
<td>5</td>
<td>dB</td>
</tr>
</tbody>
</table>

Adapted from: Caplan, D. “Free-Space Laser Communications”, 2008

Optical system has a **70 dB advantage**

All system parameters are matched, except wavelength
Motivation

- Rapid growth of small satellite market
- Increasing downlink demand from science payload
- Limited capability from CubeSat RF systems

Number of satellites (1-50 kg) launched per year

Graph showing significant growth in the 1-10 kg mass range from 2000 to 2013.

Nanosatellite Optical Downlink Experiment (NODE)
NODE Architecture

- **Uplink beacon**
- **Downlink optical communication link** (1550 nm)
- **Uplink optical beacon for PAT** (850 nm)
- **Bi-directional low-rate RF link for telemetry and command**

**Low-rate RF link**

**Downlink beam**

**PAT = Pointing, Acquisition, and Tracking**

**RF = Radio Frequency**
Requirements Derivation

3-U CubeSat SWaP constraints

Lasercom payload SWaP limits

Existing CubeSat ADCS technology

Fine pointing range

RF solution throughput (“the competition”)

Link acq. time

Fine pointing accuracy

Link rate

Optical power

Downlink Beamwidth

External

Self-imposed

Derived

SWaP = Size, Weight, and Power
ADCS = Attitude Determination and Control System
## Design Parameters

### Link parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data rate</td>
<td>10 – 50 Mbps</td>
<td>User data rate</td>
</tr>
<tr>
<td>Bit error rate</td>
<td>$10^{-4}$ (no coding)</td>
<td>Conservation baseline</td>
</tr>
<tr>
<td>Path length</td>
<td>1000 km (at 20° elevation)</td>
<td>LEO orbit at 400 km altitude</td>
</tr>
</tbody>
</table>

### NODE module

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size, weight</td>
<td>10 x 10 x 5 cm, 1 kg</td>
<td>0.5U CubeSat</td>
</tr>
<tr>
<td>Power</td>
<td>10 W (transmit)</td>
<td>CubeSat constraints</td>
</tr>
<tr>
<td>Downlink beam</td>
<td>0.12° FWHM</td>
<td>Provide required data rate</td>
</tr>
<tr>
<td>Coarse pointing</td>
<td>3° (3-σ)</td>
<td>Host CubeSat ADCS</td>
</tr>
<tr>
<td>Fine pointing</td>
<td>0.03° (3-σ)</td>
<td>Fast-steering mirror</td>
</tr>
</tbody>
</table>
## Concept of Operations – I

<table>
<thead>
<tr>
<th>Step</th>
<th>Action</th>
<th>Sensors</th>
<th>Actuators</th>
<th>Pointing accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CubeSat slews toward ground station</td>
<td>CubeSat coarse sensors</td>
<td>CubeSat reaction wheels</td>
<td>3°</td>
</tr>
<tr>
<td>2</td>
<td>CubeSat closes loop around beacon offset</td>
<td>Beacon camera</td>
<td>CubeSat reaction wheels</td>
<td>1.25°</td>
</tr>
<tr>
<td>3</td>
<td>Fine steering mechanism is activated</td>
<td>Beacon camera</td>
<td>Fast-steering mirror</td>
<td>0.03°</td>
</tr>
</tbody>
</table>

**Diagram:**
- **Uplink beacon**
- **Beacon camera’s FOV**
- **CubeSat slews toward ground station**
- **Pointing accuracy 3°**
- **CubeSat closes loop around beacon offset**
- **Pointing accuracy 1.25°**
- **Fine steering mechanism is activated**
- **Pointing accuracy 0.03°**
**Concept of Operations - II**

1. **CubeSat slews toward ground station**
   - **Sensors**: CubeSat coarse sensors
   - **Actuators**: CubeSat reaction wheels
   - **Pointing accuracy**: 3°

2. **CubeSat closes loop around beacon offset**
   - **Sensors**: Beacon camera
   - **Actuators**: CubeSat reaction wheels
   - **Pointing accuracy**: 1.25°

3. **Fine steering mechanism is activated**
   - **Sensors**: Beacon camera
   - **Actuators**: Fast-steering mirror
   - **Pointing accuracy**: 0.03°
### Concept of Operations - III

