



Lecture 20. Wind Lidar (1)

Overview Wind Technologies

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



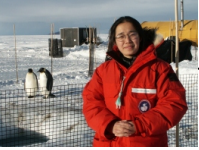
Motivations for Wind Measurements

❑ **Global atmospheric wind profiles** from the ground to the thermosphere are important for weather forecast, for validation of global atmosphere models, and for studies of the complex space-atmosphere interactions and the atmosphere dynamics such as general circulation and various waves.

❑ **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.

Atmospheric winds are referred to the bulk motion of the atmosphere, not individual velocities of individual particles due to thermal motion.



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

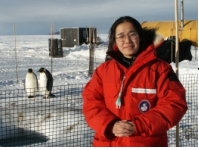
❑ Doppler (Shift) Wind Technique:

$$\Delta\omega = -\vec{k} \cdot \vec{v} \quad \text{or} \quad \Delta\omega = -2\vec{k} \cdot \vec{v}$$

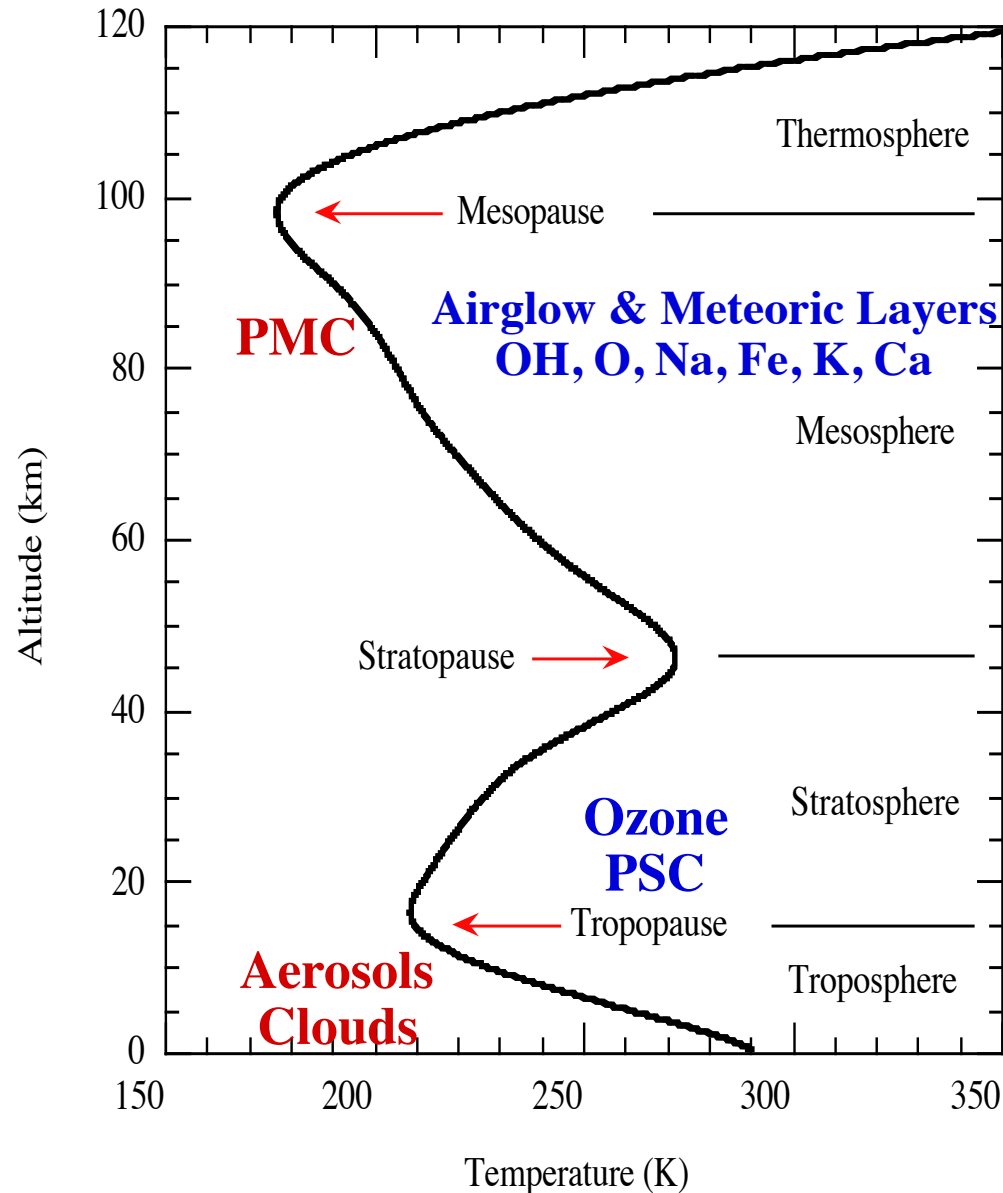
- (1) Coherent Detection Doppler Wind Lidar
(Heterodyne & Homodyne)
- (2) Direct Detection Doppler Wind Lidar

❑ Geostrophic Wind Detection:

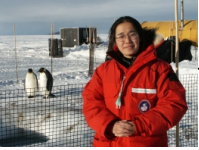
Temperature + Density \Rightarrow Pressure Gradients \Rightarrow Geostrophic Wind



Overview Wind Techniques



- 75–200km: resonance fluorescence (Na, Fe, K)
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)



