A Methane Lidar for Greenhouse Gas Measurements

Haris Riris (GSFC), Kenji Numata (GSFC), Stewart Wu (GSFC), Brayler Gonzalez (GSFC), Mike Rodriguez (Sigma Space), Molly Fahey (GSFC), Stan Scott (GSFC), Jianping Mao (UMD), Xiaoli Sun (698)

Julie Nicely (NPP), Bryan Duncan (GSFC), Benjamin Poulter (GSFC)

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Haris.Riris@nasa.gov

Outline

- Motivation - Why measure Methane?
- GSFC Measurement Approach
- Current Status
- Future Plans
- Summary

MOTIVATION - WHY MEASURE METHANE?

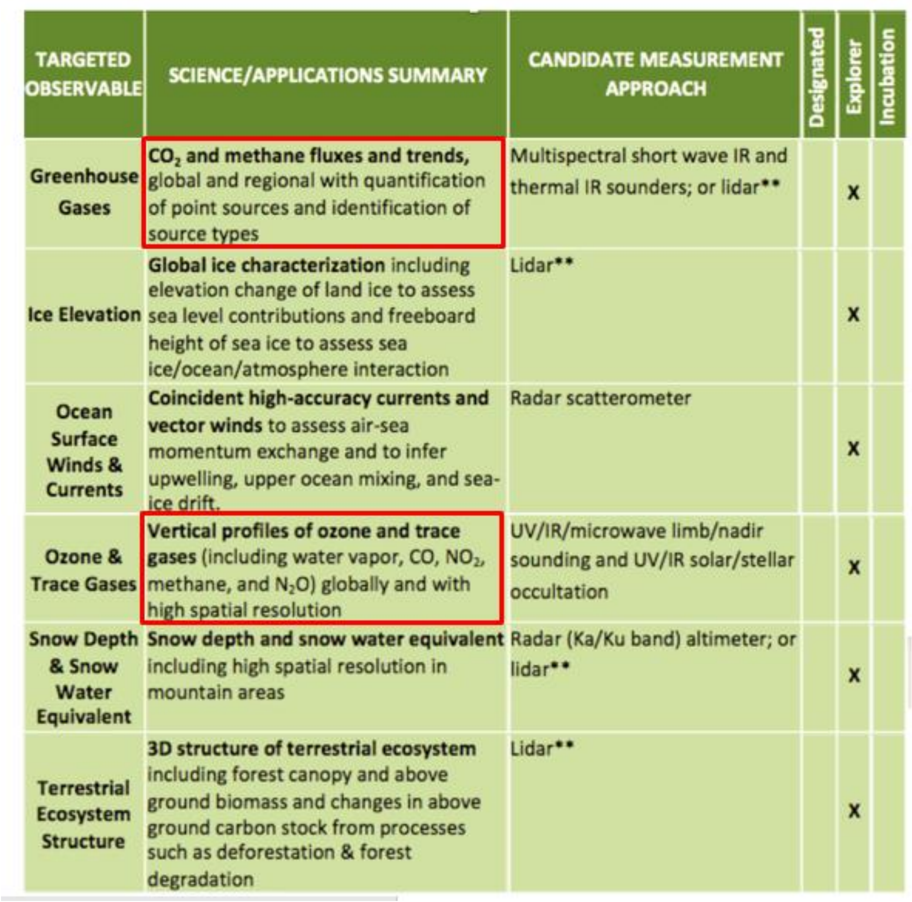
Methane and the 2017 Earth Science Decadal Survey

QUESTION W-8. What processes determine observed atmospheric methane (CH4) variations and trends and what are the subsequent impacts of these changes on atmospheric composition/chemistry and climate?

> **W-8a.** Reduce uncertainty in tropospheric CH4 concentrations and in CH4 emissions, including regional anthropogenic sources and from a process level for natural sources.

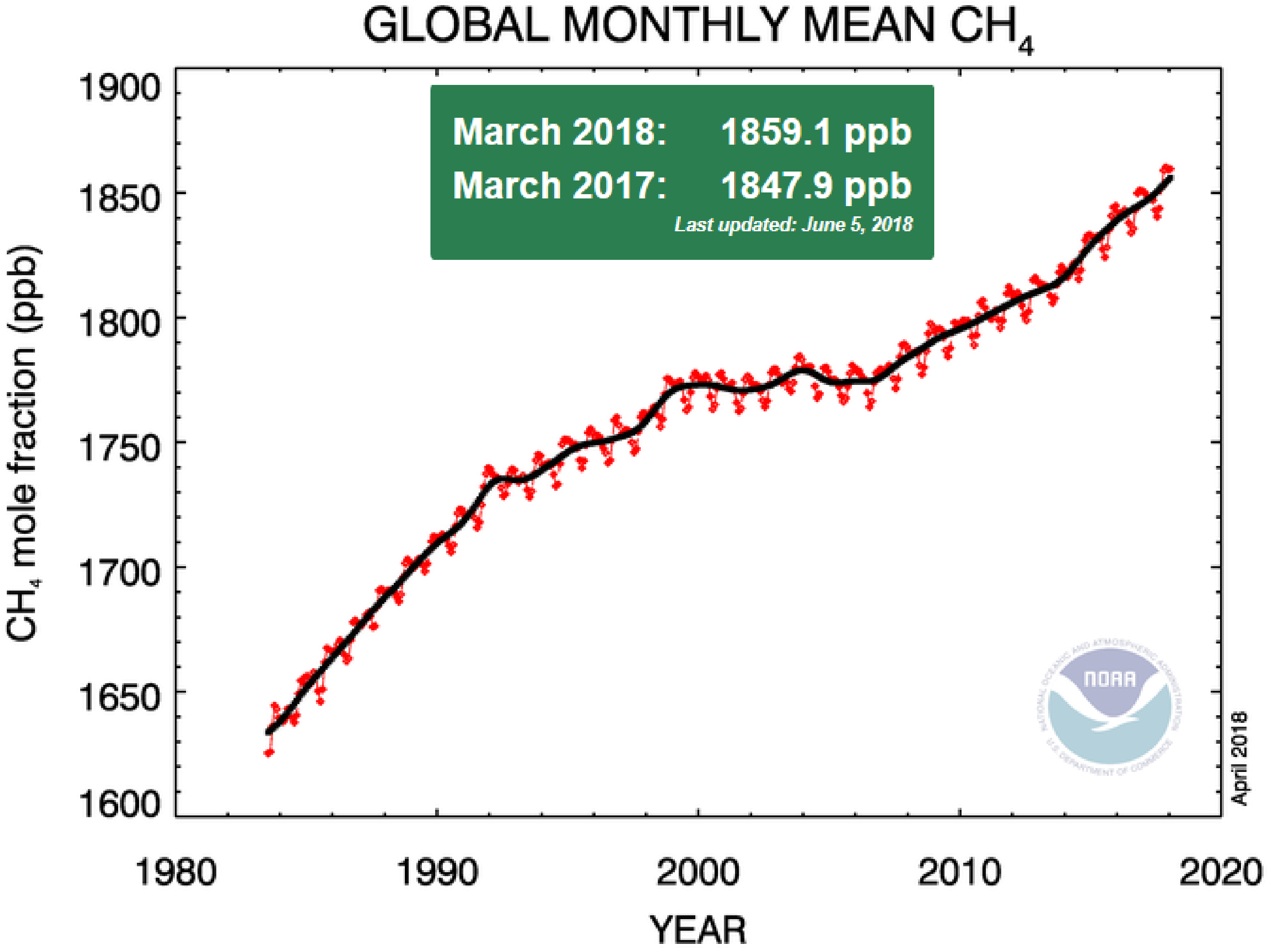
QUESTION C-8. What will be the consequences of amplified climate change already observed in the Arctic and projected for Antarctica on global trends of sea level rise, atmospheric circulation, extreme weather events, global ocean circulation, and carbon fluxes?

> **C-8f.** Determine how permafrost-thaw driven land cover changes affect turbulent heat fluxes, above and below ground carbon pools, resulting greenhouse gas fluxes (carbon dioxide, methane) in the Arctic, as well as their impact on Arctic amplification.

