A Compact Remote Sensing Lidar for High Resolution Measurements of Methane

Haris Riris, Kenji Numata, Stewart Wu
ESTF October 2014

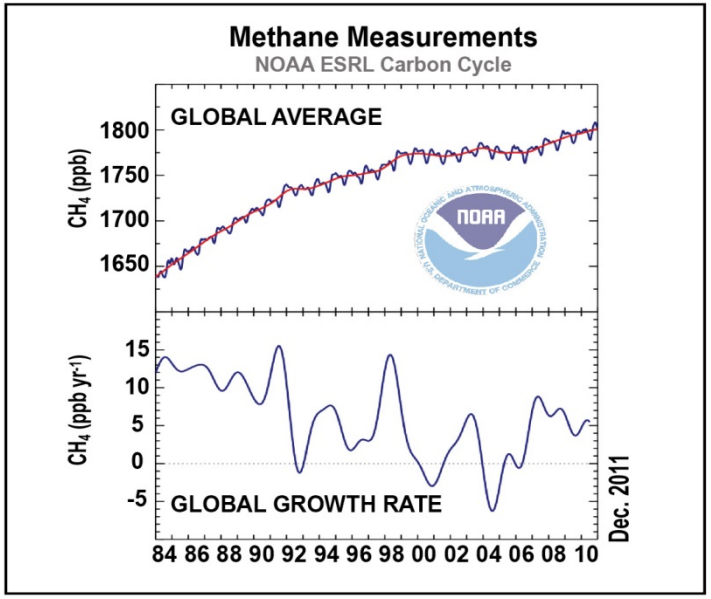
Funded by: ESTO ACT and GSFC IRAD Programs

Outline

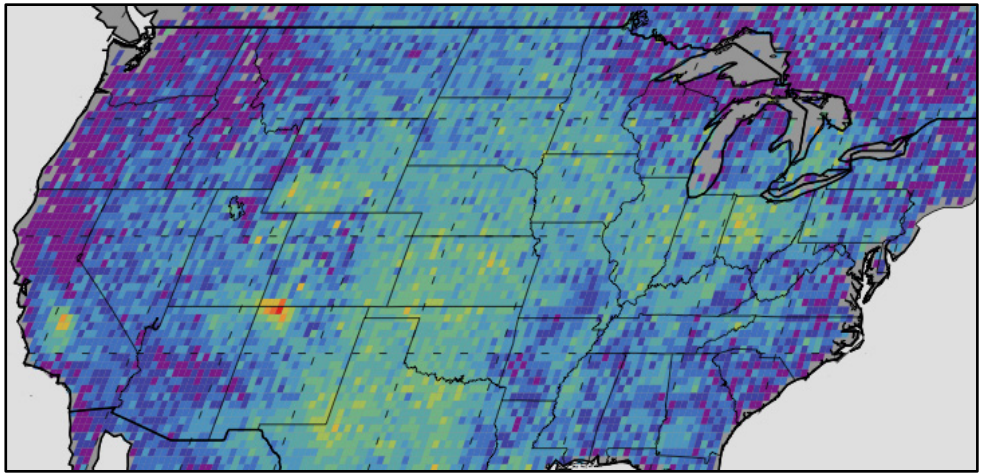
- Need for Methane Measurements
- Why Lidar?
- GSFC Approach
  - Initial Results
  - Power scaling of laser transmitter
  - Current Status
- Summary

Earth Science - Methane as a Greenhouse Gas

- **CH_4 is a strong greenhouse gas (x 23 stronger than CO_2). Increasing concern that the concentration of CH_4 may be increasing as the permafrost thaws. Carbon Budget needs accurate CH_4/CO_2 estimates.**
- **NASA Decadal Survey: *"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."***
- **The ratio of CO_2/CH_4 may provide significant information for anthropogenic vs. natural sources.**
- **GSFC demonstrated CH_4 measurements from a high flying aircraft (2011).**
- **MERLIN Methane Lidar (Franco-German collaboration) scheduled to launch in 2019 uses a two-wavelength OPO transmitter.**



Source: NOAA



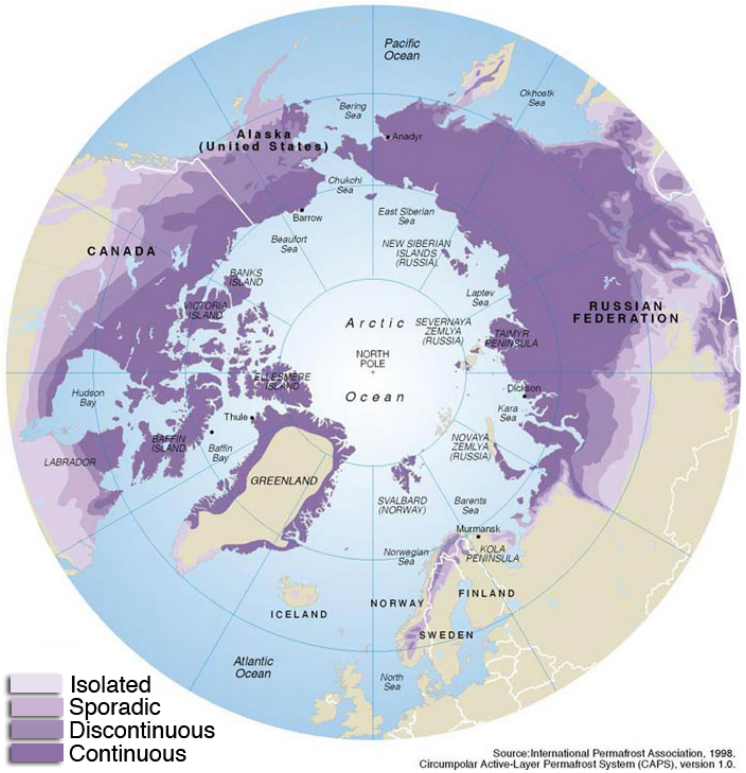
"Four corners: The largest US methane anomaly viewed from space", Kort et.al., Geophys. Res. Lett., 41, 2014. doi:10.1002/2014GL061503

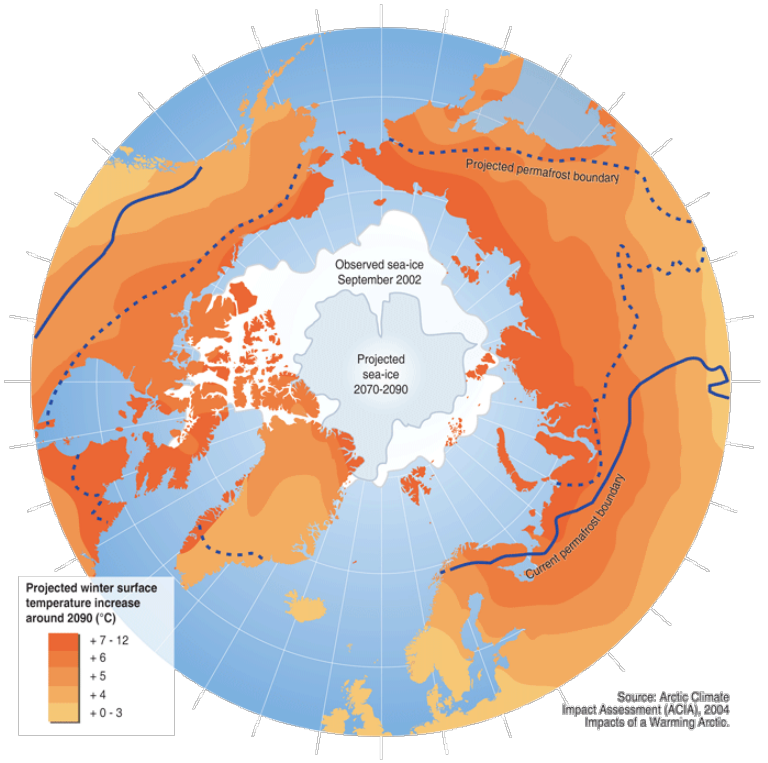
Why Active (Laser) Sensing?

