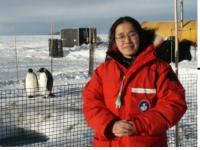
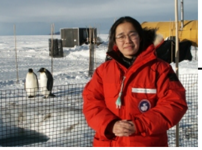


Lecture 21. Wind Lidar (2) Wind Vector Determination & Direct Motion Detection Tech

- ❑ Direct Motion Detection Wind Lidar
- ➢ Lidar tracking of aerosol motions
- ➢ Laser time-of-flight velocimetry
- ➢ Laser Doppler velocimetry
- ❑ Determination of Wind Vector
- ➢ Different wind technologies vs. 3D wind
- ➢ Determination of Doppler wind vector
- ❑ Summary



Direct Motion Detection Wind Tech

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

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

- 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

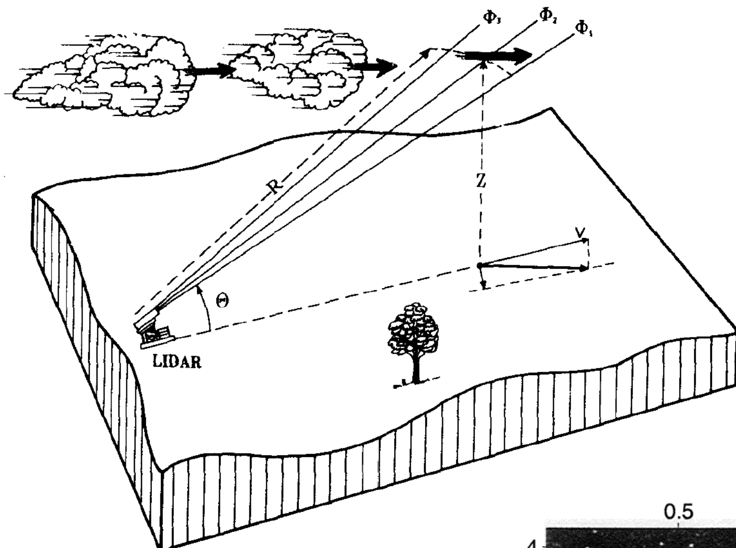
- Crosswind determination by pattern correlation

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

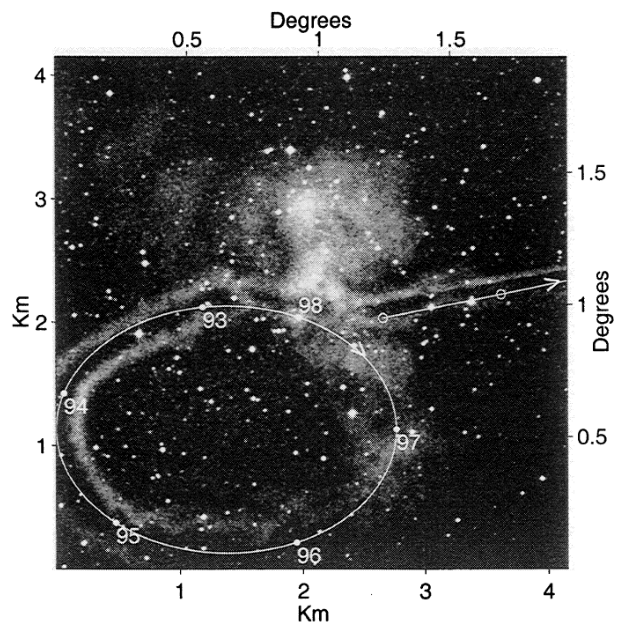
(2) Tracking Aerosol/cloud motion by lidars

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

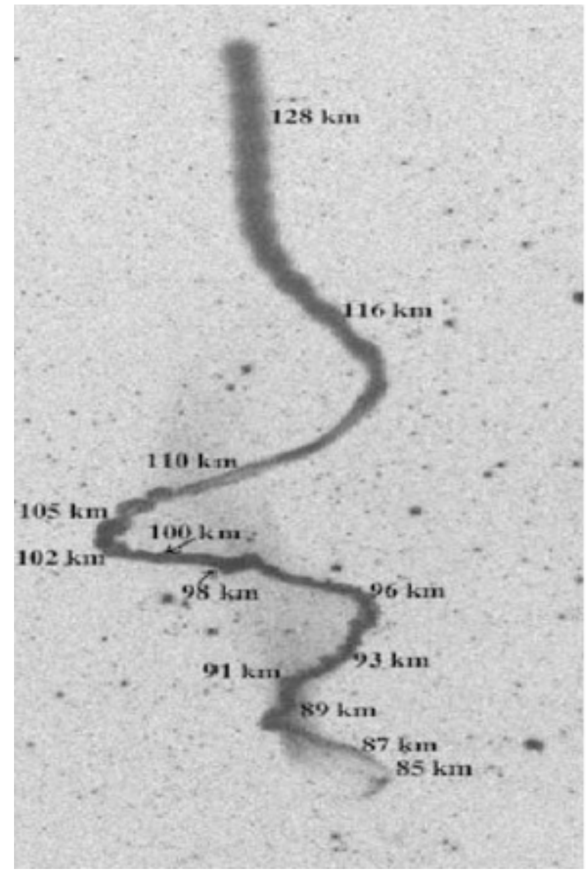
Tracking Motions of Aerosols, Meteor Trails, or Chemical Release Plumes, etc.



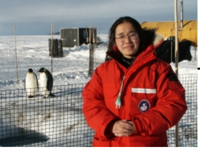
[Sroga et al., JAM, 1980]



[Drummond et al., JGR, 2001]



[Larsen, 2013]



Cross-Correlation of Cloud Pattern

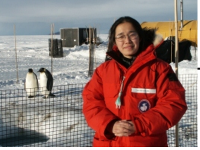
- The inhomogeneities, such as aerosol particles, cloud droplets, smoke-stack plumes, show patterns easily recognized with naked eyes. If the positions of these patterns are tracked at consecutive time, then the wind that causes the patterns to shift can be derived.

- One way of doing so is to take images of such pattern at two points in time, t_1 and t_2. If the geometric parameters such as distance, angle of observation, and imaging scales are known, 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 $(\Delta x, \Delta y)$ 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:

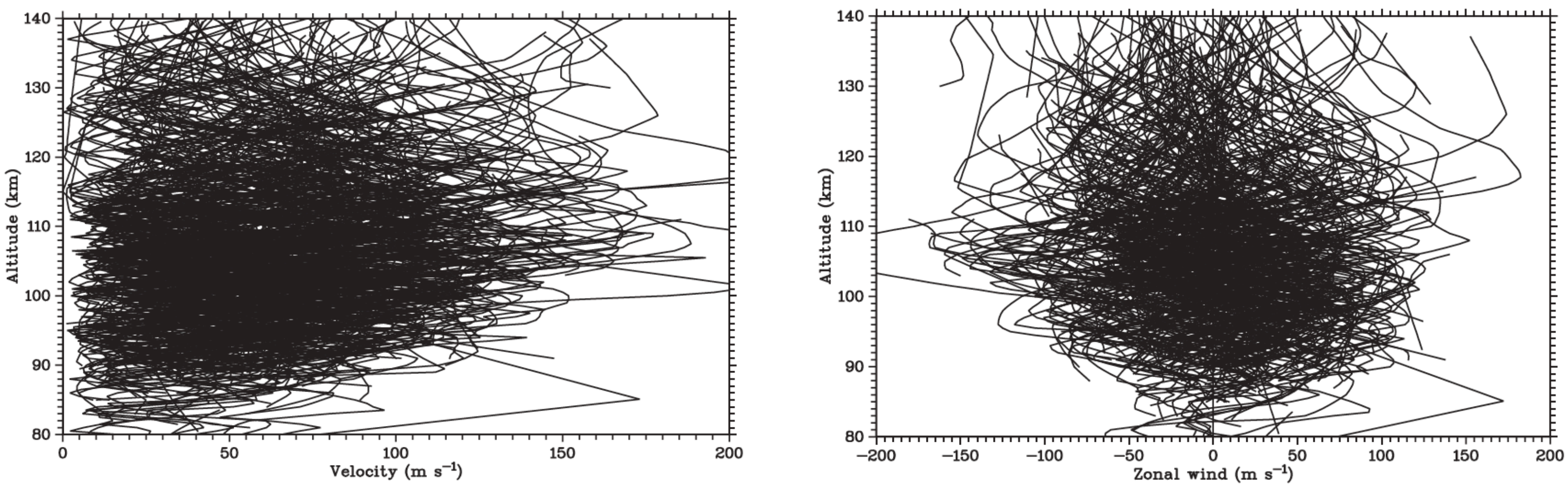
$$\boxed{\vec{u}_{horizontal} = \frac{1}{t_2 - t_1} (\Delta x, \Delta y)}$$



