Lecture 40. Lidar Class Review (2)

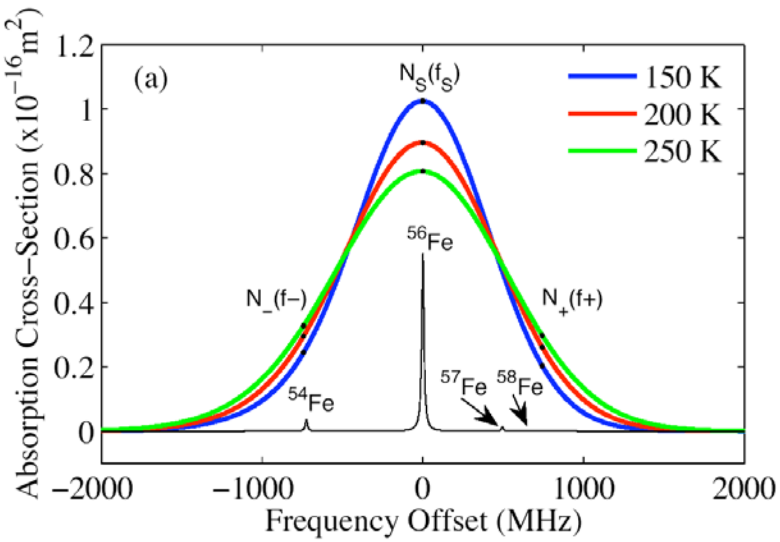
- Temperature Lidar
- Wind Lidar
- Aerosol Lidar
- Constituent Lidar
- Target Lidar
- Lidar Simulation and Error Analysis
- Accuracy versus Precision
- Lidar Design Considerations
- Summary and Outlook

Temperature Lidar Techniques

- Temperature-dependent and temperature-sensitive effects and phenomena are utilized in the temperature lidars to measure atmosphere temperatures.
- Resonance Fluorescence Doppler Technique
  (Na, K, and Fe Doppler lidars)
- Boltzmann Technique
  (Fe and N_2^+ Boltzmann lidars, imagers, Bomem mappers)
- Integration Technique
  (searchlight, Rayleigh & vibrational Raman lidars, falling sphere)
- Rayleigh Doppler Technique
  (Rayleigh Doppler lidar and high-spectral-resolution Lidar)
- Rotational Raman Technique
  (Rotational Raman lidar)
- Differential Absorption Technique
  (DIAL lidar)

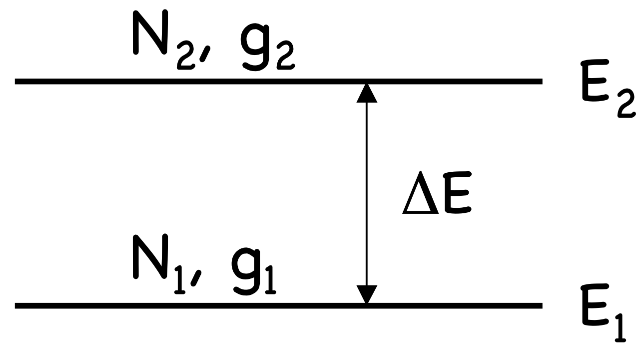
Doppler & Boltzmann Techniques

❑ Doppler effect and Boltzmann distribution are two effects that are directly temperature-dependent. The Doppler technique and Boltzmann technique are "straight-forward" in the sense of deriving temperature or wind. However, the lidar architecture is usually complicated and sophisticated, due to the high demands on frequency accuracy, linewidth, and power combination.



$$\Delta\omega = \omega - \omega_0 = -\vec{k}\cdot\vec{v} = -\omega_0 \frac{v\cos\theta}{c}$$

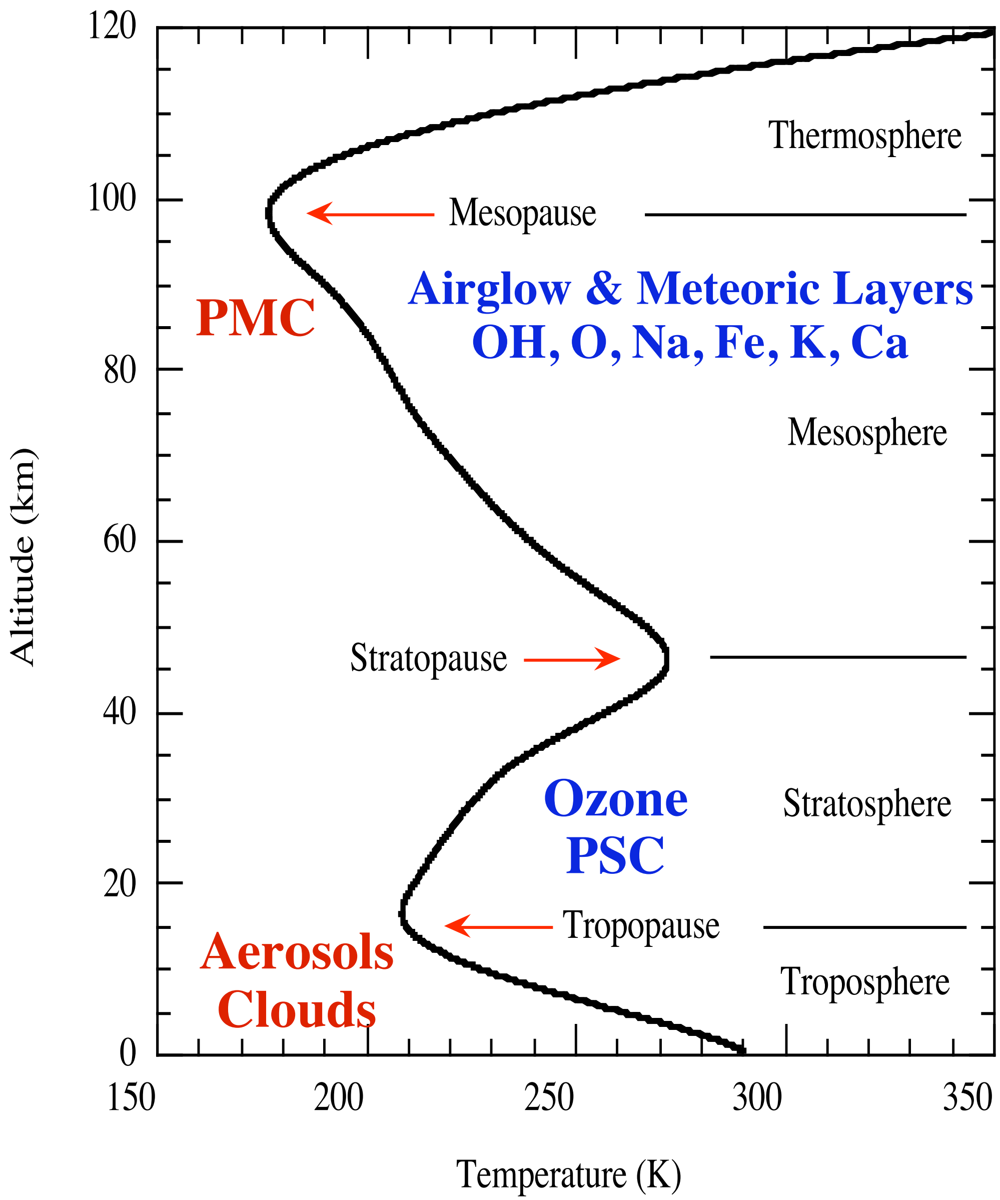
$$\sigma_{rms} = \frac{\omega_0}{c}\sqrt{\frac{k_B T}{M}} = \frac{1}{\lambda_0}\sqrt{\frac{k_B T}{M}}$$



$$\frac{N_2}{N_1} = \frac{g_2}{g_1}\exp\left\{-\left(E_2 - E_1\right)/k_B T\right\}$$

$$T = \frac{\Delta E / k_B}{\ln\left(\frac{g_2}{g_1}\cdot\frac{N_1}{N_2}\right)}$$