- Coverage at all latitudes (day & night) and through optically thin clouds
- Estimate range (pathlength) - altimetry
- Detect scatter from aerosols and clouds - backscatter profile
- Estimate and remove bias errors
- High spectral resolution
- Potentially higher sensitivity

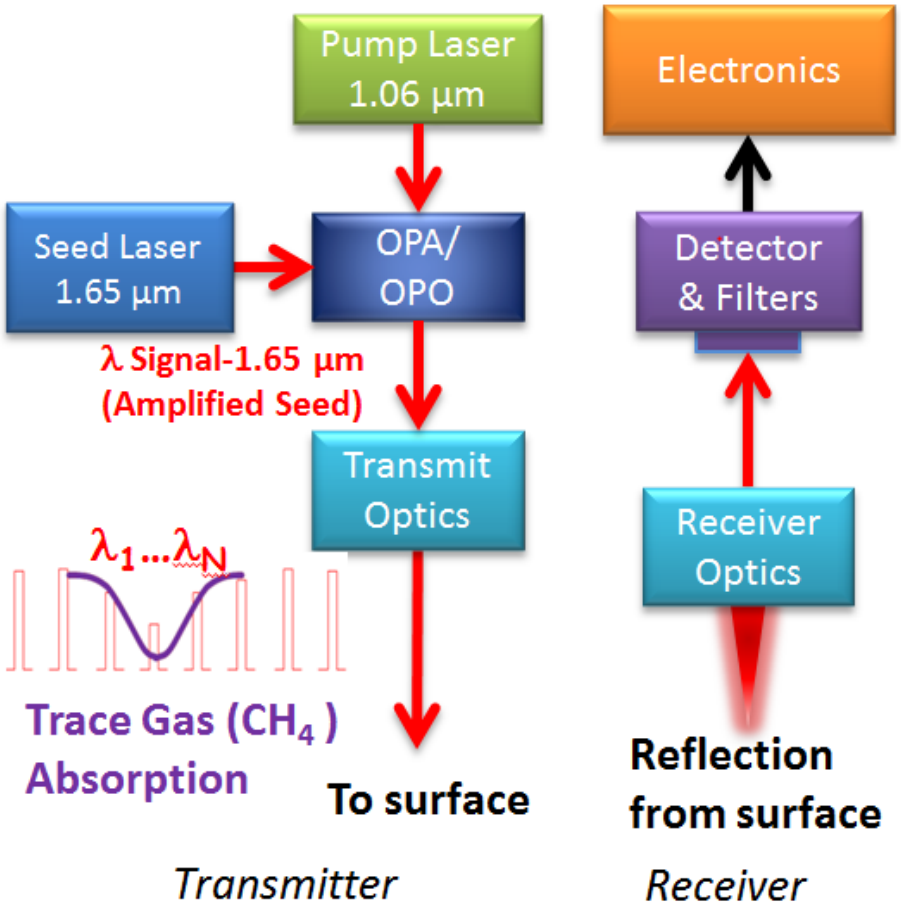
Global Permafrost Carbon

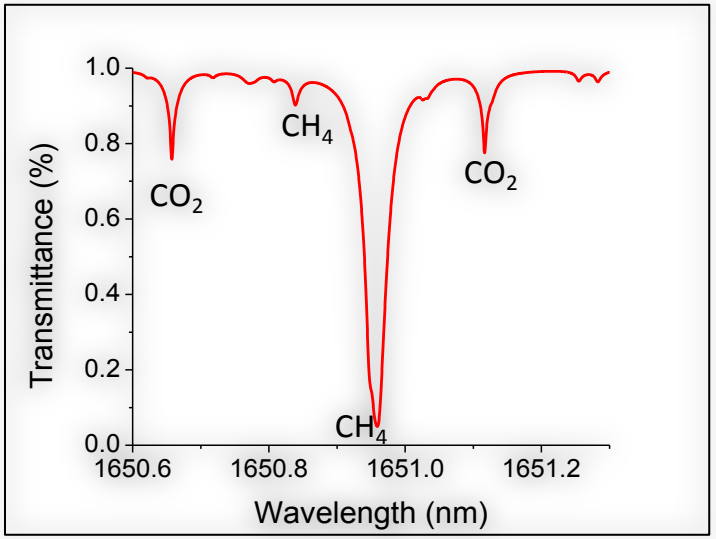
- 23 million square kilometers of permafrost across the globe
- 1500 Gt of frozen carbon, about twice as much carbon as contained in the atmosphere (*Tarnocai, et al 2008*)
- Arctic warming likely to mobilize this Carbon to the atmosphere, but flux magnitudes and breakdown between CO_2 and CH_4 remain unknown.





