A Methane Lidar for Greenhouse Gas Measurements

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NASA ESTO ACT and GSFC IRAD programs

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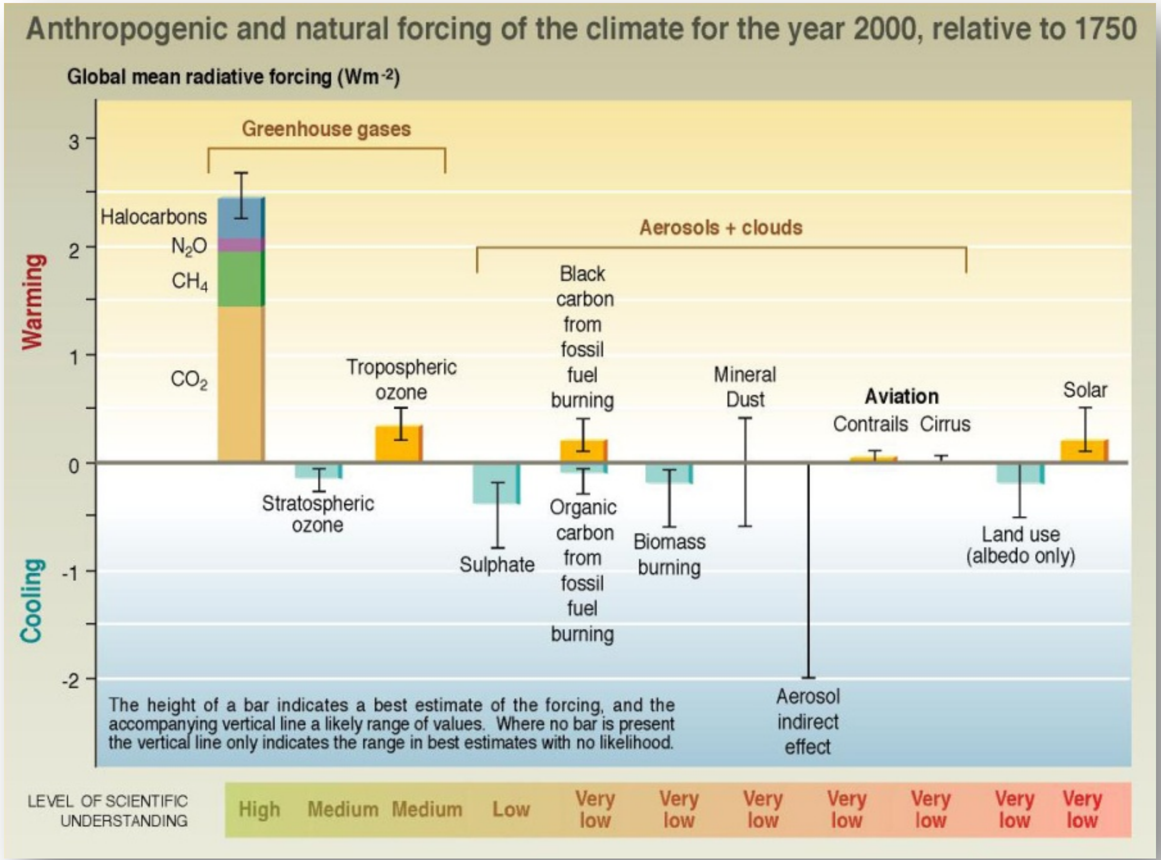
Outline

- Motivation - Why measure Methane?
- GSFC CH_4 Measurements for Earth & Planetary Science.
  - – Measurement Approach
  - – Technology and Challenges
  - – Results
  - – Plans for Airborne Campaign

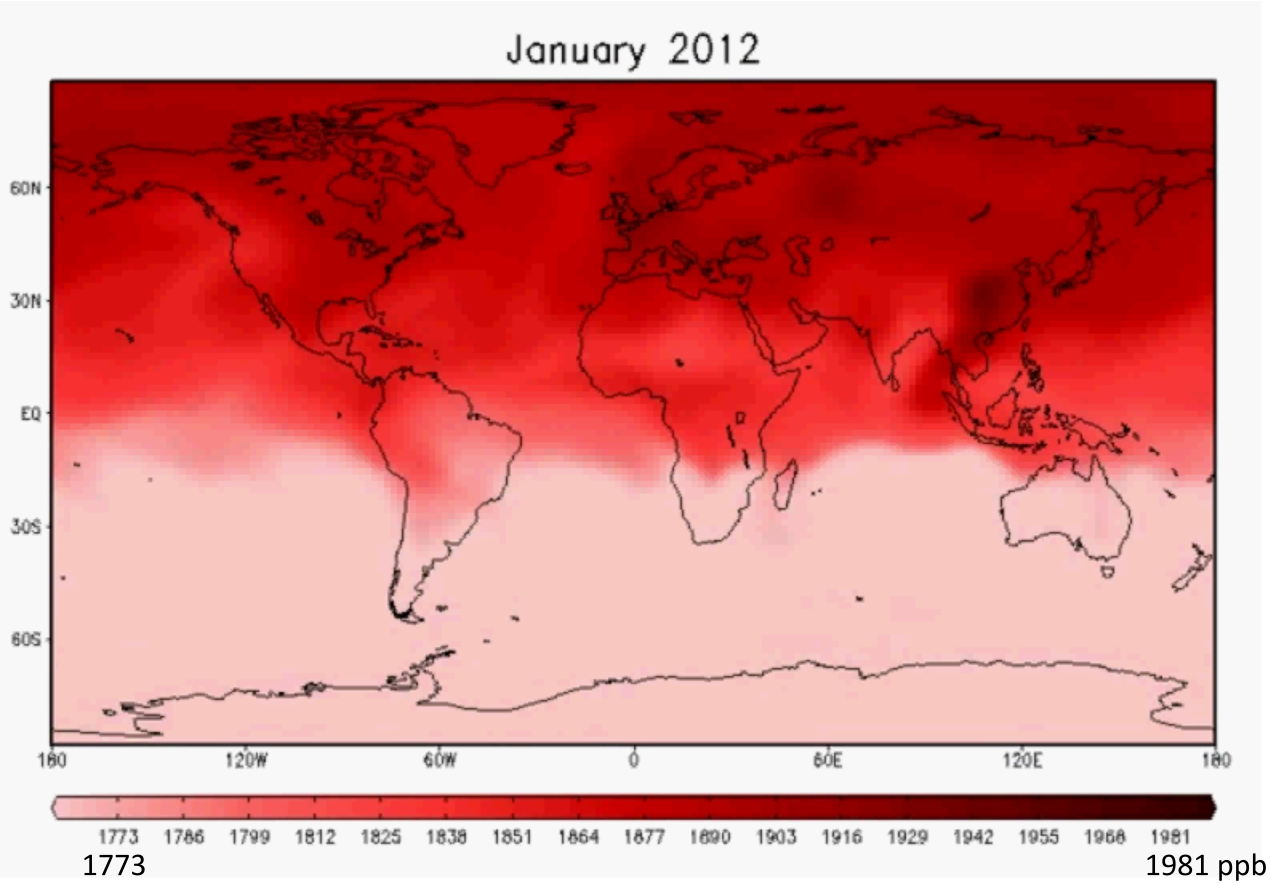
Why measure Methane?



Source: IPCC Report

- 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.****"*

A Year in the Life of CH_4



Source: Finnish Meteorological Institute (Carbon Tracker Europe Project)

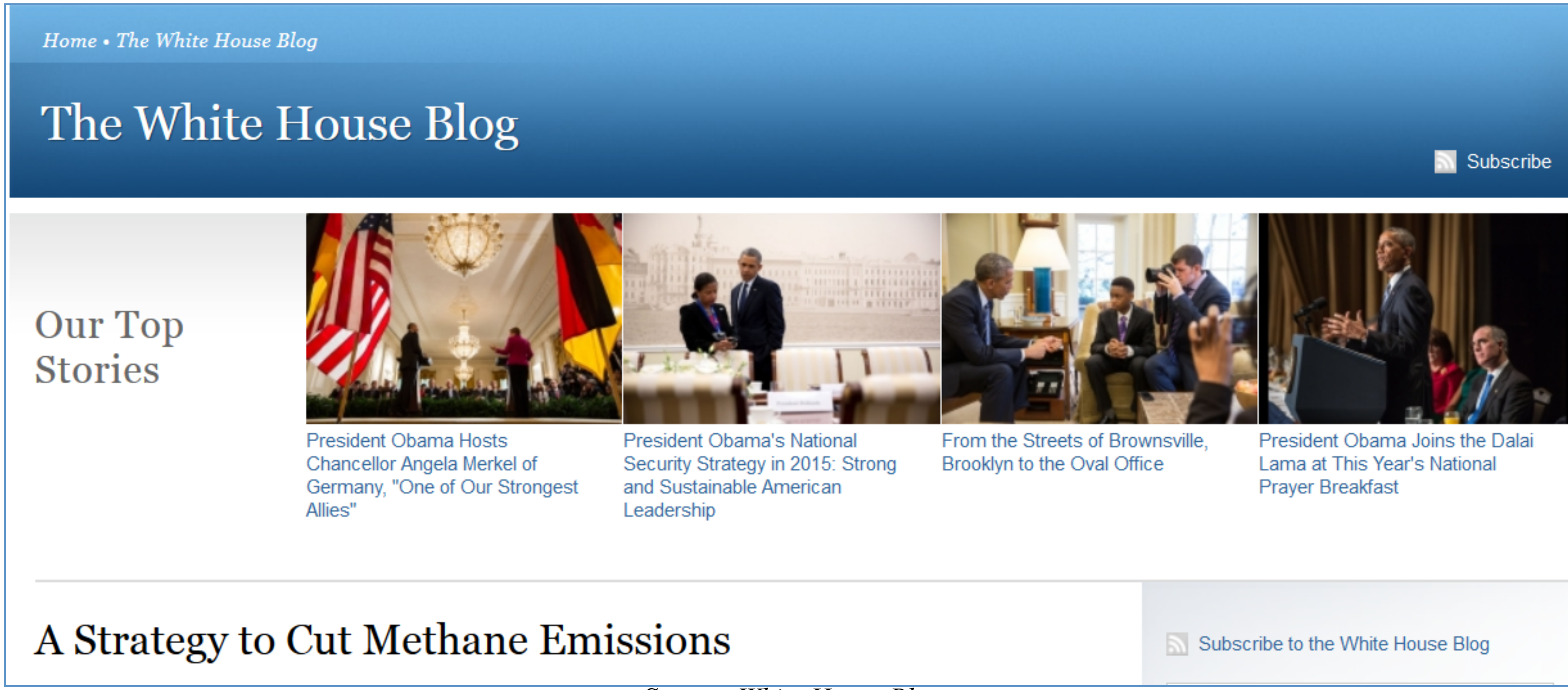
Methane in the Arctic – "Arctic Time Bomb"

- 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.*

Source: United Nations Environment Program (UNEP)