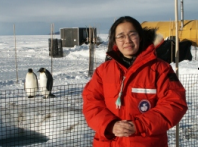
Overview: Direct Motion Detection

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

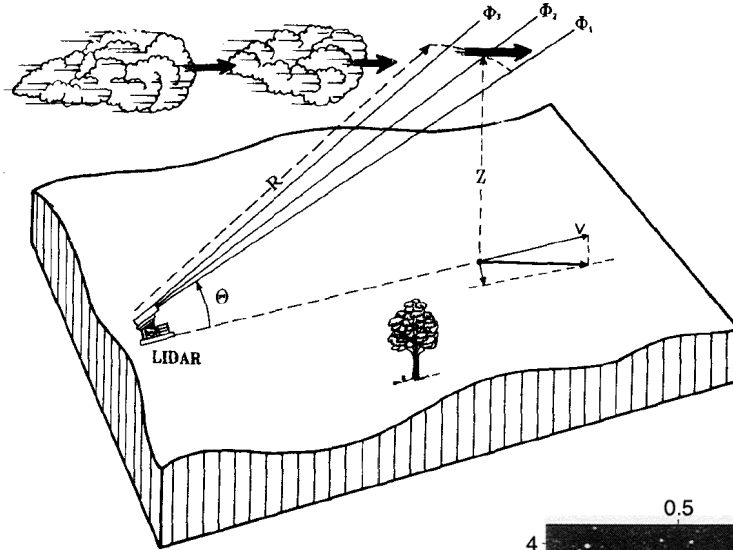
$$\vec{v} = \frac{d\vec{r}}{dt}$$

Common approaches for detecting motion remotely

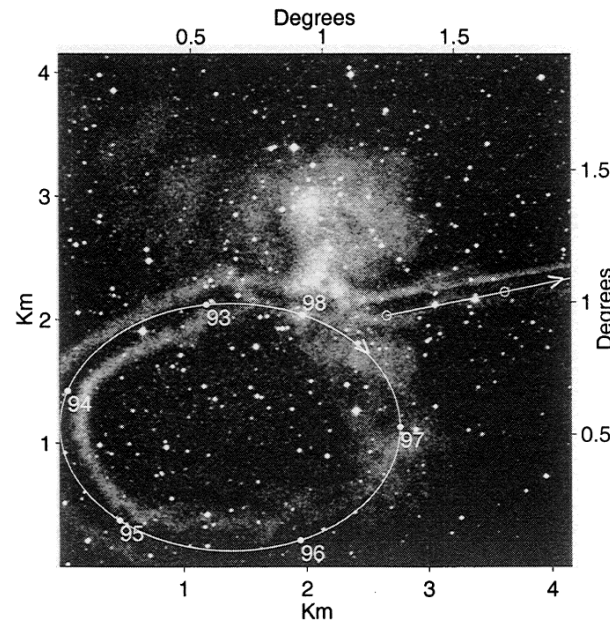
- ❑ Crosswind determination by pattern correlation
 - (1) Tracking aerosols, clouds, plumes, trails by images
 - (2) Tracking Aerosol/cloud motion by lidars
- ❑ Laser Time-of-Flight Velocimetry (LTV)
- ❑ Laser Doppler Velocimetry (LDV)



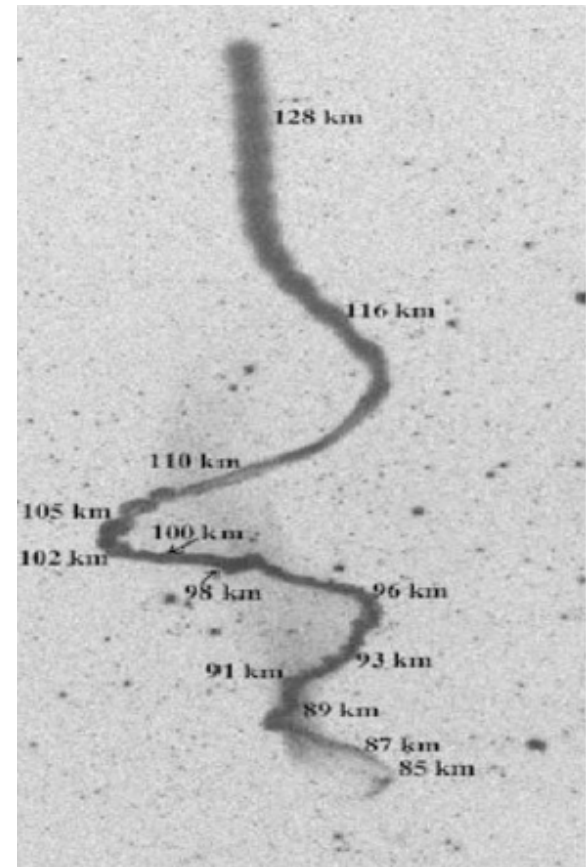
Tracking Motions of Aerosols, Meteor Trails, or Chemical Release Plumes, etc.



[Sroga et al.,
JAM, 1980]



[Drummond et al.,
JGR, 2001]

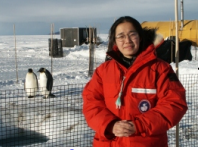


[Larsen, 2013]



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 expanding universe. Because the relative shift $\Delta f/f = V_R/c$ and distance stars move away fast, these measurements were easy to make, compared to Earth atmosphere.



Doppler Shift for Different Processes

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

Momentum Conservation

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

Energy Conservation

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



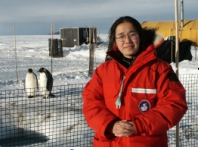
$$\omega_1 = \omega_2 + \vec{k}_1 \cdot \vec{v}_1 - \vec{k}_2 \cdot \vec{v}_2 + \frac{\hbar k_1^2}{2m} - \frac{\hbar k_2^2}{2m}$$

- ❑ The Doppler frequency shift is given by

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

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

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



Doppler Shift for Different Processes

- For resonant atomic absorption, the resonance absorption frequency for an atom at rest is given by

$$\omega_0 = (E_2 - E_1)/\hbar$$

Momentum Conservation

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

Energy Conservation

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



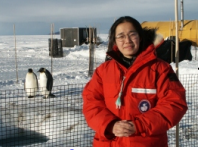
$$\omega_1 = \omega_0 + \vec{k}_1 \cdot \vec{v}_1 + \frac{\hbar k_1^2}{2m}$$

- The Doppler frequency shift is given by

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

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

$$\sigma_{abs}(\nu) = \frac{1}{\sqrt{2\pi}\sigma_D} \frac{e^2 f}{4\epsilon_0 m_e c} \exp\left\{-\left[\nu_o - \nu\left(1 - \frac{V_R}{c}\right)\right]^2 / 2\sigma_D^2\right\} \quad \sigma_D = \sqrt{\frac{k_B T}{M\lambda_0^2}}$$



Doppler Shift for Different Processes

- For atomic spontaneous emission,

Momentum Conservation

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

Energy Conservation

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



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

- The Doppler frequency shift is given by

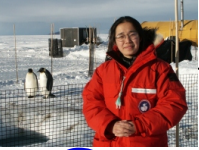
$$\Delta\omega_{sp} = \omega_2 - \omega_0 = \vec{k}_2 \cdot \vec{v}_3$$

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

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

- For backward spontaneously emitted photon, the Doppler shift is

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



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 equal to the Doppler shift due to the moving particles.

