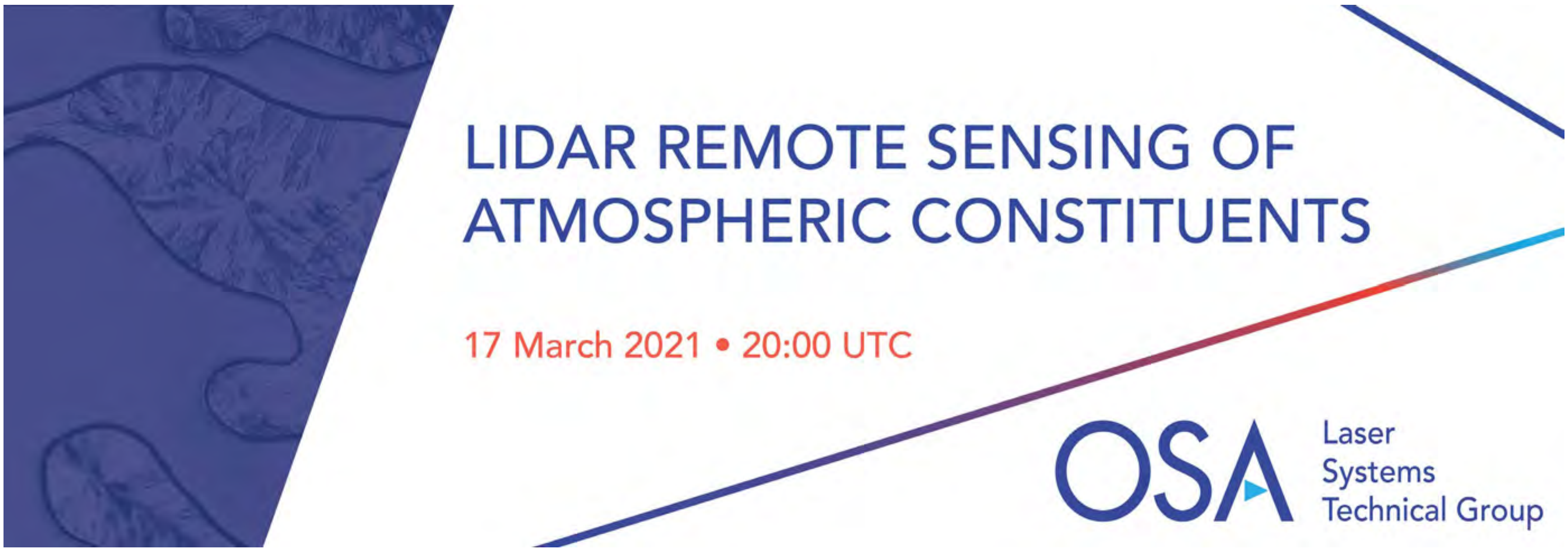
The OSA Laser Systems Technical Group Welcomes You!



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OSA Laser Systems Technical Group

Technical Group at a Glance

- **Focus**
  - This group encompasses novel laser system development for a broad range of scientific, industrial, medical, remote sensing and other directed-energy applications.
- **Mission**
  - To benefit *YOU*
  - Webinars, e-Presence, publications, technical events, business events, outreach
  - Interested in presenting your research? Have ideas for TG events? Contact us at osa.lasersystechgroup@gmail.com.
- **Find us here**
  - Website: www.osa.org/LaserSystemsTG
  - Facebook: https://www.facebook.com/groups/378463153017808/
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Today’s Webinar

Lidar Remote Sensing of Atmospheric Constituents

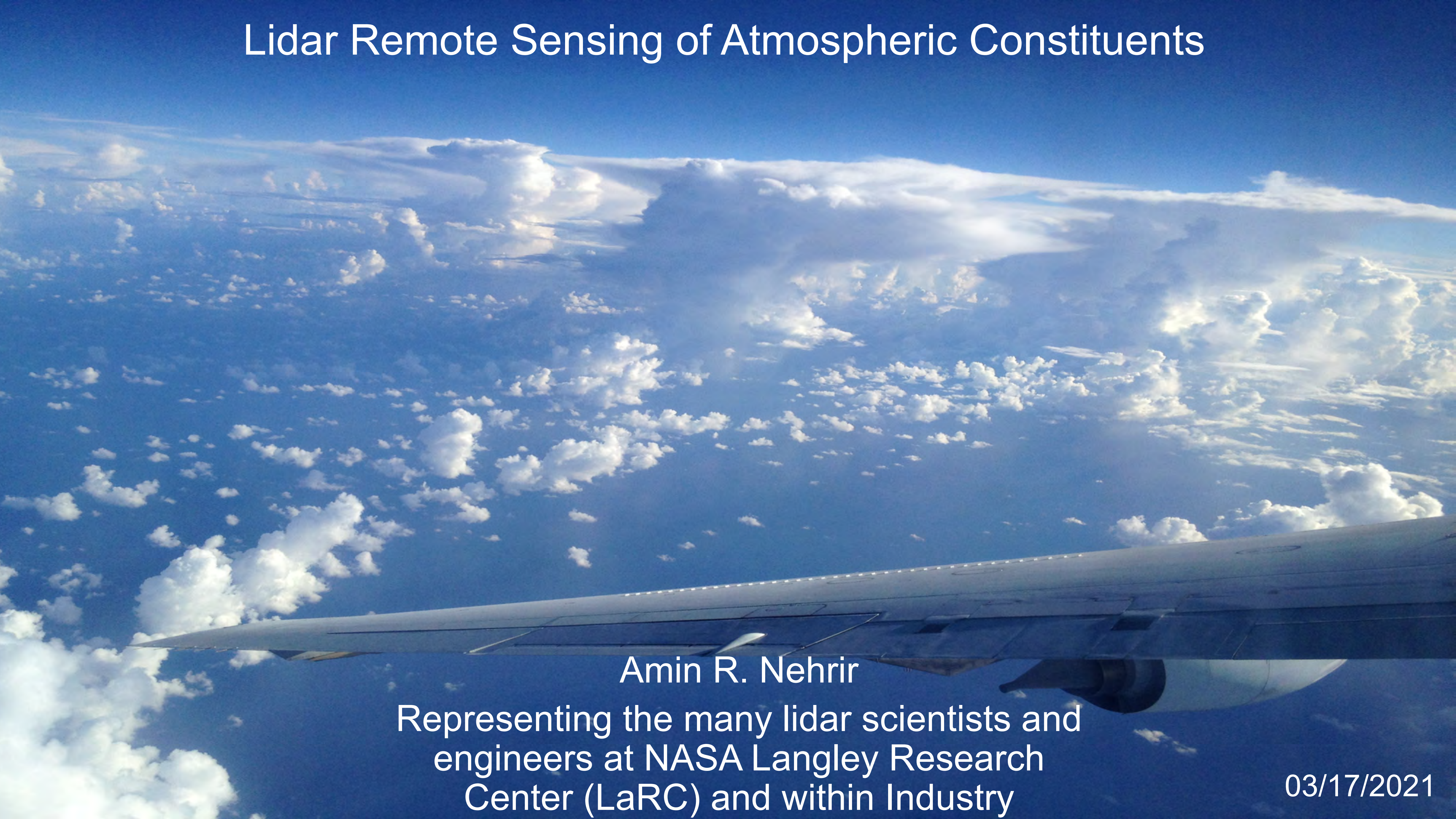
Dr. Amin Nehrir

NASA Langley Research Center, USA

Speaker’s Short Bio:

Dr. Amin Nehrir is an Instrument Scientist for Active Remote Sensing in the Science Directorate at NASA Langley Research Center and has over 16 years’ experience in ground-based, airborne, and space-borne lidar with focus on advancing laser source development and optical instrumentation for remote sensing applications. Amin serves as the Active Remote Sensing co-product line lead at NASA Langley where he is currently engaged in the development of the next generation of space-based aerosol/cloud and water vapor profiling lidar. Amin is the PI of the HALO H2O and CH4 DIAL/HSRL lidar which has supported a broad range of airborne science investigations across different NASA science focus areas ranging from atmospheric dynamics to carbon cycle science. Amin is also the PI of the Atmospheric Boundary Layer Lidar Pathfinder (ABLE) project that is advancing on DIAL transmitter and receiver technologies to enable the world’s first water vapor profiling lidar from space.

Lidar Remote Sensing of Atmospheric Constituents



Amin R. Nehrir

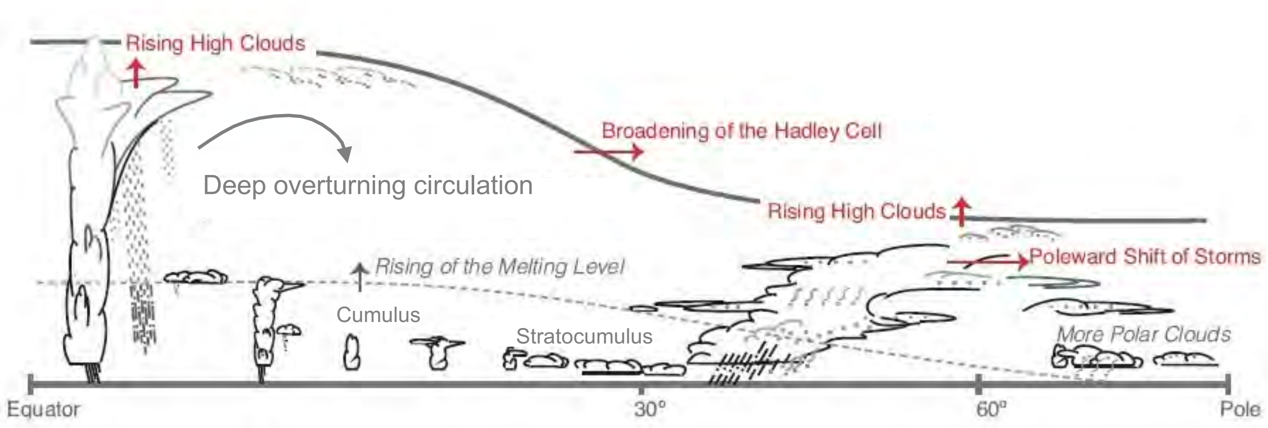
Representing the many lidar scientists and engineers at NASA Langley Research Center (LaRC) and within Industry

03/17/2021

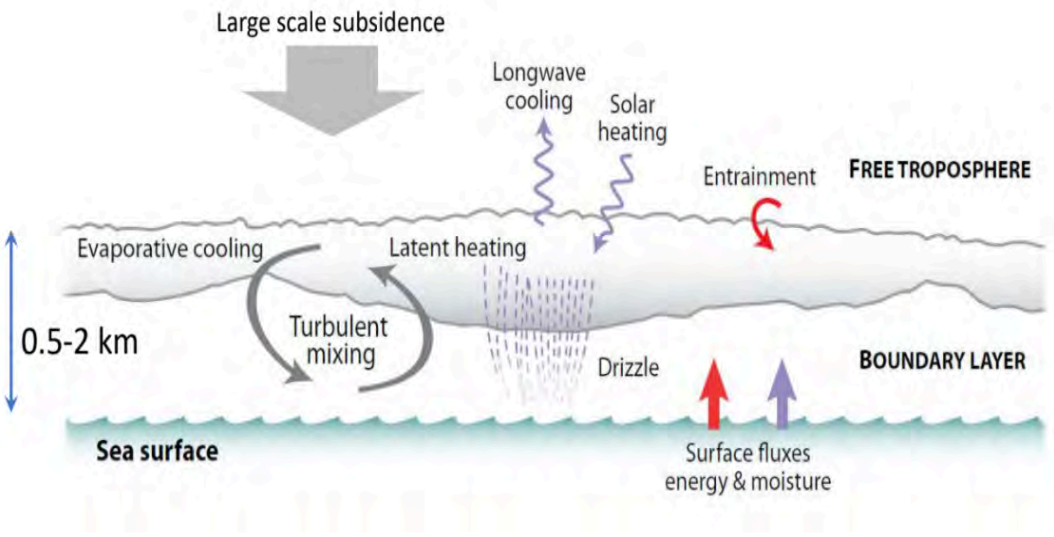
Observational Needs from Grand Challenges to the Decadal Survey

The 2017 Decadal Survey and the World Climate Research Program Grand Challenges highlight:

- need for accurate, high vertical resolution water vapor measurements in PBL and aloft
- a deeper understanding of the role of clouds in weather and climate systems requiring high vertical resolution humidity observations in and around clouds



Adapted from 2013 IPCC 5AR



Wood 2012, Monthly Weather Review

Observational Needs from Grand Challenges to the Decadal Survey

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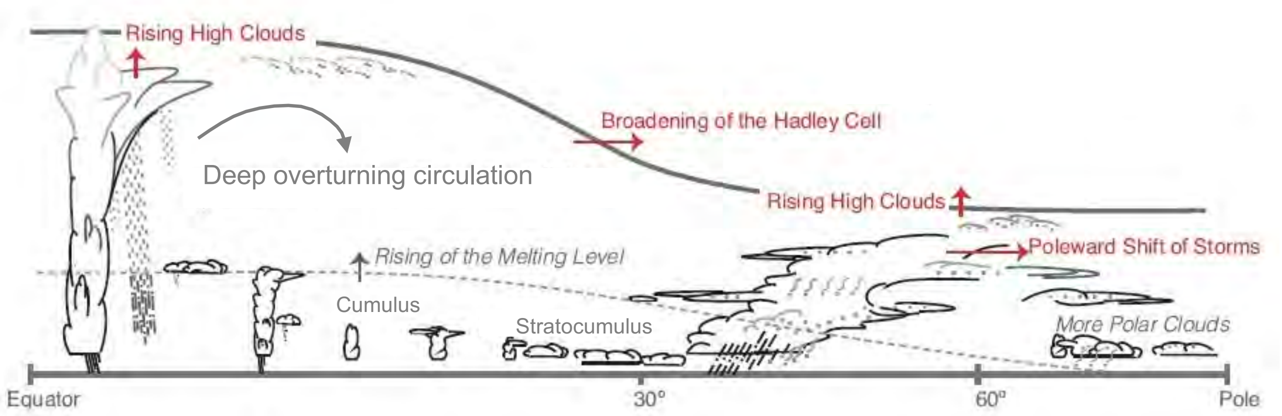

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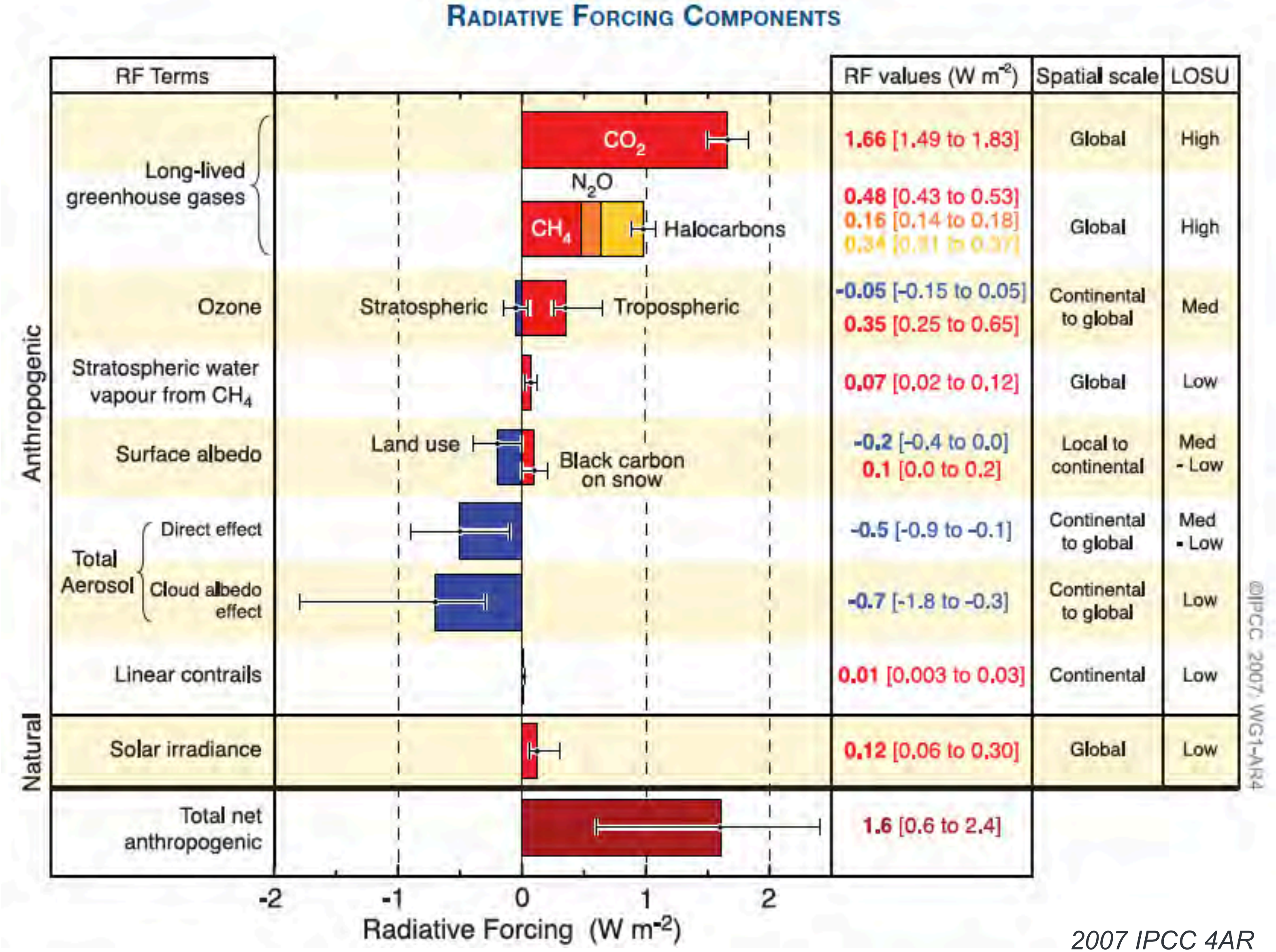
Radiative Forcing and Earth's Radiation Budget

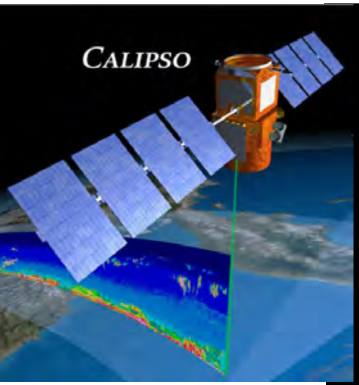


2007 IPCC 4AR

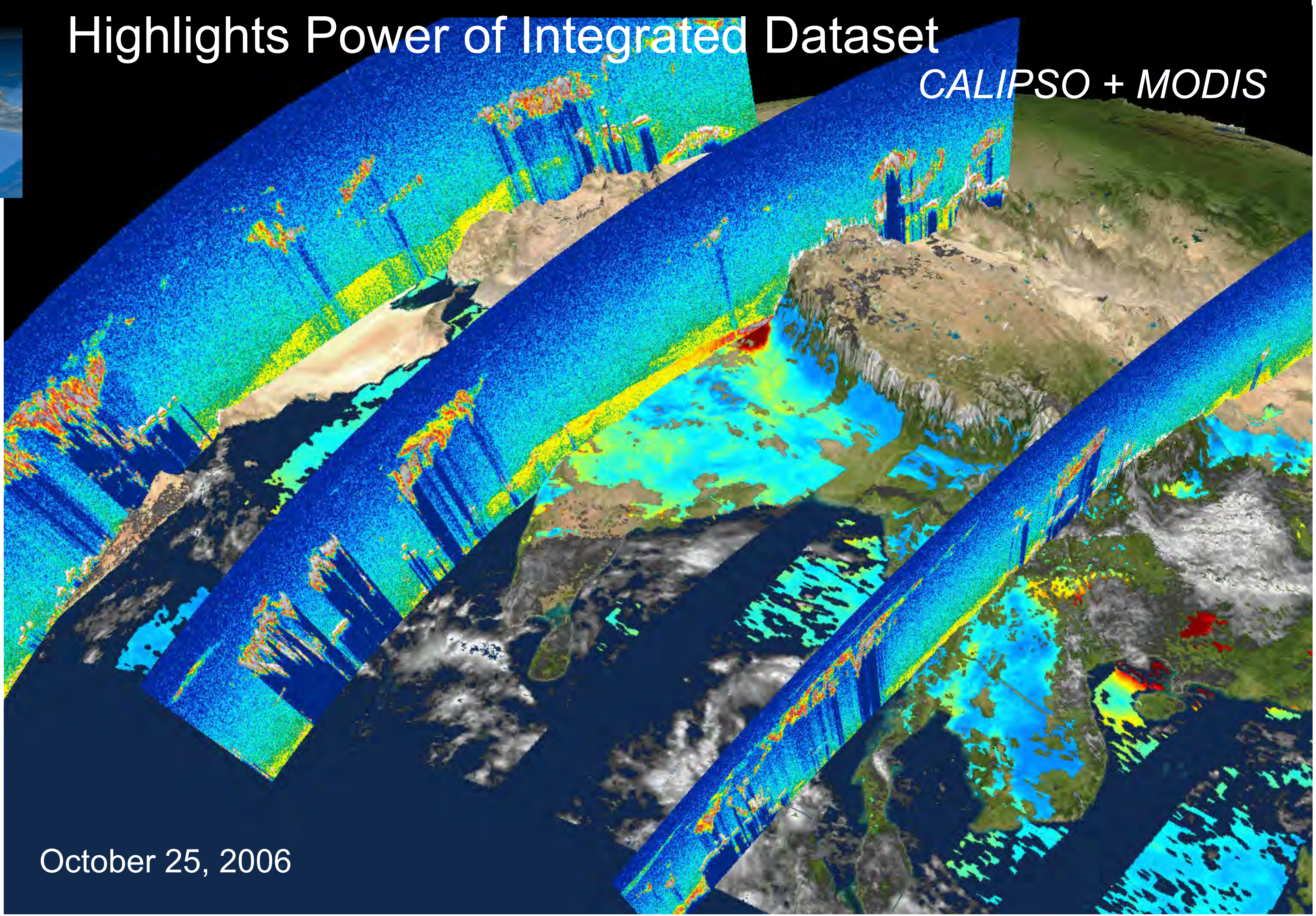
Outline

- Scientific Motivation
- Measurement Techniques and driving requirements
- Systems and Technology
- Data Examples
- Future Outlook

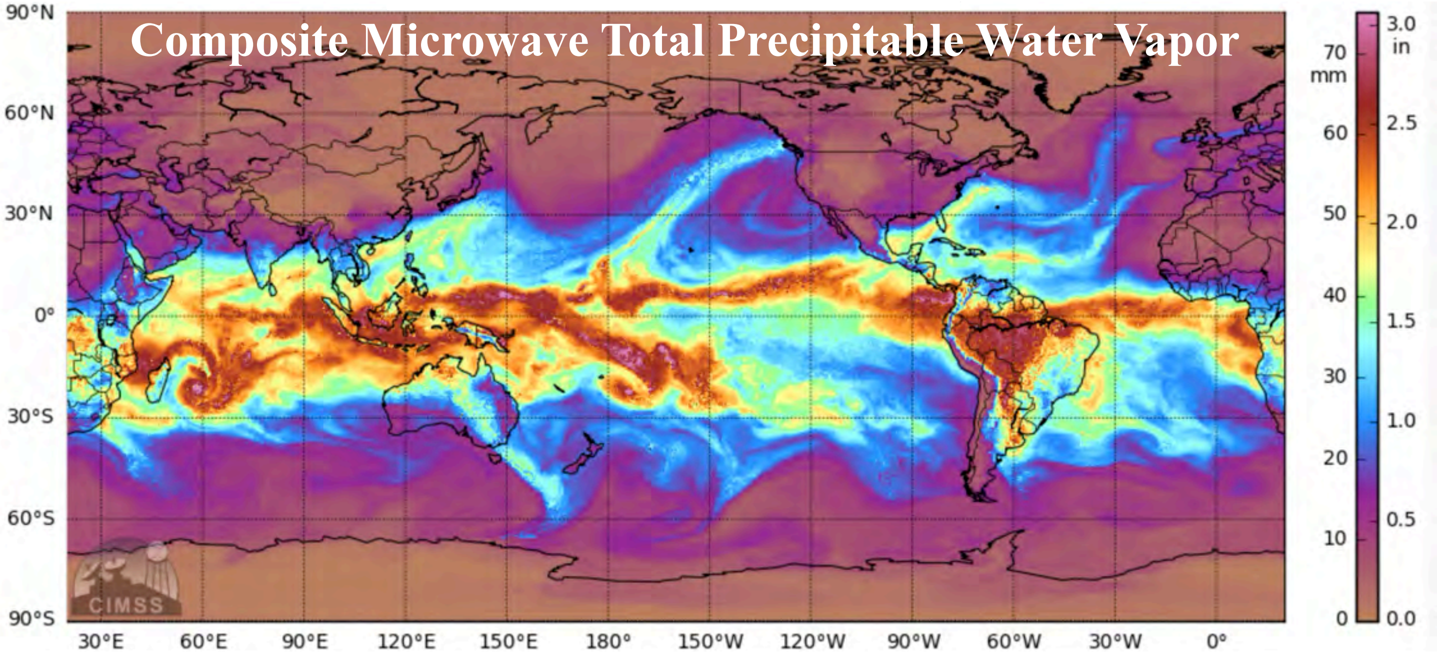
- Seed Questions :
  1. How can lidar be used to quantify changes to Earth's atmosphere in a warming climate?
  2. What laser technologies are required to accurately profile atmospheric constituents relevant on the climate and weather time scales?

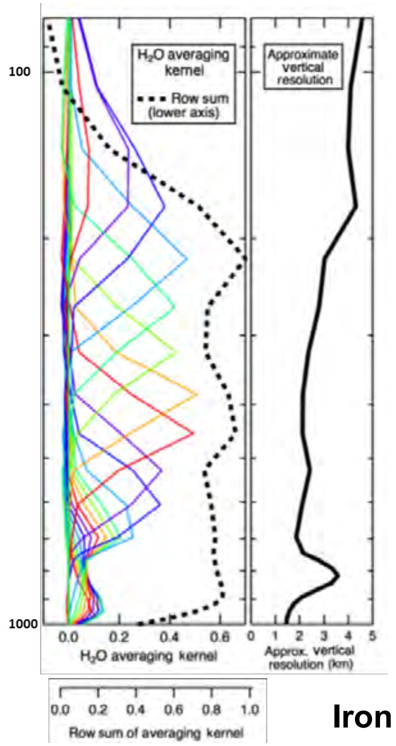


Aerosol and Cloud Observations over South Asia Highlights Power of Integrated Dataset



How Do we Currently Observe Atmospheric Water Vapor?



