A Methane Lidar for Greenhouse Gas Measurements

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NASA ESTO ACT and GSFC IRAD programs

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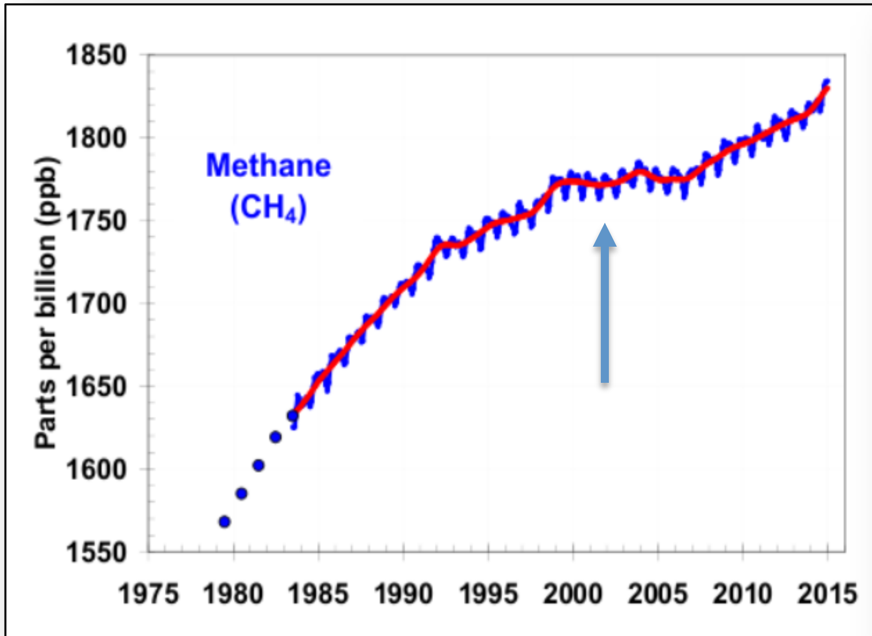
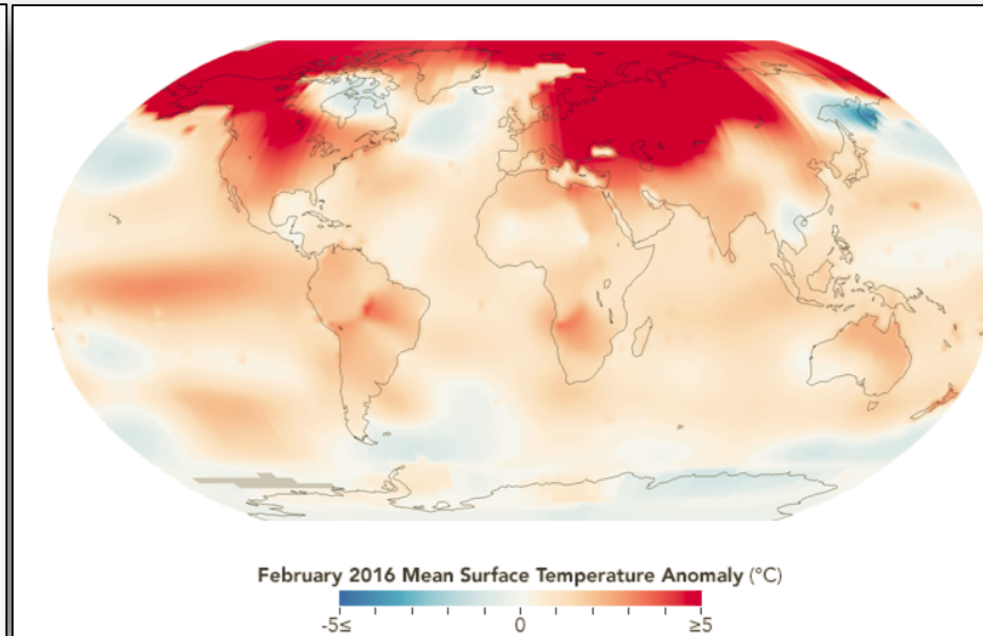
Outline

- Motivation - Why measure Methane?
- GSFC Measurement Approach
- Technology and Challenges
- Current Status
- Airborne Campaign
- Summary

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.

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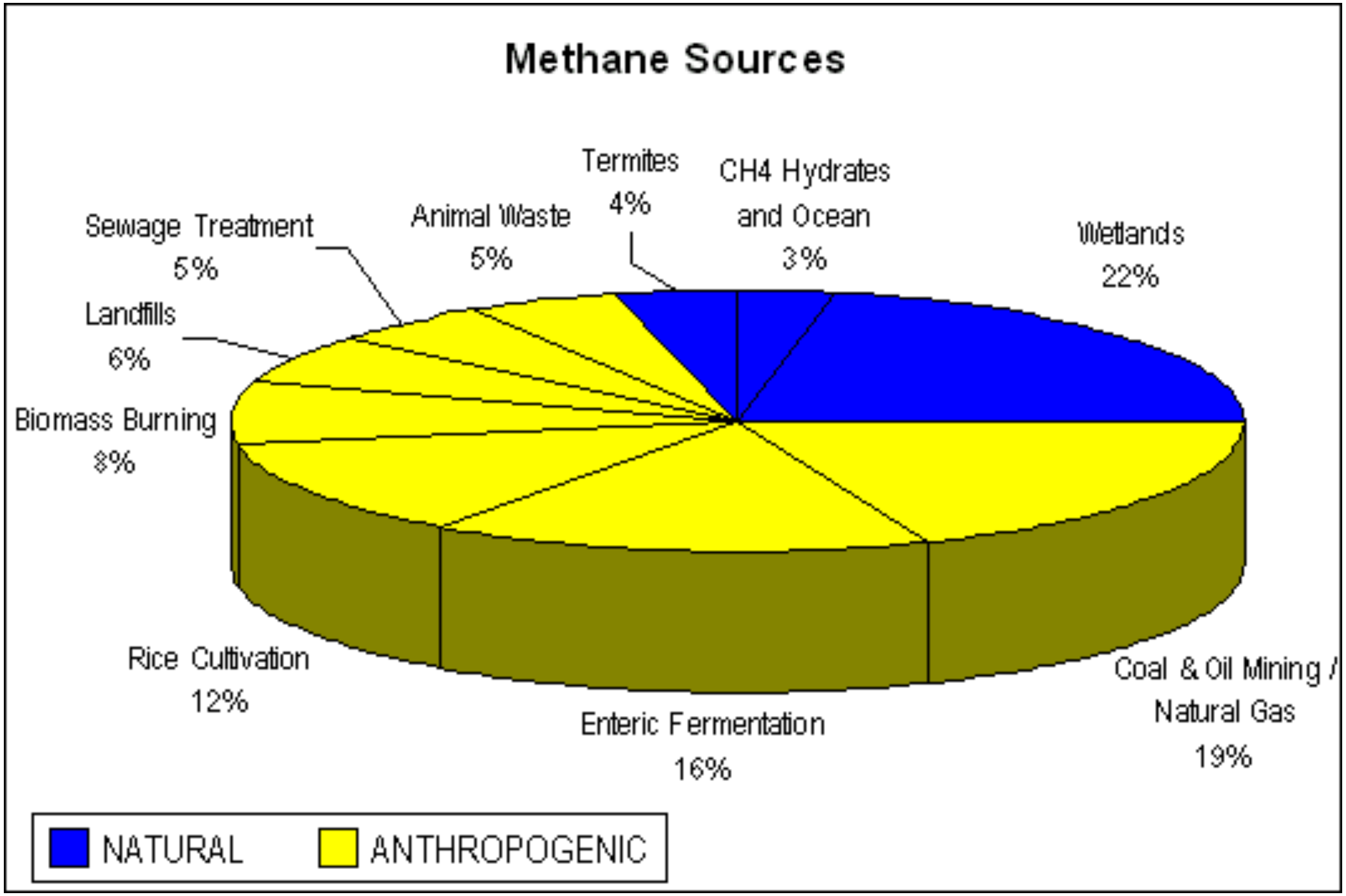
Sources of Methane



Source: http://icp.giss.nasa.gov/education/methane/intro/cycle.html

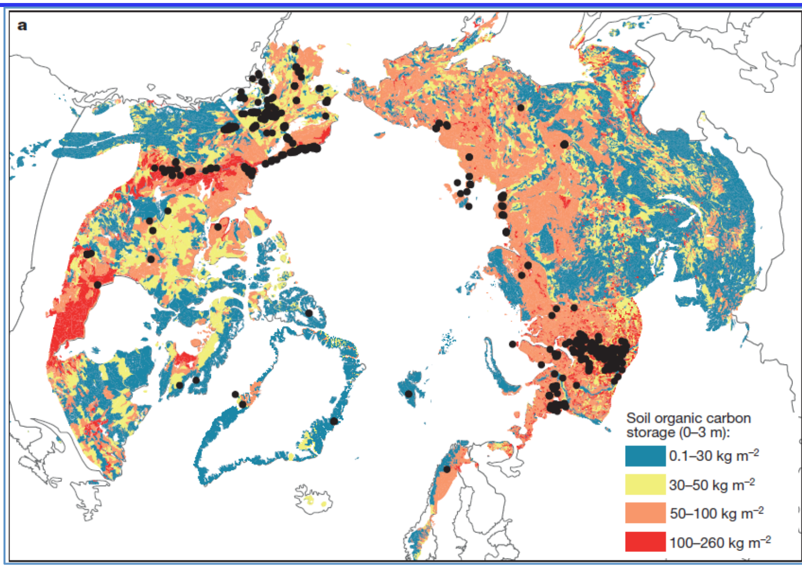
Arctic Methane

Katey Walter Anthony Univ. of Alaska Fairbanks *https://www.youtube.com/watch?v=YegdEOSQotE*

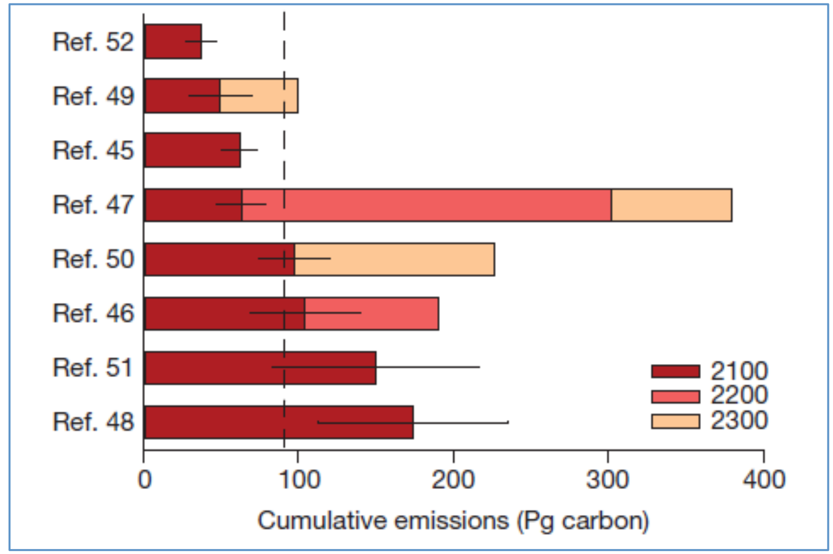
FEATURE 20 May 2015 **New Scientist**

Methane apocalypse? Defusing the Arctic's time bomb

Methane "Arctic Time Bomb" requires year-round observations



Soil organic carbon maps. a, Soil organic carbon pool (kg cm[2]) 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*