Chemical Release Wind Measurements

- Exciting applications of the "cross-correlation of pattern" approach:

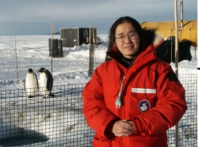
(1) Tracking a plume sent by a rocket (chemical release) to derive wind vector and how it varies with time;



Wind speed (left) and zonal wind component (right) measured by chemical release.

Once the tracer is released, the wind profiles are determined by tracking the trails with cameras from two or more sites. The star background is generally used to determine the viewing angles to points on each part of the trail, and the intersections of the lines-of-sight from two or more sites determine the trail positions at a given time. The change in position with time as a function of altitude then gives the velocity profile.

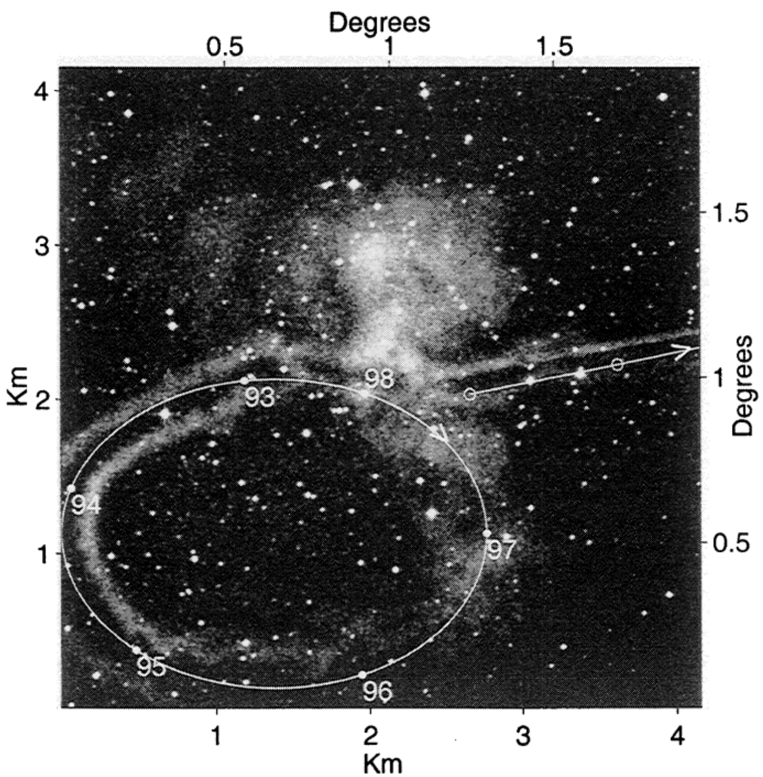
-- [Larson, JGR, 2002]

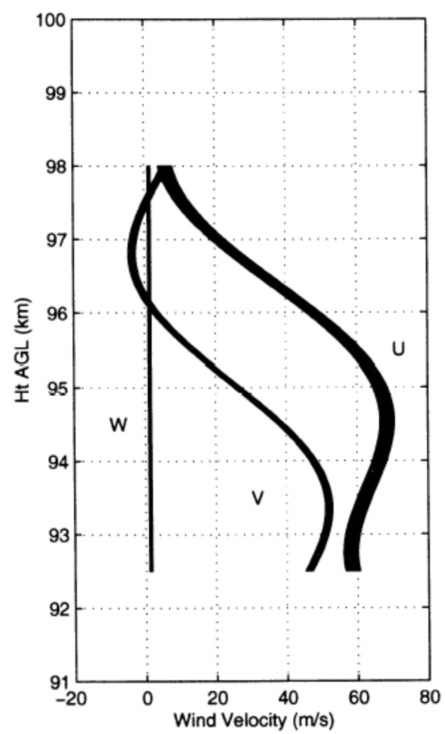


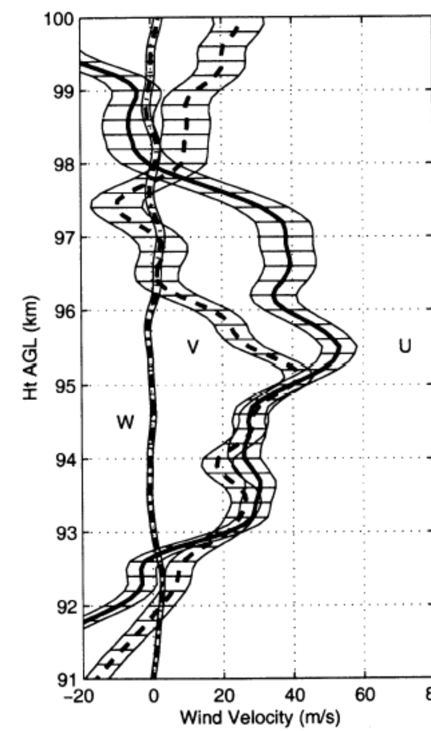
Tracking Meteor Trail for Wind

- Exciting applications of the "cross-correlation of pattern" approach:

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

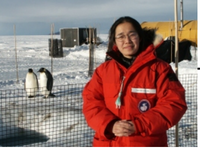






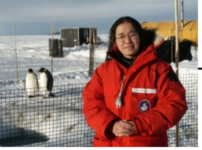
1998 Leonid Meteor Shower at SOR

-- [Drummond et al., JGR, 106 (A10), 21517-21524, 2001]

