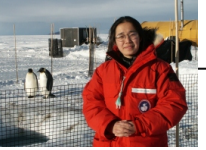
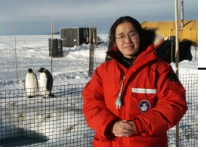


Lecture 19. Temperature Lidar (8) Rayleigh Doppler, HSRL & DIAL Tech

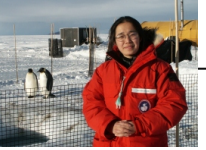
- Resonance-Doppler vs. Rayleigh-Doppler
- Rayleigh Doppler Lidar:
  - Fringe Imaging vs. Edge-Filter
  - 3-frequency Na-DEMOF lidar
- High-Spectral-Resolution Lidar
  - HSRL using FPI
  - HSRL using iodine filter
- Complication by Rayleigh-Brillouin Scattering
- DIAL Temperature Technique
- Summary



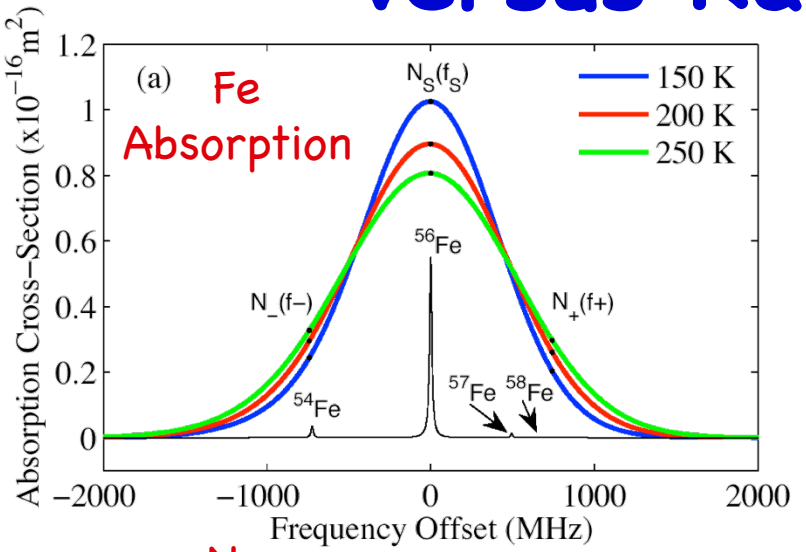
Recall "Resonance-Doppler vs. Rayleigh-Doppler Techniques"

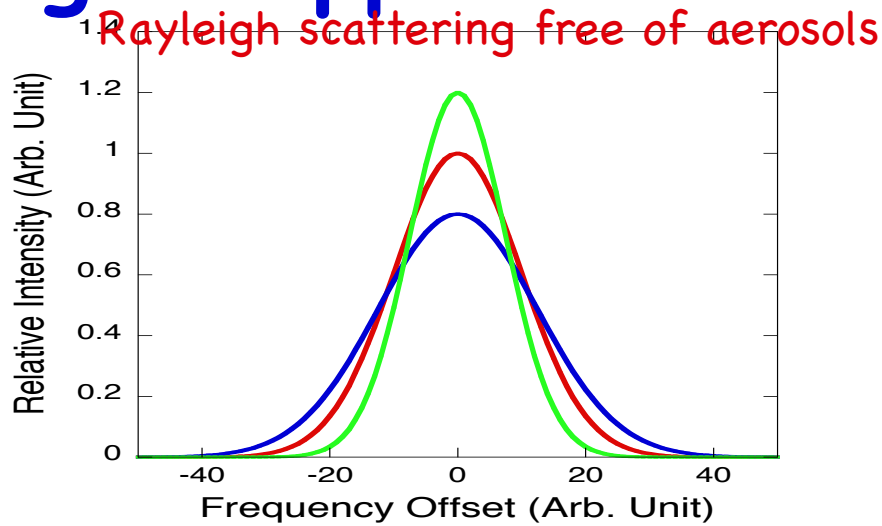
- Atomic absorption lines provide a natural frequency analyzer or frequency discrimination. This is because the absorption cross section undergoes Doppler shift and Doppler broadening. Thus, when a narrowband laser scans through the absorption lines, different absorption and fluorescence strength will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

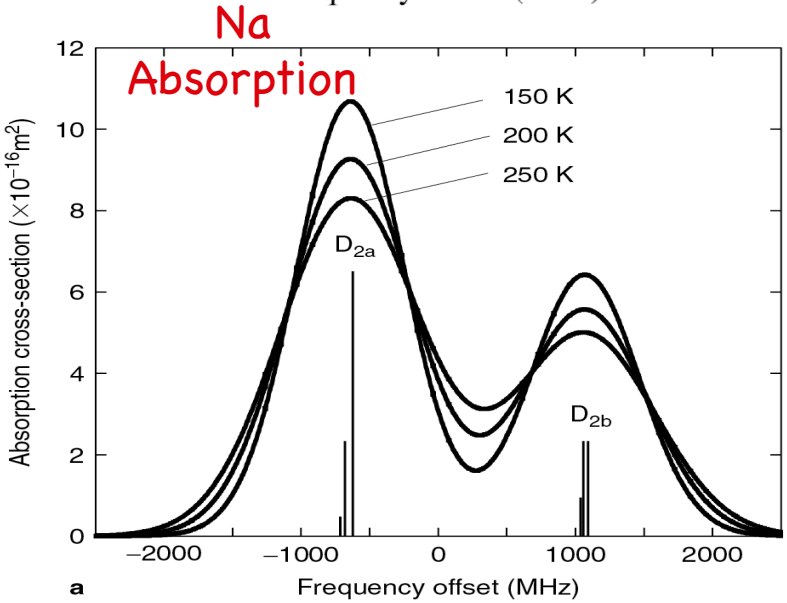
- Rayleigh scattering also undergoes Doppler shift and broadening, however, it is not frequency discriminated. In other words, when scanning a laser frequency, the backscattered Rayleigh signal gives nearly the same Doppler broadened line width, independent of laser frequency. Thus, the atmosphere molecule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

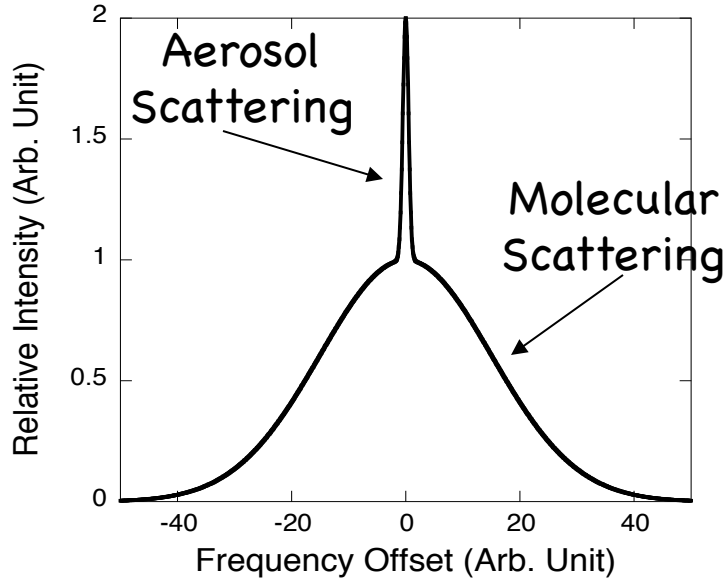


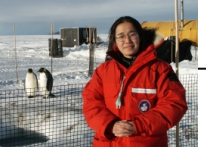
Resonance Fluorescence Doppler versus Rayleigh Doppler