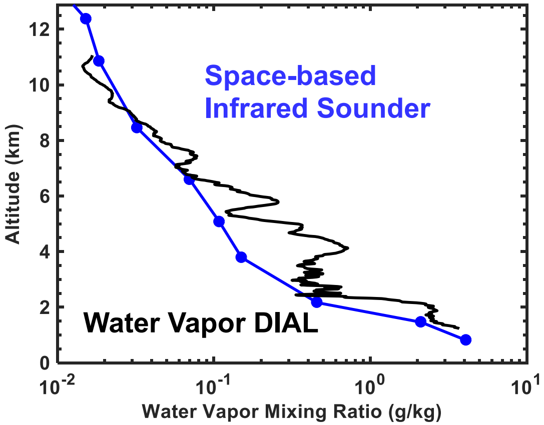


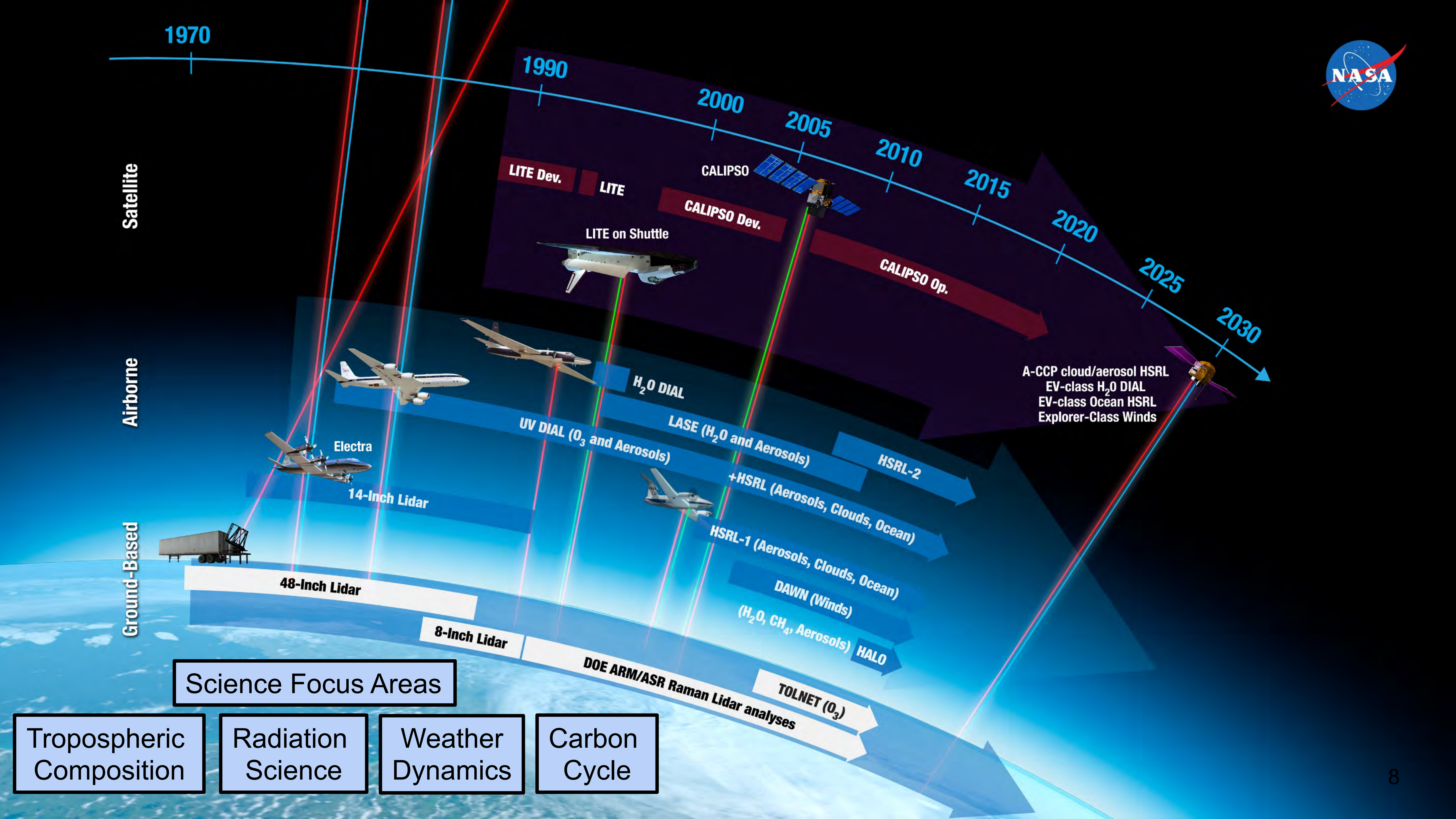
Iron et al., AMT 2018

- Passive infrared (IR) and microwave (MW) observations form the backbone of NWP and climate science communities

- IR and MW sounders provide global coverage, but have limited sensitivity to the lower troposphere and have coarse vertical resolution

- GNSS-RO provides extremely high vertical resolution, however, unraveling temperature from humidity signal poses a challenge





1970
1990
2000
2005
2010
2015
2020
2025
2030
Satellite
Airborne
Ground-Based
LITE Dev.
LITE
CALIPSO
CALIPSO Dev.
LITE on Shuttle
CALIPSO Op.
A-CCP cloud/aerosol HSRL
EV-class H_2O DIAL
EV-class Ocean HSRL
Explorer-Class Winds
H_2O DIAL
LASE (H_2O and Aerosols)
UV DIAL (O_3 and Aerosols)
HSRL-2
Electra
+HSRL (Aerosols, Clouds, Ocean)
14-Inch Lidar
HSRL-1 (Aerosols, Clouds, Ocean)
DAWN (Winds)
(H_2O, CH_4, Aerosols) HALO
48-Inch Lidar
8-Inch Lidar
DOE ARM/ASR Raman Lidar analyses
TOLNET (O_3)
Science Focus Areas
Tropospheric Composition
Radiation Science
Weather Dynamics
Carbon Cycle

LaRC Airborne DIAL and HSRLs

UV DIAL/HSRL
O_3 and aerosols
1983 - Present

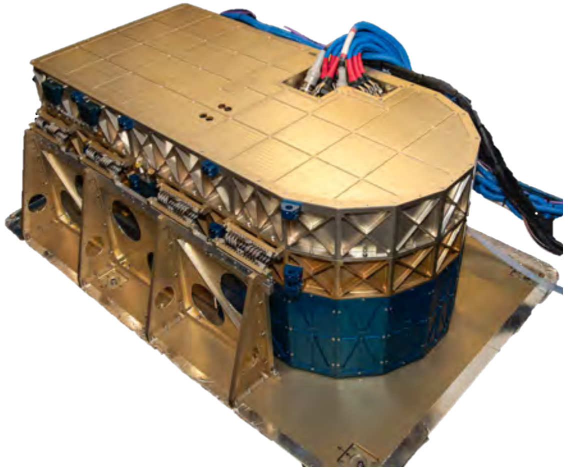
- Deploys on most large R&A-sponsored chemistry field missions
- Nadir and zenith viewing
- DC-8 aircraft only

HSRL-2
Aerosols, clouds, ozone, ocean
2012 - Present

- World's most capable aerosol/cloud and ocean lidar
- World's most capable ocean lidar
- King Air, P3, ER-2, etc.
- Prototype for A-CCP lidar

HSRL-1
Aerosols, clouds, ocean
2004 – Present

- First NASA HSRL for aerosols
- First HSRL for ocean
- Pressurized platforms as small as King Air
- Modularity useful for technology assessment (e.g., advanced receivers)

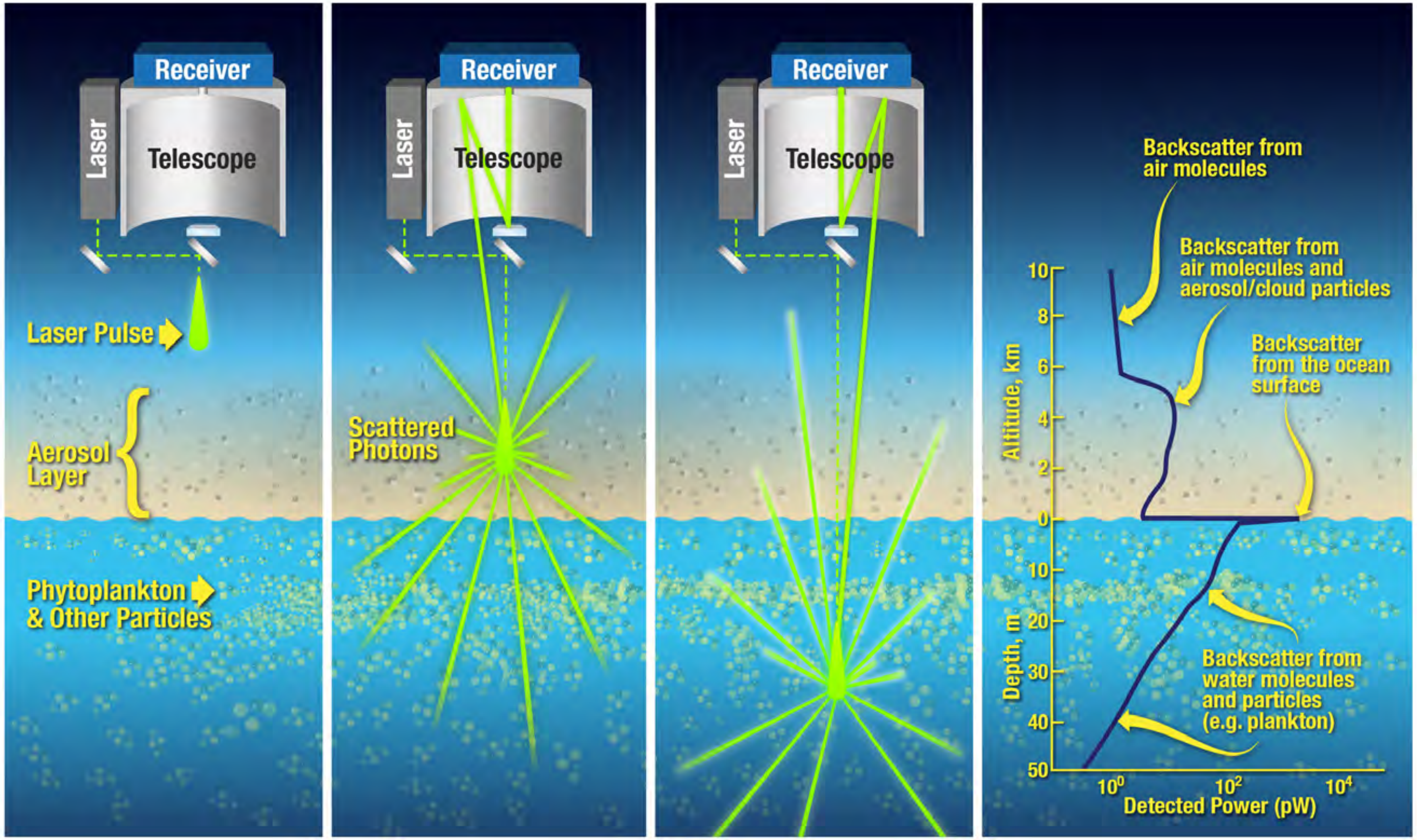


HALO
water vapor, CH_4, aerosols, clouds, ocean
2018 - Present

- Worlds most compact DIAL
- Multi-functionality supports broad range of science
- Replaces LASE water vapor lidar
- Provides new capability for CH_4
- Tech demonstrator for space

Backscatter Lidar – Principles and Characteristics

$$P(r,\lambda) = \frac{C(r,\lambda)}{r^2}\left[\beta_m(r,\lambda) + \beta_p(r,\lambda)\right]e^{-2\left[\int_0^r \sigma_m(r',\lambda)+\sigma_p(r',\lambda)+\sigma_g(r',\lambda)\right]dr'}$$



High Spectral Resolution Lidar – aerosol/cloud profiling

$$P(r,\lambda) = \frac{C(r,\lambda)}{r^2}\left[\beta_m(r,\lambda) + \beta_p(r,\lambda)\right] e^{-2\left[\int_0^r \sigma_m(r',\lambda)+\sigma_p(r',\lambda)+\sigma_g(r',\lambda)\right]dr'}$$

- Known parameters
- Retrieved parameters

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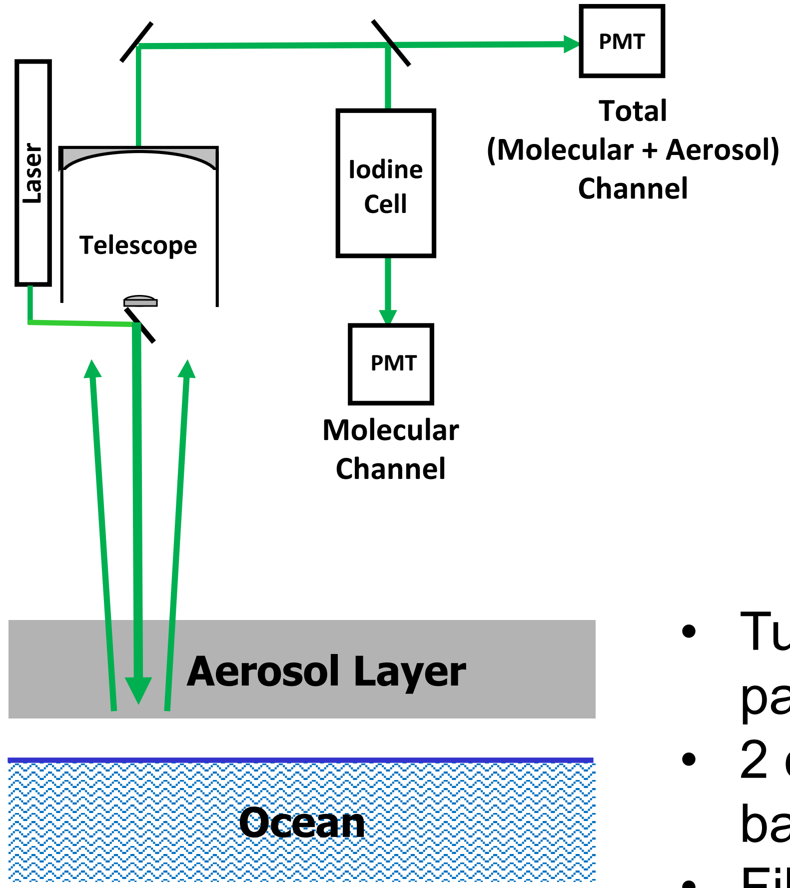
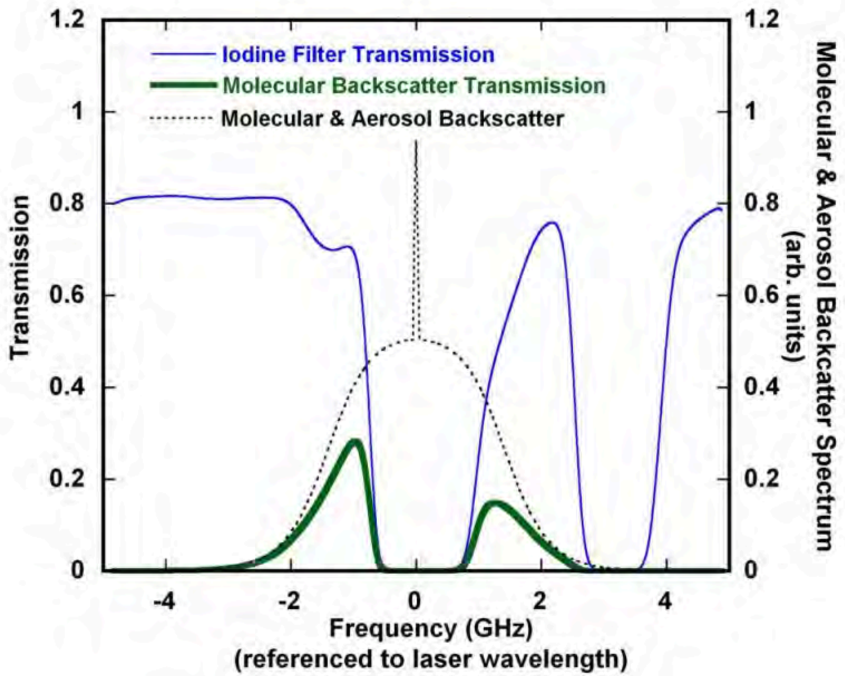


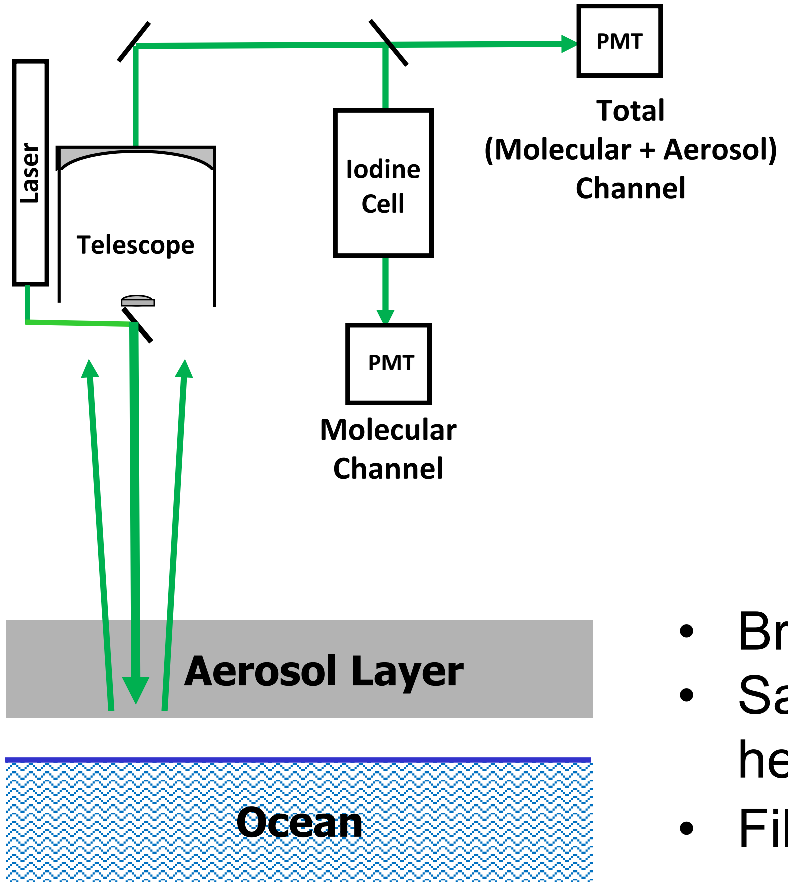


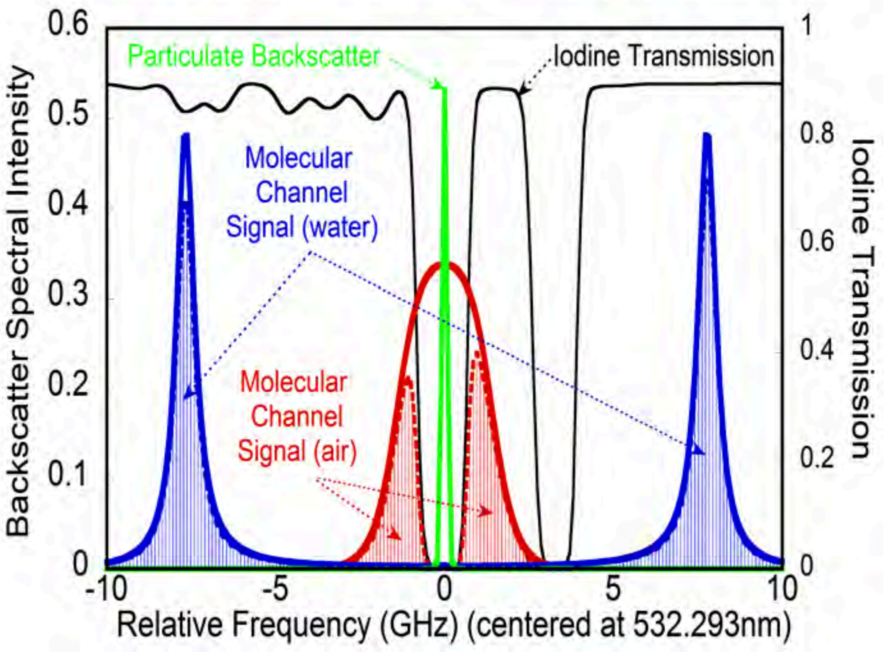
- Tuning laser to an I_2 absorption line near 532 nm blocks particulate backscatter from 'Molecular Channel'
- 2 channels enable 2 equations to solve for 2 unknowns: aerosol backscatter and extinction
- Filtering can be implemented interferometrically at any wavelength

High Spectral Resolution Lidar – ocean profiling

$$P(r,\lambda) = \frac{C(r,\lambda)}{r^2}\left[\beta_m(r,\lambda) + \beta_p(r,\lambda)\right]e^{-2\left[\int_0^r \sigma_m(r',\lambda)+\sigma_p(r',\lambda)+\sigma_g(r',\lambda)\right]dr'}$$

- Known parameters
- Retrieved parameters



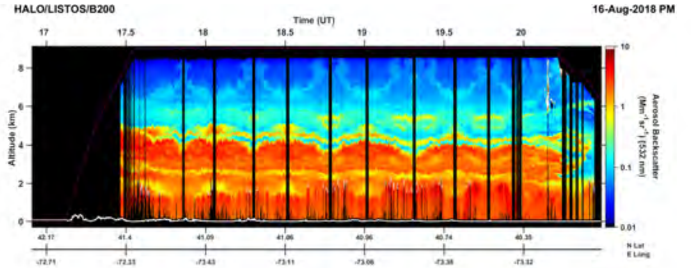


- Brillouin scattering shifts signal in water by ~+/8 GHz
- Same 2 channels enable 2 equations to solve for 2 unknowns: hemispherical backscatter ($\beta_p(\pi)$) and diffuse attenuation (K_d)
- Filtering can be implemented interferometrically at any wavelength

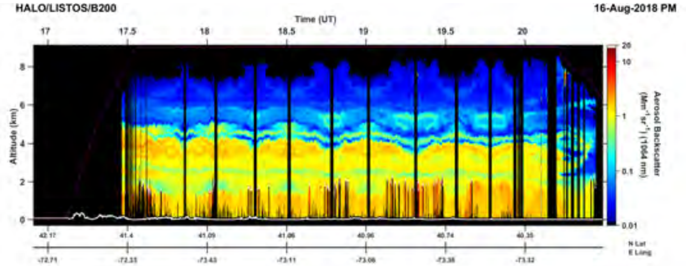
High Spectral Resolution Lidar – Atmospheric products

Aerosol Extensive Parameters

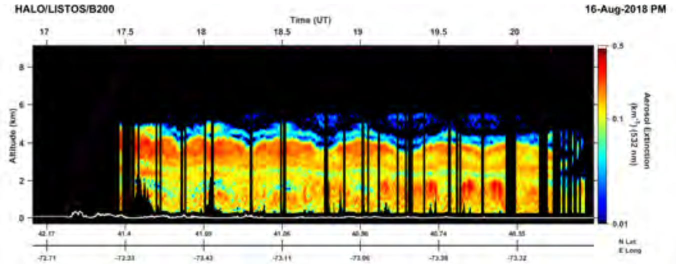
532 nm Backscatter



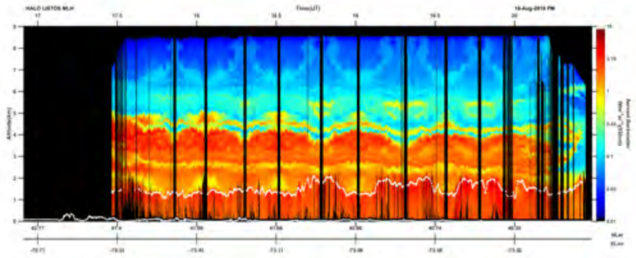
1064 nm Backscatter



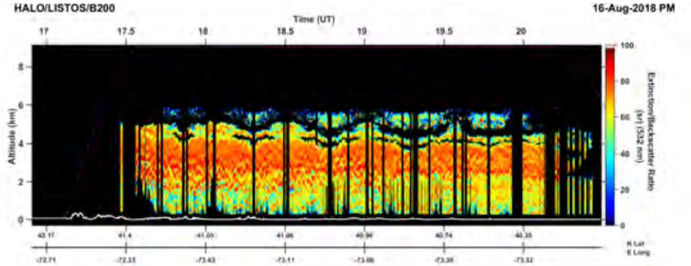
532 nm Extinction



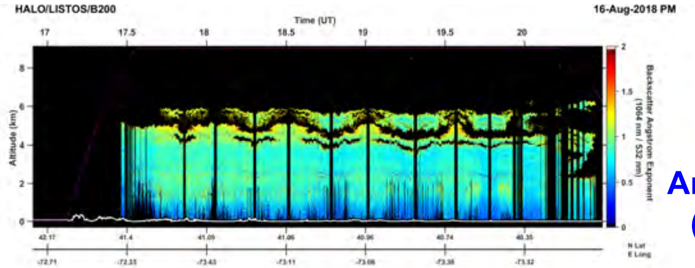
Mixed Layer Heights



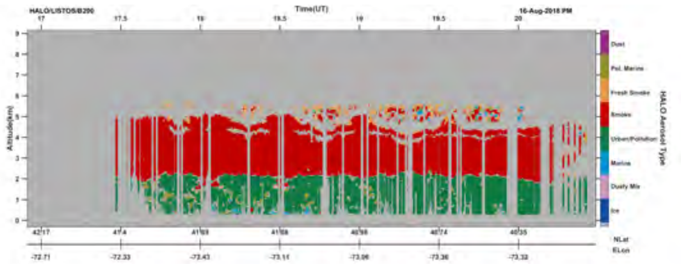
Aerosol Intensive Parameters



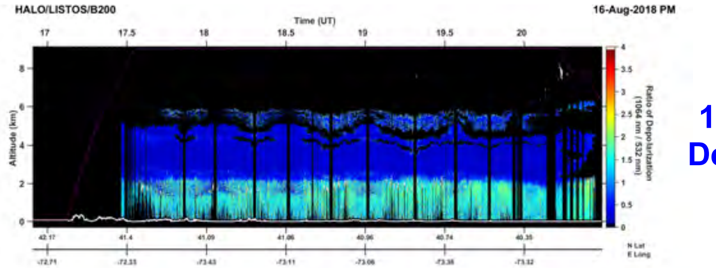
532 nm Lidar Ratio



1064/532 nm Backscatter Angstrom Coeff. (particle size)

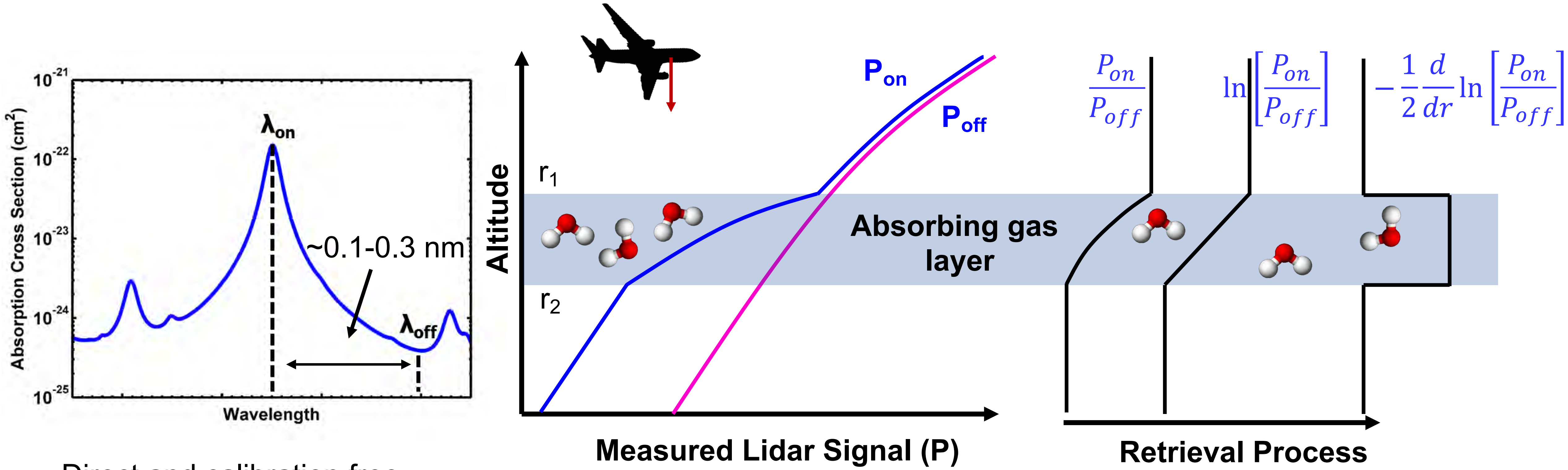


Aerosol Typing



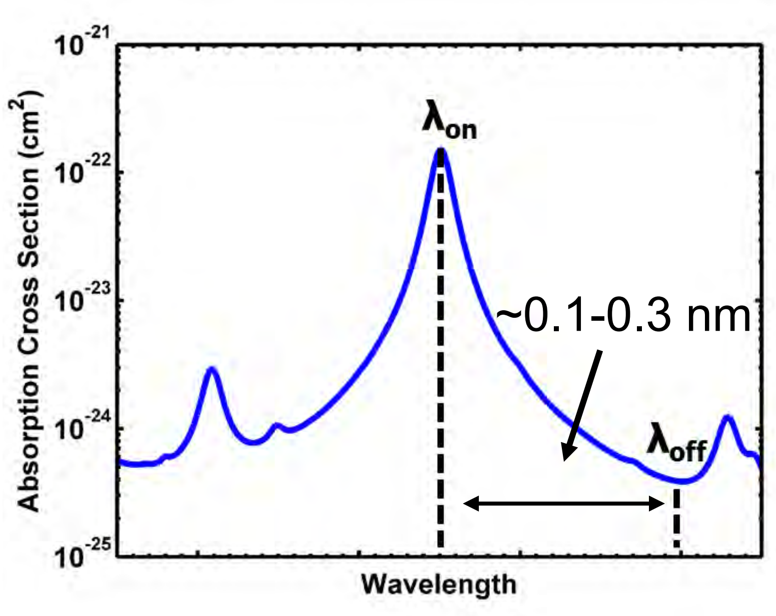
1064/532 nm Depolarization Ratio

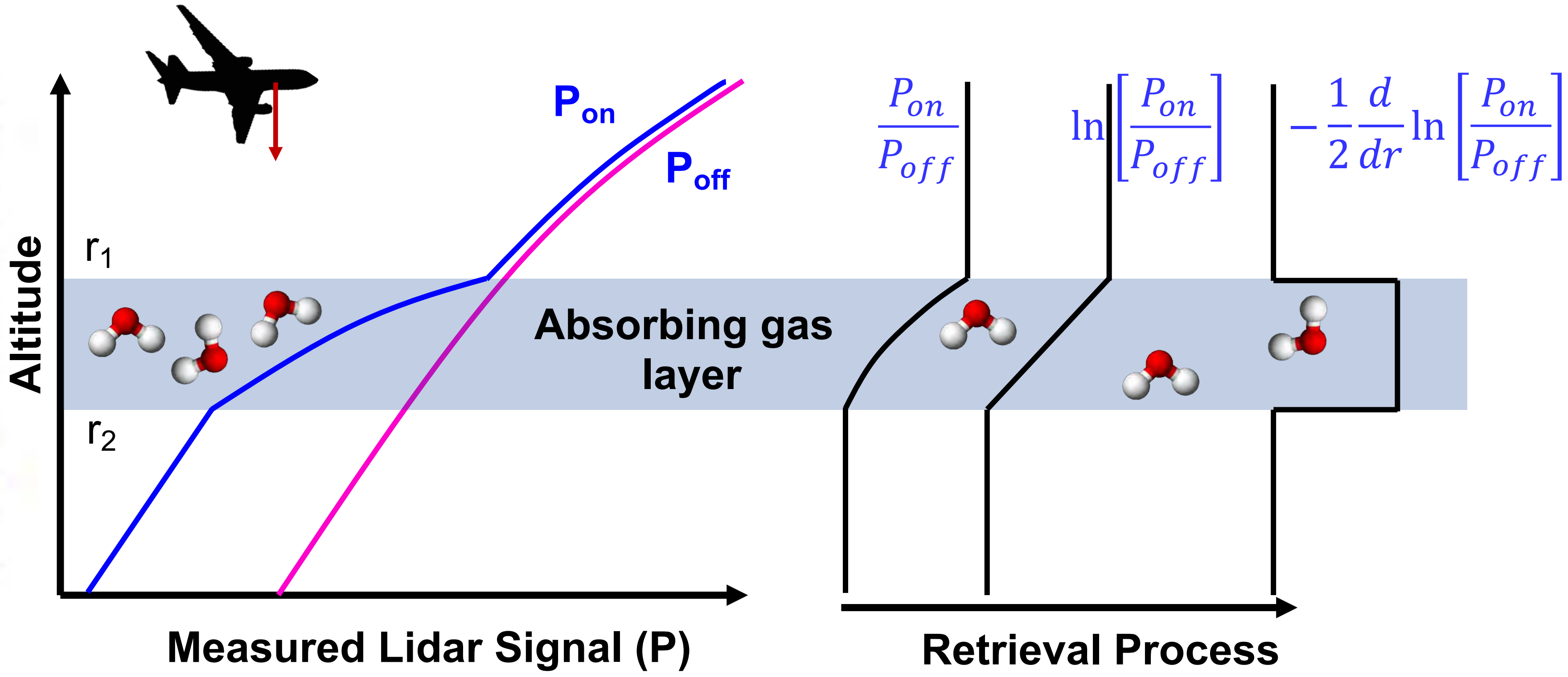
Differential Absorption Lidar (DIAL) – Principles and Characteristics