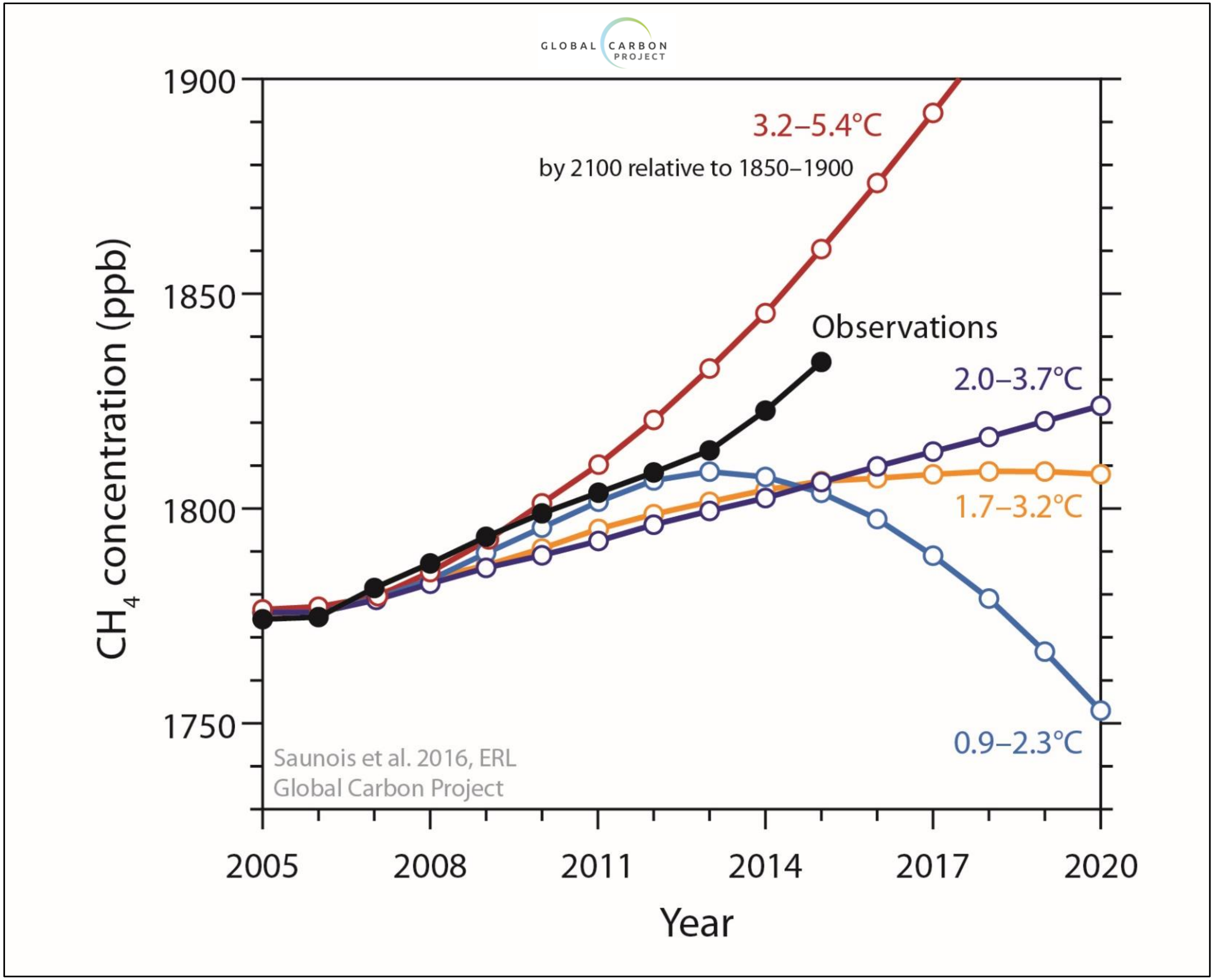


TARGETED OBSERVABLE	SCIENCE/APPLICATIONS SUMMARY	CANDIDATE MEASUREMENT APPROACH	Designated	Explorer	Incubation
Greenhouse Gases	**CO$_2$ and methane fluxes and trends,** global and regional with quantification of point sources and identification of source types	Multispectral short wave IR and thermal IR sounders; or lidar**		x	
Ice Elevation	**Global ice characterization** including elevation change of land ice to assess sea level contributions and freeboard height of sea ice to assess sea ice/ocean/atmosphere interaction	Lidar**		x	
Ocean Surface Winds & Currents	**Coincident high-accuracy currents and vector winds** to assess air-sea momentum exchange and to infer upwelling, upper ocean mixing, and sea-ice drift.	Radar scatterometer		x	
Ozone & Trace Gases	**Vertical profiles of ozone and trace gases** (including water vapor, CO, NO$_2$, methane, and N$_2$O) globally and with high spatial resolution	UV/IR/microwave limb/nadir sounding and UV/IR solar/stellar occultation		x	
Snow Depth & Snow Water Equivalent	**Snow depth and snow water equivalent** including high spatial resolution in mountain areas	Radar (Ka/Ku band) altimeter; or lidar**		x	
Terrestrial Ecosystem Structure	**3D structure of terrestrial ecosystem** including forest canopy and above ground biomass and changes in above ground carbon stock from processes such as deforestation & forest degradation	Lidar**		x	

Why measure Methane?

