Atmospheric Boundary Layer Lidar PathfindEr (ABLE): Crosscutting DIAL for Humidity Profiling

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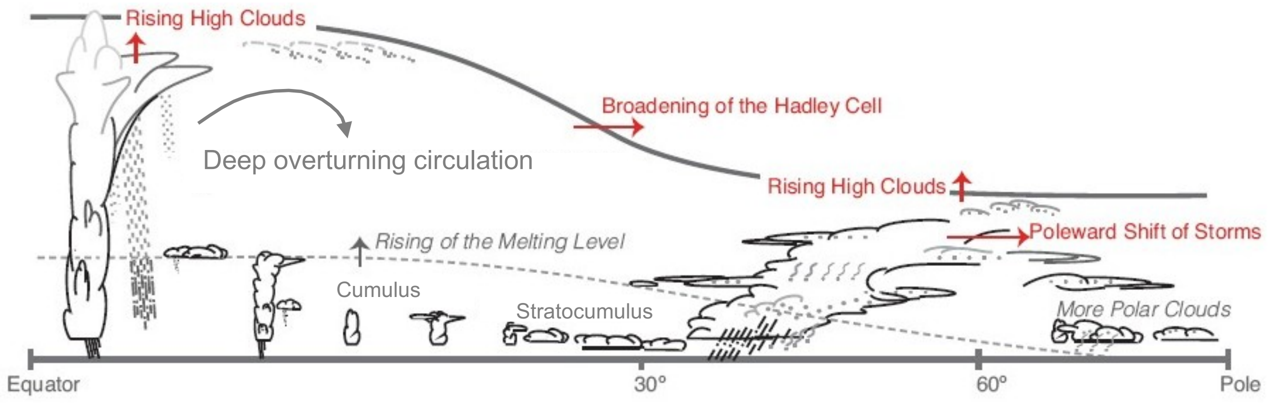
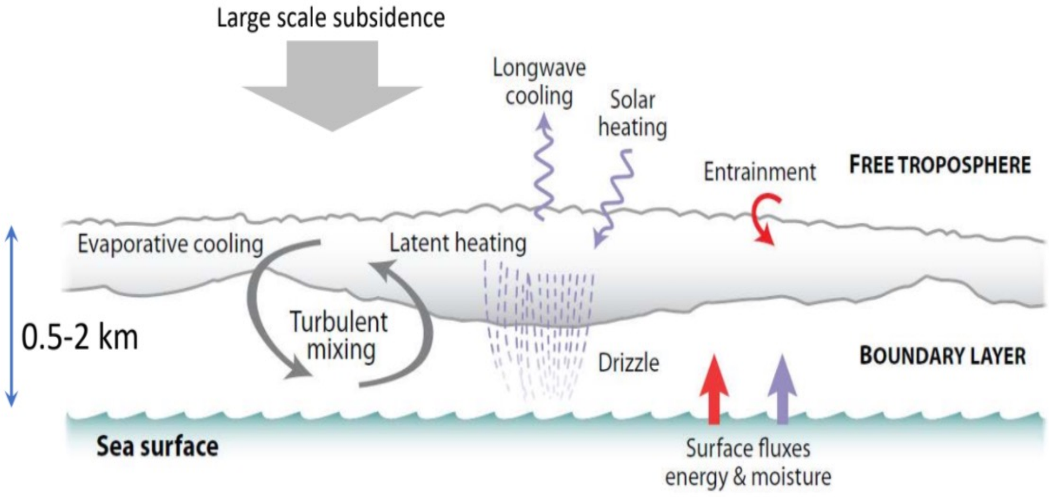
Observational Needs from Grand Challenges to the Decadal Survey

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

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



Adapted from 2013 IPCC 5AR



Wood 2012, Monthly Weather Review

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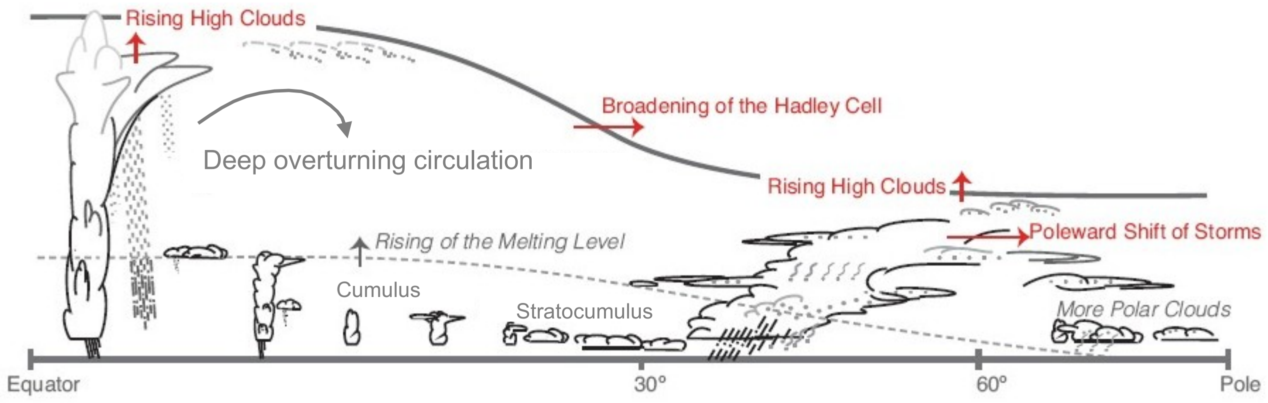

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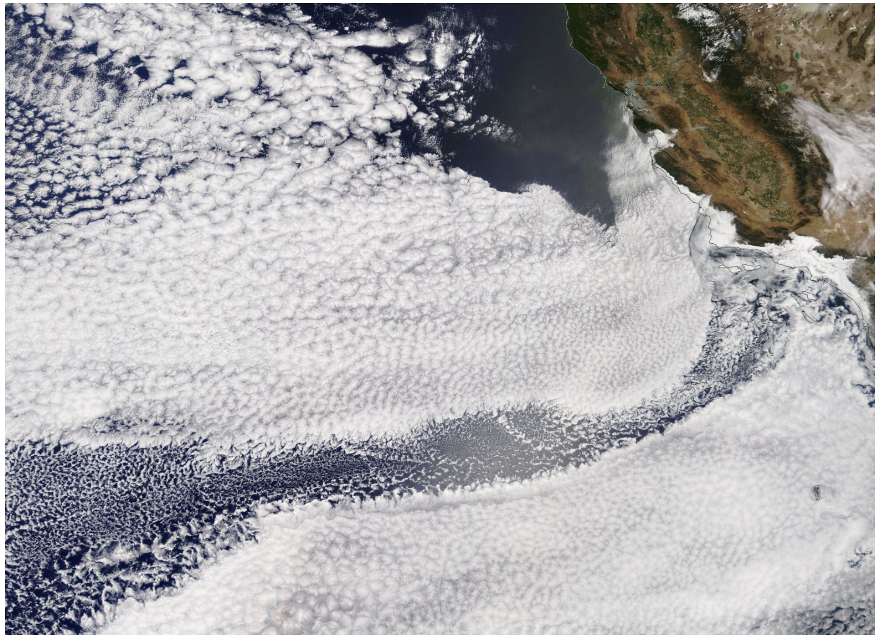
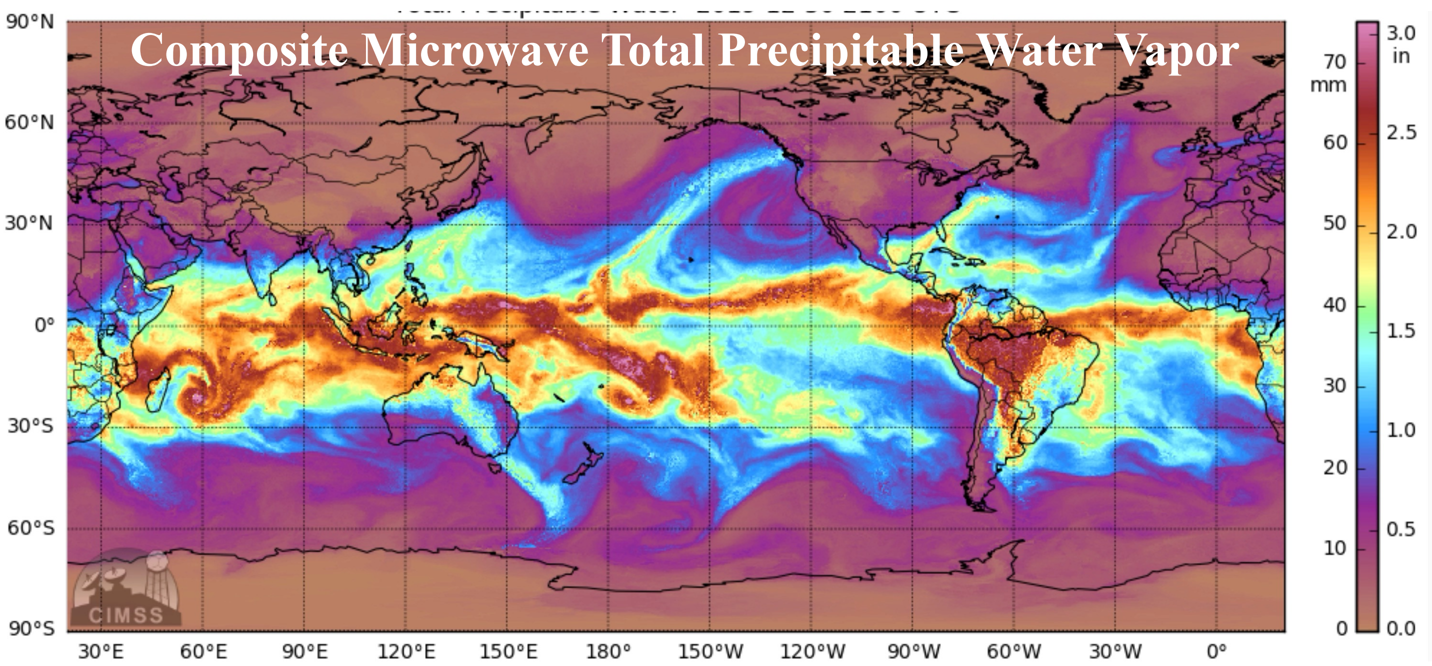
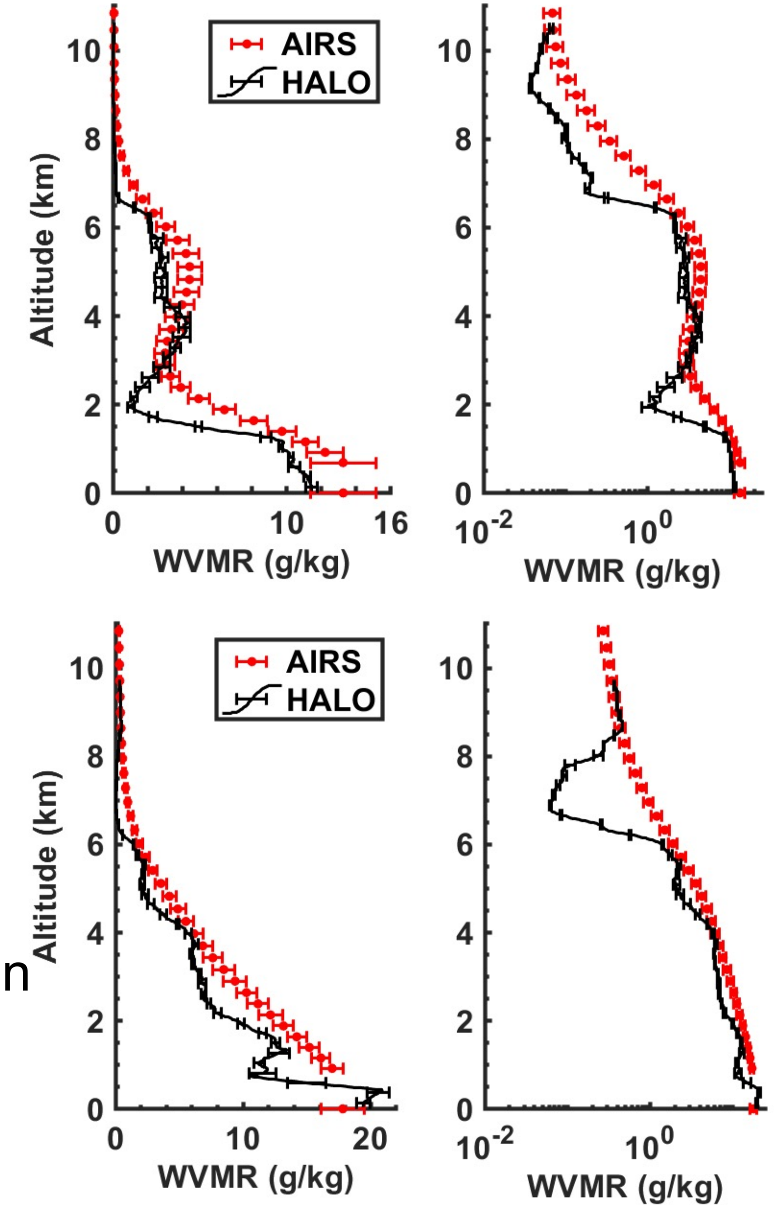