Temperature Technique vs Altitude



- 75-120km & above 120km: resonance fluorescence Doppler technique (Na, K, Fe, He, O) & Boltzmann technique (Fe, OH, O_2, N_2^+)
- 30-90km: Rayleigh integration technique & Rayleigh Doppler technique
- Below 30 km: scattering Doppler technique, and vibrational and rotational Raman techniques (Boltzmann and integration)
- Boundary layer: DIAL, HSRL, Rotational Raman

Comparison of Temperature Technique

Technique	Lidars	Applications
Doppler Technique: temperature dependence of Doppler broadening (1 time Doppler shift and Doppler broadening for single absorption or emission process) (2 times Doppler shift and Doppler broadening for Rayleigh scattering)	Resonance Fluorescence Doppler Lidar: Doppler broadening and Doppler shift of resonance fluorescence absorption cross-section (scan and ratio techs)	Mesosphere and Lower Thermosphere temperature and wind (75-120 km) Thermosphere (above 120 km)
	Rayleigh Doppler Lidar : Doppler broadening of molecular scattering	Lower mesosphere, stratosphere and troposphere temperature and wind (up to 60 km)
	High-Spectral-Resolution Lidar: Doppler broadening of molecular scattering, ratio of two signals	Stratosphere and troposphere temperature and wind (up to 30 km)
Boltzmann Technique: temperature dependence of population ratio	Resonance Fluorescence Boltzmann Temperature Lidar: population ratio on the lowest two ground states	Mesosphere and Thermosphere temperature (75-120 km and above 120 km)
	Rotation Raman Temperature Lidar: ratio of two Raman line intensities and population on different initial energy states	Troposphere and stratosphere temperature
Integration Technique: hydrostatic equilibrium and ideal gas law	Rayleigh or Raman Integration Temp Lidar: atmospheric density ratio to temperature, integration from upper level	Stratosphere and mesosphere temperature (30-90 km) Troposphere temperature (< 30 km)
DIAL	Differential Absorption Lidar: Temp-dependence of line strength and lineshape	Boundary layer temperature

Techniques for Wind Measurements

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

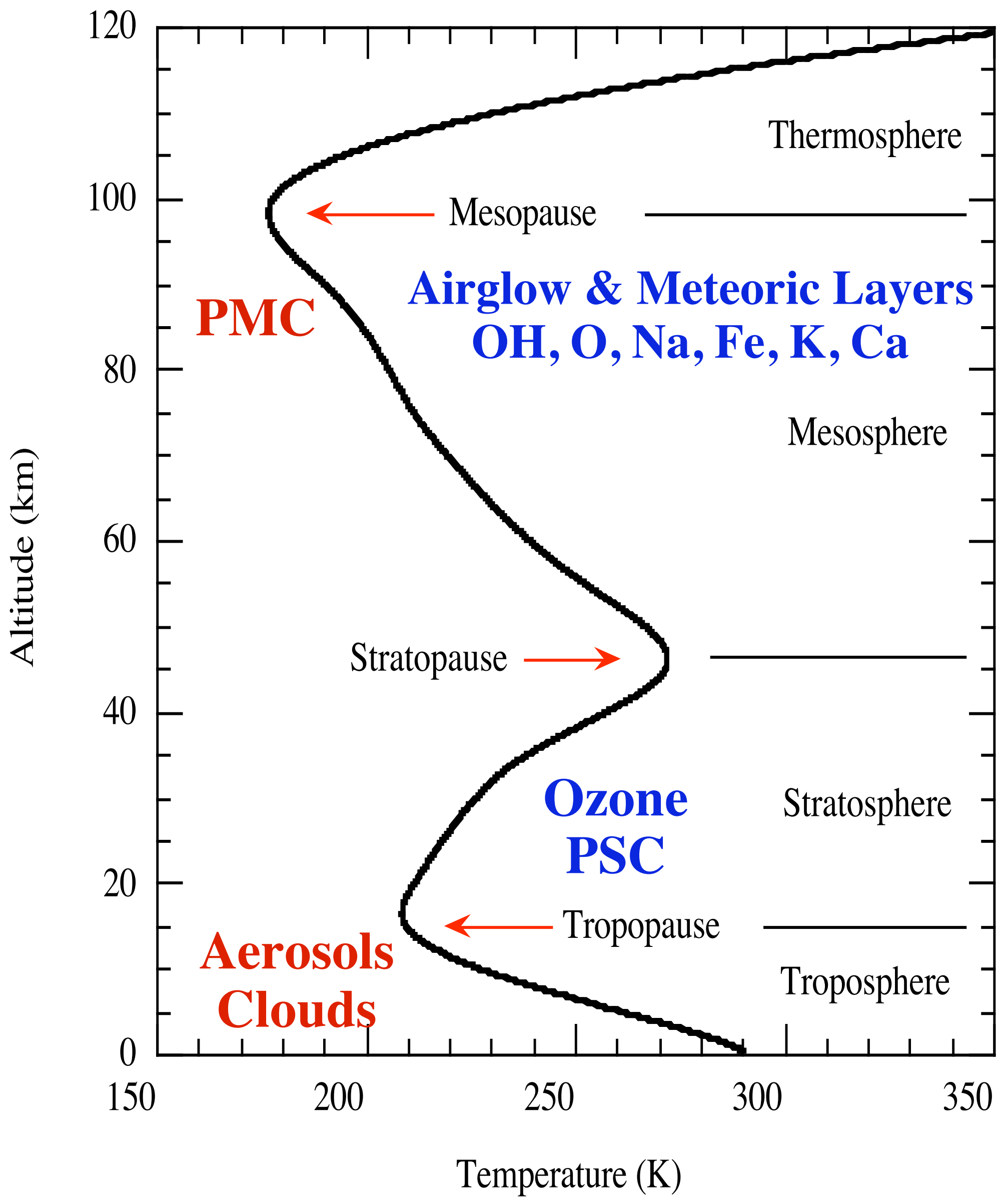
(1) Coherent (Heterodyne) Detection Doppler Wind Lidar

