Lecture 21. Wind Lidar (1)

- Motivations to Measure Global Wind
- Techniques for Wind Measurements

(Direct motion detection technique, Doppler wind technique)

- Direct Motion Detection Technique

(Tracking aerosol/cloud motion, LTV, LDV)

- Coherent Detection Doppler Wind Lidar
- Direct Detection Doppler Wind Lidar

(Atomic absorption lines, Edge filters, Fringe imaging)

- Wind Technique Comparison
- Summary

Motivations for Wind Measurements

- Global atmospheric wind profiles from ground to 120 km are important for validation of the output of global atmosphere models, and for study of the atmosphere dynamics, as wave information can be inferred from the wind measurements.

- Temperature measurements are mainly for science-oriented purpose - model validation and climate change monitoring. But wind/velocity measurements have much more applications in industry, environment, and defense business. For example,

(1) Aircraft true airspeed, aircraft wake vortices

(2) Clear air turbulence, wind shear, gust fronts

(3) Air pollution monitoring

(4) Vibration of objects

(5) Laboratory, machine shop, production facility, wind tunnel

… … etc.

Techniques for Wind Measurements

Use wind-dependent effects or use definition of wind

- ❑ **Direct Motion Detection Technique:**

(using the definition of velocity)

$$\boxed{\vec{v} = \frac{d\vec{r}(t)}{dt}}$$

(1) Tracking aerosol/cloud motions
(2) Laser Time-of-Flight Velocimetry
(3) Laser Doppler Velocimetry

- ❑ **Doppler (Shift) Wind Technique:** $\boxed{\Delta\omega = -\vec{k}\cdot\vec{v}}$ or $\boxed{\Delta\omega = -2\vec{k}\cdot\vec{v}}$

(1) Coherent (Heterodyne) Detection Doppler Wind Lidar

(2) Direct Detection Doppler Wind Lidar

- ❑ **Geostrophic wind detection:**

Temperature ⇒ Pressure Gradients ⇒ Geostrophic Wind

Direct Motion Detection for Wind

- Use the definition of velocity, i.e., velocity is the derivative of displacement vector

$$\vec{v} = \frac{d\vec{r}}{dt}$$

- Wind tracers are needed to track the motion, i.e., the position changes with time
- Aerosols, clouds, or smokestack plumes, i.e., any inhomogeneities in the atmosphere provide excellent tracers.

Common approaches for detecting motion remotely

- Crosswind determination by pattern correlation

(1) Tracking aerosols, clouds, plumes, trails by images

(2) Tracking Aerosol/cloud motion by lidars

- Laser Time-of-Flight Velocimetry (LTV)
- Laser Doppler Velocimetry (LDV)

Cross-Correlation of Cloud Pattern

- The inhomogeneities, such as aerosol particles, cloud droplets, smoke-stack plumes, show patterns easily recognized with naked eyes. If the positions of these patterns are tracked at consecutive time, then the wind that causes the patterns to shift can be derived.

- One way of doing so is to take images of such pattern at two points in time, t_1 and t_2. And if the geometric parameters such as distance, angle of observation, and imaging scale are known, then the two-dimensional pattern H(x, y) of the object can be determined from the images. Then it is sufficient to find those two values (Δx, Δy) by which the second image must be shifted to give maximum similarity with the first one. This is to maximize the cross-correlation coefficient between the two images:

$$\boxed{Q(\Delta x, \Delta y) = \iint H(x, y, t_1) H(x - \Delta x, y - \Delta y, t_2)\, dx dy = \text{maximum}}$$

- The two-component velocity vector in the plane perpendicular to the line of sight is then given by the simple relation:

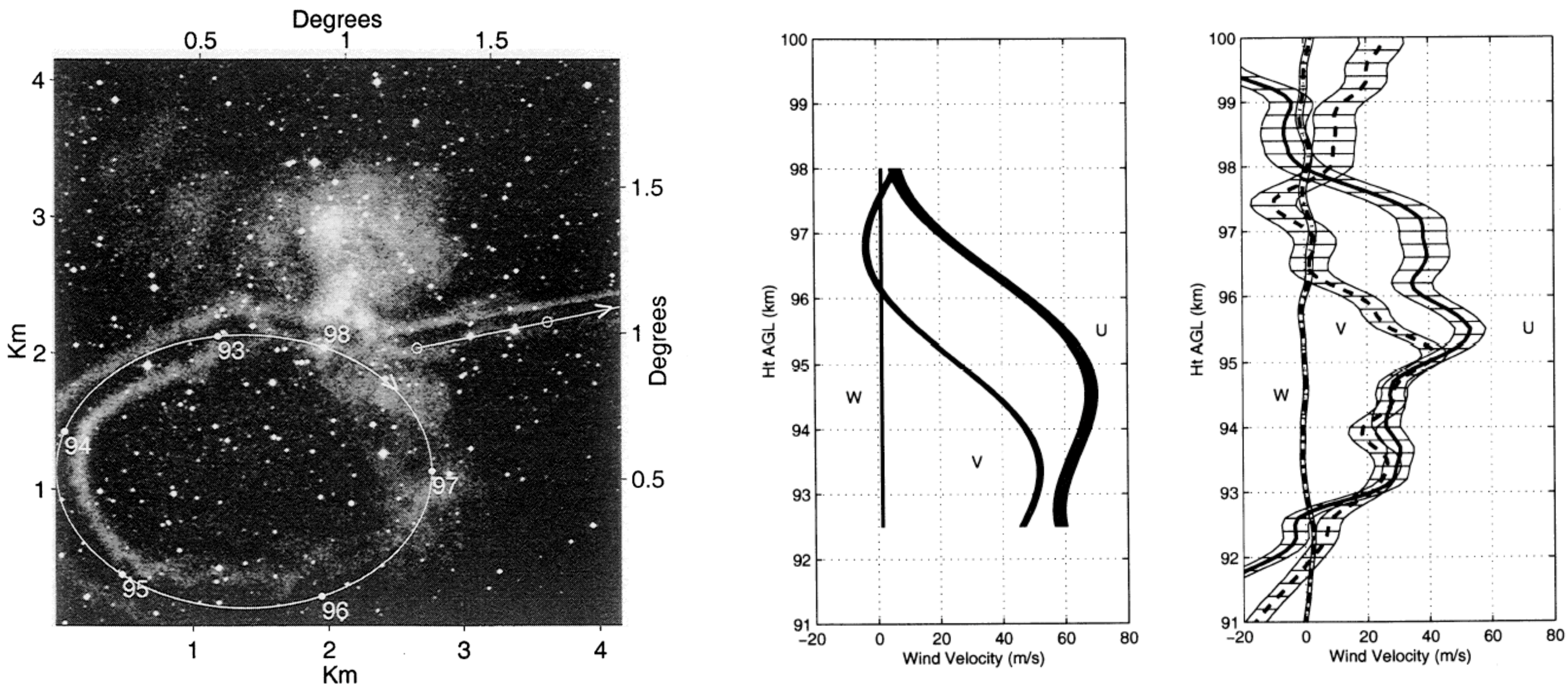
$$\boxed{\vec{u}_{hor} = \frac{1}{t_2 - t_1} (\Delta x, \Delta y)}$$

Cross-Correlation of Cloud Pattern

- Some exciting applications of this approach include

(1) tracking a plume sent by a rocket (chemical release) to derive wind vector and how it varies with time;

(2) tracking long lifetime meteor trails to derive wind vector.



