Lecture 20. Wind Lidar (2)
Vector Wind Determination

- Vector wind determination
- Ideal vector wind measurement
- VAD and DBS technique for vector wind
- Coherent versus incoherent Detection
  - Doppler wind lidar techniques
- Summary

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 -

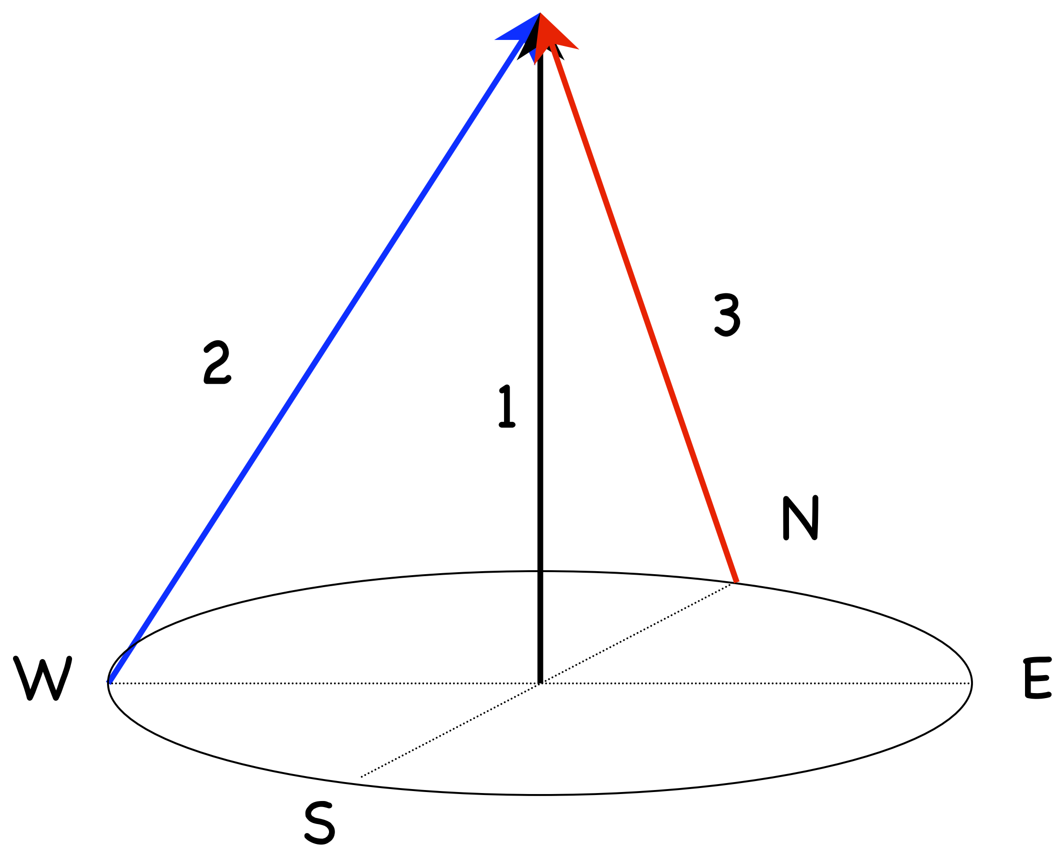
(1) the Velocity-Azimuth-Display (VAD) technique:

