Lecture 24. Wind Lidar (6)
Direct Motion Detection Lidar

- Direct Motion Detection Wind Lidar
- Lidar tracking of aerosol motions
- Laser time-of-flight velocimetry
- Laser Doppler velocimetry
- Comparison of wind lidar techniques
- Summary

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:

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

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

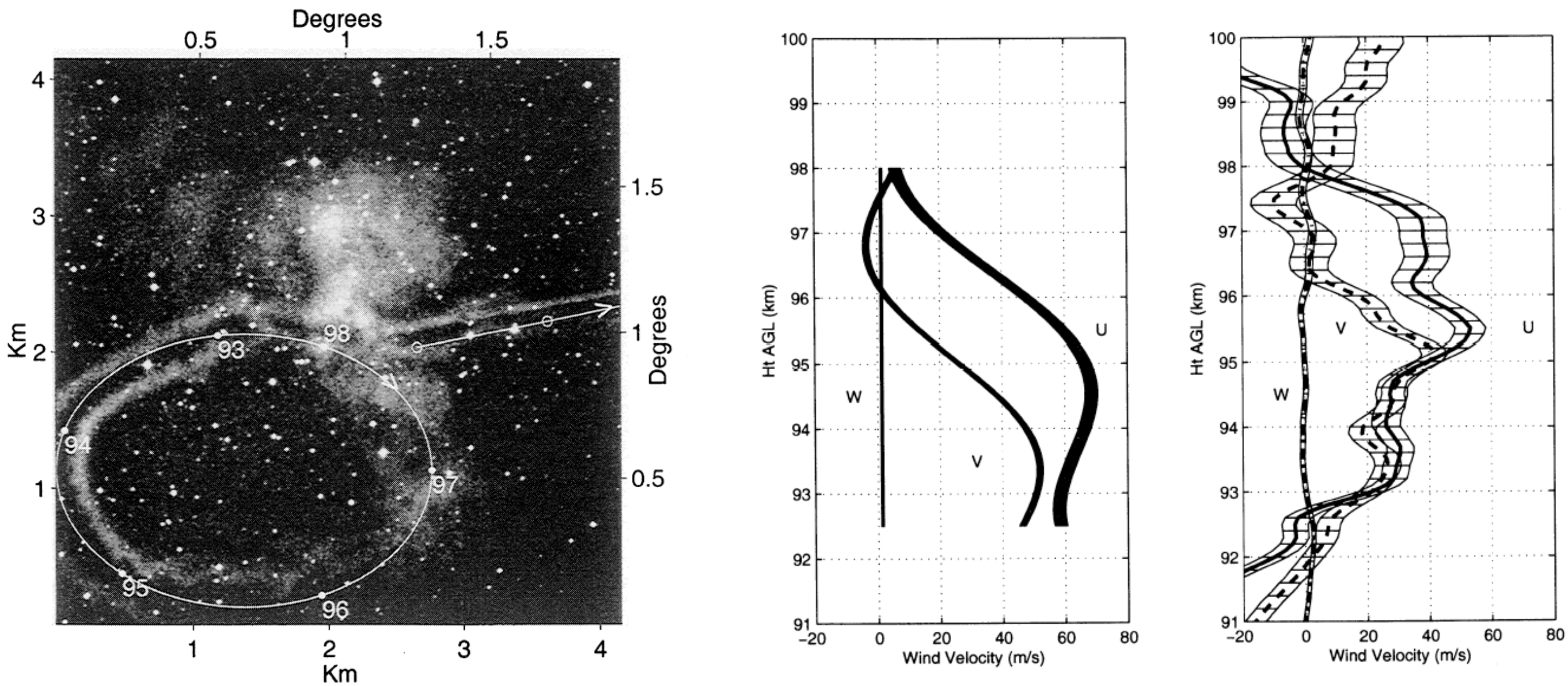
$$\vec{u}_{hor} = \frac{1}{t_2 - t_1} (\Delta x, \Delta y)$$

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.



