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

Mark Stephen, Anthony Yu, Jeff Chen, Kenji Numata, Stewart Wu, Brayler Gonzales, Lawrence Han, Mike Plants, Molly Fahey
NASA-GSFC
Mike Rodriguez, Graham Allan, Bill Hasselbrack - Sigma Space Corp.
Jeff Nicholson, Anand Hariharan – OFS, Inc.
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

GSFC

ASCENDS

Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) Mission

Science Mission Definition Study

Draft

ASCENDS Ad Hoc Science Definition Team:

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April 15, 2015

Avail from:
http://cce.nasa.gov/ascends_2015/index.html

National Aeronautics and Space Administration

+ NASA Homepage
+ NASA Carbon Cycle and Ecosystems

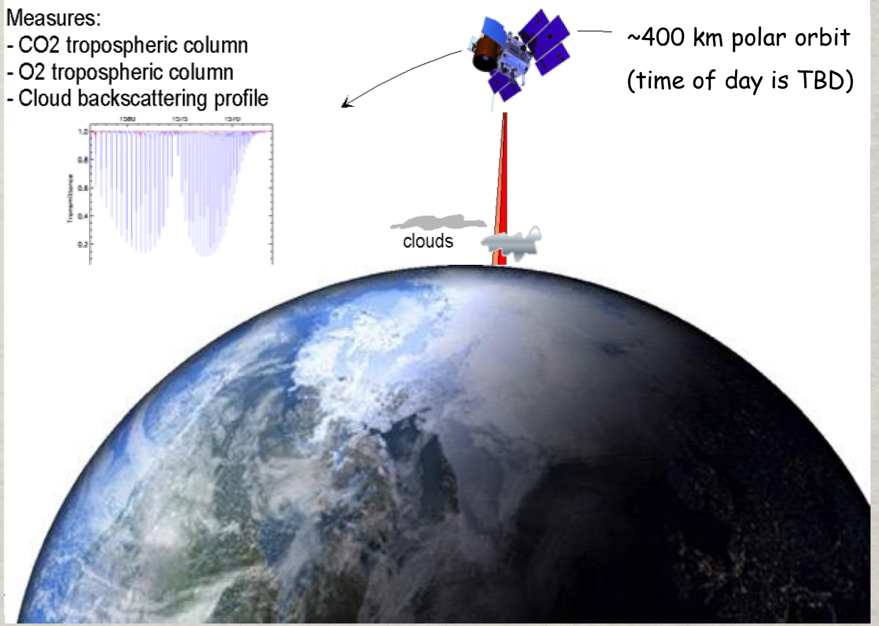
ASCENDS 2015 Workshop

Home | Agenda and Presentations | | ad hoc Science Definition Team

ASCENDS Workshop
June 19, 2015
California Institute of Technology

This workshop will be held after the *11th International Workshop on Greenhouse Gas Measurements from Space* at California Institute of Technology, Pasadena, California, USA, Friday, June 19th.

View their website for logistical information: https://sites.google.com/site/iwggms11/



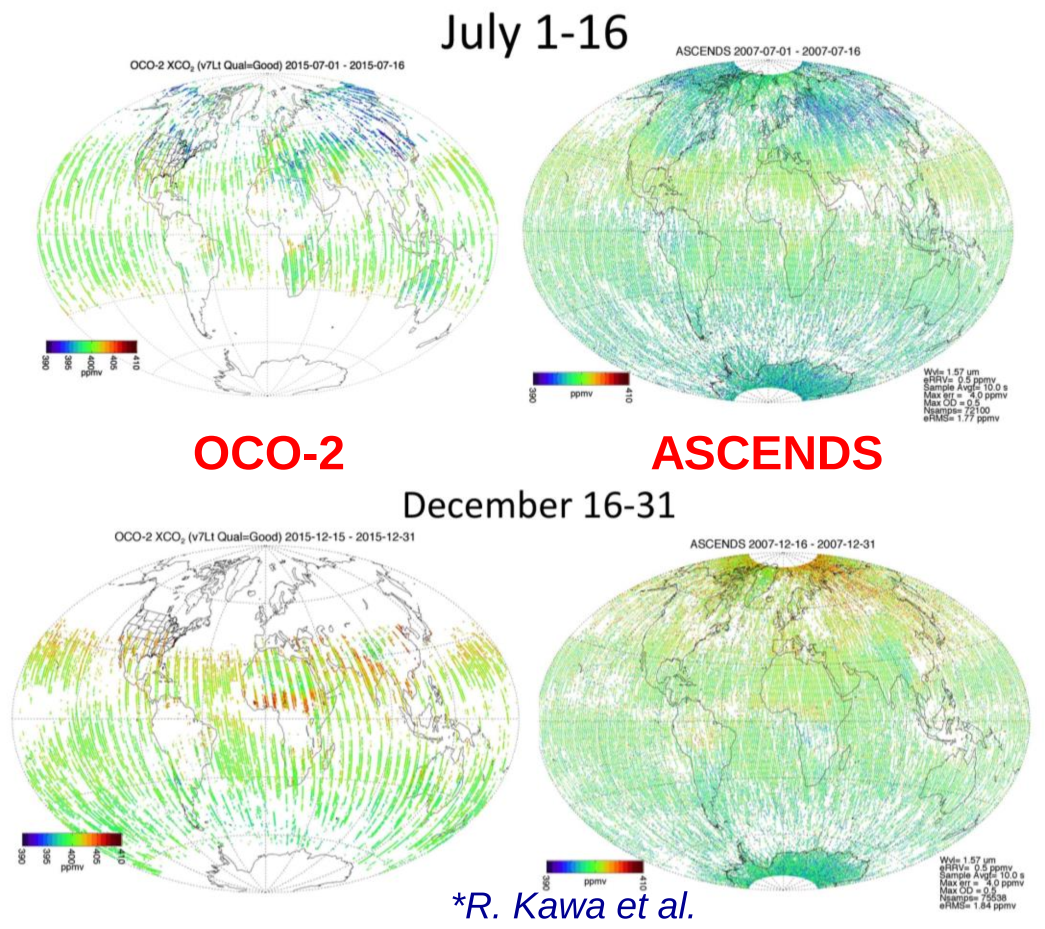
Requirements for CO_2 Mixing Ratio:

***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*



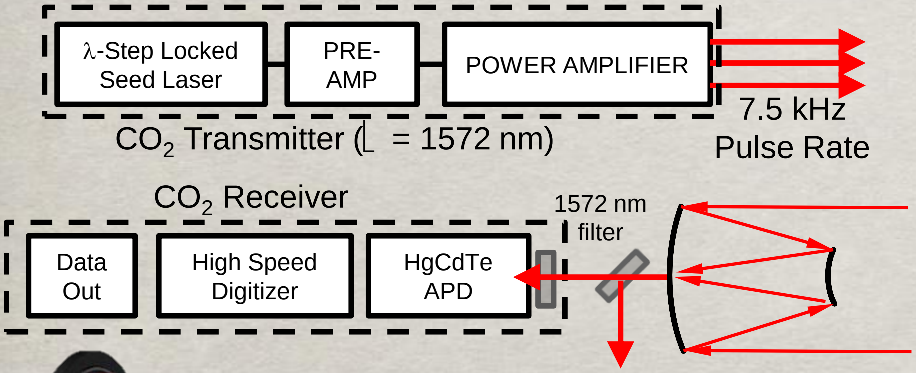
*R. Kawa et al.

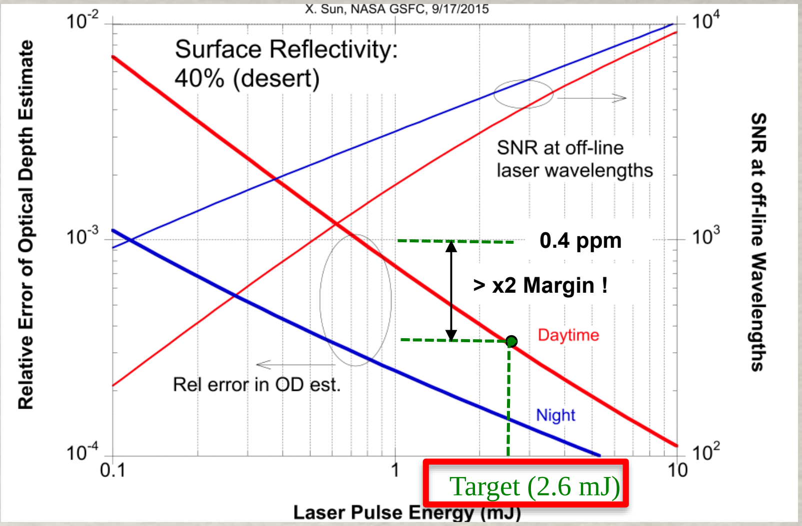
ASCENDS shows:

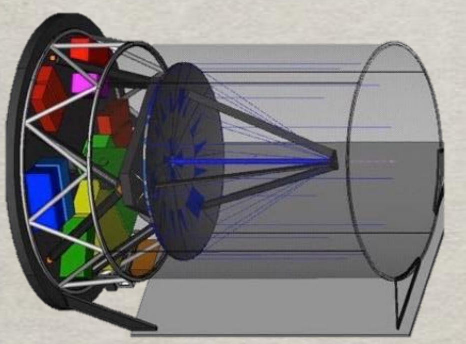
1. *More spatially* ***uniform coverage***
2. *Coverage* **is** ***uniform throughout year***
3. ***Much better sampling*** **in key areas:**

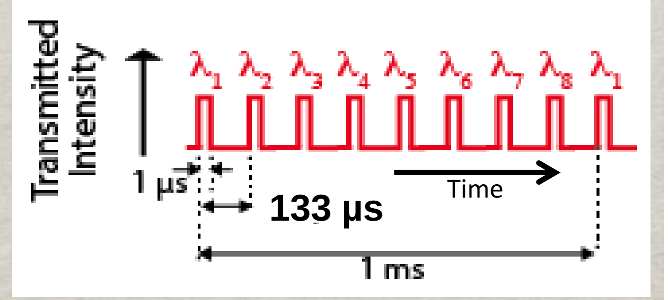
- **Tropics, N. Hemisphere, S**outh. **Ocean**

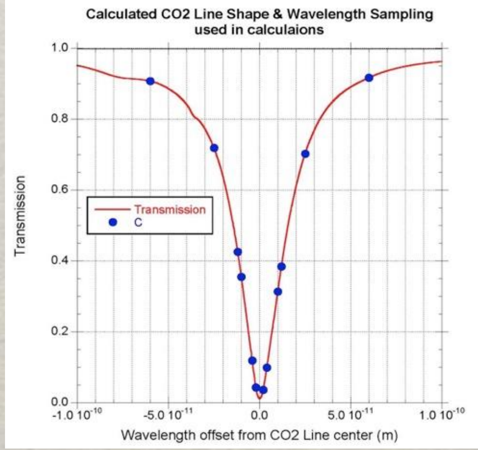
Scaling CO_2 Sounder Lidar to Space











Ref: J. Abshire, et. al., "Progress in developing the CO2 sounder Lidar as a candidate for the ASCENDS Mission," presented at SPIE Optical Engineering and Applications, San Diego, CA, August 2015.