-- 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

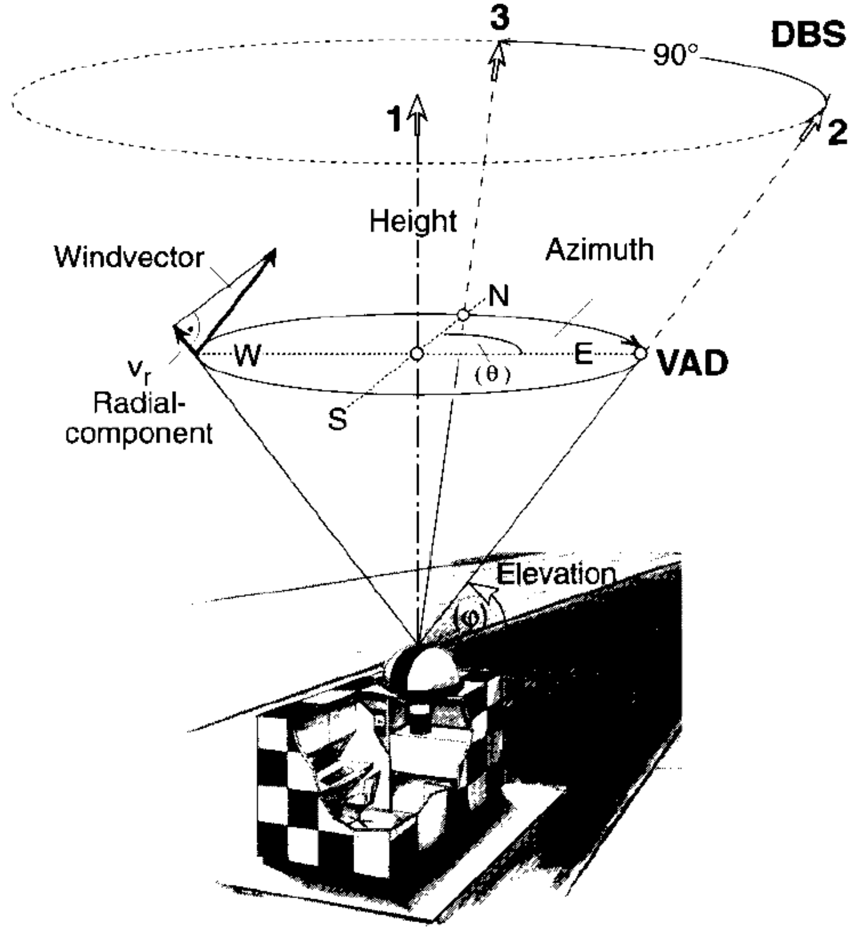
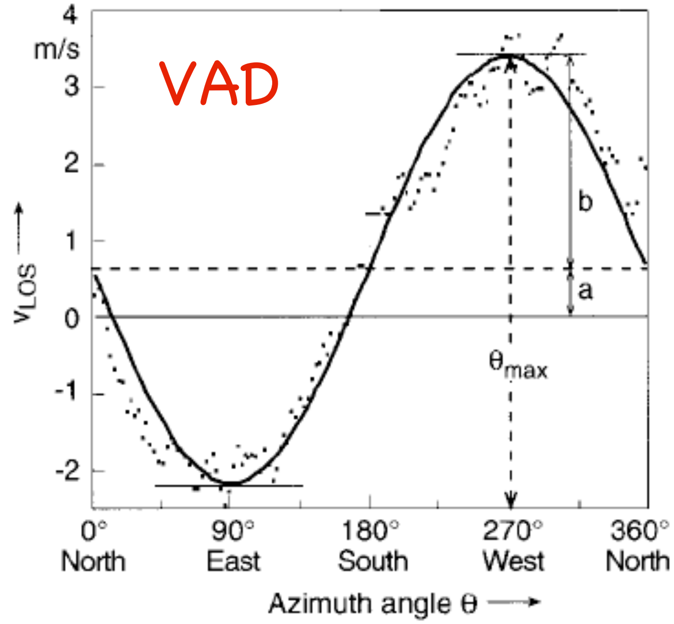


Fig. 12.8. Schematic of the scan technique of a Doppler lidar. Lower part: VAD scan, upper part: DBS scan.

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}.

