Measuring Middle Atmosphere Winds With Lasers

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Santa Fe, NM
Light Detection and Ranging (LIDAR)

- Rayleigh Scattering From Air Molecules
- Na Scattering
- Resonant Fluorescence From Metal Atoms
- Mie Scattering From Aerosols
- 120 km
- 80 km
- 30 km
- Ground

Figure showing various scattering phenomena at different altitudes.
This photon count profile illustrates the rich variety of atmospheric constituents and processes that can be studied with lidar systems.
Historical Perspective

• First lidar systems constructed in 1930s and 40s using mechanically modulated searchlights to study clouds, aerosols, and stratospheric temperatures [Elterman, J. Geophys. Res., 1951a,b; 1953]

• In 1980s M. L. Chanin and colleagues used frequency-doubled Nd:YAG lasers to measure stratospheric temperatures and winds (Rayleigh scattering) [Chanin and Hauchecorne, J. Geophys. Res., 1981; Chanin et al., GRL, 1989]

• First lidar in space (aerosol/Rayleigh) flew aboard the shuttle Discovery in September 1994 and provided global measurements of tropospheric/stratospheric clouds, aerosols, and temperatures [McCormick et al., Bul. Am. Met. Soc., 1993]

• Today powerful UV laser-based Rayleigh lidars can measure winds in the stratosphere to ~50 km and temperatures to altitudes in excess of 85 km

• First resonance fluorescence lidar measurements were conducted in late 1960s when Bowman et al. [Nature, 1969] reported measurements of mesospheric Na profiles using a tunable dye laser; since then Fe, K, Ca, Ca+, and Li have also been measured

• A crude Na temperature lidar was first demonstrated in late 1970s [Gibson et al., Nature, 1979]

• Today Na, K, and Fe lidars are used routinely to measure mesopause region (80~105 km) temperatures while several Na systems are also capable of measuring wind velocities
Rayleigh Scattering

If an atmospheric molecule (or particle) is illuminated by a laser beam of frequency $f_L$ and wavelength $\lambda_L$, the Doppler shift is

$$f_D = 2V_R/\lambda_L$$

where $V_R$ is the radial velocity of the particle.

Resonance Fluorescence Scattering

If the molecule emits light of frequency $f_E$ and wavelength $\lambda_E$, the Doppler shift is

$$f_D = V_R/\lambda_E$$
Spectra of isolated fluorescence lines and Rayleigh scattered light are approximately Gaussian

- Width is related to temperature (Thermal Broadening)
- Center frequency is related to velocity (Doppler Shift)

\[
S(f) = \frac{N_S}{\sqrt{2\pi \sigma_S^2}} \exp\left[-\frac{(f - f_S + f_D)^2}{2\sigma_S^2}\right]
\]

- **Doppler Shift** \( f_D = \frac{V_R}{\lambda_S} \)

**Mean Square Width** \( \sigma_S^2 = \frac{k_B T}{\lambda_S^2 m_S} \rightarrow \sigma_S \approx 33\sqrt{T} \text{MHz} = 464 \text{MHz} @ 200K \) for Fe

**Temperature and Velocity Sensitivity**

\[
\frac{\partial \sigma_S}{\partial T} = \frac{\sigma_S}{2T} = 1.2 \text{MHz/K} = \left[0.25\% / K\right] \cdot \sigma_S \quad \text{and} \quad \frac{\partial f_D}{\partial V_R} = \frac{1}{\lambda_S} = 1.7 \text{MHz/(m/s)} = \left[0.37\% / (m/s)\right] \cdot \sigma_S
\]
Rayleigh Scattering

Doppler Shift \( f_D = \frac{2V_R}{\lambda_L} \)

Mean – Square Width \( \sigma_{Ray}^2 = \frac{4k_BT}{\lambda_L^2 m_{Atmos}} \)

\( \sigma_{Ray} \approx 64\sqrt{T} \text{MHz} = 905 \text{MHz} \quad @ \quad T = 200K \quad \text{and} \quad \lambda_L = 532 \text{ nm} \)

Temperature and Velocity Sensitivity

\[
\frac{\partial \sigma_{Ray}}{\partial T} = \frac{\sigma_{Ray}}{2T} = 2.3 \text{MHz/K} = [0.25\% /K] \cdot \sigma_{Ray}
\]

\[
\frac{\partial f_D}{\partial V_R} = \frac{2}{\lambda_L} = 3.8 \text{MHz/(m/s)} = [0.42\%/(m/s)] \cdot \sigma_{Ray}
\]