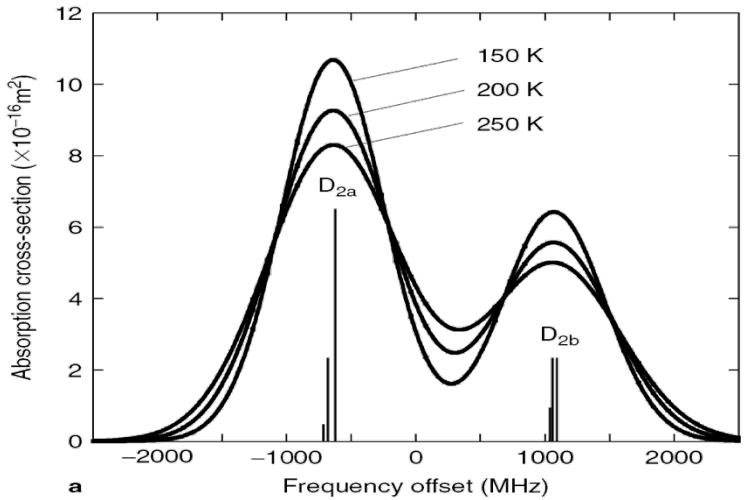


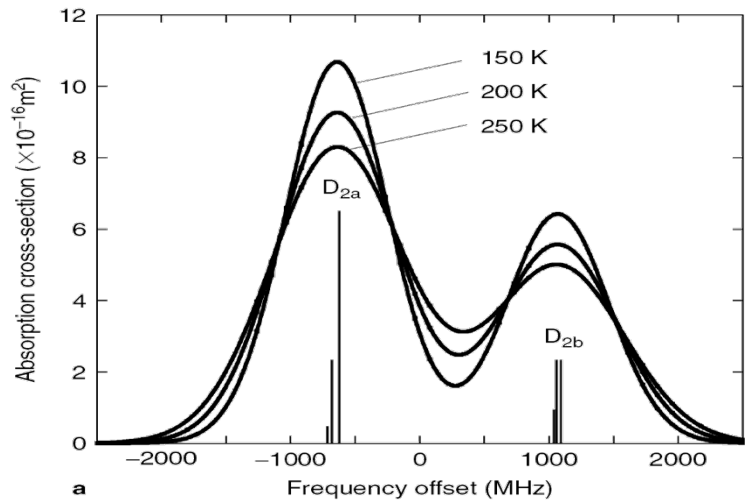


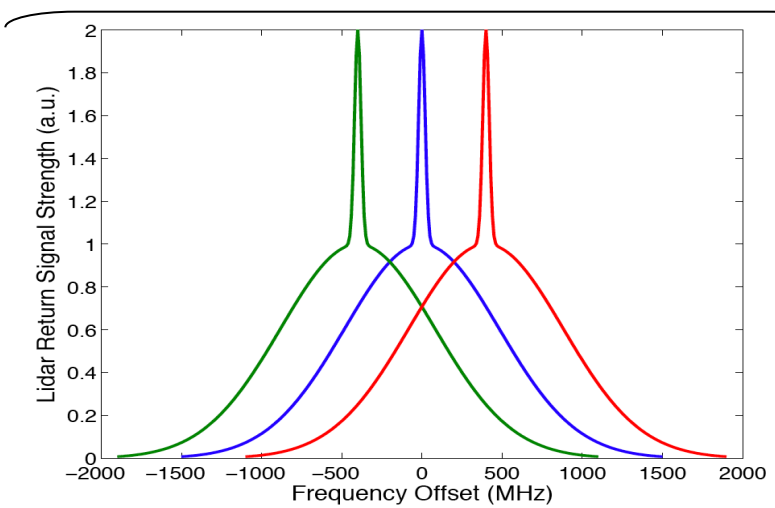


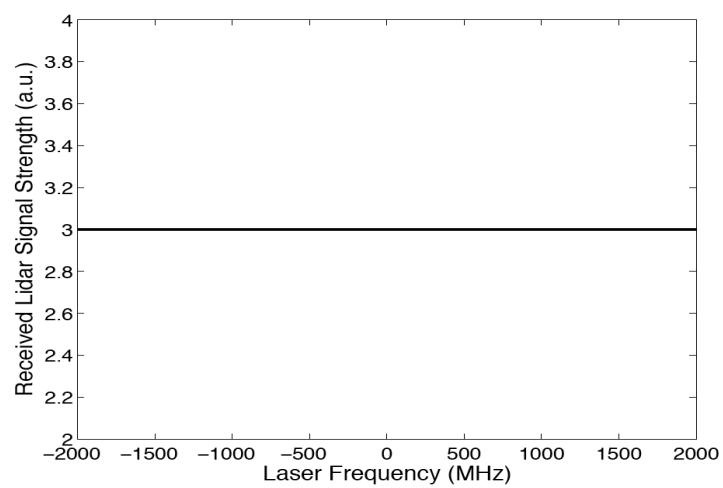


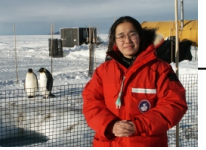
Resonance Fluorescence Doppler versus Rayleigh Doppler





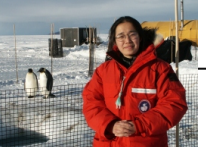






Rayleigh Doppler Lidar

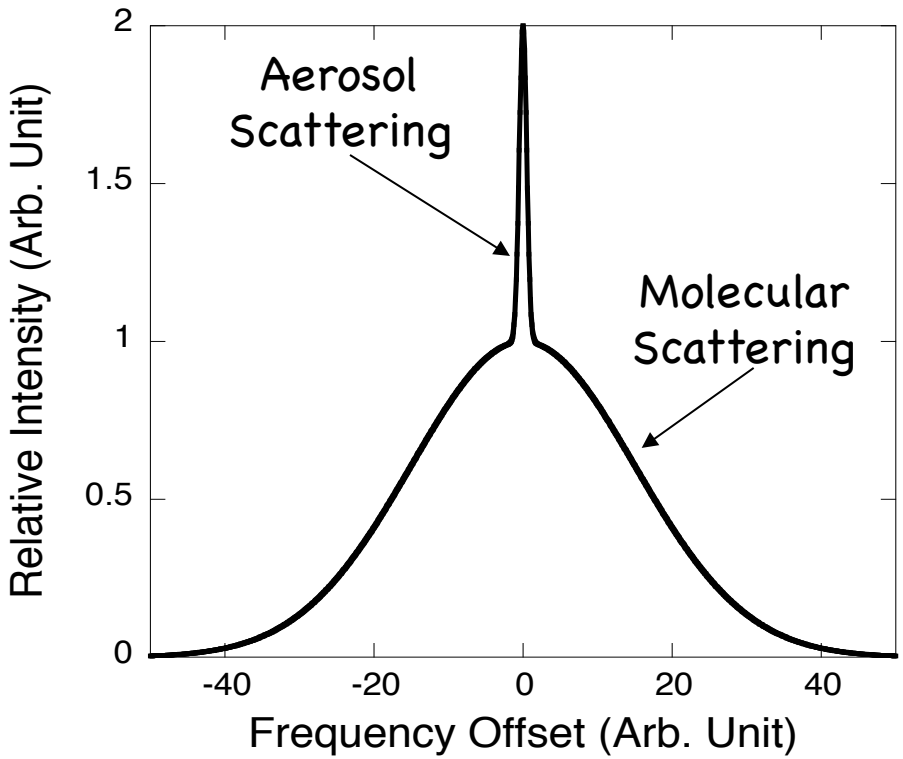
- Below MLT region, there is no resonance fluorescence but pure molecular scattering or "molecular + aerosol" scattering.
- Since the Rayleigh scattering spectral width has sensitive dependence on temperature, it is possible to measure this Rayleigh spectral width to derive the atmosphere temperature.
- 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.



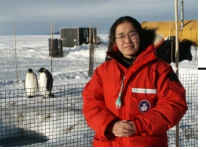
Doppler Effect in Rayleigh Scattering

- Rayleigh backscatter signals have 2 times of Doppler shift thus 2 times of Doppler broadening.

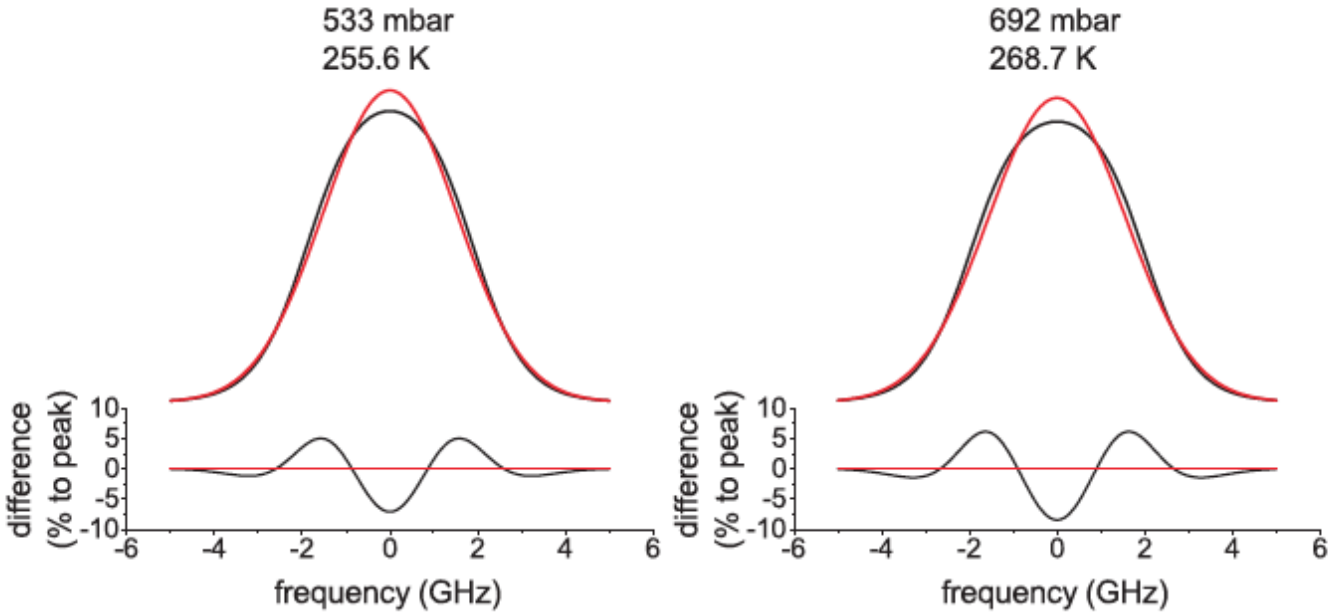
$$\sigma_{rms} = 2\sqrt{\frac{k_B T}{M \lambda_0^2}}$$



- 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.
- Under high atmosphere pressures, the Doppler broadening is further complicated by pressure broadening via spontaneous Brillouin scattering.