Source: GISS

Climate Action Plan - Strategy to Cut Methane Emissions

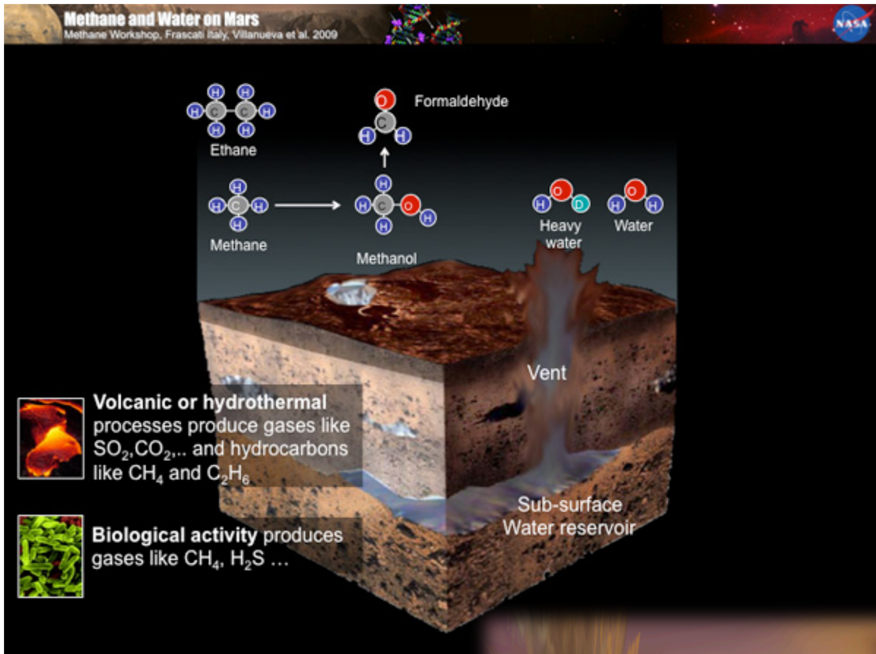


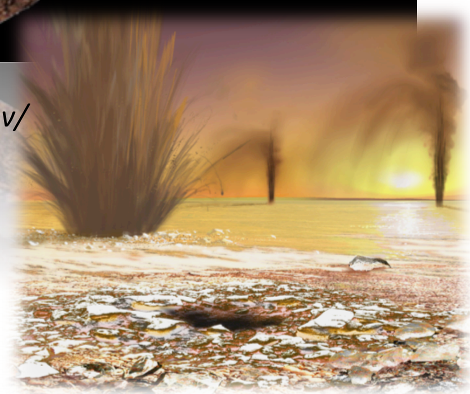
Source: White House Blog

- From the White House Climate Action Plan – Strategy to Cut Methane Emissions (March 2014):
  - *"Reducing methane emissions is a powerful way to take action on climate change; and putting methane to use can support local economies with a source of clean energy that generates revenue, spurs investment, improves safety, and leads to cleaner air. That is why in his Climate Action Plan, President Obama directed the Administration to develop a comprehensive, interagency strategy to cut methane emissions."*

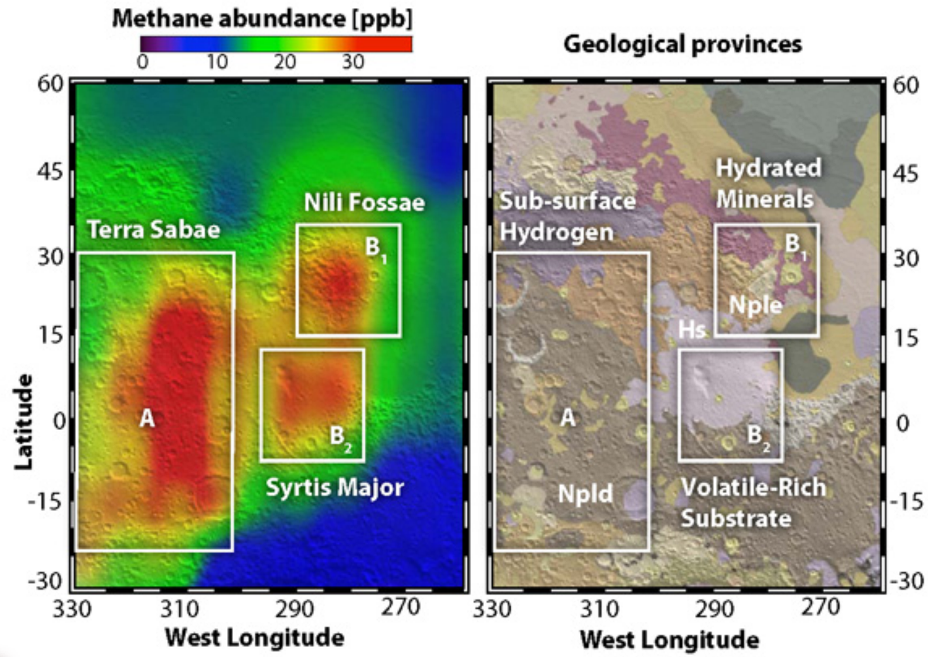
Astrobiology- Methane as a Biomarker

LIDAR can localize ***methane or other trace gas*** *sources for a lander*





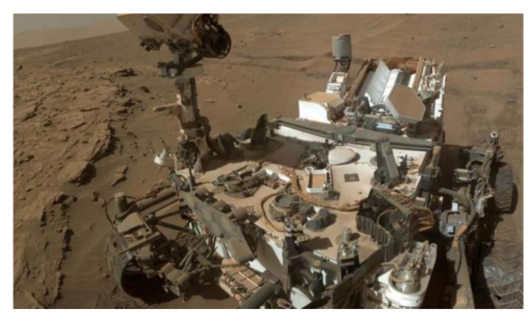
Source: astrobiology.gsfc.nasa.gov/



Source : Mumma, Villanueva, Novak, et al. (Science 2009)

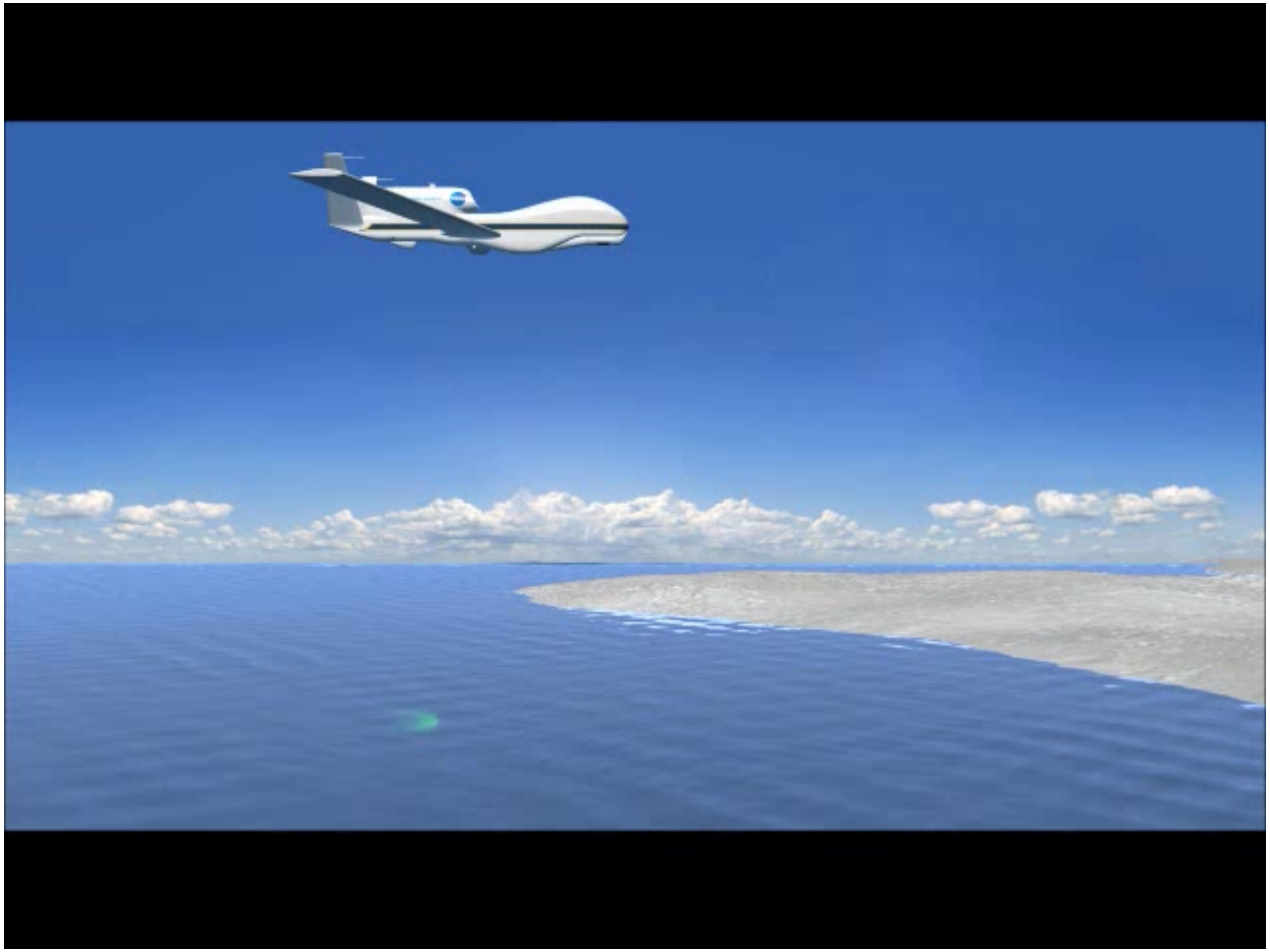
Mystery methane on Mars: The saga continues

May 15, 2015 by Johnny Bontemps, Astrobiology Magazine

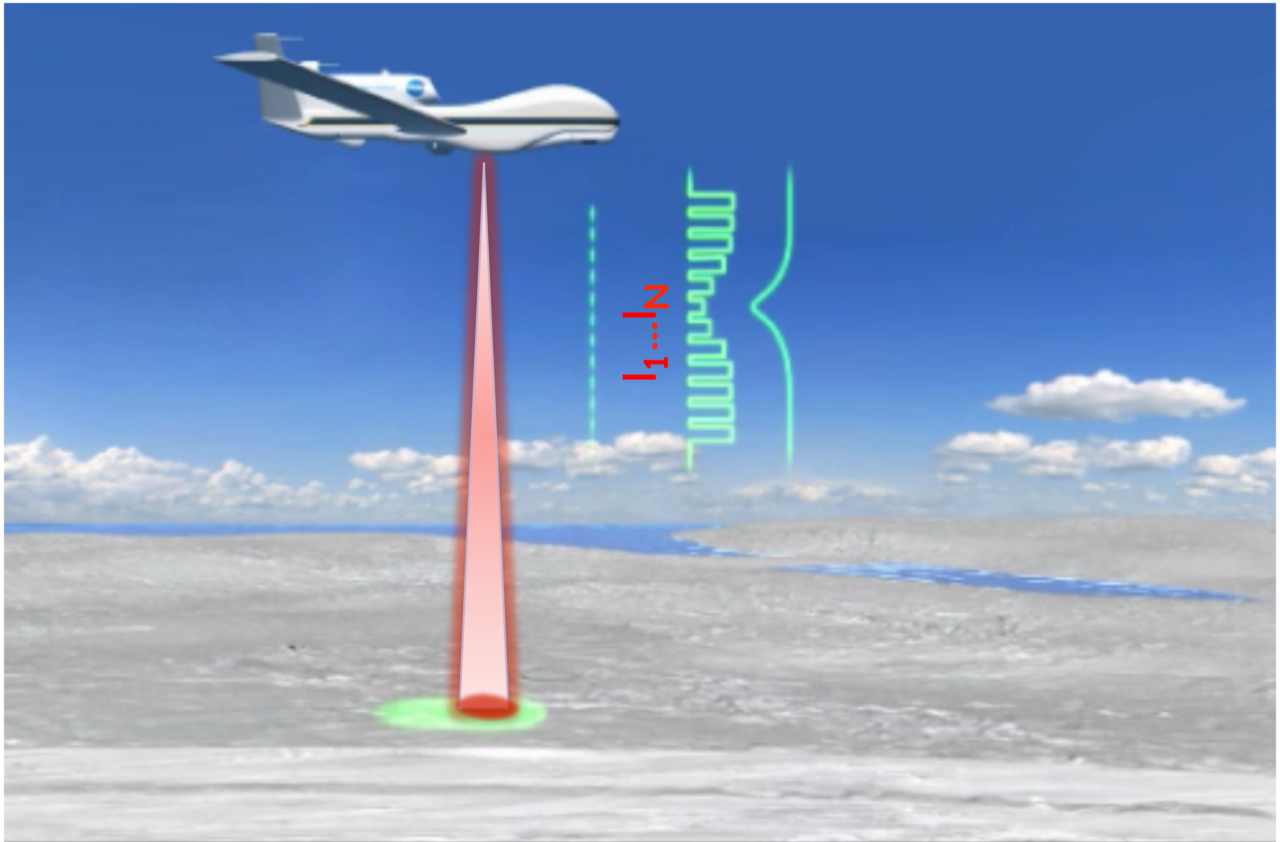


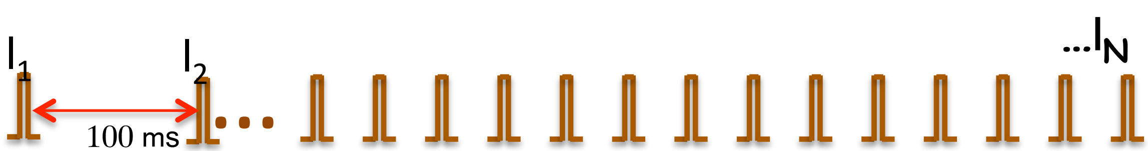
Source : NASA/JPL

GSFC CH_4 Lidar with Integrated Path Differential Absorption Lidar (IPDA)

