Lecture 26. Wind Lidar (4)
Direct Detection Doppler Lidar

- ❑ Considerations (Accuracy and Precision) for DDL
- ❑ Na-DEMOF DDL

-- Multi-frequency edge-filter DDL

- ❑ New development of DDL

-- DDL based on Fizeau etalon

-- Optical Auto-covariance Wind Lidar (OAWL)

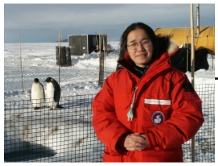
- ❑ Resonance fluorescence DDL
- ❑ Comparison of Wind Techniques
- ❑ Summary

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.



Papers on DDL wind measurements with a Cabannes-Mie lidar

- She et al., Appl. Opt., 46, 4434-4443, 2007: Comparison between iodine vapor filter and FPI
- She et al., Appl. Opt., 46, 4444-4454, 2007: impact of aerosol variations on the iodine filter methods
- There are several classic papers on the edge filter techniques providing good insight of the DDL techniques:
  - C. L.Korb, Bruce M. G. and C. Y. Weng, Edge technique: theory and application to the lidar measurement of atmosphere wind, Appl. Opt., **31**, 4202-4212, (1992).
  - M. L. Chanin, A. Hauchecorne, A. Garnier and D. Nedeljkovic, Recent lidar developments to monitor stratosphere-troposphere exchange, J. Atom. Sol. Terr. Phys., **56**, 1073-1081 (1994).
  - C. Flesia and C. L. Korb, heory of the double-edge molecular technique for Doppler lidar wind measurement, Appl. Opt., **38**, 432-440 (1999).

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 I2 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.

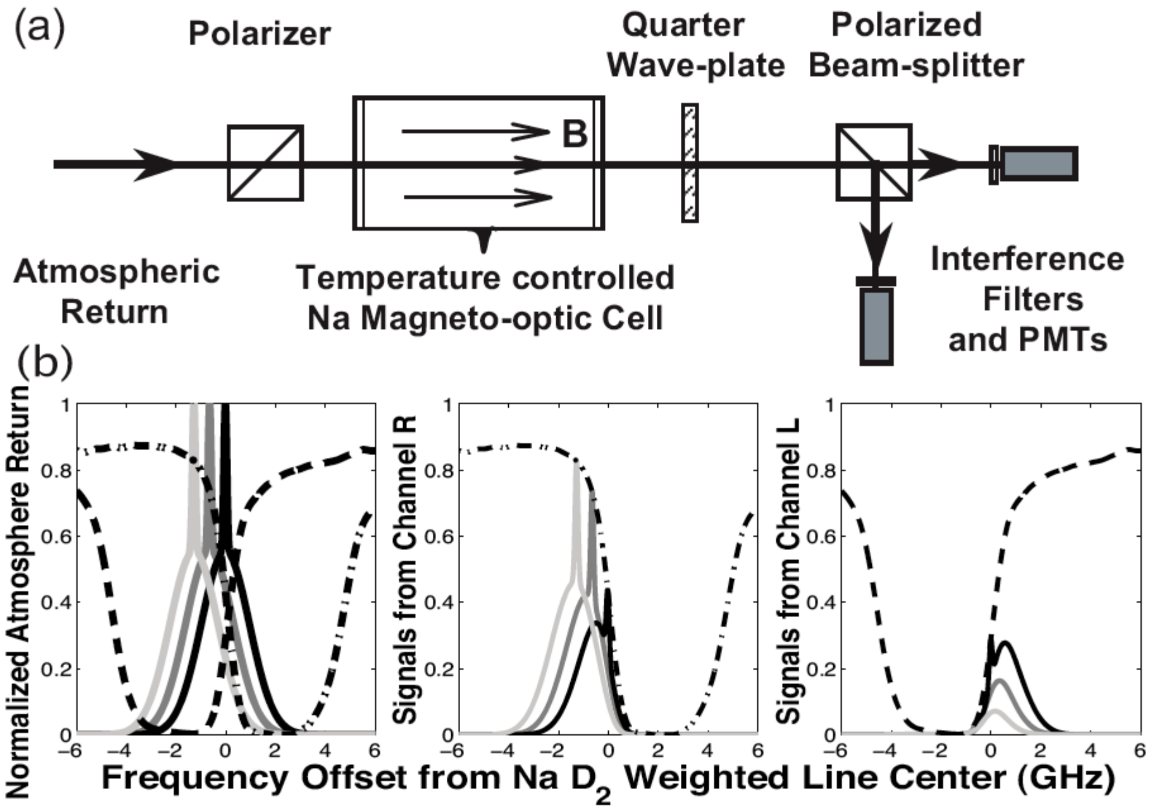
- Background counts in each channel.

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

Considerations for DDL

- Precision requirement: for δV = 1 m/s velocity precision, the freq measurement precision required for the optical freq analyzer in a DDL is $\delta\nu = 2(\delta V)/\lambda$ = 5.6 MHz for 355 nm.
- Accuracy requirement: accuracy should surpass the precision level. This is usually achieved by monitoring the transmitted laser pulse signal or alternatively measuring the backscatter signal from a stationary or very low velocity target or lock the laser and the filter transmission to each other.
- Calibration or accuracy is a main problem for non-resonance DDL, because the burden is on the receiver chain which is variable through time or surrounding conditions, especially in FPI case.
- On the other hand, resonance fluorescence Doppler lidars put the discriminator to the atomic absorption lines, which do not change with time. Their receivers can be much simpler.