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

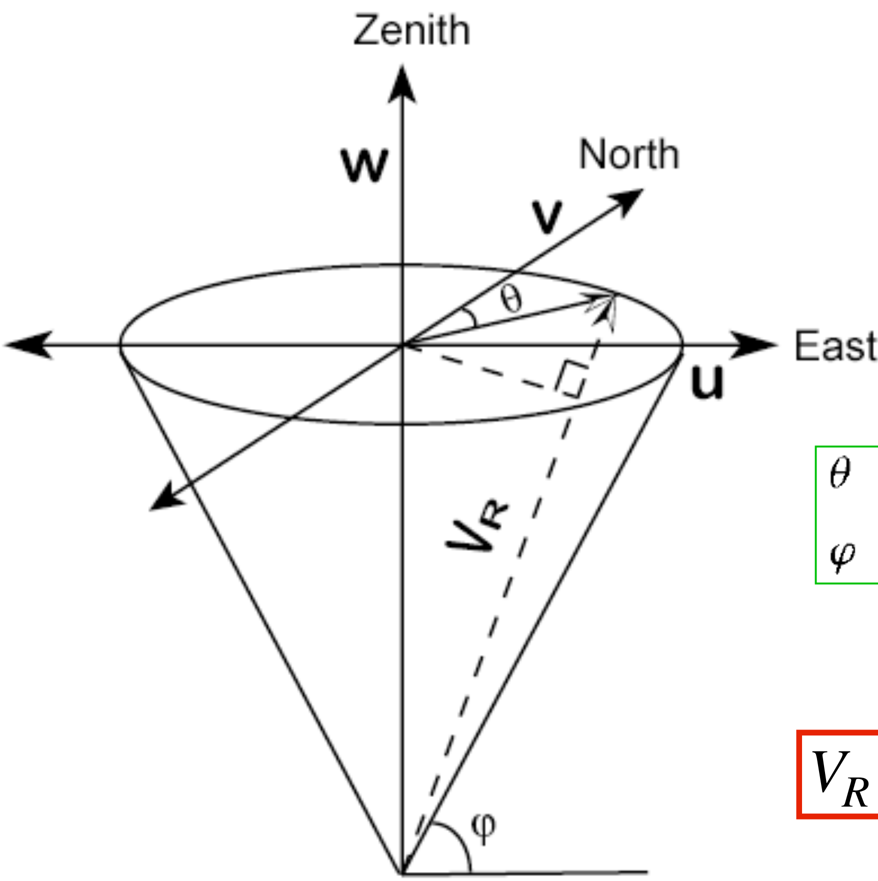
- For DBS technique, the three components are obtained as

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

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:

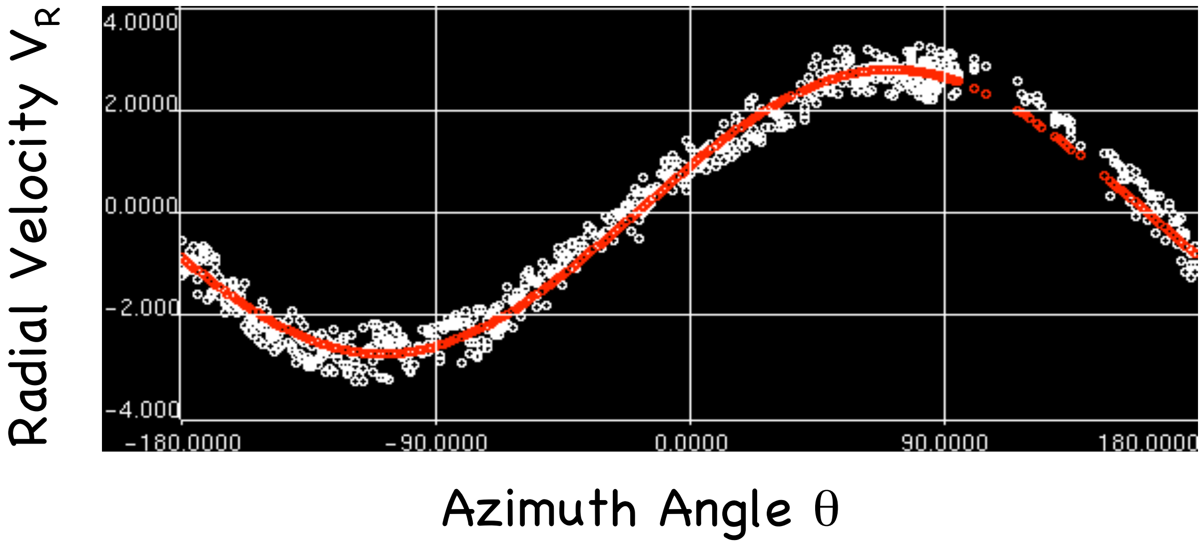
Zonal wind contribution	$u \sin\theta \cos\varphi$
Meridional contribution	$v \cos\theta \cos\varphi$
Vertical contribution	$w \sin\varphi$