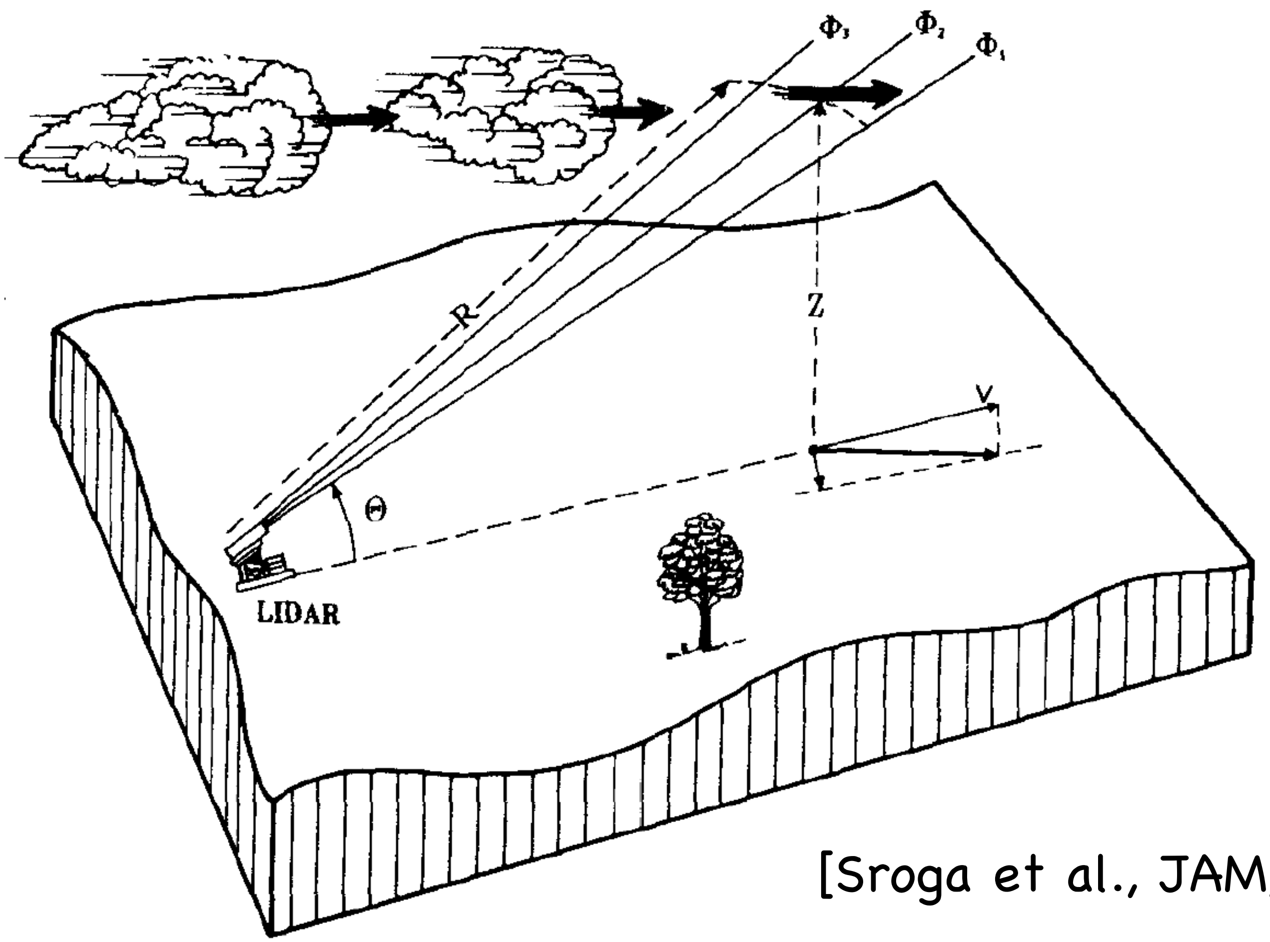
1998 Leonid Meteor Shower at SOR

-- [Drummond et al., JGR, 106 (A10), 21517-21524, 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)