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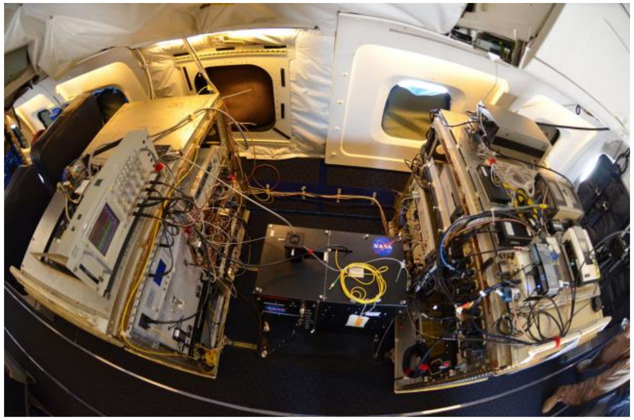
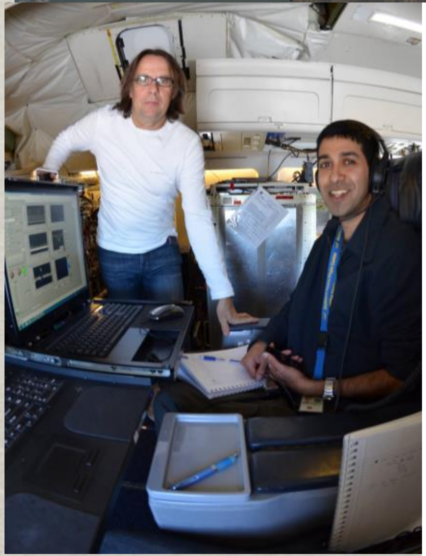
CO_2 Sounder Airborne Lidar



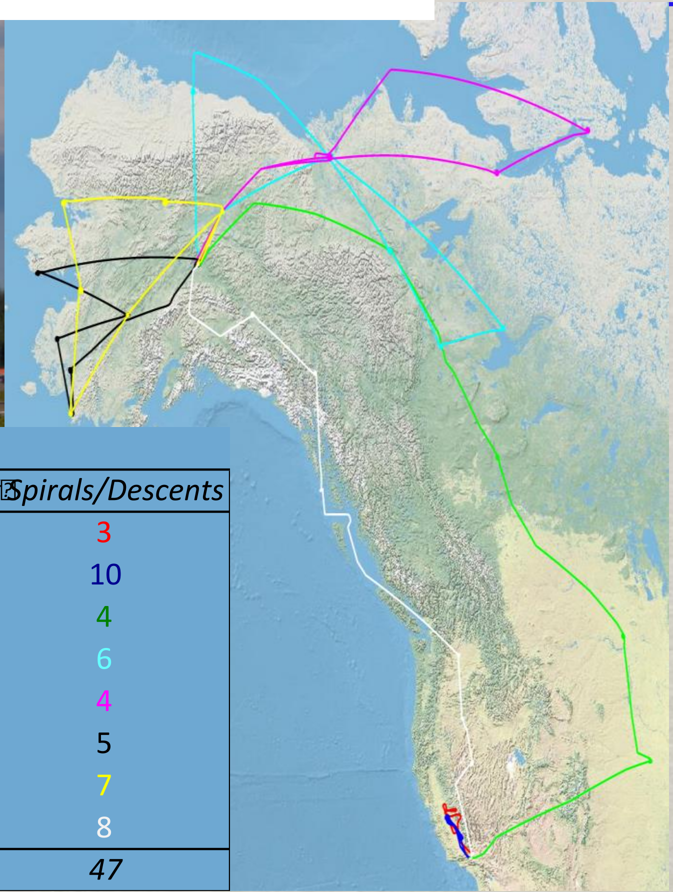


Improvements for recent ASCENDS flights:

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

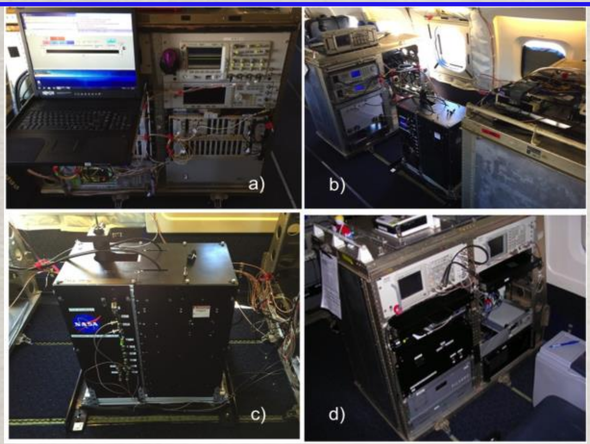

NASA DC-8 Landing at Fairbanks Alaska on July 27

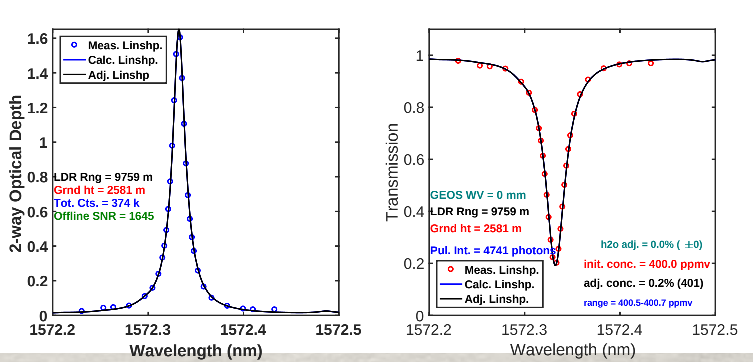


Flights & Legend:

Dates	Name	Duration (hrs)	# Spirals/Descents
20-Jul	Engineering	4.4	3
21-Jul	Calibration	5.6	10
27-Jul	Northbound science/transit	9.4	4
31-Jul	Western NWT	8	6
2-Aug	Northern NWT	6.6	4
5-Aug	South-Central Alaska	6.2	5
6-Aug	Central Alaska	7	7
8-Aug	Southbound science/transit	8.1	8
8	*Totals:*	*55.3*	*47*

CO_2 Sounder Lidar & other campaign instruments





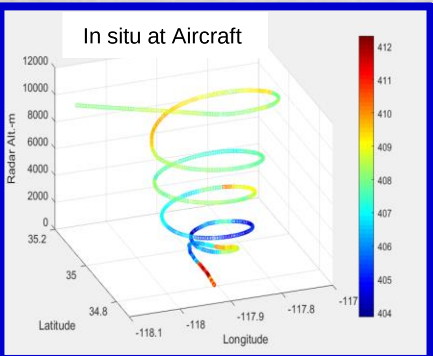
Other science instruments on ASCENDS 2017 campaign

- 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 CO_2 absorption using 1572.33 nm line.
  - Laser pulses - stepped in 30 wavelengths across line.
- Wavelengths are locked relative to CO_2 absorption line center
  - Time resolved receiver uses HgCdTe APD detector
- Measures backscatter profile, range & samples of CO_2 line shape
- XCO_2 Retrievals:
  - Line shape samples, range to scattering surface
  - Atmospheric state (measurements or model)

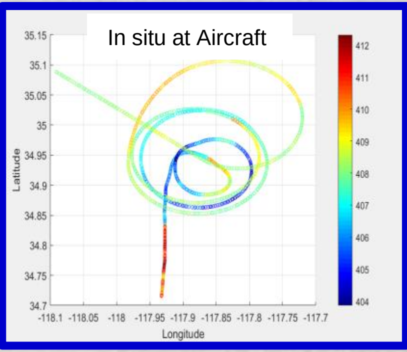
Engineering Flight July 20, 2017
Spiral over Edwards CA: CO2 & XCO2 Retrievals



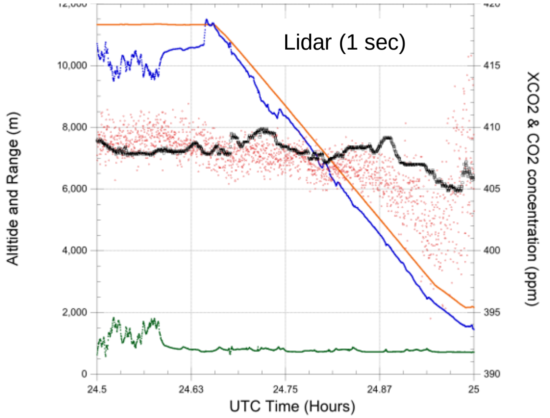
Picarro (in situ) CO_2 measurements at aircraft made during spiral

<- Side view

Top view->

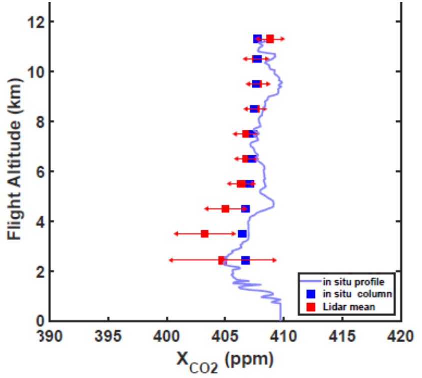


Red dots: XCO_2 from CO_2 Sounder Lidar
Black dots: CO_2 (at altitude) from in situ
All XCO_2 Retrievals use 1 second averaging time



