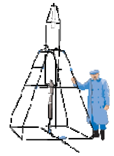

Methane measurements from space: technical challenges and solutions

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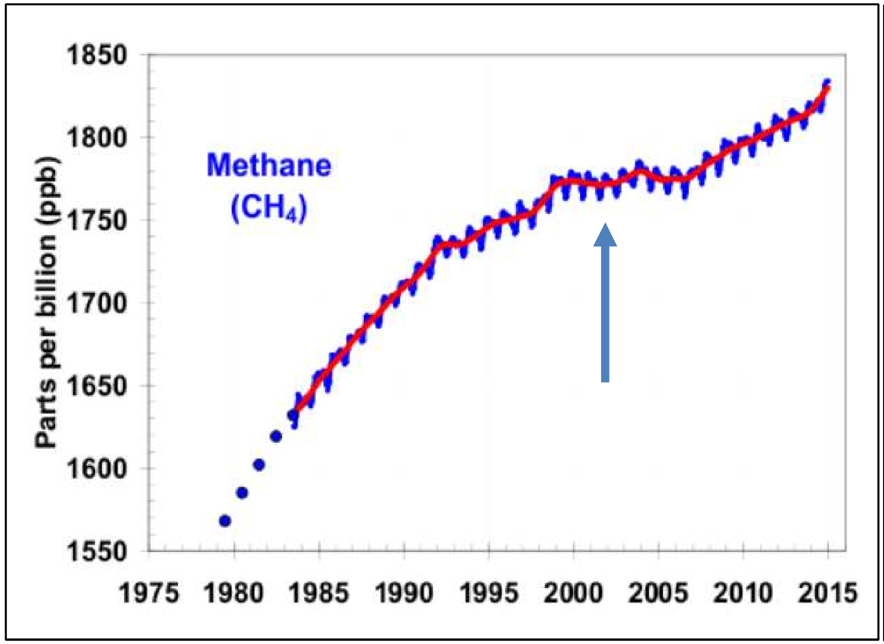
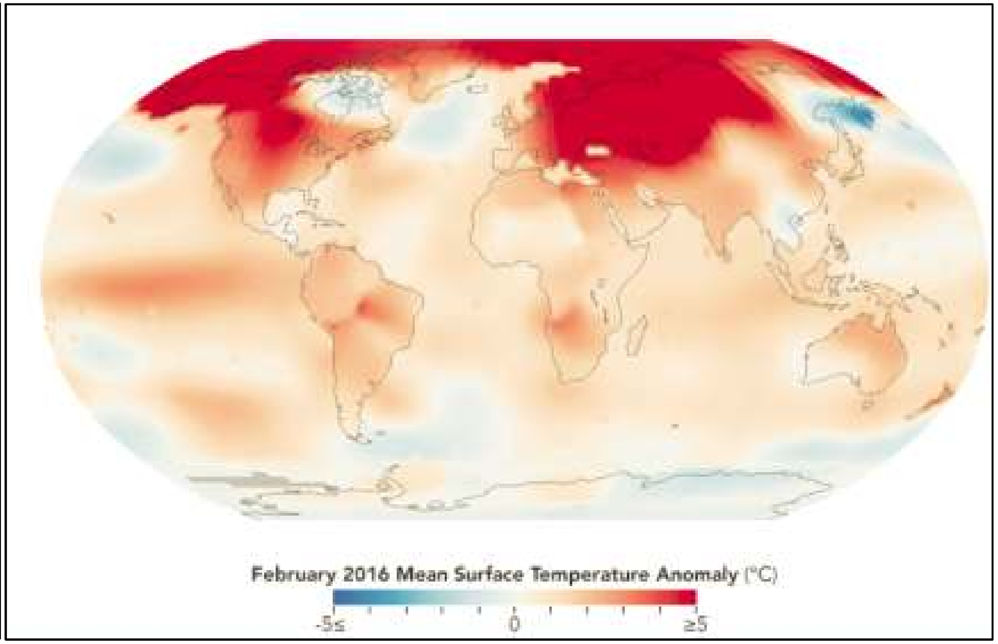
Outline

- 1. Motivation
  - Why measure Methane?
- 2. Measurement Approach
  - Technology and Challenges
- 3. 2015 Airborne Demonstration
  - OPA
  - OPO
- 4. Summary

1. Motivation

- Why measure methane?





Source: www.esrl.noaa.gov/gmd/aggi/aggi.html

Source: http://www.giss.nasa.gov/research/features/201603_gistemp/

Methane Trend since 1975

February 2016 was the warmest February in 136 years of modern temperature records. That month deviated more from normal than any month on record.

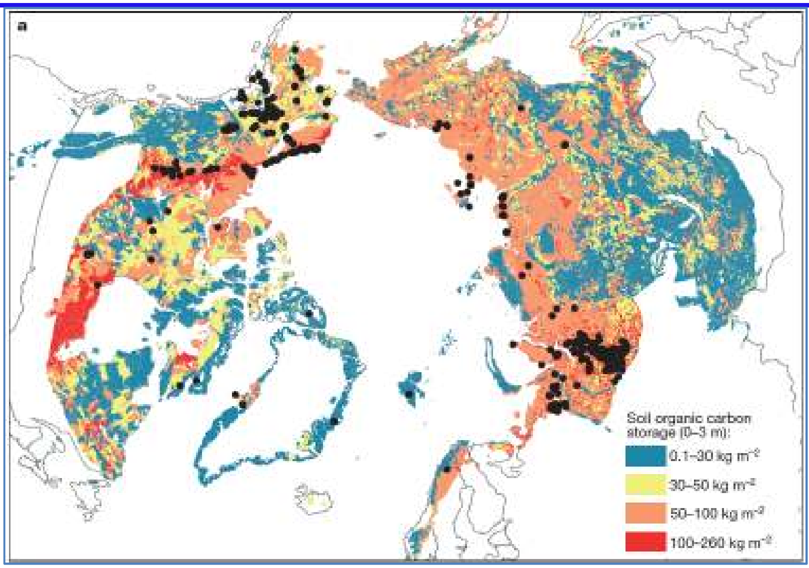
Methane Lifetime

Gas	Estimated 1750 tropospheric concentration[1]	Recent tropospheric concentration[2]	GWP[3](100-yr time horizon)	Atmospheric lifetime[4](years)	Increased radiative forcing [5] (W/m^2)
Concentrations in parts per million (ppm)					
Carbon dioxide (CO_2)	278[6]	397.2[7]	1	~ 100-300[4]	1.91
Concentrations in parts per billion (ppb)					
Methane (CH_4)	722[8]	1823[2]	28	12[4]	0.50
Nitrous oxide (N_2O)	270[9]	327[2]	265	121[4]	0.19
Tropospheric ozone (O_3)	237[1]	337[2]	n.a.[3]	hours-days	0.40