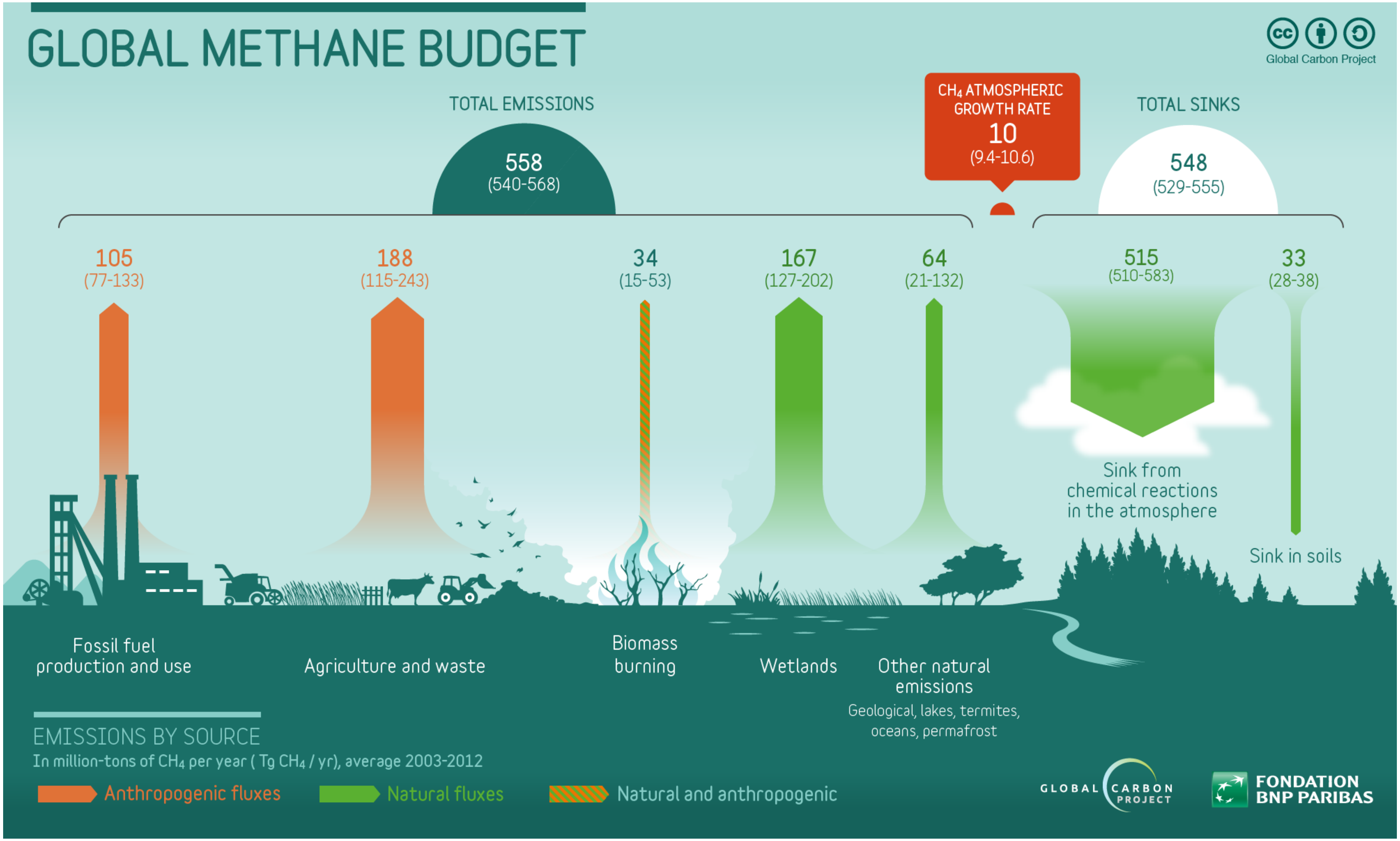


Observed Concentrations Compared to IPCC Projections



Source: www.globalcarbonproject.org

Global Methane Budget



Source: www.globalcarbonproject.org and http://www.globalcarbonatlas.org

Methane Missions

CH4 Mission	Agency	Cov. (days)	Spatial Res. (km^2)	Swath (km)	Err.	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	+
Solar backscatter (1.65 nm or 2.3 nm)																								
SCIAMACHY	ESA	6	30x60	960	1.5%	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧								
GOSAT TANSO-FTS	JAXA	3	10x10	520	0.7%								🟩	🟩	🟩	🟩	🟩	🟩	▨	▨	▨	▨		
Sentinel-5P Tropomi	ESA	1	7x7	2600	0.6%															🟩	🟩	🟩		
GOSAT-2 (3)	JAXA	3	10x10	632	0.4%																	🟦	🟦	🟦
MetOp Sentinel 5	ESA		7x7	2600																				🟦
CarbonSAT	ESA	5-10	2x2		0.4%																			🟦
Thermal emissions (8.0 nm)																								
IASI	CNES	0.5	12x12	100	1.2%					🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
AIRS	NASA	0.5	45x45		1.5%	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
TES	NASA		5x8		1.0%			🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩								
CrIS	NOAA		14x14		1.5%										🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
IASI-NG	CNES	0.5	12x12																					🟦
Active (lidar)																								
MERLIN	DLR-CNES			100	1-2%																			🟦
Geostationary / CUBESAT / ISS (1.65 nm or 2.3 nm)																								
geoCARB	NASA	2 hours	3x3 +		1%																			🟦
ghgSAT	Private	targets	0.05x		1-5%															🟩	🟩	🟩		
Bluefield (COOL)	Private	targets	0.02x	38																				🟦
methaneSAT	Private																							🟦
HISUI	JAXA																						🟩	

Table courtesy of Dr. Benjamin Poulter (GSFC)

Why use a laser?

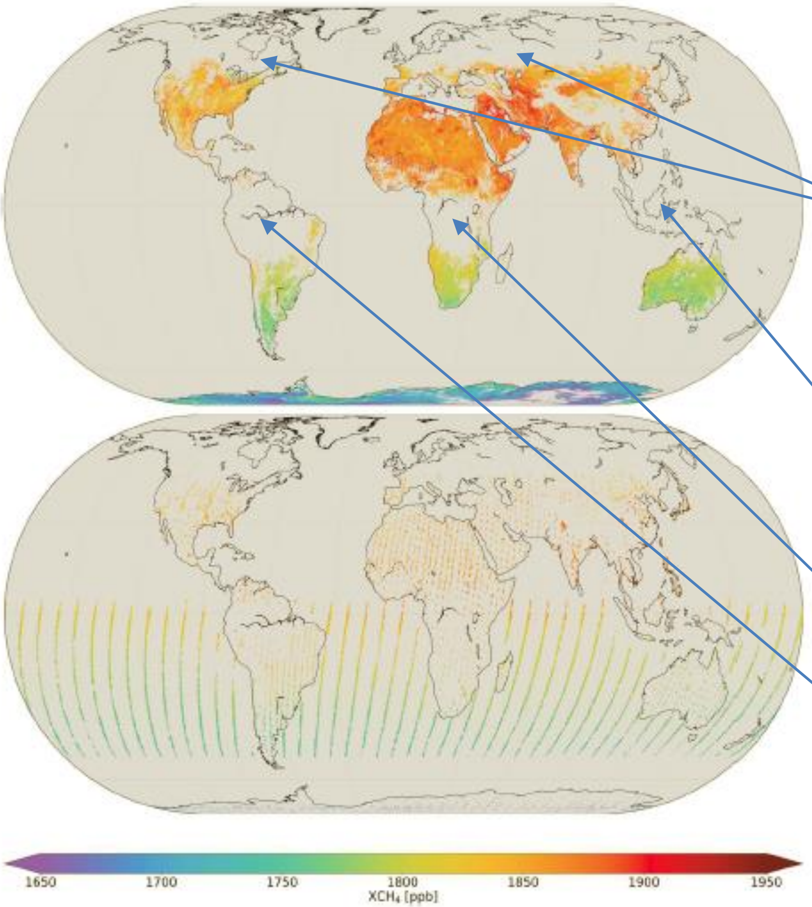
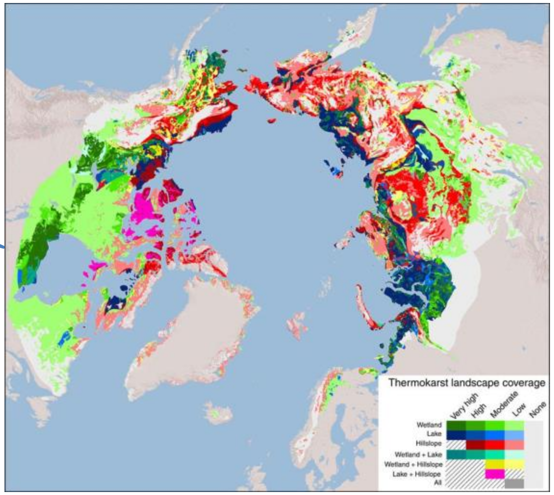


Figure 2. Global XCH$_4$ distribution as obtained with TROPOMI (top) and GOSAT (bottom) measurements averaged over the period of 12 November to 30 December 2017. Please note that for TROPOMI we have only used the observations over land so far. The GOSAT CH$_4$ product also contains observations over ocean for sunglint geometries.

Hu, Haili, et.al. "Toward global mapping of methane with TROPOMI: first results and intersatellite comparison to GOSAT." Geophysical Research Letters 45, no. 8 (2018): 3682-3689.



Credit: Olefeldt et al., 2016, NATURE COMMUN. DOI: 10.1038/ncomms13043

Methane Hydrates could be a source of energy

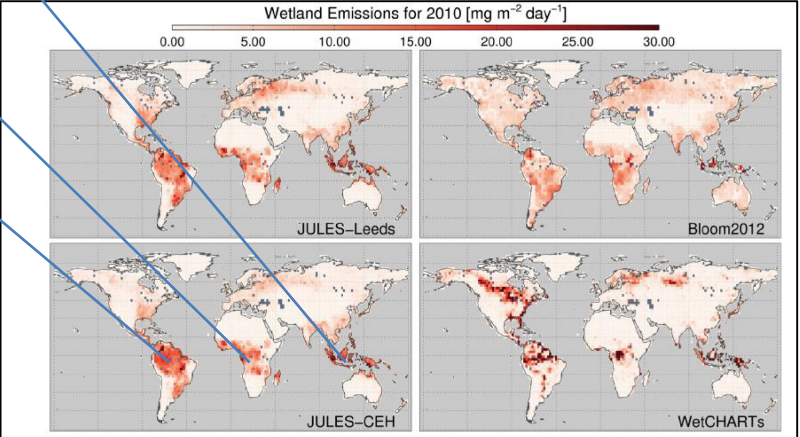


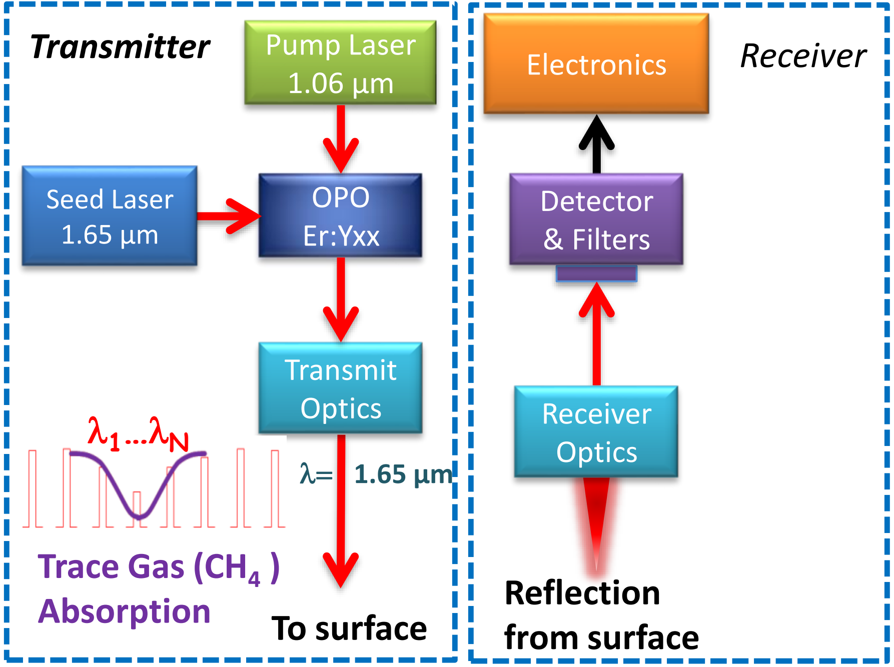
Fig. 1. Global maps showing the CH$_4$ wetland emission data for 2010 from the four different estimates used in this study.

