Non-Topographic Space-Based Laser Remote Sensing

Anthony W. Yu, James B. Abshire, Haris Riris, Michael Purucker, Diego Janches, Stephanie Getty, Michael A. Krainak, Mark A. Stephen, Jeffrey R. Chen, Steve X. Li, Kenji Numata, Molly E. Fahey, Stewart Wu

NASA Goddard Space Flight Center
Greenbelt, MD 20771

Graham R. Allan
Sigma Space Inc., Lanham-Seabrook, MD 20706

Oleg Konoplev
Science Systems and Applications, Inc., Lanham, MD USA 20706
Outline

• Introduction
• Space Laser Altimetry Instruments
• Progress on On-Going Programs
  – Earth Science
  – Planetary Science
  – Heliophysics
  – Astrophysics
• Summary
INTRODUCTION
EARTH SCIENCE APPLICATIONS
CO$_2$ LIDAR
CH$_4$ LIDAR
CARBON DIOXIDE LIDAR
NASA’s ASCENDS Mission

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

Science Mission Definition Study
Draft
ASCENDS Ad Hoc Science Definition Team:

Kenneth W. Jucks,1 Steven Neeb,1 James B. Abshire,1 David F. Baker,1 Edward V. Browell,1 Abhisek Chatterjee,1 David Crisp,1 Sean M. Crewell,1 Scott Denning,1 Dierk Hammerling,1 Fenton Harrison,2 Jason J. Hynes,2 Stephan R. Kawa,3 Bang Liu,4 Byron L. Meadows,5 Robert H. Mendes,4 Anna Michalski,7 Bernier Moore,5 Keith E. Murray,10 Leslie E. Ott,10 Peter Rayner,10 Osita I. Rodriguez-Iturbe,6 Andrew Schubert,2 Yoshisige Shiga,1 Gary D. Spero,25 James Shab Wanz,26 and T. Scott Zeebe.27

April 15, 2015

Avail from:

Measures:
- CO₂ tropospheric column
- O₂ tropospheric column
- Cloud backscattering profile

~400 km polar orbit
(time of day is TBD)

~400 km polar orbit
(time of day is TBD)

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.
CO$_2$ Sounder Approach:
Airborne CO$_2$ Line Sampling & Absorption line analysis

- **Line at 1572.33 nm**
- **Lidar** measures “dots” (wavelength samples) to all scattering surfaces
- **Post flight: Retrievals** (based on model atmosphere) calculates range, normalized line shapes & solves for best fit concentration

HgCdTe APD Detector in 2014 flights
Scaling CO₂ Sounder Lidar to Space

**CO₂ Transmitter (λ = 1572 nm)**
- λ-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**

**Transmitted Intensity**

**Calculated CO₂ Line Shape & Wavelength Sampling used in calculations**

**Surface Reflectivity:**
- 40% (desert)

**SNR at off-line laser wavelengths**

**Target (2.6 mJ)**

**SNR at off-line Wavelengths**

**0.4 ppm**

**Rel error in OD est.**

**Daytime**

**Night**

**OSA CLEO 2016**
# 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>≤ 100 MHz (TBR)</td>
</tr>
<tr>
<td>Pulse repetition frequency</td>
<td>7.5 KHz</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>1-1.5 µs</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>
</tbody>
</table>

- Pulse energy stability (long term – 1 hr) < 5%
- Optical Output: Free space, PM, ~100 µrad divergence, beams co-aligned to better than ~20 µrad
- Beam quality: M² <1.3 (TBR)
- PER [TBR]: 20 dB (TBR)
- Environmental: Launch to ISS (TBR)
- Wall-plug Efficiency: > 6%
Seed laser approach

- DFB master laser is locked to CO₂ reference cell.
- Digital Supermode-DBR slave laser is dynamically offset-locked to the master DFB laser using an optical phase-locked loop (OPLL).
- Slave laser output is source for remaining laser stages.
- Frequency-stepped pulse train carved by MZM and subsequently amplified.
- Demonstrated laser frequency noise suppression (to < 0.2 MHz), tuning speed (< 40 µs) and tuning range (~32 GHz) – all satisfy or exceed ASCENDS requirements.

Pre-Amplifier Development

Preliminary Stage 1 Pre-amplifier breadboard Results

- 4.5 meter IXF-EDF-FGL-PM
- Core pumped
- Pump power 200mW @ 976 nm
- Input 9mW of 1572.3nm
- Measured Output ~80mW
- Measured Gain ~10dB
- ASE filtered with FBG

Packaging Approach
Power Amplifier

Pulse Train

\( V_1 \), \( V_2 \), \( V_3 \), \( V_4 \)

100 \( \mu s \), 1 \( \mu s \)

---

MZM

---
OFS PM-VLMA Power Amplifier Performance

GSFC In-House Seed Laser & Preamplifier for VLMA test

OFS PM-VLMA Amplifier

Raman Pump

Thermal profile of Raman amp at full power

Pre-shaped pulses from seed (yellow) and preamplifier (blue) and VLMA Output Pulse shape (Green); Red is ASE from VLMA