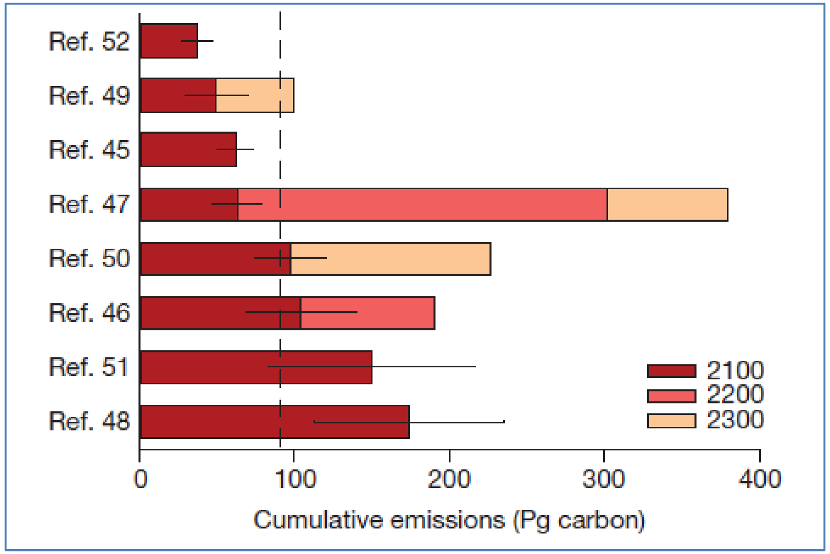
Source: DoE http://cdiac.esd.ornl.gov/ and IPCC Chapter 8

CH_4 is removed from the atmosphere by a single process, oxidation by the hydroxyl radical (OH), but the effect of an increase in atmospheric concentration of CH_4 is to reduce the OH concentration, which, in turn, reduces destruction of additional methane, effectively lengthening its atmospheric lifetime.

Methane “Arctic Time Bomb” requires year-round observations



Soil organic carbon maps. a, Soil organic carbon pool (kg cm²) contained in the 0–3m depth interval of the northern permafrost zone



Model estimates of potential cumulative carbon release from thawing permafrost by 2100, 2200, and 2300.

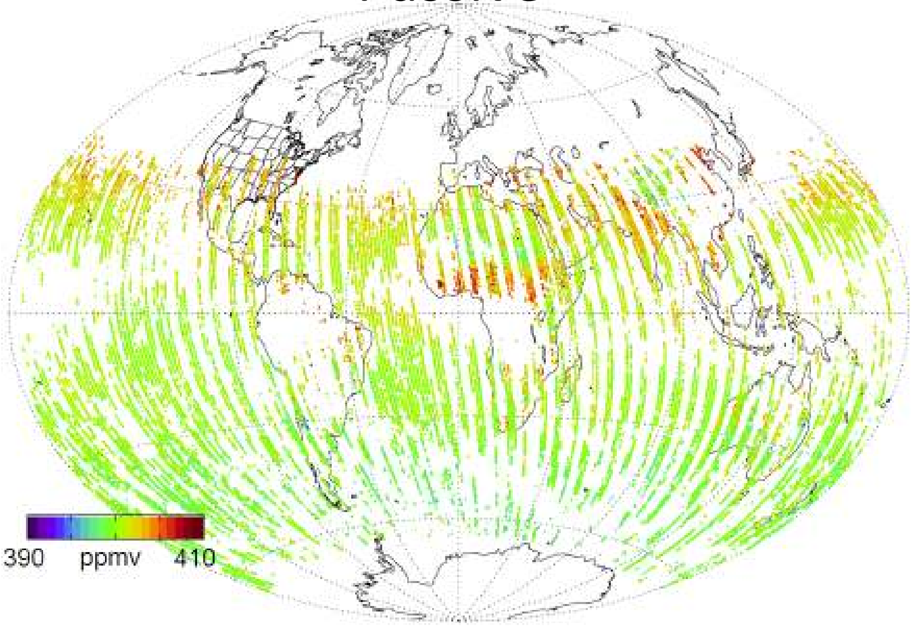
Source: E. A. G. Schuur, et.al., N AT U R E, VO L 5 2 0 , 9 A P R I L 2 0 1 5, 174

- *“Large quantities of organic carbon are stored in frozen soils (permafrost) within Arctic and sub-Arctic regions. A warming climate can induce environmental changes that accelerate the microbial breakdown of organic carbon and the release of the greenhouse gases carbon dioxide and methane. This feedback can accelerate climate change, but the magnitude and timing of greenhouse gas emission from these regions and their impact on climate change remain uncertain...” E. A. G. Schuur, et.al., N AT U R E, VO L 5 2 0 , 9 A P R I L 2 0 1 5, 174*
- *“Here, we report year-round CH_4 emissions from Alaskan Arctic tundra eddy flux sites and regional fluxes derived from aircraft data. We find that emissions during the cold season (September to May) account for ≥50% of the annual CH_4 flux, with the highest emissions from noninundated upland tundra.” Donatella Zonaa et.al., “Cold season emissions dominate the Arctic tundra methane budget”. PNAS, January 5, 2016 , vol. 113 , no. 1, 40–45*

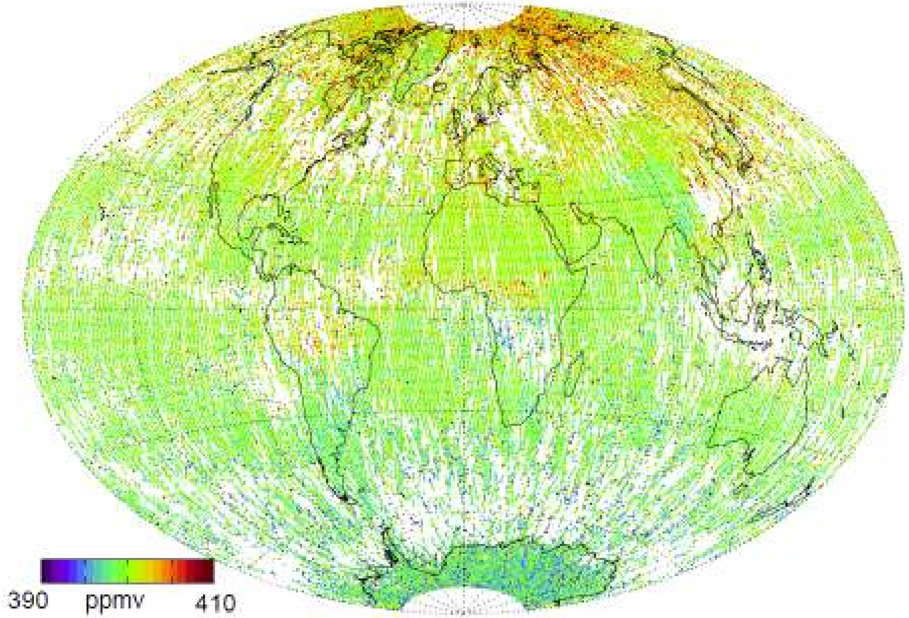
2. Measurement approach

- Why use a laser?

