Lecture 25. Wind Lidar (3)
Direct Detection Doppler Lidar

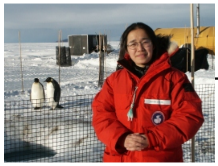
- Overview of Direct Detection Doppler Lidar (DDL)
- Fringe imaging DDL
- Scanning FPI DDL
- FPI edge-filter DDL
- Iodine absorption-line edge-filter DDL
- High-Spectral-Resolution Lidar (HSRL)
- Na-DEMOF DDL
- Summary

Direct Detection Doppler Wind

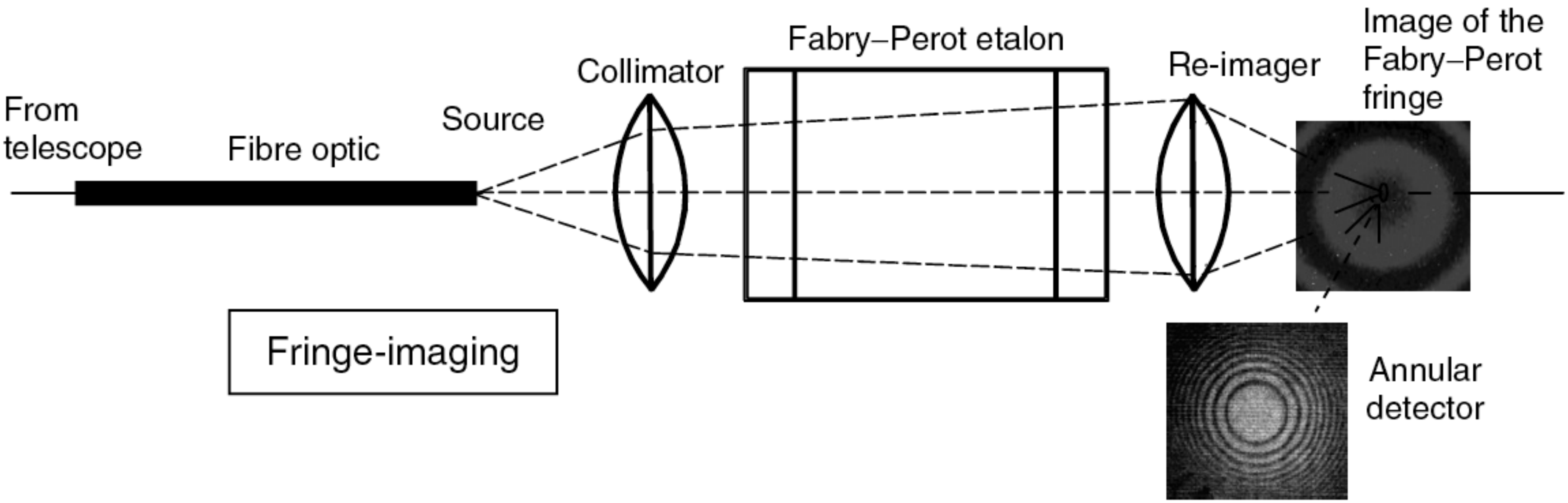
- Direct detection Doppler lidars (DDL) convert the Doppler frequency shift to the change of intensity, or intensity ratio, or intensity spatial distribution for wind measurements.
- One of the key components for non-resonance DDL is the optical frequency discriminator or frequency analyzer, usually implemented in the lidar receiver if it is not available in the atmosphere.
- Current available optical frequency discriminators include

(1) Fringe imaging with optical interferometers (Fabry-Perot or Fizeau)
(2) Scanning FPI: tune the FPI peak transmission frequency
(3) Interferometer edge-filter: the edge of a transmission fringe of an optical interferometer (e.g., Fabry-Perot etalon or Fizeau etalon)
(4) Molecular absorption-line edge-filter (e.g., iodine I_2 absorption lines)
(5) Atomic absorption-line edge-filter (e.g., Na or K magneto-optic filter)
(6) Michelson or Mach-Zehnder interferometer with optical autocovariance

- A major difference between resonance DDL and non-resonance DDL lies in where the frequency discriminator is - in the atmosphere or in the receiver chain! Because the Na, K, or Fe absorption lines are in the atmosphere, the lidar receiver is allowed to be broadband, rather than the narrowband employed in the non-resonance DDL.



Fringe-Imaging DDL

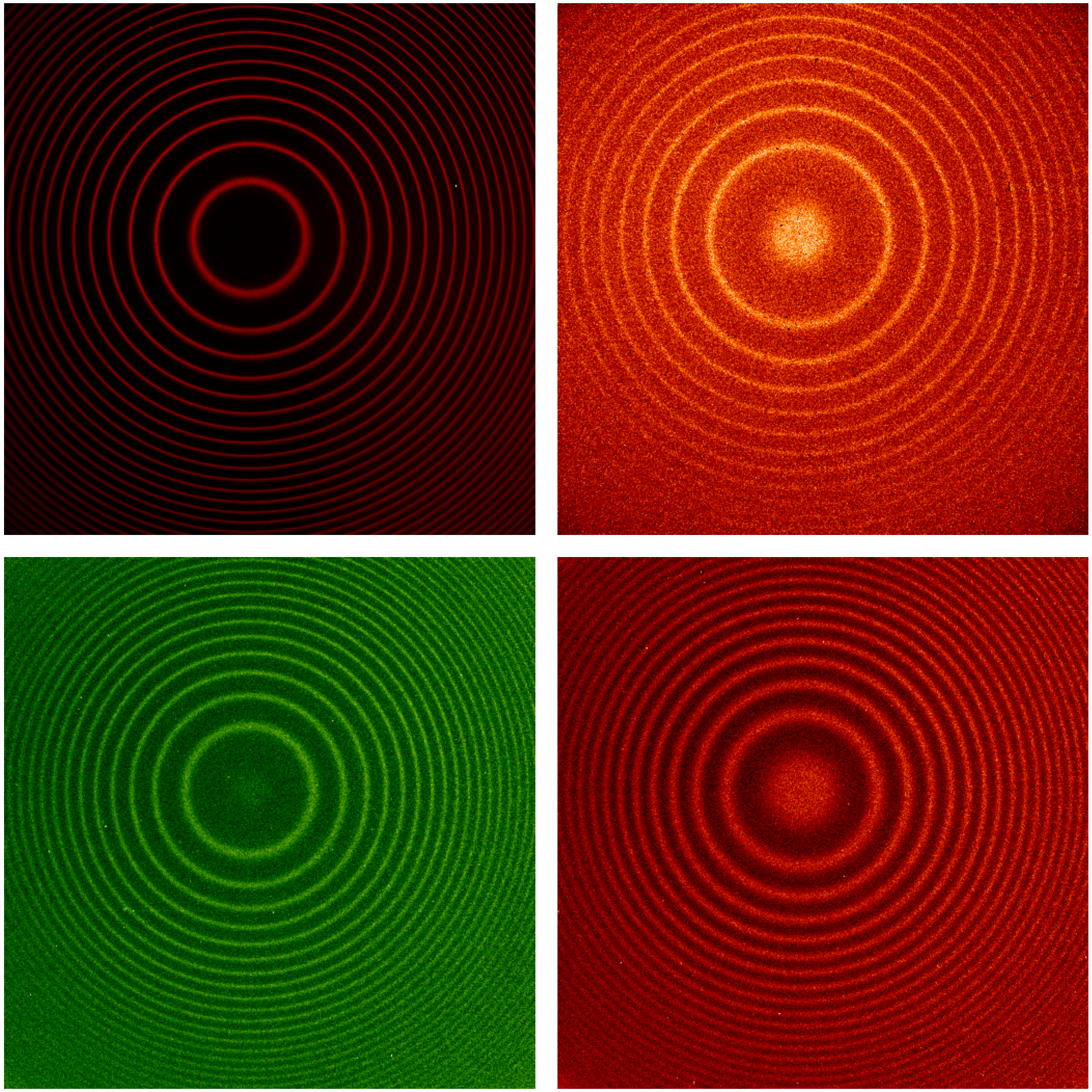


- The basic concept of fringe-imaging discriminator is to utilize a high-resolution interferometer to produce a spatial irradiance distribution, which is representative of the receiver-plane signal spectrum.
- In principle, fringe imaging can measure both wind (from frequency shift) and temperature (from fringe width).
- Similar to passive F-P Interferometer, the diameter and width of the concentric rings can be used to determine the frequency shift and Doppler broadening, thus the LOS wind and temperature.

Passive FPI Fringes from Airglow

Laser

8920 A
~87 km
OH



5577 A
~ 97 km
Atomic O

6300 A
~250 km
Atomic O

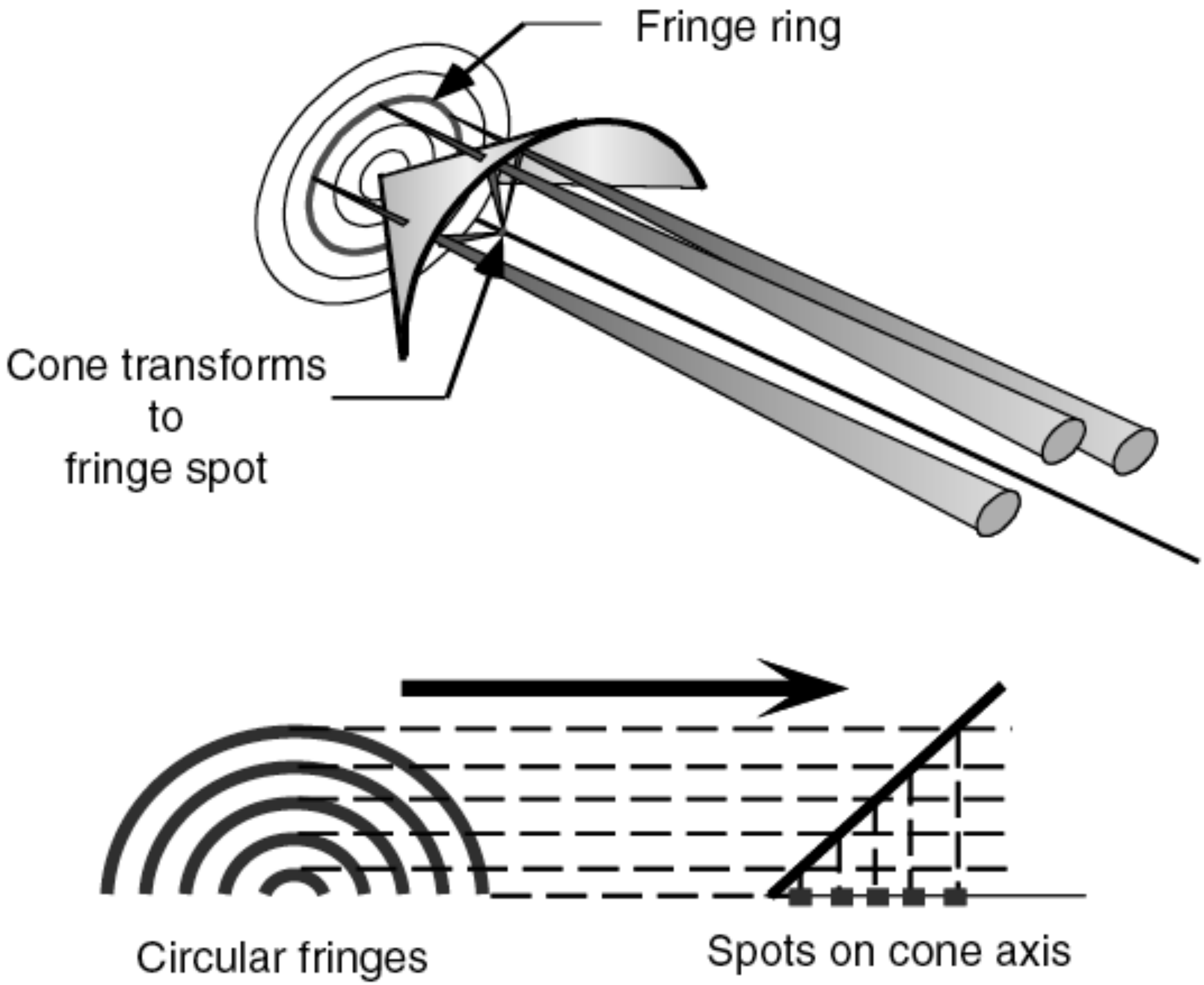
Thermosphere
is very hot!