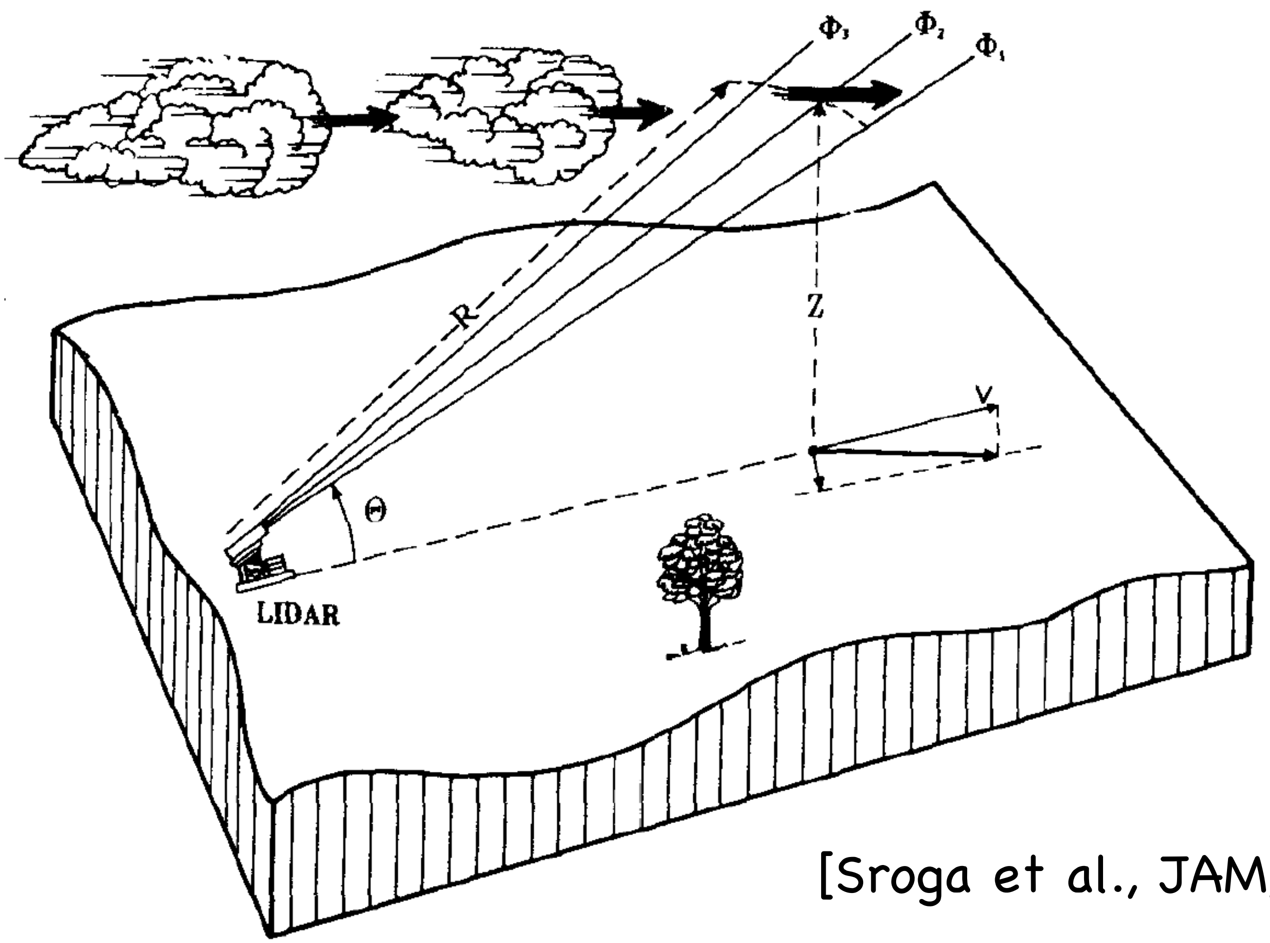
1998 Leonid Meteor Shower at SOR

-- [Drummond et al., JGR, 2001]

Lidar Tracking of Aerosol Motions

- Using lidar to track aerosol/cloud patterns is a much efficient way and can measure wind during both day and night.
- Lidar signals backscattered from the planetary boundary layer are dominated by scattering from aerosol particles. The fluctuations in aerosol content are easily detected with lidar. By observing the drift of these spatial inhomogeneities, lidar can be used to determine wind velocities remotely. Temporal and/or spatial correlation techniques using lidar profiles of aerosol backscatter intensity were developed by Eloranta et al. in 1970s at the University of Wisconsin-Madison.
- In the example on the next page, the lidar is elevated by a small angle and is rapidly scanned between three closely spaced azimuth angles.
- The horizontal wind component perpendicular to the lidar beam is obtained by measuring the time interval needed for aerosol inhomogeneities to drift from one azimuth angle to the next.
- The longitudinal component of the wind is determined from the radial displacement that occurs during this cross-path drift time.
- Today scanning HSRL has made the wind measurement via tracking aerosol/cloud to a high degree of sophistication (Eloranta group).

Lidar Tracking of Aerosol Motions



[Sroga et al., JAM, 1980]

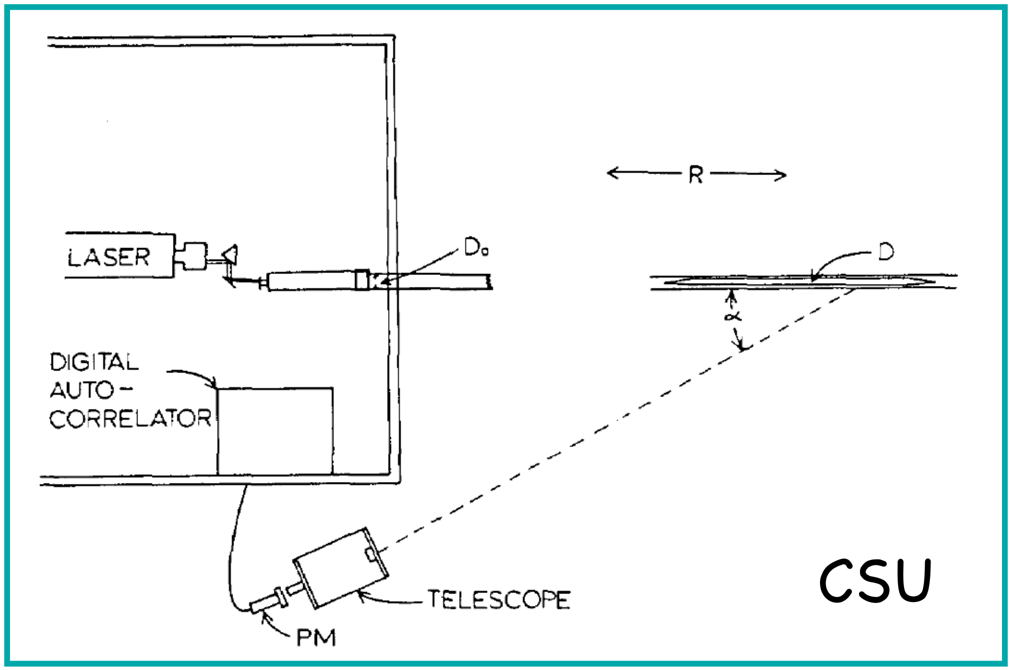
FIG. 1. The geometry used for lidar wind measurements. The lidar is operated at a constant small elevation angle and scanned back and forth between three closely spaced azimuth angles ϕ_1, ϕ_2 and ϕ_3. Range-resolved profiles of backscattered intensity are recorded at ~1 s intervals for a period of 2–5 min to produce a wind measurement. Wind velocities are calculated in terms of a radial component v and a cross-path component u.

Laser Time-of-Flight Velocimetry (LTV)

- This dual-beam technique measures the speed of a cross wind by determining a particle's time of flight across two approximately parallel beams with a small spatial separation, as illustrated in the plot.
- The output of a cw laser is focused into two parallel beams of equal intensity, with a beam-to-beam separation D. A single aerosol particle traveling across both focused spots scatters two light pulses (flashes) by the time of flight T, which depends on its speed and the predetermined separation distance D.
- The perpendicular component of wind speed is then given by

$$\boxed{V_{\perp} = D/T}$$

- Field demonstrate went up to 100 m range under natural aerosol conditions.