Global maps showing the CH4 wetland emission data for 2010 from four different estimates
Credit: Parker et.al., 2018, Remote Sensing of the environment, 2018, 261-276

GSFC MEASUREMENT APPROACH

GSFC CH_4 IPDA Lidar

- ***Transmitter (Laser) technology***
  - **Optimum wavelength for CH_4 Earth Detection: ~1.64-1.66 µm**
  - **Optical Parametric Oscillator (OPO) is the "baseline" solution for the transmitter.**
  - **Other options (Er:YAG and Er:YGG) available.**
- ***Receiver (Detector) Technology***
  - **DRS e-APD (ESTO)**



Transmitter

Pump Laser 1.06 µm

Seed Laser 1.65 µm

OPO Er:Yxx

Transmit Optics

$\lambda_1 \ldots \lambda_N$

$\lambda =$ 1.65 µm

Trace Gas (CH_4) Absorption

To surface

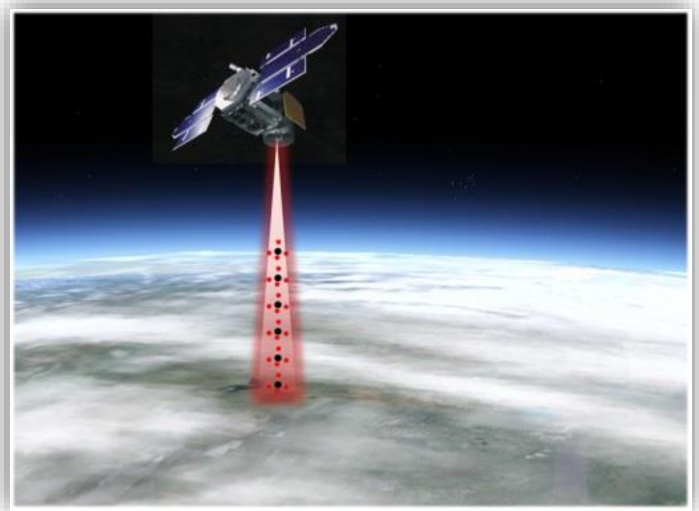
Electronics

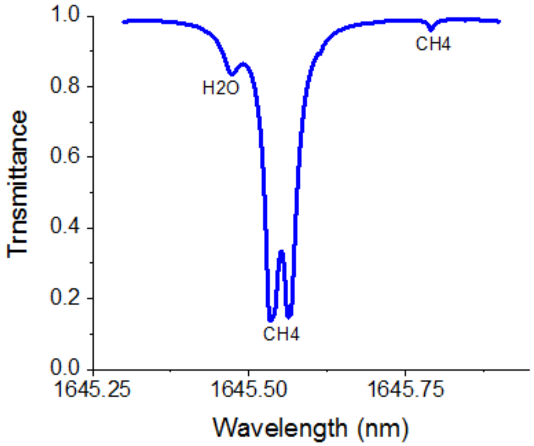
Receiver

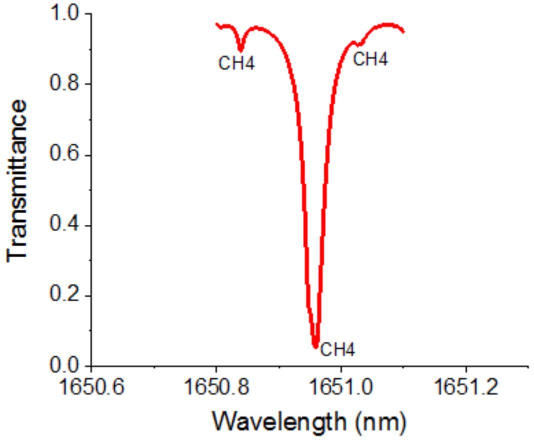
Detector & Filters

Receiver Optics

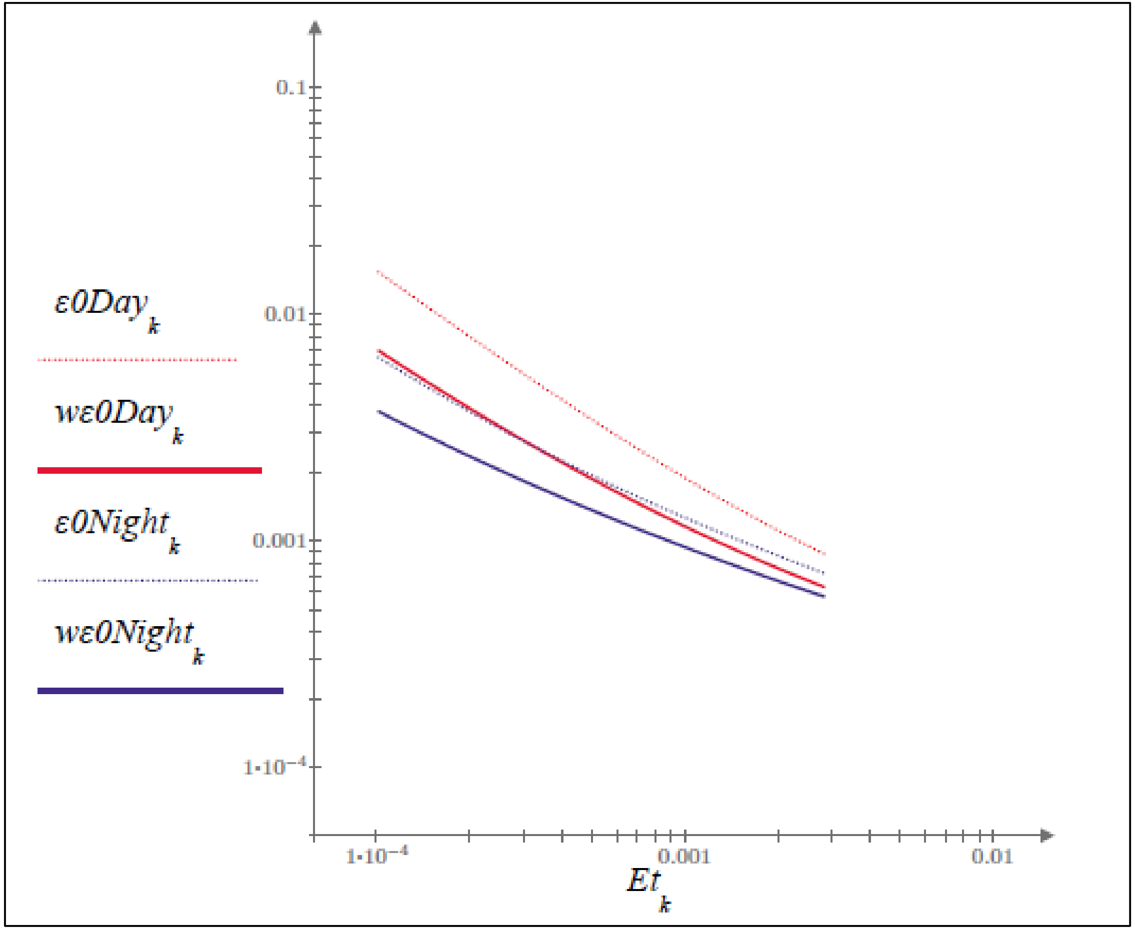
Reflection from surface







Why use multiple wavelengths?