(2) Direct Detection Doppler Wind Lidar

- **Geostrophic wind detection:**

Temperature + Density ⇨ Pressure Gradients ⇨ Geostrophic Wind

Wind Techniques vs Altitude



- 75-120 km and above 120 km: resonance fluorescence (Na, K, Fe, He, O) Doppler technique (Direct Detection Lidar)
- 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 aerosols, LDV, LTV)

- Geostrophic wind in regions where pressure or geopotential gradients can be measured

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); possible in thermosphere with other species
	Rayleigh/Mie Direct Detection Doppler Lidar : Doppler frequency shift of molecular and/or aerosol scattering using edge filters (absorption lines or etalons) or fringe imaging or scanning FPI or Michelson Interferometer	Lower mesosphere, stratosphere and troposphere wind (up to 50-60-70 km if there are enough photon counts)
	Coherent Detection Doppler Lidar: Doppler frequency shift of aerosol scattering using heterodyne detection technique	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, fluid mechanics research, etc

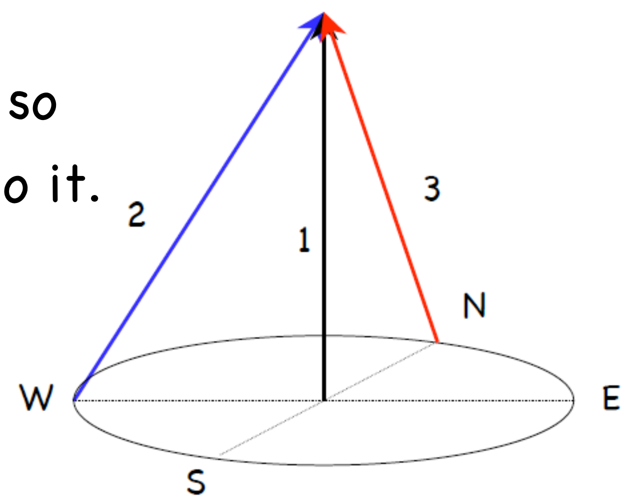
Vector Wind Velocity Determination

- 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 –

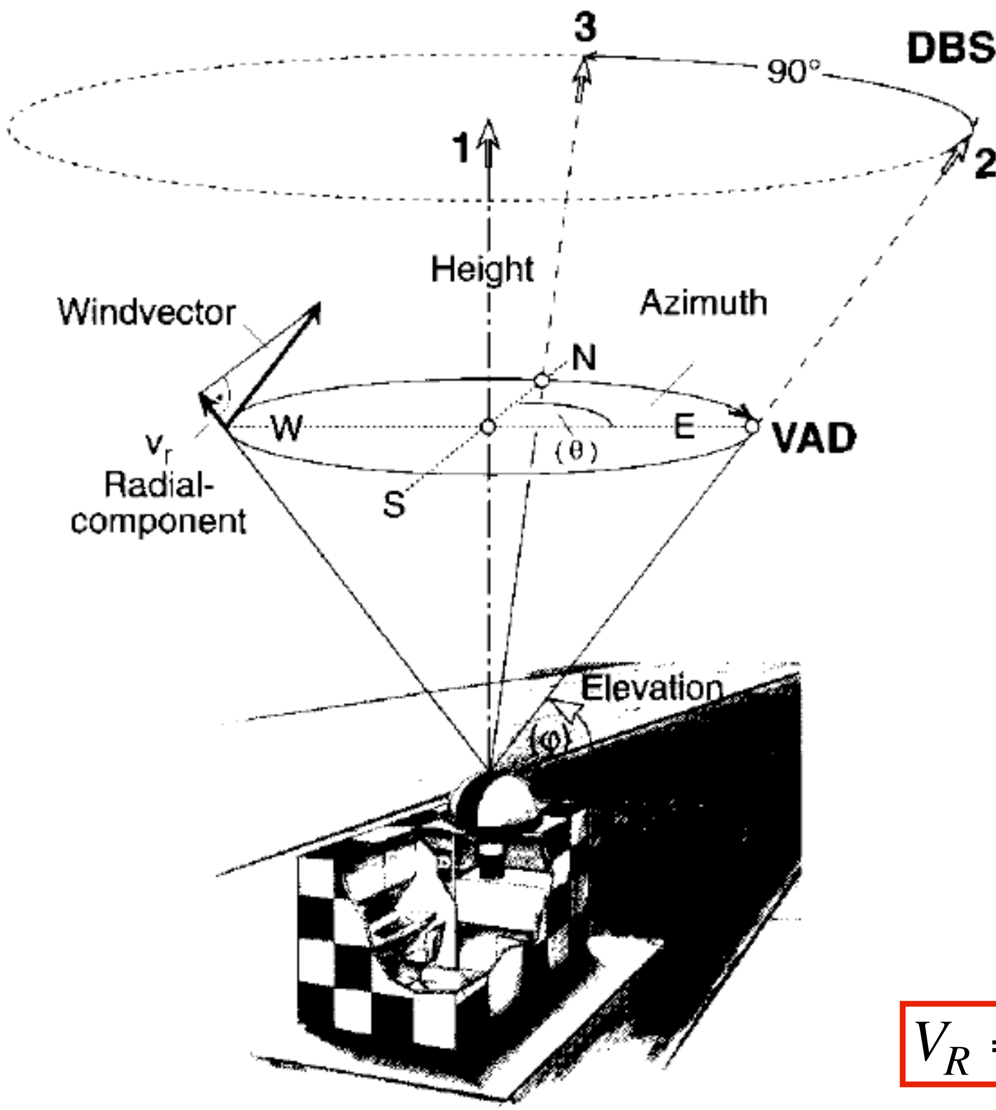
(1) the Velocity-Azimuth-Display (VAD) technique:

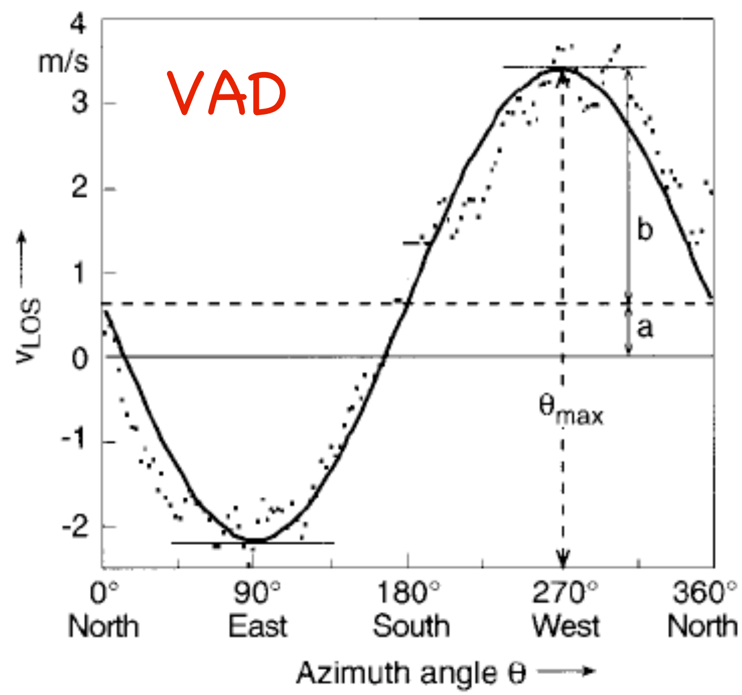
-- conical scan lidar beam at a fixed elevation angle