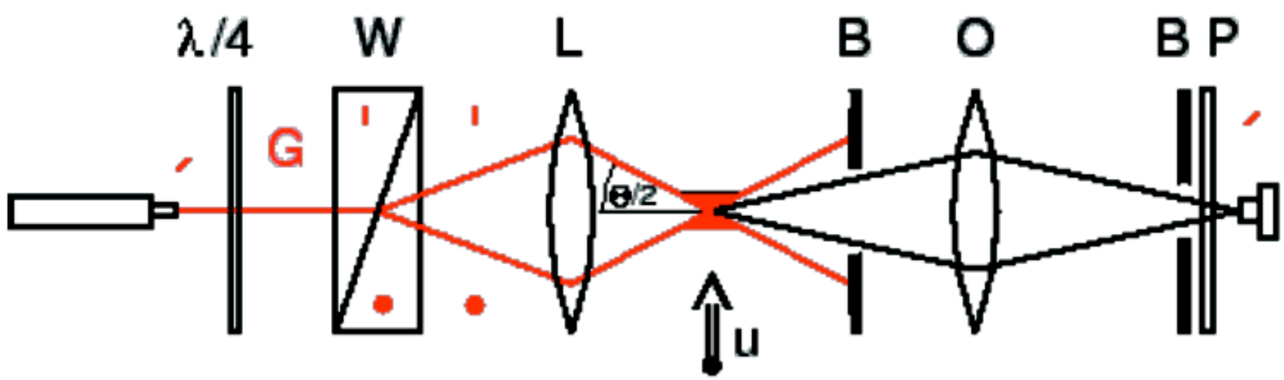
[Bartlett and She, Opt. Lett., 1977]

Laser Doppler Velocimetry (LDV)

- Two laser beams split from the same laser beam cross with each other and form interference pattern, acting as a periodic field of regions with high and low intensity.
- Particles transversely cross the field and scatter light (strong and weak) periodically with a frequency that is proportional to their speed.

$$\boxed{u = \frac{\lambda f}{2\sin(\theta/2)}}$$

u is the speed perpendicular to interference pattern, λ is the laser wavelength, f is the frequency of particle scattering light, θ is the angle between two laser beams.



One Way to Understand LDV

- The interference between two laser beams forms a lattice with the interval given by

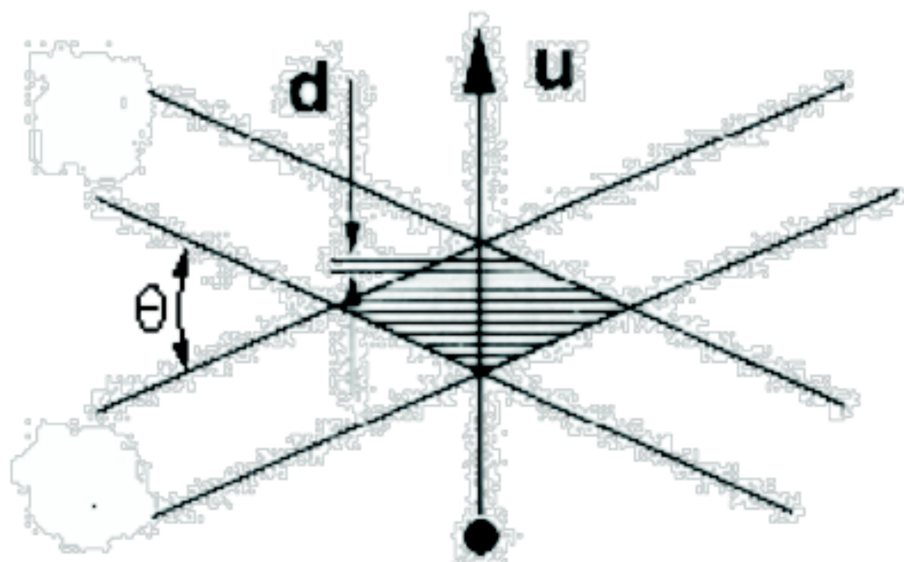
$$\boxed{d = \frac{\lambda}{2\sin(\theta/2)}}$$

- Particles pass through the lattice with a speed of u, so the frequency of particles scattering strong light is given by

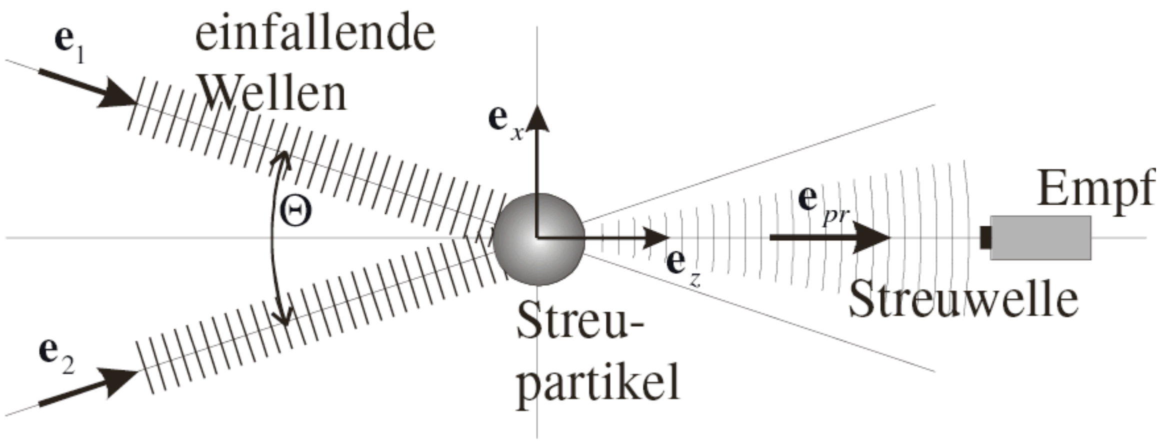
$$\boxed{f = \frac{1}{T} = \frac{1}{d/u} = \frac{u}{d}}$$

$$\Downarrow$$

$$\boxed{u = df = \frac{\lambda f}{2\sin(\theta/2)}}$$



Another Way to Understand LDV



$\vec{e}_1, \vec{e}_2, \vec{e}_x, \vec{e}_y, \vec{e}_{pr}$ are unit vectors

- When a particle scatters light in the intersection, both laser beams are scattered, suffering Doppler shift due to the motion of the particle.
- Due to the slightly different angle of the beams, the Doppler shifted laser frequencies are slightly different, given by

$$f_1 = f_L \frac{1 - \vec{v}_p \cdot \vec{e}_1 / c}{1 - \vec{v}_p \cdot \vec{e}_{pr} / c} \qquad f_2 = f_L \frac{1 - \vec{v}_p \cdot \vec{e}_2 / c}{1 - \vec{v}_p \cdot \vec{e}_{pr} / c}$$

- The light received at the photo-detector is a superposition of the two scattered light beams - a superposition of the amplitudes, not intensities.

$$E_1 = A_1 \sin(2\pi f_1 t) \qquad E_2 = A_2 \sin(2\pi f_2 t)$$

Continued for LDV

- The superposed amplitude is given by $\vec{E} = \vec{E}_1 + \vec{E}_2$
- So the intensity at the photo-detector is

DC components — Filtered out by bandwidth

$$I \propto \vec{E} \cdot \vec{E}^* = \boxed{A_1^2 \sin^2(2\pi f_1 t) + A_2^2 \sin^2(2\pi f_2 t)} + \boxed{A_1 A_2 \cos[2\pi(f_1 + f_2)t]}$$
$$+ A_1 A_2 \cos[2\pi(f_1 - f_2)t]$$

- The beat frequency shown at the photo-electric signal is determined by

$$f_D = f_1 - f_2 = f_L \frac{\vec{v}_p \cdot (\vec{e}_2 - \vec{e}_1)}{c} = f_L \frac{2\sin(\theta/2)}{c} \vec{v}_p \cdot \vec{e}_x = v_x \frac{2\sin(\theta/2)}{\lambda}$$