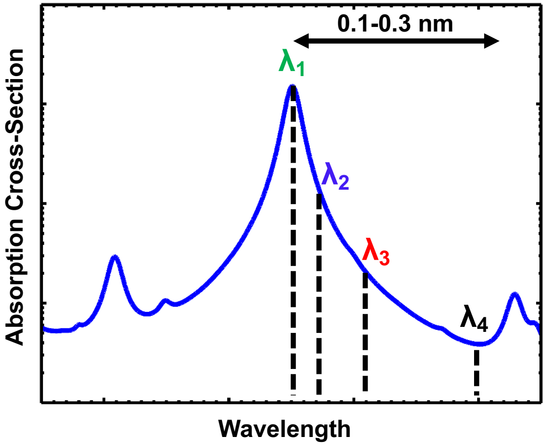
How Do we Currently Observe Atmospheric Water Vapor?

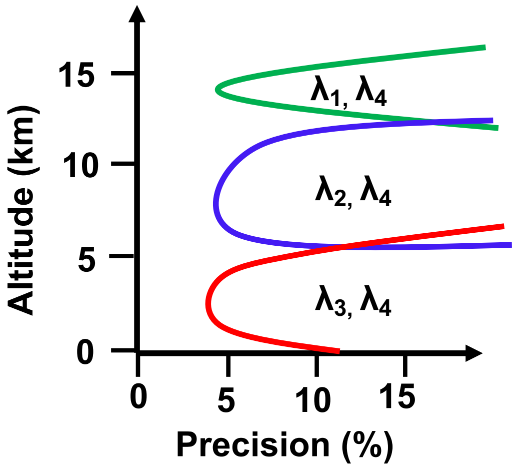


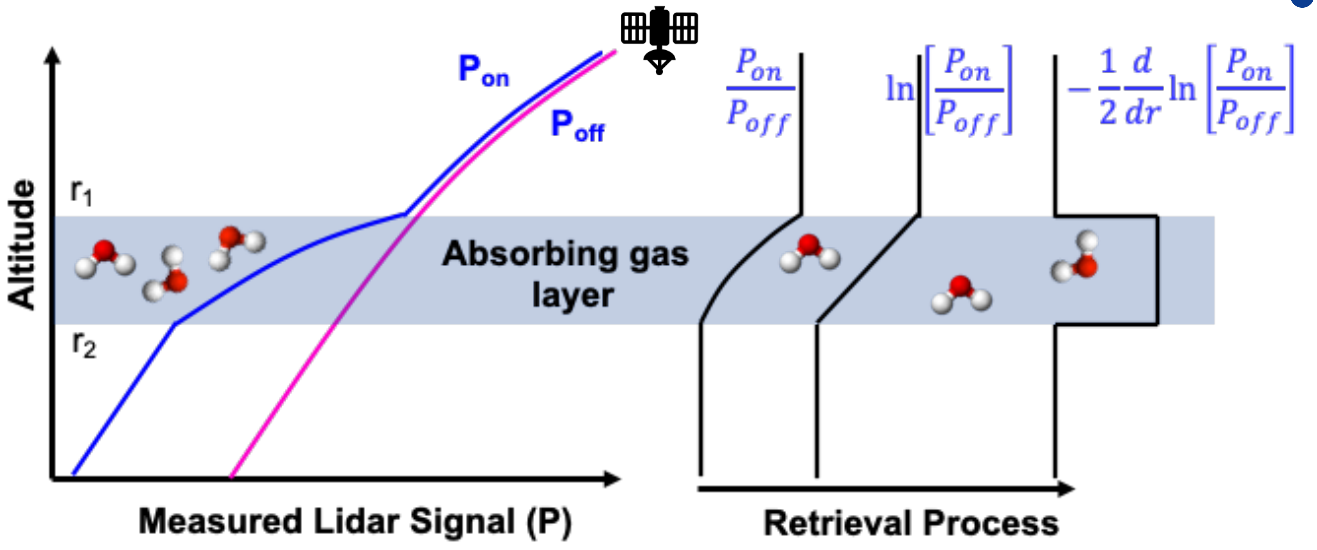


- Passive infrared (IR) and microwave (MW) observations form the backbone of NWP and climate science communities
- IR and MW sounders provide global coverage, but have limited sensitivity to the lower troposphere and have coarse vertical resolution
- GNSS-RO provides extremely high vertical resolution, however, unraveling temperature from humidity signal poses a challenge

