Lecture 14. Temperature Lidar (4) Rayleigh Doppler Technique

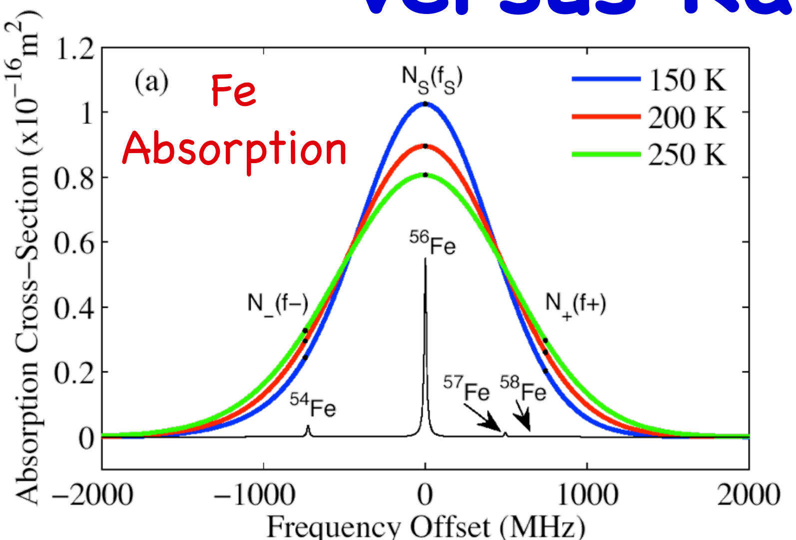
- Resonance fluorescence Doppler technique vs. Rayleigh Doppler technique
- Rayleigh Doppler lidar:
  Fringe Imaging vs. Edge-Filter
- High-spectral-resolution lidar using FPI
- High-spectral-resolution lidar using iodine filter
- Double-Edge Magneto-Optic Filter (DEMOF)
- Summary

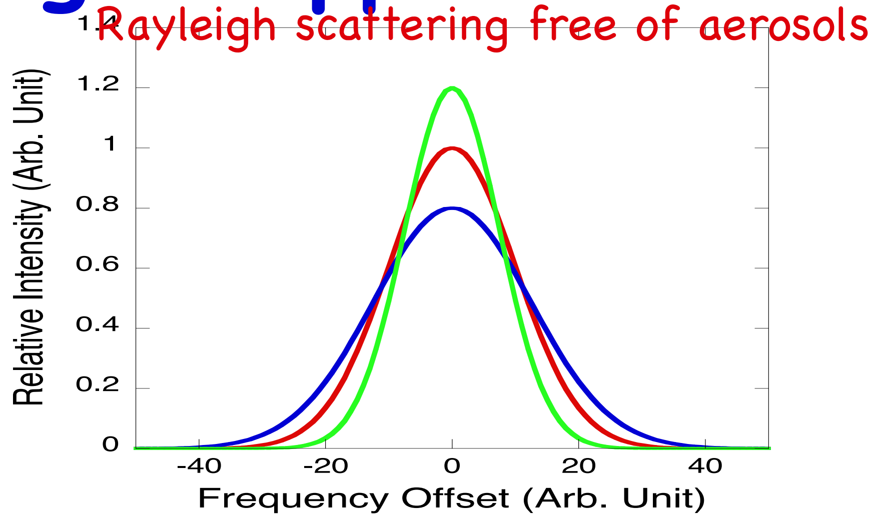
Resonance Fluorescence Doppler versus Rayleigh Doppler

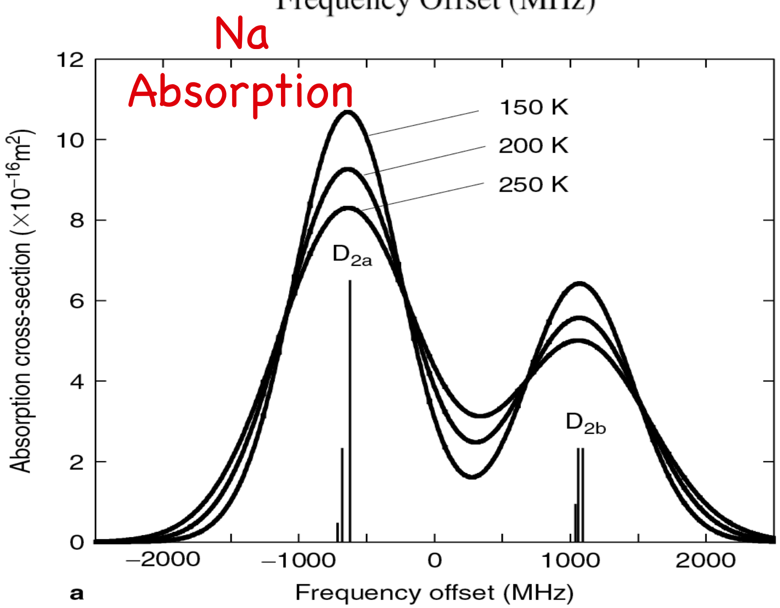
- Atomic absorption lines provide a natural frequency analyzer or frequency discrimination. This is because the absorption cross section undergoes Doppler shift and Doppler broadening. Thus, when a narrowband laser scans through the absorption lines, different absorption and fluorescence strength will 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. - Resonance fluorescence Doppler technique

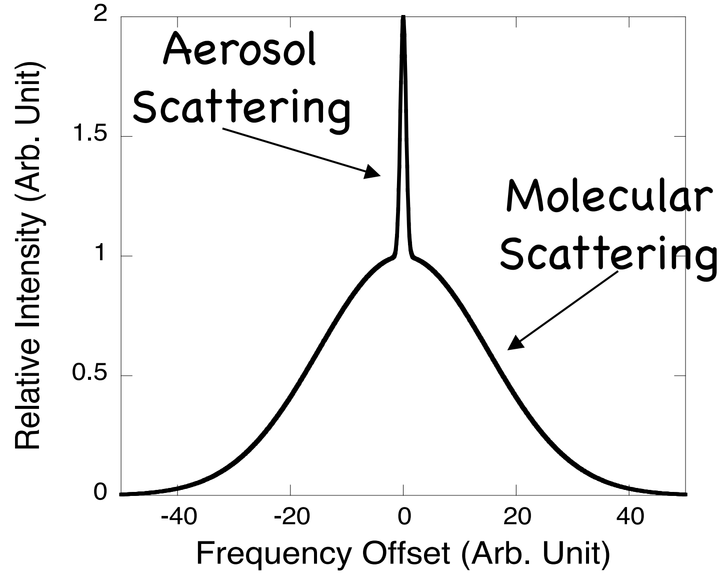
- Rayleigh scattering also undergoes Doppler shift and broadening, however, it is not frequency discriminated. In other words, when scanning a laser frequency, the backscattered Rayleigh signal gives nearly the same Doppler broadened line width, independent of laser frequency. Thus, the atmosphere molecule 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