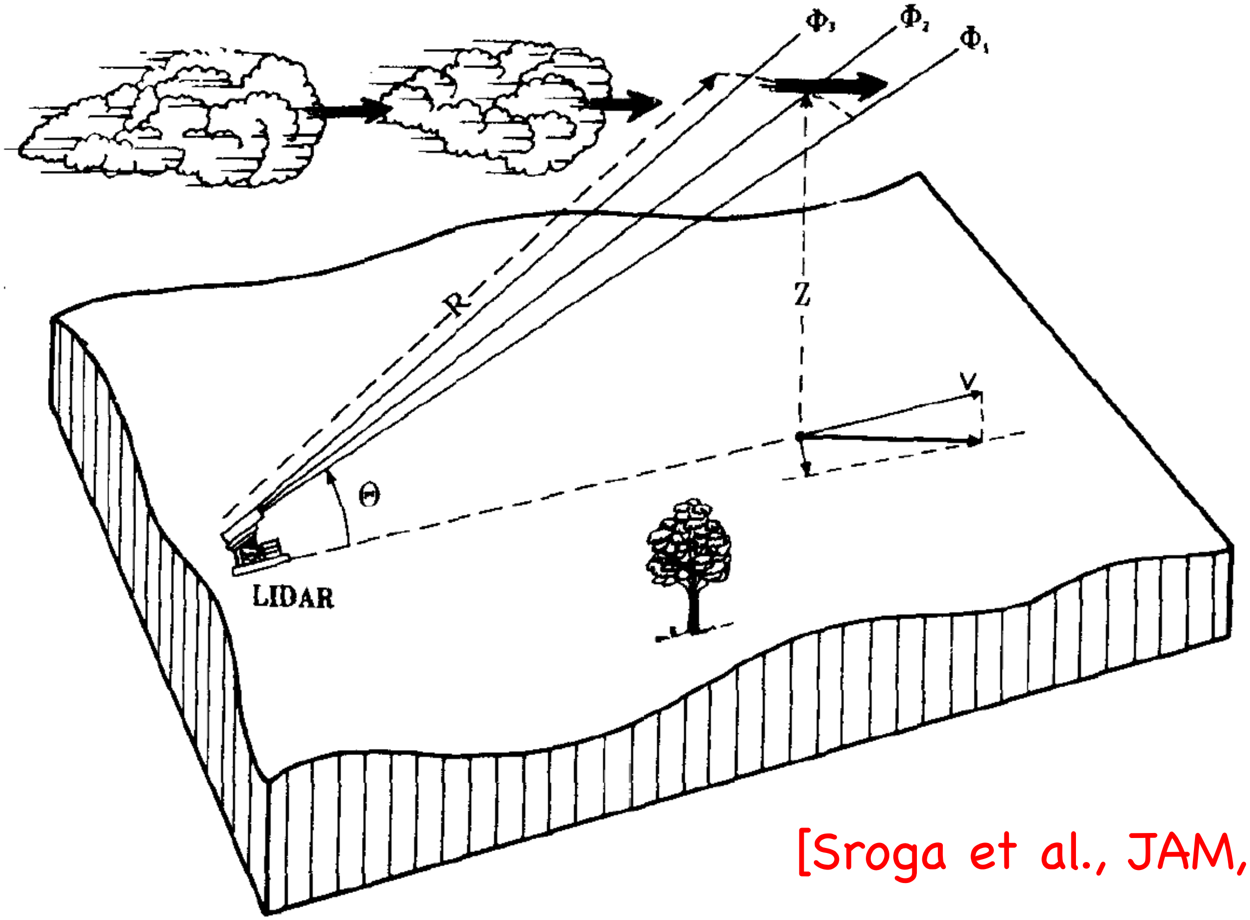


Lidar Tracking of Aerosol Motions

- Using lidar to track aerosol/cloud patterns is a much efficient way and can measure winds 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 measurements via tracking aerosol/cloud to a high degree of sophistication (Eloranta group).

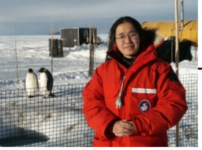


Lidar Tracking of Aerosol Motions



[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.

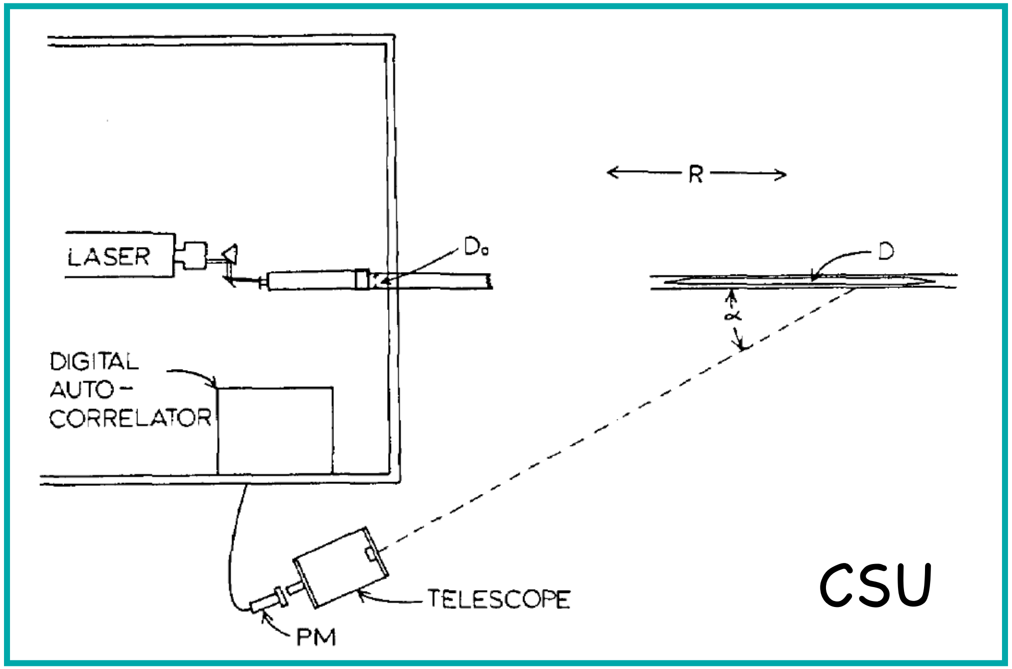


Laser Time-of-Flight Velocimetry (LTV)

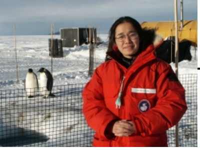
- This dual-beam technique measures the speed of a cross wind by determining a particle's time of flight across two approximately parallel beams with a small spatial separation, as illustrated in the plot.
- The output of a cw laser is focused into two parallel beams of equal intensity, with a beam-to-beam 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 demonstrations went up to 100 m range under natural aerosol conditions.



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

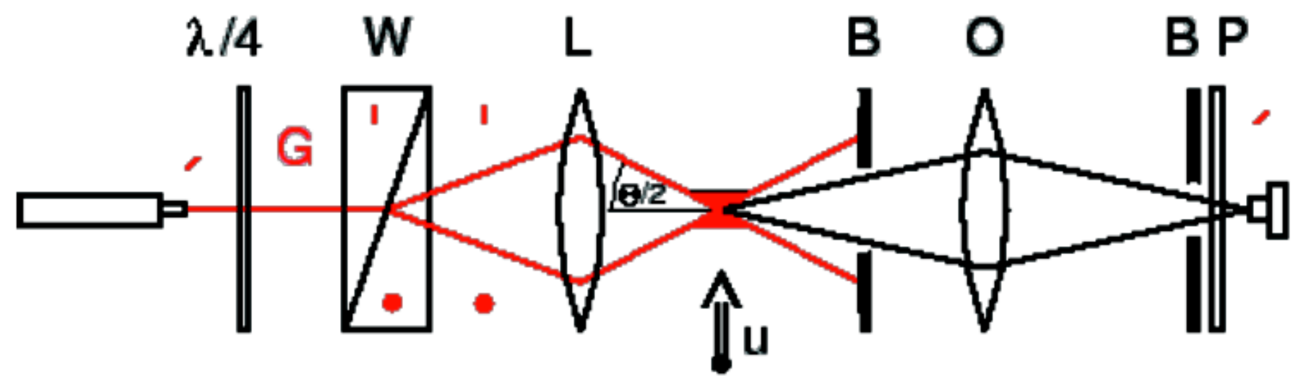


Laser Doppler Velocimetry (LDV)

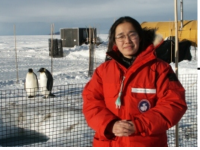
- Two laser beams split from the same laser beam cross with each other and form interference pattern, acting as a periodic field of regions with high and low intensity.
- Particles transversely cross the field and scatter light (strong and weak) periodically with a frequency that is proportional to their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

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

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.



