Lecture 23. Wind Lidar (3)

- Review of Wind Lidar Techniques

(Direct Motion Detection & Doppler Wind Lidar)

- Vector and Horizontal Wind Determination

(VAD, DBS, and Modified DBS)

- Wind Technique Comparison
- Coherent Detection Doppler Lidar Architecture
- Direct Detection Doppler Lidar Architecture
- GroundWinds Doppler Lidar
- Summary

Review of Wind Techniques

- Wind techniques can be classified in two main categories: the direct motion detection technique and the Doppler wind technique.

- Direct motion detection technique is to measure the time series of displacement of some inhomogeneities (e.g., aerosols, clouds, smoke plumes), and then derive the wind velocity using the definition of velocity (the time derivative of displacement).

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

- Common methods in data processing are (1) taking cross-correlation coefficients to derive the changes of displacement, (2) getting the displacement directly from the measurements and then taking the ratio of displacement to the time of flight.

- Three major techniques of direct motion detections are

(1) Tracking aerosol/cloud/smoke motion by lidars or imagers

(2) LTV: laser time-of-flight velocimetry

(3) LDV: laser Doppler velocimetry

Direct Motion Detection Illustration

- Three major techniques of direct motion detections are

(1) Tracking aerosol/cloud/smoke motion by lidars or imagers

(2) LTV: laser time-of-flight velocimetry

(3) LDV: laser Doppler velocimetry

Review of Wind Techniques

- Doppler wind technique is to measure the Doppler frequency shift of backscattered photons (e.g., aerosol scattering, molecular scattering, resonance fluorescence) caused by the wind velocity along the line of sight, and then derive the wind velocity from the frequency shift using the following Doppler shift relationship:

$$\boxed{\Delta\omega_{abs/sp} = -\vec{k}\cdot\vec{v}} \quad \text{or} \quad \boxed{\Delta\omega_{scattering} = -(\vec{k}_1\cdot\vec{\mathrm{v}}_1 - \vec{k}_2\cdot\vec{\mathrm{v}}_2)}$$

- Two major techniques of Doppler wind lidar techniques are

(1) Coherent Detection Doppler Wind Lidar (heterodyne detection)

(2) Direct Detection Doppler Wind Lidar (direct detection of photon)

- Coherent Doppler lidars rely on aerosol scattering that has very narrow bandwidth. By taking the beat signal between the returned light and the local oscillator, the frequency shift caused by the collective motion (i.e., the radial wind) of aerosols can be determined thus the radial wind can be derived.

Direct Detection Doppler Wind

- Direct detection Doppler lidars can use resonance fluorescence from mesospheric atoms, molecular scattering, or aerosol scattering. They do not take the heterodyne signal. Instead, they convert the Doppler frequency shift to the change of intensity, intensity ratio, or intensity spatial distribution. One of the key components is the optical frequency discriminator or frequency analyzer.

- The optical frequency discriminators include

(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, like the transmission edge of a molecular absorption line (e.g., iodine I_2 absorption lines), or the edge of a transmission fringe of an optical interferometer (e.g., Fabry-Perot etalon)

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

- A difference between resonance fluorescence Doppler lidar and other direct detection Doppler lidar lies in where the frequency discriminator is - in the atmosphere or in the receiver chain! Because the Na, K, or Fe absorption lines are in the atmosphere, the lidar receiver is allowed to be broadband, rather than the narrowband employed in the other DDL.

Vector Wind Determination

- Vector (u, v, w) wind velocity estimates require radial velocity measurements from at least three independent Line-Of-Sight (LOS).

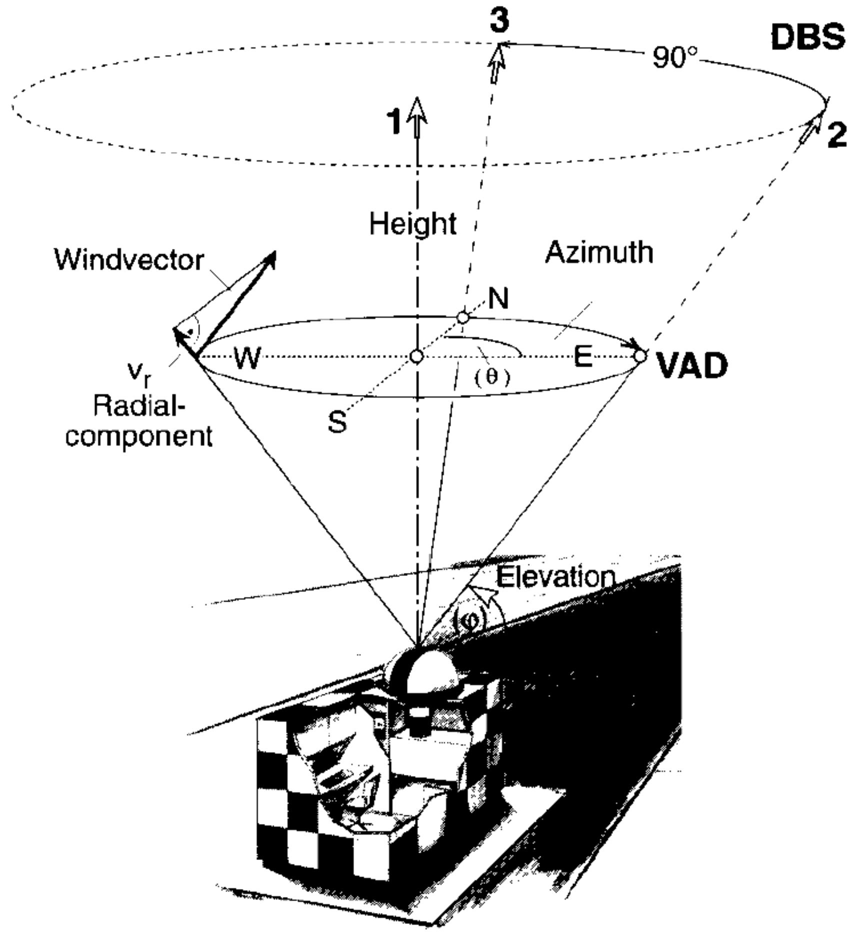
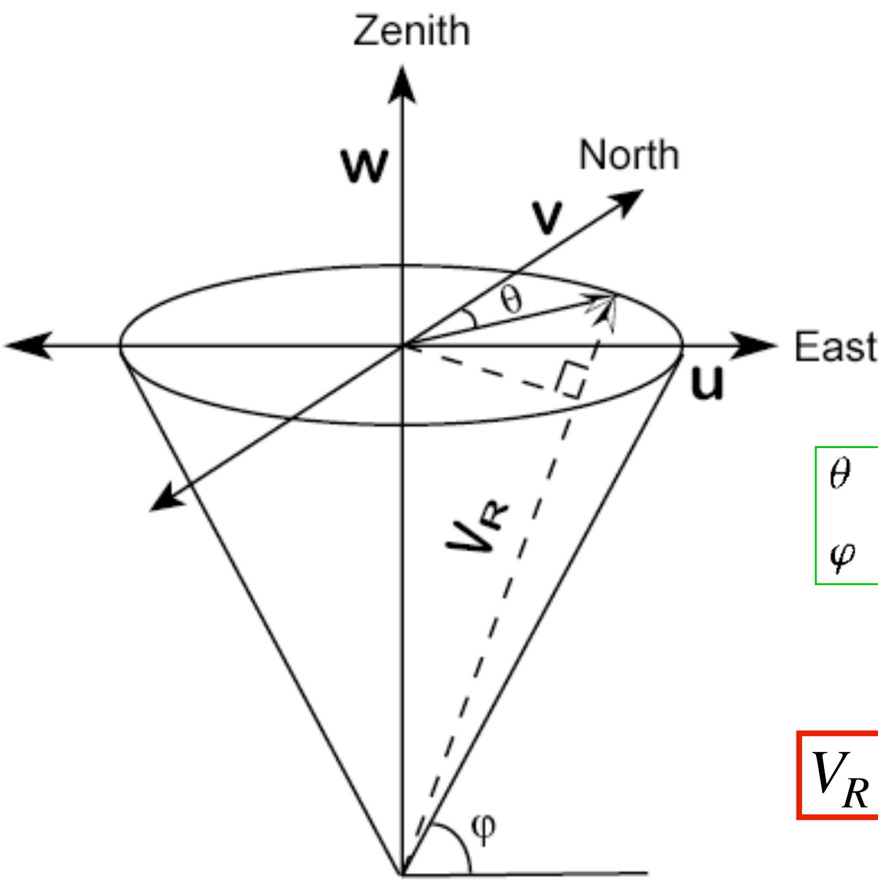


Fig. 12.8. Schematic of the scan technique of a Doppler lidar. Lower part: VAD scan, upper part: DBS scan.

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.