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

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

VAD and DBS Techniques



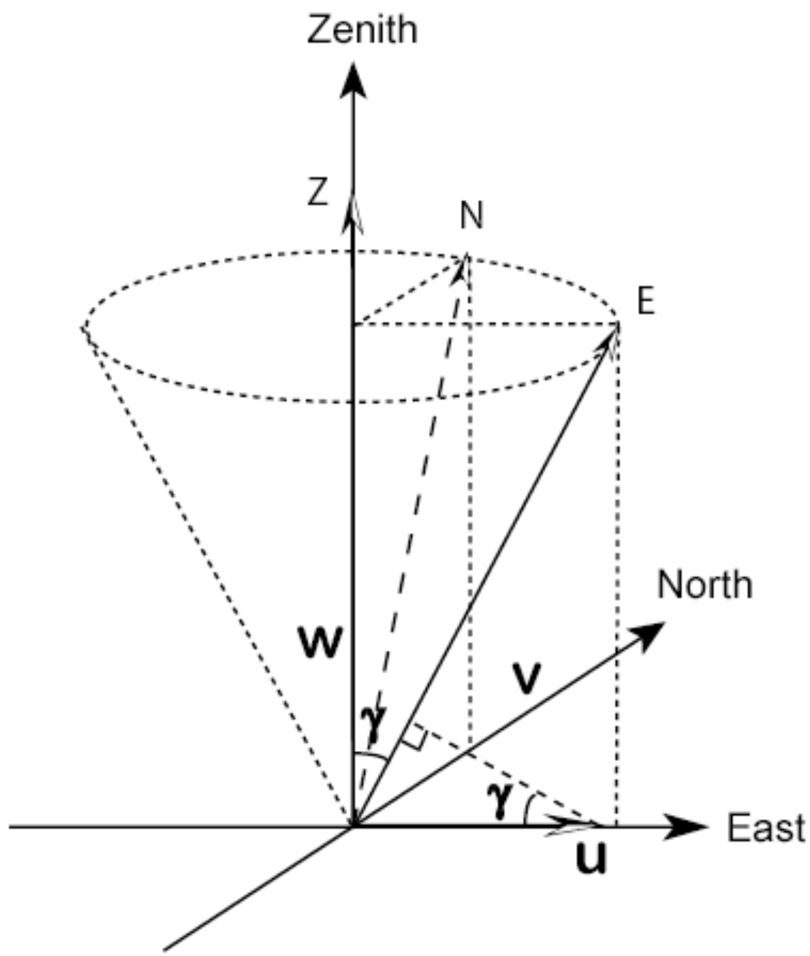


$$V_R = u\sin\theta\cos\varphi + v\cos\theta\cos\varphi + w\sin\varphi$$

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

DBS Techniques for Vector Wind

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



γ is the off-zenith angle

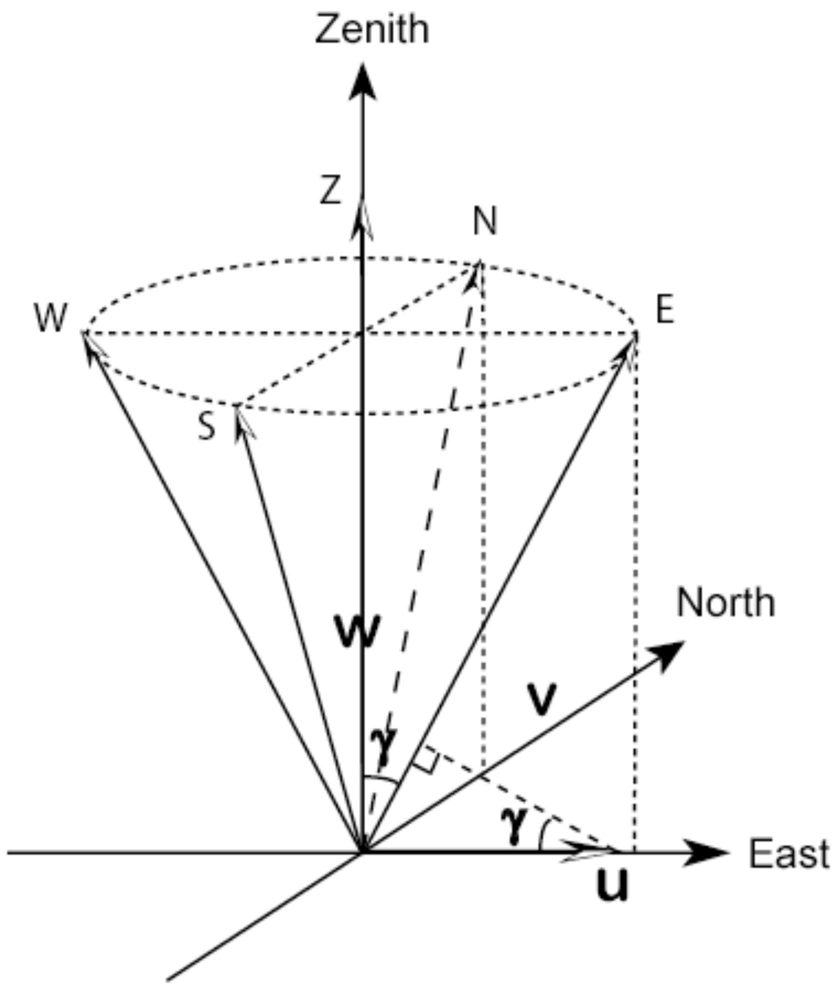
$$V_{RE} = u\sin\gamma + w\cos\gamma$$
$$V_{RN} = v\sin\gamma + w\cos\gamma$$
$$V_{RZ} = w$$

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

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).