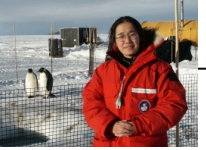


Rayleigh-Brillouin Scattering



[Gu and Ubachs, J. Chem. Phys., 2014]

FIG. 12. Calculated spectral profiles of Rayleigh-Brillouin scattering for air in a typical LIDAR back-scattering (180°) geometry probed with a 355 nm laser (black lines). The figure on the left represents the profile of air at $p =$ 533 mbar and $T = 255.6$ K, the condition of 5 km altitude in the standard atmosphere, while the figure on the right represents the back-scattering profile at 3 km altitude level. The calculations are based on the Tenti S6 model with transport coefficients as calculated by Eqs. (3) and (4) and the value for the bulk viscosity presently determined. For comparison purely Gaussian Doppler profiles for the same conditions are plotted (red lines). 7% and 8.5% differences between Gaussian and Tenti calculations are found.

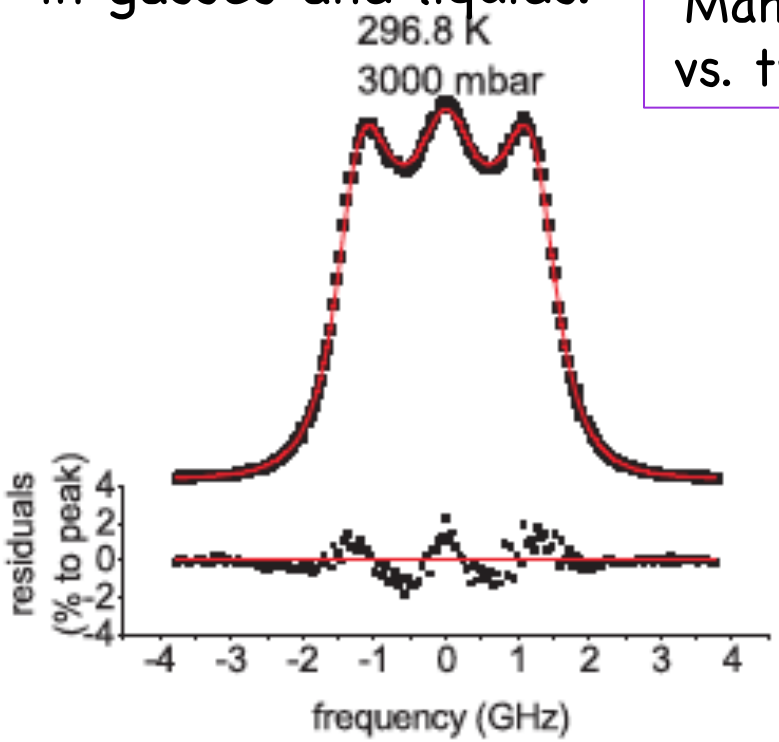


Spontaneous Rayleigh-Brillouin Scattering

Brillouin doublet peaks, frequency-shifted from the central elastic Rayleigh peak, were detected in both liquids and solids, as well as in gases. The Brillouin doublet peaks are also temperature dependent, so can be used to measure temperature in gasses and liquids.

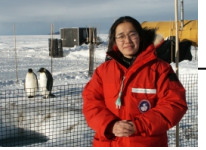
Many-body collisions vs. two-body collisions

Phonons vs. Photons



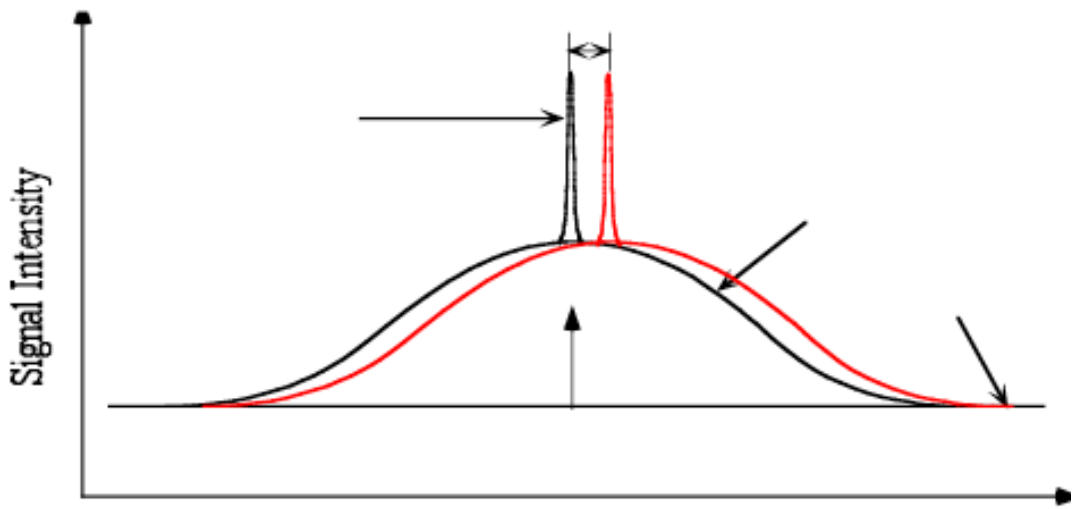
The Tenti S6 model, describing the collision integrals in 6 basis functions with their coefficients represented by the values of the macroscopic transport coefficients, has proven to be the most accurate model to represent the RB-scattering profile in the kinetic regime. It is also accurate in the hydrodynamic regime.

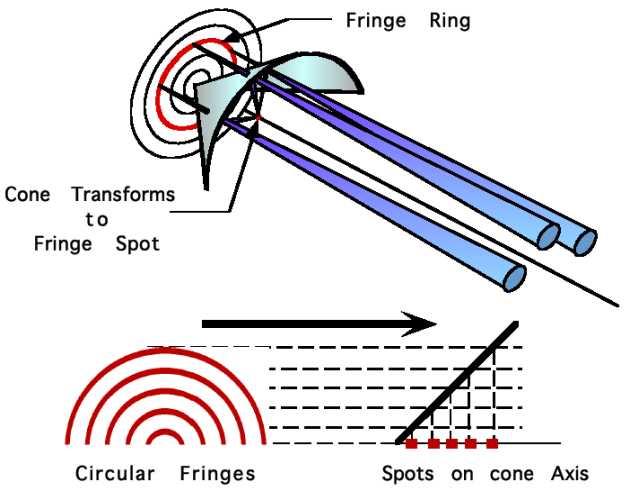
[Gu and Ubachs, J. Chem. Phys., 2014]