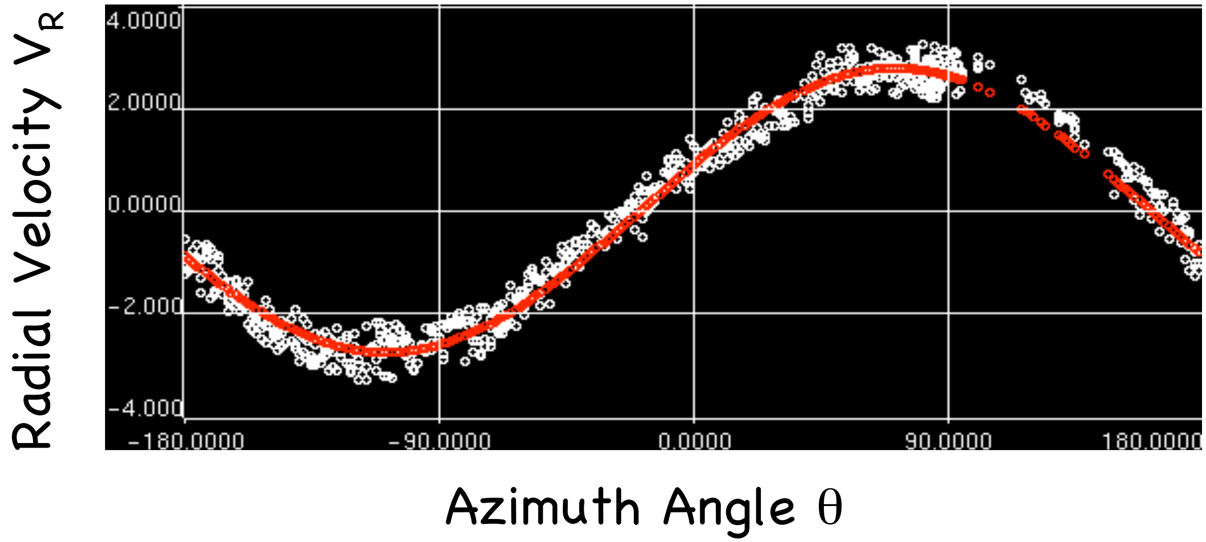
Radial velocity V_R consists of components from u, v, and w:

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.

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

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



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

- 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:

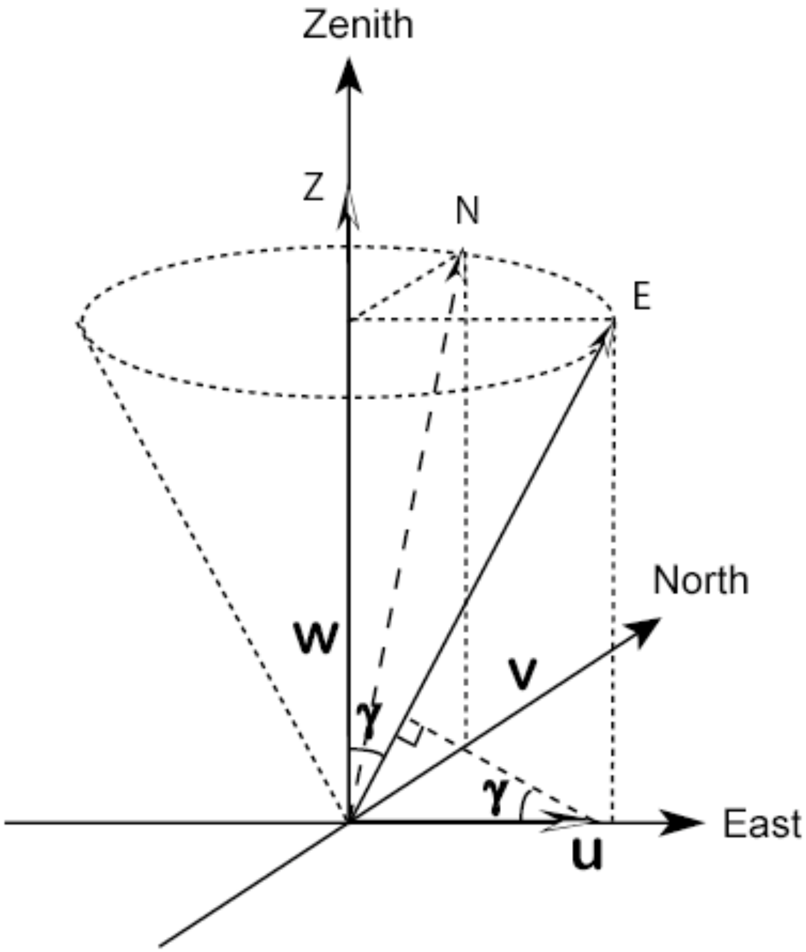
$$\boxed{V_R = a + b\cos(\theta - \theta_{\max}) = b\sin\theta_{\max}\sin\theta + b\cos\theta_{\max}\cos\theta + a}$$

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

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

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

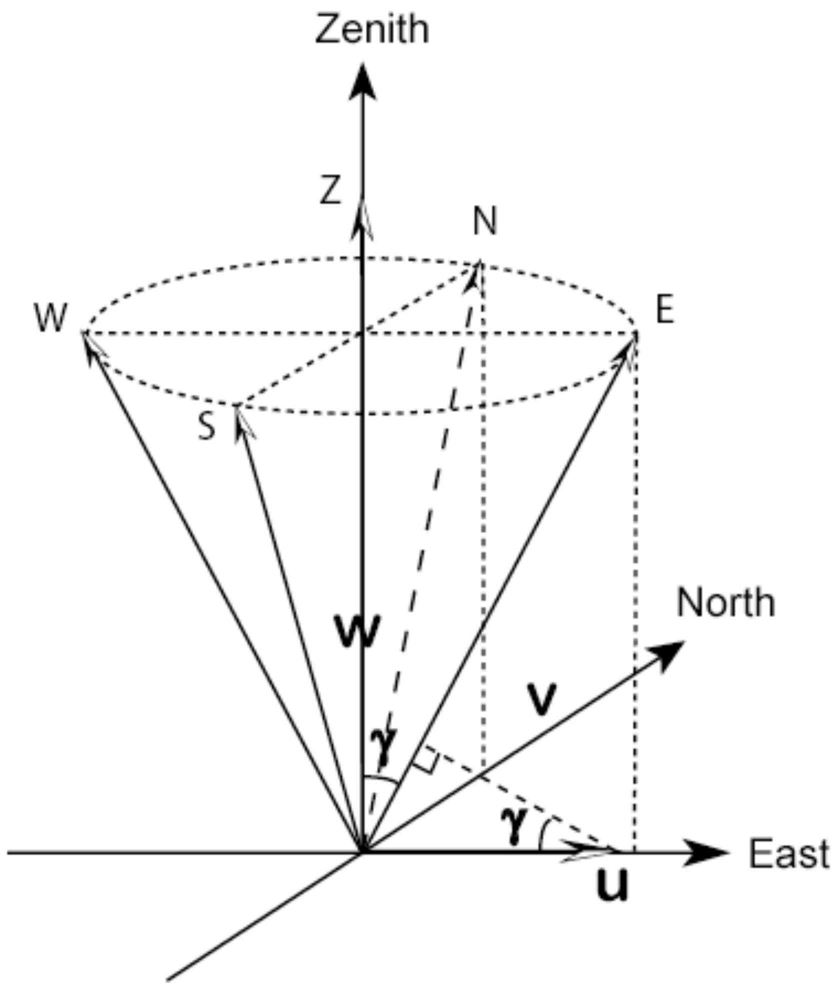
$$V_{RE} = u\sin\gamma + w\cos\gamma$$
$$V_{RN} = v\sin\gamma + w\cos\gamma$$
$$V_{RZ} = w$$

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

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).