Na/K Double-Edge Magneto-Optic Filter DDL

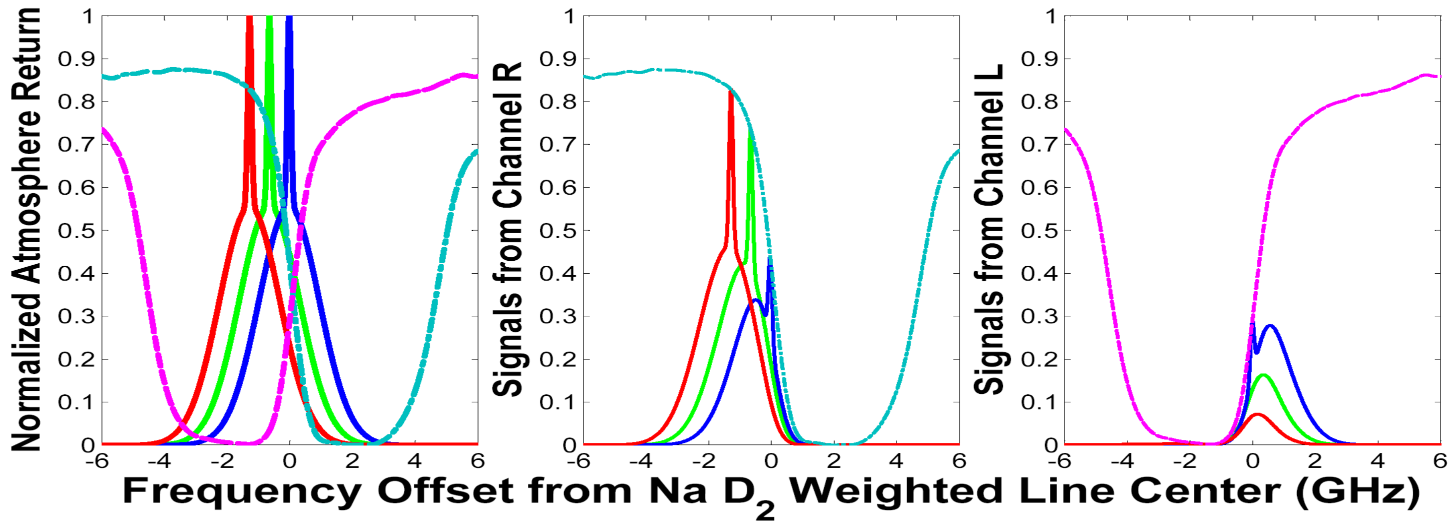


Na Double-Edge Magneto-Optic Filter (Na-DEMOF)