Courtesy of Dr. Qian Wu, NCAR/HAO

Detectors for Fringe Imaging DDL

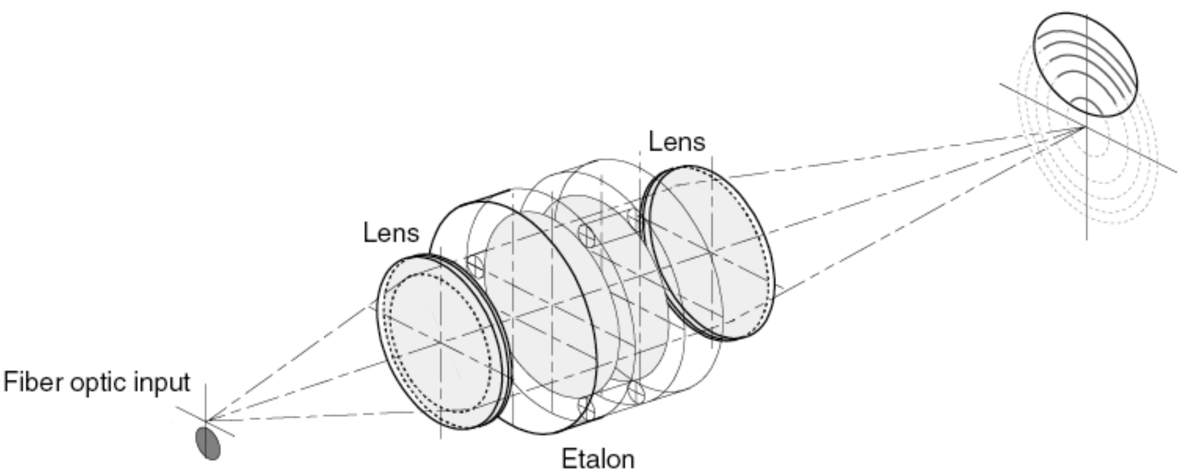
- For the fringe-imaging technique, by its nature, a multi-element imaging detector is required. Furthermore, the detector has to be capable of being used in a time-gated mode, in order to provide the essential range-resolved sampling of the backscattered signal. There is a further subtle difficulty that the Fabry-Perot etalon presents its spectral information as concentric circular fringes.
- 3-D detection: spatial distribution, altitude range, and time
- Multi-channel detectors like an imaging photomultiplier tube (IPD), incorporating a 24-channel concentric-ring anode read-out designed to match the fringe pattern presented by the F-P etalon. It uses a stack of microchannel plates to achieve high electronic gain. Each of 24-channel is time-gated to achieve range-resolved data.
- Circle-to-Line Imaging Optics (CLIO) can be used to convert the circular fringes formed by a F-P etalon into a linear pattern of spots. Then a conventional linear array detector, such as a CCD, can be used to read the linear fringe pattern.
- CCD response is slower than PMT and PD - problem in range resolution.

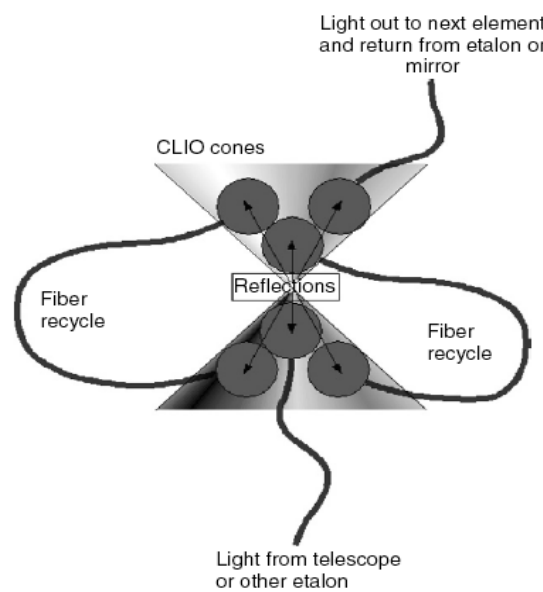
Circle-to-Line Imaging Optics (CLIO)



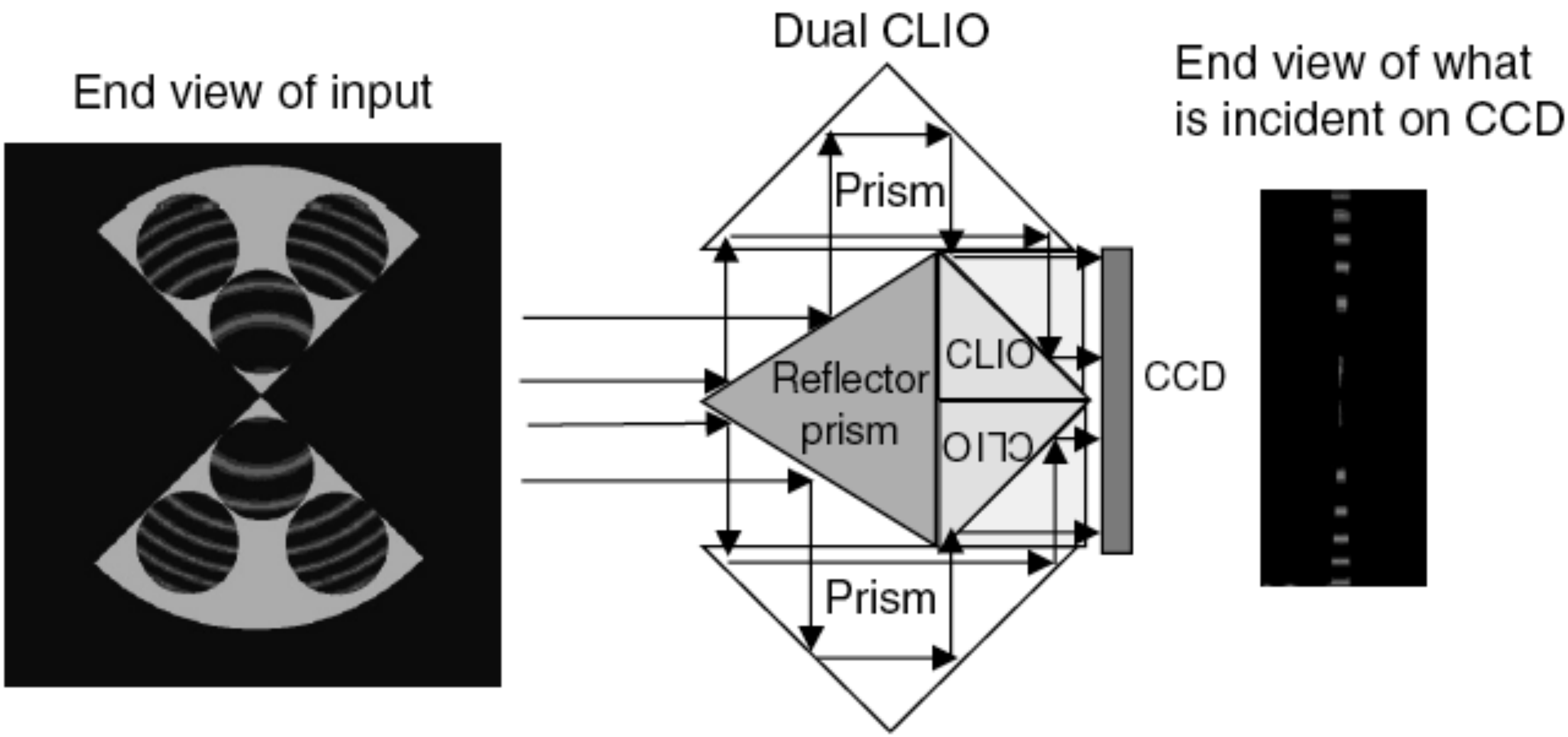
Improving Fringe-Imaging Efficiency

- When F-P etalon is used, only a portion of the incident light is transmitted through the interferometer, and majority of the incident light is reflected out. Three methods to improve this situation –
- Fractional Fringe Illumination: the etalon is illuminated by a solid angle corresponding to only a fraction of the full FSR, which can result in a significantly higher fraction of the signal being transmitted by the etalon.
- Interferometer Photon Recycling: reflected photons are collected by fibers and then re-illuminate the etalon.
- Channel Photon Recycling: the aerosol channel transmits the aerosol scattering while the light reflected from aerosol channel is fed to the molecular channel.