❑ More accurately, the traditional/classical Coherent Detection Doppler Wind lidar should be called “**Heterodyne**” Detection Doppler Wind lidar.

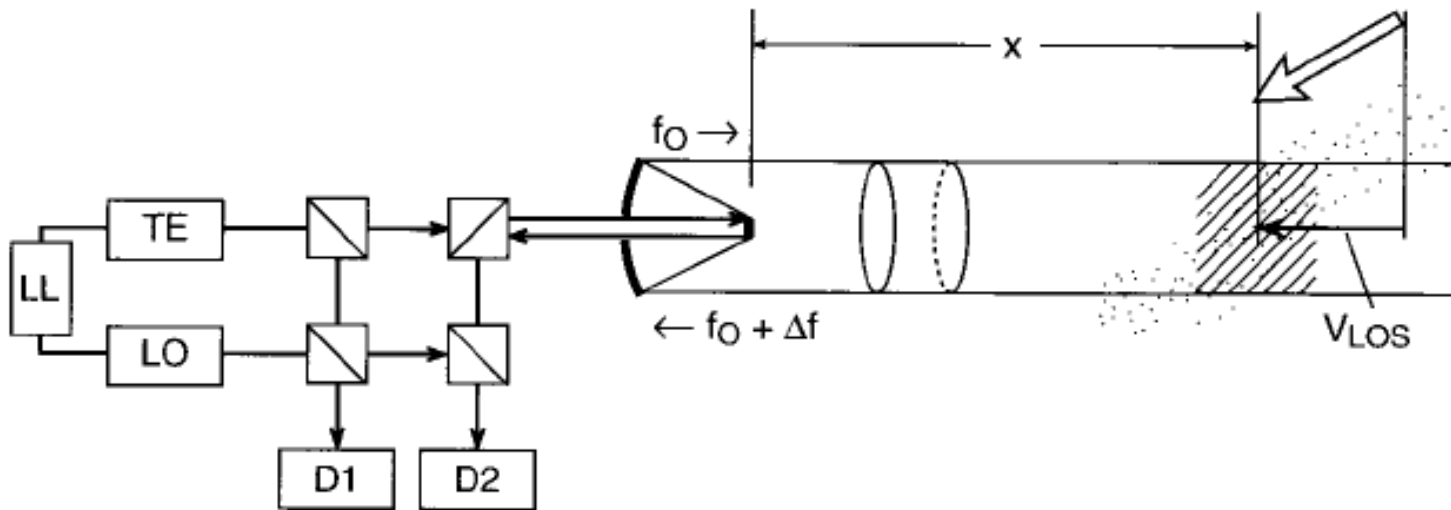
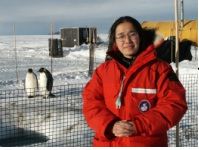


Fig. 12.6. Principle of a heterodyne-detection Doppler lidar.

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

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!¹



Overview: Heterodyne CDL

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.

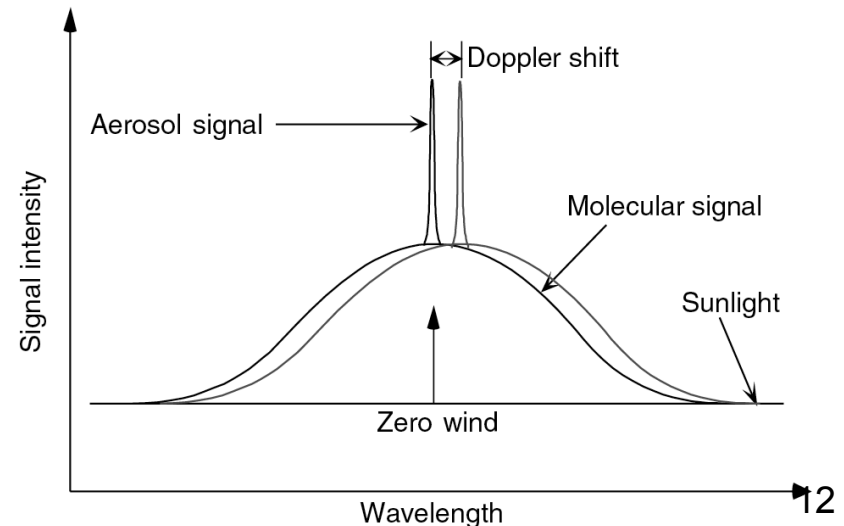
❑ The sum frequency is well above the frequency cutoff of the detector, but the beat frequency is a low-frequency signal that can be determined with high accuracy.

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

❑ 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: Homodyne CDL

Homodyne coherent Doppler lidar becomes practical when the image-rejection technology developed from telecommunication is applied to CDL for resolving the ambiguity associated with the direction of wind.

