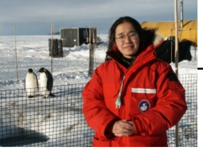
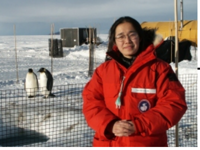




# Lecture 23. Wind Lidar Overview & Direct Motion Detection

- Motivations to measure global wind
- Overview of wind measurement techniques
  - Direct Motion Detection Technique
  - Coherent Detection Doppler Wind Technique
  - Direct Detection Doppler Wind Technique
  - Geostrophic Wind Technique
- Direct Motion Detection Techniques
- Vector Wind Determination
- Summary





# Motivations for Wind Measurements

- Global atmospheric wind profiles from ground to the upper atmosphere are important for weather forecast, 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 purposes - model validation and climate change monitoring. But wind/velocity measurements have much more applications in industry, environment, and defense business. For example,

(1) Wind turbine / wind farm

(2) Aircraft true airspeed, aircraft wake vortices

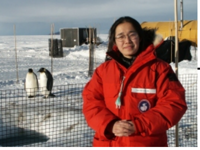
(3) Clear air turbulence, wind shear, gust fronts

(4) Air pollution monitoring

(5) Vibration of objects

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

... ... etc.





# Wind Measurements 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 $\Delta\omega = -2\vec{k}\cdot\vec{v}$

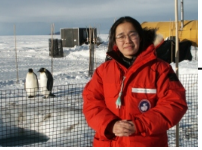
(1) Coherent Detection Doppler Wind Lidar

(Heterodyne & Homodyne)

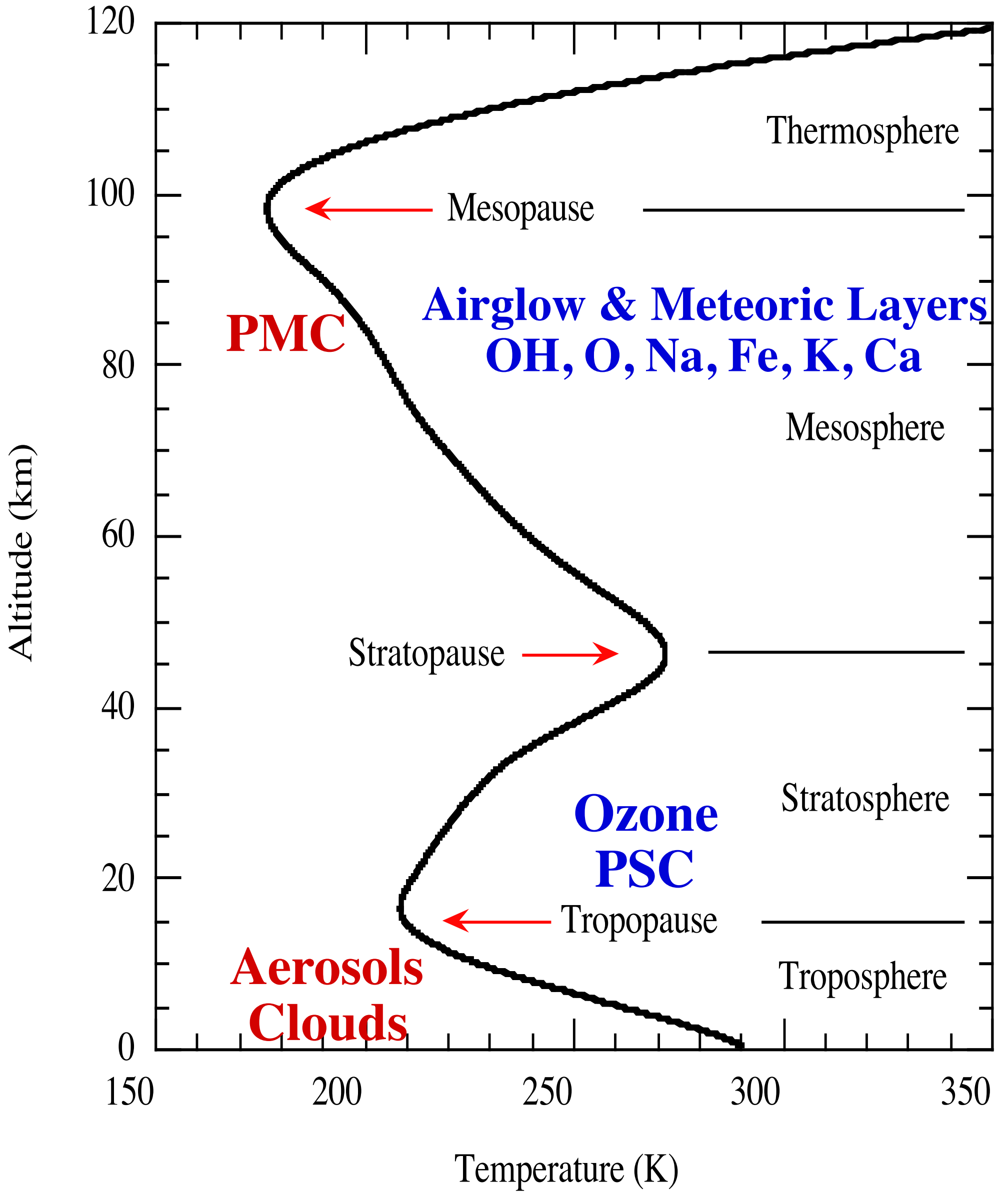
(2) Direct Detection Doppler Wind Lidar

- Geostrophic wind detection:

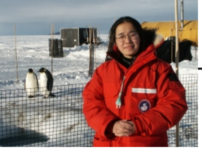
Temperature + Density ⇨ Pressure Gradients ⇨ Geostrophic Wind



# Overview Wind Techniques




- 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 aerosol, LDV, LTV)



# Overview: Direct Motion Detection

- 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.

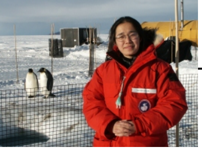
Common approaches for detecting motion remotely

- Crosswind determination by pattern correlation

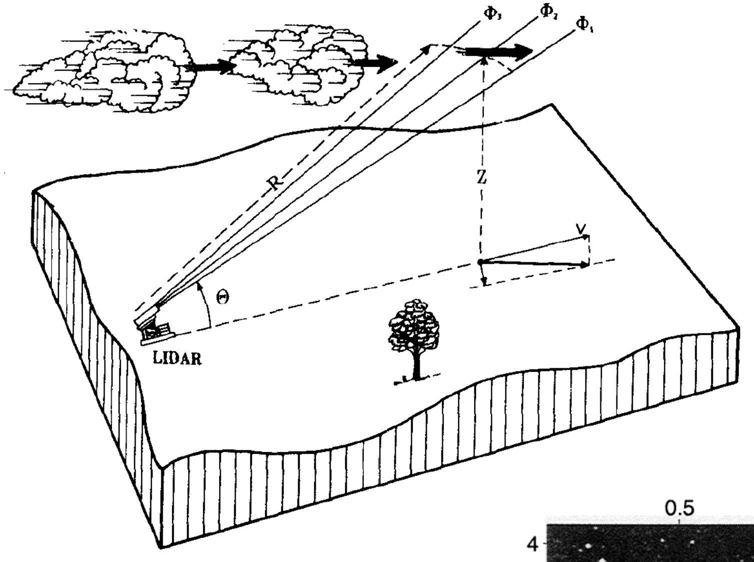
(1) Tracking aerosols, clouds, plumes, trails by images

(2) Tracking Aerosol/cloud motion by lidars

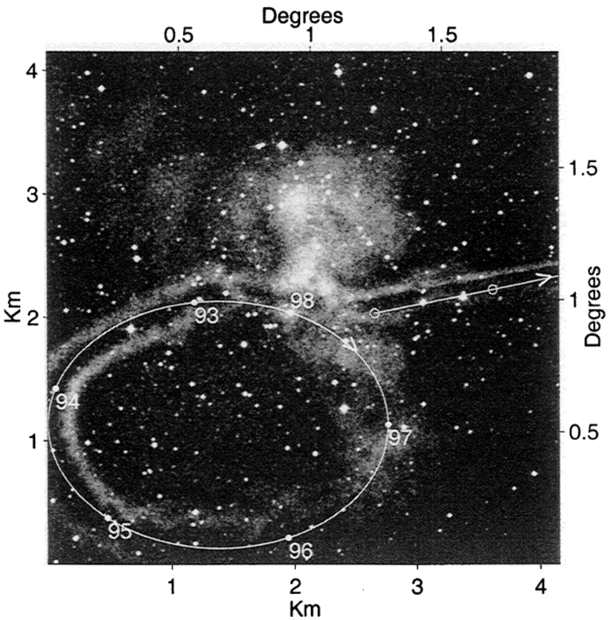
- Laser Time-of-Flight Velocimetry (LTV)
- Laser Doppler Velocimetry (LDV)