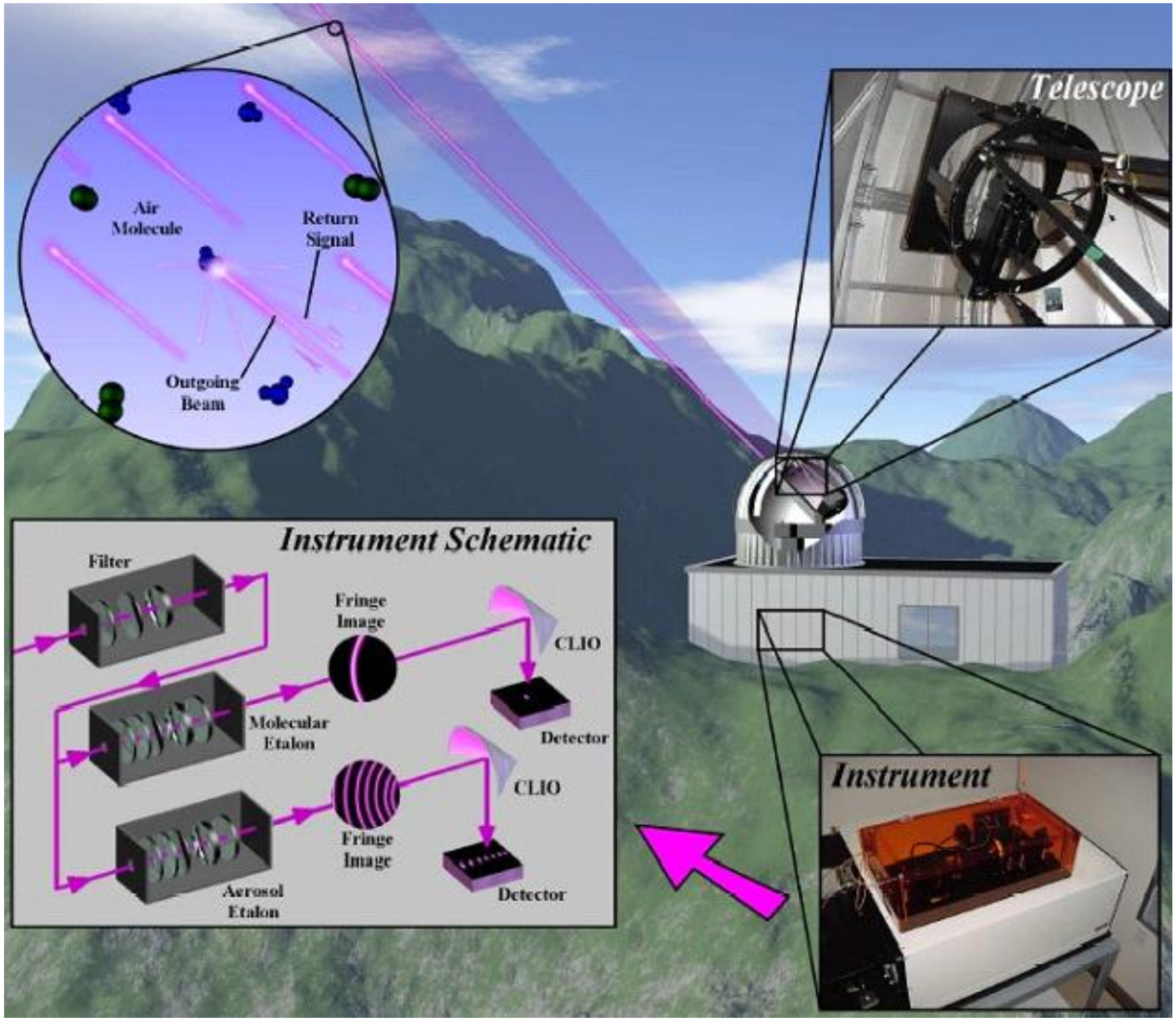




Photon Recycling + CLIO



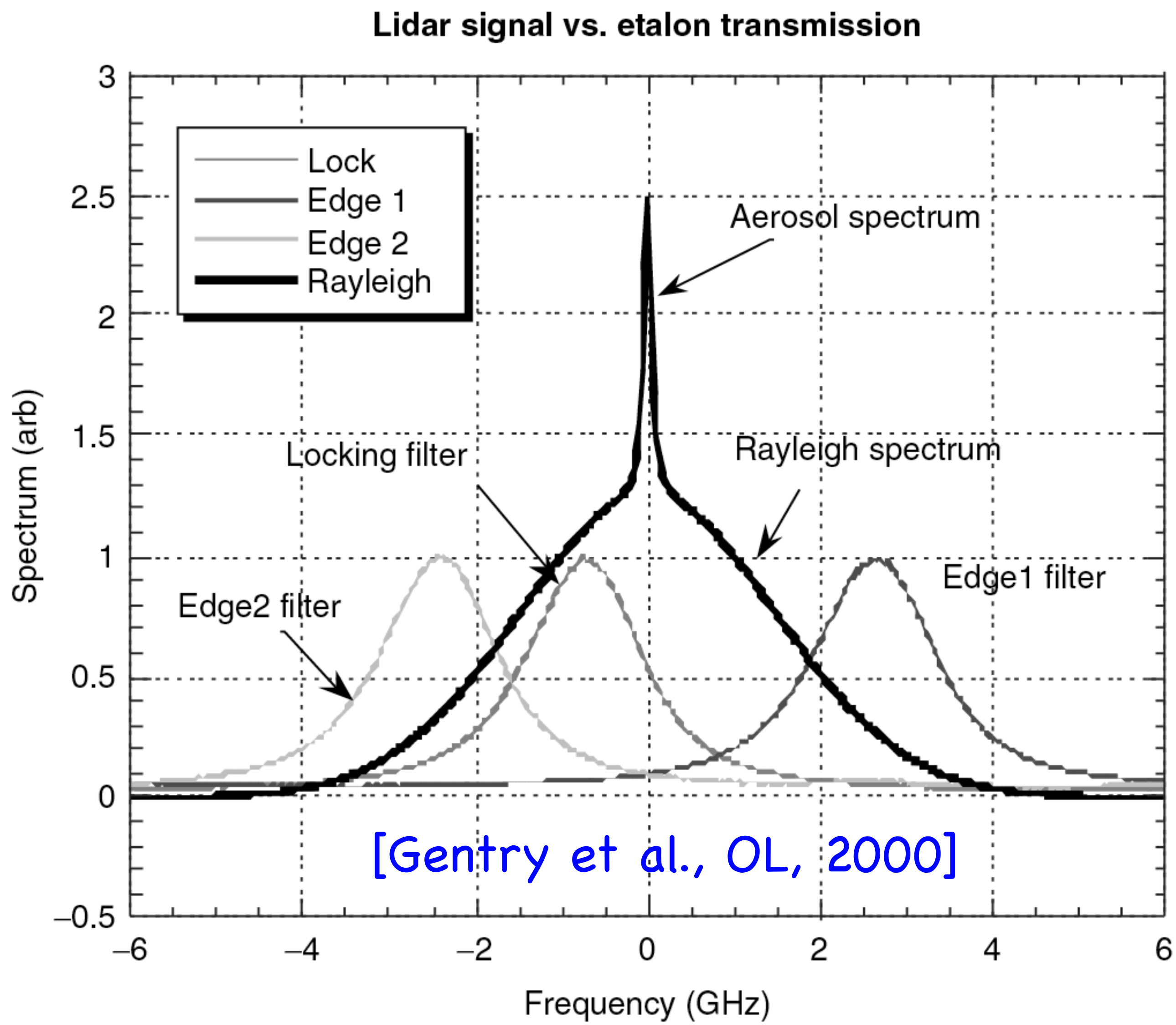
Example DDL: GroundWinds



http://groundwinds.sr.unh.edu/

Scanning FPI DDL, FPI Edge-Filter DDL

- Tepley et al. [1993, 1994] demonstrated 15-60 km wind measurements using scanning FPI.
- However, it is likely that signals were from PMT saturation response, not real.
- But scanning FPI is doable and practical.
- Many researchers turn attention to the edge-filter techniques.



[Gentry et al., OL, 2000]

The locking filter channel is to ensure the optimum balance of the Edge 1 and Edge 2 filters (F-P etalons) on the zero Doppler-shifted laser signal.

How Does Scanning FPI Work?

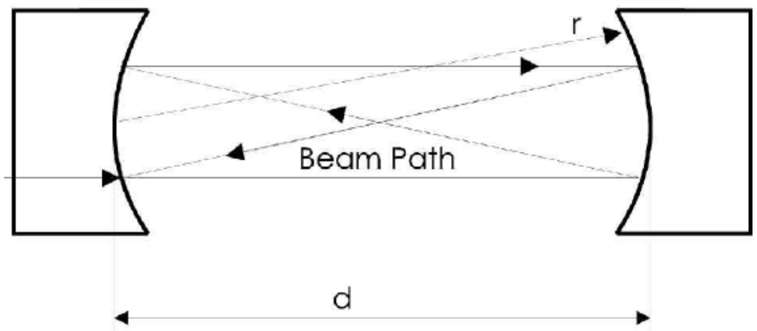
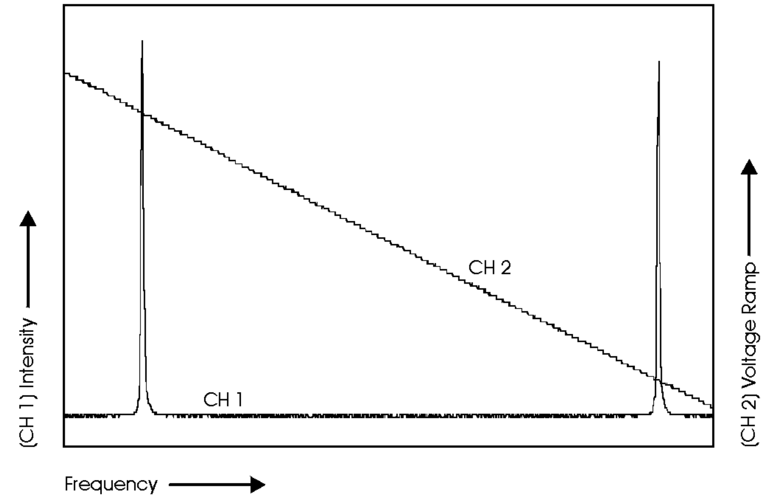
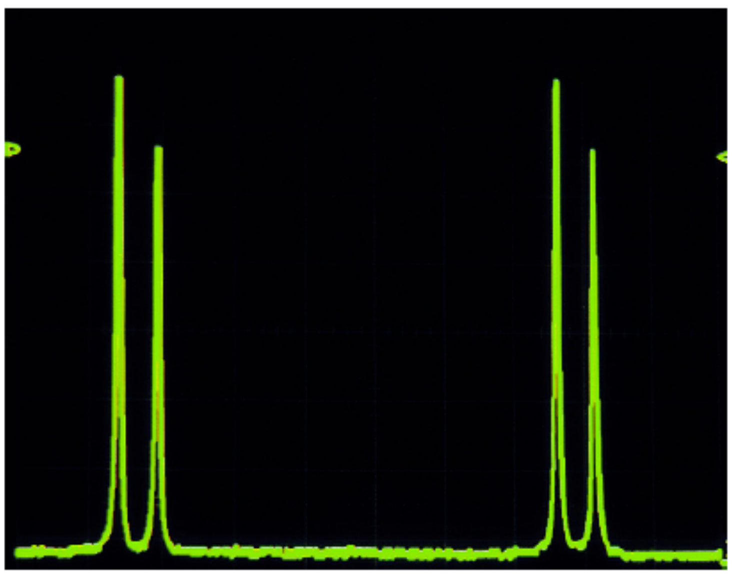


Figure 1 Confocal Interferometer Configuration

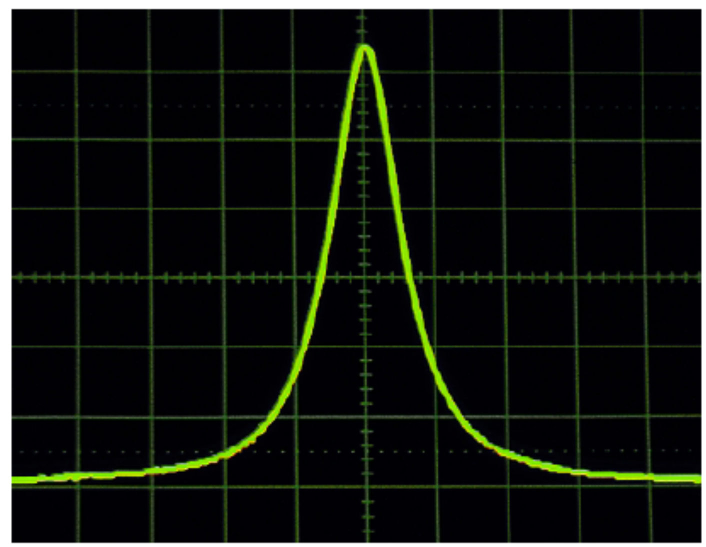
Courtesy of Toptica FPI-100 manual



Results on cw laser

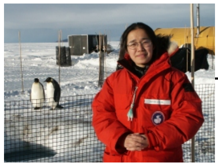


Two laser modes displayed twice during Spectrum Analyzer scan of ~1.6 FSR



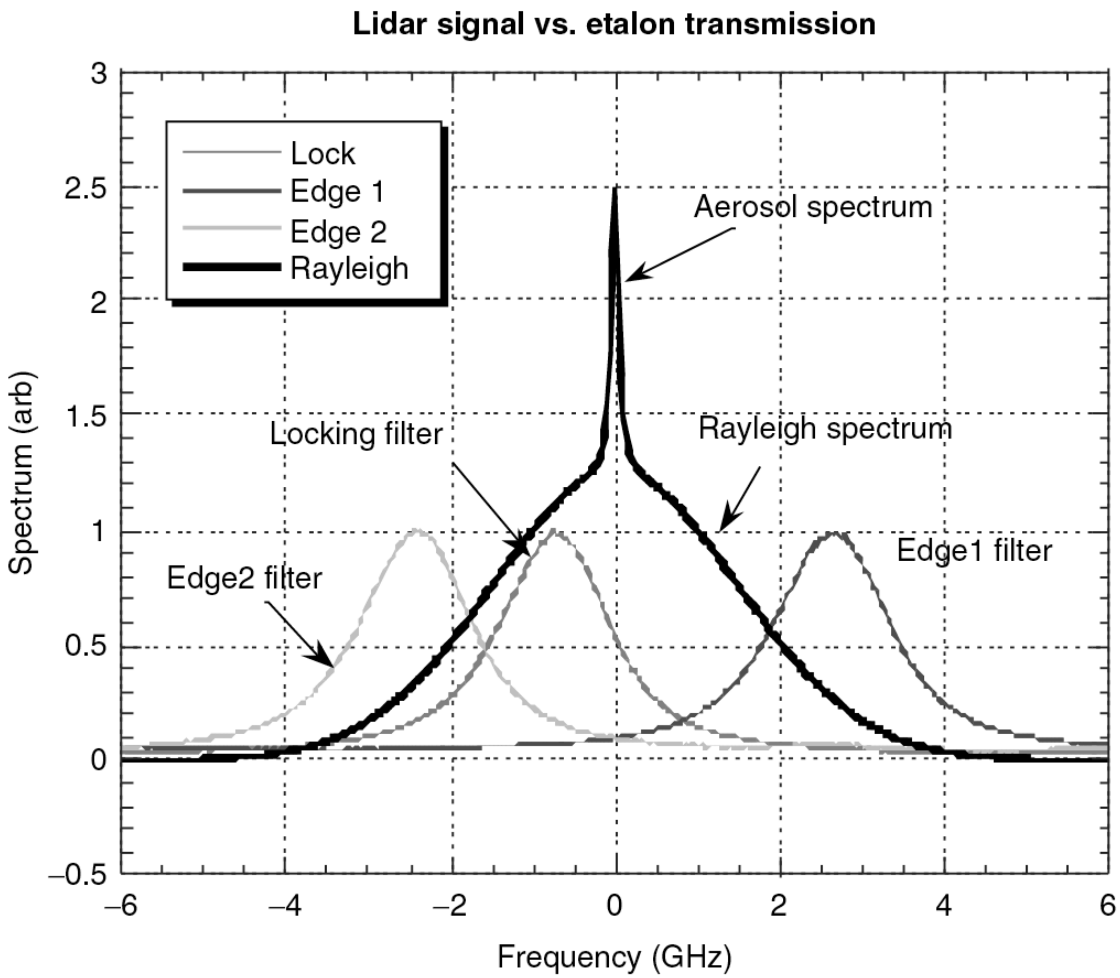
Single mode using Spectrum Analyzer

Courtesy of Coherent, Inc.