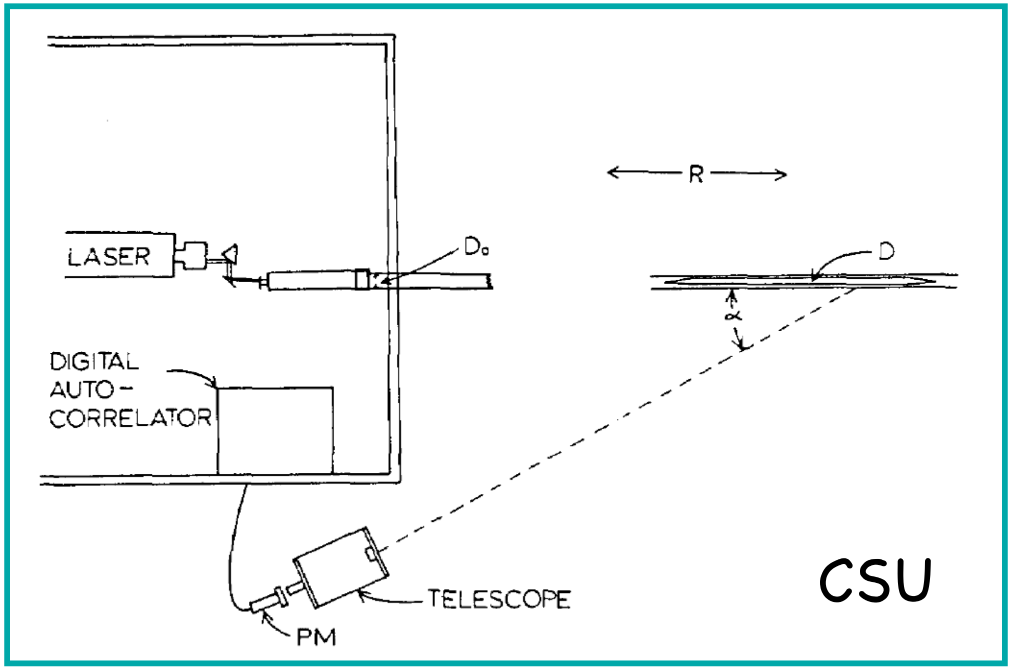
- This dual-beam technique measures the speed of a cross wind by determining a particle's time of flight across two approximately parallel beams with a small spatial separation, as illustrated in the plot.

- 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

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

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



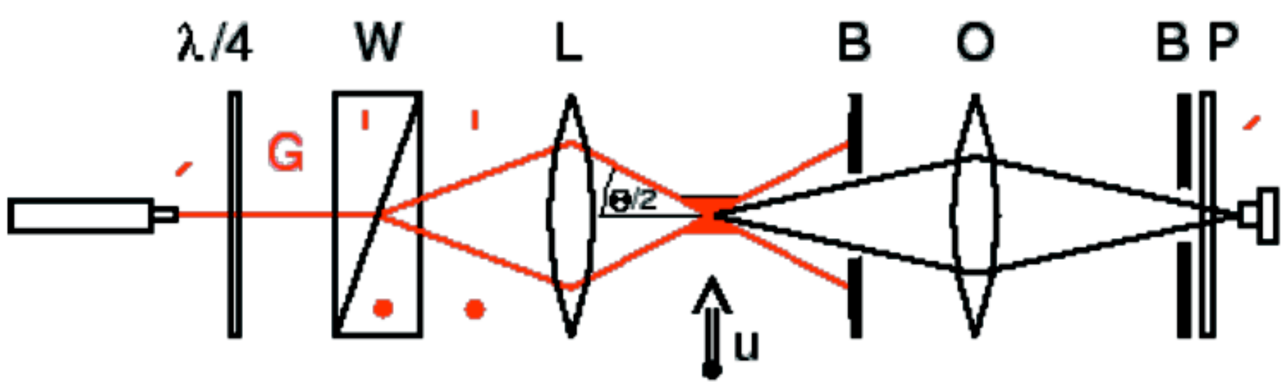
[Bartlett and She, Opt. Lett., 1, 175, 1977]

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.