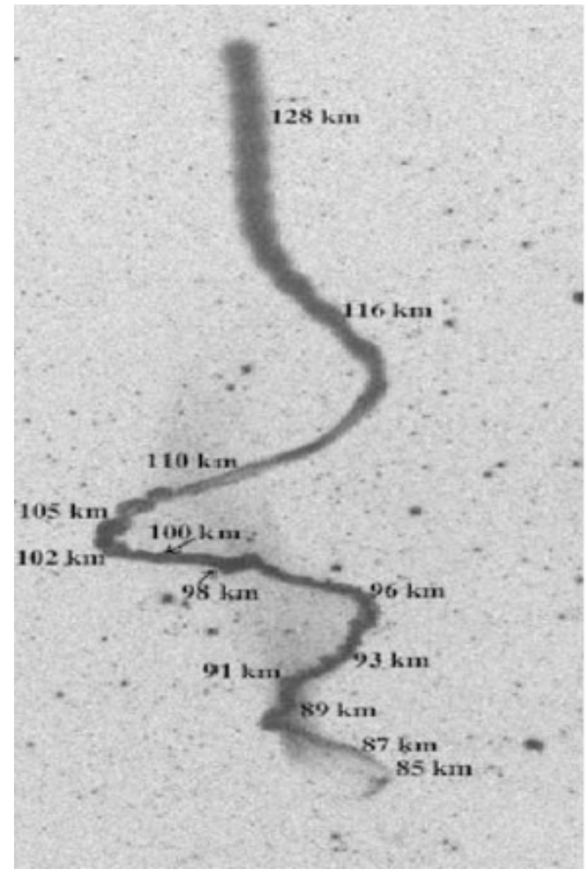
# Tracking Motions of Aerosols, Meteor Trails, or Chemical Release Plumes, etc.



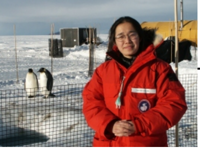

[Sroga et al., JAM, 1980]




[Drummond et al., JGR, 2001]



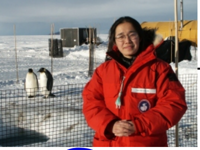

[Larsen, 2013]





# Overview: 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 (the 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.





# Overview: Coherent Detection Doppler Lidar

- 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.
- Coherent detection Doppler wind lidar used to be called "heterodyne" detection Doppler lidar, but modern homodyne detection has emerged with image-rejection technique.

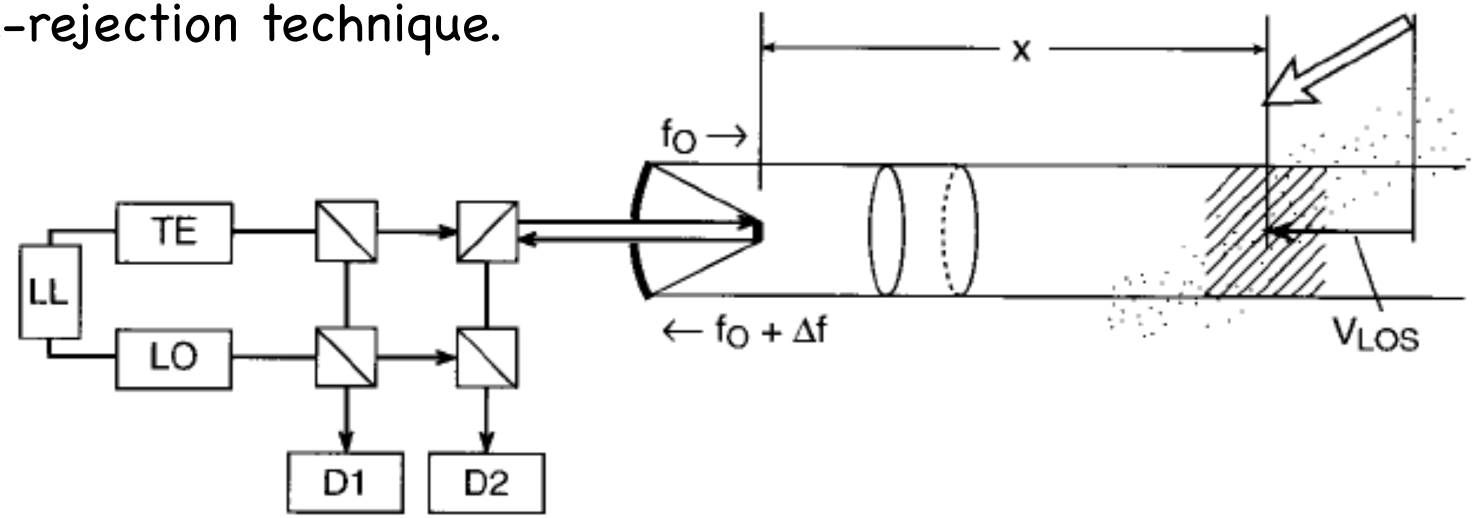
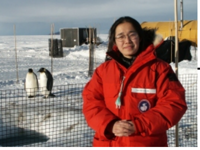



**Fig. 12.6.** Principle of a heterodyne-detection Doppler lidar.

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

Laser pulse duration is a few μs. The freq difference between TE and LO must be determined with high accuracy & maintained as stable as possible.





# Coherent Detection Doppler Wind

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

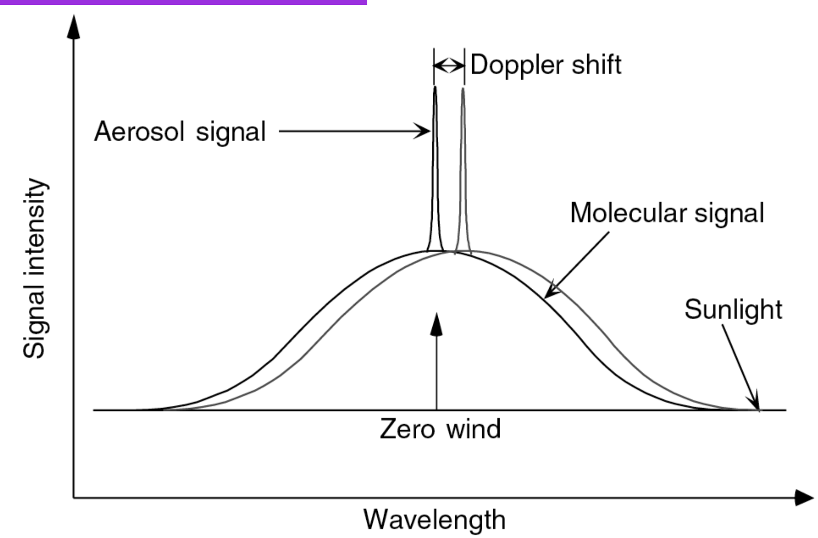
The pulsed transmitter has a frequency of $f_0 = f_{LO} + f_{offset}$

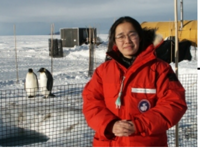
The return signal (Doppler shifted) has a freq of $f_{Sig} = f_0 + \Delta f$

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

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

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







# Overview: Direct Detection Doppler Lidar

- 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.

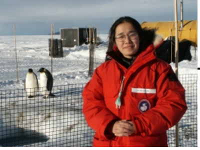
- The optical frequency discriminators include mainly three (or four) types

(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: transmission edge of an atomic or a molecular absorption line (e.g., iodine $I_2$ absorption lines), or edge of transmission fringes of an optical interferometer (e.g., Fabry-Perot or Fizeau etalon).

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

(4) Scanning FPI or other scanning and non-scanning interferometers such as Michelson, Mach-Zehnder, etc.



# 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. The atomic absorption lines act as natural frequency analyzers.

- Non-resonance direct detection Doppler lidars utilize aerosol scattering, or molecular scattering, or both.

