Fiber-based, Trace-gas, Laser Transmitter Technology Development for Space

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Billy Mamakos – Design Interface, Inc.
Brian Bean – SOBO, Inc.
Outline

• Introduction
• Instrument Performance
• Transmitter Development
• Transmitter Packaging
• Future Directions
• Conclusions
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NASA's ASCENDS Mission

Active Sensing of CO₂ Emissions over Nights, Days, and Seasons (ASCENDS) Mission

Science Mission Definition Study
Draft
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April 15, 2015

Avail from:

Requirements for CO₂ Mixing Ratio:

Random error: ~ 1 ppm in ~100 km along track, or
~ 0.5 ppm in ~10 sec over deserts

Bias: < 0.5 ppm (< 1 part in 800)

Lower errors provide more benefit for flux est’s.
Comparison of Coverage: Actual OCO-2 with ASCENDS simulator

ASCENDS shows:
1. More spatially uniform coverage
2. Coverage is uniform throughout year
3. Much better sampling in key areas:
   - Tropics, N. Hemisphere, South Ocean

*R. Kawa et al.
Scaling CO₂ Sounder Lidar to Space

CO₂ Transmitter ($\ell = 1572$ nm)

- Step Locked Seed Laser
- PRE-AMP
- POWER AMPLIFIER
- 7.5 kHz Pulse Rate

CO₂ Receiver

- Data Out
- High Speed Digitizer
- HgCdTe APD

1572 nm filter

Target (2.6 mJ)

0.4 ppm

> x2 Margin!

Power Amplifier

CO₂ Receiver

CO₂ Receiver

CO₂ Transmitter ($\ell = 1572$ nm)

Improvements for recent ASCENDS flights:

1. Step-locked laser seed source
2. Wider wavelength sampling across CO2 line
3. Optimized wavelength spacing
4. HgCdTe APD detector in receiver
5. Analog digitizer data recording
6. 10 Hz recording & retrieval resolution
7. Larger laser footprint (2016)
8. Allow 15 or 30 wavelength samples (2016)
Overview - 2017 ASCENDS Airborne Campaign
Jul 20- Aug 8, 2017

Flights & Legend:

<table>
<thead>
<tr>
<th>Dates</th>
<th>Name</th>
<th>Duration (hrs)</th>
<th># Spirals/Descents</th>
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<tbody>
<tr>
<td>20-Jul</td>
<td>Engineering</td>
<td>4.4</td>
<td>3</td>
</tr>
<tr>
<td>21-Jul</td>
<td>Calibration</td>
<td>5.6</td>
<td>10</td>
</tr>
<tr>
<td>27-Jul</td>
<td>Northbound science/transit</td>
<td>9.4</td>
<td>4</td>
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<td>31-Jul</td>
<td>Western NWT</td>
<td>8</td>
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<tr>
<td>2-Aug</td>
<td>Northern NWT</td>
<td>6.6</td>
<td>4</td>
</tr>
<tr>
<td>5-Aug</td>
<td>South-Central Alaska</td>
<td>6.2</td>
<td>5</td>
</tr>
<tr>
<td>6-Aug</td>
<td>Central Alaska</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>8-Aug</td>
<td>Southbound science/transit</td>
<td>8.1</td>
<td>8</td>
</tr>
<tr>
<td>8</td>
<td>Totals:</td>
<td>55.3</td>
<td>47</td>
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</table>
CO₂ Sounder Lidar & other campaign instruments

Other science instruments on ASCENDS 2017 campaign

- Picarro (Randy Kawa) – in situ CO₂ and WV
- AVOCET (Josh DiGangi/LaRC) – in situ CO₂, CH₄, CO
- DLH (Glenn Diskin/LaRC) – in situ WV
- ACES (Mike Obland/LaRC) – IPDA lidar to measure XCO₂ using a line near 1571 nm
  - Uses modulated CW lasers at 3 wavelengths

- Direct Detection IPDA lidar - emits 10 kHz train of laser pulses
- Measures column CO₂ absorption using 1572.33 nm line.
- Laser pulses - stepped in 30 wavelengths across line.
- Wavelengths are locked relative to CO₂ absorption line center
- Time resolved receiver uses HgCdTe APD detector
- Measures backscatter profile, range & samples of CO₂ line shape
  - XCO₂ Retrievals:
    - Line shape samples, range to scattering surface
    - Atmospheric state (measurements or model)
Spiral over Edwards CA: CO2 & XCO2 Retrievals

Red dots: XCO2 from CO2 Sounder Lidar
Black dots: CO2 (at altitude) from in situ
All XCO2 Retrievals use 1 second averaging time

Picarro (in situ) CO2 measurements at aircraft made during spiral
<- Side view
Top view->

Comparison of XCO2 measurements:
• Red – lidar
• Blue dots - In situ, ave’d to surface

Reference atmosphere (LUT) for XCO2 retrievals based on:
DC-8 T & P
PICARRO H2O

Same format used for other sample results
Space Laser Transmitter (TRL 6) Roadmap