- Direct and calibration free

Differential Absorption Lidar (DIAL) – Principles and Characteristics

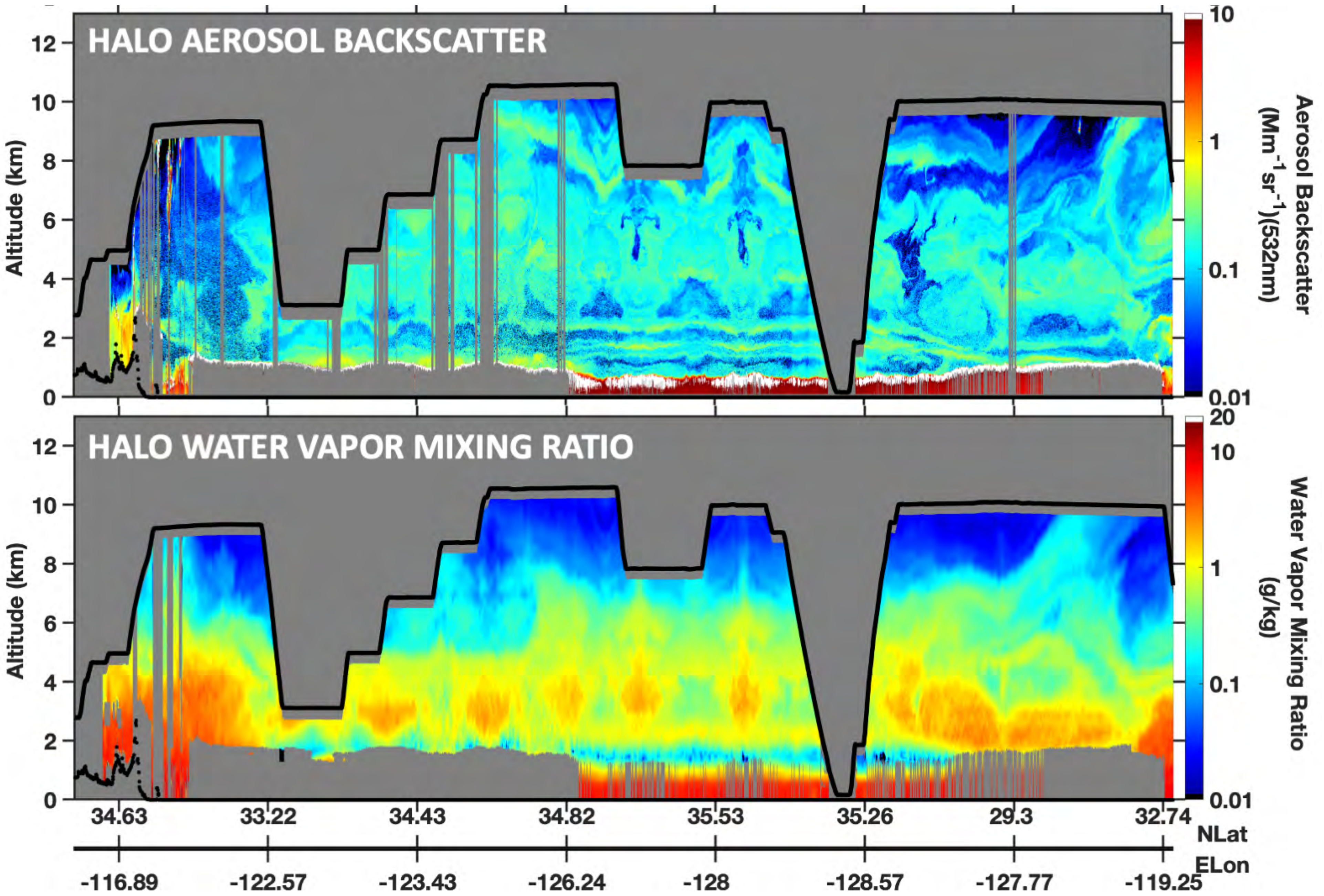




- Direct and calibration free
- Measurements in lower atmosphere are independent of humidity and aerosol signals aloft
- Direct measure of uncertainty for every retrieval within the profile

Retrieved Number Density Profile

$$n(r) = \frac{1}{2\Delta r \Delta\sigma(r)} \ln\left(\frac{P_{off}(r_2)}{P_{on}(r_2)} \cdot \frac{P_{on}(r_1)}{P_{off}(r_1)}\right)$$

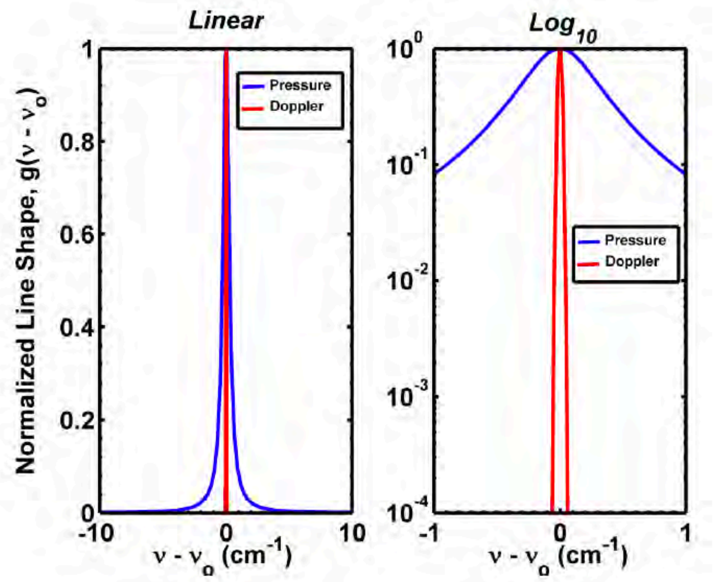

HALO AEROSOL BACKSCATTER
HALO WATER VAPOR MIXING RATIO
Altitude (km)
Aerosol Backscatter (Mm-1 sr-1)(532nm)
Water Vapor Mixing Ratio (g/kg)
NLat
ELon
34.63
33.22
34.43
34.82
35.53
35.26
29.3
32.74
-116.89
-122.57
-123.43
-126.24
-128
-128.57
-127.77
-119.25

Primary Sources of Systematic Error in DIAL/HSRL

- Knowledge of transmitted laser wavelength
- Knowledge of laser spectral shape
- Mismatch in volume backscatter between on and off wavelengths
- Beam pointing jitter between on and off wavelengths
- Pressure shifts of absorption lines
- Temperature sensitivity of absorption line and lack of accurate temperature profiles
- Rayleigh-Doppler broadening of elastic backscatter signal

Spectral Shape and knowledge of transmitted wavelength

- Linewidth and stability requirement of the laser driven by accuracy requirements in the upper trop.
  - Absorption line is pressure broadened to ~ 3-5 GHz in the lower troposphere – requires ~100-300 MHz linewidth and stability to maintain systematic errors below 5%
  - Absorption line is Doppler broadened to ~1-2 GHz in the upper troposphere – requires on order ~60 MHz linewidth and stability to maintain systematic errors below 5%



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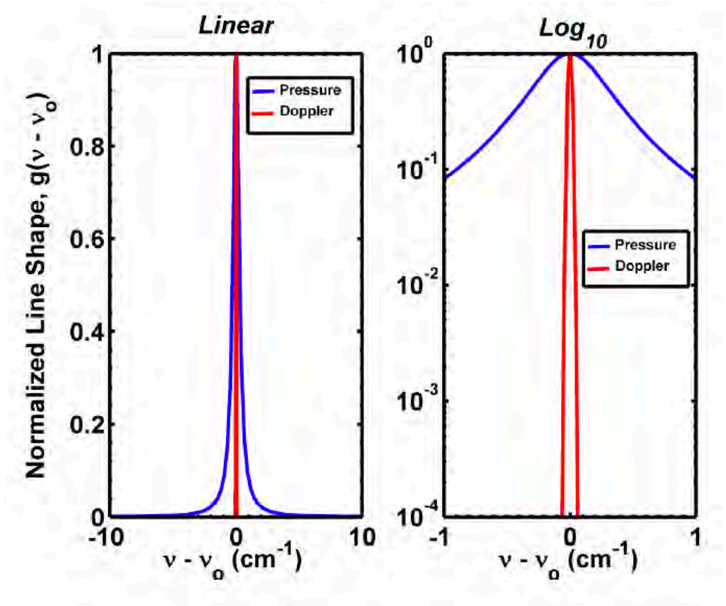
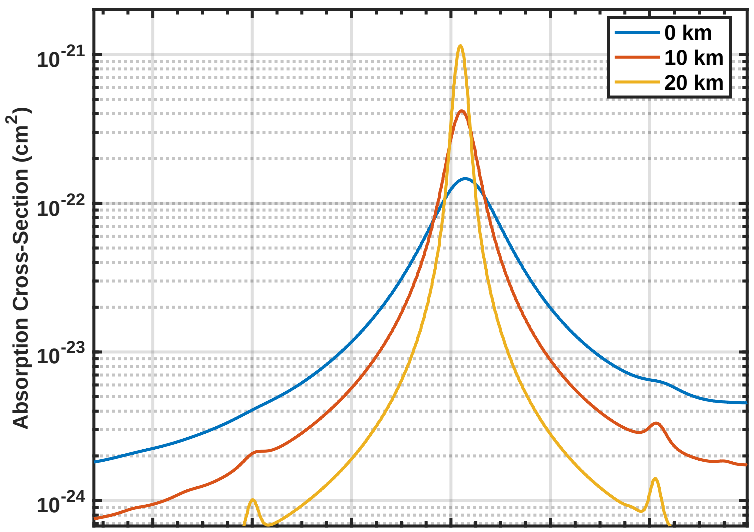
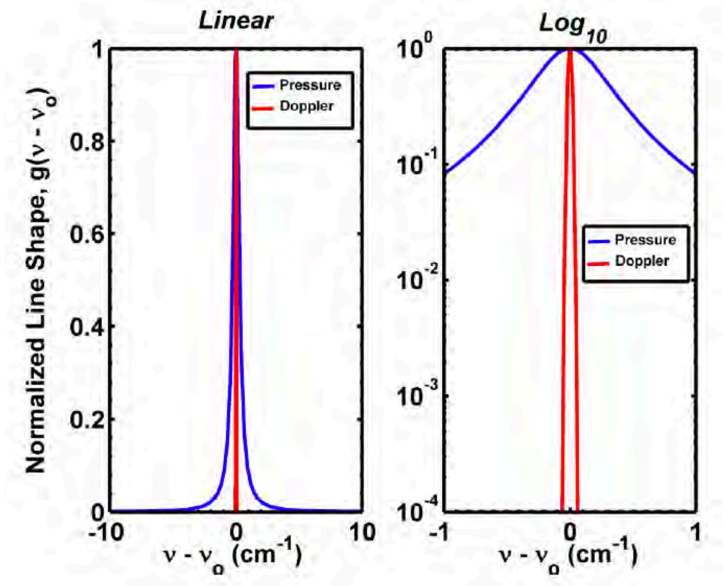
  - The effective line width is a convolution of the Doppler (Gaussian) and Pressure (Lorentz) broadened linewidths and described by a Voigt function.

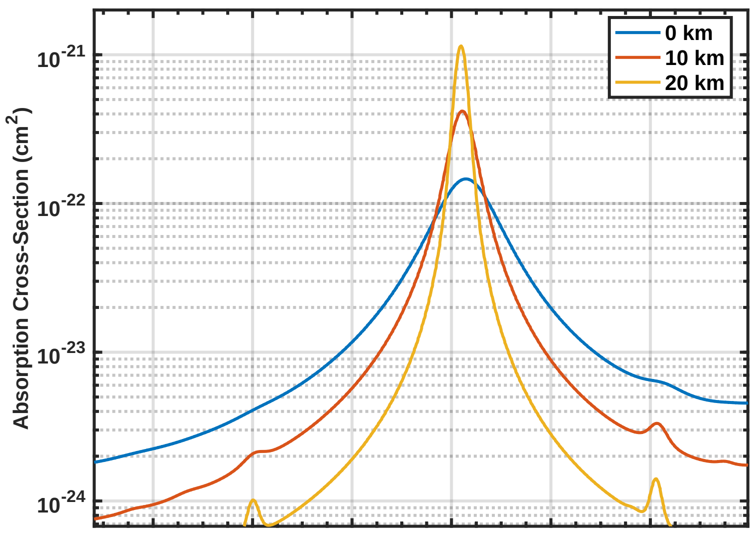


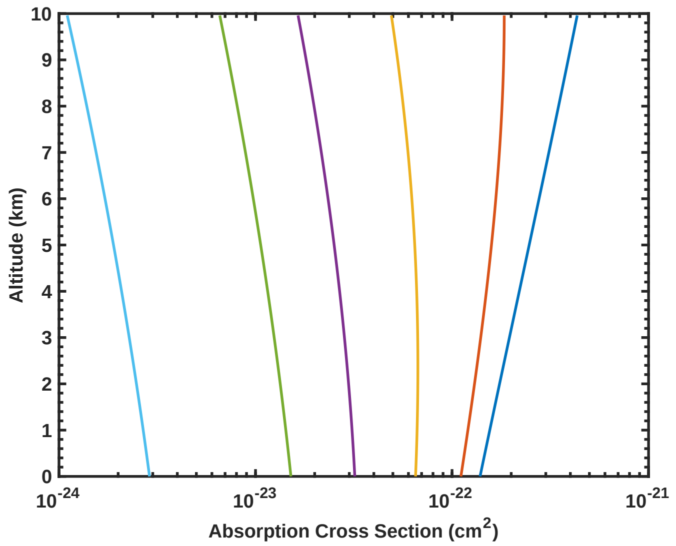


Spectral Shape and knowledge of transmitted wavelength

- Linewidth and stability requirement of the laser driven by accuracy requirements in the upper trop.
- Spectral purity (∝) – Defined as the ratio of the energy within the acceptable spectral limits to the total energy transmitted. Acceptable limit is often set to the Doppler broadened regime of ~1-2 GHz
- Laser tunability driven by requirement to measure water vapor over large dynamic range
  - Water vapor concentration varies over 4 orders of magnitude from the surface to the Upper troposphere/lower stratosphere
  - At least 3 online wavelengths are required to profile water vapor from 20km down to the surface
  - Wavelengths on the peak and wing of the line have sensitivity to the upper and lower troposphere, respectively
  - Tunability is required on a shot-to-shot basis to sample the same atmospheric volume between all transmitted wavelengths







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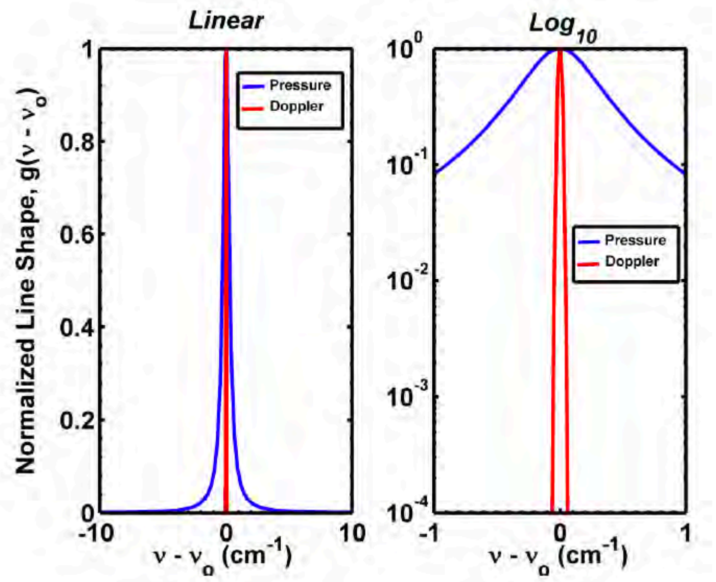

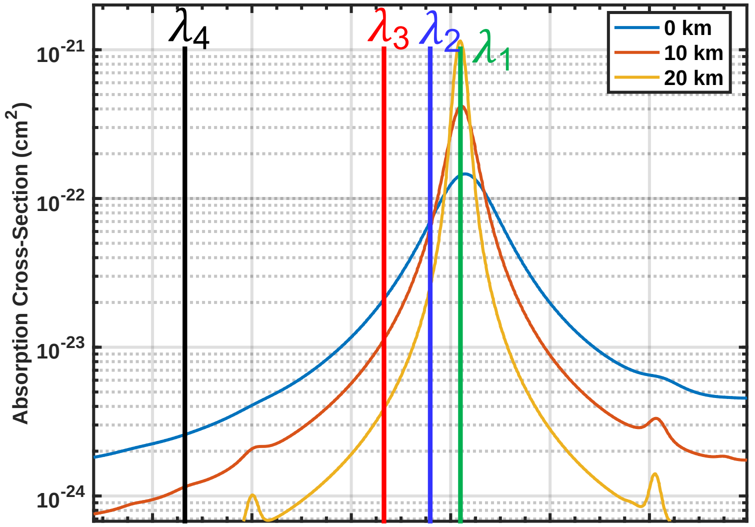

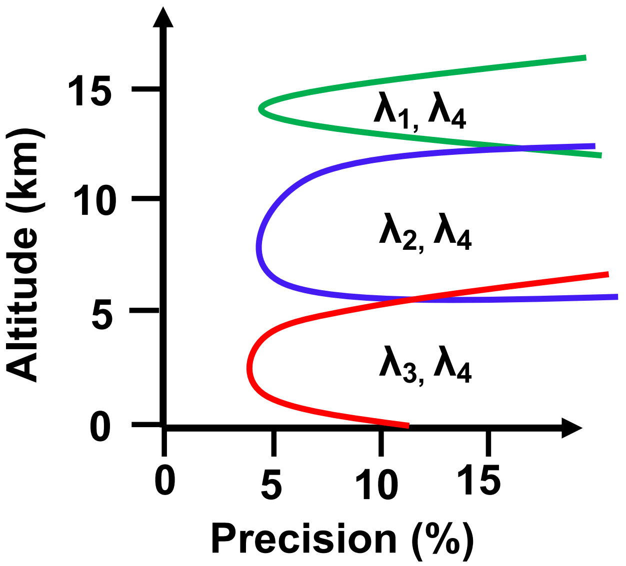

Spectral Shape and knowledge of transmitted wavelength

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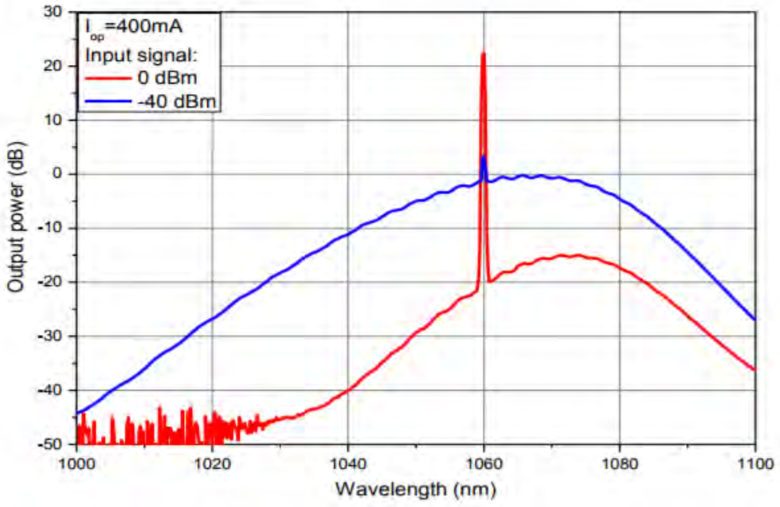
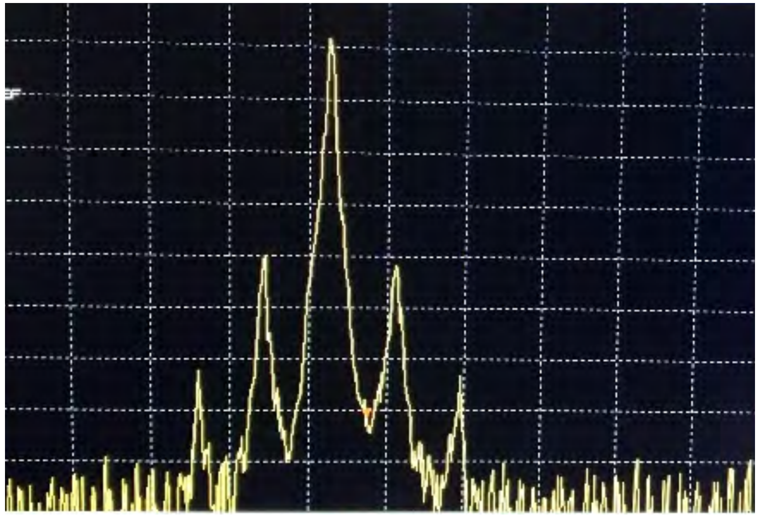
- Spectral purity (∝) – Defined as the ratio of the energy within the acceptable spectral limits to the total energy transmitted. Acceptable limit is often set to the Doppler broadened regime of ~1-2 GHz
  - Spectral impurity can result from ASE (amplifiers) or higher order axial modes (injection seeded systems) and is treated as unabsorbed laser energy and thereby reduces the 'effective' absorption cross section
  - The unabsorbed energy is treated like offline signal and the online signal is modified as: $S_{on} = S_{off}\left[(1-\propto)+\propto e^{-2\tau}\right]$
  - In general, spectral purity of better than 100:1 is required for profiling in the lower troposphere.
  - > 1000:1 required for profiling in the mid-upper troposphere

ASE from Semiconductor Laser Master Oscillator



Poor Injection Seeding

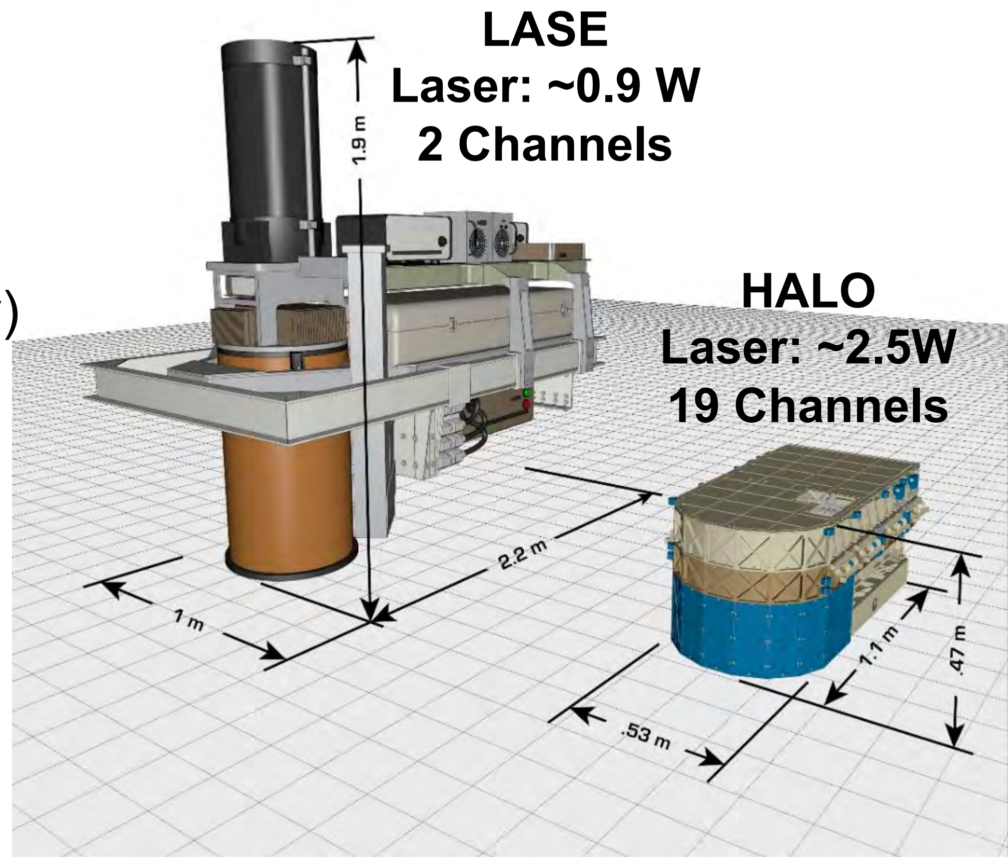


DIAL and HSRL share similar laser requirements

- Laser requirements for DIAL and HSRL are similar, but not identical
- Both require single frequency and tunable laser sources to interrogate molecular absorption lines (or tune to interferometer passband)
- High peak power
  - Overcome solar and detection noise
- High average power (high PRF lasers)
  - ‘freeze’ atmosphere between DIAL on and off measurements
  - HSRL SNR benefits from high average power
- Primary technology focus is on robust laser transmitters:
  - Pulsed lasers
  - Seed lasers

Technology and Scientific Motivation

- Develop a more capable, robust, and operationally flexible replacement for the LASE water vapor DIAL
  - H_2O DIAL, CH_4 DIAL/IPDA, and HSRL
- Airborne science provides unique contributions to atmospheric characterization
  - Planetary Boundary layer processes (2017 Decadal Survey)
  - Weather and dynamics
  - Upper atmospheric research program
  - Quantify biogenic and anthropogenic XCH_4 fluxes (2017 Decadal Survey)
  - Satellite calibration/validation and model evaluation
- Technology testbed for risk mitigation of future satellite programs



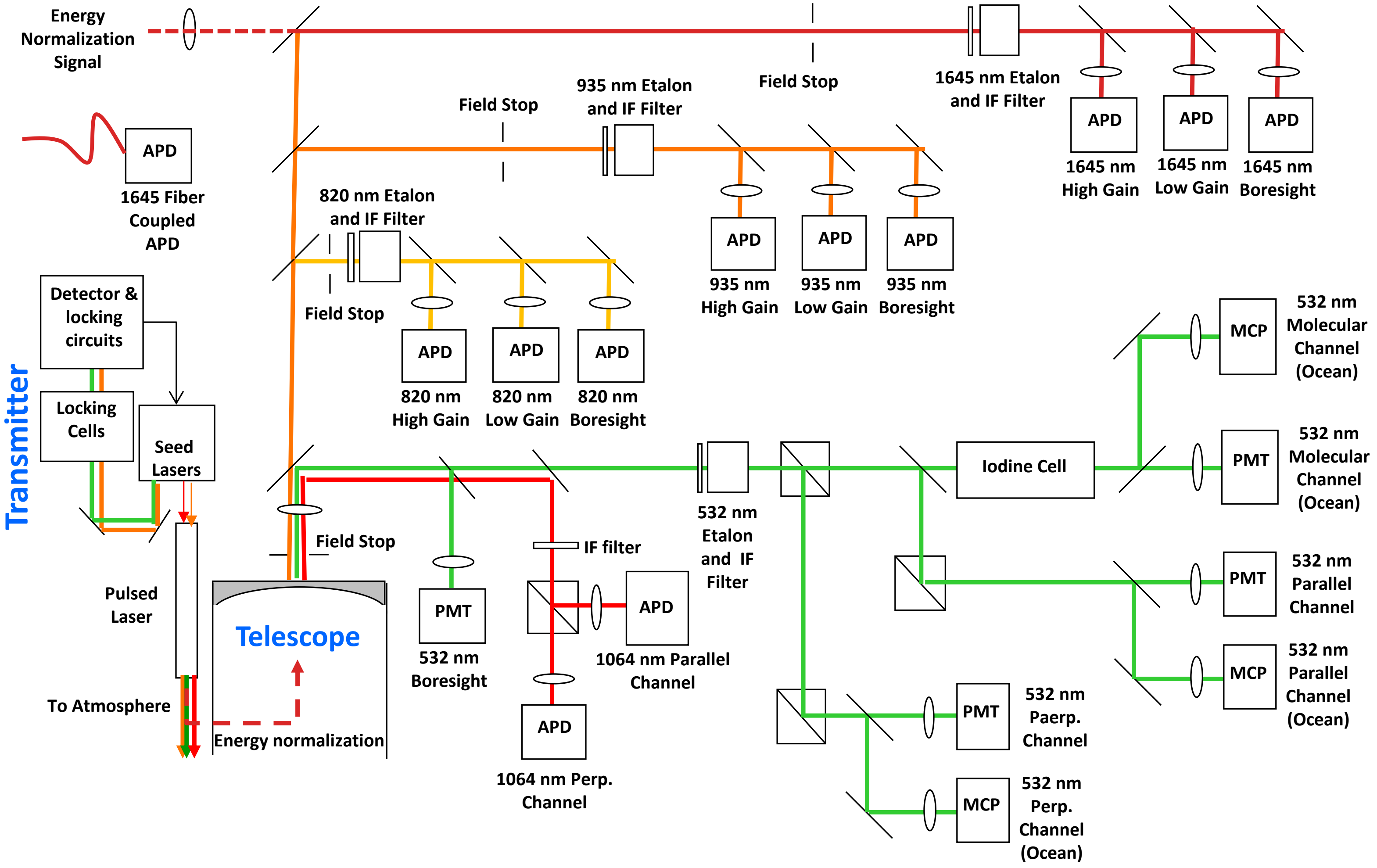
FIBERTEK, INC.
ESTO
EARTH SCIENCE TECHNOLOGY OFFICE
WELCH MECHANICAL DESIGNS

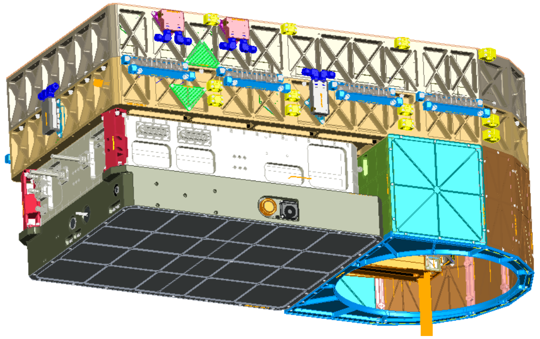
HALO System Architecture

- H_2O DIAL : 4 λDIAL
  - Accuracy: <5%
  - Precision: <10%
  - Sensitivity: .001-30 g/kg
  - PWV: σ~1%, bias ~ 1%

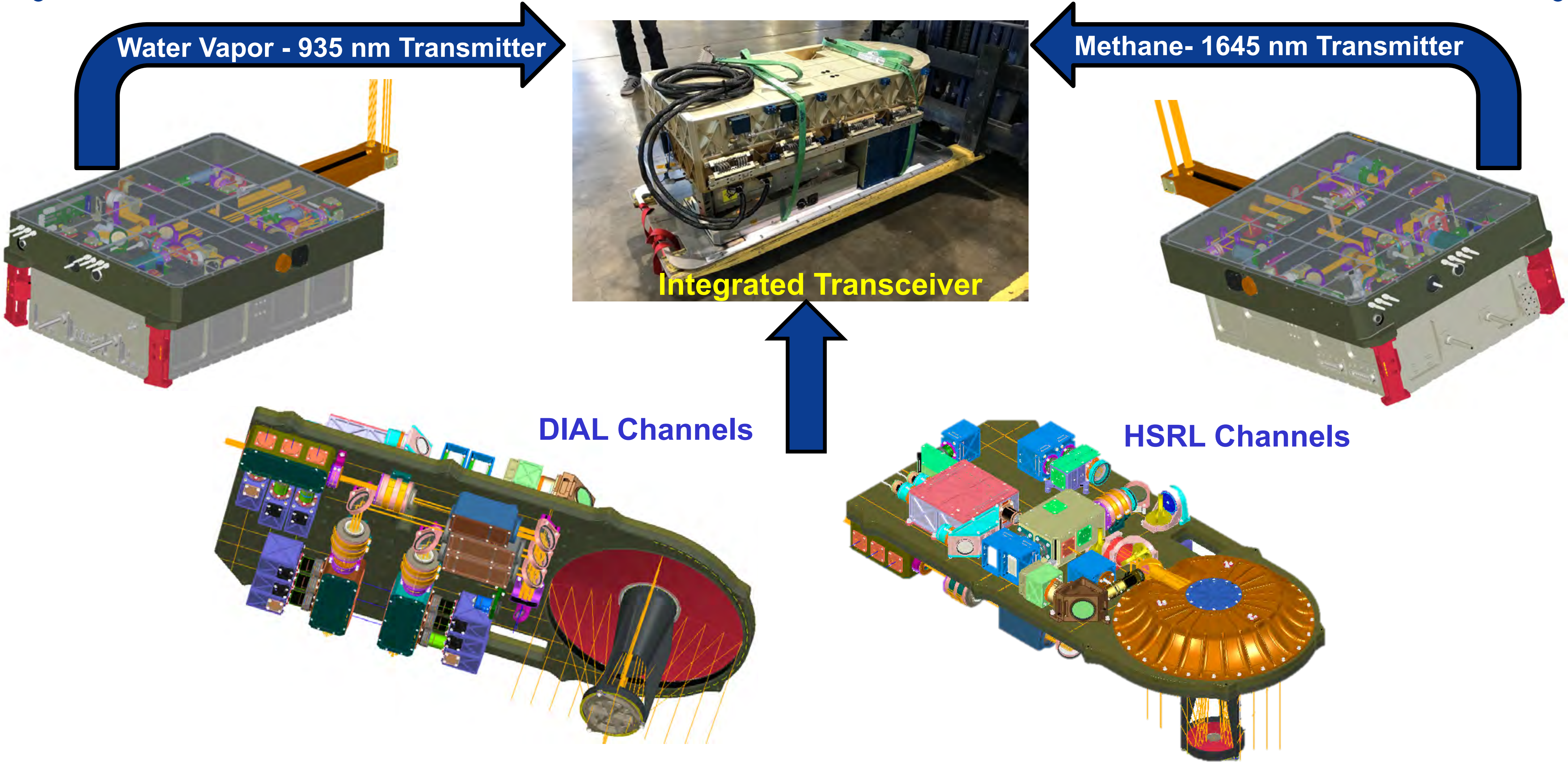
- CH_4 IPDA : 2λ IPDA
  - Column XCH_4: Precision (accuracy) 8 ppb (<4ppb)