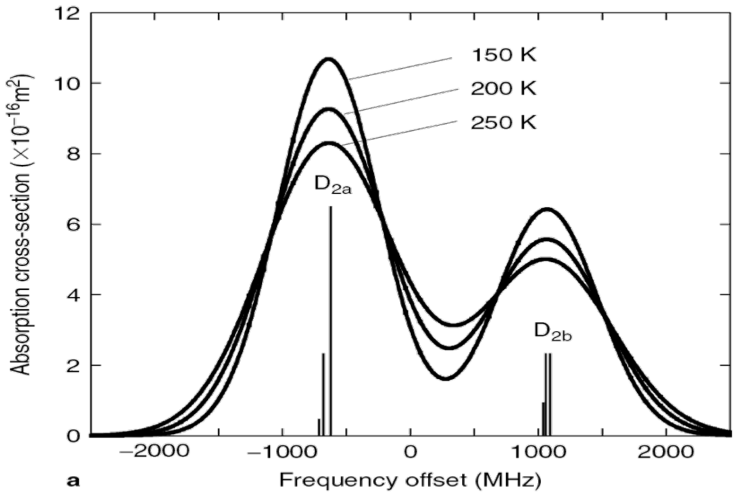


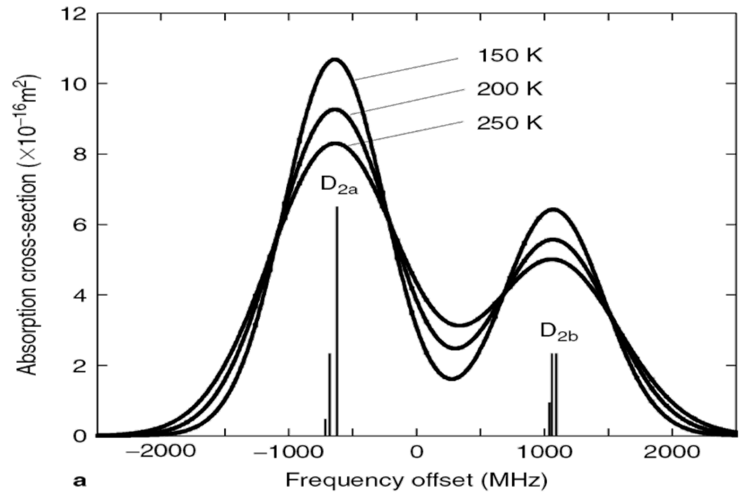


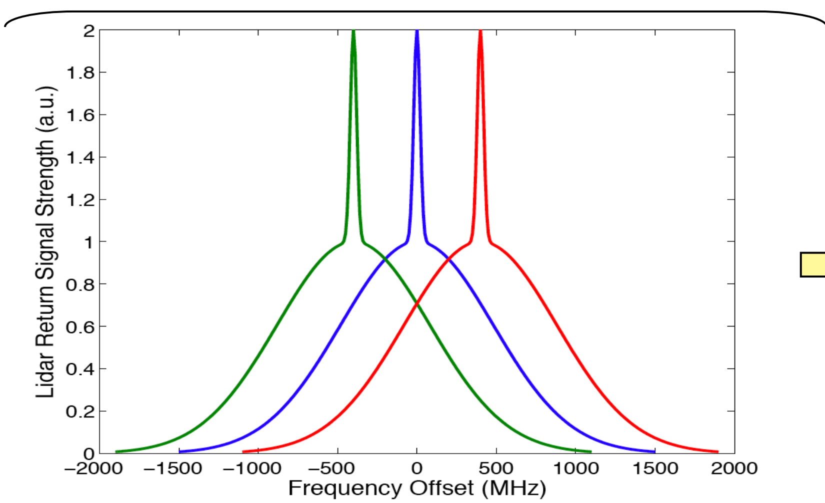


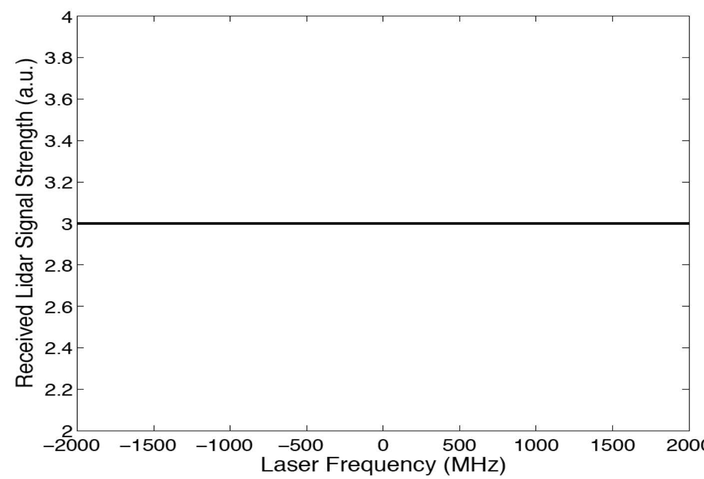


Resonance Fluorescence Doppler versus Rayleigh Doppler









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.

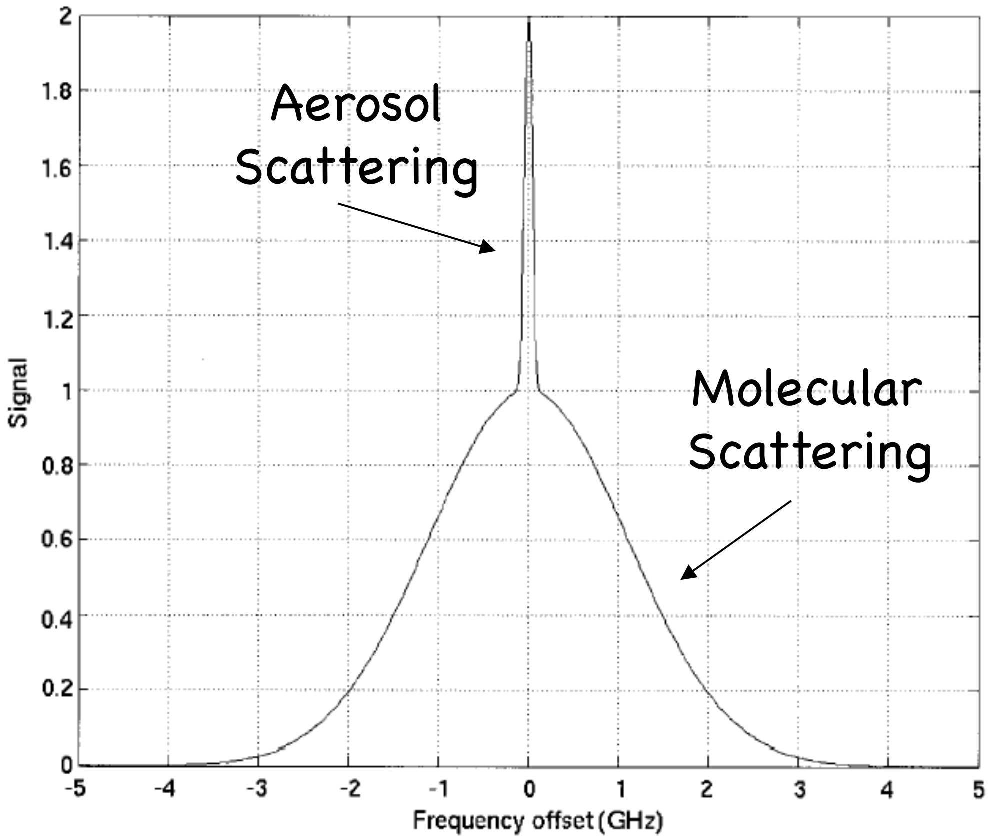


Fig. 5.1. Spectral profile of backscattering from a mixture of molecules and aerosols for a temperature of 300 K. The spectral width of the narrow aerosol return is normally determined by the line width of the transmitting laser.

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

Energy Conservation
$$\frac{1}{2}m v_1^2 + \hbar\omega_1 = \frac{1}{2}m v_2^2 + \hbar\omega_2$$

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

- 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

$$\omega = \omega_0 \left(1 - \frac{2v_R}{c}\right) \Rightarrow v_R = \frac{\omega_0 - \omega}{2\omega_0 / c} = \frac{\nu_0 - \nu}{2\nu_0 / c}$$

- 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,

$$I \propto \exp\left(-\frac{M(\nu_0 - \nu)^2}{2k_B T (2\nu_0 / c)^2}\right)(c / 2\nu_0) d\nu$$

- Therefore, the rms width of the Doppler broadening is

$$\sigma_{rms} = 2\nu_0 / c \sqrt{k_B T / M} = \frac{2}{\lambda_0}\sqrt{k_B T / M}$$

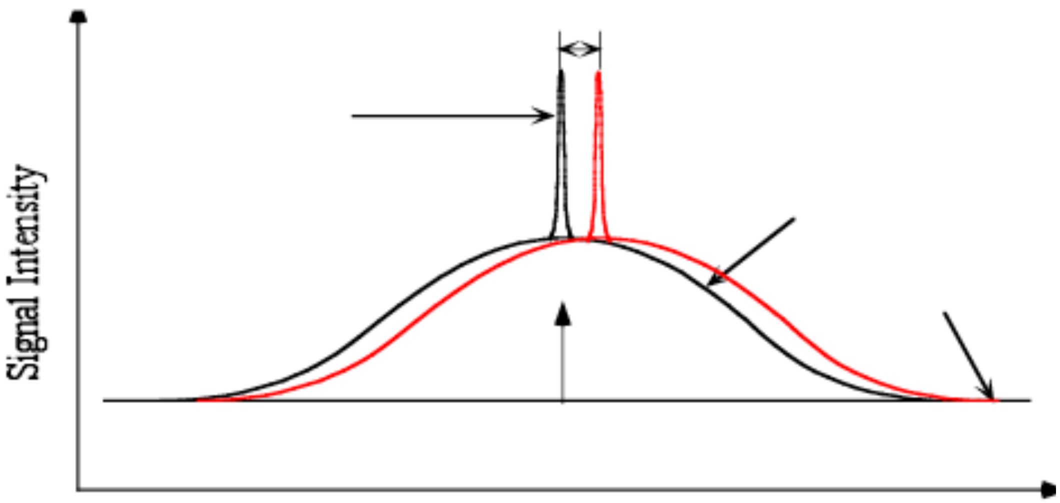
2 times !

