



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

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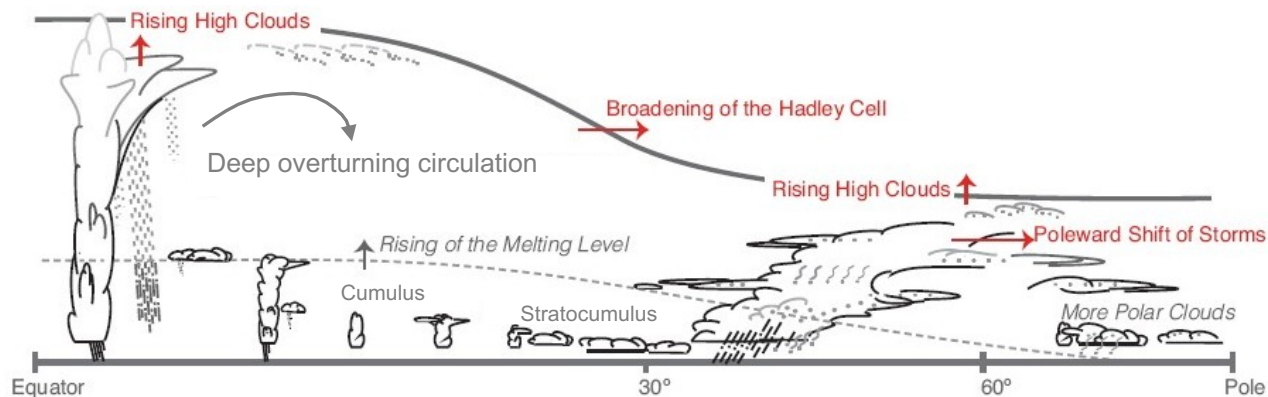
⁵Welch Mechanical Designs, Aberdeen, MD

Observational Needs from Grand Challenges to the Decadal Survey

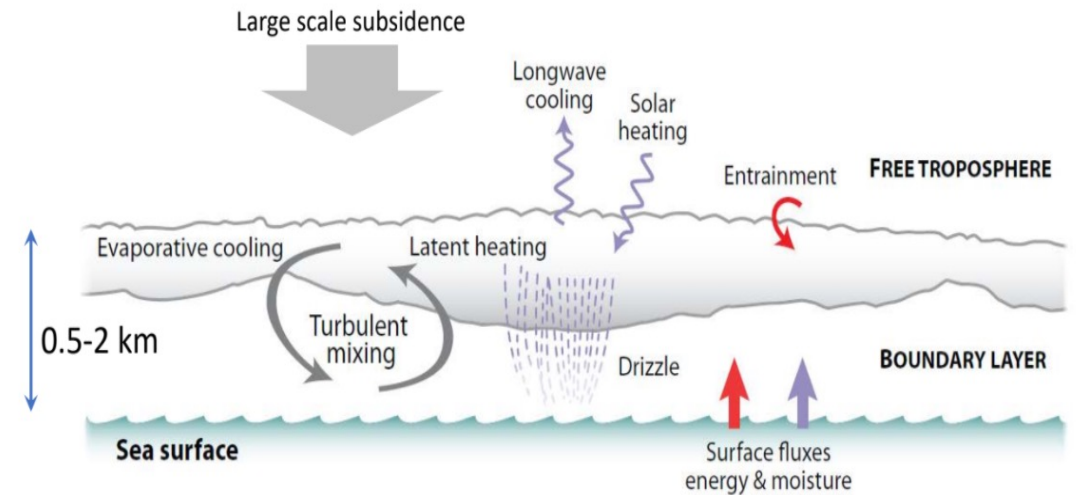


The 2017 Decadal Survey and the World Climate Research Program Grand Challenges highlight:

- 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

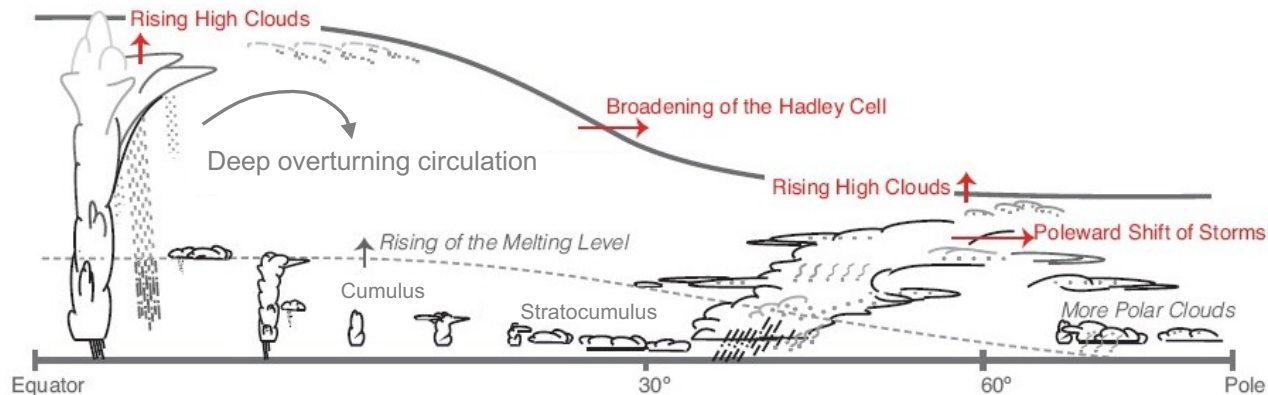


Observational Needs from Grand Challenges to the Decadal Survey

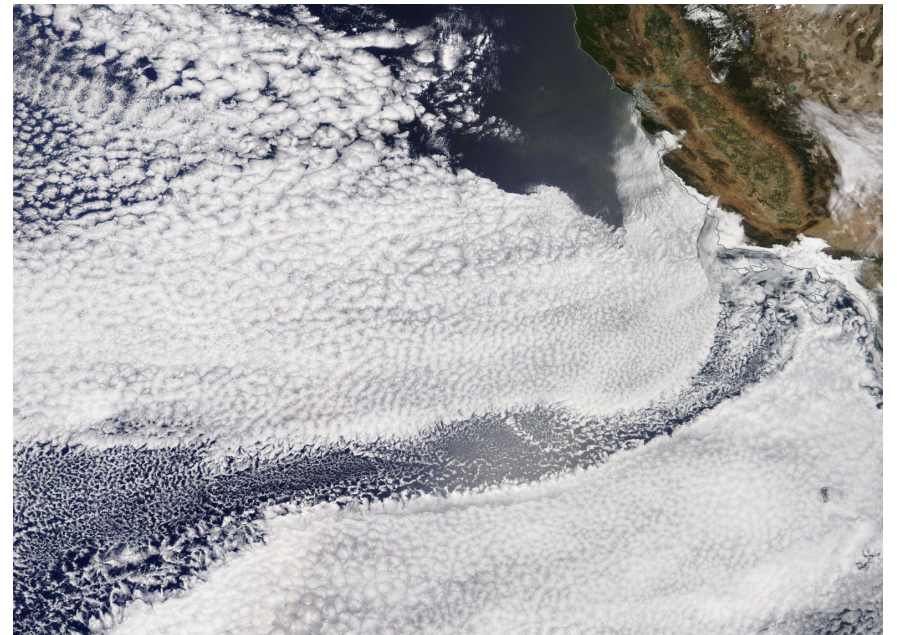


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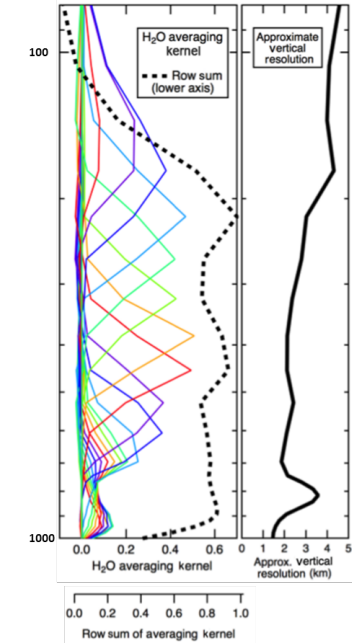
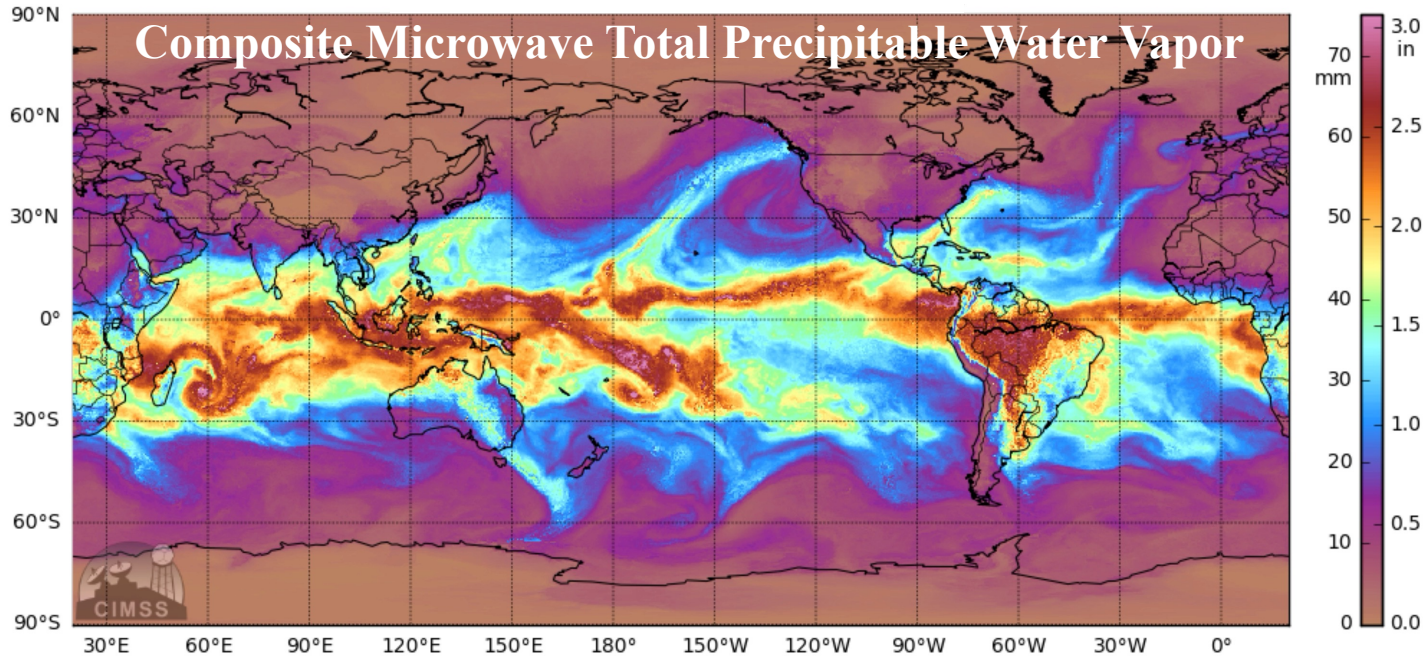
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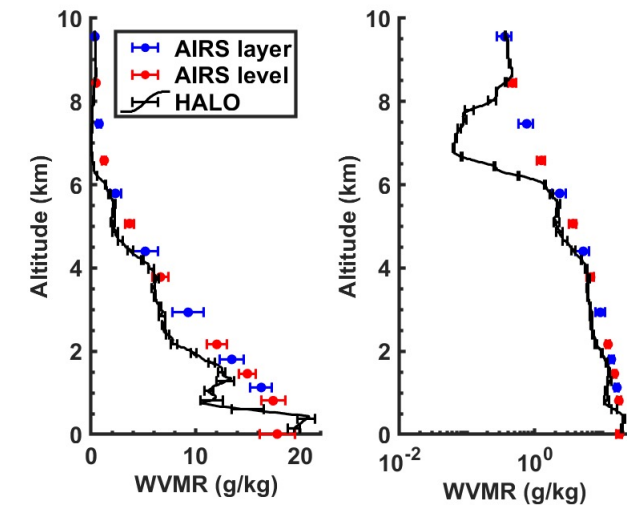