Breadboard Performance (w/o optimized pre-shape pulse – 460 µJ at 7.5 kHz, 1 µs pulse

6X would provide ~2.8 mJ
METHANE LIDAR
Methane radiative forcing

- CH$_4$ is a strong greenhouse gas (~×23-25 higher radiative forcing than CO$_2$ on a per molecule basis).
- Earth Science Decadal Survey (NRC 2007):
  - “Ideally, to close the carbon budget, methane should also be addressed, but the required technology is not now obvious. **If appropriate and cost-effective methane technology becomes available, methane capability should be added.**”
Methane “Arctic Time Bomb”

• Increasing concern about CH$_4$ in the Arctic: “Is a Sleeping Climate Giant Stirring in the Arctic?”. Large amounts of organic carbon are stored as CH$_4$ and CO$_2$ in the Arctic permafrost. Thawing Arctic permafrost soil, is a cause for concern as a rapid, positive greenhouse gas/climate feedback. In addition, large but uncertain amounts of CH$_4$ are sequestered as gas hydrates in shallow oceans and permafrost soils, which are also subject to potential rapid release.
CH$_4$ Detection with Lidar

- **Transmitter (Laser) technology**
  - Current (optimum) Wavelength for CH$_4$ Earth Detection: $\sim$1.64-1.66 $\mu$m
  - Optical Parametric Oscillators (OPO) and Optical Parametric Amplifiers (OPA) are the best solutions currently available for a transmitter.
  - Other options (Er:YAG and Er:YGG) also possible

- **Receiver (Detector) Technology**
  - DRS e-APD

- **Transmitter**
  - Seed Laser 1.65 $\mu$m
  - OPA/OPO
  - Transmit Optics
  - Trace Gas (CH$_4$) Absorption
  - To surface

- **Transmitter**
  - Pump Laser 1.06 $\mu$m

- **Electronics**
  - Detector & Filters

- **Receiver**
  - Receiver Optics
  - Reflection from surface
Methane Transmitter Components

**Pump**: a high power, single frequency, narrow linewidth fiber or solid state laser at ~1064 nm or 1030 nm

**Seed**: a (low) power, single frequency diode laser at 1651 nm.

Optical Parametric Oscillator (OPO) or Optical Parametric Amplifier (OPA).
A non-linear crystal that amplifies the seed laser to the energy needed for space **without** degrading the spectral characteristics

All components are critical and require technology development.
**Transmitter Technology - OPA**

**OPA:** OPA samples the CH$_4$ line at several wavelengths using a single, continuously tuned seed laser. Easy to align, easy to tune, hard to achieve power scaling while maintaining narrow linewidth. Need to increase seed laser power. Burst mode pump laser an alternative approach.
Transmitter Technology - OPO

• OPO samples the CH$_4$ line at several discrete wavelengths using multiple seed lasers.
• Complicated to align and tune; power scaling easier to achieve while maintaining narrow linewidth.
• Master laser locked to the CH$_4$ absorption
• Cavity locked to master laser
• Remaining seed lasers offset-locked by integral number of cavity modes
Summary

- Methane measurements are needed over all latitudes and seasons.
- Airborne demonstration with DRS detector and two candidate architectures for a CH$_4$ transmitter: 20-wavelength OPA and 5-wavelength OPO.
  - DRS detector worked well during flight. Its performance is close to CO$_2$ (as expected).
  - Both OPA and OPO performance was better than expected during flight.
    - 20 wavelength OPA gave better results (precision) but there is no simple path to scale the power of the transmitter to space.
    - 5 wavelength OPO gave good results (when detector was not saturated). Can use more wavelengths but is already close to the energy we need for space.
- Transmitter Plan - Many different approaches and options for laser transmitter were investigated.
  - Er:YGG/Er:YAG (Baseline)
  - OPO (Backup):
    - Burst Mode OPA (no easy path to space)
    - Single Pulse OPA (no easy path to space)
- Plan will provide at least one baseline configuration (Er:YGG) and at least one backup configuration (OPO) that can be flown.
- Leveraged SBIR, IRAD, and Tipping Point programs.
- Significant progress has been made with modest investments.
Science of Gravitational Waves/eLISA

- **eLISA (evolved Laser Interferometer Space Antenna)**
  - Planned late 2020s ~ early 2030s launch
  - https://www.elisascience.org

- **New way to observe the universe**
  - Expected astrophysical GW sources in eLISA
    - Black holes and galaxy formation
    - Merging massive black holes in galaxies at all distances
    - Massive black holes swallowing smaller compact objects
eLISA laser requirement

- Unique requirements for precision interferometry
  - Continuous-wave laser
  - Single-mode & frequency
  - Extreme stability in frequency & intensity