Although the temperature and velocity sensitivity for Rayleigh scattering is about double that for resonance fluorescence, because the backscattered linewidth is also about double, the measurement accuracies are comparable for comparable SNRs.
Signal Processing

Temperature and Winds can be measured by:

1) Measuring full spectrum of backscattered signal (RF & Ray)

2) Scanning laser through full fluorescence spectrum and measuring backscattered signal at each frequency (RF only)

3) Probing fluorescence spectrum with laser at 3-frequencies and measuring backscattered signal at each frequency (RF only)

4) Measuring spectrum of backscattered signal at 3-frequencies (RF & Ray)

\[ SNR = \frac{\text{Signal Power}}{\text{Noise Power}} \]

\[ \frac{N_S}{\sqrt{2\pi\sigma^2_S}} \exp\left[-\frac{(f - f_S + f_D)^2}{2\sigma^2_S}\right] \]

\[ \sigma^2_S = \frac{k_B T}{\lambda^2_S m_S} \quad f_D = \frac{V_R}{\lambda_S} \]
Theoretical Optimum

Ideal Receiver - No background noise (Nighttime)

Receiver measures precise frequency of each detected photon
(Infinitesimal Spectral Resolution Receiver)

Detected photon frequency is Gaussian distributed random variable

\[ p(f_i) = \exp\left[-\frac{(f_i - f_S + f_D)^2}{2\sigma_S^2}\right] / \sqrt{2\pi\sigma_S} \]

Mean frequency = \( f_S - f_D \)  Frequency variance = \( \sigma_S^2 \)

Minimum-mean-square-error estimators of velocity and temperature are related to sample mean frequency and sample frequency variance

\[ \hat{V}_R = -\frac{\lambda_S}{N_S} \sum_{i=1}^{N_S} (f_i - f_S) \quad \Delta \hat{V}_R = \frac{\lambda_S \sigma_S}{\sqrt{N_S}} = \frac{173 \text{ m/s}}{\sqrt{\text{SNR}}} \rightarrow \text{SNR} = 30,000 = 45 \text{ dB for Fe} \]

\[ \hat{T} = \frac{\lambda_S^2 m_S}{k_B N_S} \sum_{i=1}^{N_S} (f_i - f_S + \hat{V}_R / \lambda_S)^2 \quad \Delta \hat{T} = \frac{\sqrt{2} T}{\sqrt{N_S}} = \frac{283 \text{ K}}{\sqrt{\text{SNR}}} \rightarrow \text{SNR} = 80,000 = 49 \text{ dB} \]

[Gardner, Applied Optics, 2004]  SNR = \( N_S \) @ Night
Optimized 3-Frequency Resonance Fluorescence Lidar

Laser probes fluorescence line at three frequencies \( f_s \) and \( f_s \pm \Delta f \)
Dwell time at each frequency and offset \( \Delta f \sim 600 \text{ MHz} \) are both chosen to minimize error
Optimization different for temperature and wind and for day and night observations

\[
R_T = \frac{N_S^2(f_s)}{N_S(f_s + \Delta f)N_S(f_s - \Delta f)} = \exp\left(\frac{\Delta f^2}{\sigma_S^2}\right) = \exp\left(\frac{\Delta f^2}{\gamma T}\right)
\]

\[
R_V = \frac{N_S(f_s - \Delta f)}{N_S(f_s + \Delta f)} = \exp\left(\frac{2\Delta f}{\lambda_S \sigma_S^2} V_R\right) \quad V_R = \frac{\lambda_S \Delta f}{2} \ln\left(\frac{R_V}{R_T}\right)
\]

[\text{Gardner, Applied Optics, 2004}]

Rayleigh Lidar

3 narrowband filters centered at \( f_s \) and \( f_s \pm \Delta f \) can be used to process Rayleigh scattered signals. Filter bandwidths and offset frequency \( \Delta f \) are chosen to minimize error.
Fe lidar has smallest error because Fe is heaviest atom

Optimized 3-frequency Fe lidar performs within 3.3 dB of Theoretical Min @ night

To achieve ±1 m/s accuracy with optimized 3-frequency Fe lidar requires

SNR~ 64,000 = 48 dB @ Night and SNR~ 130,000 = 51 dB @ Day
Hyperfine Lines and Isotopes