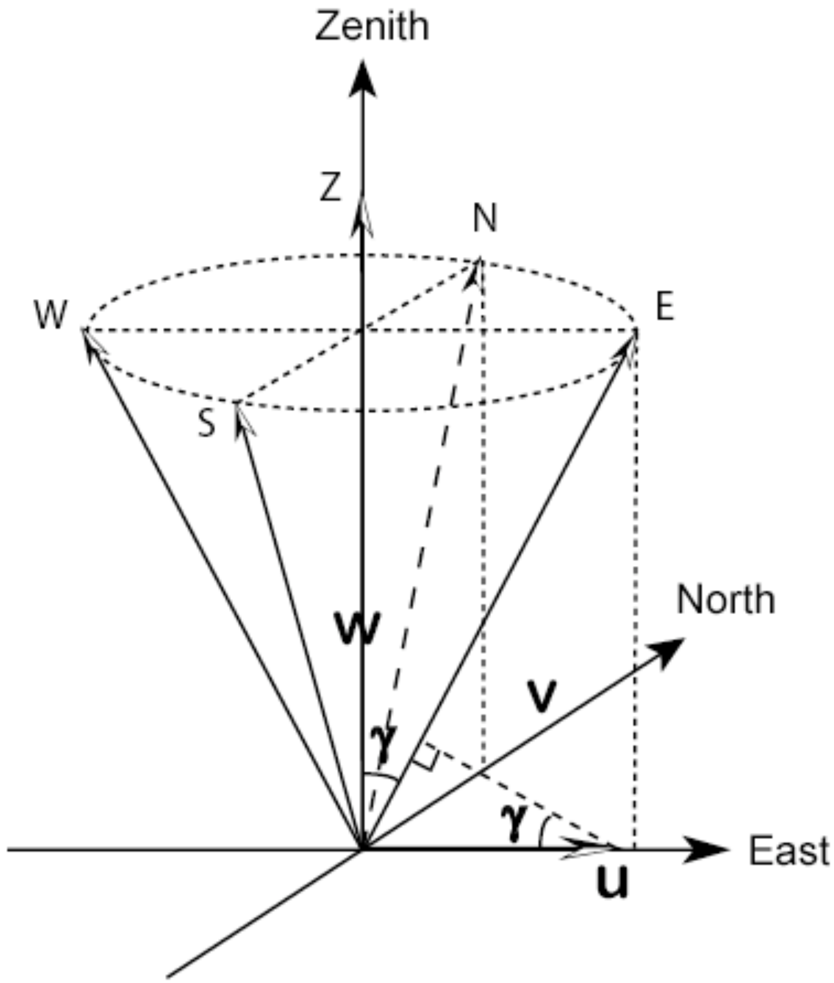
γ is the off-zenith angle

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

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

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

Modified DBS Technique

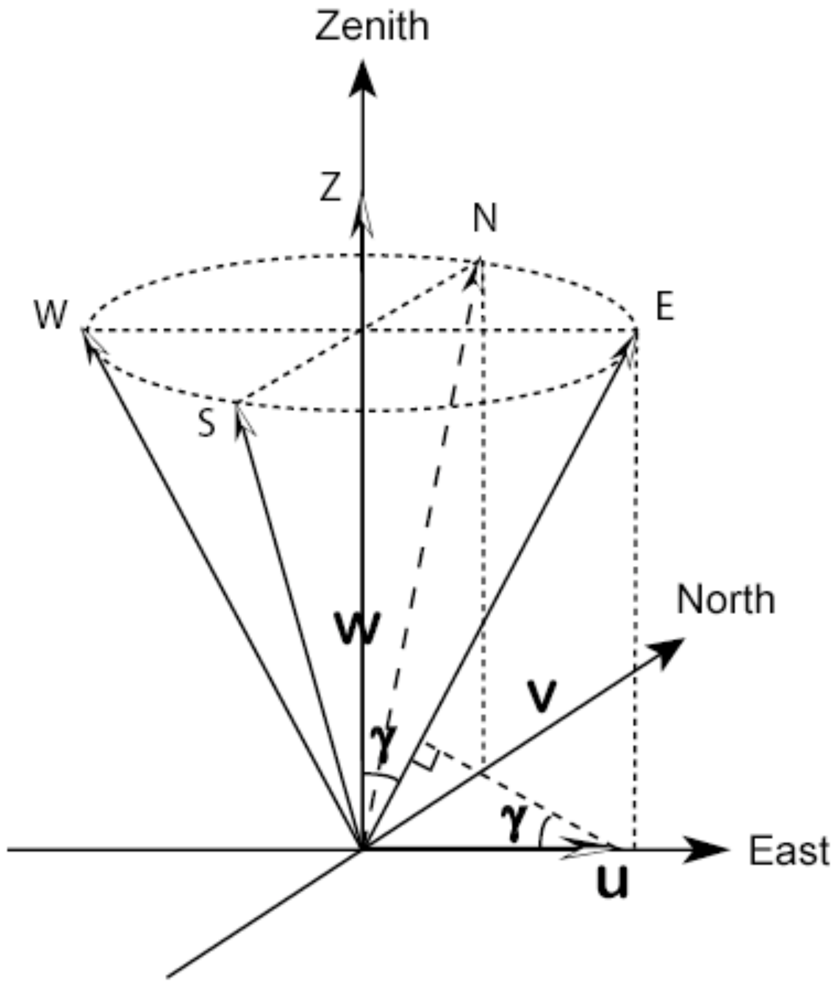


$$V_{RE} = u\sin\gamma + w\cos\gamma$$
$$V_{RW} = -u\sin\gamma + w\cos\gamma$$
$$V_{RN} = v\sin\gamma + w\cos\gamma$$
$$V_{RS} = -v\sin\gamma + w\cos\gamma$$
$$V_{RZ} = w$$

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

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

Modified DBS Technique



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

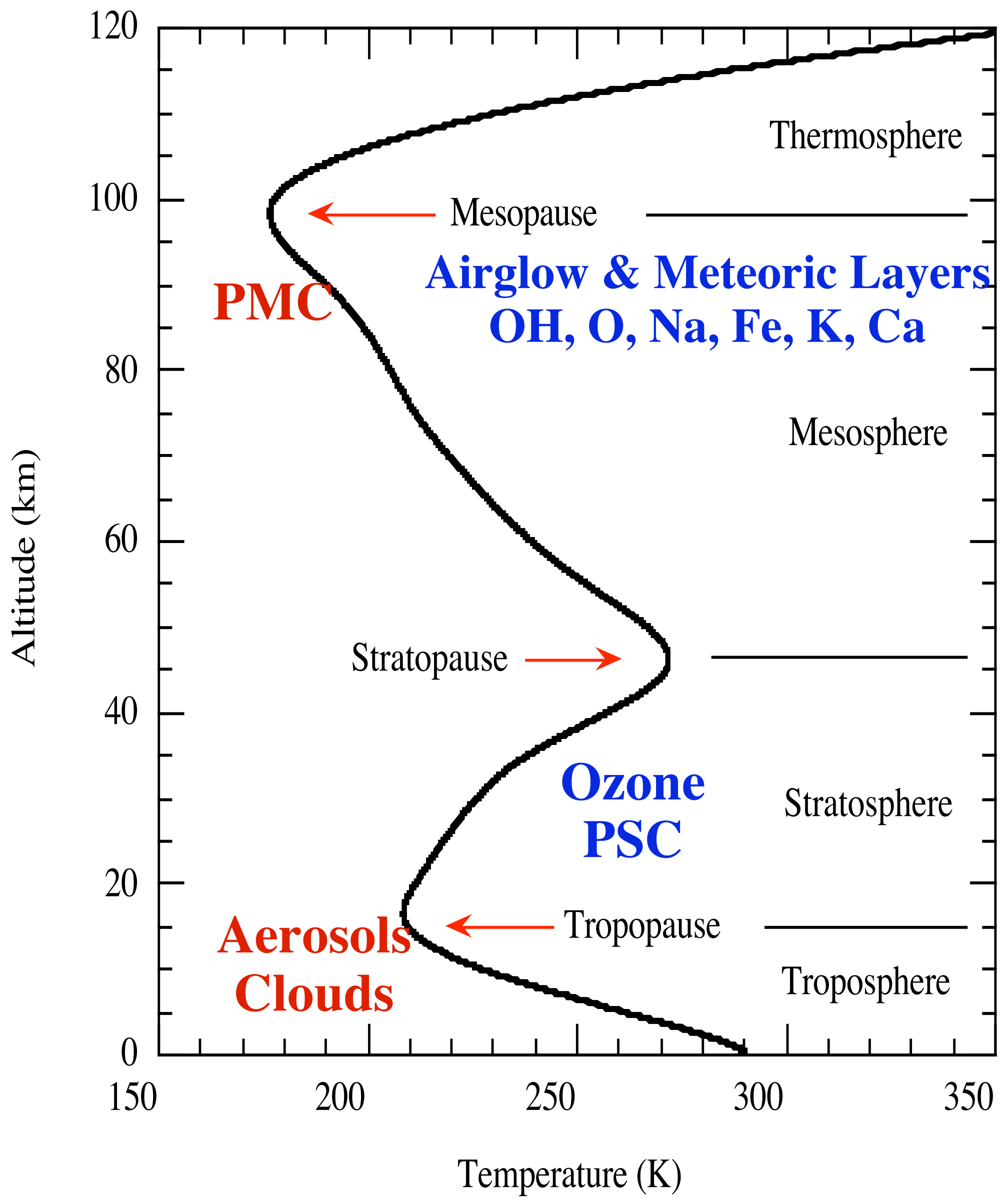
$$u = V_{RE}/\sin\gamma$$
$$u = -V_{RW}/\sin\gamma$$
$$v = V_{RN}/\sin\gamma$$
$$v = -V_{RS}/\sin\gamma$$
$$w = V_{RZ}$$

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.

Comparison of Wind Techniques

Technique	Lidars	Applications
Doppler Wind Technique (Direct Detection or Coherent Detection): wind dependence of Doppler frequency shift (1 time Doppler shift for single absorption or emission process) (2 times Doppler shift for Mie and Rayleigh scattering)	Resonance Fluorescence Doppler Lidar: Doppler frequency shift and broadening of resonance fluorescence absorption cross-section (scan and ratio techniques)	Mesosphere and Lower Thermosphere temperature and wind (75-120 km)
	Rayleigh/Mie Doppler Lidar : Doppler frequency shift of molecular and aerosol scattering using edge filters and/or fringe imaging	Lower mesosphere, stratosphere and troposphere wind (up to 50-60 km)
	Coherent Detection Doppler Lidar: Doppler frequency shift of aerosol scattering using heterodyne detection tech	Troposphere wind, especially in boundary layers (up to 15 km), where aerosols are abundant
Direct Motion Detection Technique: derivative of displacement (the definition of velocity) (direct application of velocity definition or cross-correlation coefficient)	High-Spectral-Resolution Lidar: tracking aerosol / cloud motion through time	Troposphere wind, where aerosols and clouds are abundant
	(Scanning) Aerosol Lidar: tracking aerosol motion through time	Troposphere wind, where aerosols and clouds are abundant
	Laser Time-of-Flight Velocimeter: measuring time-of-flight of aerosol across two focused and parallel laser beams	Within the first km range, laboratory, machine shop, etc.
	Laser Doppler Velocimeter: measuring the frequency of aerosol scattering across the interference fringes of two crossed laser beams	Within the boundary layers, wind tunnel, production facility, machine shop, laboratory, etc