- The main ideas are

Intensity ratio (like in Na, K, and Fe Doppler lidar)

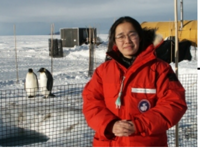
⇨ Frequency shift ⇨ radial velocity (LOS)

Intensity change (like in HSRL or some Rayleigh Doppler lidar)

⇨ Frequency shift ⇨ radial velocity (LOS)

Intensity spatial distribution (like in some Rayleigh Doppler lidar)

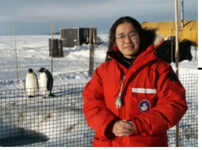
⇨ Frequency shift ⇨ radial velocity (LOS)





# Frequency Analyzers in ATM or Receiver

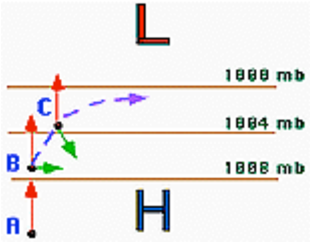
- The resonance fluorescence Doppler lidar is one kind of direct detection Doppler lidars (DDL). It uses intensity ratios (photon count ratios) to derive wind and temperature. The spectral analyzer is in the atmosphere - atomic absorption lines.
- For atmosphere below the MLT resonance fluorescence region, molecular and aerosol scatterings are used to infer Doppler shift caused by line of sight wind. Since there is no spectral analyzer in the atmosphere, some frequency discriminator must be implemented in the lidar receiver.
- Unlike the temperature measurements where only molecular scattering can be utilized, wind information can be inferred from aerosol scattering, especially in the lower atmosphere where aerosol scattering dominates.
- Any optical or spectroscopic methods that can distinguish frequency shift or difference could be applied to DDL. Therefore, new methods are still being proposed ……



# Overview: Geostrophic Wind

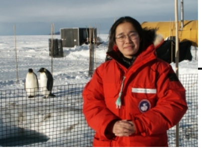
- Geostrophic wind is the horizontal wind velocity for which the Coriolis force exactly balances the pressure gradient force (horizontal pressure force): $f\vec{k} \times \vec{V}_g = -g\vec{\nabla}_p Z$

$$\vec{V}_g = \frac{1}{f}\vec{k} \times \vec{\nabla}\Phi = \frac{g}{f}\vec{k} \times \vec{\nabla}Z = \frac{1}{\rho f}\vec{k} \times \vec{\nabla}P = \frac{RT}{f}\vec{k} \times \vec{\nabla}\ln P$$



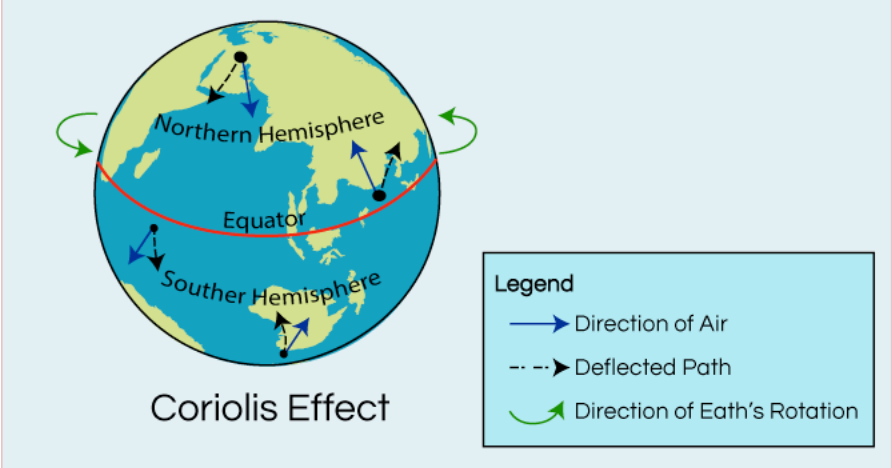

where $V_g$ is the geostrophic wind (horizontal), f = 2Ω sinφ is the local Coriolis parameter (Ω - earth's rotation rate, φ - latitude), k is the vertical unit vector, Φ is the geopotential, g is the gravitational acceleration, Z is the geopotential height, ρ is the mass density, P is pressure, R is atmosphere constant, and T is temperature.

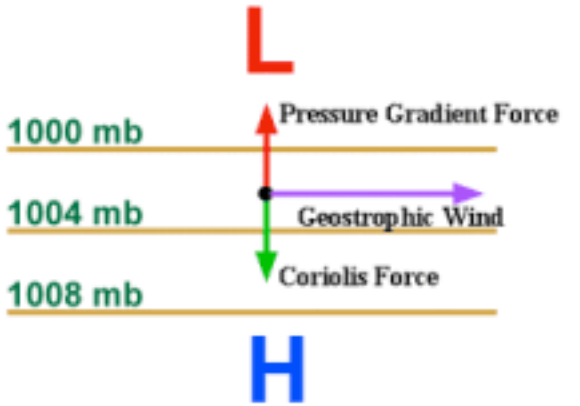
- If we can somehow obtain geopotential, geopotential height, or density and temperature or pressure data with horizontal distribution, then we may derive the geostrophic wind using above equation. Rayleigh lidar can be used to measure atmosphere density and temperature, thus, atmospheric pressure.



# Geostrophic Wind vs. Gradient Wind

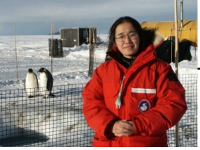
An air parcel initially at rest will move from high pressure to low pressure because of the pressure gradient force (PGF). However, as that air parcel begins to move, it is deflected by the Coriolis force to the right in the northern hemisphere (to the left on the southern hemisphere). As the wind gains speed, the deflection increases until the Coriolis force equals the pressure gradient force. At this point, the wind will be blowing parallel to the isobars. When this happens, the wind is referred to as geostrophic.




http://ww2010.atmos.uiuc.edu/%28Gh%29/guides/mtr/fw/geos.rxml

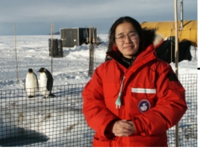
http://ww2010.atmos.uiuc.edu/%28Gh%29/guides/mtr/fw/grad.rxml





# Summary (1)

- 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 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).





# 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.

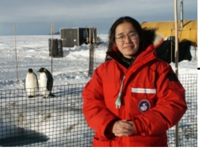
Common approaches for detecting motion remotely

- Crosswind determination by pattern correlation

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

(2) Tracking Aerosol/cloud motion by lidars

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





# Cross-Correlation of Cloud Pattern

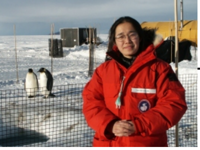
- The inhomogeneities, such as aerosol particles, cloud droplets, smoke-stack plumes, show patterns easily recognized with naked eyes. If the positions of these patterns are tracked at consecutive time, then the wind that causes the patterns to shift can be derived.

- 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:

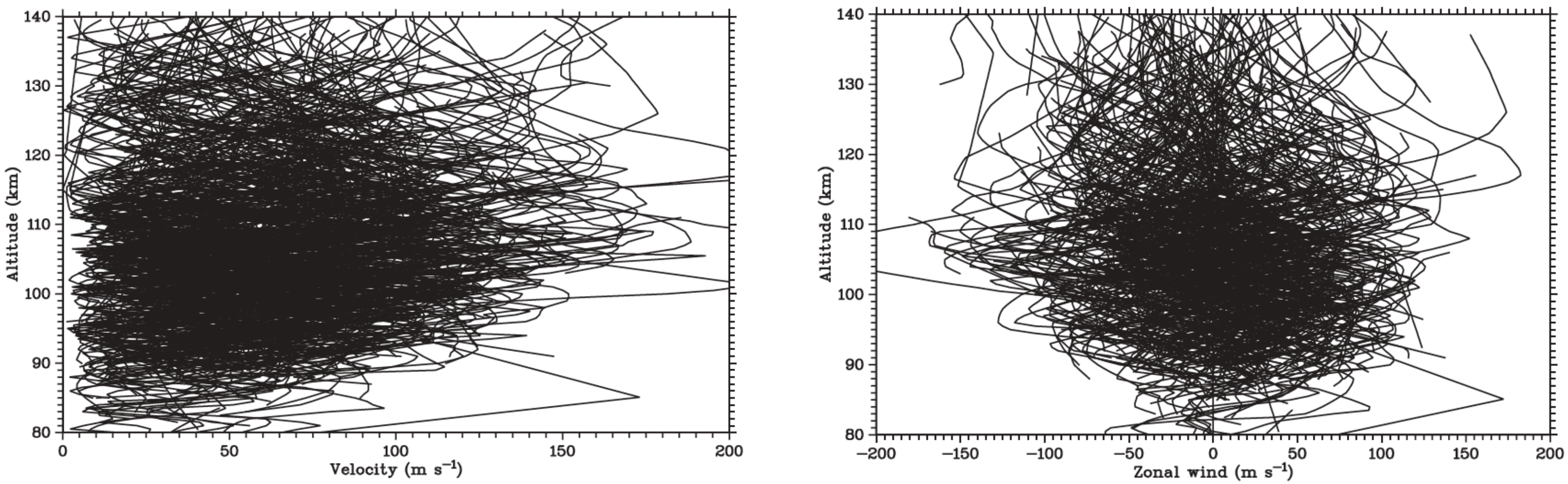
$$\vec{u}_{hor} = \frac{1}{t_2 - t_1} (\Delta x, \Delta y)$$





# Chemical Release Wind Measurements

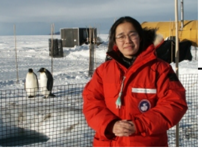
❑ Exciting applications of the "cross-correlation of pattern" approach: (1) tracking a plume sent by a rocket (chemical release) to derive wind vector and how it varies with time;




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 look 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]

