Lecture 20. Wind Lidar (2)
Direct Motion Detection Wind Lidar

- Direct Motion Detection Wind Lidar
- Lidar tracking of aerosol motions
- Laser time-of-flight velocimetry
- Laser Doppler velocimetry
- Coherent versus incoherent Detection

    Doppler 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:

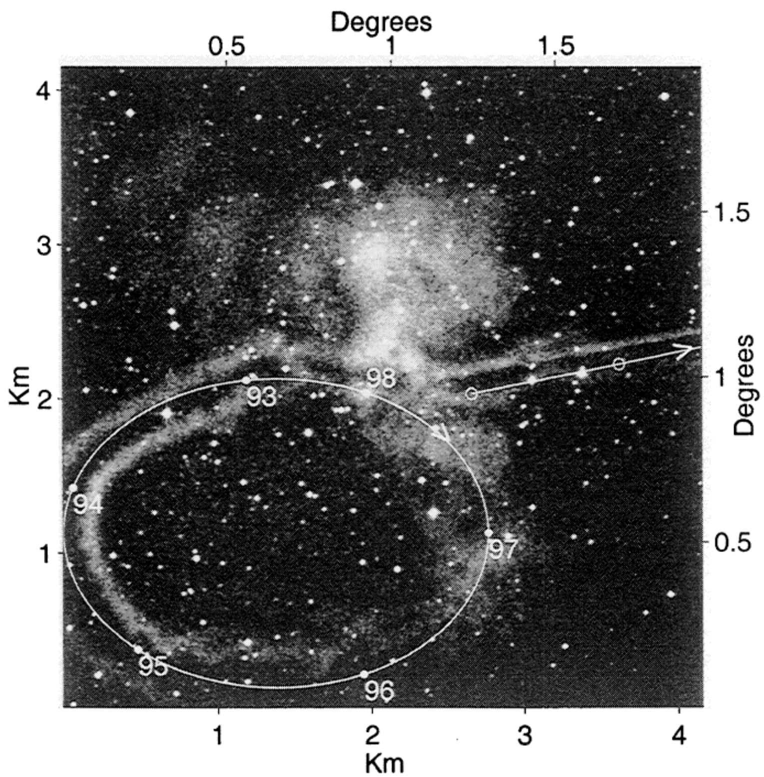
$$\vec{u}_{hor} = \frac{1}{t_2 - t_1} (\Delta x, \Delta y)$$

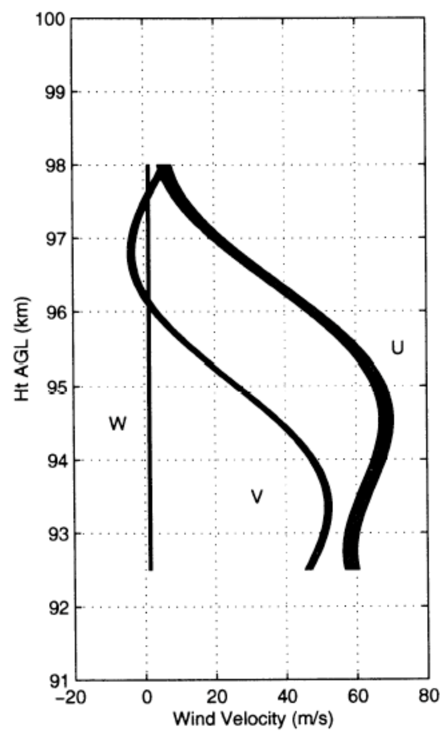
Cross-Correlation of Cloud Pattern

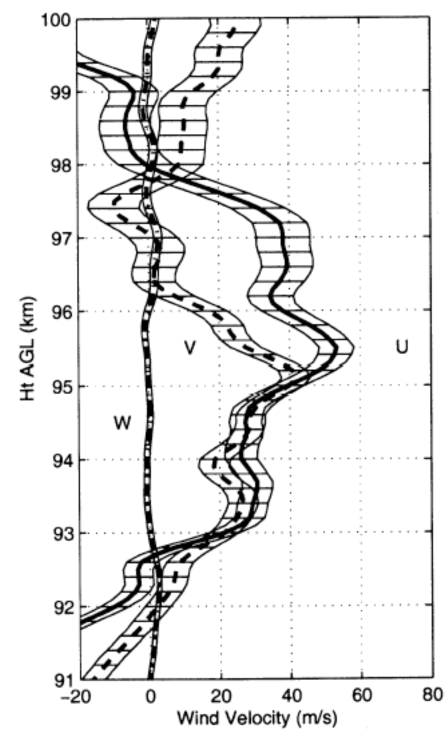
- Some exciting applications of this approach include

(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.