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 wind or temperature information is then derived from the ratio of signals from these two channels.

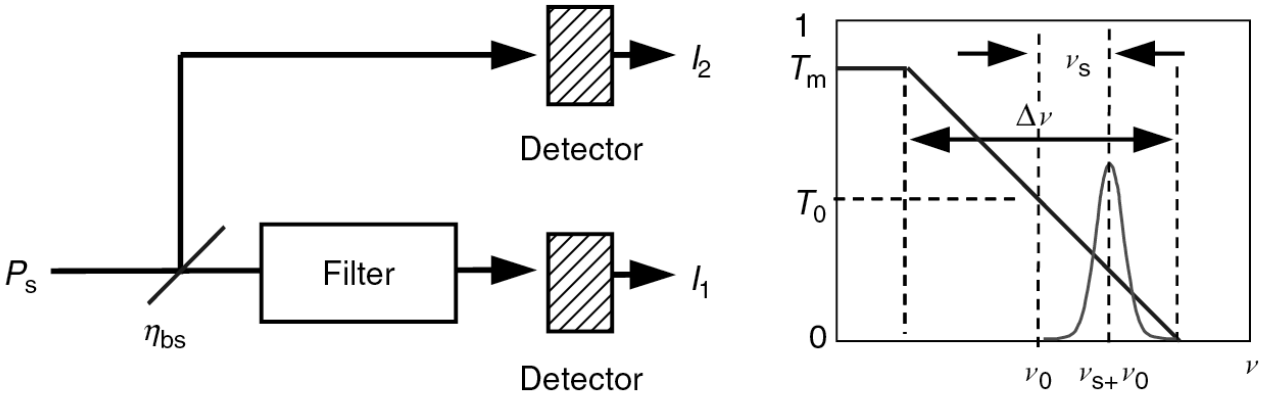


$$\frac{N_1}{N_2} = \frac{\xi_1 f_{m1}(T, P, V_R)}{\xi_2 f_{m2}(T, P, V_R)}$$

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

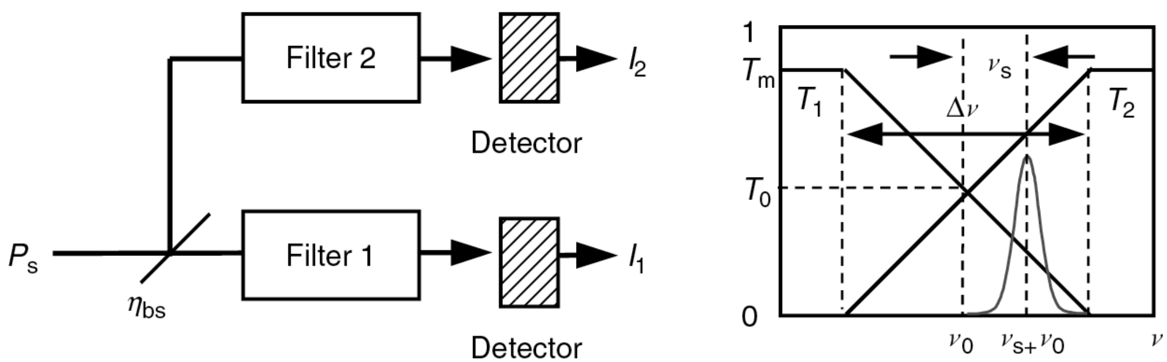
- Edge filter has single-edge and double-edge filters. See our textbook Chapter 7 "Wind Lidar" Direct-Detection Lidar.



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

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

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.

Freq Analyzer: Single-Edge Filter

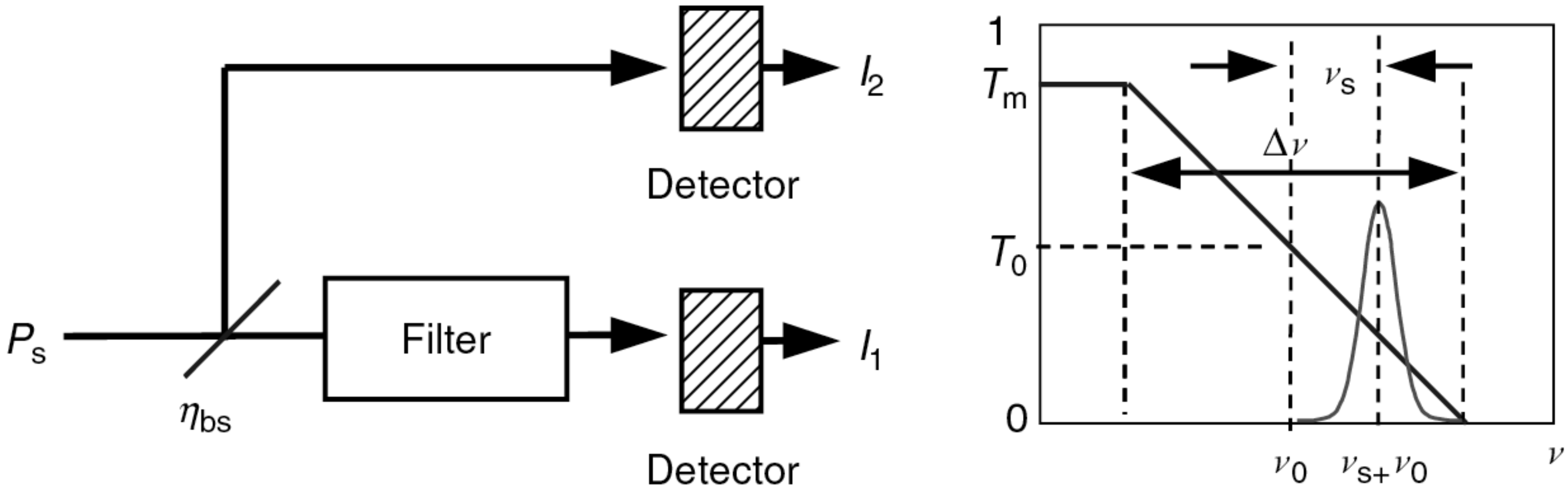


Figure 7.31 Single-edge functional diagram and filter transmission.

- A Fabry-Perot etalon is usually employed as the edge filter. The etalon is locked to the zero-Doppler laser frequency, ν_0, such that the frequency of the transmitted laser is matched to the mid-point of the quasi-linear transmission edge of the etalon.

- The intensity ratio of these two channels is a function of the Doppler frequency shift ν_s.

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

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

Freq Analyzer: Double-Edge Filter

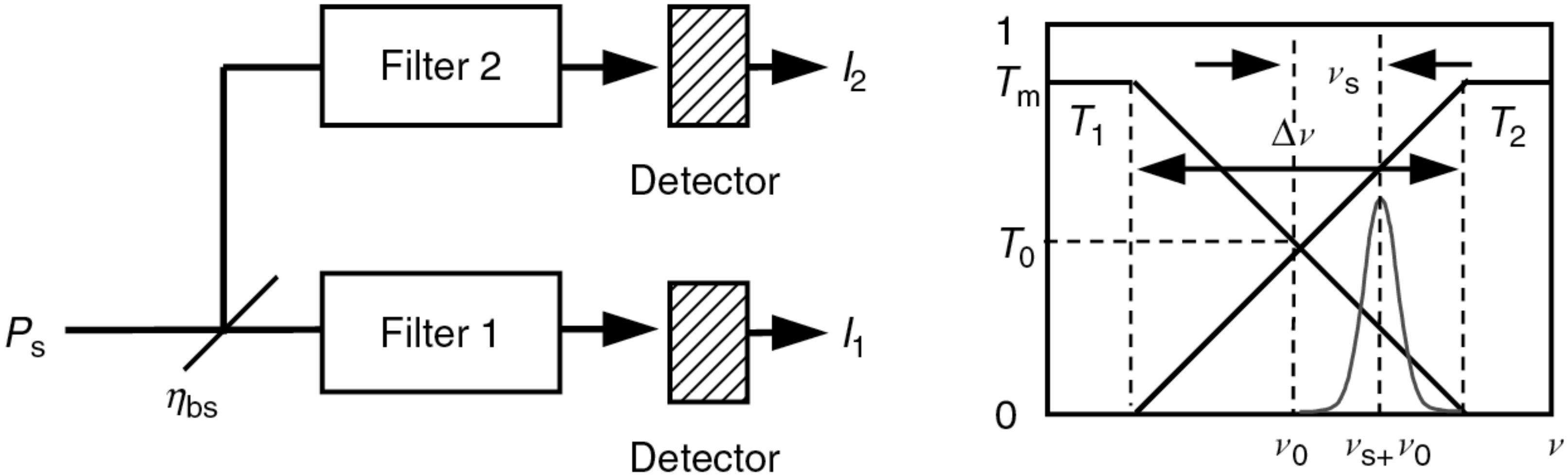


Figure 7.32 Double-edge functional diagram and filter transmission.

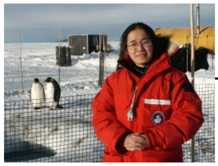
- Two oppositely sloped quasi-linear discriminator edges are used for the two receiver channels in the double-edge design. Usually etalon transmission fringes are used to create the edges. The etalons are locked together (mid-point) to the zero-Doppler transmitted laser frequency ν_0.

- The intensity ratio of the difference between the two signals to the sum is a sensitive function of the Doppler frequency shift ν_s.