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

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

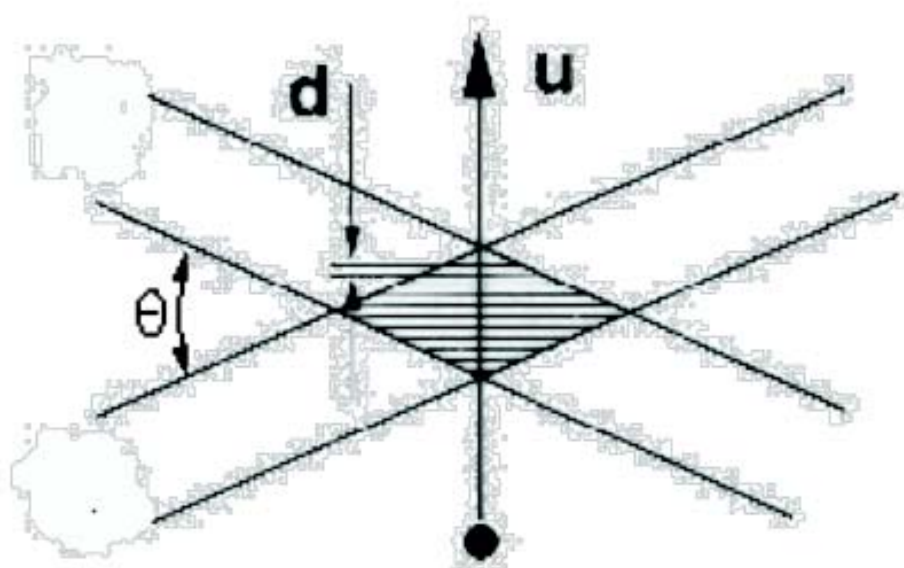
$$d = \frac{\lambda}{2\sin(\theta/2)}$$

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

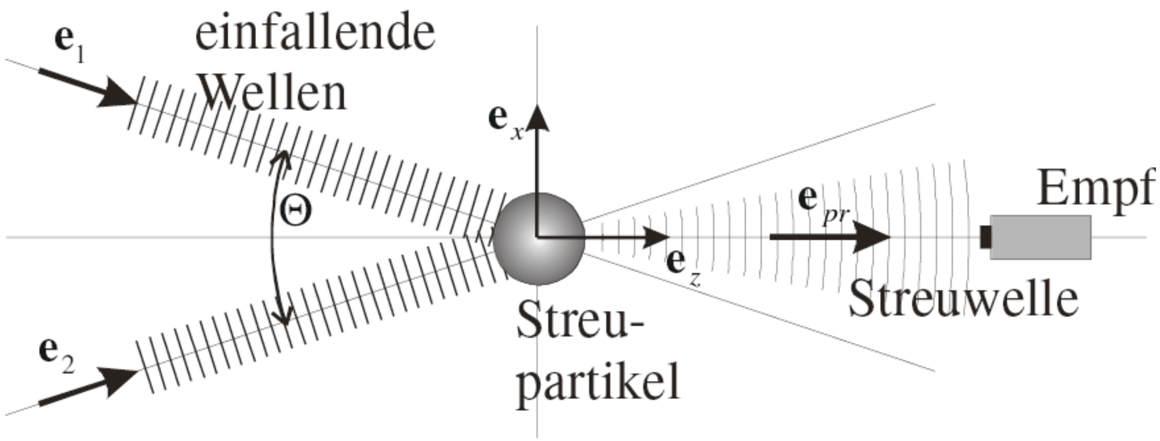
$$f = \frac{1}{T} = \frac{1}{d/u} = \frac{u}{d}$$