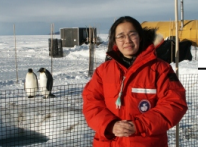
Fringe Imaging

- 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



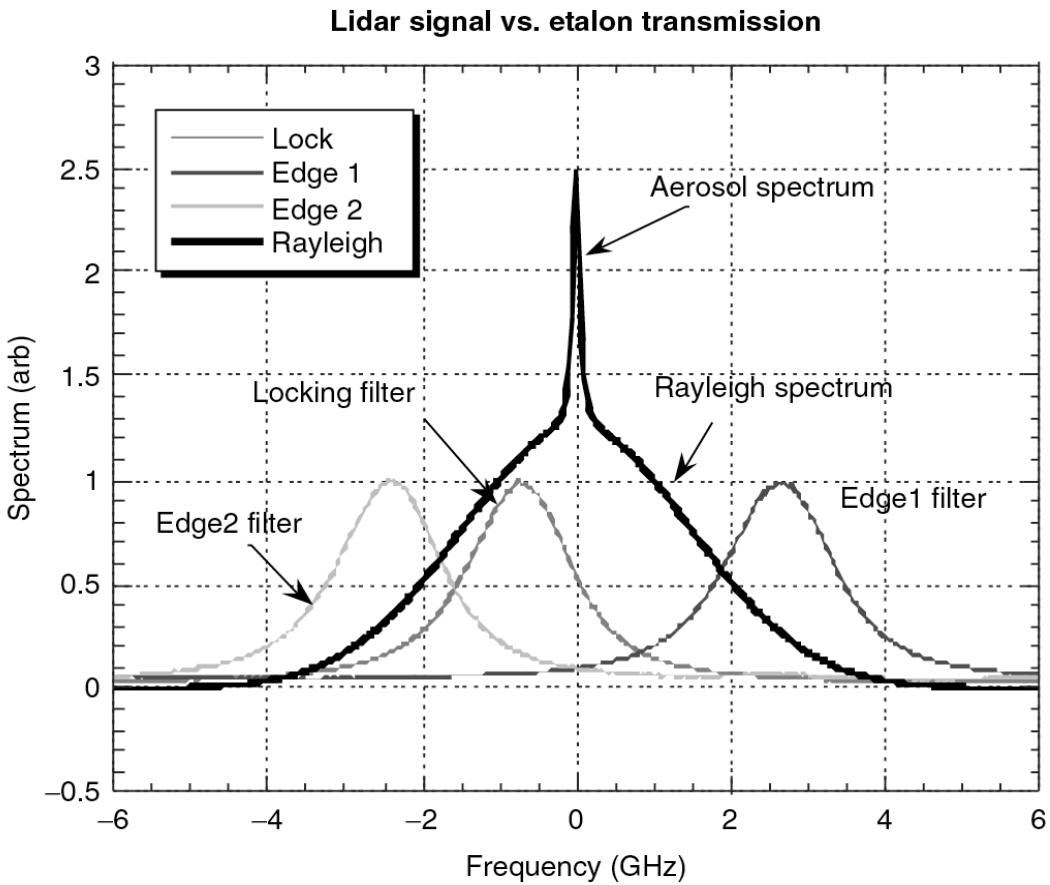


- Diameters of the circles give the Doppler shift when compared with a known wavelength fringe, while the fringe width is an indication of Rayleigh temperature.
- Current issues: suffer low signal levels above 50 km because of decreasing atmospheric density and "waste" of photons in fringes.



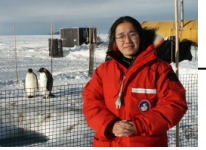
Edge Filter

- 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.



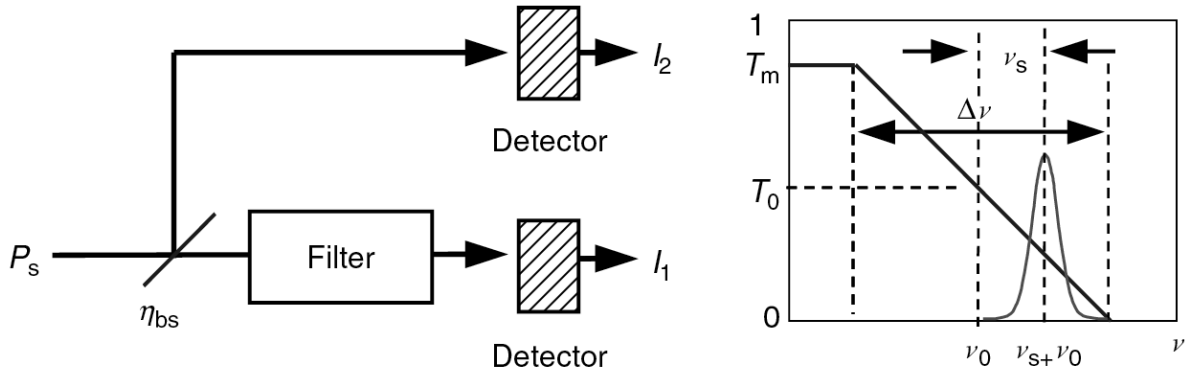
$$\frac{N_1}{N_2} = \frac{\xi_1 f_{m1}(T,P,V_R)}{\xi_2 f_{m2}(T,P,V_R)}$$

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

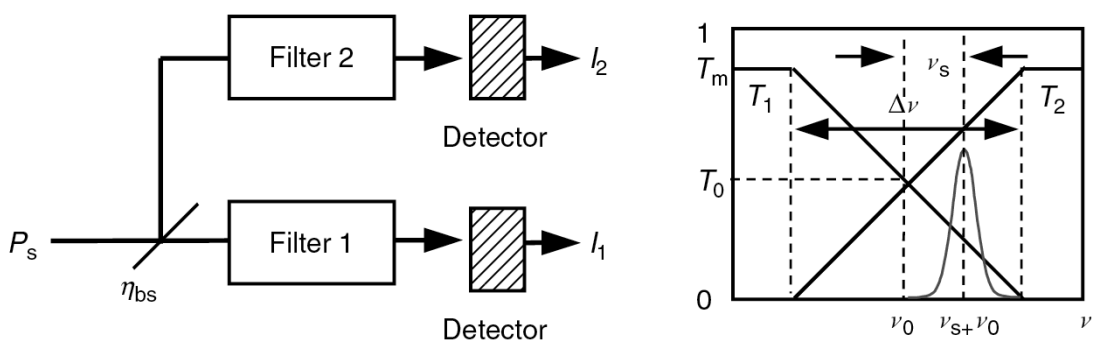
- Edge filter has single-edge and double-edge filters. See our textbook Chapter 7 "Wind Lidar" Direct-Detection Lidar.



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

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

Figure 7.31 Single-edge functional diagram and filter transmission.

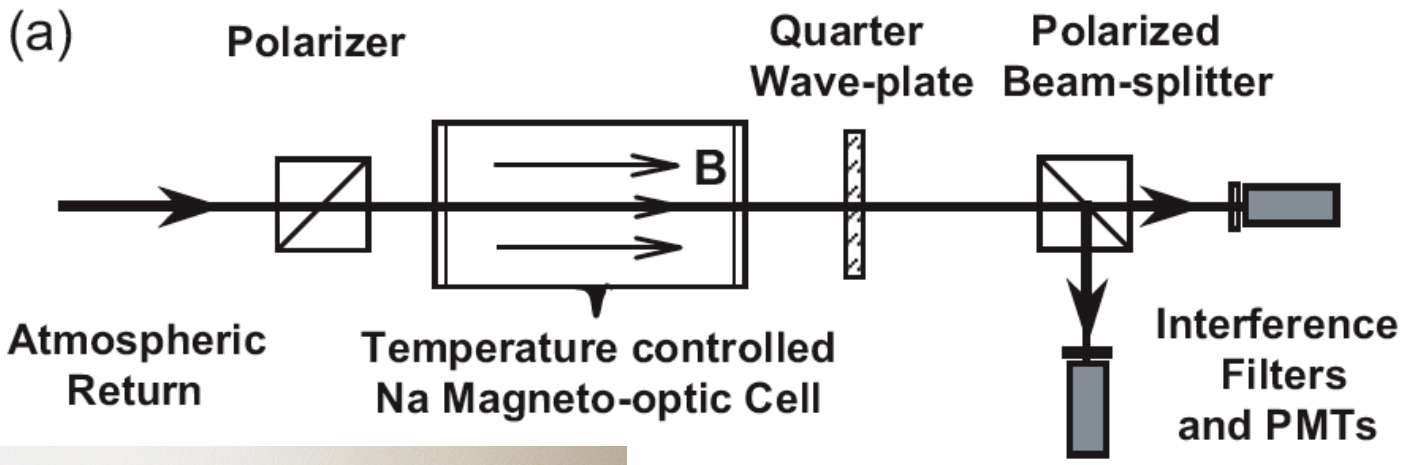


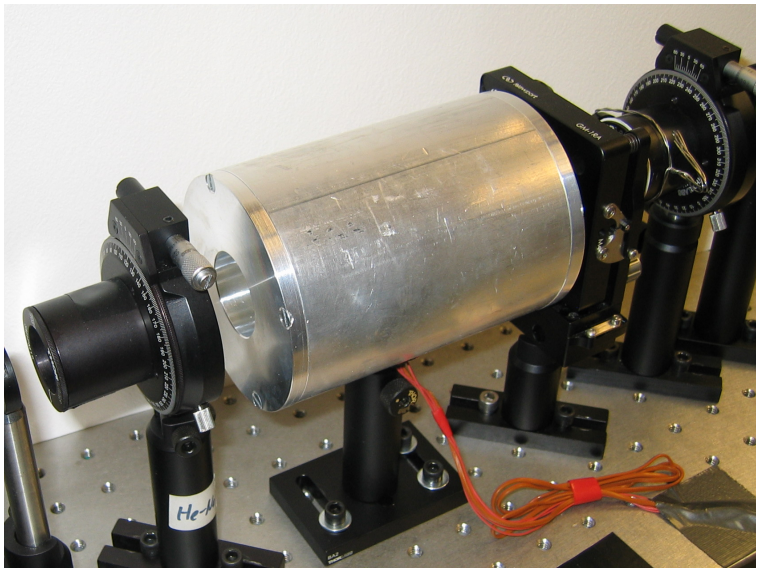
$$S = \frac{I_\Delta}{I_\Sigma} = \frac{I_1 - I_2}{I_1 + I_2} = \frac{T_{s_1} - T_{s_2}}{T_{s_1} + T_{s_2}} = \frac{2\nu_s}{\Delta\nu}$$

Figure 7.32 Double-edge functional diagram and filter transmission.