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1</strong></td>
<td>CubeSat slews toward ground station</td>
<td></td>
</tr>
<tr>
<td>Sensors</td>
<td>CubeSat coarse sensors</td>
<td></td>
</tr>
<tr>
<td>Actuators</td>
<td>CubeSat reaction wheels</td>
<td></td>
</tr>
<tr>
<td>Pointing accuracy</td>
<td>$3^\circ$</td>
<td></td>
</tr>
<tr>
<td><strong>2</strong></td>
<td>CubeSat closes loop around beacon offset</td>
<td></td>
</tr>
<tr>
<td>Sensors</td>
<td>Beacon camera</td>
<td></td>
</tr>
<tr>
<td>Actuators</td>
<td>CubeSat reaction wheels</td>
<td></td>
</tr>
<tr>
<td>Pointing accuracy</td>
<td>$1.25^\circ$</td>
<td></td>
</tr>
<tr>
<td><strong>3</strong></td>
<td>Fine steering mechanism is activated</td>
<td></td>
</tr>
<tr>
<td>Sensors</td>
<td>Beacon camera</td>
<td></td>
</tr>
<tr>
<td>Actuators</td>
<td>Fast-steering mirror</td>
<td></td>
</tr>
<tr>
<td>Pointing accuracy</td>
<td>$0.03^\circ$</td>
<td></td>
</tr>
</tbody>
</table>
NODE System Layout

**Top View**
- 9.5 cm length
- Focal plane array
- High-Speed Electronics
  - Focal-plane Readout
  - Centroiding
  - FEC, interleaving, framing
  - Modulation
- Bandpass filter
- UV-cut filter
- Beacon
- FSM
- Fiber collimator
- Downlink
- Fine-Steering Mirror Driver

**Side View**
- Uplink Aperture (2.5 cm)
- Downlink Aperture (~1 cm)
- Fast-steering mirror
- Optics Bench
- Fiber Amplifier
- Seed Laser
- Fiber components (e.g. FBG filter)

3U CubeSat (30x10x10 cm)
Lasercom Payload (5x10x10 cm)
Coarse Control Stage

- Three-axis stabilized CubeSat ADCS
- Common pointing capability: $1 - 5^\circ$ RMS $^{2,4}$

<table>
<thead>
<tr>
<th>Attitude Sensors</th>
<th>Attitude Actuators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun sensors</td>
<td>Reaction wheels</td>
</tr>
<tr>
<td>Magnetometers</td>
<td>Magnetorquers</td>
</tr>
<tr>
<td>Earth horizon sensors</td>
<td></td>
</tr>
<tr>
<td>Gyroscopes</td>
<td></td>
</tr>
</tbody>
</table>

Miniaturized reaction wheels
[credit: Blue Canyon Tech].

Magnetorquers
[credit: Maryland Aerospace Inc.].

Earth horizon sensors
Fine Control Stage

- MEMS fast steering mirror
  - Mirrorcle Tech. Inc.
  - 2-axis tip/tilt
  - Range: ±1.25°
  - No integrated feedback

Fast-steering mirror from Mirrorcle Tech.

Repeatability Test Results

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS error</td>
<td>0.0007° (12 μrad)</td>
</tr>
<tr>
<td>Pointing requirement</td>
<td>0.03° (525 μrad)</td>
</tr>
</tbody>
</table>

Lab bench setup for FSM characterization

Test pattern
# Transmitter Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Notes/Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>10 x 10 x 2 cm</td>
<td>Allocation to the transmitter portion of the lasercom terminal.</td>
</tr>
<tr>
<td>Mass</td>
<td>&lt;300 g</td>
<td></td>
</tr>
<tr>
<td>Electrical Input Power</td>
<td>&lt; 8 W</td>
<td></td>
</tr>
<tr>
<td>Operating Temp. Range</td>
<td>0-40 C</td>
<td>Typical CubeSat values</td>
</tr>
<tr>
<td>Optical Output Power</td>
<td>&gt;200 mW avg.</td>
<td>Link budget, PPM-16 assumed</td>
</tr>
<tr>
<td>Modulation Type</td>
<td>PPM, M=[8-64]</td>
<td>ER implications, “power robbing”</td>
</tr>
<tr>
<td>Modulation BW</td>
<td>&gt; 1 GHz desired</td>
<td>Future pointing improvements</td>
</tr>
<tr>
<td>Wavelength stability</td>
<td>+/- 1 nm</td>
<td>Ground receiver filter</td>
</tr>
</tbody>
</table>
• Challenge: achieving ER > 33dB with directly modulated laser (DML)
  – Needed to prevent “power robbing” in EDFA