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:

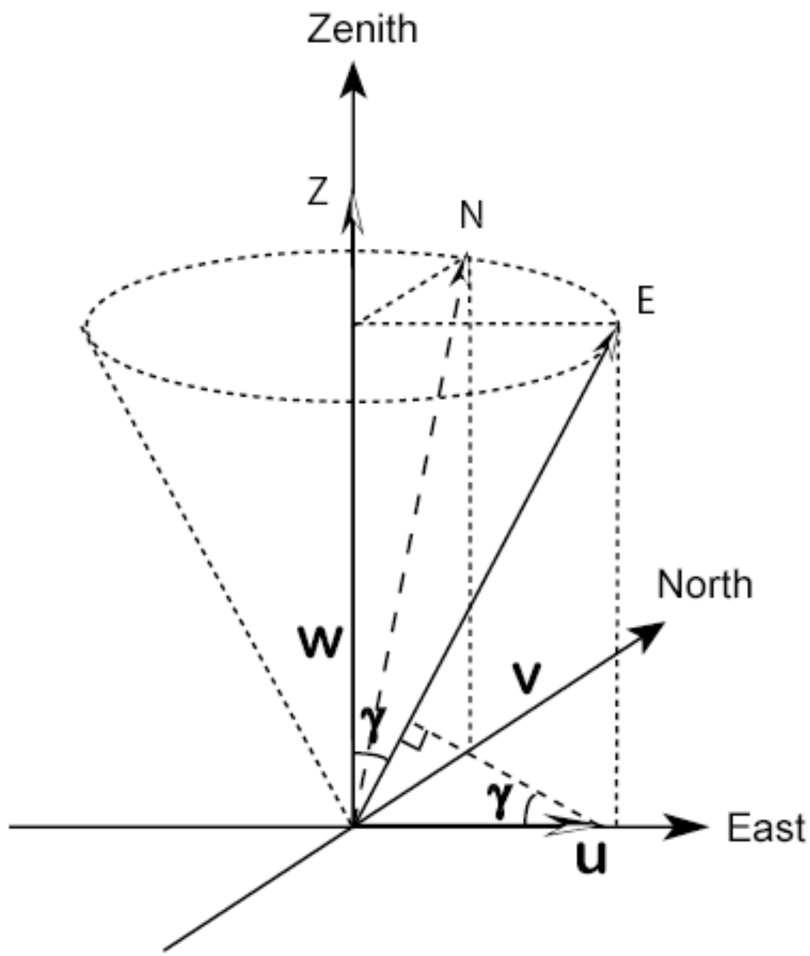
$$V_R = a + b\cos(\theta - \theta_{max}) = b\sin\theta_{max}\sin\theta + b\cos\theta_{max}\cos\theta + a$$