- HSRL : 1-α, 2-β, 2-δ
  - HSRL at 532 nm
  - Backscatter 1064 nm
  - Depolarization at both 532, 1064 nm



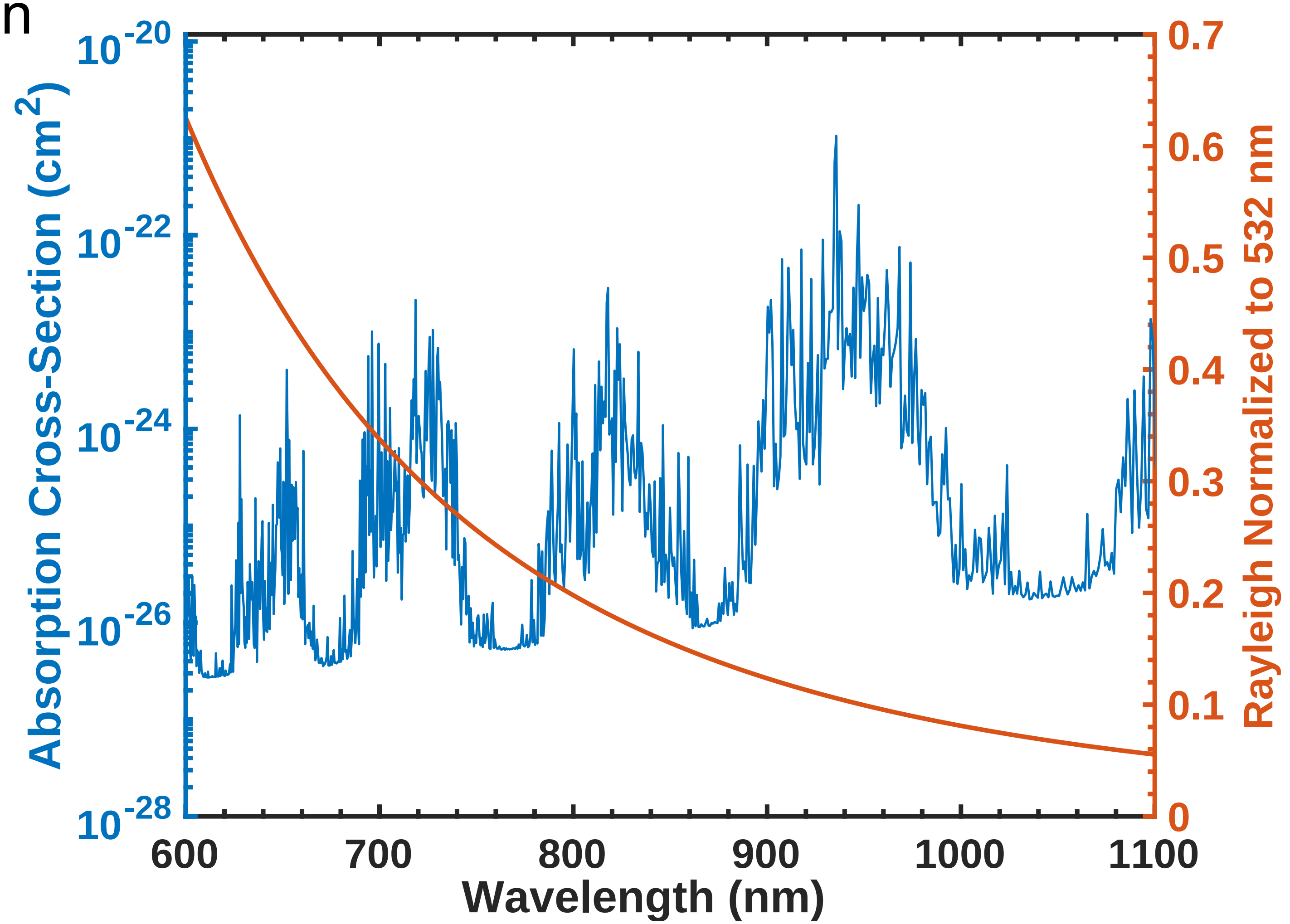


Integration and Flight Demonstrations on NASA Aircraft



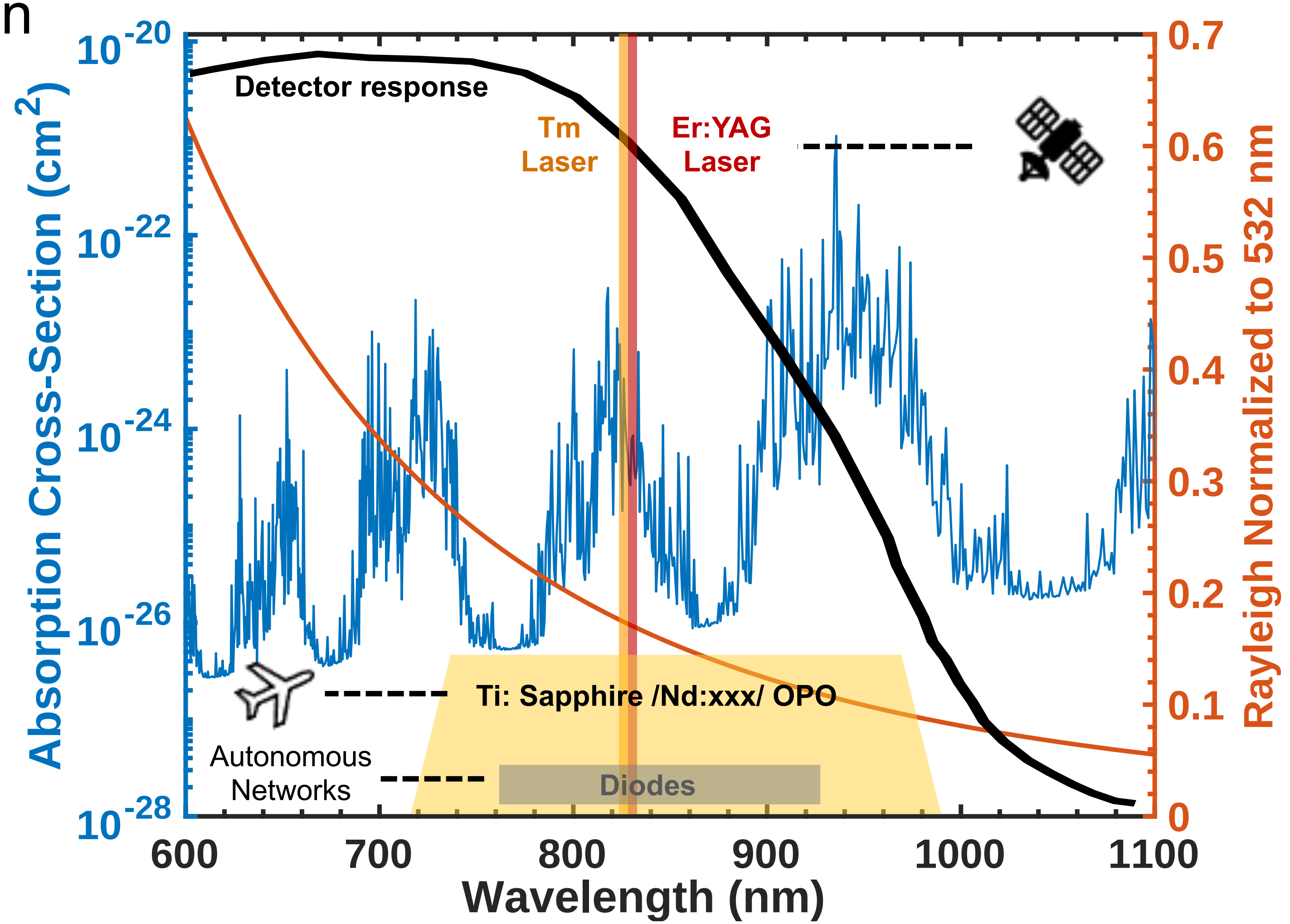
Practical Considerations

- Design and performance depends on
  - Appropriate line strength
  - Atmospheric scattering
  - Detection efficiency
  - Laser technology
- Different Considerations for ground, air, and space-based systems
  - Laser physics
  - Laser electrical efficiency
  - Peak and average laser power
  - Detection efficiency and noise



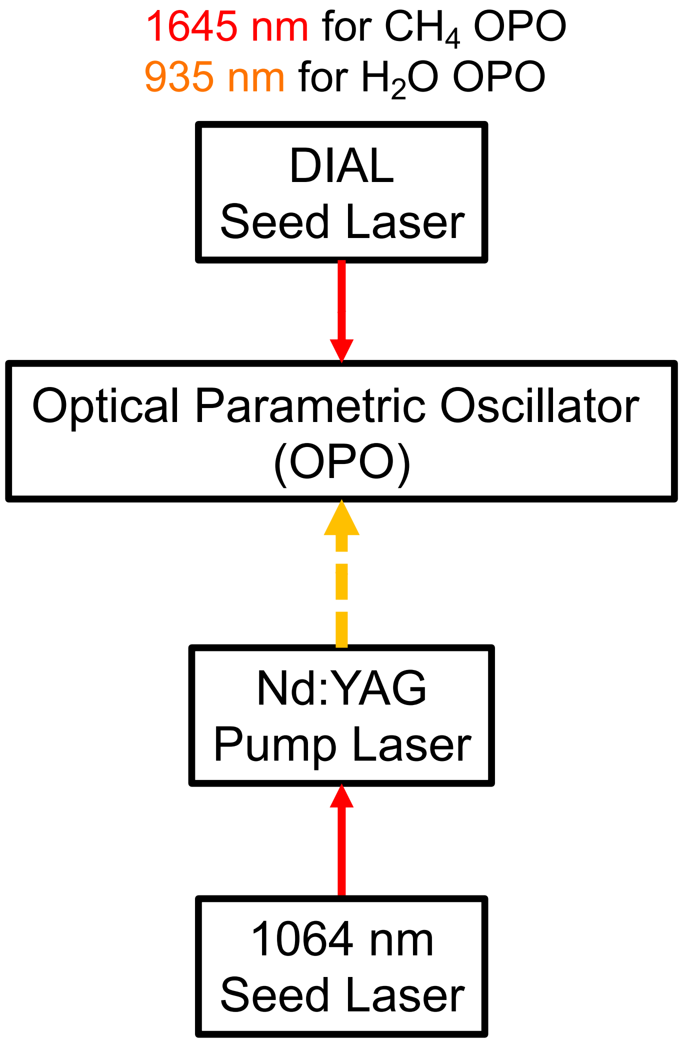
Practical Considerations

- Design and performance depends on
  - Appropriate line strength
  - Atmospheric scattering
  - Detection efficiency
  - Laser technology
- Different Considerations for ground, air, and space-based systems
  - Laser physics and complexity
  - Laser electrical efficiency
  - Peak and average laser power
  - Detection efficiency and noise



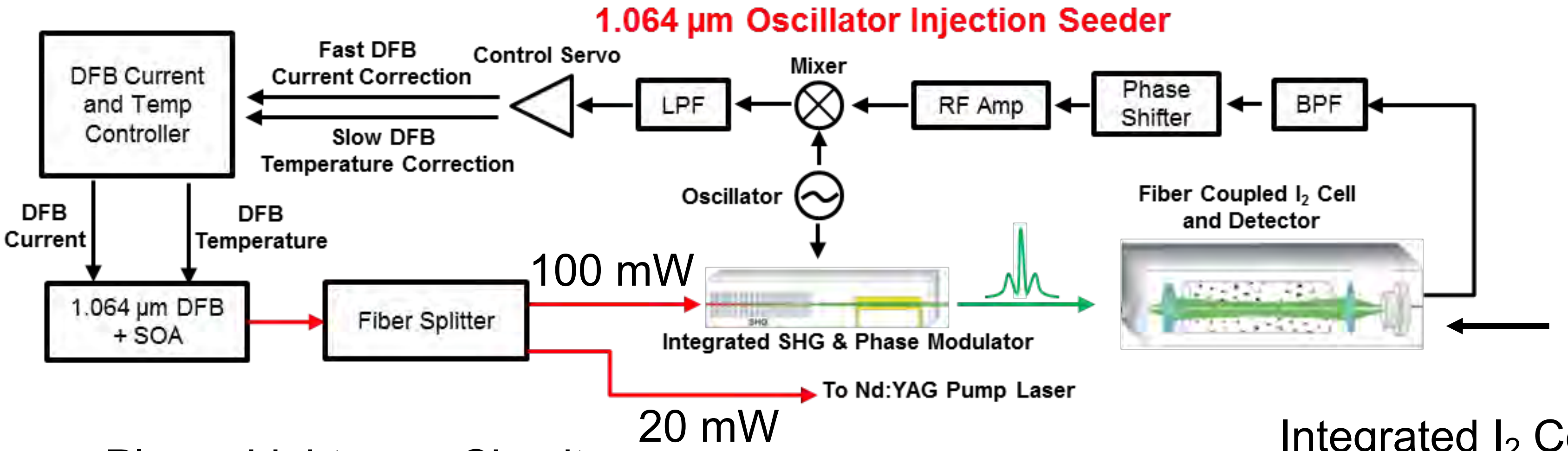
Laser System Architecture

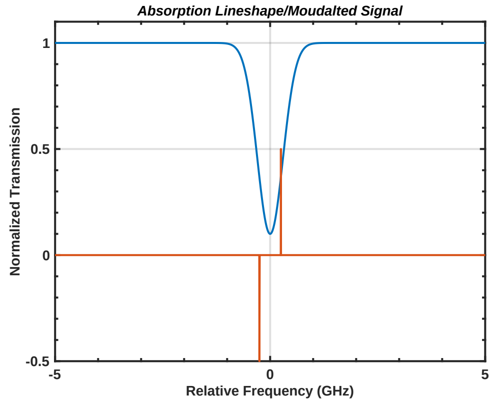
- Pulsed lasers can have high peak and average power but exhibit poor spectral properties
- Semiconductor lasers have good spectral properties but suffer from low power
- Injection seeding of pump and OPO laser cavities employed to enable tunable, single frequency transmitters
- Seed Laser Requirements
  - >15 mW CW output power to pulsed laser
  - <20 MHz linewidth
  - Frequency stabilized to <~10 MHz with respect to atomic transition
  - Frequency agile
    - On/off sampling < 1 ms (to freeze the atmosphere)
    - Tunable over 200-400 pm
  - Stable over environment
  - Compact packaging



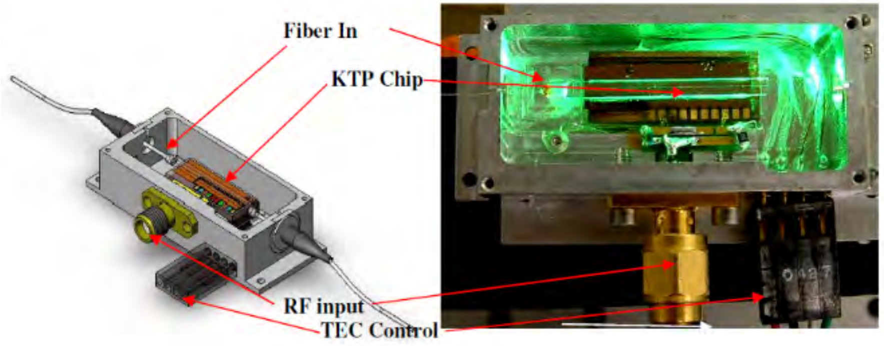
HSRL Seed Laser: Architecture

- 1 U 1064 nm laser for injection seeding both Fibertek OPO pump lasers
- Frequency stabilized to I_2 absorption line at 532 nm using PDH approach ensures backscattered photons are resonant with I2 filter in receiver

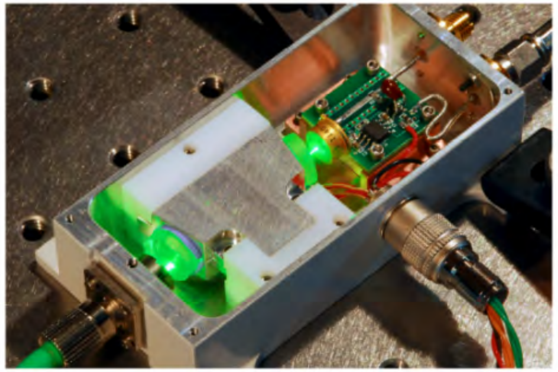




Planar Lightwave Circuit

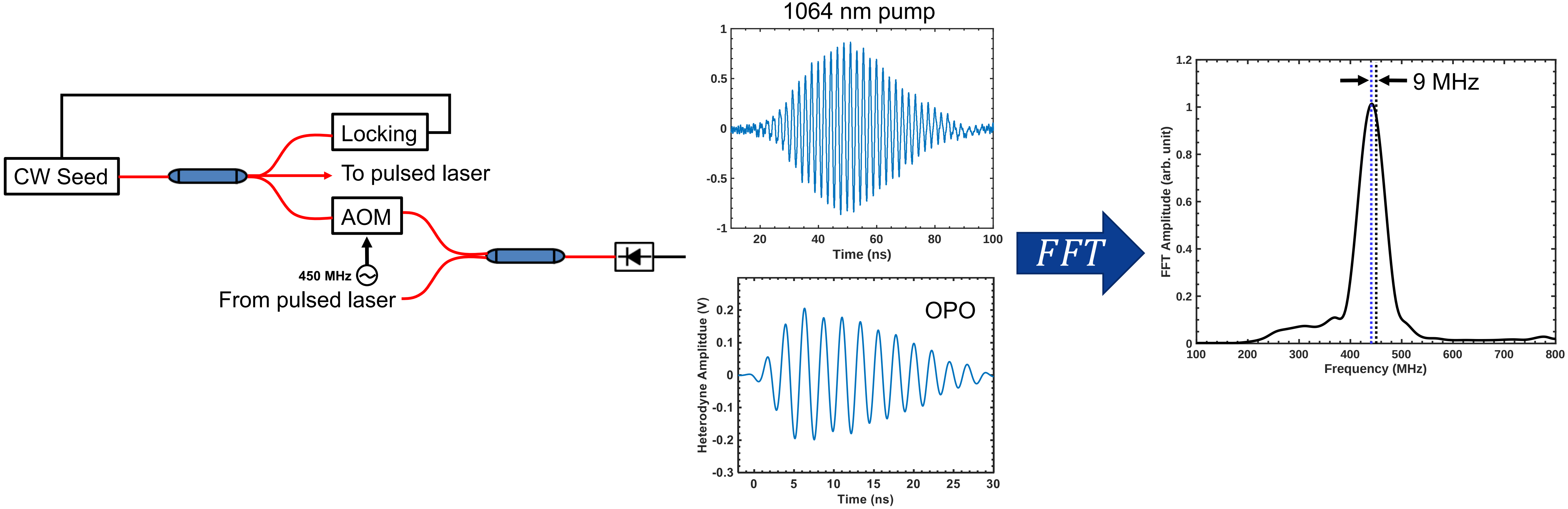


Integrated I_2 Cell

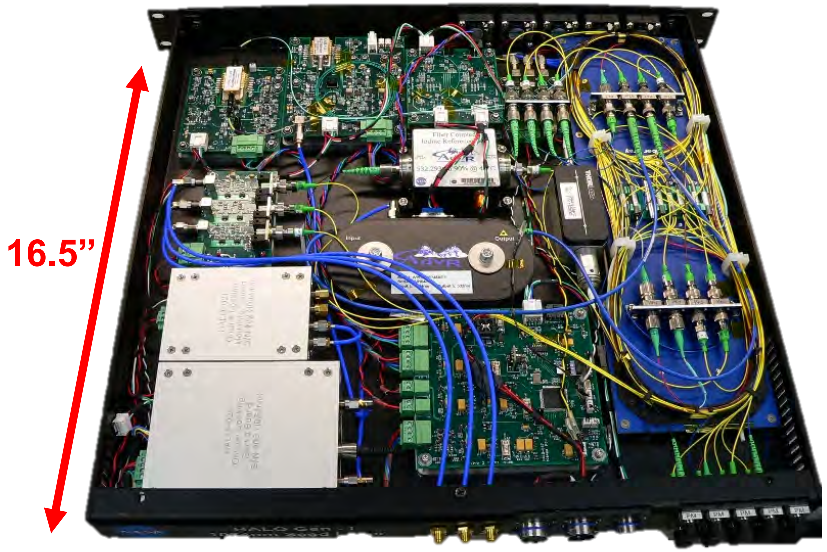


HSRL Seed Laser: Frequency Offset Diagnostics

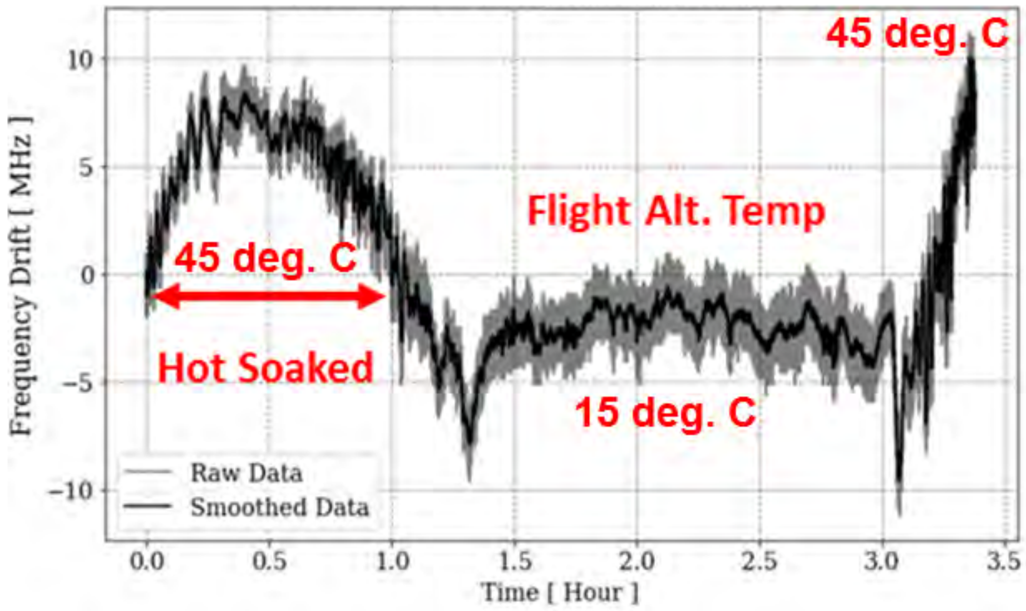
- 1 U 1064 nm laser for injection seeding both Fibertek OPO pump sources
- Frequency stabilized to I_2 absorption line at 532 nm using PDH approach
- Optical heterodyne channels between pulsed and seed lasers
  - Critical for real time assessment of offset between seed and pulsed laser



HSRL Seed Laser: 1064 nm



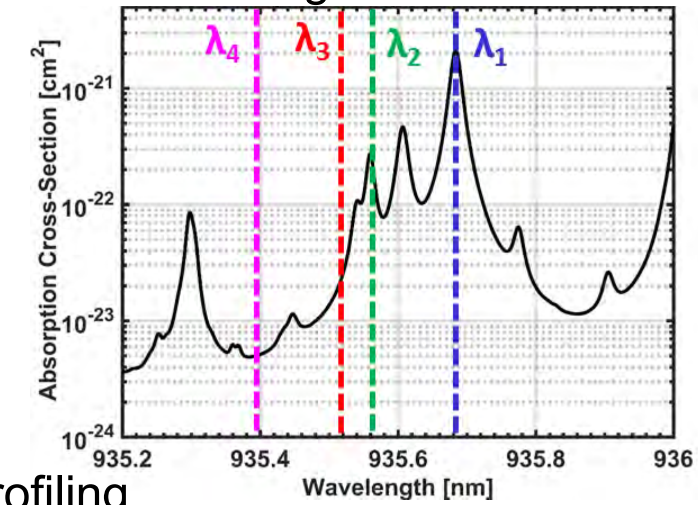
- Compact design allows for operation on wide range of aircraft including automatous operations on high altitude NASA ER-2
- Good thermal and polarization management results in stable performance over environment



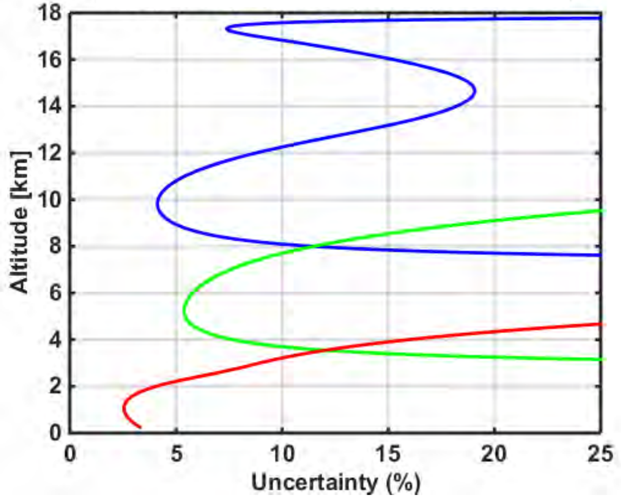
DIAL Seed Laser: 935/1645 Requirements

H_2O Profiling

Targeted Lines



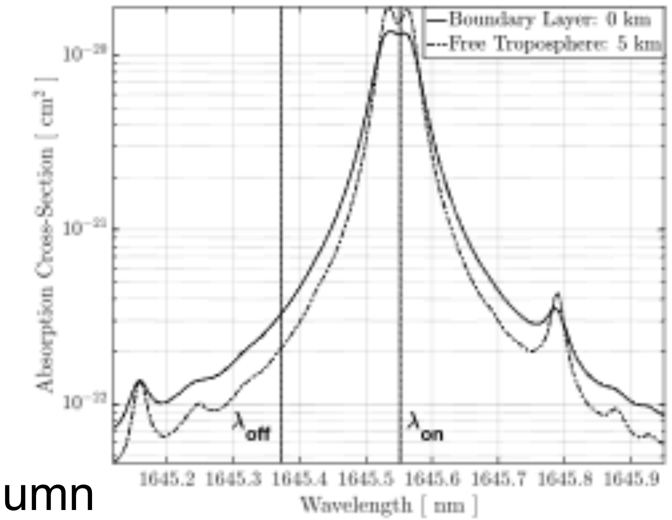
Random Error Profiles



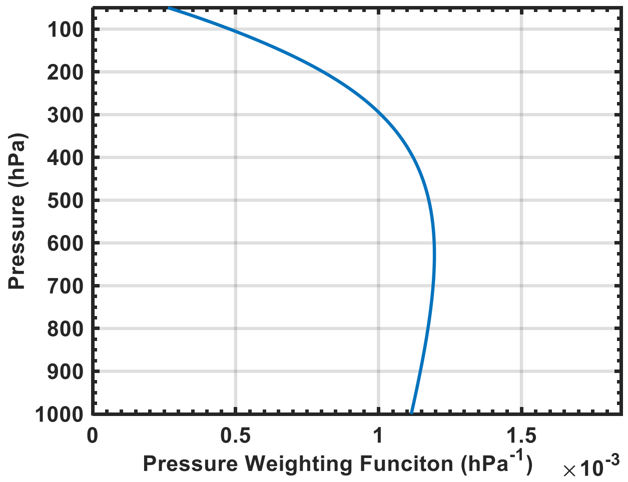
- Four wavelengths required to profile water vapor throughout entire troposphere
- Frequency stability requirement of ~40-60 MHz dictated by stringent error budget for profiling in the upper troposphere
- Wavelength agility over 300 pm (100 GHz at 935 nm)
- Continuous tuning over 20 GHz

