Lecture 18. Temperature Lidar (7)
Rayleigh Doppler Technique

- Review of integration technique
- Resonance fluorescence Doppler technique vs. Rayleigh Doppler technique
- Rayleigh Doppler lidar
- High-spectral-resolution lidar
- Rotational Raman technique
- DIAL temperature technique
- Comparison of temperature techniques
- Summary

Review of Integration Technique

❑ Integration technique relies on the hydrostatic equilibrium equation and ideal gas law in the atmosphere. It involves integrating the atmosphere relative density profile downward using a starting temperature at an upper altitude to derive temperature downward.

$$\mathrm{d}P(z) = -\rho(z)g(z)\,\mathrm{d}z \quad + \quad P(z) = \frac{\rho(z)RT(z)}{M(z)}$$

⇓

$$T(z) = T(z_0)\frac{n(z_0)}{n(z)} + \frac{M(z)}{R}\int_z^{z_0} \frac{n(z')g(z')}{n(z)}\,\mathrm{d}z'$$

Number density ratio (relative number density) ⇨ Temperature

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

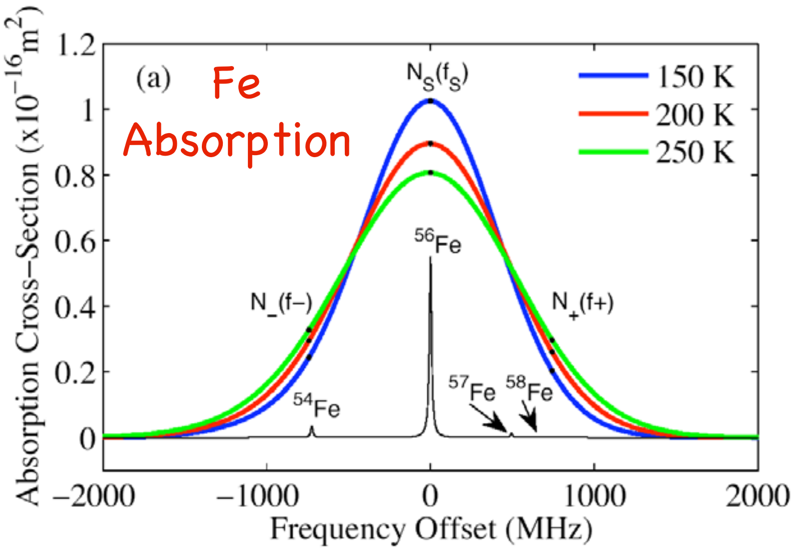
Large $N_R(z)$ ⇨ smaller temperature errors

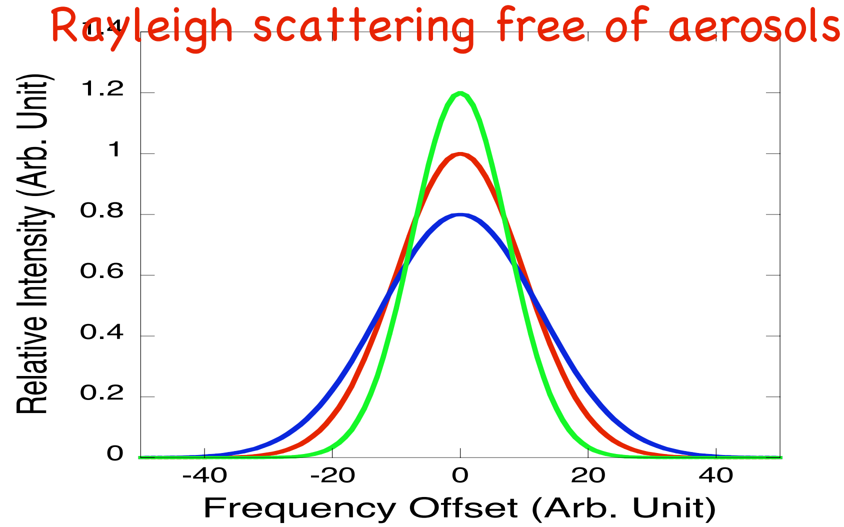
Resonance Fluorescence Doppler versus Rayleigh Doppler

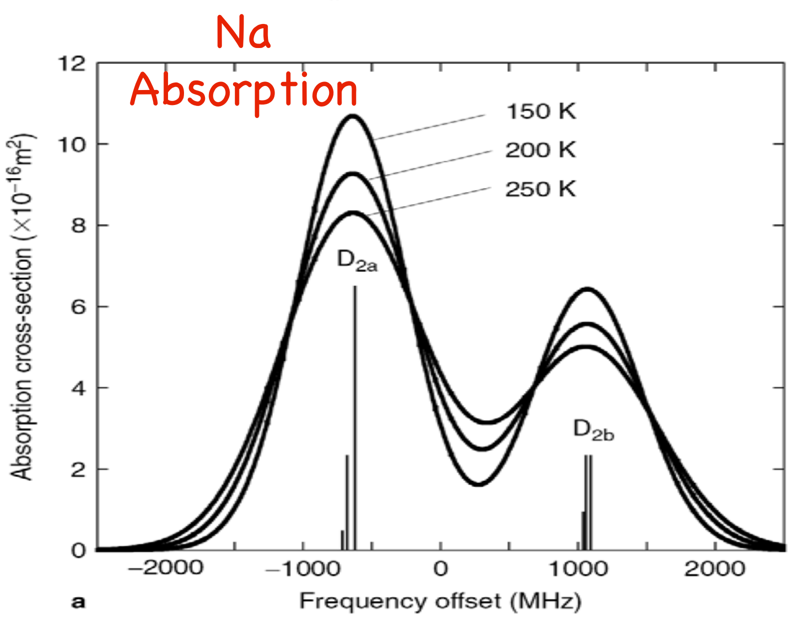
- Atomic absorption lines provide a natural frequency analyzer or frequency discrimination. This is because the absorption cross section undergoes Doppler shift and Doppler broadening. Thus, when a narrowband laser scans through the absorption lines, different absorption and fluorescence strength will be resulted at different laser frequencies. By using a broadband receiver to collect the returned resonance fluorescence, we can easily obtain the line shape of the absorption cross section so that we can infer wind and temperature. There is no need to measure the fluorescence spectrum. This is resonance fluorescence Doppler technique.

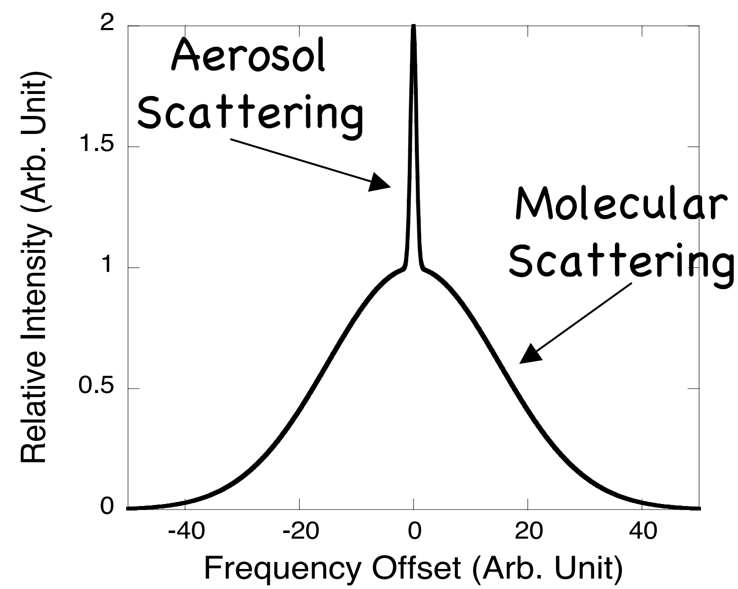
- Rayleigh scattering also undergoes Doppler shift and broadening, however, it is not frequency discriminated. In other words, when scanning a laser frequency, the backscattered Rayleigh signal gives nearly the same Doppler broadened line width, independent of laser frequency. Thus, the atmosphere molecule scattering does not provide frequency discrimination. A frequency analyzer must be implemented into the lidar receiver to discriminate the return light frequency, i.e., analyze Rayleigh scattering spectrum to infer wind and temperature. – Rayleigh Doppler technique

Resonance Fluorescence Doppler versus Rayleigh Doppler









Doppler Effect in Rayleigh Scattering

❑ In the 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.