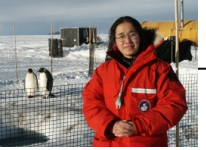
Na-DEMOF for Na Lidar Profiling of Temperature & Wind in Lower ATM

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



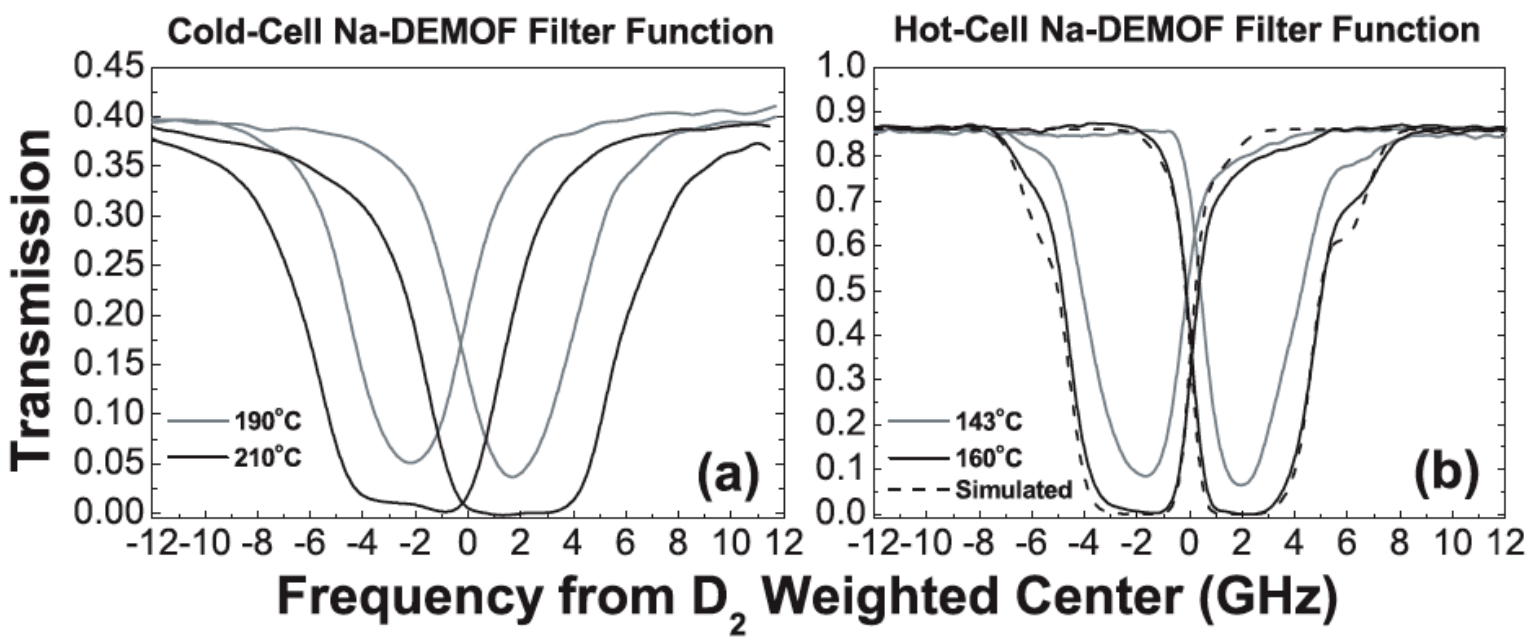


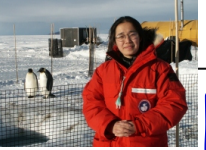
[Huang, Chu, Williams, et al., Optics Letters, 34, pp.199, 2009]



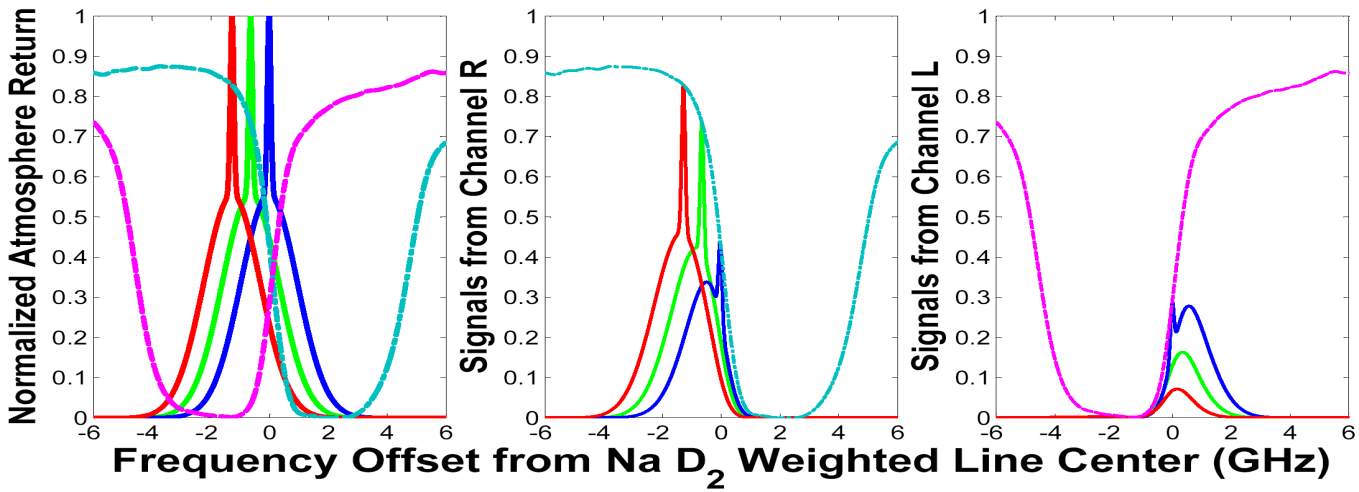
DEMOF vs. Faraday Filter

- 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

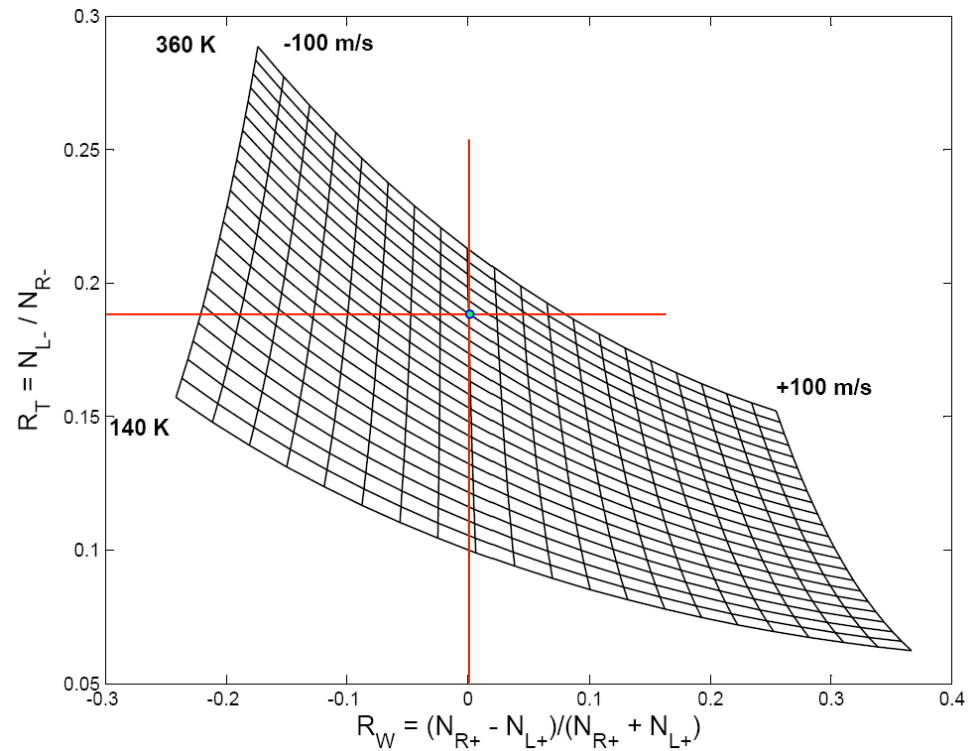


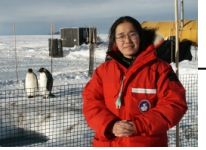
Calibration curves for ratio technique with Na-DEMOF