Differential Absorption Lidar (DIAL) – Principles and Characteristics







Retrieved Number Density Profile

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

Random Error

$$\frac{\Delta n}{n} \propto (\Delta x)^{-0.5}(\Delta R)^{-1.5}$$

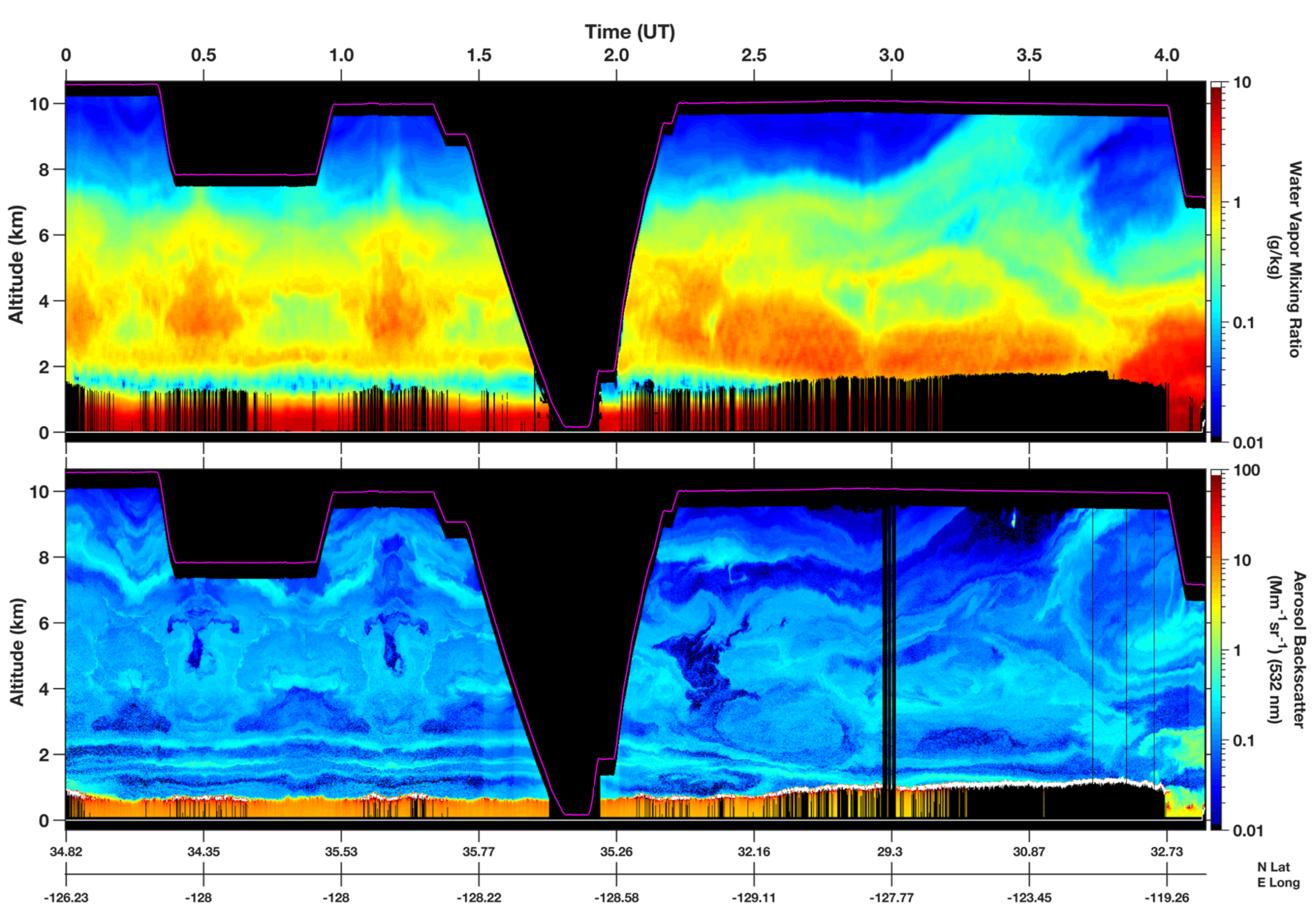
trade precision for resolution

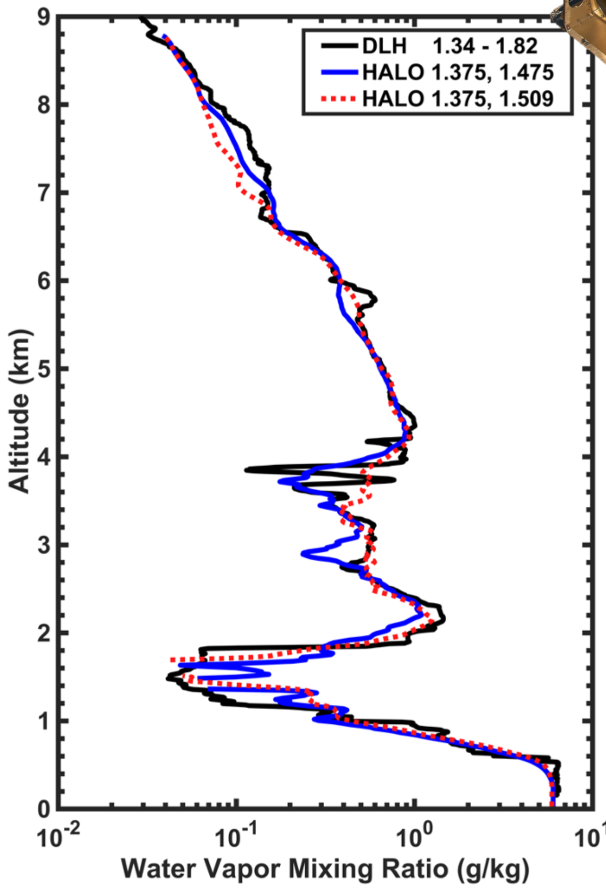
along track averaging

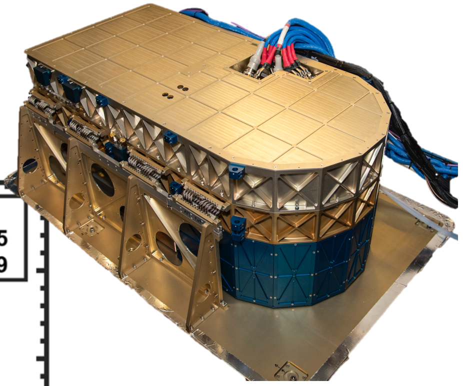
vertical averaging

- DIAL measures the differential attenuation of lidar signals between on and off transmitted wavelengths
- Multiple wavelengths can extend dynamic range from UT/LS down to PBL
- Accuracy in the PBL is independent of humidity and aerosol signals aloft
- DIAL directly measures water vapor without need for calibration or a priori information on atm. state

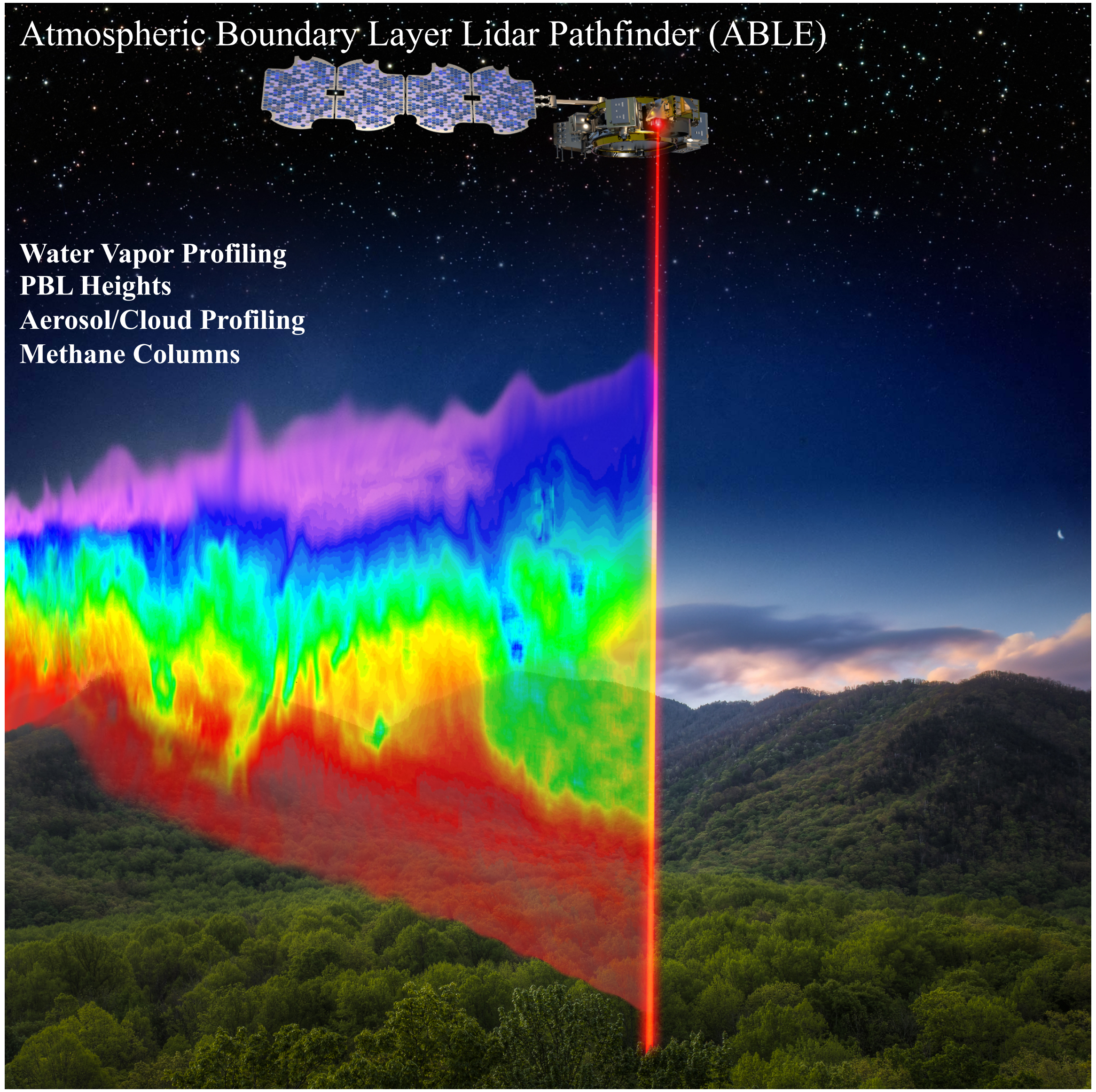
Airborne DIAL Heritage – High Altitude Lidar Observatory (HALO)







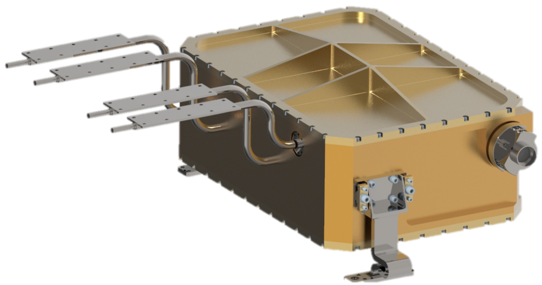
DIAL Pathfinder – Atmospheric Boundary Layer Lidar PathfindEr



- Develop a pathfinder mission concept and advance associated technologies to enable the first demonstration of DIAL in space
  - Water vapor profiling from mid-troposphere to PBL
  - 200-400 m resolution in the PBL, 1 km in mid-trop
  - 50-75km along track resolution
- Novel laser technologies enable *crosscutting science* spanning disparate science focus areas
  - Weather and dynamics (including PBL)
  - Atmospheric composition and radiation
  - Carbon Cycle
- Set stage for synergistic observing system with other active and passive sounders
- Balance performance/complexity with affordable and flexible design to fit within future cost capped missions