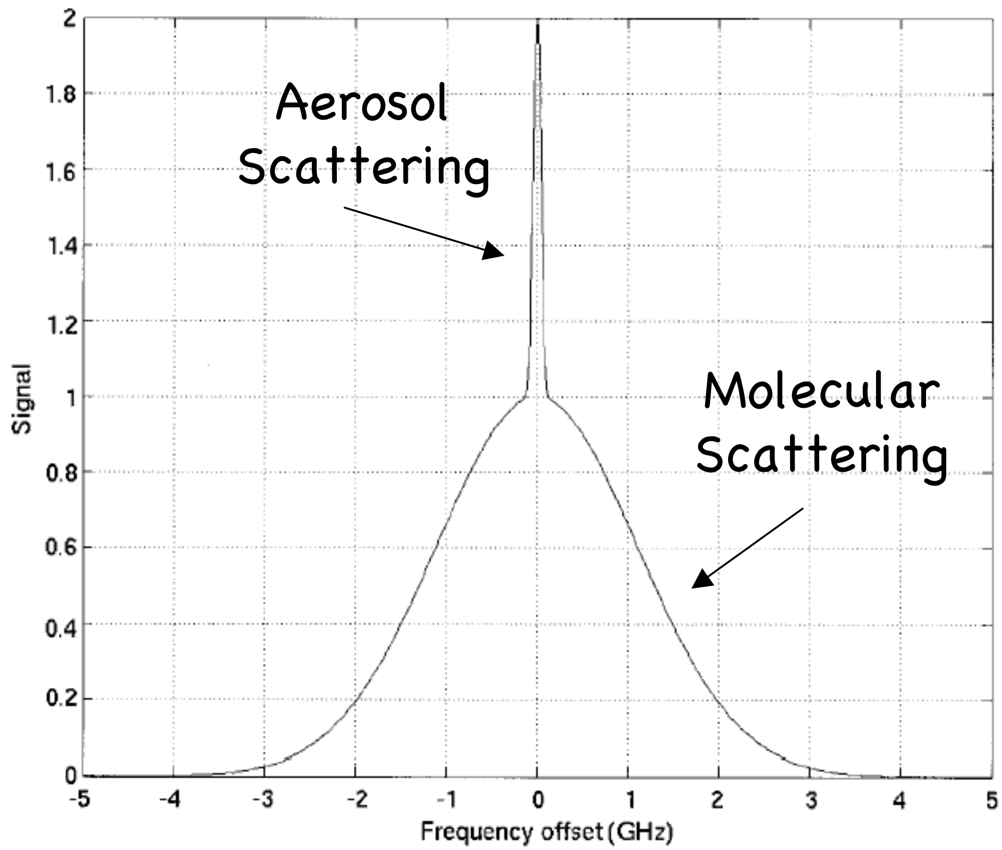


Fig. 5.1. Spectral profile of backscattering from a mixture of molecules and aerosols for a temperature of 300 K. The spectral width of the narrow aerosol return is normally determined by the line width of the transmitting laser.

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

Because Rayleigh backscatter signals have 2 times of Doppler shift!

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

Momentum Conservation $\quad m\vec{v}_1 + \hbar\vec{k}_1 = m\vec{v}_2 + \hbar\vec{k}_2$

Energy Conservation $\quad \frac{1}{2}mv_1^2 + \hbar\omega_1 = \frac{1}{2}mv_2^2 + \hbar\omega_2$

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

- For Rayleigh or radar backscatter signals, we have

$$\vec{k}_2 \approx -\vec{k}_1 \qquad \vec{v}_2 \approx \vec{v}_1$$

- The frequency shift for Rayleigh or radar backscattering is

$$\boxed{\Delta\omega_{Rayleigh,backscatter} = \omega_2 - \omega_1 = -2\vec{k}_1 \cdot \vec{v}_1}$$

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

$$P(v_R \to v_R + dv_R) \propto \exp\left(-Mv_R^2 / 2k_B T\right) dv_R$$

- Substitute the v_R equation into the Maxwellian distribution,

$$I \propto \exp\left(-\frac{M(\omega_0 - \omega)^2}{2k_B T(2\omega_0 / c)^2}\right)(c / 2\omega_0) d\omega$$

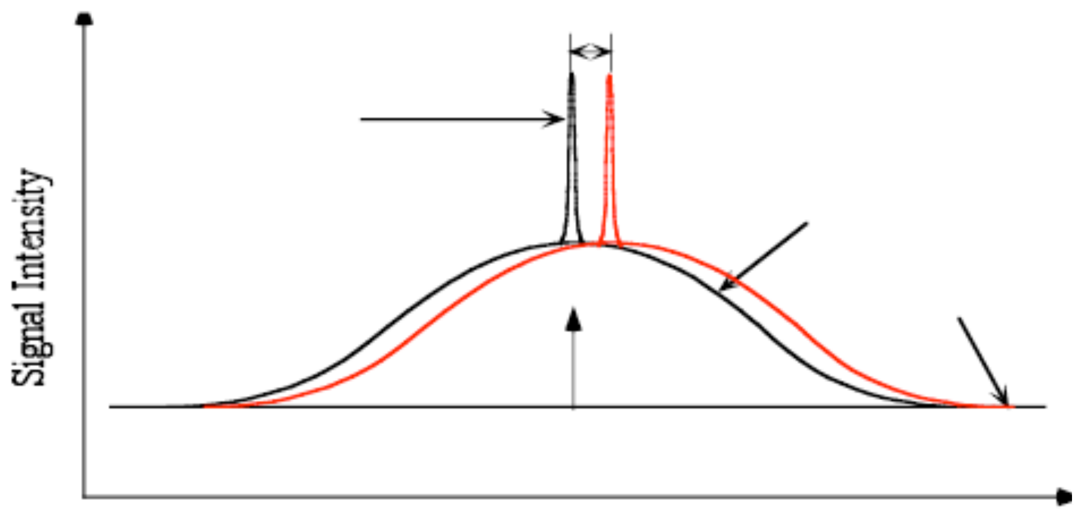
- Therefore, the rms width of the Doppler broadening is

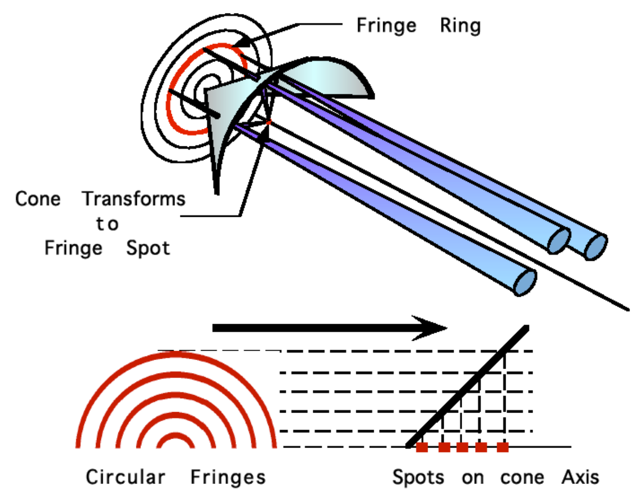
$$\sigma_{rms} = 2\omega_0 / c\sqrt{k_B T / M} = \frac{2}{\lambda_0}\sqrt{k_B T / M}$$

2 times !