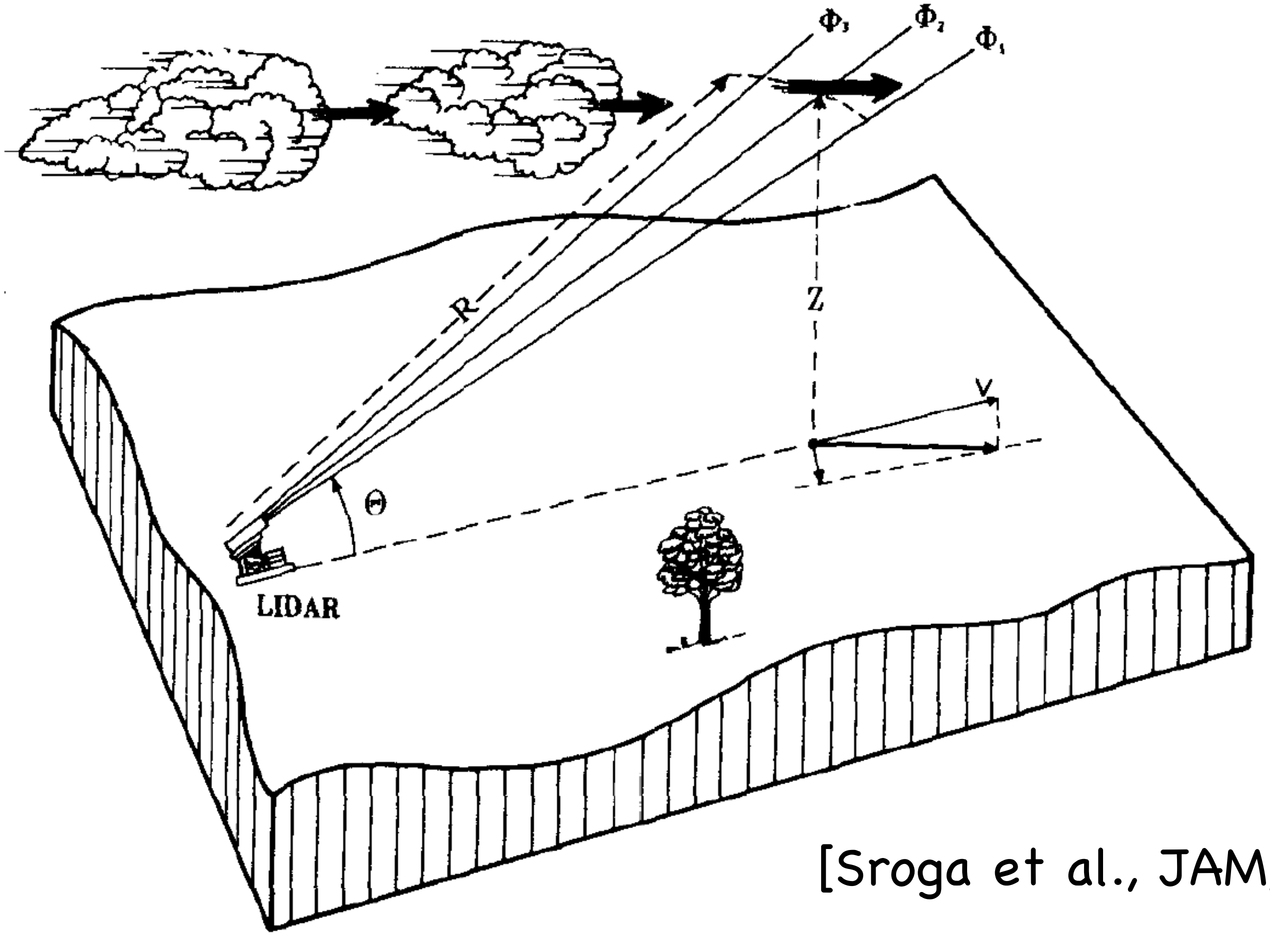
1998 Leonid Meteor Shower at SOR

-- [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]