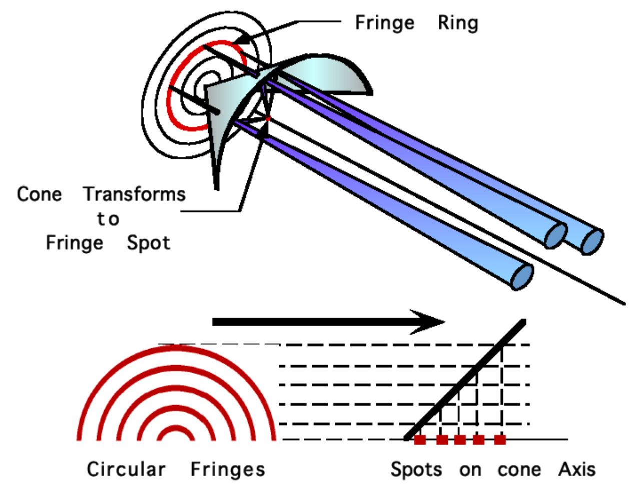
Rayleigh Doppler Lidar

- Below MLT region, there is no resonance fluorescence but pure molecular scattering or "molecular + aerosol" scattering.
- Since the Rayleigh scattering spectral width has sensitive dependence on temperature, it is possible to measure this Rayleigh spectral width to derive the atmosphere temperature.
- On the other hand, the aerosols are much heavier than the air molecules, so the Doppler broadening of aerosol scattering is negligible but dominated by the laser linewidth itself. Therefore, aerosol scattering cannot be used to measure temperature, but it is a good tracer for wind measurements.
- 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

- Fringe imaging is to use high resolution Fabry-Perot etalon to image the lidar returns, i.e., turn spectral distribution to spatial distribution.
- Fringe width is used to derive temperature

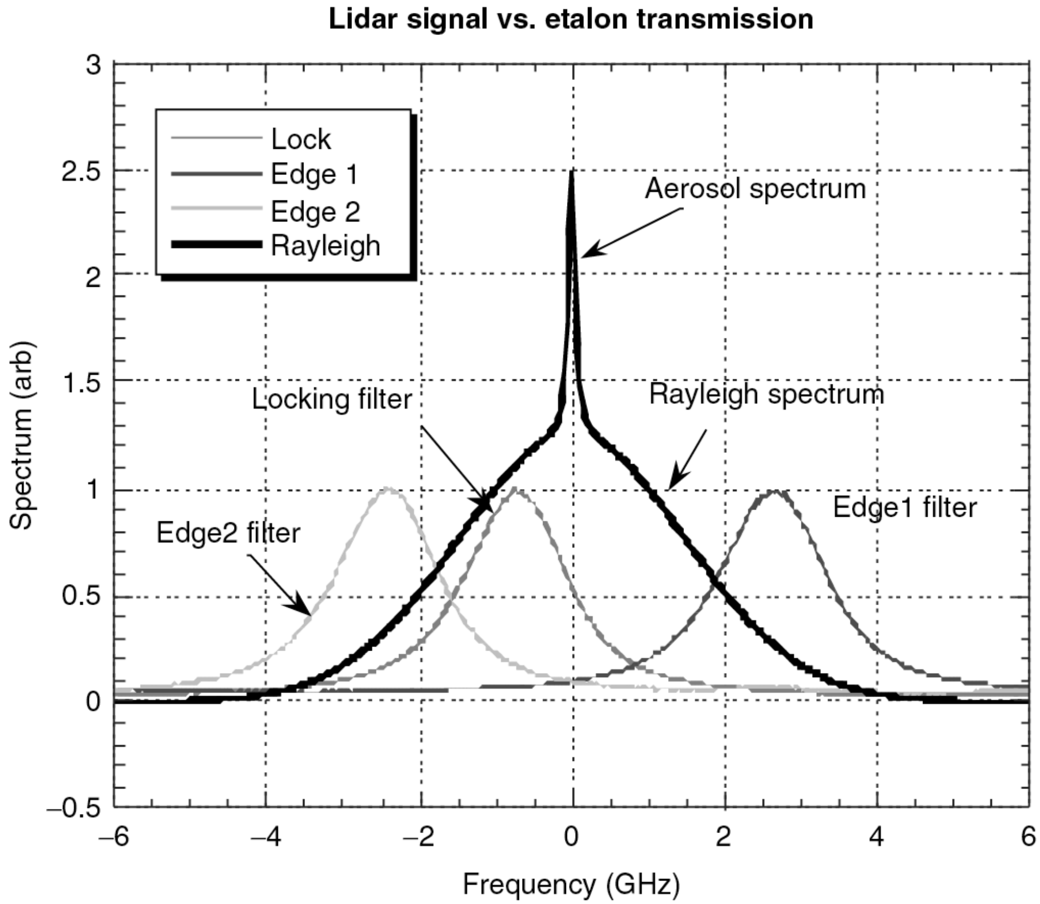




- Diameters of the circles give the Doppler shift when compared with a known wavelength fringe, while the fringe width is an indication of Rayleigh temperature.
- Current issues: suffer low signal levels above 50 km because of decreasing atmospheric density and "waste" of photons in fringes.

Edge Filter

- 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 passing 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.

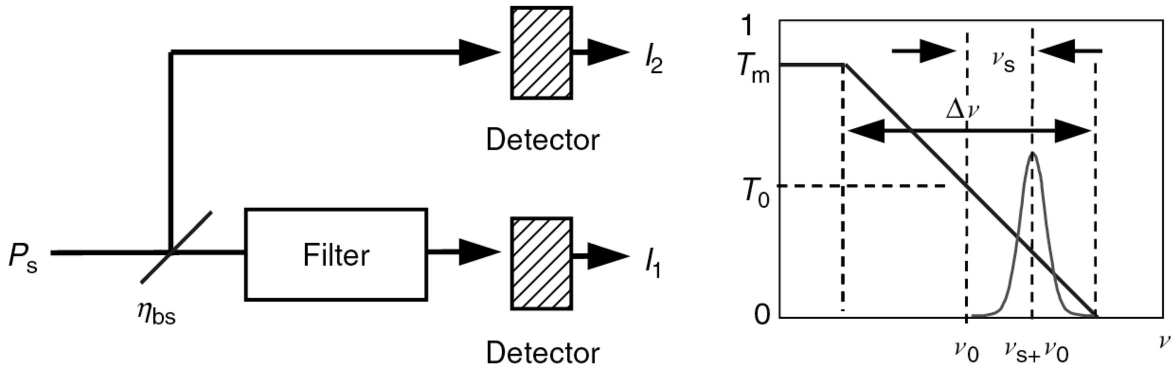


$$\frac{N_1}{N_2} = \frac{\xi_1 f_{m1}(T, P, V_R)}{\xi_2 f_{m2}(T, P, V_R)}$$

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

Single-Edge vs. Double-Edge

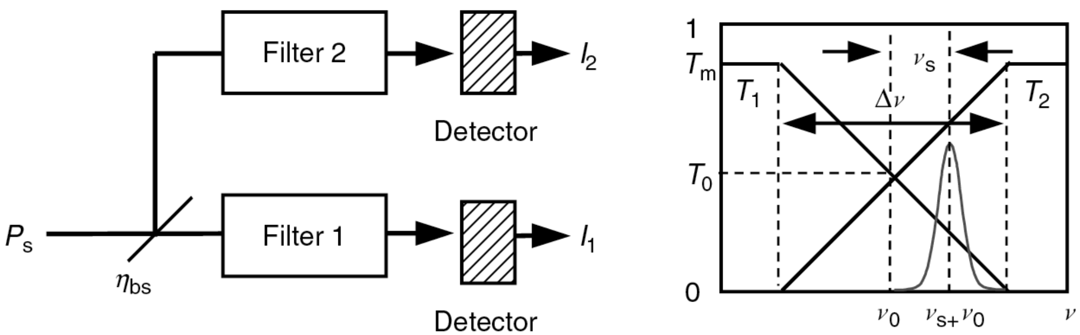
- Edge filter has single-edge and double-edge filters. See our textbook Chapter 7 "Wind Lidar" Direct-Detection Lidar.



