Water Vapor lidar: The Vaisala Broadband Differential Absorption Lidar (DIAL)

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There is a need for a national network of (small and cheap) ground-based instruments capable of profiling water vapor and temperature in the atmospheric boundary layer.

Back in the spring of 2017, Vaisala approached ARM about deploying their new water vapor Differential Absorption Lidar (DIAL) to SGP for evaluation.

Conducted a field campaign at SGP C1 to access performance the Vaisala DIAL:
- 15 May to 12 June 2017
- Deployed the DIAL next to the Raman lidar
- Compared water vapor mixing ratio from the DIAL to:
  - Raman lidar
  - Radiosonde
  - AERI
## Vaisala DIAL Specs

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser eye-safety classification</td>
<td>1M</td>
</tr>
<tr>
<td>Averaging time/reporting interval</td>
<td>20 min / 2 min</td>
</tr>
<tr>
<td>Maximum range</td>
<td>3000 m reported</td>
</tr>
<tr>
<td>Range resolution</td>
<td>100 – 500 m</td>
</tr>
<tr>
<td>Average power per unit</td>
<td>44 mW</td>
</tr>
<tr>
<td>Pulse energy</td>
<td>5.5 µJ</td>
</tr>
<tr>
<td>Pulse peak power</td>
<td>25 W</td>
</tr>
<tr>
<td>FWHM pulse width</td>
<td>220 ns (33 m)</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>8 kHz</td>
</tr>
<tr>
<td>Wavelength (online/offline)</td>
<td>911.0 nm/ 910.6 nm</td>
</tr>
<tr>
<td>FWHM spectral width (near/far range)</td>
<td>0.19 nm/0.17 nm</td>
</tr>
<tr>
<td>Telescope diameter (near/far range)</td>
<td>150 mm/280 mm</td>
</tr>
<tr>
<td>Receiver detector</td>
<td>APD</td>
</tr>
</tbody>
</table>

Weight = 130 kg

![Telescope Dimensions](image)
The Vaisala Broadband DIAL

The Vaisala DIAL is unique in the sense that it uses a broadband approach. Normalized water vapor absorption cross section at 296K and 1 atm (black). The normalized laser spectra for the far-field (solid) and near-field (dashed) are shown in red for the online laser, and blue for the offline laser spectra.
Water Vapor Retrieval Using the Broadband Approach

Ratio of the online-to-offline return signals

\[ \frac{P'_{\text{on}}}{P'_{\text{off}}} = \frac{\int_{-\infty}^{\infty} S_{\text{on}}(\nu - \nu_{\text{on}}) T_{\text{WV}}^2(\nu, z) d\nu}{\int_{-\infty}^{\infty} S_{\text{off}}(\nu - \nu_{\text{off}}) T_{\text{WV}}^2(\nu, z) d\nu} \]  

(1)

\[ S_x(\nu - \nu_x) \] = Laser spectra

\[ T_{\text{WV}}(\nu, z) = \exp \left( -\int_{0}^{z} N(z) \gamma(\nu, z) dz \right) \] = Transmission due to water vapor absorption

Assumes aerosol backscatter >> molecular backscatter

Online-to-offline aerosol backscatter ratio \( \sim 1 \)

Spectrally flat receiver transmission function

Goal is to find \( N(z) \), the water vapor density, as a function of height. In general, a closed-form solution for \( N(z) \) is not possible. Instead, \( N(z) \) must be found using some sort of numerical optimization technique such that equation (1) is satisfied. This is a retrieval problem.
In the case of narrowband DIAL the laser spectral widths are much narrower than the absorption feature of interest. In that case, the laser spectra can be approximated as delta functions, $S_x (\nu - \nu_x) \rightarrow \delta(\nu - \nu_x)$

Equation (1) becomes

$$\frac{P'_{\nu_{on}}}{P'_{\nu_{off}}} \approx \frac{T^2_{WV} (\nu_{on}, z)}{T^2_{WV} (\nu_{off}, z)}$$

A closed-form solution for the H$_2$O density can then be obtained

$$N(z) = \frac{\ln\left(\frac{P'_{\nu_{off}} (z)}{P'_{\nu_{on}} (z)}\right)}{2\left(\gamma(\nu_{on}, z) - \gamma(\nu_{off}, z)\right)}$$
Qualitative Comparisons

Mixing Ratio (g kg⁻¹)

a) DIAL
b) Raman Lidar
c) AERI
d) Radiosonde (interpolated)
Quantitative comparisons

Profiles

<table>
<thead>
<tr>
<th></th>
<th>DIAL-Sonde</th>
<th>RL-Sonde</th>
<th>AERI-Sonde</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bias (g kg(^{-1}))</strong></td>
<td>-0.01</td>
<td>0.07</td>
<td>-0.23</td>
</tr>
<tr>
<td><strong>StDev (g kg(^{-1}))</strong></td>
<td>0.65</td>
<td>0.74</td>
<td>1.23</td>
</tr>
<tr>
<td><strong>Corr</strong></td>
<td>0.98</td>
<td>0.97</td>
<td>0.92</td>
</tr>
<tr>
<td><strong>Mean percent difference (%)</strong></td>
<td>0.42</td>
<td>0.87</td>
<td>-2.0</td>
</tr>
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Data Availability

Data availability for the DIAL was greater than 90% below 900 m, but then decreases rapidly with height above this level to less than 10% above 1500 m AGL.

Data availability is computed by adding the number of valid samples at a fixed height and dividing by the total number of time samples that were possible.
Pros: The Vaisala DIAL showed excellent agreement with the radiosonde (and the Raman lidar) during the SGP field campaign
- Bias ~ -0.01 g kg⁻¹, stDev ~ 0.65 g kg⁻¹, corr ~ 0.98
- Experienced no failures during the campaign

Cons: The range was somewhat limited
- Roughly 1.5 km max range
- 90% data availability below 900 m, but decreased rapidly with height above 900 m.

Calibration?
- Estimates of the online and offline laser spectral widths were obtained by optimizing the agreement with the radiosonde measurements over the course of the entire experiment. This is essentially a calibration procedure.
- Linear trend analysis of the DIAL-sonde difference did not show significant drift with time over the course of the field campaign.