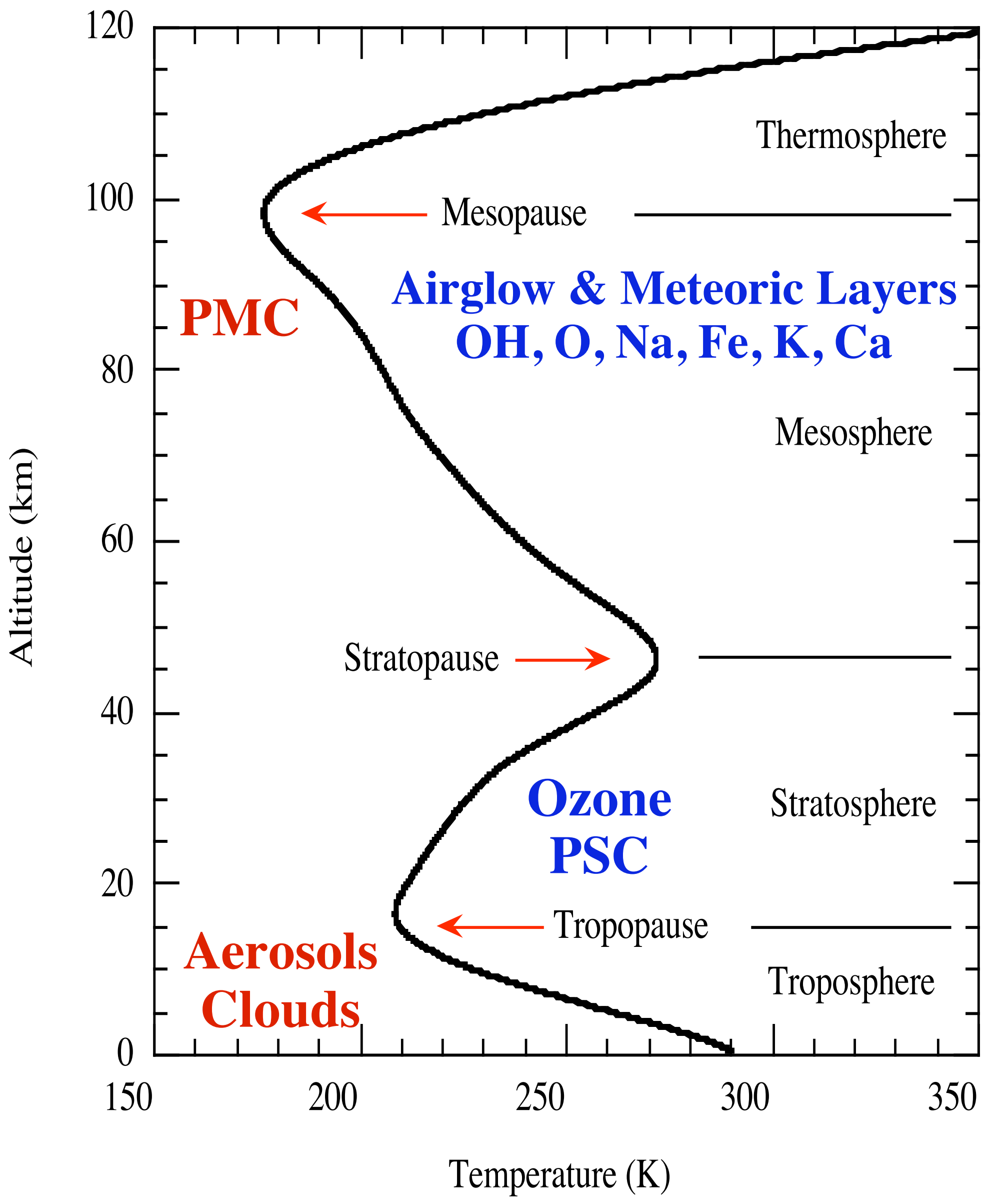
γ is the off-zenith angle

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

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

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

Aerosol Lidar Technique Comparison



- Aerosols in mesosphere (Mesospheric Clouds ~ 85 km): Rayleigh/Mie lidar, resonance fluorescence lidar (detuned)
- Aerosols in upper stratosphere (Polar Stratospheric Clouds ~ 20 km): Rayleigh/Mie lidar, resonance fluorescence lidar
- Aerosols in lower stratosphere and troposphere: Rayleigh/Mie elastic-scattering lidar, Raman scattering lidar, High-Spectral-Resolution Lidar (HSRL)
- White light lidar in the future
- In all altitude range, polarization & multi-wavelength detections help reveal aerosol microphysical properties

HSRL

❑ High-Spectral-Resolution-Lidar (HSRL) is to measure the molecule scattering separately from the aerosol scattering, utilizing the different spectral distribution of the Rayleigh and Mie scattering.

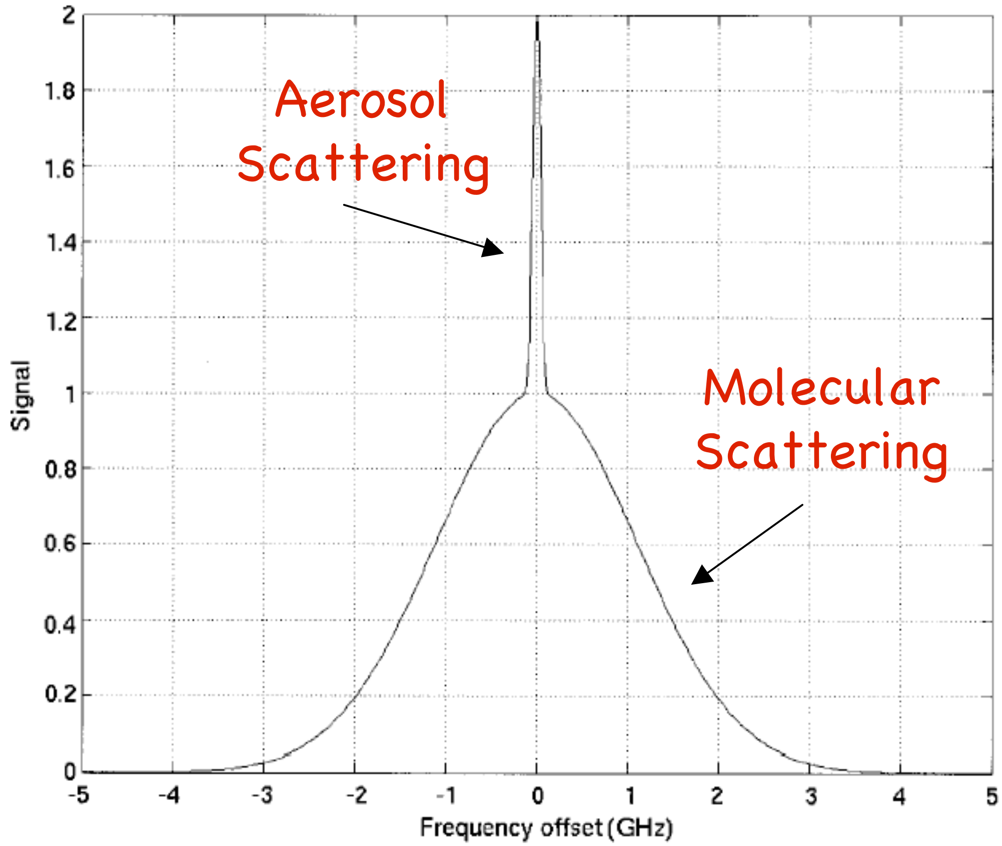
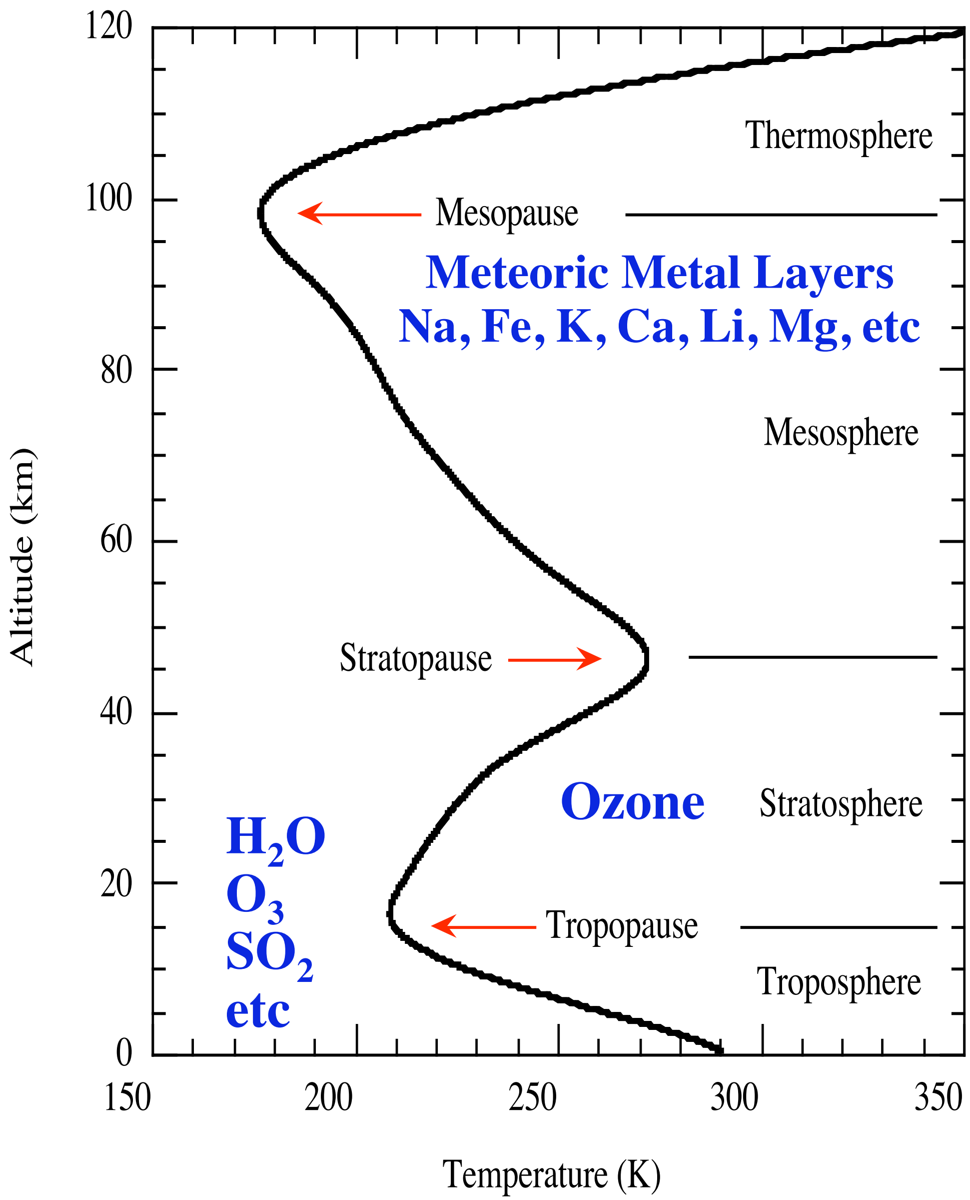