• DML ER can be improved with narrow-band optical filtering via FM-AM conversion

• Typical DML FM response vs modulation frequency:
FPGA Modulation

- Electro-optic modulator not feasible in this design due to power constraints

- Direct FPGA drive demonstrated with Xilinx Spartan 6 FPGA evaluation board
  - Adjustable: duty cycle, slot rate
  - GPIO drives 50 mA into 50 ohms

- SelectIO SERDES enables >600 MHz rates while maintaining low fabric clock rates
  - Not using RocketIO/GTP interfaces
  → power savings

PPM-16 waveform (electrical)

5 ns pulses
Laser Selection & Characterization

- **Telecom DFB Lasers**: TOSA
  - Transmitter Optical Sub-Assembly
  - Compact packaging
  - **Low TEC power**
    (Measured <0.4 W across expected range)

- Custom mounting jig for characterization

- Measured laser tuning parameters:
  
  **FPGA 50mA drive provides ~10 GHz of frequency shift**
Extinction Filter Characterization

- Waveform ER is enhanced through FM-to-AM conversion
- Athermal Fiber Bragg grating filter
  - Bandwidths: 10 GHz and 5 GHz
  - >40 dB stop band
- Temperature/DC bias wavelength tuning aligns seed laser with filter

5 GHz filter provides ER > 33 dB → permits PPM-64 w/o power robbing
EDFA Selection

- Modified COTS Fiber Amplifier (NuPhoton)
  - Customized fiber egress, increased gain
  - Vendor has similar units with flight heritage

- Key Parameters
  - Optical output: 200 mW average
  - Electrical input: 5.7 W at 5 V
  - Gain: 40 dB
  - “Wall plug” efficiency: 3.5%

Industry-standard “MSA” form factor is a good match for CubeSat volume constraints
Measured Electrical/Optical Waveforms

FPGA

Seed Laser + ER Filter

EDFA

FPGA Electrical Output

PPM-16 5 ns pulse

EDFA Filtered Optical Input

ER>33dB

EDFA Optical Output

High fidelity waveform ASE<0.2 dB

-7 dBm

+23 dBm

11/4/2015
# Transmitter Power Budget

<table>
<thead>
<tr>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EDFA</strong></td>
<td>5.7 W Manuf. worst case, (we measured: 4.1 W)</td>
</tr>
<tr>
<td><strong>Seed laser TEC</strong></td>
<td>0.4 W Peak power, over temp</td>
</tr>
<tr>
<td><strong>Seed laser DC bias</strong></td>
<td>0.2 W Worst case</td>
</tr>
<tr>
<td><strong>Seed laser AC drive</strong></td>
<td>0.01 W 50 mA, 1/16 duty</td>
</tr>
<tr>
<td><strong>FPGA logic</strong></td>
<td>0.2 W Only TXer related portion of FPGA</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td>6.51 W</td>
</tr>
<tr>
<td><strong>Margin:</strong></td>
<td>1.49 W 8 W budgeted</td>
</tr>
</tbody>
</table>

Transmitter meets power budget with **18% margin**
Flight Receiver BER Curves

- Theoretical sensitivity from link budget

**Sensitivity vs. Theory at BER=1e-4**

<table>
<thead>
<tr>
<th>M</th>
<th>8</th>
<th>16</th>
<th>32</th>
<th>64</th>
<th>128</th>
</tr>
</thead>
<tbody>
<tr>
<td>dB</td>
<td>2.9</td>
<td>2.5</td>
<td>2.3</td>
<td>2.2</td>
<td>2.2</td>
</tr>
</tbody>
</table>

System is currently 2.2–3.0 dB from theory (mode dependent).
Beacon Camera

- CMOS focal plane array (5 Mpixels)
- COTS camera lens system (1”, f = 35 mm)
- Bandpass filter – reject background light
- UV/VIS-cut filter – reduce system heating