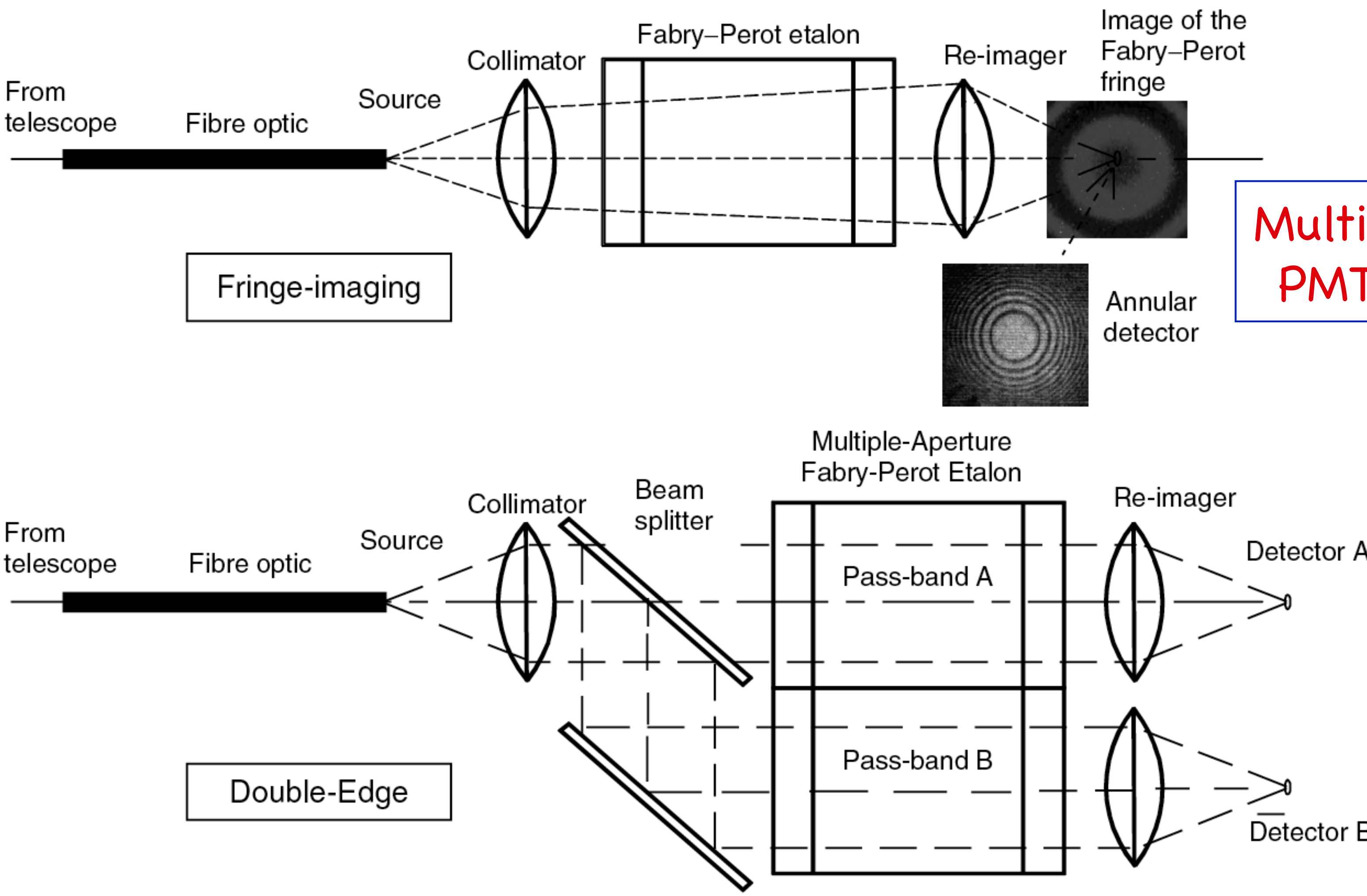
$$S = \frac{I_\Delta}{I_\Sigma} = \frac{I_1 - I_2}{I_1 + I_2} = \frac{T_{s_1} - T_{s_2}}{T_{s_1} + T_{s_2}} = \frac{2\nu_s}{\Delta\nu}$$

Detectors for FPI Edge-Filter DDL

- The information presented to the detector in an edge detection system is the image of the small on-axis solid angle corresponding to the central on-axis fringe of the Fabry-Perot etalon with the necessary spectral FWHM. A suitable detector will be one that has high quantum efficiency, low noise, the capability for photon counting or analog read-out, depending on the intensity of the signal, and which can be "time-gated" to provide range-resolved information.
- The conventional PMT, the APD, and the CCD are among several that have been used successfully, depending on the spectral region of the wind lidar. The PMT is a device that is essentially noise-free when used in photon-counting mode. Due to the negligible read-out and electronic noise, the PMT signal may be post-integrated with complete flexibility, leading to the PMT being widely used as a detector of choice, particularly at 355 and 532 nm. Its drawback is the modest quantum efficiency of the photocathode of the device, normally limited to values of order 40% or less, depending on the spectral region.
- 2-D detection: altitude range and time, similar to other lidars, except the fringe-imaging lidars.



Fringe Imaging vs Edge Filters

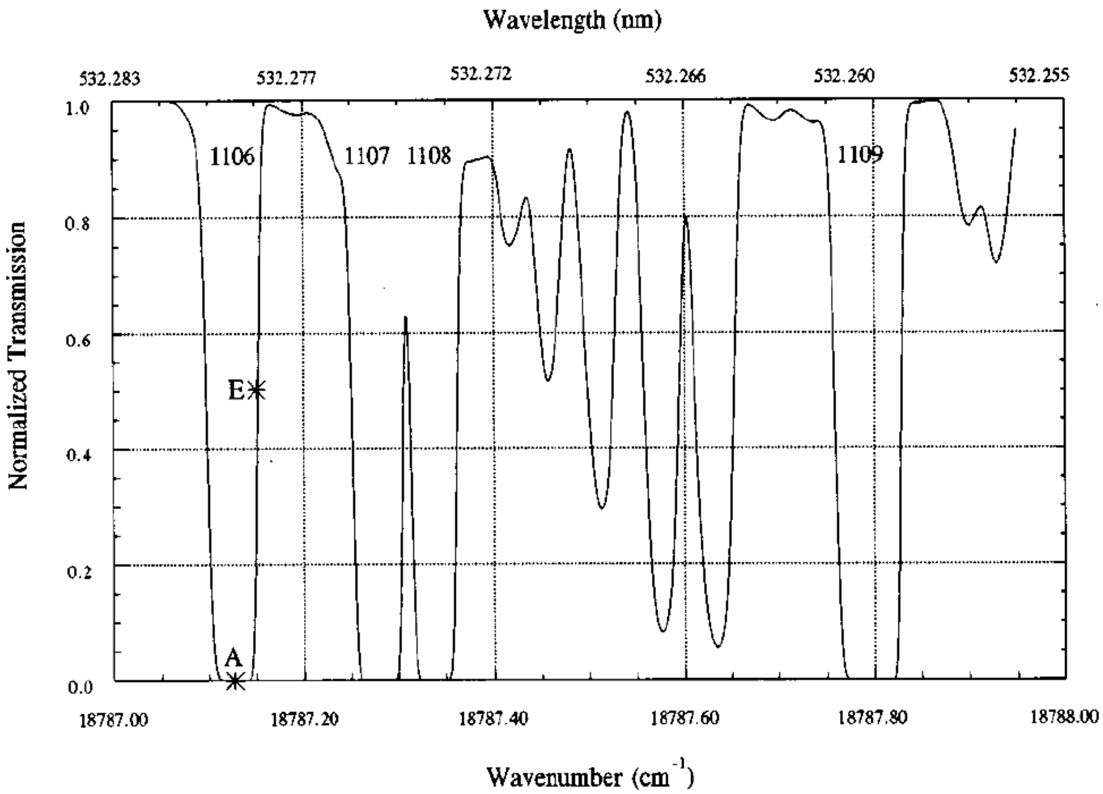


Multi-Channel PMT or CCD

PMT
APD
CCD

Figure 7.45 The fringe-imaging and double-edge detection methods for direct detection are shown conceptually.

I_2 Absorption Lines Edge-Filter DDL



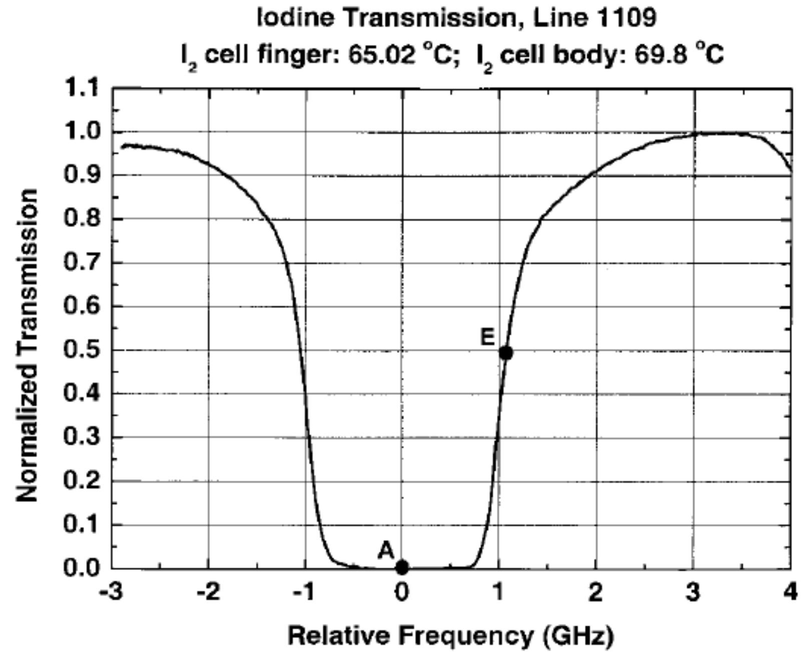
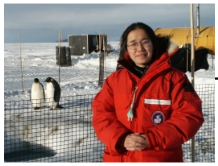
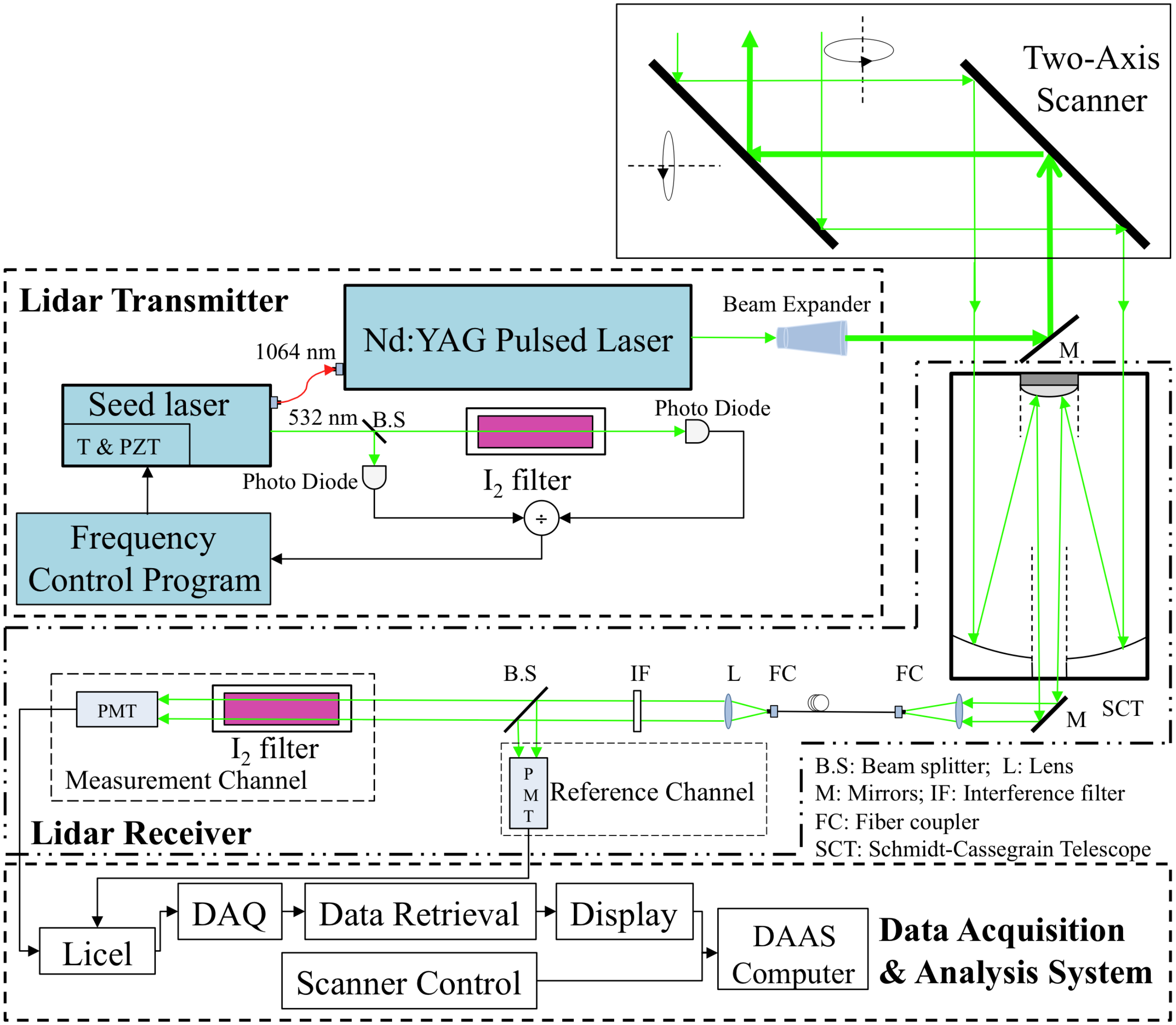


Fig. 2. Normalized transmission for absorption line 1109 of the iodine filter near 532 nm. The temperature of cell finger and cell body are 65.02 °C and 69.8 °C, respectively. The wave numbers at reference point A and locking point E are 18787.796 and 18787.830 cm^{-1} (1.02 GHz apart), respectively.