Fig. 5.1. Spectral profile of backscattering from a mixture of molecules and aerosols for a temperature of 300 K. The spectral width of the narrow aerosol return is normally determined by the line width of the transmitting laser.

Constituent Lidar Techniques



- He and N_2^+ in thermosphere: resonance fluorescence lidar
- O in thermosphere: resonance fluorescence lidar or DIAL from space
- Metal atoms in 75-120 km: resonance fluorescence lidar (broadband or narrowband transmitter)
- Molecular species in lower stratosphere & troposphere: Differential absorption lidar (DIAL), Raman scattering lidar, Raman DIAL, RVR Raman DIAL, Multiwavelength DIAL

- The key is to use spectroscopy detection for distinguish species.

Comparison of Constituent Lidar Tech

Technique	Signal Source & Trace Gas		Interests
Resonance Fluorescence Lidar	Resonance fluorescence from metal atoms in middle and upper atmosphere		Temp, Wind, Density, Wave
Resonance Fluorescence Lidar	Resonance fluorescence from He, N_2^+, O in thermosphere		Density, Temp Wind, etc
Conventional DIAL	Elastic-scattering from air molecules and aerosols	Trace gas absorption in the extinction terms	Species, Density
Raman Lidar	Inelastic Raman scattering from trace gas and reference N_2 or O_2 (no aerosol scattering)	Trace gas scattering in the backscatter terms, Trace gas absorption in the extinction terms	Species, Density, Mixing ratio
Raman DIAL	Inelastic Raman scattering from N_2 or O_2	Trace gas absorption in the extinction terms	Species, Density
RVR Raman DIAL	Pure rotational Raman scattering from N_2 and O_2 and Vibrational-Rotational Raman scattering from N_2 or O_2	Trace gas absorption in the extinction terms	Species, Density
Multiwavelength DIAL	Elastic scattering from air molecules and aerosols	Trace gas absorption in the extinction terms	Species, Density

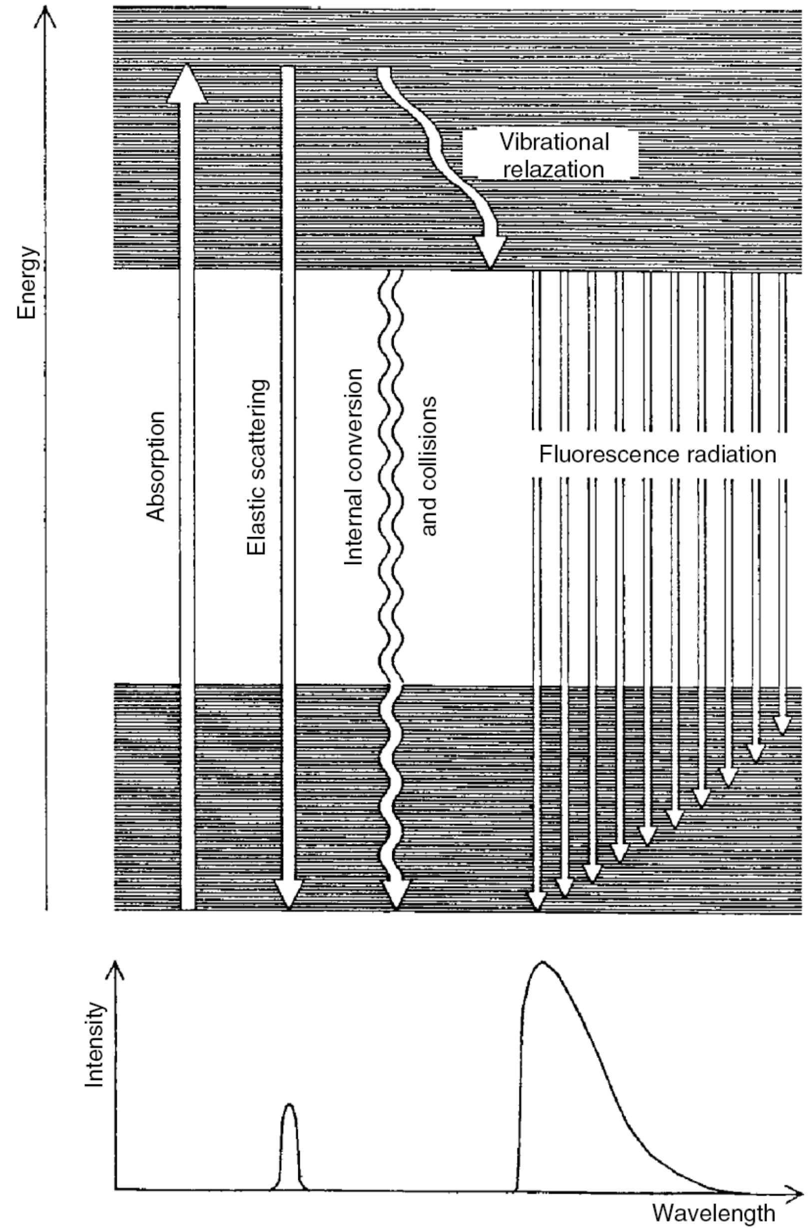
Range-Resolved spatial & temporal distribution of these species, density, temp, wind and waves