Rayleigh Doppler Lidar

- Rayleigh Doppler lidar uses the Doppler effect of molecular scattering - again, 2 times of the Doppler shift and broadening!
- Since molecular scattering does not provide frequency discrimination, frequency analyzers have to be implemented in receiver. Mainly two methods: fringe imaging and edge filter.
- Fringe imaging is to use high resolution Fabry-Perot etalon to image the lidar returns, i.e., turn spectral distribution to spatial distribution.

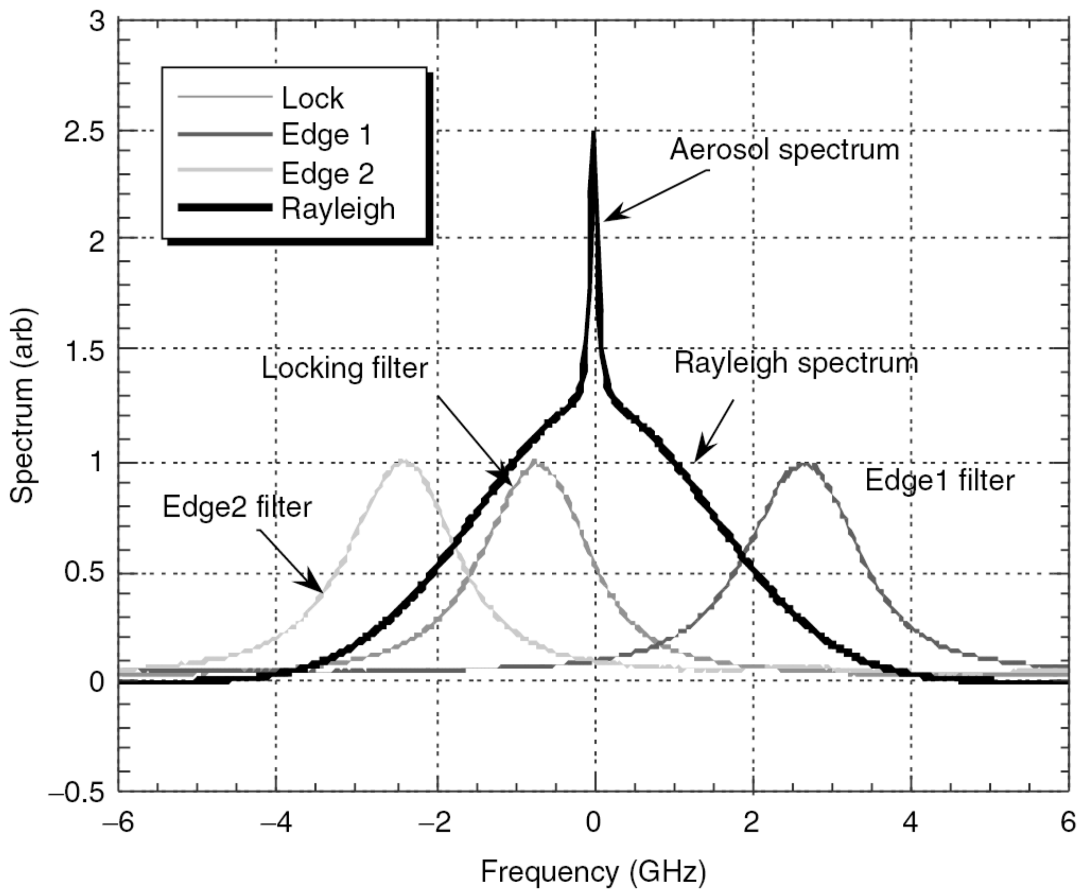




- Current issues: suffer low signal levels above 50 km because of decreasing atmospheric density

Rayleigh Doppler Lidar

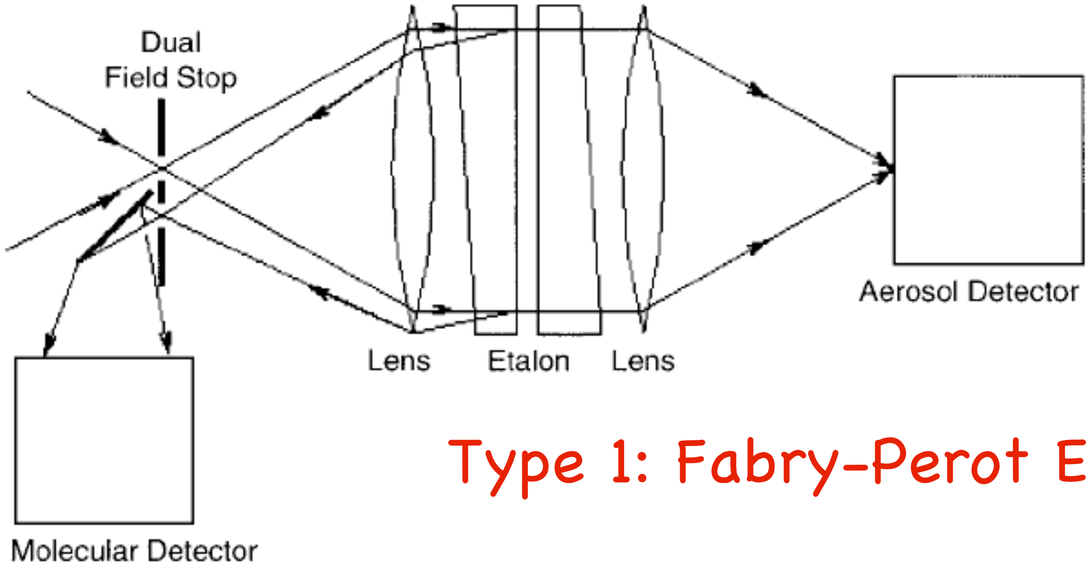
- Edge filter is to use either high resolution Fabry-Perot etalons or atomic/molecular vapor cell filters to reject part of the return spectra while pass the other part of the spectra to two different channels. The temperature information is then derived from the ratio of signals from these two channels.