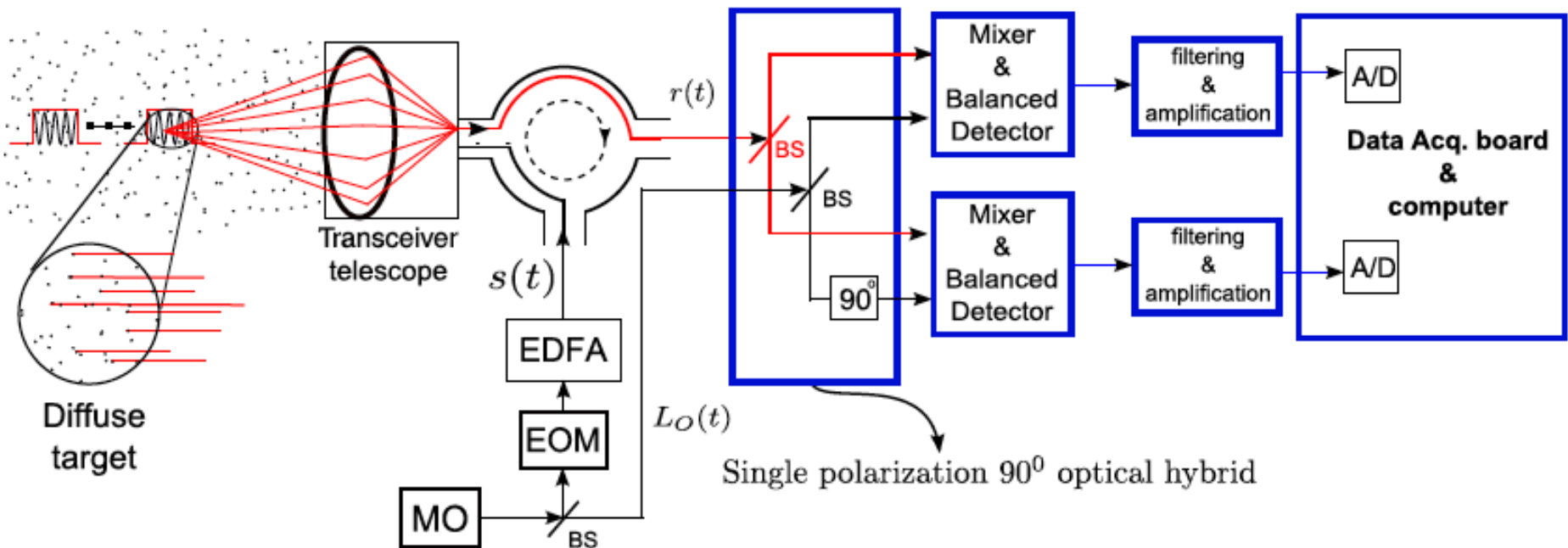
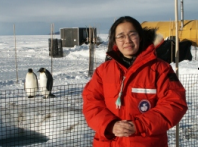


Fig. 4. Single polarization image-reject homodyne pulsed CDL. In this system, the pulse generator can be an EOM, which does not introduce any frequency offset in the transmit signal. The image-reject homodyne receiver translates the Doppler signal into baseband for further processing. The image-reject homodyne receiver, also known as direct-conversion receiver, eliminates the need for an IF offset (enabling the detection of Doppler signal sign).

[Abari et al., AO, 2014; Abari et al., AO, 54, 8999, 2015]

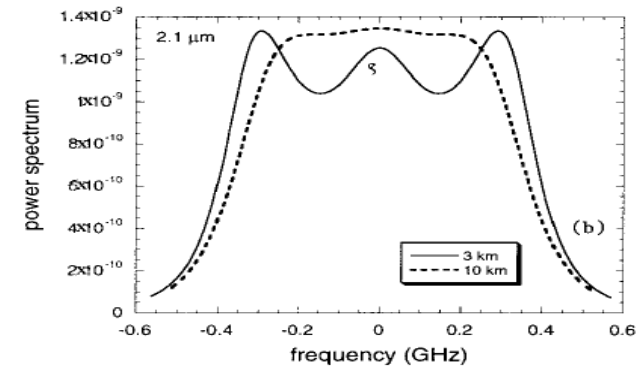
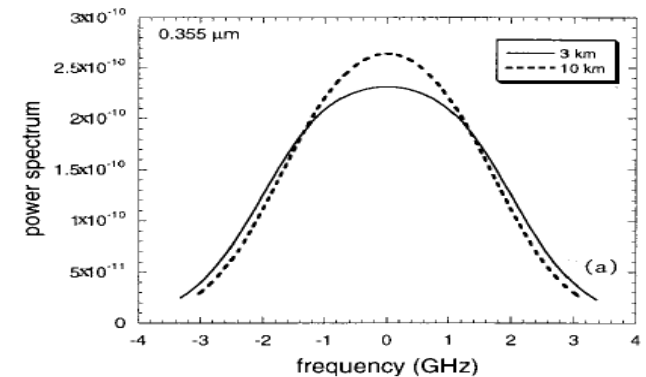


Overview: Molecular Backscatter CDL

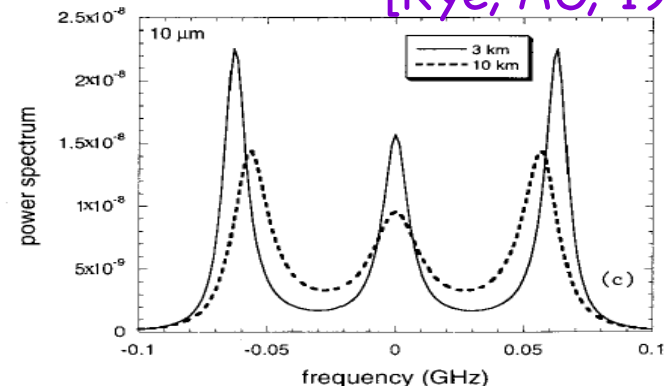
❑ Rye [1998] analyzed the potential of using molecular backscatter, instead of aerosol backscatter, to do coherent Doppler lidar detection at infrared wavelengths.

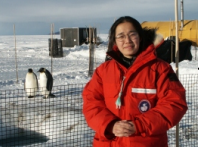
❑ Rayleigh-Brillouin scattering in the kinetic and hydrodynamic (collisional) regimes encountered in the infrared is of particular interest because the observed spectrum approaches a triplet of relatively narrow lines that are more suitable for wind, temperature, and pressure measurements [Rye, 1998].

❑ It is possible to detect the beat signal of molecular backscatter with a local oscillator at very high sampling rate (very large bandwidth) in time-domain. Signal processing technique can be applied to analyze the spectral information of the beat signal to derive the temperature-dependent broadening, thus temperature measurements [Abari et al., ILRC, 2015].