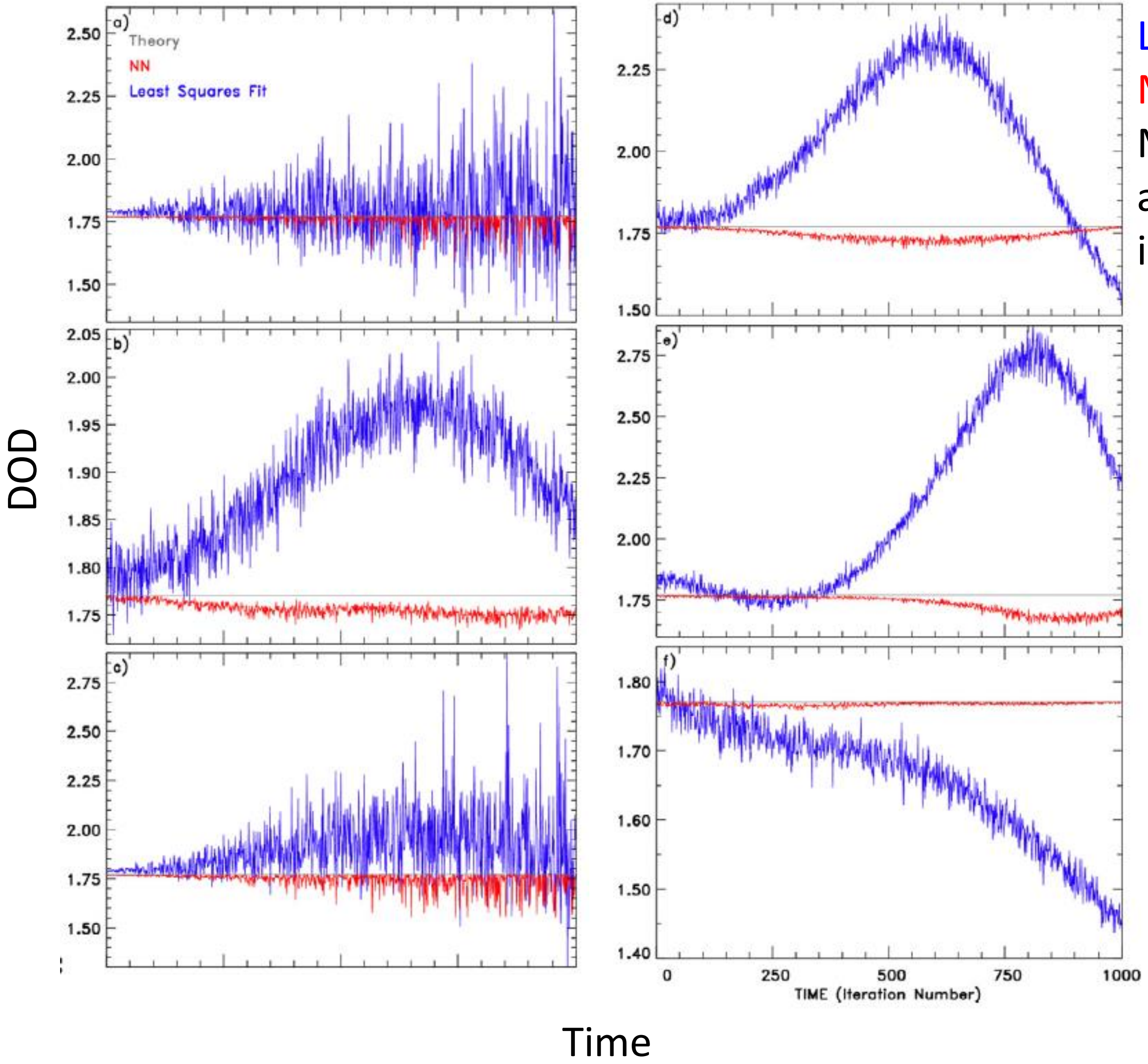


"Ideal" Instrument – has only random noise which can be averaged indefinitely.
Two wavelengths can adequately sample the lineshape. Averaging always helps.
Real Instrument – has random and non-random noise which can NOT always be averaged.
Two wavelengths can NOT adequately sample the lineshape or reduce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

CH_4 Laser Transmitter “Requirements”

- Emission wavelength must coincide with suitable CH_4 absorption lines (1645.5 nm and 1651 nm)
- Must have high pulse energy (~600 µJ) and high pulse repetition rate. Depending on the receiver size and other instrument parameters we calculate that approximately 600 µJ is needed to make a measurement with a 0.5% precision.
- Must be tunable (~300-500 pm) and scan rapidly (0.5-1 KHz) over the CH_4 absorption line
- Must have narrow linewidth (~100 MHz).

Bias, Drift, Non-stationary noise,…



Least Squares Optimization

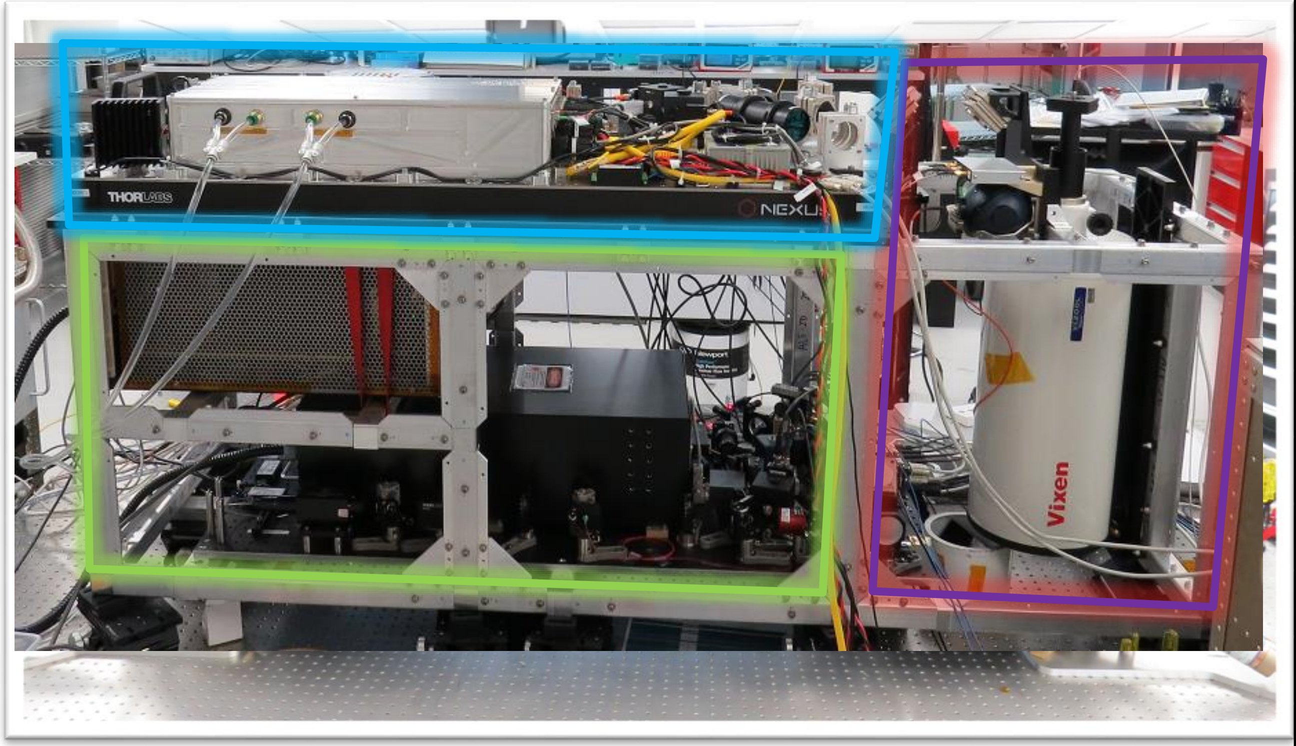
Machine Learning (NN)

Machine learning is an additional tool to reduce impact of “biases”

Nicely, Julie et.al., Journal of Quantitative Spectroscopy and Radiative Transfer, Volume 211, May 2018, 115-122