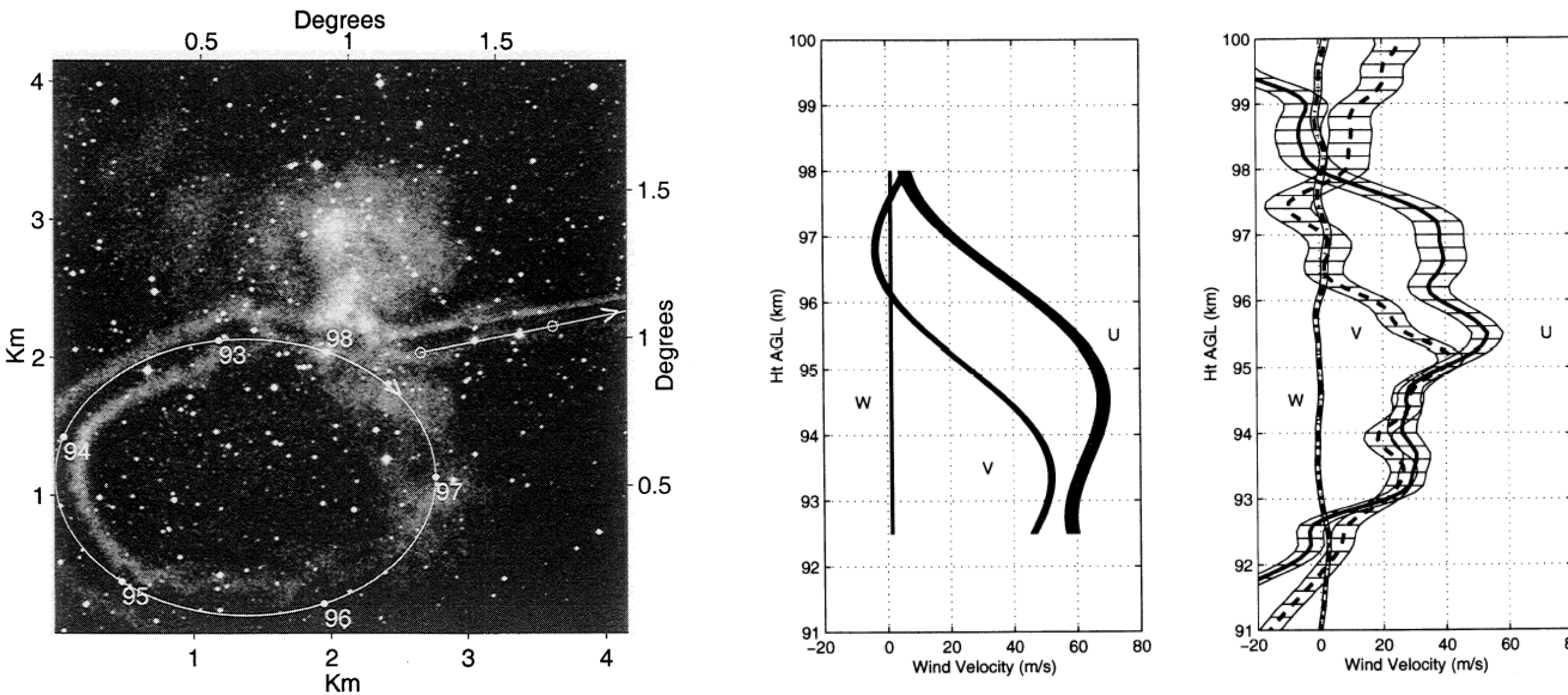




# Tracking Meteor Trail for Wind

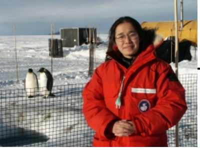
- Exciting applications of the "cross-correlation of pattern" approach:

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




1998 Leonid Meteor Shower at SOR

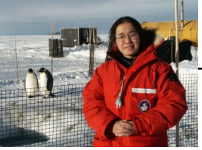
-- [Drummond et al., JGR, 106 (A10), 21517-21524, 2001]





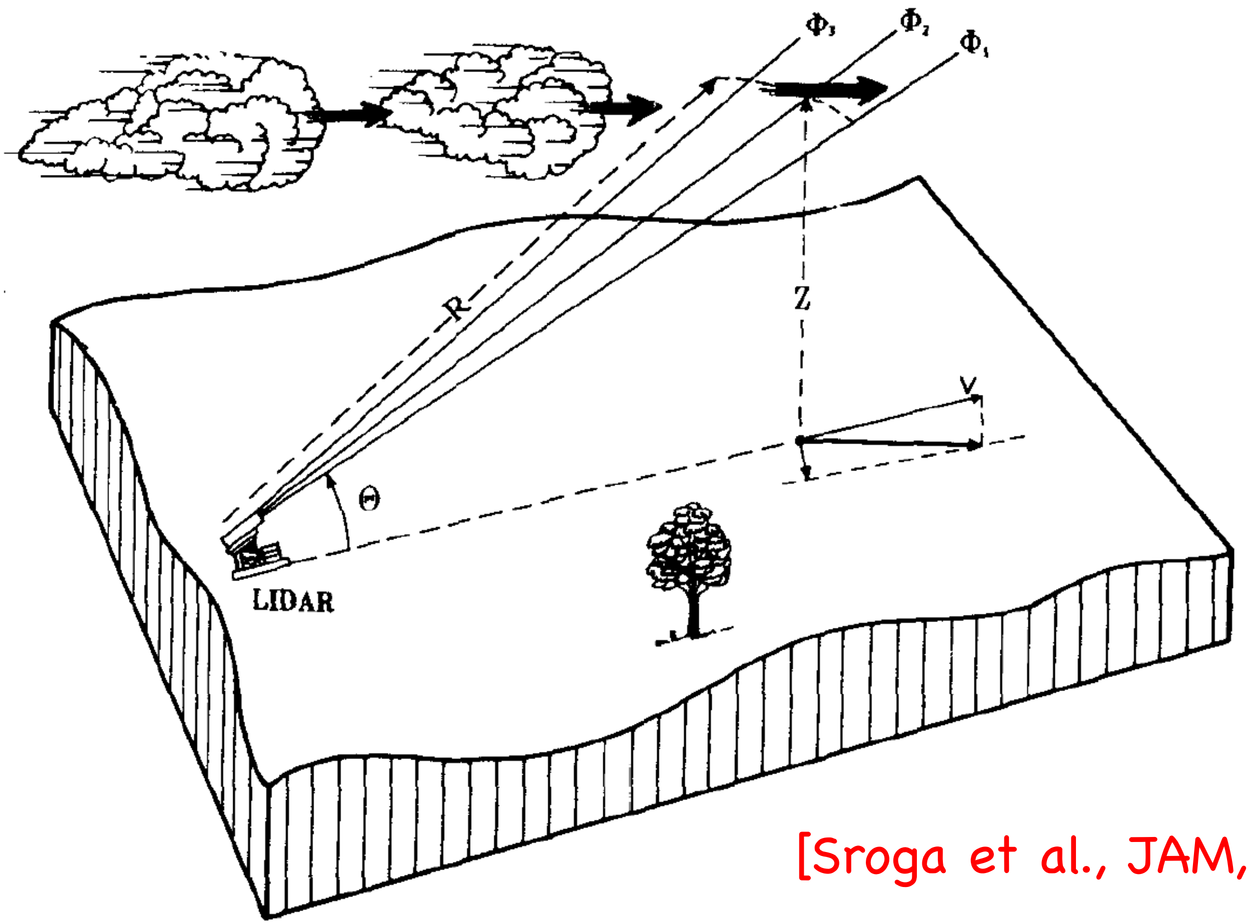
# Lidar Tracking of Aerosol Motions

- Using lidar to track aerosol/cloud patterns is a much efficient way and can measure 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).



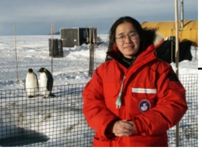


# Lidar Tracking of Aerosol Motions




[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 $\phi_1$, $\phi_2$ and $\phi_3$. 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 $u$.