$$\frac{N_1}{N_2} = \frac{\xi_1 f_{m1}(T,P,V_R)}{\xi_2 f_{m2}(T,P,V_R)}$$

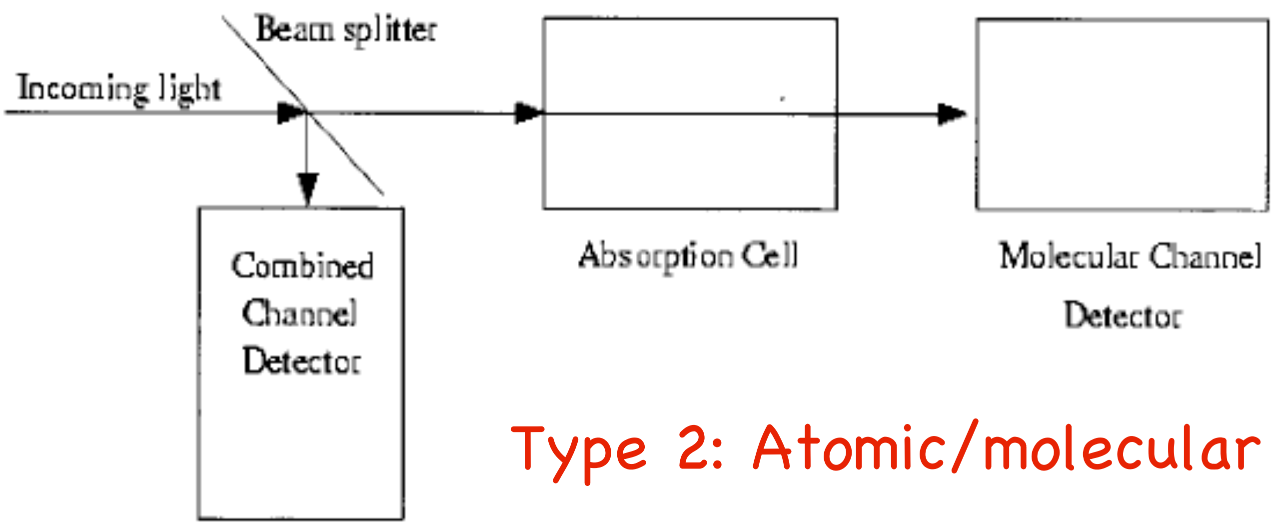
If V_R is known, then T can be derived.
If T is known, then V_R can be derived.

High Spectral Resolution Lidar



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

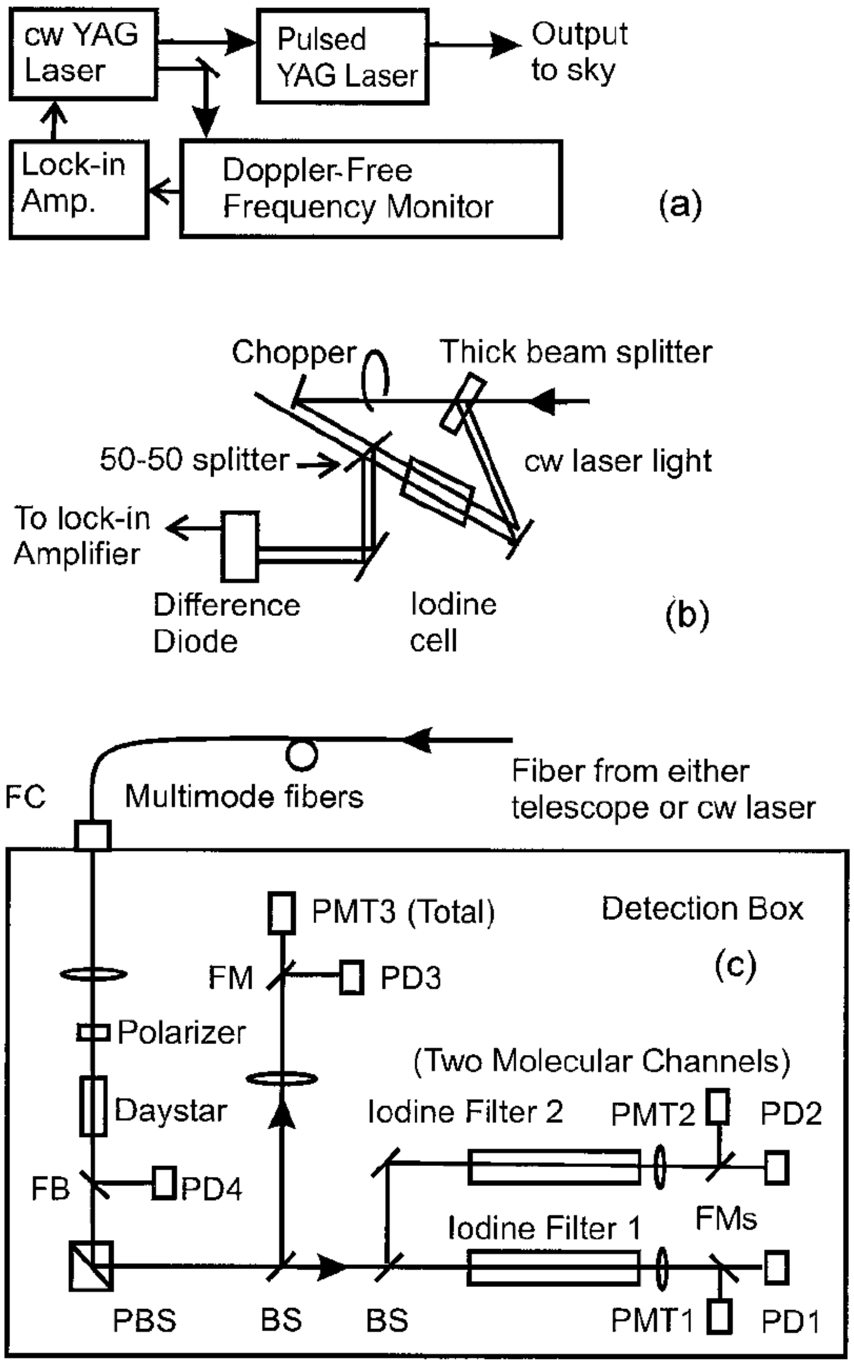
Type 1: Fabry-Perot Etalon/Interferometer

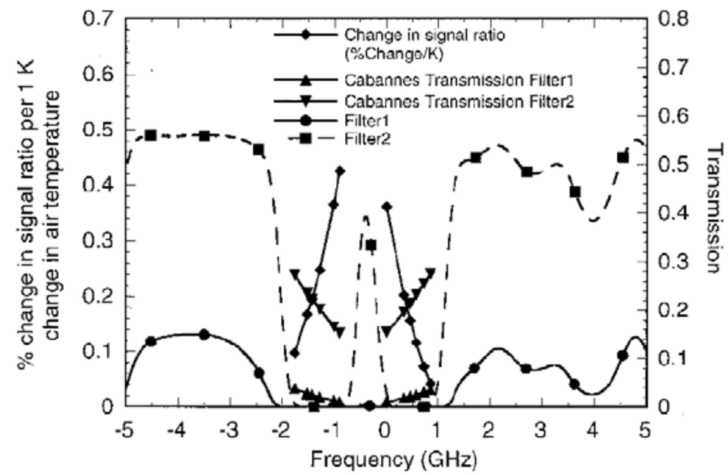


Atomic or molecular absorption block the aerosol scattering

Type 2: Atomic/molecular blocking filter

HSRL Using I_2 Filter





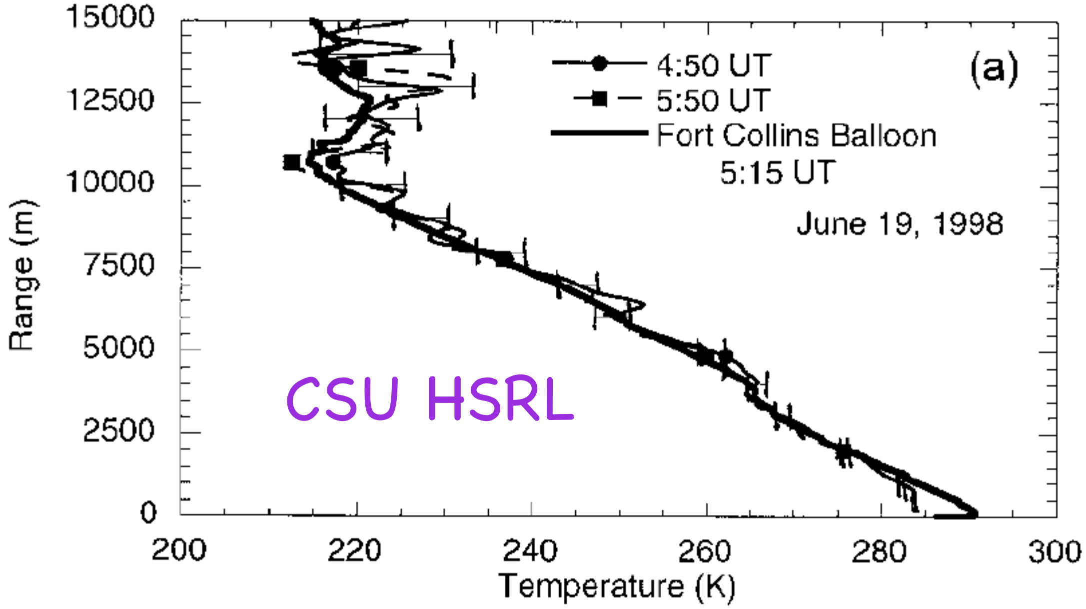
CSU HSRL

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!