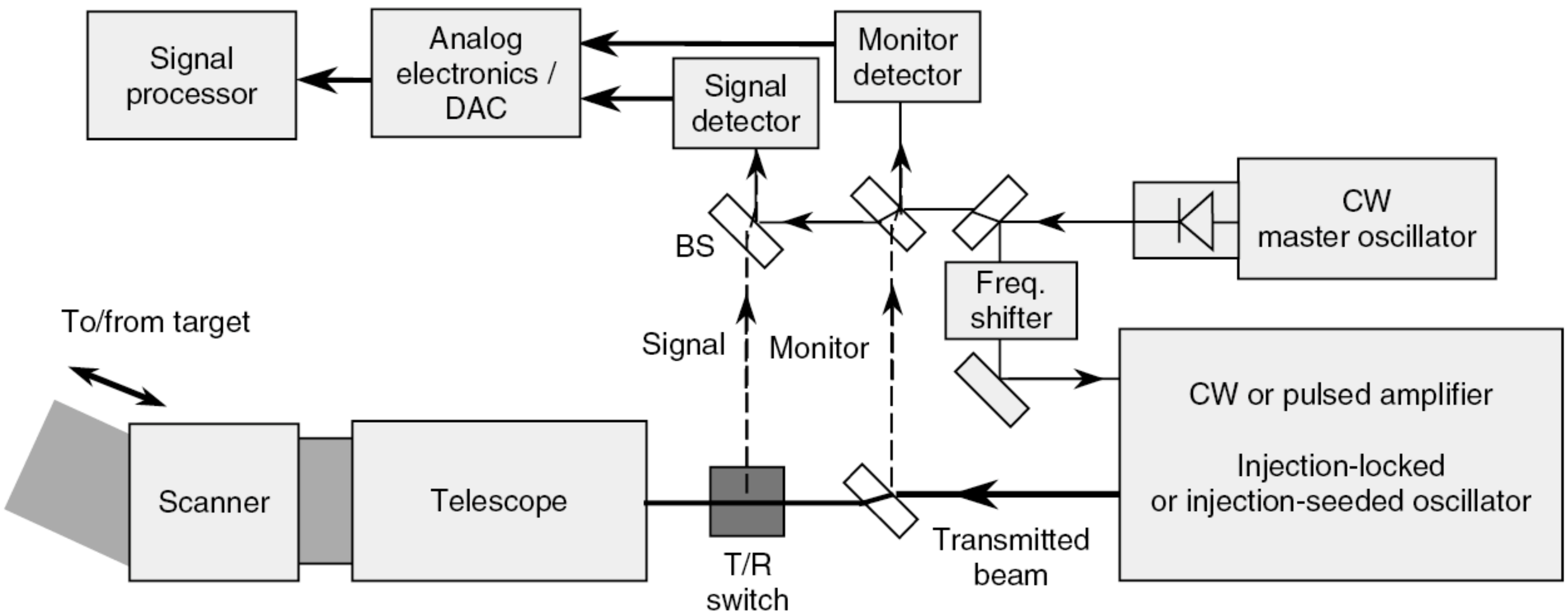
Wind Techniques vs Altitude



- 75-120km: resonance fluorescence (Na, K, Fe) Doppler technique (DDL)
- FPI: Fabry-Perot Interferometer
- Below 60km: Rayleigh Doppler technique (DDL)
- Below 30 km: Direct Detection Doppler technique
- In troposphere:

Coherent Detection Doppler tech,
Direct Detection Doppler tech,
Direct motion Detection tech (tracking aerosols, LDV, LTV)

Coherent Detection Lidar Architecture



- The master oscillator (MO) is a stabilized single-frequency CW laser
- Frequency shifter (usually AOM) is to add frequency offset to the transmitted beam - the offset removes the ambiguity between positive and negative frequency shifts, associated with positive and negative radial velocity of target.
- Returned backscatter signal mixes with the local oscillator (usually provided by the MO) and the beat signal (heterodyne) is used to estimate the frequency shift caused by the radial wind velocity.

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.

MOPA vs SOPA Transmitters

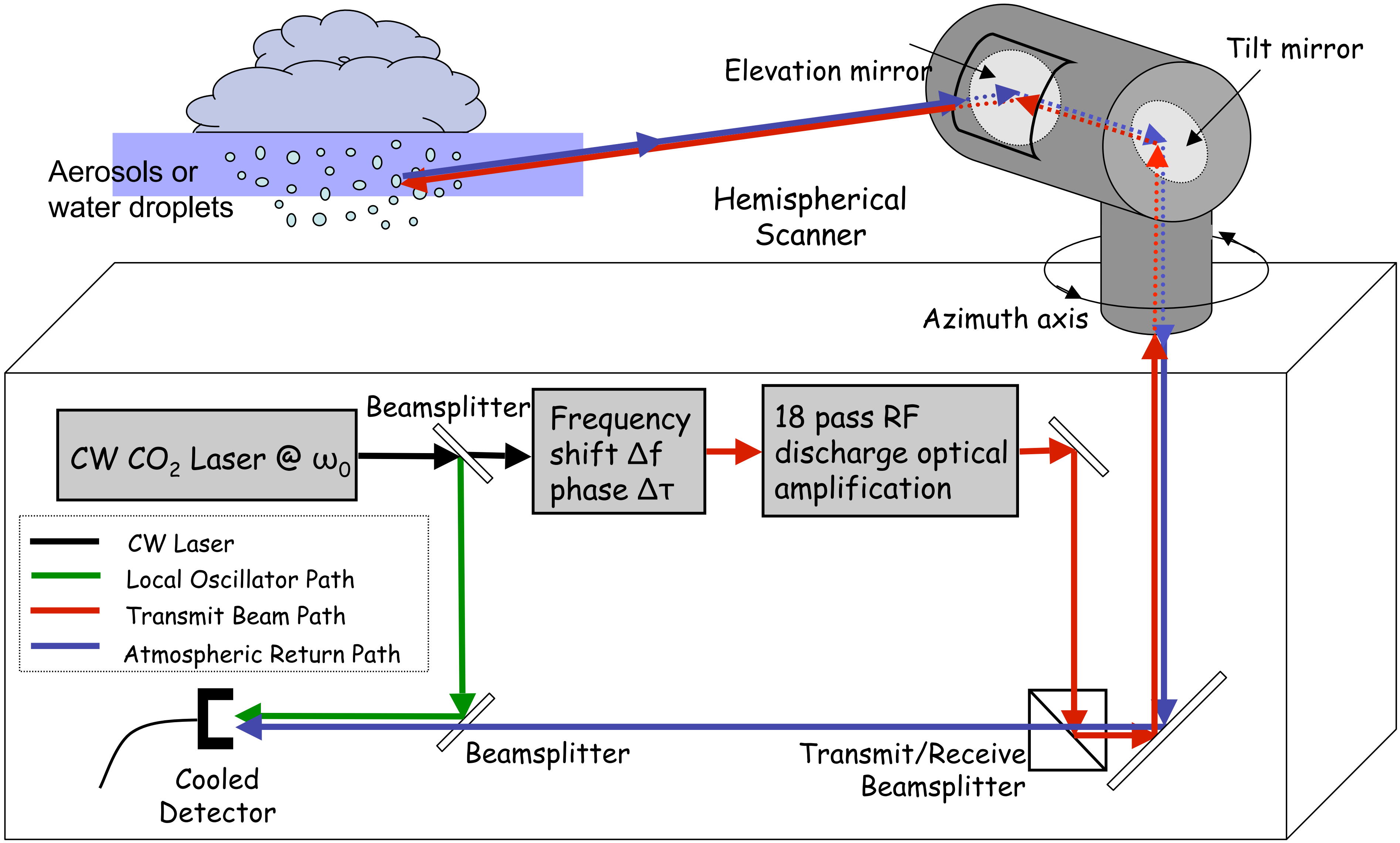
- There are two main types of transmitters used in coherent detection Doppler wind lidars: the MOPA and the SOPA.

- MOPA is master oscillator and power amplifier.
- Usually CW master oscillator is amplified to a powerful CW beam, then amplitude modulator (e.g., AOM) is used to chop the beam to pulsed laser for transmitting to the sky.

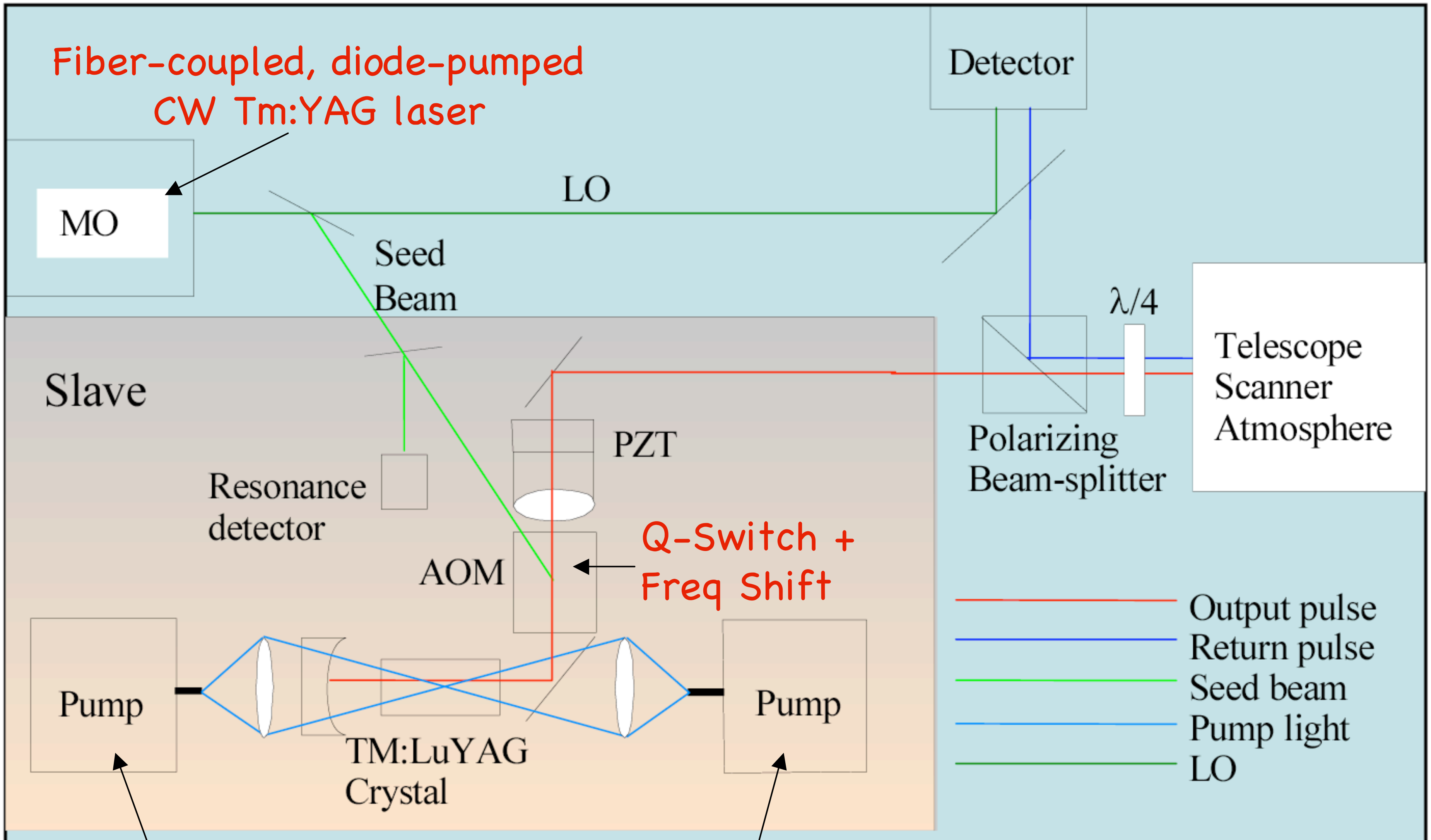
- SOPA is injection-seeded slave oscillator and power amplifier.
- The seed laser is usually a low-power but single-frequency CW laser.
- The slave laser is usually a high-power, Q-switched pulsed laser.