❑ 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

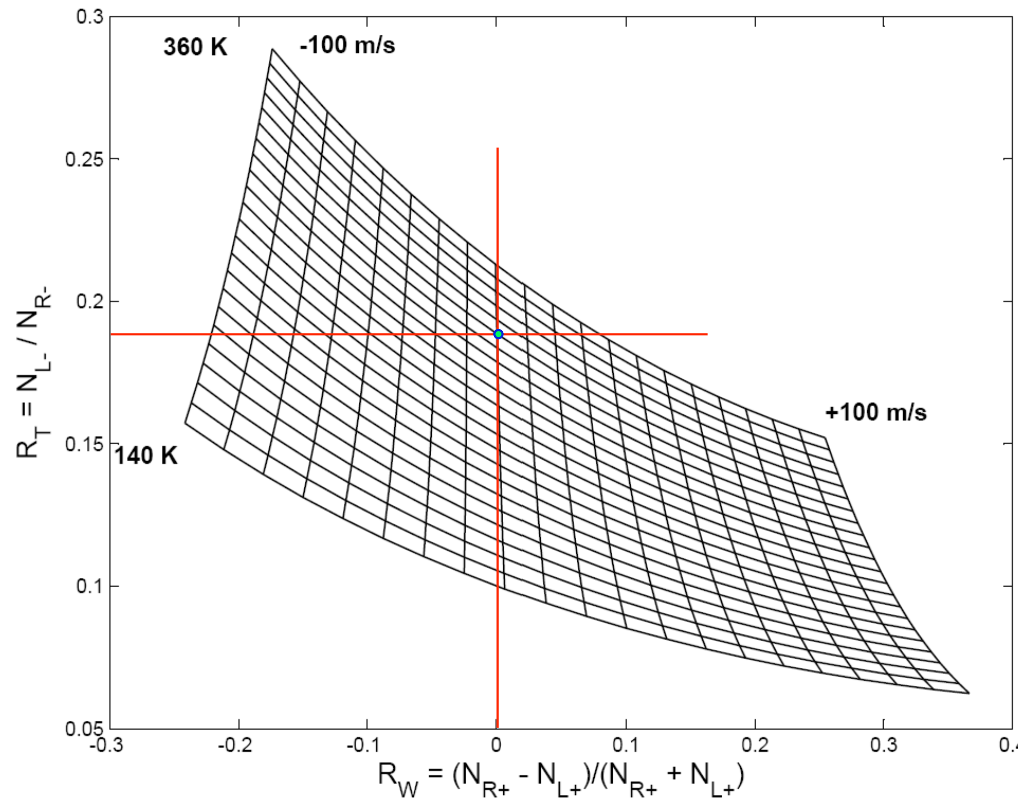


Calibration curves for ratio technique with Na-DEMOF

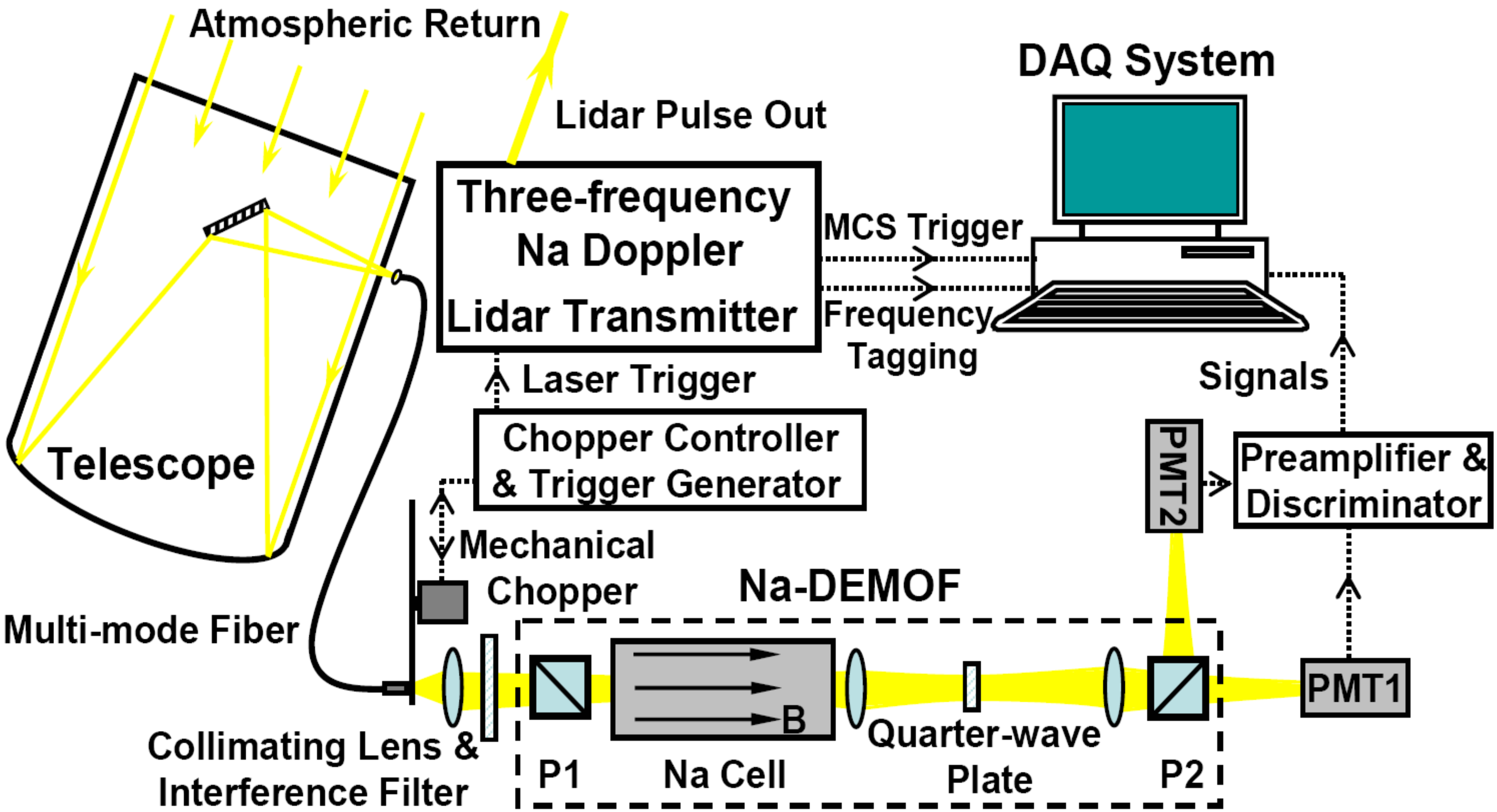
$$R_W(V_{LOS}, T, R_b) = \frac{N_{R+} - N_{L+}}{N_{R+} + N_{L+}}$$

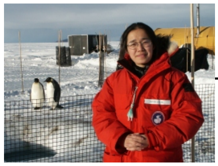
$$R_T(V_{LOS}, T, R_b) = \frac{N_{L-}}{N_{R-}}$$

