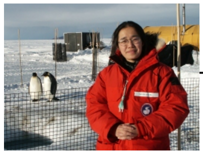


# Lecture 40. Lidar Class Review

- Overview and Clue of Lidar Class
- Concept and Picture of Lidar Remote Sensing
- General Lidar Equation and Basic Assumptions
- Physical Processes Involved in Lidar
- Lidar Equation in Different Forms
- Lidar Architecture
- Altitude and Range Determination
- Lidar Calibration Considerations



# Lidar Class Review

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



# Overview and Clue of Lidar Class

- What have we gone through?
  - Introduction to Remote Sensing (x1) #2
  - Fundamentals of Lidar Remote Sensing (x5) #3-7
  - Lidar Simulations (x2) #8-9
  - Lidar Data Inversion (x3) #17-18 and #29
  - Topical Lidars:
    - Overview (x1) #10
    - Temperature Lidar (x6) #11-16
    - Constituent Lidar (x4) #19-22
    - Wind Lidar (x6) #23-26 and #30-31
    - Aerosol/Cloud Lidar (x3) #27-28 and #34
    - Fluorescence Lidar (x1) #32
    - Laser Rangefinder (x4) #33, #35-37
  - Lidar Error Analysis (x2) #9 and #38
  - Lidar Architecture and Lidar Design (x1) #39
  - Lidar Class Review (x1) #40



# Overview and Clue of Lidar Class

- What are my expectations?

➢ To give you a full and complete picture of lidar remote sensing, including fundamental lidar principles and how lidars are connected to the fundamental physical processes, spectroscopy, and laser, optical, electronic, and computing technologies.

➢ All are based on the lidar fundamentals, especially the physical processed involved in the remote sensing procedure.

➢ I hope you have gained a clear picture and good concepts of lidar principles and technologies through this class, and then you will work out details through your lidar class projects and actual research work.

- What are for the future?

➢ Lidar is a very active research field. As new technologies and principles become available, many new lidars are being built and many new applications of lidars are being found. Therefore, we do not aim to cover all lidars in this class, but aim to help you to build a solid foundation in the lidar field so that you can go out to do research in any chosen lidar or remote sensing fields. You will apply the knowledge you learned from this class and make innovations and advancements through your work.



# Concept of Remote Sensing

- Remote Sensing is the science and technology of obtaining information about an object without having the sensor in direct physical-contact with the object.
- The nature of remote sensing is one kind of measurements, i.e., to obtain or acquire information of an object through experimental methods.
- There must be some interaction between the object and the instruments in order to acquire the information of the object. The interaction can be direct (local) or remote.
- For remote sensing, remote interaction must be introduced to carry away the object information so that the information can be acquired by the sensor remotely.
- The interaction between radiation and the object is the most common interaction used in modern remote sensing. The radiation includes electromagnetic radiation and acoustic waves.