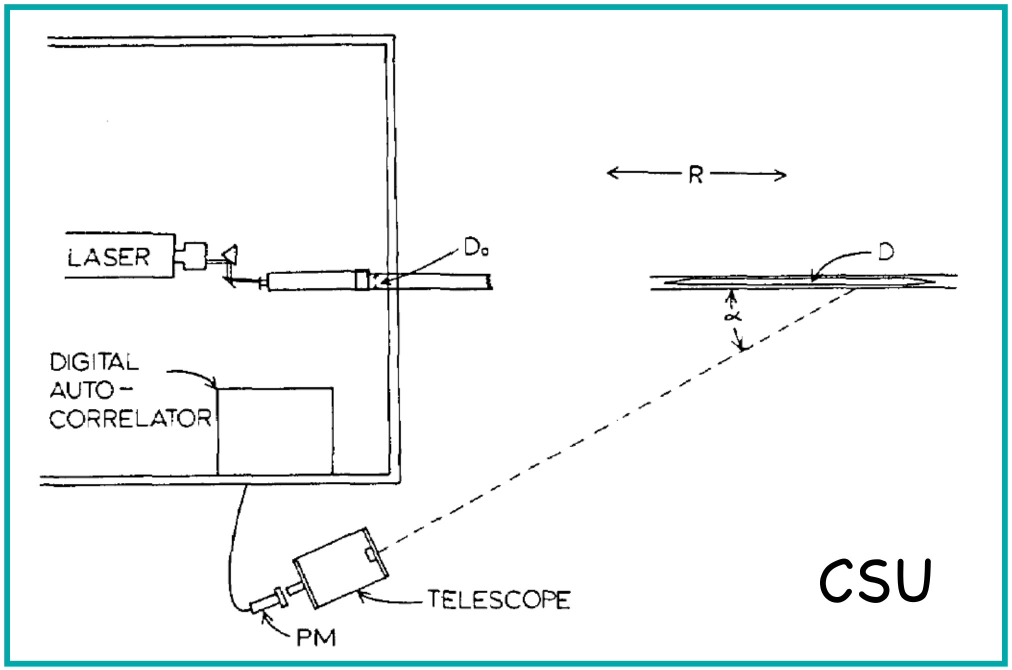
FIG. 1. The geometry used for lidar wind measurements. The lidar is operated at a constant small elevation angle and scanned back and forth between three closely spaced azimuth angles ϕ_1, ϕ_2 and ϕ_3. Range-resolved profiles of backscattered intensity are recorded at ~1 s intervals for a period of 2–5 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.



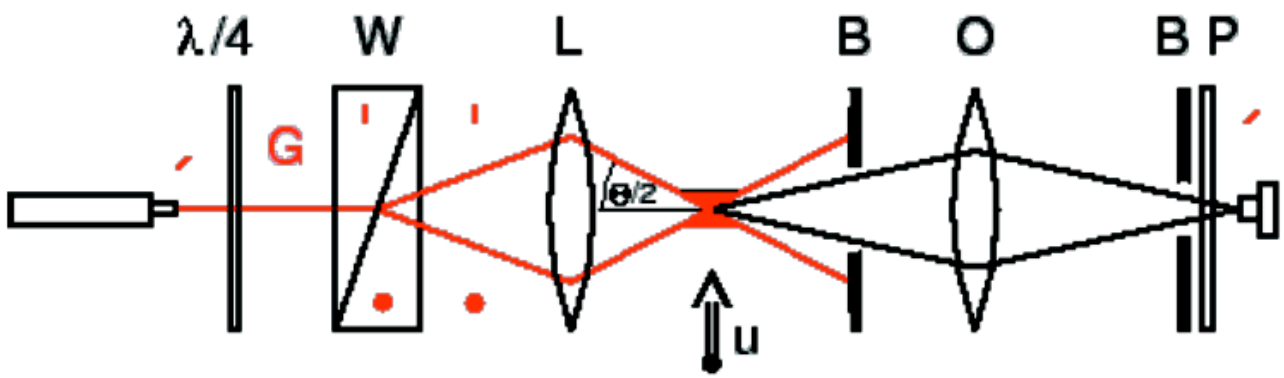
[Bartlett and She, Opt. Lett., 1, 175, 1977]

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.