[Rye, AO, 1998]





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 **non-resonance 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, main efforts are placed onto the spectral resolved receivers.
- ❑ The **optical frequency discriminators** include mainly five types --
 - (1) Atomic absorption lines, like Na, K, and Fe Doppler lidars, using the resonance fluorescence from the entire absorption 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 (Fabry-Perot or Fizeau etalon: multiple-beam interf.)
 - (3) Fringe pattern imaging of the output of an optical interferometer.
 - (4) Scanning FPI or other scanning interferometers
 - (5) Mach-Zehnder and Michelson interferometers (two-beam interference)



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)

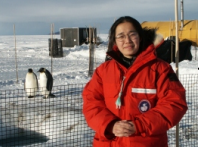
Intensity spatial distribution (like in some Rayleigh Doppler lidar)

⇒ Frequency shift ⇒ radial velocity (LOS)



Frequency Analyzers in ATM or Receiver

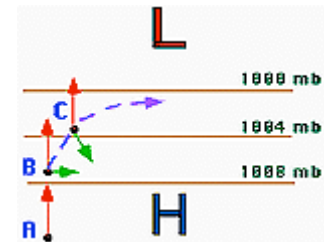
- ❑ The resonance fluorescence Doppler lidar is one kind of direct detection Doppler lidars (DDL). It uses intensity ratios (photon count ratios) to derive wind and temperature. The spectral analyzer is in the atmosphere - atomic absorption lines.
- ❑ For atmosphere below the MLT resonance fluorescence 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

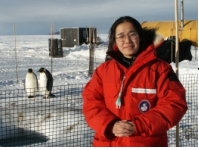
□ Geostrophic wind is the horizontal wind velocity for which the Coriolis force exactly balances the pressure gradient force (horizontal pressure force): $f\vec{k} \times \vec{V}_g = -g\vec{\nabla}_p Z$

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



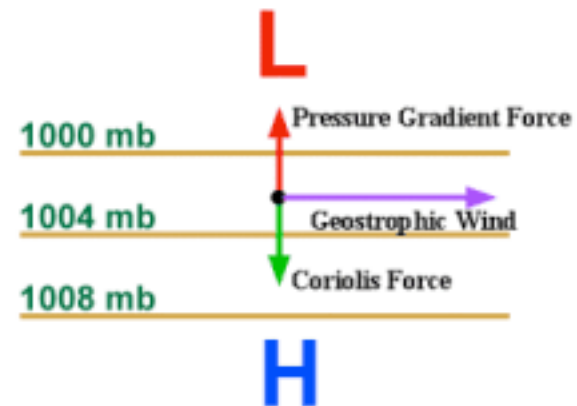
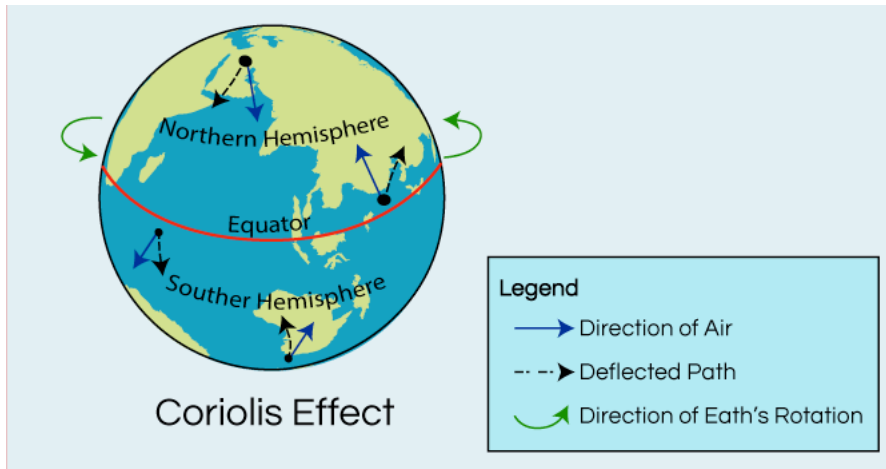
where V_g is the geostrophic wind (horizontal), $f = 2\Omega \sin\varphi$ is the local Coriolis parameter (Ω - earth's rotation rate, φ - latitude), k is the vertical unit vector, Φ is the geopotential, g is the gravitational acceleration, Z is the geopotential height, ρ is the mass density, P is pressure, 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.



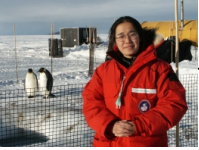
Geostrophic Wind vs. Gradient Wind

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.



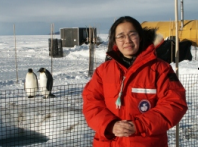
<http://ww2010.atmos.uiuc.edu/%28Gh%29/guides/mtr/fw/geos.rxml>