- For coherent detection, transmitter is required to have very narrow bandwidth (about 1 MHz), thus, the laser pulse must have long duration time so that the transform-limited spectral bandwidth is within 1 MHz.

NOAA mini-MOPA CO_2 Coherent Lidar



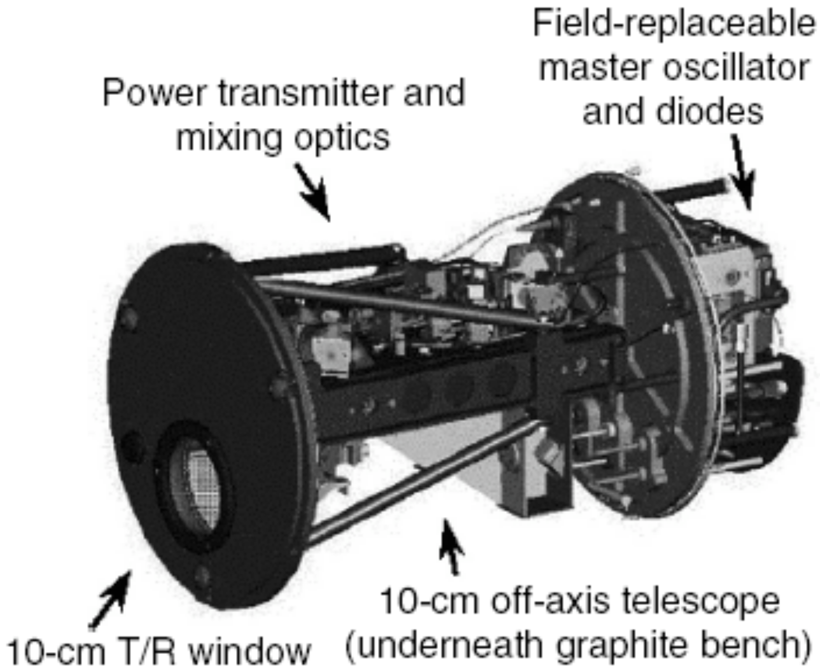
NOAA HRDL (A SOPA Lidar)



Fiber-coupled diode bars
CW @ 785 nm

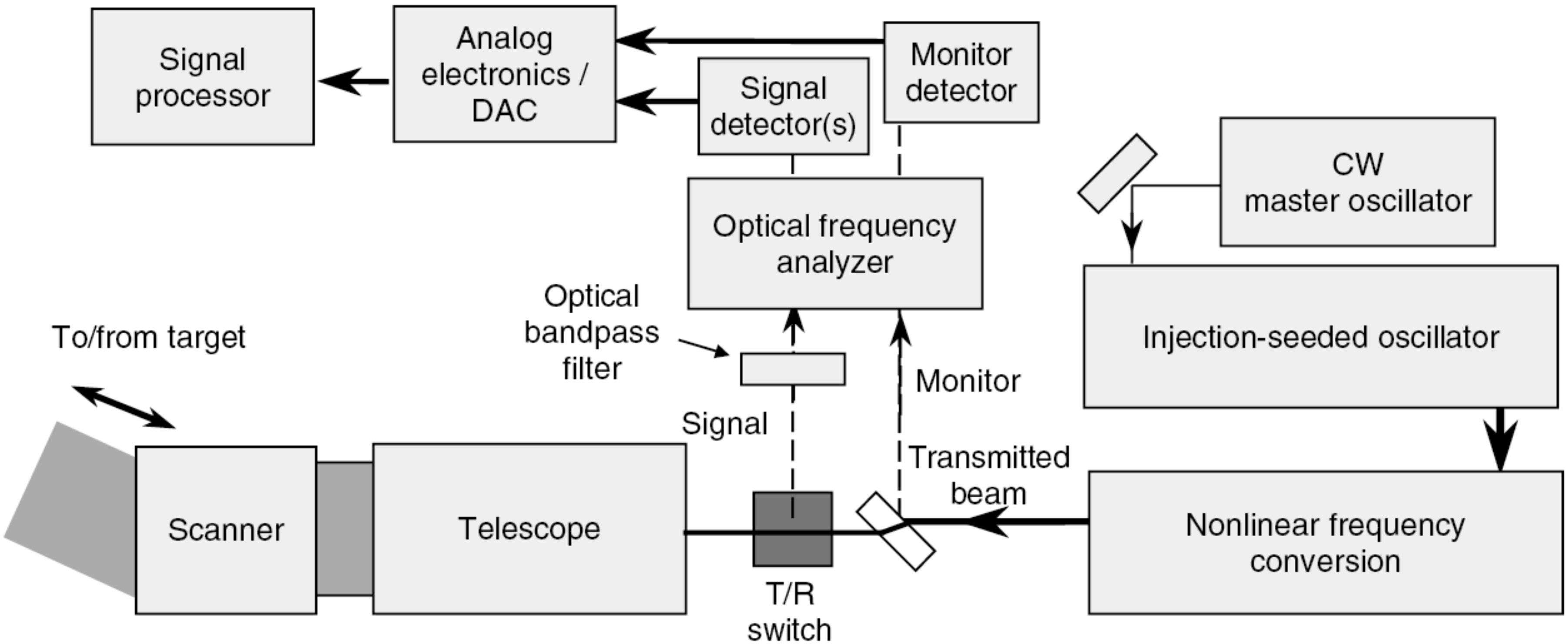
200ns, 2mJ per pulse

Coherent Technologies WindTracer



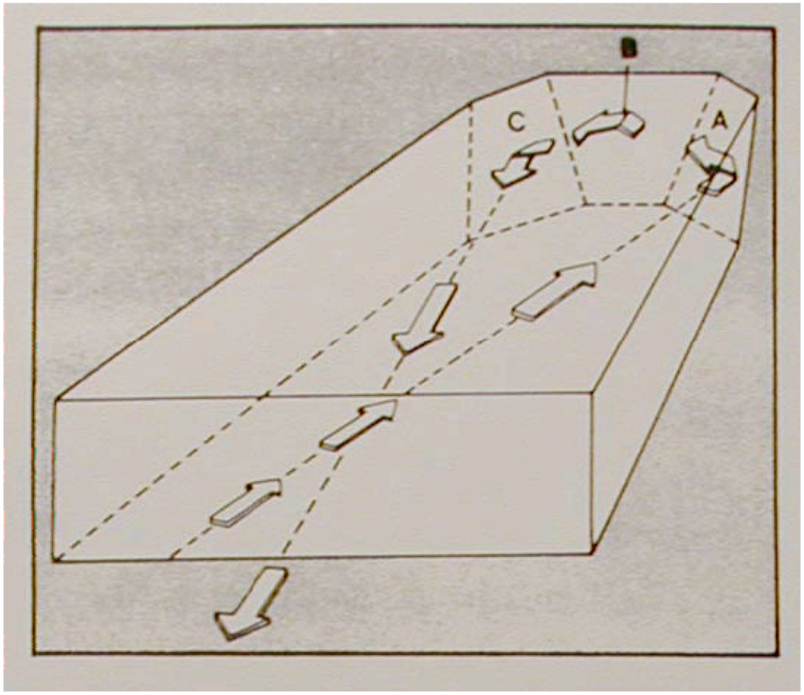
2 μm operating wavelength for good atmospheric transmission and eye-safety

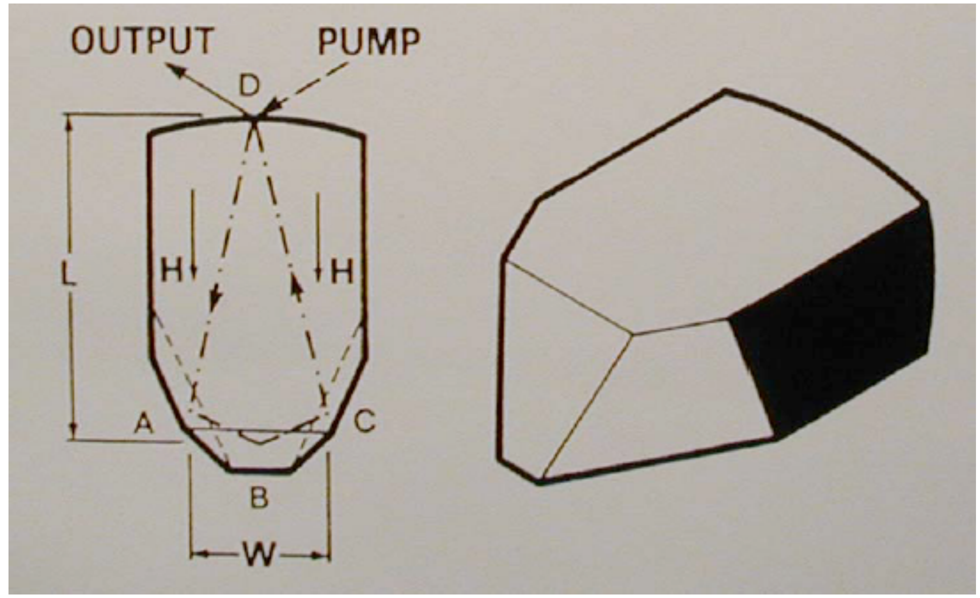
Direction Detection Lidar Architecture



- Transmitter: need single-freq laser (narrowband and stabilized freq)
- Commonly used are injection-seeded, Q-switched Nd:YAG laser with frequency doubling (532nm), tripling (355nm), or quadrupled (266nm)
- CW master oscillator is usually provided by monolithic CW Nd:YAG laser or external cavity diode laser (ECDL)

Monolithic CW Nd:YAG Laser





- ❑ The YAG laser is pumped by diode laser
- ❑ YAG laser cavity is a ring-cavity inside a single YAG crystal (monolithic crystal)

Wavelength and Pulse Length for DDL

- For direct detection lidar, especially 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.

