Compact, Automated Differential Absorption Lidar for Tropospheric Profiling of Water Vapor

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Mesoscale Meteorology

- Meteorological observations at the mesoscale (10s to 100s km) support many national needs:
  - Weather prediction
  - Climate monitoring
  - Air quality monitoring

- Increasing spatial and temporal resolution needed:
  - Improve precision of forecasting
  - Decrease losses from severe weather events
  - Improve climate forecasting

- No systematic national capability exists for these measurements, which are critical to the dynamical prediction of high impact weather and/or chemical weather.

- Observing Weather and Climate from the Ground Up, A Nationwide Network of Networks
  - Committee on Developing Mesoscale Meteorological Observational Capabilities to Meet Multiple National Needs
  - National Research Council
Met Balloons and Radiosondes
Successfully measuring H₂O profiles since the 1930s

- A radiosonde is a small, expendable instrument payload that is suspended 25 m below a weather balloon.
- Sensors measure pressure, temperature, and relative humidity.
- Wind speed and direction aloft are obtained by tracking position using GPS.
- Radio transmitter telemeters data to ground tracking station.
- Flight can last > 2 hours; radiosonde can ascend to > 35 km and drift > 300 km from launch point.

- Network has 100 sites, 2 launches/day, 73,000 launches/year
- Network costs $25-30M/year
- Radiosondes cost $8-10M/year, $160/unit
Vision for Water Vapor Profiling

- **NWS/NOAA vision**
  - An Integrated Upper Atmosphere Water Vapor Sensor, built around a DIAL, will supplement, then replace existing met balloons.
  - *Create compact, low cost, automated, eye safe, water vapor DIAL profiler for widespread deployment*
  - Precedent – small elastic backscatter lidars for cloud, aerosol, and wind profiling now commercially available, e.g. MPLnet.

- **PSI/MSU**
  - MSU has developed 3 generations of WV DIAL
  - MSU & PSI have teamed to create a commercial product.
    - Develop a design to enable 24/7 unattended operation in controlled environment.
    - Improved measurement performance.
      - Improve daytime performance
      - Decrease range to full overlap
    - Improved operational performance
      - Improve long term stability.
    - *Use mature & highly reliable components*
Operating Wavelength
Water Absorption vs Laser Operating Windows

- Plot of water vapor absorption from HITRAN 2012 database vs. wavelength in the near-IR.
- US Standard Atmosphere, 296 K, 1 atm, 10 m horizontal, 30% RH
- **Design Trades**: Laser availability, detector availability, eye safety
• HITRAN model of operational line showing On Line, Side Line Range, and Off Line wavelengths (296 K, 100 m horizontal at 0 AGL, 1 atm pressure, US Standard Atm.)

• Another Side Line wavelength is shown for modeling purposes.
Transmitter Schematic & Characteristics

- Separate DBR lasers for On and Off
  - ~ 10 mW
- Operating wavelength selected using 2x1 MEMs switch
  - Switch λ's every 6 sec
- TSOA amplifier
  - Operated in saturated mode
  - Pulsed using pulsed current supply
  - 5 μJ pulse energy
  - 1 μs pulsewidth
  - 10 kHz rep rate
  - 5 W/50 mW peak/average power
- Beam expander provides Class I (eye-safe) beam profile wrt aircraft
- Frequency lock via wavemeter
Transmitter – DBR & Wavelength Locking

- **Current Tuning vs. Temp**
  - Mode hops of 22 GHz
  - “On” wavelength – green dashed line
  - “Off” wavelength – red dashed line
  - Choose conditions so operating wavelength is in center of mode range

- **Wavelength Locking**
  - Done with Bristol wavemeter
  - Locks to within wavemeter precision
  - $\Delta \nu_{\text{off}} = \pm 17$ MHz
  - $\Delta \nu_{\text{on}} = \pm 24$ MHz
Transmitter – TSOA Performance

- **Pulsing**
  - TSOA pulsed via current pulser

- **Switching**
  - Switching time ~ 400 $\mu$s

- **Amplifier Saturation**
  - TSOA saturated for seed power $>~$2-3 mW
  - Operation in saturated mode maximizes stability
- DBR lasers originally in commercial mount and interfaced to system through “cage mount” optics
- Source of some mechanical instability
- New laser mounting:
  - Vendor-supplied fiber pigtailed butterfly package
  - Highly robust custom mount
14 inch diameter telescope
- Uniaxial configuration
- Pulse energy normalization
- Narrow FOV channel
  - Narrow BPF
  - Etalon, stabilized
- Wide FOV channel
- Si APD SPCM x 2
- Multichannel scalar
- Spatial binning to 150 m
- Temporal averaging to 10-15 minutes
Diffuse Solar Background & Clouds