FY2015-18

TRL 6 Laser Transmitter

Detector
(HgCdTe Array supported by ESTO)

Instrument Aircraft Demo

FY2018

CO₂ Sounder Readiness for Space Mission

ASCENDS (or similar)

- Previous work has demonstrated most key elements needed for ASCENDS
- The main obstacle remaining for a CO₂ Sounder-based mission is the laser TRL
- A CO₂ precursor mission could be an intermediate step, as a science and technology demonstration (e.g., for Earth Venture, or similar)
- **This program will increase laser TRL to 6 for flight opportunities in 2018 & beyond**
- This high peak power fiber laser also serves as a pathfinder for other space applications
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# Laser Requirements

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>Laser Transmitter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center Wavelength</td>
<td>Nominally centered at 1572.335 nm</td>
</tr>
<tr>
<td>Linewidth (each wavelength channel)</td>
<td>(&lt; 100) MHz</td>
</tr>
<tr>
<td>Pulse repetition frequency</td>
<td>7.5 KHz</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>1-1.5 (\mu) s</td>
</tr>
<tr>
<td>Pulse Energy</td>
<td>(&gt;3.2) mJ/pulse (goal); (&gt;2.6) mJ/pulse (operating, 18% derating)</td>
</tr>
<tr>
<td>PER [TBR]</td>
<td>20 dB (TBR)</td>
</tr>
<tr>
<td>Wall-plug Efficiency</td>
<td>(&gt; 6%)</td>
</tr>
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Architecture Overview

- Seed Module includes CW amp and Mach-Zehnder Modulator (MZM)
- Pulsed Pre-Amp Module
  - being built by Nuphoton, Inc.
- Power Amplifier
  - Design uses 3 amplifier modules - Packaging concept has 2 amps per module
**Seed Laser Pulse-Shaping**

- **Laser Transmitter**
  - Pulsed Seed Laser
  - Amplifiers
  - Master Laser
  - CO\(_2\) Gas Cell
  - Slave Laser
  - EDFA
  - MZ
  - Pulsed
  - DAC
  - FPGA
  - PC
  - AM
  - RF switch
  - Bias card
  - CW

- **Key Points**
  - Pulse shaping will compensate for distortions by Pre-Amp and Power Amp modules. Desire “flat top” output pulses.
  - Capability to perform pulse-shaping through use of high-speed DAC currently in development.
  - The DFB master laser is locked to CO\(_2\) reference cell.
  - A single DS-DBR slave laser is dynamically offset-locked to the master DFB laser using an optical phase-locked loop (OPLL).
  - The demonstrated laser frequency noise suppression (to < 0.2 MHz), tuning speed (< 40 µs) and tuning range (~32 GHz) satisfies ASCENDS requirements.
Frequency Drift of Master Laser

Less than 1 MHz absolute drift between two independently locked sources over a 1-day test
The unit has 1 input and 13 outputs (including 7 monitor ports)
Each output provides >5 µJ pulse energy
OFS requires 2.5 µJ for the power amplifier
Three serial interface for controlling different sections with hyper-terminal
Module meets all optical performance requirements
Worked with vendor to use vacuum compatible components
30W Raman Amplifier 1480nm Pump: Detailed schematic

[Diagram showing detailed schematic of 30W Raman Amplifier 1480nm Pump]
PM-VLMA-Er schematic

- PM VLMA Er fiber ~ 3.25 to 4 m
- Pump leg PM SMF
- Signal leg PM SMF
- PM 1480/1572 WDM
- PM 1572 tap
- PM isolator
- I.L. PD
- S.S. PD
- Lens
- Pump filter

Endcap
PM VLMA amplifier
Pulse energy and peak power

Pulse energy : 531 µJ
Peak power : 675 W
Power Amplifier Summary

• Raman laser –
  • 30 W output power at 1480 nm (after slanted FBG and 1480/1550 WDM) for 49.2 W diode power
  • O-O efficiency = 61%
  • Sufficient for pumping two PM VLMA amplifiers

• PM VLMA amplifier
  • 531 μJ, 675 W peak power, single frequency microsecond pulses at 7.2 kHz rep rate.
  • 1480 nm power required for 500 mJ pulses = 14.2 W
  • O-O efficiency = 25%
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Completed Seed Module

- Completed seed laser module with reference laser, tunable laser detector/divider board, CW Er-amplifier and Mach-Zehnder modulator
- Meets optical performance requirements
- Dimensions: ~25-cm x 18-cm x 7-cm
Herriott cell filled with CO$_2$ gas with integration optics in a ruggedized package to lock the reference laser to an absolute wavelength standard. Module Dimensions: 25.5-cm x 12.5-cm x 10-cm
Pre-Amplifier Module

- Photo of pre-amplifier prototype.
- Built by NuPhoton, Inc.
- Meets optical requirements
- Module dimensions: 28-cm x 28-cm x 5-cm
Potting amplifier fiber in thermal compound