- Doubled (532 nm), injection-seeded, Q-switched Nd:YAG laser is very reliable and commercially available, thus, usually chosen as the DDL transmitter.

- These Nd:YAG lasers usually have pulse length of 5-20 ns, with transform-limited spectral width of 100 MHz to 30 MHz @ 1064 nm.

- Increasingly, tripled (355 nm) or quadrupled (266 nm) Nd:YAG lasers are used in DDL, because of their significant improvement in eye-safety (the near-UV radiation is NOT transmitted by the eye's cornea and lens) and stronger molecular scattering.

Direct Detection Receiver

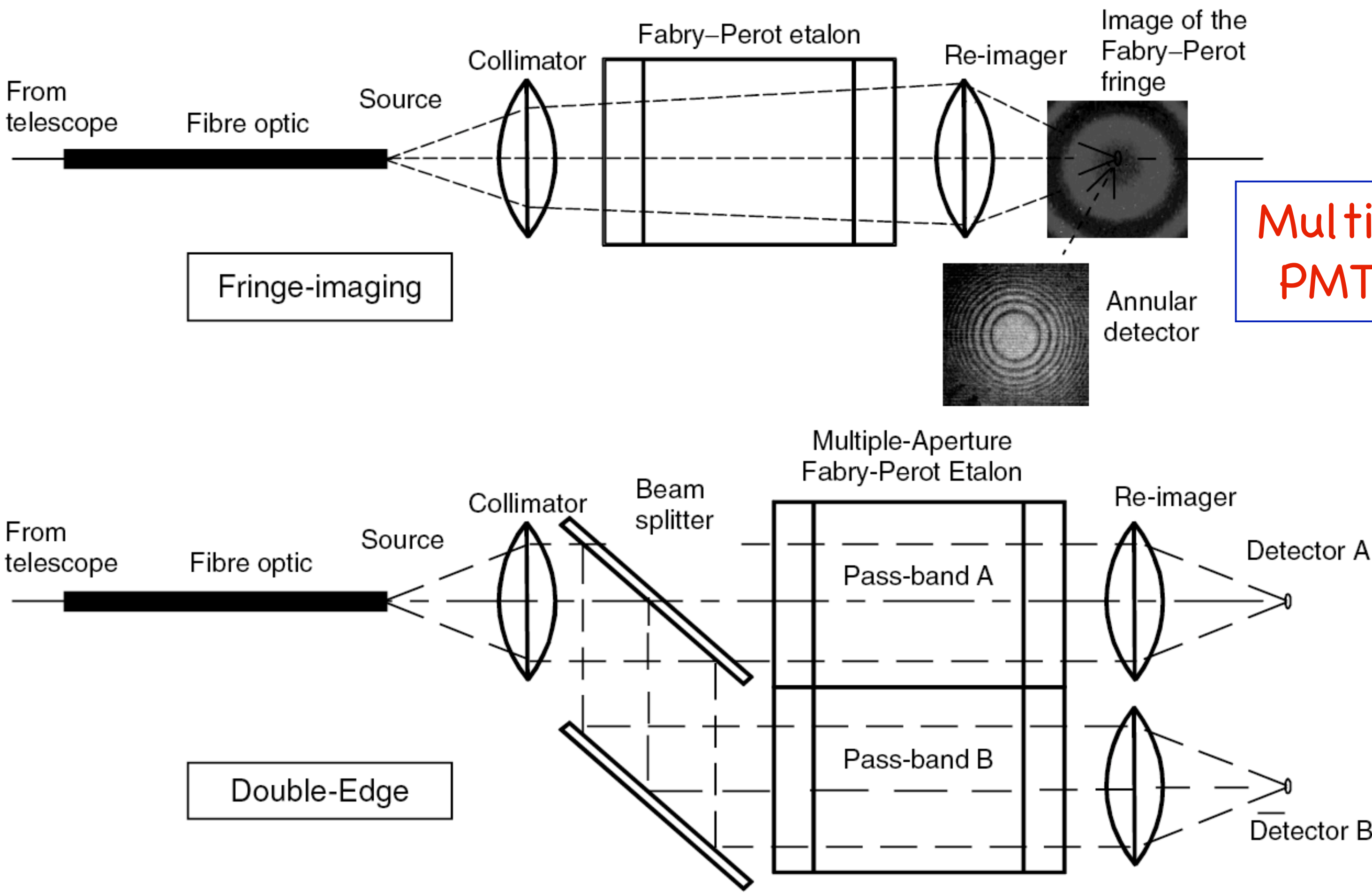
- Precision requirement: for δV = 1 m/s velocity precision, the freq measurement precision required for the optical freq analyzer in a DDL is $\delta\nu = 2(\delta V)/\lambda$ = 5.6 MHz for 355 nm.

- Accuracy requirement: accuracy should surpass the precision level. This is usually achieved by monitoring the transmitted laser pulse signal or alternatively measuring the backscatter signal from a stationary or very low velocity target.

- Still, calibration or accuracy is a main problem for non-resonant direct detection lidars, because the burden is on the receiver chain which is variable through time or surrounding conditions.

- On the other hand, resonance fluorescence Doppler lidars put the discriminator to the atomic absorption lines, which do not change with time. Their receivers can be much simpler.

Edge Filters vs Fringe Imaging

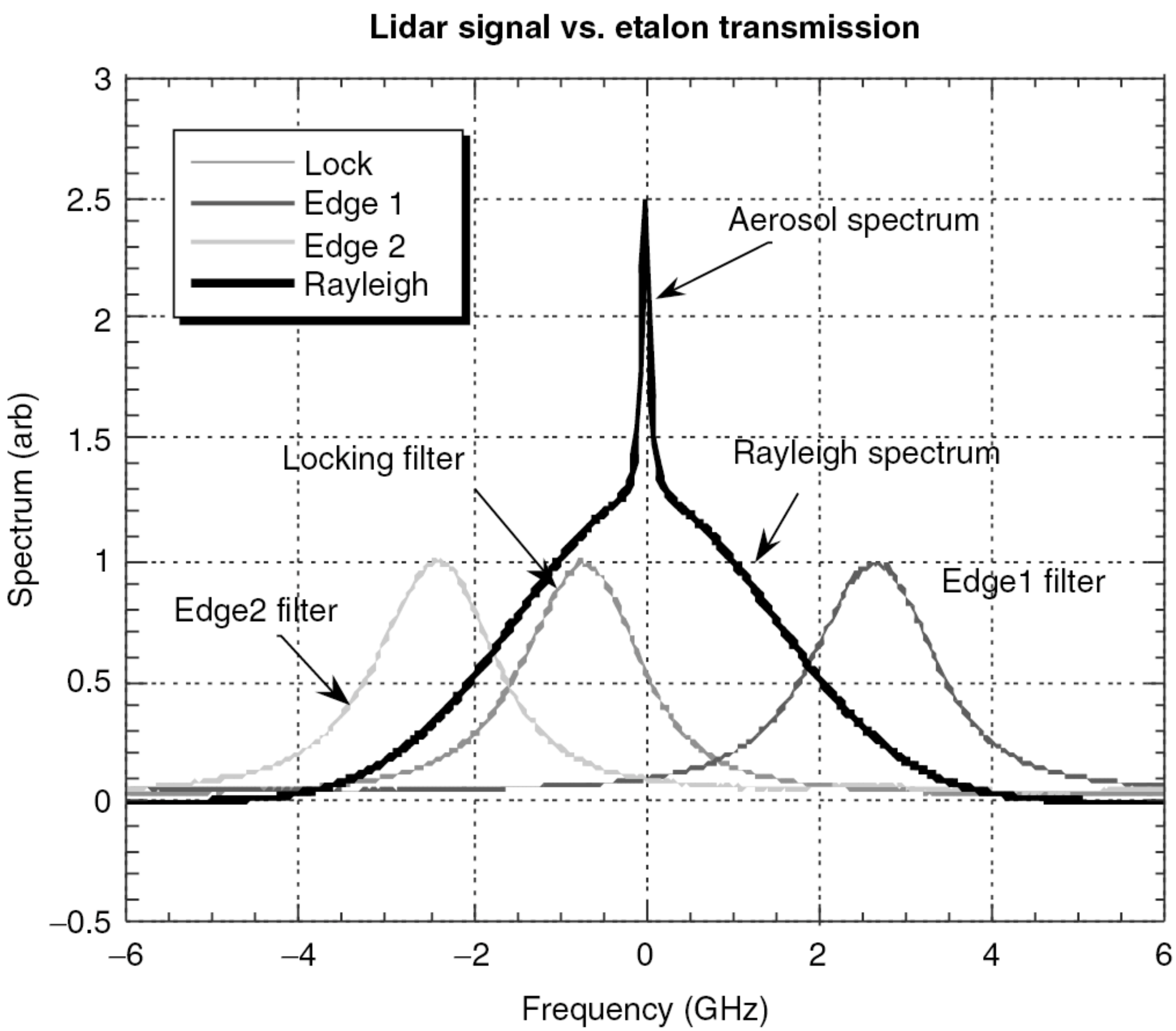


Multi-Channel PMT or CCD

PMT
APD
CCD

Figure 7.45 The fringe-imaging and double-edge detection methods for direct detection are shown conceptually.