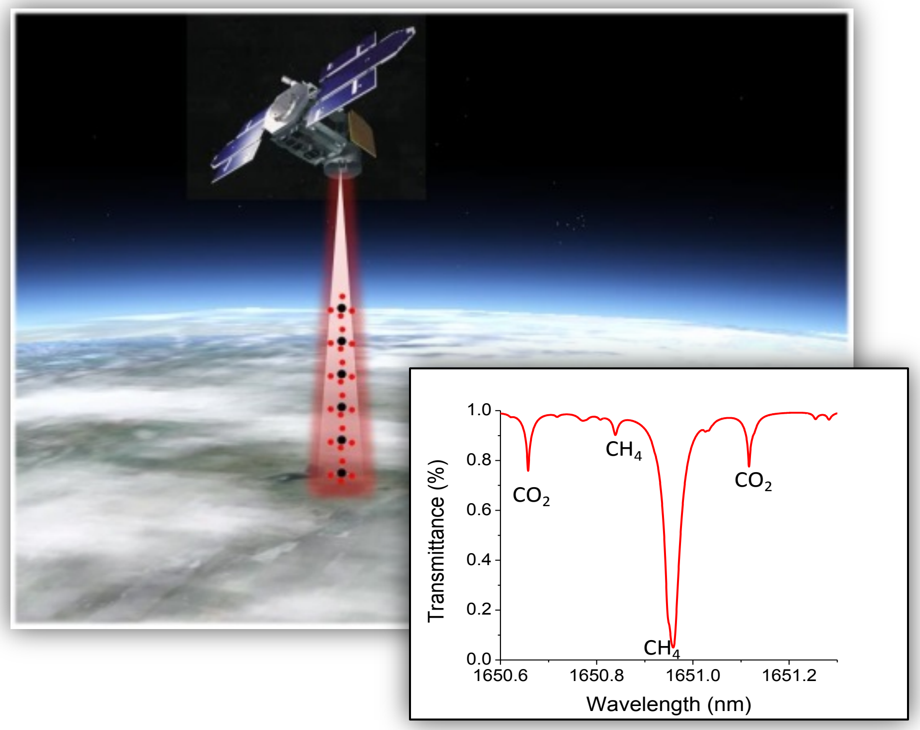


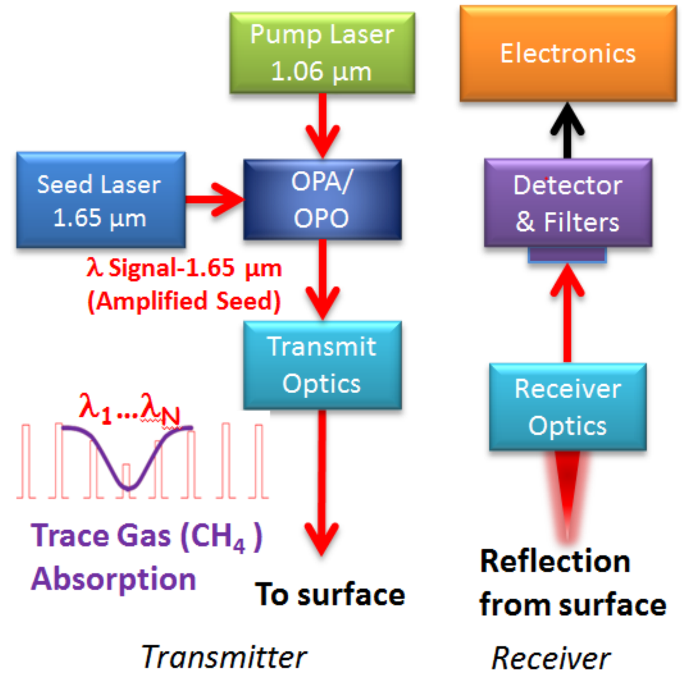
GSFC CH_4 Lidar with Integrated Path Differential Absorption Lidar (IPDA)





GSFC CH_4 Lidar

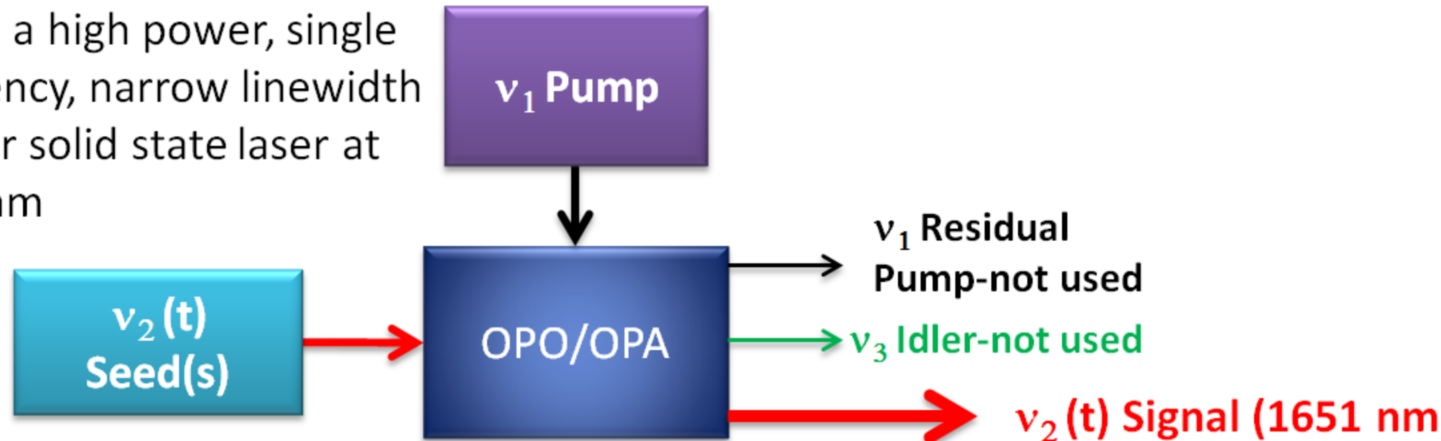




- **Need : Laser transmitter technology**
  - ➢ **3-5 µm for planetary**
  - ➢ **<u>1.64-165 µm on Earth</u>**
  - ➢ **Optical Parametric Generation (OPG) is the best solution currently available**

CH_4 Laser Transmitter Components

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

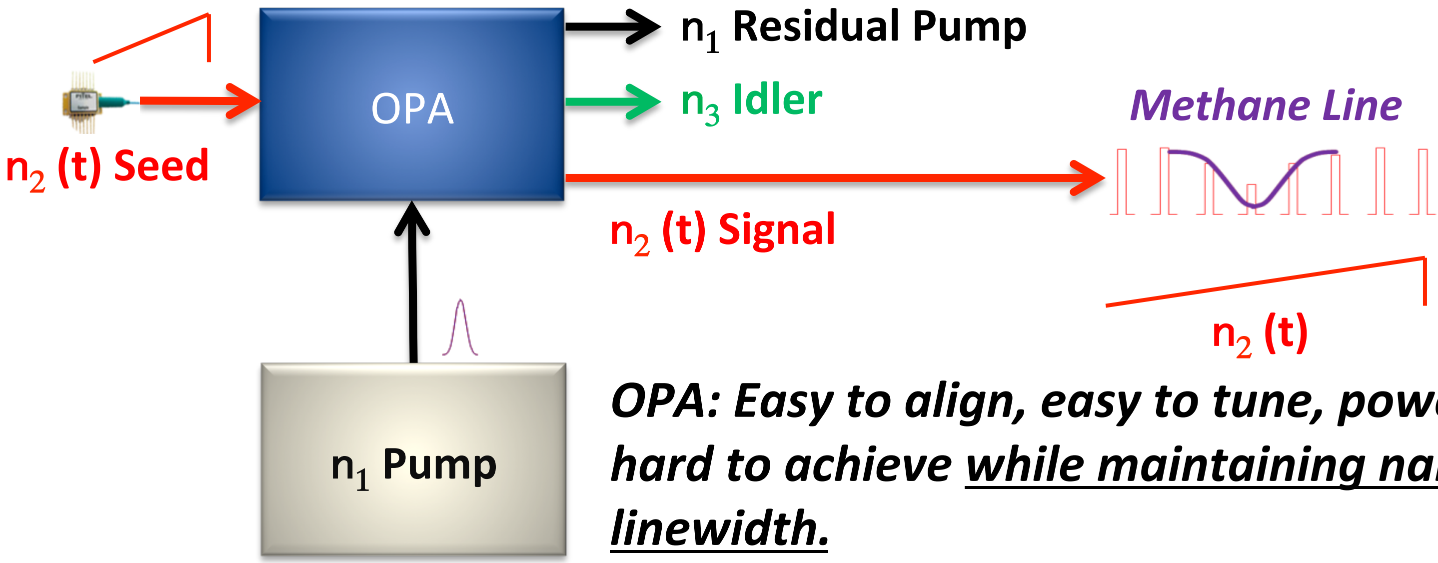


Seed: a low power, single frequency diode laser at 1651 nm.

Optical Parametric Oscillator (OPO) or Optical Parametric Amplifier (OPA). A non-linear crystal that amplifies the seed laser to the energy needed for space (250-300 μJ) ***without*** degrading the spectral characteristics

Used OPO/OPAs to measure CH4 at near and mid IR, CO2, H2O and CO

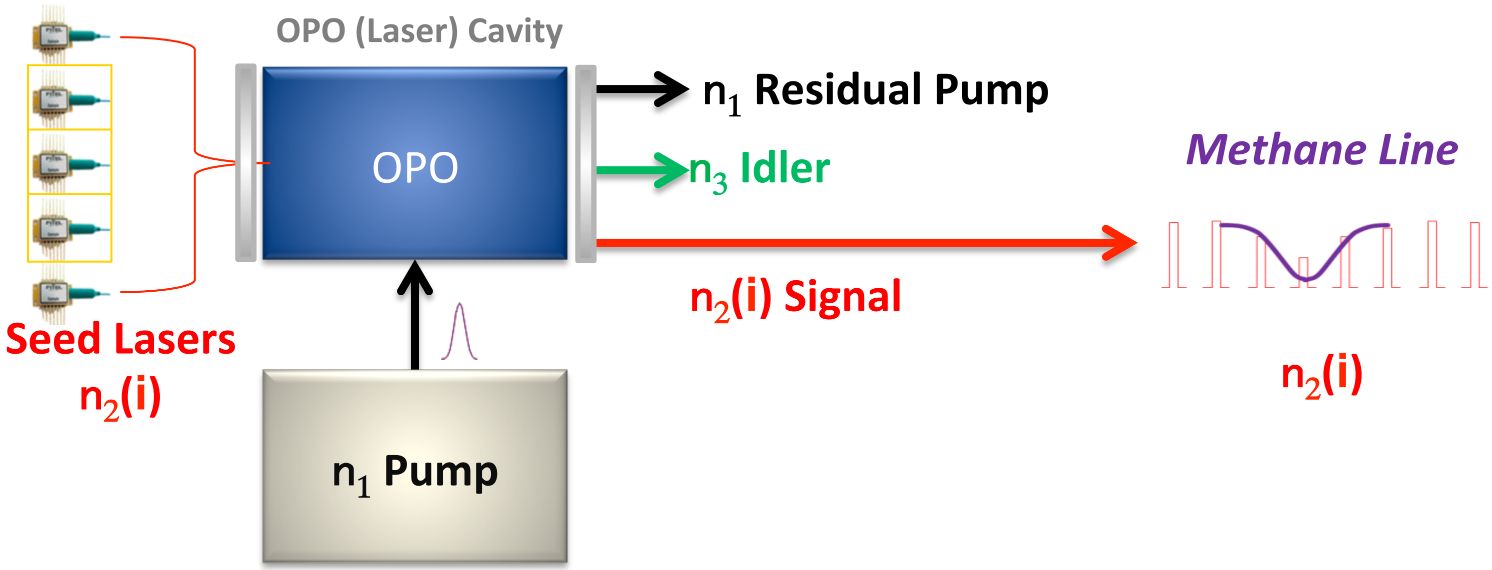
CH4 Transmitter Technology - OPA



OPA: Easy to align, easy to tune, power scaling hard to achieve <u>while maintaining narrow linewidth.</u>