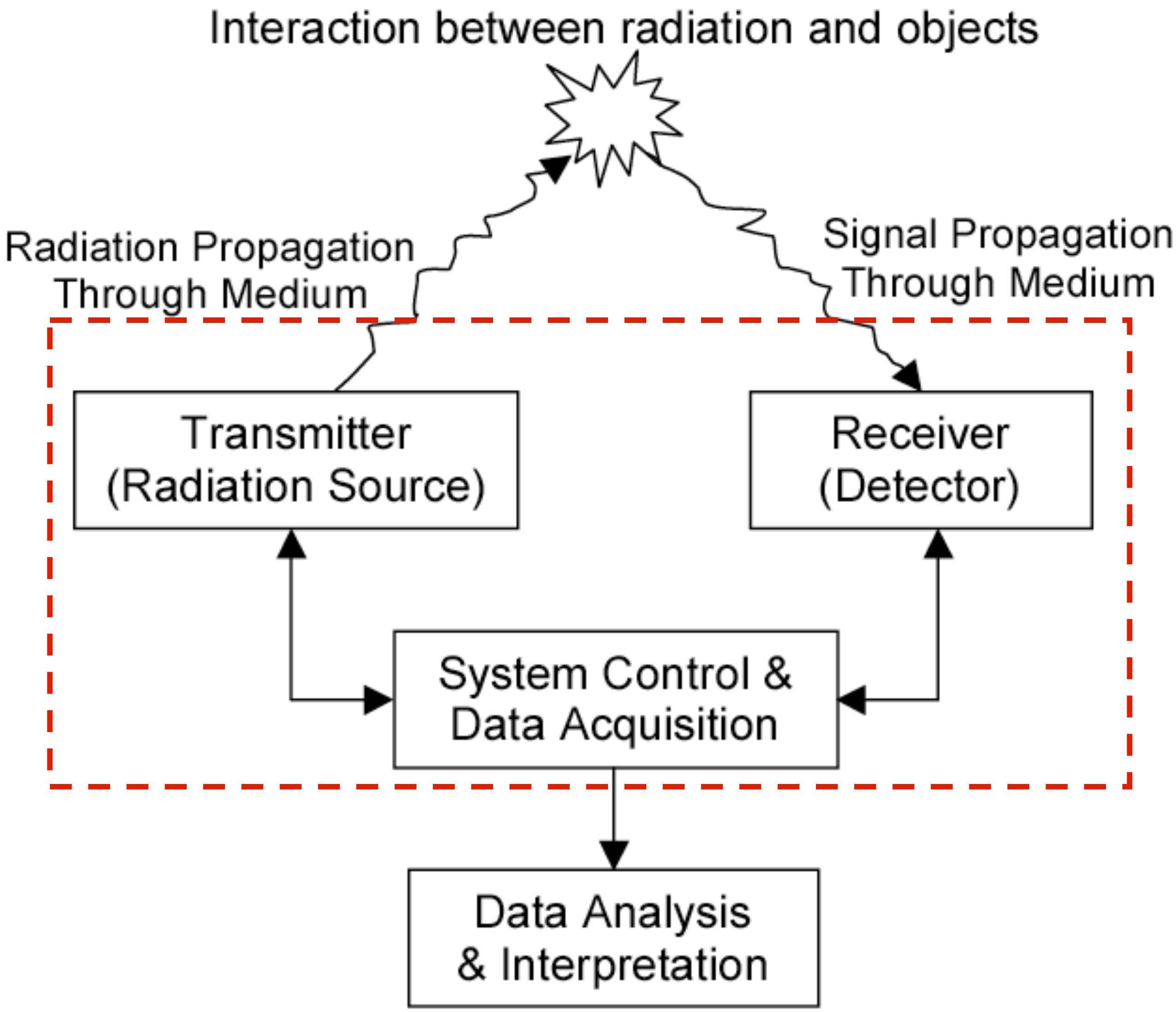


# Concept of Lidar Remote Sensing

- Remote sensing can be classified to passive and active remote sensing in optical, radio, and acoustic frequency ranges.
- LIDAR, RADAR, and SODAR are three main active remote sensing technologies, sharing similar principles.
- LIDAR stands for Light Detection And Ranging.

  \- a laser radar in optical frequency range.
- Lidar started in the pre-laser times in 1930s with searchlight, and then quickly evolved to modern lidars using ns laser pulses.
- Due to its unique feature and advanced laser spectroscopy and technology, lidar provides much higher accuracy, precision, and resolution in measurements of atmosphere and environmental parameters as well as targets and objects, than many other remote sensing approaches.