Single- and Double-Edge Filters



The locking filter channel is to ensure the optimum balance of the Edge 1 and Edge 2 filters (F-P etalons) on the zero Doppler-shifted laser signal.

Detectors for Direct Detection Lidars

- The information presented to the detector in an edge detection system is the image of the small on-axis solid angle corresponding to the central on-axis fringe of the Fabry-Perot etalon with the necessary spectral FWHM. A suitable detector will be one that has high quantum efficiency, low noise, the capability for photon counting or analog read-out, depending on the intensity of the signal, and which can be "time-gated" to provide range-resolved information.

- The conventional PMT, the APD, and the CCD are among several that have been used successfully, depending on the spectral region of the wind lidar. The PMT is a device that is essentially noise-free when used in photon-counting mode. Due to the negligible read-out and electronic noise, the PMT signal may be post-integrated with complete flexibility, leading to the PMT being widely used as a detector of choice, particularly at 355 and 532 nm. Its drawback is the modest quantum efficiency of the photocathode of the device, normally limited to values of order 35% or less, depending on the spectral region.

- 2-D detection: altitude range and time, similar to other lidars, except the fringe-imaging lidars.

Detectors for Direct Detection Lidars

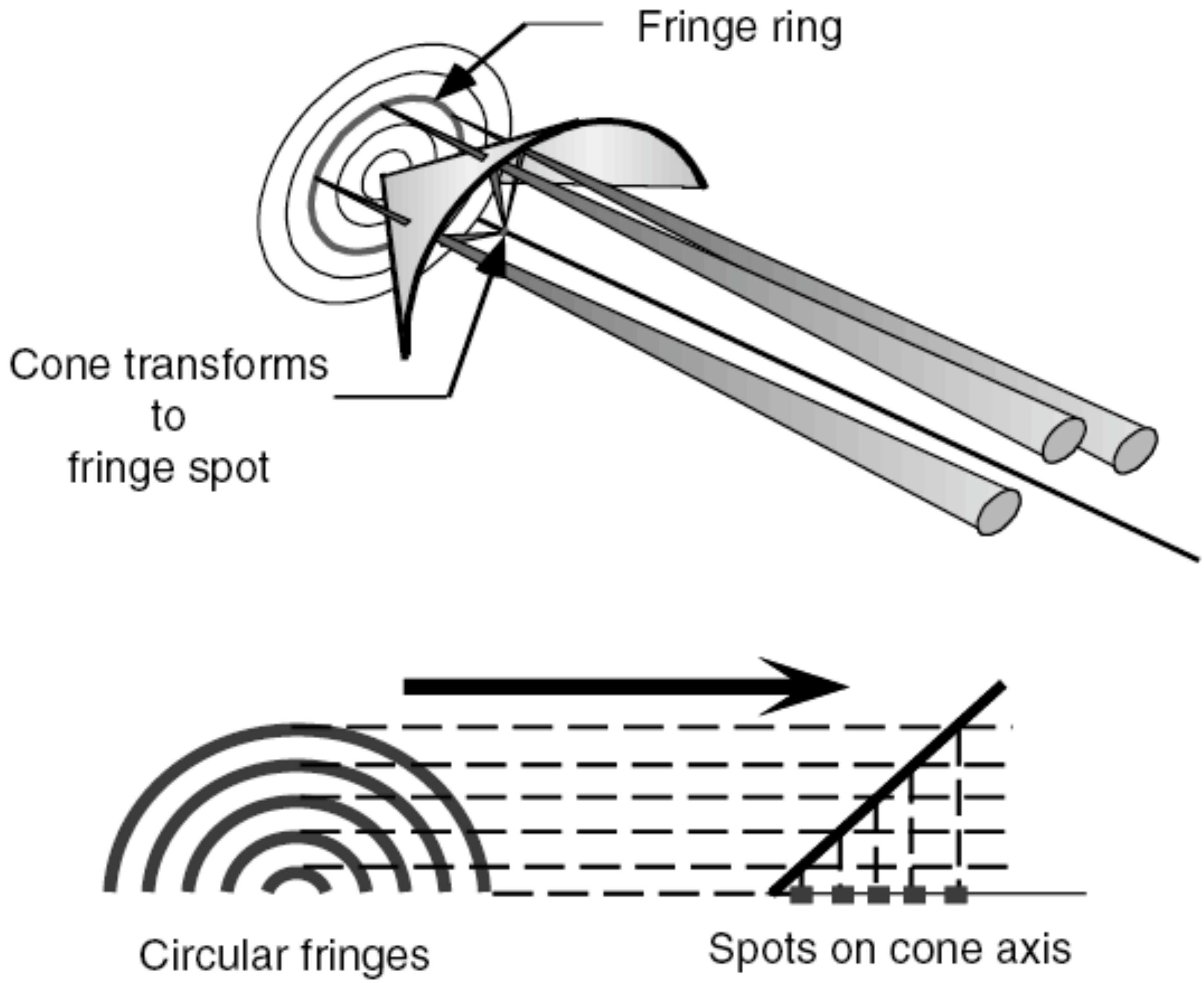
- For the fringe-imaging technique, by its nature, a multi-element imaging detector is required. Further, the detector has to also be capable of being used in a time-gated mode, in order to provide the essential range-resolved sampling of the backscattered signal. There is the further subtle difficulty that the Fabry-Perot etalon presents its spectral information as concentric circular fringes.

- 3-D detection: spatial distribution, altitude range, and time

- Multi-channel detectors like an imaging photomultiplier tube (IPD), incorporating a 24-channel concentric-ring anode read-out designed to match the fringe pattern presented by the F-P etalon. It uses a stack of microchannel plates to achieve high electronic gain. Each of 24-channel is time-gated to achieve range-resolved data.

- Circle-to-Line Imaging Optics (CLIO) can be used to convert the circular fringes formed by a F-P etalon into a linear pattern of spots. Then a conventional linear array detector, such as a CCD, can be used to read the linear fringe pattern.

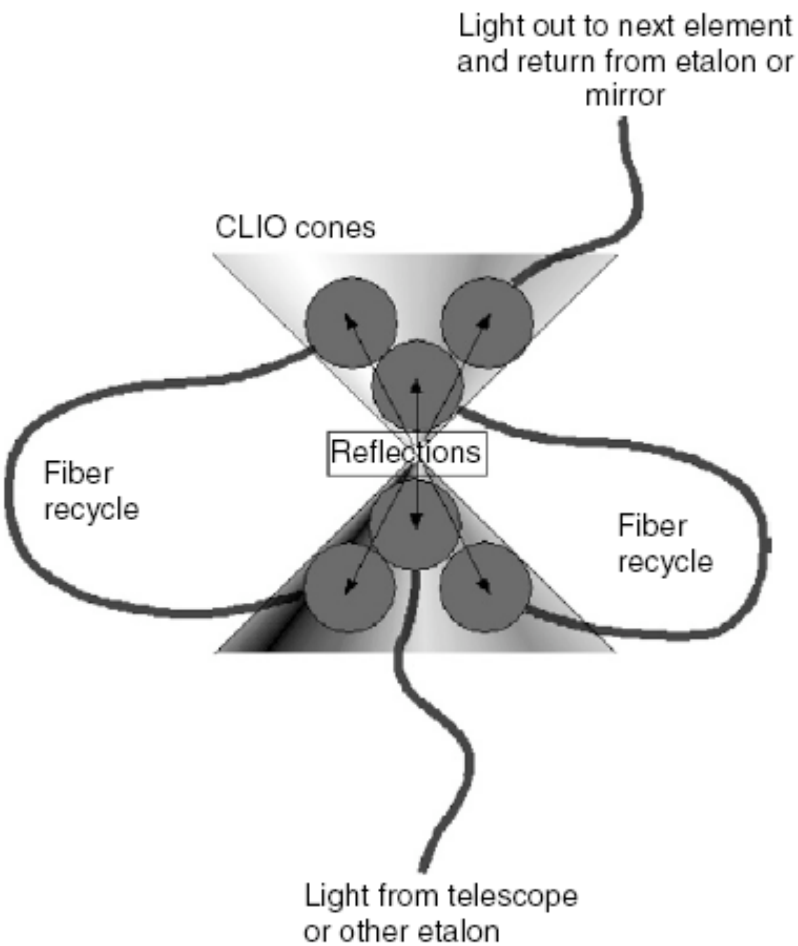
Circle-to-Line Imaging Optics (CLIO)