### CMOS array - Aptina MT9P031

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical format</td>
<td>1/2.5”</td>
</tr>
<tr>
<td>Resolution</td>
<td>2592H x 1944V</td>
</tr>
<tr>
<td>Pixel's pitch</td>
<td>2.2 μm</td>
</tr>
<tr>
<td>QE at 850 nm</td>
<td>15%</td>
</tr>
</tbody>
</table>

### Lens + filters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length</td>
<td>35 mm</td>
</tr>
<tr>
<td>Aperture</td>
<td>1”</td>
</tr>
<tr>
<td>Band-pass filter</td>
<td>(850 5) nm</td>
</tr>
<tr>
<td>Long-pass filter</td>
<td>&gt; 700 nm</td>
</tr>
</tbody>
</table>

Beacon camera prototype

cm = Commercial Off the Shelf

11/4/2015
## Beacon Simulation

### Link analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Unit 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit power</td>
<td>10</td>
<td>W</td>
</tr>
<tr>
<td>Wavelength</td>
<td>850</td>
<td>nm</td>
</tr>
<tr>
<td>Beamwidth</td>
<td>5</td>
<td>mrad</td>
</tr>
<tr>
<td>Range (20° elevation)</td>
<td>984</td>
<td>km</td>
</tr>
<tr>
<td>Atmospheric absorption/scattering</td>
<td>-6</td>
<td>dB</td>
</tr>
<tr>
<td>Sky radiance^5</td>
<td>180</td>
<td>W/m²/sr/µm</td>
</tr>
<tr>
<td>Receiver bandwidth</td>
<td>10</td>
<td>nm</td>
</tr>
<tr>
<td>Optics loss (Tx + Rx)</td>
<td>-8</td>
<td>dB</td>
</tr>
<tr>
<td>Received power</td>
<td>0.013</td>
<td>nW</td>
</tr>
<tr>
<td>Margin</td>
<td>10</td>
<td>dB</td>
</tr>
</tbody>
</table>

### Scintillation statistics

<table>
<thead>
<tr>
<th>Profile</th>
<th>Huffnagel-Valley model^3 1°/s slew speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scintillation index</td>
<td>Strong-turbulence model^3</td>
</tr>
<tr>
<td>Spatial diversity (4 beams)</td>
<td></td>
</tr>
<tr>
<td>Distribution</td>
<td>Log-normal</td>
</tr>
</tbody>
</table>

Simulated beacon image and centroid
Beacon Simulation Results

Fade probability per frame (10 W) 2.3 %
Attitude knowledge accuracy 30 μrad (< 1/10 required accuracy)
Control Simulation

Disturbance Torque

- Reaction Wheel
- Gyroscope
- Detector (FPA)

Spacecraft

- Fast Steering Mirror

Attitude Correction

- Low-pass Filter
- Attitude Control
- Kalman Filter

Angular Rate

Beacon Position

4 Hz

- Sensors
- Actuators
- Software

10 Hz

Cmd. Torque

Ref. Att.

Ang. Rate

11/4/2015
Control Simulation Results

Pointing Results ($3-\sigma$)

<table>
<thead>
<tr>
<th></th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse stage only</td>
<td>$\pm 0.09^\circ$</td>
</tr>
<tr>
<td></td>
<td>(1.6 mrad)</td>
</tr>
<tr>
<td>Coarse + fine stage</td>
<td>$\pm 0.005^\circ$</td>
</tr>
<tr>
<td></td>
<td>(80 $\mu$rad)</td>
</tr>
<tr>
<td>Requirement</td>
<td>$\pm 0.03^\circ$</td>
</tr>
<tr>
<td></td>
<td>(525 $\mu$rad)</td>
</tr>
</tbody>
</table>

Limitation: Result does not consider pointing bias.
Nanosatellite Optical Downlink Experiment (NODE)

- CubeSat-sized laser communication module
- Pointing performance
  - Attitude knowledge: 30 μrad (2.3% fading)
  - Tracking accuracy: 80 μrad

Future work

- Hardware checkout and model validation
- Camera readout and image processing implementation
- Hardware-in-the-loop testing and integration
- On-orbit calibration algorithm development


Overview

- **Introduction**
  - CubeSats 101

- **Communications**
  - NODE
    - Laser communication downlink

- **Laser Occultation**
  - Bending angle and T,P profile recovery
    - GPS Radio Occultation for validation