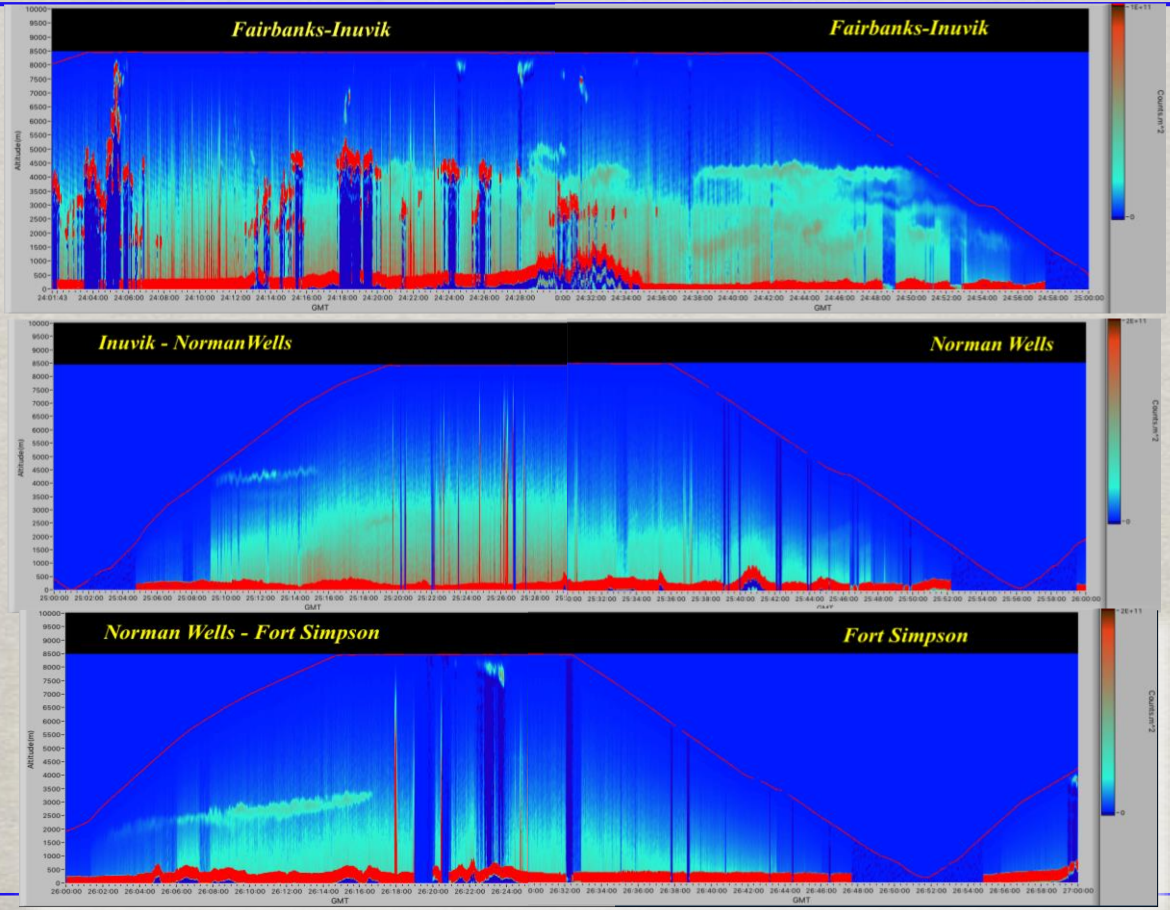
Reference atmosphere (LUT) for XCO2 retrievals based on:
DC-8 T & P
PICARRO H2O

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

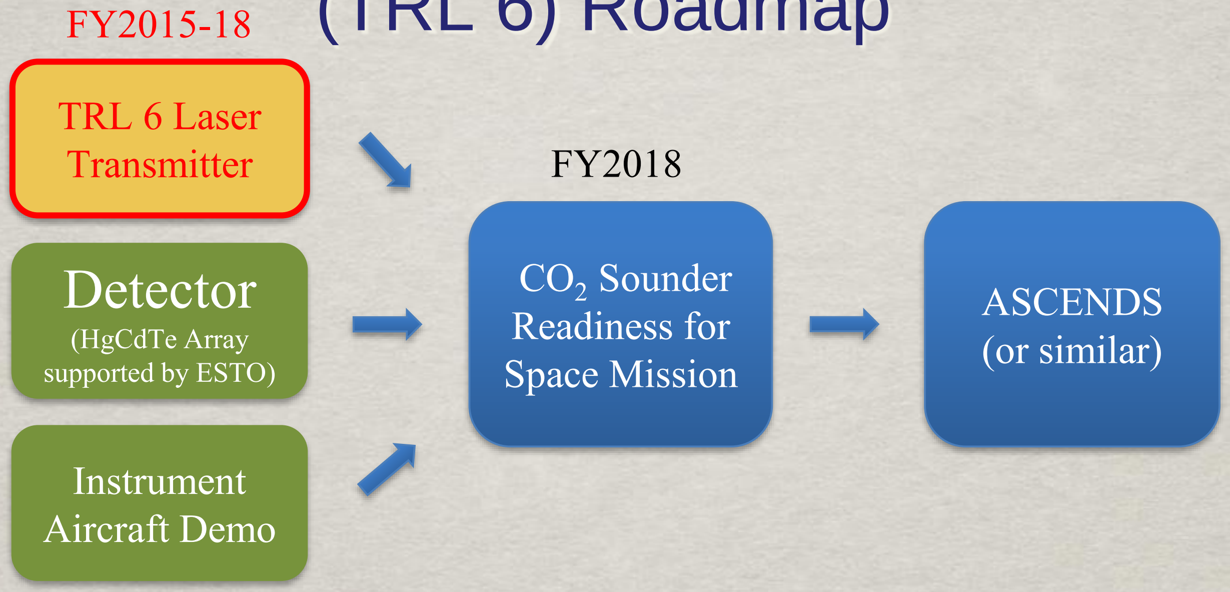


Same format used for other sample results

Lidar Measured Backscatter History - NWT Flight 1



Space Laser Transmitter (TRL 6) Roadmap



- Previous work has demonstrated most key elements needed for ASCENDS
- The main obstacle remaining for a CO_2 Sounder-based mission is the laser TRL
- A CO_2 precursor mission could be an intermediate step, as a science and technology demonstration (eg. 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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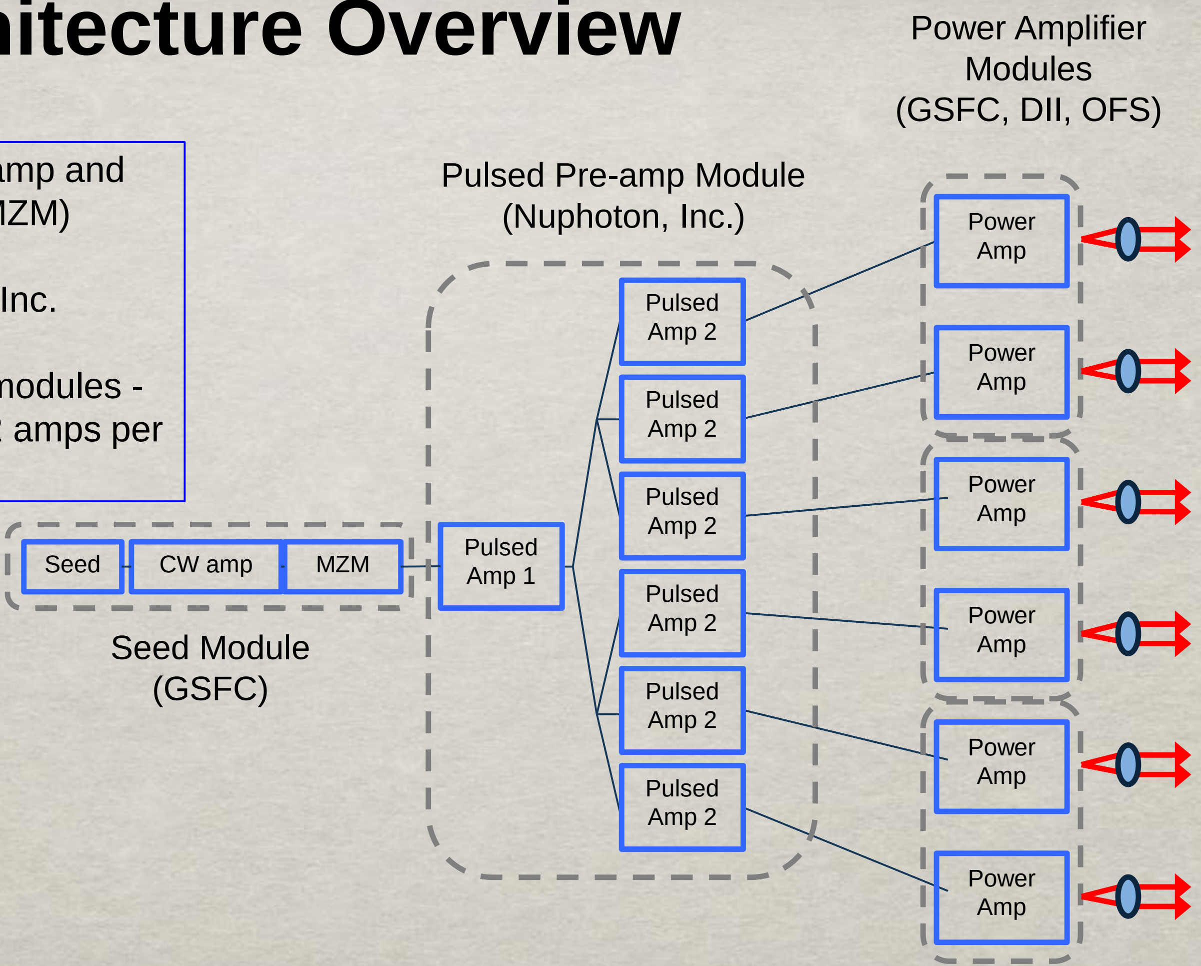
laser Requirements