Raman Scattering of N_2 and O_2

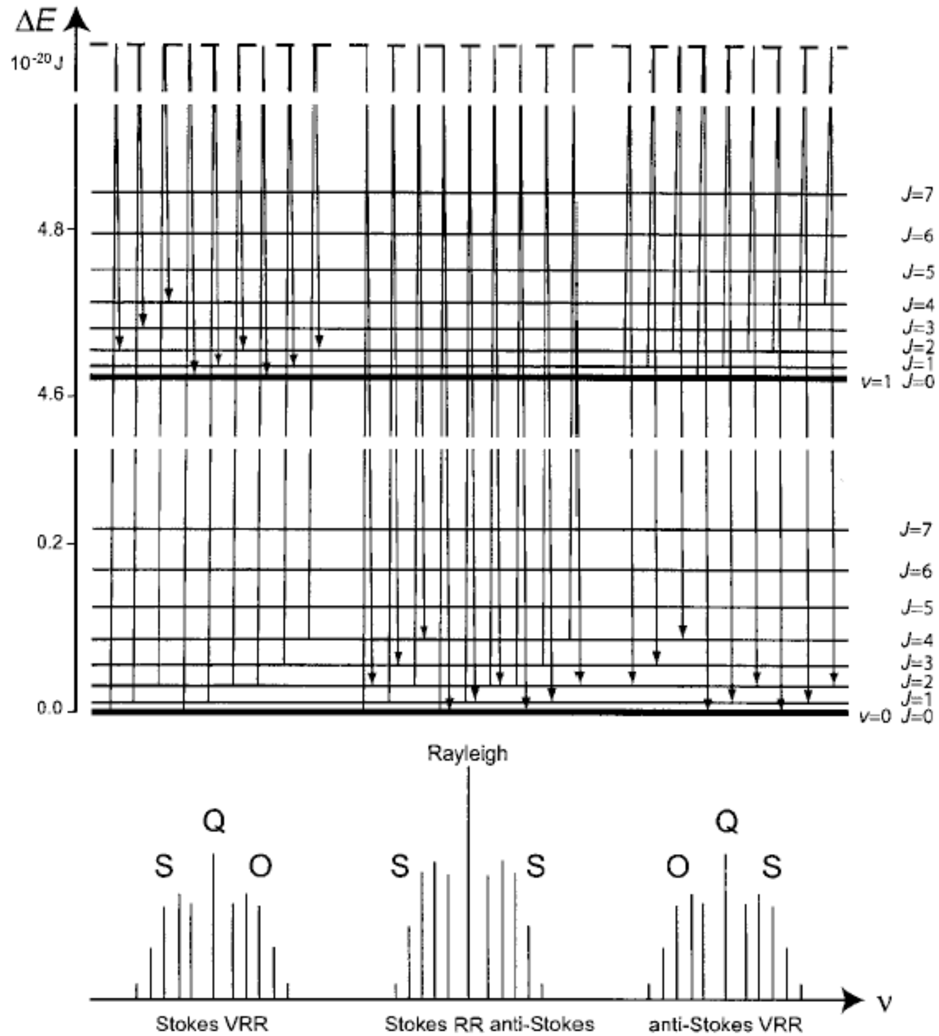


Fig. 9.1. Vibration–rotation energy levels of the N_2 molecule, Raman transitions, and resulting spectrum.

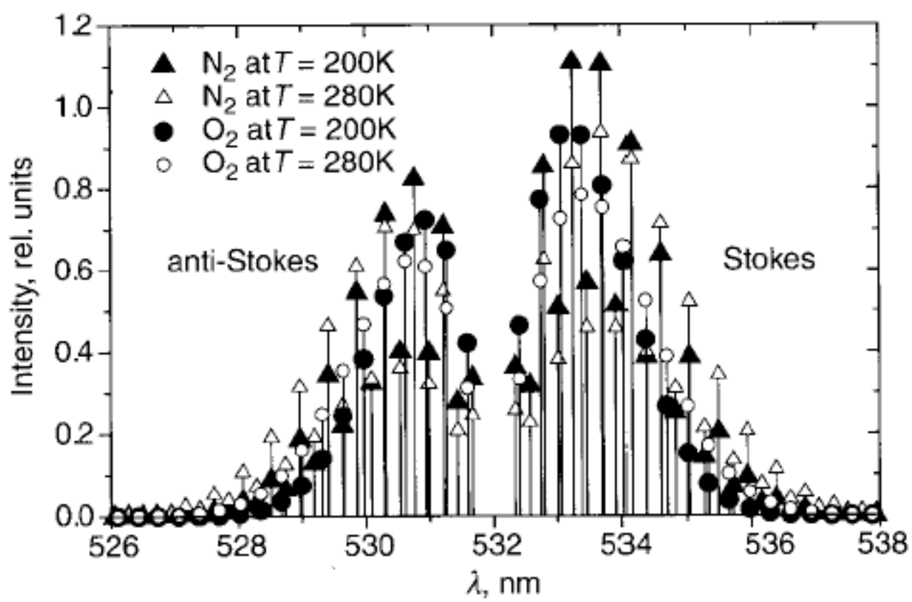
- Raman shift amount is independent of incident laser wavelength

Raman Scattering

- Volume backscatter coefficient for single Raman lines

$$\left(\frac{d\sigma}{d\Omega}\right)_J^{RR,VRR} = k_{\tilde{\nu}}(\tilde{\nu}_1 \mp |\Delta\tilde{\nu}|)^4 \frac{g_N \Phi_J}{Q} \exp\left[-\frac{B_i h c_0 J(J+1)}{k_B T}\right]$$

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!