Naturally Occurring Isotopes of Na, K, Fe, and Ca
(http://www.webelements.com/webelements/)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Natural Abundance (Atom%)</th>
<th>Nuclear Spin (I)</th>
<th>Magnetic Moment (m/m_N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{23}$Na</td>
<td>100</td>
<td>3/2</td>
<td>2.217520</td>
</tr>
<tr>
<td>$^{54}$Fe</td>
<td>5.85</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$^{56}$Fe</td>
<td>91.75</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$^{57}$Fe</td>
<td>2.12</td>
<td>1/2</td>
<td>0.09062294</td>
</tr>
<tr>
<td>$^{58}$Fe</td>
<td>0.28</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$^{39}$K</td>
<td>93.26</td>
<td>3/2</td>
<td>0.3914658</td>
</tr>
<tr>
<td>$^{40}$K</td>
<td>0.012</td>
<td>4</td>
<td>-1.298099</td>
</tr>
<tr>
<td>$^{41}$K</td>
<td>6.73</td>
<td>3/2</td>
<td>0.2148699</td>
</tr>
<tr>
<td>$^{40}$Ca</td>
<td>96.94</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$^{41}$Ca</td>
<td>0.65</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$^{43}$Ca</td>
<td>0.14</td>
<td>7/2</td>
<td>-1.31727</td>
</tr>
<tr>
<td>$^{44}$Ca</td>
<td>2.09</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$^{46}$Ca</td>
<td>0.004</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$^{48}$Ca</td>
<td>0.19</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Na systems employ dye ring-laser for local oscillator and pulsed dye amplifier.
Lidar Equation

Lidar Equation

Received Photocount = System Efficiency \times \# Photons Transmitted \times Probability of Scattering \times Probability Scattered Photon is Received

\[ N(z) = \eta T_A^2 \times \frac{Pr}{hc/\lambda} \times \sigma_B \rho(z) \Delta z \times \frac{A}{4\pi z^2} \]

- \( \eta \) = lidar system efficiency
- \( T_A \) = atmospheric transmittance
- \( \frac{hc/\lambda}{} \) = photon energy (J)
- \( P_L \) = average laser power (W)
- \( A_R \) = telescope aperture area (m^2)
- \( z \) = altitude (m)

\[ SNR_{\text{Night}} = \frac{N_S^2(z)}{N_S(z) + N_B} \approx N_S(z) \]
\[ SNR_{\text{Day}} = \frac{N_S^2(z)}{N_S(z) + N_B} \approx \frac{N_S^2(z)}{N_B} \approx \frac{SNR_{\text{Night}}^2}{N_B} \]

\[ N_S(z) \propto (PA\Delta z \Delta t)[T_A^2 \sigma_B \rho_S(z)] \]
\[ N_B \propto S_{\text{Sky}}(\lambda) \Delta \lambda \Omega_{\text{Field-of-View}} \]
Backscatter Cross-Section

<table>
<thead>
<tr>
<th>Species</th>
<th>Central Wavelength $\lambda_s$ (nm)</th>
<th>Peak Cross-Section $\sigma_B$ ($10^{-12}$ cm$^2$)</th>
<th>Peak Density $\rho_S$ (cm$^3$)</th>
<th>Altitude (km)</th>
<th>$\sigma_B\rho_S$ ($10^8$ m$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na ($D_2$)</td>
<td>588.995</td>
<td>14.87</td>
<td>3500</td>
<td>91.5</td>
<td>520</td>
</tr>
<tr>
<td>Fe</td>
<td>371.994</td>
<td>0.944</td>
<td>9000</td>
<td>88.3</td>
<td>85</td>
</tr>
<tr>
<td>K ($D_1$)</td>
<td>769.896</td>
<td>13.42</td>
<td>40</td>
<td>91.0</td>
<td>5.4</td>
</tr>
<tr>
<td>Ca</td>
<td>422.673</td>
<td>38.48</td>
<td>40</td>
<td>90.5</td>
<td>15</td>
</tr>
<tr>
<td>Ca$^+$</td>
<td>393.366</td>
<td>13.94</td>
<td>80</td>
<td>95.0</td>
<td>11</td>
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<tr>
<td>Rayleigh</td>
<td>532.070</td>
<td>$7.6 \times 10^{15}$</td>
<td>$7.1 \times 10^{13}$</td>
<td>90.0</td>
<td>$0.0054$</td>
</tr>
<tr>
<td>Rayleigh</td>
<td>532.070</td>
<td>$7.6 \times 10^{15}$</td>
<td>$6.4 \times 10^{15}$</td>
<td>60.0</td>
<td>0.49</td>
</tr>
<tr>
<td>Rayleigh</td>
<td>532.070</td>
<td>$7.6 \times 10^{15}$</td>
<td>$3.8 \times 10^{17}$</td>
<td>30.0</td>
<td>29</td>
</tr>
</tbody>
</table>

