Lecture 20. Temperature Lidar (4)

- Review of Rayleigh Integration Technique
- High-Spectral-Resolution Lidar & Rayleigh Doppler Technique
- Rotational Raman Technique
- DIAL Temperature Profiling
- Comparison of Temperature Lidar Techniques
- Newly Developing Temperature Lidars (K Doppler, Solid-state Na and Fe Doppler)
- Summary
Rayleigh integration technique is applicable in the regions free of aerosols, clouds, and resonance fluorescence, i.e., where the lidar returns are dominated by pure Rayleigh scattering signals. When using non-resonant wavelength, e.g., 532 or 355 nm, it is about 30-100 km, depending on the product of power, aperture, cross-section and efficiency.

\[ dP(z) = -\rho(z)g(z)\,dz \quad + \quad P(z) = \frac{\rho(z)RT(z)}{M(z)} \]

\[ T(z) = T(z_0) \frac{n(z_0)}{n(z)} + \frac{M(z)}{R} \int_{z_0}^{z} \frac{n(z')g(z')}{n(z)} \,dz' \]

Number density ratio (relative number density) \(\Rightarrow\) Temperature

\[ \text{var}[T(z)] \approx \frac{T^2(z)}{N_R(z)} + \left\{ \text{var}[T(z_0)] + \frac{T^2(z_0)}{N_R(z_0)} \right\} \exp\left[-2(z_0 - z)/H\right] \]

Large \(N_R(z)\) \(\Rightarrow\) smaller temperature errors
High-Spectral-Resolution Lidar

- In the lower atmosphere when aerosols present, the lidar returns contains a narrow spike near the laser frequency caused by aerosol scattering riding on a Doppler broadened molecular scattering profile.

At $T = 300$ K, the Doppler broadened FWHM for Rayleigh scattering is $2.58$ GHz, not $1.29$ GHz. Why?

Because Rayleigh backscatter signals have 2 times of Doppler shift!

Fig. 5.1. Spectral profile of backscattering from a mixture of molecules and aerosols for a temperature of 300 K. The spectral width of the narrow aerosol return is normally determined by the line width of the transmitting laser.

Courtesy of Dr. Ed Eloranta
University of Wisconsin
Doppler Shift in Rayleigh Scattering

- Refer to textbook 5.2.2.4 Lidar wind vs radar wind measurements

\[ \begin{align*}
\text{Momentum Conservation} & \quad m\vec{v}_1 + \hbar \vec{k}_1 = m\vec{v}_2 + \hbar \vec{k}_2 \\
\text{Energy Conservation} & \quad \frac{1}{2} m v_1^2 + \hbar \omega_1 = \frac{1}{2} m v_2^2 + \hbar \omega_2
\end{align*} \]

\[ \omega_1 = \omega_2 + \vec{k}_1 \cdot \vec{v}_1 - \vec{k}_2 \cdot \vec{v}_2 + \frac{\hbar k_1^2}{2m} - \frac{\hbar k_2^2}{2m} \]

- For Rayleigh or radar backscatter signals, we have

\[ \vec{k}_2 \approx -\vec{k}_1 \quad \vec{v}_2 \approx \vec{v}_1 \]

- The frequency shift for Rayleigh or radar backscattering is

\[ \Delta \omega_{\text{Rayleigh, backscatter}} = \omega_2 - \omega_1 = -2\vec{k}_1 \cdot \vec{v}_1 \]
Doppler Broadening in Rayleigh Scatter

- To derive the Doppler broadening, let’s write the Doppler shift as
  \[ \omega = \omega_0 \left(1 - \frac{2v_R}{c}\right) \rightarrow v_R = \frac{\omega_0 - \omega}{2\omega_0 / c} \]

- According to the Maxwellian velocity distribution, the relative probability that an atom/molecule in a gas at temperature T has its velocity component along the line of sight between \( v_R \) and \( v_R + dv_R \) is
  \[ P(v_R \rightarrow v_R + dv_R) \propto \exp\left(-\frac{Mv_R^2}{2k_B T}\right)dv_R \]

- Substitute the \( v_R \) equation into the Maxwellian distribution,
  \[ I \propto \exp\left(-\frac{M(\omega_0 - \omega)^2}{2k_B T(2\omega_0 / c)^2}\right)\left(c / 2\omega_0\right)d\omega \]

- Therefore, the rms width of the Doppler broadening is
  \[ \sigma_{rms} = 2\omega_0 / c \sqrt{k_BT/M} = \frac{2}{\lambda_0} \sqrt{k_BT/M} \]

2 times!
**HSRL Receiver Filters**

1. Aerosol scattering pass the transmission band
2. Molecular scattering is reflected outside the transmission band

**Type 1: Fabry-Perot Etalon/Interferometer**

**Type 2: Atomic/molecular blocking filter**
HSRL
Instrumentation Using $I_2$ Filter

CSU HSRL
Hair, She, et al. [2001]
HSRL Temperature Measurements

- The ratio of the Rayleigh scattering signals passing through two vapor cell filters operating at different temps is a function of atmosphere temperature.

- Laser has to be single frequency and locked to the narrowband filter. Measurements can go to 15 km.

- Majority of the Rayleigh scattering is filtered out!
Rayleigh Doppler Lidar

- Rayleigh Doppler lidar uses the same Doppler effect of molecular scattering – again, 2 times of the Doppler shift and Doppler broadening!
- One approach is to use high resolution F-P etalon to image the lidar returns, i.e., turn spectral distribution to spatial distribution.