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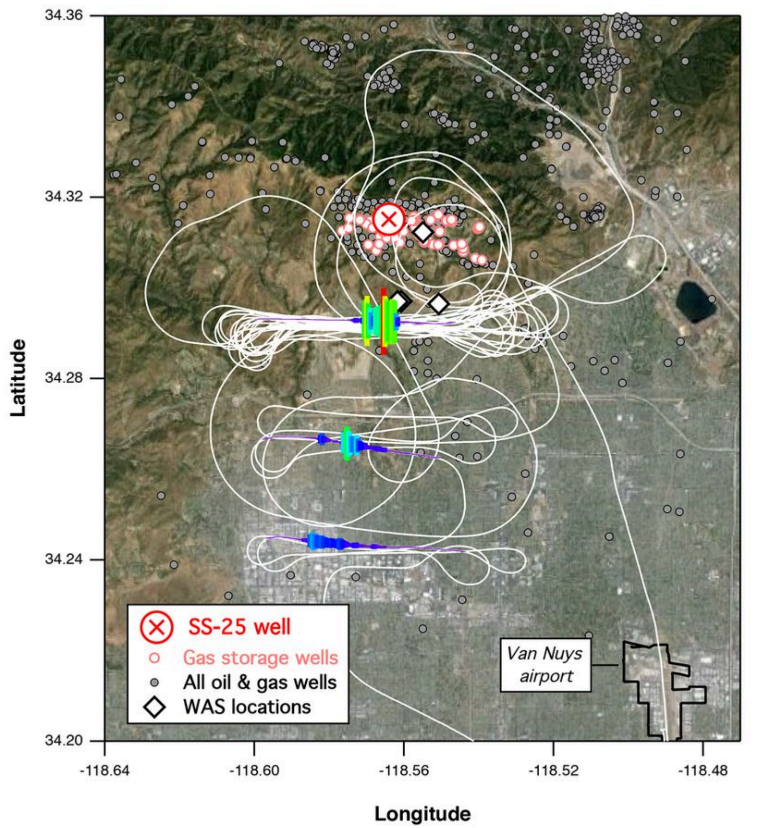
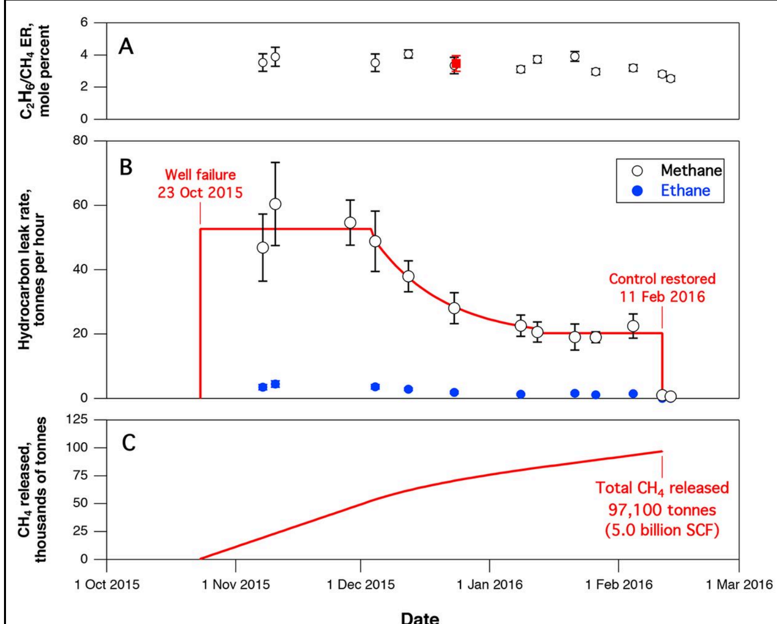
Porter Ranch, CA CH_4 Leak



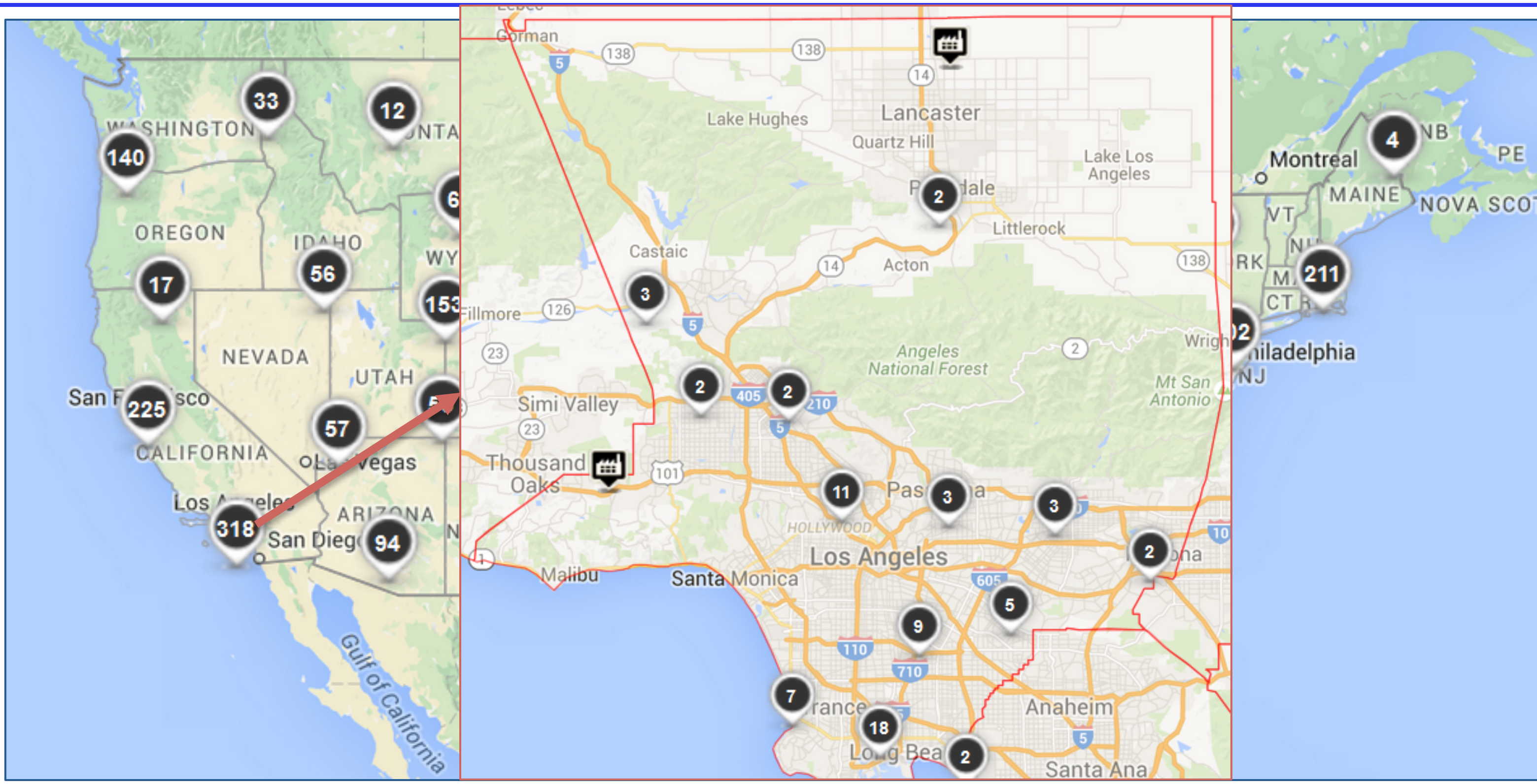
REPORT

Methane emissions from the 2015 Aliso Canyon blowout in Los Angeles, CA



"The 23 October 2015 blowout of a well connected to the Aliso Canyon underground storage facility in California resulted in a massive release of natural gas. Analysis of methane (CH_4) and ethane (C_2H_6) data from dozens of plume transects from 13 research aircraft flights between 7 Nov 2015 and 13 Feb 2016 shows atmospheric leak rates of up to 60 metric tonnes of CH_4 and 4.5 metric tonnes of C_2H_6 per hour. At its peak this blowout effectively doubled the CH_4 emission rate of the entire Los Angeles Basin, and in total released 97,100 metric tonnes of methane to the atmosphere." S. Conley et.al. Science 25 Feb 2016, pp. DOI: 10.1126/science.aaf2348

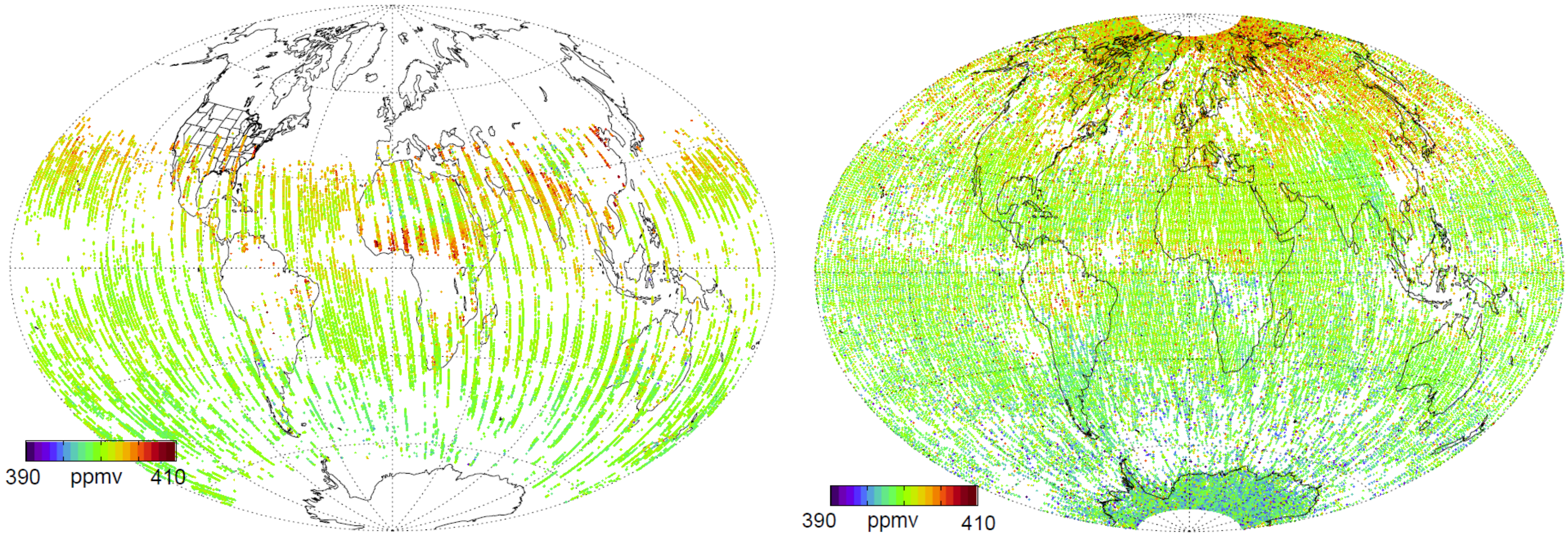
Climate Action Plan - Strategy to Cut Methane Emissions



"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."