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

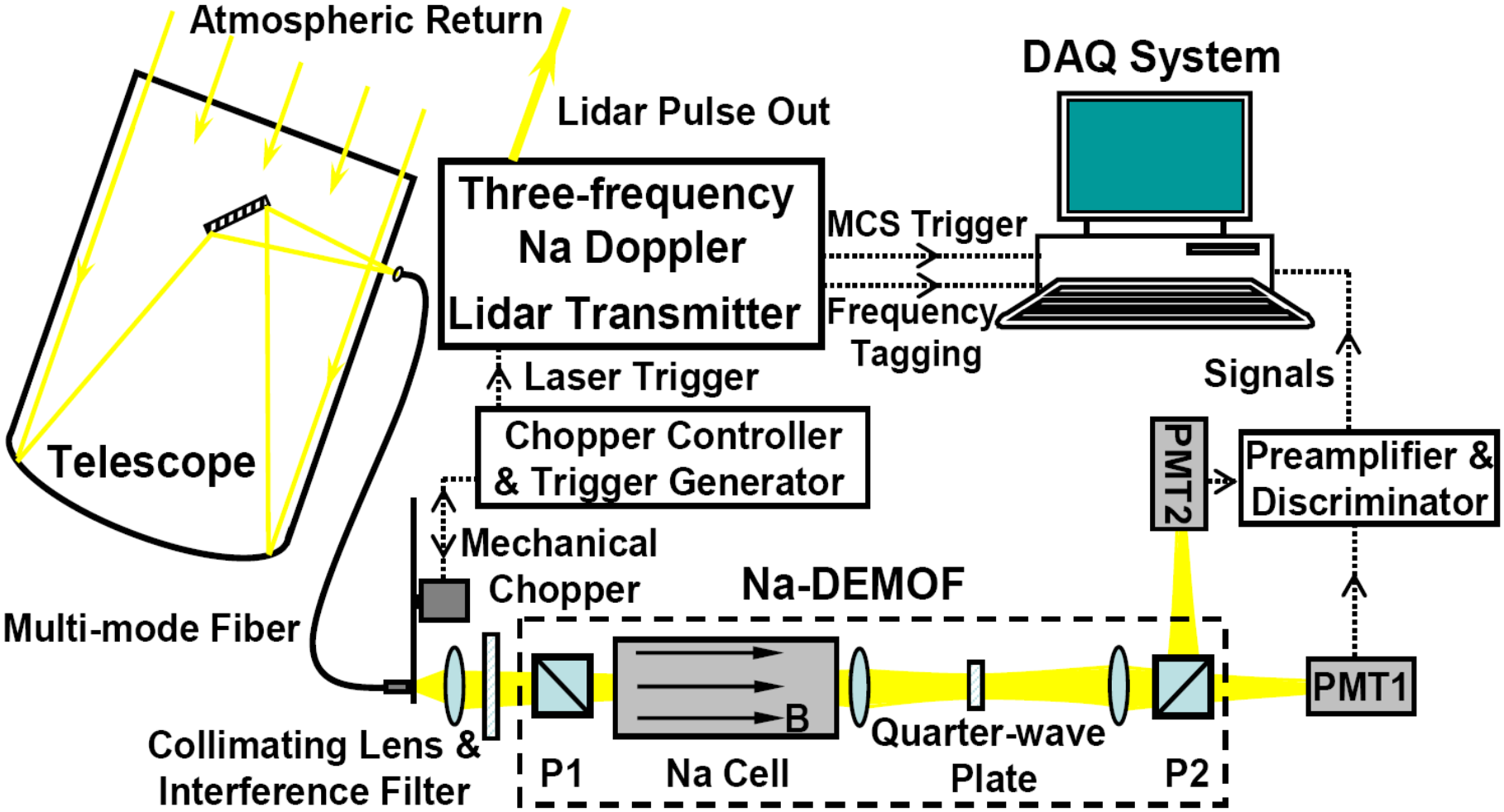
$$R_T(V_{LOS},T,R_b) = \frac{N_{L-}}{N_{R-}}$$

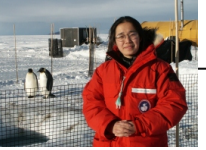
- Temperature and wind are determined simultaneously from two ratios.



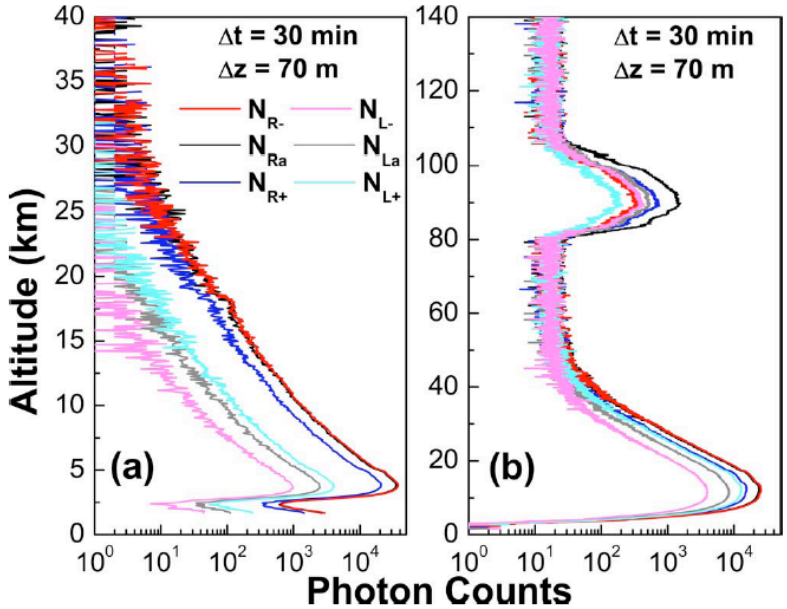


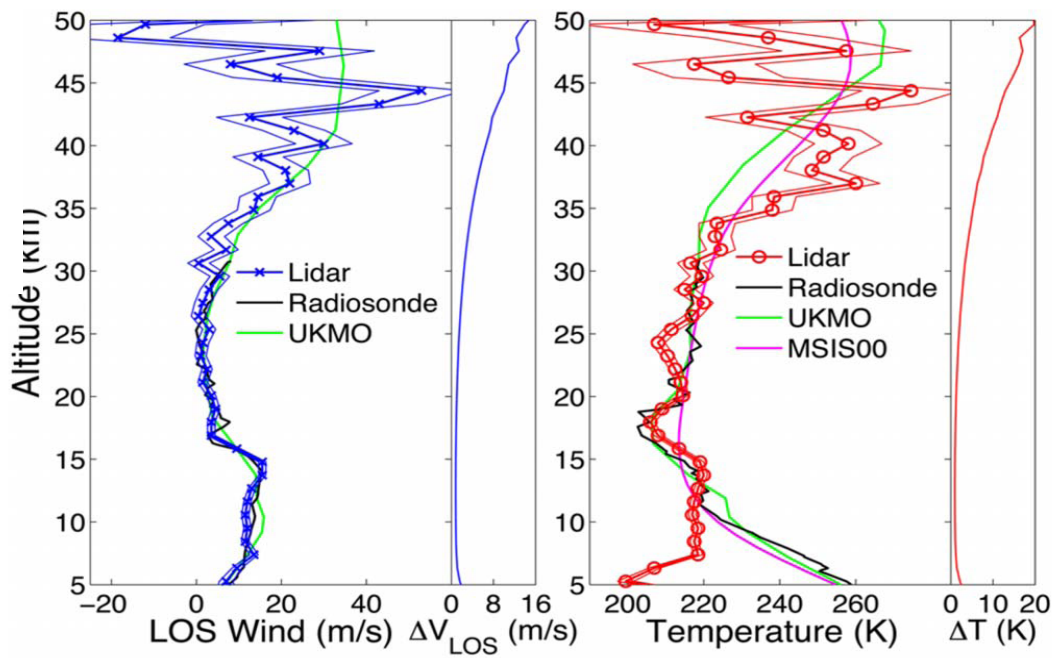
Field Demonstration of Simultaneous Wind and Temperature Measurements (10-45 km) with Na-DEMOF and 3-Frequency Na Lidar



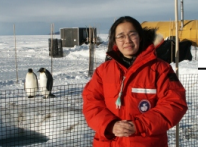


Field Demonstration of Simultaneous Wind and Temperature Measurements (10-45 km) with Na-DEMOF and 3-Frequency Na Lidar