Passive



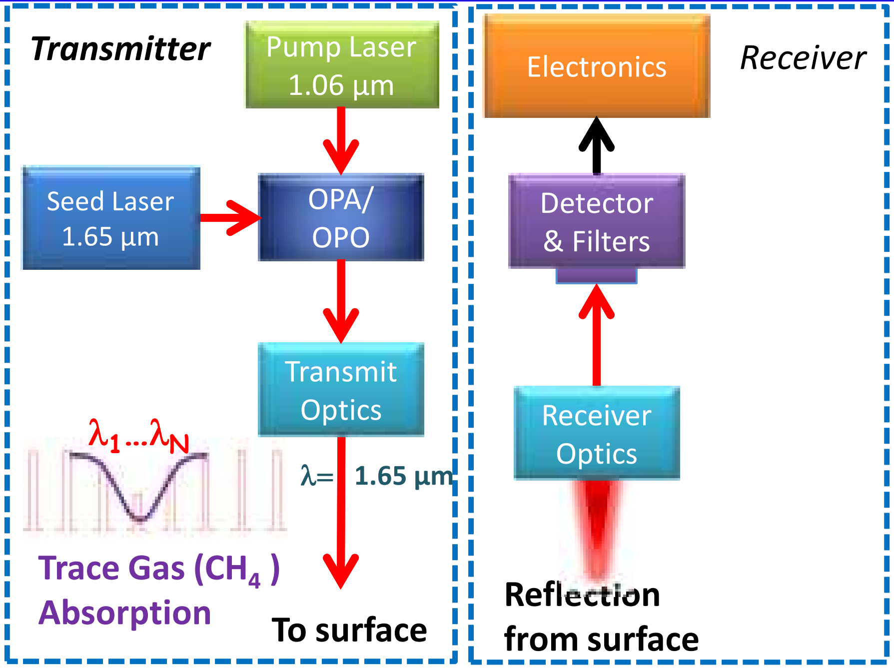
Active

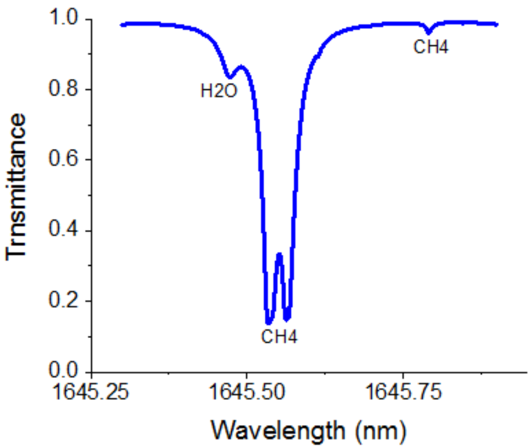


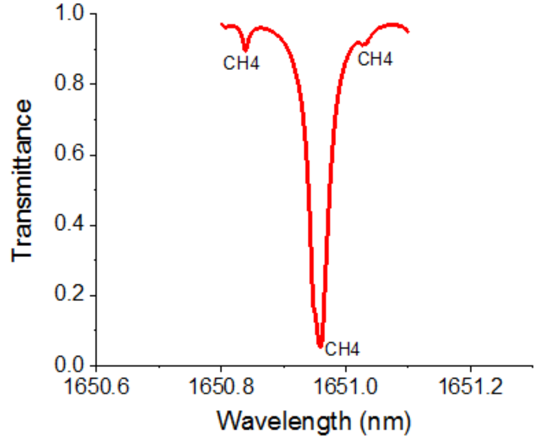
Comparison of actual OCO-2 coverage (left) vs. simulated ASCENDS coverage for December 16-31 2015. The sparse sampling OCO-2 coverage at high latitudes is a major drawback of passive remote sensing missions. (Simulation provided by Dr. Stephan R. Kawa, 614).

CH_4 IPDA Lidar

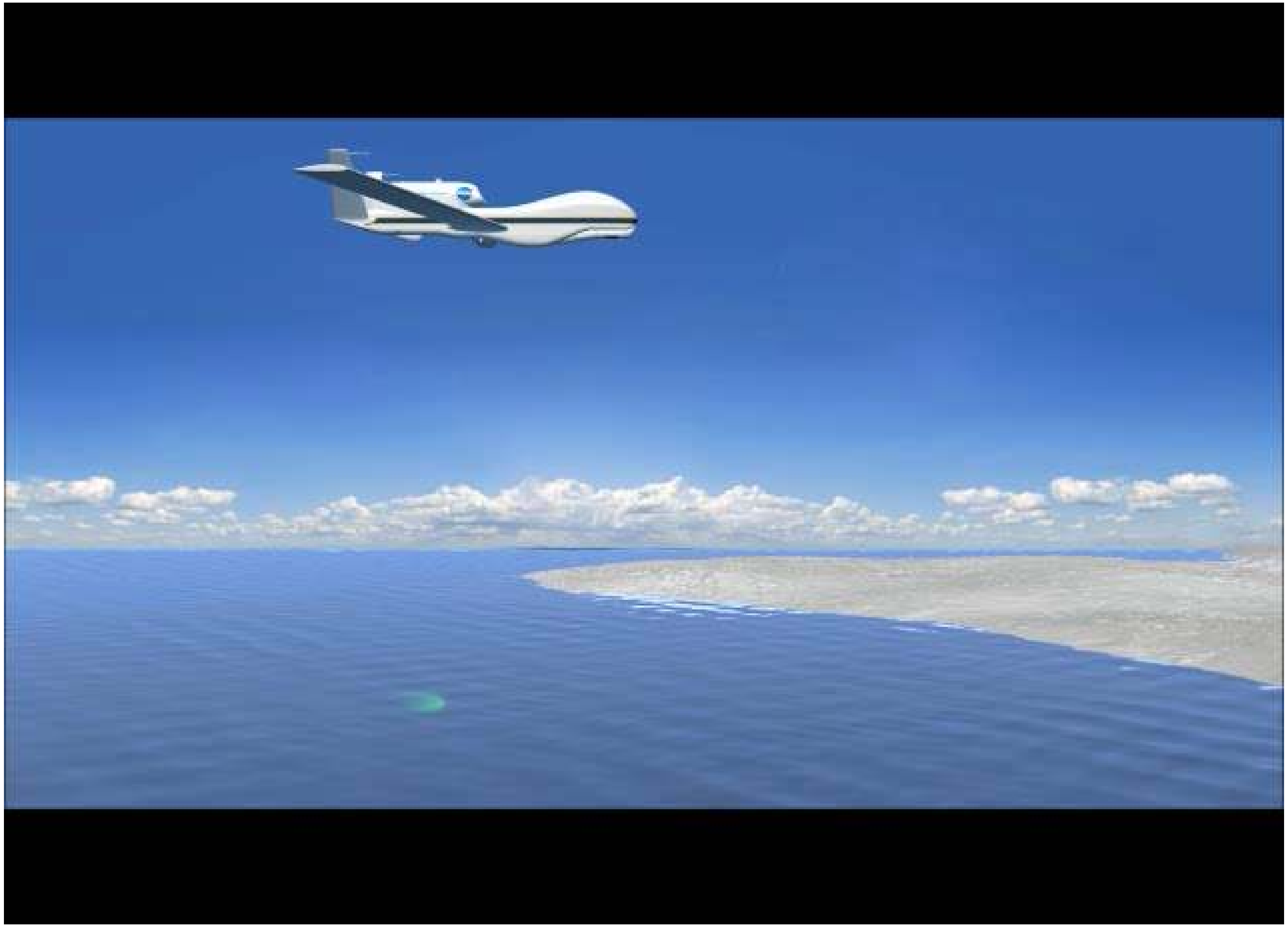
- ***Transmitter (Laser) technology***
  - **Current (optimum) Wavelength for CH_4 Earth Detection: ~1.64-1.66 µm**
  - **Optical Parametric Oscillators (OPO) and Optical Parametric Amplifiers (OPA) are the "baseline" solutions for the transmitter.**
  - **Other options (Er:YAG and Er:YGG) now feasible.**
- ***Receiver (Detector) Technology***
  - **DRS e-APD**