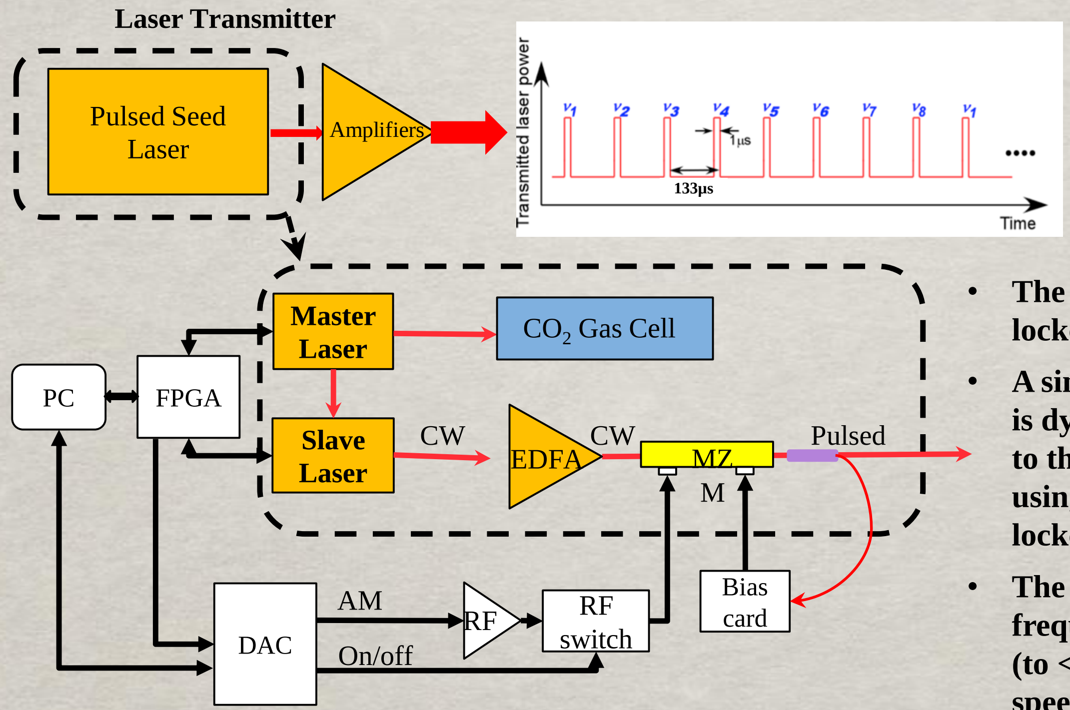
Performance Parameter	Laser Transmitter
Center Wavelength	Nominally centered at 1572.335 nm
Linewidth (each wavelength channel)	≤ 100 MHz
Pulse repetition frequency	7.5 KHz
Pulse Width	1-1.5 μs
Pulse Energy	>3.2 mJ/pulse (goal); >2.6 mJ/pulse (operating, 18% derating)
PER [TBR]	20 dB (TBR)
Wall-plug Efficiency	> 6%

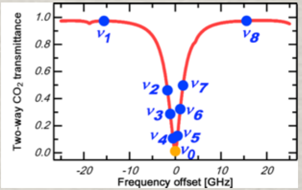
Architecture Overview

- 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

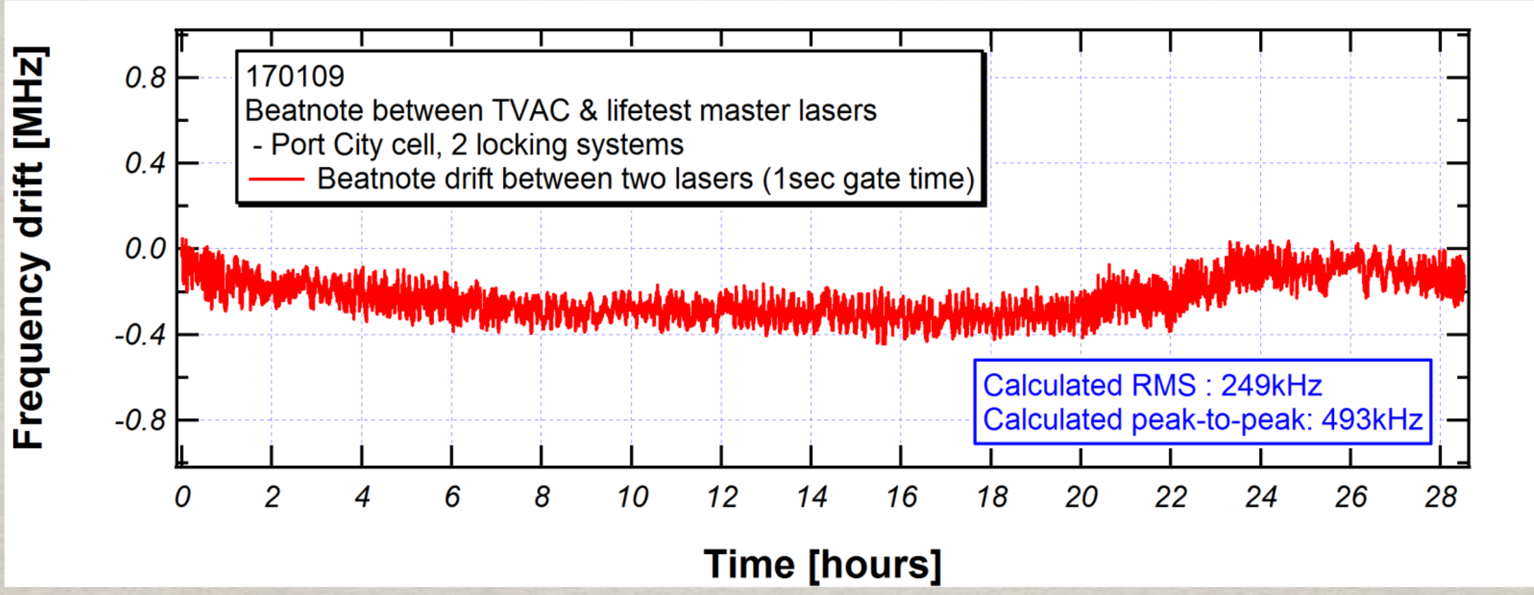




- **The DFB master laser is locked to CO_2 reference cell**
- **A single DS-DBR slave laser is dynamically offset-locked to the master DFB laser using an optical phase-locked loop (OPLL)**
- **The demonstrated laser frequency noise suppression (to < 0.2 MHz), tuning speed (< 40 μs) and tuning range (~32 GHz) satisfies ASCENDS requirements**

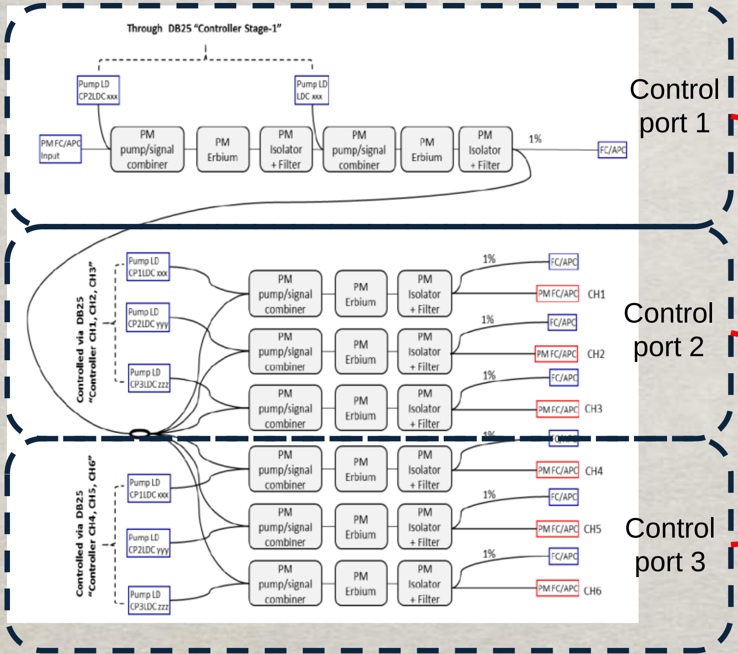
- Pulse shaping will compensate for distortions by Pre-Amp and Power Amp modules. Desire "flat top" output pulses.
- Capability to perform pulse-shaping through use of high-speed DAC currently in development

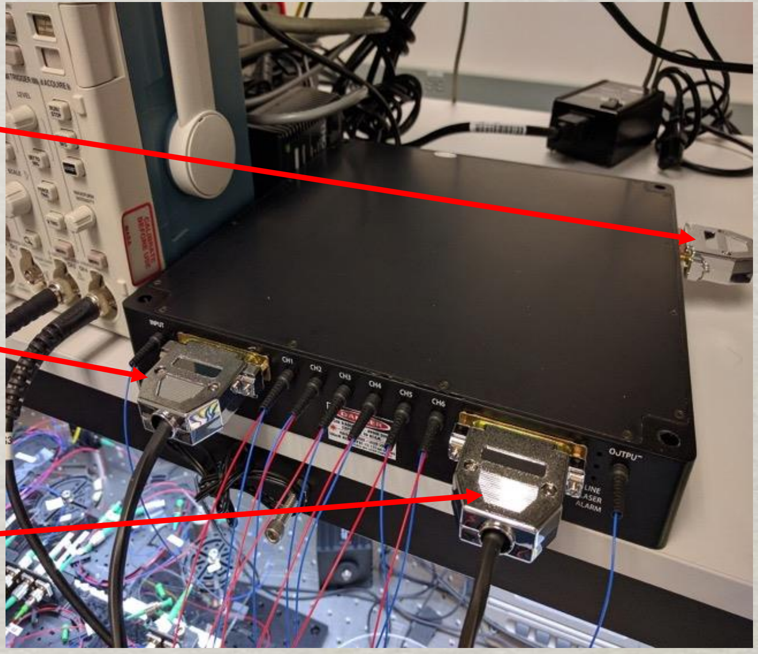
Frequency Drift of Master Laser



Less than 1 MHz absolute drift between two independently locked sources over a 1-day test