$$\Downarrow$$

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



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

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

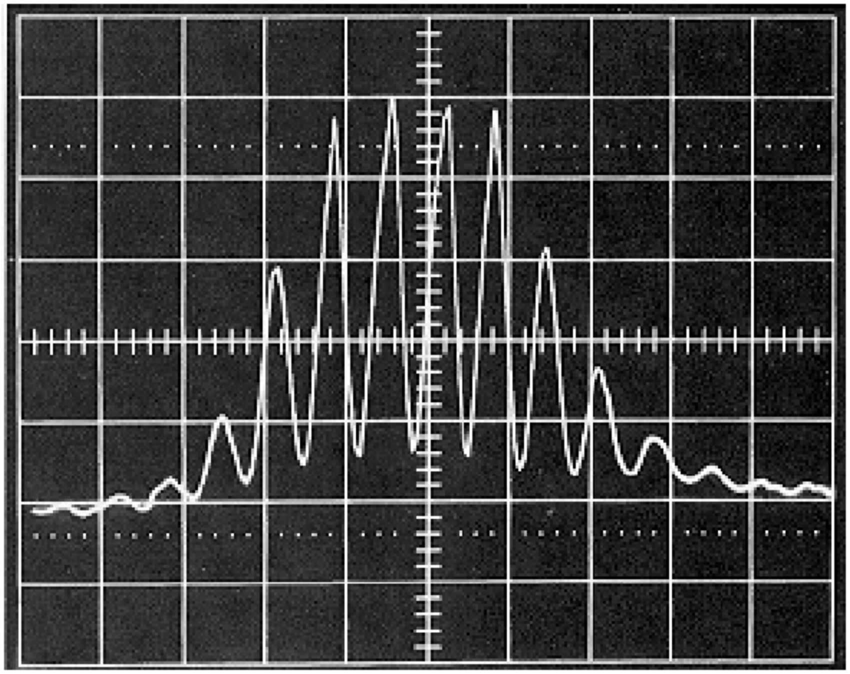
- So the transverse velocity is

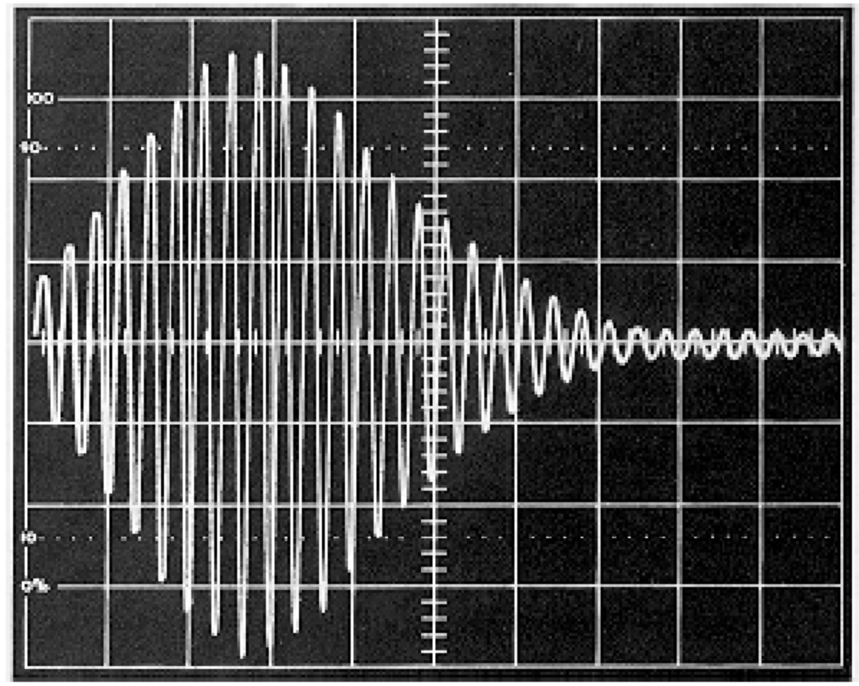
$$\boxed{\vec{e}_2 - \vec{e}_1 = \vec{e}_x \cdot 2\sin(\theta/2)}$$

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

- 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





Comparison of Wind Techniques

Use wind-dependent effects or use definition of wind

- **Direct Motion Detection Technique:**

(using the definition of velocity)