# Physical Picture in LIDAR Remote Sensing





# General Lidar Equation

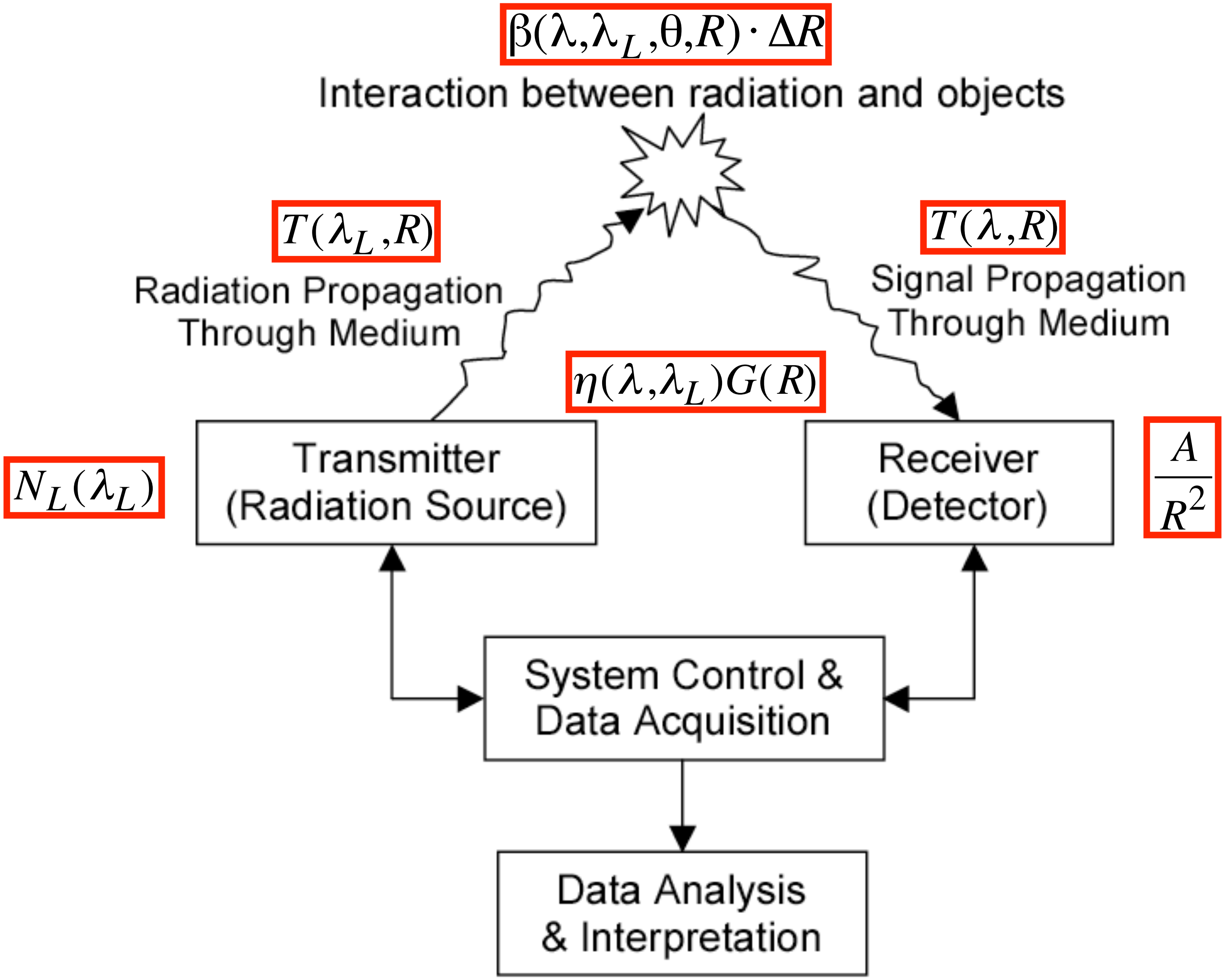
- Lidar equation is the fundamental equation in lidar remote sensing field to relate the received photon counts (or light power) to the transmitted laser photon numbers (or laser power), the light transmission in atmosphere or medium, the physical interaction between light and objects, the photon receiving probability, and the lidar system efficiency and geometry, etc.

# Basic Assumptions for Lidar Equation

## Independent scattering & Single scattering

- Independent scattering: particles are separated adequately and undergo random motion so that the contribution to the total scattered energy by many particles have no phase correlation. Thus, the total intensity is simply a sum of the intensity scattered from each particle.
- Single scattering: a photon is scattered only once. Multiple scatter is excluded in most of our considerations.

# Physical Picture for Lidar Equation





# General Form of Lidar Equation

$$N_S(\lambda,R) = N_L(\lambda_L)\cdot\left[\beta(\lambda,\lambda_L,\theta,R)\Delta R\right]\cdot\frac{A}{R^2}\cdot\left[T(\lambda_L,R)T(\lambda,R)\right]\cdot\left[\eta(\lambda,\lambda_L)G(R)\right]+N_B$$

$$P_S(\lambda,R) = P_L(\lambda_L)\cdot\left[\beta(\lambda,\lambda_L,\theta,R)\Delta R\right]\cdot\frac{A}{R^2}\cdot\left[T(\lambda_L,R)T(\lambda,R)\right]\cdot\left[\eta(\lambda,\lambda_L)G(R)\right]+P_B$$

# General Lidar Equation in β and α

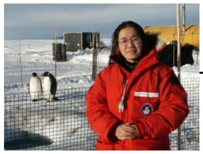
$$N_S(\lambda,R) = \left[\frac{P_L(\lambda_L)\Delta t}{hc/\lambda_L}\right]\cdot\left[\beta(\lambda,\lambda_L,R)\Delta R\right]\cdot\left(\frac{A}{R^2}\right)$$
$$\cdot\exp\left[-\int_0^R \alpha(\lambda_L,r')dr'\right]\cdot\exp\left[-\int_0^R \alpha(\lambda,r')dr'\right]\cdot\left[\eta(\lambda,\lambda_L)G(R)\right]+N_B$$

Volume scatter coefficient

$$\beta(\lambda,\lambda_L,R) = \sum_i\left[\frac{d\sigma_i(\lambda_L)}{d\Omega}n_i(R)p_i(\lambda)\right]$$