How Do we Currently Observe Atmospheric Water Vapor?

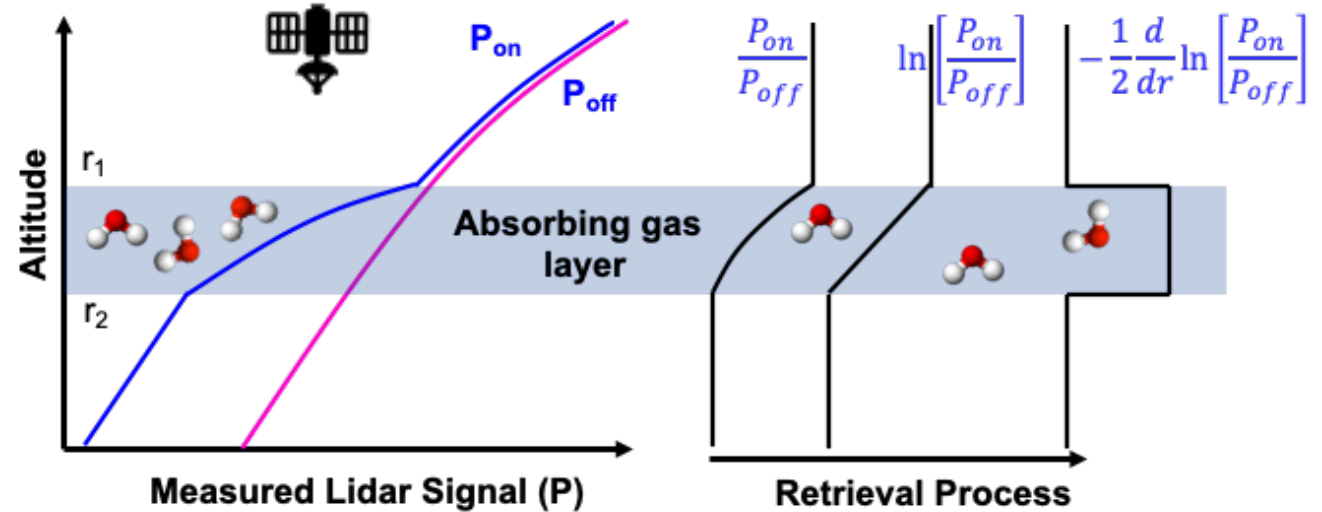
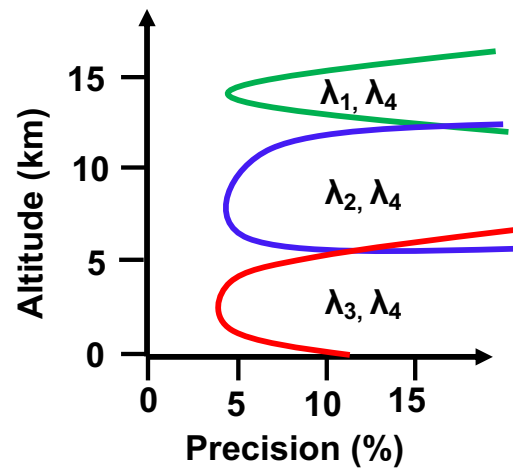
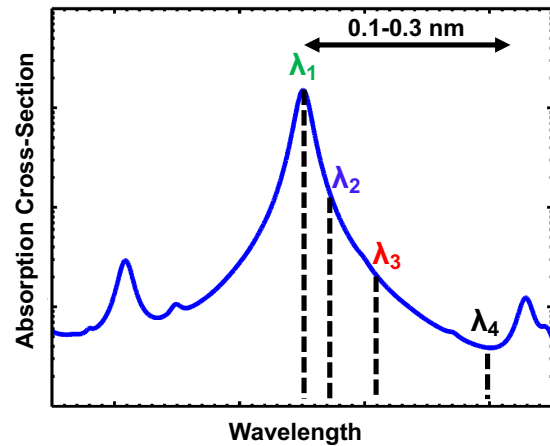


Iron et al., AMT 2018

- 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



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

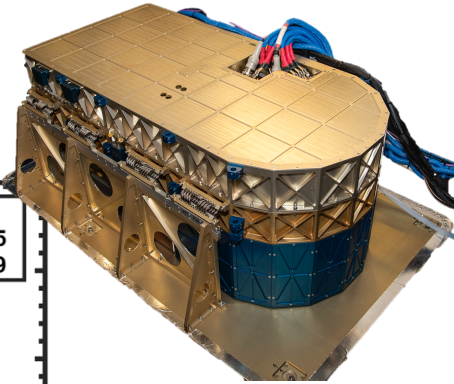
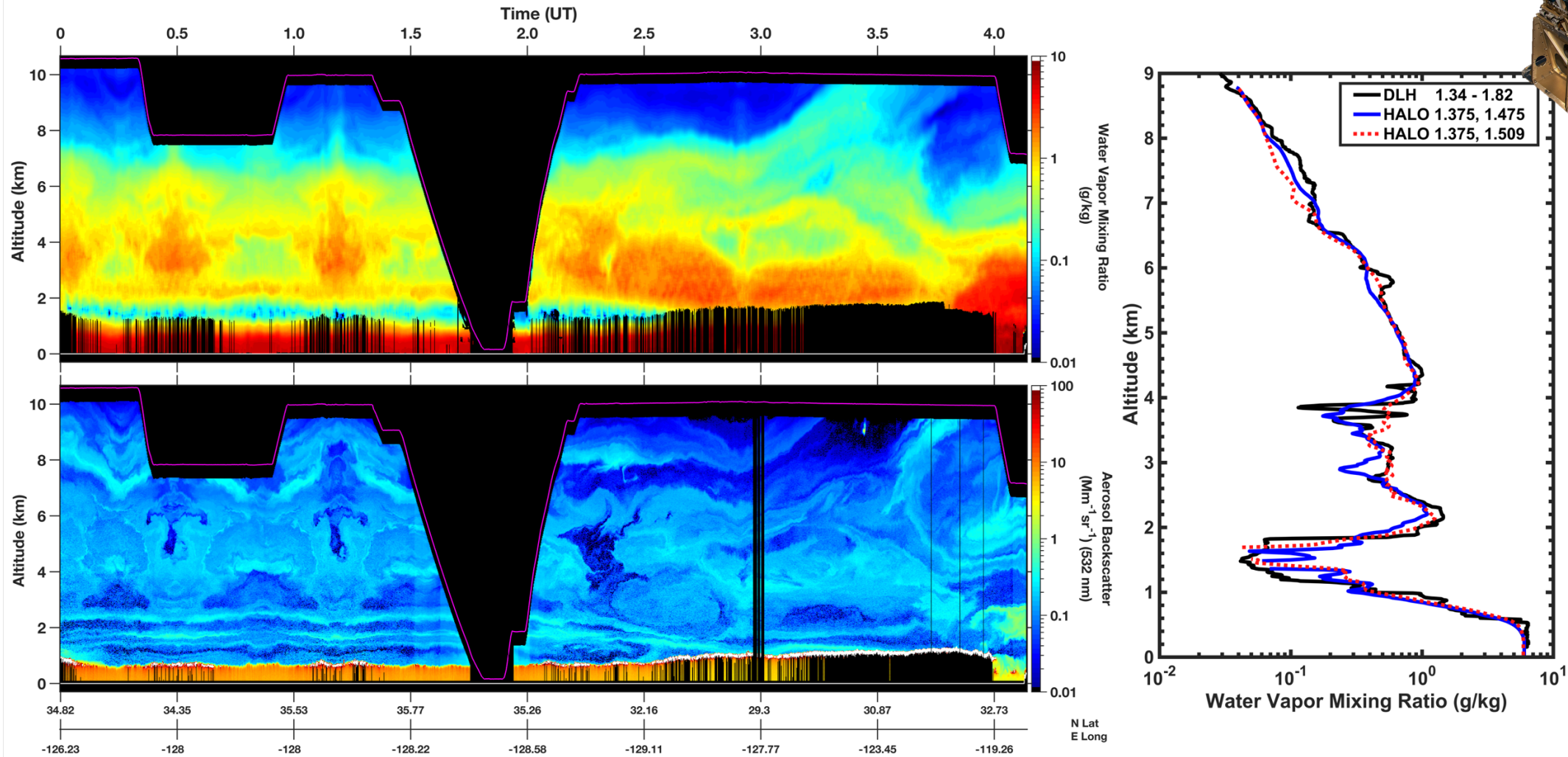
$$\frac{\Delta n}{n} \propto (\Delta x)^{-0.5} (\Delta R)^{-1.5}$$