OPA samples the CH_4 line at several wavelengths using a <u>single, continuously tuned</u> seed laser

CH4 Transmitter Technology - OPO



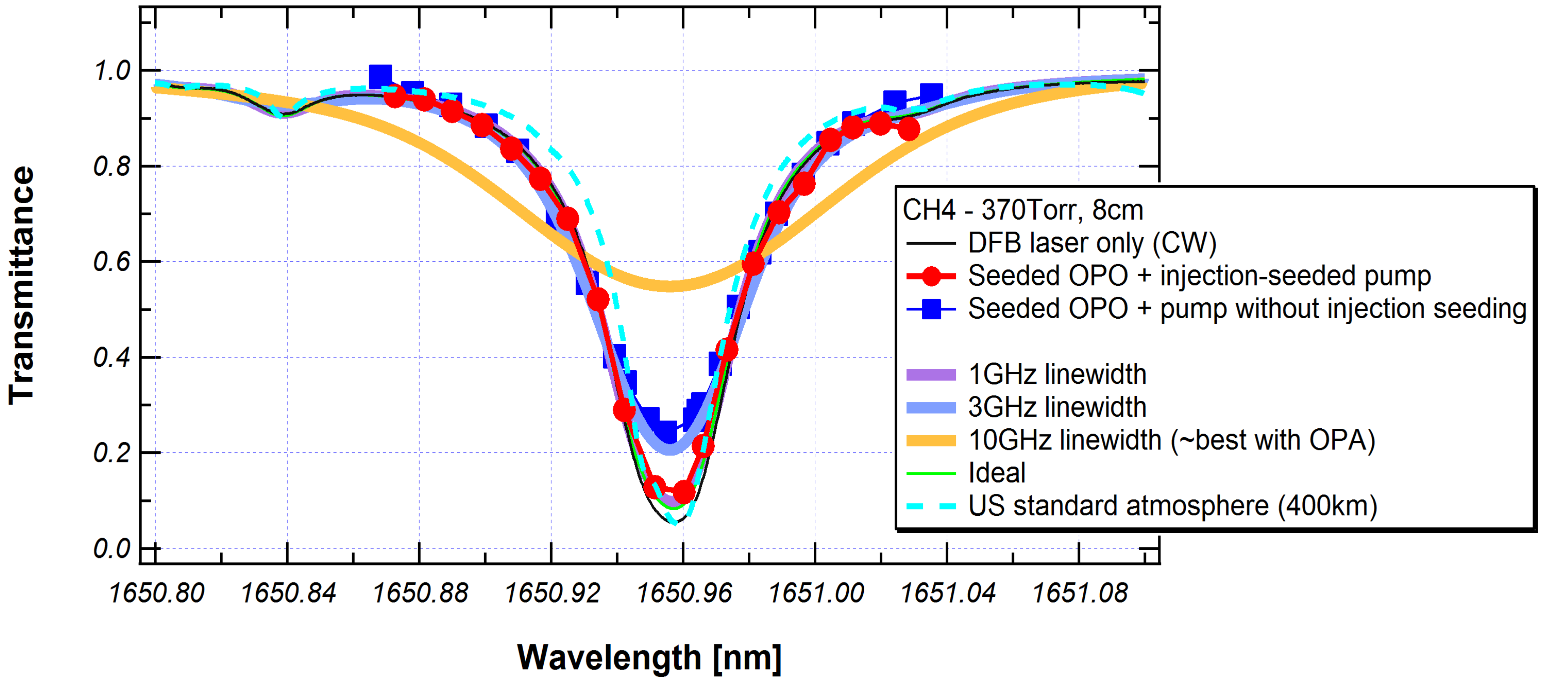
OPO: Complicated to align and tune; power scaling easier to achieve while maintaining narrow linewidth.

OPO samples the CH_4 line at <u>several discrete wavelengths using multiple seed lasers.</u>

All lasers must be locked.

Why is Linewidth important? Demonstration with a CH_4 cell

- Result with simulated US standard atmosphere
  - Red is the result with OPO
  - Orange is close to the best with dual-stage OPA
  - Green - theoretical

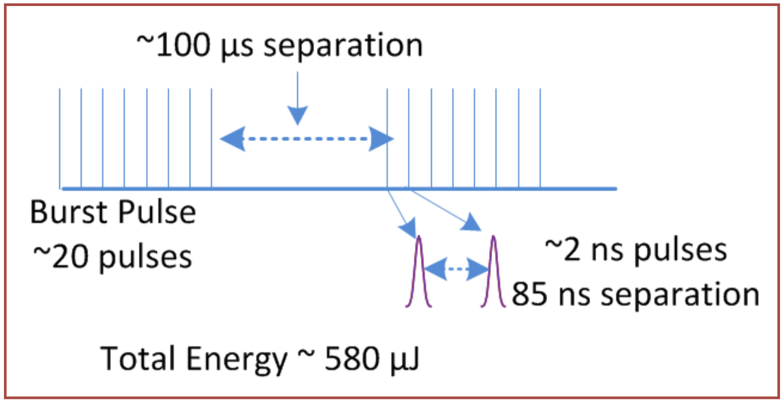


Power Scaling Approaches

Approach	#1. OPA with smaller burst pulses	#2. OPA with large pump pulse	#3. OPO with large pump pulse
Pump laser	Difficult (due to SBS, damage, pulse variation)	Relatively easy (more traditional)	Relatively easy (more traditional)
Pump laser type	Fiber (robust, higher efficiency)	Free space	Free space
Seed laser (1651nm)	Existing DFB is OK but could use higher power	High seed power required	Existing DFB is OK
Output linewidth	Should be OK (~500MHz)	Becomes wider without sufficient seed power	Narrowed by optical feedback (<300 MHz)
Parametric stage	Single OPA stage possible (simple)	Need for multiple OPA stages	Need for cavity locking & step tuning (complicated)
Status	**•Achieved power & linewidth requirement with external solid state amplifier but need to improve packaging and pulse power variation**	**Put on hold due to lack of good seed laser source**	**•Tried with in-house injection seeded laser •Demonstrated 5 wavelength OPO •Achieved power & linewidth requirement**