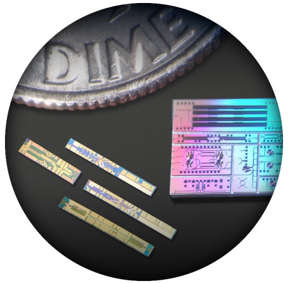
Development approach

1. Develop space qualifiable Er:YAG laser transmitter
2. Increase efficiency of 1532 nm pump diodes to enable operation on smallsat
3. Develop photonic integrated circuit seed laser as injection seeding source
4. Develop satellite instrument concept capable of rideshare launch on ESPA Grande

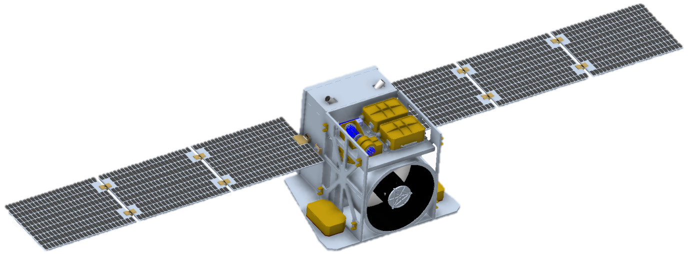


FIBERTEK, INC.

nLIGHT



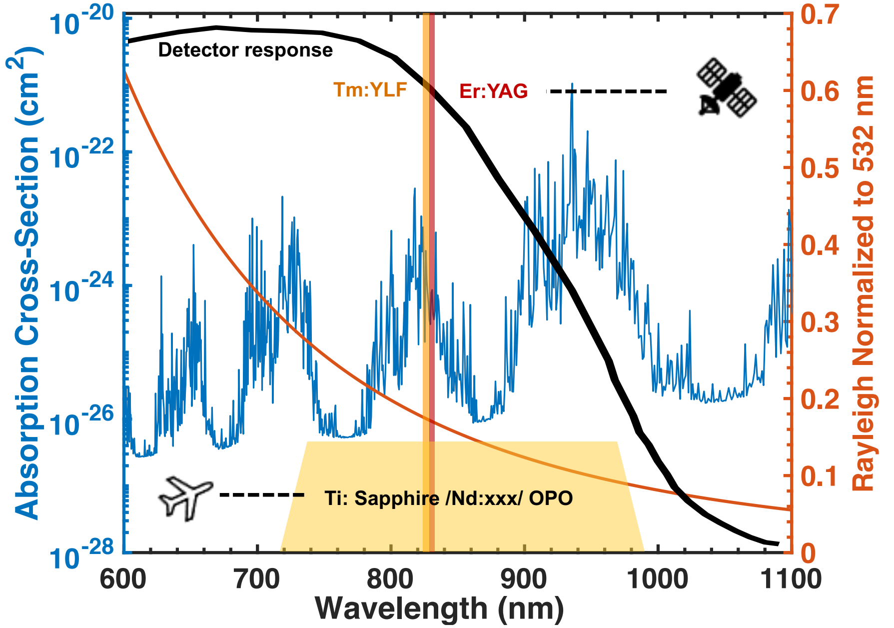
FREEDOM PHOTONICS



WMD WELCH MECHANICAL DESIGNS

Pulsed Laser Advancement – Challenges and Driving Requirements

- 820 nm spectral band is attractive for space-based water vapor DIAL
  - Absorption lines provide sensitivity to the mid-lower troposphere
  - Enhanced Rayleigh scattering compared to SWIR
  - Allows for use of efficient, single photon sensitive Si detectors
  - Spectrum accessed by efficient emerging laser technologies
- Laser transmitter is one of the primary challenges for space-based DIAL
  - High efficiency and low complexity for small SWaP
  - High peak and average power, frequency agile and good beam quality



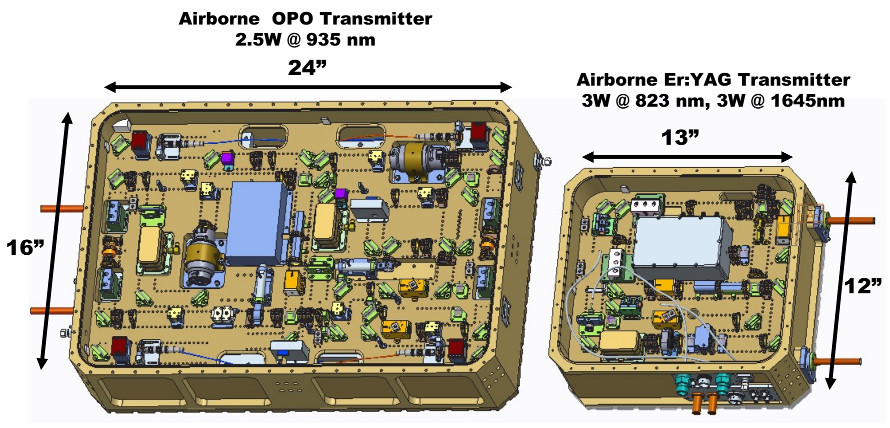
Near Infrared Laser Survey

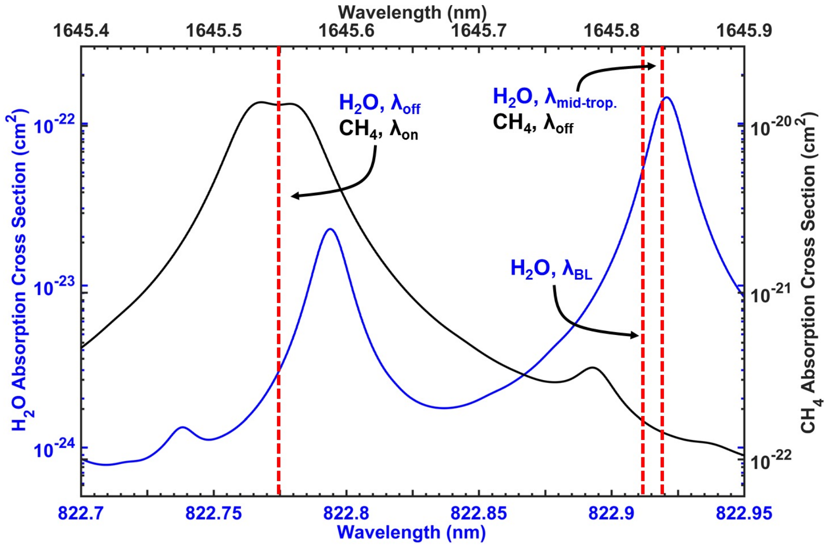
	Laser	Efficiency to 820 nm	Power (W)	~Pulse Energy	Complexity	Maturity	
	Ti:Sapphire	1-2%	5-10	100 mJ	5 parts	Mature	Diodes → Nd → 2x → Ti:Sapphire →
	OPO	1-2%	5-10	50-80 mJ	5 part	Mature	Diodes → Nd → 2x → OPO/OPA →
ACT-17, T.Y, Fan	Tm:LiYF$_4$ (YLF)	5-8%	20-30	10-15 mJ	2 parts	Emerging	Diodes → Tm:YLF →
IIP-19, ABLE	Er:YAG	2-3%	6-10	3-5 mJ	3 parts	Emerging	Diodes → Er:YAG → 2x →

A transmitter for space-based mission has been a challenge pursued for >3 decades

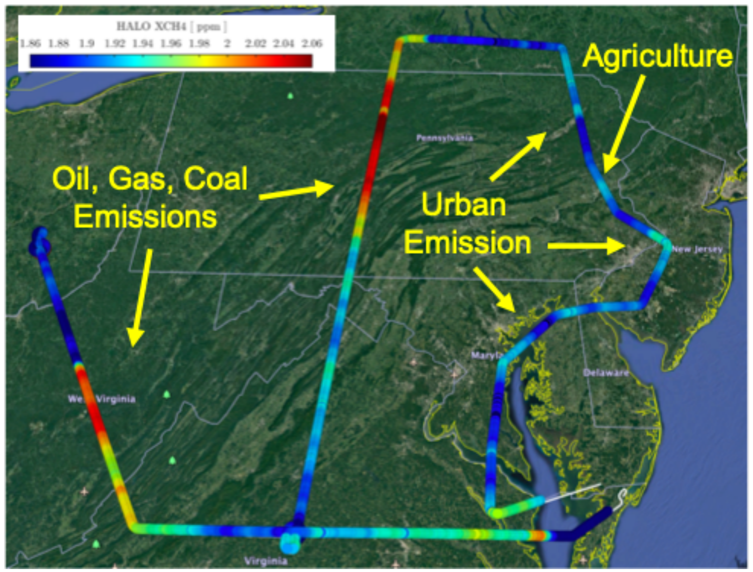
Pulsed Laser Advancement – Reducing complexity and enabling crosscutting science

- Doubled Er:YAG provides access to appropriate strength water vapor lines in the NIR
- Reduced complexity compared to heritage airborne DIAL transmitters
- Dual wavelength Er:YAG allows for crosscutting science that addresses several 2017 Decadal Survey Target Observables
  - Water vapor profiles and PBL heights – PBL Incubation
  - Methane columns – Earth Explorer
  - Aerosol/cloud distributions – ACCP Continuity