Trade precision for resolution

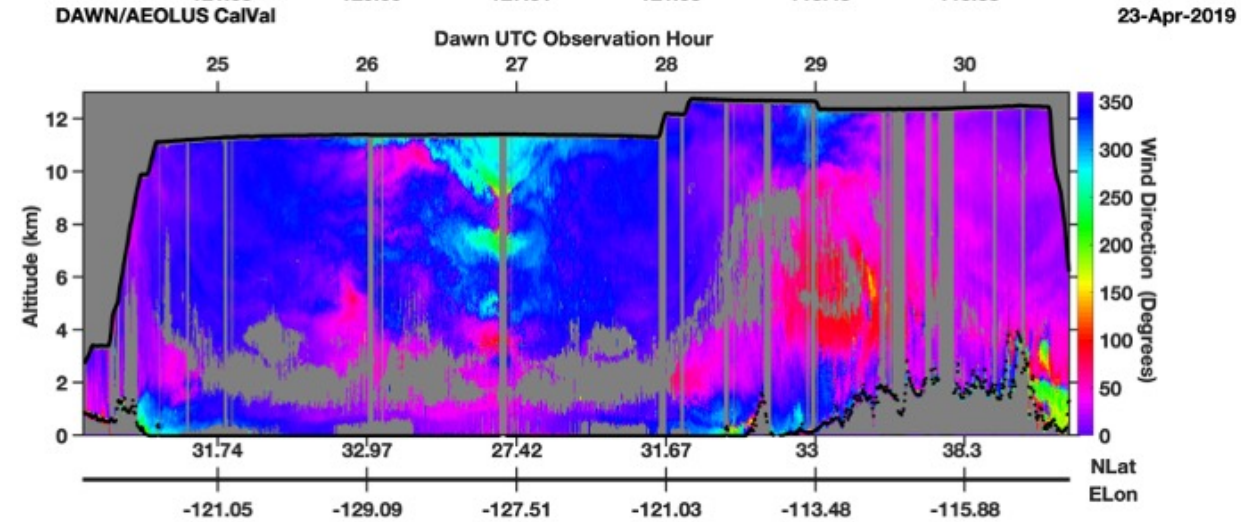
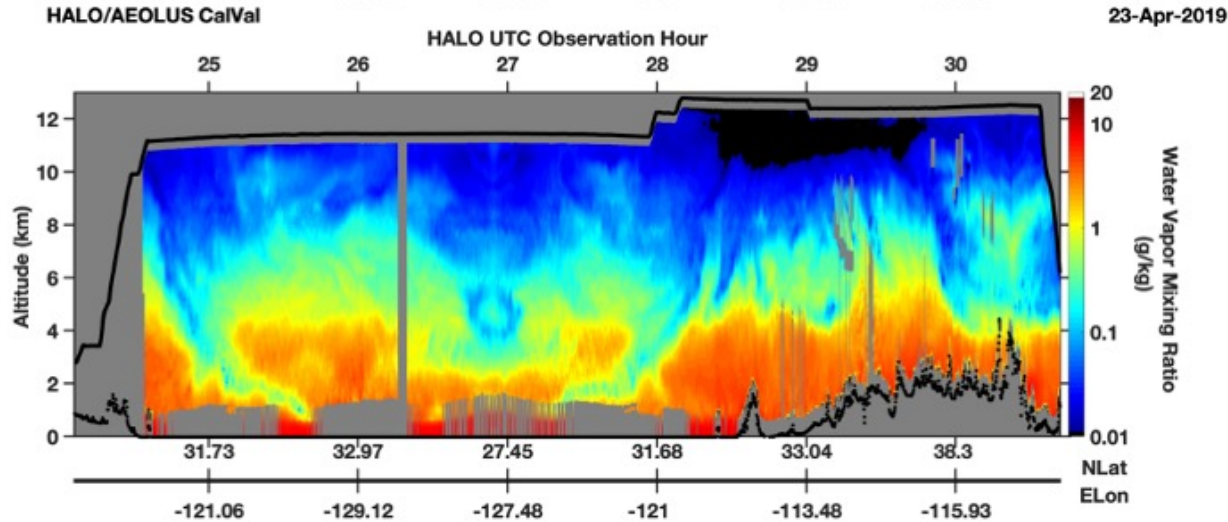
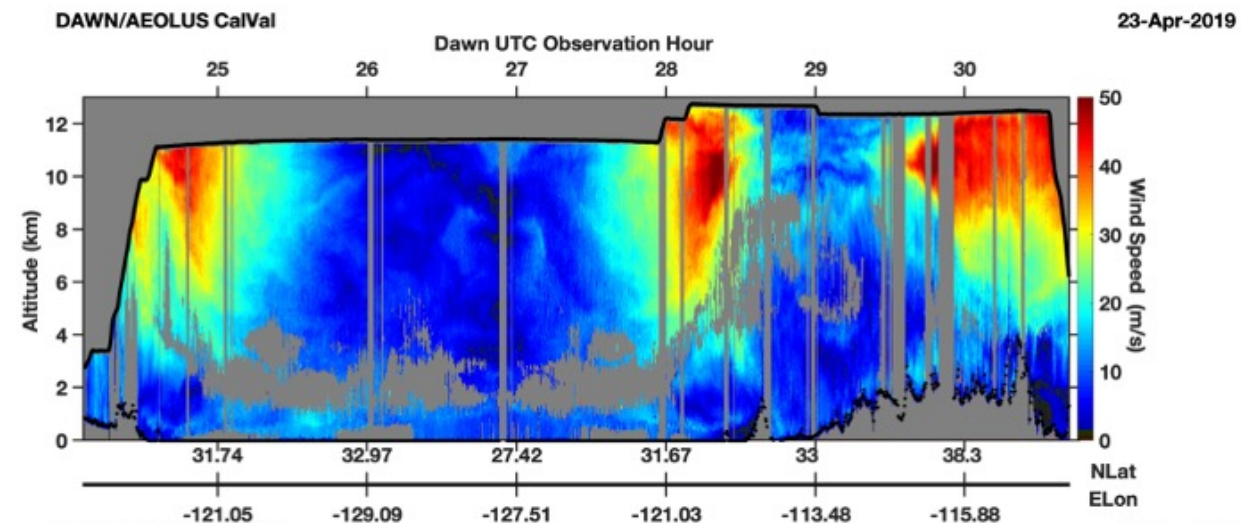
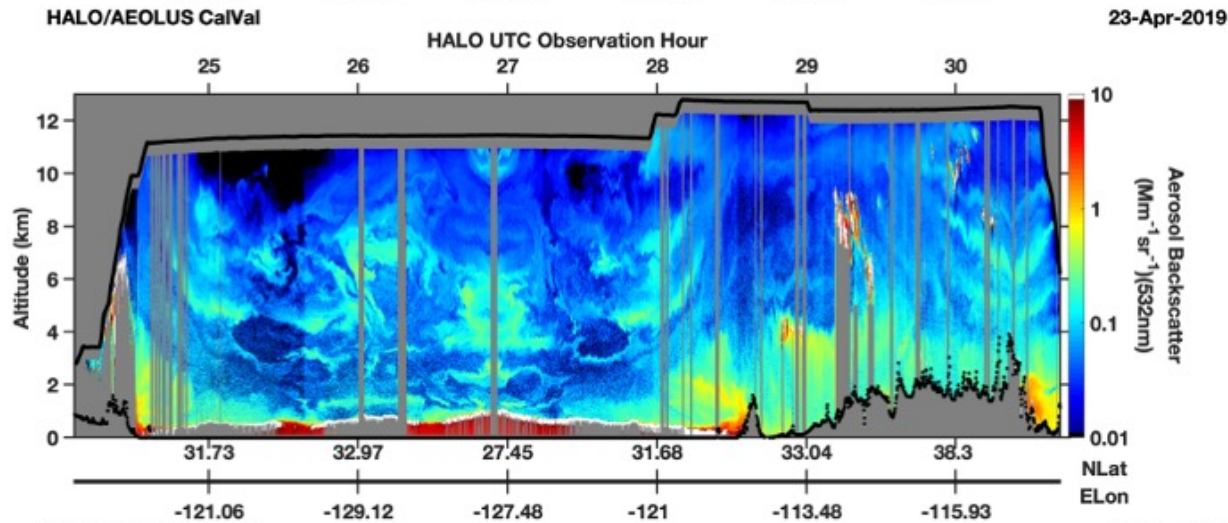
Along track averaging Vertical averaging