CH_4 Column

Targeted Lines

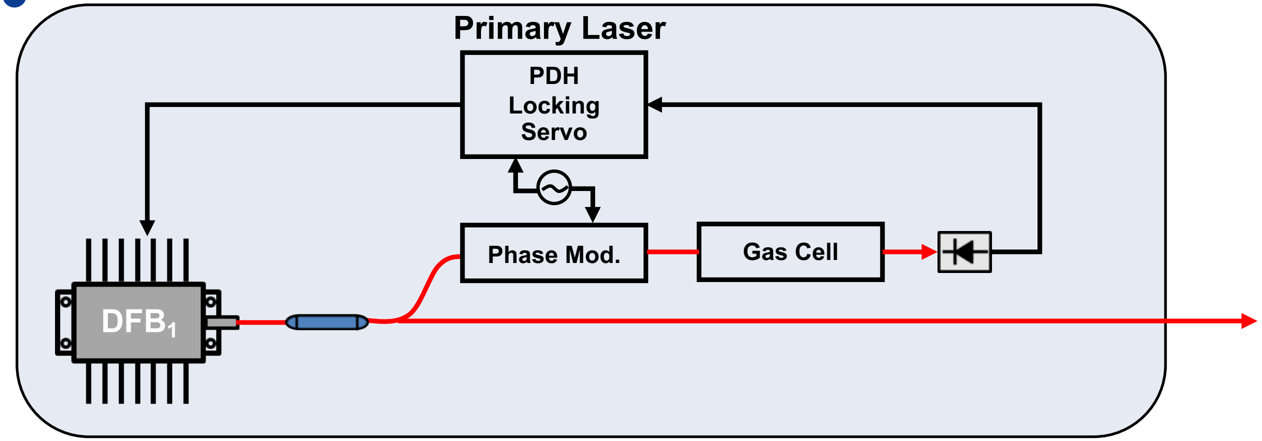


Column Weighting Function



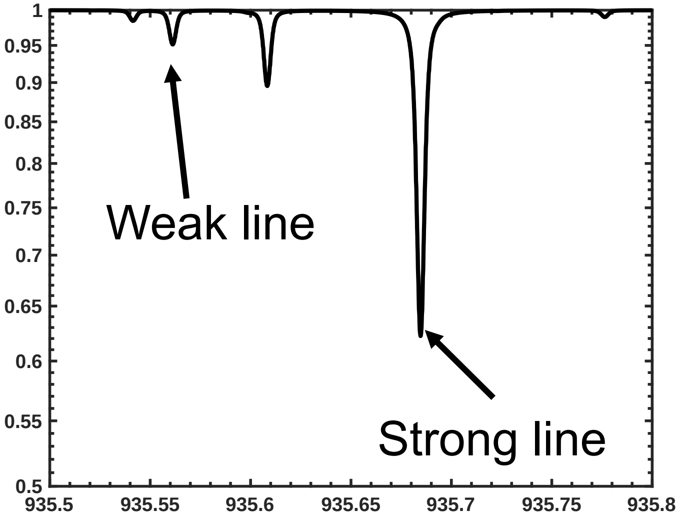
- CH_4 measured over the column using strong surface echo
- Two wavelengths required for uniform sensitivity throughout troposphere
- Better than 10 MHz accuracy to maintain total error budget < 0.5%
- Wavelength agility over 200 pm (~20 GHz at 1645 nm)

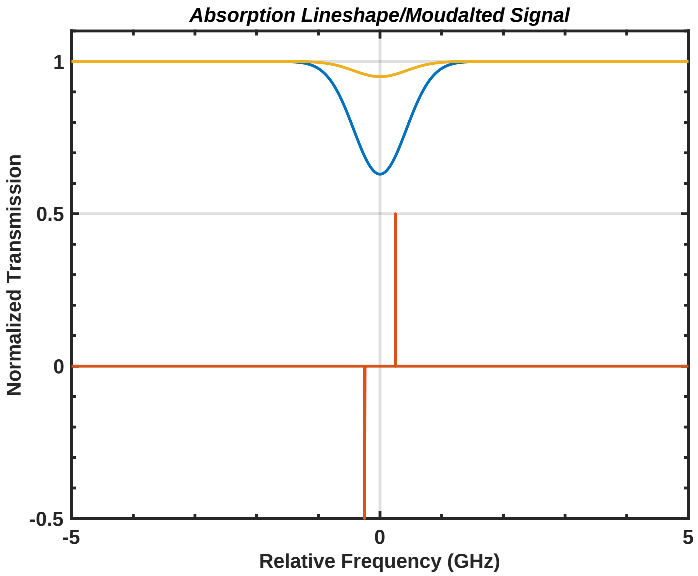
DIAL Seed Laser: Line Center locking

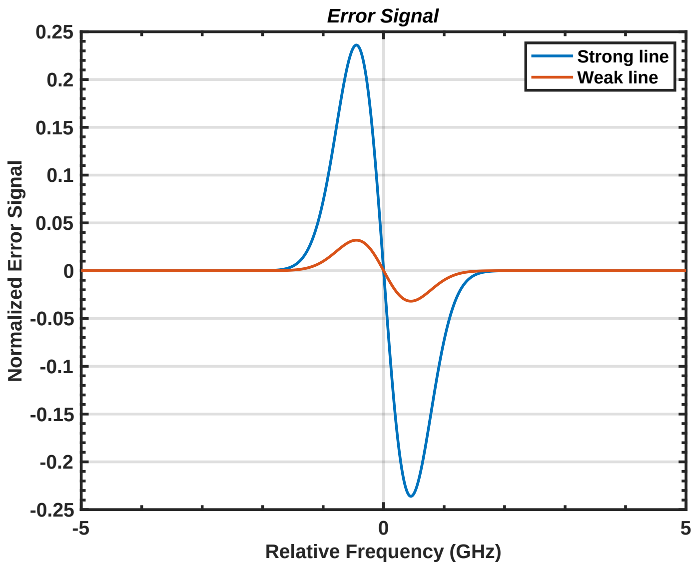


- H_2O and CH_4 DIAL have different locking requirements and hence architectures
- A single frequency 'primary' DFB is stabilized to an absorption line using the PDH technique
  - Magnitude and slope of error signal drives locking stability

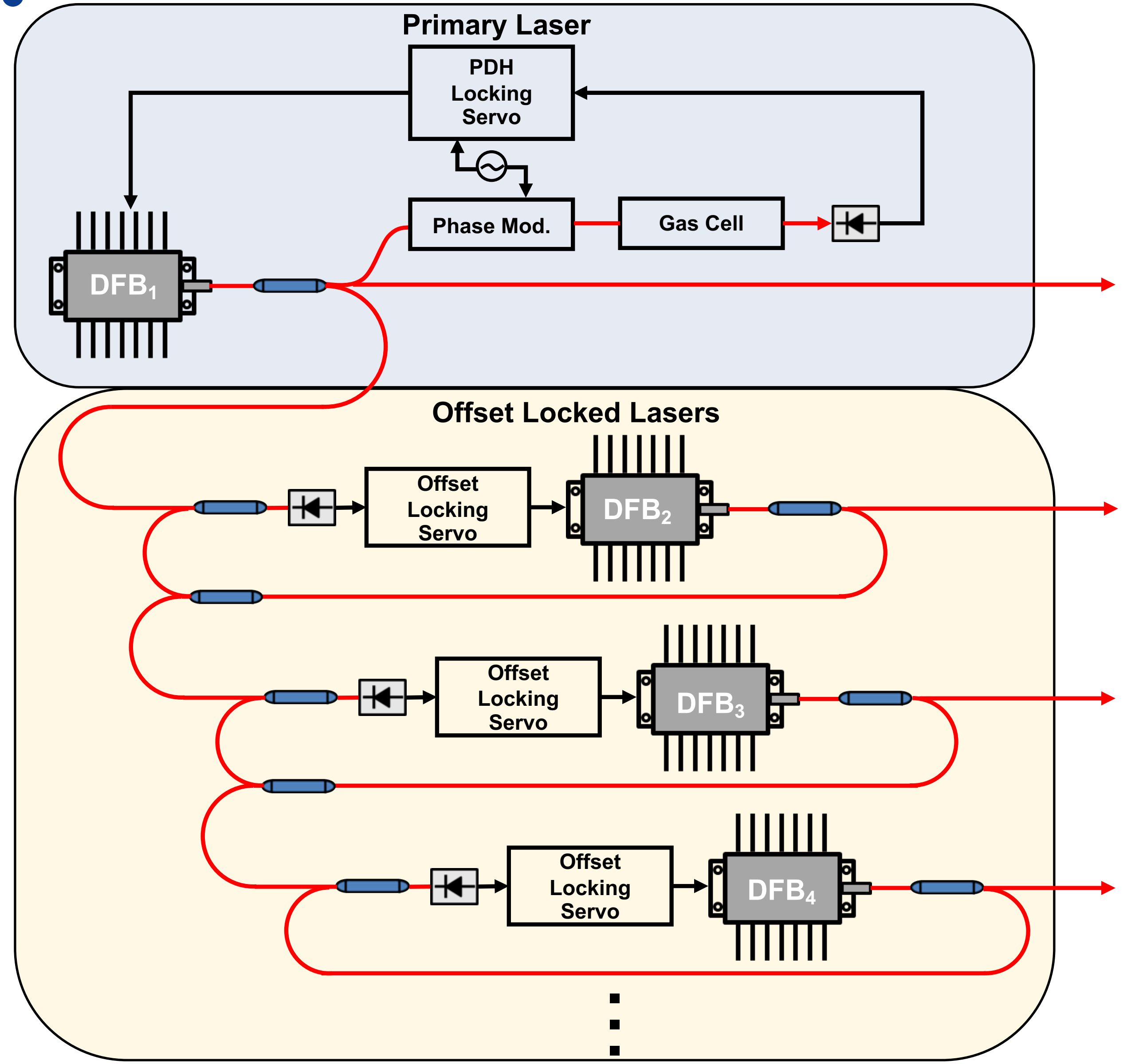
80 cm H_2O Cell Transmission



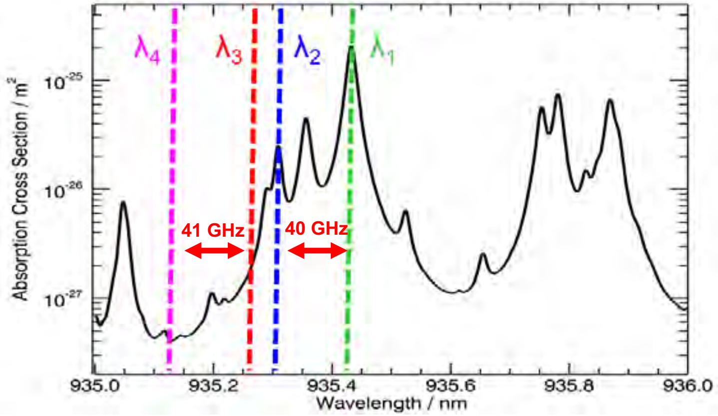




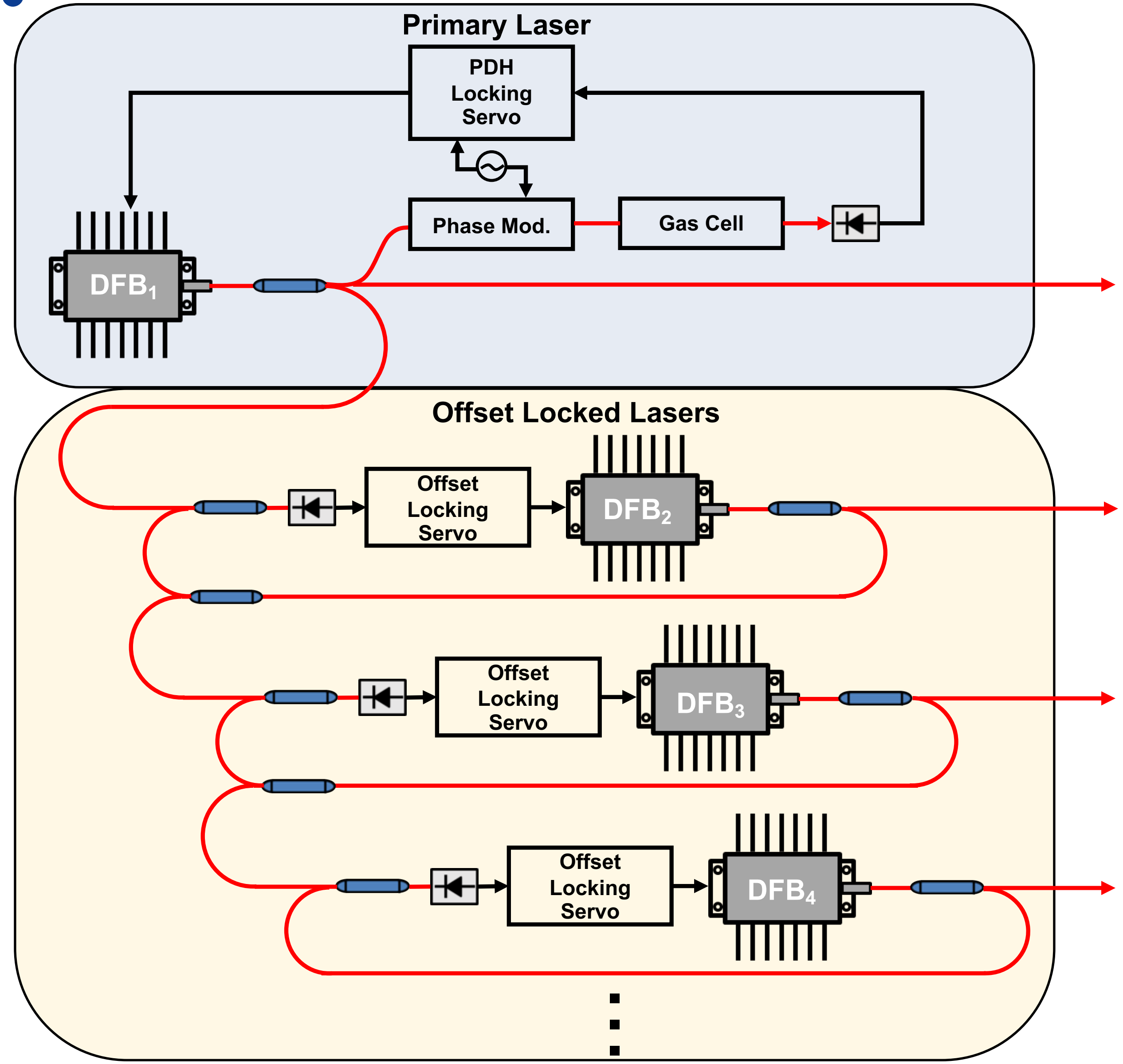
DIAL Seed Laser: Offset Locking



- H_2O and CH_4 DIAL have different locking requirements and hence architectures
- A single frequency 'primary' DFB is stabilized to an absorption line using the PDH technique
  - Magnitude and slope of error signal drives locking stability
- Sideline and offline DIAL wavelengths are 'offset locked' with respect to the primary using an optical phase locked loop (OPLL)
- H_2O DIAL wavelengths spread out over ~100 GHz
  - λ_2 offset locked 40 GHz with respect to λ_1
  - λ_3 offset locked 1-25 GHz with respect to λ_2
  - λ_4 offset locked 41 GHz with respect to λ_3



DIAL Seed Laser: Architecture



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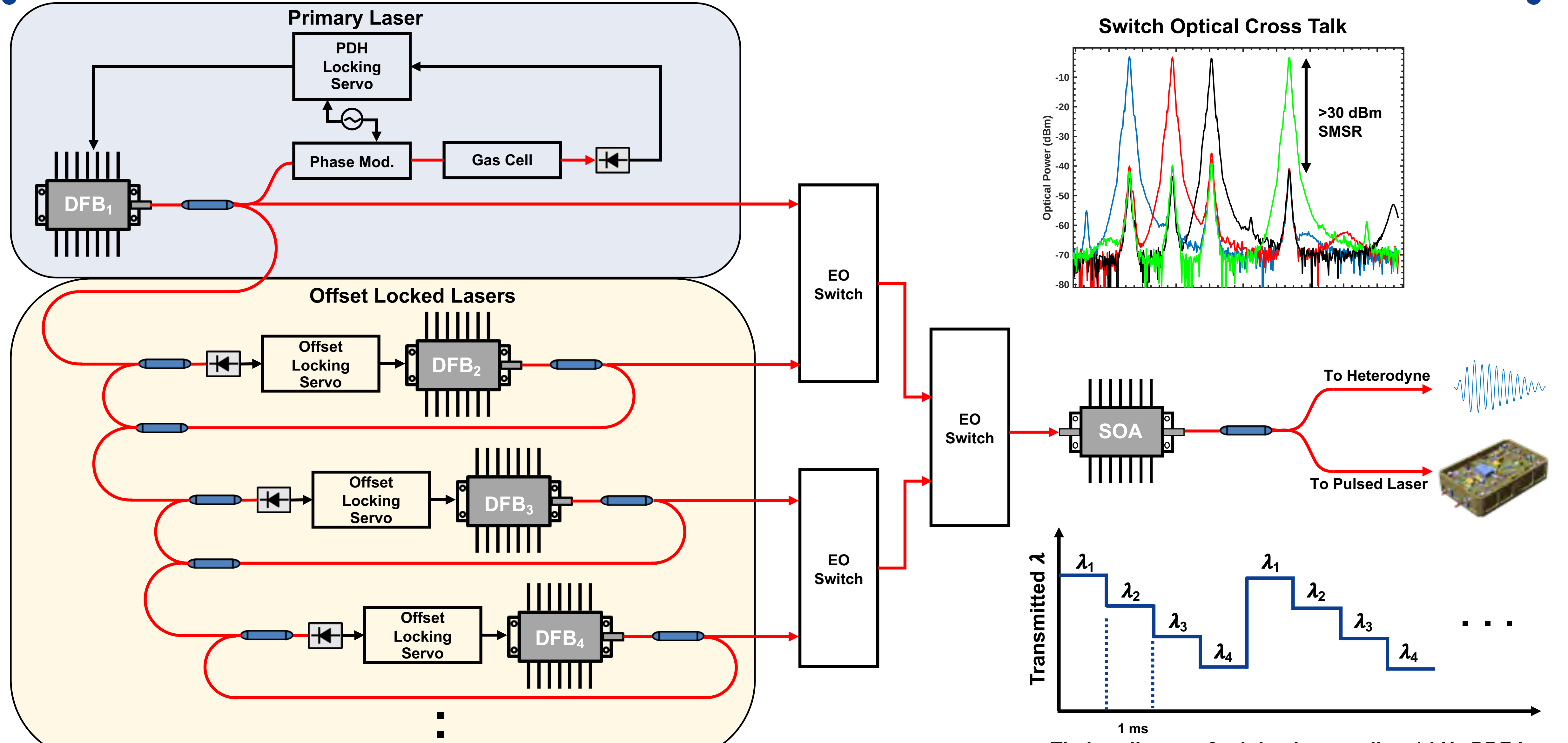
  - λ_2 offset locked 40 GHz with respect to λ_1
  - λ_3 offset locked 1-25 GHz with respect to λ_2
  - λ_4 offset locked 41 GHz with respect to λ_3
- CH_4 DIAL wavelengths spread out over ~20 GHz
  - Design simplified with 2 wavelength requirement
  - Sideline wavelength offset locked with respect to primary

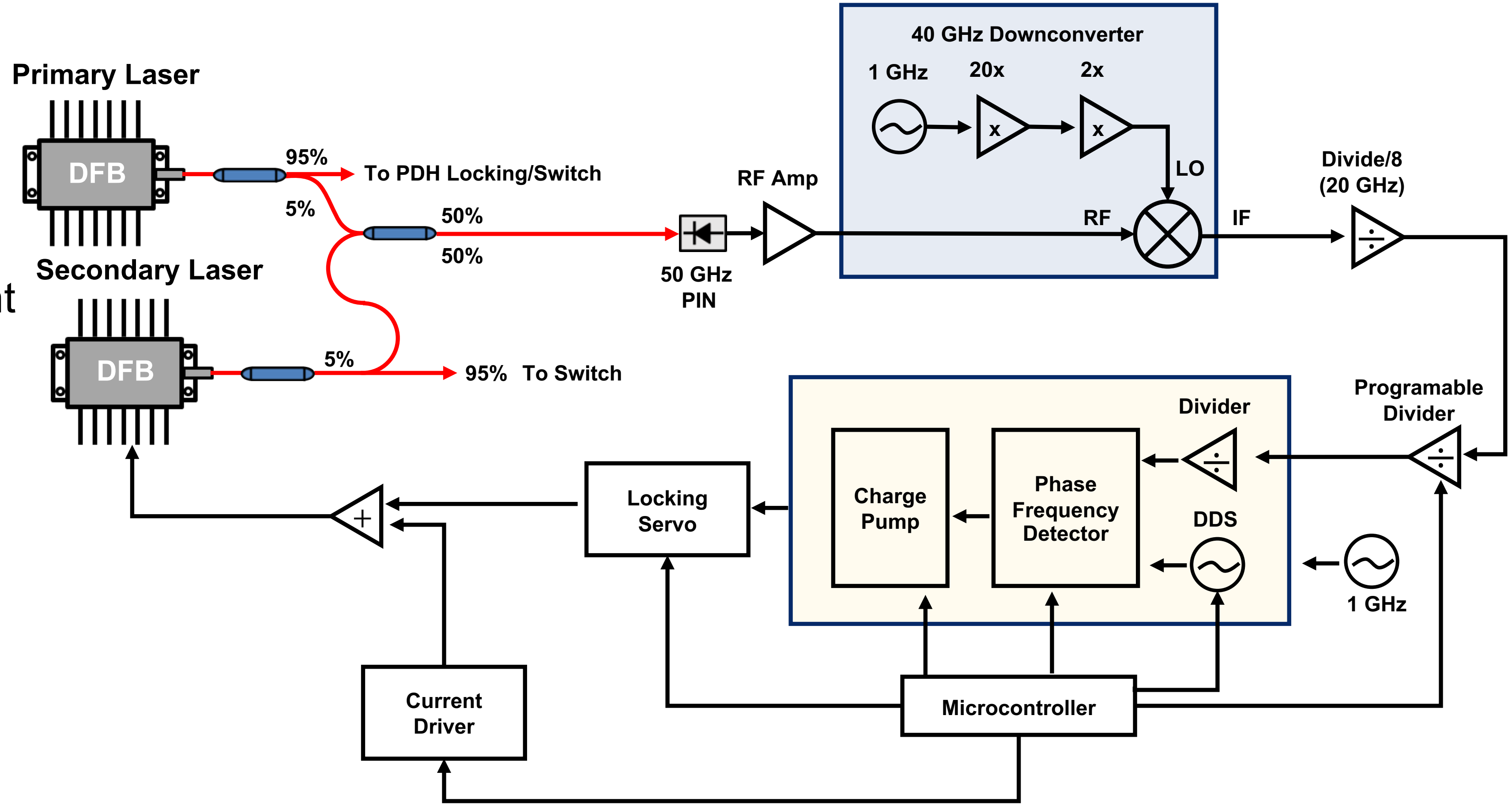
DIAL Seed Laser: Spectral Discrimination



Timing diagram for injection seeding 1 kHz PRF laser

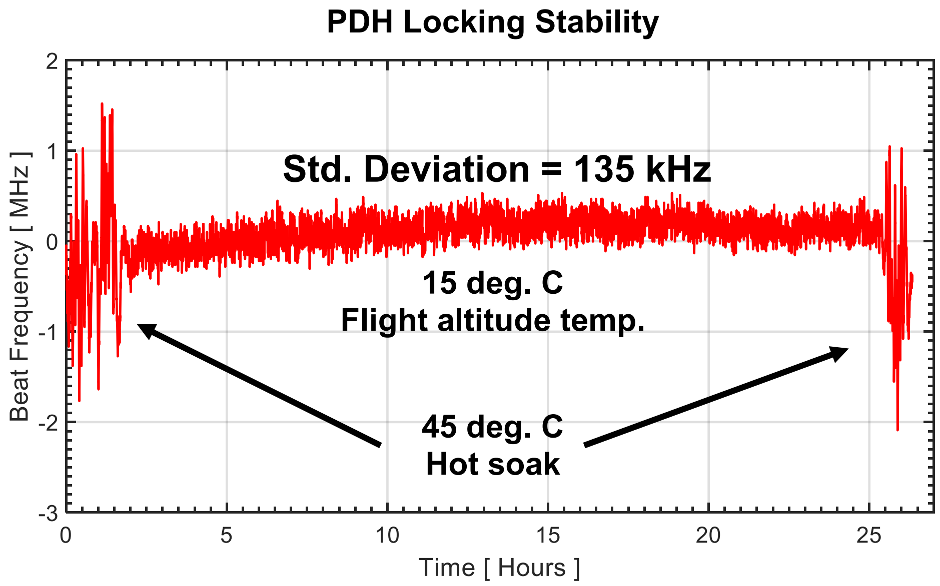
Offset Locking

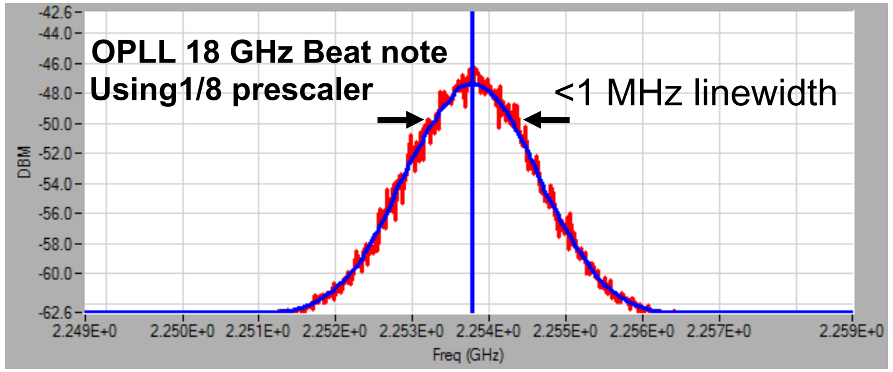
- Absolute offset locking achieved using an OPLL
- Discrete RF electronics provide flexible method to scale beat note down to baseband
- The frequency down conversion method is measurement dependent
- Example here places downconverter in the middle of the desired tuning range
  - Provides ± 12 GHz tuning centered about 40 GHz offset from primary
  - Removing downconverter allows for 20 GHz tunability with respect to primary
- Transitioning to use of monolithic microwave integrated circuits (MMIC) will allow for use of single high bandwidth digital prescaler and significantly reduce complexity

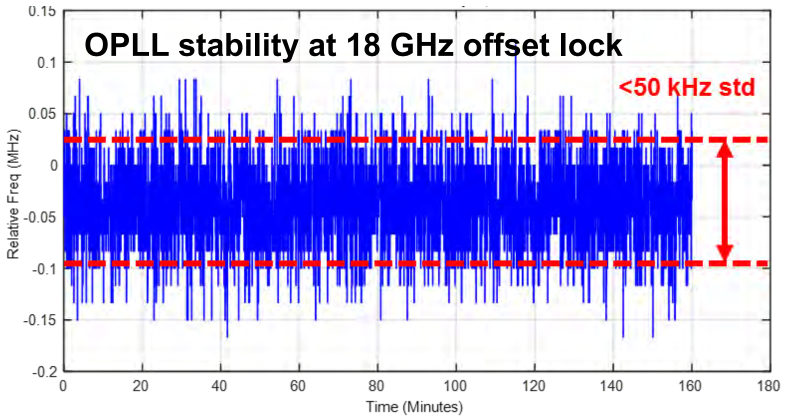


Seed Laser Stability

- Compact design allows for operation on wide range of aircraft including automatous operations on high altitude NASA ER-2
- Good thermal and polarization management results in stable performance over environment
- Demonstrated < 1part per billion stability over environment





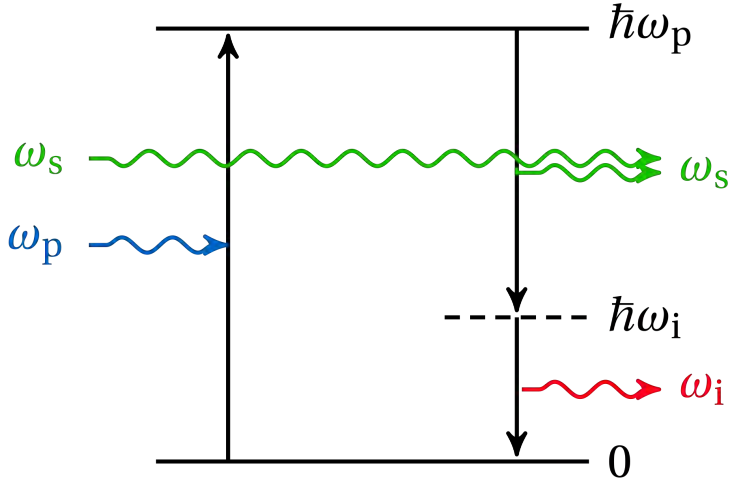


Pulsed Laser Requirements for DIAL

- Require a laser that operates near trace gas absorption feature (NIR)
- Narrow linewidth - <100 MHz
  - Enables high accuracy measurements
- Frequency agile – >200 pm
  - On/off DIAL sampling
  - Allow for optimization in different conditions
- High peak and average power – mJ (W) class
  - Overcome solar background and detection noise
- Good beam quality
  - Reduces complexity off transmitter design
- High repetition rate or double pulses
  - On/off sampling < 1 ms
  - Required to ‘freeze’ the atmosphere between on and off pulses

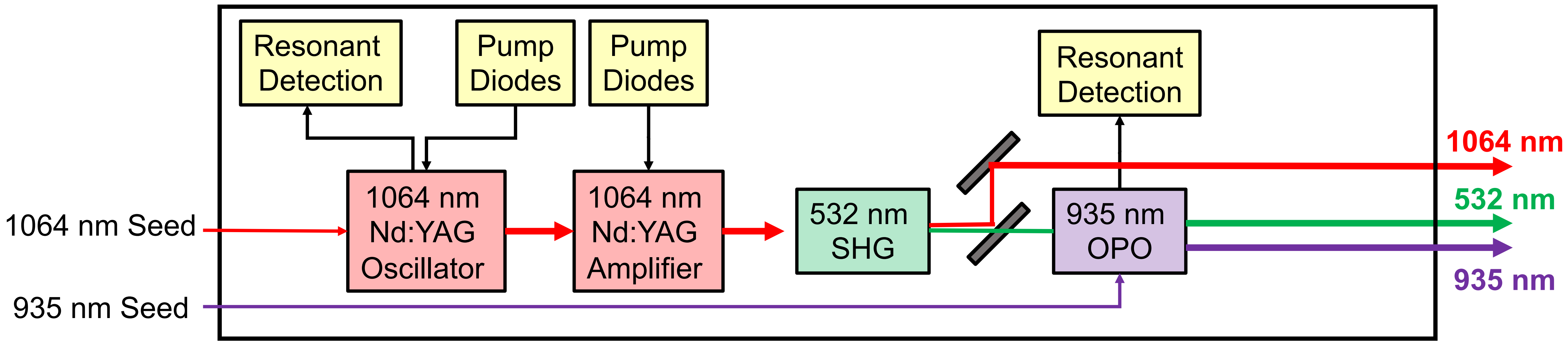
Optical Parametric Generation

$$\frac{1}{\lambda_1} - \frac{1}{\lambda_2} = \frac{1}{\lambda_3}$$



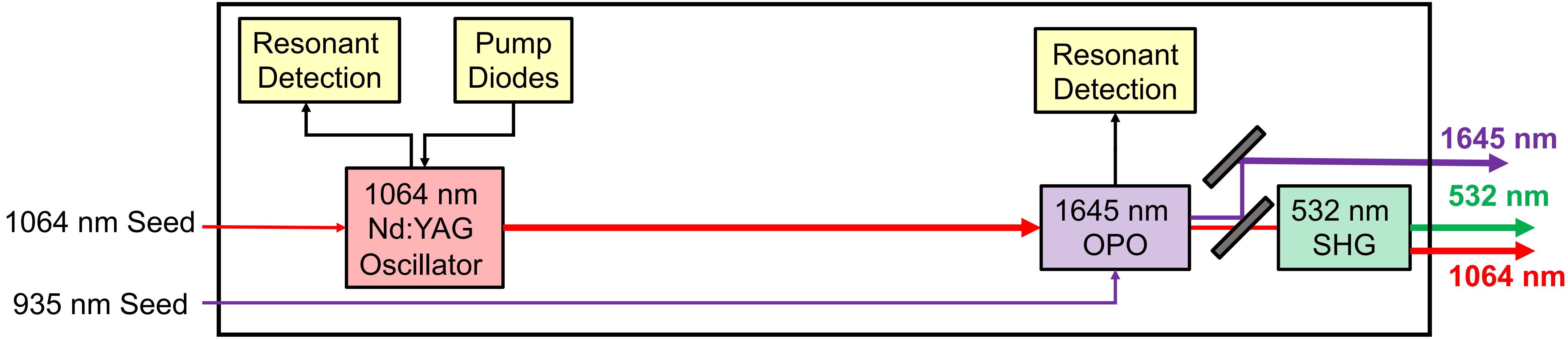
Pulsed Laser Architecture: Water Vapor Laser