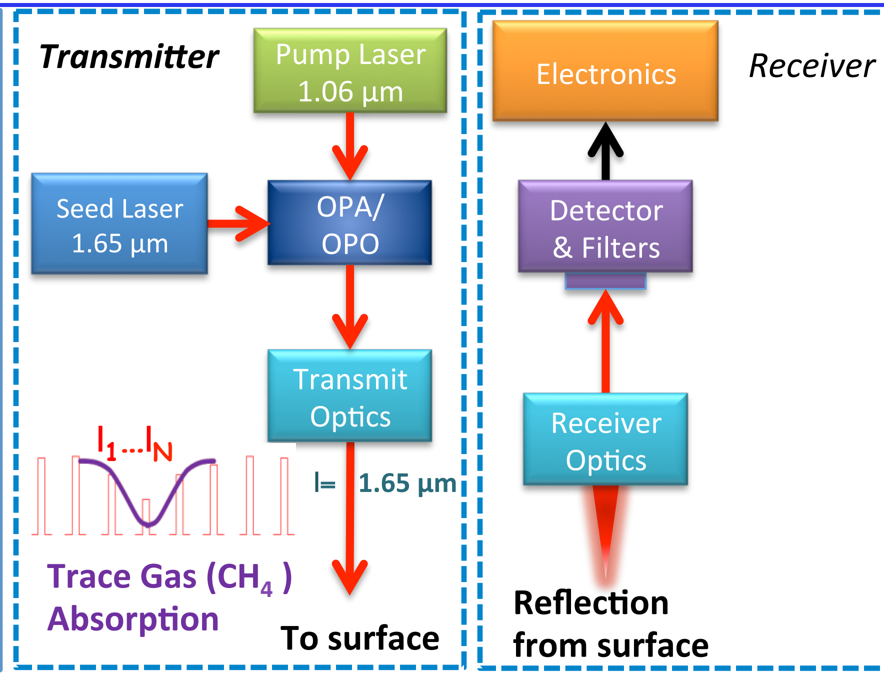
White House Climate Action Plan – Strategy to Cut Methane Emissions (March 2014)

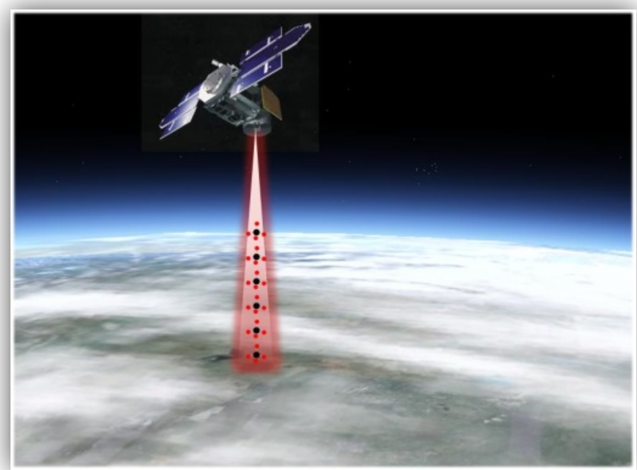
Why use a laser?

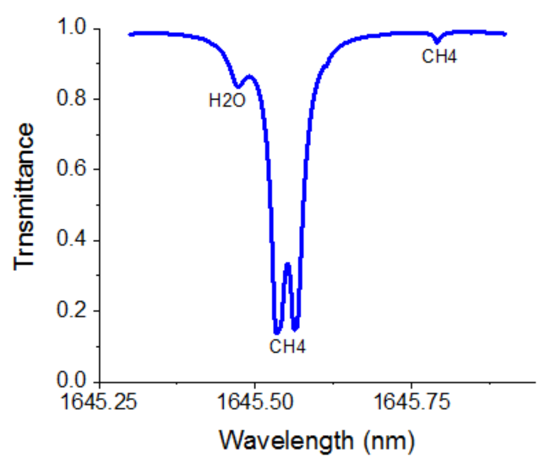


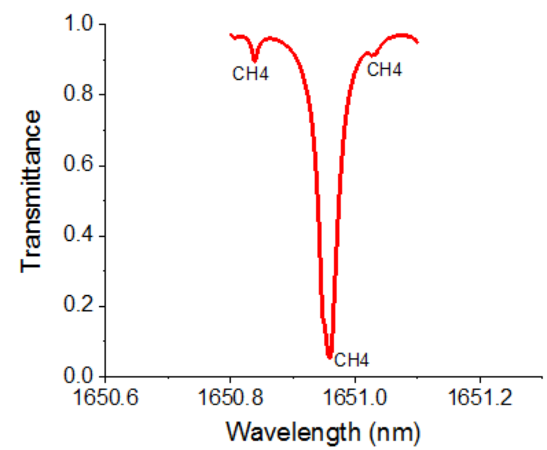
Comparison of actual OCO-2 coverage (left) vs. simulated ASCENDS coverage for December 16-31 2015. The sparse sampling OCO-2 coverage at high latitudes is a major drawback of passive remote sensing missions. (Simulation provided by Dr. Stephan R. Kawa, GSFC).

- ***<u>Transmitter (Laser) technology</u>***
  - ➢ **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 possible.**
- ***<u>Receiver (Detector) Technology</u>***
  - ➢ **DRS e-APD**

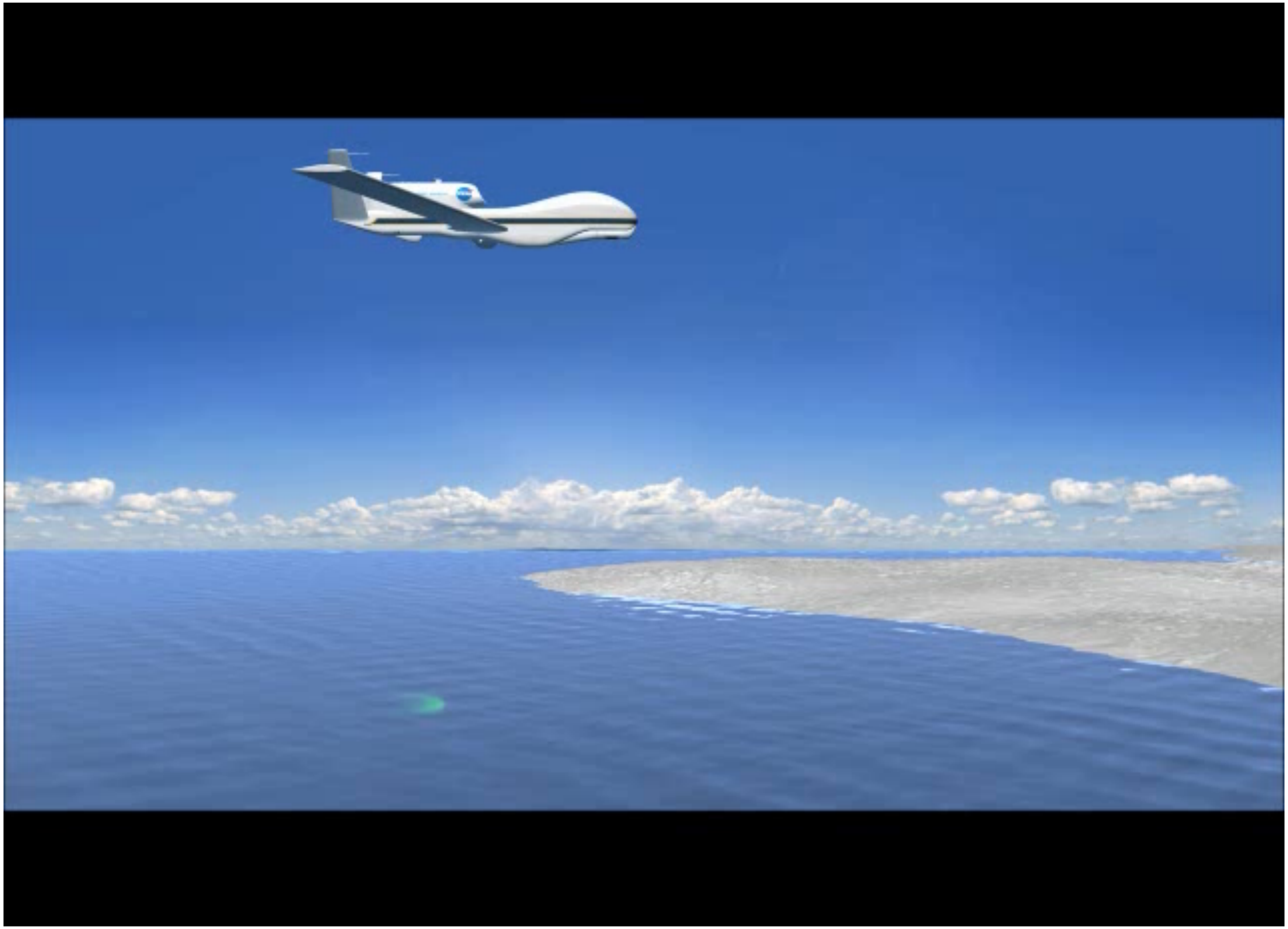




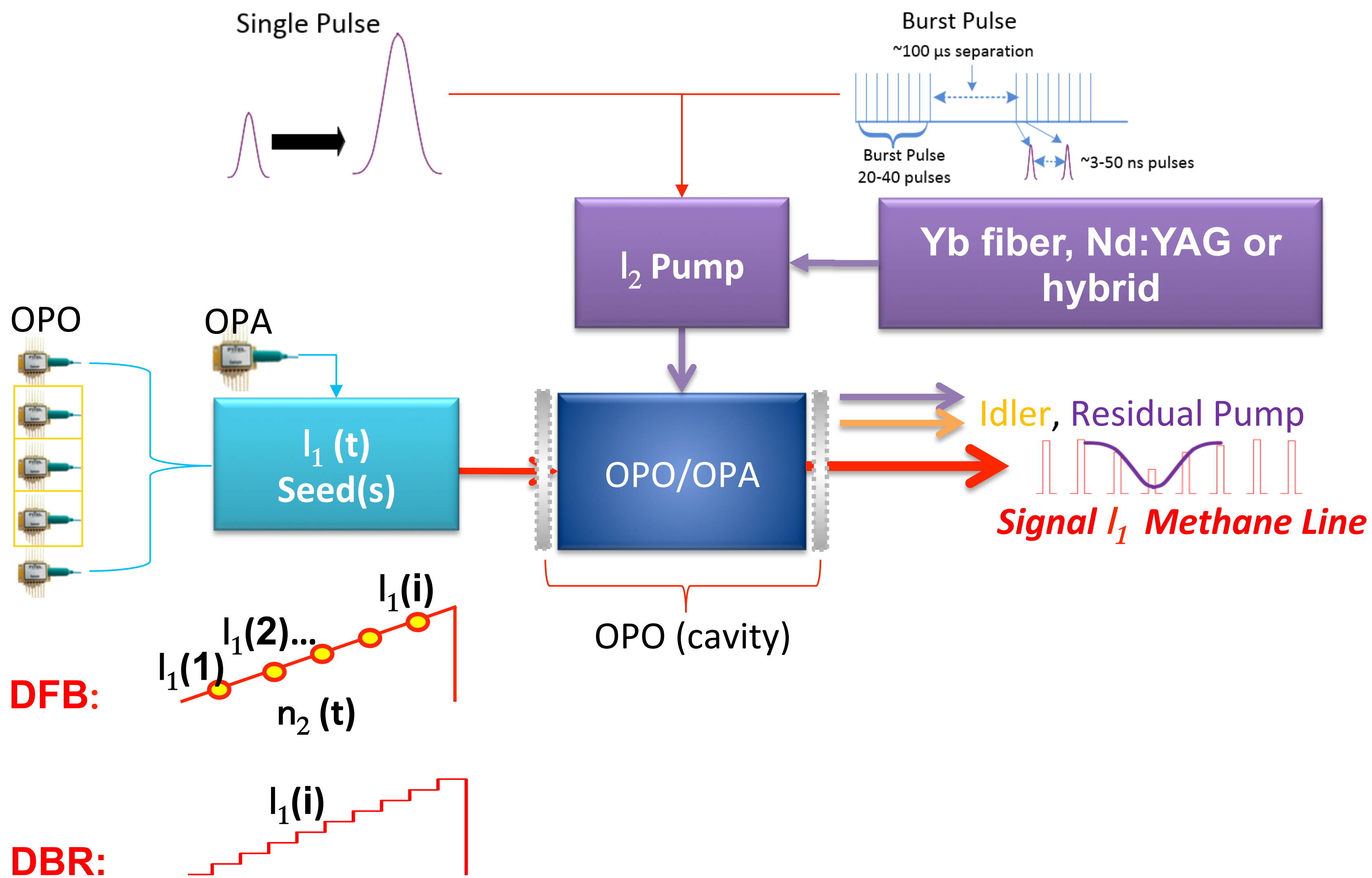




GSFC CH_4 Lidar with Integrated Path Differential Absorption Lidar (IPDA)