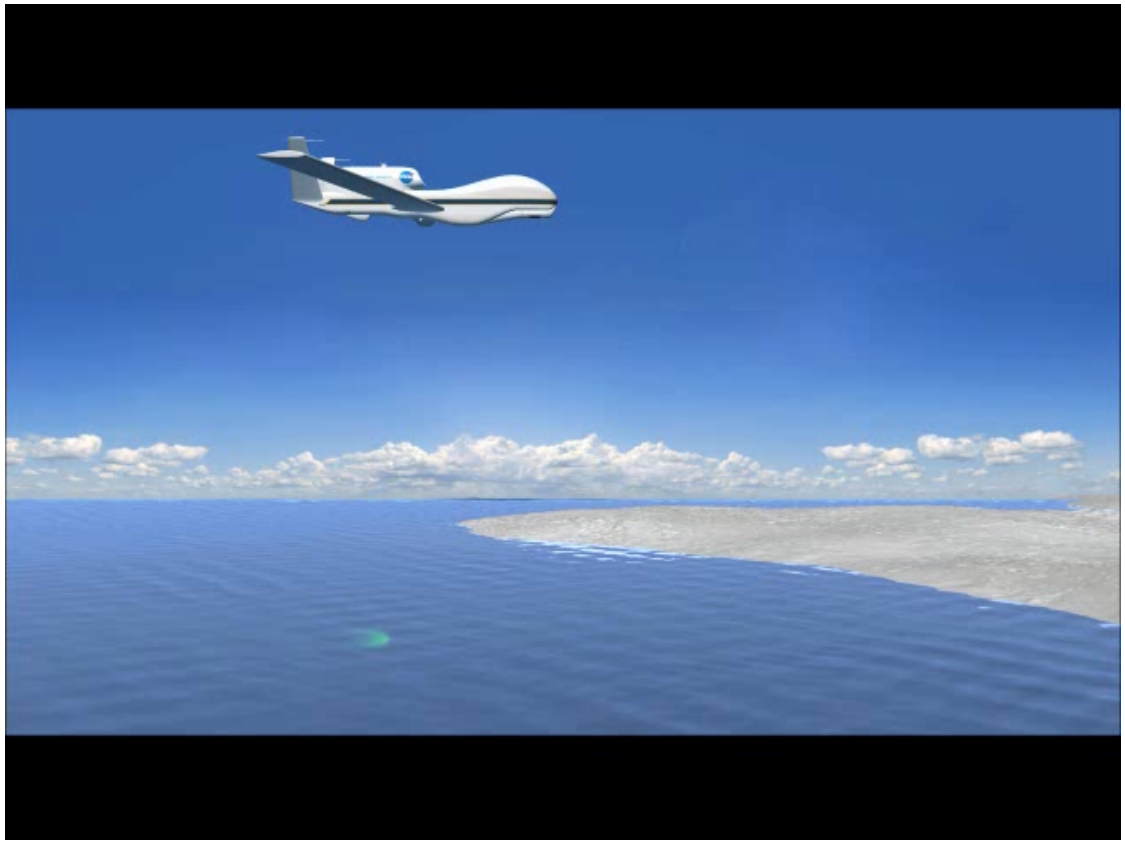
Trace Gas (CH_4) Detection with Lidar





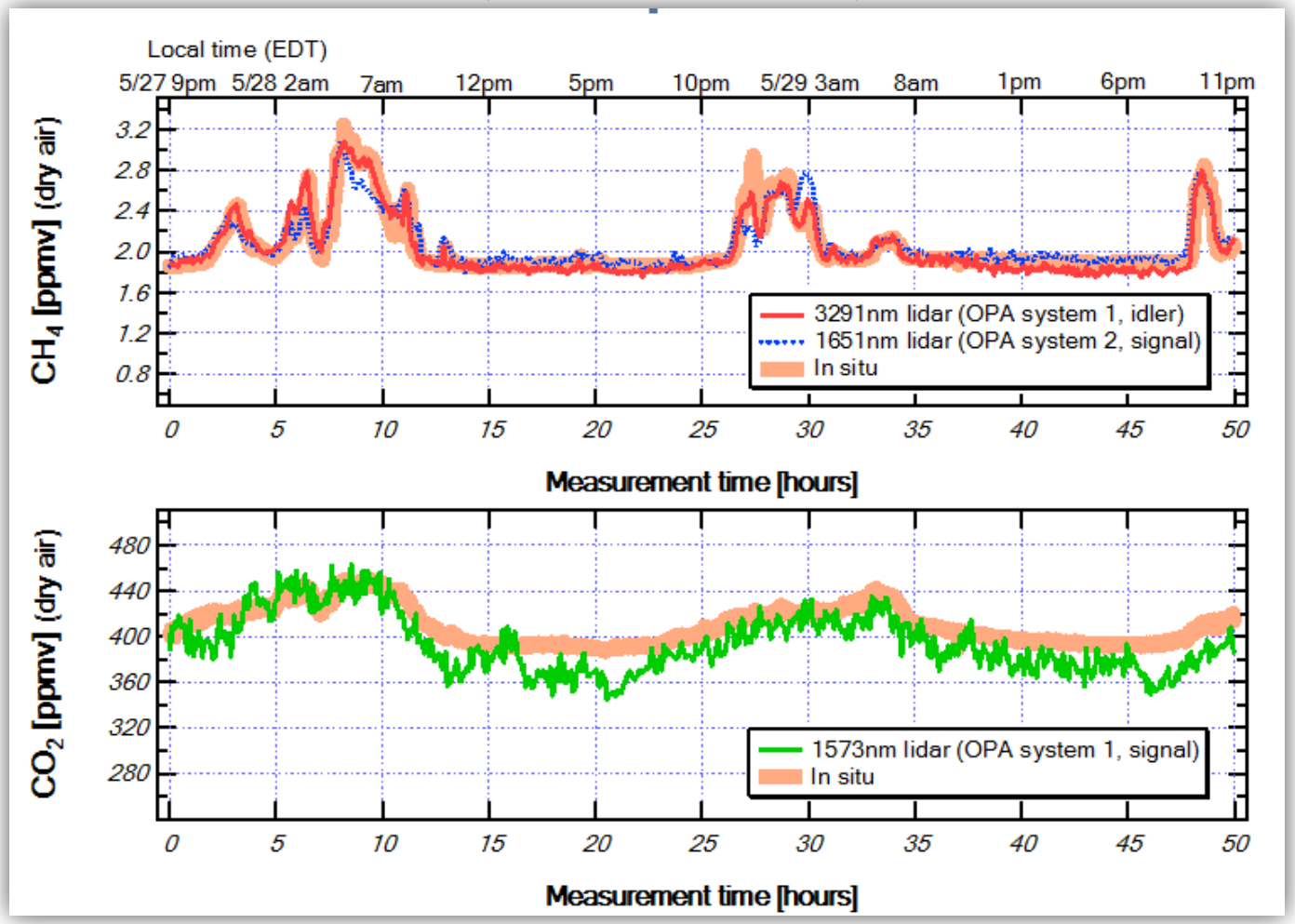
Parameter	Value
Repetition Rate	10 KHz
Pulsewidth	6 nsec
Orbit altitude	400 km
Ground Speed	5 km/s
Laser Spot Diameter	48 m
Detector Quantum Eff.	70%
Telescope Diameter	0.5 m
Receiver Field of View	200 µrad
Surface reflectivity	0.31
Receiver Optical Bandwidth	0.8 nm
Averaging Time	1 sec
Energy	250-300 µJ

GSFC Approach - Integrated Path Differential Absorption Lidar



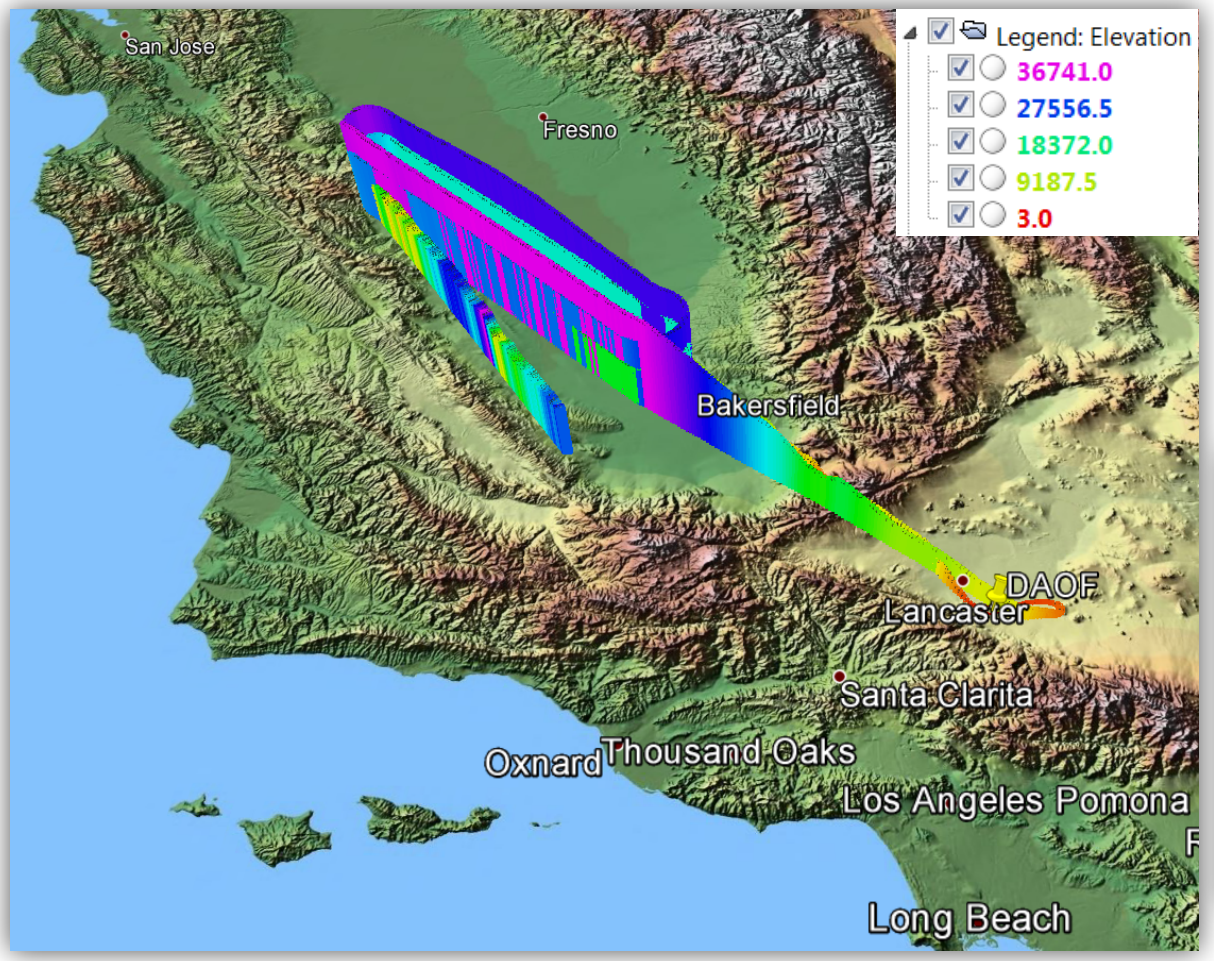
- Pulsed Lidar approach isolates the return from the ground
- Measures range to the ground – unambiguous pathlegth determination
- Samples a single absorption line at multiple points
- Can make measurements at all latitudes, day & night, and through thin clouds

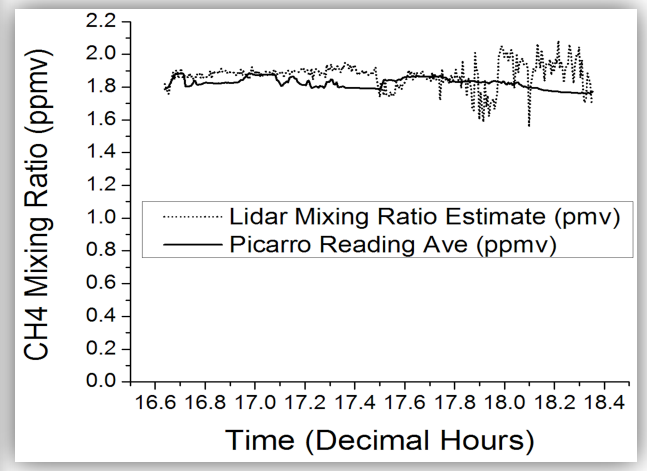
Ground Testing with two IPDA lidars using OPA – 3.29 µm and 1.65 µm