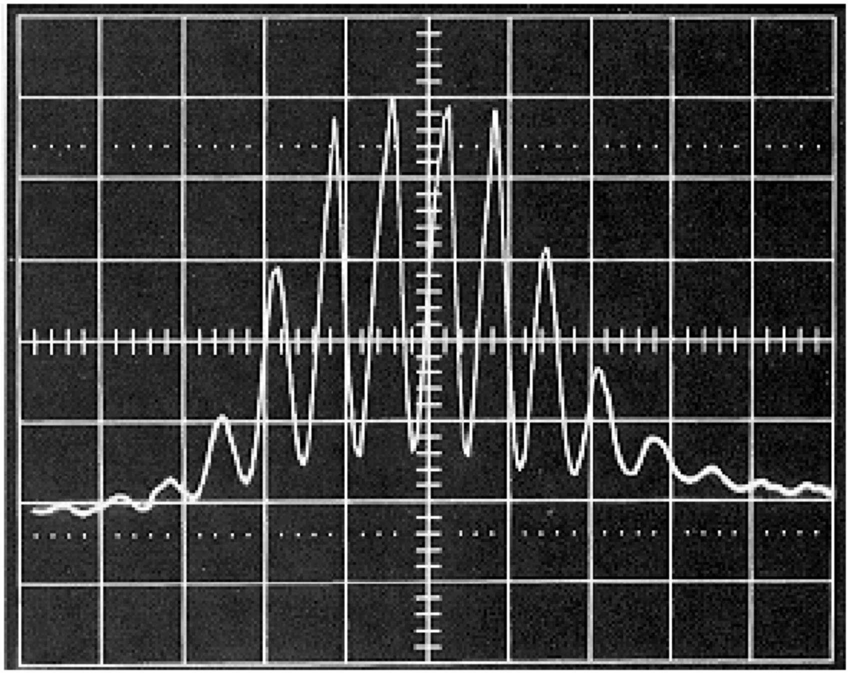
- So the transverse velocity is

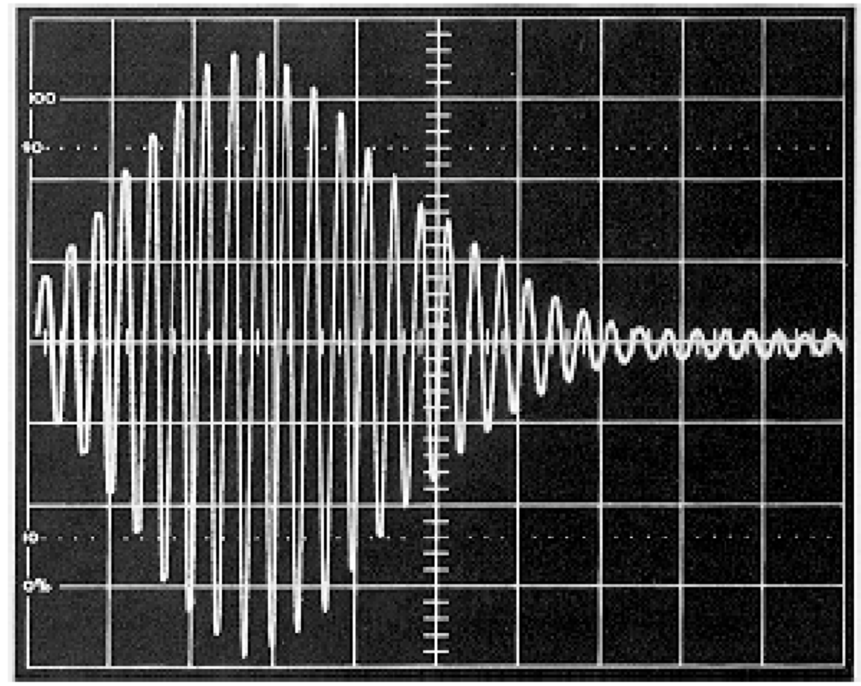
$$\boxed{\vec{e}_2 - \vec{e}_1 = \vec{e}_x \cdot 2\sin(\theta/2)}$$

$$\boxed{v_x = \frac{\lambda f_D}{2\sin(\theta/2)}}$$

- Note: the measured velocity component is the transverse component, not the radial component. This is different from the modern Doppler wind lidar.

Actual Measurement Result of LDV





Doppler Wind Technique

- Doppler Shift is the apparent frequency change of radiation perceived or emitted by a particle moving relative to the source or receiver of the radiation, compared to when particle at rest.
- This phenomenon was first described by Austrian physicist Christian Doppler (1803-1853) for acoustic waves. It also occurs for electromagnetic (including optical) waves/radiation as well.
- If the frequency change can be measured, the relative velocity of the source with respect to the receiver can be determined. Note: the directly measured speed is the velocity component along the line of sight of the radiation beam, i.e., the radial velocity.
- A spectacular application of the Doppler effect was the determination of the freq shift of light emitted from distant stars or galaxies, all toward longer wavelengths (universe red shift), leading to our present notion of an expending universe. Because the relative shift $\Delta f/f = V_R/c$ and distance stars move away fast, these measurements were easy to make, compared to Earth atmosphere.

Doppler Shift for Different Processes

- As we explained before (textbook 5.2.2.4), the Doppler shift for different processes (absorption/emission versus scattering) is different.
- For non-resonant scattering (aerosol, molecular, or radar),

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

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

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

- The Doppler frequency shift is given by

$$\boxed{\Delta\omega_{scattering} = \omega_2 - \omega_1 = -(\vec{k}_1 \cdot \vec{v}_1 - \vec{k}_2 \cdot \vec{v}_2)}$$

- Therefore, for forward scattering, $\vec{k}_2 \approx \vec{k}_1, \vec{v}_2 \approx \vec{v}_1,$ so $\Delta\omega = 0$
- For backward scattering, $\vec{k}_2 \approx -\vec{k}_1, \vec{v}_2 \approx \vec{v}_1,$ so $\Delta\omega = -2\vec{k}_1 \cdot \vec{v}_1$

Doppler Shift for Different Processes

- For resonant atomic absorption, the resonance absorption frequency for an atom at rest is given by $$\omega_0 = (E_2 - E_1)/\hbar$$

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

Energy Conservation $\quad E_1 + \frac{1}{2}mv_1^2 + \hbar\omega_1 = E_2 + \frac{1}{2}mv_2^2$

$$\boxed{\omega_1 = \omega_0 + \vec{k}_1 \cdot \vec{v}_1 + \frac{\hbar k_1^2}{2m}}$$

- The Doppler frequency shift is given by

$$\boxed{\Delta\omega_{abs} = \omega_0 - \omega_1 = -\vec{k}_1 \cdot \vec{v}_1}$$

- The atomic absorption cross-section is Doppler shifted and broadened

$$\sigma_{abs}(\nu) = \frac{1}{\sqrt{2\pi}\sigma_D}\frac{e^2 f}{4\varepsilon_0 m_e c}\exp\left\{-\left[\nu_o - \nu\left(1 - \frac{V_R}{c}\right)\right]^2 / 2\sigma_D{}^2\right\} \qquad \sigma_D = \sqrt{\frac{k_B T}{M\lambda_0{}^2}}$$

Doppler Shift for Different Processes

- For atomic spontaneous emission,

  Momentum Conservation $\quad m\vec{v}_2 = m\vec{v}_3 + \hbar\vec{k}_2$

  Energy Conservation $\quad E_2 + \frac{1}{2}mv_2^2 = E_1 + \frac{1}{2}mv_3^2 + \hbar\omega_2$

$$\boxed{\omega_2 = \omega_0 + \vec{k}_2 \cdot \vec{v}_3 + \frac{\hbar k_2^2}{2m}}$$

- The Doppler frequency shift is given by

$$\boxed{\Delta\omega_{sp} = \omega_2 - \omega_0 = \vec{k}_2 \cdot \vec{v}_3}$$

- The Doppler frequency shift between the spontaneously emitted photon and incident photon is given by

$$\boxed{\Delta\omega_{overall} = \omega_2 - \omega_1 = \vec{k}_2 \cdot \vec{v}_3 - \vec{k}_1 \cdot \vec{v}_1}$$

- For backward spontaneously emitted photon, the Doppler shift is

$$\boxed{\Delta\omega_{overall} = \omega_2 - \omega_1 = -2\vec{k}_1 \cdot \vec{v}_1, \qquad \vec{k}_3 \approx -\vec{k}_1, \vec{v}_3 \approx \vec{v}_1}$$

Coherent Detection Doppler Wind

- This topic will be covered in details by Dr. Sara Tucker in the next lecture on Thursday. Here we only briefly introduce the basic principle.
- Basic Principle: the return signal is optically mixed with a local oscillator laser, and the resulting beat signal has the frequency (except for a fixed offset) equal to the Doppler shift due to the moving particles.
- More accurately, the Coherent Detection Doppler Wind lidar should be called "Heterodyne" Detection Doppler Wind lidar.