[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]

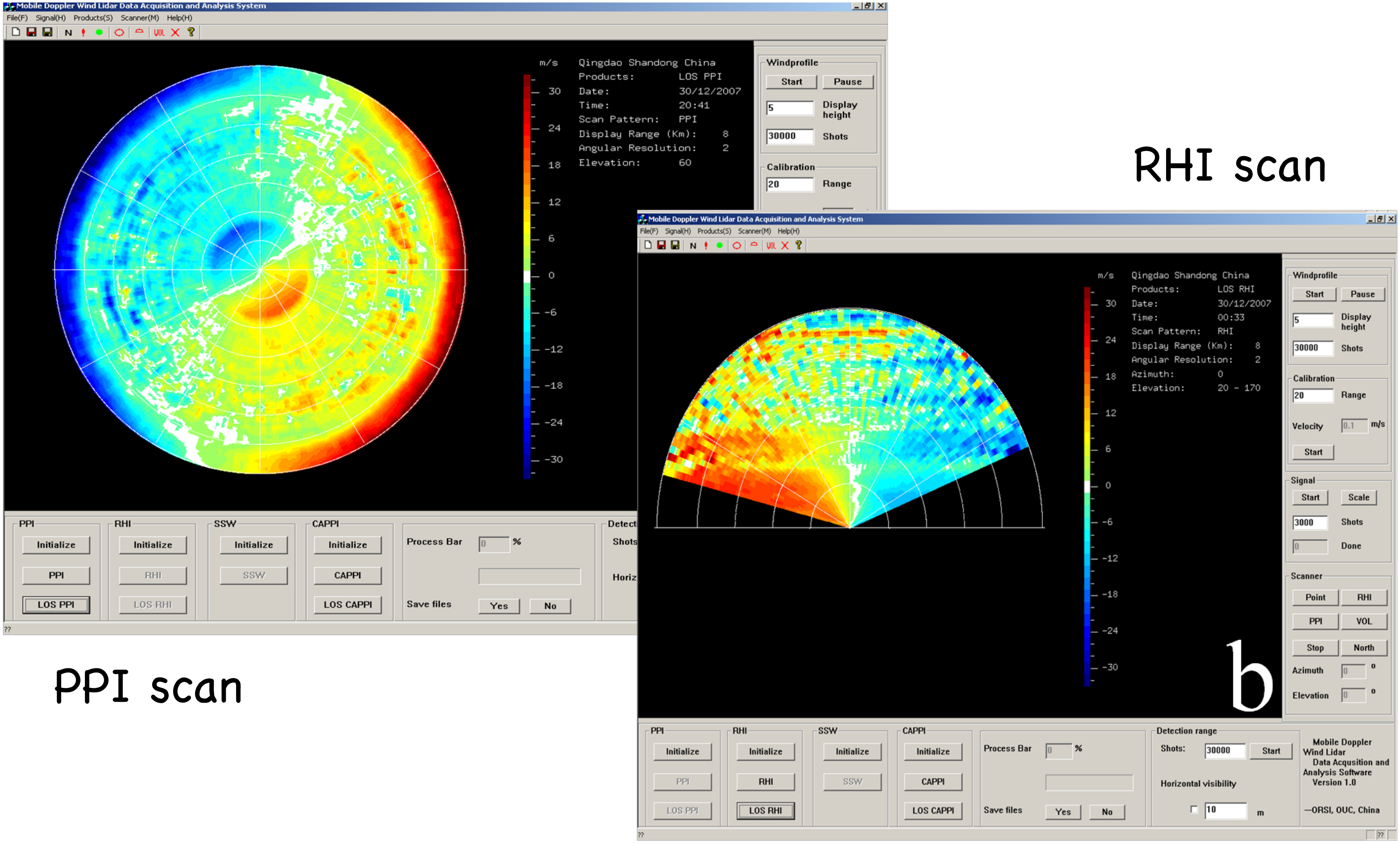


Iodine-filter-based Doppler Lidar



[Wang et al., Applied Optics, 49, 6960-6978, 2010]

Wind Measurements by I_2 Doppler Lidar



RHI scan

PPI scan

[Wang et al., Applied Optics, 49, 6960-6978, 2010]

Assumptions in Edge-Filter DDL

- To derive wind from edge-filter DDL, several quantities have to be taken from models or from independent measurements.

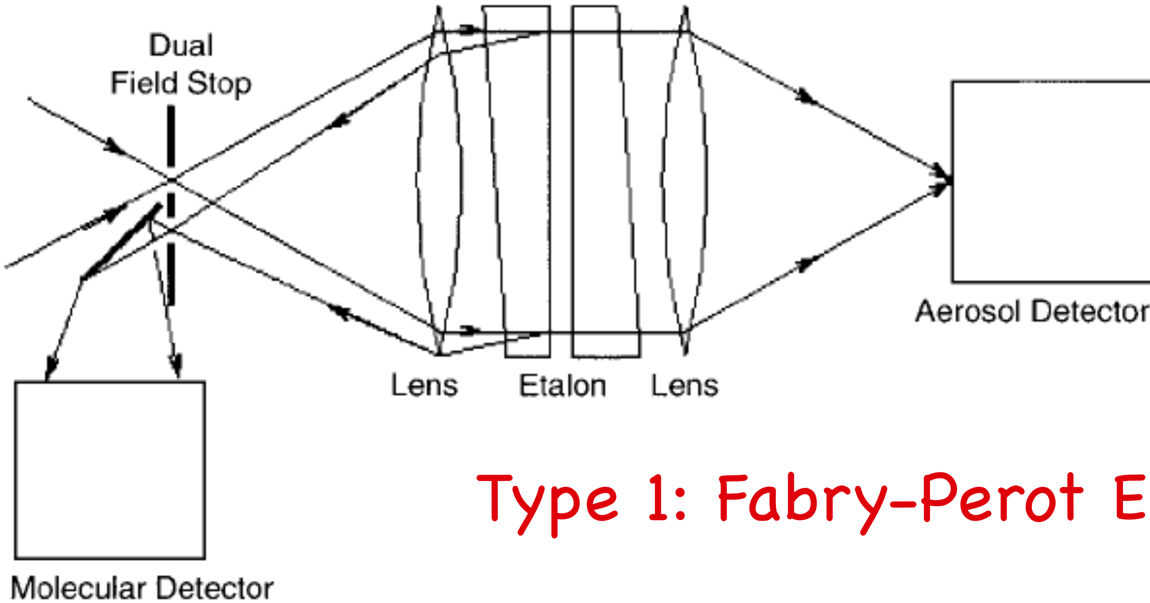
- Temperature profile: since the Doppler broadening (depending on temperature) affects the transmitted signal strength, it has to be pre-determined or taken from models for single or double-edge filters.

- Aerosol-scattering ratio also has to be determined independently when in the atmosphere region with aerosols. For example, in the I_2 filter case, tuning the Nd:YAG laser to point A can eliminate aerosol signal thus deriving the aerosol scattering ratio when combined with the reference channel.

- Background counts in each channel.

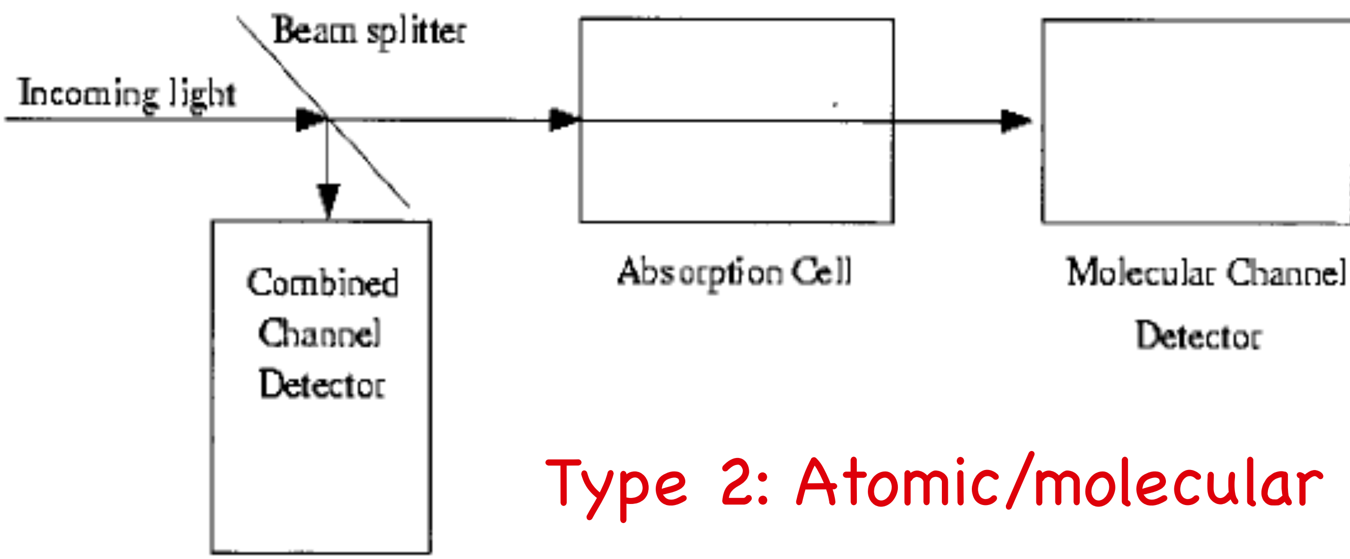
- Of course, filter transmission functions have to be known and determined to high precision and accuracy.

High Spectral Resolution Lidar



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

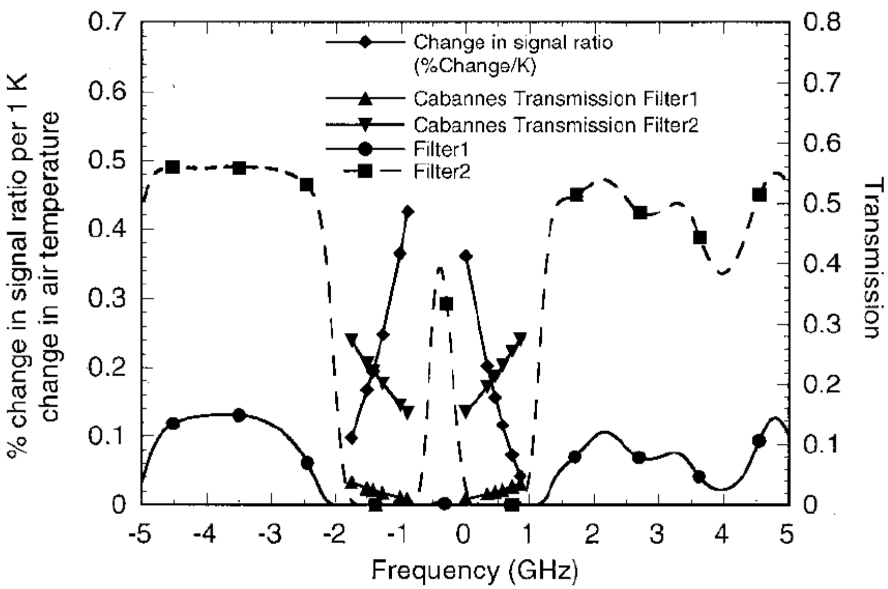
Type 1: Fabry-Perot Etalon/Interferometer