➢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





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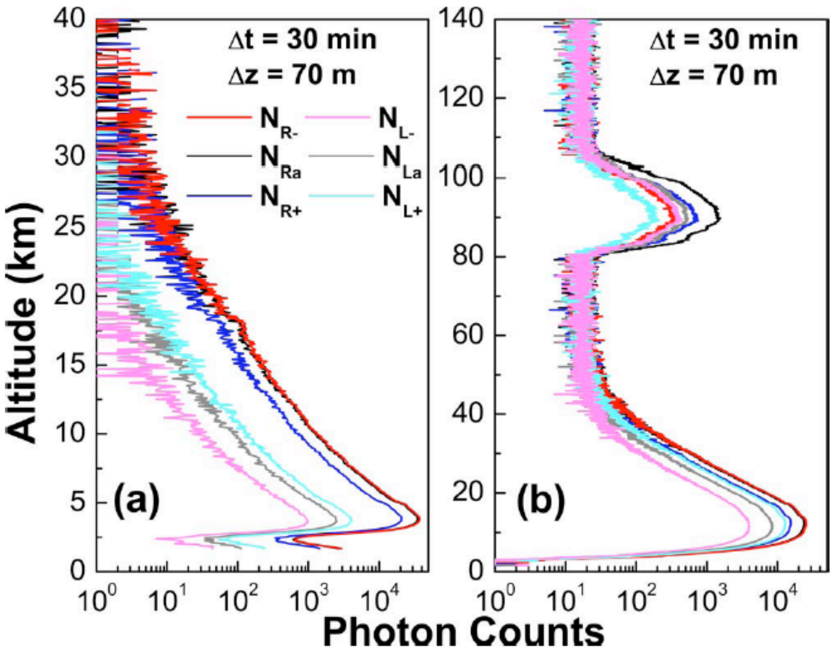
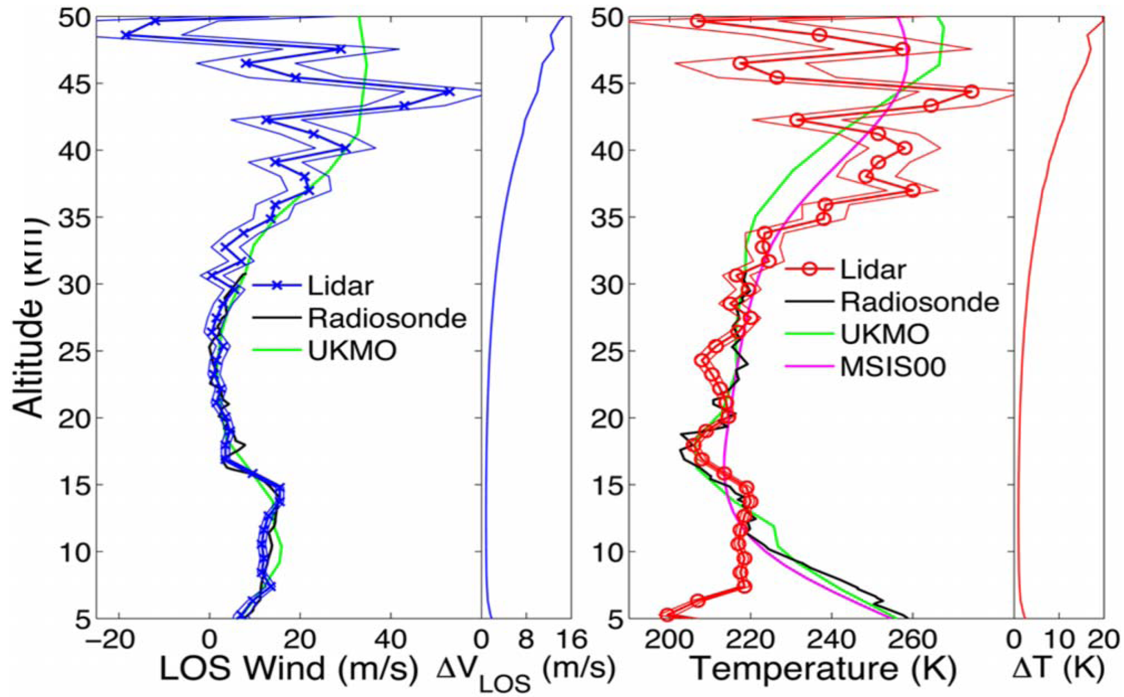
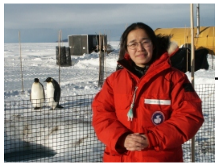


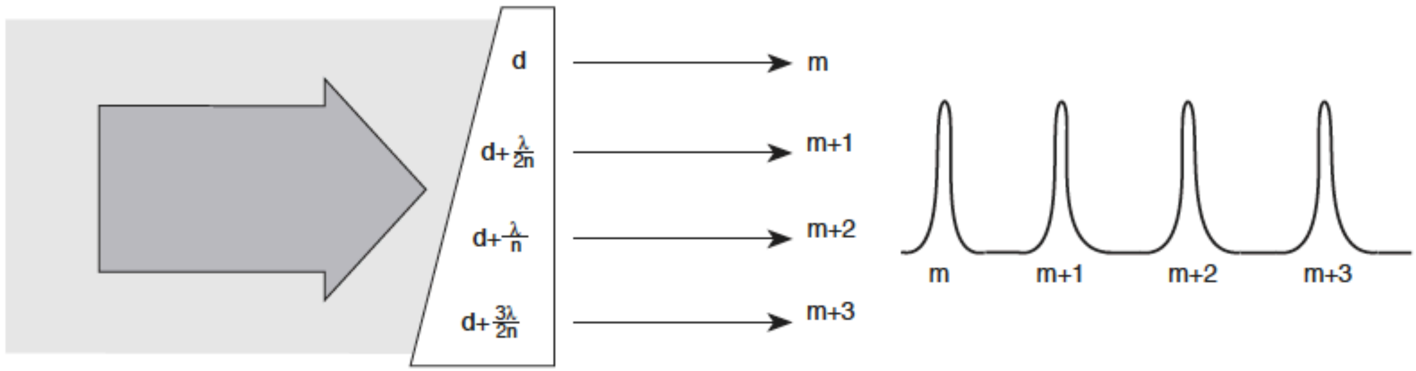


[Huang, Chu, et al., Optics Letters, 34, pp. 1552, 2009]