$$S = I_1/I_2 = \frac{\eta_{bs}}{(1-\eta_{bs})}\frac{\Re_1}{\Re_2}T_s$$

$$= \frac{\eta_{bs}}{(1-\eta_{bs})}\frac{\Re_1}{\Re_2}(T_0 - T_m\nu_s/\Delta\nu)$$

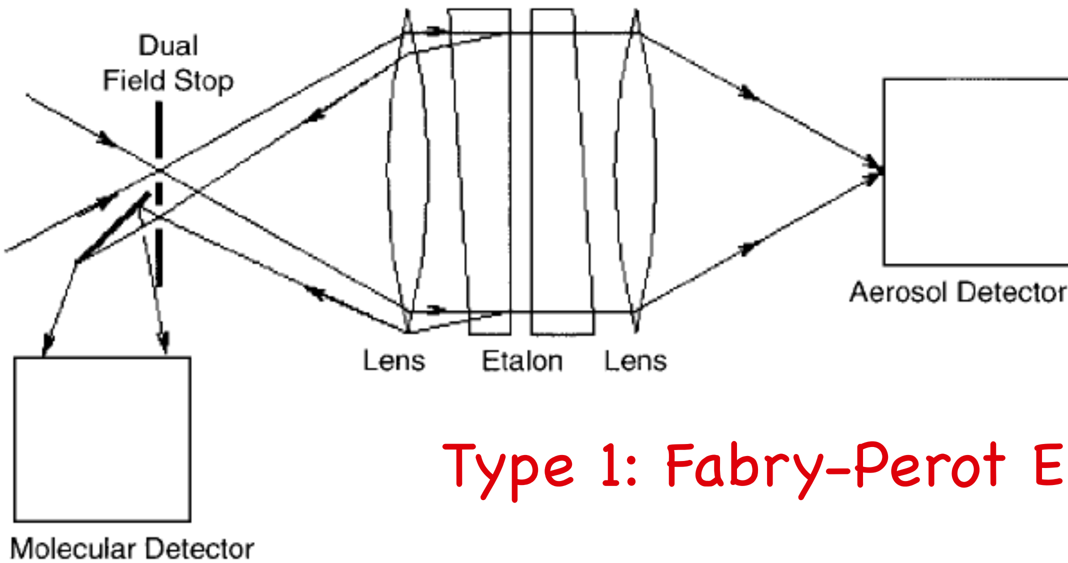
Figure 7.31 Single-edge functional diagram and filter transmission.



$$S = \frac{I_\Delta}{I_\Sigma} = \frac{I_1 - I_2}{I_1 + I_2} = \frac{T_{s_1} - T_{s_2}}{T_{s_1} + T_{s_2}} = \frac{2\nu_s}{\Delta\nu}$$

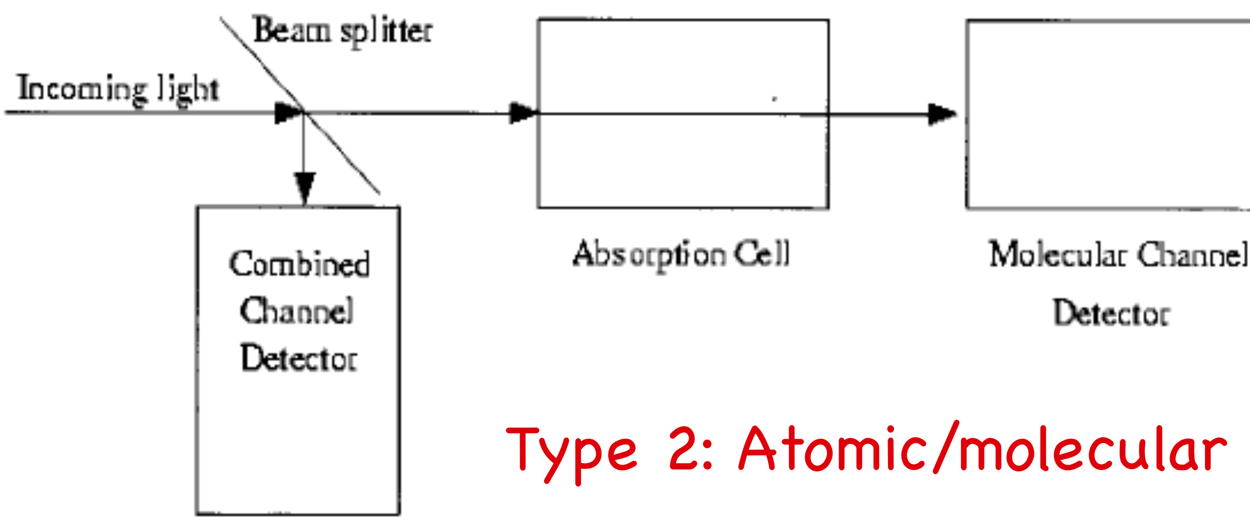
Figure 7.32 Double-edge functional diagram and filter transmission.

High Spectral Resolution Lidar



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

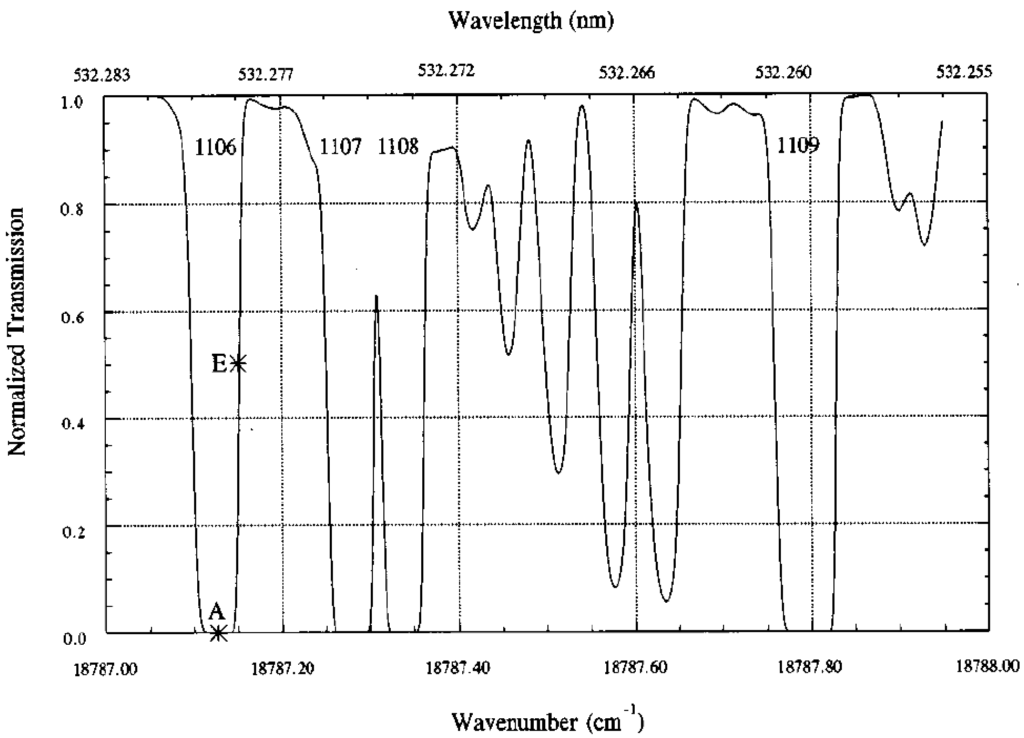
Type 1: Fabry-Perot Etalon/Interferometer