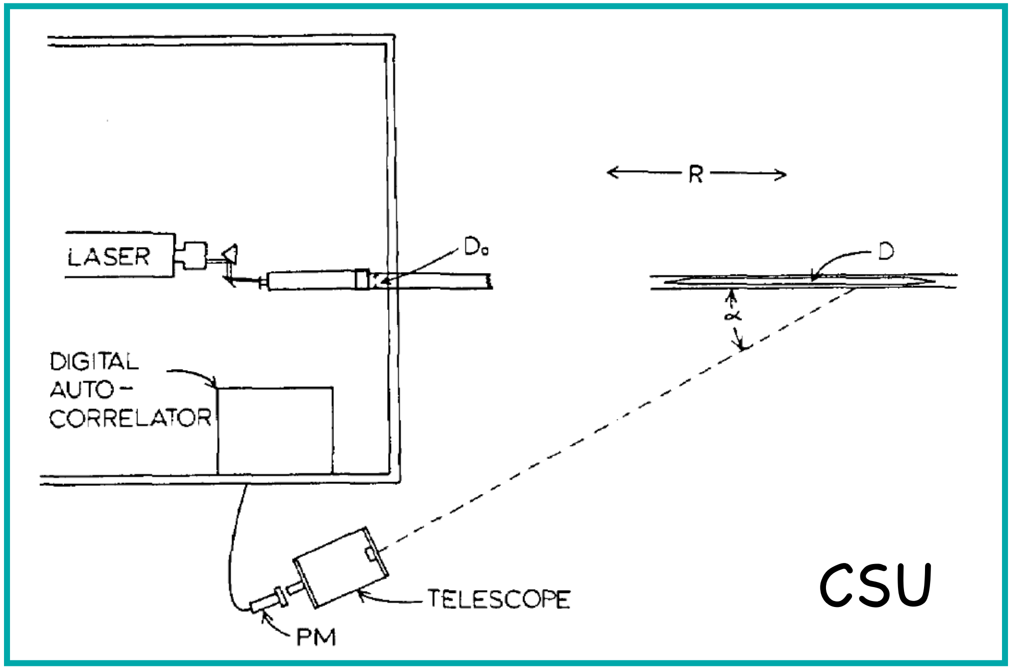


# Laser Time-of-Flight Velocimetry (LTV)

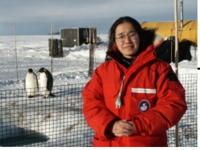
- This dual-beam technique measures the speed of a cross wind by determining a particle's time of flight across two approximately parallel beams with a small spatial separation, as illustrated in the plot.
- The output of a cw laser is focused into two parallel beams of equal intensity, with a beam-to-beam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

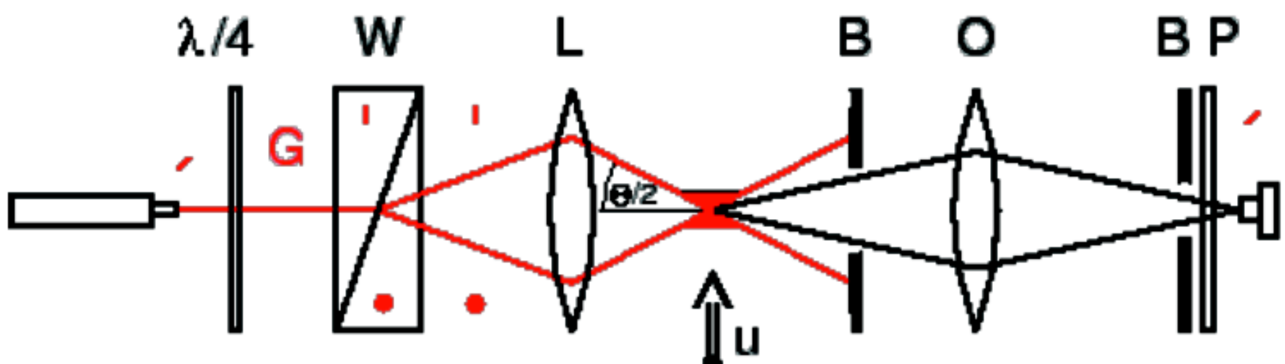


# Laser Doppler Velocimetry (LDV)

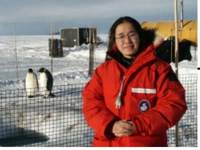
- Two laser beams split from the same laser beam cross with each other and form interference pattern, acting as a periodic field of regions with high and low intensity.
- Particles transversely cross the field and scatter light (strong and weak) periodically with a frequency that is proportional to their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

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

u is the speed perpendicular to interference pattern, $\lambda$ is the laser wavelength, f is the frequency of particle scattering light, $\theta$ is the angle between two laser beams.




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

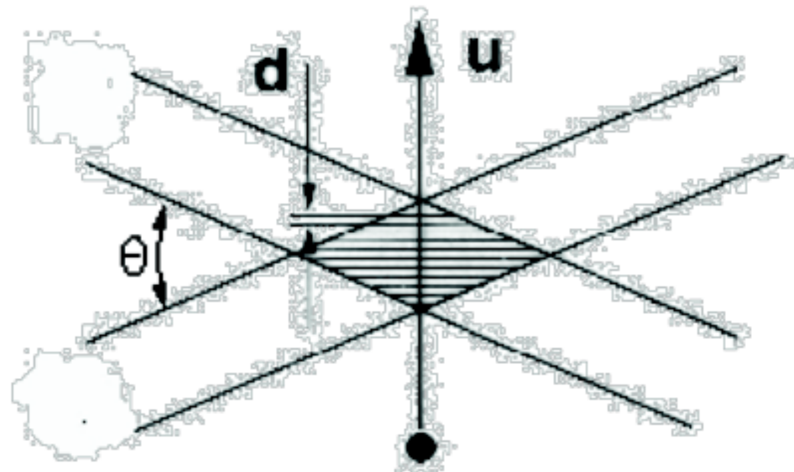




# One Way to Understand LDV

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

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



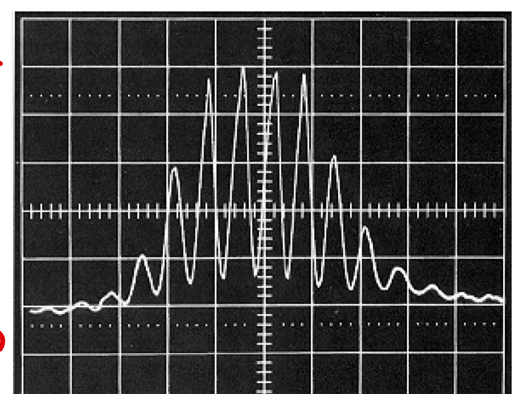

- Particles pass through the lattice with a speed of u, so the frequency of particles scattering strong light is given by

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

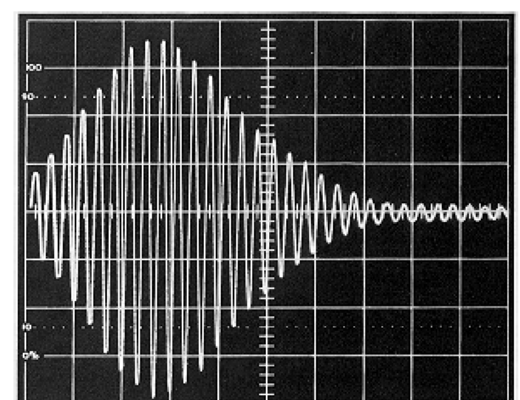
⇩

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

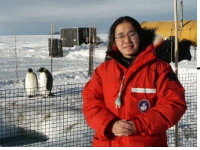
Light Intensity



Time

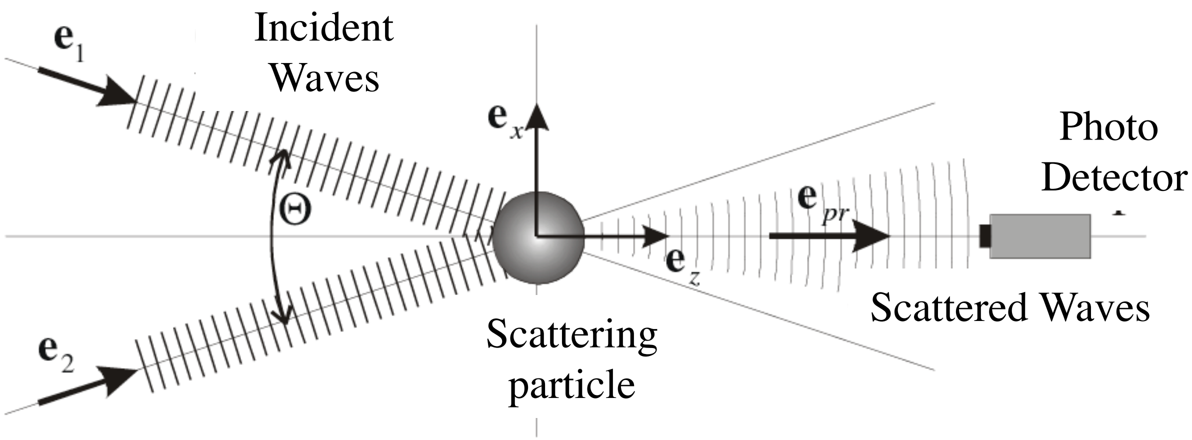


Doppler burst processor





# Another Way to Understand LDV



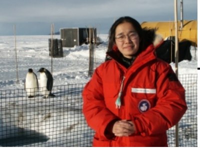

$\vec{e}_1, \vec{e}_2, \vec{e}_x, \vec{e}_y, \vec{e}_{pr}$ are unit vectors

- 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

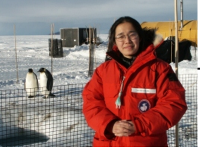
$$f_D = f_1 - f_2 = f_L \frac{\vec{v}_p \cdot (\vec{e}_2 - \vec{e}_1)}{c} = f_L \frac{2\sin(\theta/2)}{c} \vec{v}_p \cdot \vec{e}_x = v_x \frac{2\sin(\theta/2)}{\lambda}$$

- So the transverse velocity is

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

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

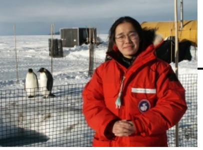
- Note: the measured velocity component is the transverse component, not the radial component. This is different from the modern Doppler wind lidar.