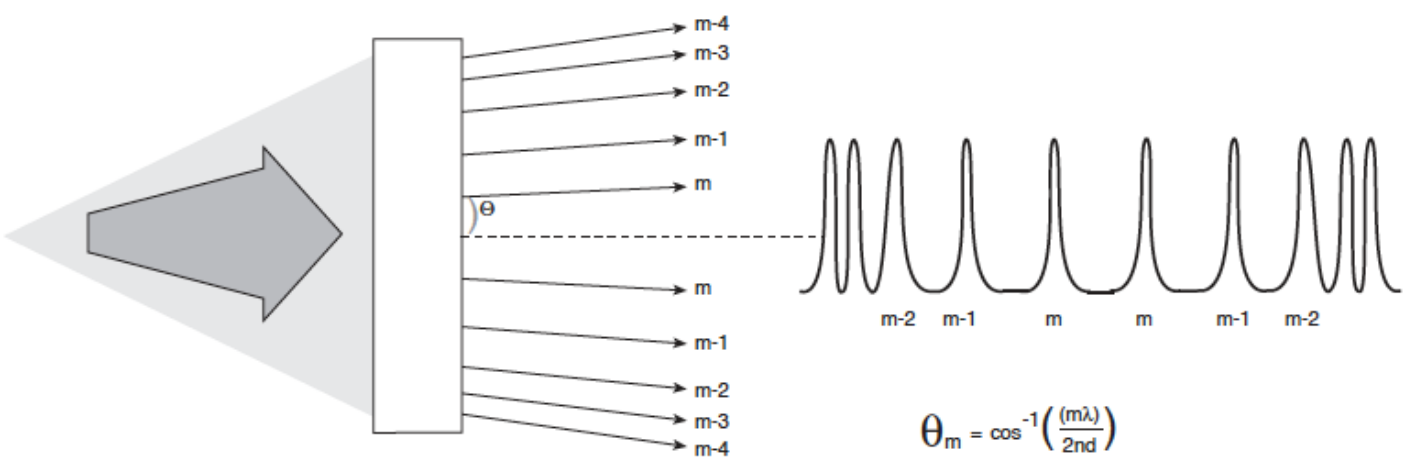


New Development of DDL Recently

- DDL based on Fizeau interferometer: linear fringes.