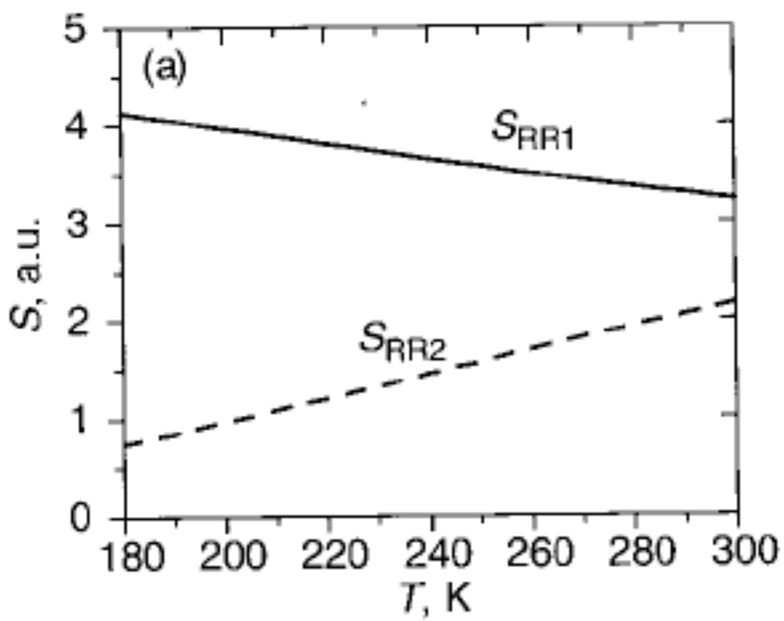


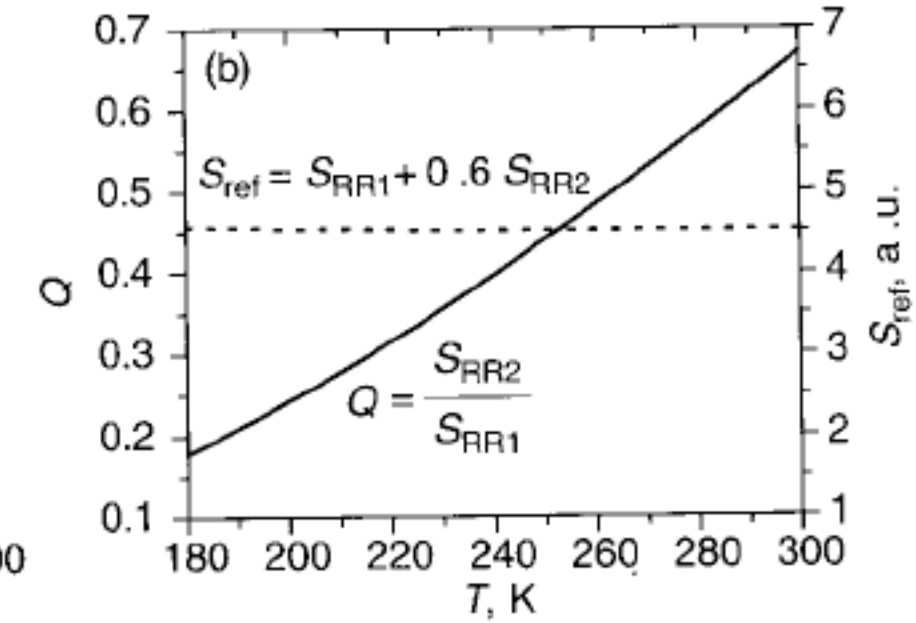
Rotation Raman Lidar

- 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.