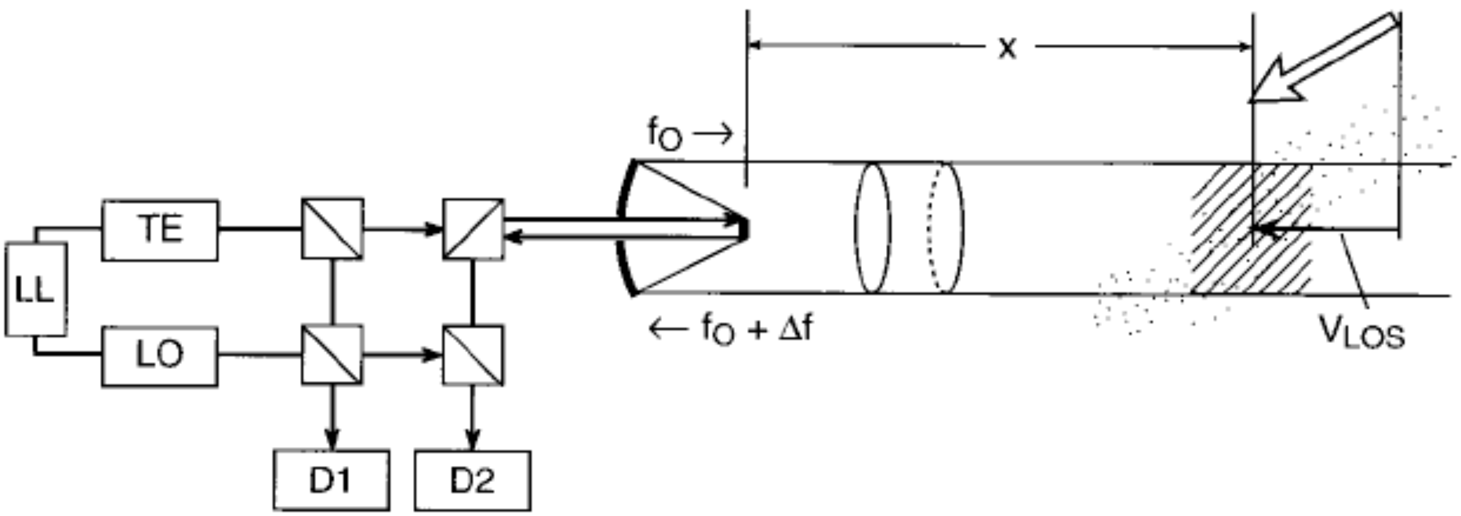


Fig. 12.6. Principle of a heterodyne-detection Doppler lidar.

LO: Local Oscillator; TE: pulsed laser transmitter; LL: Locking Loop

Coherent Detection Doppler Wind

The local oscillator laser has a frequency of f_{LO}

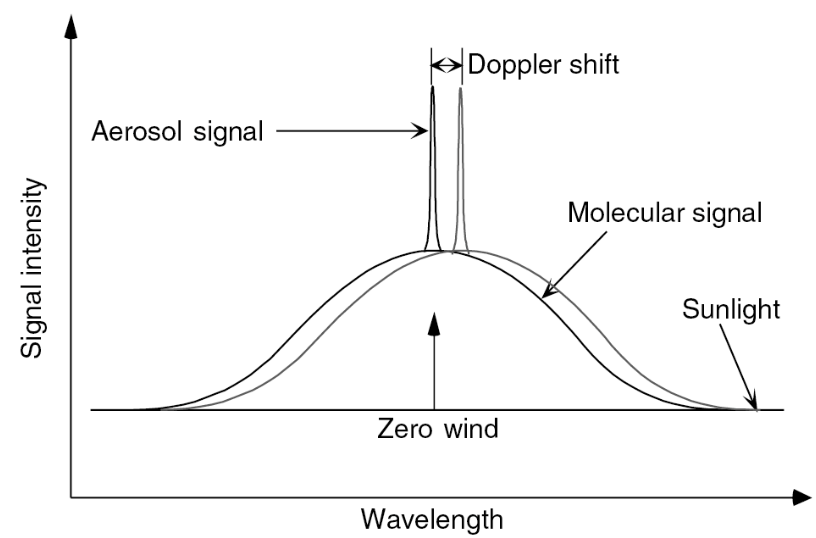
The pulsed transmitter has a frequency of $f_0 = f_{LO} + f_{offset}$

The return signal (Doppler shifted) has a freq of $f_{Sig} = f_0 + \Delta f$

- The optical mixing results in frequencies of $|f_{LO} \pm f_{Sig}|$, i.e., sum frequency and beat frequency.
- The sum frequency is way above the frequency cutoff of the detector, but the beat frequency is a low-frequency signal that can be determined with high accuracy.

$$\boxed{f_{beat} = \left| f_{LO} - f_{Sig} \right| = \Delta f + f_{offset}}$$

- Aerosol scattering signal is utilized, owing to its narrow bandwidth and strong signals
- Accuracy: No bias in principle
- Precision: independent of the wind velocity



Direct Detection Doppler Wind

- Principle: no local oscillator is used. Instead, an optical frequency discriminator or spectrum analyzer is used to convert the Doppler frequency shift to a change in optical intensity or power, or to intensity / power spatial distribution, which is in turn directly detected.
- In these direct detection (or incoherent) lidar systems, the return optical signal is filtered or resolved into its spectral components prior to detection. Besides a narrowband lidar transmitter with stable frequency, the main efforts are placed onto the spectral resolved lidar receivers.
- The optical frequency discriminators include mainly three (or four) types

(1) Atomic absorption lines, like Na, K, and Fe Doppler lidar, using the resonance fluorescence from the entire line, not just the edge

(2) Edge-filters, like the transmission edge of a molecular absorption line (e.g., iodine I_2 absorption lines), or the edge of a transmission fringe of an optical interferometer (e.g., Fabry-Perot etalon)

(3) Fringe pattern imaging of the output of an optical interferometer.

Direction Detection Doppler Wind

- For resonance fluorescence Doppler lidar, the resonance fluorescence from atoms, e.g., Na, K, Fe, in the mesosphere and lower thermosphere is utilized.
- Non-resonant direct detection Doppler lidars utilize aerosol scattering, or molecular scattering, or both.
- The main ideas are

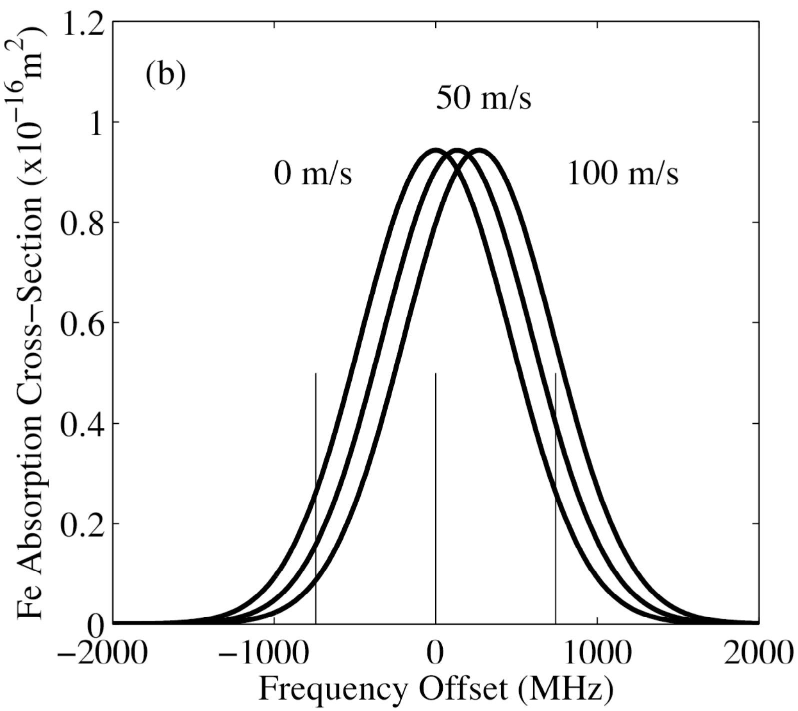
Intensity ratio ⇨ Frequency shift ⇨ radial velocity (LOS)