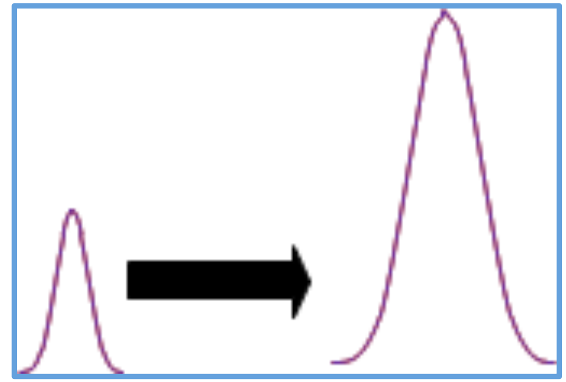
Pump Laser Options

A. Burst Mode



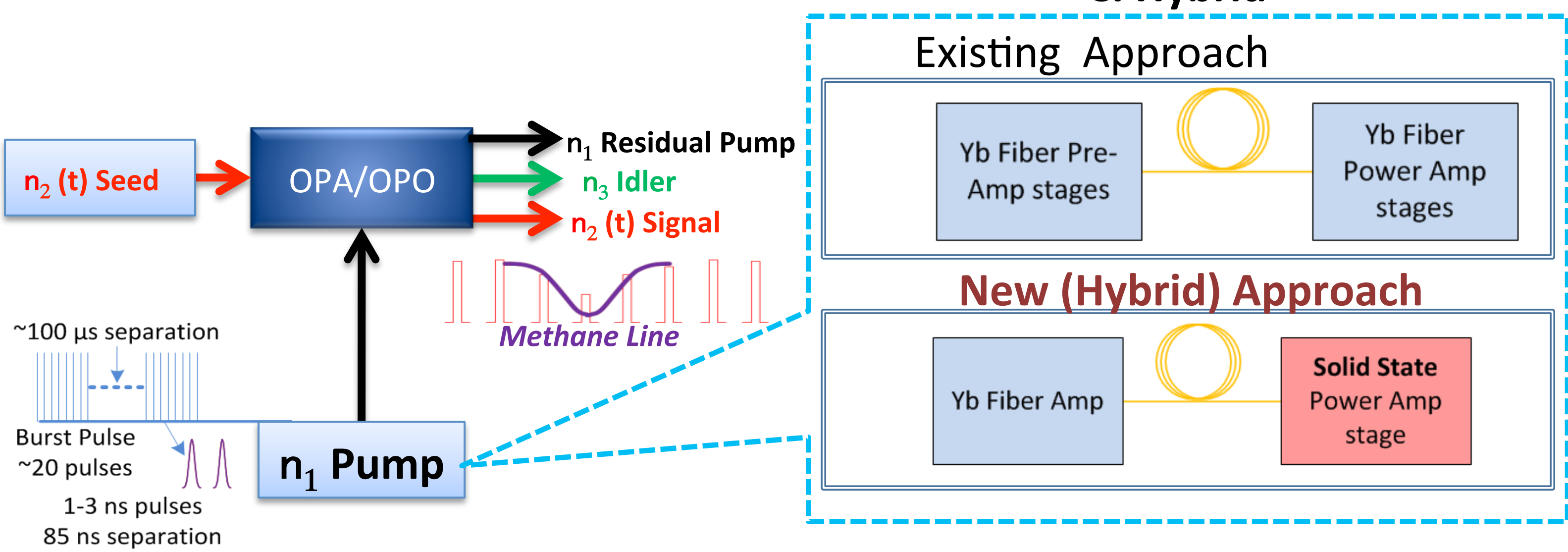
Yb Fiber MOPA

B. "Single" (Mono) Pulse



GSFC or other laser

C. Hybrid

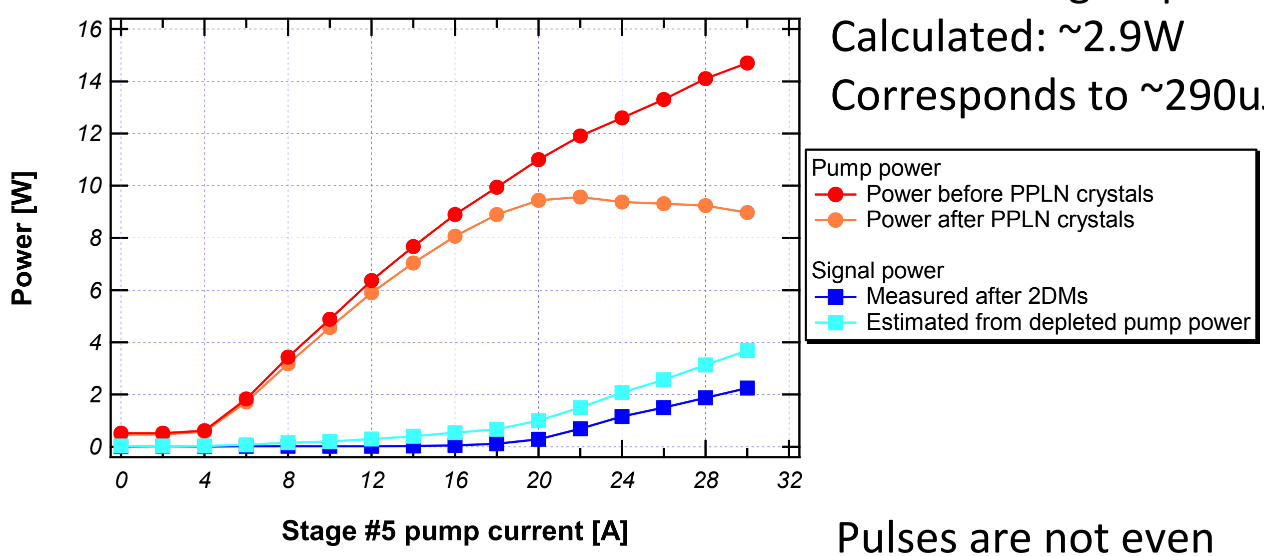


Burst OPA with Hybrid Pump

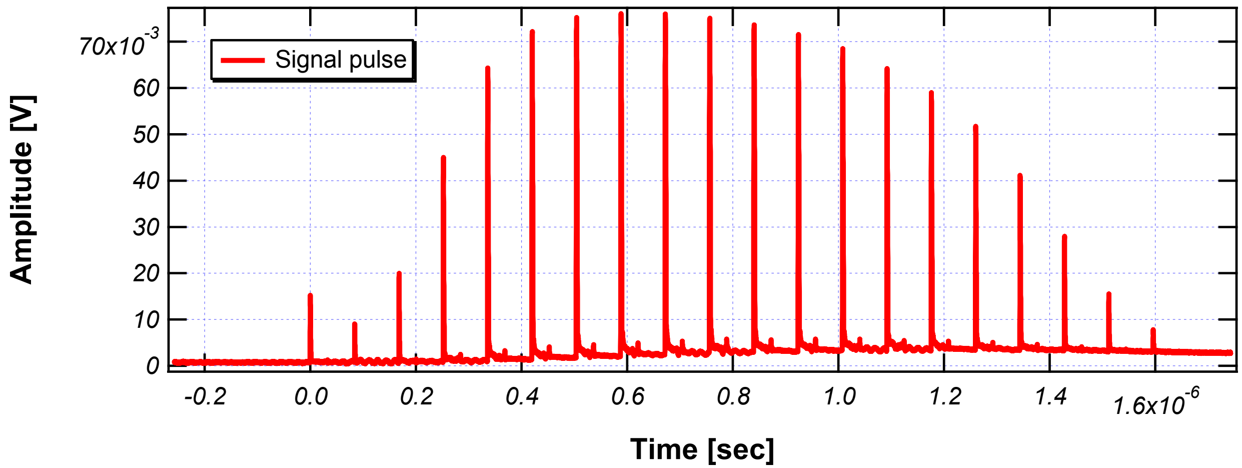
Measured signal power: ~2.1W

Calculated: ~2.9W

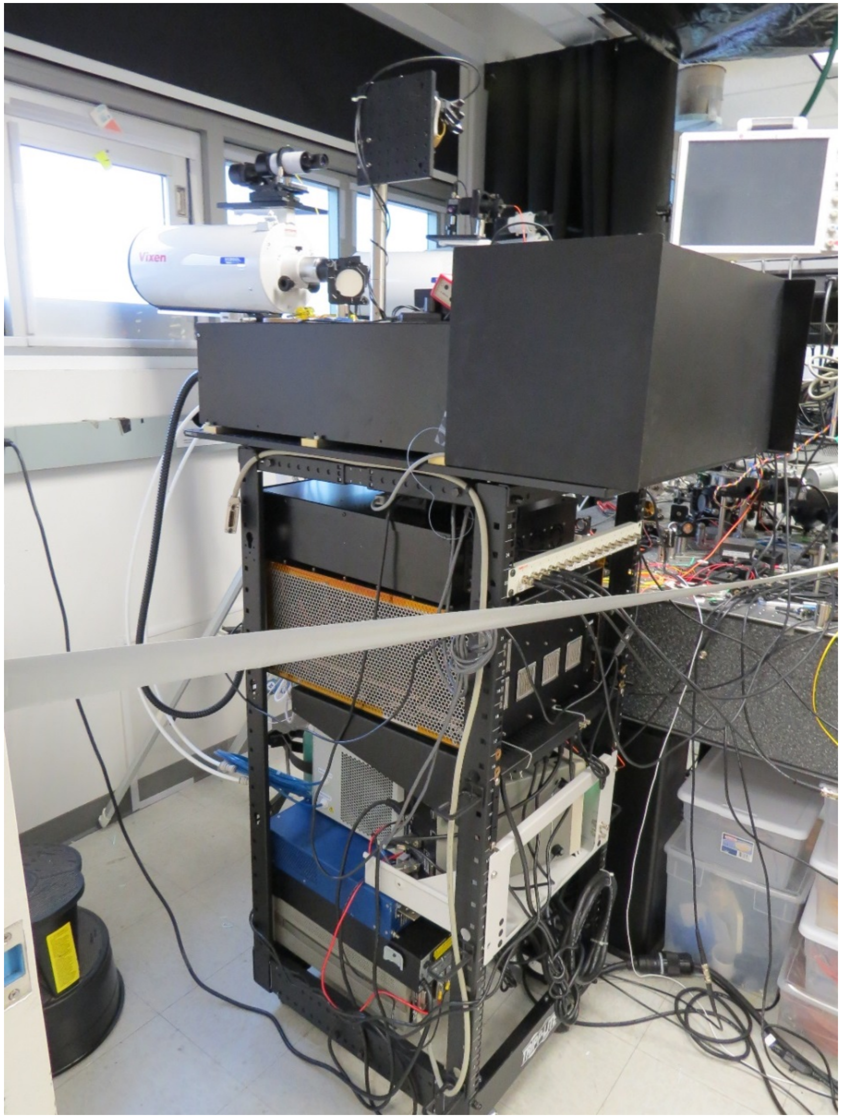
Corresponds to ~290uJ per burst



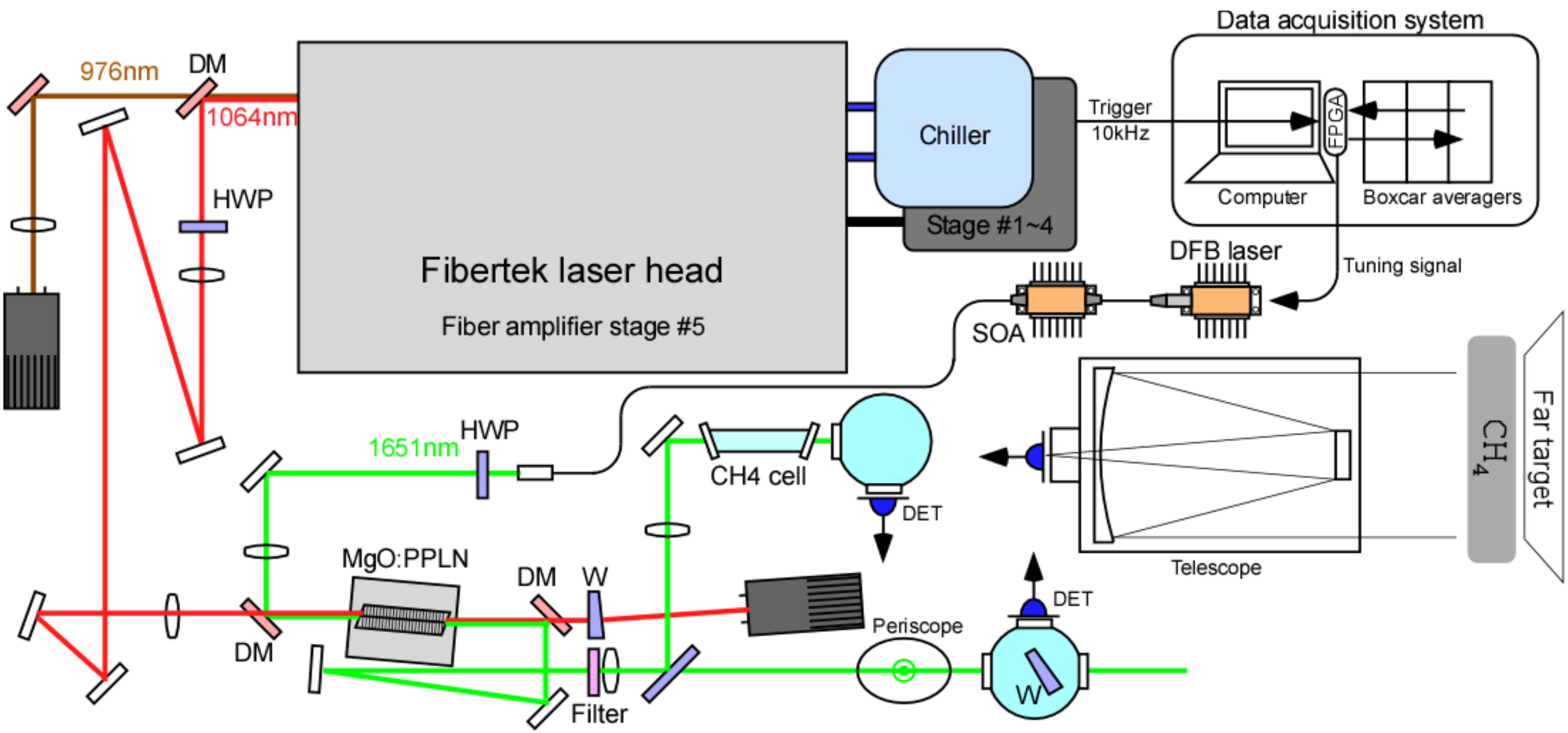
Pulses are not even



OPA and Open Path Setup