<table>
<thead>
<tr>
<th>Power</th>
<th>λ (nm)</th>
<th>Intensity noise (Hz/(1/2))</th>
<th>Frequency noise (Hz/(Hz/(1/2)))</th>
<th>Differential phase noise (rad/(Hz(1/2)))</th>
<th>Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 W</td>
<td>1064</td>
<td>(10^{-4}) ((\text{@} 10^{-3} \text{ Hz})) (10^{-8}) ((\text{@} 10^{7} \text{ Hz}))</td>
<td>300 ((\text{@} 10^{-2} \text{ Hz}))</td>
<td>6(\times)10(^{-4}) ((\text{@} 10^{-2} \text{ Hz}))</td>
<td>2.5 years</td>
</tr>
</tbody>
</table>

- eLISA laser configuration
  - All-fiber master oscillator power amplifier (MOPA)
Current Activities & Future Work

• Master oscillator
  – Working with RIO to build low noise planar-waveguide ECL
  – Environmental test to be completed soon at RIO
  – On-chip phase modulator planned

• Pre-amplifier
  – ~150mW CW output
  – Prototype was built, packaged, and tested
  – Environmental testing being done

• Power amplifier
  – All-fiber design, ~2.4W CW output
  – Noise measurement & stabilization being done
  – Full laser system noise & reliability tests planned
PLANETARY SCIENCE
TIME OF FLIGHT MASS SPECTROMETER
Science Motivation

All these bodies contain volatiles, including water just waiting to be analyzed

Our science motivation is to seek a solution with “Universal” detector for
• Comprehensive sample analysis
• Flexibility to adapt for different mission architectures including flybys, orbiters, landers, and/or rovers!
L2MS Instrument Overview

- Wavelengths are selected based on key vibrational and electronic resonances in the targeted species aligned with the organic diversity and mineralogy expected for future planetary missions of high priority to NASA
  - 2.75 μm - IR vibrational resonances of hydrated minerals
  - 3.4 μm - C-H vibration resonance of organic species
  - 266 nm - coincides with a short-lived metastable state in many aromatic molecules
- Matching MIR laser wavelength allows for selective desorption
L2MS Instrument Overview

- Typical delay between Laser 1 and Laser 2 ($\Delta t$) range between 0.3-2 μs
# L2MS Laser Requirements

<table>
<thead>
<tr>
<th>Lasers Requirement</th>
<th>MIR Laser</th>
<th>UV Laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse Repetition Frequency (PRF)</td>
<td>1 – 20 Hz</td>
<td>1 – 20 Hz</td>
</tr>
<tr>
<td>Wavelength</td>
<td>2.8X µm and 3.40±0.05 µm</td>
<td>266 nm</td>
</tr>
<tr>
<td>Energy</td>
<td>~ 100 µJ</td>
<td>~ 18 µJ</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>&lt; 7 ns</td>
<td>&lt; 7 ns</td>
</tr>
<tr>
<td>Peak Power</td>
<td>~14 kW</td>
<td>~2.5 kW</td>
</tr>
<tr>
<td>Peak Intensity (assuming 100 µm beam diameter)</td>
<td>180 MW/cm²</td>
<td>~30 MW/cm²</td>
</tr>
<tr>
<td>Spectral Width</td>
<td>Few GHz</td>
<td>Few GHz</td>
</tr>
<tr>
<td>Timing</td>
<td>$t_0$</td>
<td>$t_0 + \Delta t; \sim 100$ ns $&lt; \Delta t &lt;$ few µs</td>
</tr>
<tr>
<td>Laser Lifetime</td>
<td>3 year mission at 10% duty cycle $\sim 64$ Mshots @ 20 Hz</td>
<td></td>
</tr>
</tbody>
</table>
Future Work

Laser 1 – MIR Laser
- Test 3.4 \( \mu m \) breadboard with L2MS laboratory instrument and compare with commercial OPO
- Complete 2.75 \( \mu m \) breadboard laser
- Finalize design for dual wavelength (2.75 \( \mu m \) and 3.4 \( \mu m \)) concept

Laser 2 – UV Laser
- Investigate other non-linear optical crystals for SHG and FHG – leverage ICESat-2/ATLAS LBO aging study
- Optimize overall 4\(^{th}\) harmonic conversion efficiency
- Test breadboard with L2MS laboratory instrument and compare with commercial UV laser
- Develop epoxy-free opto-mechanical design for mounting optics to minimize UV induced contamination on optical surfaces

Laser Transmitter
- Improve packaging of the laser transmitter for space flight
- Build brass board laser transmitter that will generate both MIR and UV wavelengths on a single laser bench
Preparing for the Future

- Use nonlinear optical processes to generate specific wavelengths for laser spectroscopy
- New approaches in laser architectures
  - High rep rate, lower pulse energy, sub-ns pulse for high resolution mapping (8-10 kHz, >50 µJ, <2 ns)
  - High efficiency laser systems (>15% wall plug)
  - Highly reliable laser systems (multi-Billion shots)
  - High sensitivity detector and detector arrays with low-noise, high speed ROICs
    - linear mode PC in the NIR because of its wavelength advantages
  - Data volume management
    - On-board data processing
    - Data compression
    - High data downlink rate
- Common requirements for all laser based instruments
  - Lifetime
  - Reliability
  - Efficiency