The High Altitude Lidar Observatory (HALO): A multi-function lidar and technology test-bed for airborne and space-based measurements of water vapor and methane

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Motivation

- New capability to measure H$_2$O profiles from smaller and high altitude airborne platforms
  - Currently: LASE is only capable of going on large aircraft (DC-8, and possibly P3, C130)
- Development of more compact H$_2$O DIAL system with additional (CH$_4$) DIAL and HSRL measurement capabilities
- DIAL measurements along with measurements of aerosol/cloud properties combines many of the measurement requirements for airborne campaigns and satellite calibration and validation
- Flight demonstration of advanced lidar technologies on various airborne platforms
Use combined lidar profiles of water vapor, aerosols, and clouds to better understand...

1. Boundary layer processes (2017 Decadal Survey)
   - Shallow clouds, shallow and deep convection, convective aggregation, arctic mixed phase clouds, aerosol cloud interactions...

2. Weather and dynamics (2017 Decadal Survey)
   - Genesis and intensification of hurricanes, land-atmosphere feedbacks

3. Upper atmospheric transport and chemistry
   - Moistening of the stratosphere in a warming climate

4. Assessment and improvement of GCM and CRM and comparison of satellite data products
Combine lidar measurements of XCH$_4$, aerosols/clouds to better understand...

1. Quantify XCH$_4$ surface fluxes (2017 Decadal Survey)
   – Survey carbon stocks in warming Arctic (ABOVE) and tropics, survey oil and gas production....

2. Assessment and improvement of chemical transport models and comparison of satellite data products
   – Mixed layer vs free tropospheric mixing and transport
   – Validation of MERLIN CH$_4$ Lidar, TROPOMI
System Architecture

Interchange two common architecture lasers and single receiver to enable $\text{H}_2\text{O} \text{ DIAL+HSRL}$ or $\text{CH}_4 \text{ DIAL+HSRL}$ measurements.

- Water vapor profiles
- Total perceptible water
- Aerosol, cloud, and ocean profiling
- Column weighted $\text{XCH}_4$
- Clear air mixed layer $\text{XCH}_4$
System Block Diagram

Energy Normalization Signal

APD
1645 Fiber Coupled APD

Detector & locking circuits

Locking Cells

Seed Lasers

Pulsed Laser

Telescope

Energy normalization

To Atmosphere

1064 nm Parallel Channel

532 nm Paerp. Channel (Ocean)

MCP

532 nm Parallel Channel

MCP

532 nm Paerp. Channel (Ocean)

Energy normalization

15 science chan.
4 boresight chan.
8 types of det.
Detection and Acquisition Subsystems

Packaged APD detector modules

Packaged PMT/MCP detector modules

Power Acquisition and Control

<<0.05% overshoot
Completed Receiver

HSRL Channels

DIAL Channels
Laser Architecture

1645 nm for CH₄ OPO
935 nm for H₂O OPO

- Three seed laser: 1064, 1645, 935 nm
  - Frequency stability, robust and compact packaging
- Two pulsed lasers: 1645, 935 nm
  - Transmit power, spectral purity, and robust packaging
Seed Laser: 1064 nm Architecture

- 1 U 1064 nm laser for injection seeding both Fibertek OPO pump sources
- Frequency stabilized to I₂ absorption line at 532 nm using PDH approach
- 3 channel optical heterodyne between pulsed and seed lasers

**Diagram:**

**1.064 µm Oscillator Injection Seeder**

- DFB Current and Temp Controller
- Fast DFB Current Correction
- Control Servo
- Slow DFB Temperature Correction
- Mixer
- RF Amp
- Phase Shifter
- BPF
- Fiber Coupled I₂ Cell and Detector

**Planar Lightwave Circuit**

- Integrated SHG & Phase Modulator
- To Nd:YAG Pump Laser

**Integrated I₂ Cell**

- Fiber In
- KTP Chip
- RF input TEC Control
Seed Laser: 1064 nm Performance

20170731 - 1064nm Thermotron Locking Test

- 45 deg. C
- Flight Alt. Temp
- Hot Soaked
- 15 deg. C

Frequency Drift [MHz]