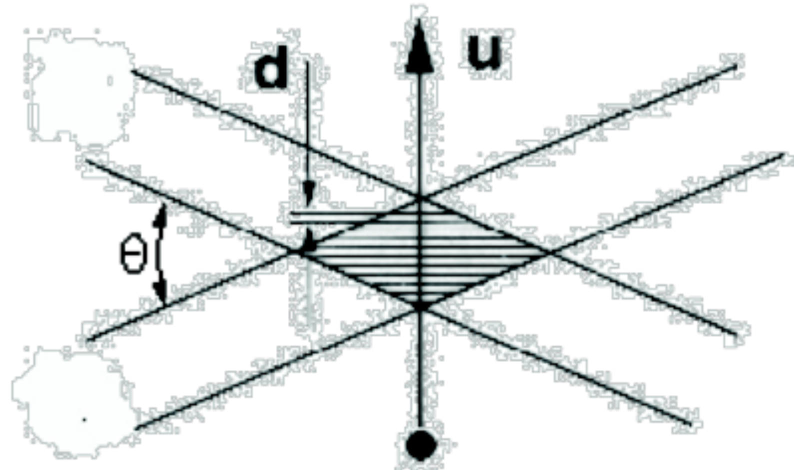
- LDV is widely used in fluid mechanics research, and has been extended to 3-D measurements.



One Way to Understand LDV

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

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

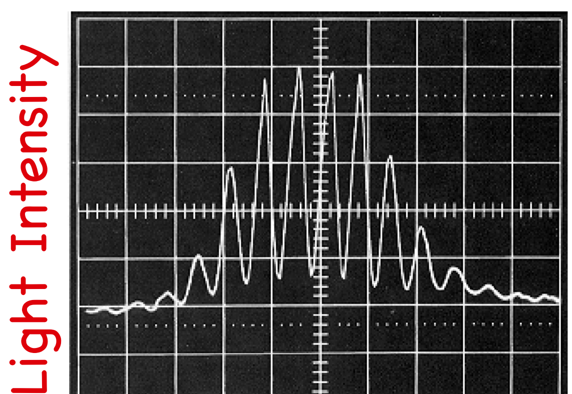


- Particles pass through the lattice with a speed of u, so the frequency of particles scattering strong light is given by

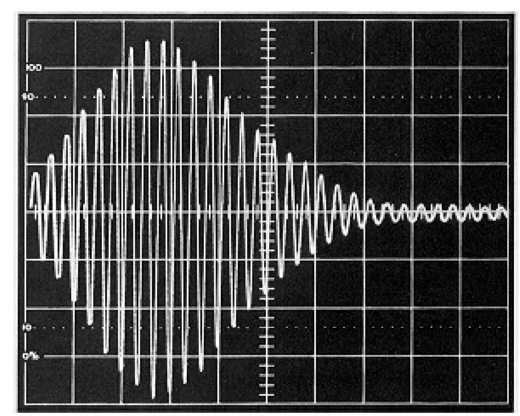
$$\boxed{f = \frac{1}{T} = \frac{1}{d/u} = \frac{u}{d}}$$

$$\Downarrow$$

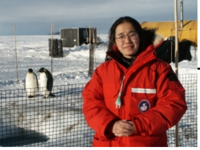
$$\boxed{u = d \cdot f = \frac{\lambda f}{2\sin(\theta/2)}}$$



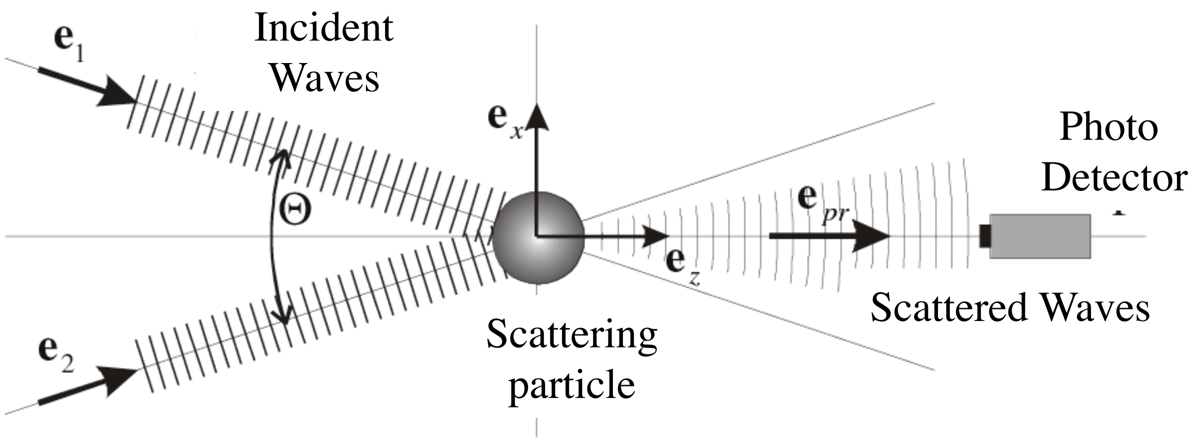
Time



Doppler burst processor



Another Way to Understand LDV



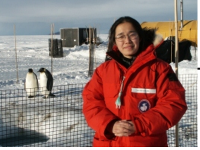
$\vec{e}_1, \vec{e}_2, \vec{e}_x, \vec{e}_y, \vec{e}_{pr}$ are unit vectors

- 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

$$I \propto \vec{E} \cdot \vec{E}^* = \underbrace{\boxed{A_1^2 \sin^2(2\pi f_1 t) + A_2^2 \sin^2(2\pi f_2 t)}}_{\text{DC components}} + \underbrace{\boxed{A_1 A_2 \cos[2\pi(f_1 + f_2)t]}}_{\text{Filtered out by bandwidth}}$$
$$+ A_1 A_2 \cos[2\pi(f_1 - f_2)t]$$

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

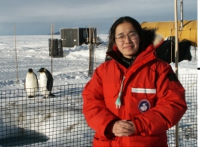
$$f_D = f_1 - f_2 = f_L \frac{\vec{v}_p \cdot (\vec{e}_2 - \vec{e}_1)}{c} = f_L \frac{2\sin(\theta/2)}{c} \vec{v}_p \cdot \vec{e}_x = v_x \frac{2\sin(\theta/2)}{\lambda}$$

- So the transverse velocity is

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

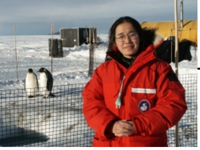
$$\boxed{v_x = \frac{\lambda f_D}{2\sin(\theta/2)}}$$

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



Determination of Wind Vector

- Estimates of vector (u, v, w) wind velocity require radial velocity measurements from at least three independent line-of-sight (LOS).
- Different wind measurement technologies have different advantages or disadvantages on the vector wind determination –
  - LTV and LDV of the direct motion detection measure the transverse wind, not the radial wind. Measurements from more than one direction are needed to determine the 3-D wind vector.
  - "Cross-correlation of pattern" with imagers measure the two components of velocity vector in the plane perpendicular to the line of sight. Imaging the same pattern from two or more sites can determine the position vectors of the pattern, thus deriving vector winds.
  - Lidar tracking of the motions of aerosols or other inhomogeneity can derive the wind vector in 3-D directly by taking the time derivative of position vectors.
  - Doppler wind techniques measure the radial velocity (i.e., LOS wind), so three LOS measurements are needed to determine the wind vector.