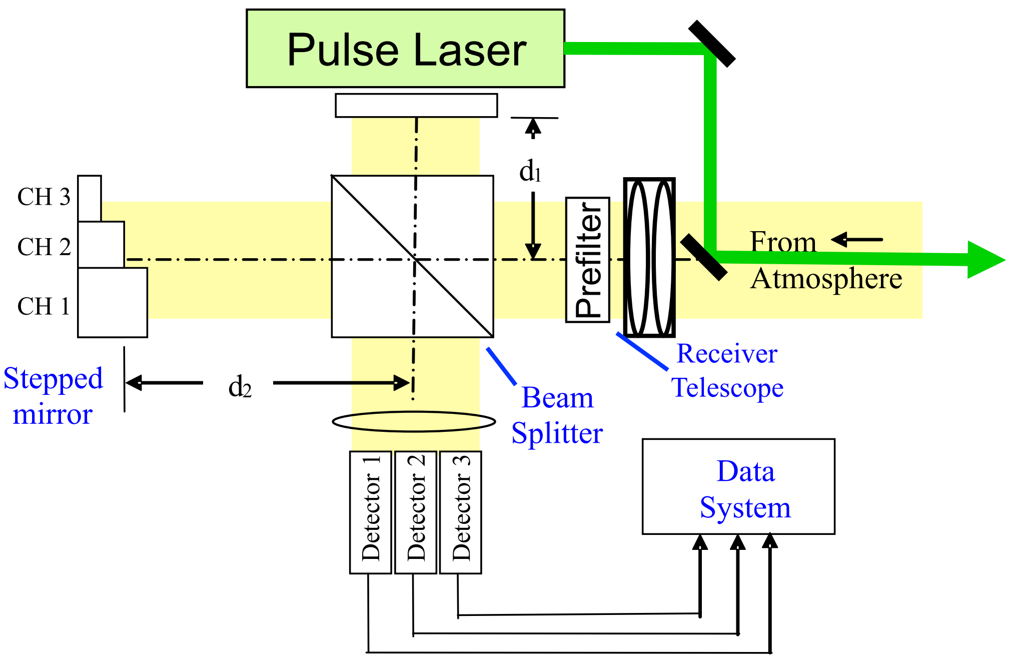
Fizeau etalon

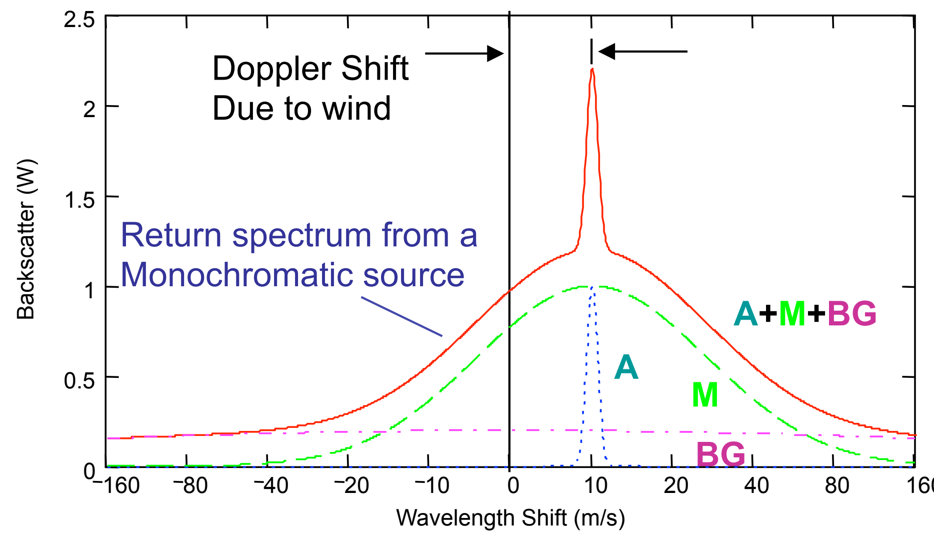


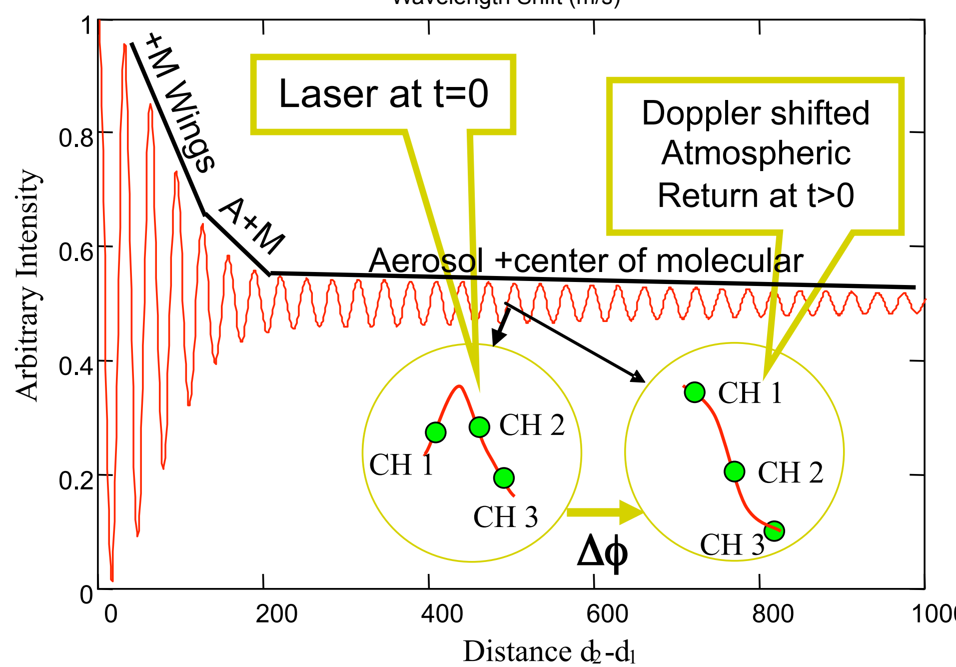
Fabry-Perot etalon

New Development of DDL Recently

- Optical Autocovariance Wind Lidar (OAWL):







$$V_{LOS} = \lambda * \Delta\phi * c / (4 * (d_2 - d_1))$$

Measured as a fraction (of $\Delta\phi$)