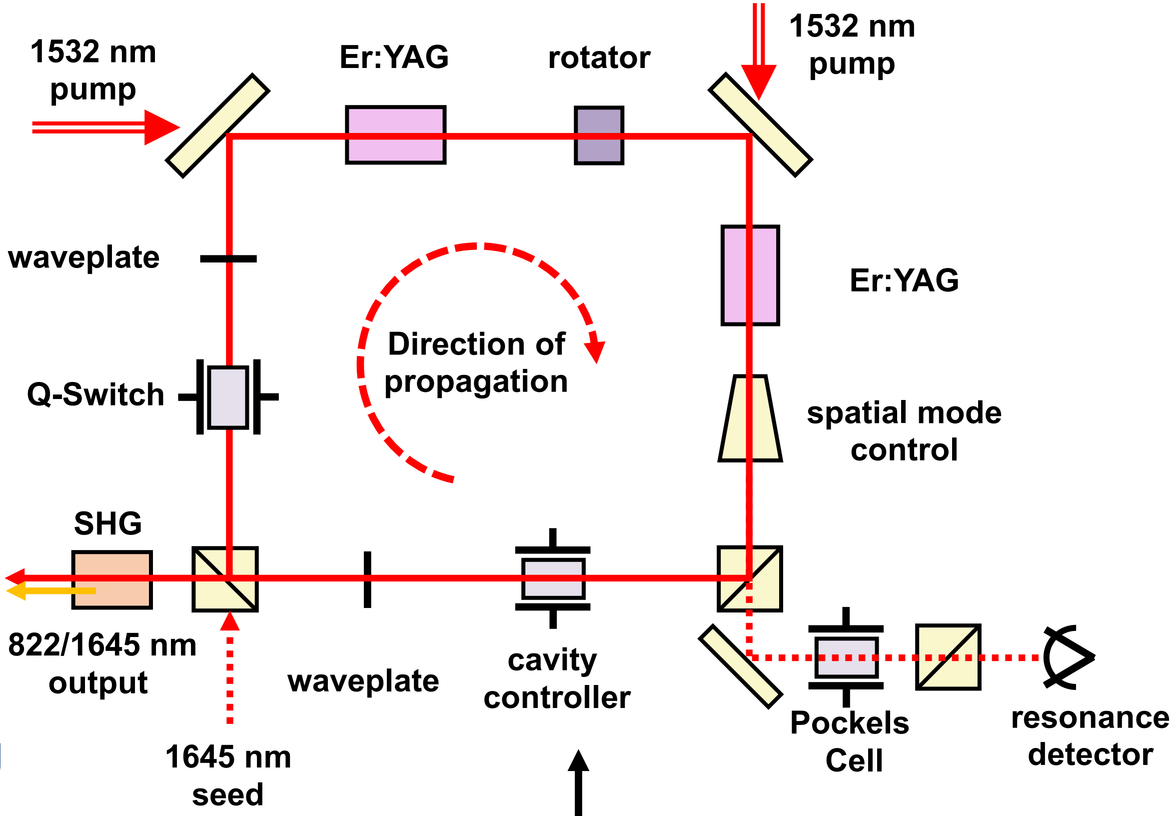


HALO Methane Columns

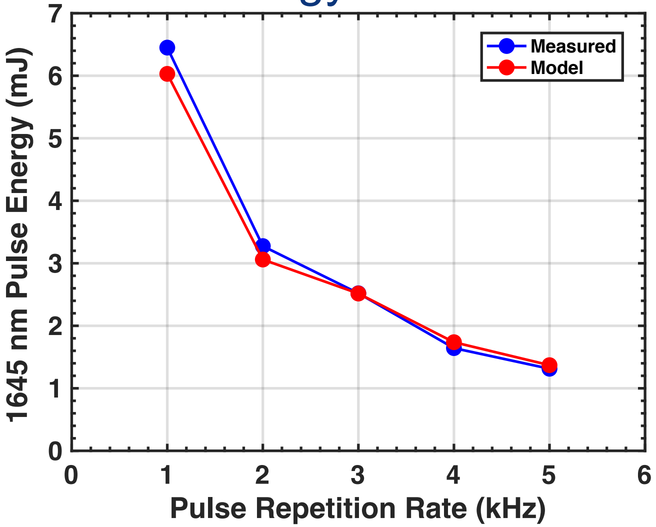


Pulsed Laser Advancement – Er:YAG Performance

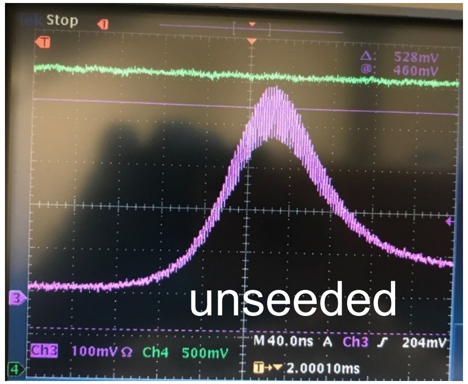
- Er:YAG laser developed for airborne applications meets many of the requisite characteristics for space-based DIAL
- Observed 1645/822 nm pulse energy agrees with laser rate equation models
- Single frequency and high spectral purity operation demonstrated via injection seeding
- Worlds first and only demonstration of all electro-optic cavity stabilization (i.e. no moving parts)

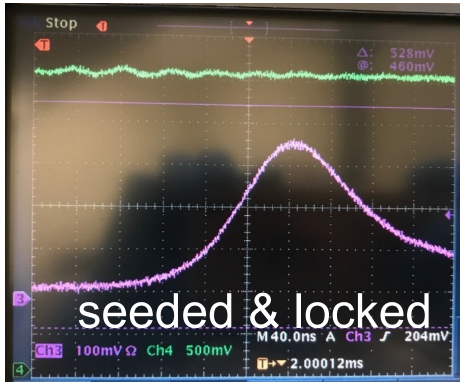


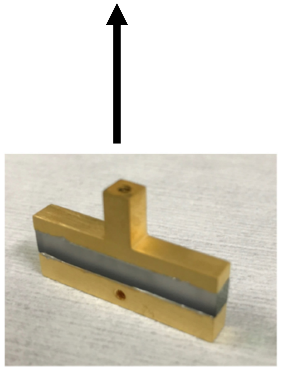
Energy vs PRF



Injection Seeding







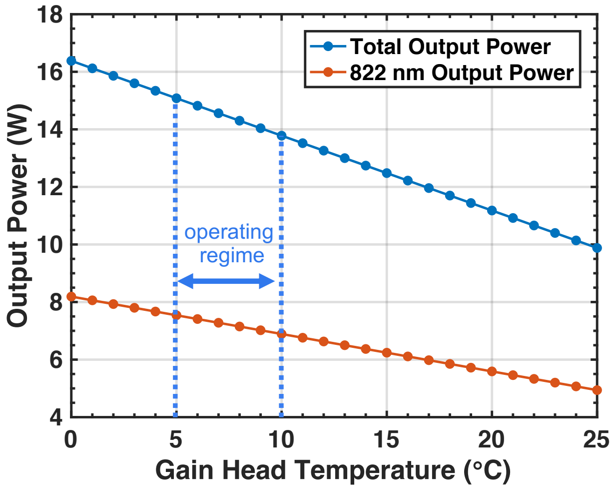
High Voltage Driver

Pulsed Laser Advancement – Technology Advances

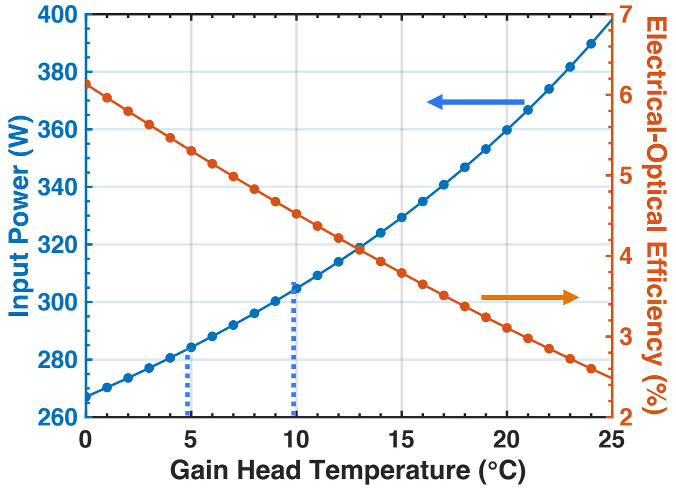
- Er:YAG technology advances
  - Increase PRF from 1kHz to >2kHz with >6 mJ at 1645 nm
  - Increase optical to optical efficiency from 10% to 20%
  - Replace TEC for Er:YAG gain heads with heat pipes resulting in 25% reduction in power consumption
  - Heat pipe thermal management of optical bench
- Design and build a TRL 5 laser optical module for future qualification
- Er:YAG offers the world's first direct measure of the critical water vapor cycle plus the highest resolution spatial sampling of methane sources

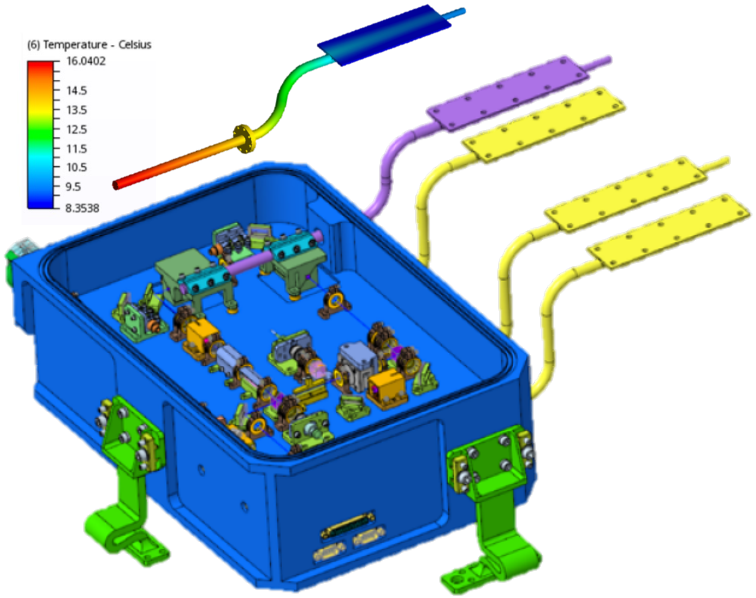
Parameter	Results	Objective
Wavelength	1645/823 nm	1645/823 nm
Pulse Energy	6.5 mJ	6-7 mJ
Repetition Rate	1 kHz	2-3 kHz
Average Power	6.5 W	13-14 W
SHG Efficiency	50%	50-60%
Pulse Width	120 ns	100-120 ns
Linewidth	19 MHz	<100 MHz
Spectral Purity	1000:1	≥ 1000:1
Wavelength Tuning	shot-to-shot	shot-to-shot
System Efficiency	1.4%	≥ 5%