# Summary (2)

- 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.





# Vector Wind Velocity Determination

- 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.

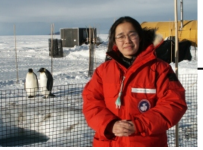
- Practically: under a necessary assumption of horizontal homogeneity of the wind field over the sensed volume, lidar beam scanning techniques can be used to determine the vector wind velocity.
- Two main techniques for this scanning -

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

-- conical scan lidar beam at a fixed elevation angle

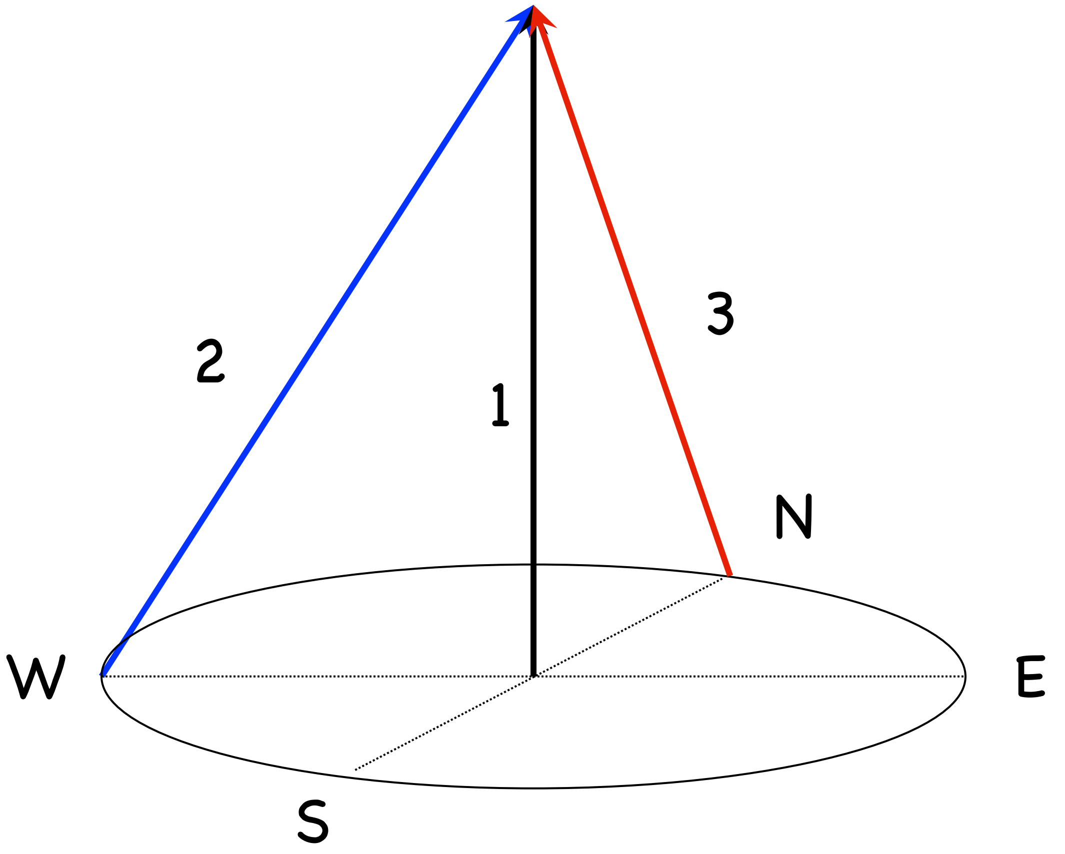
(2) the Doppler-Beam-Swinging (DBS) techniques:

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

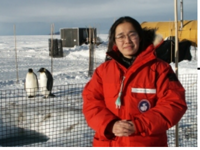




# Ideal Vector Wind Measurement




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

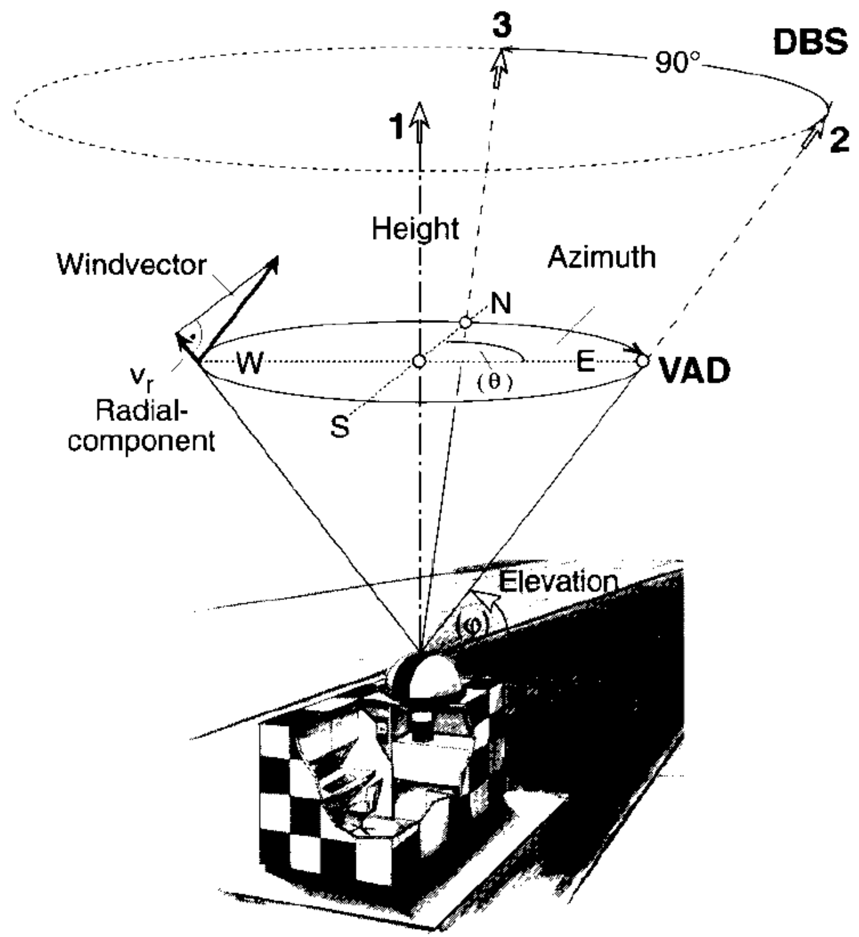
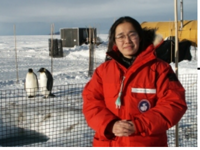
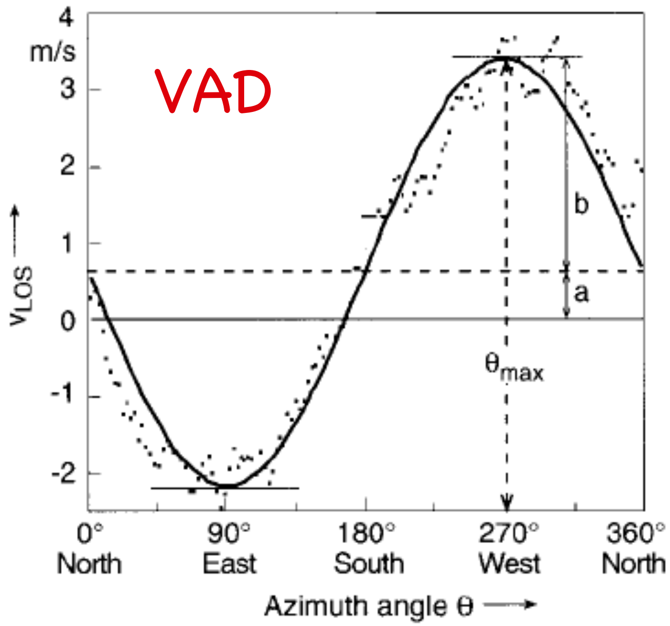



**Fig. 12.8.** Schematic of the scan technique of a Doppler lidar. Lower part: VAD scan, upper part: DBS scan.





# VAD and DBS Techniques




Radial velocity is given by

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

$\theta$ the azimuth angle, clockwise from North, and

$\varphi$ the elevation angle.

Fit the scanning results with

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

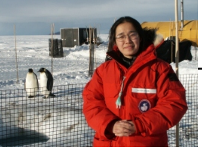
offset $a$, amplitude $b$, and phase shift $\theta_{max}$.