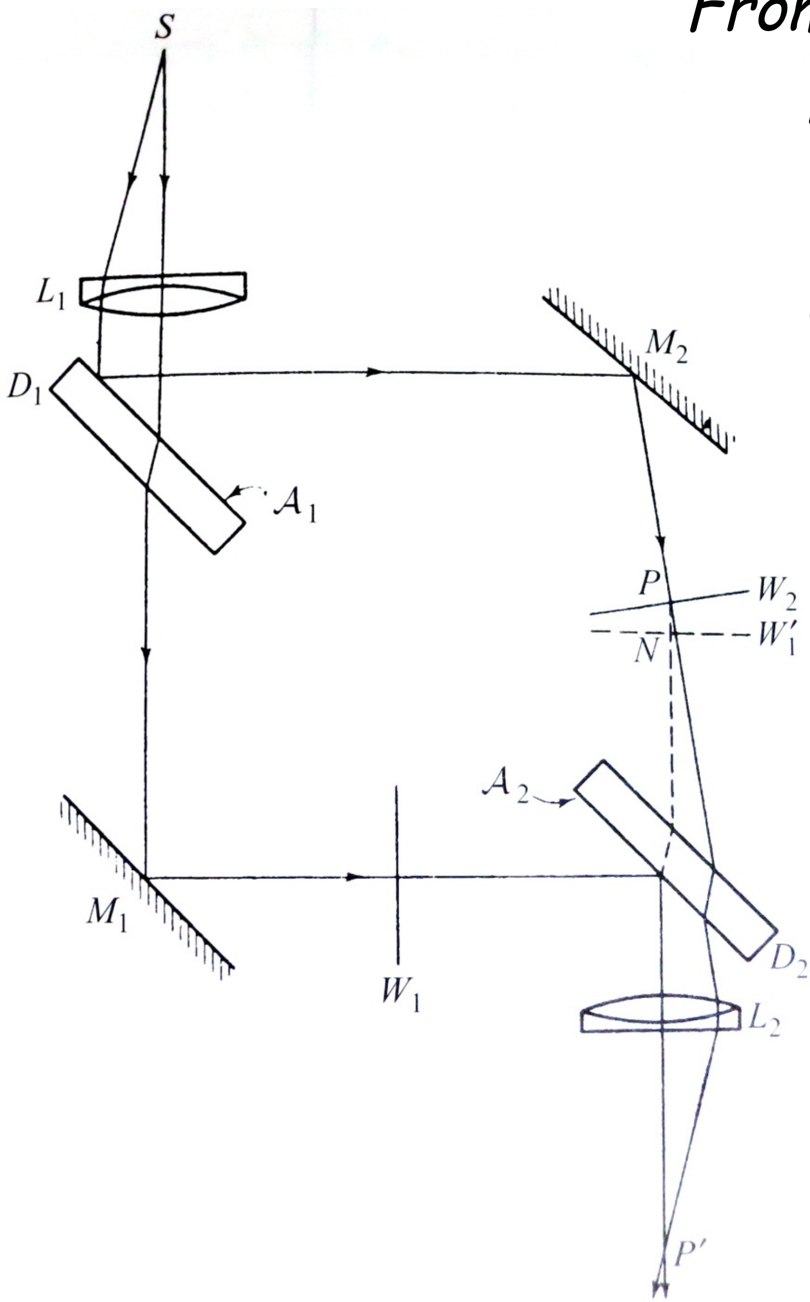
Optical Autocovariance Wind Lidar

By Christian J. Grund et al., ILRC, 2008

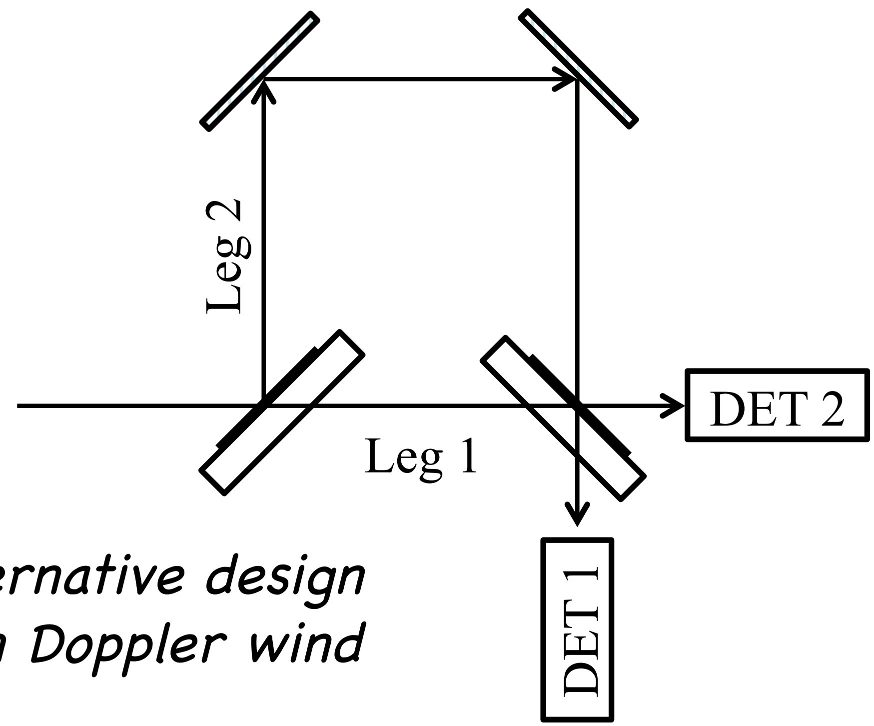
Conceptualized by Grund, Tucker, et al.

What is a Mach-Zehnder interferometer?

From Born and Wolf, 1999

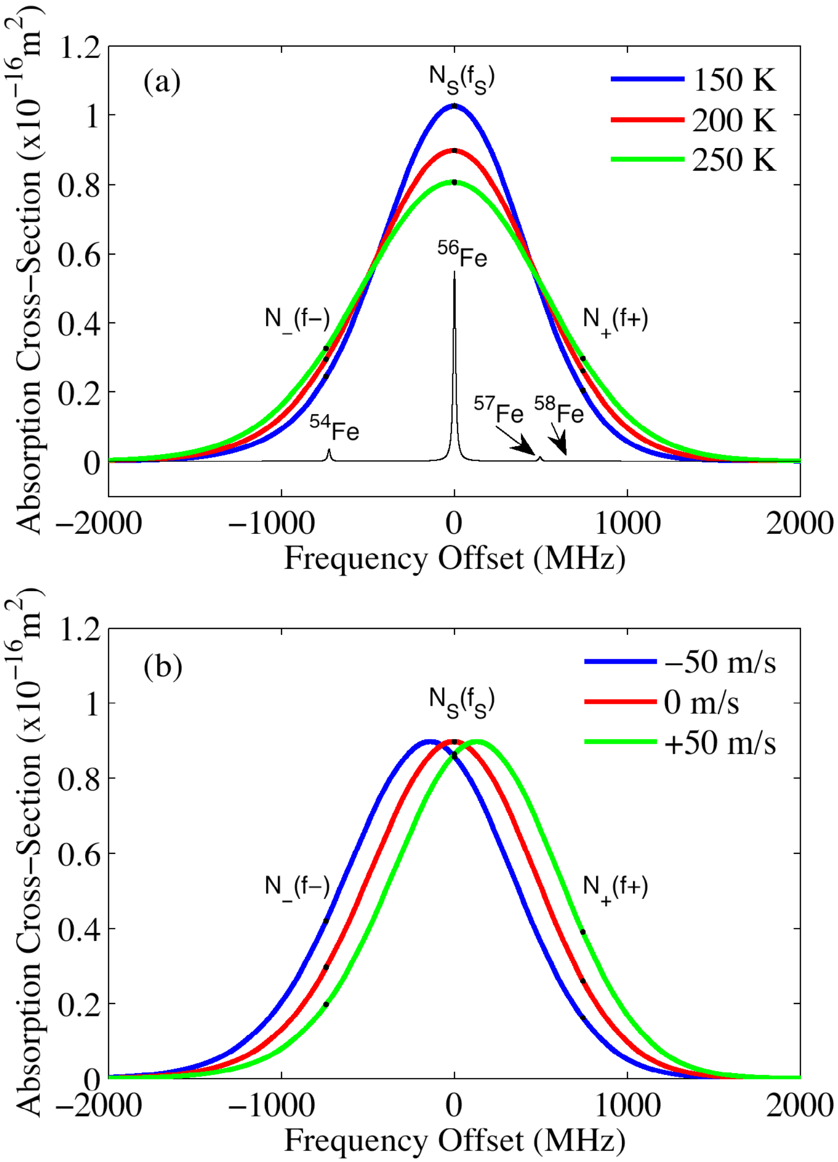


A Mach-Zehnder interferometer (MZI) consists of two (usually 50/50) beam splitters and two high reflectance mirrors in a fixed geometry. The optical path difference between each leg is related to the free spectral range and therefore analogous to the spacing of an etalon.