Modeled Er:YAG Output Power



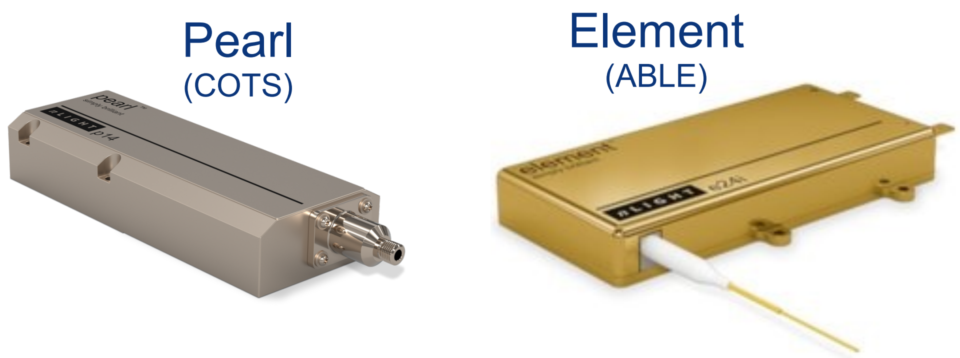
Modeled Power Consumption/Efficiency



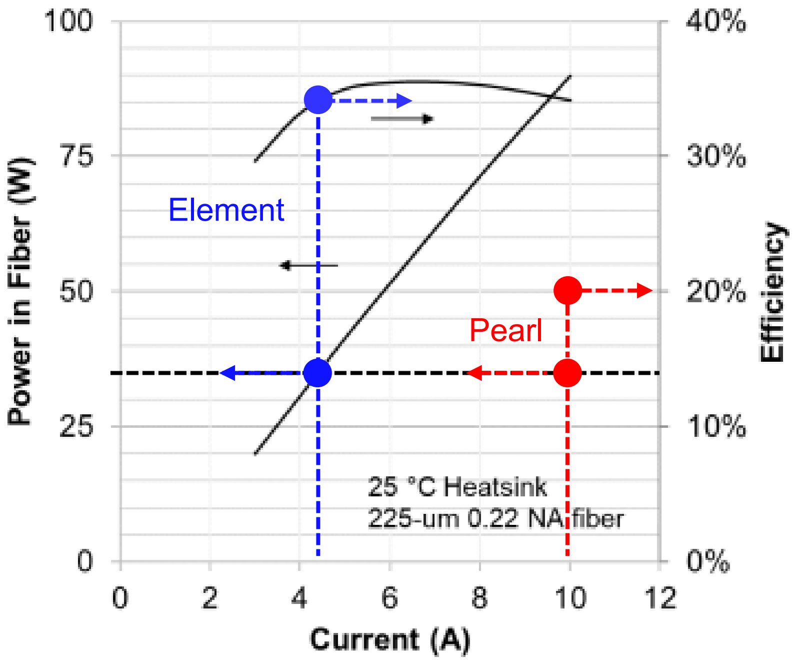


Pump Laser– Increase Efficiency and Brightness

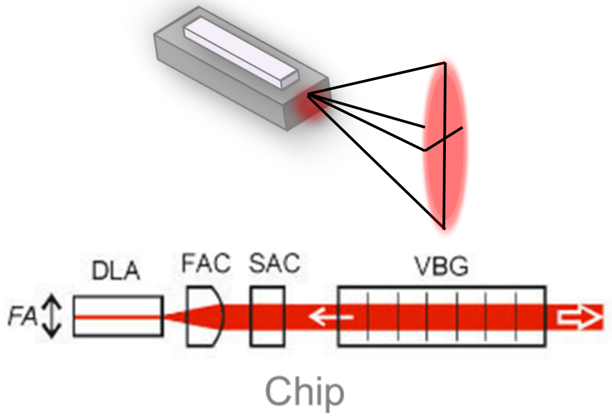
- Increase efficiency of commercially available 1532 nm pump diodes from ~20% to >40% with ≥ 35 W output power
- Multi-pronged approach to increasing efficiency
  - Optimize diode epitaxial design
  - Achieve higher brightness through optical mode control
  - Increase optical throughput
  - Increase thermal conductivity
- Preliminary results demonstrate >35% efficiency with 3x brightness
- Improved efficiency and brightness allows for optimization of pulsed laser architecture and power scaling for more capable mission concepts

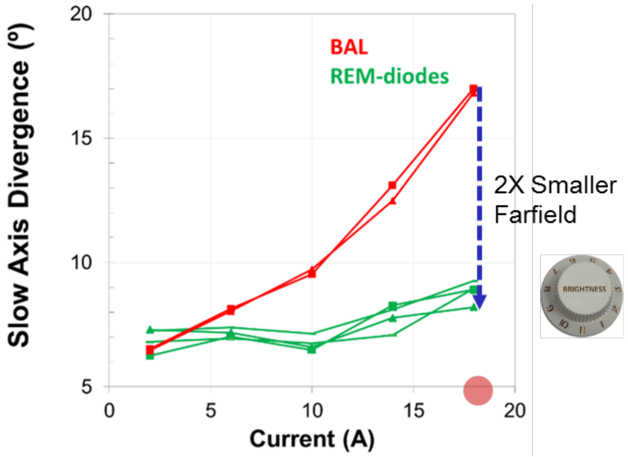


Optical – Electrical Efficiency



Mode Control

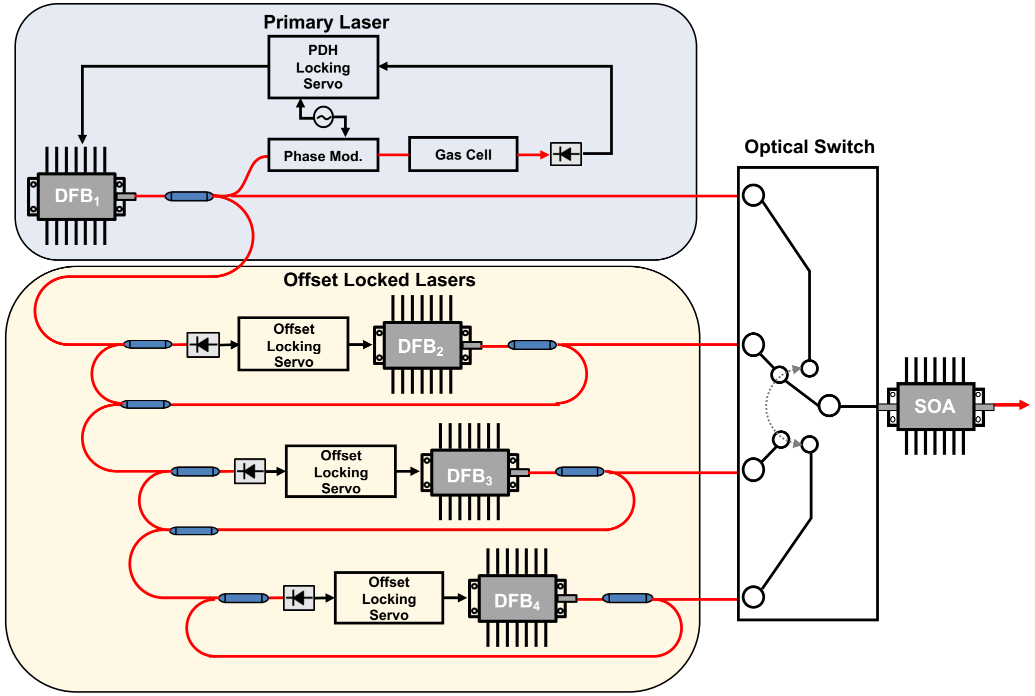


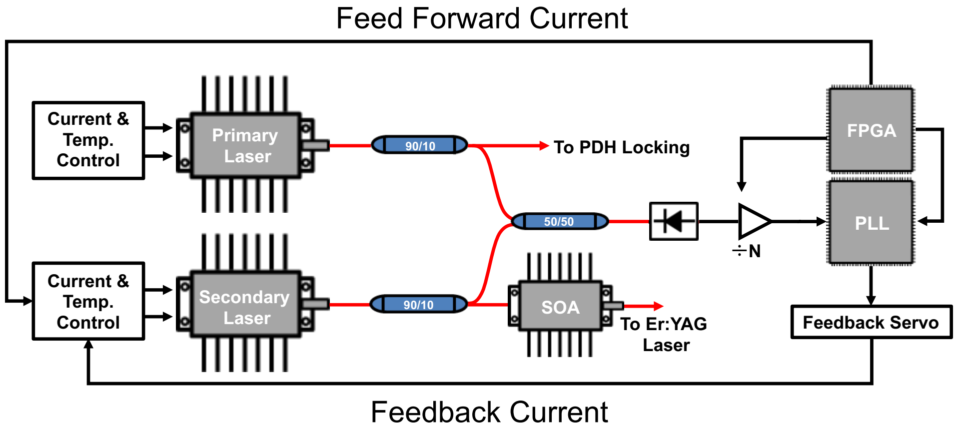


Seed Laser – Bridging the gap from airborne to flight

- Seed laser is the heart of DIAL systems and can affect the accuracy of the DIAL retrieval
- Discrete components used in airborne systems not compatible with SWaP constraints on SmallSats
- Photonic integration employed to significantly reduce SWaP and increase reliability