CH_4 Laser Transmitter: OPO-OPA



Current GSFC Power scaling options OPA/OPO

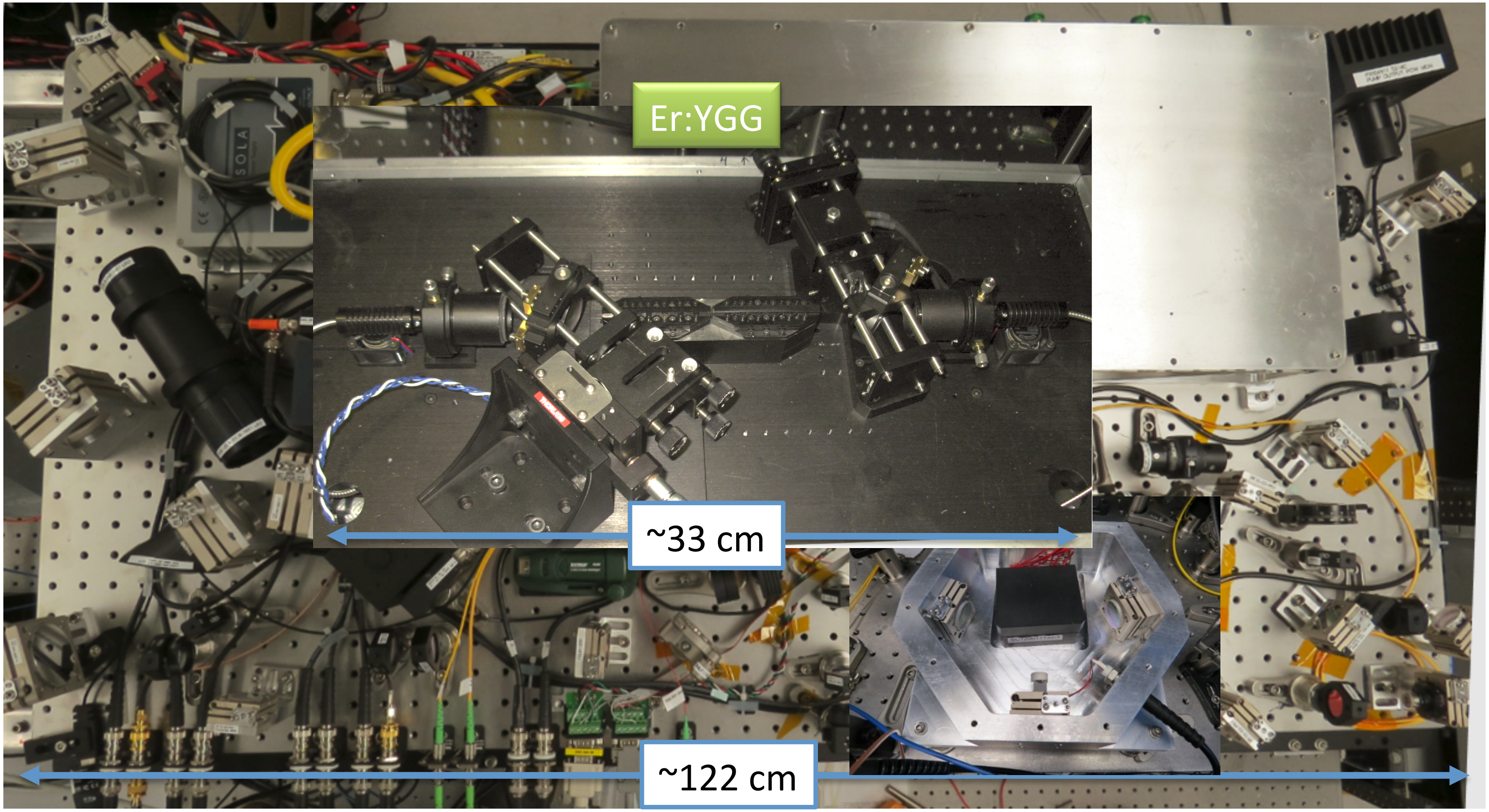
Approach	#1. OPA with smaller burst pulses	#2. OPA with large pump pulse	#3. OPO with large pump pulse
Pump laser	1. Burst mode laser. Need to achieve higher energy and pulse uniformity. Hybrid shown to work. 2. Burst mode fiber MOPA with Waveguide Amplifier shows promise	1. High power Yb fiber laser (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 and Er:YGG

Other transmitter options: Er:YAG and Er:YGG

- Why consider other transmitter options?
  - OPAs and OPOs are parametric conversion techniques. They are complex and difficult to implement are sensitive to vibration.
  - Size/mass of airborne instrument needs to reduced.
  - Erbium Yttrium-aluminum-garnet (YAG) 1.645 nm
  - Erbium Yttrium-gallium-garnet (YGG) 1.651 nm
- Potential for "simpler" and more efficient transmitter technology.
- Tuning remains an issue.

OPO



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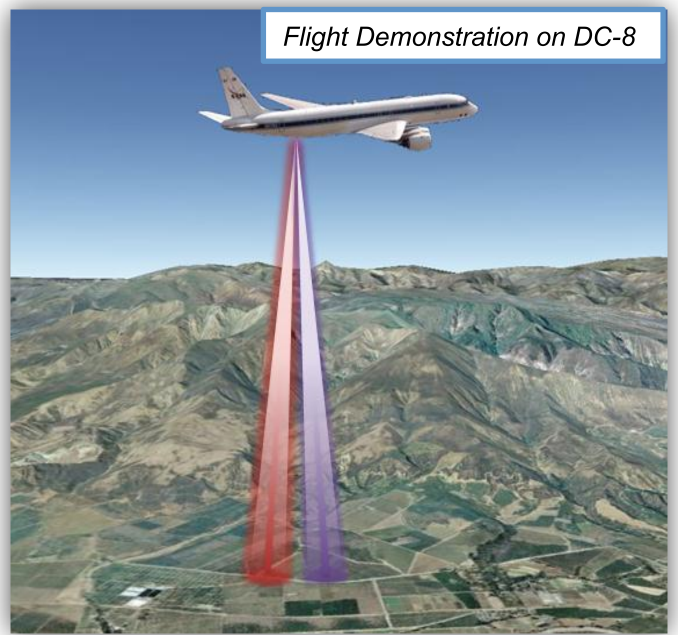
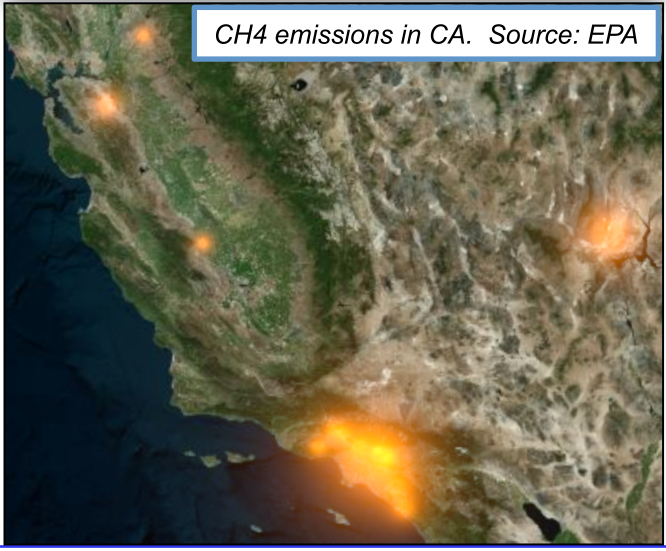
2015 Airborne Demonstration



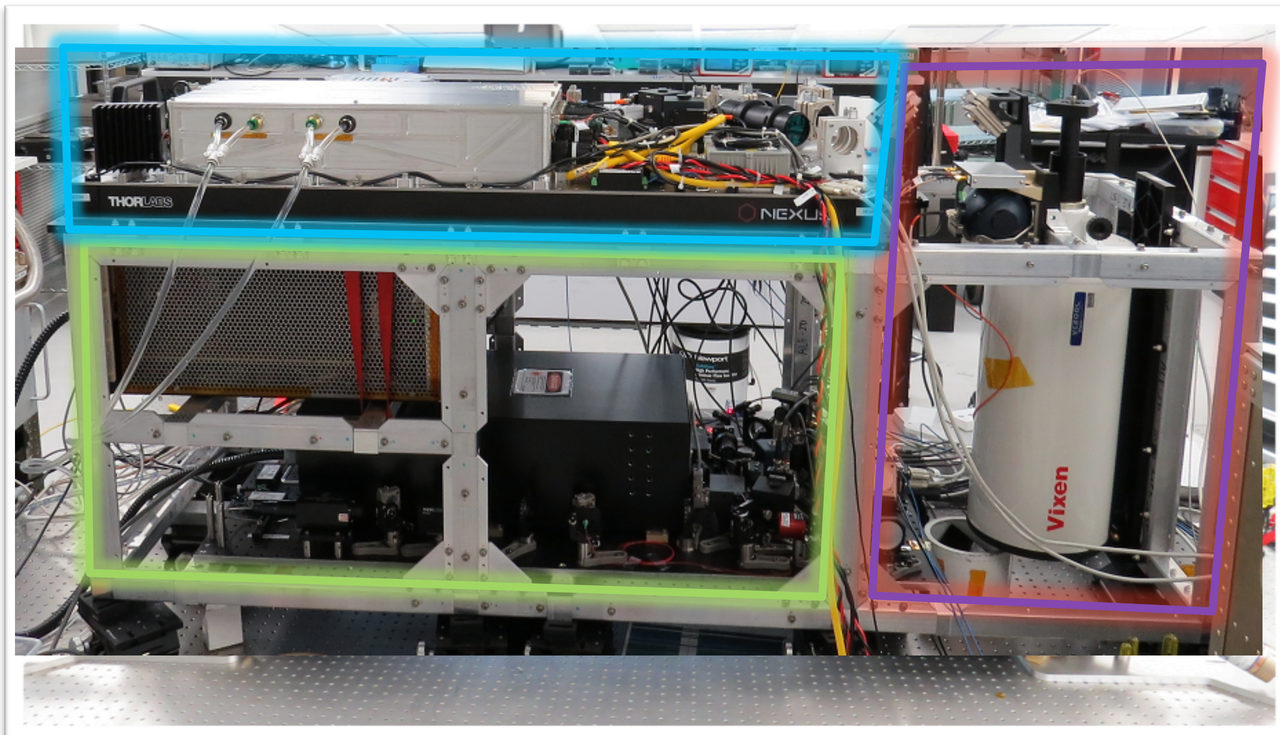
Flight Demonstration on DC-8



CH4 emissions in CA. Source: EPA

- **Flight Test Methane LIDAR Instruments:**
  - **GSFC Methane Sounder (20-l OPA and 5-l 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.**