CURRENT STATUS & FUTURE PLANS

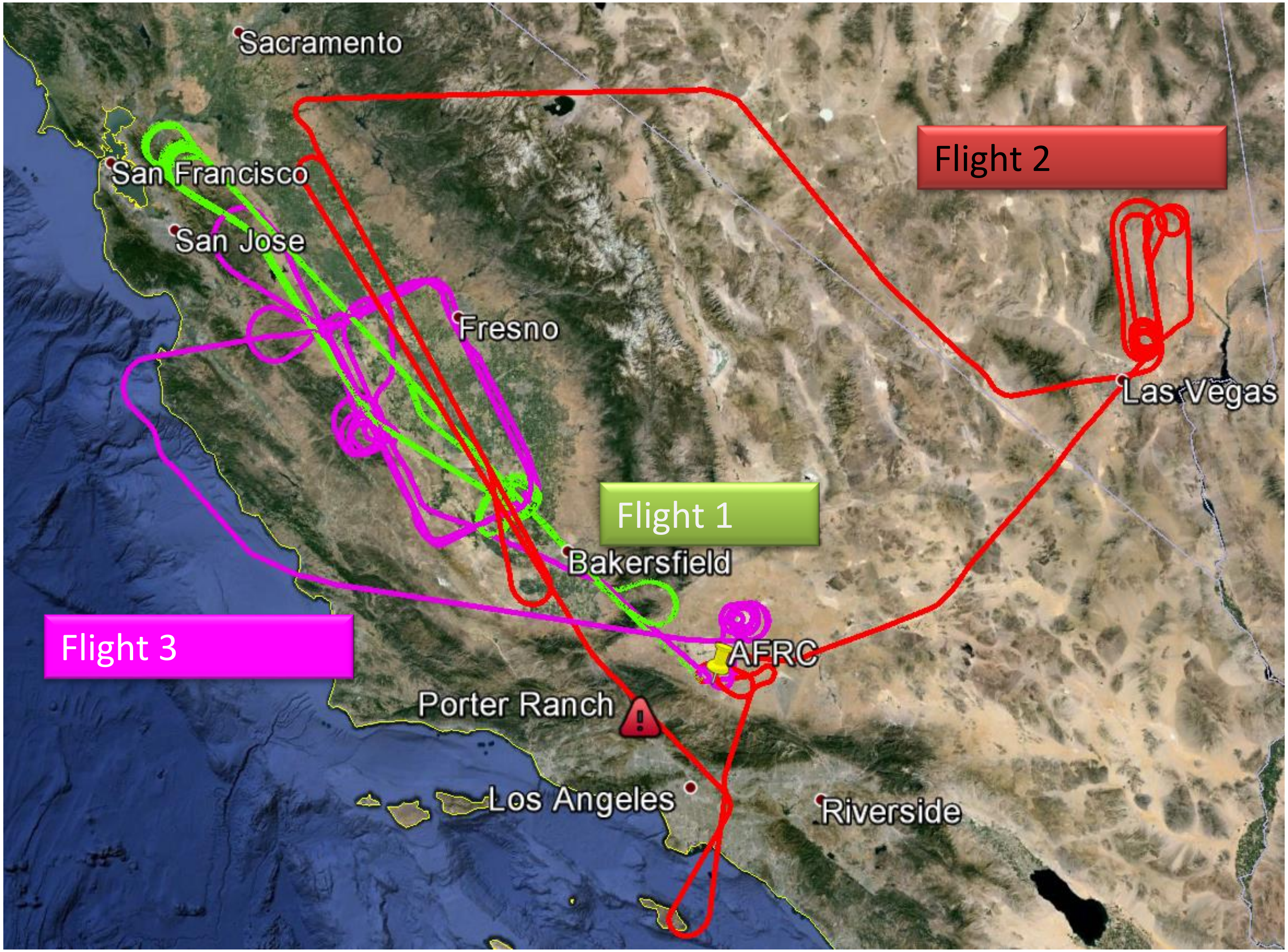
2015 CH_4 Airborne Instrument



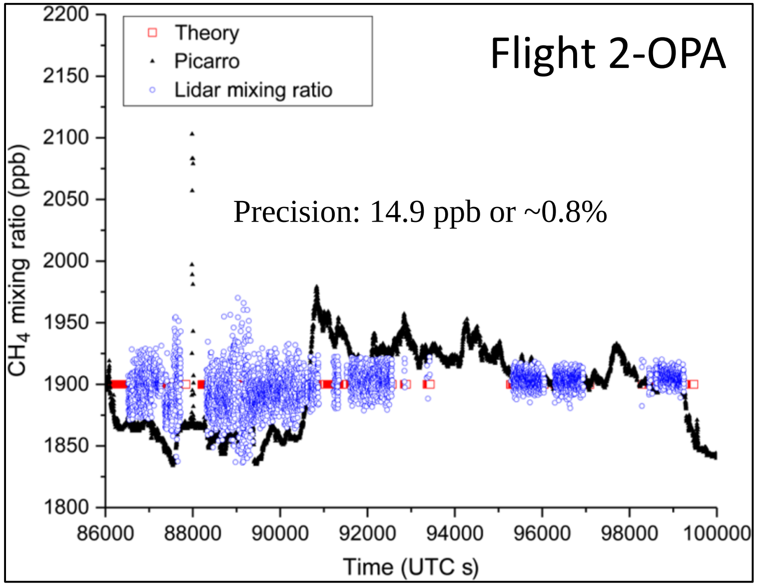
Parameter	Value (OPA/OPO)
Center λ	1650.9 nm
Number of λ	20/5
Pulse Width	~700/80 ns
Energy/pulse	~25/250 μJ
Bin width	4 ns
Divergence	~150 μrad
Receiver diam.	20 cm
Field of view	300 μrad
Receiver BP	0.8 nm (FWHM)
Averaging time	1/16 s *
Detector Resp.	~1-1.5 x 10^9 V/W

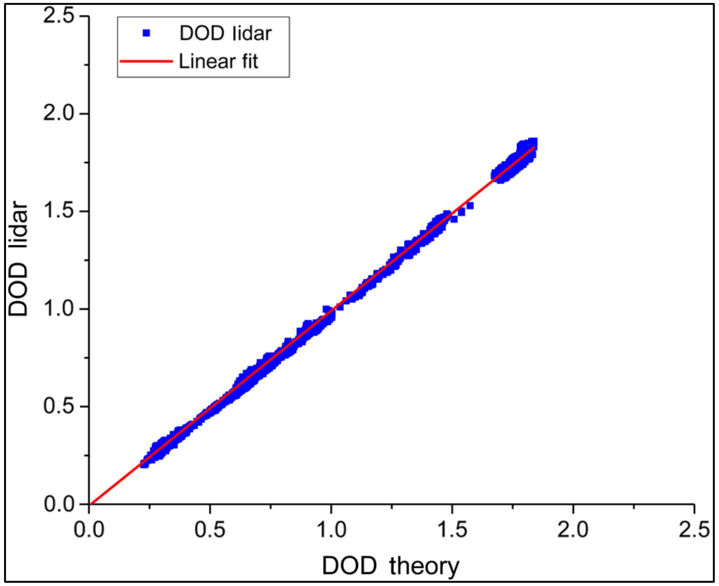
*Data analysis uses 1s averages

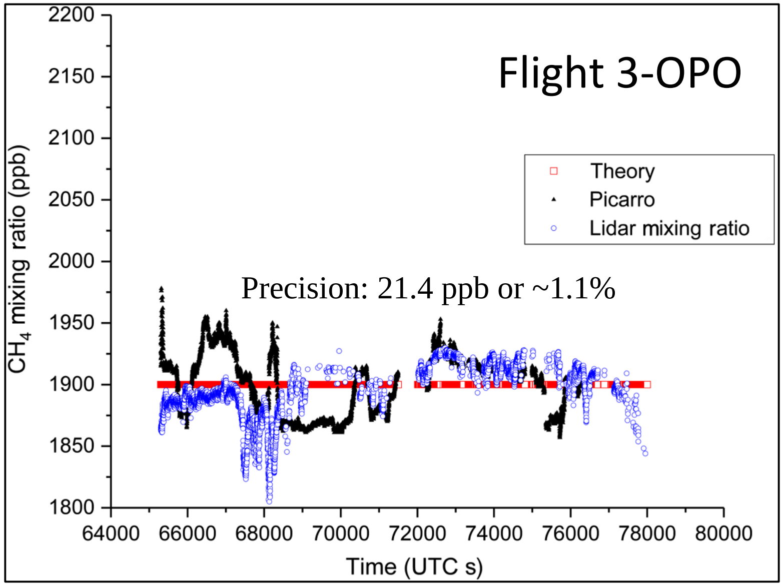
2015 Airborne Demonstration Flight Tracks