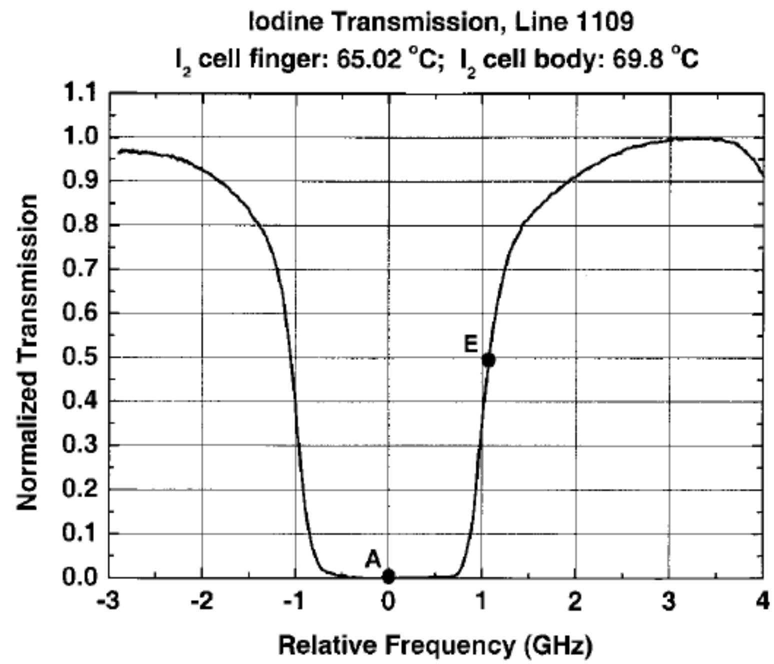


Atomic or molecular absorption block the aerosol scattering

Type 2: Atomic/molecular blocking filter

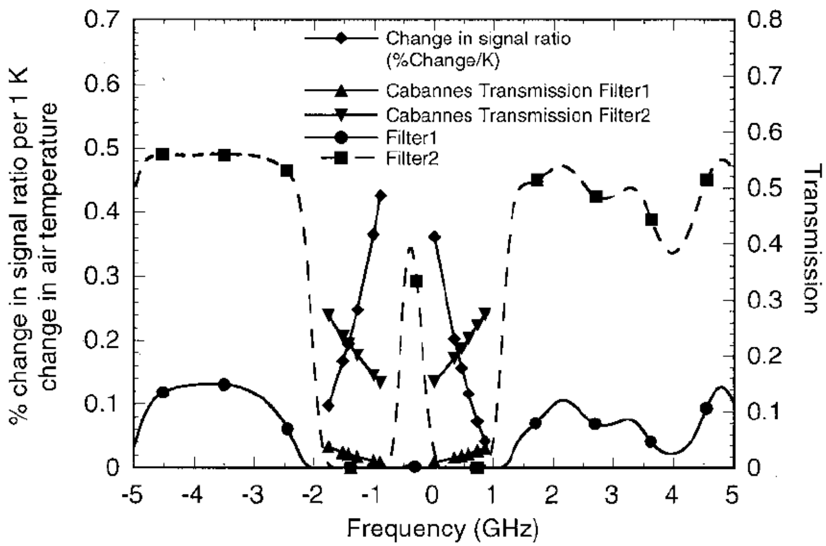
Iodine Filter Using I_2 Absorption Lines

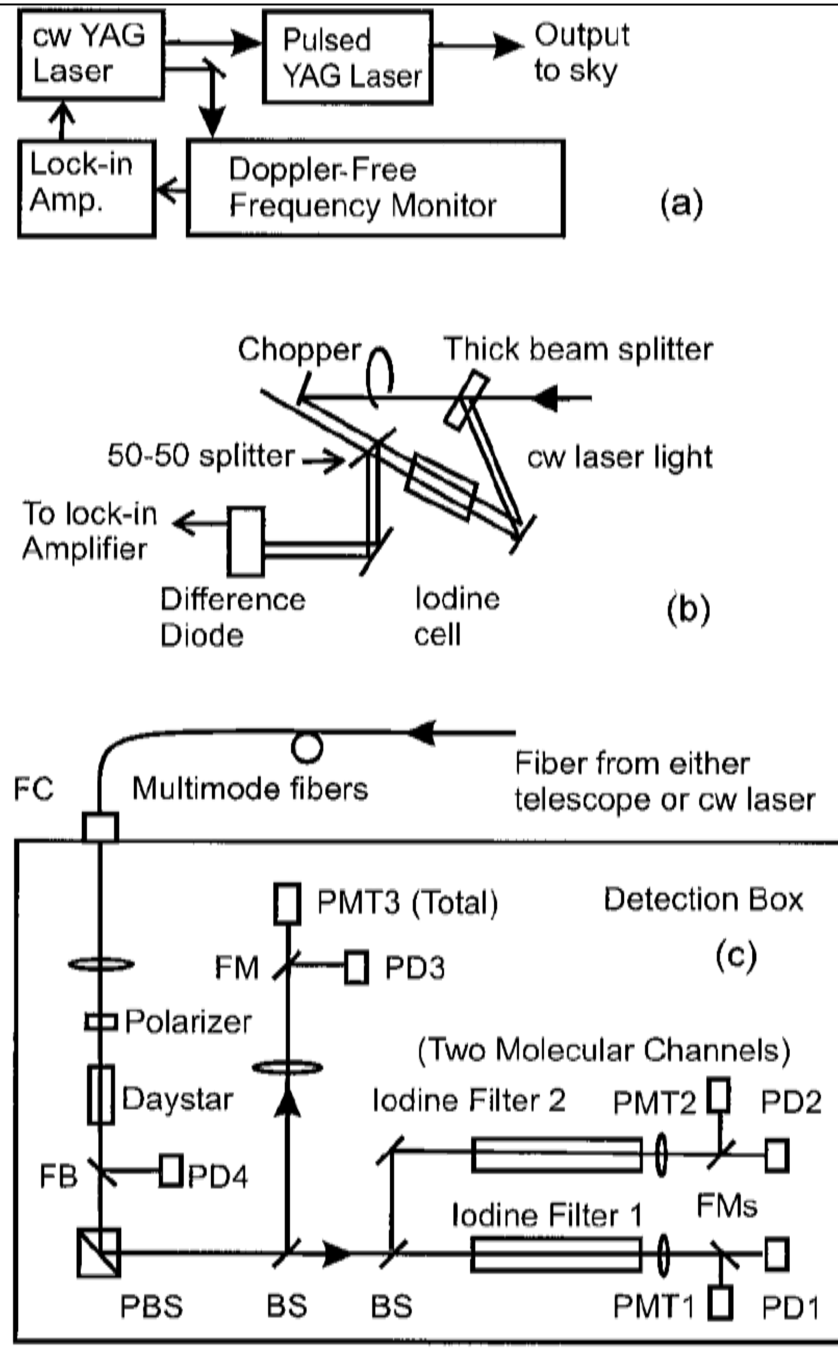




[Liu et al., Appl. Phys. B 64, 561-566, 1997]
[Friedman et al., Opt. Lett., 22, 1648-1650, 1997]
[Liu et al., Appl. Opt., 41, 7079-7086, 2002]
[Wang et al., Applied Optics, 49, 6960-6978, 2010]

HSRL Using I_2 Filter



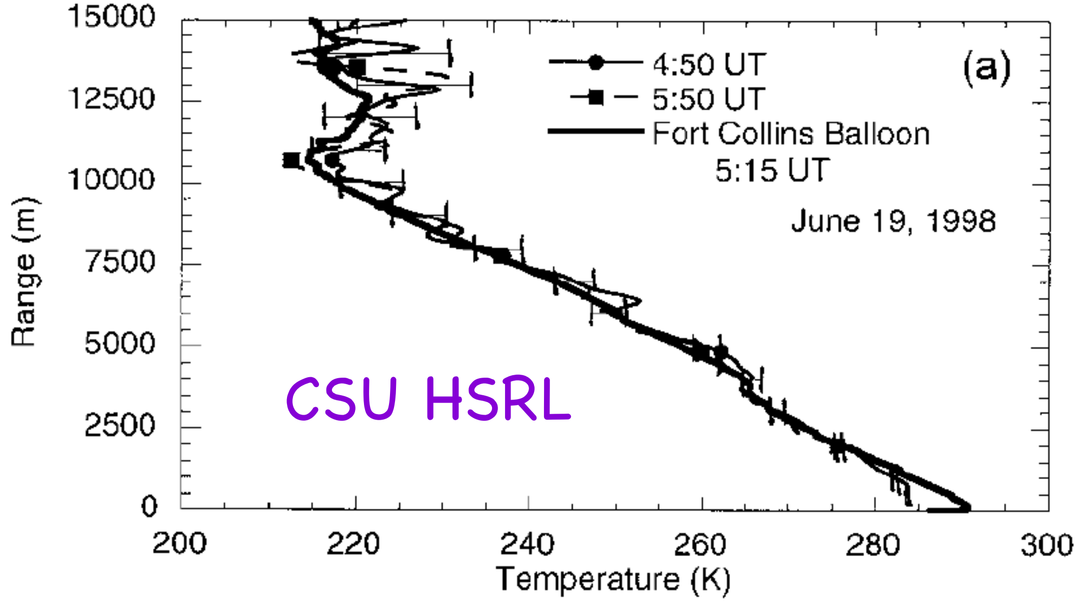


CSU HSRL
[Hair et al., Applied Optics, 40, 5280-5294, 2001]