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

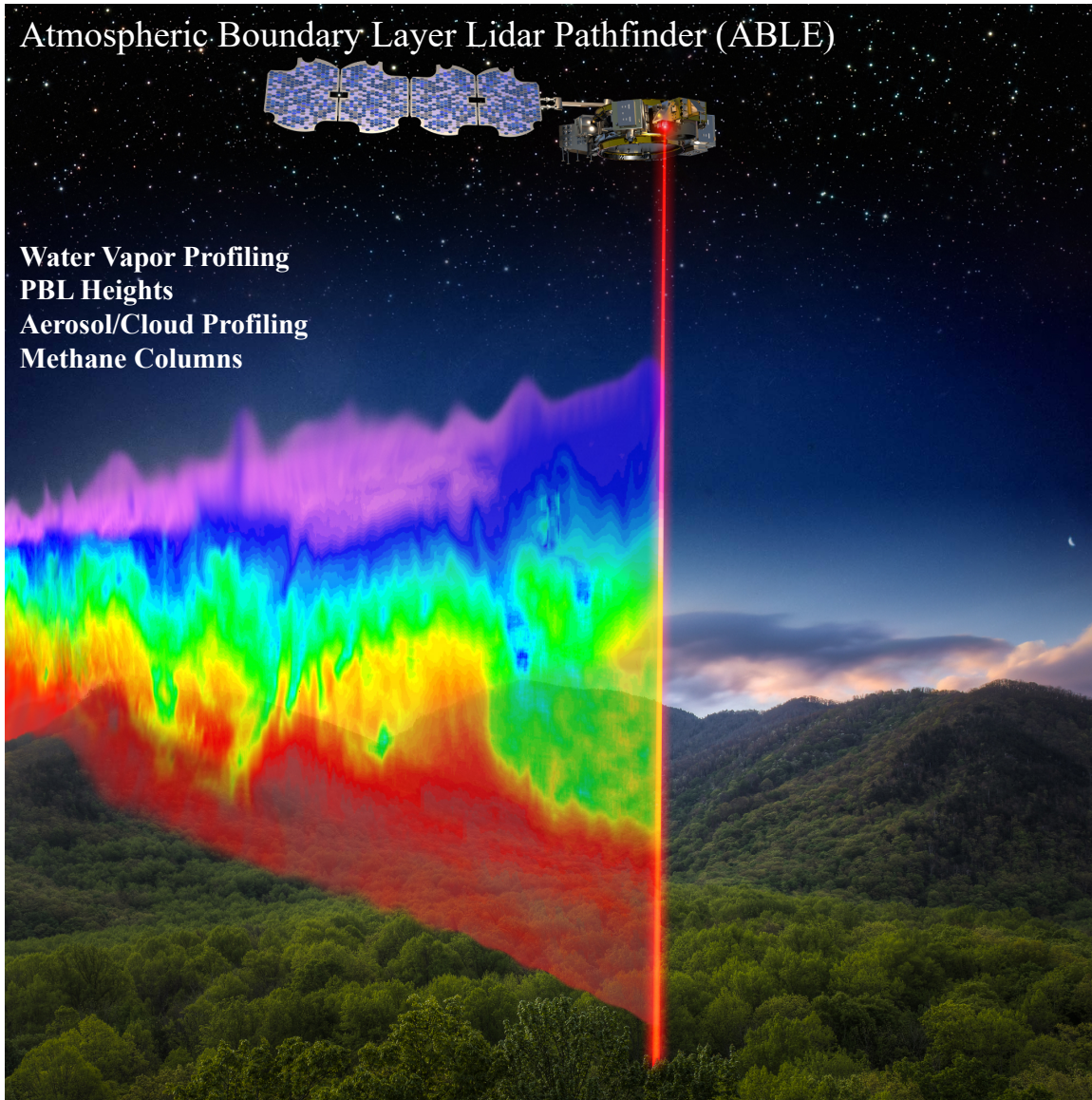
Airborne DIAL Heritage – High Altitude Lidar Observatory (HALO)



Synergistic Measurements



DIAL Pathfinder – Atmospheric Boundary Layer Lidar Pathfinder

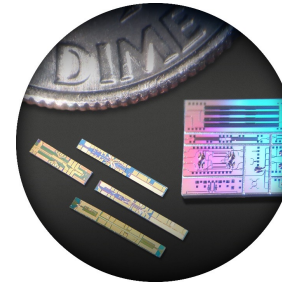
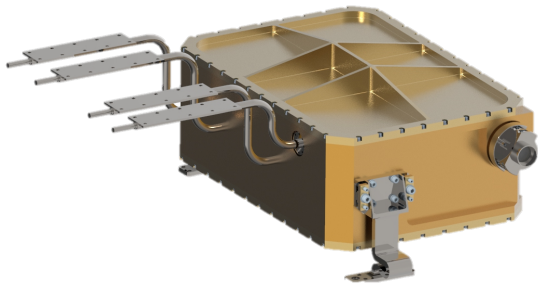


- Develop a pathfinder mission concept and advance associated technologies to enable the first demonstration of DIAL in space
 - Water vapor profiling from mid-troposphere to PBL
 - 200-400 m resolution in the PBL, 1 km in lower free
 - 50-75km along track resolution
- Novel laser technologies enable **cross-cutting science** spanning disparate science focus areas
 - Weather and dynamics (including PBL)
 - Atmospheric composition and radiation
 - Carbon Cycle
- Technology advances enabling for worlds first DIAL mission
- Balance performance/complexity with affordable and flexible design so as to fit within future cost capped missions

Development approach



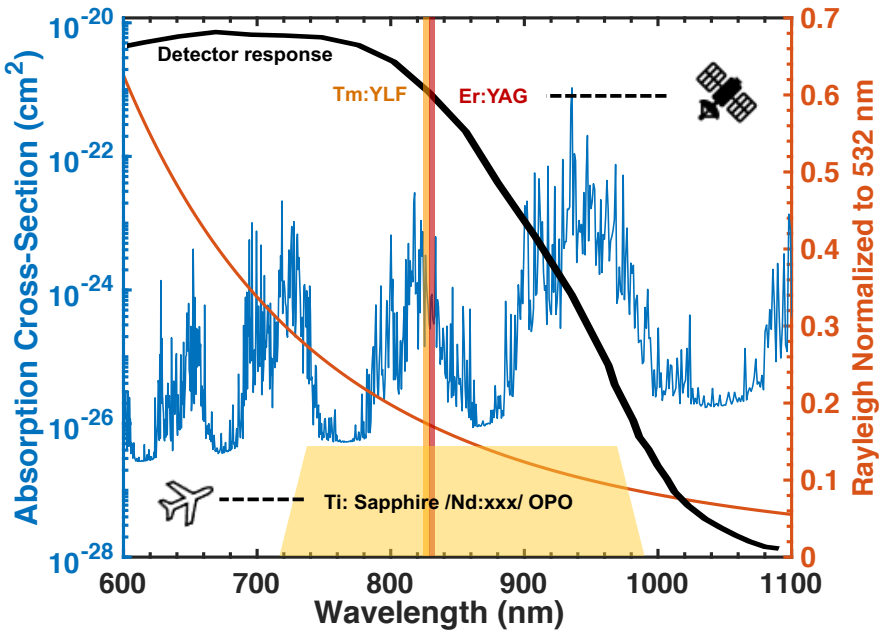
1. Develop space qualifiable Er:YAG laser transmitter
2. Increase efficiency of 1532 nm pump diodes to enable operation on smallsat
3. Develop photonic integrated circuit seed laser as injection seeding source
4. Develop satellite instrument concept capable of rideshare launch on ESPA Grande



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

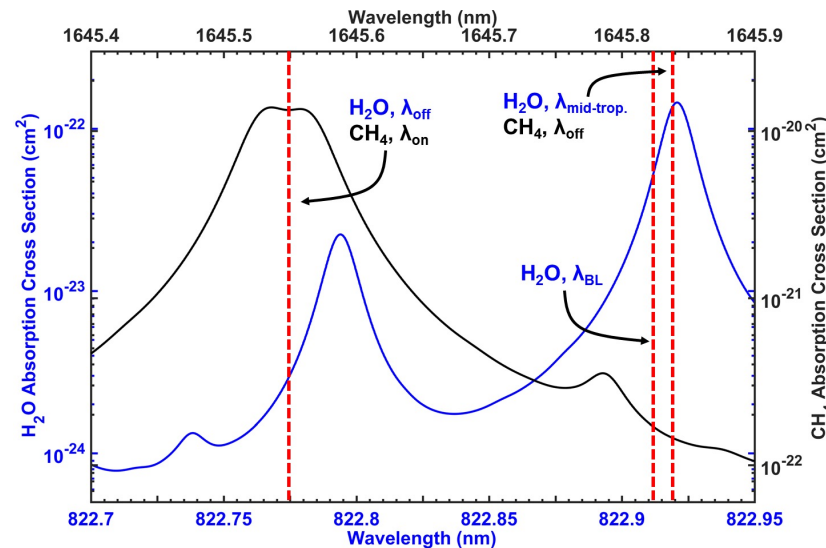
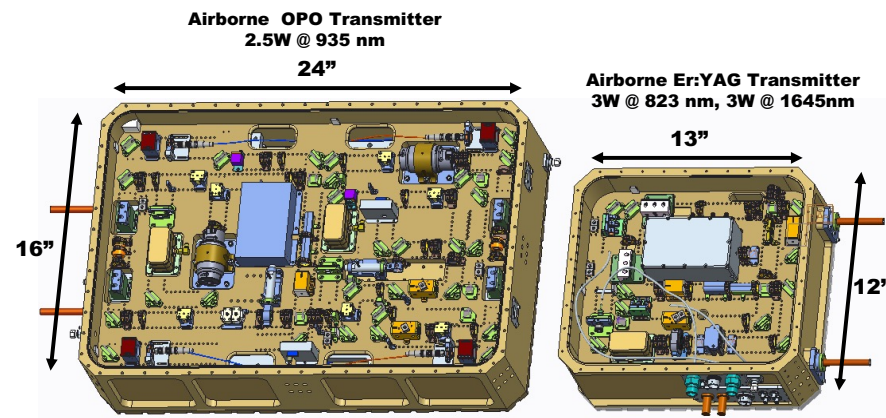
Laser	Efficiency to 820 nm	Power (W)	~Pulse Energy	Complexity	Maturity	
Ti:Sapphire	1-2%	5-10	100 mJ	5 parts	Mature	Diodes → Nd → 2x → Ti:Sapphire →
OPO	1-2%	5-10	50-80 mJ	5 part	Mature	Diodes → Nd → 2x → OPO/OPA →
Tm:LiYF ₄ (YLF)	5-8%	20-30	10-15 mJ	2 parts	Emerging	Diodes → Tm:YLF →
Er:YAG	2-3%	6-10	3-5 mJ	3 parts	Emerging	Diodes → Er:YAG → 2x →