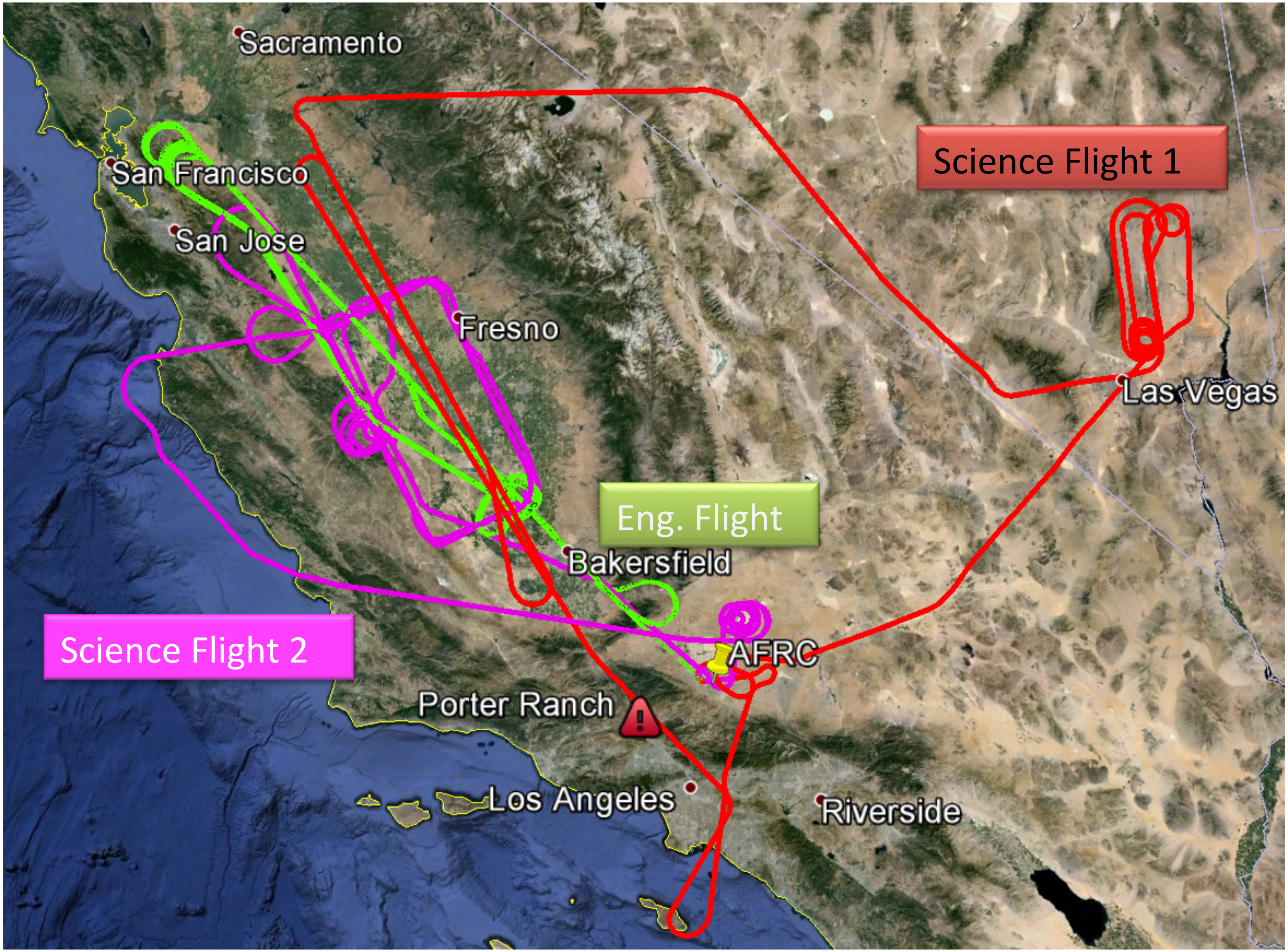
CH_4 Airborne Instrument



Parameter	Value (OPA/OPO)
Center l	1650.9 nm
Number of l	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