Ground demonstration of trace gas lidar based on optical parametric amplifier, Journal of Applied Remote Sensing 063561-1 Vol. 6, 2012

Airborne Tests in 2011 with an OPA and a PMT

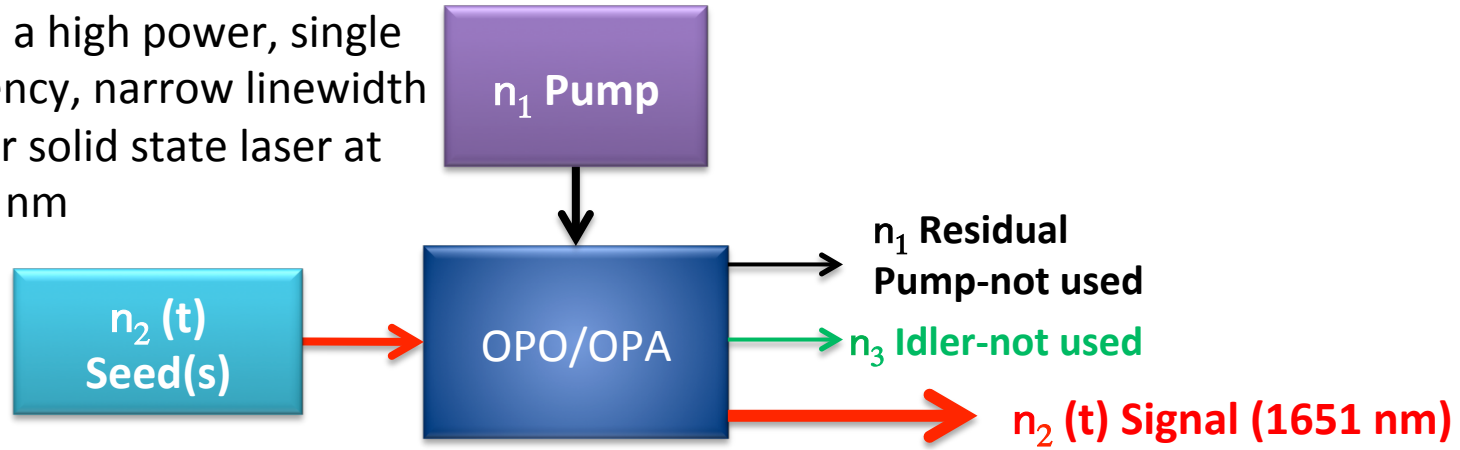




"Airborne measurements of atmospheric methane column abundance using a pulsed integrated-path differential absorption lidar", APPLIED OPTICS / Vol. 51, No. 34 / 1 December 2012

Methane Transmitter Components

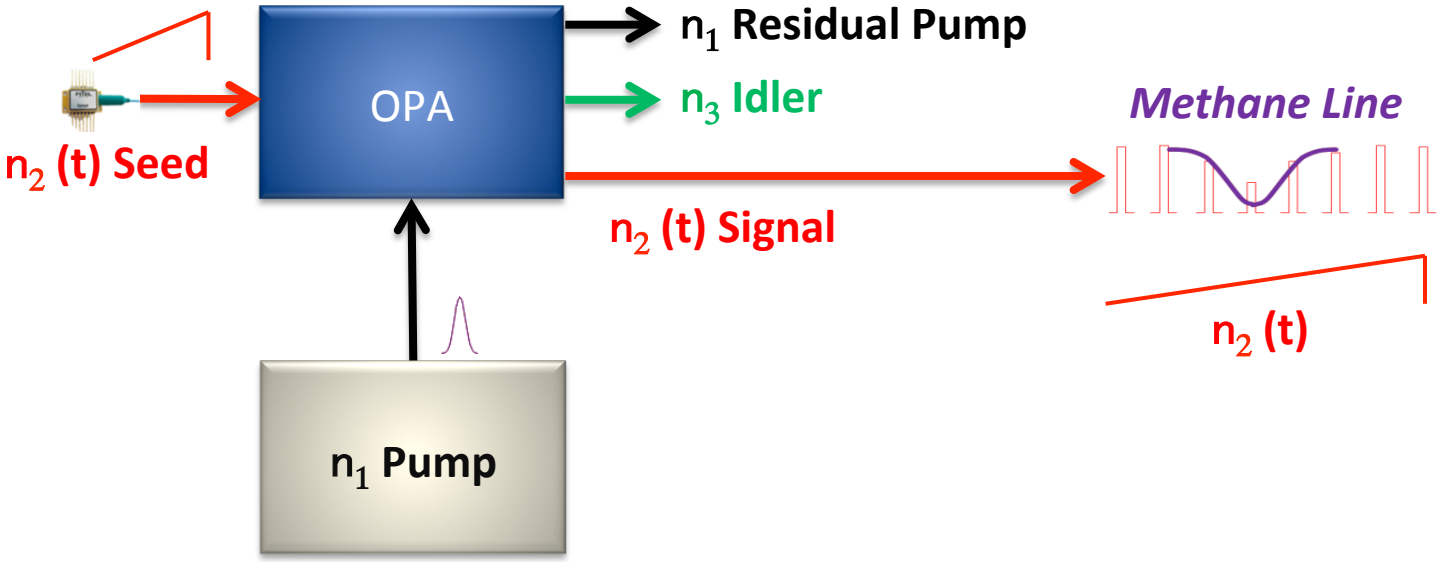
Pump: a high power, single frequency, narrow linewidth fiber or solid state laser at ~1064 nm



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 ***without*** degrading the spectral characteristics