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

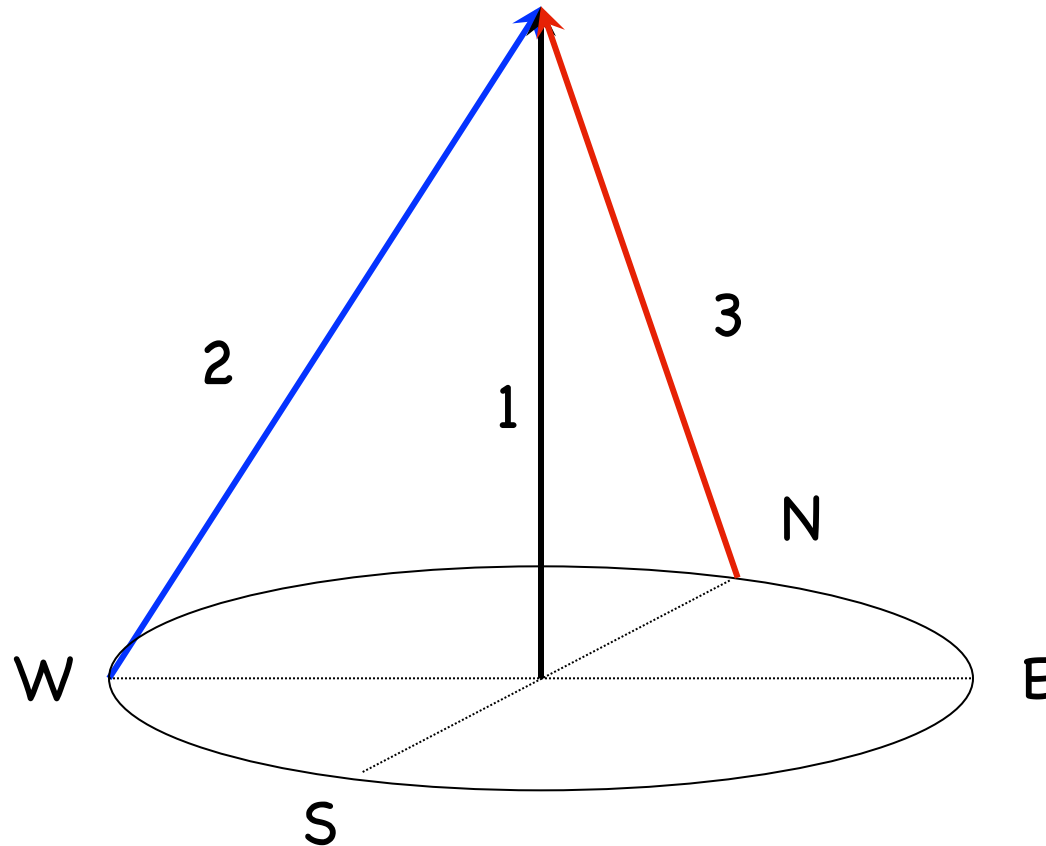


Vector Wind Velocity Determination

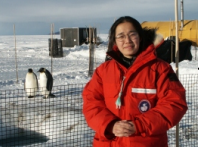
- ❑ **Vector (u, v, w) wind velocity** estimates require radial velocity measurements from at least three independent Line-Of-Sight (LOS).
- ❑ **Ideally:** to obtain a vector wind at a given point in space is to view the same point from 3 or more LOS directions
 - (1) Three or more lidar systems are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

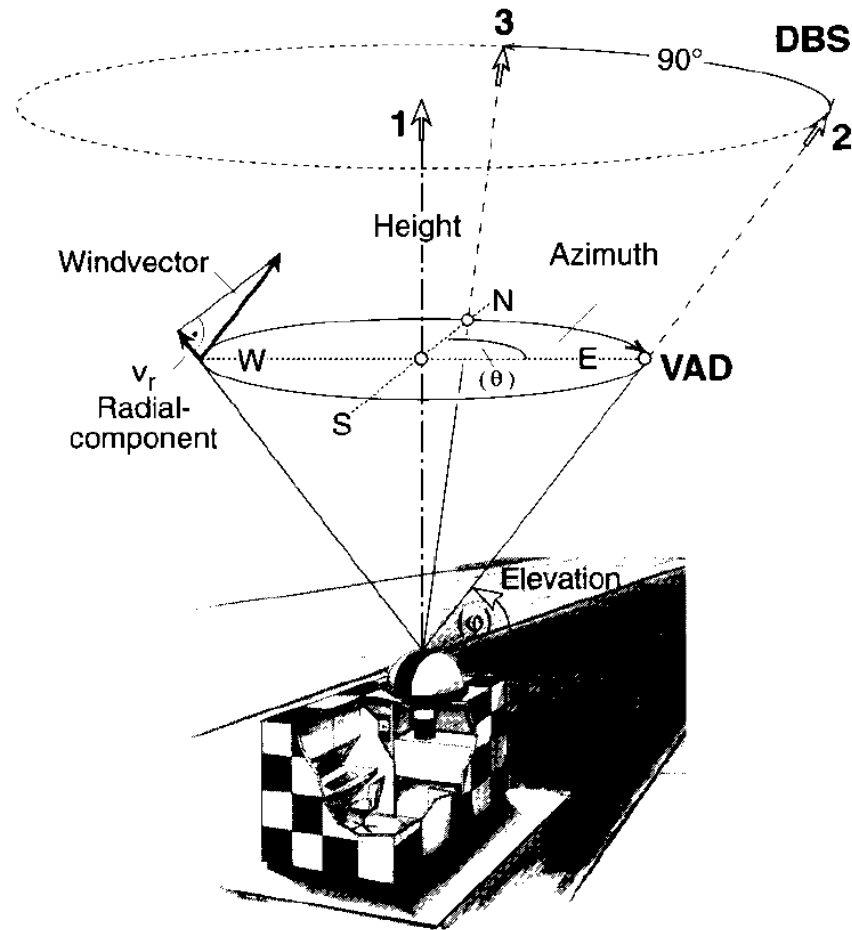
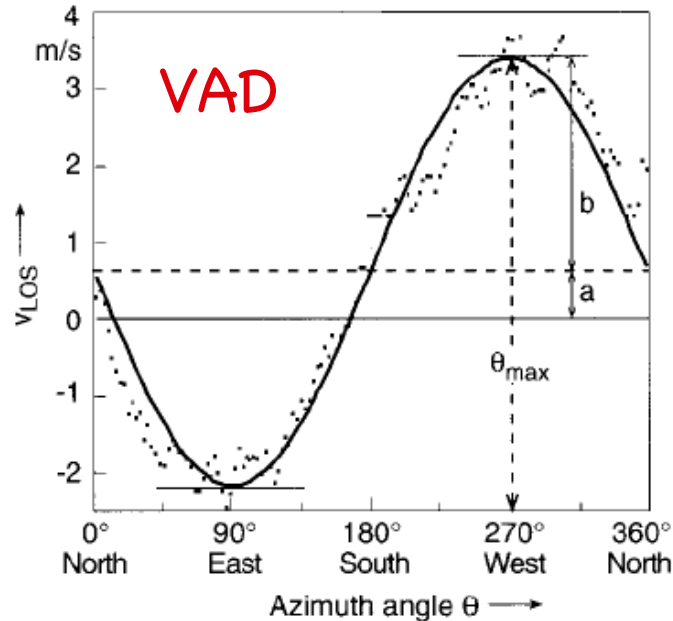


Fig. 12.8. Schematic of the scan technique of a Doppler lidar. Lower part: VAD scan, upper part: DBS scan.