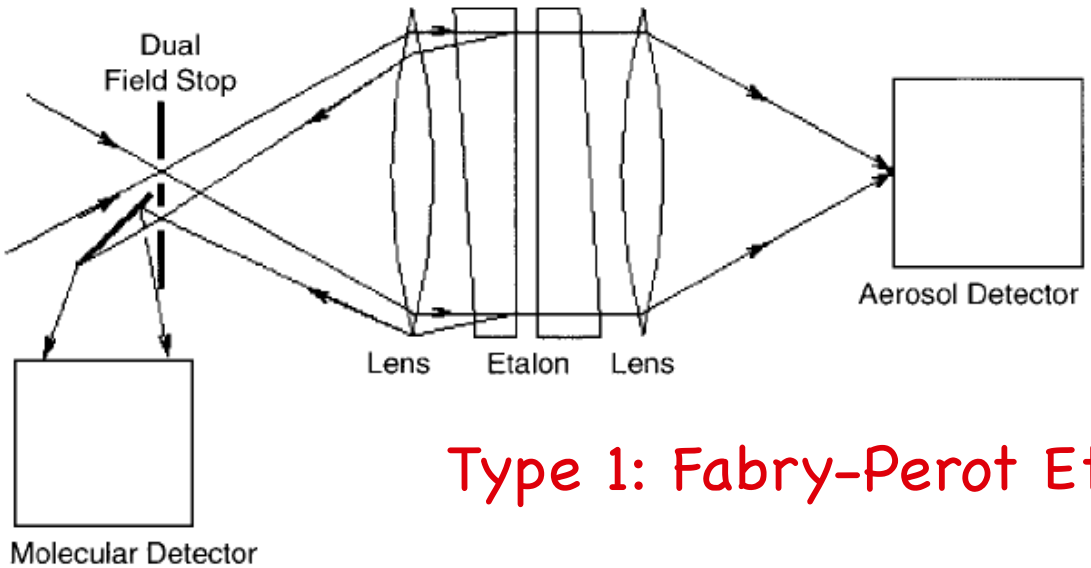




[Huang, Chu, et al., Optics Letters, 34, pp. 1552, 2009]

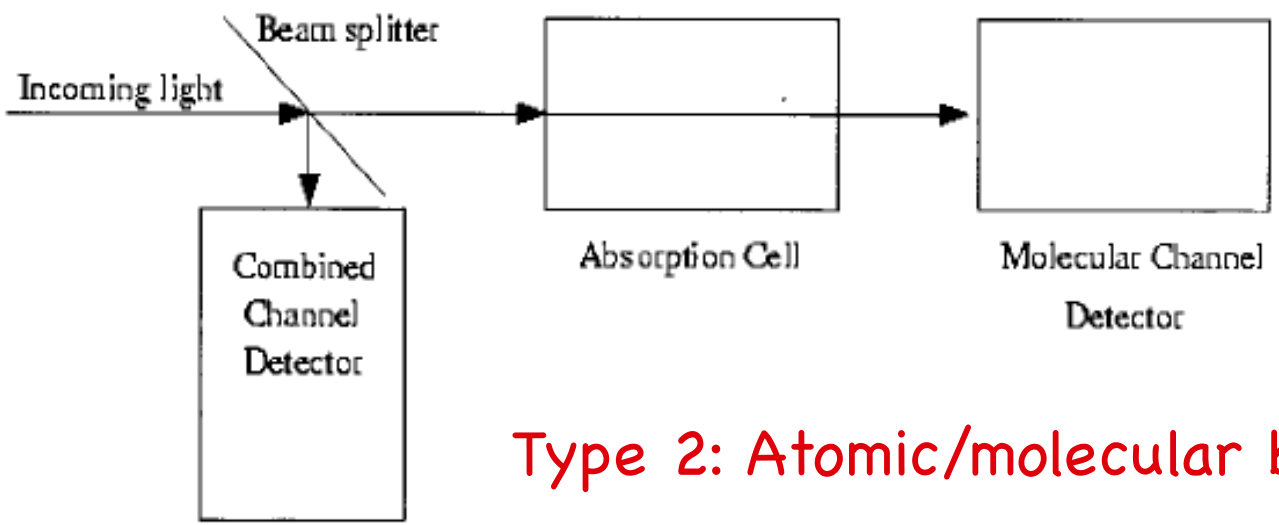


High Spectral Resolution Lidar



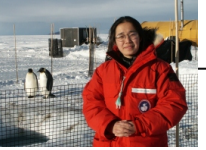
1. Aerosol scattering pass the transmission band
2. Molecular scattering is reflected outside the transmission band

Type 1: Fabry-Perot Etalon/Interferometer

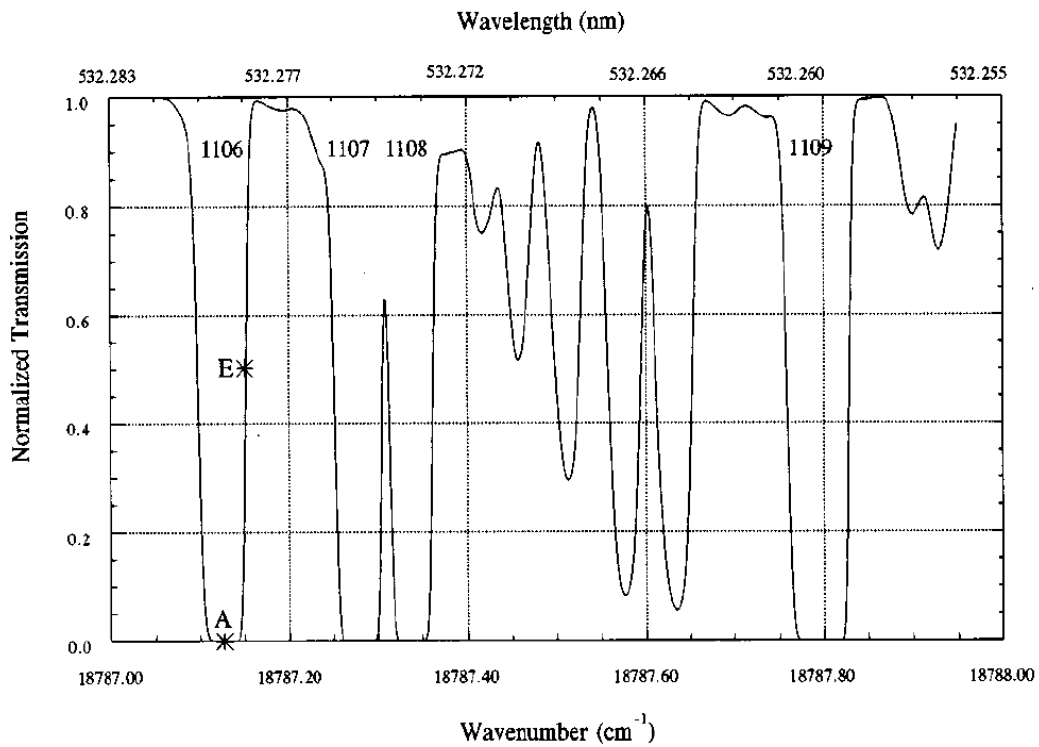


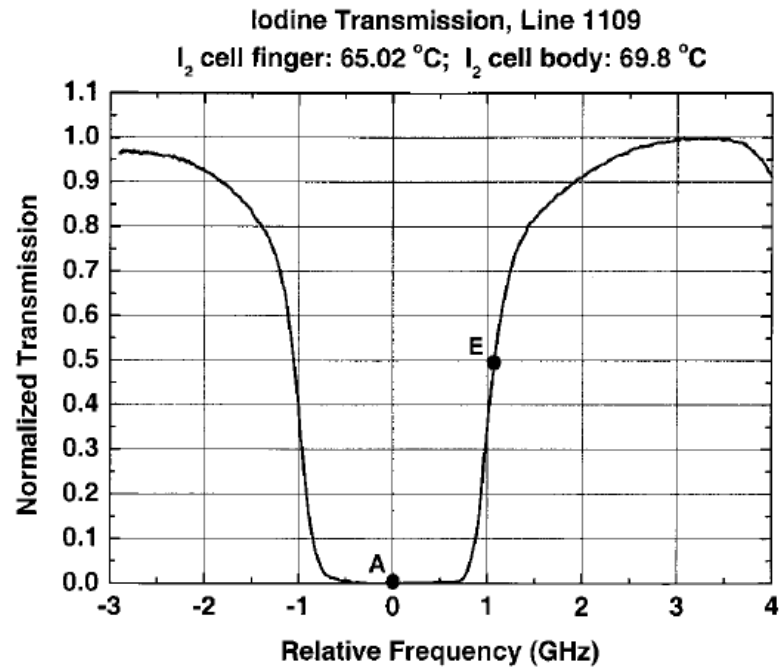
Atomic or molecular absorption block the aerosol scattering