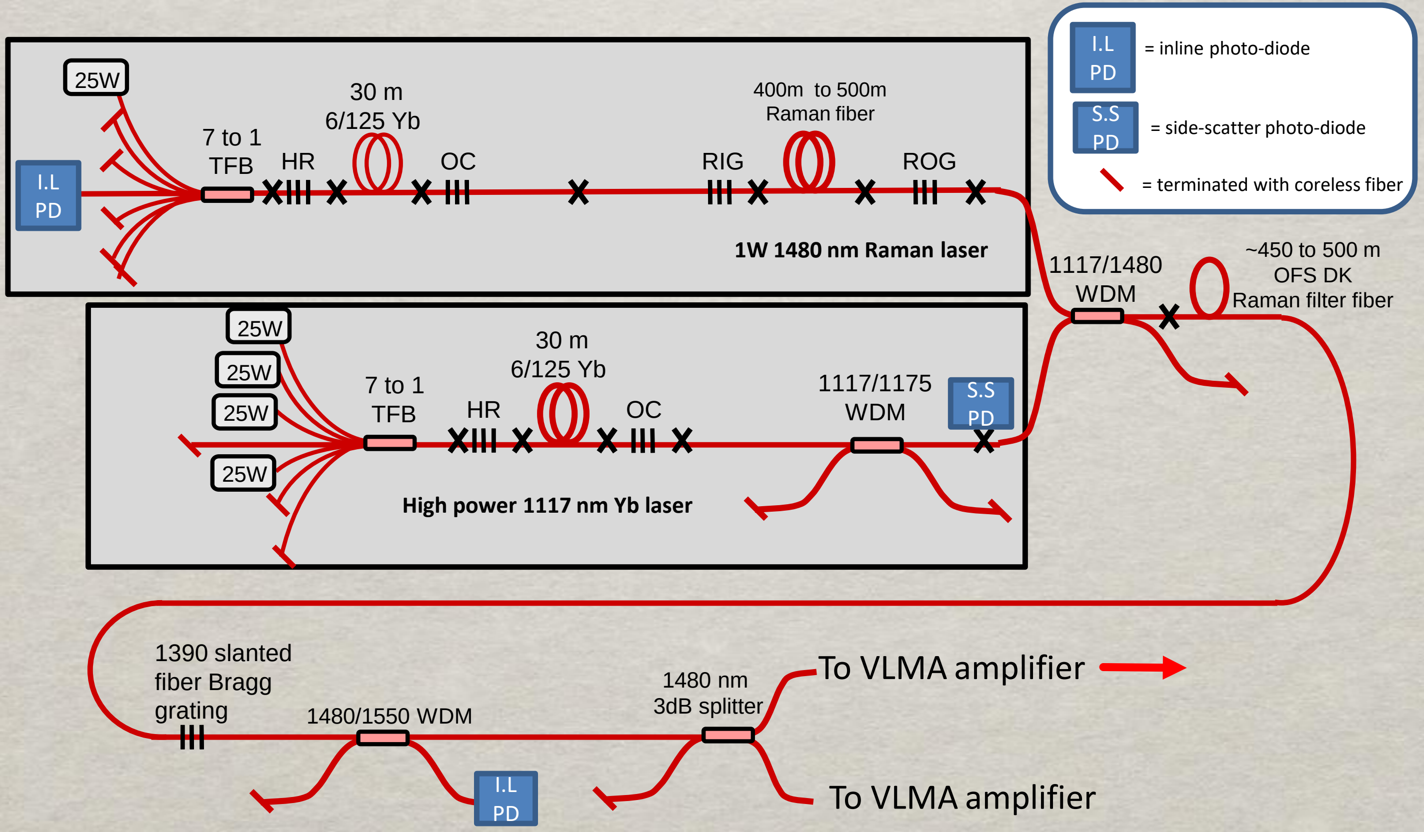
Nuphoton Pre-Amp Module



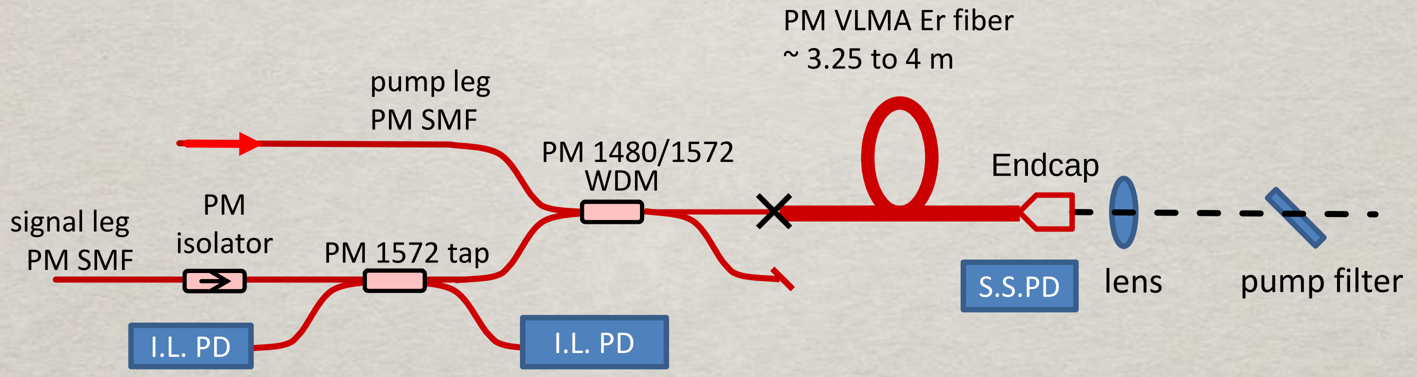


- The unit has 1 input and 13 outputs (including 7 monitor ports)
- Each output provides >5 µJ pulse energy
- OFS requires 2.5 µJ for the power amplifier
- Three serial interface for controlling different sections with hyper-terminal
- **Module meets all optical performance requirements**
- **Worked with vendor to use vacuum compatible components**

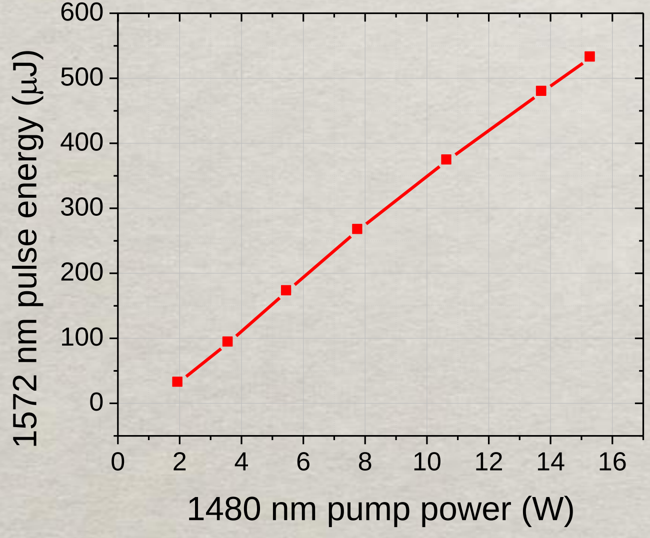
30W Raman Amplifier 1480nm Pump: Detailed schematic

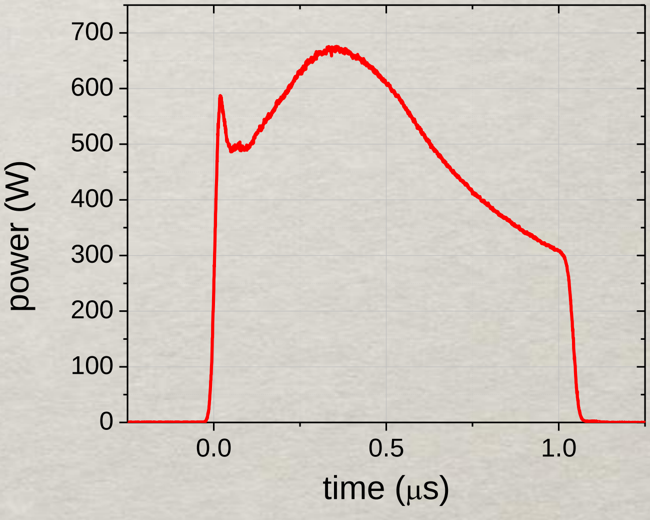


PM-VLMA-Er schematic



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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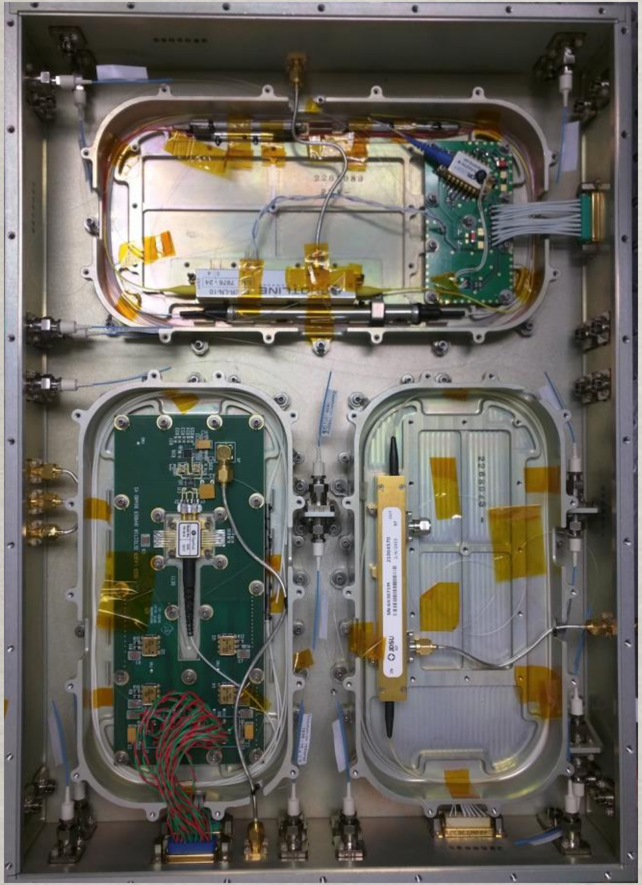
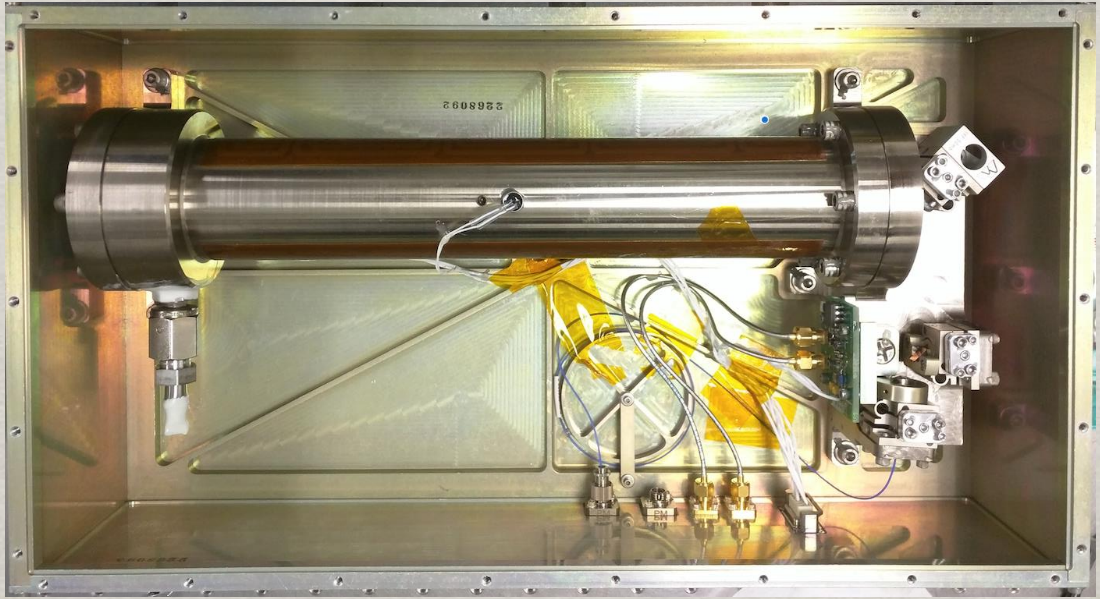
Completed Seed Module