Determination of Doppler Wind Vector

- 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.

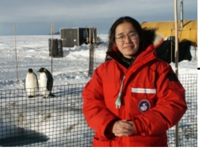
- Practically: under a necessary assumption of horizontal homogeneity of the wind field over the sensed volume, lidar beam scanning techniques can be used to determine the vector wind velocity.
- Two main techniques for this scanning -

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

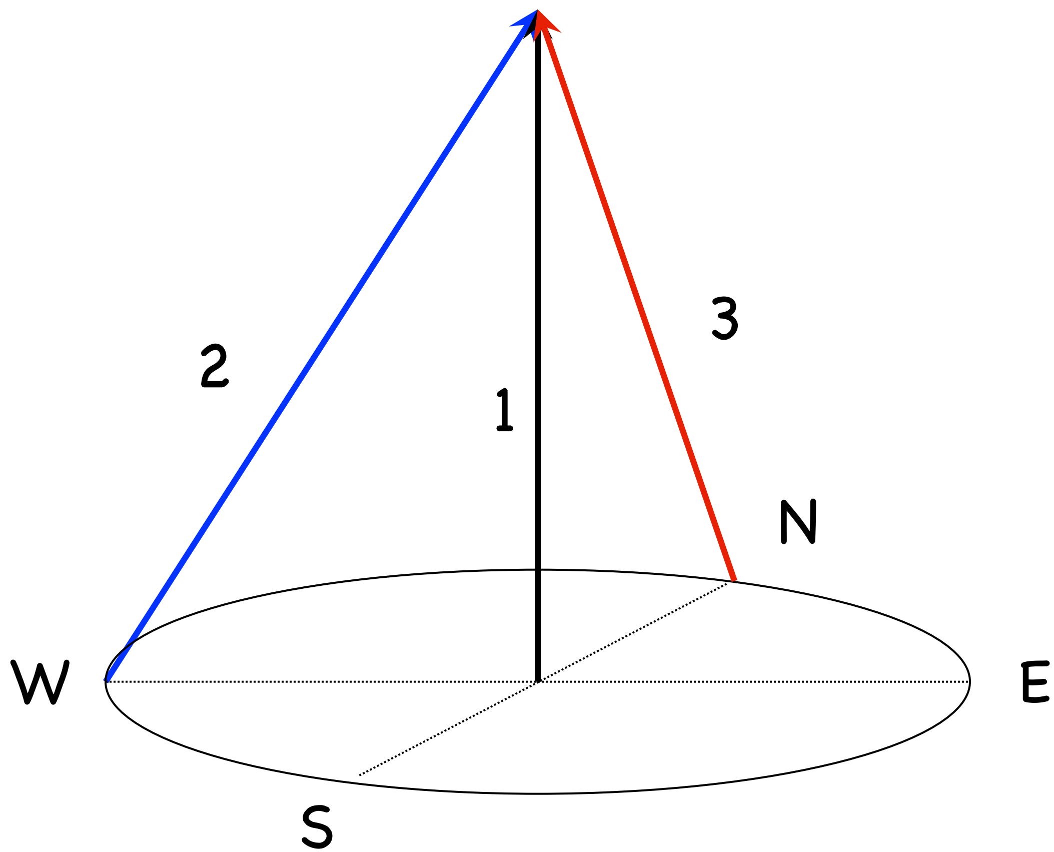
-- conical scan of lidar beam at a fixed elevation angle

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

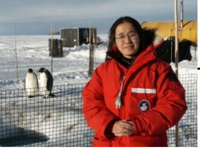
-- pointing lidar beam to vertical, tilted east, and tilted north



Ideal Vector Wind Measurement



A possibility is to detect the same volume from Table Mountain and Fort Collins simultaneously for wind and gravity wave study.



VAD and DBS Techniques

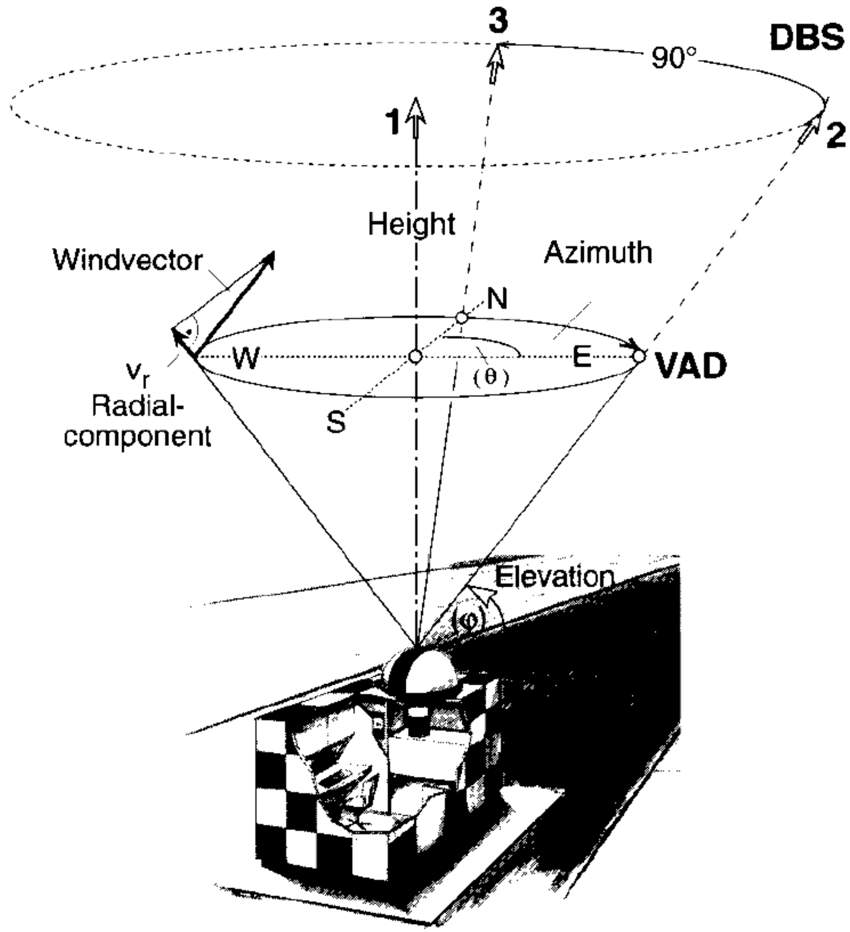
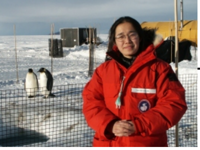
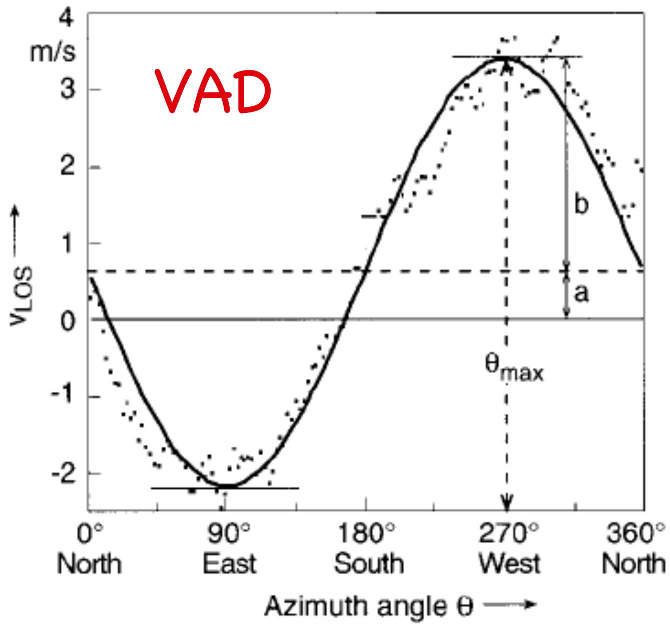


Fig. 12.8. Schematic of the scan technique of a Doppler lidar. Lower part: VAD scan, upper part: DBS scan.