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

- For DBS technique, the three components are obtained as

$$u = -(V_{r2} - V_{r1}\sin\varphi)/\cos\varphi$$
$$v = -(V_{r3} - V_{r1}\sin\varphi)/\cos\varphi$$
$$w = -V_{r1}$$

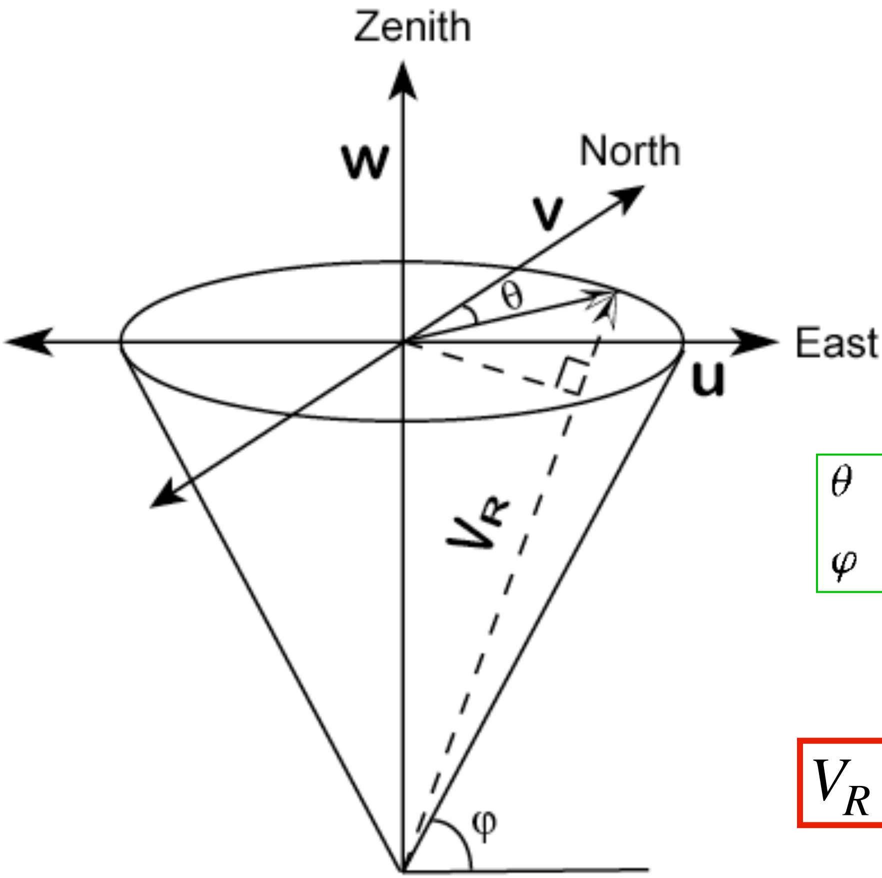
$V_{r1}$, $V_{r2}$, $V_{r3}$ are the vertical, east, and north radial velocities





# 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:

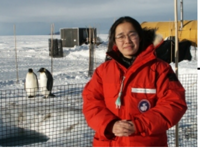
| | |
|---|---|
| Zonal wind contribution | $u \sin\theta \cos\varphi$ |
| Meridional contribution | $v \cos\theta \cos\varphi$ |
| Vertical contribution | $w \sin\varphi$ |

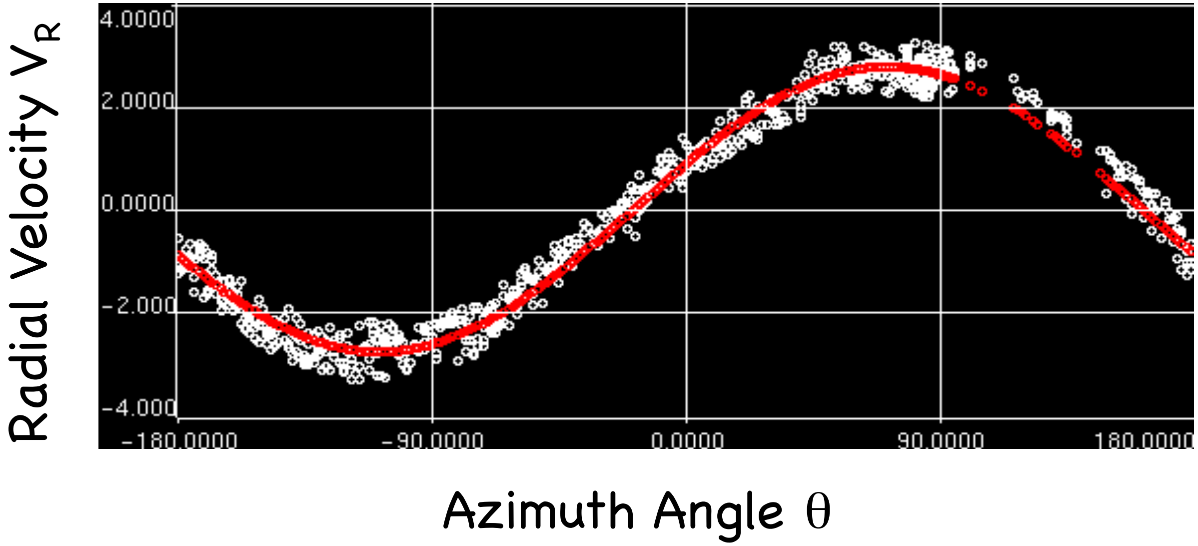
$\theta$ the azimuth angle, clockwise from North, and

$\varphi$ the elevation angle.

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

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





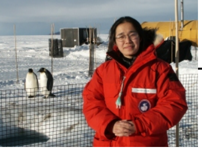

$$V_R = u\sin\theta\cos\varphi + v\cos\theta\cos\varphi + w\sin\varphi$$

- 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 $\theta_{max}$ is the phase shift

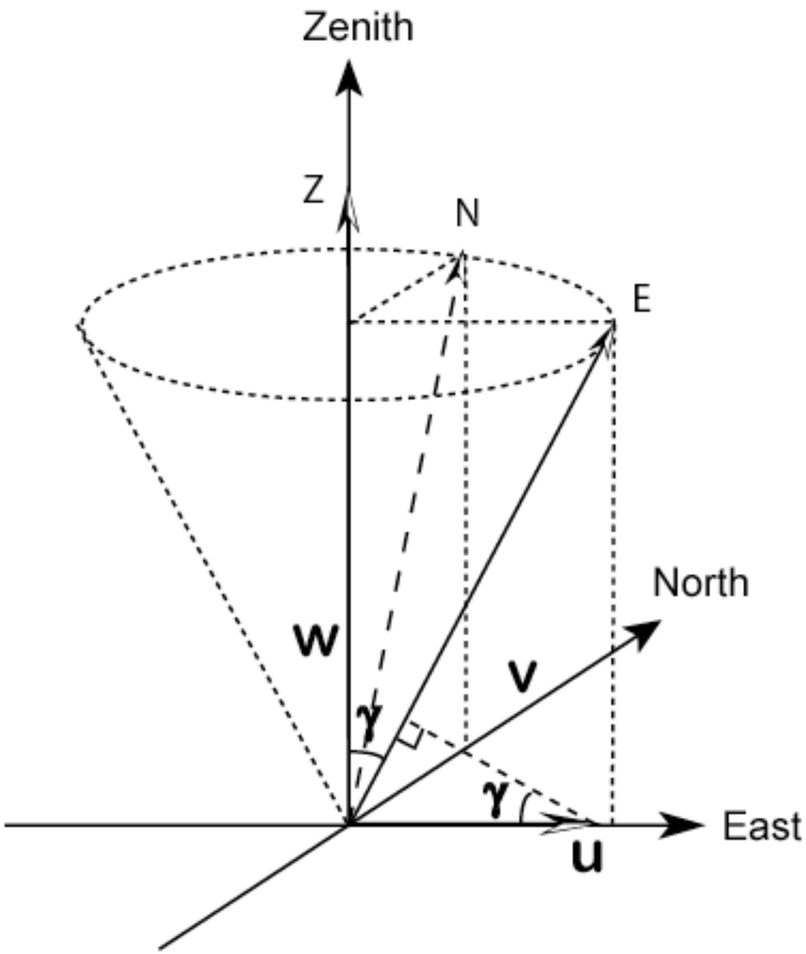
$$VectorWind = (u,v,w) = (b\sin\theta_{\max}/\cos\varphi, b\cos\theta_{\max}/\cos\varphi, a/\sin\varphi)$$