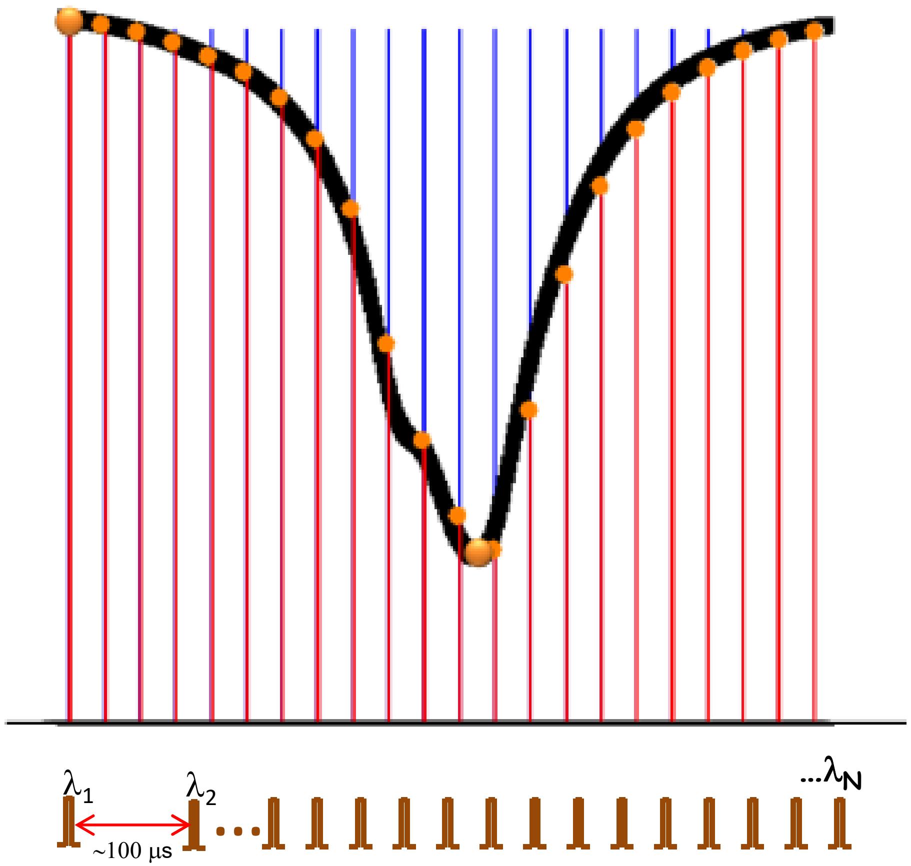




GSFC CH_4 Integrated Path Differential Absorption (IPDA) Multi-Wavelength Lidar



Why use multiple wavelengths?



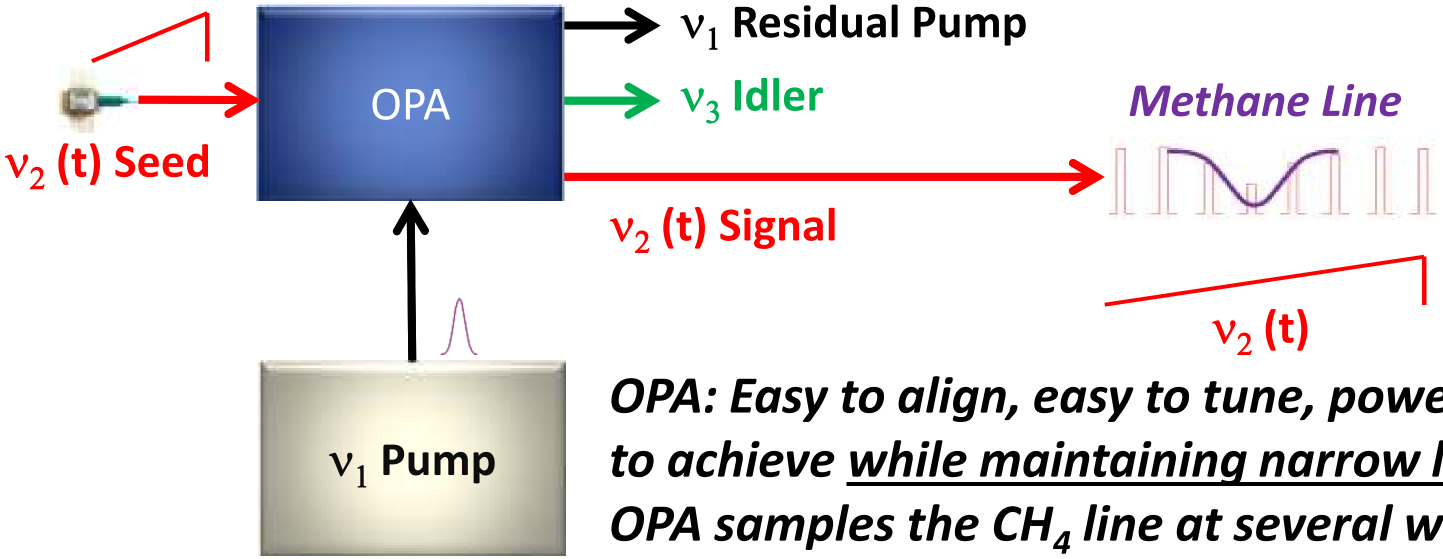
"Ideal" Instrument – has only random noise which can be averaged indefinitely.
Two wavelengths can adequately sample the lineshape. Averaging always helps.
Real Instrument – has random and non-random noise which can NOT always be averaged.
Two wavelengths can NOT adequately sample the lineshape or reduce biases.

Current GSFC Power scaling options

Approach	#1. OPA with smaller burst pulses	#2. OPA with large pump pulse	#3. OPO with large pump pulse
Pump laser	1. Burst mode laser. Need to achieve higher energy and pulse uniformity. Hybrid shown to work. 2. Burst mode fiber MOPA with Waveguide Amplifier shows promise	1. High power Yb fiber laser (1030 nm). 2. Planar Wave Amplifier with commercial laser as Master Oscillator. 3. Custom Nd:YAG laser	1. Custom Nd:YAG laser (1064 nm) 2. High power Yb fiber laser (1030 nm).
Seed laser	Existing DFB lasers are OK but would prefer a DBR laser and higher power	High seed power needed Would prefer a DBR	Existing DFB laser is OK would prefer a DBR laser and higher power
Parametric stage	Single OPA stage possible but currently at low energy.	Need multiple OPA stages to achieve high power	Need for cavity locking & step tuning

Er:YAG or Er:YGG: Achieved high power with Er:YAG (>500 µJ); Er:YAG in progress; Linewidth and tunability still remain an issue