$$\sigma_{Rayleigh}\rho_{Atmosphere}(z) = 3.7 \times 10^{-31} \frac{P(mb)}{T(K)} \frac{1}{\lambda(m)^{4.0117}}$$

$$N_S(z) \propto (PA\Delta z\Delta t)[T_A^2\sigma_B\rho_S(z)]$$
Atmospheric Transmittance

Atmospheric attenuation decreases with increasing altitude.
Sky Brightness and Background Noise

\[ N_B \propto S_{Sky}(\lambda) \Delta \lambda \Omega_{Field-of-View} \]

Sky brightness decreases with increasing altitude

## Atmospheric Parameters

<table>
<thead>
<tr>
<th>Species or Laser</th>
<th>$\lambda_s$ (nm)</th>
<th>2-Way Atmospheric Transmittance $T_A$</th>
<th>Sky Spectral Radiance Continuum $\mathcal{R}_{\mathcal{C}}$ ($10^3$ W/m$^2$/nm/sr)</th>
<th>Fraunhofer Line Relative Depth $\mathcal{D}$ (% Continuum)</th>
<th>Fraunhofer Linewidth $\mathcal{L}$ (GHz)</th>
<th>Narrowband Sky Spectral Radiance $\mathcal{R}_{\mathcal{C}}$ ($10^3$ W/m$^2$/nm/sr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na</td>
<td>588.995</td>
<td>0.49</td>
<td>86.3</td>
<td>9.6</td>
<td>14.5</td>
<td>8.28</td>
</tr>
<tr>
<td>Fe</td>
<td>371.994</td>
<td>0.25</td>
<td>34.8</td>
<td>8.1</td>
<td>36.0</td>
<td>2.82</td>
</tr>
<tr>
<td>K</td>
<td>769.896</td>
<td>0.64</td>
<td>67.7</td>
<td>21.7</td>
<td>5.9</td>
<td>14.69</td>
</tr>
<tr>
<td>Ca</td>
<td>422.673</td>
<td>0.37</td>
<td>67.7</td>
<td>7.6</td>
<td>23.2</td>
<td>5.15</td>
</tr>
<tr>
<td>Ca$^+$</td>
<td>393.366</td>
<td>0.30</td>
<td>41.0</td>
<td>9.9</td>
<td>554.0</td>
<td>4.06</td>
</tr>
<tr>
<td>Frequency Doubled Nd:YAG</td>
<td>532.070</td>
<td>0.46</td>
<td>90.0</td>
<td>na</td>
<td>na</td>
<td>90.0</td>
</tr>
<tr>
<td>Frequency Tripled Nd:YAG</td>
<td>354.713</td>
<td>0.23</td>
<td>27.9</td>
<td>na</td>
<td>na</td>
<td>27.9</td>
</tr>
</tbody>
</table>

1. Zenith viewing at sea level, solar zenith angle 45°, excellent visibility
2. Includes 5% Ring effect for all lines, 3. Full width @ twice depth
4. Receiver bandwidth much smaller than Fraunhofer linewidth
Maui: MALT Na Lidar @ Haleakala, HI

Temperature (K)

Na Density (cm⁻³)

Zonal Wind (m/s)

Meridional Wind (m/s)

Vertical Wind (m/s)

Na Wind/Temperature Lidar, Maui, HI

April 13, 2002
Conclusions

• Lidars are making crucial contributions to MLT science

• Technology exists to extend observations into daytime and wind measurements into lower mesosphere (Rayleigh)

• Technology also exists to obtain global temperature measurements throughout MLT (Fe/Rayleigh + HIAPER)

• New techniques and technologies are needed to extend observations into thermosphere