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

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

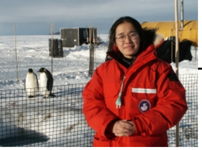
offset a, amplitude b, and phase shift θ_{max}.

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

- For DBS technique, the three components are obtained as

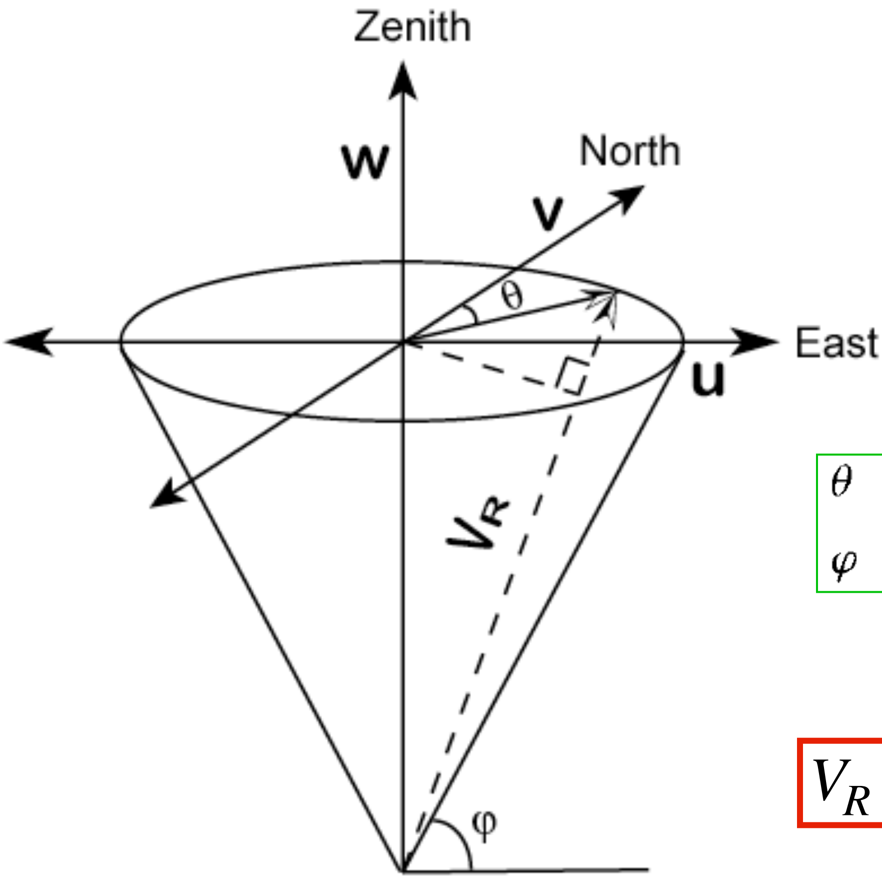
$$\boxed{\begin{aligned} u &= -(V_{r2} - V_{r1}\sin\varphi)/\cos\varphi \\ v &= -(V_{r3} - V_{r1}\sin\varphi)/\cos\varphi \\ w &= -V_{r1} \end{aligned}}$$

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



VAD Technique for Vector Wind

- Velocity-Azimuth-Display (VAD) technique: conical scan lidar beam at a fixed elevation angle
- For groundbased lidar, we define positive u, v, w as the wind blowing towards east, north, and upward, and positive radial wind V_R as the wind blowing away from the lidar.



Radial velocity V_R consists of components from u, v, and w:

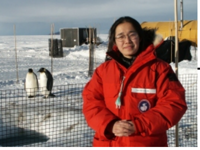
Zonal wind contribution	$u\sin\theta\cos\varphi$
Meridional contribution	$v\cos\theta\cos\varphi$
Vertical contribution	$w\sin\varphi$

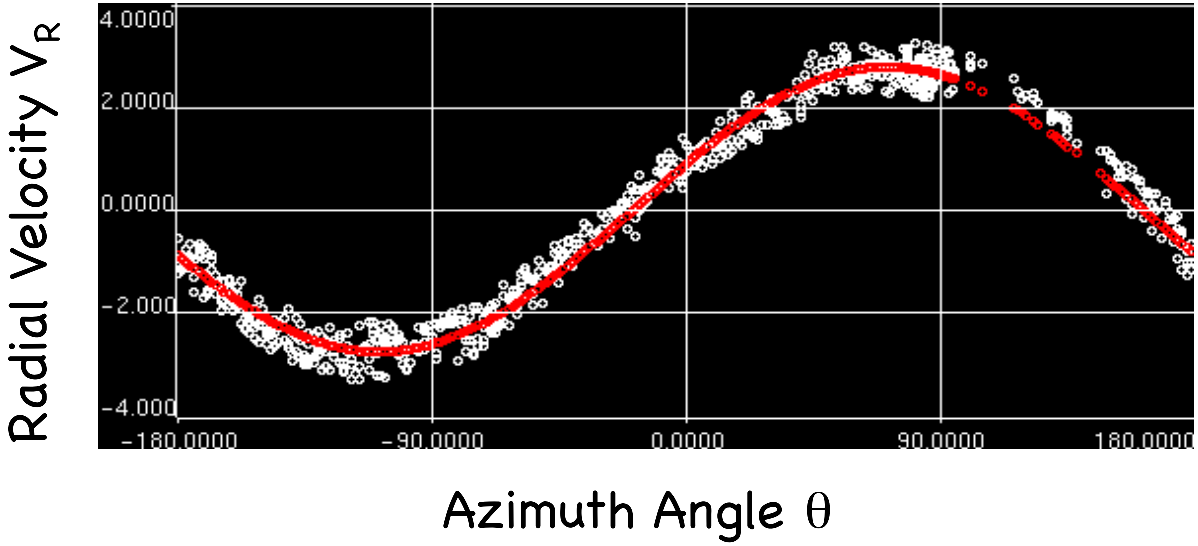
θ the azimuth angle, clockwise from North, and

φ the elevation angle.

$$\theta_N = 0^\circ, \theta_E = 90^\circ, \theta_S = 180^\circ, \theta_W = 270^\circ$$

$$V_R = u\sin\theta\cos\varphi + v\cos\theta\cos\varphi + w\sin\varphi$$





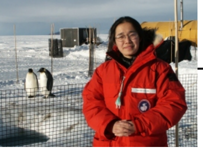
$$V_R = u\sin\theta\cos\varphi + v\cos\theta\cos\varphi + w\sin\varphi$$

- For VAD scan, elevation angle φ is fixed (constant) and known, azimuth angle θ is varied but also known. V_R is measured, so the three unknown parameters u, v, and w can be derived directly from fitting the data with above equation.
- Another approach is to fit the scan data with the following equation:

$$V_R = a + b\cos(\theta - \theta_{max}) = b\sin\theta_{max}\sin\theta + b\cos\theta_{max}\cos\theta + a$$