- **Observed Background**
- **Detector saturation**
- **Cloud Background**
- **Average Background**

### Detector Background Counts

![Detector Background Counts](image)

### Observed Background

- Background counts from diffuse solar too high (2xNBF fwhm = 160 pm)
- Add etalon
- FSR 1.3 cm⁻¹, 99 pm
- Finesse 13
- Spectral width 7 pm

### Diffuse Solar Radiance Model

\[ P_{bg} = L_{bg} \times A_r \times \Omega \times \Delta \lambda \]

- Background counts from diffuse solar too high (2xNBF fwhm = 160 pm)
Spectral Filtering

- Narrow Bandpass Filter
- Measured Etalon Transmission
- Etalon
  - FSR 100 pm
  - Spectral width 2 pm
  - Finesse 53
- Lock etalon temperature to $\lambda_{on}$
- Lock $\lambda_{off}$ to etalon fringe

Data
Lorentzian fit to data
Bandwidth (FWHM) = 0.0019 nm
FSR = 0.1 nm
Finesse = 53
Error Propagation

- The fundamental LIDAR equation is:
  \[
  P_{\text{trans}} F(r) A K \beta(\lambda, r) \Delta r \exp\left(-2 \int_0^r \alpha(r') \, dr'\right)
  \]
  \[
P_{\text{ret}}(r) = \frac{P_{\text{trans}} F(r) A K \beta(\lambda, r) \Delta r \exp\left(-2 \int_0^r \alpha(r') \, dr'\right)}{r^2}
  \]

- In DIAL, for 2 closely spaced wavelengths, the water vapor mixing ratio is written as:
  \[
n_C(r) = \frac{1}{2 \Delta \sigma_C(r) \Delta r} \ln \frac{P_{\text{on}}(r) P_{\text{off}}(r + \Delta r)}{P_{\text{on}}(r + \Delta r) P_{\text{off}}(r)}
  \]

- Standard error propagation techniques yield:
  \[
  \delta(n_C) = \frac{1}{\sqrt{2 \Delta \sigma_C \Delta r}} \left\{ \left[ \frac{\delta N_{\text{on}}(r)}{N_{\text{on}}(r)} \right]^2 + \left[ \frac{\delta N_{\text{off}}(r)}{N_{\text{off}}(r)} \right]^2 \right\}^{1/2}
  \approx \frac{1}{\Delta \sigma_C \Delta r} \frac{\delta N(r)}{N(r)} = \frac{1}{\Delta \sigma_C \Delta r} \frac{1}{\text{SNR}}
  \]
Error Analysis

- **(top) Simple error analysis**
  - Transmit power 5 μJ
  - Effect of various background levels

- **Good agreement with experimental observations (MSU)**

- **Predicted precision for system**
  - ~5% for altitudes ≤ 3 km, 85% of total column.
  - ~10% for altitudes ≤ 3.3 km, 89% of total column.
  - ~20% for altitudes ≤ 3.8 km, ~90% of total column.

- **System enables 5% retrievals throughout boundary layer**

- **(bottom) Fraction of total water column vs. altitude (U.S. Standard Atmosphere).**
System Tx/Rx Breadboard

Transmitter Module

Receiver Module
A cabinet level transient thermal analysis of the lidar was performed

**Assumptions**
- Solar flux based on 40°N on July 1
- Ambient temperature profile from Washington National Airport, mid-July hot conditions, still air
- AC 12 kBTU/hr
- R3 insulation in the cabinet
- White painted exterior (α=.25)
ThermoElastic Modeling - Results

- Internal temperature excursion predicted to be < 1C
- *No hotspots identified*
ThermoElastic Modeling - Results

- Rx axis moves ~2 μRad on startup; ~1 μRad for normal operation
- Tx axis moves ~30 μRad on startup; ~1 μRad for normal operation
- Responsible component(s) identified and reworked.
Cabinet Mounted System

- NEMA4 all-weather telecom cabinet
- Sliding optics rack
- Electronics bay underneath
- Window in roof
- Integral power center
- Integral a/c & heater
- Retractable wheels
- Leveling mounts
System Photographs

- Lidar in Cabinet
  - Receiver Side
- Lidar in Cabinet
  - Transmitter Side
- Lidar extended from Cabinet
Program Status

● **Status**
  – Local testing at PSI: January - February 2015
  – Howard University (Raman lidar): March 2015

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