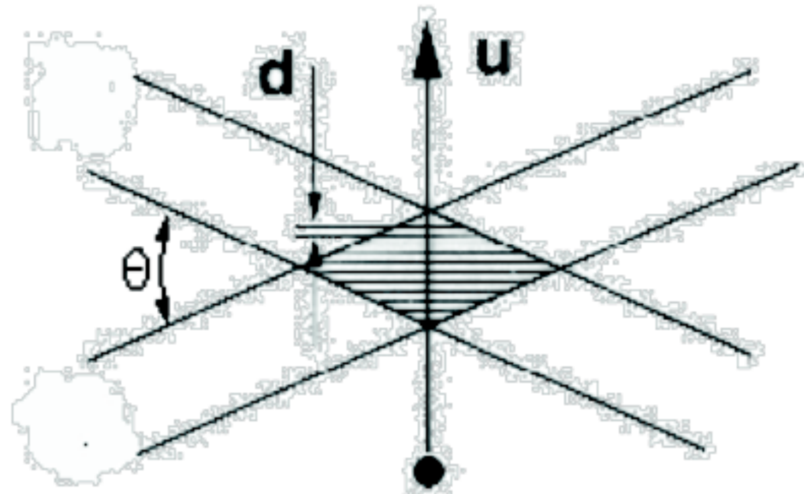


- LDV is widely used in fluid mechanics research, and has been extended to 3-D measurements.

One Way to Understand LDV

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

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



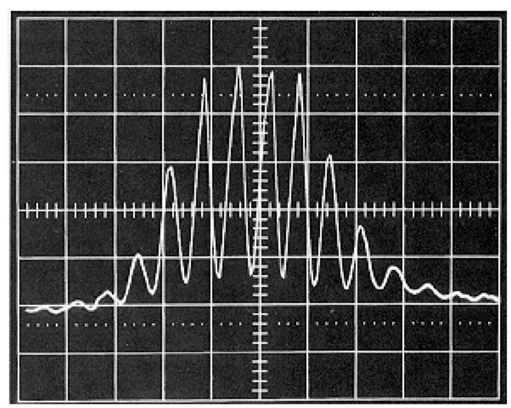
- Particles pass through the lattice with a speed of u, so the frequency of particles scattering strong light is given by

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

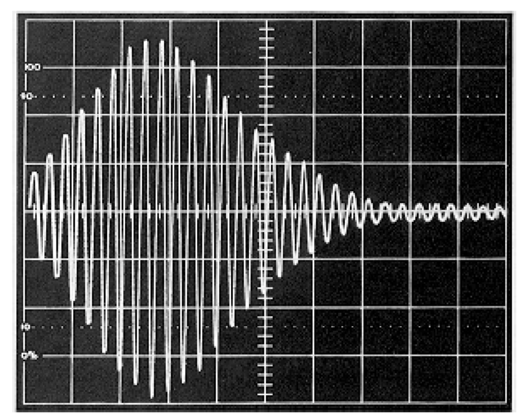
⇓

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

Light Intensity

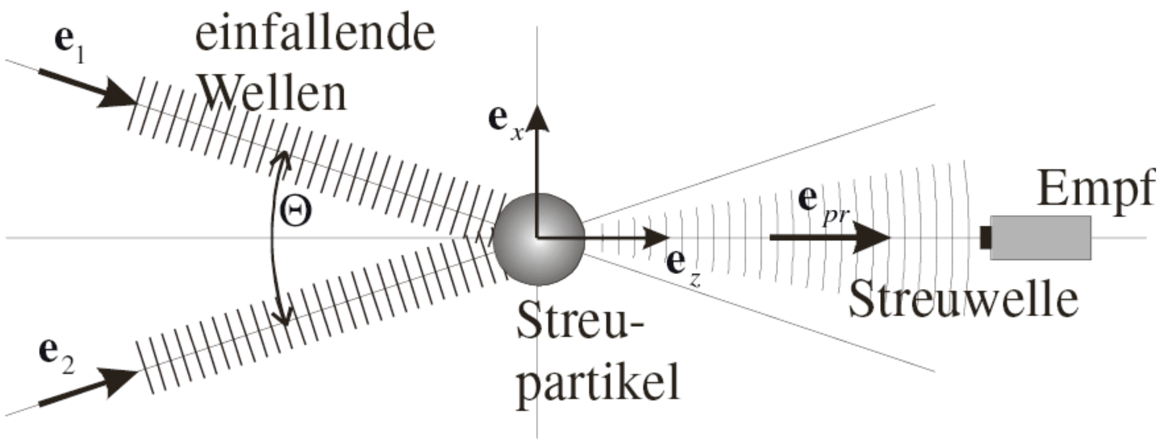


Time



Doppler burst processor

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.