Fibertek 1 KHz PRF Water Vapor DIAL Laser Optical Module

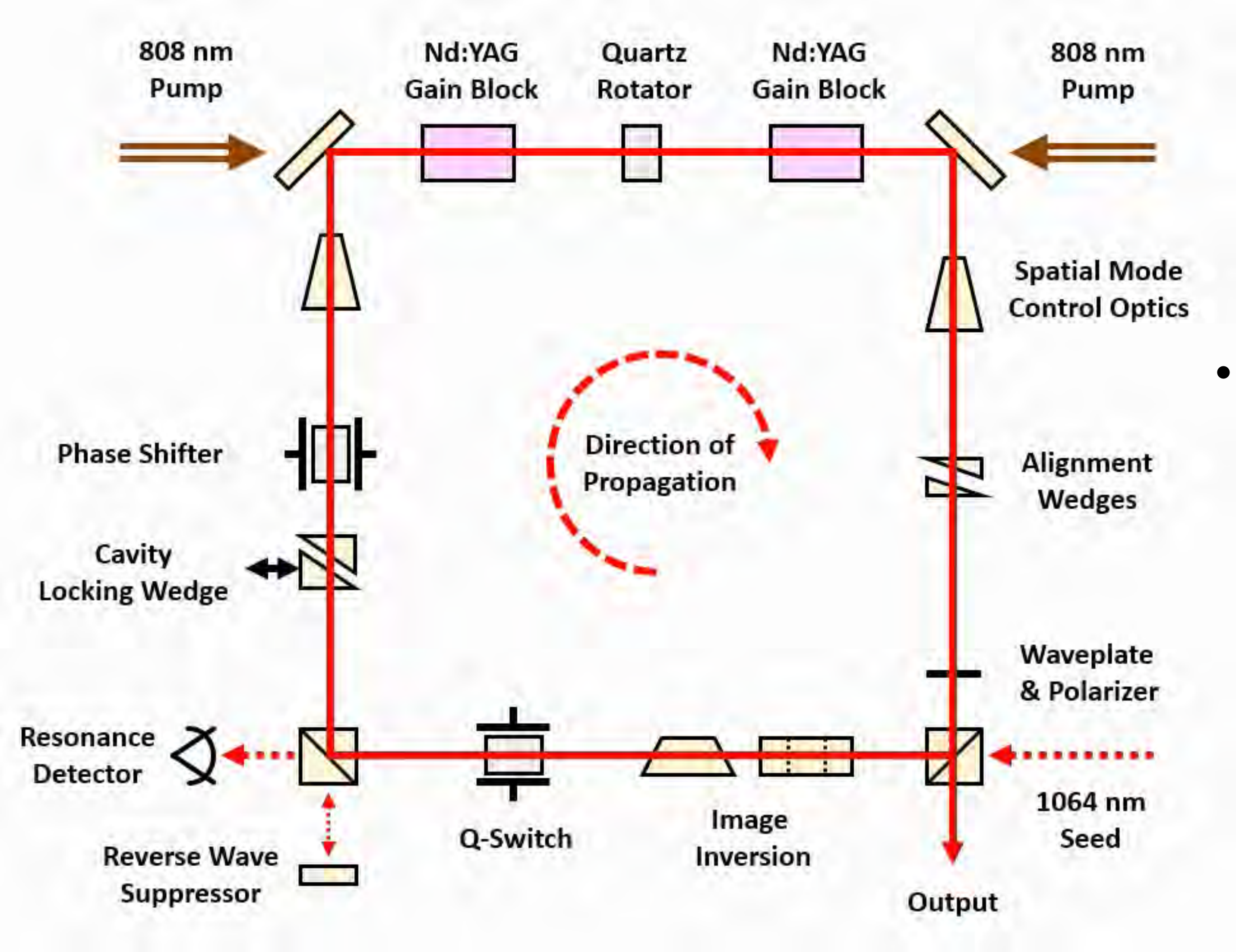


Pulsed Laser Architecture: Methane Laser

Fibertek 1 KHz PRF Methane DIAL Laser Optical Module



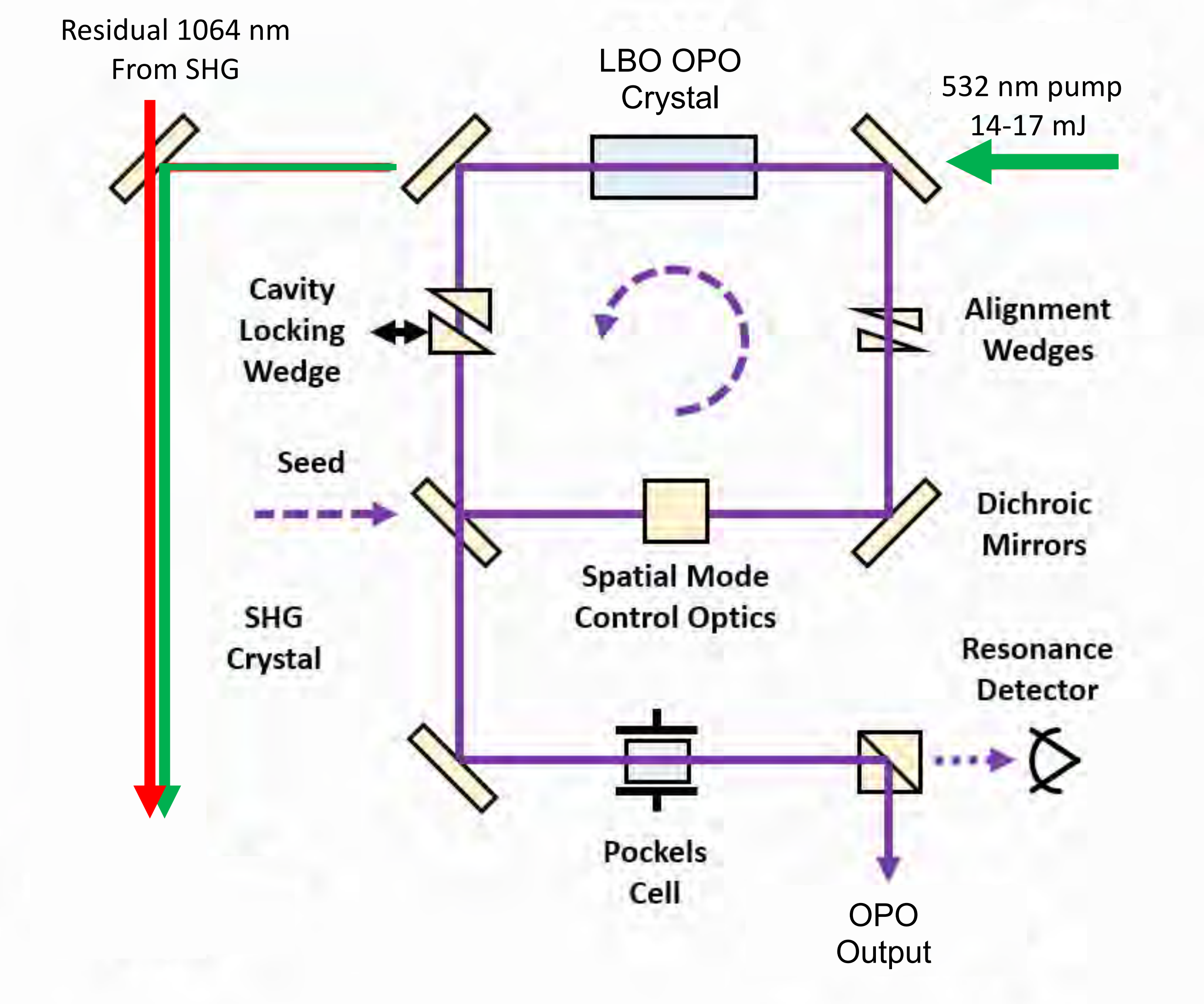
Pulsed Laser Architecture: Oscillator



- **Performance Objectives**
  - 1kHz PRF
  - 12-14 mJ pulse energy (12-14 W)
  - <20 ns pulse width
  - Near transform limited spectrum
  - Frequency Stabilized
  - Stable performance over environment

- **Design Characteristics**
  - **Non-planar unidirectional ring**
    - Simplicity of seeding and eliminating spatial hole burning
  - **Reduced sensitivity to env. Induced optical misalignment**
    - Round trip image inversion for eigenmode stabilization
    - Hard mounted optics w/risley prism alignment
  - **Active q-switching**
    - Ensures pulse timing stability
  - **Injection seeded and cavity locked**
  - **Pound-Drever-Hall (PDH) locking**

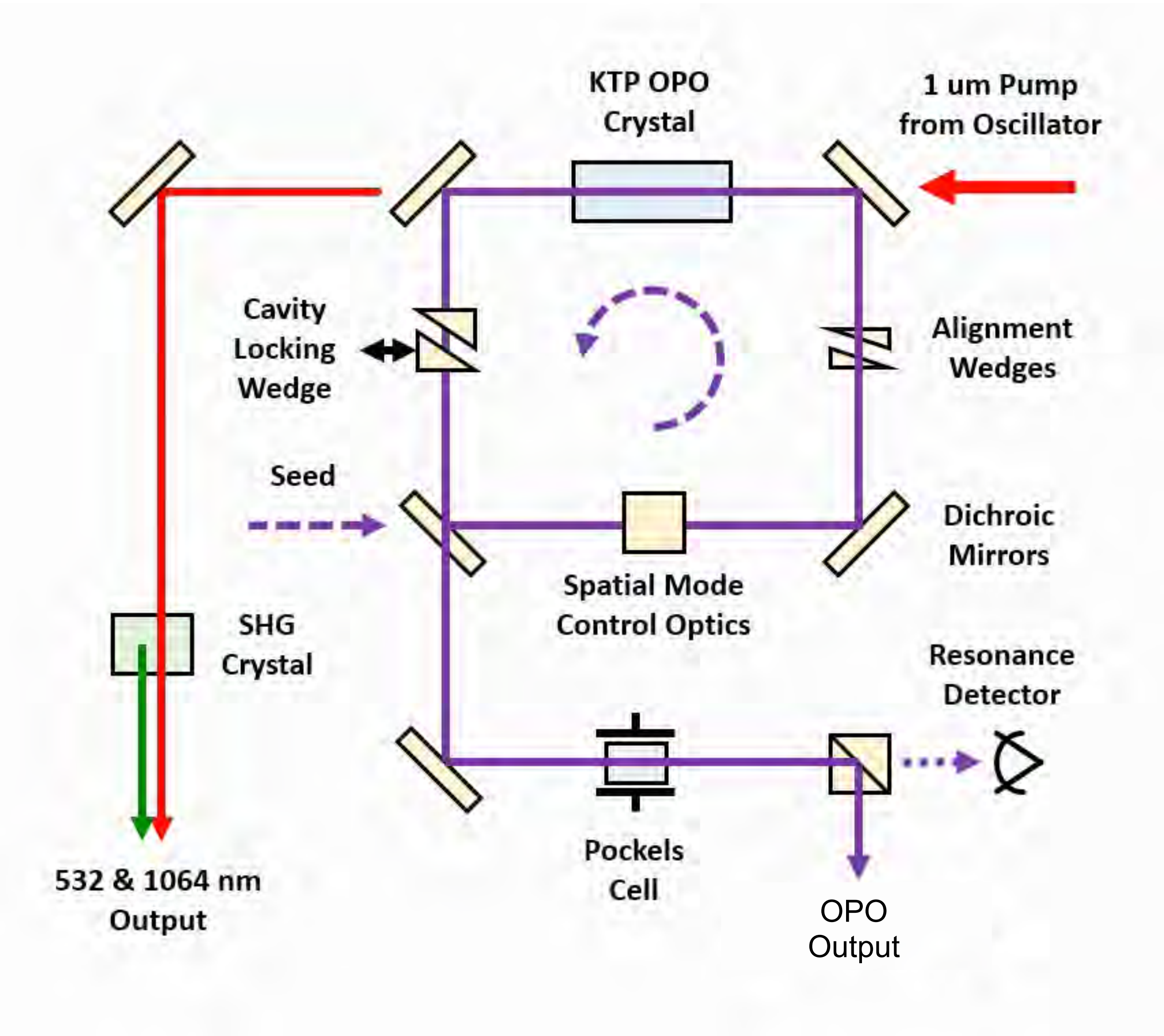
Pulsed Laser Architecture: H_2O OPO



- **Performance Objectives**
  - Conversion efficiency to 935 nm of 15-20%
    - 2.5 mJ
  - Near transform limited spectrum
  - Frequency stabilized
  - Stable performance over environment

- **Design Characteristics**
  - **Compact in-plane unidirectional ring**
  - **Singly resonant OPO at 935 nm**
  - **LBO in type I phase matching**
  - **Injection seeded and cavity locked**
  - **Pound-Drever-Hall cavity locking**
  - **Residual 1064 nm and 532 used for HSRL measurements**

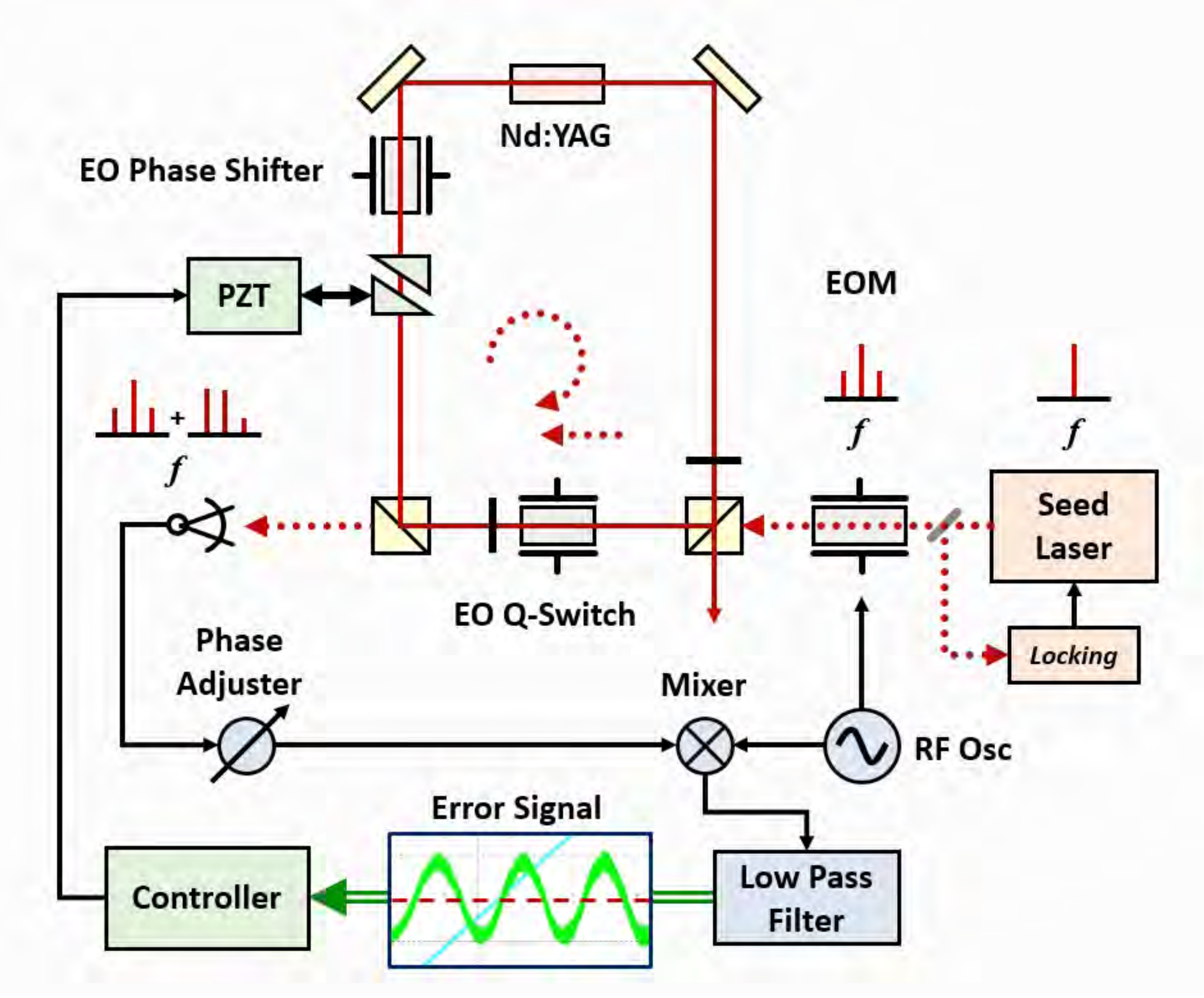
Pulsed Laser Architecture: CH_4 OPO



- **Performance Objectives**
  - Conversion efficiency to 1645 nm of 15-20 %
    - 2.5 mJ
  - Near transform limited spectrum
  - Frequency stabilized
  - Stable performance over environment

- **Design Characteristics**
  - **Compact in-plane unidirectional ring**
  - **Singly resonant OPO at 1645 nm**
  - **KTP in type II phase matching**
  - **Injection seeded and cavity locked**
  - **Pound-Drever-Hall cavity locking**
  - **Residual 1064 nm doubled and used for HSRL measurements**

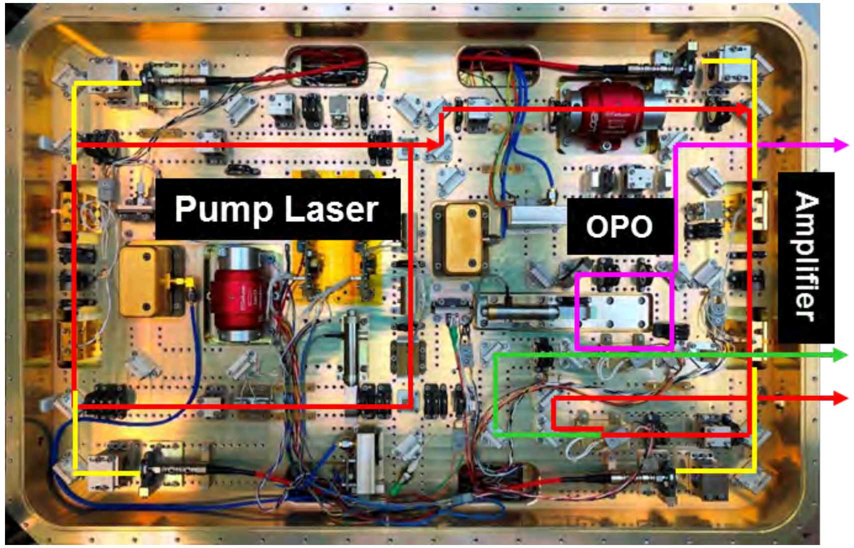
Injection Seeding and Locking

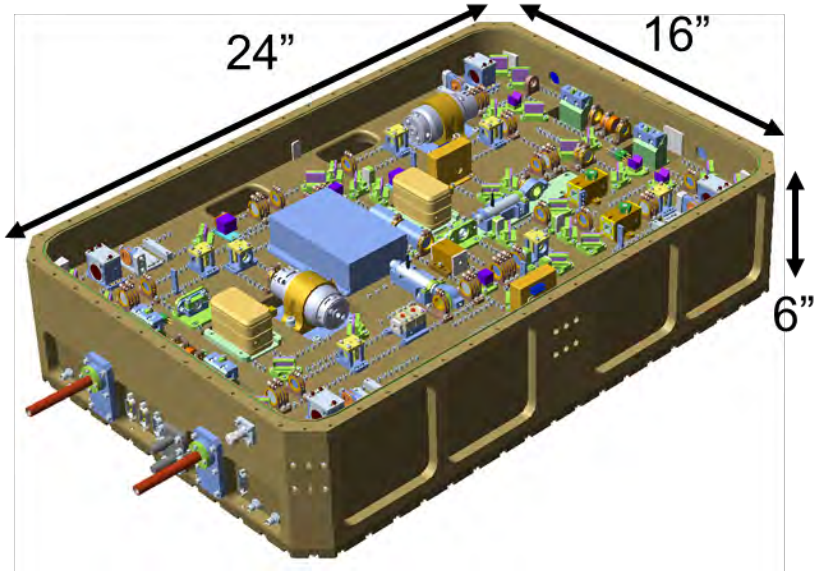


Design Characteristics

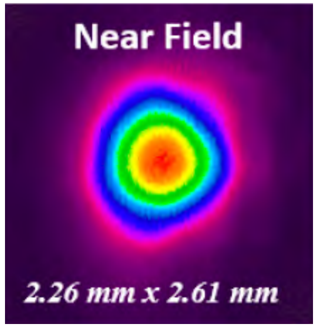
- Error signal generation based on conventional PDH approach
  - 70 MHz modulation frequency (~1/4 FSR)
- Locking accomplished with only a single cavity round trip
- Uses the ‘off’ polarization state of the cavity
- Is only active when the diode pumps are off
- An EO phase shifter is activated prior to Q-switching to compensate for phase mismatch
- Active seeding only takes place during the transient rise time of the q-switch
- OPO cavity locking is identical to oscillator

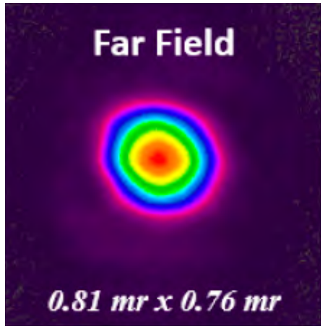
Pulsed Laser Performance: Oscillator

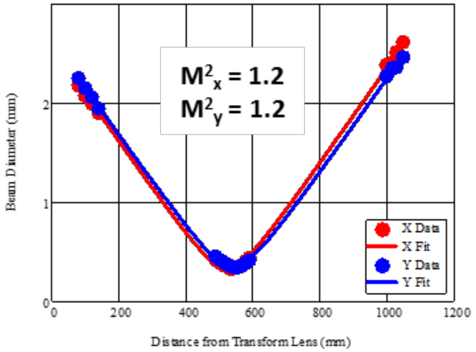




Oscillator Spatial Beam Properties

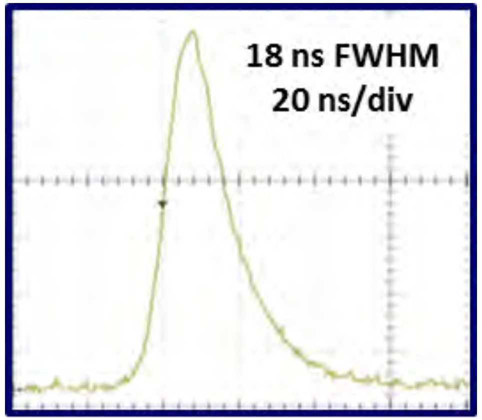




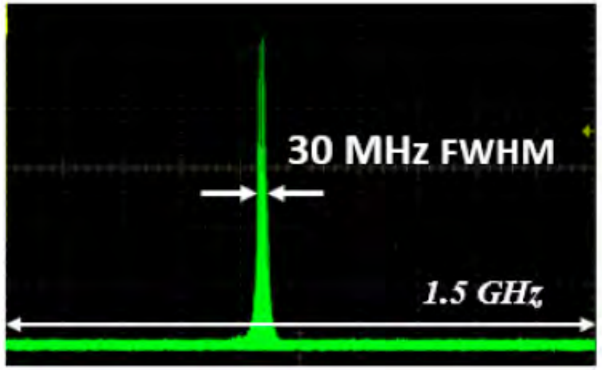


Beam Quality

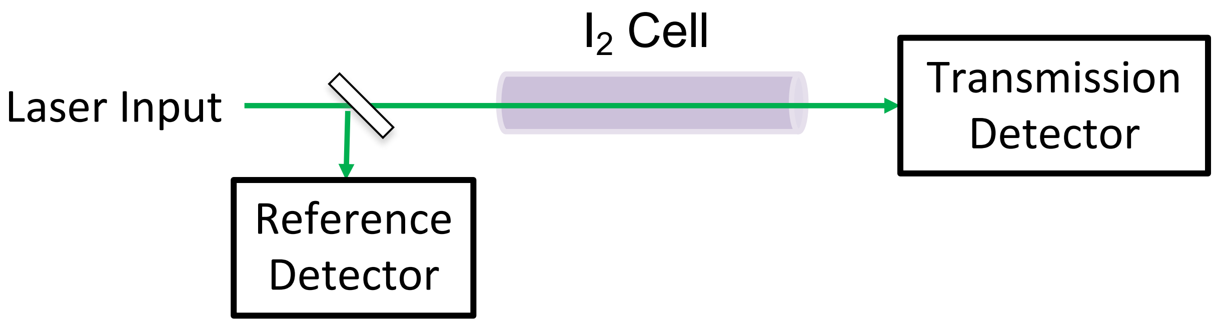
MOPA Spectral Properties



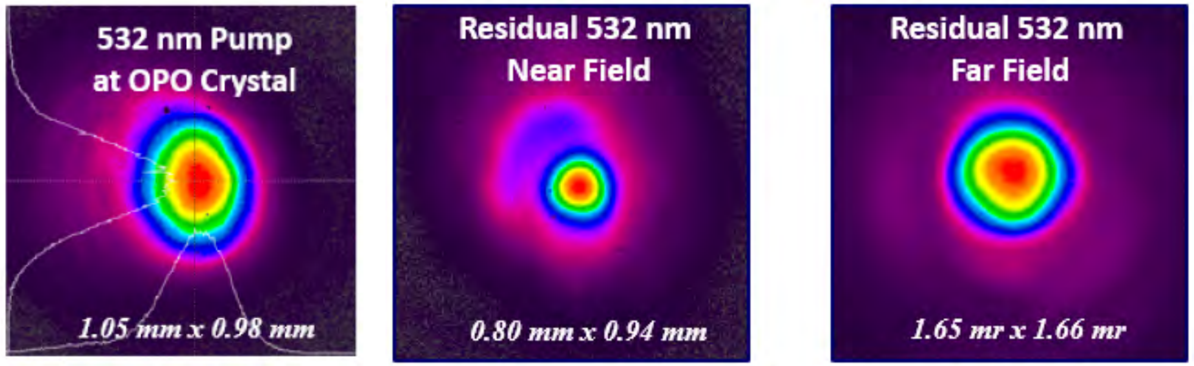
Temporal Distribution

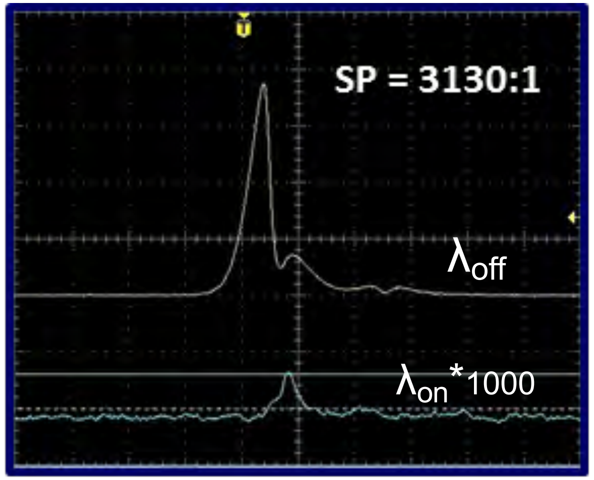


Pulsed Laser Performance: 532 nm spectral purity

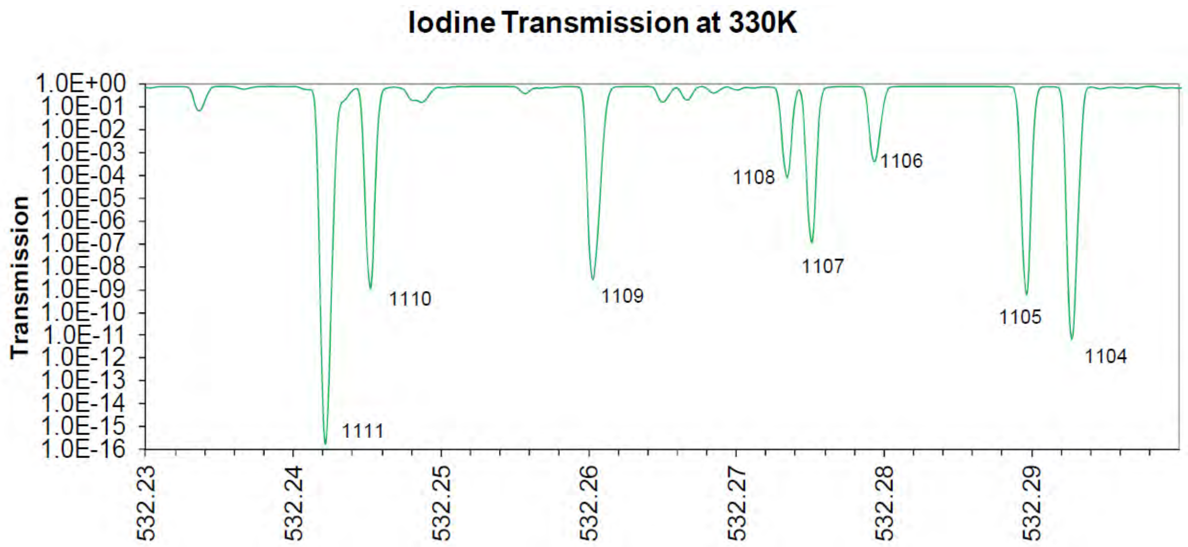


Depleted 532 nm Beam Properties



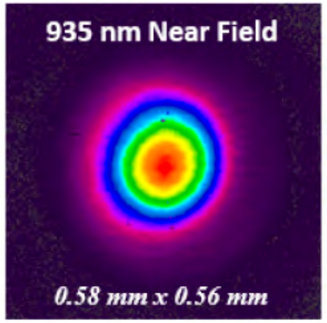


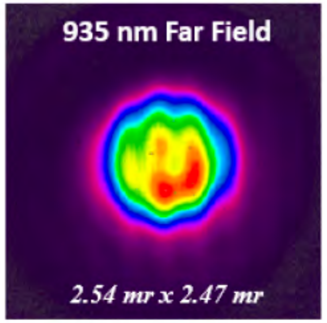
Spectral Purity w/ I_2 Cell – 1104 Line
w/ OPO locked On-Line