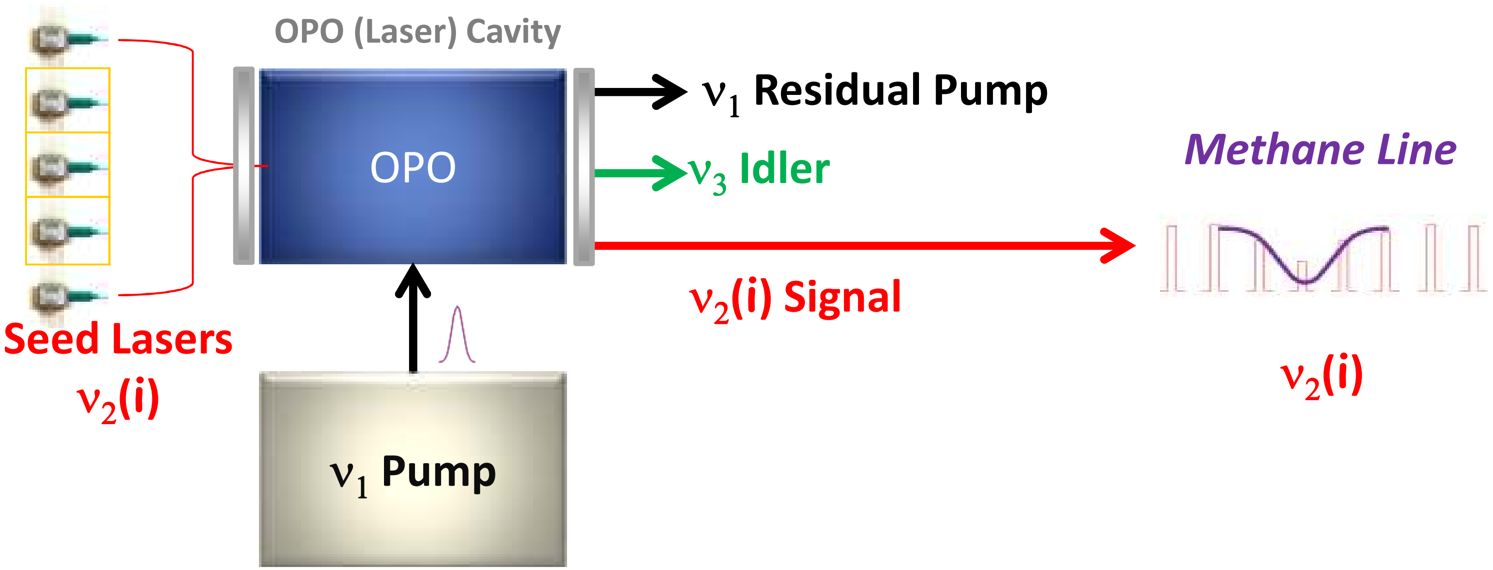
CH4 Transmitter Technology - OPA



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,</u> <u>continuously tuned</u> seed laser

CH4 Transmitter Technology - OPO



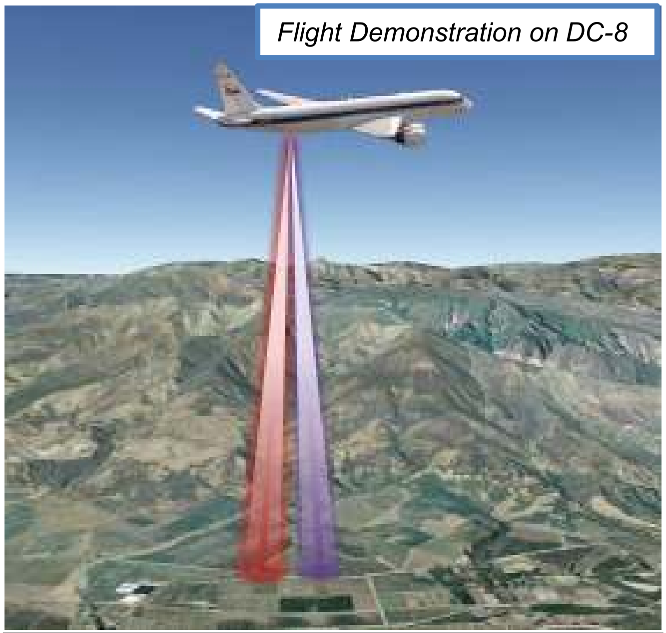
OPO: Complicated to align and tune; power scaling easier to achieve while maintaining narrow linewidth.

OPO samples the CH_4 line at <u>several discrete wavelengths.</u>

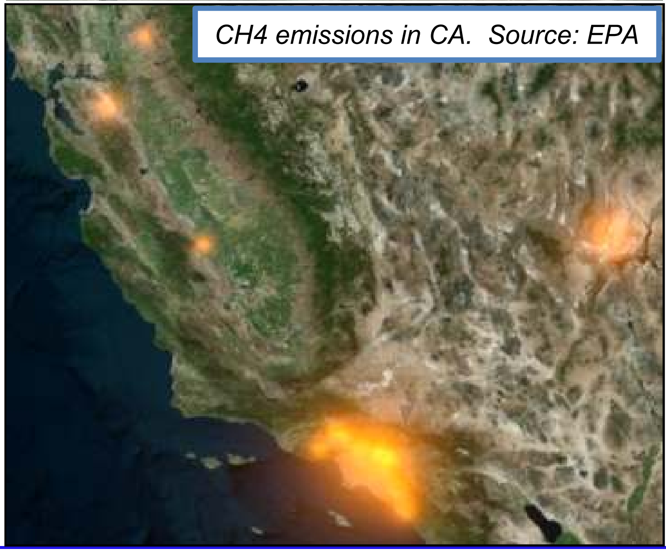
All lasers must be locked.