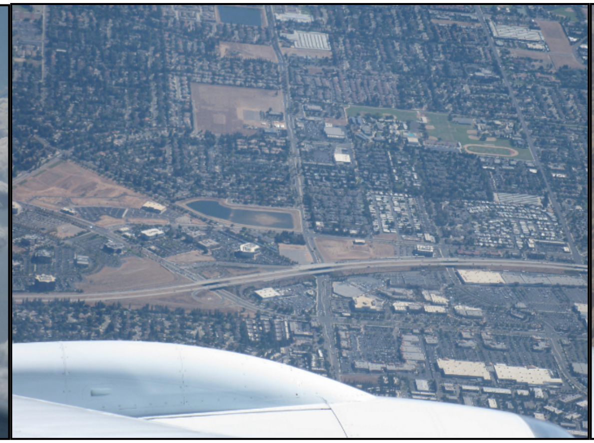
*Data analysis uses 1s averages

Flight Tracks



Flight Conditions

Clouds



Cultivated/Urban/Landfill

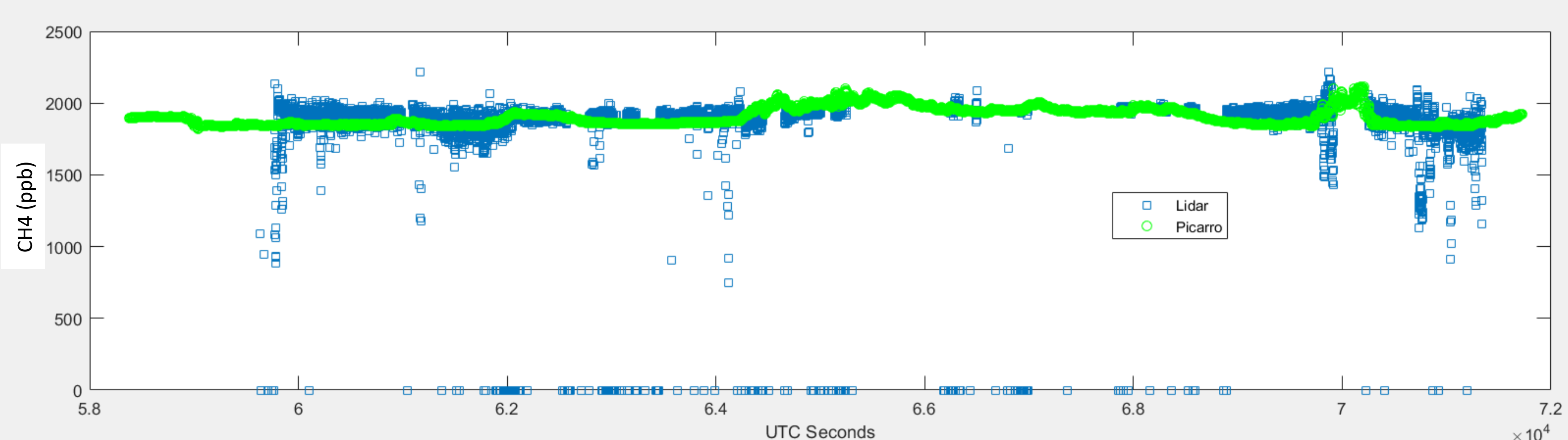
Varying Topography

Desert/Spirals

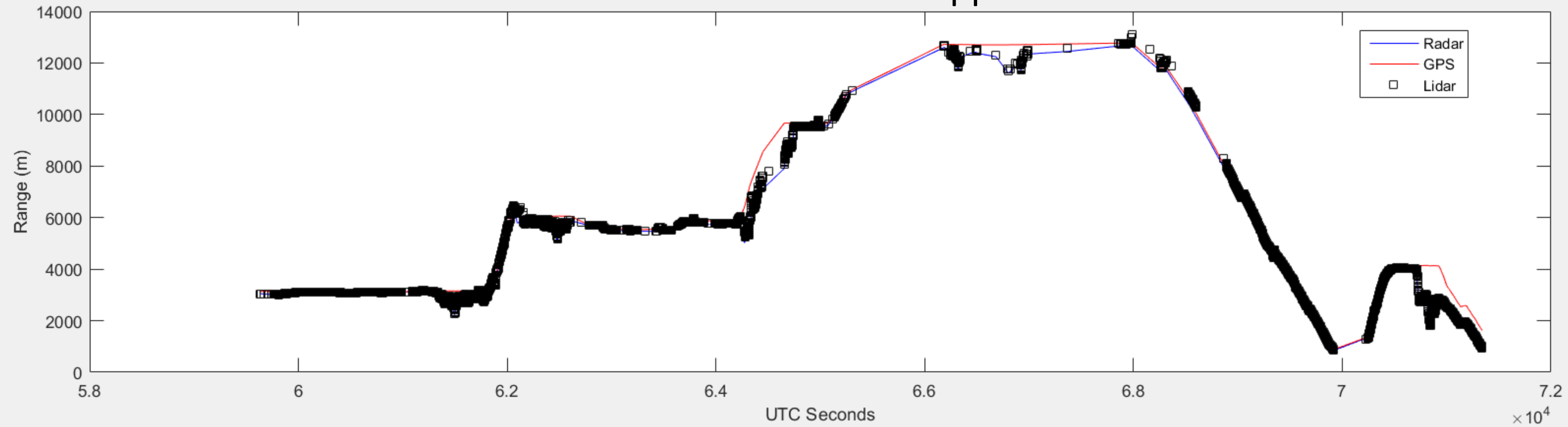
Ocean

Evening/Night

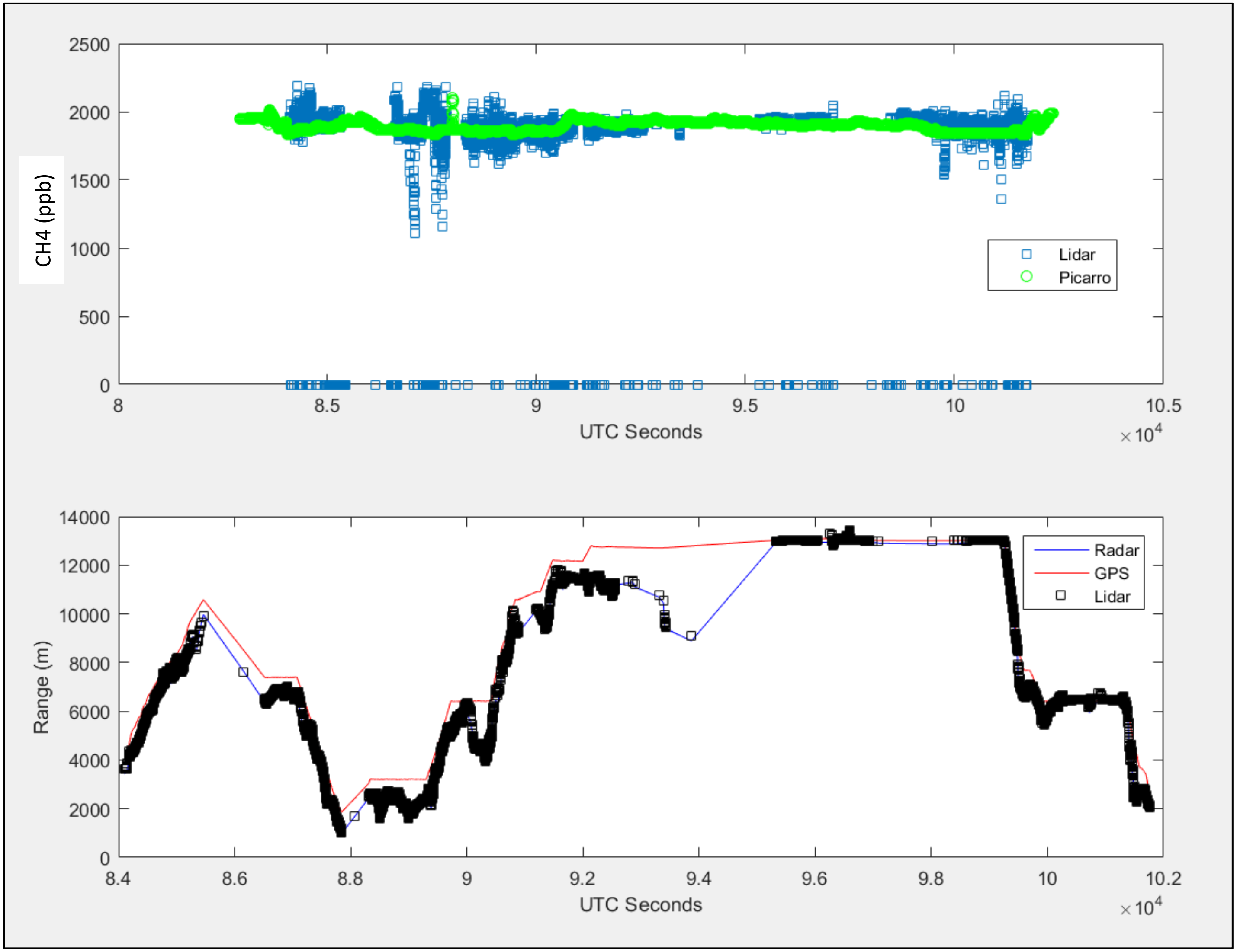
Engineering Flight CH_4 mixing Ratio



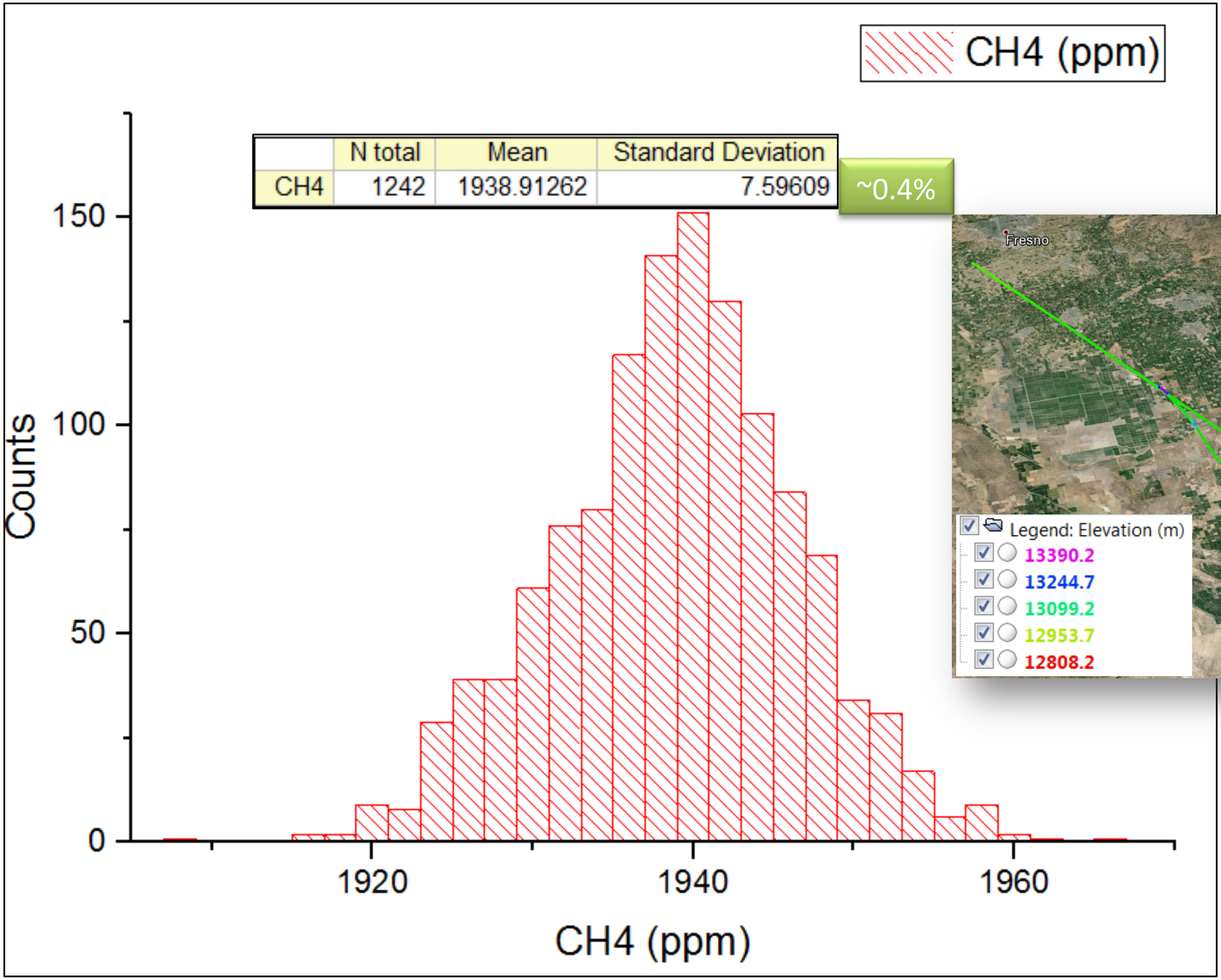
Data is filtered for Ground Returns. 1 s averaging. No DRS non-linearity correction. No GPS correction. Model assumes uniform CH4 1900 ppm.