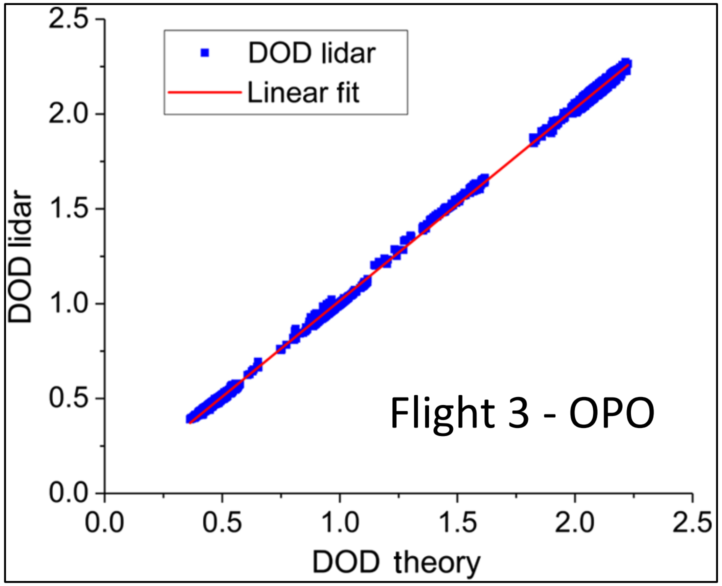


2015 Flight Results



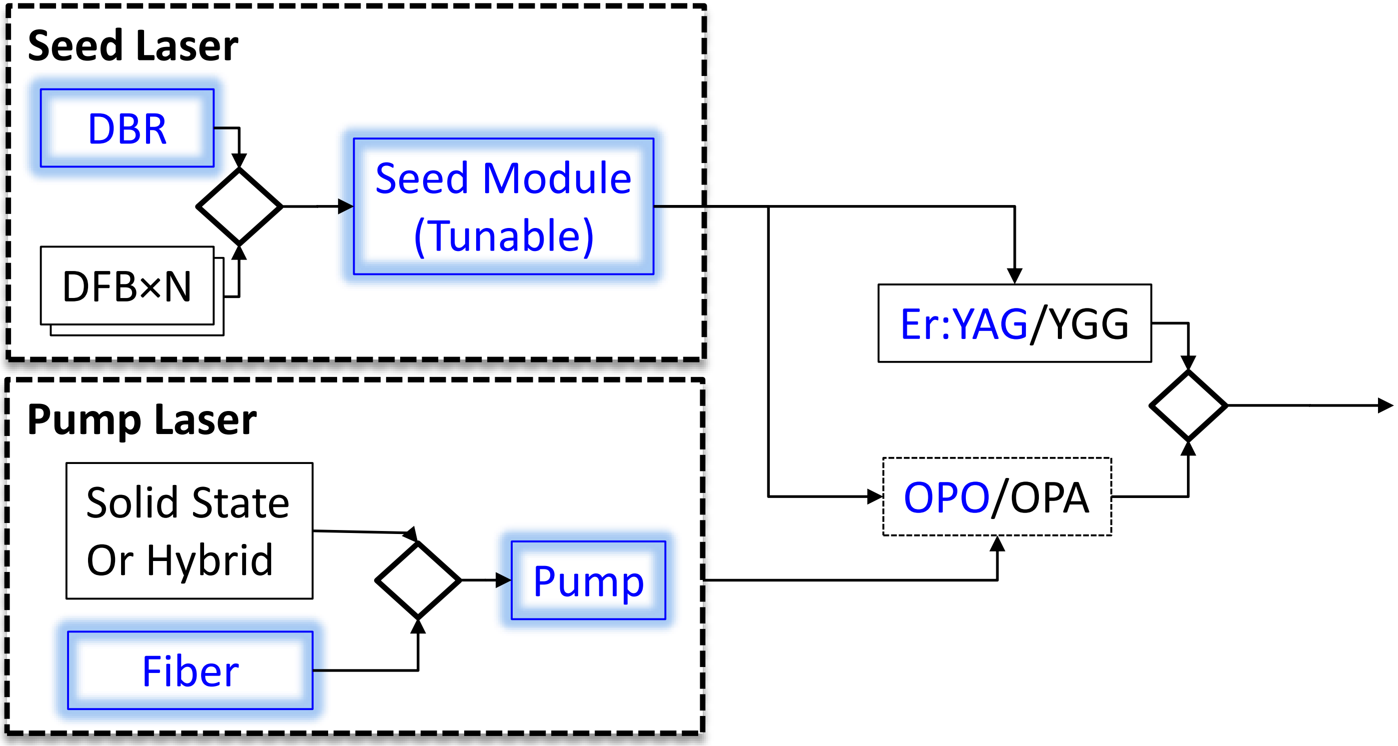






Riris, Haris, Kenji Numata, et.al. Journal of applied remote sensing 11, no. 3 (2017): 034001.