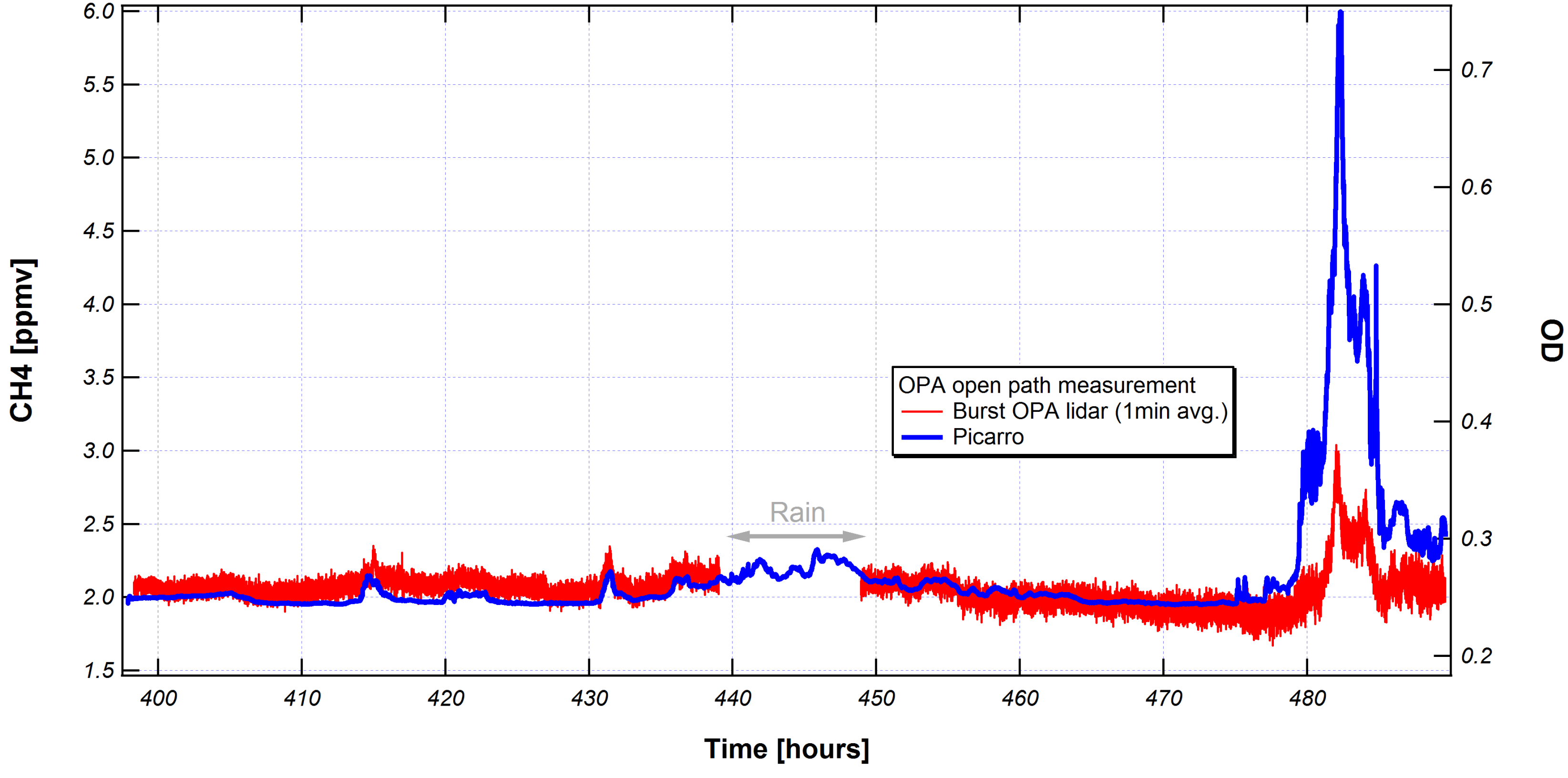


OPA Open-path measurement setup



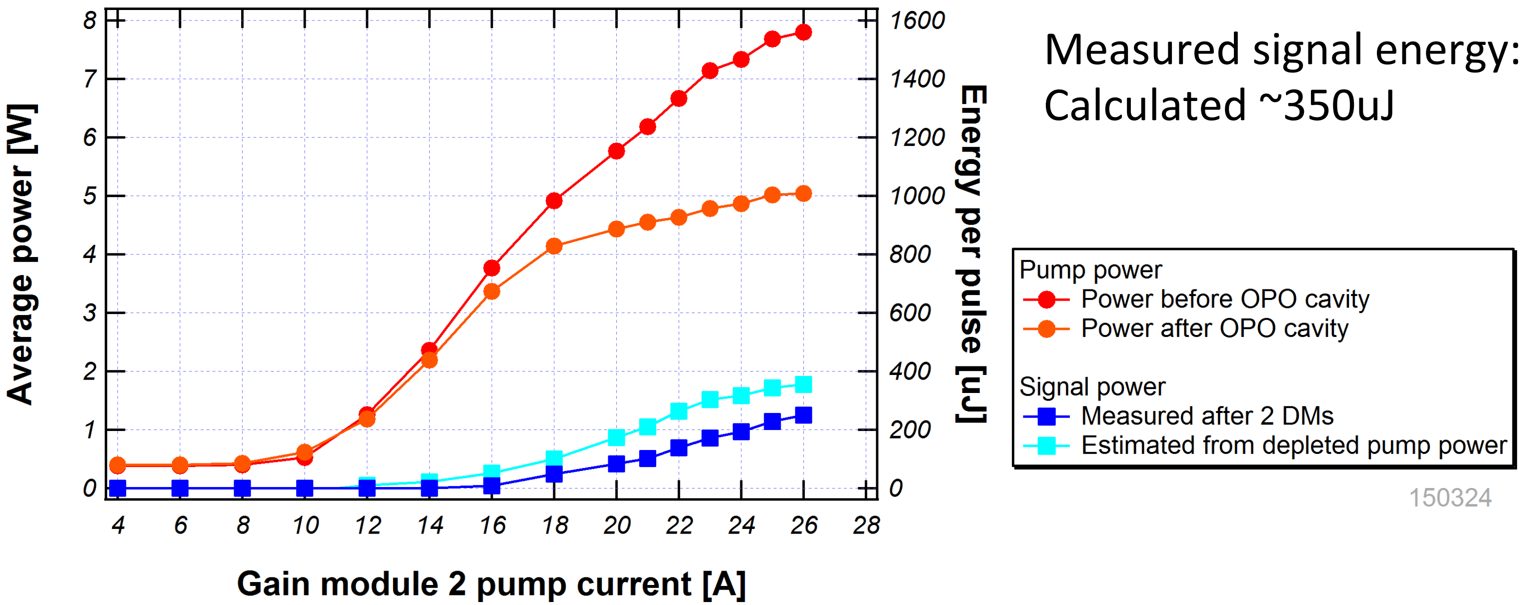
OPA open path result

- Trend agreed with Picarro
  - A smaller peak was observed by Lidar



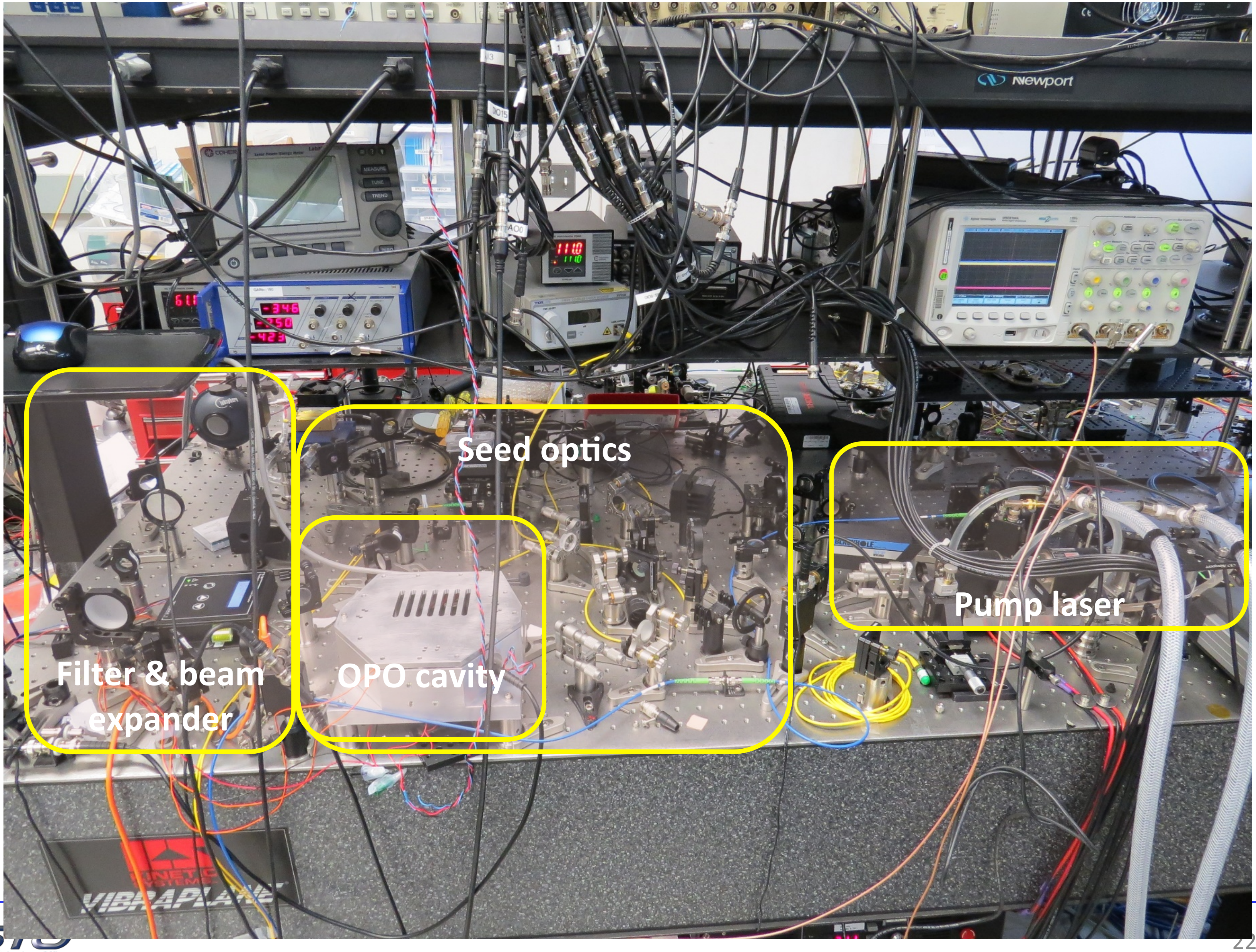
OPO

- Pros
  - Seed is enhanced by the cavity (Compensates for the insufficient seed power)
- Cons
  - Cavity length control is required.
  - Continuous tuning is difficult.



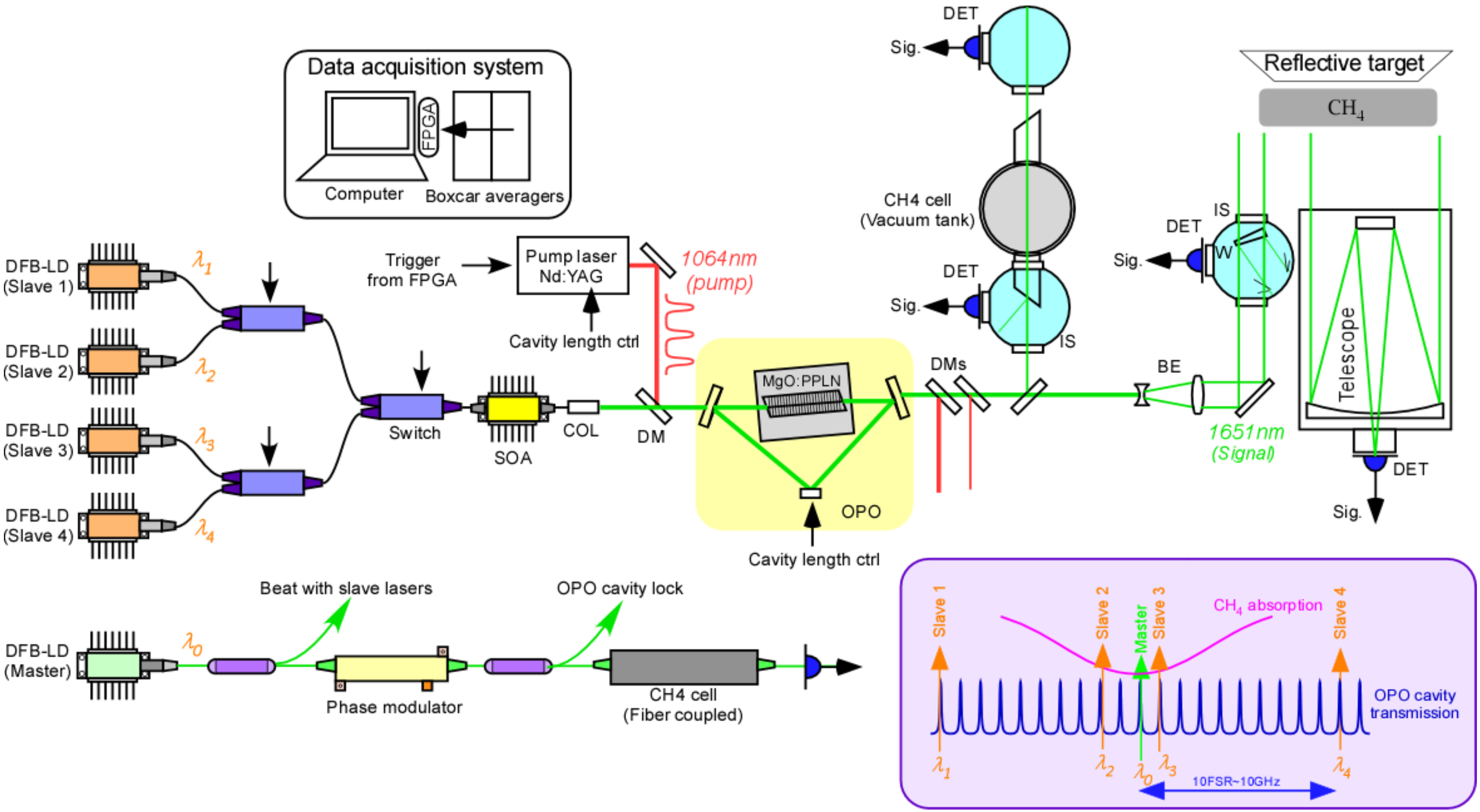
Measured signal energy: ~250uJ
Calculated ~350uJ