VAD and DBS Techniques



Radial velocity is given by

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

θ the azimuth angle, clockwise from North, and
 φ the elevation angle.

Fit the scanning results with

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

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

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

□ For DBS technique, the three components are obtained as

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

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

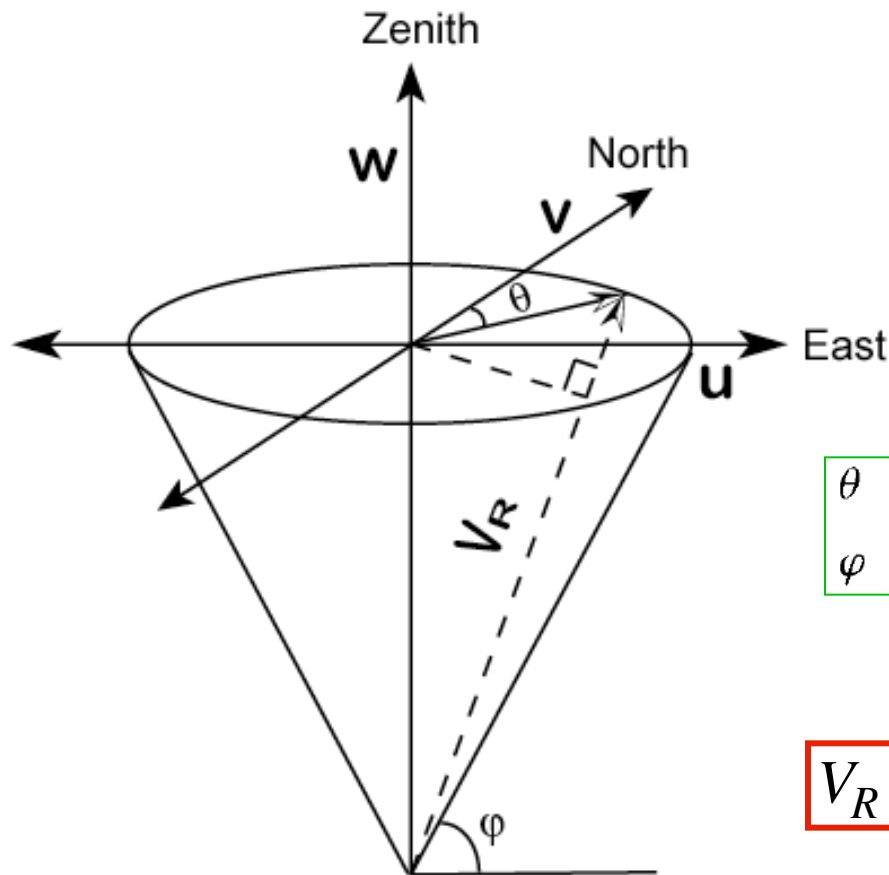
$$w = -V_{r1}$$

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.



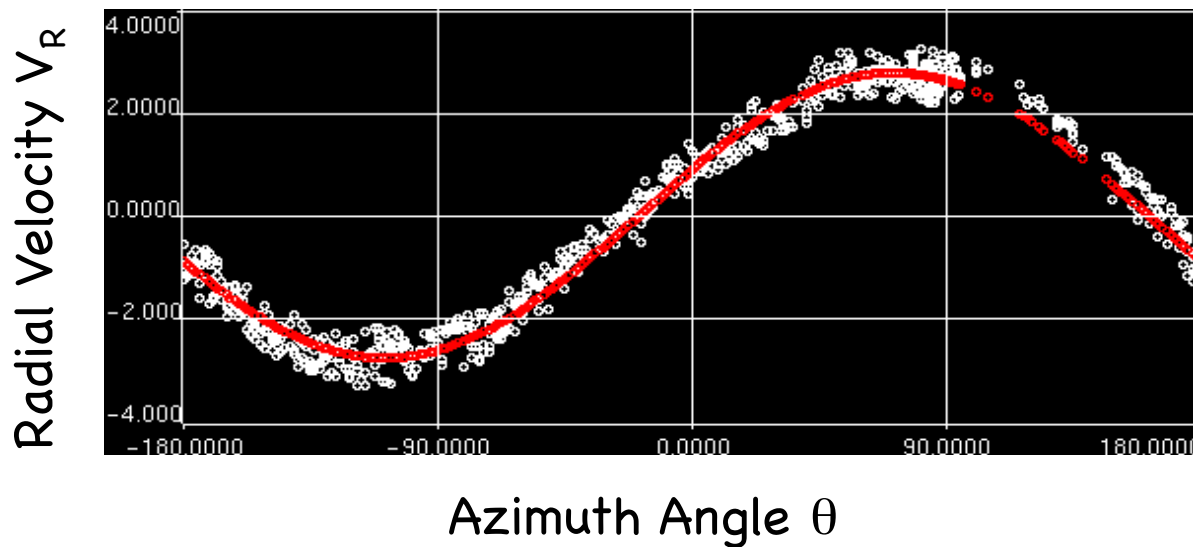
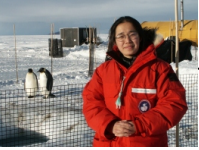
Radial velocity V_R consists of components from u , v , and w :

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

θ the azimuth angle, clockwise from North, and
 φ the elevation angle.

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

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



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

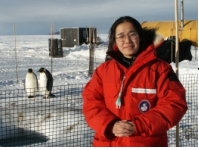
❑ For VAD scan, elevation angle φ is fixed (constant) and known, azimuth angle θ is varied but also known. V_R is measured, so the three unknown parameters u , v , and w can be derived directly from fitting the data with above equation.