# DBS Technique for Vector Wind

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

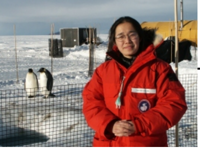



$\gamma$ is the off-zenith angle

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

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

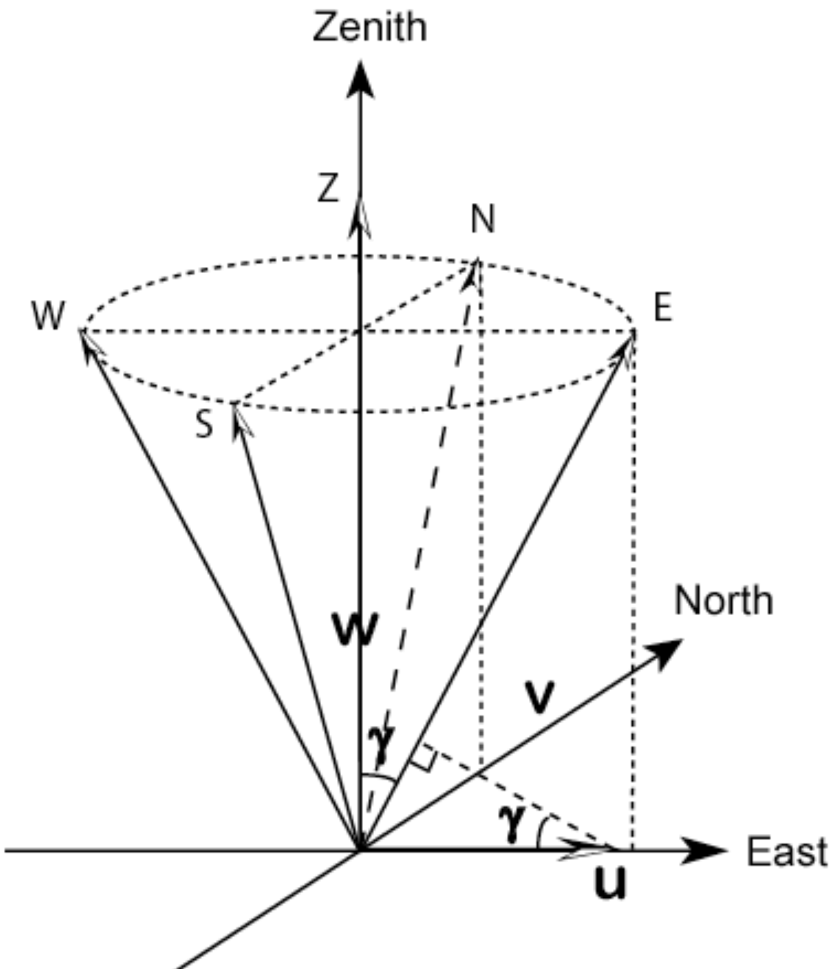
$V_{RZ}$, $V_{RE}$, $V_{RN}$ are the vertical, tilted east, and tilted north radial velocities





# Modified DBS Technique

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

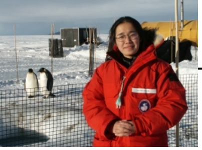



$\gamma$ is the off-zenith angle

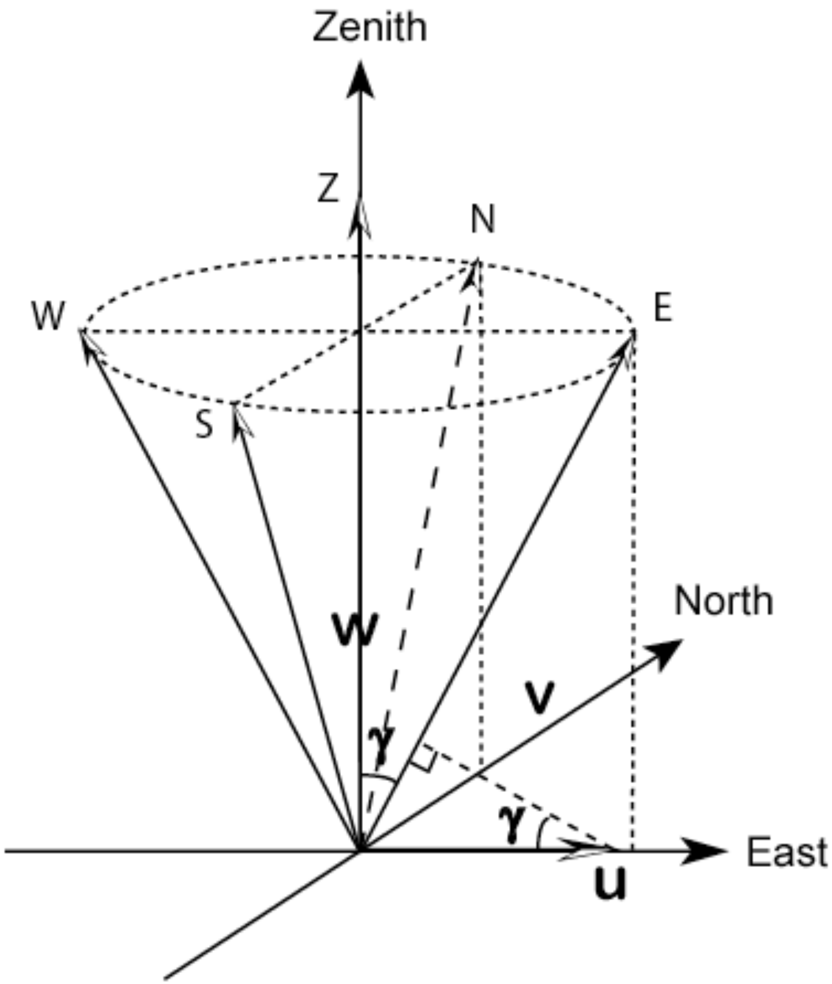
$$V_{RE} = u\sin\gamma + w\cos\gamma$$
$$V_{RW} = -u\sin\gamma + w\cos\gamma$$
$$V_{RN} = v\sin\gamma + w\cos\gamma$$
$$V_{RS} = -v\sin\gamma + w\cos\gamma$$
$$V_{RZ} = w$$

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

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



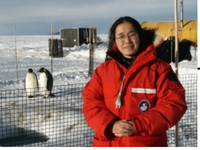
# Modified DBS Technique




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

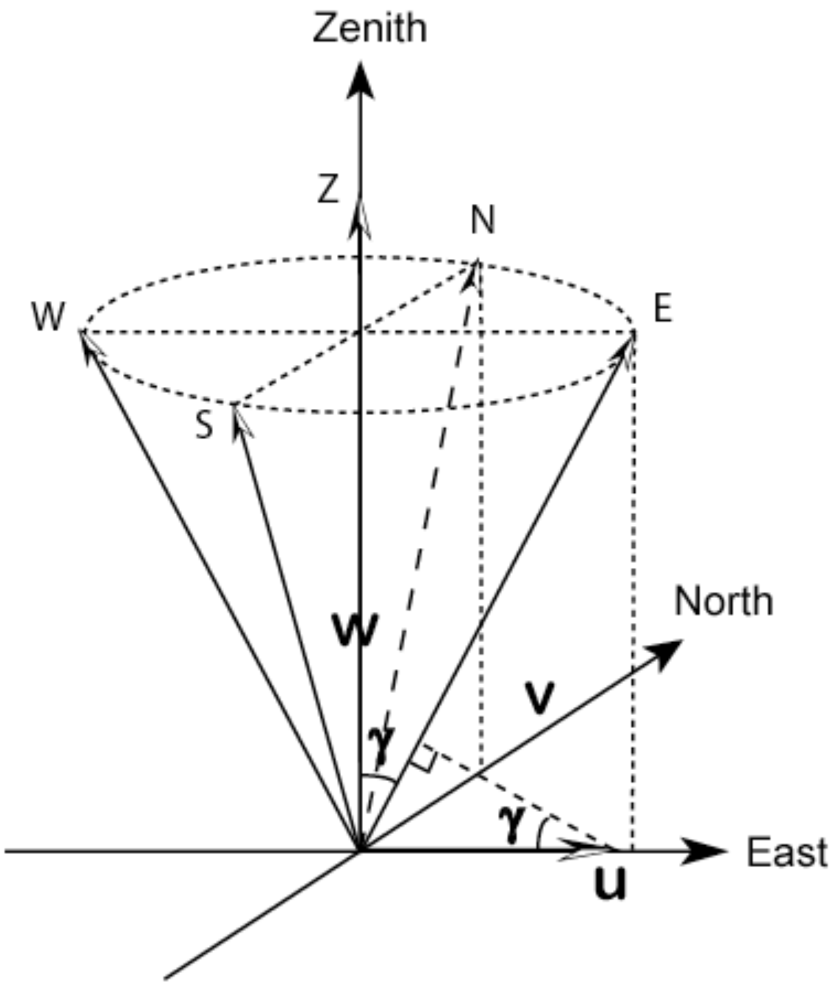
$$u = (V_{RE} - V_{RZ}\cos\gamma)/\sin\gamma$$
$$u = -(V_{RW} - V_{RZ}\cos\gamma)/\sin\gamma$$
$$v = (V_{RN} - V_{RZ}\cos\gamma)/\sin\gamma$$
$$v = -(V_{RS} - V_{RZ}\cos\gamma)/\sin\gamma$$
$$w = V_{RZ}$$

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





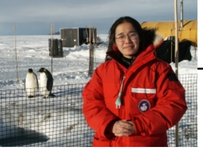
# Modified DBS Technique




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

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

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 (3)

- 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.