NanoRacks deployment of MicroMAS from the ISS Japanese Experiment Module Remote Manipulator System (JEMRMS). Photo courtesy NASA/NanoRacks
Radio Occultation Illustration

Progression of tangent point for setting (ingress) occultation

Modified from L. Cucurull

11/4/2015
Laser Occultation for Greenhouse Gas Sensing

- Laser occultation
  - Measure bending angles of laser beams directly from the attitude and position of two LEO satellites

- The bending angle ($\alpha$) and impact parameter ($a$) can be calculated if the pointing vectors $P_{RX}$ and $P_{TX}$ and the positions $R_{RX}$ and $R_{TX}$ are known.
Figure 2. New approach to obtaining both thermophysical profiles and composition with Laser Occultation measurements. The need for Radio Occultation measurements of spacecraft Doppler frequency shifts and atmospheric frequency shift predictions is eliminated. The bending angles can be measured directly with the LO payload (free space optical transmitter and receiver).
Laser Occultation Schematic

Figure 3. Prototype of Laser Occultation Instrument
<table>
<thead>
<tr>
<th>Species</th>
<th>Wavenumber (cm⁻¹)</th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abs H2O-1</td>
<td>4204.8403</td>
<td>2378.211605</td>
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<tr>
<td>Ref H2O-1</td>
<td>4226.07</td>
<td>2366.264638</td>
</tr>
<tr>
<td>Abs H2O-2</td>
<td>4475.803</td>
<td>2234.235957</td>
</tr>
<tr>
<td>Ref H2O-2</td>
<td>4770.15</td>
<td>2096.370135</td>
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<tr>
<td>Abs H2O-3</td>
<td>4747.0548</td>
<td>2106.56932</td>
</tr>
<tr>
<td>Ref H2O-3</td>
<td>4731.03</td>
<td>2113.704627</td>
</tr>
<tr>
<td>Abs 12CO2</td>
<td>4771.6214</td>
<td>2095.723688</td>
</tr>
<tr>
<td>Ref 12CO2</td>
<td>4770.15</td>
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<tr>
<td>Abs 13CO2</td>
<td>4723.415</td>
<td>2117.112301</td>
</tr>
<tr>
<td>Ref 13CO2</td>
<td>4731.03</td>
<td>2113.704627</td>
</tr>
<tr>
<td>Abs CH4</td>
<td>4344.1635</td>
<td>2301.939142</td>
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<tr>
<td>Ref CH4</td>
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<td>2313.245877</td>
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<tr>
<td>Abs O3</td>
<td>4029.1096</td>
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<td>Ref O3</td>
<td>4037.21</td>
<td>2476.958097</td>
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<tr>
<td>Abs N2O</td>
<td>4710.3408</td>
<td>2122.988638</td>
</tr>
<tr>
<td>Ref N2O</td>
<td>4731.03</td>
<td>2113.704627</td>
</tr>
</tbody>
</table>

From Kirchengast:

Need to assess 1.5-1.7 um wavelengths
Bending Angle

Bending angle w.r.t. lowest altitude of beam path

Altitude (km)

Bending Angle (deg)
Separation
“Laser-only” occultation feasibility

- It is doable
  - Bending angle for GPS signal
    - Altitudes from 0 km to 20 km: 1 deg to 0.1 deg.
  - Modern s/c attitude knowledge performance
    - Star sensors and filtering gyroscope data
      - < 10 arcsec \(\approx 0.0027\) deg
  - Modern s/c position knowledge performance
    - With GPS in LEO, error < 10 m
      - Corresponding pointing error:
        - 0.00024 deg to 0.00038 deg
        - Depends on altitude (0 to 20 km) and orbit (200 to 400 km)


Figure 3. Atmospheric and ionospheric bending for limb ray paths plotted as a function of ray path tangent height. Solid line, bending calculated for U.S. Standard Atmosphere [Champion et al., 1985]. Long-dashed line, bending calculated for U.S. Standard Atmosphere plus typical midlatitude ionosphere during daytime, solar maximum conditions. Short-dashed line, bending calculated for U.S. Standard Atmosphere plus typical midlatitude ionosphere during nighttime, solar maximum conditions.
Thank you!