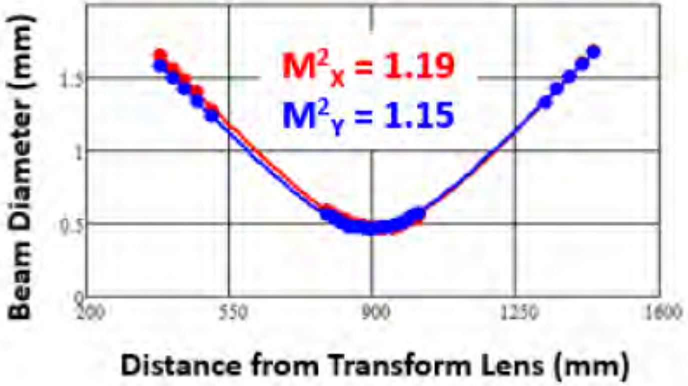


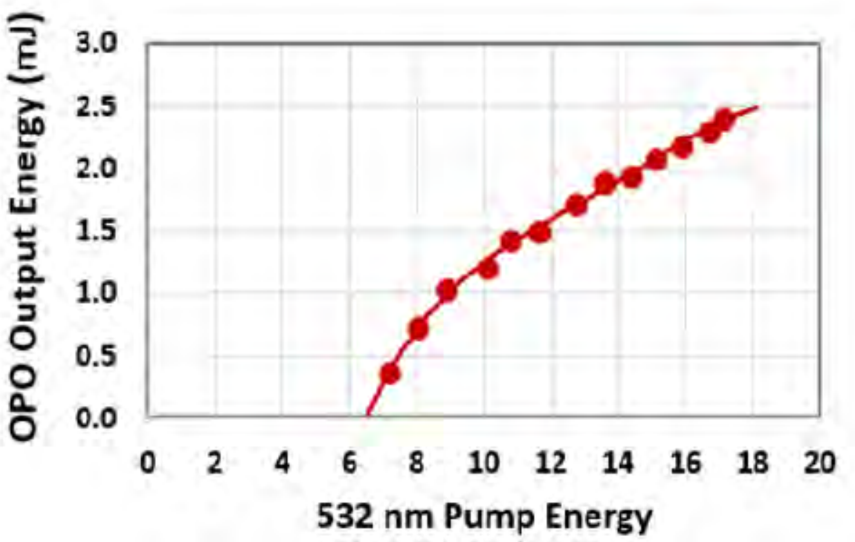
Pulsed Laser Performance: OPO

- Near diffraction limited OPO output
- Optical-to-optical efficiency of ~15% was achieved
  - O-O efficiency >20% achieved with higher intracavity fluences
- Temporal modulation observed at higher pump levels
  - Resulting from back conversion and second axial mode of resonator
- Smooth pulse profile achieved with optimization of 1 micron pump and reduced pump power

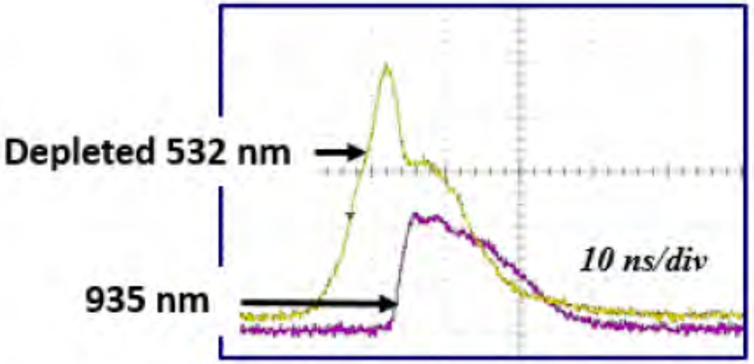




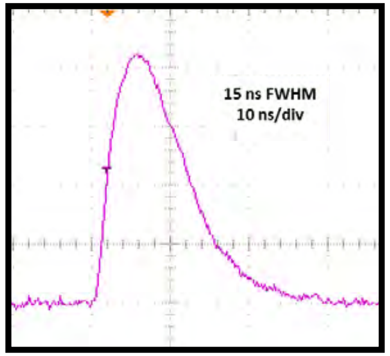




17 mJ pump

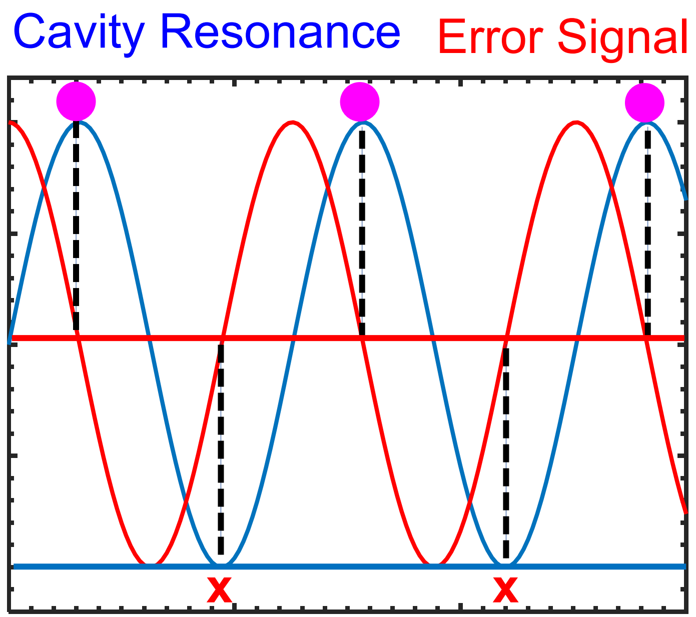


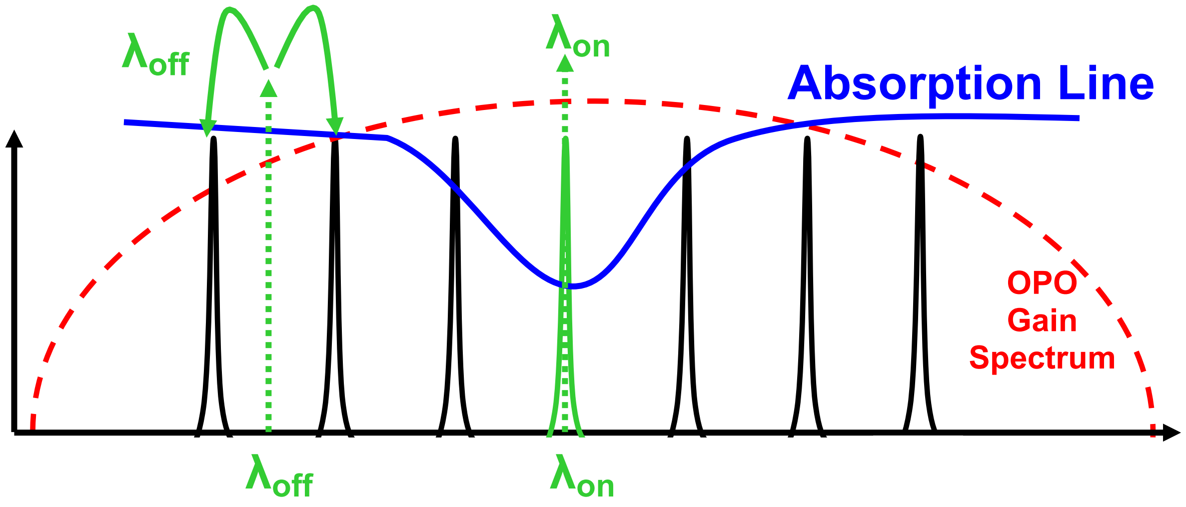
12 mJ pump



Pulsed Laser Performance: Wavelength Switching

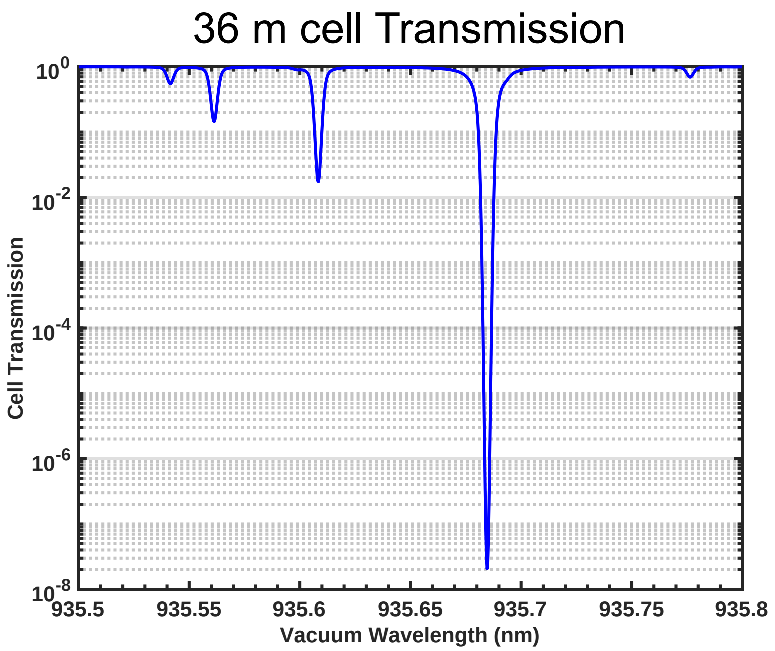
- DIAL measurement requires shot-to-shot wavelength switching to ‘freeze’ the atmosphere
- OPO uses Pound Drever Hall locking technique to stabilize laser cavity to seed
- PZT mechanism does not have the required response time to acquire lock at 1 kHz PRF
- OPO cavity locked to online wavelength
- Sideline and offline seed lasers tuned to nearest resonance condition spaced by an integer number of cavity modes
- Care must be taken to not lock OPO to PDH ’null’ mode

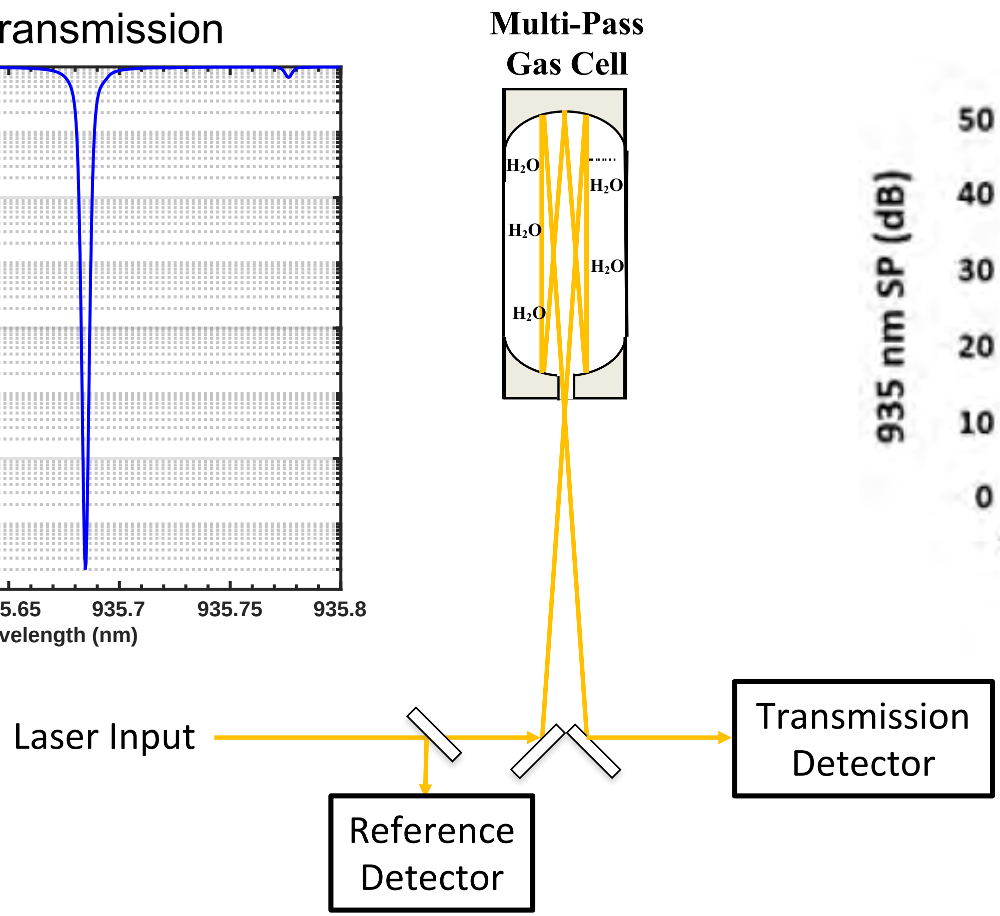


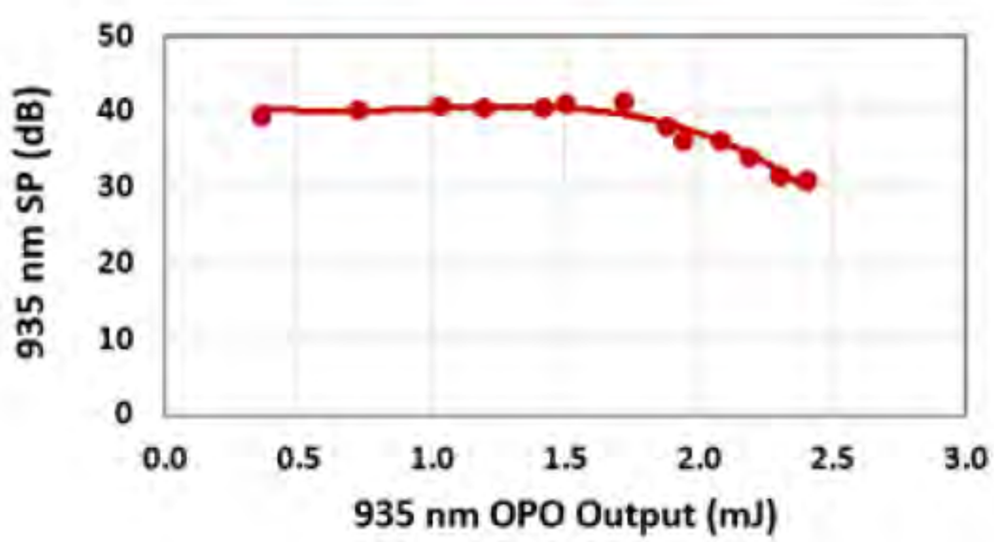


Pulsed Laser Performance: OPO Spectral Purity

- Herriott cell used at low pressure used to evaluate pulsed laser spectral purity
- OPO operated on strong line to get adequate absorption over short distances
- Degradation spectral purity at higher pump powers still meets measurement req.

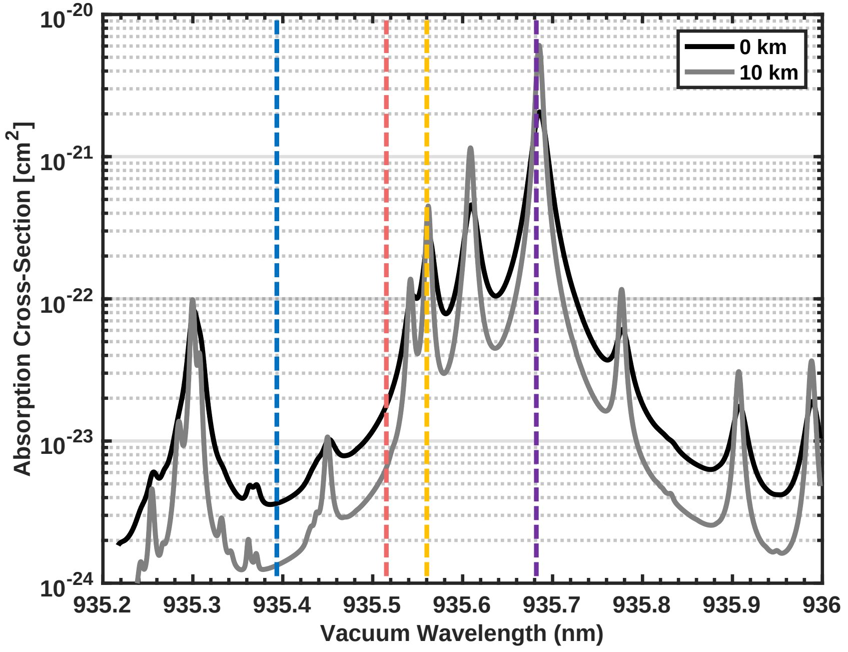


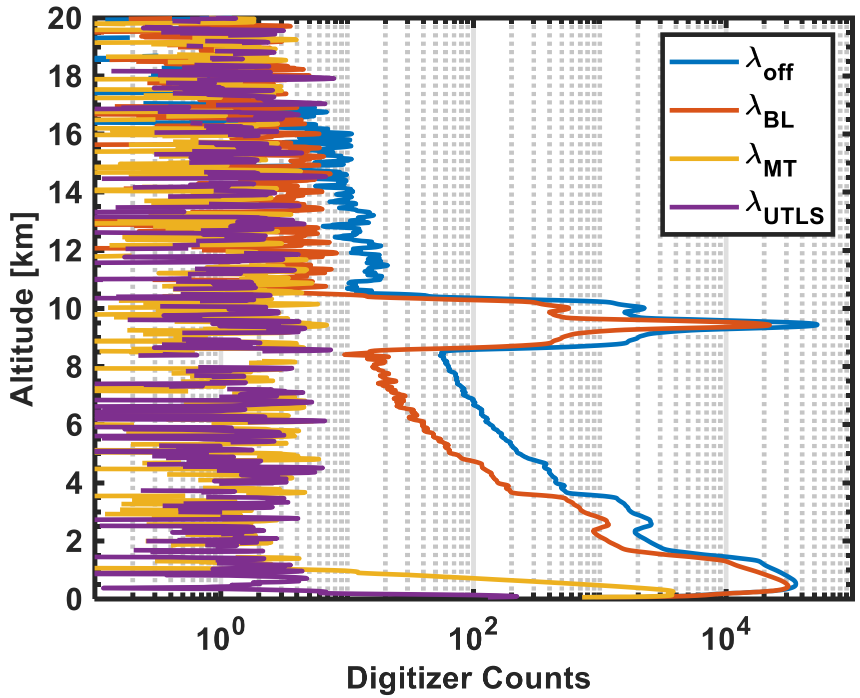


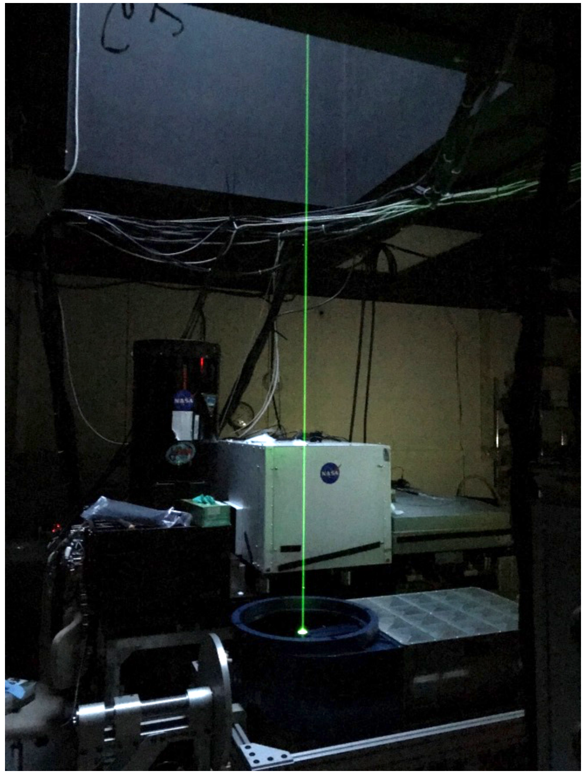


Pulsed Laser Performance: OPO Spectral Purity

- Spectral purity can also be evaluated using strong echo from high altitude clouds
- Pressure broadening in the atmosphere increases the spectral width of absorption lines compared to low pressure cell, but provides independent validation of SP
- Example below with four transmitted wavelengths demonstrates spectral purity of ~5000:1 (99.98).

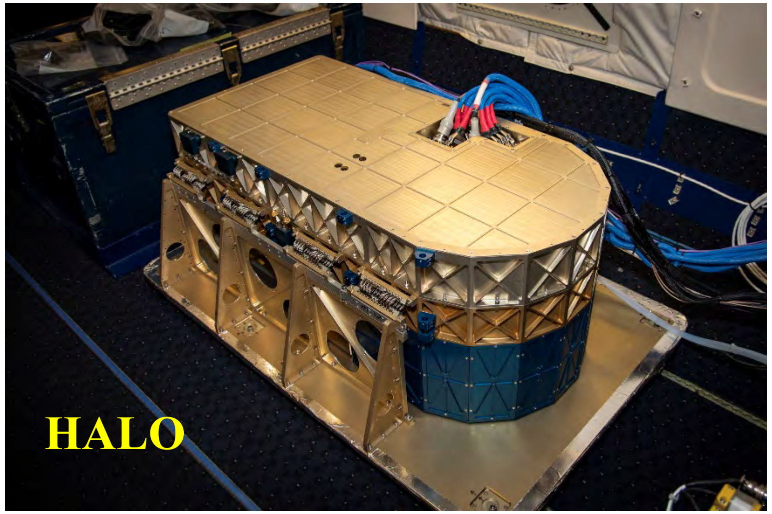


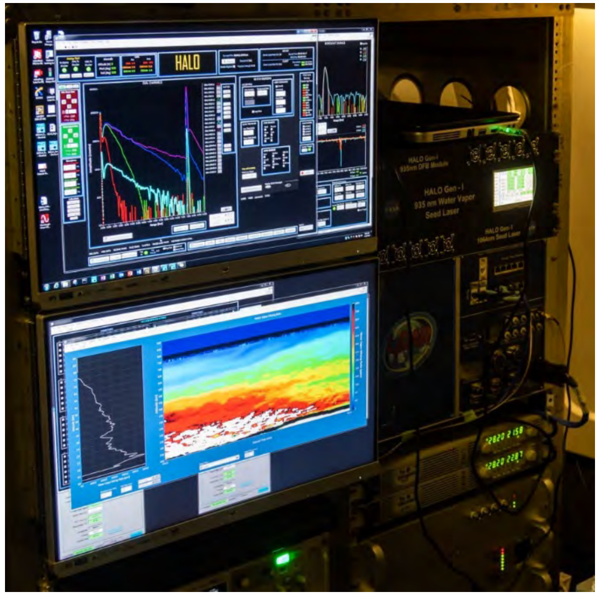


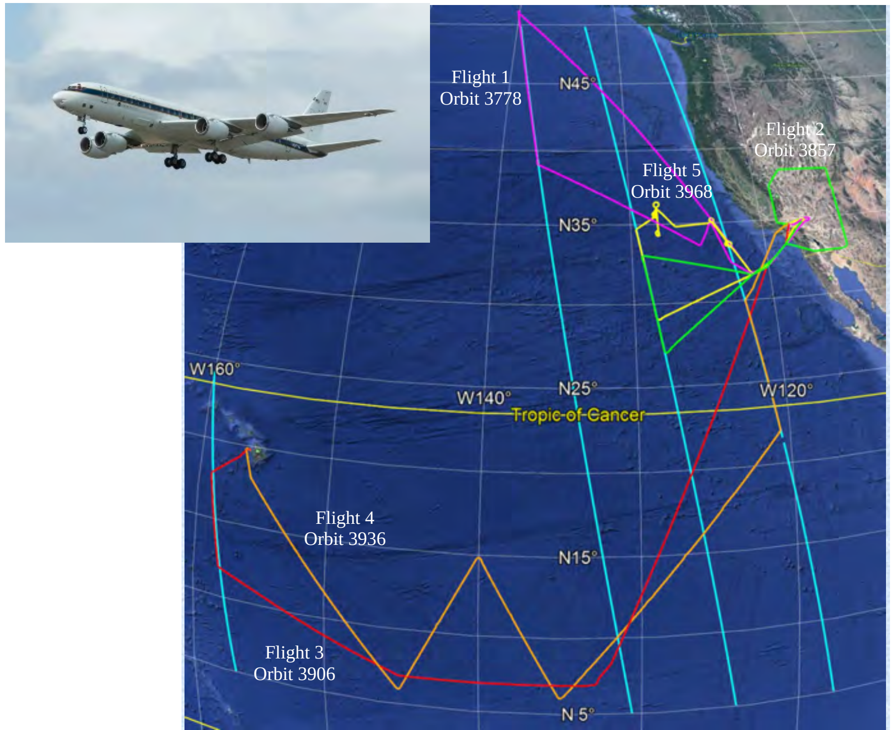


Data Examples

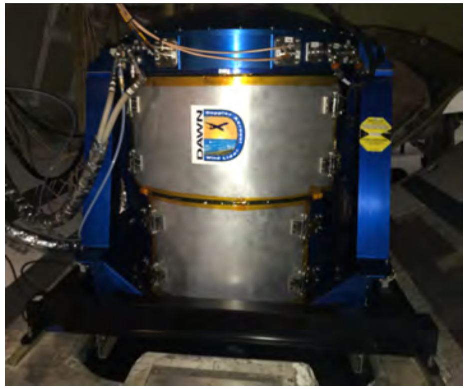
HALO Integrated on NASA DC-8 For ADM Cal/Val Mission