3. 2015 Airborne Demonstration

Flight Demonstration on DC-8

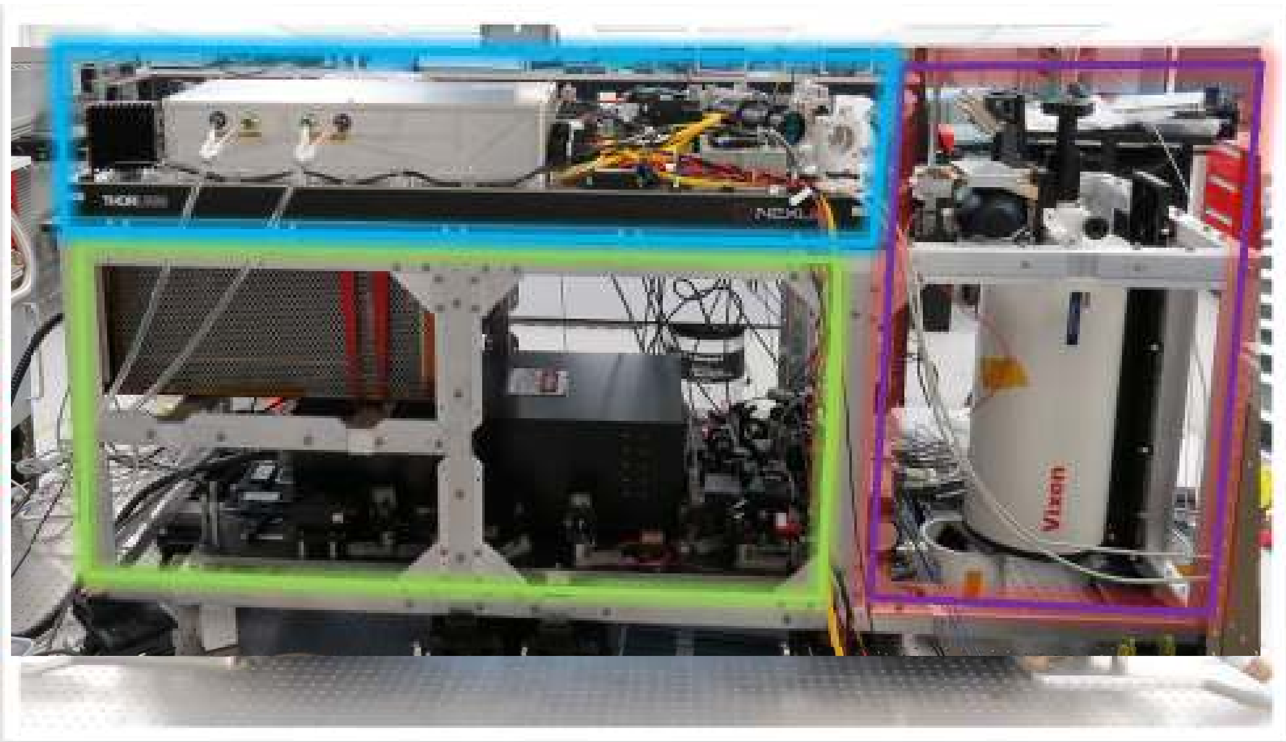


CH4 emissions in CA. Source: EPA



- **Flight Test Methane LIDAR Instruments:**
    - **GSFC Methane Sounder (20-λ OPA and 5-λ OPO)**
    - **GSFC Picarro**
    - **COSS-HSC Optec Solutions**
    - **In-situ CO2 (LaRC G. Diskin)**
- **Conduct several test flights from NASA's Armstrong Science Aircraft Integration Facility (SAIF) in Palmdale, CA:**
    - 1 Engineering flight
    - 2 science flights
    - Approximately 12 hours of flight time in mostly in CA/NV
- **Compare OPO-OPA performance**
- **Assess detector performance**
- **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.**