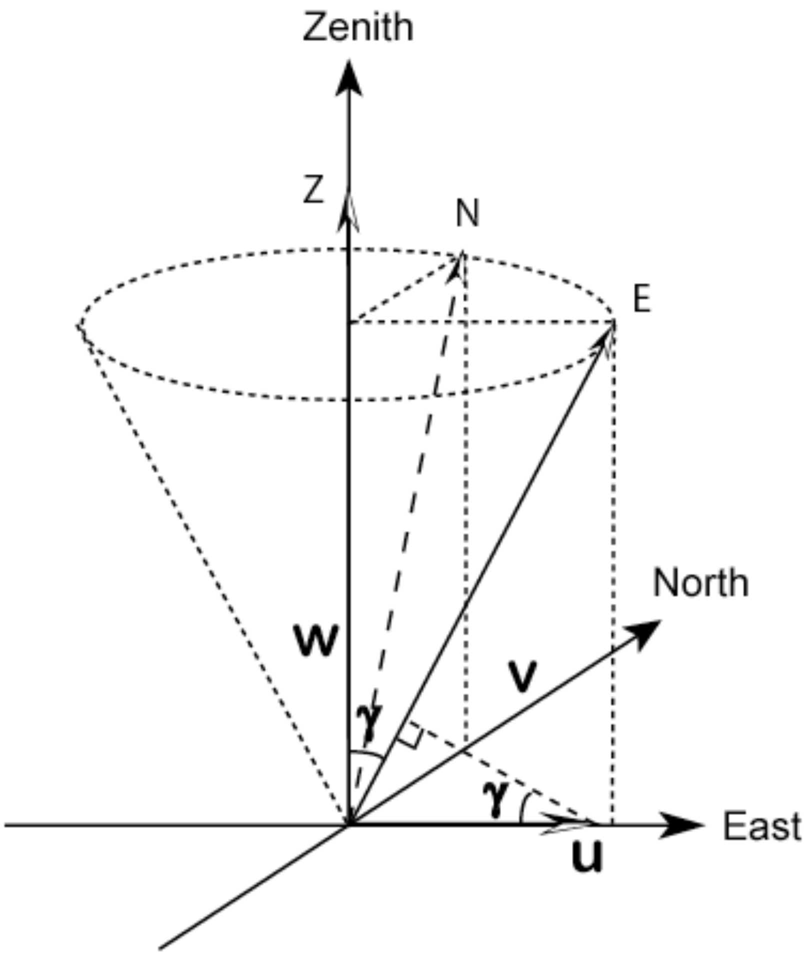
where a is offset, b is amplitude, and θ_{max} is the phase shift

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



DBS Technique for Vector Wind

- Doppler-Beam-Swinging (DBS) techniques: pointing lidar beam to vertical, tilted east, and tilted north.

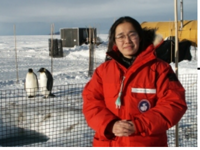


γ is the off-zenith angle

$$\boxed{\begin{aligned} V_{RE} &= u\sin\gamma + w\cos\gamma \\ V_{RN} &= v\sin\gamma + w\cos\gamma \\ V_{RZ} &= w \end{aligned}}$$

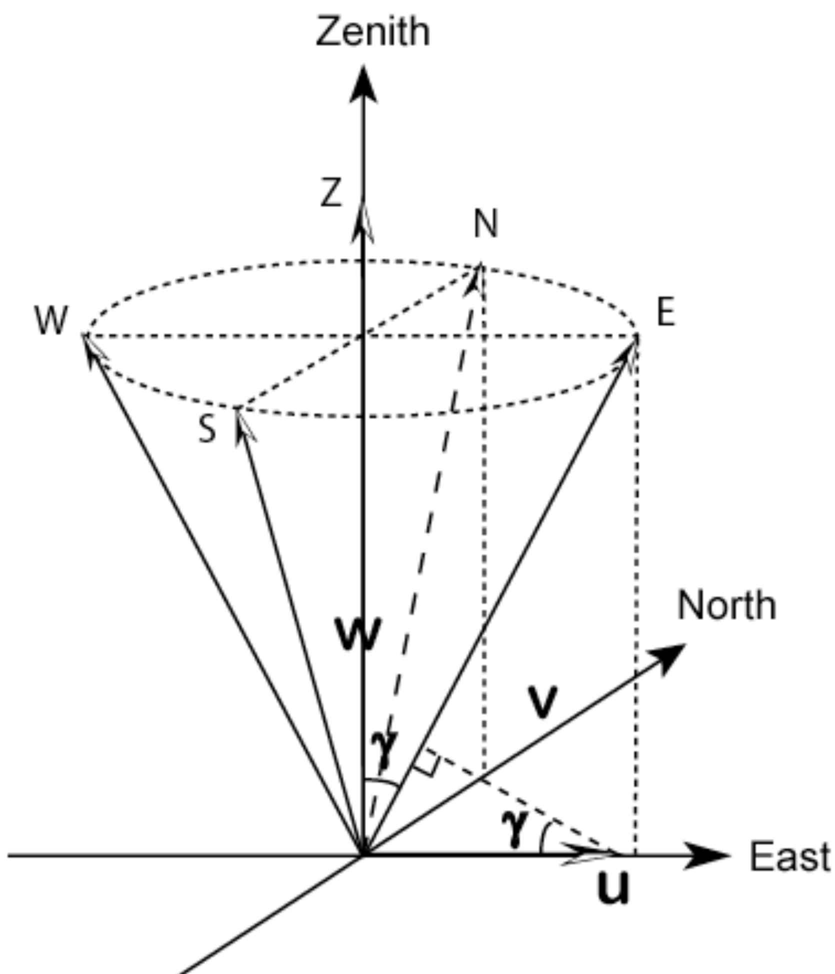
$$\boxed{\begin{aligned} u &= (V_{RE} - V_{RZ}\cos\gamma)/\sin\gamma \\ v &= (V_{RN} - V_{RZ}\cos\gamma)/\sin\gamma \\ w &= V_{RZ} \end{aligned}}$$

V_{RZ}, V_{RE}, V_{RN} are the vertical, tilted east, and tilted north radial velocities



Modified DBS Technique

❑ Pointing lidar beam to vertical, tilted north, tilted east, tilted south, and tilted west directions (ZNEZSW).