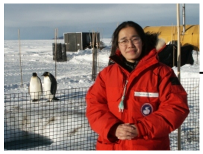
HSRL Temperature Measurements

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

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

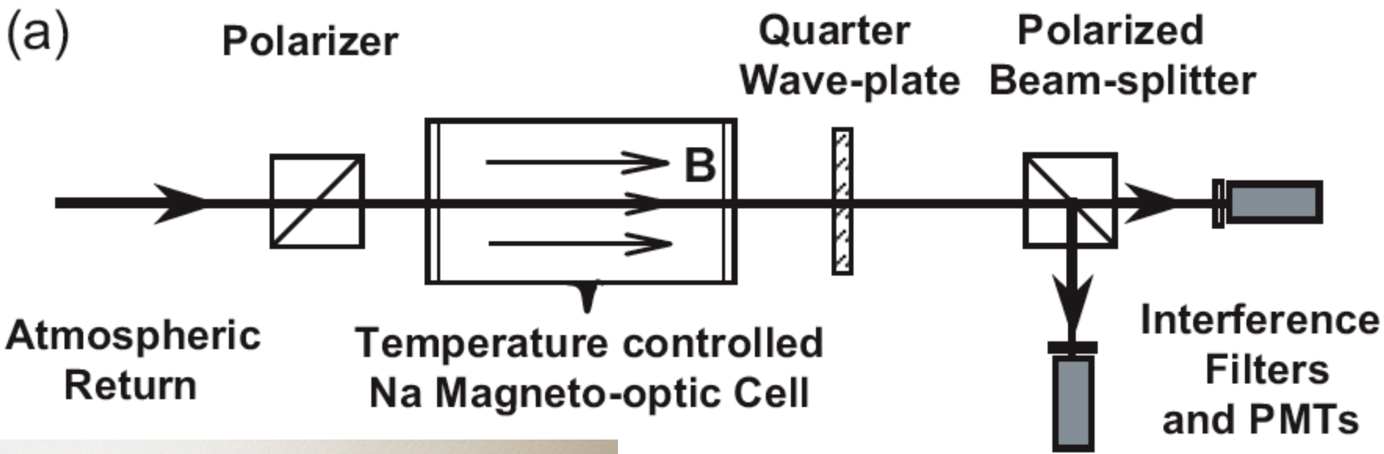


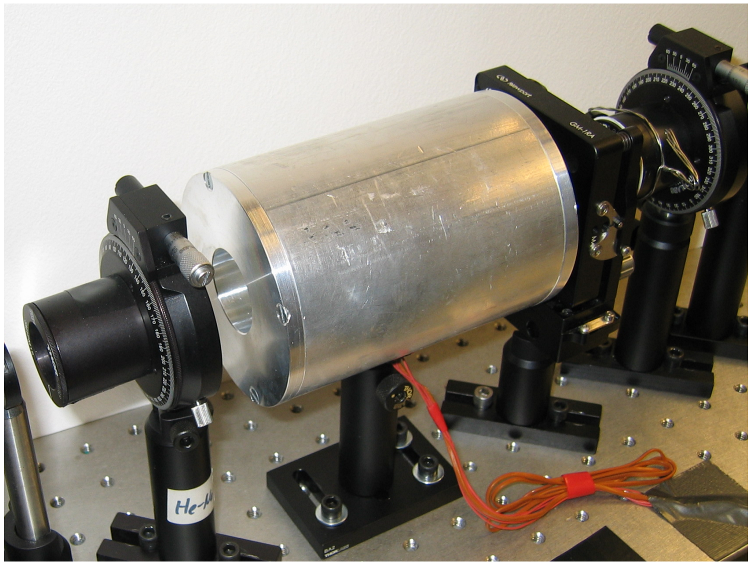
- Majority of the Rayleigh scattering is filtered out!



Na-DEMOF for Na Lidar Profiling of Temperature & Wind in Lower ATM

- Na Double-Edge Magneto-Optic Filter (Na-DEMOF) Setup

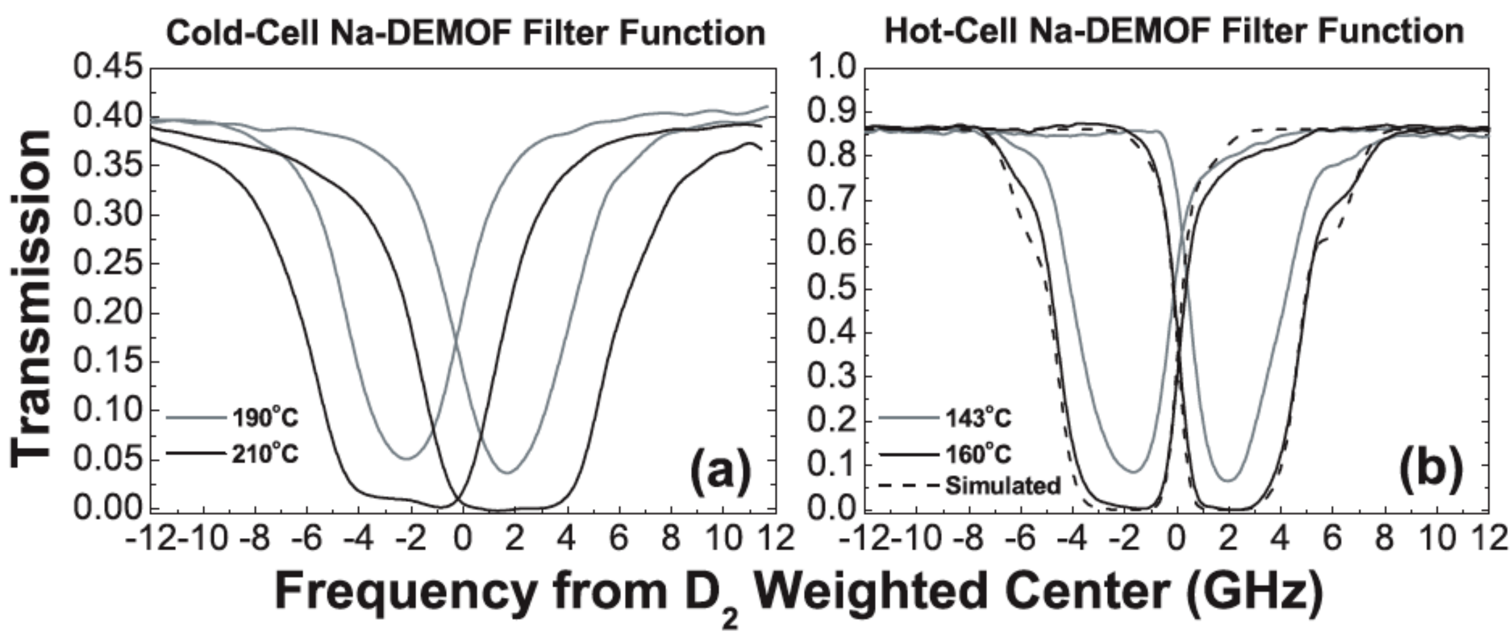


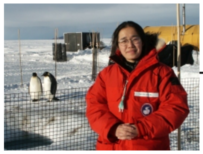


[Huang, Chu, Williams, et al., Optics Letters, 34, pp.199, 2009]