- 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

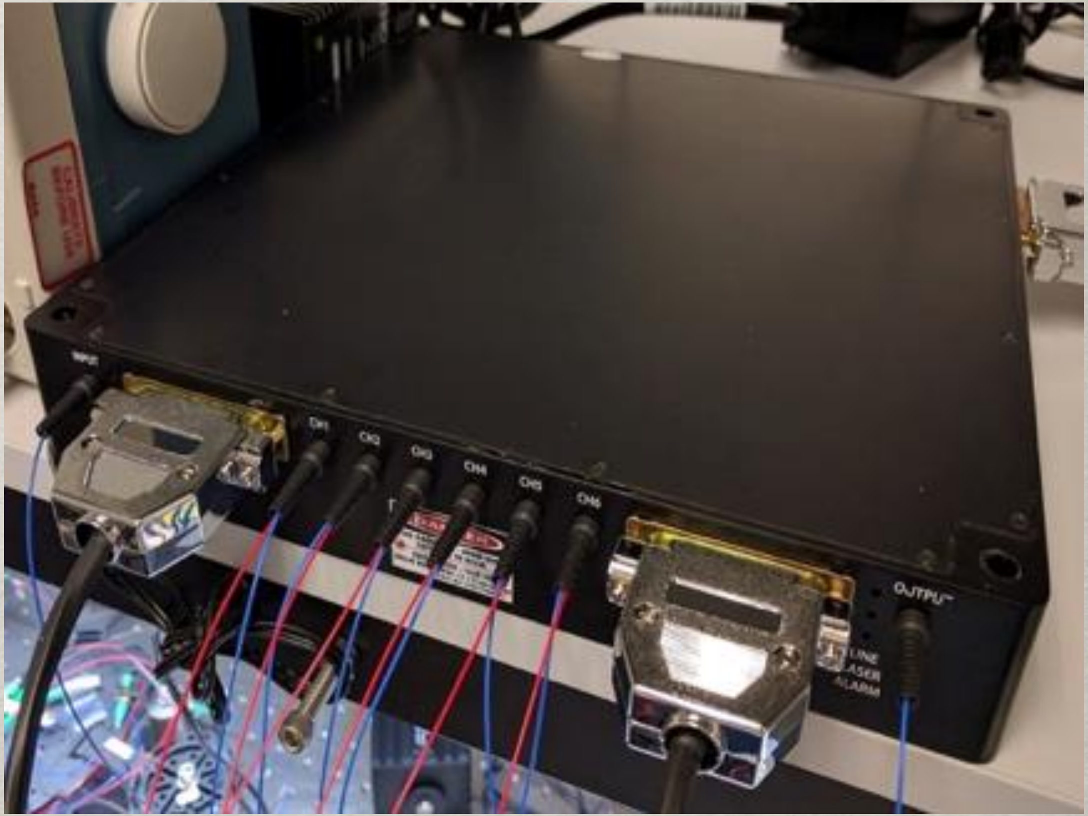
Herriott Cell



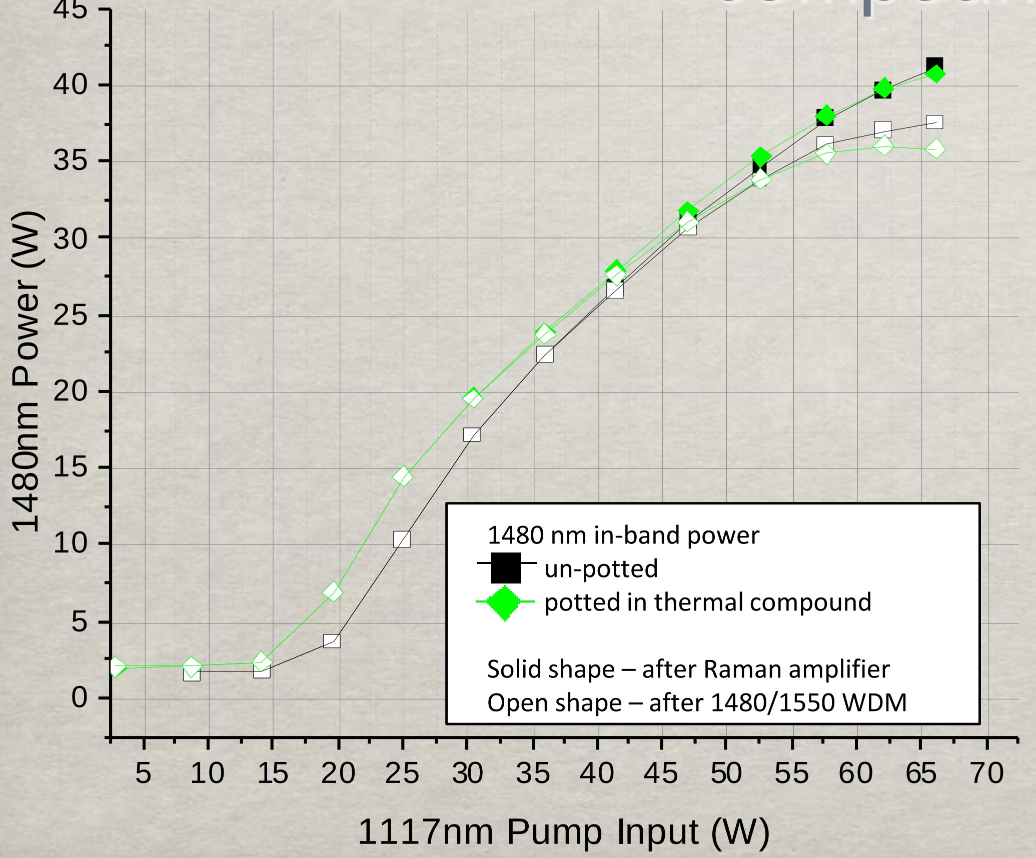
Herriott cell filled with CO_2 gas with integration optics in a ruggedized package to lock the reference laser to an absolute wavelength standard. Module Dimensions: 25.5-cm x 12.5-cm x 10-cm

Pre-Amplifier Module

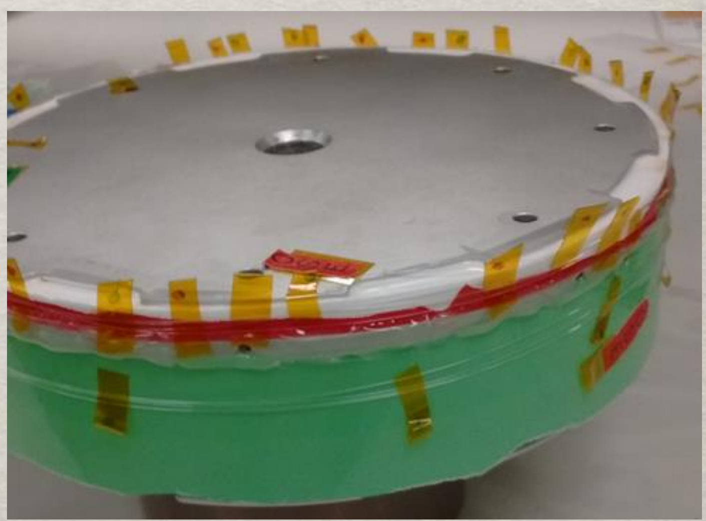
- Photo of pre-amplifier prototype.
- Built by NuPhoton, Inc.
- Meets optical requirements
- Module dimensions: 28-cm x 28-cm x 5-cm



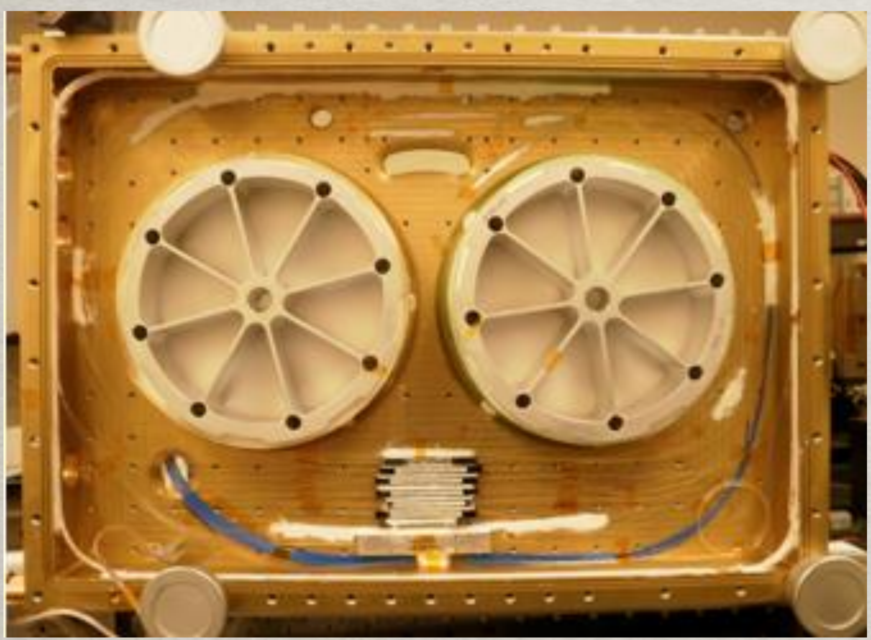
Potting amplifier fiber in thermal compound

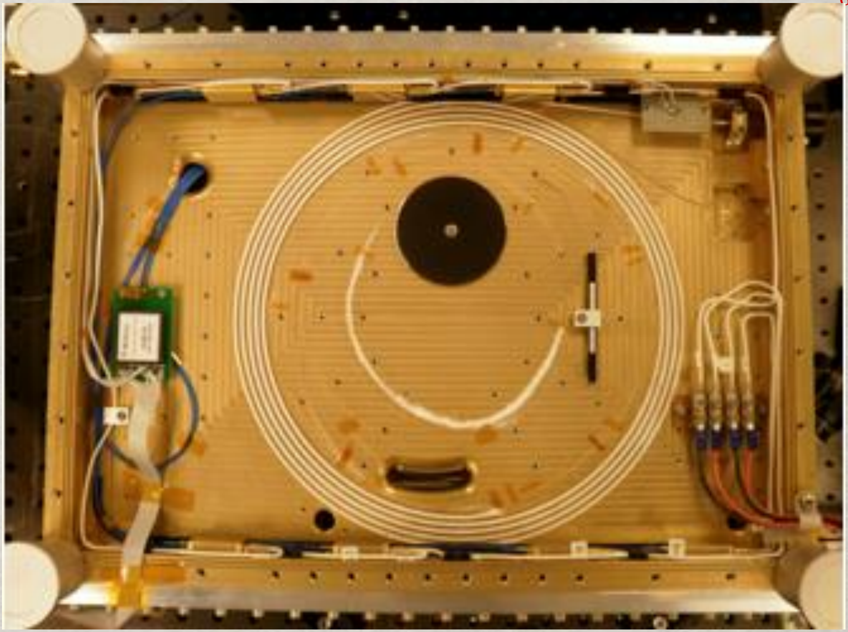


Process of vacuum potting amplifier fibers in thermal compound did not affect Yb or Raman cavity efficiencies. Over-all system efficiency was un-changed after potting process.