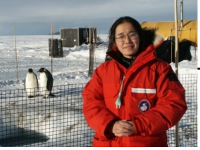


γ is the off-zenith angle

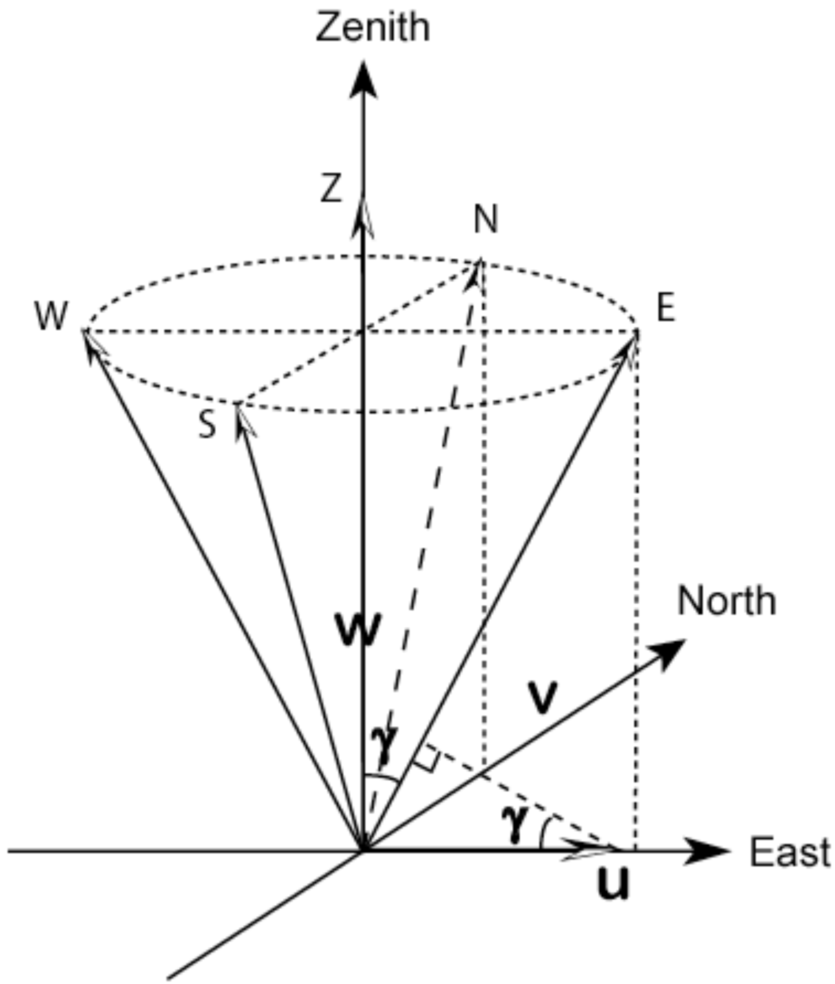
$$
\begin{aligned}
V_{RE} &= u\sin\gamma + w\cos\gamma \\
V_{RW} &= -u\sin\gamma + w\cos\gamma \\
V_{RN} &= v\sin\gamma + w\cos\gamma \\
V_{RS} &= -v\sin\gamma + w\cos\gamma \\
V_{RZ} &= w
\end{aligned}
$$

$$
\begin{aligned}
u &= (V_{RE} - V_{RW})/\sin\gamma/2 \\
v &= (V_{RN} - V_{RS})/\sin\gamma/2 \\
w &= V_{RZ}
\end{aligned}
$$

$V_R > 0$, $w > 0$, $u > 0$, $v > 0$ for wind towards away, upward, east, and north



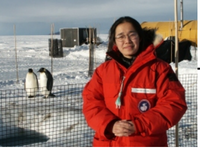
Modified DBS Technique



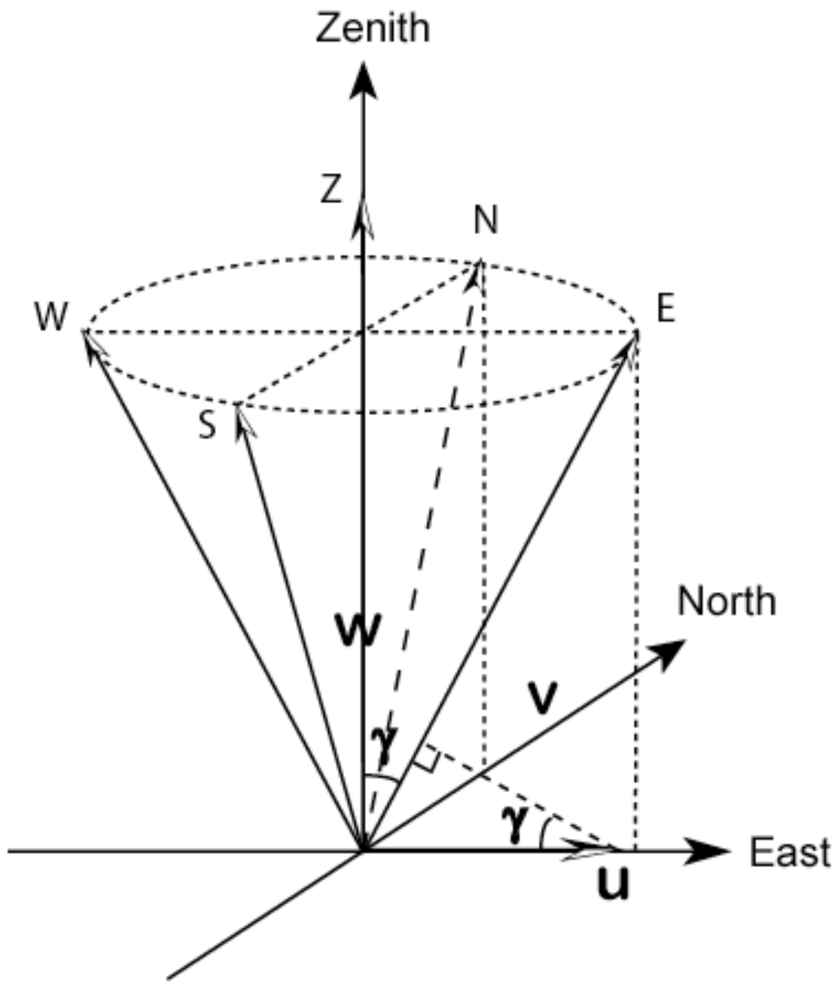
$$V_{RE} = u\sin\gamma + w\cos\gamma$$
$$V_{RW} = -u\sin\gamma + w\cos\gamma$$
$$V_{RN} = v\sin\gamma + w\cos\gamma$$
$$V_{RS} = -v\sin\gamma + w\cos\gamma$$
$$V_{RZ} = w$$

$$u = (V_{RE} - V_{RZ}\cos\gamma)/\sin\gamma$$
$$u = -(V_{RW} - V_{RZ}\cos\gamma)/\sin\gamma$$
$$v = (V_{RN} - V_{RZ}\cos\gamma)/\sin\gamma$$
$$v = -(V_{RS} - V_{RZ}\cos\gamma)/\sin\gamma$$
$$w = V_{RZ}$$

$V_R > 0$, $w > 0$, $u > 0$, $v > 0$ for wind towards away, upward, east, and north



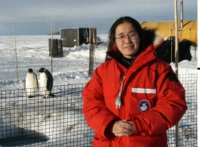
Modified DBS Technique



$$V_{RE} = u\sin\gamma + w\cos\gamma$$
$$V_{RW} = -u\sin\gamma + w\cos\gamma$$
$$V_{RN} = v\sin\gamma + w\cos\gamma$$
$$V_{RS} = -v\sin\gamma + w\cos\gamma$$
$$V_{RZ} = w$$

$$u = V_{RE}/\sin\gamma$$
$$u = -V_{RW}/\sin\gamma$$
$$v = V_{RN}/\sin\gamma$$
$$v = -V_{RS}/\sin\gamma$$
$$w = V_{RZ}$$

In the middle atmosphere, w is less than 1 m/s while the measurement precision of radial velocity is about 1 m/s. So it is reasonable to ignore the contribution from vertical wind to off-zenith radial wind.



Summary

- Using the definition of velocity (derivative of position vector), 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: 1) Crosswind determination by pattern correlation; 2) laser time-of-flight velocimetry, and 3) laser Doppler velocimetry
- Wind is a vector consisting of three components (u, v, w) corresponding to zonal, meridional, and vertical winds. Since Doppler wind technique measures the velocity along the lidar beam, it needs radial velocity measurements from at least three independent line-of-sight (LOS).
- Ideally, we want to point 3 lidar beams from three different directions (e.g., zenith, south, and west) to a given point in space.
- Practically, under some assumption of horizontal homogeneity of the wind field over the sensed volume, scanning lidar techniques can be used to determine the vector wind. Two main scanning techniques are the Velocity-Azimuth-Display (VAD) technique and the Doppler-Beam-Swinging (DBS) technique.