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

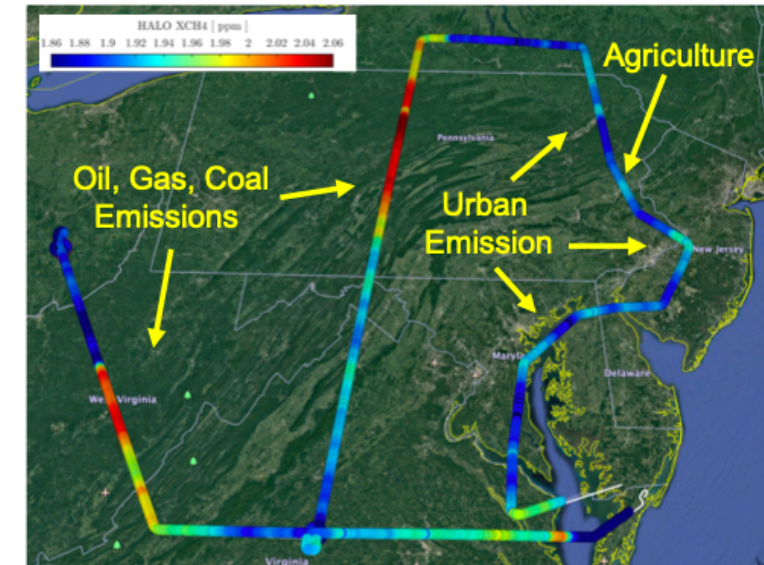
Pulsed Laser Advancement – Reducing complexity and enabling crosscutting science



- 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



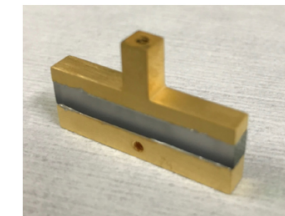
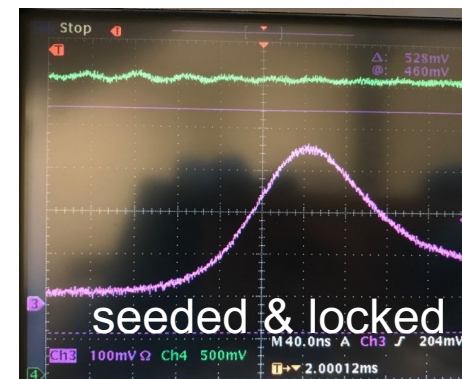
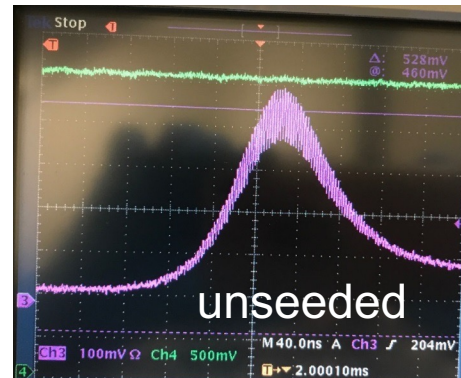
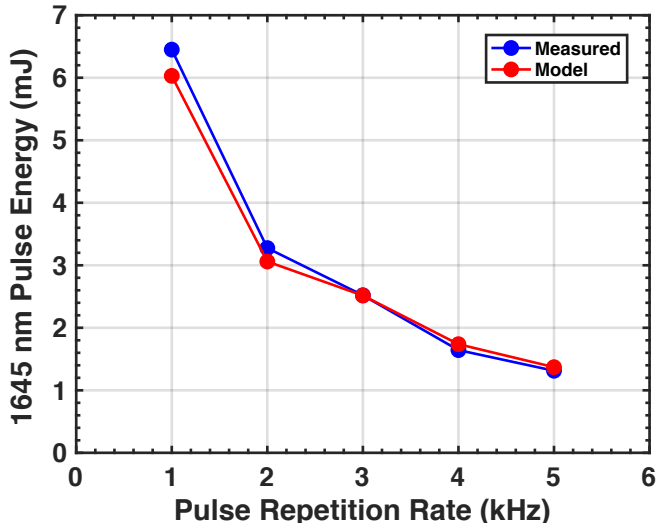
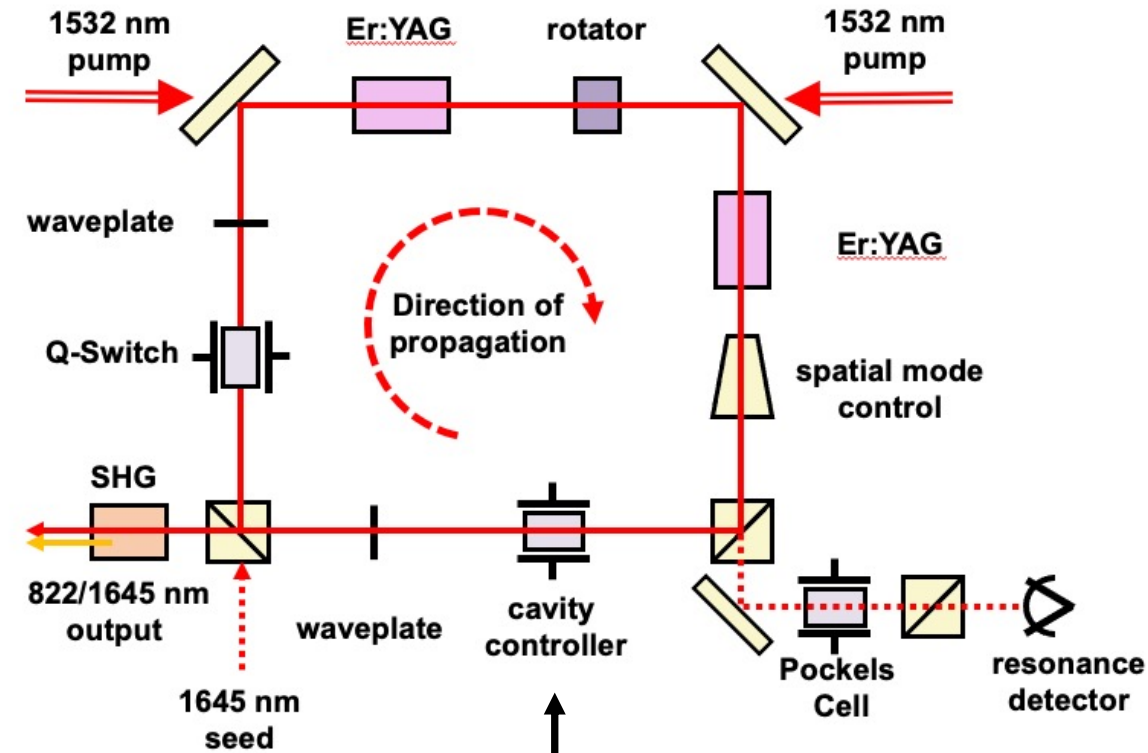
HALO Methane Columns



Pulsed Laser Advancement – Er:YAG Performance



- Er:YAG laser developed for airborne applications meets many of the requisite characteristics for space-based DIAL
 - Average power scaling
 - Conductive cooling
- 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)



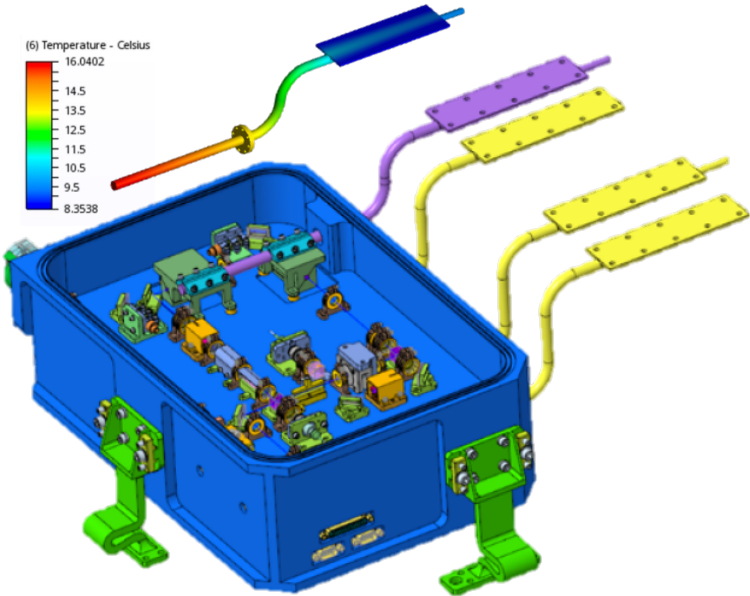
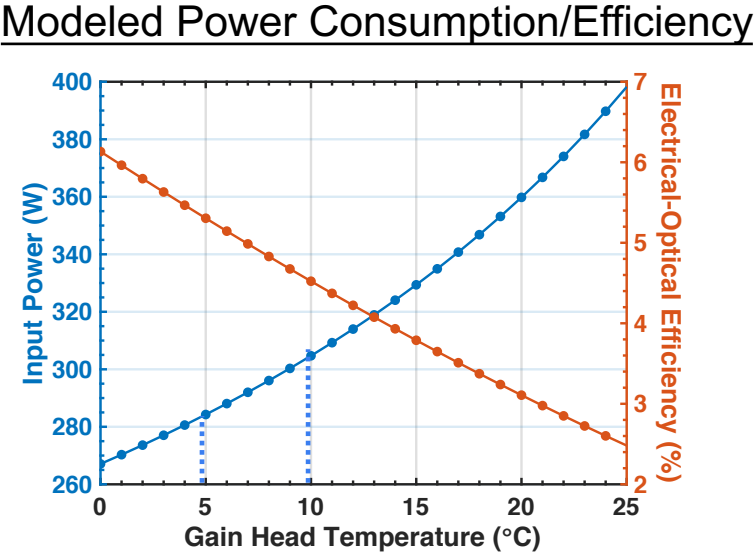
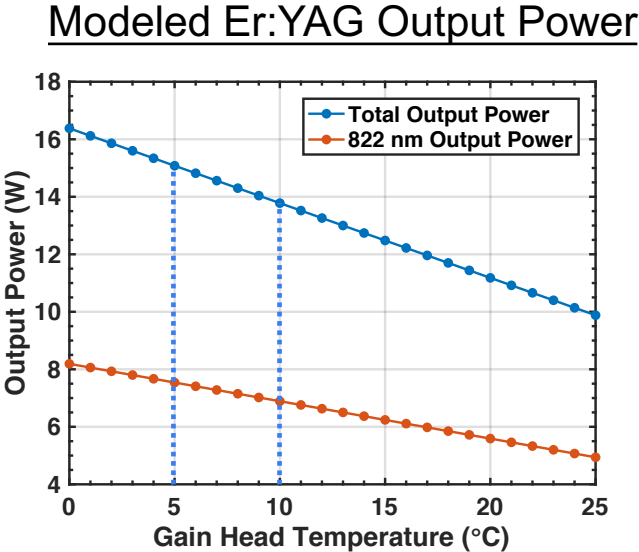
High Voltage Driver