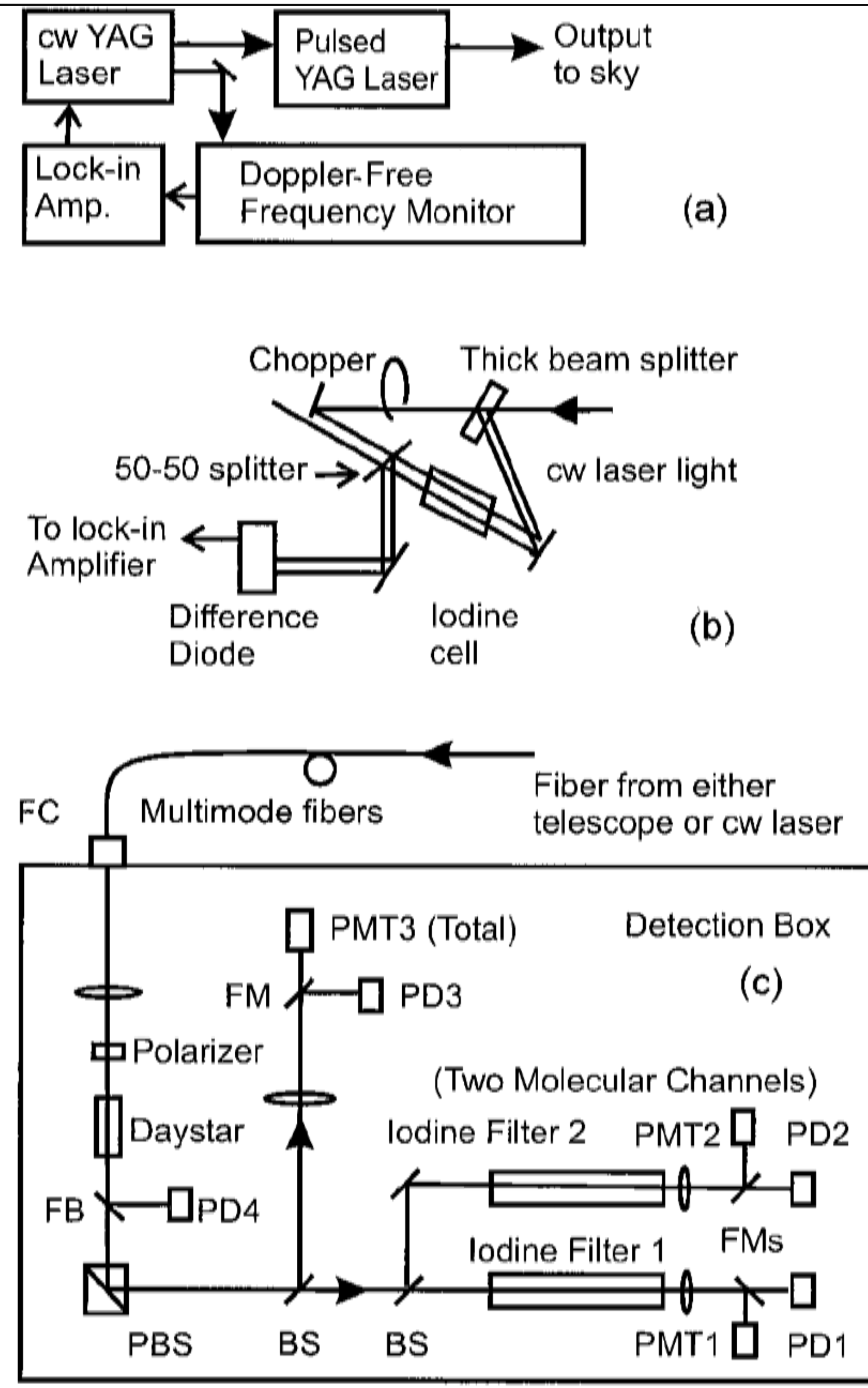


Atomic or molecular absorption block the aerosol scattering

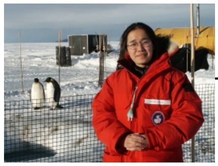
Type 2: Atomic/molecular blocking filter

HSRL Using I_2 Filter



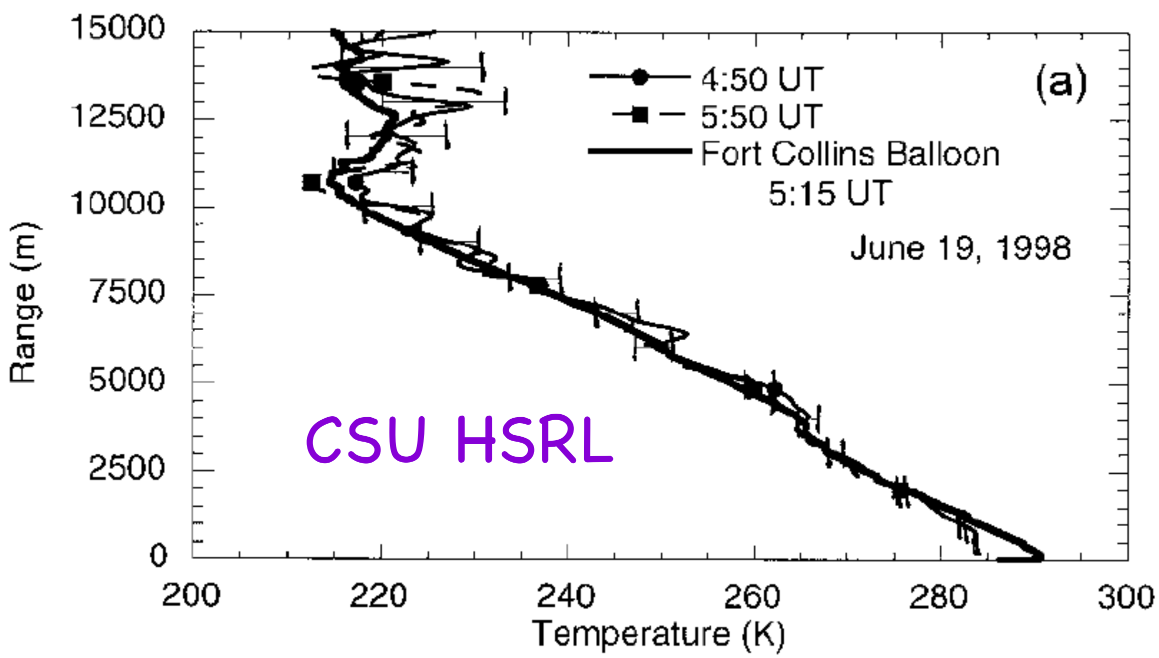


CSU HSRL
[Hair et al., Applied Optics, 40, 5280-5294, 2001]

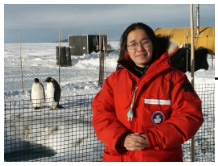


HSRL Temperature Measurements

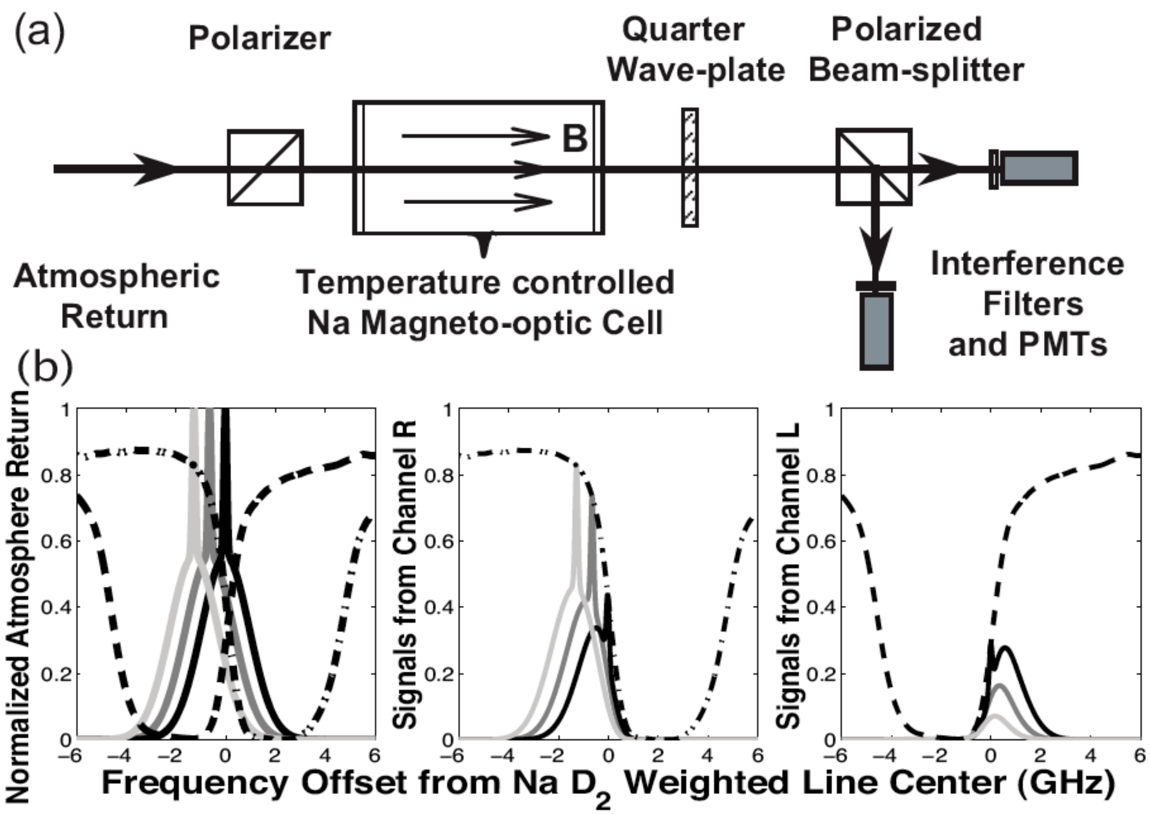
- The ratio of the Rayleigh scattering signals passing through two vapor cell filters (operating at different temperatures) is a function of atmosphere temperature.
- Laser has to be single frequency and locked to the narrowband filter. Measurements can go to 15 km.



- Majority of the Rayleigh scattering is filtered out!



Na/K Double-Edge Magneto-Optic Filter DDL

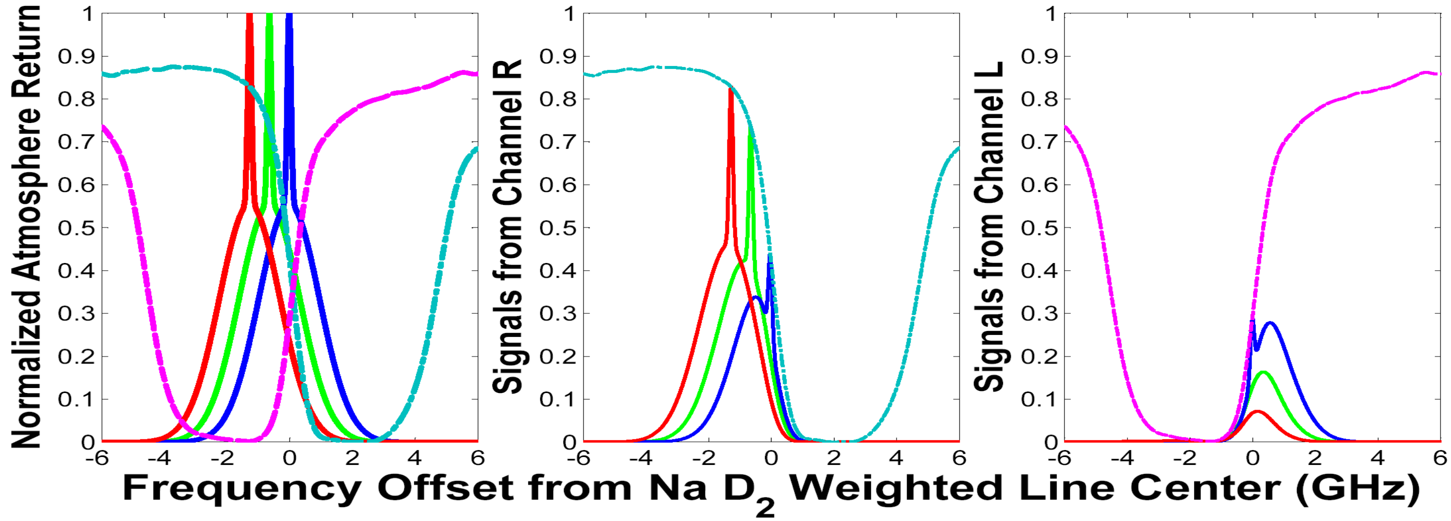


Na Double-Edge Magneto-Optic Filter (Na-DEMOF)

❑ With a 3-freq Na or K Doppler lidar, it is possible to measure wind, temperature, and aerosol simultaneously with a Na-DEMOF or K-DEMOF.