Power Amplifier Module

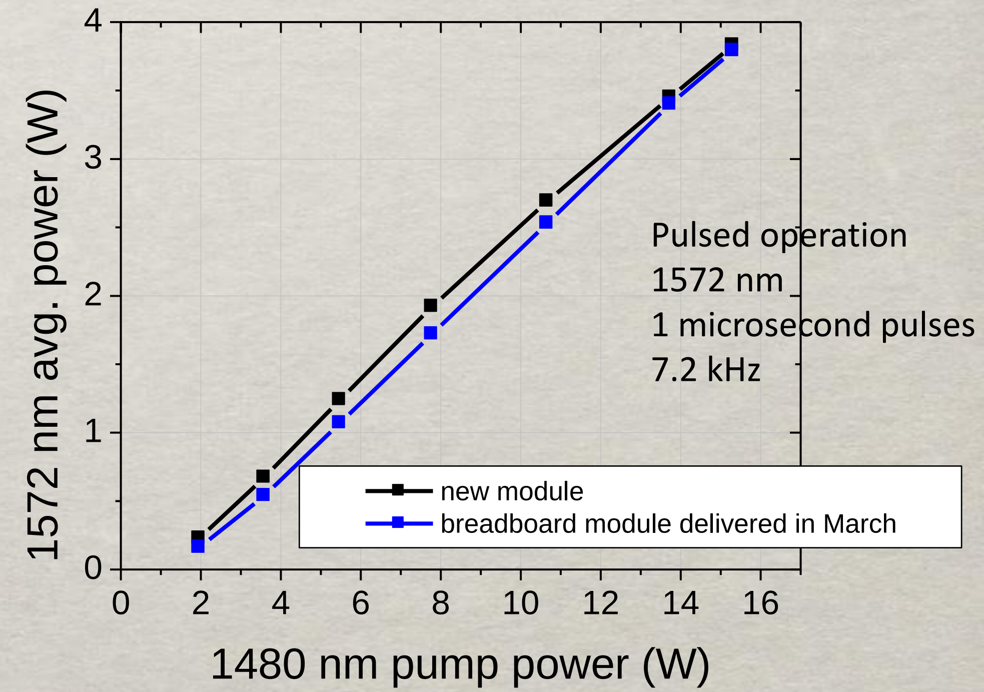




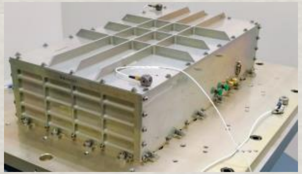
Photos of VLMA power amplifier prototype. The left photo shows the bottom half of the box with the Raman pump system. There are two spools and the fiber components are in the lower center of the photo. The right photo shows the PM-VLMA fiber. The white fiber potting material makes the spiral groove easy to visualize. Module dimensions:. 44-cm x 32-cm x 9-cm.

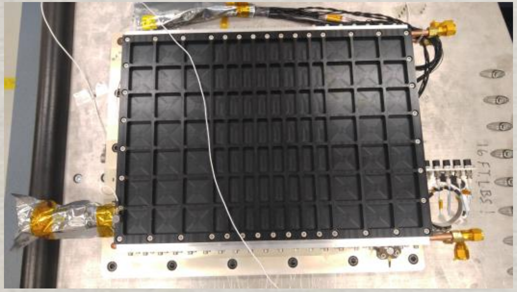
PM-VLMA amplifier Comparison with breadboard module

- 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**



Vibration Test Status

Frequency (Hz)	Normal/Vehicle Axial [g^2/Hz]	Lateral [g^2/Hz]
20	0.25	0.25
2000	0.25	0.25

Sine Sweep Testing Profile
(Performed before and after each Random Vibe)

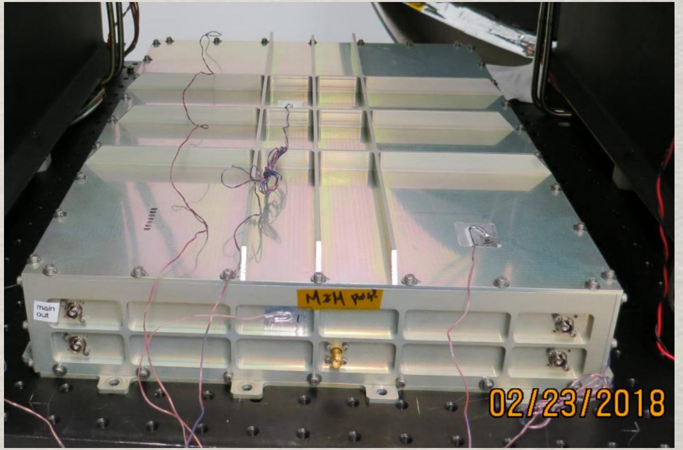
Frequency (Hz)	Normal/Vehicle Axial [g^2/Hz]	Lateral [g^2/Hz]
20	0.02	0.02
40	0.02	0.02
60	0.05	0.05
200	0.05	0.05
250	0.08	0.05
300	0.08	0.014
450	0.08	0.014
750	0.01	0.014
2000	0.01	0.014
Grms	**7.01**	**5.88**
Duration	**60 sec/axis**	**60 sec/axis**

Random Vibration Testing Profile

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 axis. 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.

Bakeout Test Status

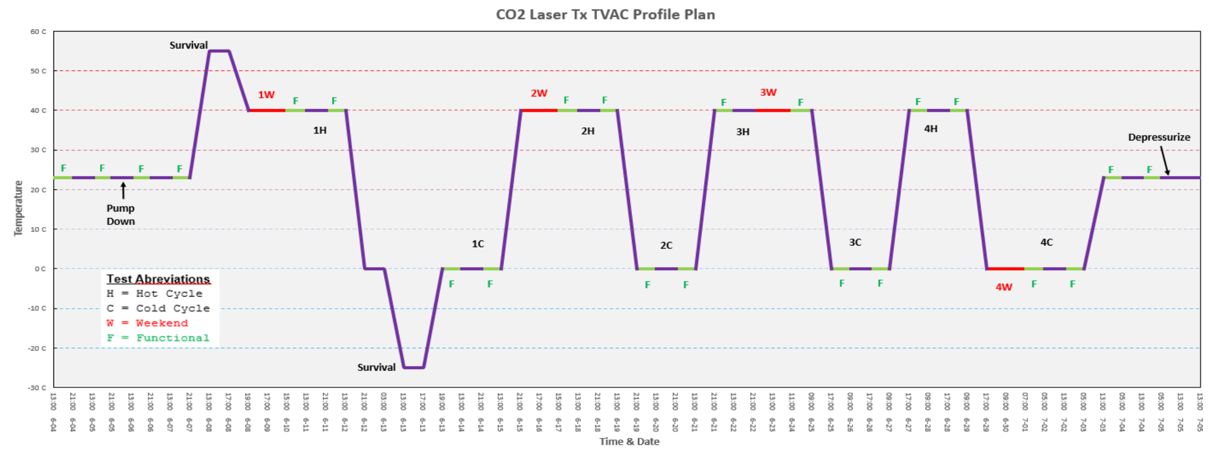


<u>Successful Bakeout on All Modules</u>

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

GSFC



Thermal Vacuum Testing Profile (example)

	Hot	Cold
Operational (with Coolant Loop)	10°C	30°C
Operational (without Coolant Loop)	-10°C	50°C
Survival	-25°C	55°C

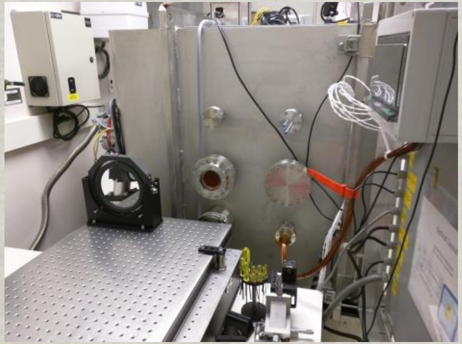
CO2 Transmitter Temperature Profile

<u>Starting TVAC Test Soon</u>

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.

ESTO Earth Science Technology Office

TVAC Chamber (562)



Cold plate measures 32” x 32” x 1”, chamber has plenty of feedthrus for fiber and cables connectors .

Radiation Requirements

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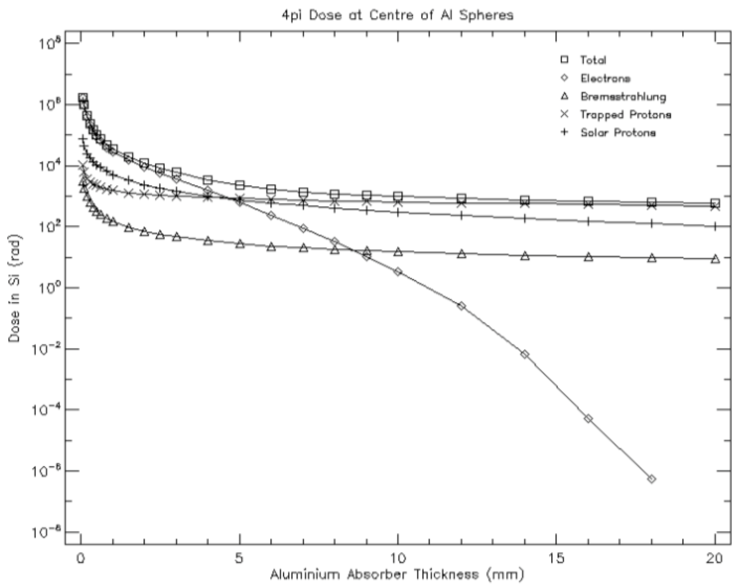
SPENVIS Orbits: CO_2 Transmitter Information

Free-Flyer Launch

Duration:	3 years
Launch Date:	2025
Orbit:	Polar, Sun-synchronous
Height	700 km
Solar Max	3 yrs
Solar Min	0 yrs



LEO ISS orbit has a total dose of .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