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 for future qualification program
- Takeaway message

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%



Pump Laser– Increase Efficiency and Brightness



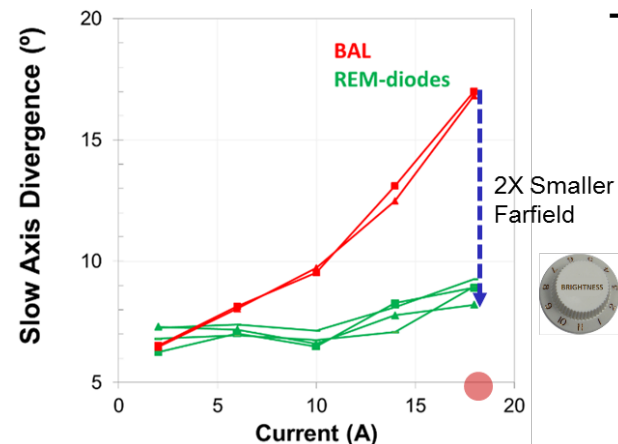
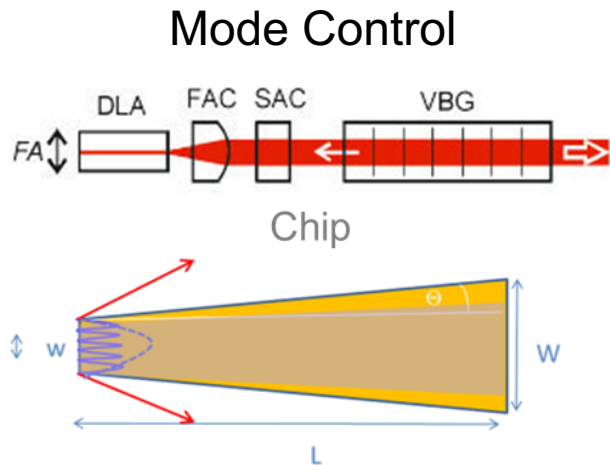
- Increase efficiency of commercially available 1532 nm pump diodes from ~20% to >40%
- Multi-pronged approach to increasing efficiency
 - Optimize diode epitaxial design
 - Achieve higher brightness through optical mode control
 - Increase thermal conductivity
 - Increase optical throughput
- Preliminary 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



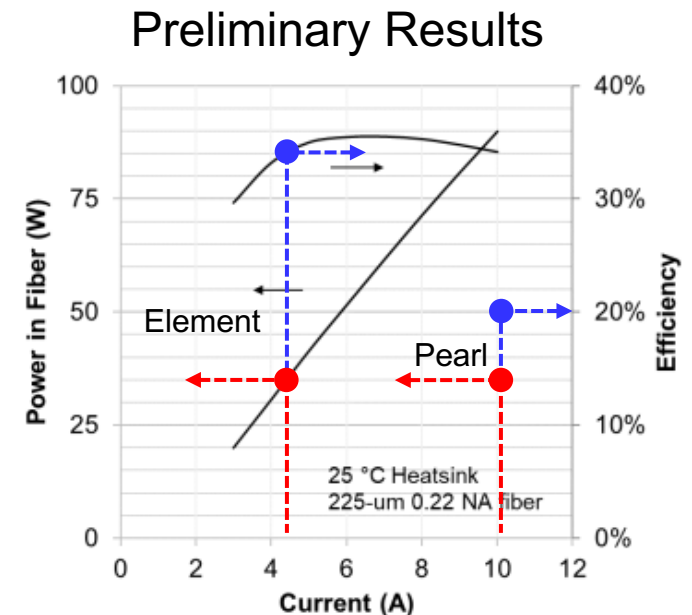
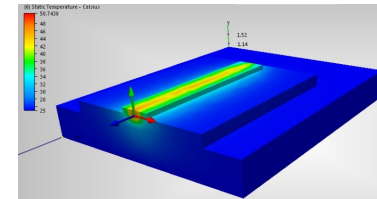
Pearl
(COTS)



Element
(ABLE)



Thermal conductivity



Seed Laser – Airborne to flight, bridging the gap

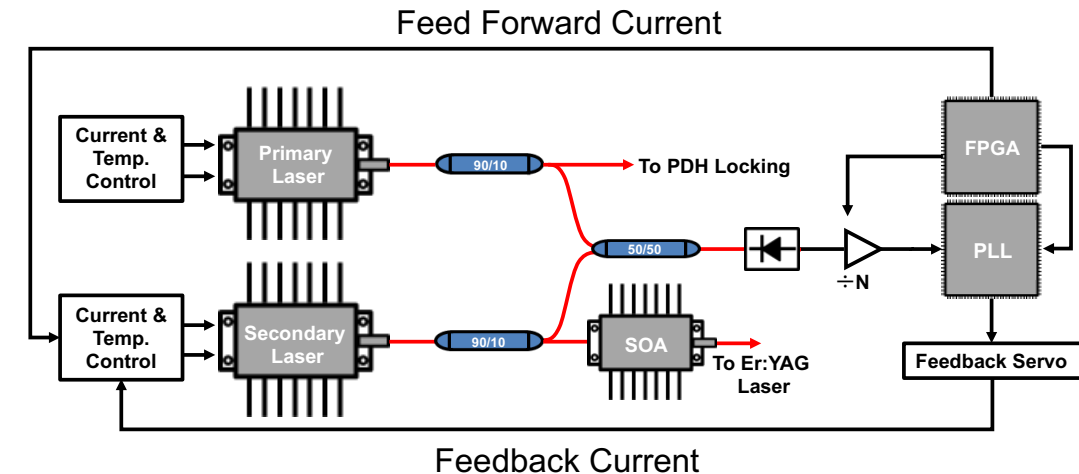
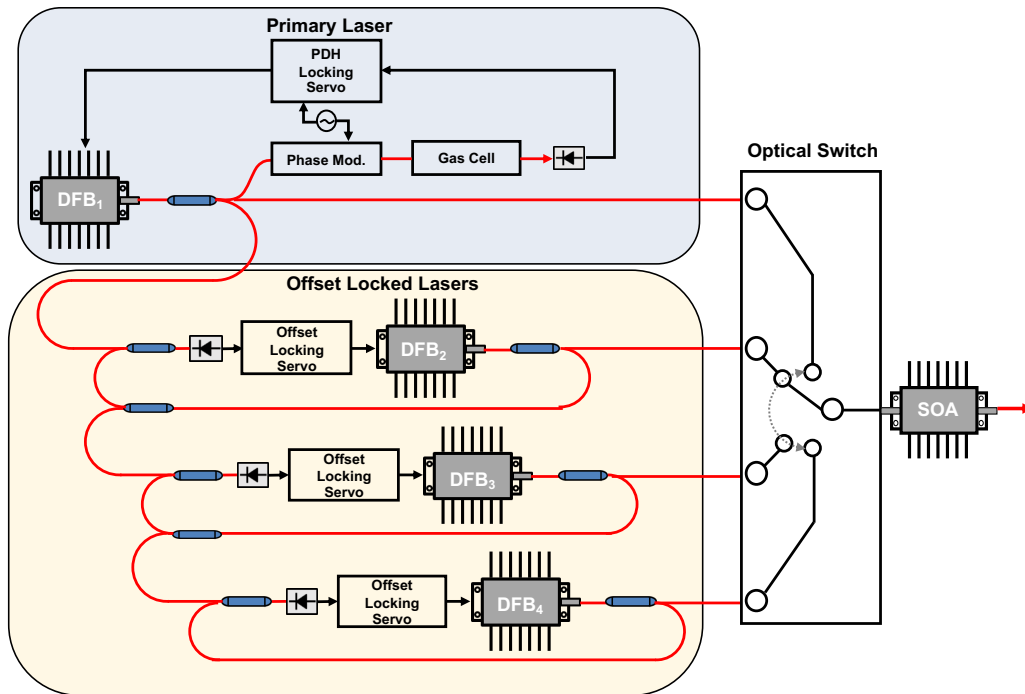


- Seed laser is the heart of DIAL systems and can affect the accuracy of the DIAL retrieval
- High TRL discrete components used in airborne systems not compatible with operation on SmallSats
- Photonic integration required to significantly reduce SWAP and increase reliability