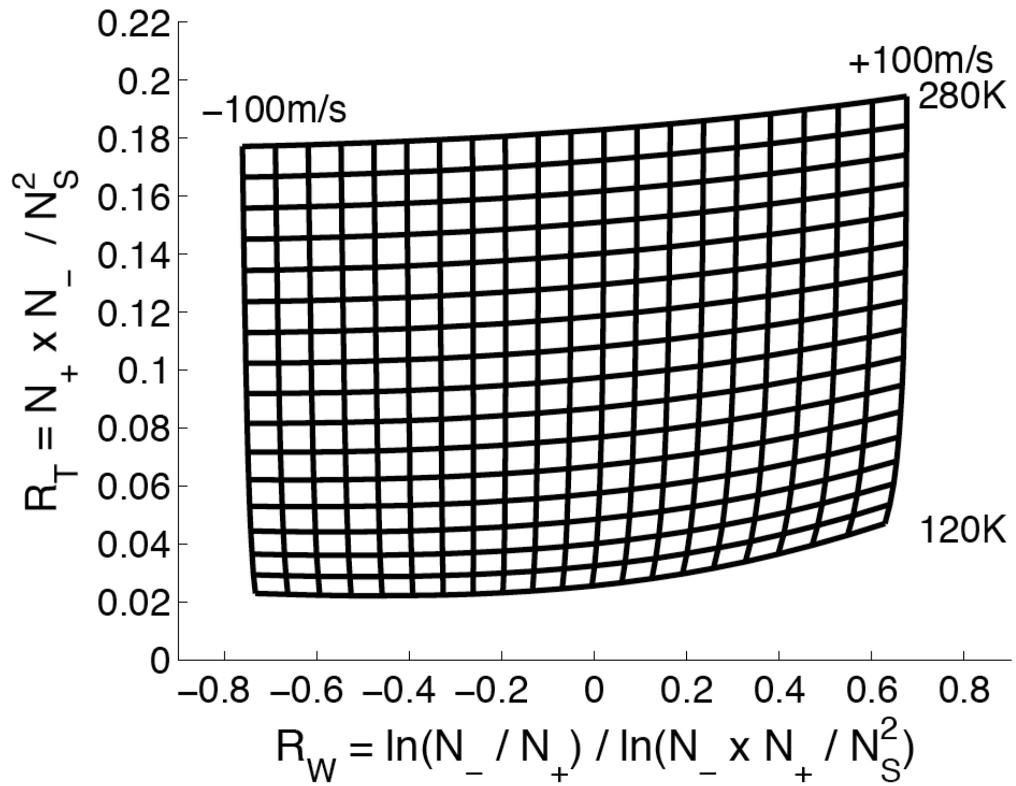


An alternative design used in Doppler wind lidars

Resonance Fluorescence DDL



Fe Doppler Lidar



Atomic Fe absorption lines undergo Doppler frequency shift & broadening, so acting as an frequency analyzer/discriminator

Comparison of Wind Techniques

Technique	Lidars	Applications
Doppler Wind Technique (Direct Detection or Coherent Detection): wind dependence of Doppler frequency shift (1 time Doppler shift for single absorption or emission process) (2 times Doppler shift for Mie and Rayleigh scattering)	Resonance Fluorescence Doppler Lidar: Doppler frequency shift and broadening of resonance fluorescence absorption cross-section (scan and ratio techniques)	Mesosphere and Lower Thermosphere temperature and wind (75-120 km); possible in thermosphere with other species
	Rayleigh/Mie Direct Detection Doppler Lidar : Doppler frequency shift of molecular and/or aerosol scattering using edge filters (absorption lines or etalons) or fringe imaging or scanning FPI or Michelson Interferometer	Lower mesosphere, stratosphere and troposphere wind (up to 50-60-70 km if there are enough photon counts)
	Coherent Detection Doppler Lidar: Doppler frequency shift of aerosol scattering using heterodyne detection technique	Troposphere wind, especially in boundary layers (up to 15 km), where aerosols are abundant
Direct Motion Detection Technique: derivative of displacement (the definition of velocity) (direct application of velocity definition or cross-correlation coefficient)	High-Spectral-Resolution Lidar: tracking aerosol / cloud motion through time	Troposphere wind, where aerosols and clouds are abundant
	(Scanning) Aerosol Lidar: tracking aerosol motion through time	Troposphere wind, where aerosols and clouds are abundant
	Laser Time-of-Flight Velocimeter: measuring time-of-flight of aerosol across two focused and parallel laser beams	Within the first km range, laboratory, machine shop, etc.
	Laser Doppler Velocimeter: measuring the frequency of aerosol scattering across the interference fringes of two crossed laser beams	Within the boundary layers, wind tunnel, production facility, machine shop, fluid mechanics research, etc

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.