$$\boxed{Q(T, z) = \frac{S_{\mathrm{RR2}}(T, z)}{S_{\mathrm{RR1}}(T, z)}}$$

Rotation Raman Lidar

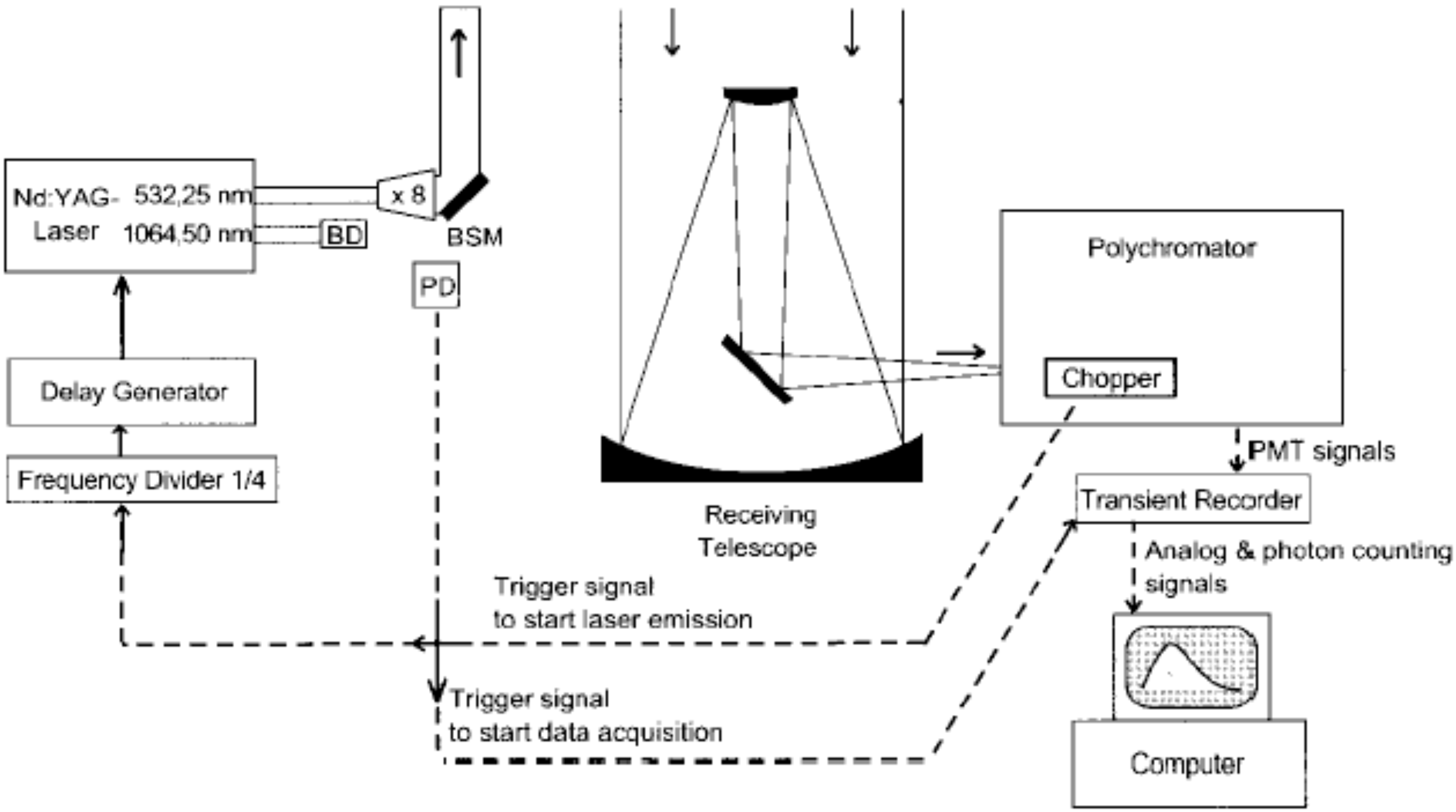




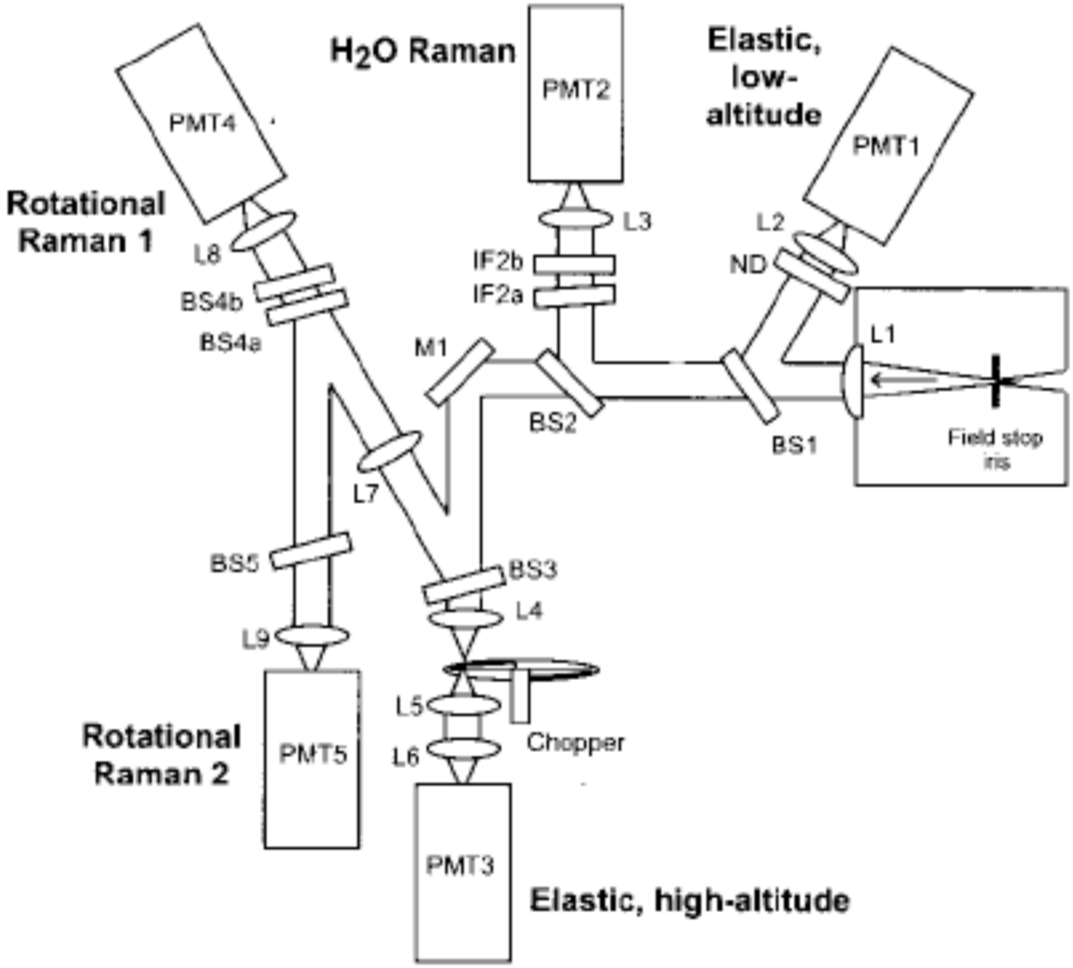
$$
Q(T) = \frac{\sum_{i=O_2,N_2} \sum_{J_i} \tau_{RR2}(J_i)\eta_i \left(\frac{d\sigma}{d\Omega}\right)_{\pi}^{RR,i}(J_i)}{\sum_{i=O_2,N_2} \sum_{J_i} \tau_{RR1}(J_i)\eta_i \left(\frac{d\sigma}{d\Omega}\right)_{\pi}^{RR,i}(J_i)}
$$

- 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

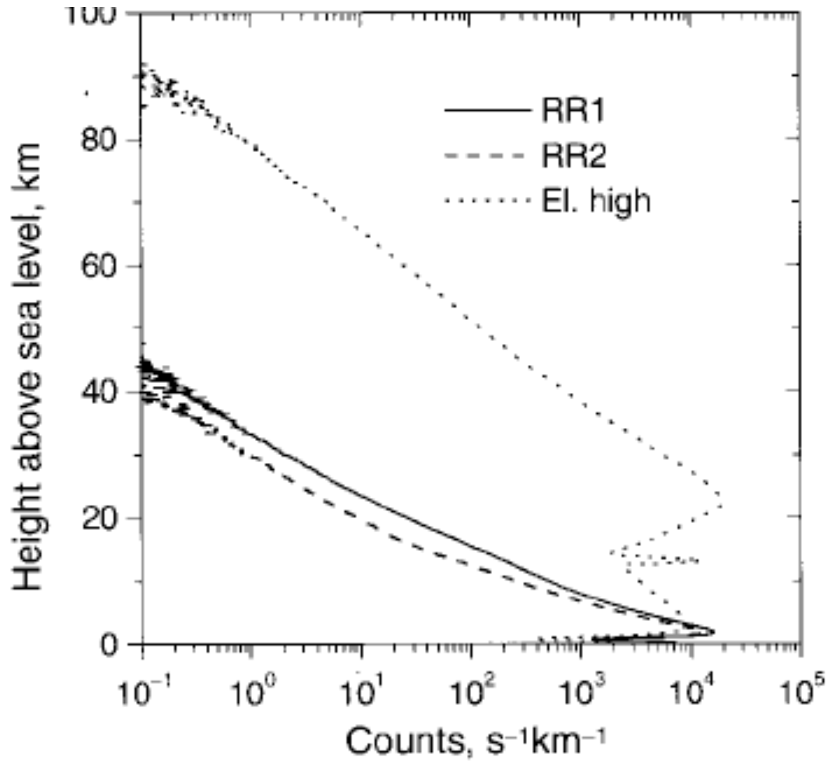


Fig. 10.11. Intensities of the RASC lidar signals for the temperature measurements: rotational Raman signals (RR1 and RR2) and high-altitude elastic signal (El. high). For this plot, 72 minutes (216,000 laser pulses) of nighttime lidar data were taken with a height resolution of 72 m, summed, the background 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 ~25 km and the signature of a cirrus cloud in ~13 km height.

Results from Combined RR and Elastic Scattering Lidar

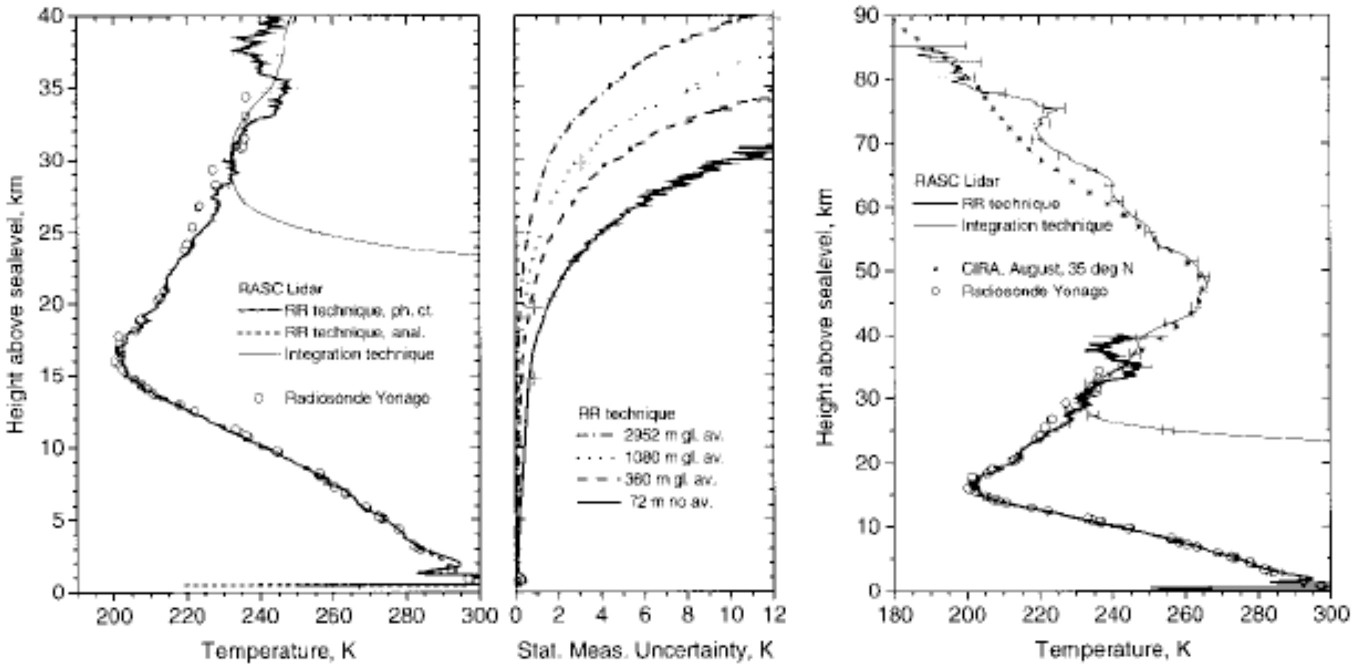


Fig. 10.12. Simultaneous temperature measurements with rotational Raman technique and with integration technique (signals see Fig. 10.11). Profiles of a climatological model atmosphere (CIRA-86 for 35°N and the month of the lidar measurements) and of a radiosonde are shown for comparison. Rotational 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 $1-\sigma$ statistical uncertainty of the measurements [48].