- Current issues: suffer low signal levels above 50 km because of decreasing atmospheric density
Raman Scattering of $N_2$ and $O_2$

- Raman shift amount is independent of incident laser wavelength.

Fig. 9.1. Vibration–rotation energy levels of the $N_2$ molecule, Raman transitions, and resulting spectrum.

- Raman shift amount is independent of incident laser wavelength.
Raman Scattering

- Volume backscatter coefficient for single Raman lines

\[
\left( \frac{d\sigma}{d\Omega} \right)_{j}^{\text{RR, VRR}} = k_\nu (\nu_1 \mp |\Delta \nu|)^4 \frac{g_N \Phi_j}{Q} \exp \left[ - \frac{B_i h c_0 J(J + 1)}{k_B T} \right]
\]

Which is the product of the transition probability and the population on the initial energy state. So the temperature dependence comes from the population distribution - Boltzmann distribution law!
Rotation Raman Lidar

- Depending on what the initial energy state is, the line intensity can increase or decrease when temperature increases.
- If the initial energy state is one of the upper levels of the ground state, increasing in temperature will increase the population on the initial state, so the Raman line intensity will increase.
- If the initial energy state is the lowest level of the ground state, increasing temperature will decrease the population on the initial state, so the Raman line intensity will decrease.
- By measuring the intensity of two Raman lines with opposite temperature dependence, the ratio of these two lines is a sensitive function of atmospheric temperature.

\[
Q(T, z) = \frac{S_{RR2}(T, z)}{S_{RR1}(T, z)}
\]
Therefore, temperature can be derived from the ratio of two pure Rotational Raman line intensity. This is essentially the same principle as Boltzmann temperature technique!
Combined Rotation Raman and Elastic Scattering Lidar
Rotation Raman + Elastic Lidar

Lidar Polychromator
Results from Combined RR and Elastic Scattering Lidar

Fig. 10.11. Intensities of the RASC lidar signals for the temperature measurements: rotational Raman signals (RR1 and RR2) and high-altitude elastic signal (El. high). For this plot, 72 minutes (216,000 laser pulses) of nighttime lidar data were taken with a height resolution of 72 m, summed, the background was subtracted, and the data were finally smoothed with a sliding average of 360 m. The photon emission rate of the laser is $\sim 8 \times 10^{19}$ photons/s. In the high-altitude elastic signal, the effect of the chopper can be seen below $\sim 25$ km and the signature of a cirrus cloud in $\sim 13$ km height.
Results from Combined RR and Elastic Scattering Lidar

Fig. 10.12. Simultaneous temperature measurements with rotational Raman technique and with integration technique (signals see Fig. 10.11). Profiles of a climatological model atmosphere (CIRA-86 for 35°N and the month of the lidar measurements) and of a radiosonde are shown for comparison. Rotational Raman temperature data: height resolution of 72 m up to 15 km height, 360 m between 15 and 20 km height, 1080 m between 20 and 30 km height, and 2952 m above 30 km. Height resolution of the integration technique data is 2952 m. Error bars show the 1–σ statistical uncertainty of the measurements [48].
DIAL Temperature Profiling

- Molecular absorption coefficient is temperature dependent: both the line strength and the lineshape are function of temperature.

- So by measuring the molecular absorption coefficient, it is possible to derive temperature if the molecular number density is known. For this purpose, O\textsubscript{2} is chosen because of its constant mixing ratio up to high altitude and suitable absorption lines.

- In the choice of suitable absorption line, a trade-off must be made between the high temperature sensitivity of the absorption cross-section (high for high initial energy state) and the suitable magnitude of absorption coefficient.

- Absorption coefficient is also dependent on pressure, making the temperature derivation more difficult.
Comparison of Temperature Technique

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Comparison of Temperature Technique

- All are temperature-dependent effects and phenomena!

- Applications of similar techniques in other remote sensing techniques –
  - Doppler effect: FPI for wind and temp measurements
  - Boltzmann distribution / rotational Raman: All-sky-imager, Bomem temp mapper
  - Integration technique: rocket falling sphere, cw searchlight, satellite drag, etc.
Solid-State K Doppler Lidar

See Lecture 18
Solid-State Na Doppler Lidar

Figure 5.36  Energy level diagram for Nd:YAG laser.

- CW Nd:YAG Laser 1.319µm
- CW Nd:YAG Laser 1.064µm
- Harmonic Generator 589 nm
- CW 589 nm
- PDA
- Pulsed 589 nm
- Pulsed Nd:YAG 532nm
Proposed Solid-State Fe Doppler Lidar

Advanced Fe-Resonance/Rayleigh/Mie Doppler Lidar

CW Injection Seed Laser

Dual Acousto-Optic Frequency Shifter

Pulsed Alexandrite Ring-Laser (Oscillator + Amplifier)

Frequency Doubler

744 nm

372 nm

High-Resolution Wavelength meter & Spectrum Analyzer

Data Acquisition and Control System

Record Pulse Spectrum

Signal

PMT

Interference Filter

Fabry-Perot Etalon

Collimating Lens

Chopper

Aircraft Viewport Window

Holographic Scanner

Cassegrain Telescope

35°
Summary

- Temperature-dependent effects and phenomena
- Doppler Technique
- Boltzmann Technique
- Integration Technique
- Rotational Raman Technique
- DIAL Technique
- High-spectral-resolution Lidar
- Rayleigh Doppler Lidar