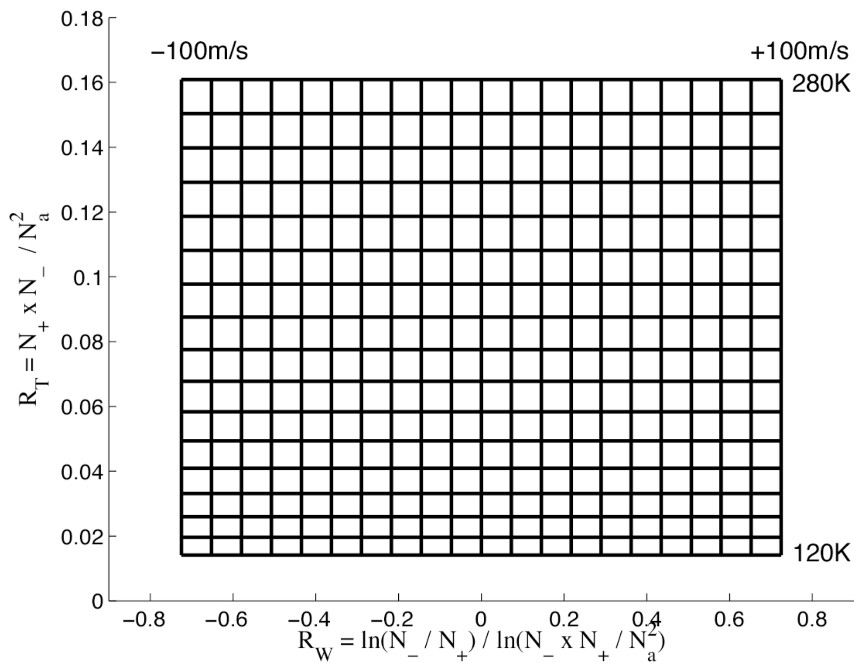
Intensity change ⇨ Frequency shift ⇨ radial velocity (LOS)

Intensity spatial distribution ⇨ Frequency shift ⇨ radial velocity (LOS)

Freq Analyzer: Atomic Absorption Lines

❑ The resonance fluorescence Doppler lidar is one of kind of direct detection Doppler lidars (DDL). It has been covered in great details in previous lectures.





From intensity ratios (photon count ratios) to derive wind and temperature

Freq Analyzer: Single-Edge Filter

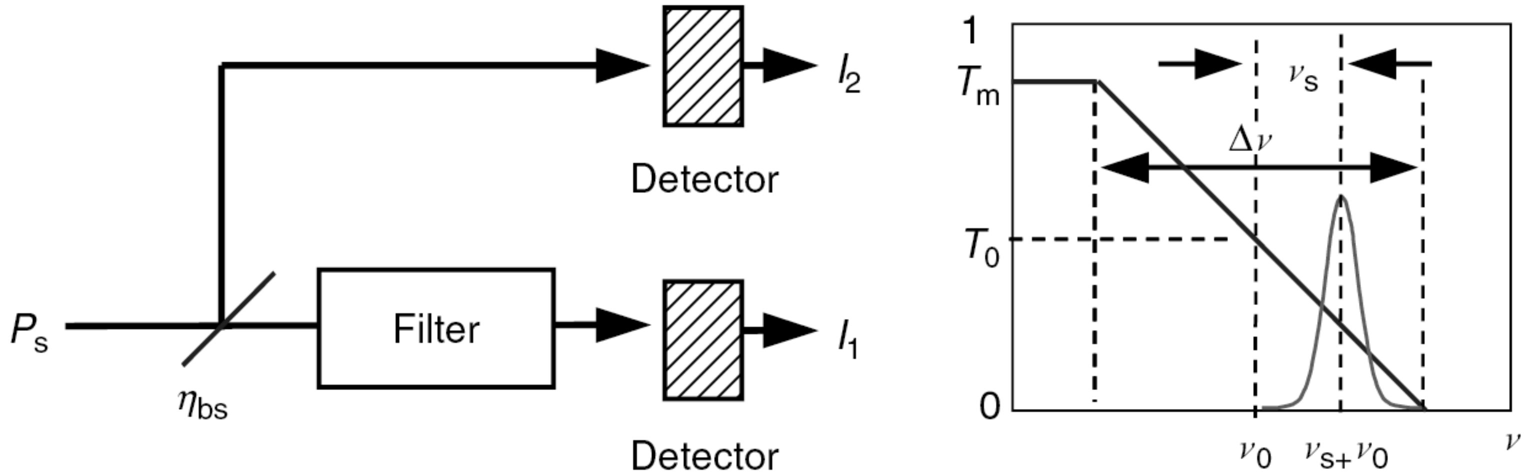


Figure 7.31 Single-edge functional diagram and filter transmission.

- 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

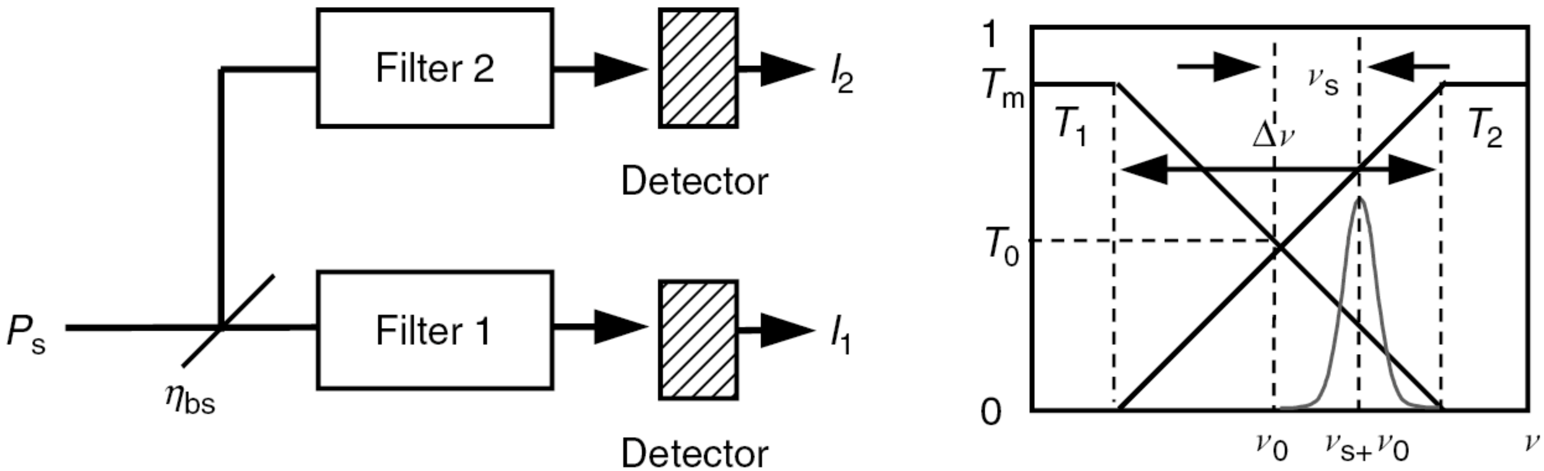


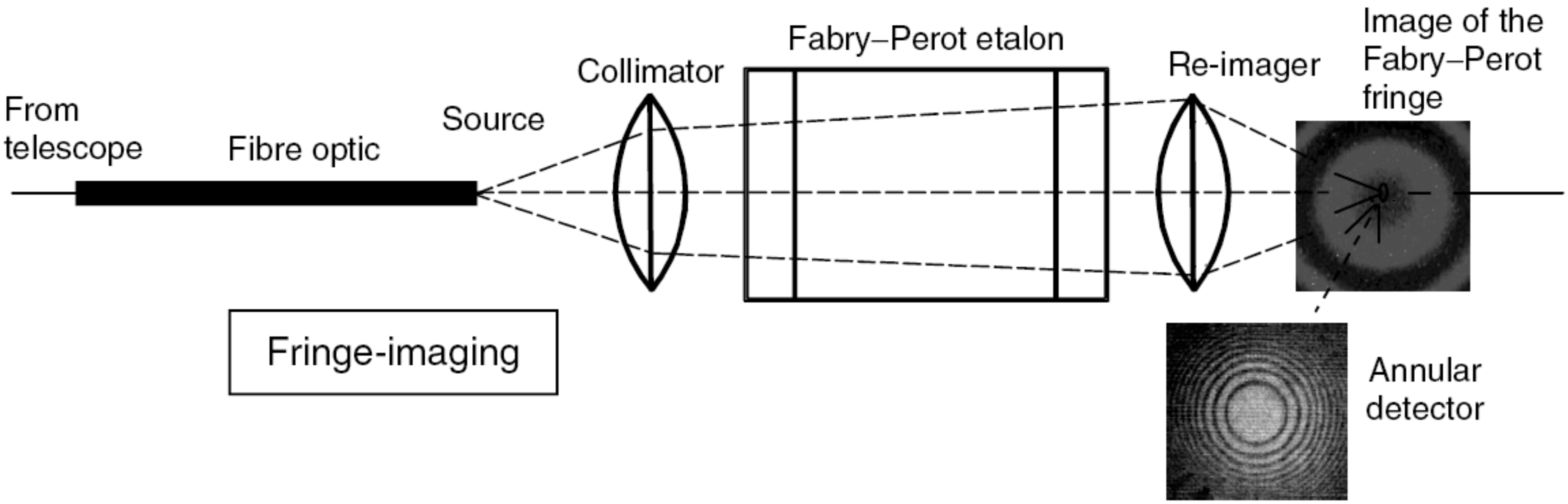
Figure 7.32 Double-edge functional diagram and filter transmission.