Type 2: Atomic/molecular blocking filter

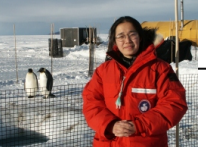


Iodine Filter Using I_2 Absorption Lines

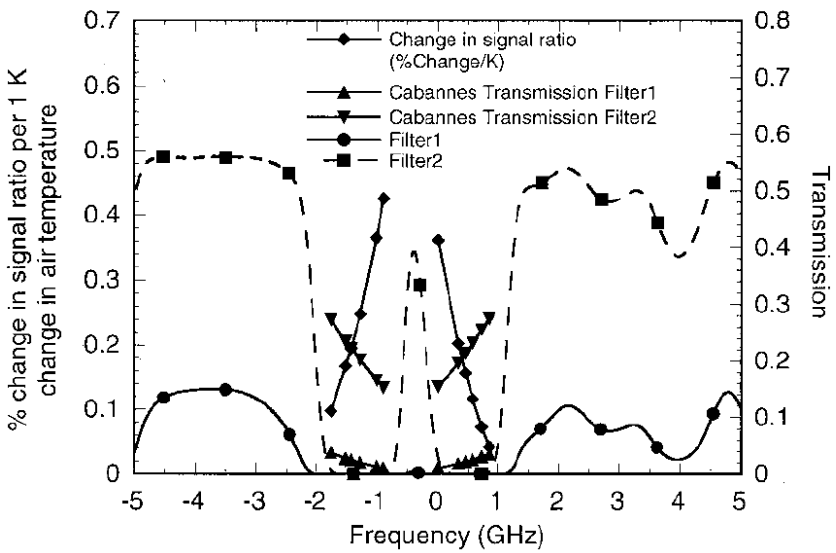


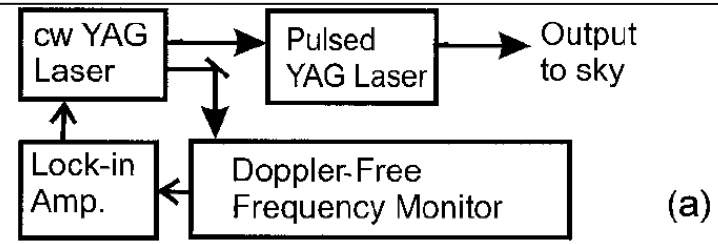


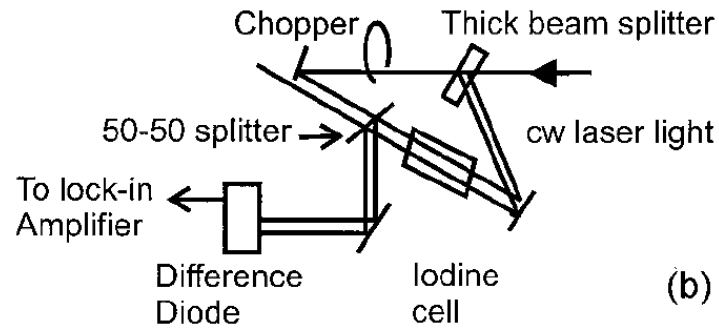
[Liu et al., Appl. Phys. B 64, 561-566, 1997]
[Friedman et al., Opt. Lett., 22, 1648-1650, 1997]
[Liu et al., Appl. Opt., 41, 7079-7086, 2002]
[Wang et al., Applied Optics, 49, 6960-6978, 2010]

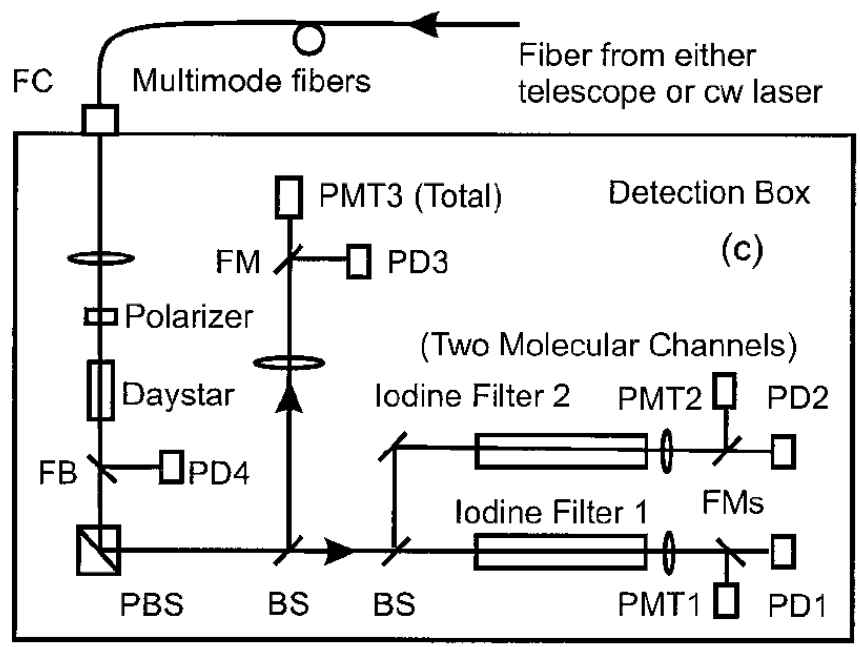


HSRL Using I_2 Filter

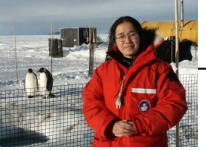








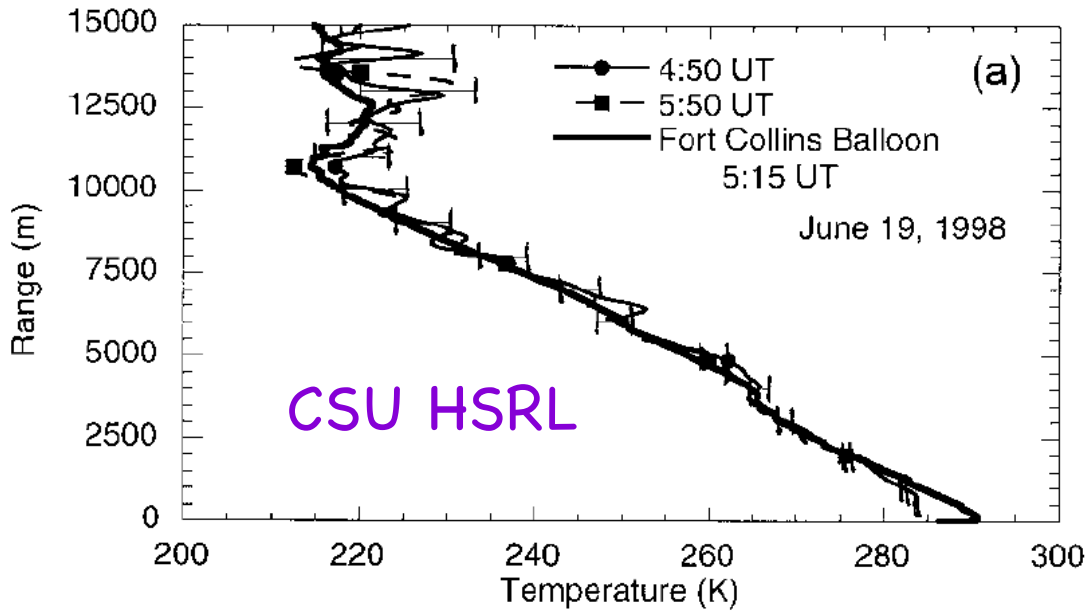
CSU HSRL
[Hair et al., Applied Optics, 40, 5280-5294, 2001]



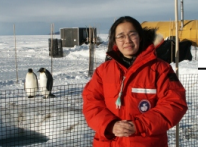
HSRL Temperature Measurements

- 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.

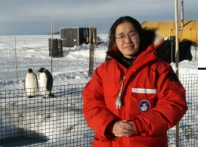


- Majority of the Rayleigh scattering is filtered out!



DIAL Temperature Technique

- Molecular absorption coefficient is temperature dependent: Both the line strength (mainly by Boltzmann distribution) and the lineshape (mainly Doppler effects and pressure broadening) are functions of temperature.
- 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. However, it is possible to use other species, e.g., water vapor and CO_2, etc.
- In the choice of suitable absorption line, a trade-off must be made between the high temperature sensitivity of the absorption coefficient (high for high initial energy state – Boltzmann factor) and the suitable magnitude of absorption coefficient.
- Absorption coefficient is also dependent on pressure and radial wind velocity, making the temperature derivation more difficult.



DIAL Temperature Technique

Based on the paper by Korb and Weng [1982] in J. App. Meteorology

$$E_\nu(R) = E^0 A \tau_0 \beta_\nu (\Delta R/R^2) \times \exp\left\{-2\int_0^R [\alpha(\nu) + K(\nu)]dx\right\}, \quad (1)$$

The absorption coefficient of a gas species in the atmosphere at frequency ν, $K(\nu)$, is given as

$$K(\nu) = qnS(T)f(\nu - \nu_0), \quad (4)$$

Line strength S(T)

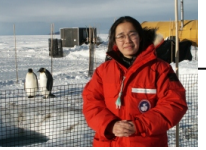
$$S(T) = S(T_0)(T_0/T) \times \exp\{-(\epsilon/k)[(1/T) - (1/T_0)]\}$$

Boltzmann distribution

Lineshape f

$$f(\nu - \nu_0) = \frac{f'a}{\pi}\int_{-\infty}^{\infty} \frac{\exp(-y^2)dy}{a^2 + (\xi - y)^2}$$

Voigt shape – the convolution of Doppler broadening Gaussian and pressure broadening Lorentzian



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 Doppler-broadened spectral width. Fringe imaging and edge filters 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 than temperature, measurements.
- High-spectral-resolution lidar (HSRL) has been successful in the lower atmosphere temperature measurements by totally blocking the aerosol (Mie) scattering and only sensing the temperature-dependent Rayleigh scattering signals.