Process of vacuum potting amplifier fibers in thermal compound did not affect Yb or Raman cavity efficiencies. Over-all system efficiency was un-changed after potting process.
Photos of VLMA power amplifier prototype. The left photo shows the bottom half of the box with the Raman pump system. There are two spools and the fiber components are in the lower center of the photo. The right photo shows the PM-VLMA fiber. The white fiber potting material makes the spiral groove easy to visualize. Module dimensions: 44-cm x 32-cm x 9-cm.
PM-VLMA amplifier
Comparison with breadboard module

- Output power is slightly higher at low pump power in new module
- Could be due to differences in end-cap type
- Packaged Power Amplifier meets optical requirements

![Graph showing comparison of 1572 nm avg. power and 1480 nm pump power between new module and breadboard module.]

- Pulsed operation
  - 1572 nm
  - 1 microsecond pulses
  - 7.2 kHz
- Output power is slightly higher at low pump power in new module
- Could be due to differences in end-cap type
- Packaged Power Amplifier meets optical requirements
Successful Vibration Test on All Modules

Vibration test plan: Signature characterizing Sine Sweep followed by a Random Vibe, and finish with a Sine Sweep, repeat for all three axes. The sine sweep gives you a baseline to compare the test article after going through random vibration, this makes sure nothing came loose or shifted during testing.
Successful Bakeout on All Modules

To mitigate outgassing of materials during TVAC testing all the modules and cables were subjected to a thermal vacuum bakeout. Outgassing is the release of volatiles from materials. The outgassed molecules then deposit on line-of-sight surfaces and are more likely to deposit on cold surfaces. This molecular contamination can affect optical properties of vehicle and payload surfaces and spacecraft performance, particularly for sensitive optics.
Thermal Vacuum Testing Plans

<table>
<thead>
<tr>
<th>Thermal Vacuum Testing Profile (example)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2 Transmitter Temperature Profile</td>
</tr>
</tbody>
</table>

 Starting TVAC Test Soon
Baseline TVAC testing plan: Start with survival hot cycle (mini bakeout), followed by a hot cycle, survival cold cycle, cold cycle and then 3 more hot and cold cycles before returning to ambient.
Cold plate measures 32" x 32" x 1", chamber has plenty of feedthrus for fiber and cables connectors.
Radiation Requirements

LEO ISS orbit has a total dose of 0.437 kRad for 0.1” Aluminum material thickness
Polar, Sun-synchronous orbit has a total does of 8.6 kRad for 0.1” Aluminum material thickness
Progress toward the CO$_2$ Sounder Lidar to Space

1. **Laser** with space needed performance in testing: TRL-6 by October 2018

2. **Receiver telescope:**
   - 80 & 100 cm diameter telescopes: affordable & flight proven

3. **Measurement model**
   - For space shows < 1 ppm random error

   - **Orbit average**
     - Orbit Altitude 400 km, Laser: 2.7 m/pulse at 7.5 kHz, 16 Wavelengths, Laser Divergence: 150 urad, Receiver FOV: 225 urad

4. **Detector:**
   - Highly sensitive HgCdTe APD detector in cryocooler - passed space radiation & environ. tests

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Image 1:

- Laser module with dimensions and specifications

Image 2:

- Receiver telescope setup with specifications

Image 3:

- Graph showing measurement model with various environmental conditions

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The recent Earth Science Decadal Survey significantly reduced the anticipated funding for a potential ASCENDS-like measurement.
IMPRESS Lidar: Integrated Micro-Photonics for Remote Earth Science Sensing Lidar - The IMPRESS Lidar PIC concept will enable more frequent and lower cost missions for remote Earth science sensing from small craft and/or small satellite platforms.

The figures illustrate how miniaturization enables new measurement flexibility and alternative platforms. Close integration of photonics (PIC) and electronics (EIC) further improves performance while reducing SWaP.
PIC Schematic

PIC Schematic mirroring a fiber and bulk component based design that we have designed, built and tested for atmospheric CO₂ spectroscopic measurements.

Monolithic PIC

Master DFB LD

Master SG-DBR LD

Slave SG-DBR LD

To Monitor

MON

From Cell

MON

IL: 4 dB

6 dBm

To CO₂ Stabilization Cell

PM

50%

2x2

0 dBm

50%

-3 dBm

To OPLL Electronics

DET

10 dBm

10 dBm

10 dBm

EX: 40 dB

10 dBm

1 us pulses to pre-amp

1x2

90%

10%

10 dBm

10 dBm

10 dBm

EXT: 40 dB

10 dBm

10 dBm

10 dBm

10 dBm

10 dBm
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Conclusion & Next Steps

• Demonstrated all optical performance requirements with margin
• Mechanical design complete
• Mechanical and Thermal analysis complete
• Prototype Build complete
• Environmental testing underway
  • Vibration Complete
  • Thermal vacuum and Radiation testing coming up
• Full power demonstration with all 6 amplifier channels planned