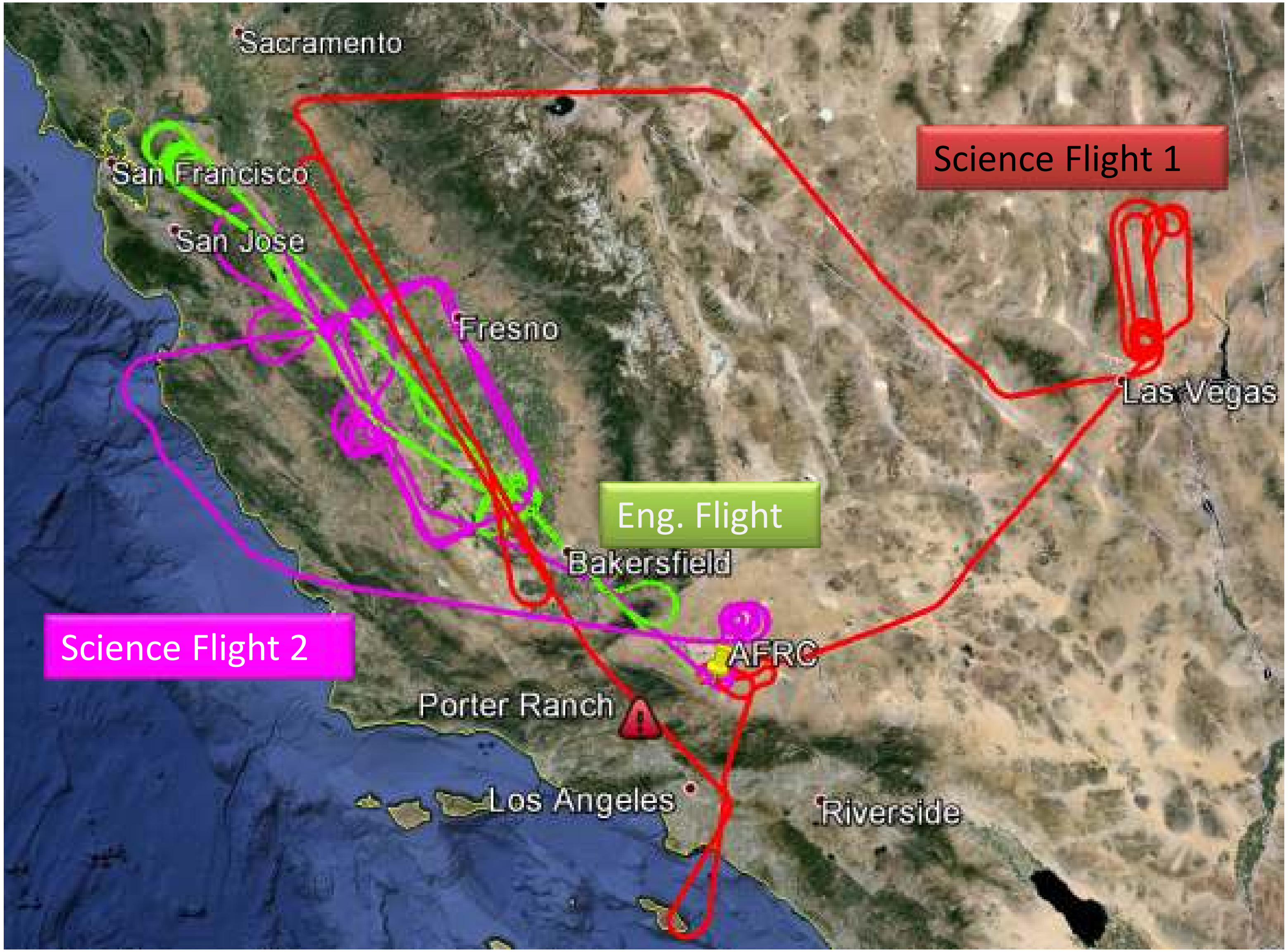
CH_4 Airborne Instrument



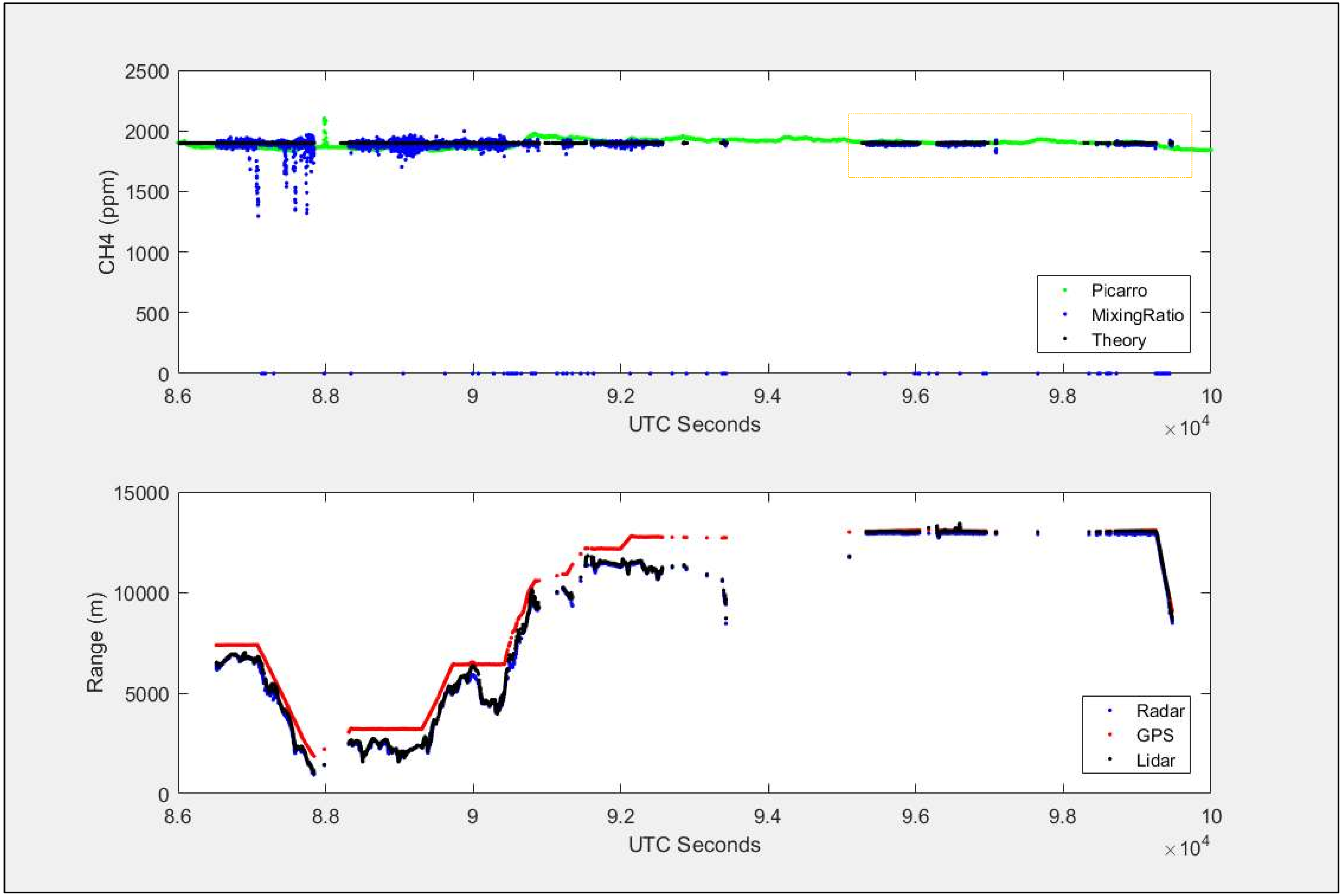
Parameter	Value (OPA/OPO)
Center λ	1650.9 nm
Number of λ	20/5
Pulse Width	~700/80 ns
Energy/pulse	~30/250 μJ
Bin width	4 ns
Divergence	~150 μrad
Receiver diam.	20 cm
Field of view	300 μrad
Receiver BP	0.8 nm (FWHM)
Averaging time	1/16 s *
Detector Resp.	~1-1.5 x 10^9 V/W

*Data analysis uses 1s averages

Flight Tracks



Science Flight 1 (OPA)



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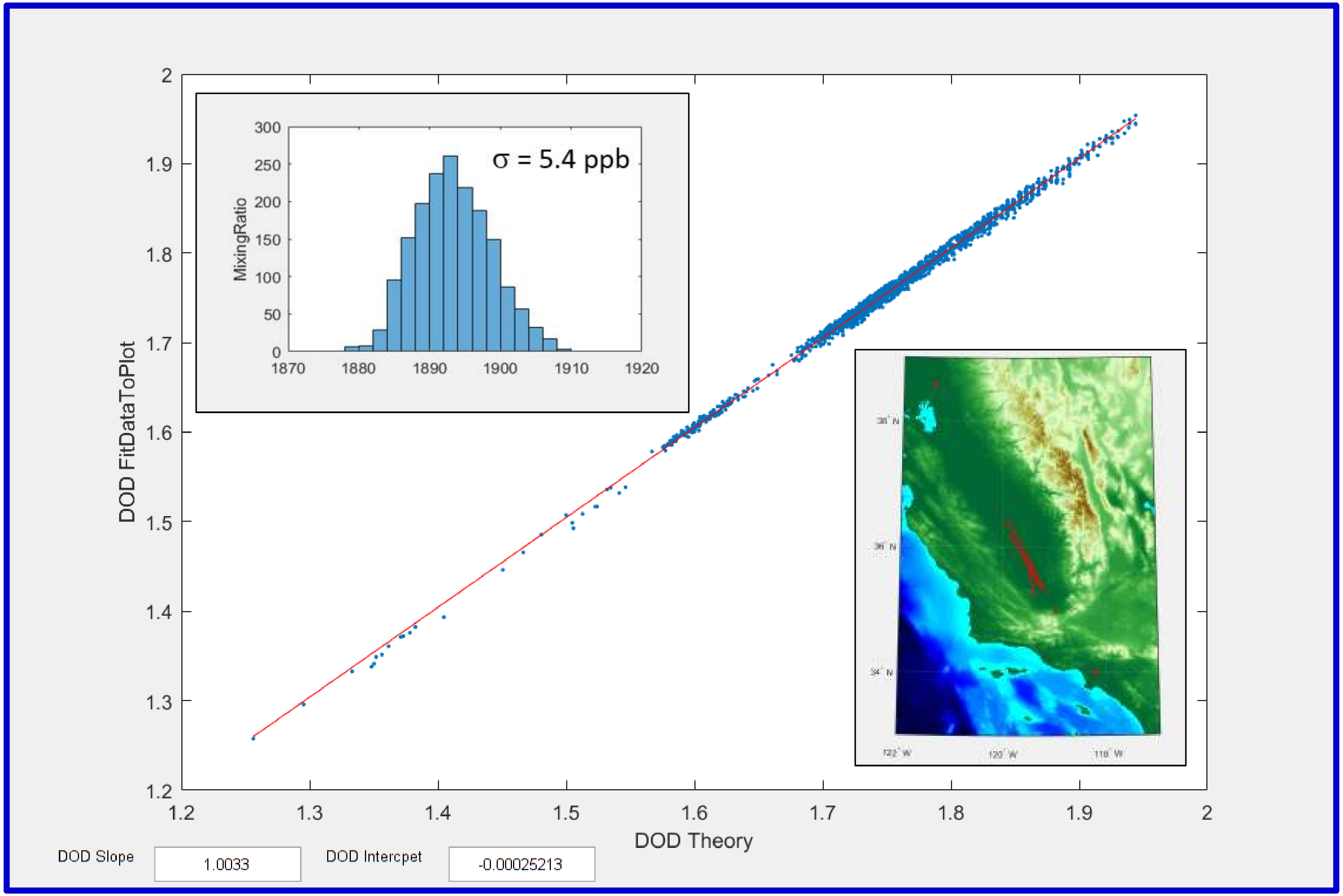
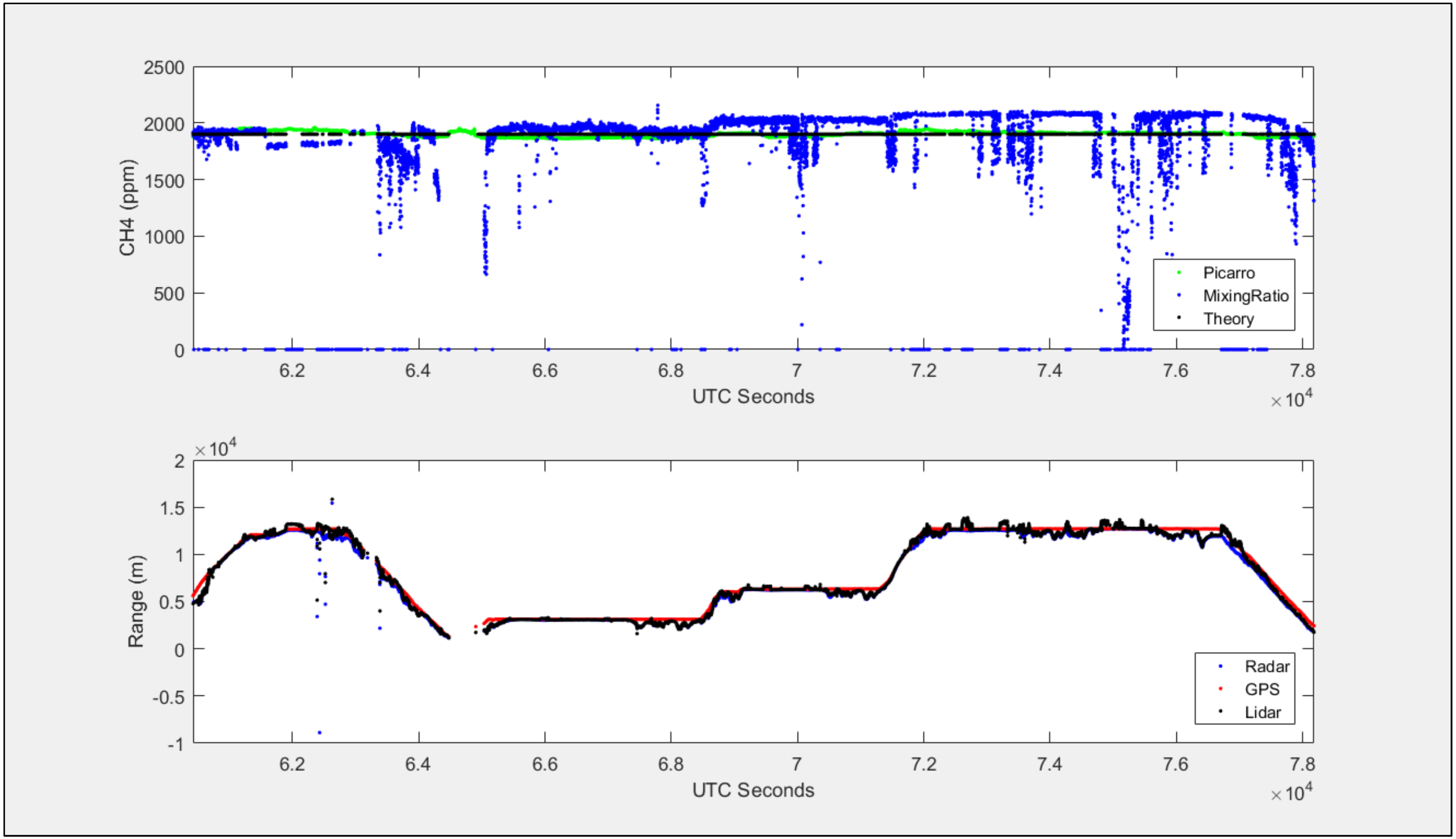
Earth Science Technology Office