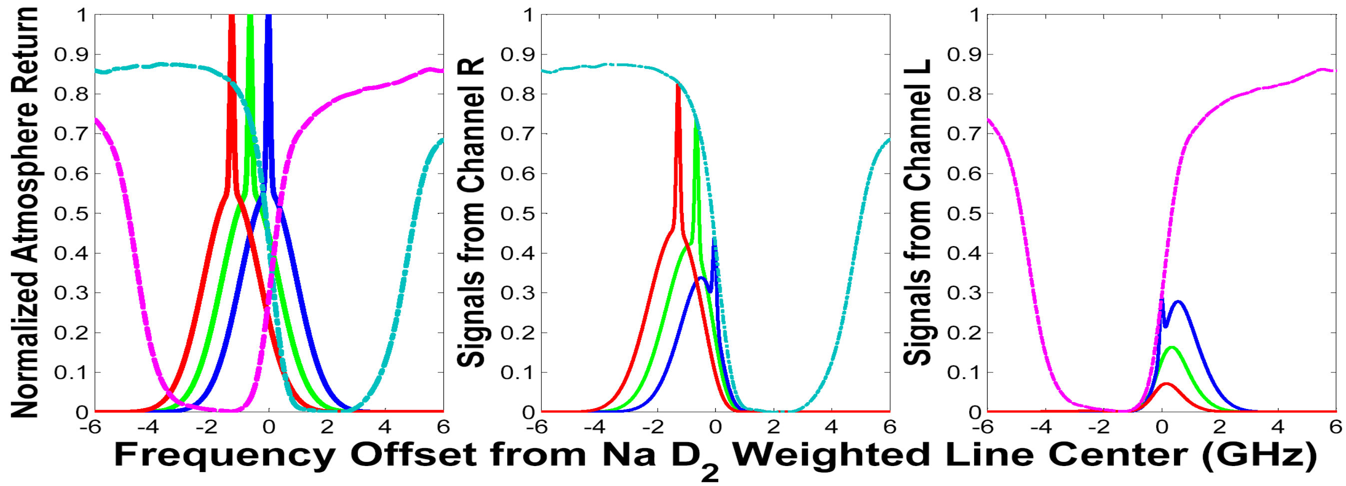
DEMOF vs. Faraday Filter

- Faraday Filter utilizes the anomalous dispersion while DEMOF uses the absorption of Na resonance.
- The Na-DEMOF is solely based on the different Na absorptions to circularly polarized light under the influence of a magnetic field, and then followed by polarization analysis with a quarter wave-plate and a polarized beam-splitter.
- The hot-cell filter exhibits superior performance over the cold-cell filter, per our laboratory tests.





DEMOF with a 3-freq Na Doppler Lidar

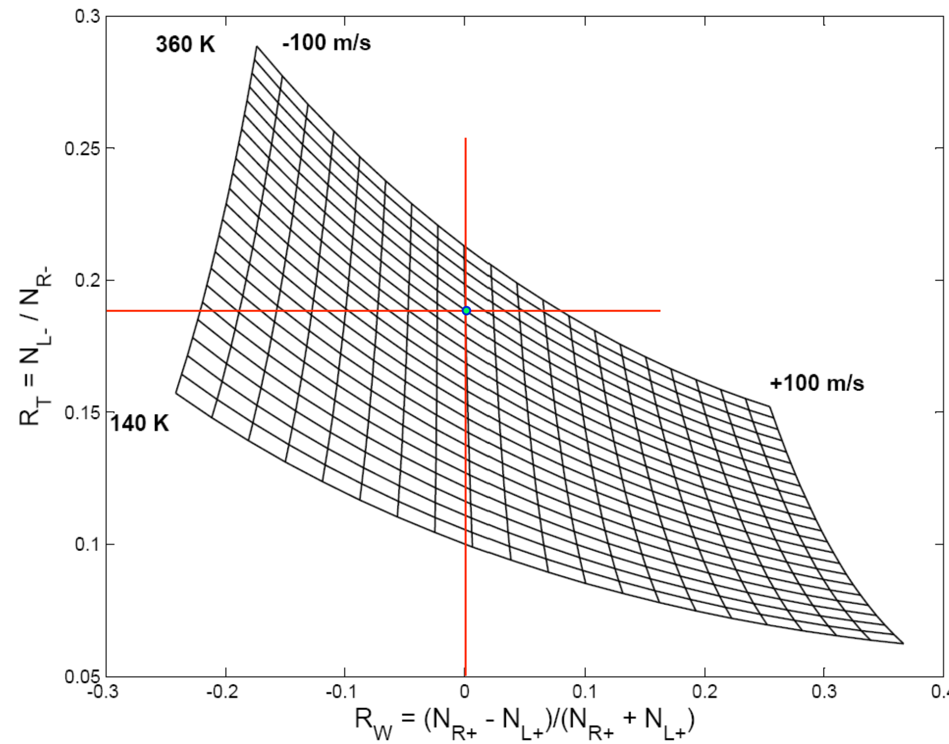


Calibration curves for ratio technique with Na-DEMOF

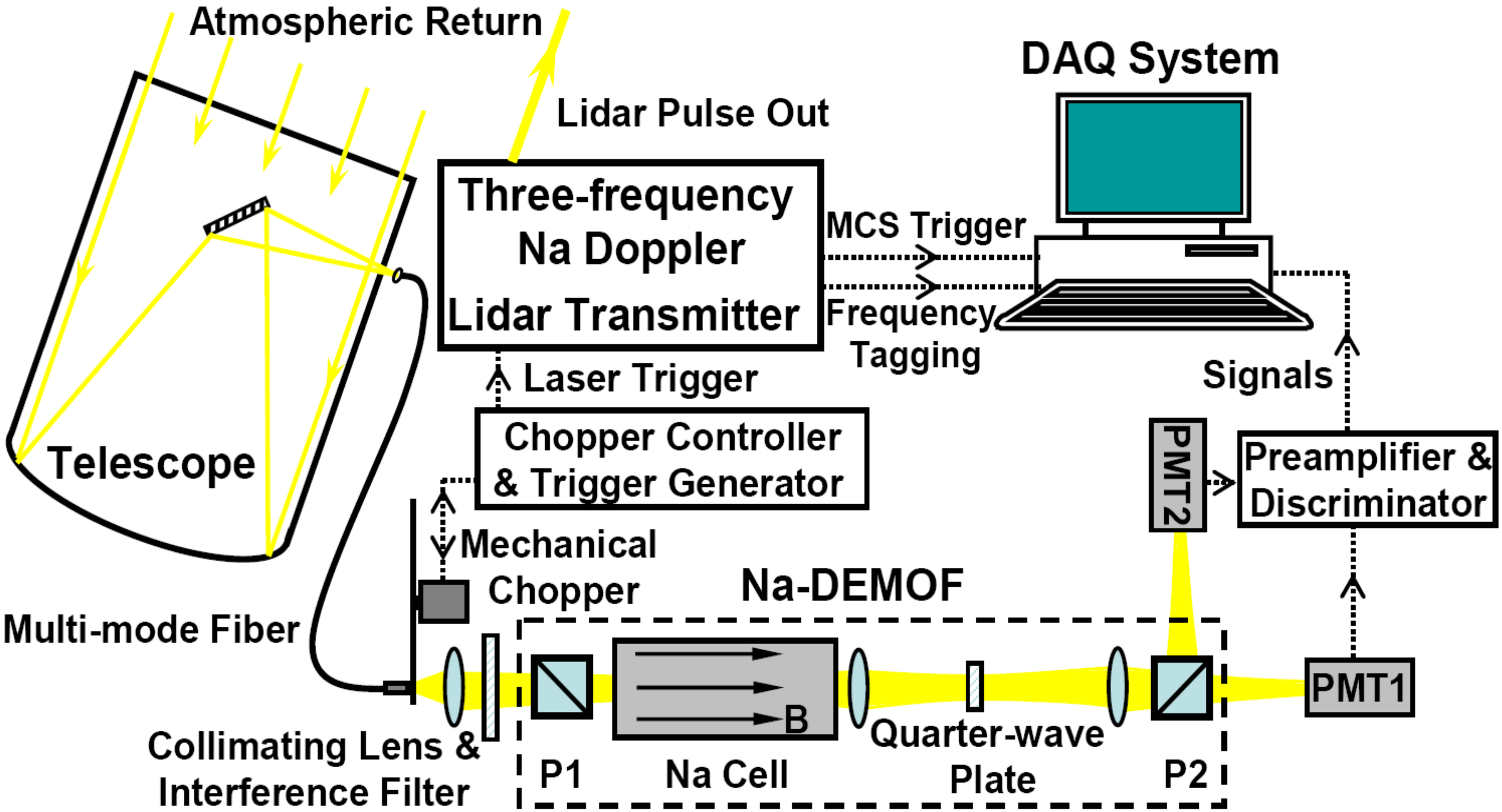
$$R_W(V_{LOS},T,R_b) = \frac{N_{R+} - N_{L+}}{N_{R+} + N_{L+}}$$

$$R_T(V_{LOS},T,R_b) = \frac{N_{L-}}{N_{R-}}$$

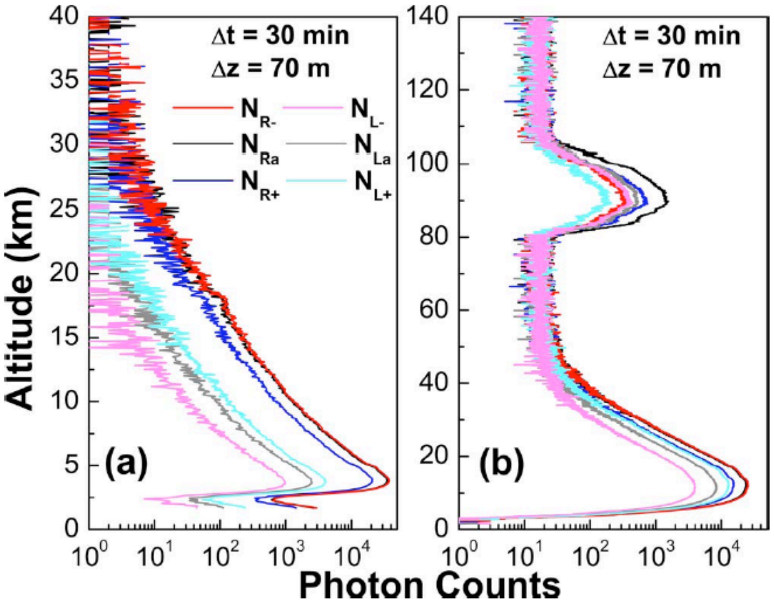
- Temperature and wind are determined simultaneously from two ratios.