ESTO Earth Science Technology Office

Progress toward the CO_2 Sounder Lidar to Space

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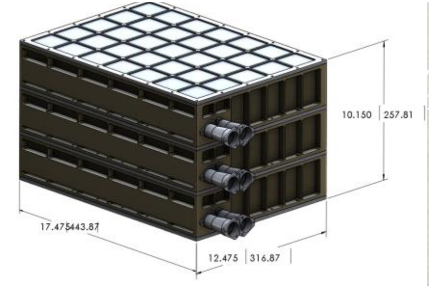
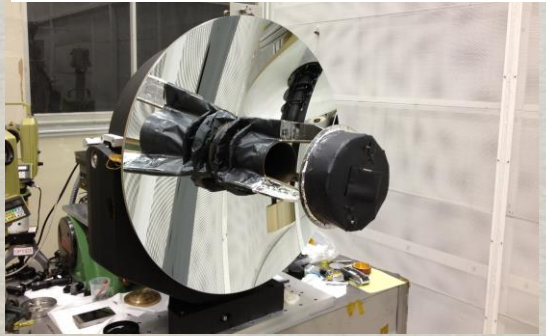
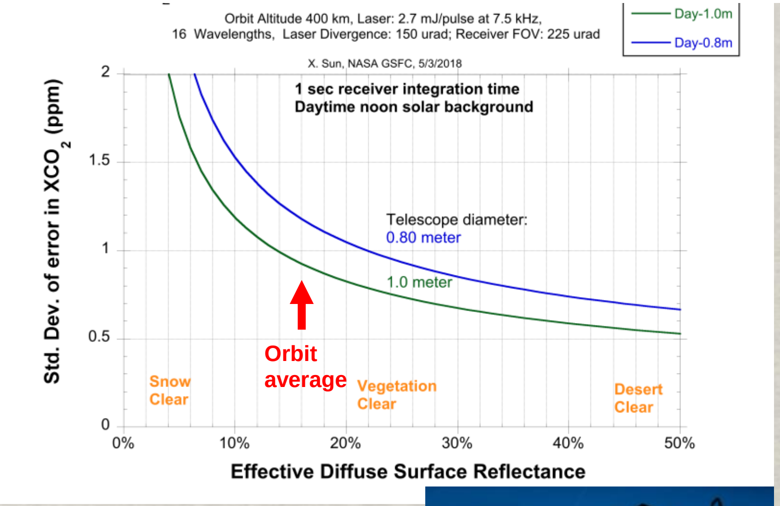
1. **Laser** with space needed performance in testing: TRL-6 by October 2018



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



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



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

ESTO Earth Science Technology Office

Outline

- Introduction
- Instrument Performance
- Transmitter Development
- Transmitter Packaging
- **Future Directions**
- Conclusions

2018 NSF Decadal Survey

Recommended NASA Priorities: Explorer

TARGETED OBSERVABLE	SCIENCE/APPLICATIONS SUMMARY	CANDIDATE MEASUREMENT APPROACH	Designated	Explorer	Incubation
Greenhouse Gases	**CO_2 and methane fluxes and trends,** global and regional with quantification of point sources and identification of source types	Multispectral short wave IR and thermal IR sounders; or lidar**		X	

- **The recent Earth Science Decadal Survey significantly reduced the anticipated funding for a potential ASCENDS-like measurement.**

2017 ACT summary

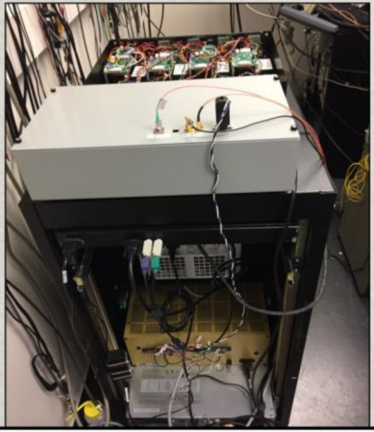
GSFC

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.

Rack of equipment

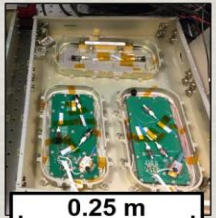
- PLL electronics
- Control electronics
- Electronic amplifiers



1 m

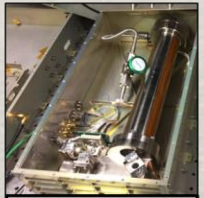
Photonic components

- Seed module
- Optical amplifiers



0.25 m

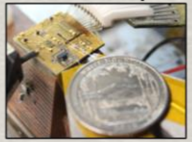
Herriott gas reference cell



0.25 m

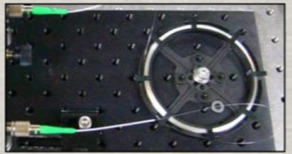
Fully integrated PIC-EIC

- Photonic seed module
- PLL electronics
- Control electronics
- Electronic amplifiers



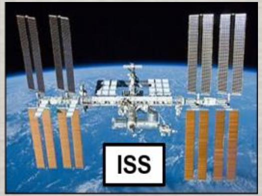
Footprint = 1.8 cm x 1.5 cm

Compact all-fiber gas reference cell



10 cm

~150 ft.



~300 ft.

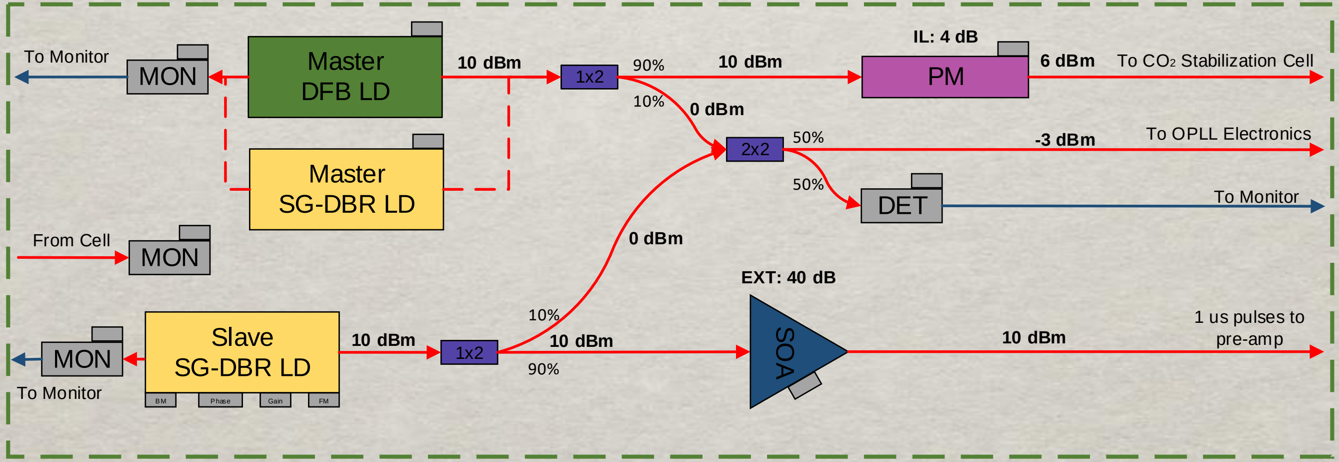
~1 ft.

~36 ft.

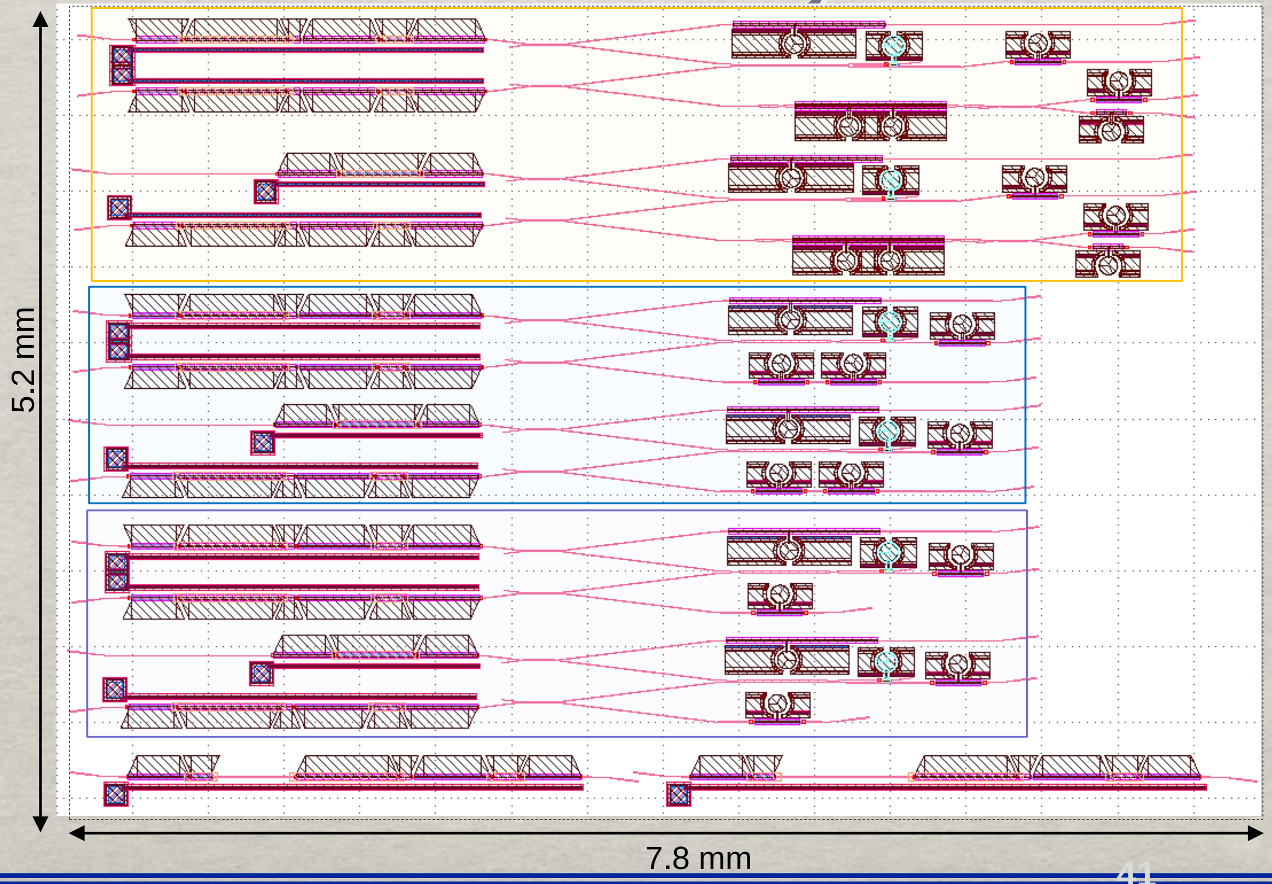
PIC Schematic

PIC Schematic mirroring a fiber and bulk component based design that we have designed, built and tested for atmospheric CO_2 spectroscopic measurements.

Monolithic PIC



PIC Layout



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Conclusion & Next Steps

GSFC

- 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