TRL 9 Airborne → **Photonic Integration** → **TRL 5 Flight**





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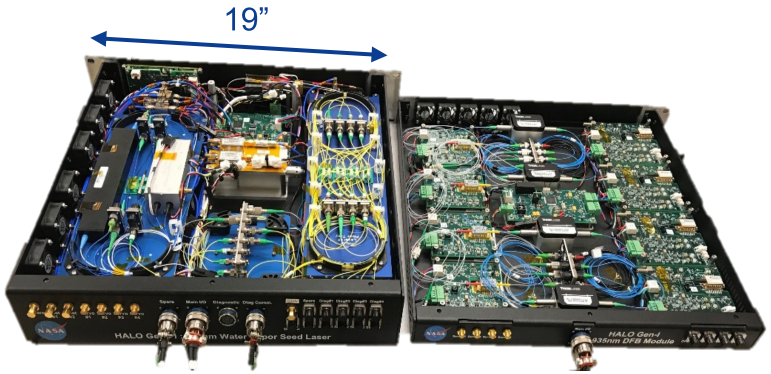
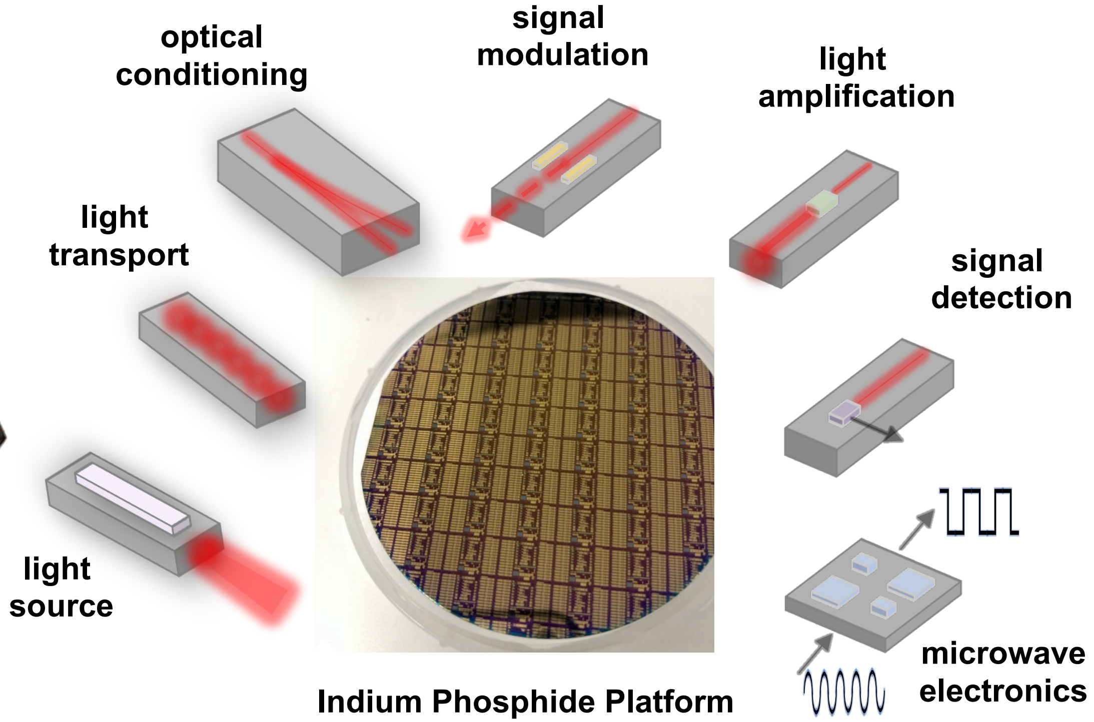
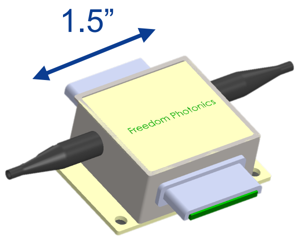
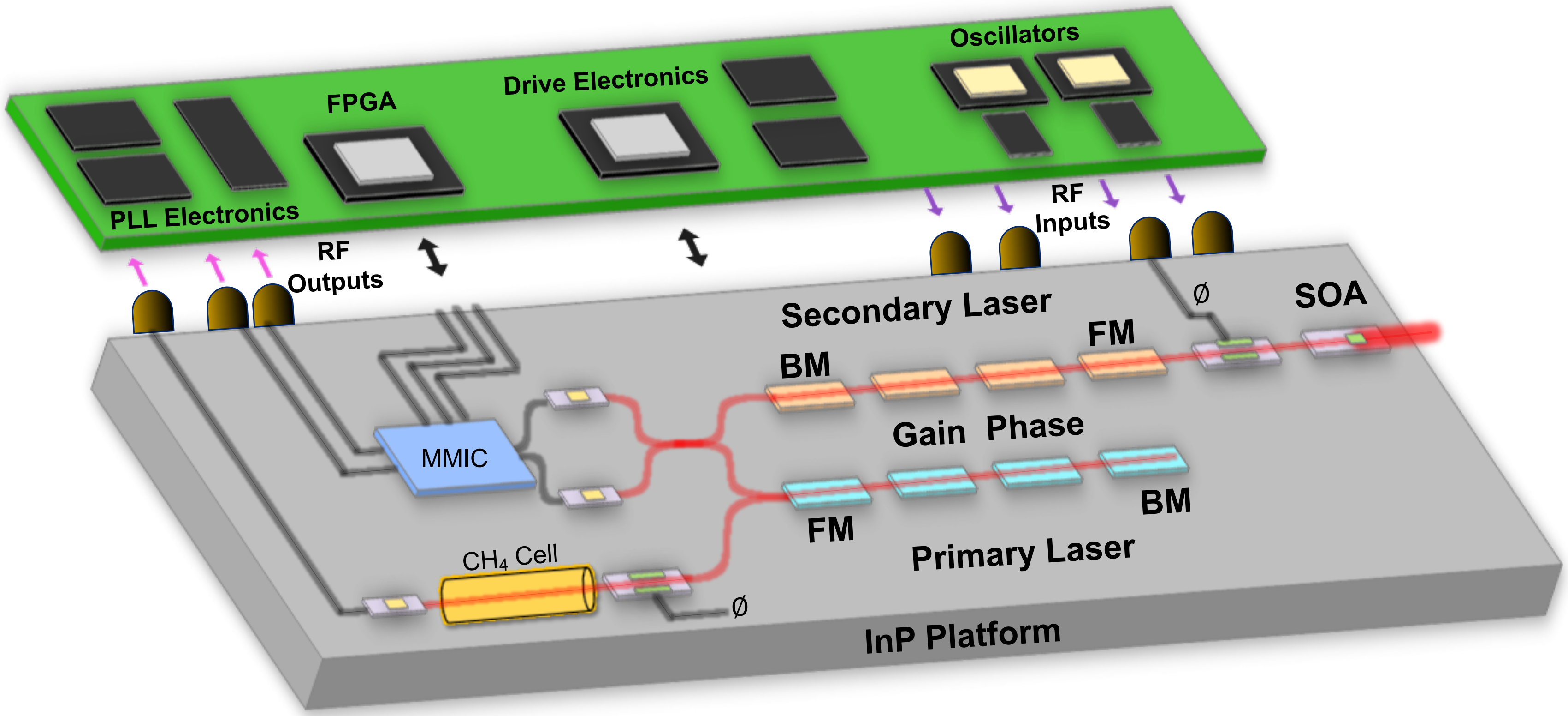