Science Flight 1 CH_4 mixing Ratio

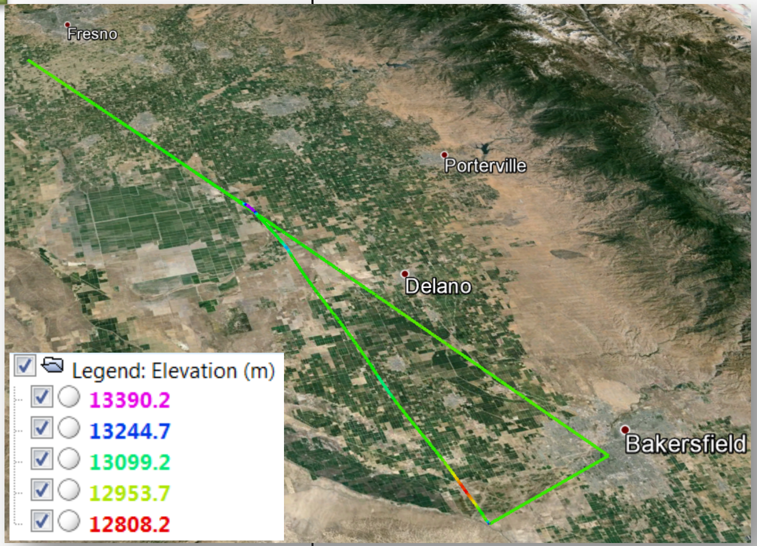


OPA Precision 1s averaging



	N total	Mean	Standard Deviation
CH4	1242	1938.91262	7.59609

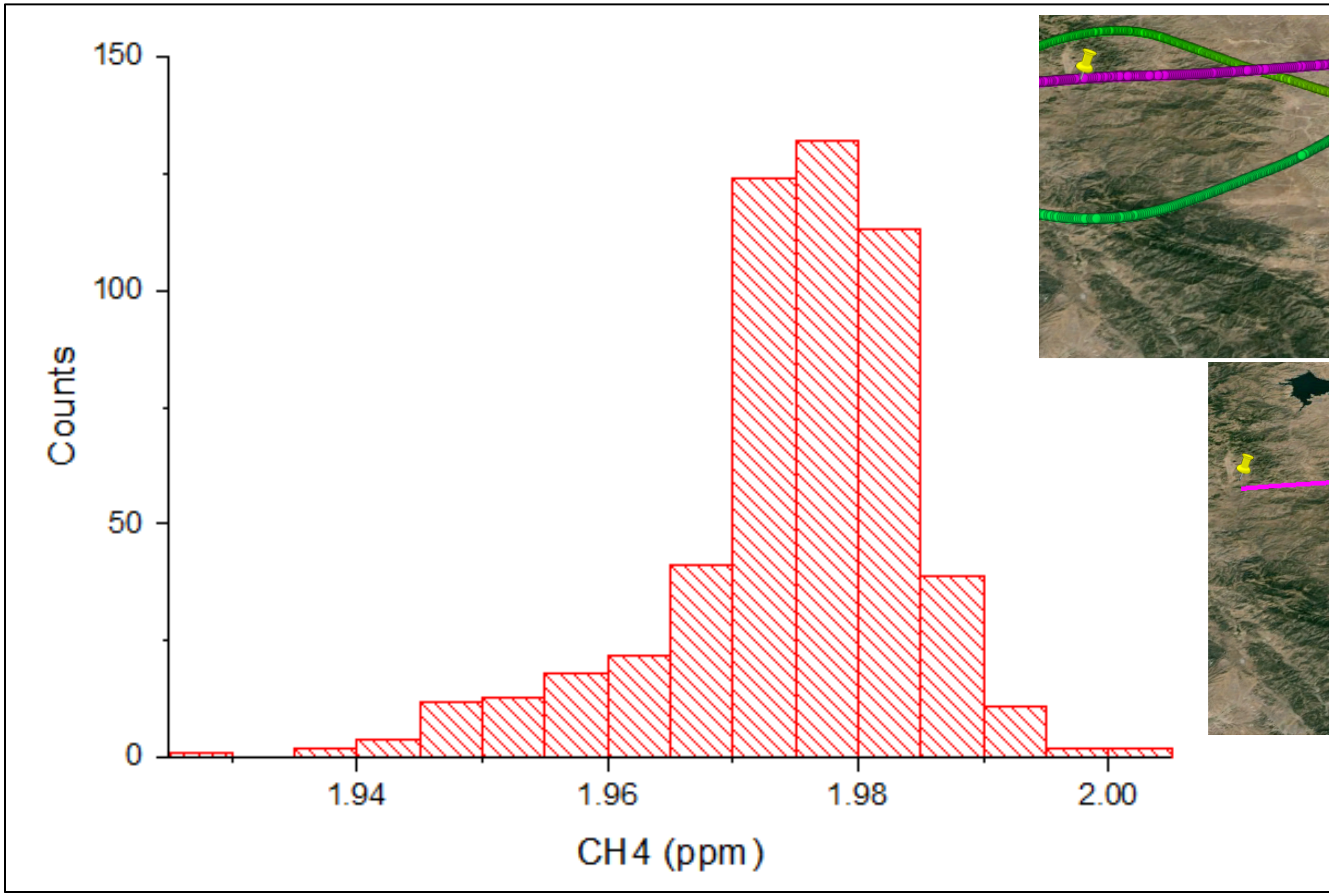
~0.4%

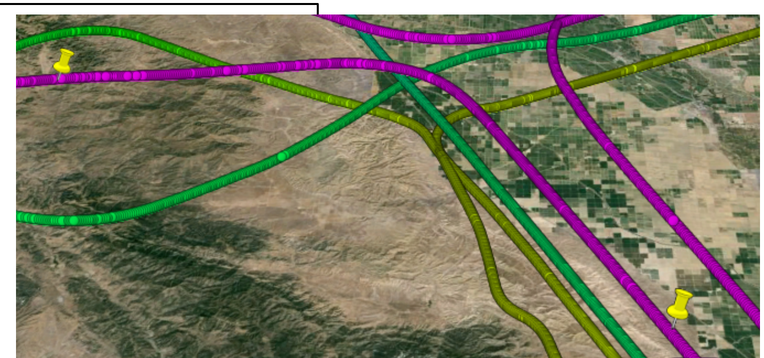


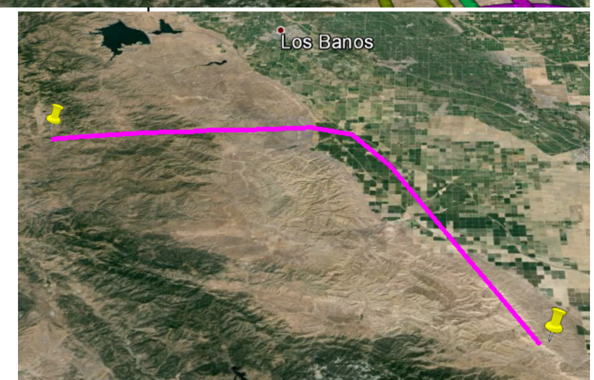
OPO Precision 1s averaging*

Descriptive Statistics	N total	Mean	Standard Deviation
KNCH4	536	1.97477	0.01008

~0.5%







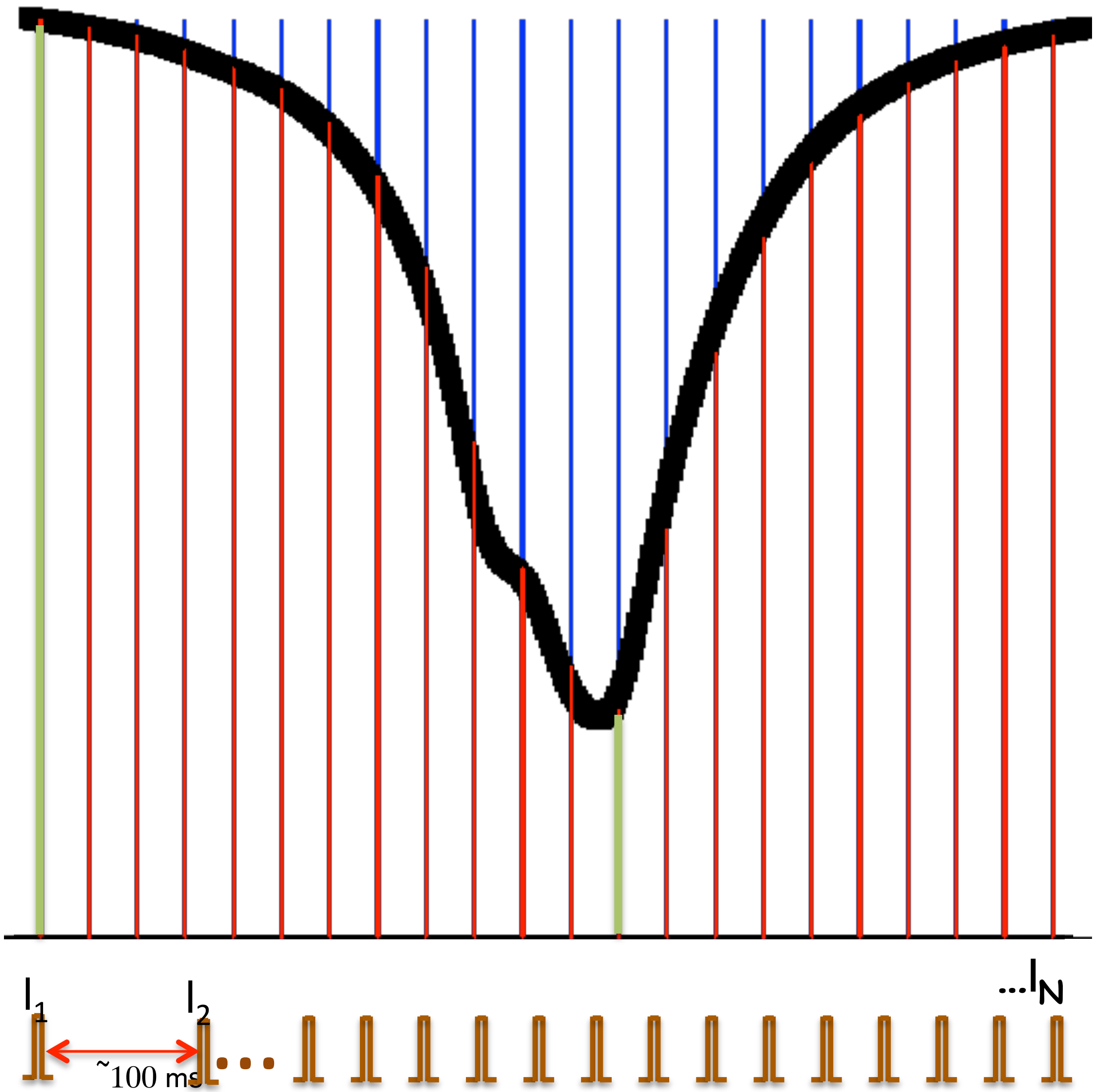
*Using K. Numata's retrievals

Airborne Demonstration Summary

- ✓ DRS e-ADP works very well at 1651 nm.
- ✓ Responsivity is close to what we have for CO_2 but there is still some uncertainty on the actual value.
- ✓ DRS is linear over at least two to three orders of magnitude.
- ✓ Signal strength (link margin) during flight is roughly what we expected. Return signal estimation is complicated by burst pulse shape of the OPA and the high OPO energy and clouds/topography.
- ✓ Both OPA and OPO worked better than expected.
- ✓ Best precision for: OPA ~ 0.4% and OPO ~ 0.5%.
- ✓ 20 wavelengths (OPA) produced better fits than 5 (OPO) but OPA was extremely sensitive to LMA fiber and cabin temperature fluctuations and does not have adequate energy for space unless external amplifiers are used and/or the present OPA laser is improved.
- ✓ OPO cavity is sensitive to temperature and pressure but still worked well.
- ✓ OPO has the required (high) energy but the OPO flight was complicated by our inability to effectively attenuate the laser.
- ✓ OPO energy was more stable than OPA during flight.

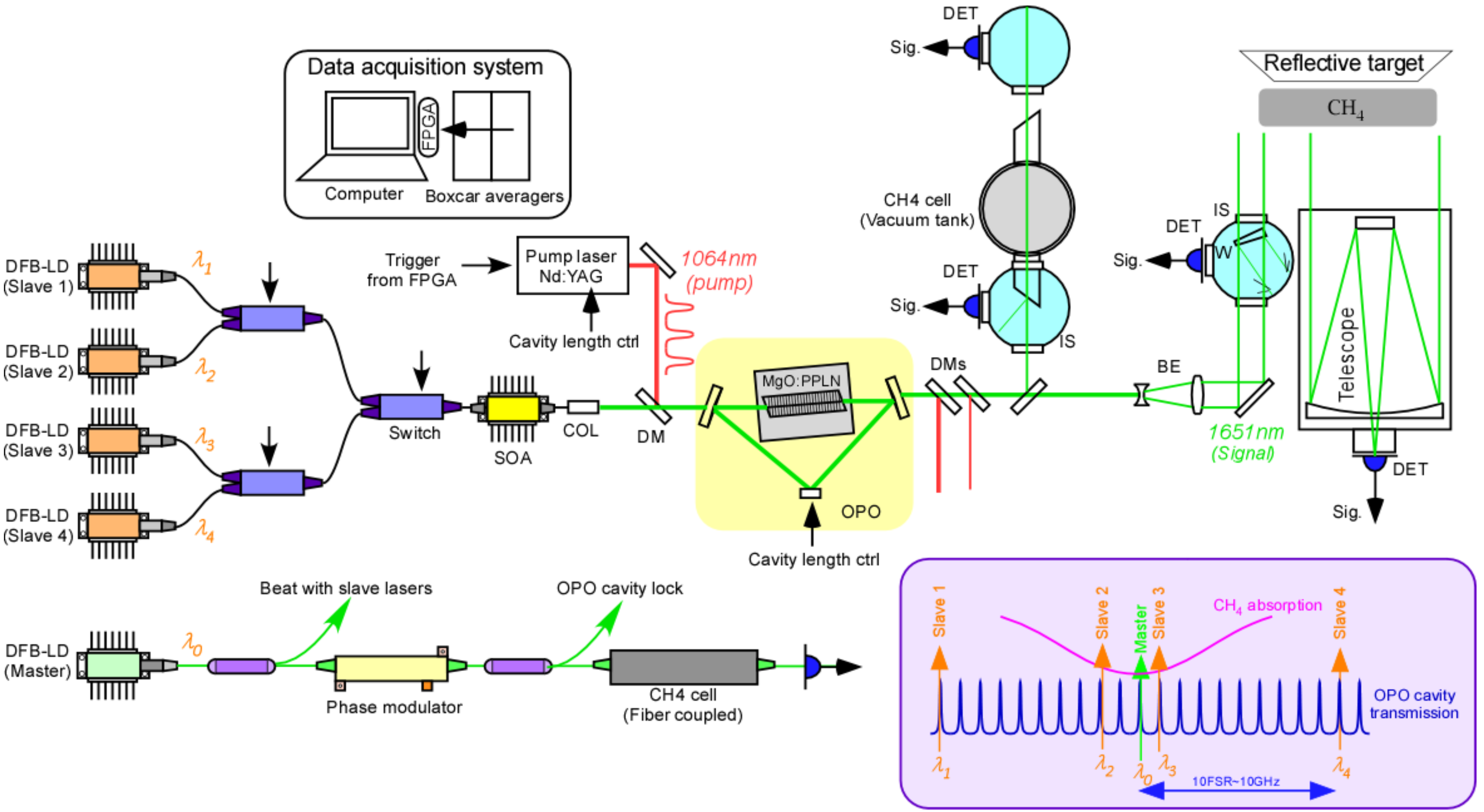
Summary

- ✓ 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 airborne measurements using the two lidar transmitters.
- ✓ Other laser transmitter options being investigated
- **We would like to thank ESTO and GSFC IRAD for their support.**