❑ Another approach is to fit the scan data with the following equation:

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

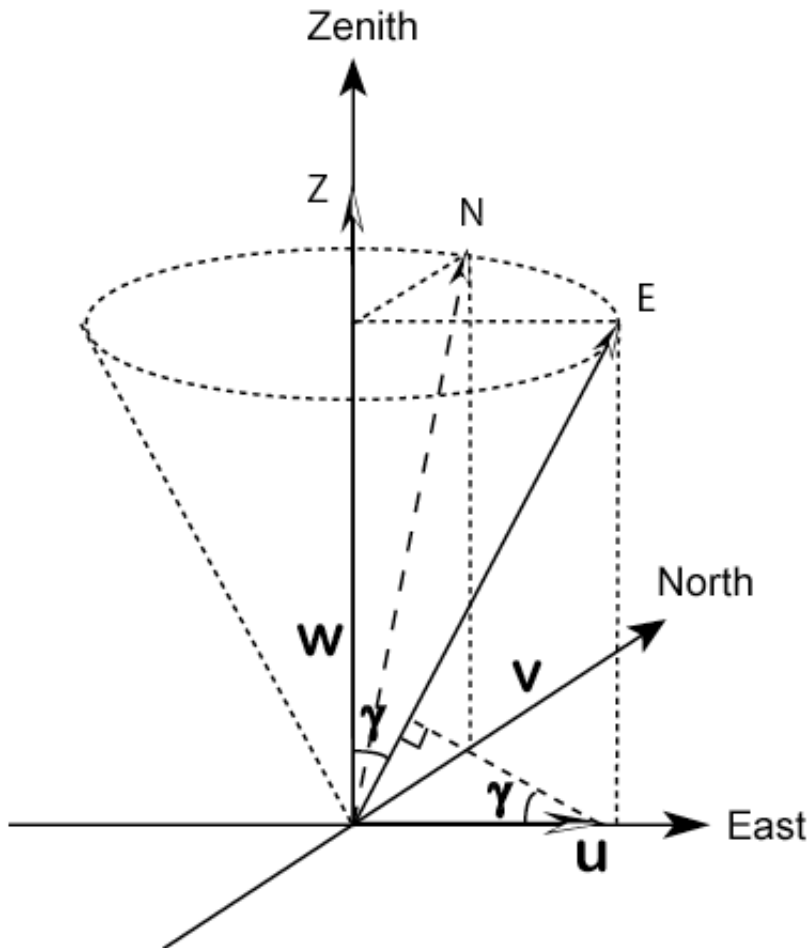
where a is offset, b is amplitude, and θ_{\max} is the phase shift

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



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

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

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

$$V_{RZ} = w$$



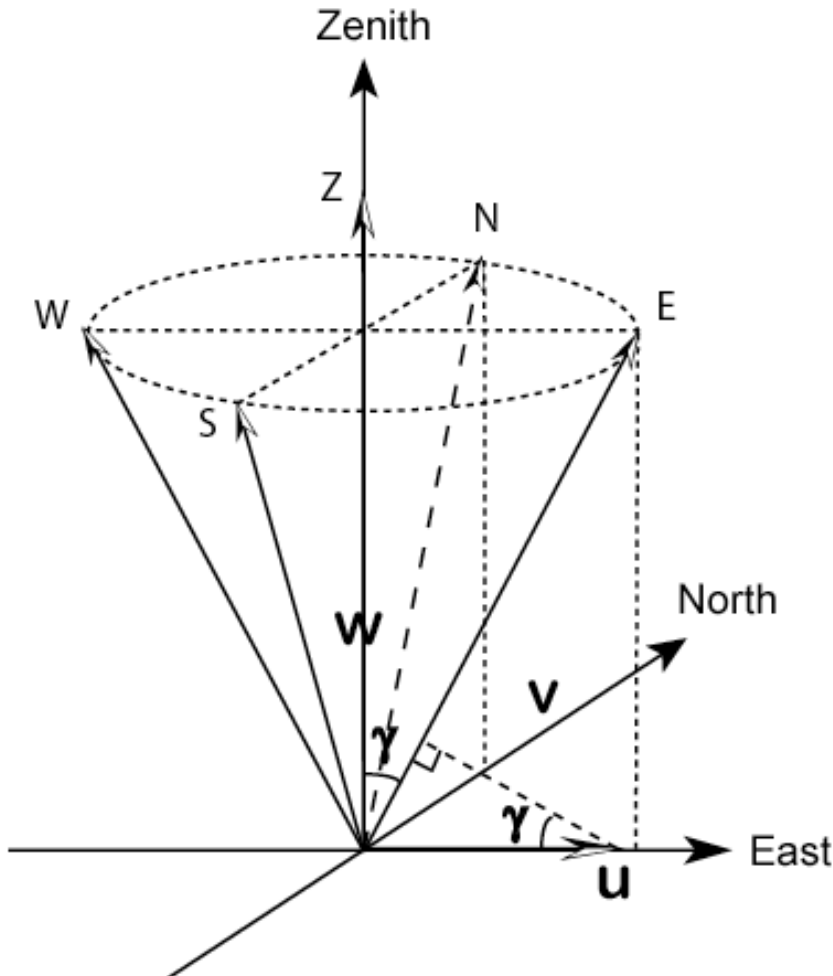
$$u = (V_{RE} - V_{RZ} \cos \gamma) / \sin \gamma$$

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

$$w = V_{RZ}$$

V_{RZ} , V_{RE} , V_{RN} are the vertical, tilted east, and tilted north radial velocities 26

- γ is the off-zenith angle

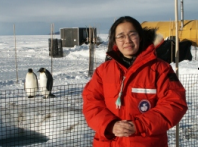


$$V_{RZ} = w$$



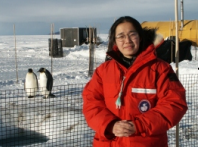
$$w = V_{RZ}$$

$V_R > 0, w > 0, u > 0, v > 0$ for wind towards away, upward, east, and north²⁷



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 and homodyne) detection & 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).



Summary (2)

- ❑ 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.