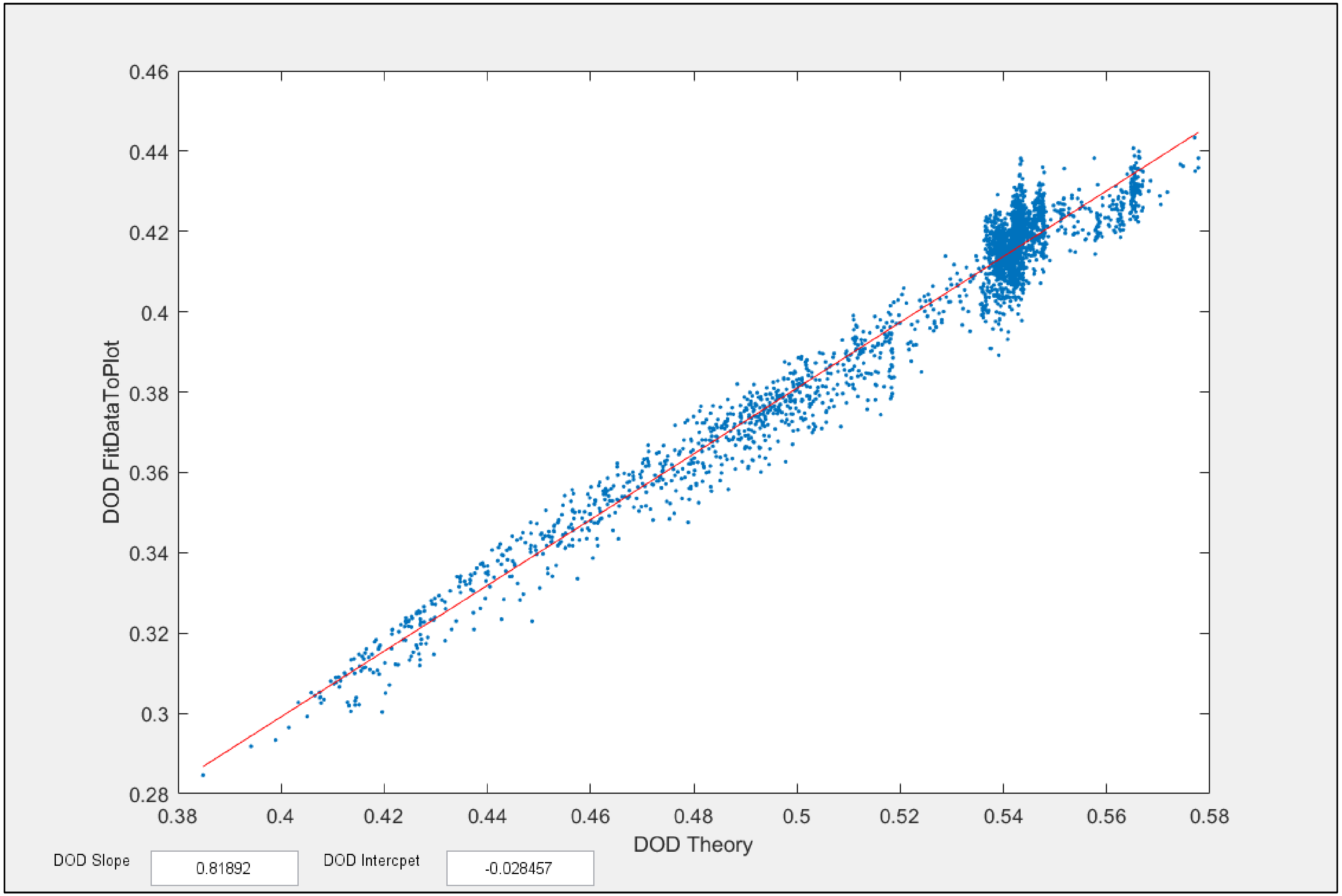
Science Flight 1 (OPA)



Science Flight 2 (OPO)



Science Flight 2



4. Summary

- ✓ Active measurements will be a key step in obtaining measurements of CH_4 with sufficient coverage, sampling, and precision to address these science questions.
- ✓ Multi-wavelength IPDA lidar needed for low bias CH_4 measurements.
- ✓ Major technology challenges for the transmitter are being addressed.
- ✓ Demonstrated CH_4 airborne measurements using the two lidar transmitters (OPA and OPO).