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

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

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

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

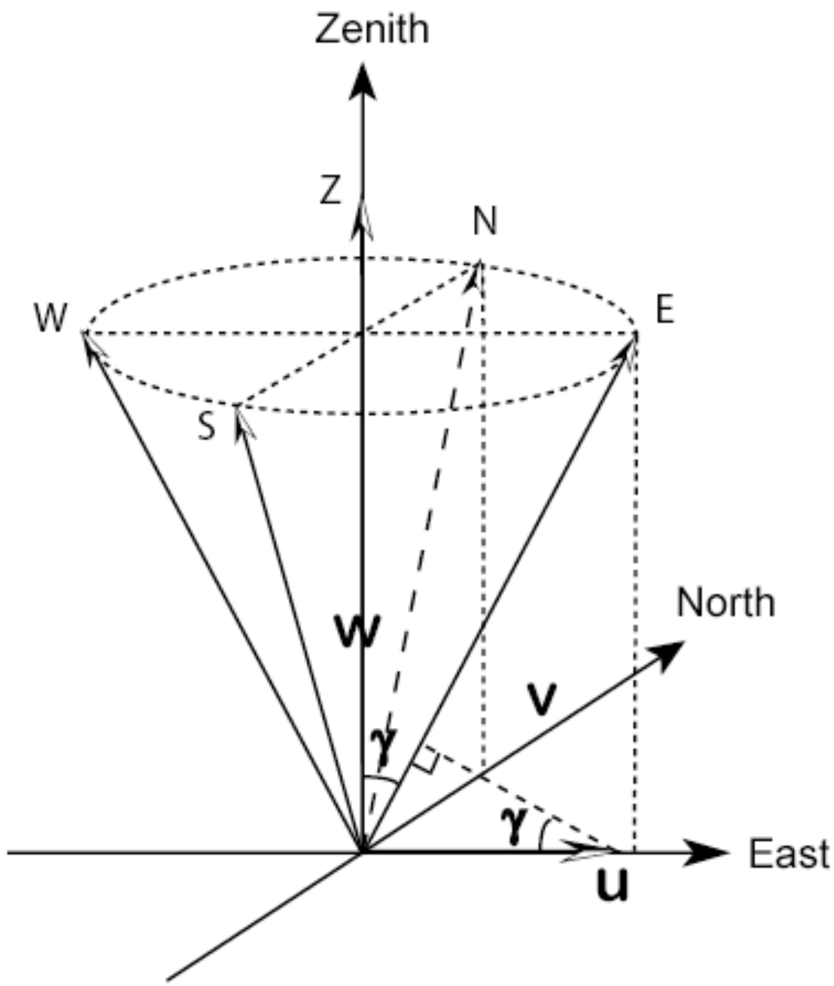
⇩

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

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

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

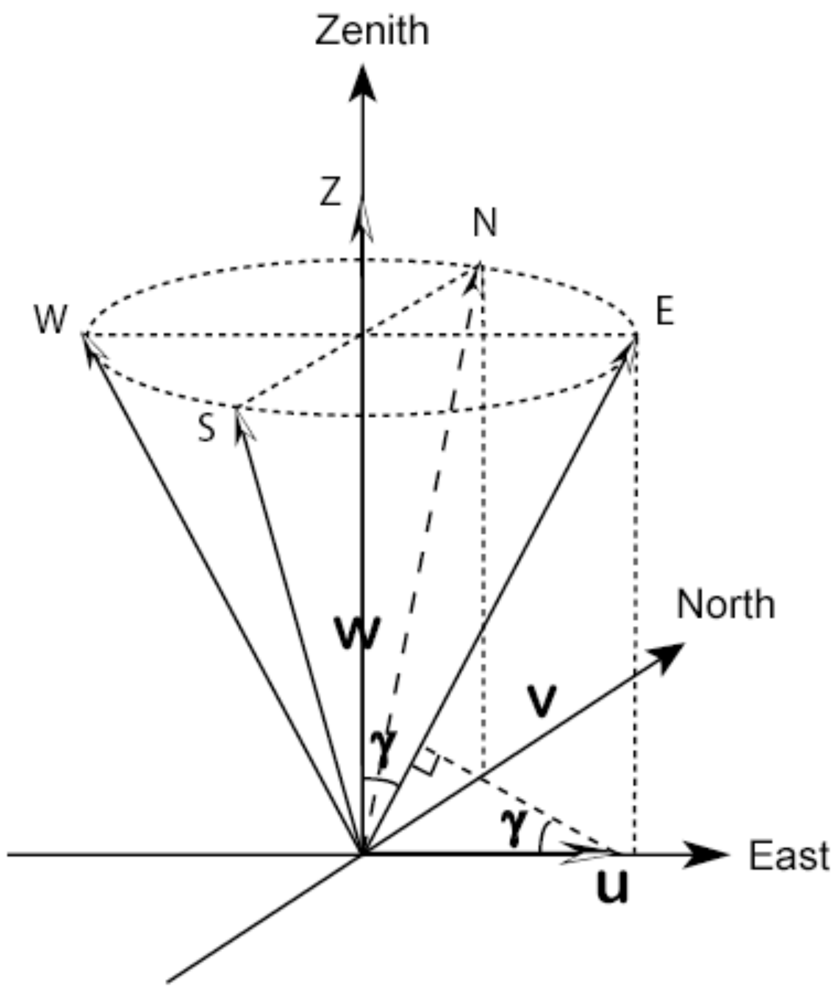
$$V_{RE} = u\sin\gamma + w\cos\gamma$$
$$V_{RW} = -u\sin\gamma + w\cos\gamma$$
$$V_{RN} = v\sin\gamma + w\cos\gamma$$
$$V_{RS} = -v\sin\gamma + w\cos\gamma$$
$$V_{RZ} = w$$