TRL 9 Airborne

Photonic Integration

TRL 5 Flight



Seed Laser – Photonic Integrated Circuit

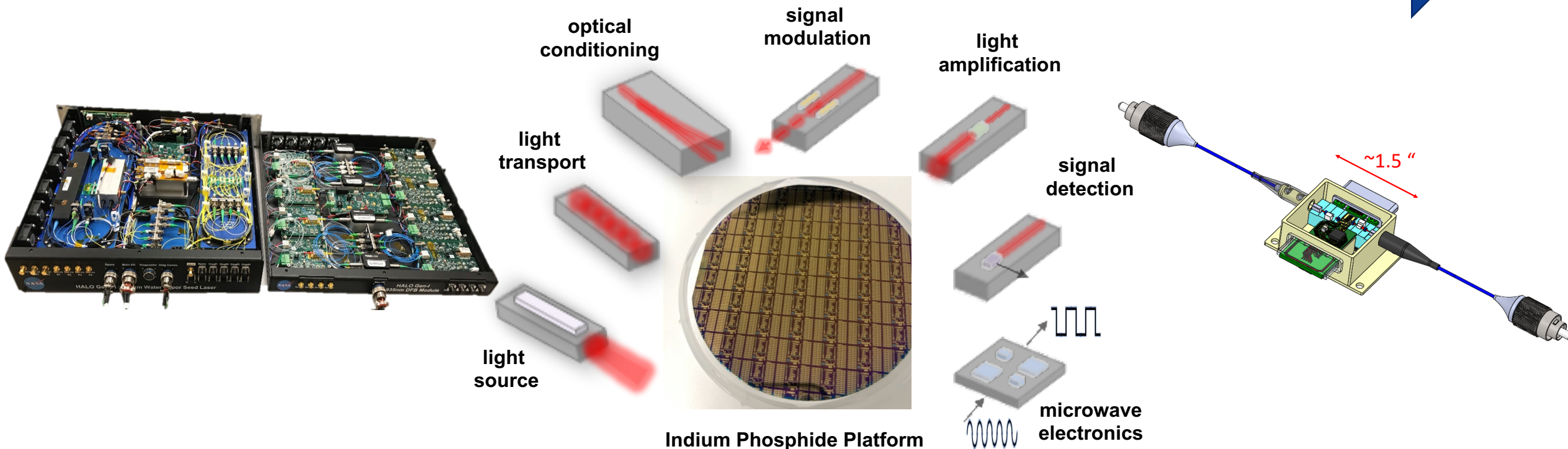


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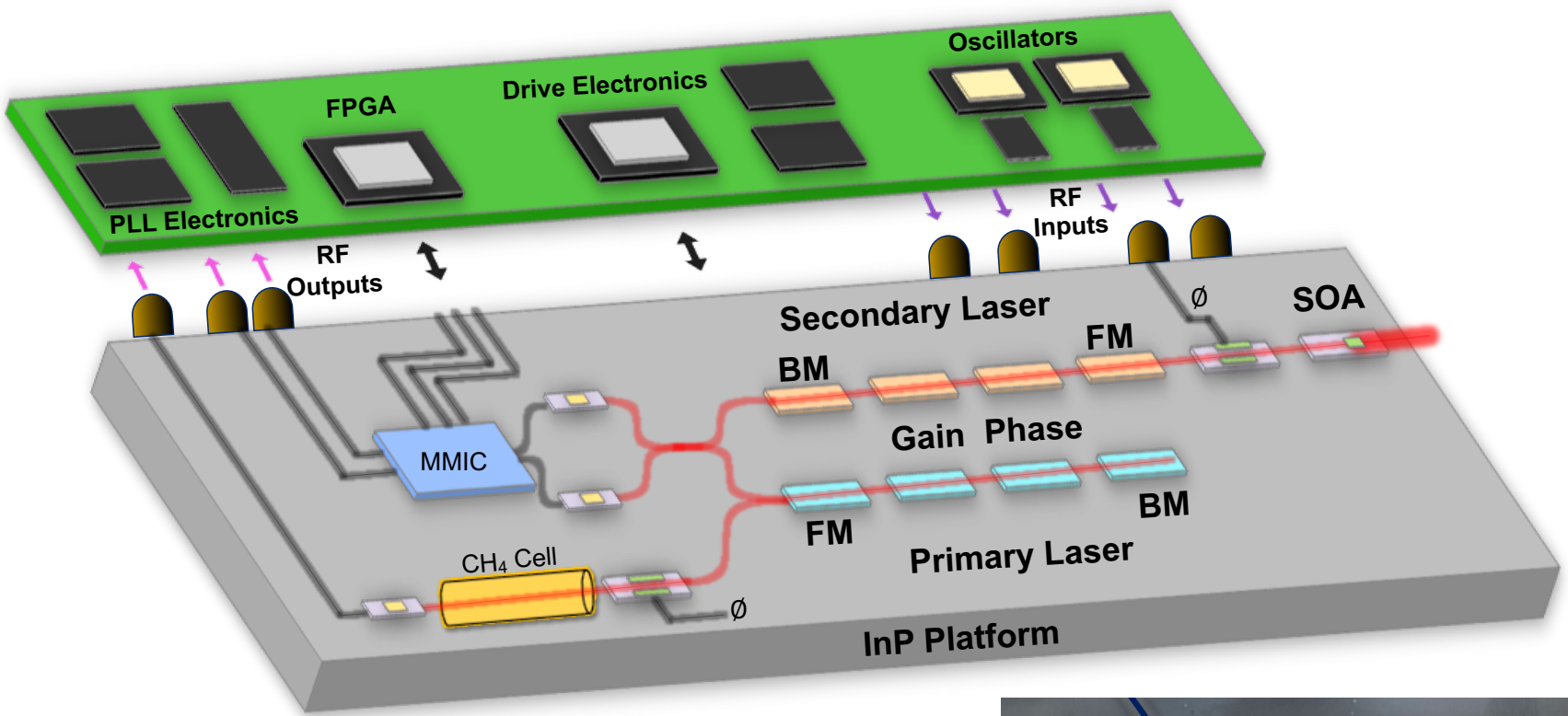
TRL 9 Airborne

Photonic Integration

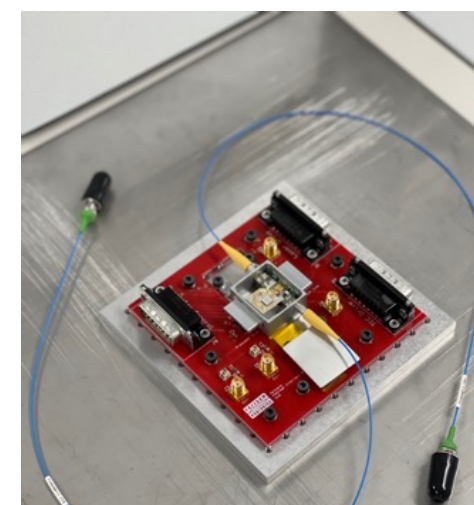
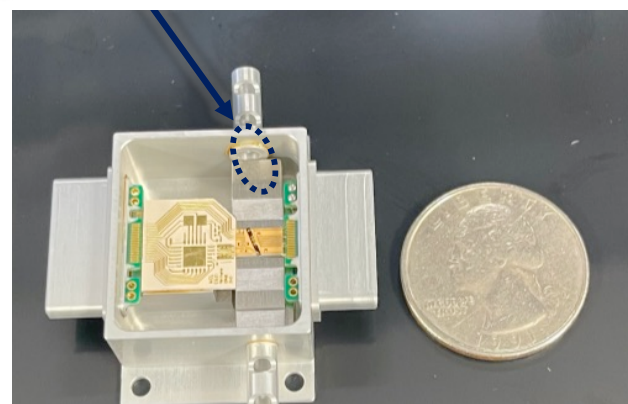
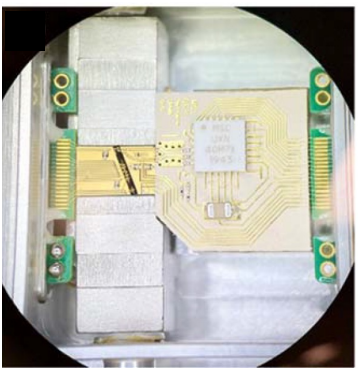
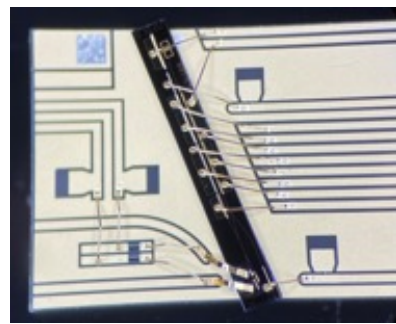
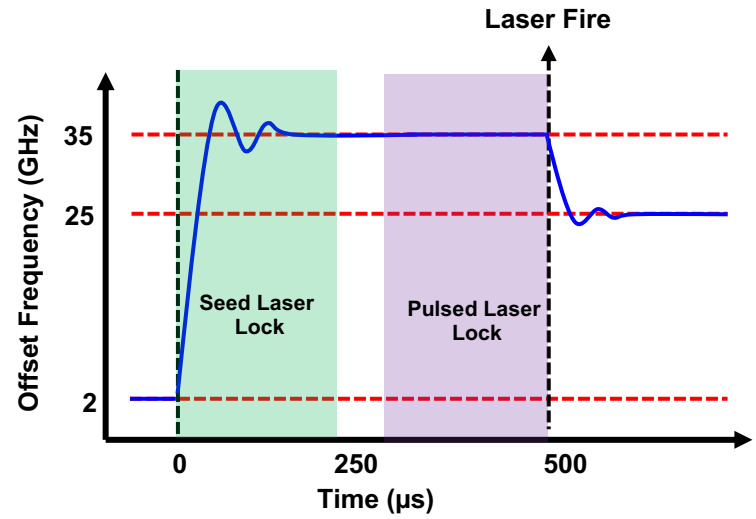
TRL 5 Flight