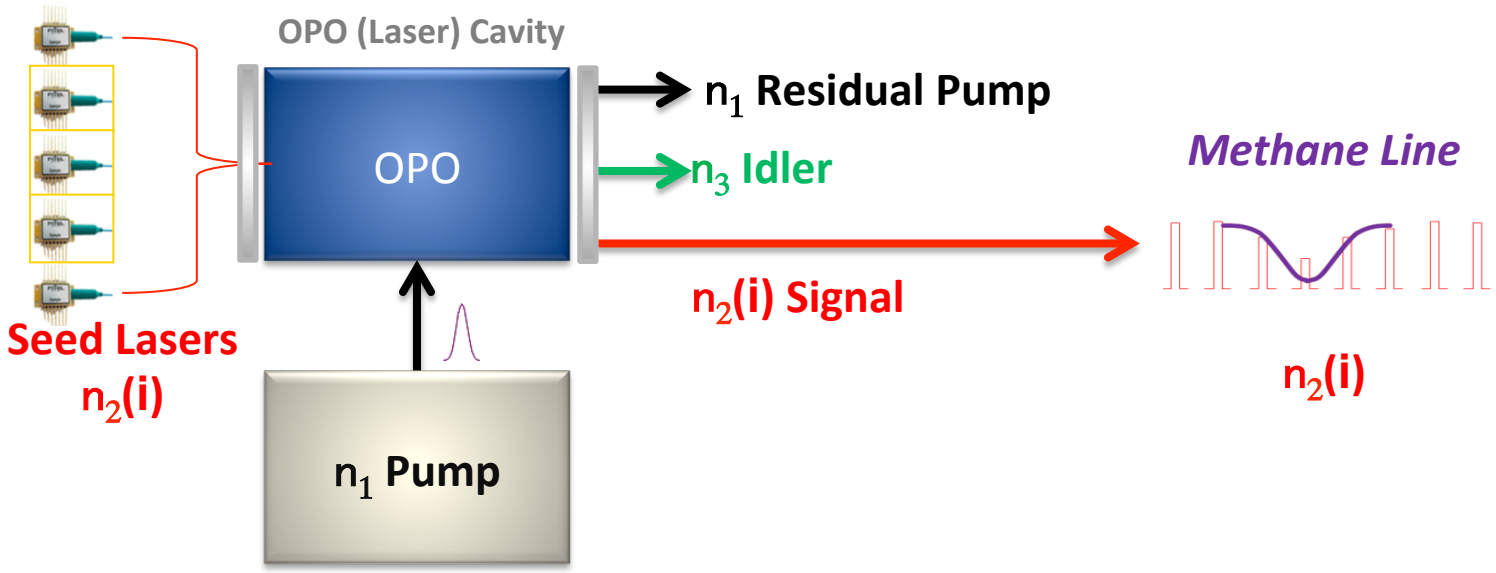
Transmitter Technology - OPA



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

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

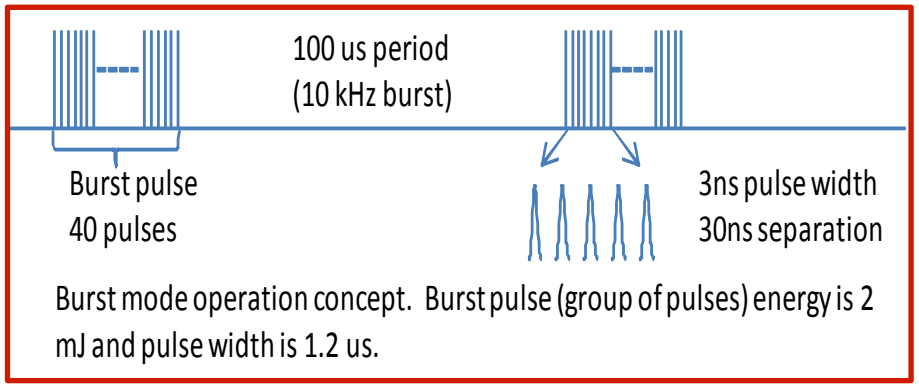
Transmitter Technology - OPO



OPO samples the CH_4 line at <u>several discrete wavelengths using multiple seed lasers.</u> Complicated to align and tune; power scaling easier to achieve while maintaining narrow linewidth.

Pump Laser Options Summary

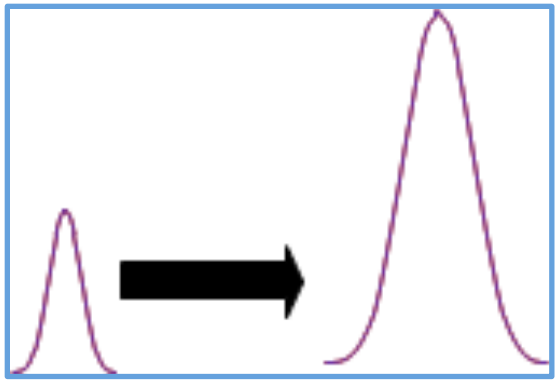
A. Burst Mode



Burst mode operation concept. Burst pulse (group of pulses) energy is 2 mJ and pulse width is 1.2 us.