OPO Setup

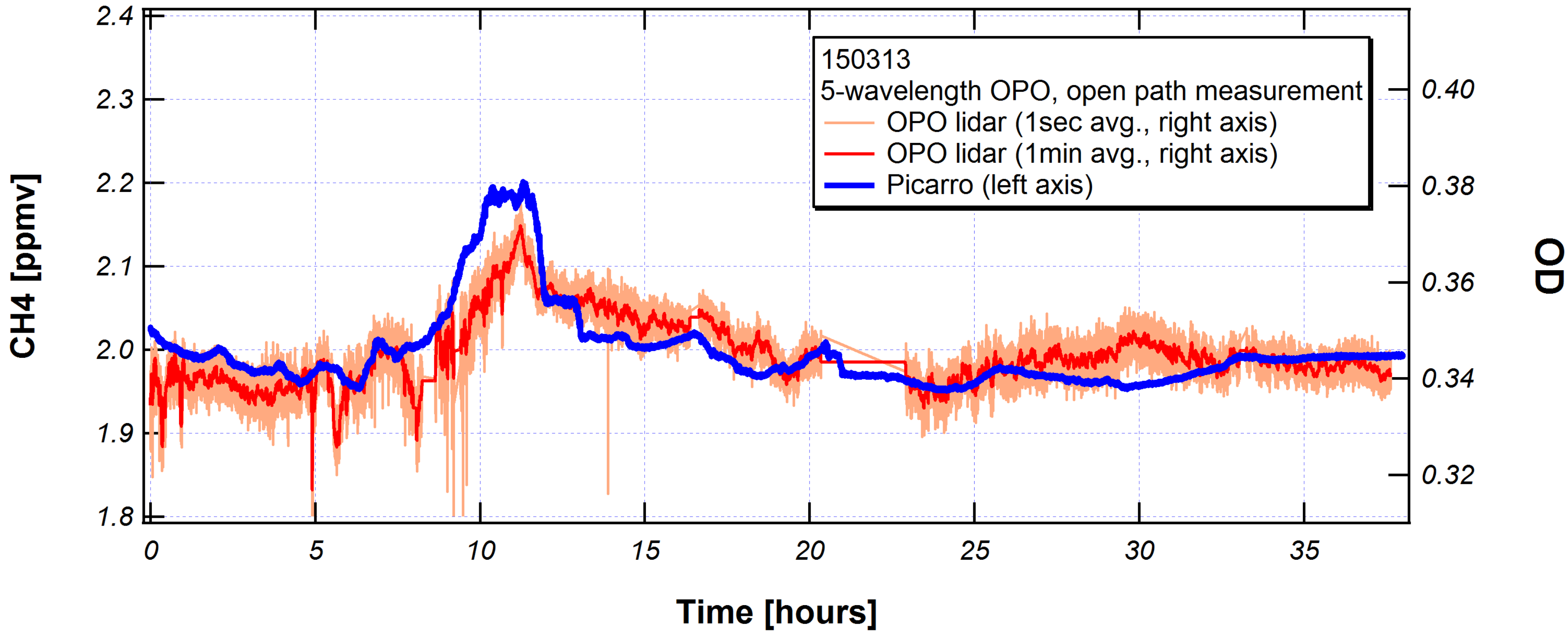


Newport
Seed optics
Pump laser
Filter & beam expander
OPO cavity
VIBRAPLANE

Setup for 5-wavelength OPO

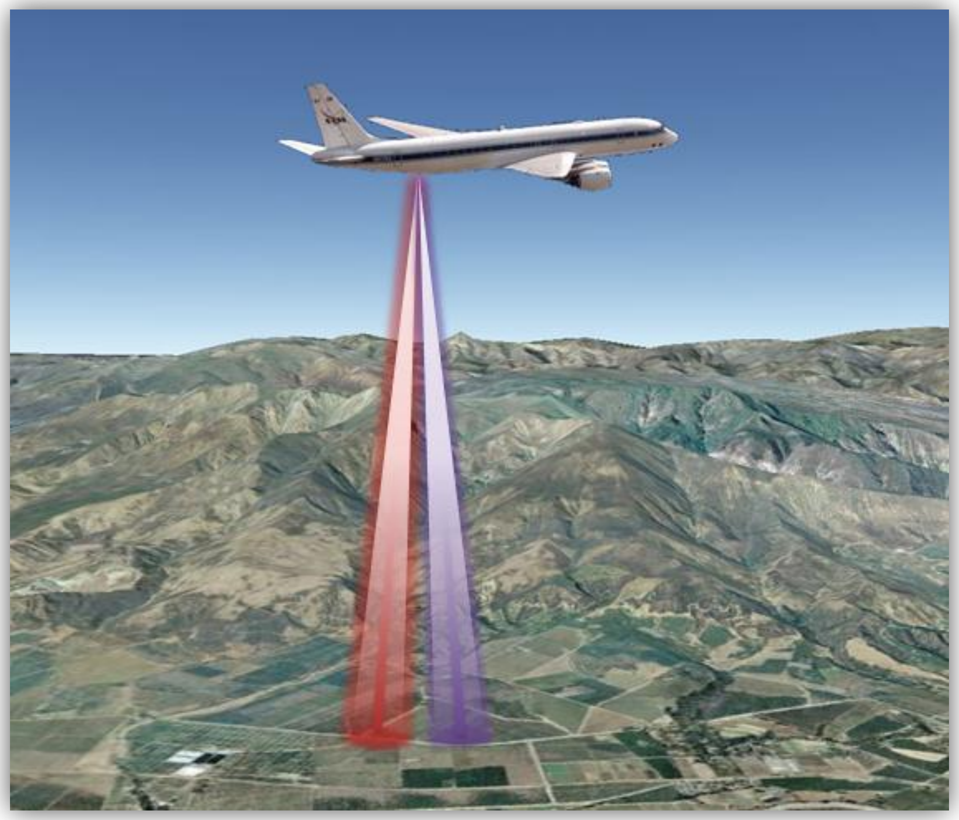


Open path result with 5 wavelength OPO



Trend agreed with Picarro
Lidar showed smaller peak than in-situ

2015 Airborne Demonstration



- **Flight Test Methane LIDAR Instruments:**
  - **GSFC Methane Sounder**
  - **GSFC Picarro**
- **Conduct several test flights from NASA's Armstrong Science Aircraft Integration Facility (SAIF) in Palmdale, CA:**
  - 1 Engineering flight
  - 2-3 science flights
  - Approximately 12-15 hours of flight time in mostly in CA
- **Assess CH_4 LIDAR measurements over Western US**
- **Evaluate derivation of XCH_4 from LIDAR observations and compare with in-situ and calibrations sites whenever possible.**
- **Evaluate OPA and OPO performance**

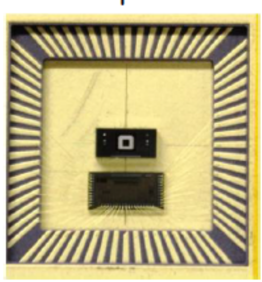
DRS Technologies e-ADP

HgCdTe e-APD 4x4 Array Test Results at GSFC

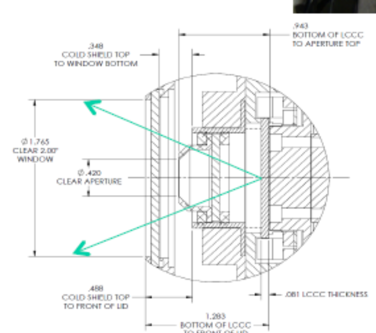
GSFC

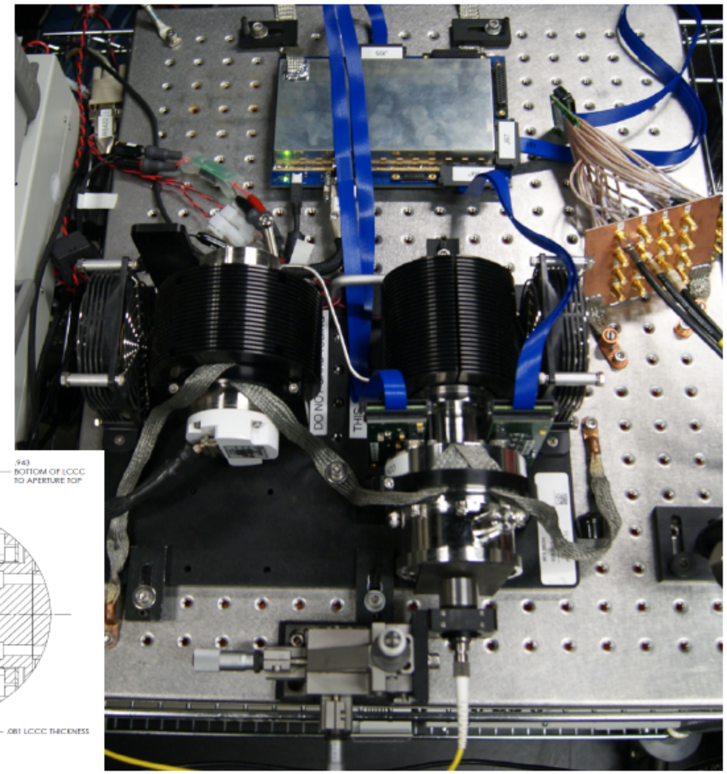
- First 4x4 HgCdTe e-APD array for the CO_2 lidar received in April 2013 and met requirements

FPA on chip carrier



F/1.5 Dewar Cold Shield with Cold Filter





ESTO
Earth Science Technology Office

Developed under ESTO IIP Xiaoli Sun – Jim Abshire (PI)