Coherent vs Incoherent Doppler Wind

- Doppler wind technique relies on the well-know Doppler effect. The radial (LOS) velocity is inferred from the measured Doppler frequency shift. Thus, some spectral analysis must be used to measure the Doppler frequency shift - either coherent detection to measure the beat frequency or incoherent detection to measure the spectrum of return signals.
- Coherent (heterodyne) Detection Doppler Wind Lidar (CDL) is to measure the frequency of the beat signal obtained by optically mixing the return signal with the cw local oscillator. Thus, both the local oscillator and the return signal need to have narrow bandwidths in order to have sufficient coherent length.
- Therefore, coherent detection lidar relies on the aerosol scattering with very narrow Doppler broadening, thus only applying to the atmospheric regions with sufficient amount of aerosols.
- Molecular scattering in atmosphere has the Doppler broadening with more than 1GHz width - not suitable for coherent detection.

Wavelength Considerations for CDL

- In principle, Doppler wind lidar can choose random laser wavelength, as there is no specific resonance absorption wavelength required.

- However, because the aerosol (Mie) scattering is better suited for frequency analysis in the coherent detection lidar than the molecular (Rayleigh) scattering, the choice of the wavelength to be used will depend on the expected magnitude of the return signal and the expected ratio of aerosol-to-molecular backscatter.

- The molecular scattering cross-section is proportional to λ^{-4}, and the aerosol signal is proportional to between λ^{-2} and λ^{+1}, depending on the wavelength and particle size/shape. Thus, even if the aerosol return decreases with an increase wavelength, the molecular background decreases much faster so the aerosol-to-molecular backscatter ratio gets more favorable.

- Therefore, longer wavelength is desirable to minimize the influence from molecular (Rayleigh) scattering. Usually coherent Doppler lidar uses laser wavelength between 1-11 μm.

Direct Detection Doppler Wind Lidar

- Direction Detection Doppler Wind Lidar (DDL) uses incoherent detection to measure the spectrum of return signals - one kind of Doppler wind technique with very bright future potential.
- This is because DDL can exploit aerosol scattering, molecular scattering, and/or resonance fluorescence, thus possessing the capability to measure wind from ground to upper atmosphere.
- There are several different ways to do spectral analysis for DDL

(1) Resonance fluorescence Doppler lidar: use the atmospheric atomic or molecular absorption lines as the frequency analyzer / discriminator

(2) Direct detection Doppler lidar based on molecular-absorption-edge-filter: e.g., iodine (I_2) vapor filter, Na or K magneto-optic filter

(3) Direct detection Doppler lidar based on optical interferometer edge-filter: e.g., Fabry-Perot etalon transmission edge

(4) Direct detection Doppler lidar based on fringe pattern imaging of an optical interferometer: e.g., FPI imaging

(5) Direct detection Doppler lidar based on scanning FPI or Michelson interferometer

Wavelength Considerations for DDL

- For resonance fluorescence Doppler lidar, certain specific frequencies are required to match the atomic absorption lines. For example, 589 nm for Na, 770 nm for K, and 372 nm for Fe.
- For molecular absorption edge filter, it also depends on the available molecular absorption lines. For example, iodine has absorption in the visible and near IR, thus 532 nm is currently popular, also owing to available Nd:YAG laser technology.
- For interferometer based (both edge-filter and fringe imaging) DDL, in principle you can choose any wavelength (as long as atmospheric transmission is reasonably high) because the etalon of the interferometer can be coated to any wavelength.
- If molecular scattering is used, shorter wavelength is preferred to have much strong molecular (Rayleigh) scattering, because of $\sigma_{scatter} \propto \lambda^{-4}$.
- Since Doppler broadening of molecular scattering is in the order of a few GHz, the spectral bandwidth of the laser pulse is not necessary to be as narrow as the coherent Doppler lidar. Instead, bandwidth in the order of 100 MHz would be good for DDL. This also allows shorter duration pulse to be used in DDL systems to improve range resolution.

Summary

- Using the definition of velocity (derivative of the displacement), the direct motion detection of aerosols, clouds, or smoke plumes, by images and lidars can obtain wind measurements with high resolution mostly in lower atmosphere or in industrial shop, lab or wind tunnel.
- Three major techniques in direct motion detection:
  - Crosswind determination by pattern correlation (e.g., lidar tracking of aerosol or cloud motions)
  - Laser time-of-flight velocimetry
  - Laser Doppler velocimetry
- Considerations of different wavelength requirements for coherent and incoherent detection Doppler lidars are discussed. Coherent lidar prefers longer wavelength.