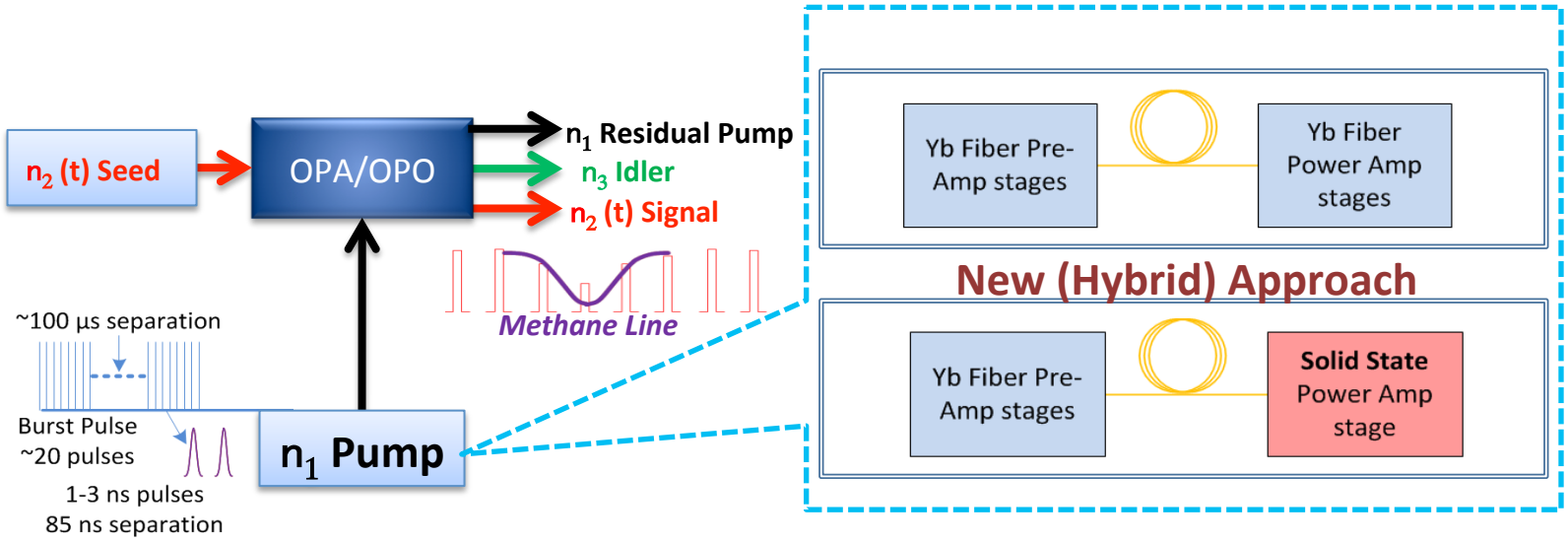
Yb Fiber MOPA

B. "Single" (Mono) Pulse



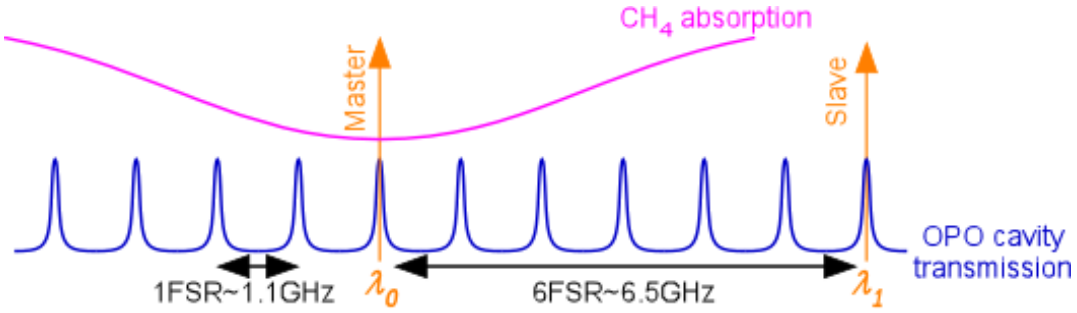
Solid State Laser

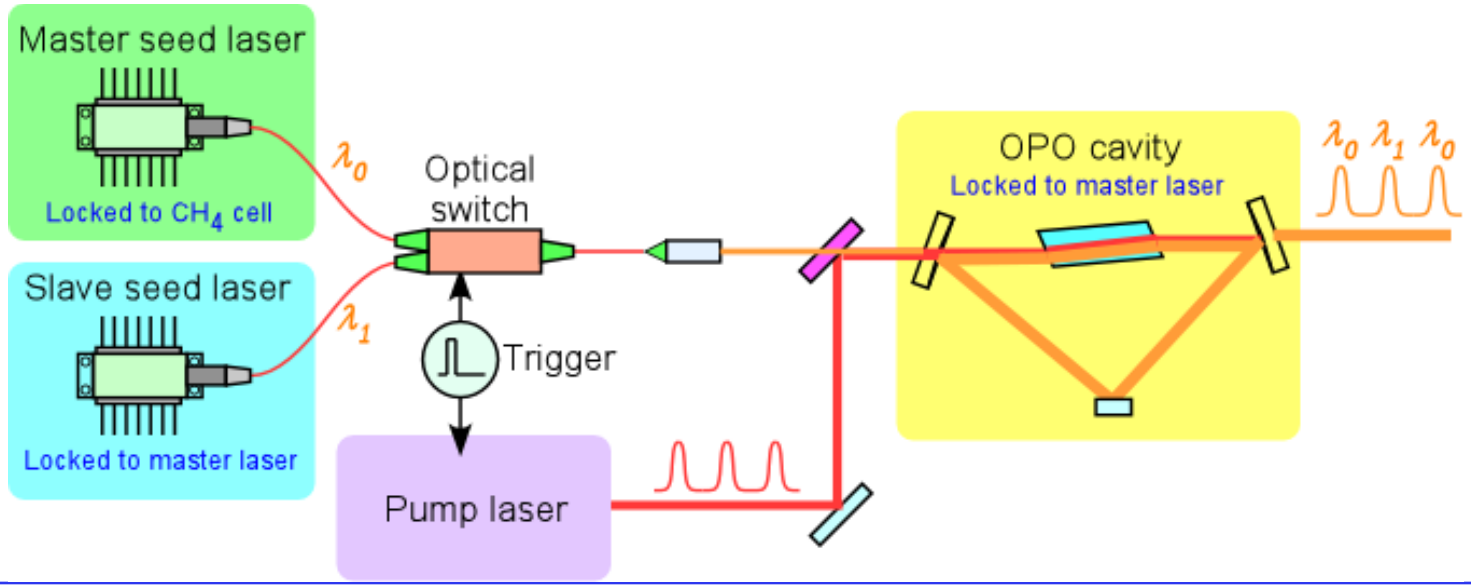
C. Hybrid



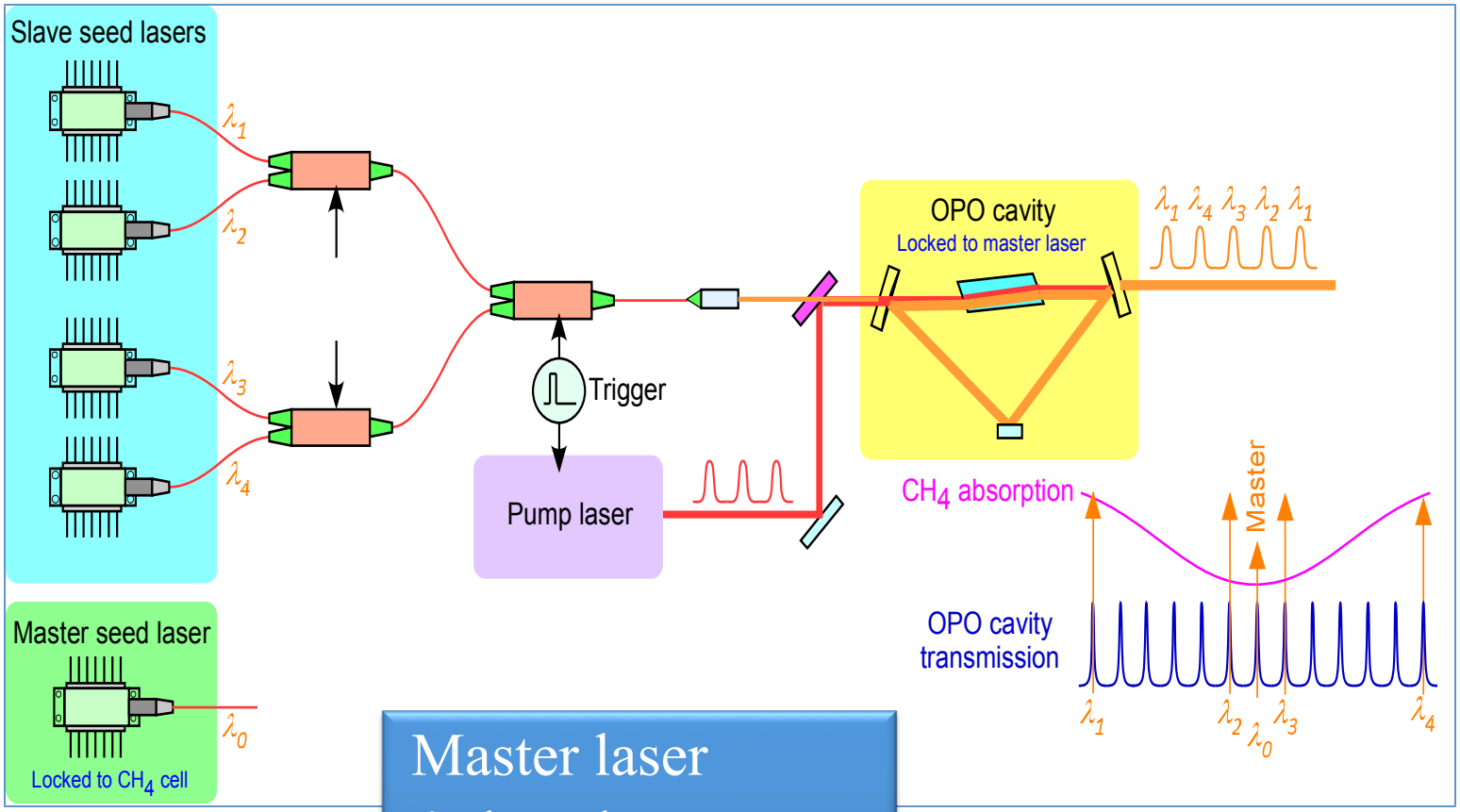
Existing 2-Wavelength OPO

- Master seed laser
- Slave seed laser
- OPO cavity
- Reference cell



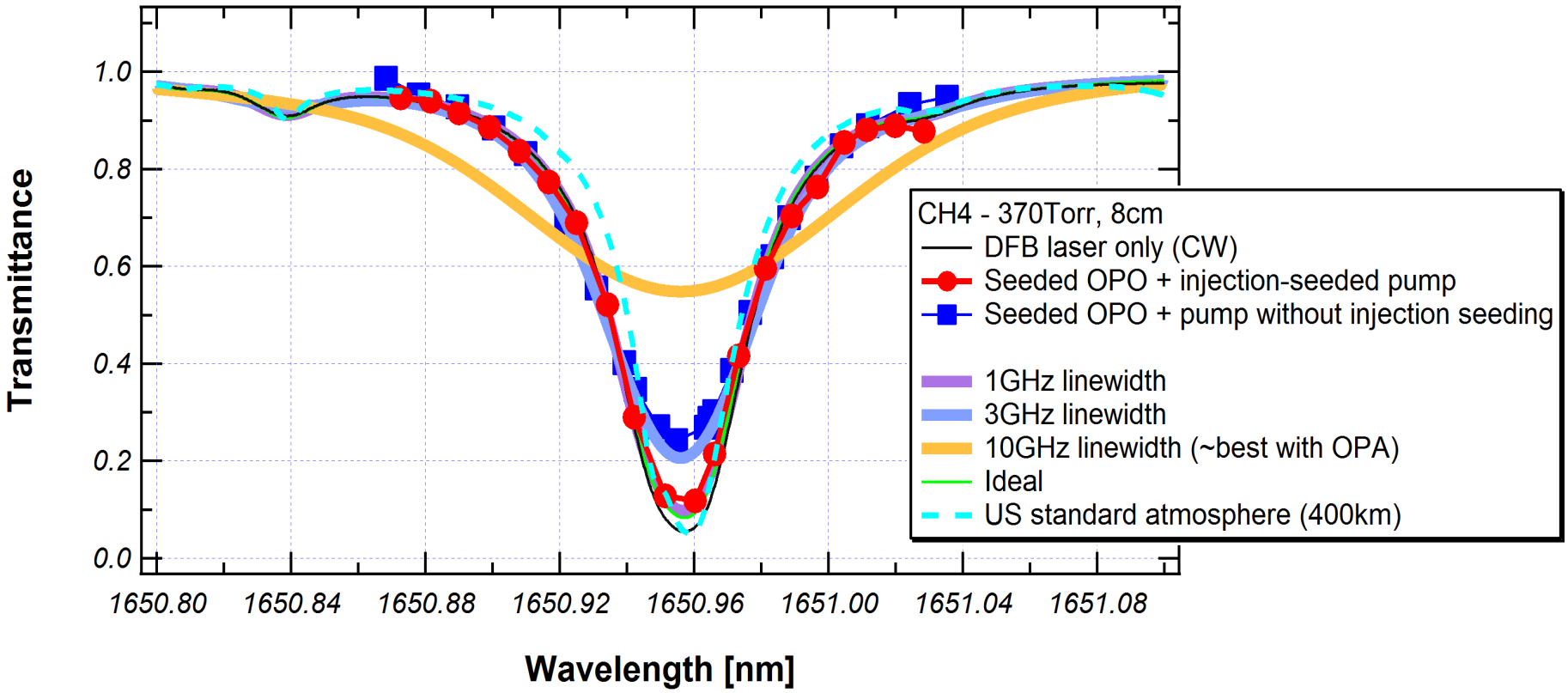


4-wavelength OPO



Master laser
4 slave lasers
3 optical switches
1 Reference Cell

The importance of linewidth

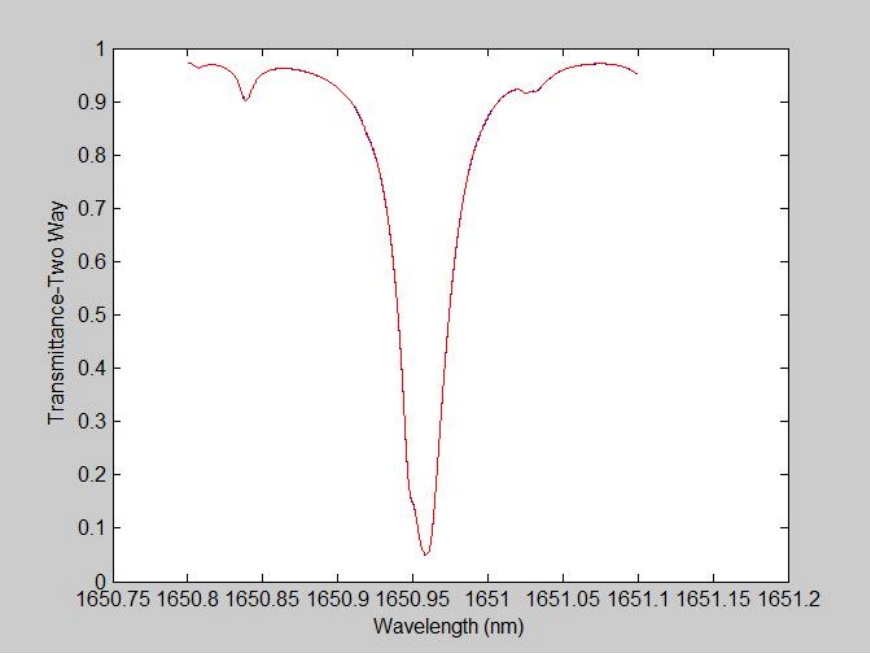


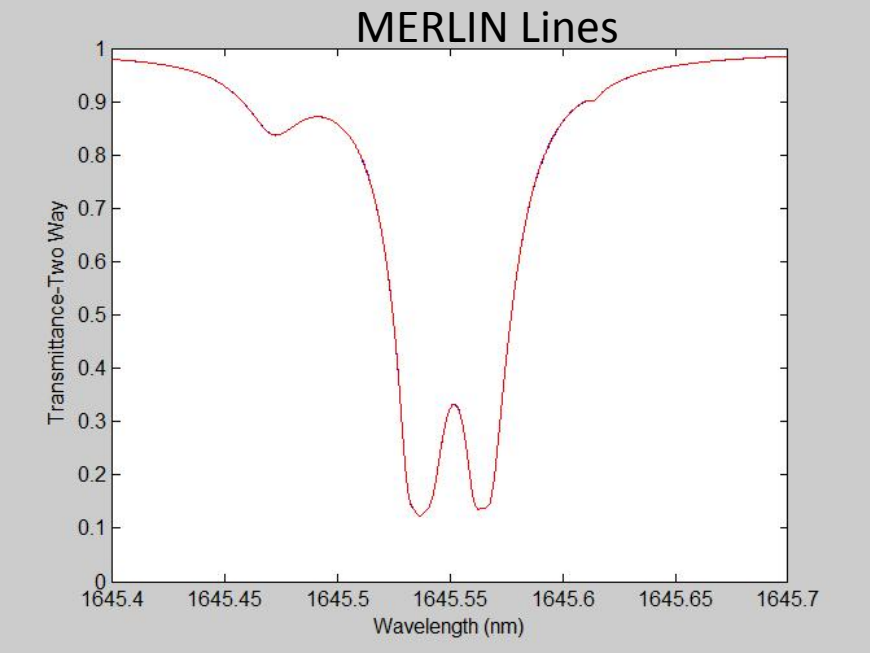
Transmitter Technology Development Summary

Approach	OPA with smaller burst pulses	OPA with large pump pulse	OPO with large pump pulse
Pump laser	Difficult (due to SBS, damage, unstable seeder…)	Relatively easy (more traditional)	Relatively easy (more traditional)
Pump laser type	Fiber (robust, higher efficiency)	Free space - contamination concerns	Free space - contamination concerns