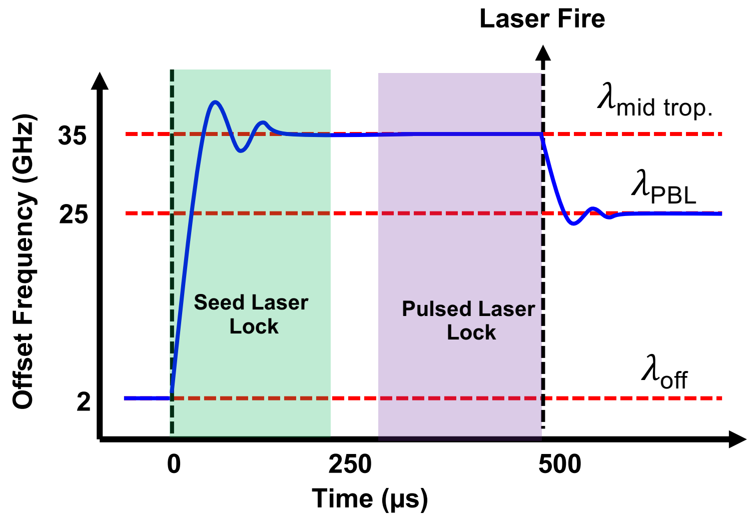
Indium Phosphide Platform

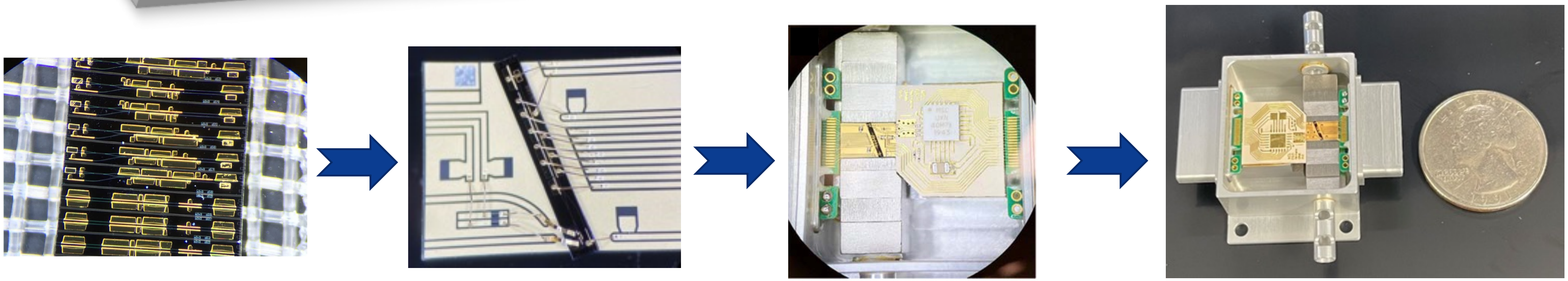


PIC Seed Laser Source – Architecture



Transmitter Timing Diagram

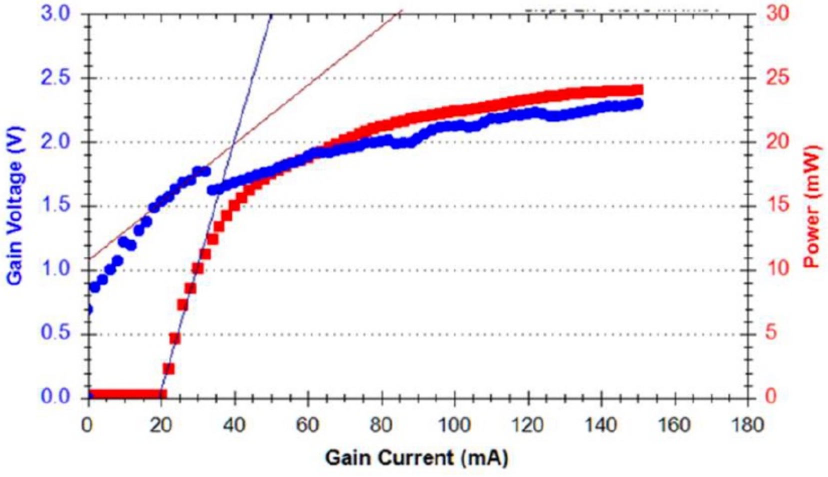




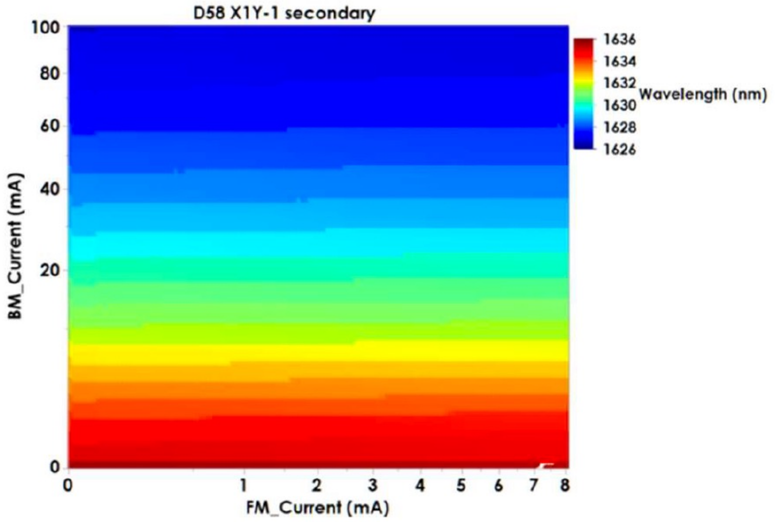
PIC Seed Laser Source – Preliminary Results

- PIC exhibits requisite performance for space-based DIAL
  - Primary seed laser has >5x the required power for line locking allowing for adequate derating
  - >20 mW from secondary seed laser allows efficient seeding of Er:YAG pulsed laser
  - Both primary and secondary lasers have broad continuous tuning range
  - Demonstrated rapid scanning across CH_4 lines suitable for step-locked optical phase lock loop
- Current focus is on characterizing bandwidth of balanced detectors and coupling to RF components

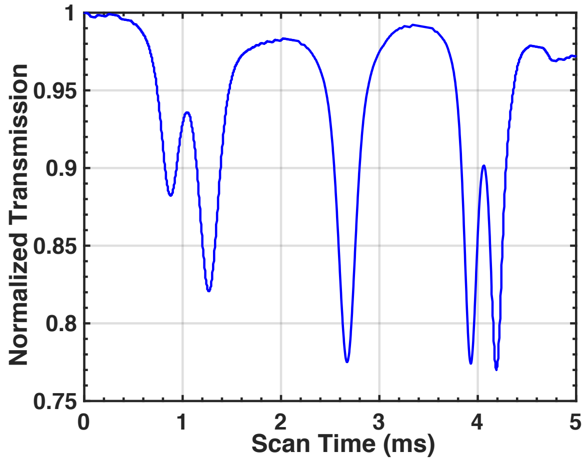
Secondary Laser LIV Curve



Secondary Laser tuning map



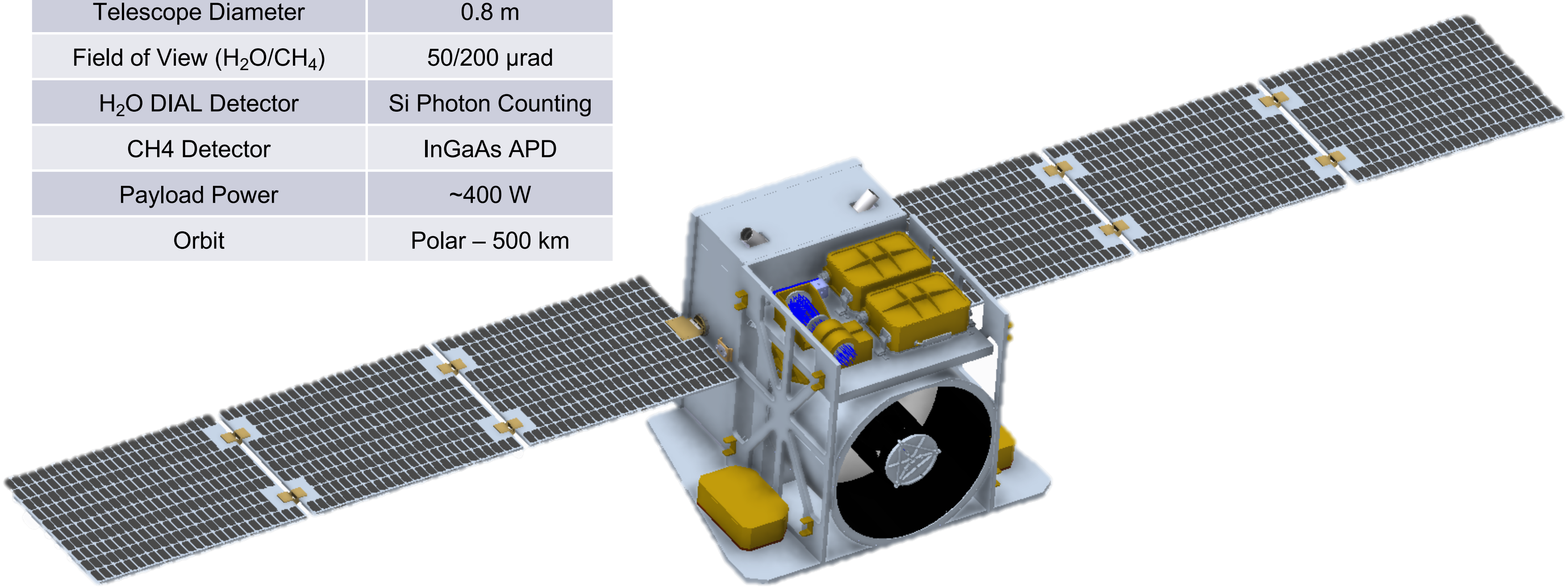
CH_4 line scan

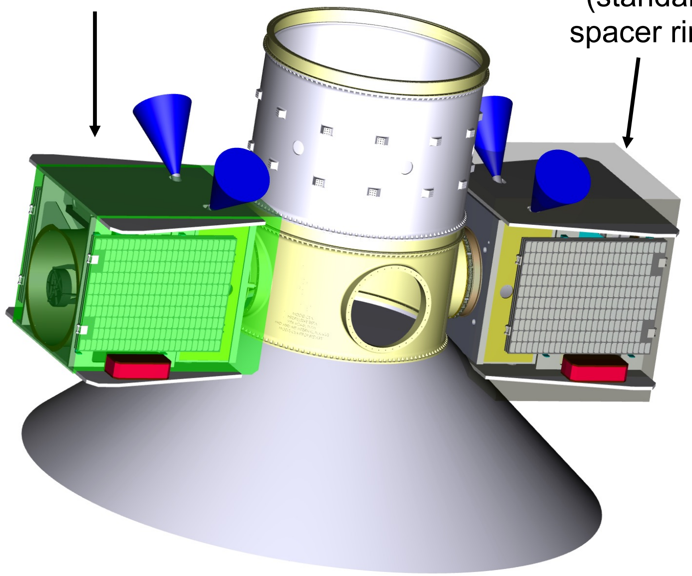


Spacecraft Accommodations and Systems Engineering

- Spacecraft accommodation survey identified several ESPA class buses suitable for capable lidars
- Highly evolving industry shows promise for accommodating space-based DIAL SWaP requirements
- Preliminary systems engineering study demonstrates the feasibility of DIAL on SmallSat platforms

Parameter	
Pulse Energy (822/1645 nm)	3.5 mJ/3.5 mJ
Repetition Frequency	2 kHz
Telescope Diameter	0.8 m
Field of View (H_2O/CH_4)	50/200 µrad
H_2O DIAL Detector	Si Photon Counting
CH4 Detector	InGaAs APD
Payload Power	~400 W
Orbit	Polar – 500 km





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