PIC Seed Laser Source – Architecture



Timing Diagram

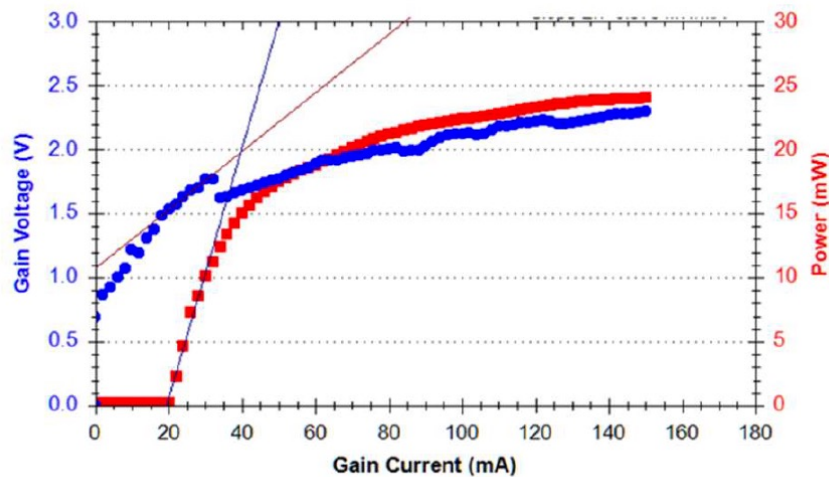


PIC Seed Laser Source – Preliminary Results

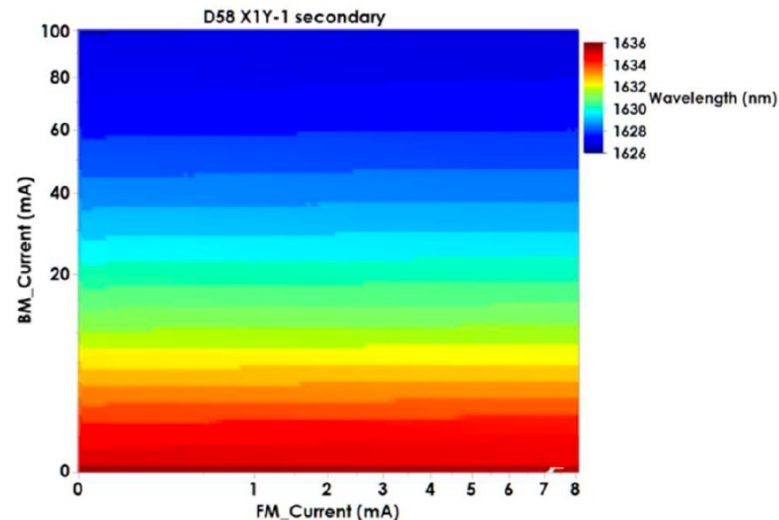


- PIC exhibits requisite performance for space-based DIAL
 - Primary seed laser has >5x the required power for line locking allowing for adequate derating
 - >20 mW from secondary seed laser allows efficient seeding of Er:YAG pulsed laser
 - Both primary and secondary lasers have broad continuous tuning range
 - Demonstrated rapid scanning across CH₄ lines with scan rates exceeding 20pm/μs
- Current focus is on characterizing bandwidth of balanced detectors and coupling to RF components

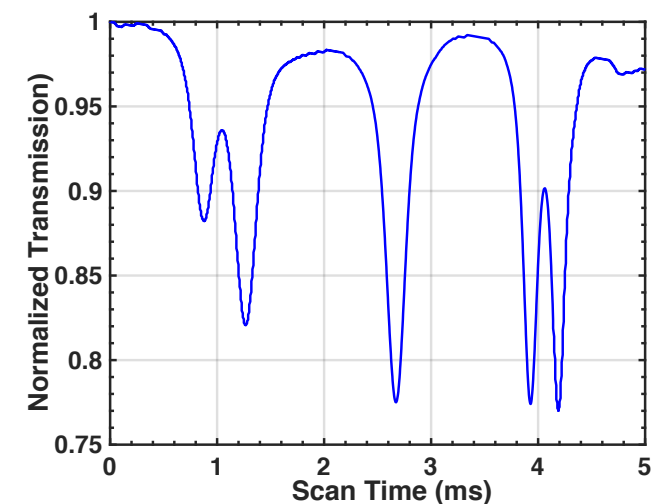
Secondary LIV Curve



Secondary tuning map



1628 nm CH₄ line scan

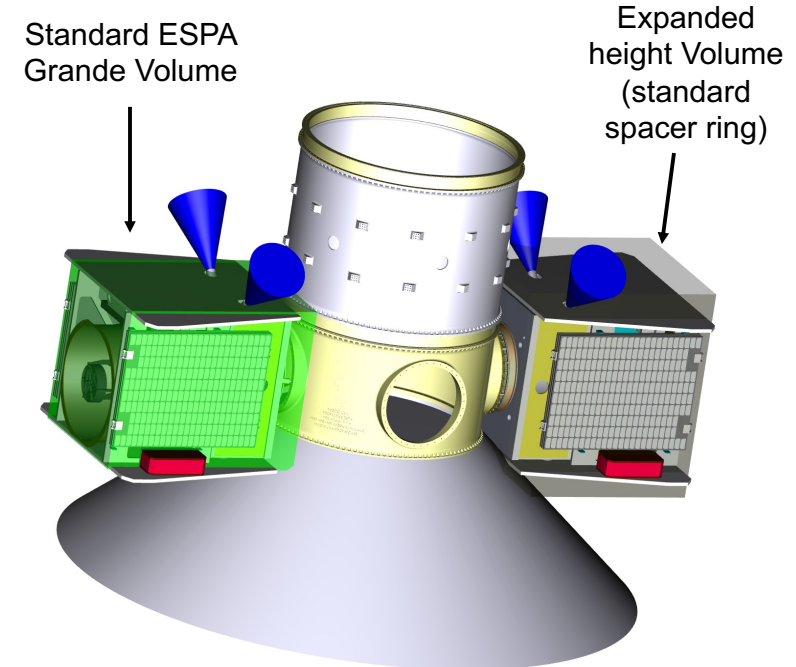
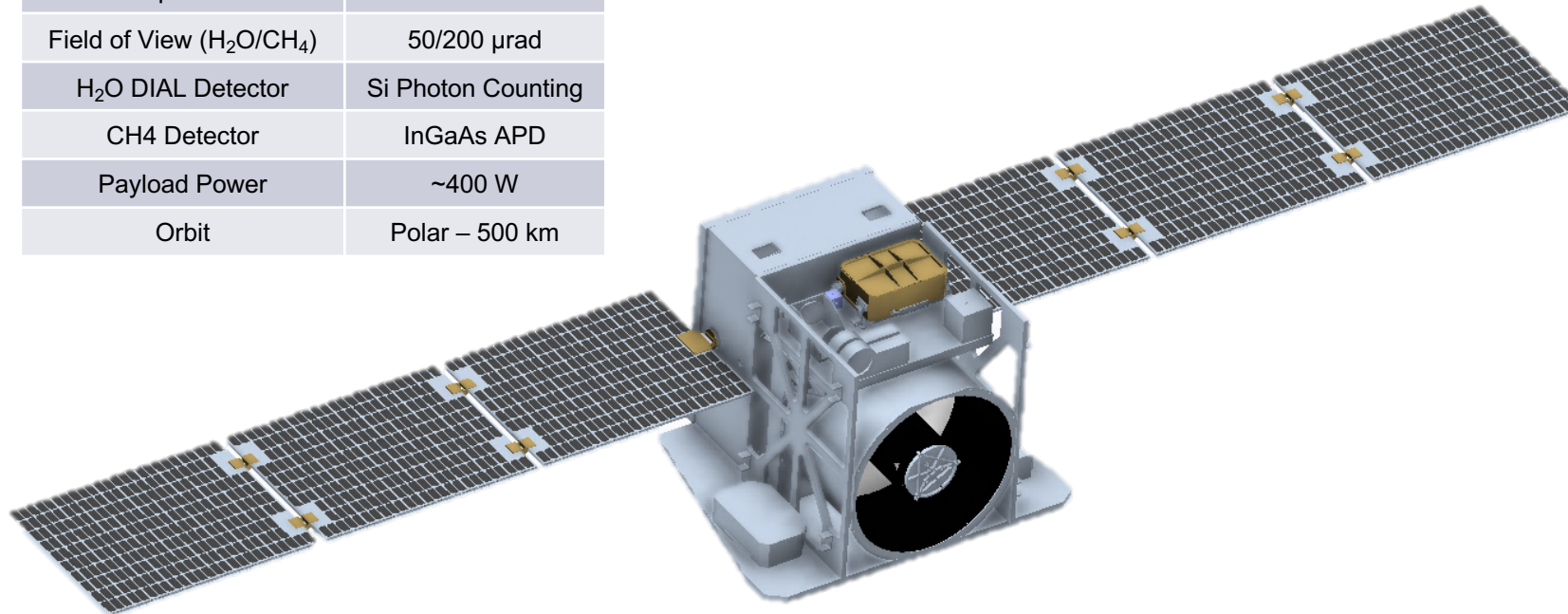


Spacecraft Accommodations and Systems Engineering



- Spacecraft accommodation survey identified several ESPA class buses suitable for capable lidars
- Highly evolving industry shows promise for accommodating SWAP required for space-based DIAL
- Lidar systems engineering study resulted in several optomechanical configurations

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 ₂ O/CH ₄)	50/200 μ rad
H ₂ O DIAL Detector	Si Photon Counting
CH ₄ Detector	InGaAs APD
Payload Power	~400 W
Orbit	Polar – 500 km





Acknowledgments



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