Seed laser (1651nm)	Existing DFB is OK	High seed power required	Existing DFBs are OK
Output linewidth	Should be the same as before (~500MHz)	Becomes wider without sufficient seed power	Expected to be narrowed by optical feedback
Parametric stage	Single OPA stage (simple)	Need for multiple OPA stages	Need for cavity locking & step tuning (complicated)
Status	Yb MOPA limited by SBS	Minimum signal linewidth obtained was >10GHz at the required energy due to the limited seed power	Achieved 200 µJ energy and narrow linewidth

Alternative Laser Approaches

- Er:YAG Lasers
  - Er:YAG laser technology has the potential for improved efficiency, reliability over OPO/OPA based methane lidars
  - High spectral purity
  - High power



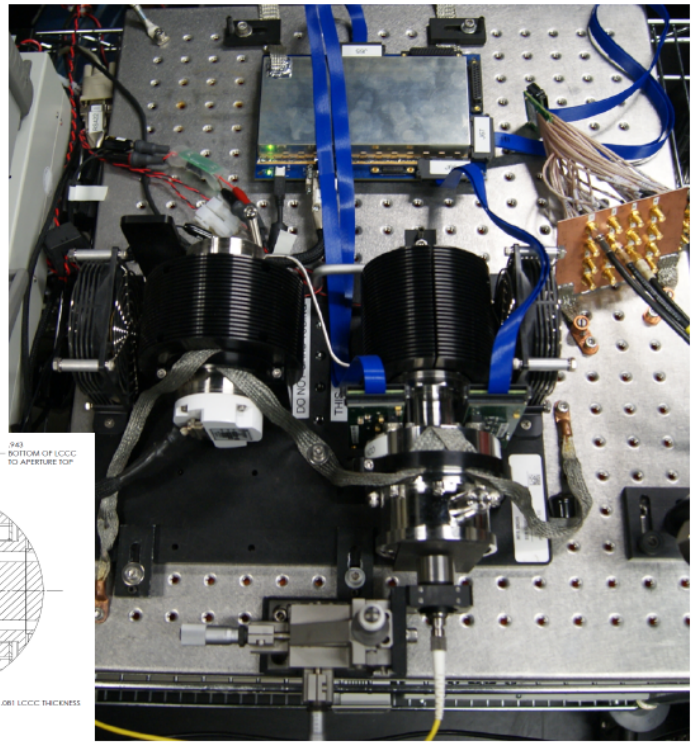


Detector (X. Sun/Jim Abshire)

HgCdTe e-APD 4x4 Array Test Results at GSFC

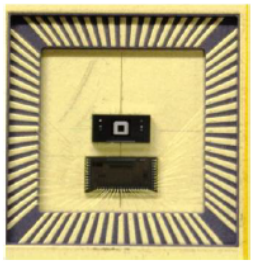
GSFC

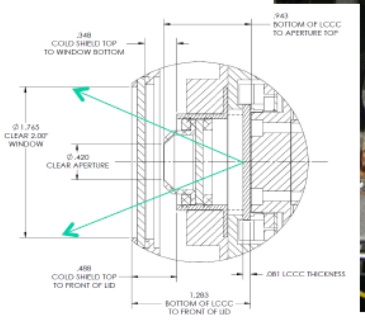
- First 4x4 HgCdTe e-APD array for the CO2 lidar received in April 2013 and met requirements