- 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.

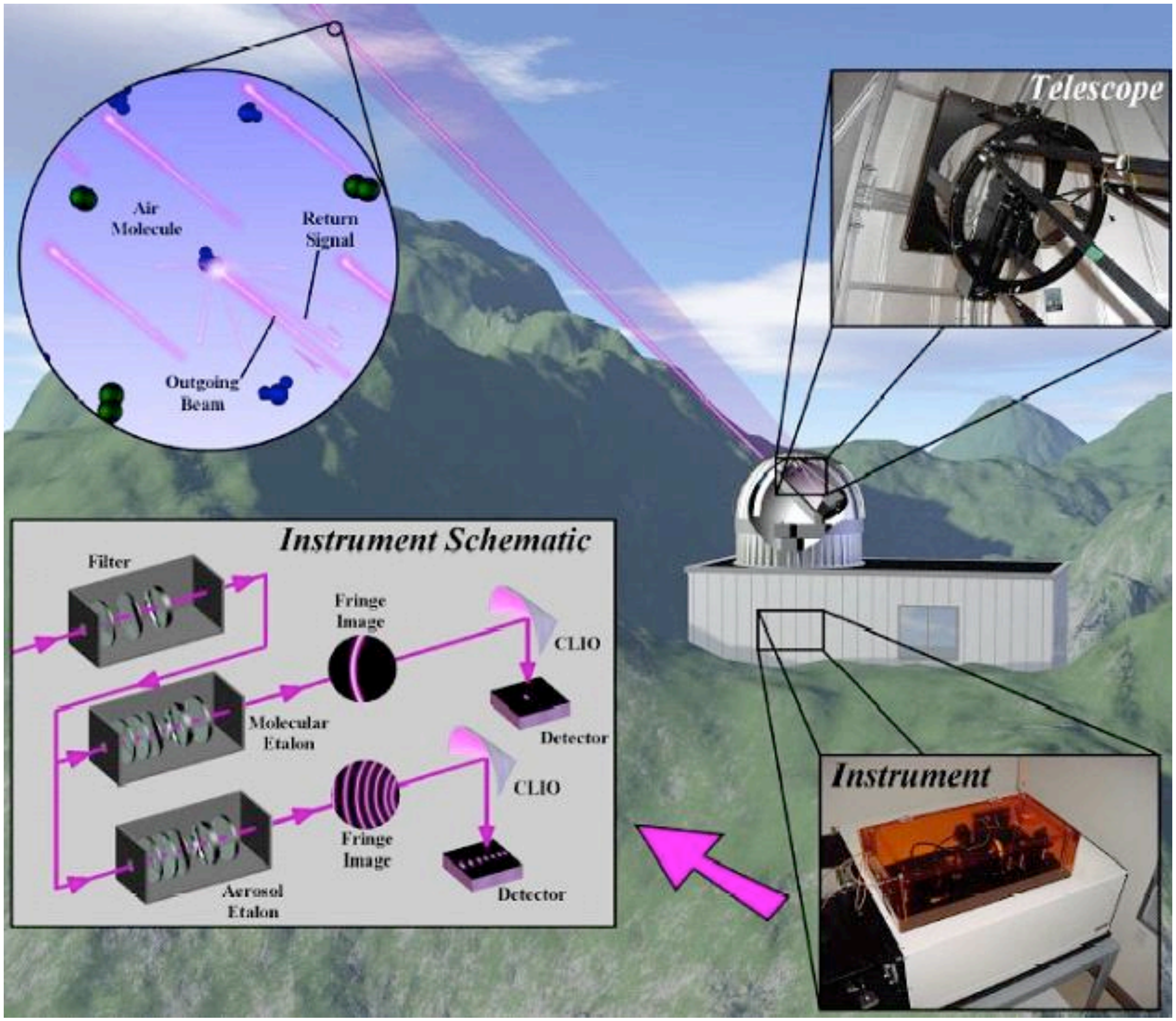
$$S = \frac{I_\Delta}{I_\Sigma} = \frac{I_1 - I_2}{I_1 + I_2} = \frac{T_{s_1} - T_{s_2}}{T_{s_1} + T_{s_2}} = \frac{2\nu_s}{\Delta\nu}$$

Freq Analyzer: Fringe-Imaging



- 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.
- The mean frequency is then estimated by one of a variety methods, e.g., the location of the irradiance peak, and the first moment of the irradiance distribution, etc.
- Similar to passive F-P Interferometer, the diameter of the concentric rings can be used to determine the frequency shift.

Example DDL: GroundWinds



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

Vector Wind Velocity Measurement

- Vector (u, v, w) wind velocity estimates require radial velocity measurements from at least three independent Line-Of-Sight (LOS).
- Ideally: to obtain a vector wind at a given point in space is to view the same point from 3 or more LOS directions

(1) Three or more lidar systems are required to do so

(2) When assuming W = 0, two lidar systems can do it.

- Practically: under a necessary assumption of horizontal homogeneity of the wind field over the sensed volume, lidar beam scanning techniques can be used to determine the vector wind velocity.
- Two main techniques for this scanning –

(1) the Velocity-Azimuth-Display (VAD) technique:

-- conical scan lidar beam at a fixed elevation angle

(2) the Doppler-Beam-Swinging (DBS) techniques:

-- pointing lidar beam to vertical, tilted east, and tilted north

VAD and DBS Techniques

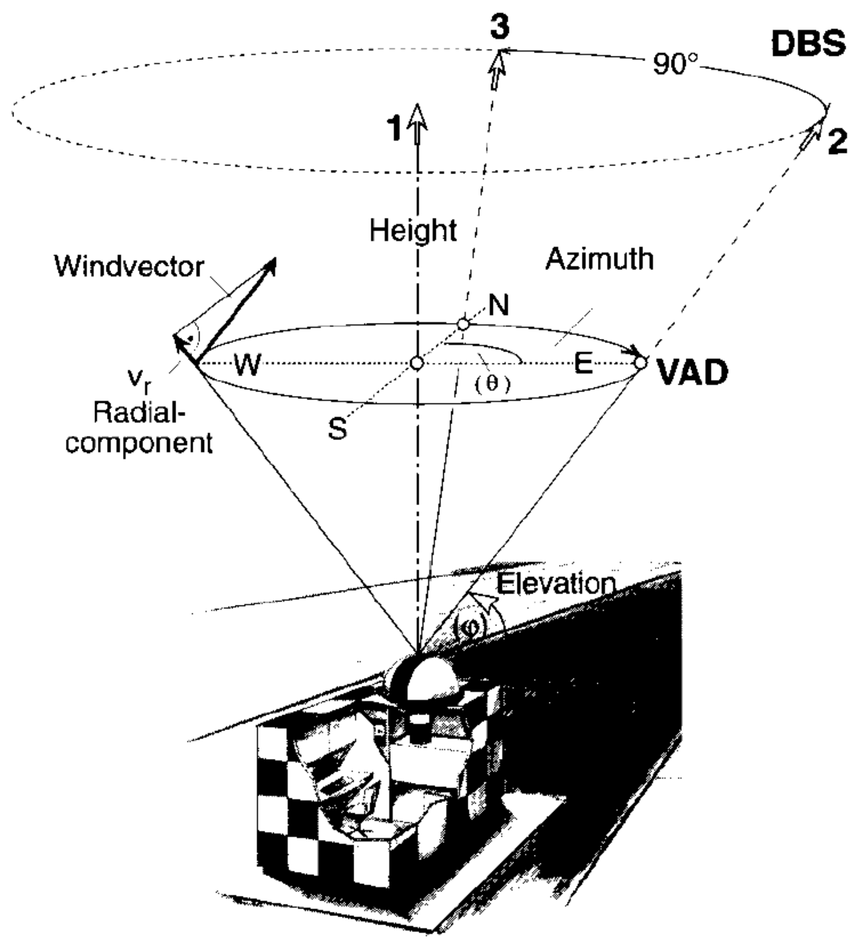
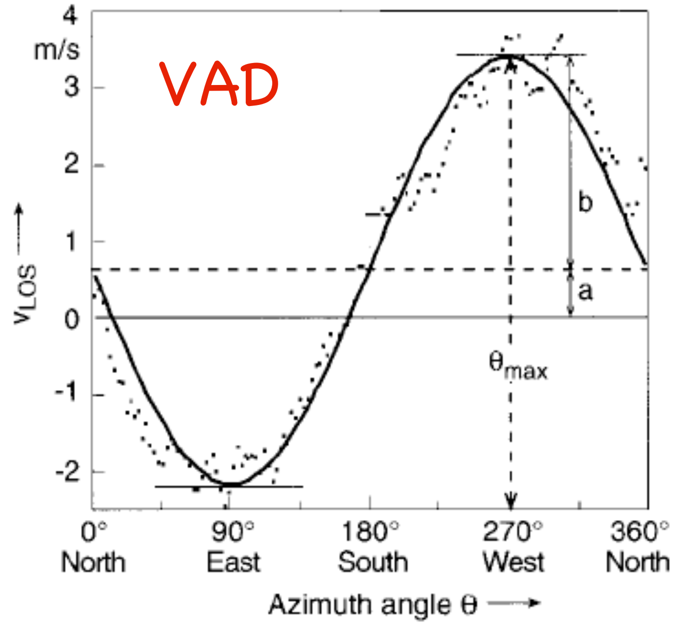


Fig. 12.8. Schematic of the scan technique of a Doppler lidar. Lower part: VAD scan, upper part: DBS scan.

VAD and DBS Techniques



Radial velocity is given by

$$\boxed{v_r = -u \sin\theta \cos\varphi - v \cos\theta \cos\varphi - w \sin\varphi,}$$

θ the azimuth angle, clockwise from North, and

φ the elevation angle.

Fit the scanning results with

$$\boxed{v_r = a + b\cos(\theta - \theta_{max})}$$

offset a, amplitude b, and phase shift θ_{max}.

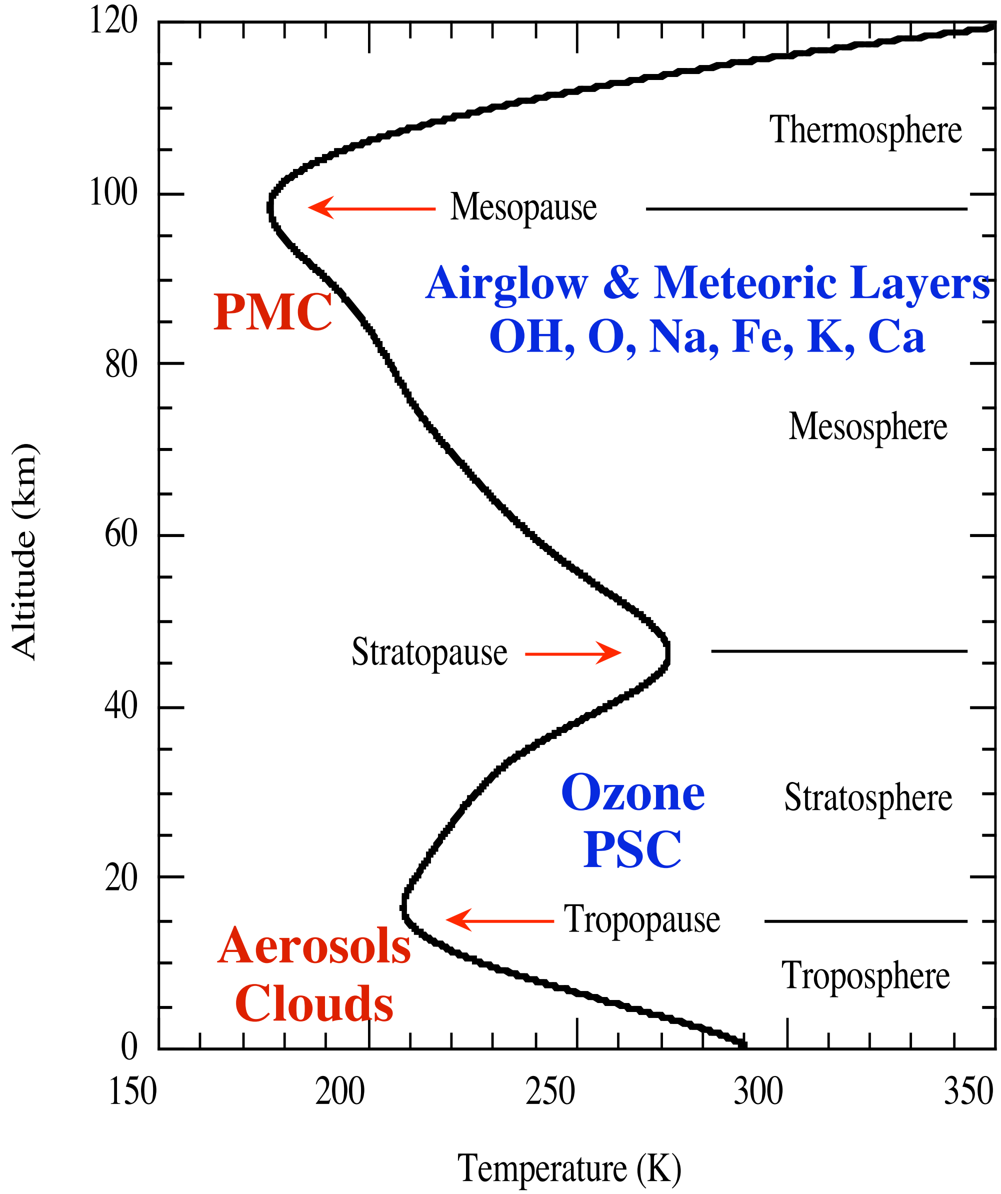
$$\boxed{VectorWind = (u, v, w) = (-b\sin\theta_{max}/\cos\varphi, -b\cos\theta_{max}/\cos\varphi, -a/\sin\varphi)}$$

- For DBS technique, the three components are obtained as

$$\boxed{\begin{aligned} u &= -(V_{r2} - V_{r1}\sin\varphi)/\cos\varphi \\ v &= -(V_{r3} - V_{r1}\sin\varphi)/\cos\varphi \\ w &= -V_{r1} \end{aligned}}$$

V_{r1}, V_{r2}, V_{r3} are the vertical, east, and north radial velocities

Wind Techniques



- 75-120km: resonance fluorescence (Na, K, Fe) Doppler technique (DDL)
- FPI: Fabry-Perot Interferometer
- Below 60km: Rayleigh Doppler technique (DDL)
- Below 30 km: Direct Detection Doppler technique
- In troposphere: Coherent Detection Doppler technique, Direct motion Detection technique (tracking aerosol motion), LDV, LTV

Summary

- Mainly two methods to measure true wind velocity: use the definition of velocity or use the Doppler shift effect.
- Using the definition of velocity (derivative of displacement), the direct motion detection of aerosols, clouds, or smoke plumes, by images and lidars can obtain wind with high resolution mostly in lower atmosphere or in industrial shop, lab or wind tunnel.
- Using the Doppler effect, the Doppler wind lidar can extend the wind measurements up to the lower thermosphere, using the resonance fluorescence, molecular and aerosol scattering.
- Two main Doppler wind lidars are the coherent (heterodyne) detection and direct detection Doppler wind lidars.
- The direct detection Doppler lidars use atomic absorption line, the edge filters, and fringe-imaging techniques to discriminate or analyze the frequency or spectrum of the return lidar signals (Doppler shifted).