Target Lidar Techniques

- Target lidars are an variant of atmospheric lidars. They share some of the same techniques used in atmospheric lidars.
- Target lidars include two main categories: laser-induced-fluorescence lidars, and laser range finders (laser altimeter).
- Fluorescence is used to measure organic materials, plants. Raman scattering by water is used to normalize the lidar returns.
- Laser altimeter and ladar use time-of-flight to determine the range of objects or surface. Many factors are involved.
- Target lidars face some different challenges and difficulties than atmospheric lidars. These challenges and difficulties also determines the growing points in this field.
- Target lidars have been deployed on different platforms for various applications. More efficient and compact target lidars on platforms like UAV, promise more applications.

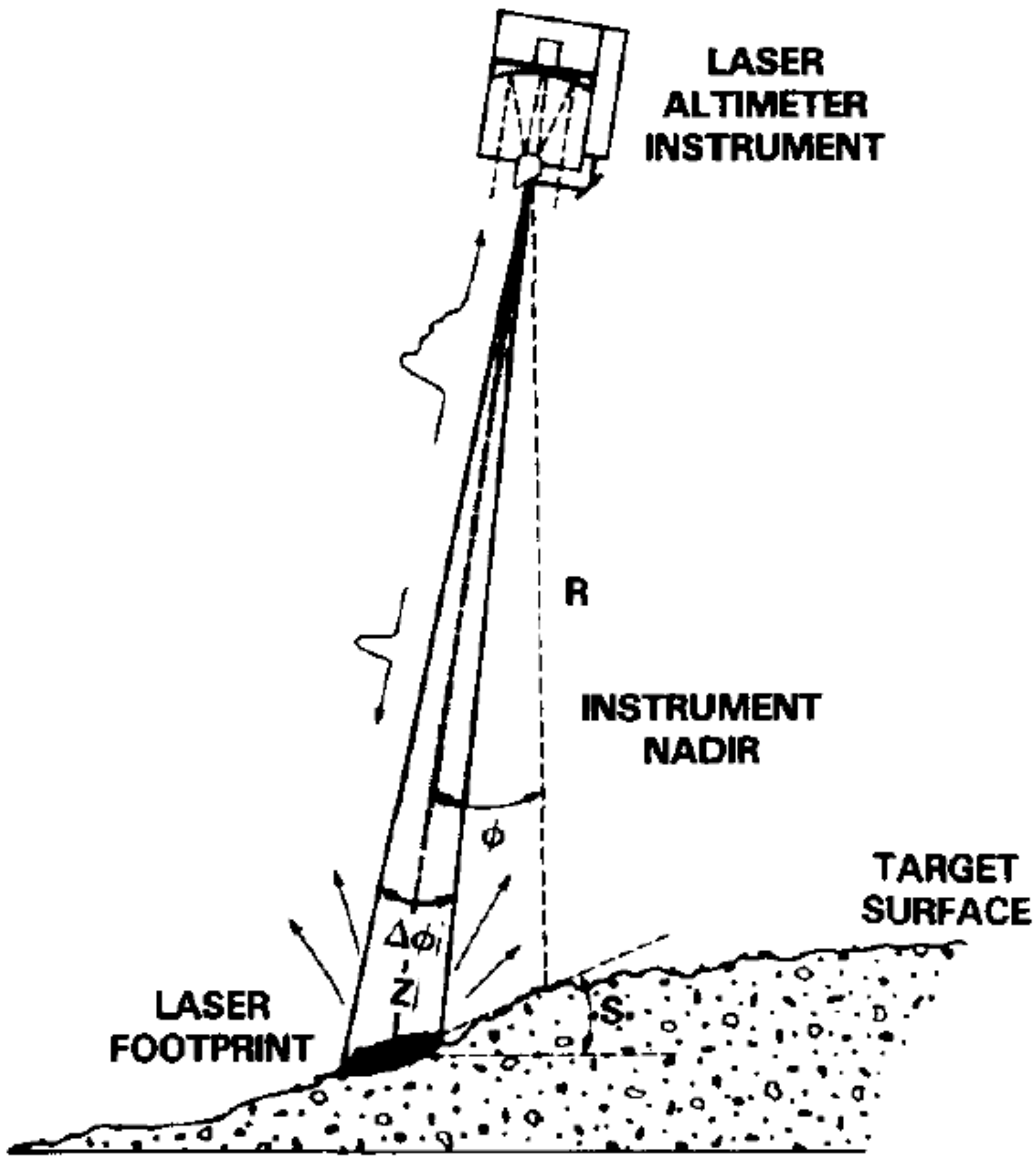
Laser Induced Fluorescence Lidar

- In contrast to free atoms and molecules, solids and liquids exhibit broad absorption and emission spectra because of the strong intermolecular interactions.
- A fixed frequency laser can be used for the excitation due to the broad absorption.
- Following the excitation, there is a very fast (ps) radiationless relaxation down to the lowest sub-level of the excited state, where the molecules remain for a typical excited-state fluorescence lifetime.
- The decay then occurs to different sub-levels of the ground state giving rise to a distribution of fluorescence light, which reflect the lower-state level distribution.
- Fixing the excitation wavelength, we can obtain fluorescence spectra. While fixing the detection channel and varying the excitation wavelength, an excitation spectrum can be recorded.



Laser Altimeter (Laser Ranging)

- The time-of-flight information from a lidar system can be used for laser altimetry from airborne or spaceborne platforms to measure the heights of surfaces with high resolution and accuracy.
- The reflected pulses from the solid surface (earth ground, ice sheet, etc) dominant the return signals, which allow a determination of the time-of-flight to much higher resolution than the pulse duration time.