F/1.5 Dewar Cold Shield with Cold Filter

FPA on chip carrier





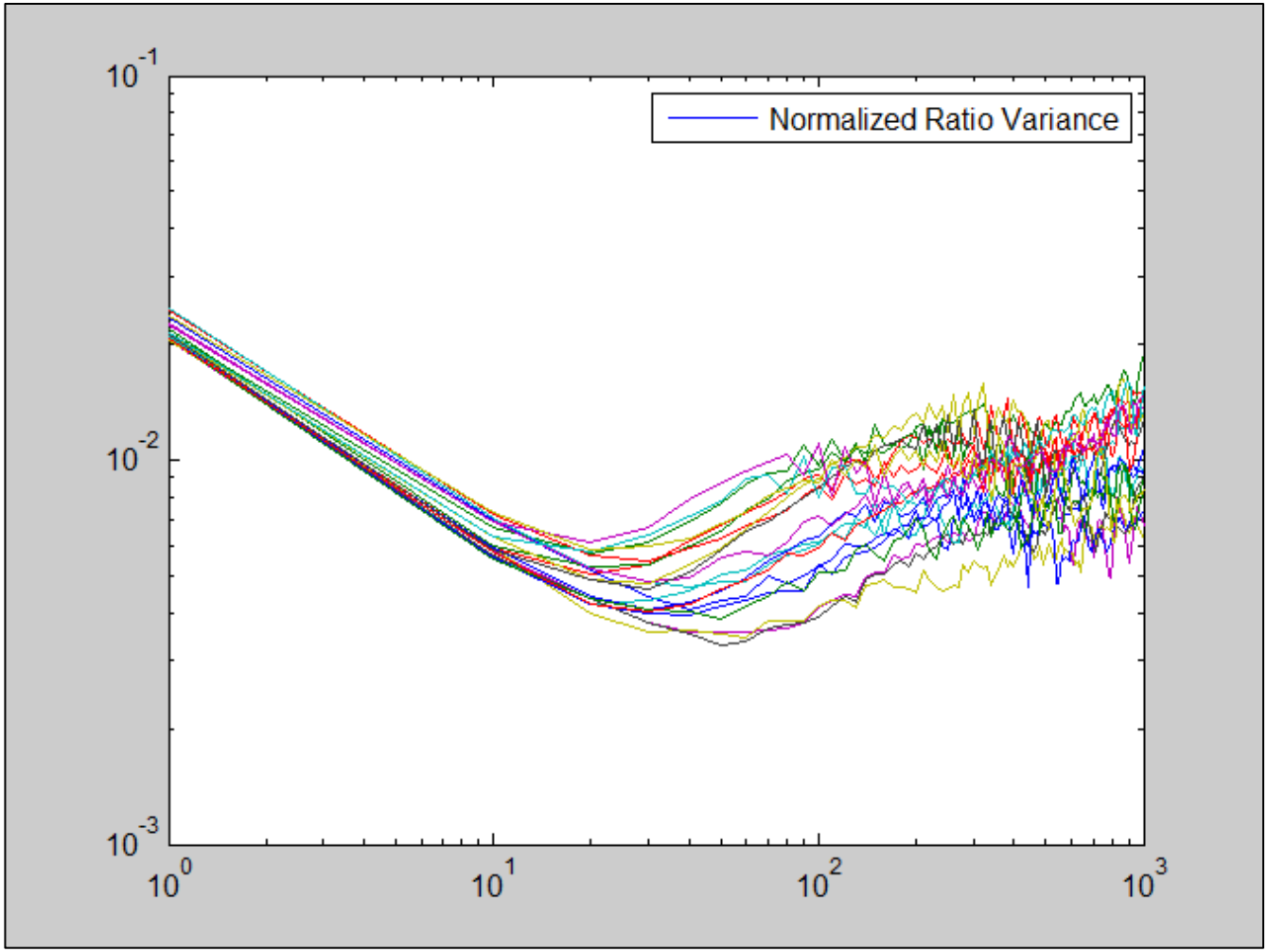
ESTO Earth Science Technology Office

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*

Methane Transmitter Technology Development Summary

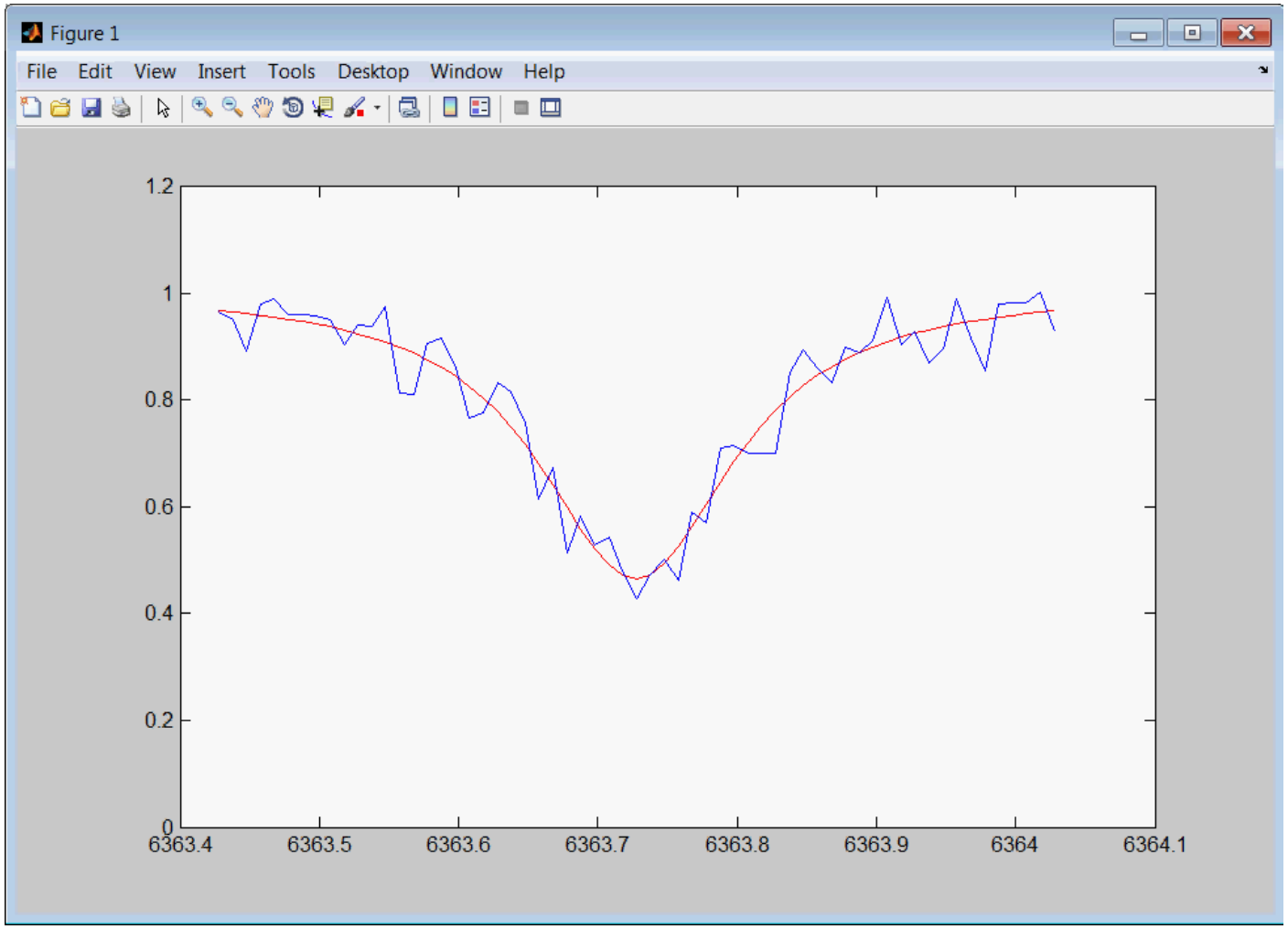
- Transmitter Components:
  1. Pump laser
  2. OPO vs. OPA
  3. Seed Laser
- Transmitter power scaling Approaches:
  - Pump laser (multiple options): Yb Fiber lasers, single frequency single pulse solid state laser, hybrid laser (fiber-solid state).
  - OPA vs OPO – current baseline design is 4-wavelength OPO
  - Seed laser: Alternatives being pursued.
- Other laser technologies are being pursued

Allan Variance



"there are cases, where the standard deviation may be held constant, but the mean varies from one observation to the next" John von Neumann et al. , Ann. Math. Stat. **12**, 153 (1941)

Simulation without instrument bias



Simulation with instrument bias