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

DEMOF with a 3-freq Na Doppler Lidar

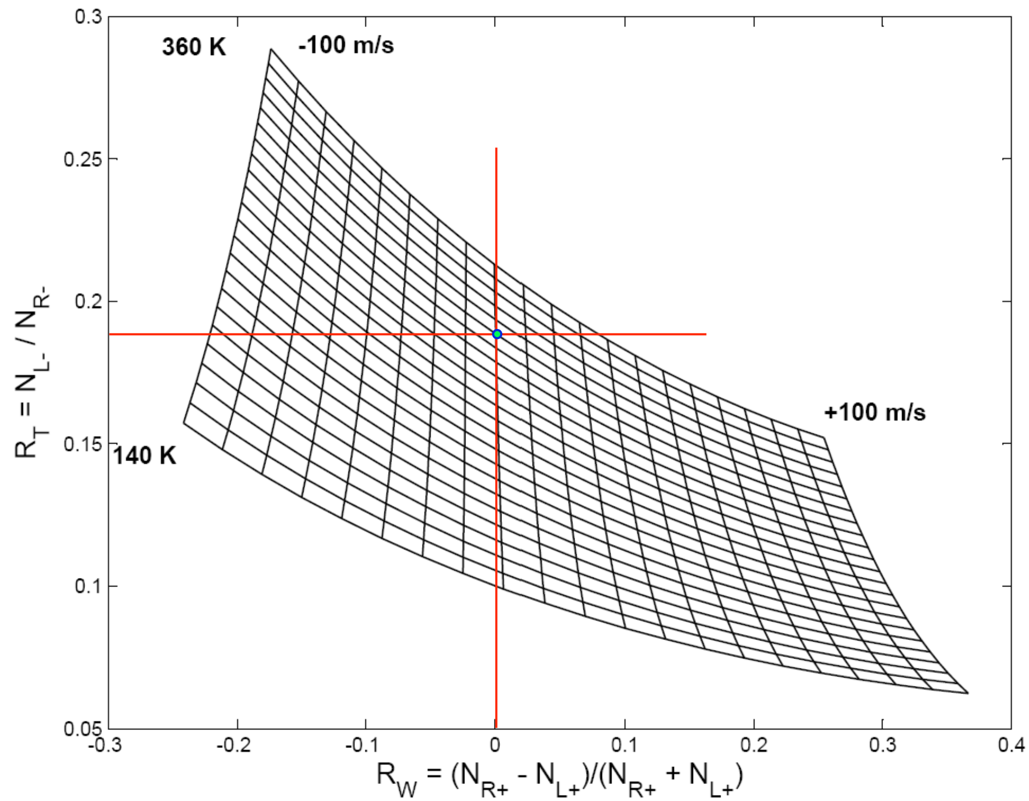


Calibration curves for ratio technique with Na-DEMOF

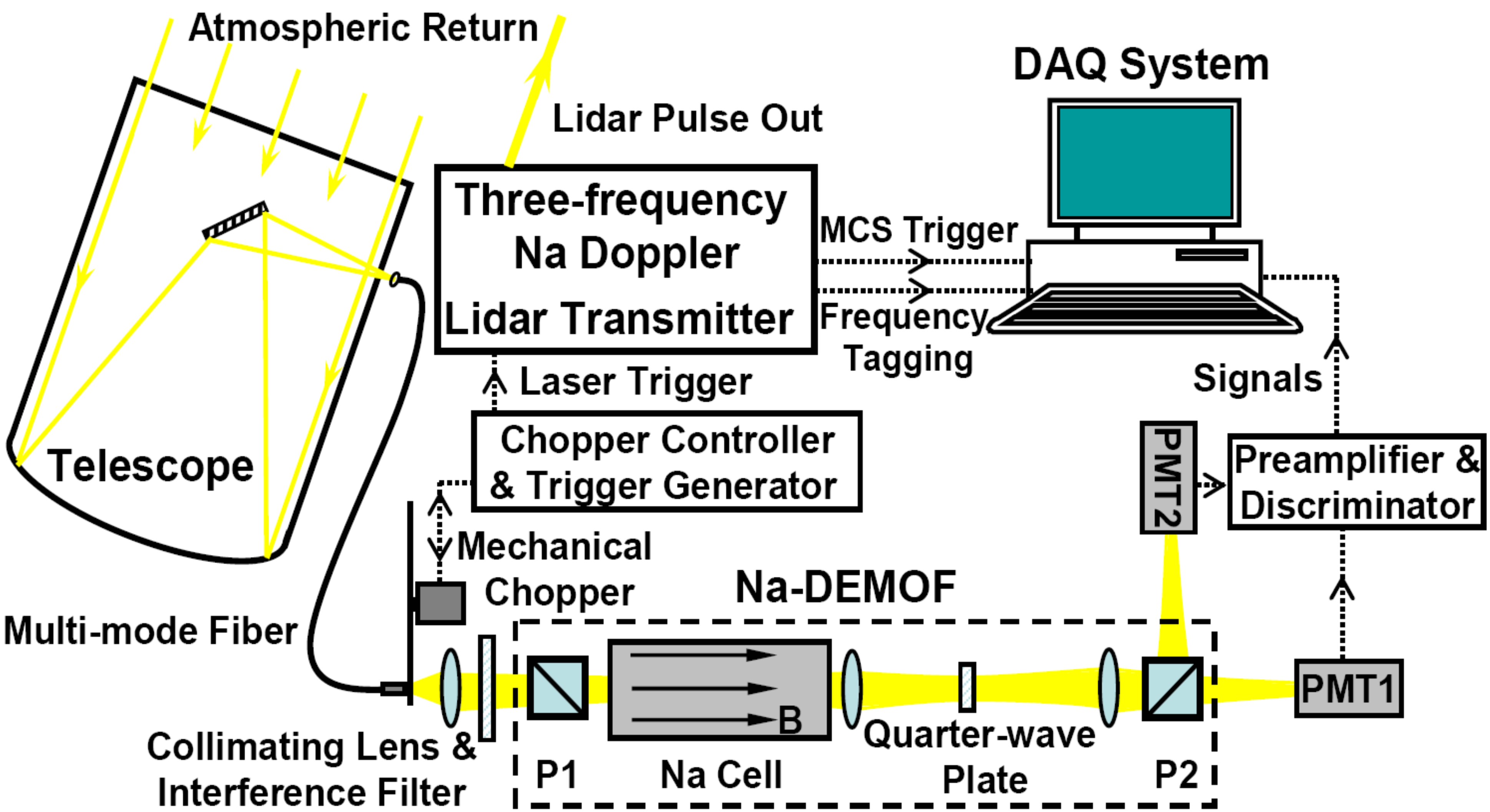
$$R_W(V_{LOS}, T, R_b) = \frac{N_{R+} - N_{L+}}{N_{R+} + N_{L+}}$$

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

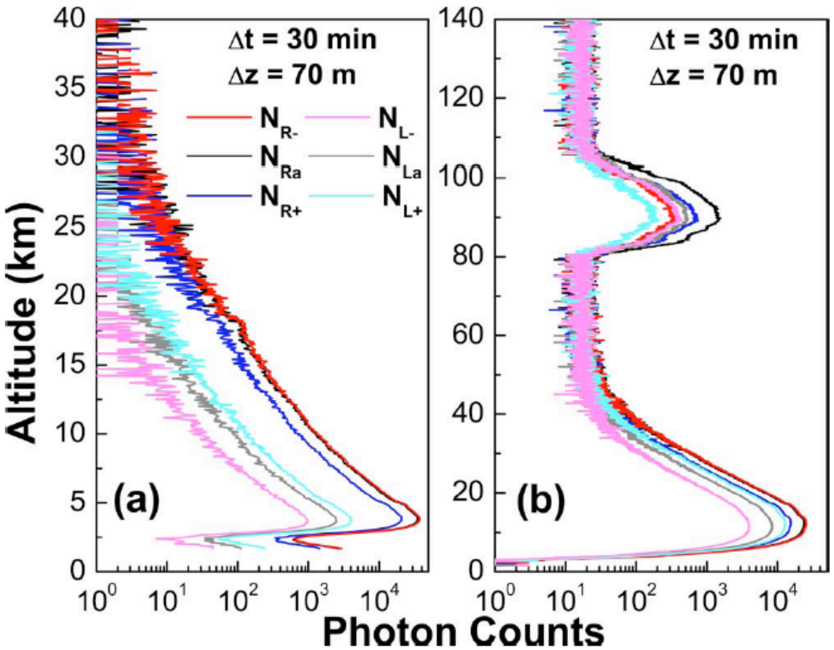
- Temperature and wind are determined simultaneously from two ratios.

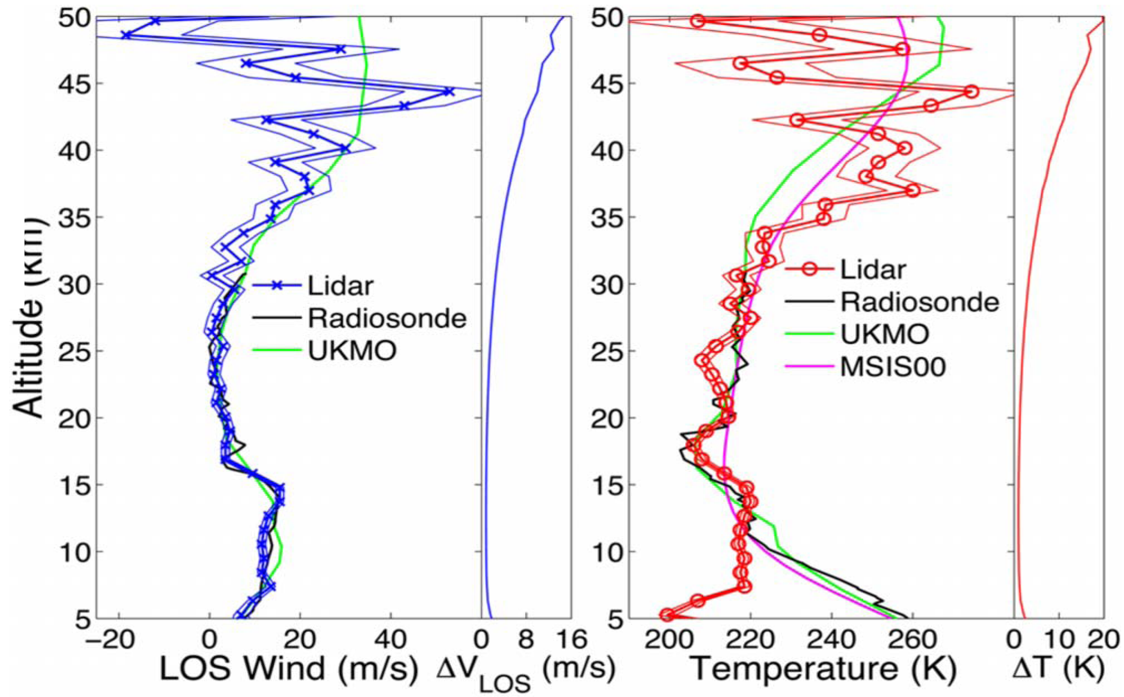


Field Demonstration of Simultaneous Wind and Temperature Measurements (10-45 km) with Na-DEMOF and 3-Frequency Na Lidar



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]

Summary

- Direct detection Doppler lidar uses atomic/molecular absorption lines, the edge filters, or fringe-imaging techniques to discriminate or analyze the frequency or spectrum of the return lidar signals (Doppler shifted and/or broadened). Potentially, DDL can measure both wind and temperature if sufficient spectral information is provided or inquired.

- For atmospheric science study, especially for waves coupling from lower to upper atmosphere, DDLs have very high potentials for the future, especially the combination of resonance DDL in MLT region with non-resonance DDL in the troposphere, stratosphere and lower mesosphere, we may be able to profile the wind and temperature from ground all the way up to 120 km. This will be a breakthrough for atmospheric science community.

Please read our textbook Chapter 7 for direct-detection Doppler lidar and for coherent-detection Doppler lidar.