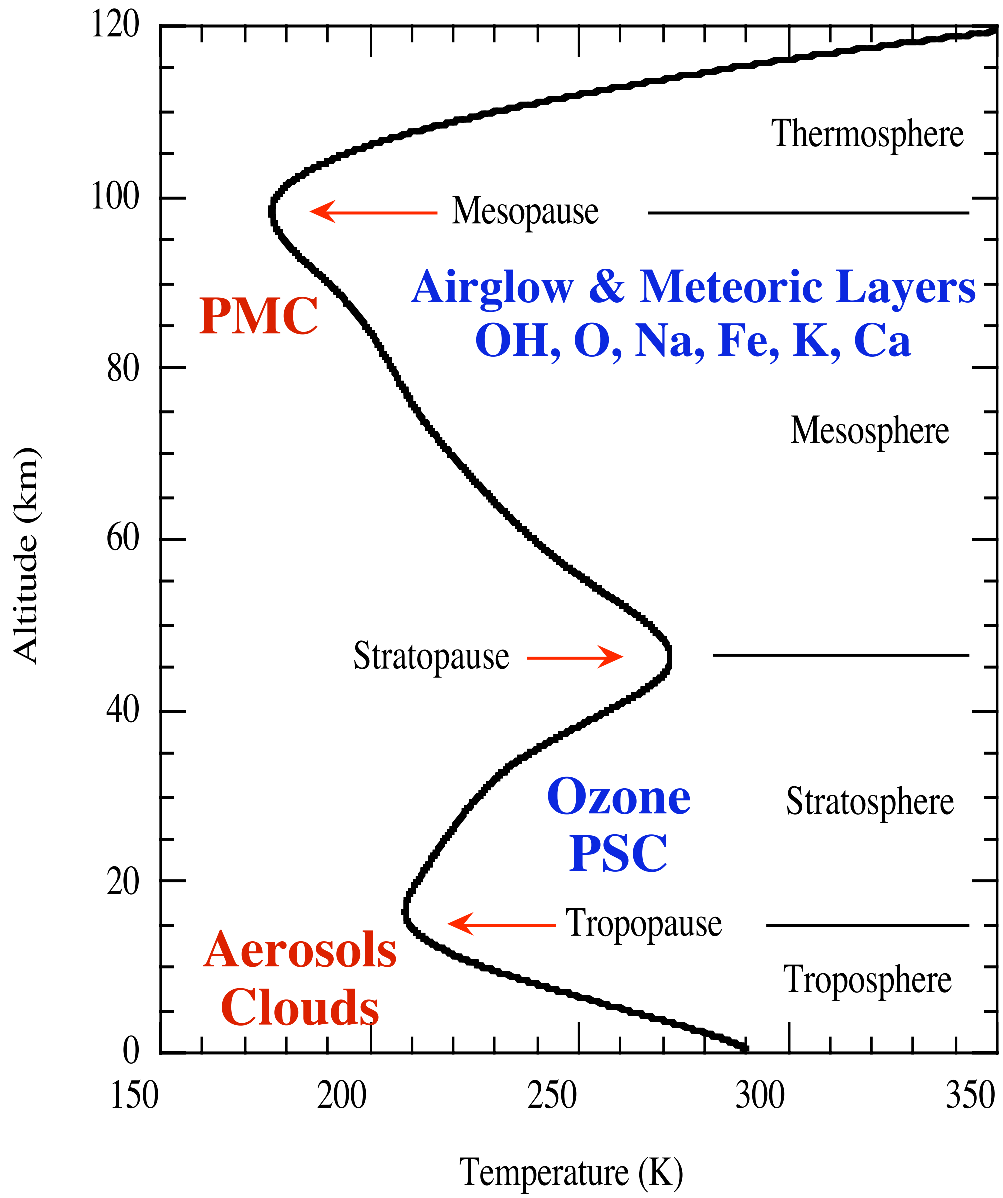
DIAL Temperature Technique

- 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_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

Technique	Lidars	Applications
Doppler Technique: temperature dependence of Doppler broadening (1 time Doppler shift and Doppler broadening for single absorption or emission process) (2 times Doppler shift and Doppler broadening for Rayleigh scattering)	Resonance fluorescence Doppler Lidar: Doppler broadening and Doppler shift of resonance fluorescence absorption cross-section (scan and ratio techs)	Mesosphere and Lower Thermosphere temperature and wind (75-120 km)
	Rayleigh Doppler Lidar : Doppler broadening of molecular scattering	Lower mesosphere, stratosphere and troposphere temperature and wind (up to 60 km)
	High-Spectral-Resolution Lidar: Doppler broadening of molecular scattering, ratio of two signals	Stratosphere and troposphere temperature and wind (up to 30 km)
Boltzmann Technique: temperature dependence of population ratio	Resonance fluorescence Boltzmann Temperature Lidar: population ratio on the lowest two ground states	Mesosphere and Lower Thermosphere temperature (75-120 km)
	Rotation Raman Temperature Lidar: ratio of two Raman line intensities and population on different initial energy states	Troposphere and stratosphere temperature
Integration Technique: hydrostatic equilibrium and ideal gas law	Rayleigh or Raman Integration Temp Lidar: atmospheric density ratio to temperature, integration from upper level	Stratosphere and mesosphere temperature (30-90 km) Troposphere temperature (< 30 km)
DIAL	Differential Absorption Lidar: Temp-dependence of line strength and lineshape	Boundary layer temperature

Temperature Lidar Techniques



- 75-120km: resonance fluorescence Doppler technique (Na, K, Fe) & Boltzmann technique (Fe, OH, O_2)
- 30-90km: Rayleigh integration technique & Rayleigh Doppler technique
- Below 30 km: scattering Doppler technique, HSRL, and Raman technique (Boltzmann and integration)
- Boundary layer: DIAL, HSRL, Rotational Raman

Summary

- Temperature-dependent and temperature-sensitive effects and phenomena are utilized in the temperature lidars to measure atmosphere temperatures.
- Resonance Fluorescence Doppler Technique
  (Na, K, and Fe Doppler lidars)
- Boltzmann Technique
  (Fe and N_2^+ Boltzmann lidars, imagers, Bomem mappers)
- Integration Technique
  (searchlight, Rayleigh & vibrational Raman lidars, falling sphere)
- Rayleigh Doppler Technique
  (Rayleigh Doppler lidar and high-spectral-resolution Lidar)
- Rotational Raman Technique
  (Rotational Raman lidar)
- Differential Absorption Technique
  (DIAL lidar)