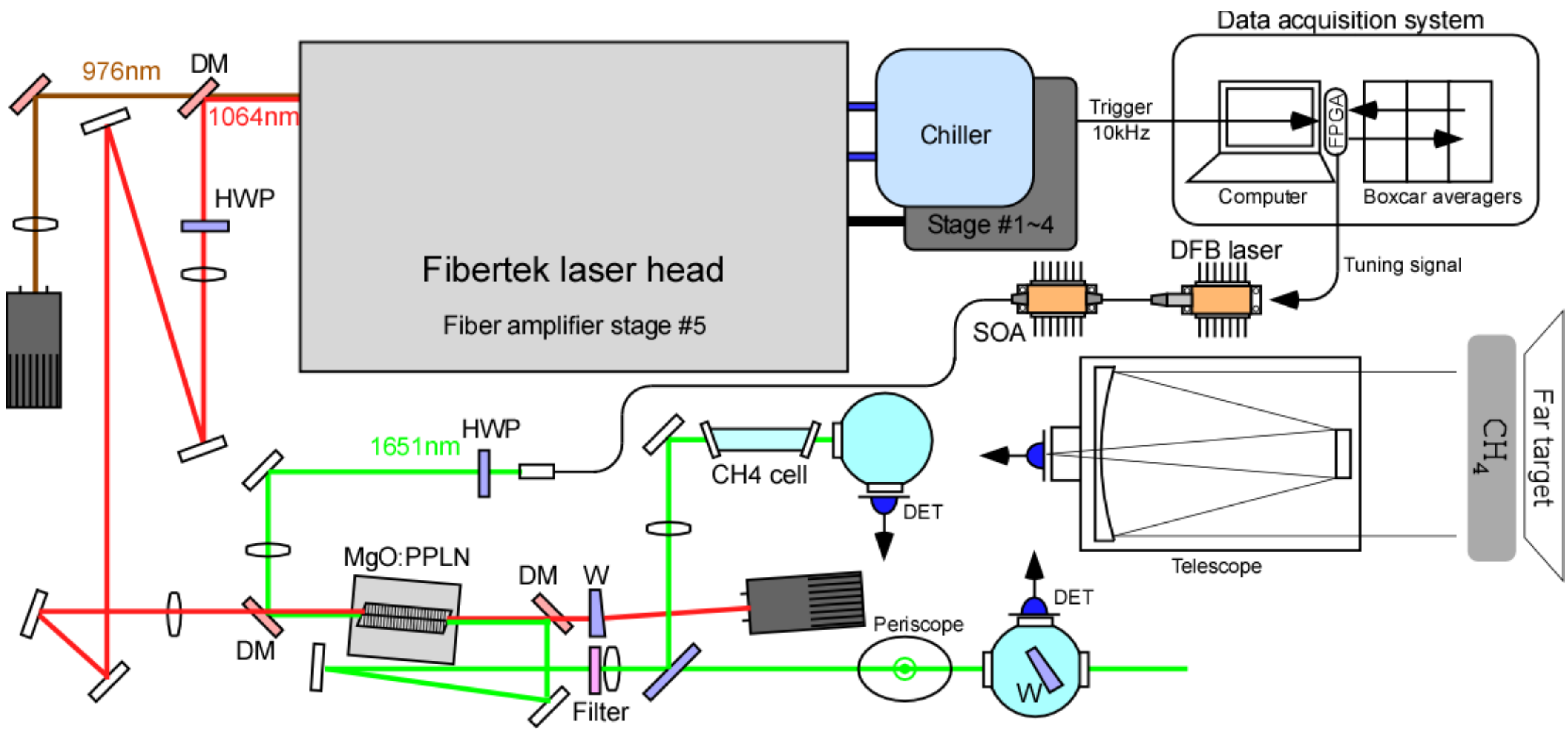


I_1
I_2
~100 ms
...I_N

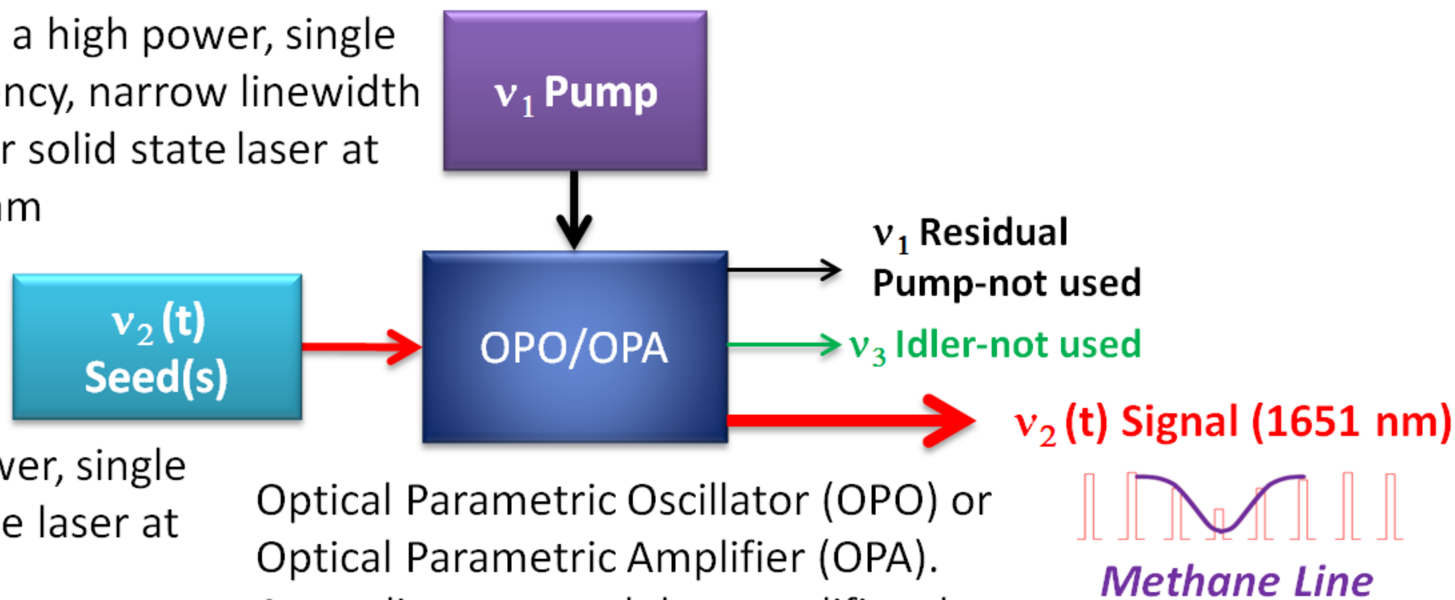
Setup for 5-wavelength OPO



OPA Open-path measurement setup



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

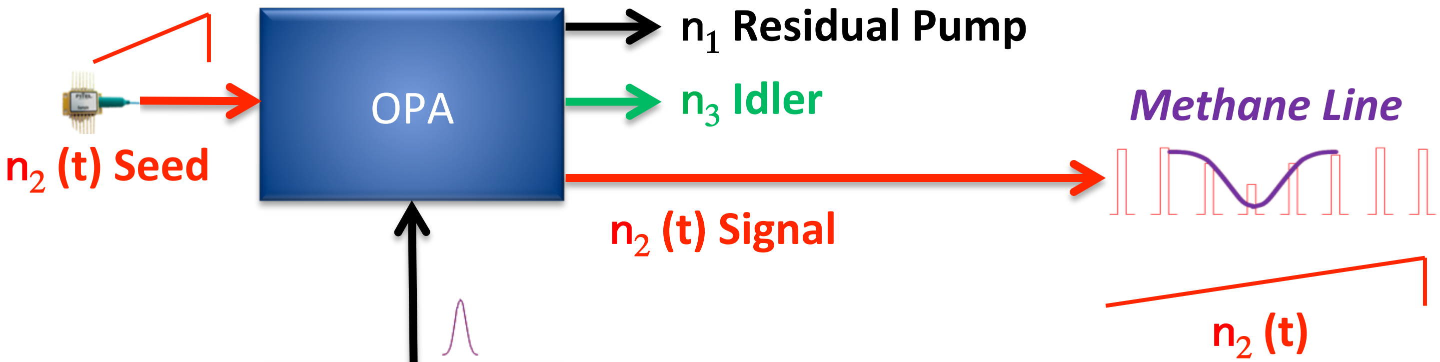


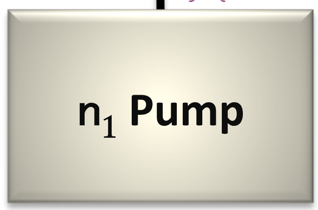
Seed: a low power, single frequency diode laser at 1651 nm.

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

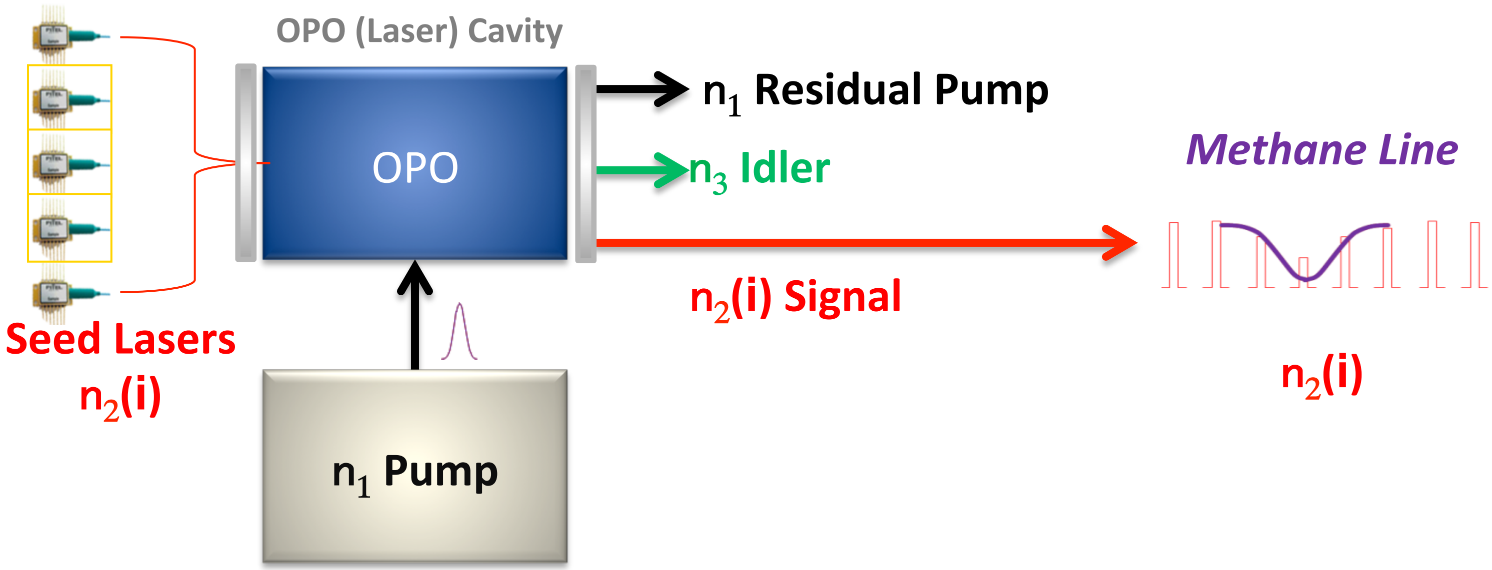




OPA: Easy to align, easy to tune, power scaling hard to achieve <u>while maintaining narrow linewidth.</u>

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.

Current GSFC Power scaling options OPA/OPO

Approach	#1. OPA with smaller burst pulses	#2. OPA with large pump pulse	#3. OPO with large pump pulse
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