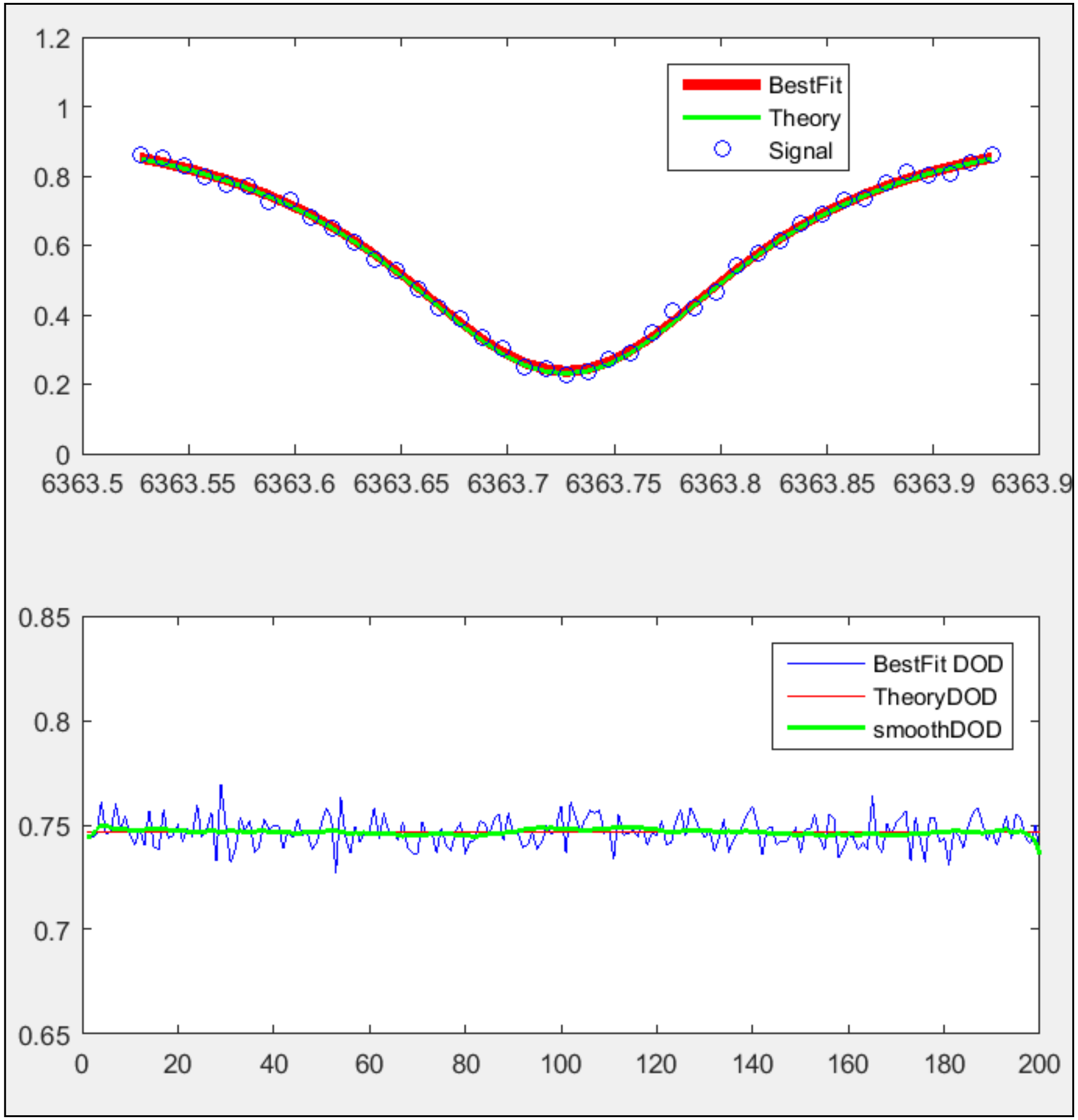
A highly sensitive multi-element HgCdTe e-APD detector for IPDA lidar applications , Proc. SPIE 8739, Sensors and Systems for Space Applications VI, 87390V (May 21, 2013); doi:10.1117/12.2018083

C

Summary

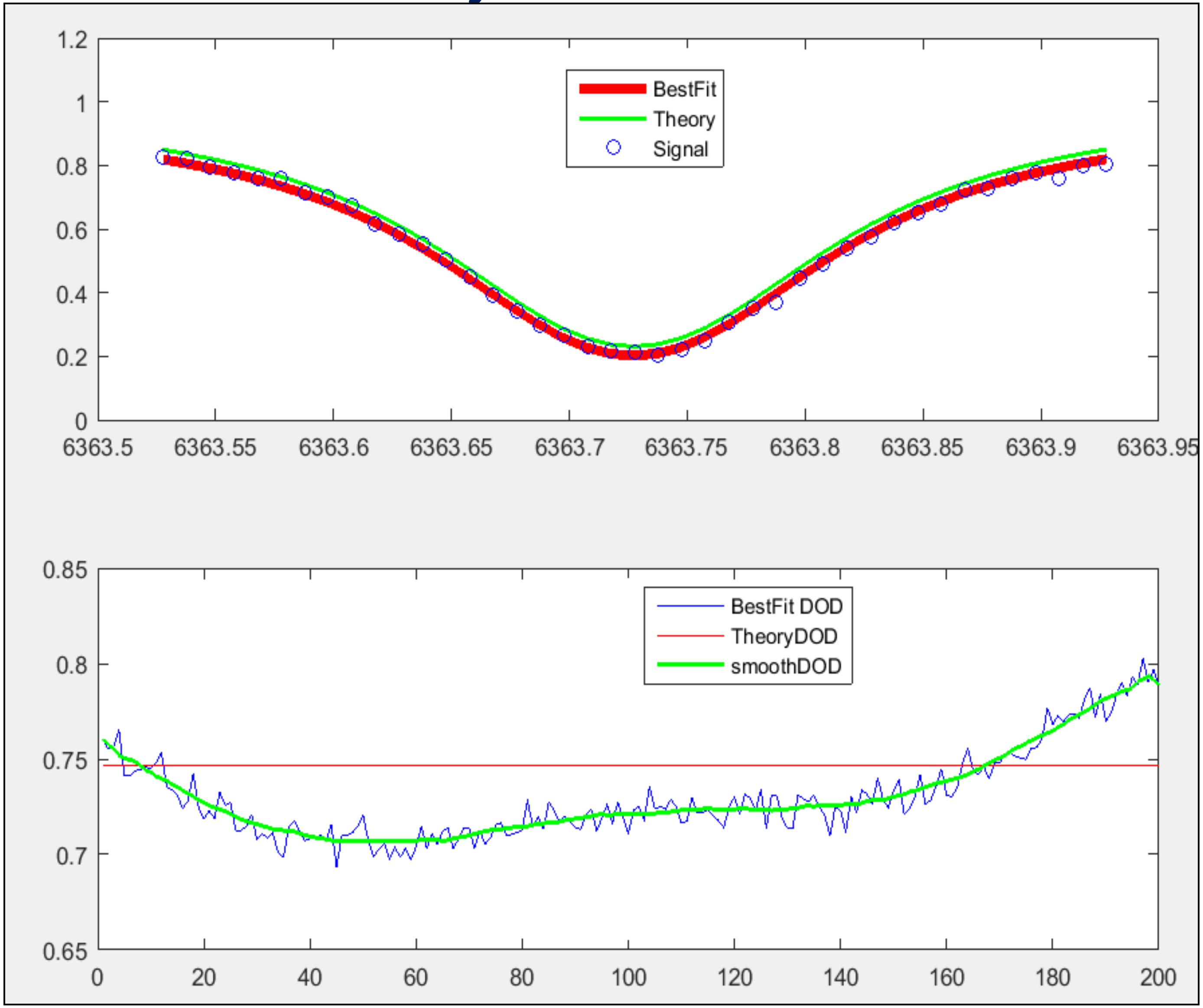
- ✓ Many different approaches and options for power scaling investigated
- ✓ Leveraged IRAD & ACT programs.
- ✓ Demonstrated two viable architectures for a CH_4 transmitter using OPA and multi-wavelength OPO
- ✓ Demonstrated power scaling to 250-290 μJ.
- ✓ Demonstrated and validated CH_4 open path measurements using the two lidar transmitters.
- ✓ Airborne demonstration in September
- ✓ Other laser transmitter options being investigated
- **We would like to thank ESTO and GSFC IRAD for their support**

Why multiple wavelengths?



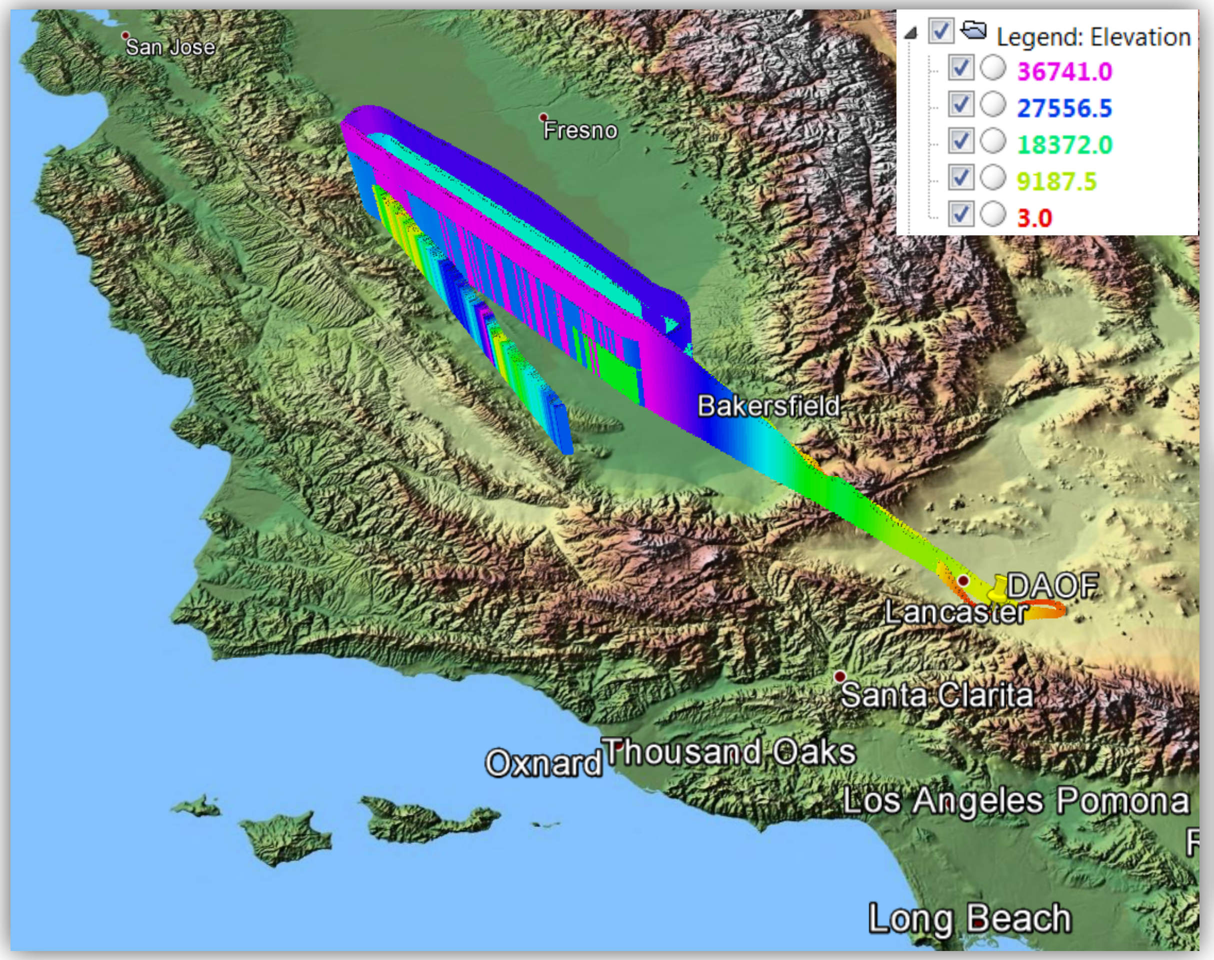
Simulation with random noise and high SNR ~ 100

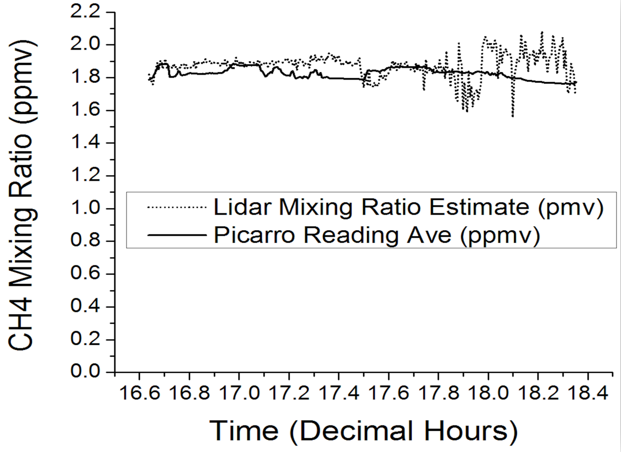
Why multiple wavelengths?
Bias or systematic errors



Simulation with random noise, high SNR ~ 100, and systematic bias

Airborne Demo 2011





"Airborne measurements of atmospheric methane column abundance using a pulsed integrated-path differential absorption lidar", APPLIED OPTICS / Vol. 51, No. 34 / 1 December 2012

Ground Testing with two IPDA lidars using OPA at 3.29 μm and 1.65 μm