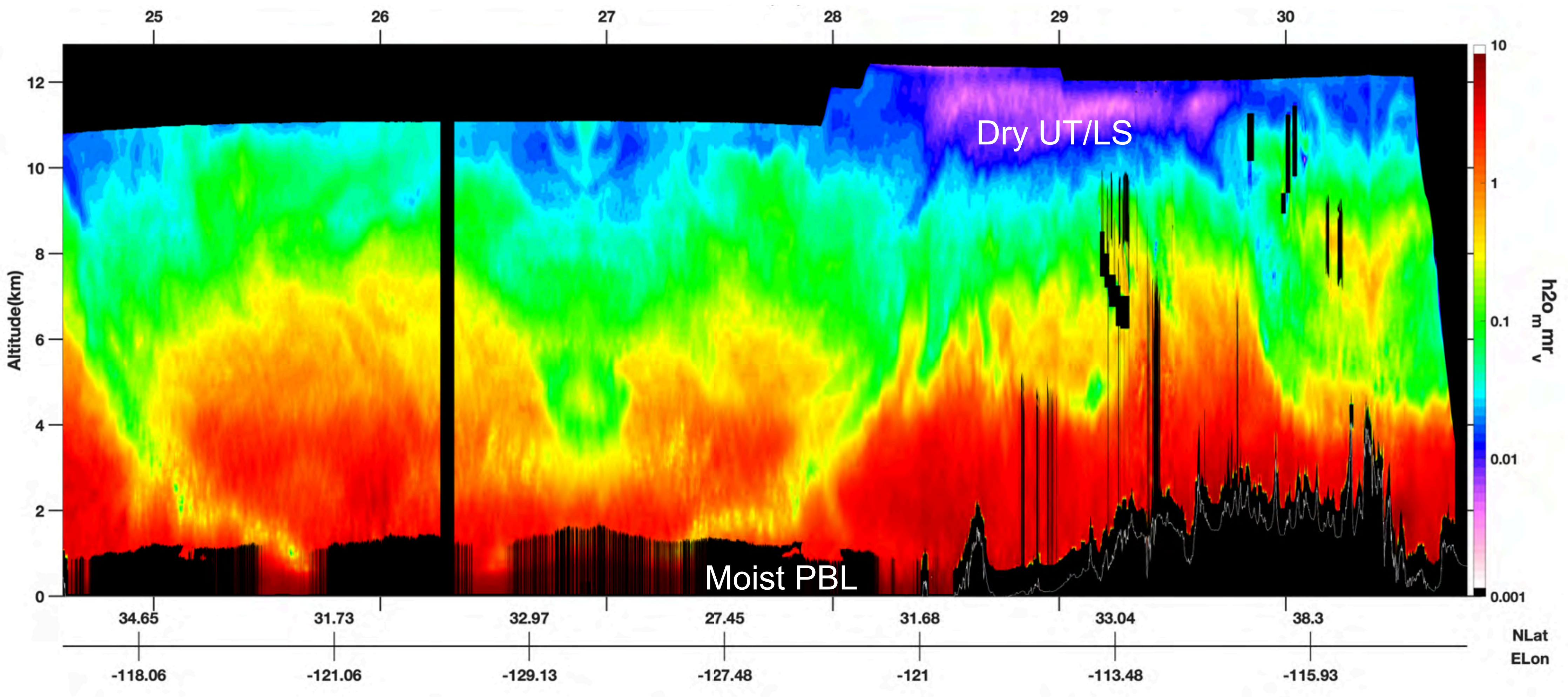




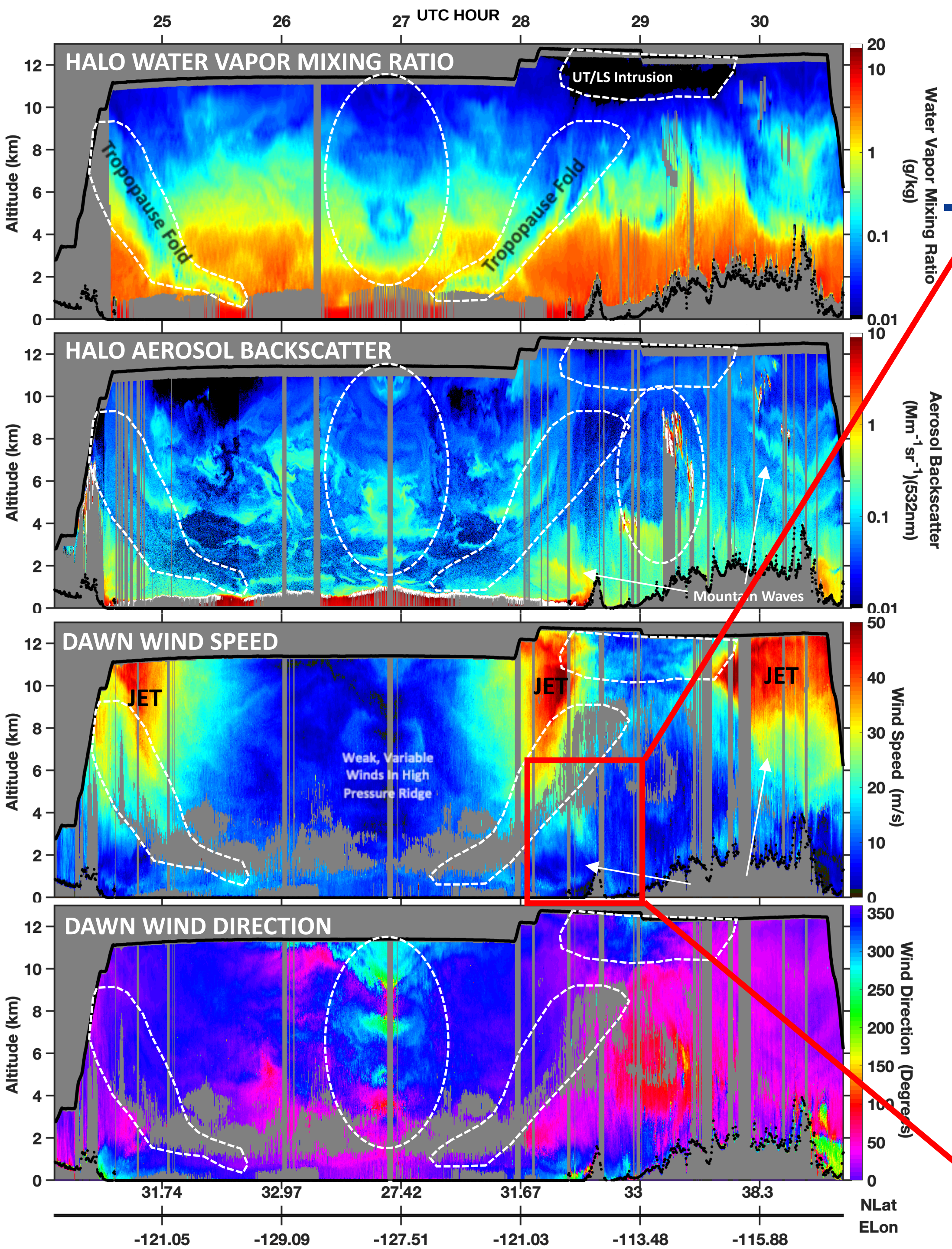
DAWN

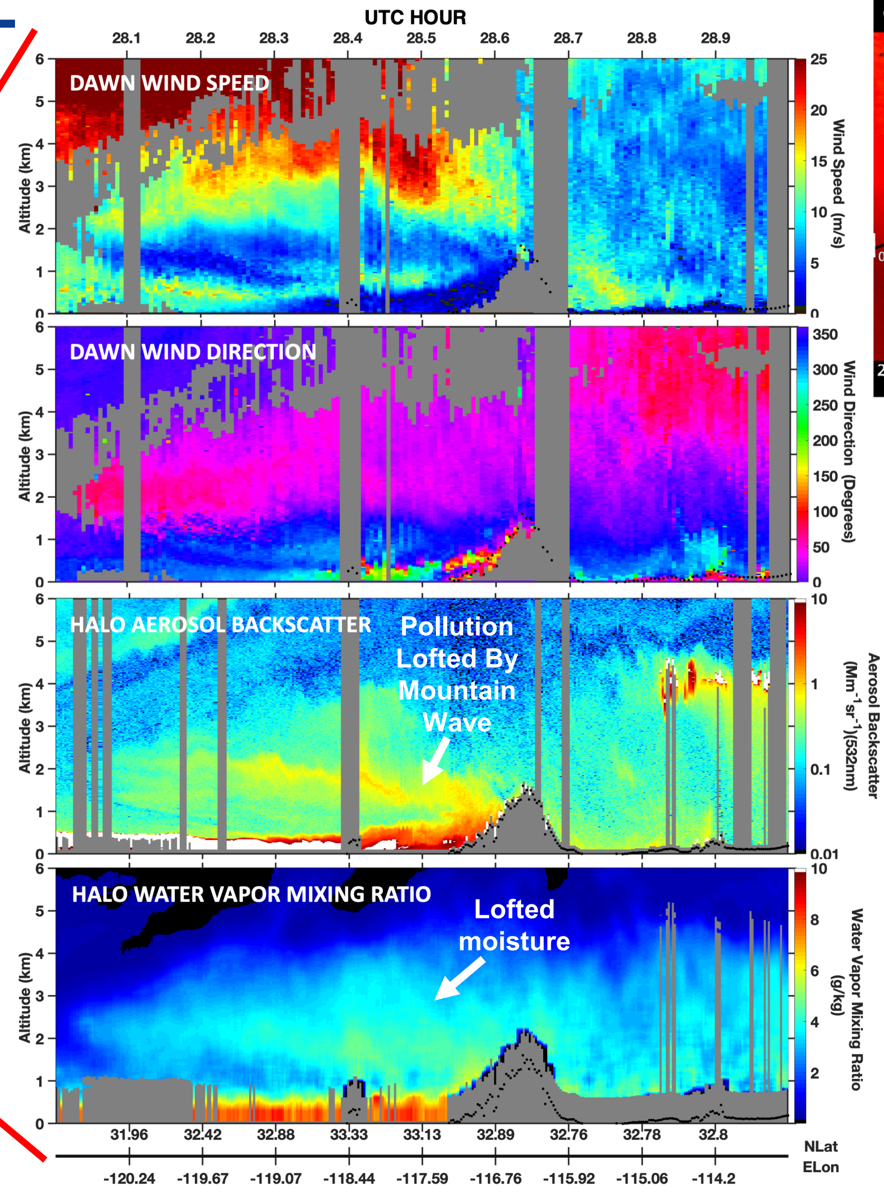


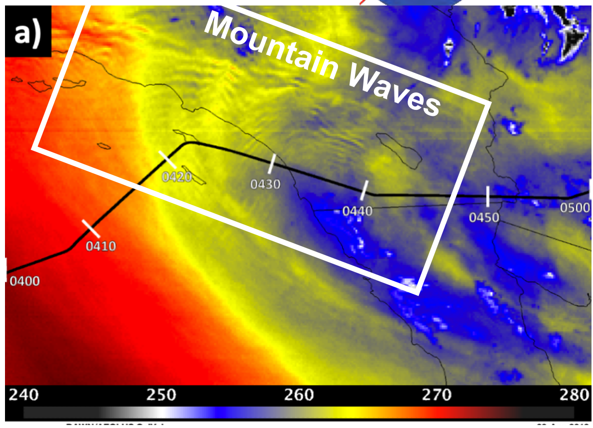
DIAL Dynamic Range



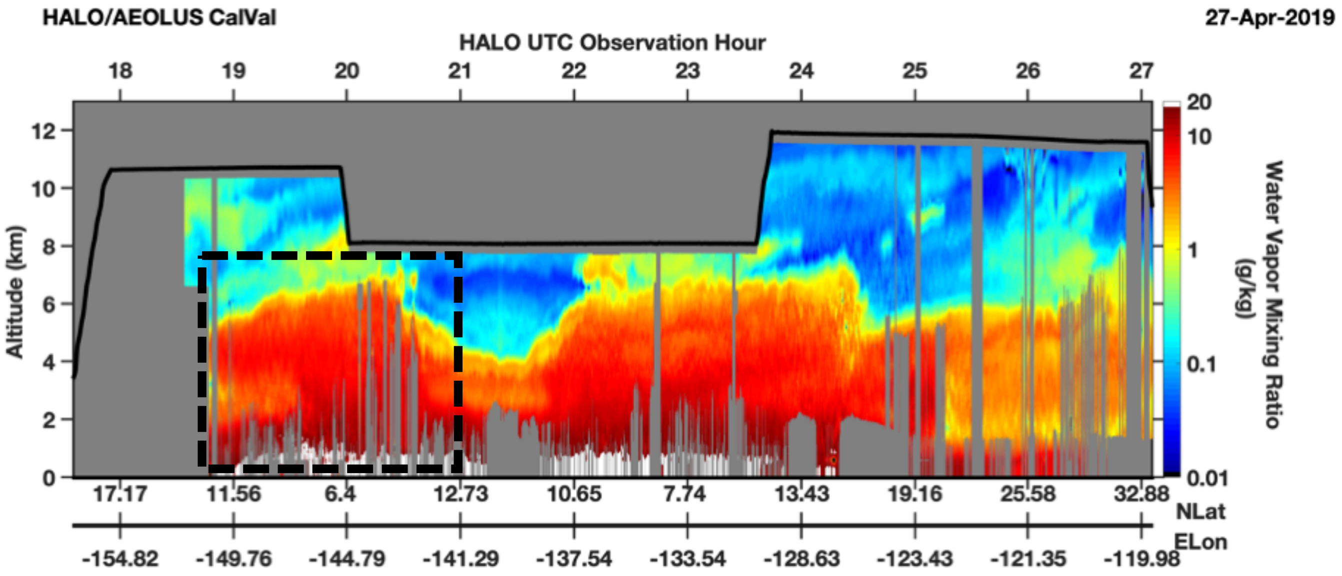
Observations across scales: From synoptic circulations to PBL profiles

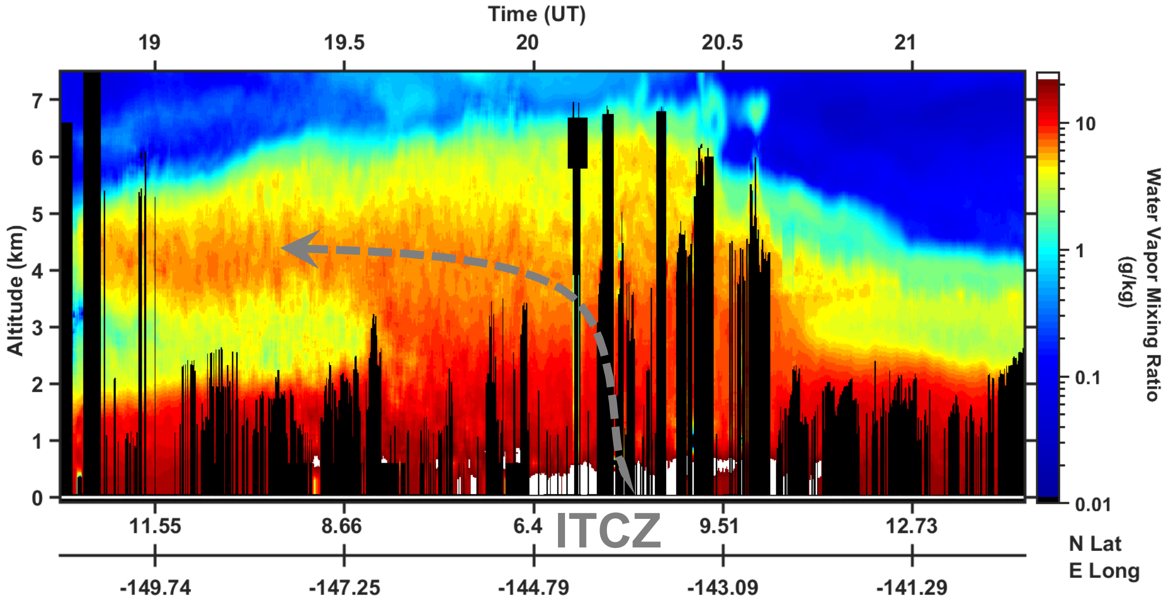


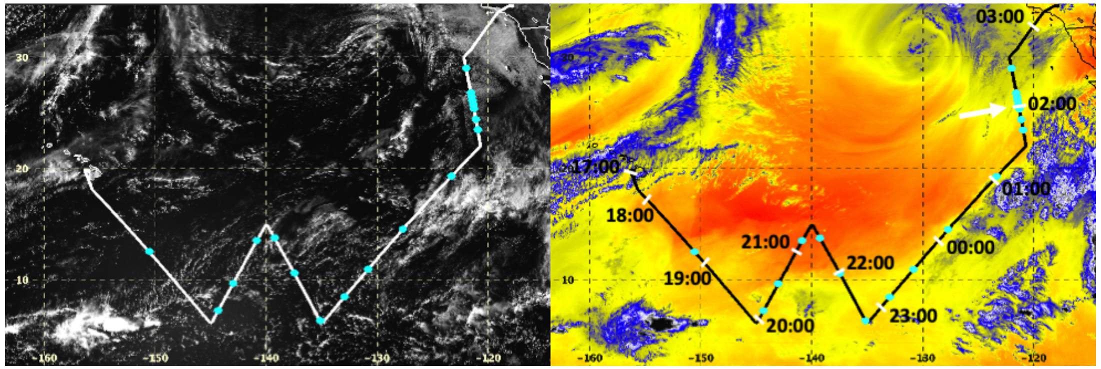


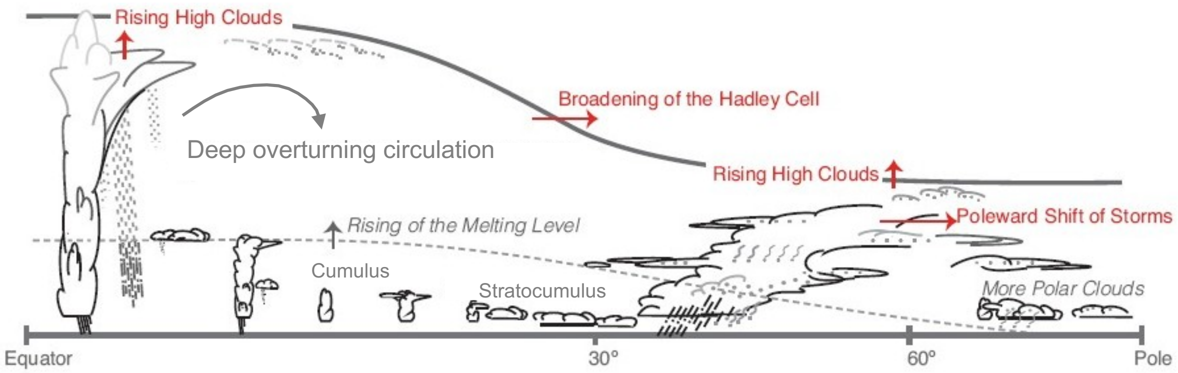


Unravelling the weak signals of atmospheric circulation



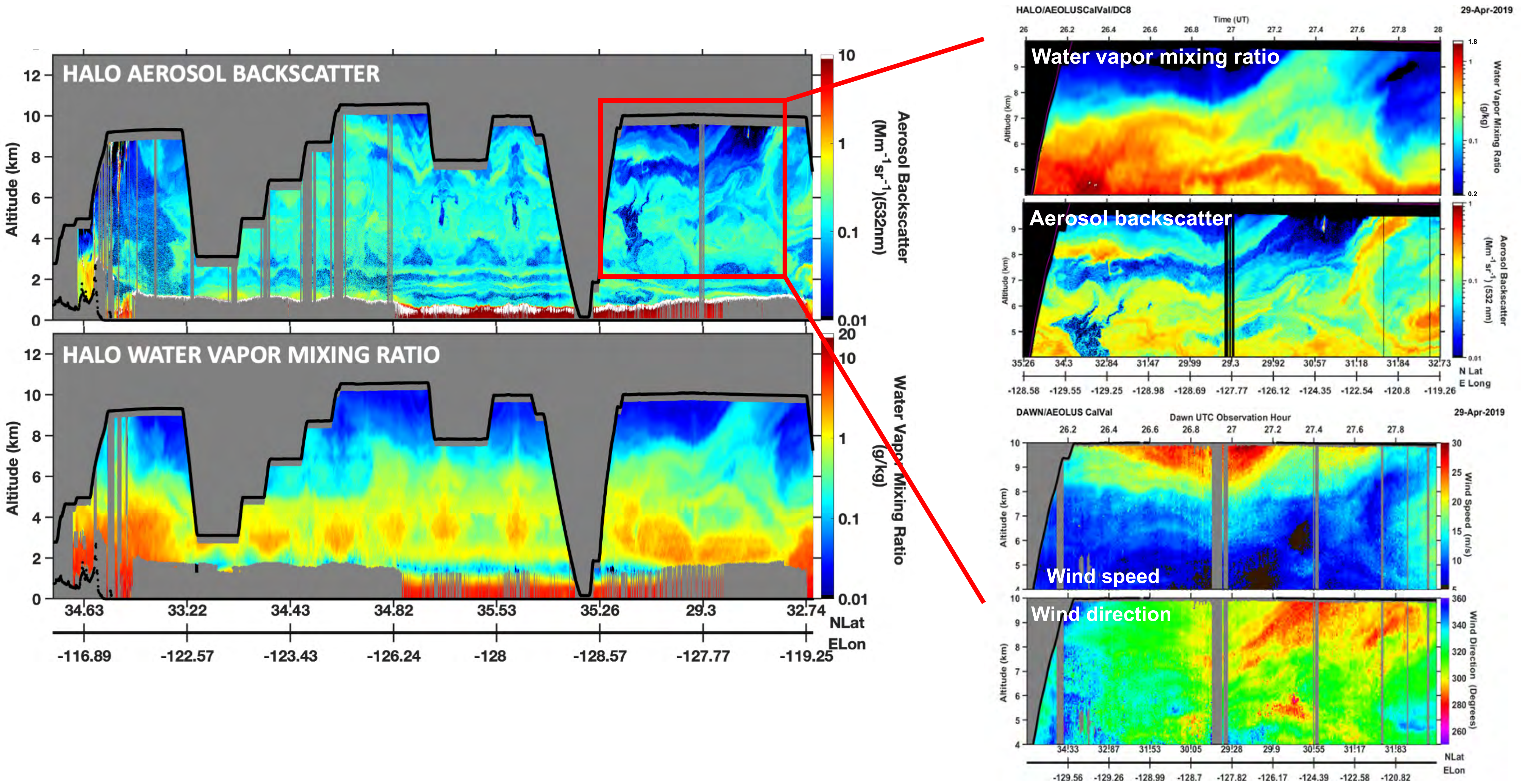




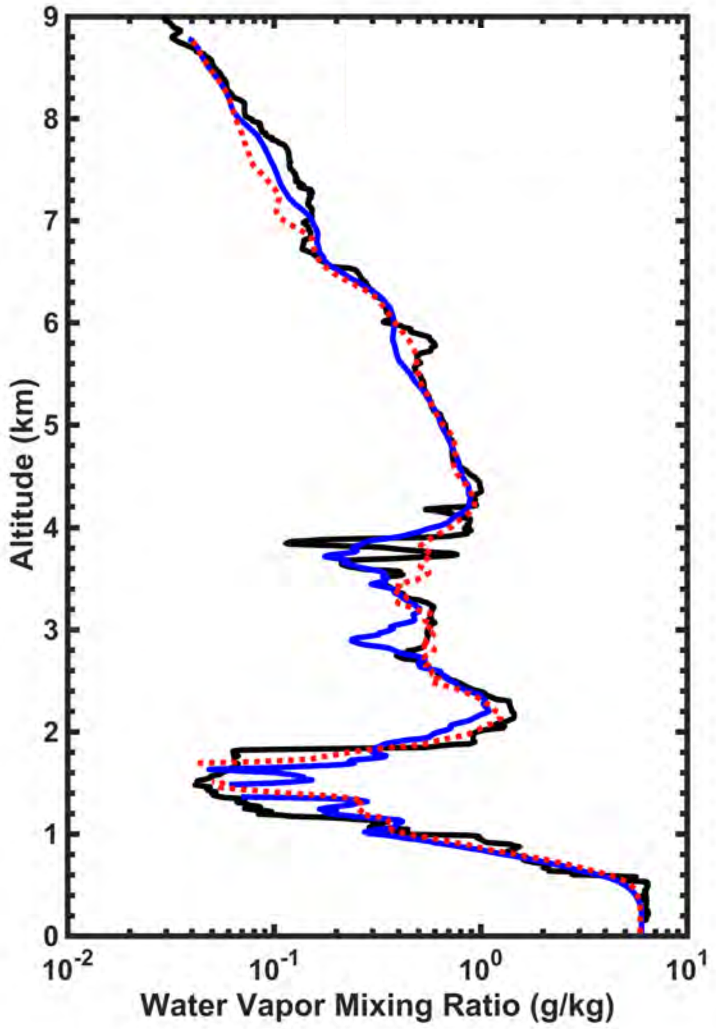


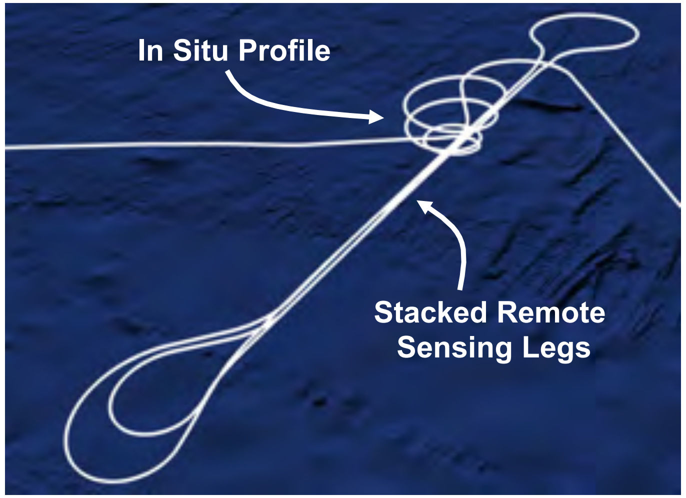
Adapted from 2013 IPCC 5AR

DIAL and HSRL provide insight into processes at all altitudes



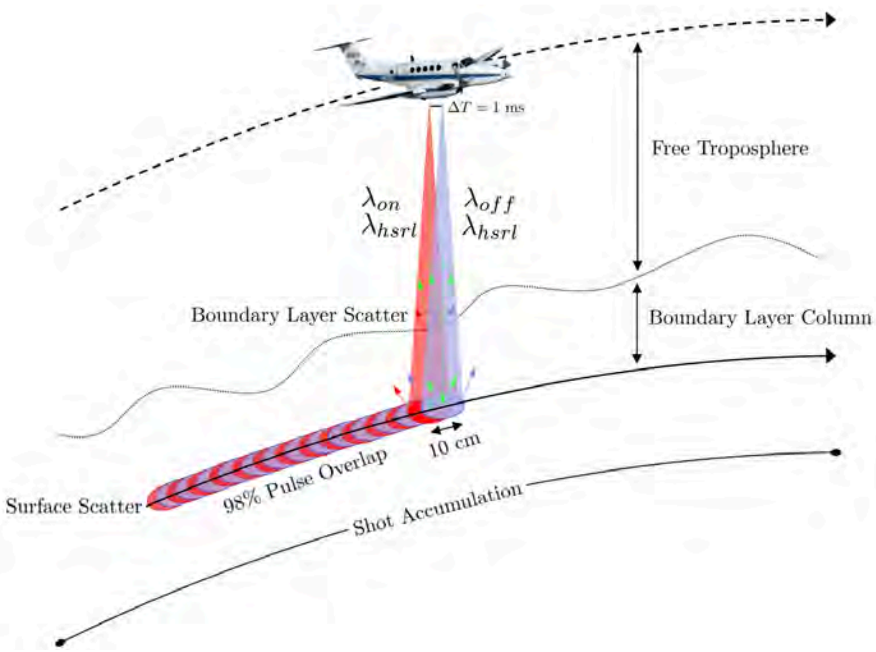
Validation with In-Situ Laser Based Hygrometer

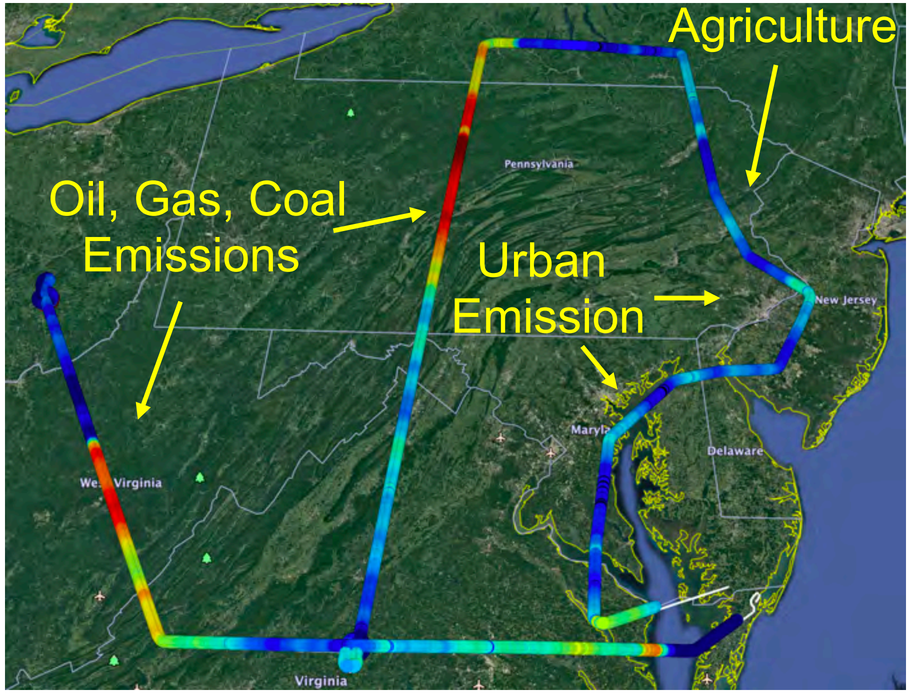


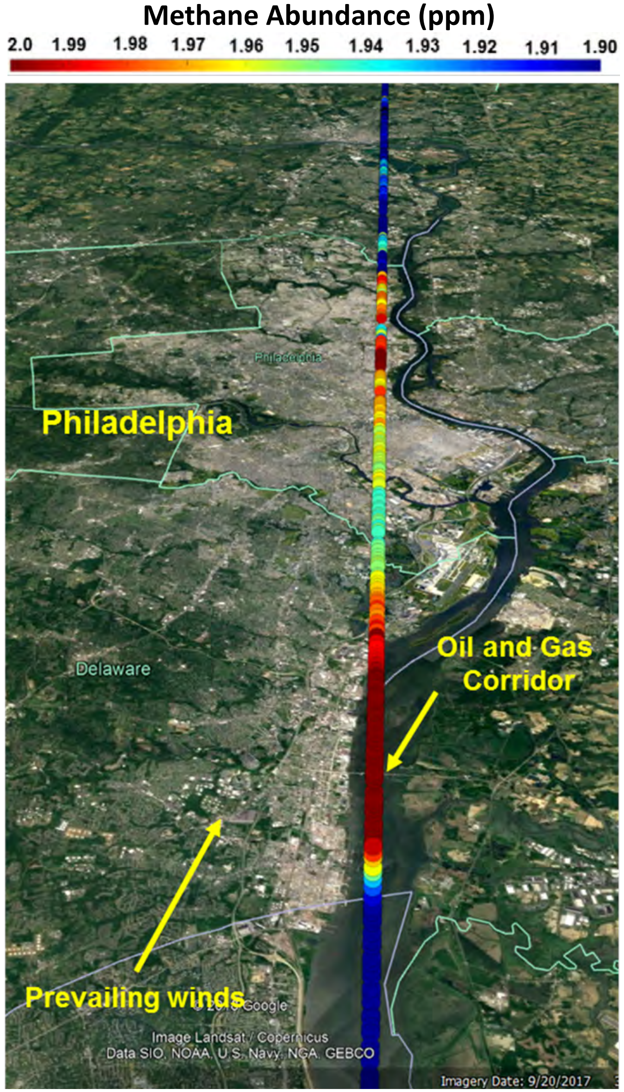


Methane

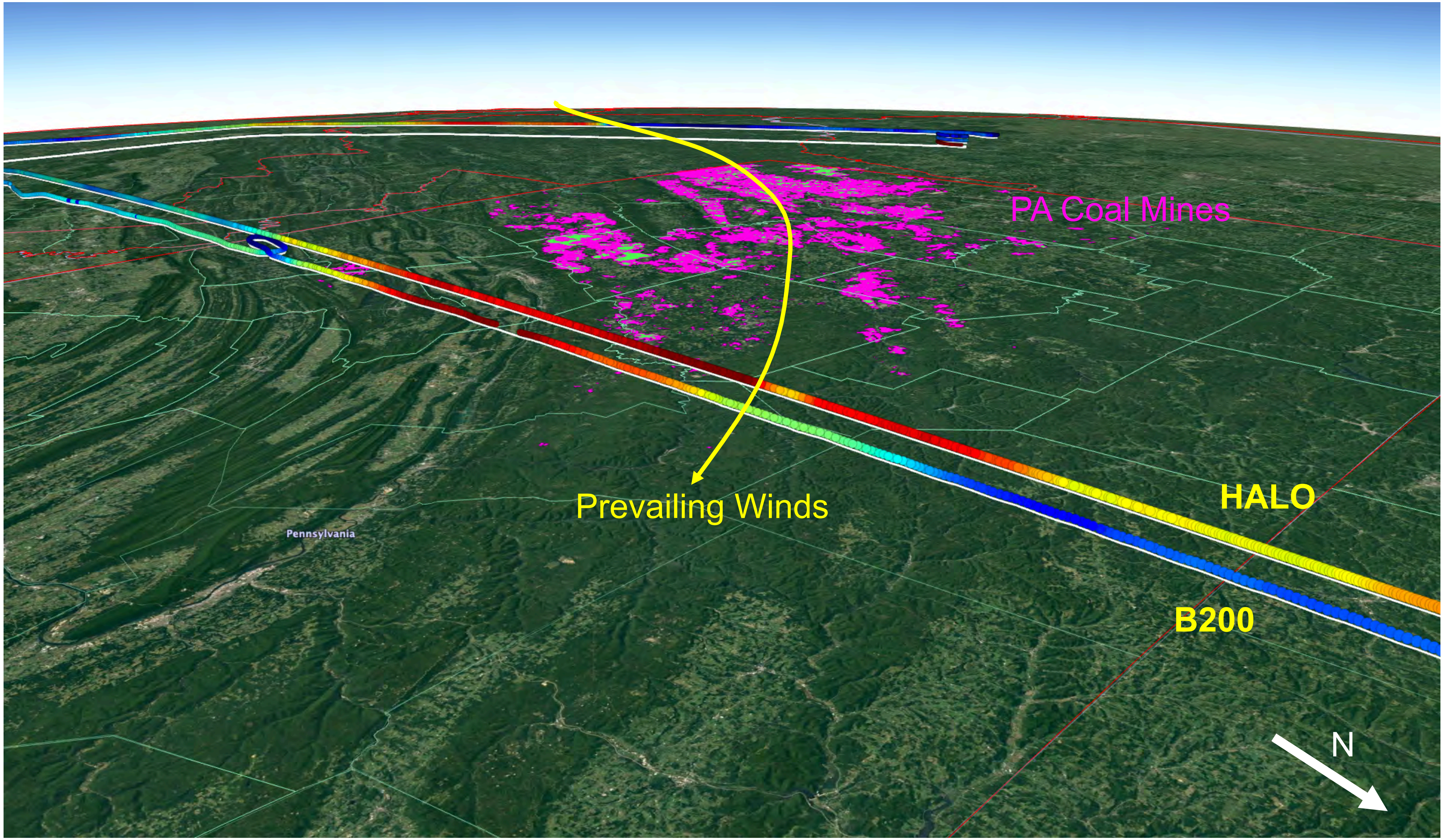
Regional CH_4 Sampling







Lidar's sensitivity to near surface emissions



What Next?

Technology Advancement for Space

- Reduction in size, weight, power and complexity is required to enable DIAL in space
- Advancing technologies with our industry and academic partners
  - Pulsed lasers including Er:YAG and Tm:YLF
  - Photonic integrated Circuits