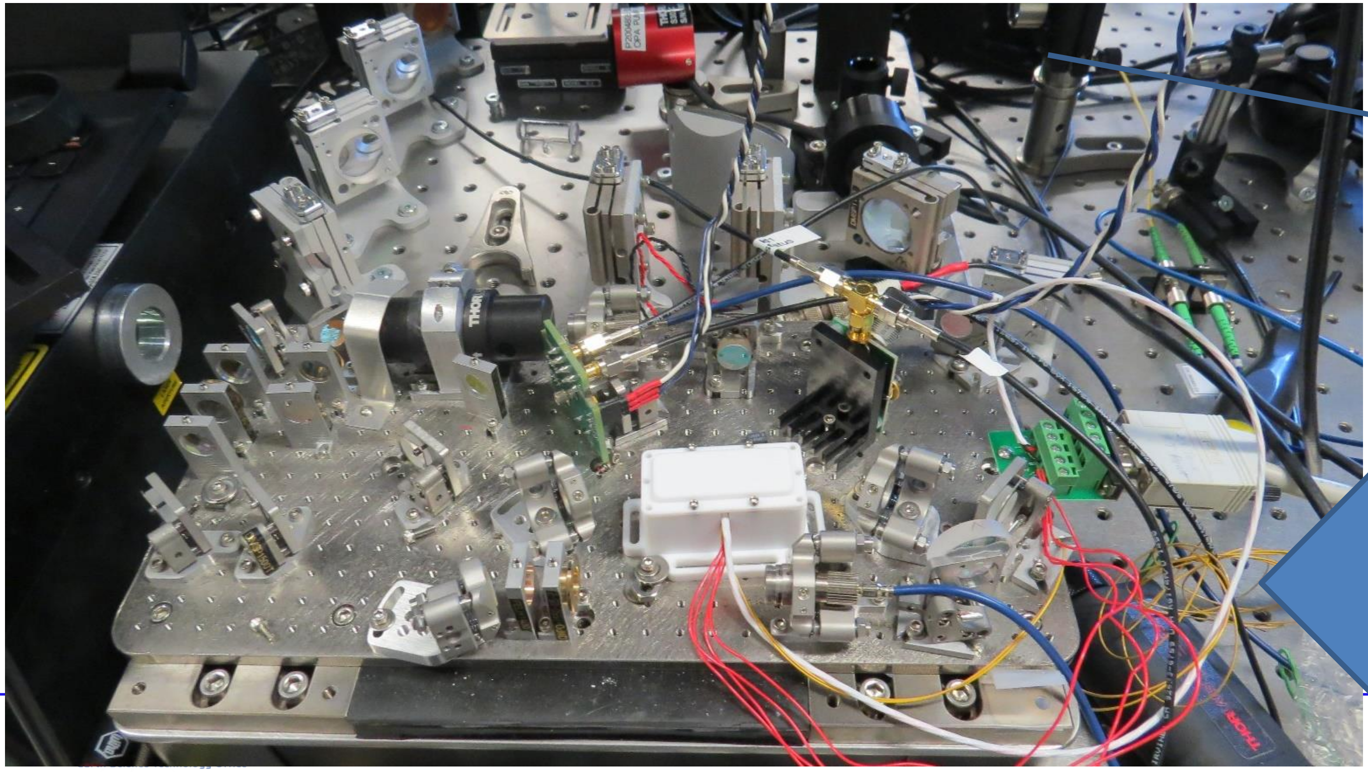
CH_4 Laser Transmitter Design for space



Blue: Current Design

GSFC New multi-wavelength OPO

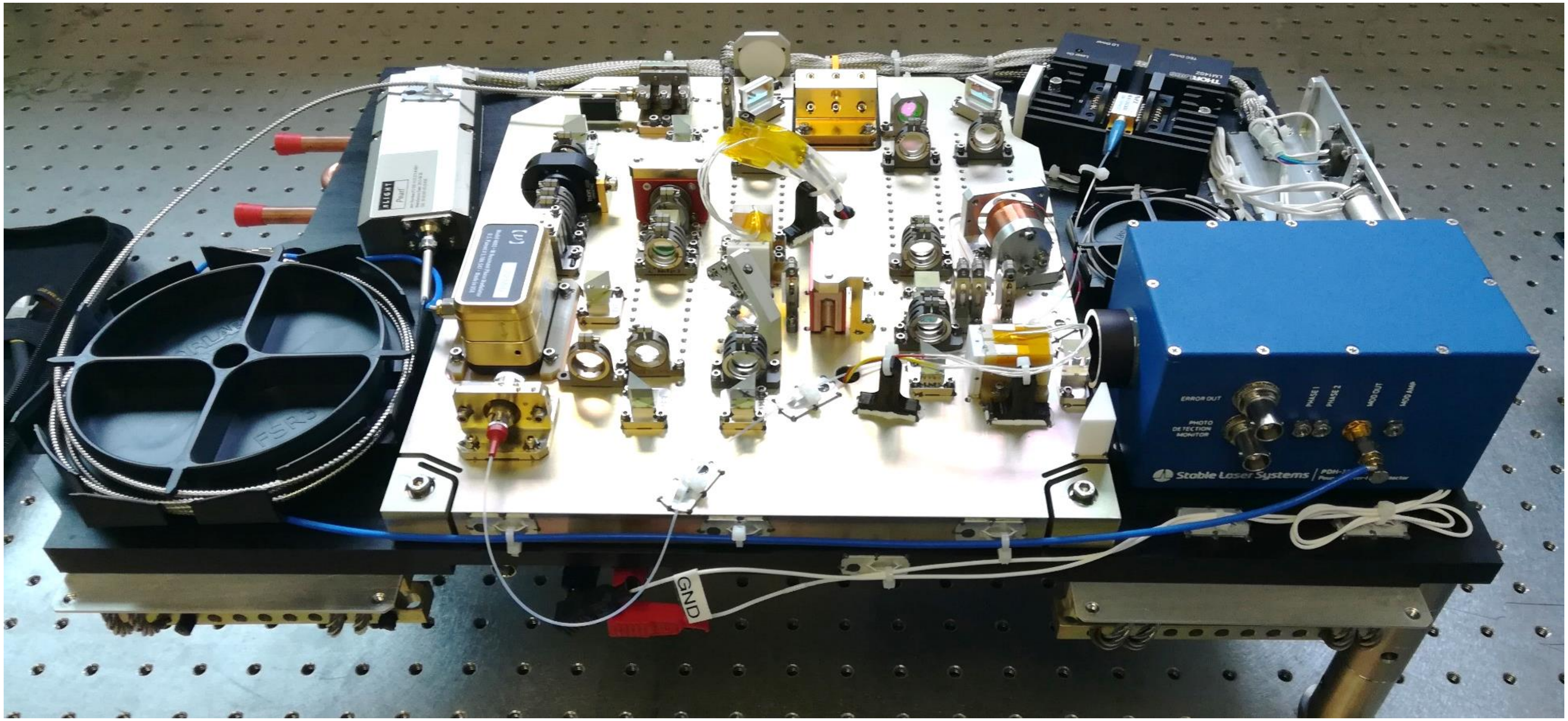
- Fiber pump (AdValue Photonics) now combined with the fast tuning DBR seed laser (Freedom Photonics – STMD GCD Program).
- Multi-wavelength OPO is now a reality. (200-250 µJ).
- Started open path measurements.



Fiber collimator for fiber coupling OPO output

OPO setup as of Mar. 2018

Fibertek Er:YAG-GSFC



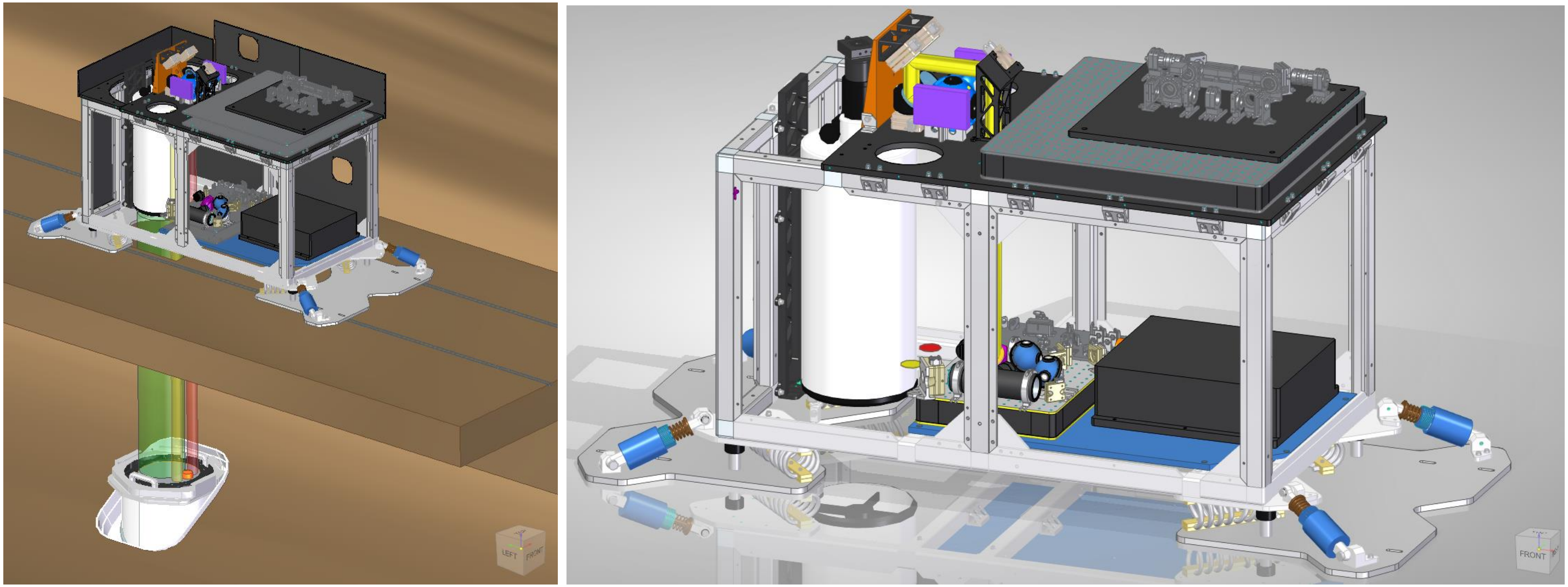
- Er:YAG laser (Fibertek SBIR Phase II) delivered last week
- High Energy (665 µJ)
- Single frequency seed.
- Open path measurements this summer with two or more wavelengths

GSFC laser transmitter current status

- Multi-wavelength OPO
  - Successful seeding with step-tuned DBR (FP) laser
  - Open path measurements started.
- Er:YAG
  - Er:YAG laser (Fibertek) delivered last week
- Fast-tuned seed laser
  - 16-wavelength locked seed laser now combined with the OPO
  - **Fast-tuned seed laser is applicable to all designs**
- Er:YGG
  - Testing Er:YAG NPRO
- OPA
  - On hiatus – available for airborne experiments.

YAG

New (improved) airborne sensor



- New transceiver uses Er:YAG and new, compact OPO
- Two beams can be fired simultaneously
- Smaller than the earlier version
- Vibration isolation maintained

Summary

- ✓ Demonstrated CH_4 airborne measurements using two lidar transmitters (OPA and OPO).
- ✓ Many different approaches and options for the laser transmitter have been investigated and two laser transmitters are now available (OPO and Er:YAG).
- ✓ New airborne instrument ready to fly.
- ✓ Looking for opportunities to fly!
- **We would like to thank ESTO and GSFC IRAD for their support.**