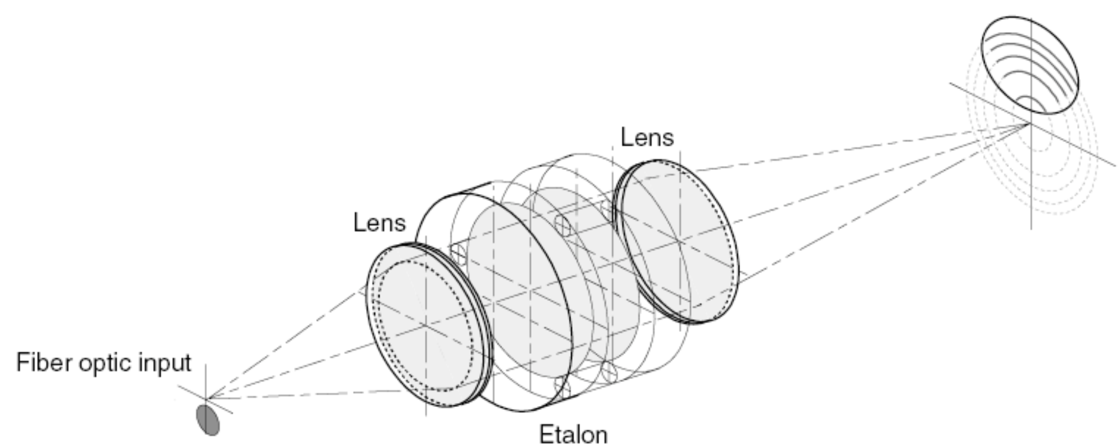


Improving Fringe-Imaging Efficiency

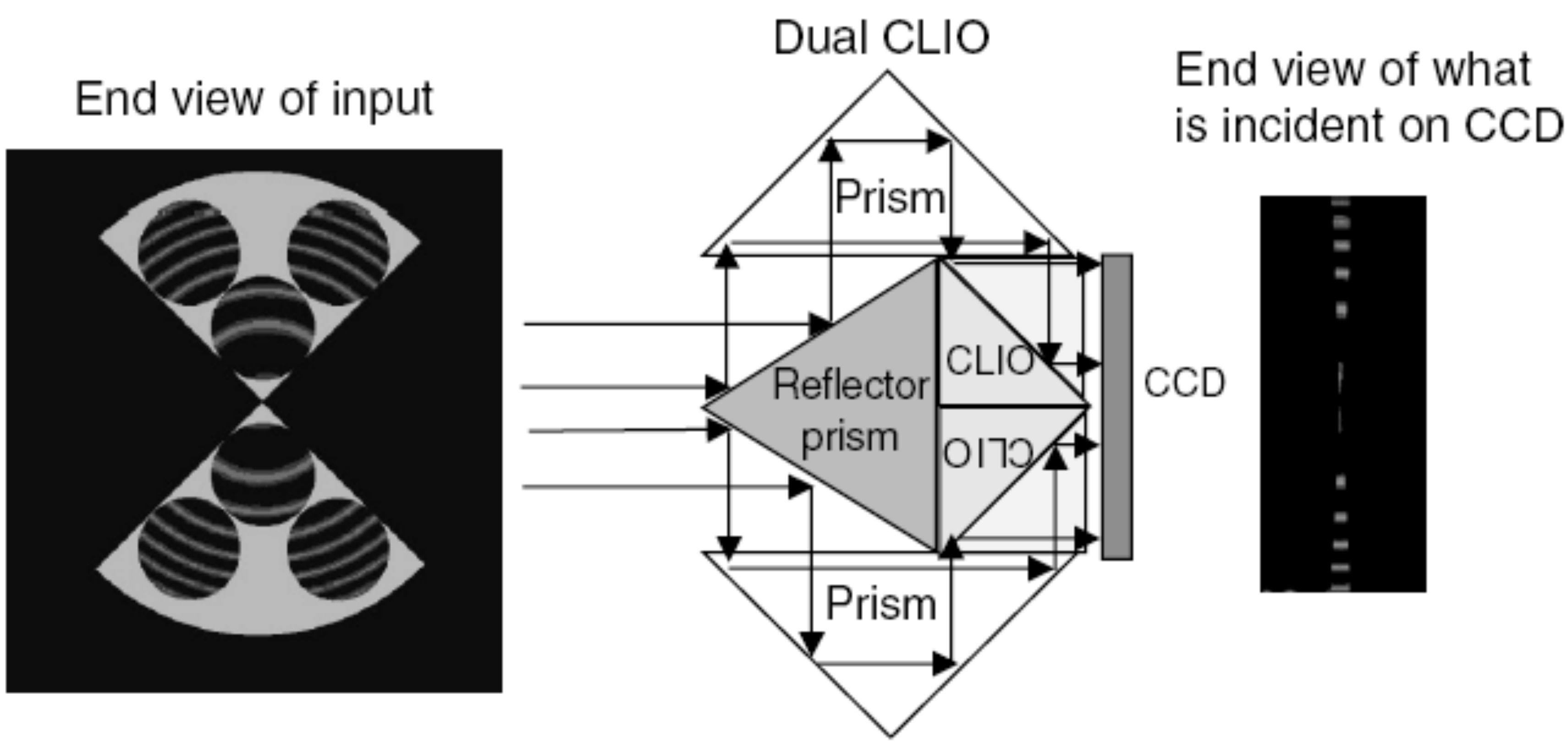
- When F-P etalon is used, only a portion of the incident light is transmitted through the interferometer, and majority of the incident light is reflected out. Three methods to improve this situation –
- Fractional Fringe Illumination: the etalon is illuminated by a solid angle corresponding to only a fraction of the full FSR, which can result in a significantly higher fraction of the signal being transmitted by the etalon.
- Interferometer Photon Recycling: reflected photons are collected by fibers and then re-illuminate the etalon.
- Channel Photon Recycling: aerosol channel and molecular channel for improvement of wind measurements.

Photon Recycling

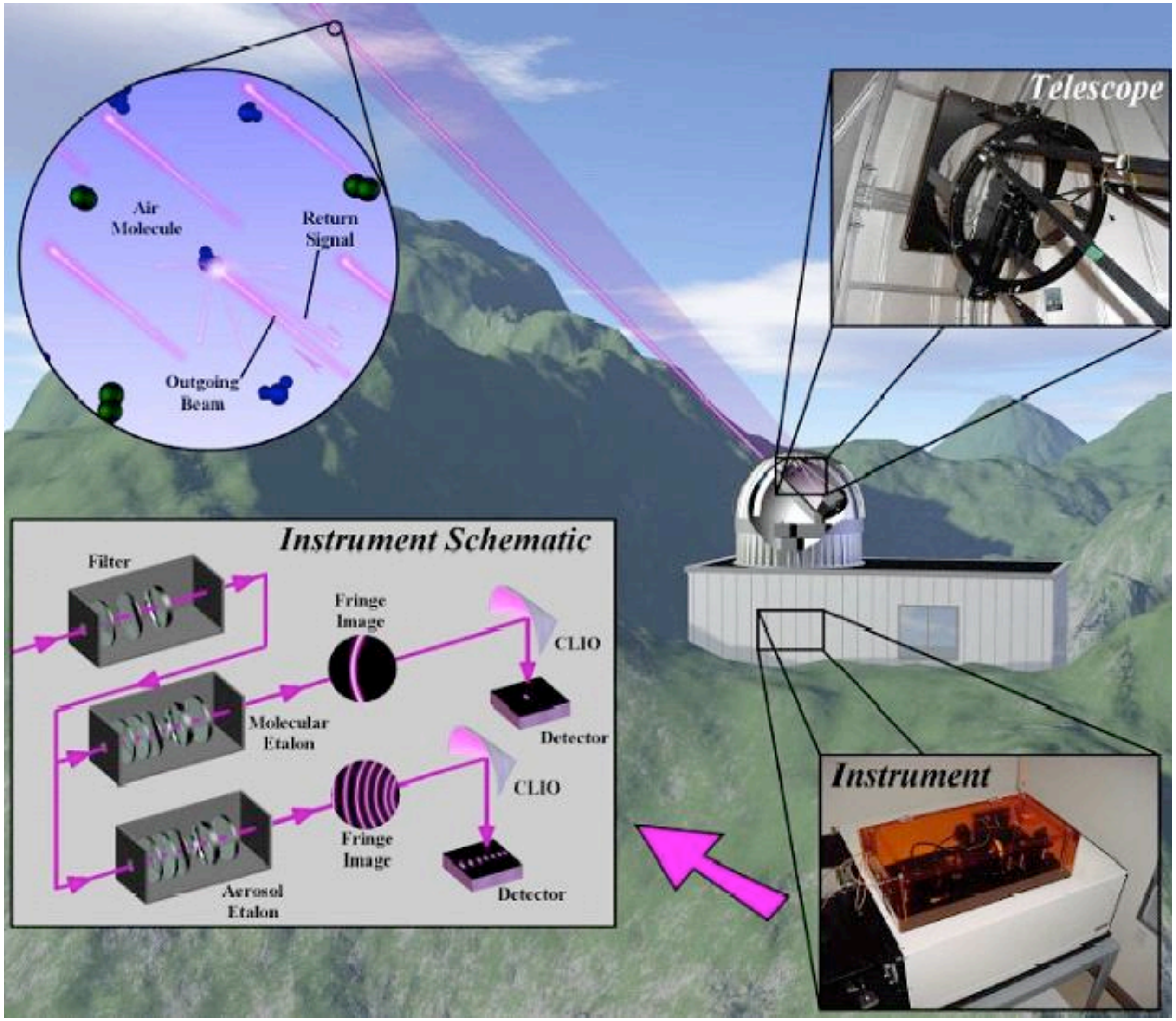




Photon Recycling + CLIO



Example DDL: GroundWinds



http://groundwinds.sr.unh.edu/

Summary

- True wind velocity can be measured by two types of techniques: the direct motion detection (of aerosols, clouds, or smoke) techniques and the Doppler wind techniques.
- Two main types of Doppler wind lidars are the coherent (heterodyne) detection and direct detection Doppler wind lidars.
- Both require narrowband lidar transmitters. Coherent lidars usually use MOPA or SOPA systems, while direct detection lidars usually use injection-seeded, Q-switched Nd:YAG laser.
- Considerations on wavelength, pulse duration, and pulse energy.
- DDL utilizes different optical frequency discriminators or analyzers, and there are several ways to improve efficiency of photon usage.
- Non-resonant DDL puts high demands on detector techniques.