Lidar Simulation and Error Analysis

- The lidar simulation and error analysis are lidar modeling to integrate complicated lidar remote sensing processes together. The basis is the lidar theory, spectroscopy, and measurement principles.
- Four major goals of lidar simulation and error analysis:

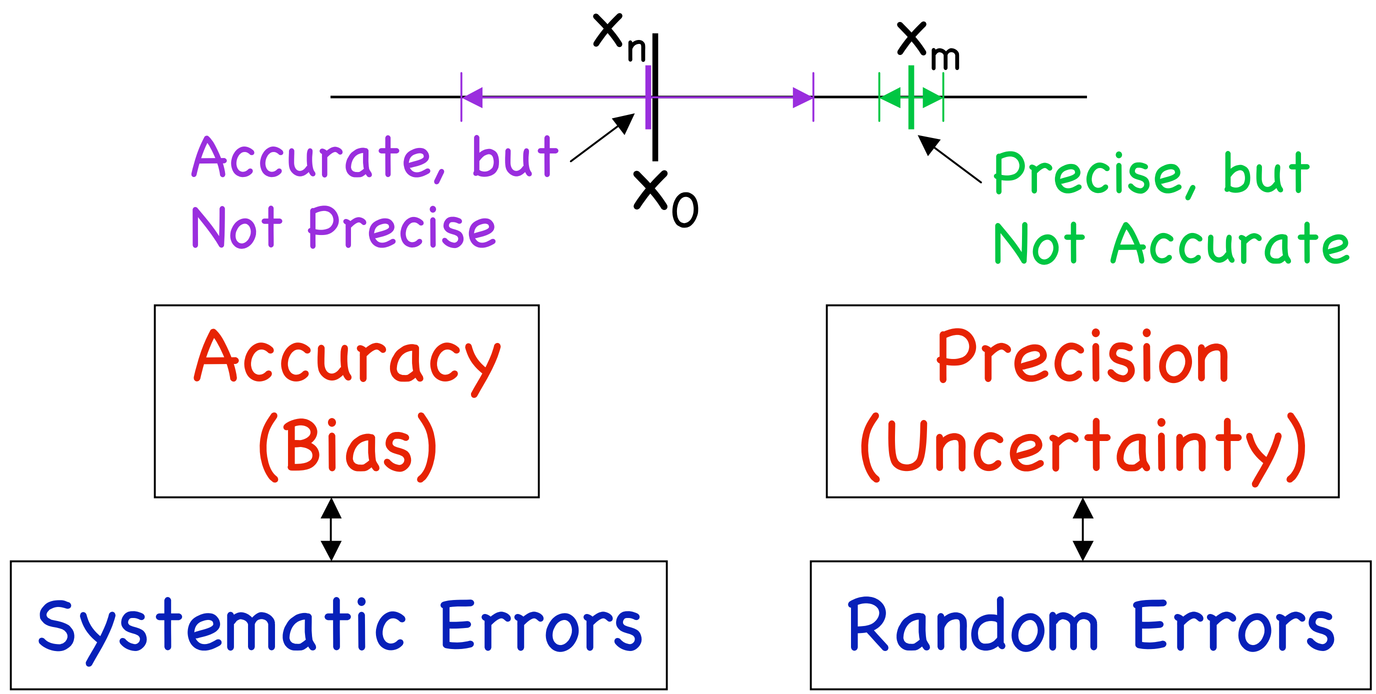
1. Estimate of expected lidar returns (signal level and shape)
2. Analysis of expected measurement precision & resolution, i.e., errors (uncertainty) introduced by photon noise and trade-off among lidar parameters (e.g., off-zenith angle determination)
3. Analysis of expected measurement accuracy & precision (caused by uncertainty in system parameters) and lidar measurement sensitivity to atomic, lidar, and atmospheric parameters
4. Forward model to test data retrieval code and metrics

- Simulation of range-resolved lidar returns should include different scattering processes for all or different altitudes:

(1) Rayleigh scattering for all altitudes
(2) Atomic resonance fluorescence from MLT region
(3) Background for all altitudes
(4) Aerosol and interference gas scattering and absorption (extinction) in the lower atmosphere
(5) Photon noise due to Possion distribution of photon counting

Accuracy versus Precision

- The accuracy of an experiment is a measure of how close the result of the experiment is to the true value.
- The precision is a measure of how well the result has been determined, without reference to its agreement with the true value. The precision is also a measure of the reproducibility of the result in a given experiment.
- Accuracy concerns about bias, i.e., how far away is the measurement result from the true value? Precision concerns about uncertainty, i.e., how certain or how sure are we about the measurement result?



Lidar Error and Sensitivity Analysis

- Systematic errors determine the measurement accuracy, and random errors determine the measurement precision.
- Error sources could be systematic bias or random jitters. Random error sources could lead to both random and systematic measurement errors, e.g., laser central frequency jitter in the 3-freq ratio technique.
- Systematic and random errors will propagate to the measurement errors of temperature and wind. T and W errors can be derived by the use of differentials of the corresponding ratios R_T and R_W.
- Sensitivity Analysis is to answer the question how sensitive the measurement errors depend on lidar, atomic, and atmospheric parameters. Sensitivity analysis helps define the requirements on instruments, and also helps to optimize the instrument and measurement designs.
- Error and sensitivity analyses share the same approaches. One approach is the "differentiation method", and another is the Monte Carlo approach.
- The differentiation of metric ratio method can apply to both systematic and random errors, depending on the nature of the errors.

$$\Delta T = \frac{\partial T}{\partial R_T}\Delta R_T + \frac{\partial T}{\partial f_a}\Delta f_a + \frac{\partial T}{\partial f_c}\Delta f_c + \frac{\partial T}{\partial \sigma_L}\Delta \sigma_L + \frac{\partial T}{\partial \mathrm{v_R}}\Delta \mathrm{v_R}$$

Lidar Design Considerations

- The key of lidar design is the understanding of physical interactions and processes involved, the lidar simulations, and the choices of lidar type, configuration, arrangement, hardware and software to meet the measurement goals (subject, accuracy, precision, resolution, coverage).
- Besides basic architecture, configuration, and arrangement, more considerations should be given to the selection of wavelengths (specific request and solar spectrum intensity), bandwidth of transmitter and receiver (application needs - spectral resolved or not, nighttime-only or full diurnal cycle), laser power/energy, repetition rate, pulse duration time, receiver area, detector efficiency and capability, data acquisition software, and system timing and coordination control. Cost, volume, mass, reliability, etc will also be important when come to reality.
- Learning existing lidar technologies and systems, and understanding their strengths and weakness is the first step to get into the door of lidar field. Be aware of the developments of related technologies (like lasers, spectroscopy, optics, electro-optics, filters, detectors, receivers, etc.) is another key aspect for designing a better lidar system.
- Understanding the applications is also very important.

Summary and Outlook

- Lidar remote sensing is an advanced technology that is not only replacing conventional sensors in science study, environmental research, and industry application, but also creating new methods with unique properties that could not be achieved before.
- Lidar technology has been advanced dramatically in the past 20 years, owing to the new availability of lasers, detectors, creative people involved, and the demanding needs from various aspects.
- Potential growing points at this stage include

(1) Solid-state resonance fluorescence lidar for mobile deployment globally

(2) Extend measurement range into thermosphere and lower mesosphere

(3) Doppler, DIAL, HSRL, and Raman lidar for lower atmosphere research

(4) Target lidar for novel applications

- Always keep eyes open for new potentials: principles, phenomena, effects to be applied in lidar and optical remote sensing.
- The exciting and growing lidar field is anxious for new “blood” - the creative, intelligent, diligent, and passionate young researchers.