Time [Hour]

16.5”
Seed Laser: 1645 nm Architecture

- 4 $\lambda$1645 nm seed laser for injection seeding Fibertek CH$_4$ OPO
- Online wavelength locked to trough of CH$_4$ R6 doublet
- Master reference locked to R6 peak. Weighted to upper troposphere
- Sideline/offline offset locked with respect to master laser
- Fast electro-optic 4x1 optical switch used to sequentially injection seed OPO
Seed Laser: 1645 nm Performance

Online Locking Stability: Online/Master Beat note

- Std. Deviation = 135 kHz
- 45 deg. C Hot soak

Offline Locking Stability: Master/Offline Beat note

- <50 kHz std
Seed Laser: 935 nm Architecture

- 4 λ 935 nm seed laser for injection seeding Fibertek H₂O OPO
- **Stratospheric line** (λ₁) locked to strong H₂O line using PDH method
- **Mid-troposphere line** (λ₂) offset locked ~ 40 GHz with respect to λ₁
- **Boundary layer line** (λ₃) offset lock with respect to (λ₂). 1-19 GHz tuning range
- **Offline** (λ₄) offset locked ~ 41 GHz with respect to λ₃.
- Fast electro-optic 4x1 optical switch used to sequentially injection seed OPO
Seed Laser: 935 nm Performance

2U Fiber Engine

3U DFB Module

40 GHz offset lock

$\lambda_1 - \lambda_2$ Relative Stability

41 GHz offset lock

$\lambda_3 - \lambda_4$ Relative Stability

Total system stability

$\lambda_4$ Absolute Stability
935 and 1645 nm lasers maintain common optical, mechanical, and electrical interfaces
Integrated 1645 nm Pulsed Laser
Fibertek CH₄ Laser Performance

- 1064 nm pump: 11 mJ, 1 kHz (11 W)
- 1645 nm OPO: 2.5 mJ (2.5W)
- Environmental testing (vibration and thermal)
- OPO and 1064 nm lasers both exhibit spectral purity > 3000:1 (validated in flight)
- CH₄ laser is integrated into system and flown on two separate campaigns

1064 nm resonator (pump)
11W, 7 W residual pump

- Near Field Spatial Distribution
- Far Field Spatial Distribution
- Beam Quality

1645 nm OPO, 2.5W

- Near Field Spatial Distribution
- Far Field Spatial Distribution
- On-Line Spectral Distribution Scanning Fabry-Perot
- In Flight Spectral Purity

532 nm (HSRL)
1 W

- Temporal Distribution
- Spectral Purity w/ I₂ Cell – 1104 Line w/ OPO locked On-Line
Fibertek 935 nm H₂O Laser Architecture

1064 nm Far Field Image

Oscillator Spectral Width

Pump Laser
OPO
Amplifier

24 W

30 MHz FWHM 1.5 GHz Full Screen
Fibertek 935 nm H$_2$O Laser Performance

- 1064 nm osc.+amplifier: 24 mJ, 1 kHz (24 W)
- 532 nm pump: 14 mJ, 60 % conversion efficiency
- 935 nm OPO: currently being built
  Target ≥ 3mJ

Simulated Performance (B200)

Simulated Performance (ER-2)
Integrated System: CH$_4$ Configuration
HALO CH$_4$ Config. Integrated on UC-12
Co-Hosted Payload

GEO-CAPE Airborne Simulator (GCAS)

1.1 m
Spring 2018 CH$_4$ Check Flights

HALO Check Flights

4 Flights
16 Hours (approx.)
2 In situ spiral overpasses (ACT-America)
First Light: Integrated Path DIAL (IPDA) Channels

- Integrated path differential absorption (IPDA) measurement between transmitted energy signal and surface return
- High SNR over low albedo targets
- Integrating spheres used to sample transmitted energy
- Five independent calibration methods