⇓

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

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

Modified DBS Technique

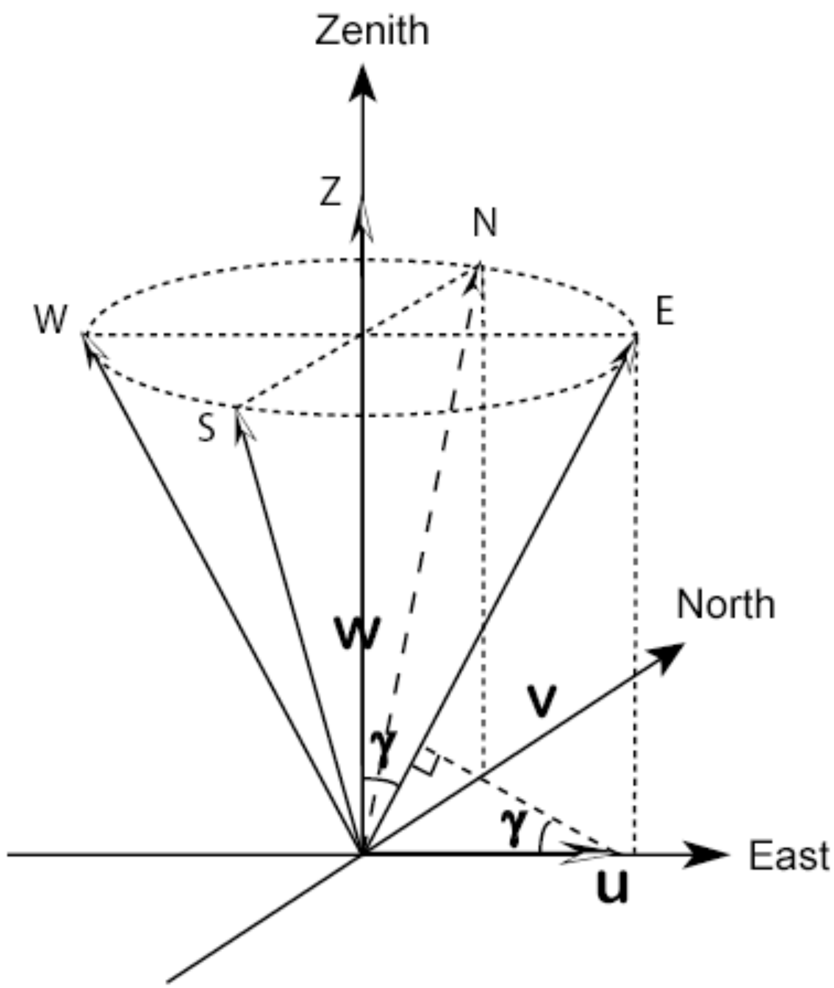


$$V_{RE} = u\sin\gamma + w\cos\gamma$$
$$V_{RW} = -u\sin\gamma + w\cos\gamma$$
$$V_{RN} = v\sin\gamma + w\cos\gamma$$
$$V_{RS} = -v\sin\gamma + w\cos\gamma$$
$$V_{RZ} = w$$

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

$V_R > 0$, $w > 0$, $u > 0$, $v > 0$ 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.

Coherent vs Incoherent Doppler Wind

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

Wavelength Considerations for CDL

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

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

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

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

Direct Detection Doppler Wind Lidar

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

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

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

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

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

Wavelength Considerations for DDL

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

Summary

- 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.
- Considerations of different wavelength requirements for coherent and incoherent detection Doppler lidars are discussed.