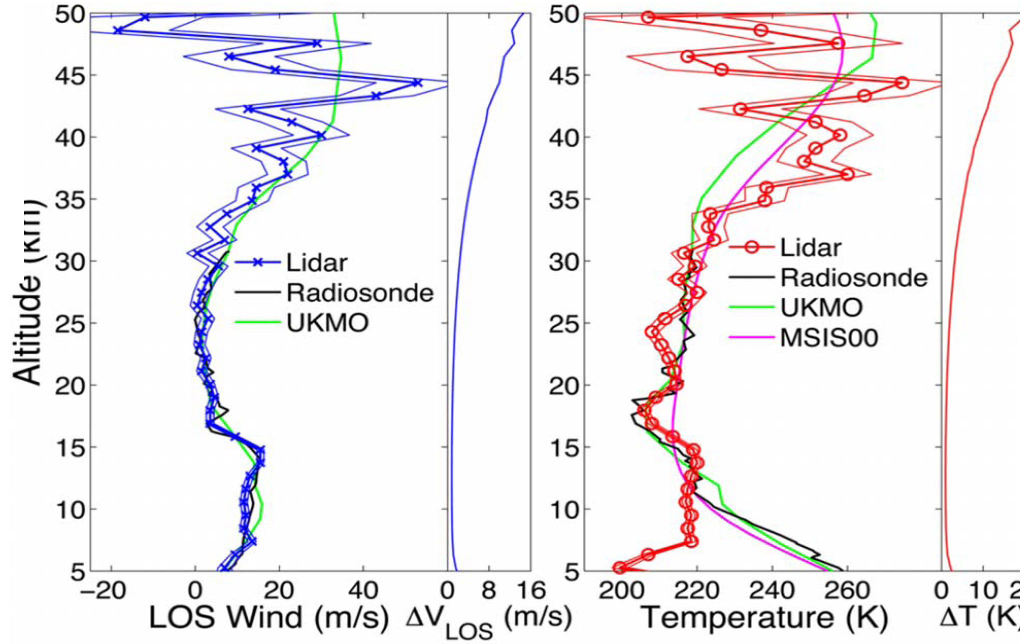


Field Demonstration of Simultaneous Wind and Temperature Measurements (10-45 km) with Na-DEMOF and 3-Frequency Na Lidar



Field Demonstration of Simultaneous Wind and Temperature Measurements (10-45 km) with Na-DEMOF and 3-Frequency Na Lidar

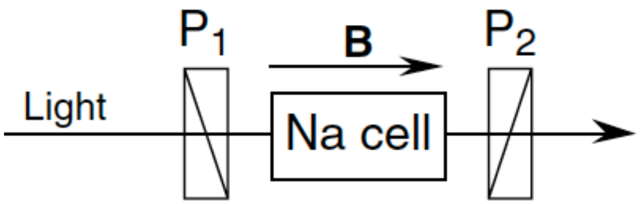




[Huang, Chu, et al., Optics Letters, 34, pp. 1552, 2009]

Faraday Filter and Doppler-Free

Na Faraday Filter



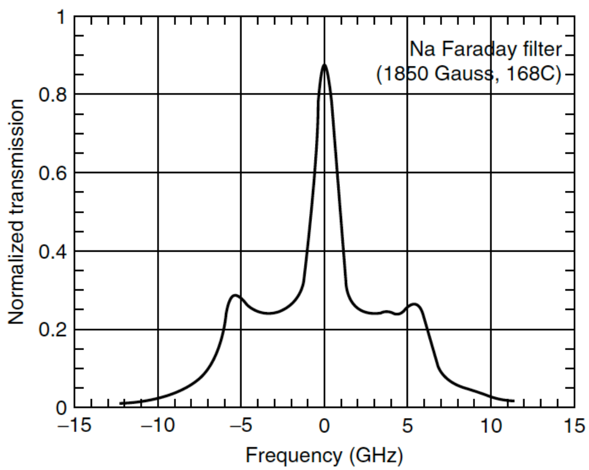
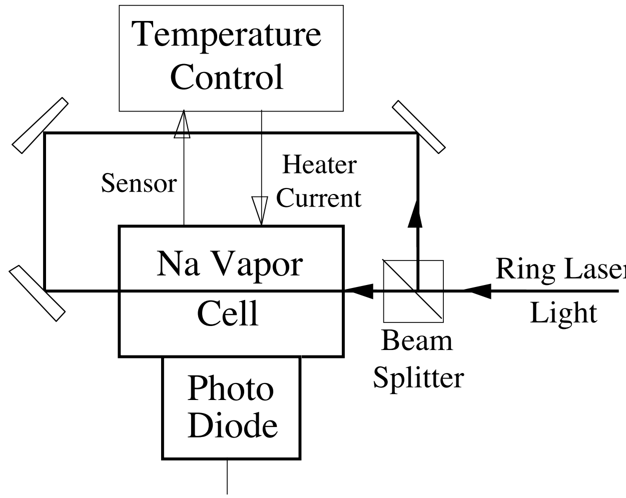
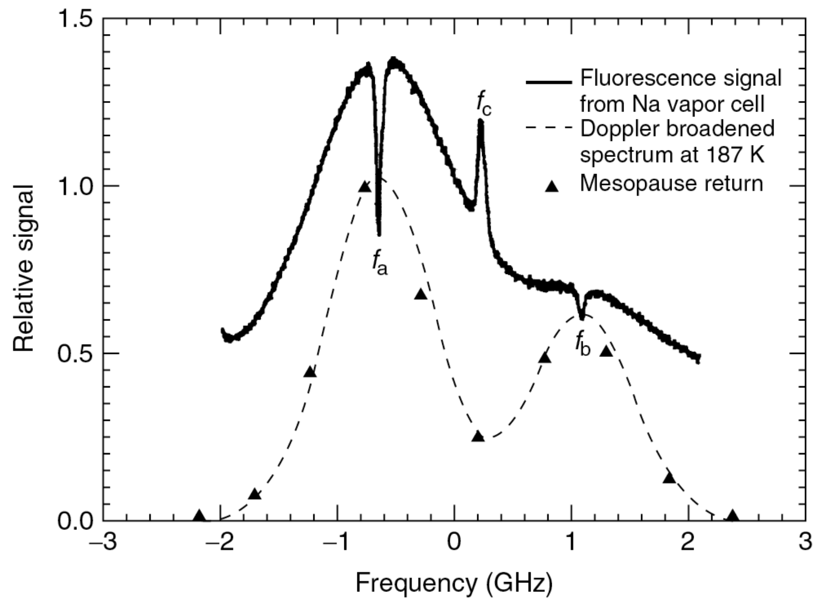


Figure 5.16 Normalized transmission curve of a CSU Na lidar Faraday filter. (From Arnold, K.S., and She, C.Y., *Contemp. Phys.*, 44, 35–49, 2003. With permission.)





Summary

- Utilizing the Doppler broadening of molecular scattering to measure the atmosphere temperature is a technique suitable for the range below MLT region when resonance fluorescence is not available. It is called Rayleigh Doppler lidar or high-spectral-resolution lidar.
- Narrowband spectral filter must be implemented in the lidar receiver to discriminate the Rayleigh spectral width.
- Fringe imaging and edge-filter are the two main techniques in Rayleigh Doppler lidar, but both face the problem of "photon waste". Most of these filters are good at wind, rather temperature, measurements.
- Edge filters continue progressing, including Fabry-Perot etalons, molecular filters like iodine filter, and atomic filters like Na-DEMOF or K-DEMOF.