**SNR**

- **off**, 0.5 sec = ~2500
- **on**, 0.5 sec = ~1000

**Calibration Signals**

- Injected signals
- Fiber coupled APD
- Window reflection

**Ocean Return**

- \( \text{SNR}_{\text{off}, 0.5 \text{ sec}} = \sim 2500 \)
- \( \text{SNR}_{\text{on}, 0.5 \text{ sec}} = \sim 1000 \)
Preliminary CH$_4$ IPDA Results

**Integrated Surface Returns**

**Surface Weighted XCH$_4$**

0.5% precision
Atmospheric Products: May 12 2018

EPA gridded CH$_4$ inventory

south westerly flow
Preliminary Aerosol Products
1645 nm Backscatter Profiles

\[ \log_{10}(P_{\text{off}} r^2) \]

[Diagram showing log_{10}(P_{\text{off}} r^2) with Spiral Overpass indicated.]
Preliminary CH\(_4\) DIAL Products

Clear air IPDA calibration region

\[ OD_{\text{CH}_4}(r) \propto \frac{P_{\text{on}}(r)}{P_{\text{off}}(r)} \]

accumulated CH\(_4\) differential absorption optical depth
Summary and Future Plans

Summary

• Developed and environmental tested three flight hardened seed lasers
• Developed high power and high spectral purity CH₄ pulsed laser
• Demonstrated spectral purity requirements in relevant aircraft environment
• Integrated and test multi-channel receiver
• Demonstrated first airborne CH₄ measurements using OPO laser on turbo prop aircraft

Future plans

• Deploy CH₄ configuration in Long Island Sound Ozone Study campaign
• Continue development of CH₄ retrievals and improvements to CH₄ meas.
• Assess feasibility of integrating HgCdTe detector for clear air CH₄ meas.
• Complete development of H₂O pulsed laser in 2018
• Demonstrate water vapor measurements from B200 in 2019
• AITT to transition instrument to ER-2 and other platforms
  • Water vapor focused upper atmospheric/boundary layer process studies
  • Co-hosted payload with Differential Radar, wind lidar, and spectrometers
  • Serve as the U.S. MERLIN validation instrument
Path to Space-Based Observations

Water Vapor OPO: H₂O Profiles+HSRL
(this program)

Er:YAG: CH₄+H₂O Profiles
(ongoing tech development)

Airborne Science

Reduction in Size Weight and Power

Technology Maturation

EVI/DS Explorer mission
Laser Transmitter for space-based water vapor lidar

PI: Tso Yee Fan / MIT Lincoln Laboratory

**Objective**

- Develop a space-based water vapor differential absorption lidar (DIAL) transmitter based on a Tm:YLF pulsed laser at 816 nm
  - Laser pulse energy ≥ 100 mJ
  - Double pulse repetition rate ≥ 50 Hz
  - Spectral purity >99.9%
  - Wall plug efficiency ≥ 5%
- Reduce the risk, cost, and development time of a future water vapor DIAL satellite instrument
- Revolutionize atmospheric remote sensing by developing laser technologies that will enable high resolution and accurate 3-D observations of water vapor profiles from space

**Approach:**

- Develop an efficient high power laser transmitter at 816 nm based on newly emerging Tm:YLF laser crystals
- Implement double pump-pulse operation and validate laser theoretical performance with varying pulse periods
- Implement laser injection seeding and cavity stabilization control system and validate that closed-cycle cooled Tm:YLF can meet all key functionalities required for space-based DIAL systems
- Develop a hardened brassboard laser for future integration into the HALO lidar instrument as an airborne prototype for a future satellite instrument

**Key Milestones**

- First light, breadboard laser 4/18
- 100 mJ/pulse from breadboard laser 9/18
- Unidirectional operation from breadboard laser 2/19
- Double pulse operation from breadboard laser 5/19
- Injection seeded, double pulse operation 9/19
- Brassboard laser transmitter design complete 1/20
- Demonstrate fully functional brassboard 9/20

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**TRL\textsubscript{in} = 2**
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