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

(1) Tracking aerosol/cloud motions

(2) Laser Time-of-Flight Velocimetry

(3) Laser Doppler Velocimetry

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

(1) Coherent (Heterodyne) Detection Doppler Wind Lidar

(2) Direct Detection Doppler Wind Lidar

- **Geostrophic wind detection:**

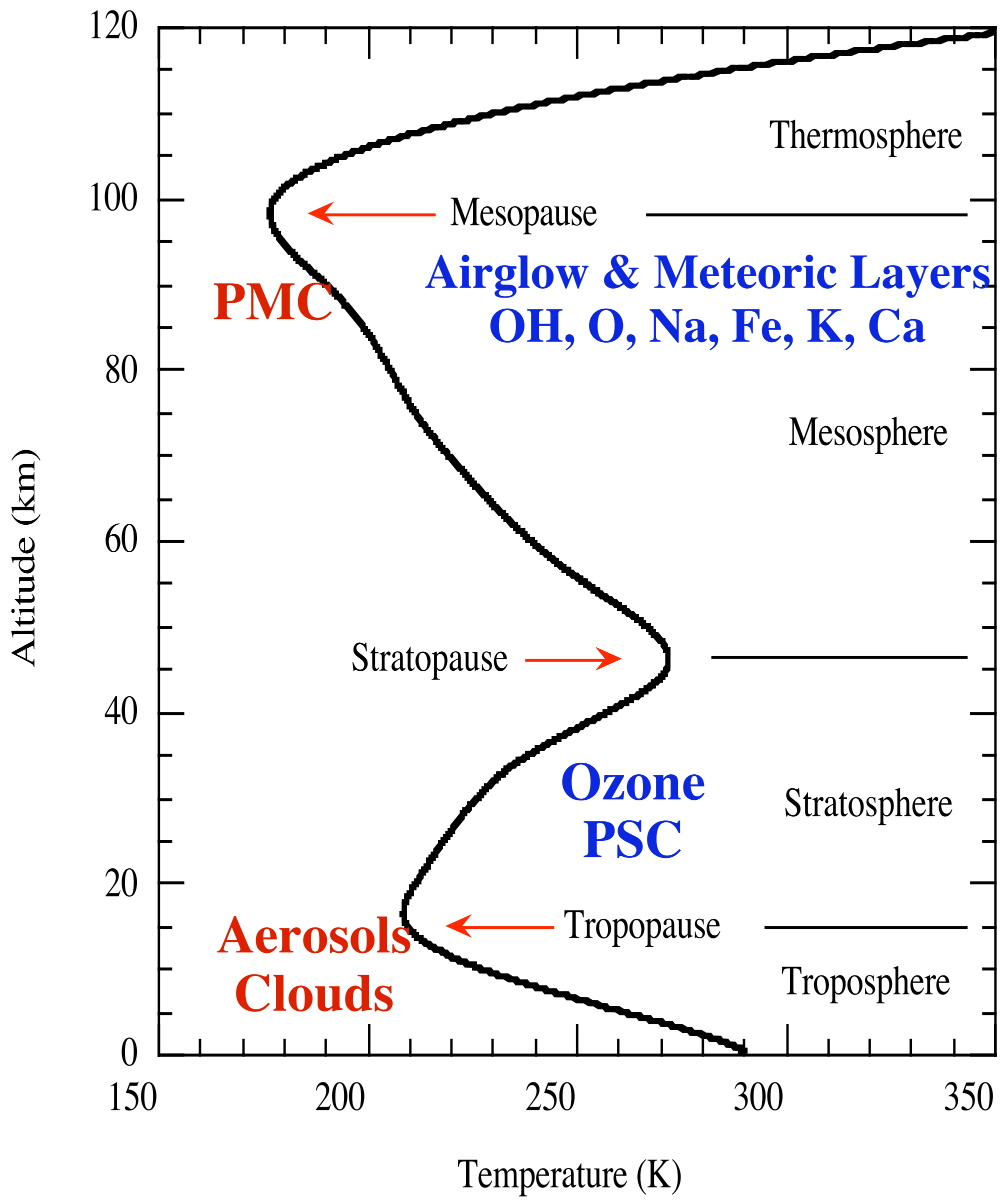
Temperature ⇒ Pressure Gradients ⇒ Geostrophic Wind

More on Direct Detection Doppler Lidar

- Direct Detection Doppler Wind Lidar - currently we can think of - includes

1. Fringe Imaging with Fabry-Perot Etalon
2. Scanning Fabry-Perot Interferometer
3. Edge filter based on etalons
4. Edge filter based on iodine absorption lines
5. Edge filter based on atomic absorption lines (Ba, Na, K, …)

Wind Techniques vs Altitude



- 75-120km: resonance fluorescence (Na, K, Fe) Doppler technique (DDL)
- FPI: Fabry-Perot Interferometer
- Direct detection Doppler lidar (DDL) techniques using molecular scattering and/or aerosol scattering
- In troposphere:

Coherent Detection Doppler tech,
Direct Detection Doppler tech,
Direct motion Detection tech
(tracking aerosols, LDV, LTV)

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)
	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	Lower mesosphere, stratosphere and troposphere wind (up to 50-60 km)
	Coherent Detection Doppler Lidar: Doppler frequency shift of aerosol scattering using heterodyne detection tech	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, laboratory, etc

Summary

- Mainly two methods to measure true wind velocity: use the definition of velocity (direct motion detection) or use the Doppler effect (Doppler wind techniques).
- 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 types of Doppler wind lidars are the coherent detection Doppler lidars (CDL) and direct detection Doppler lidars (DDL).

Summary

- Coherent detection Doppler lidar utilizes the aerosol scattering in the lower atmosphere to mixture the return signal with local oscillator. By heterodyne detection, CDL can achieve very high accuracy (0 bias) and high precision (< 10 cm/s), although it only works in the lower atmosphere with abundant aerosols. This is very important for weather forecast, pollution study and defense applications.
- Direct detection Doppler lidar uses atomic 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, I think that 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.