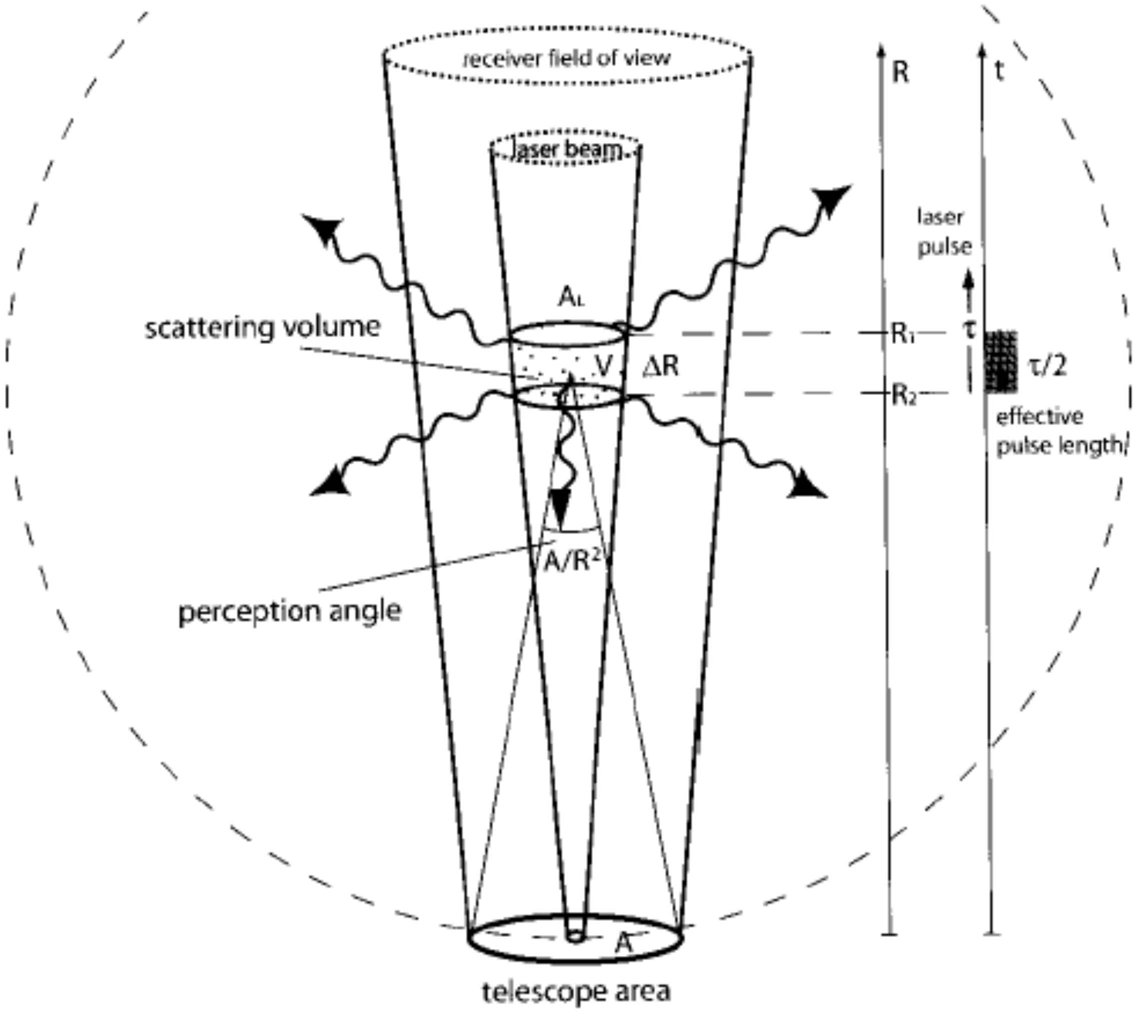
Transmission

$$T(\lambda_L,R)T(\lambda,R) = \exp\left[-\left(\int_0^R \alpha(\lambda_L,r)dr + \int_0^R \alpha(\lambda,r)dr\right)\right]$$





# Illustration for LIDAR Equation




-- Courtesy of Ulla Wandinger [Introduction to Lidar]

# Physical Processes in LIDAR

- Interaction between light and objects

(1) Scattering (instantaneous elastic & inelastic):

Mie, Rayleigh, Raman, Brillouin scattering

(2) Absorption and differential absorption

(3) Laser induced fluorescence

(4) Resonance fluorescence

(5) Doppler shift and Doppler broadening

(6) Boltzmann distribution

(7) Reflection from target or surface

- Light propagation in atmosphere or medium: transmission vs extinction

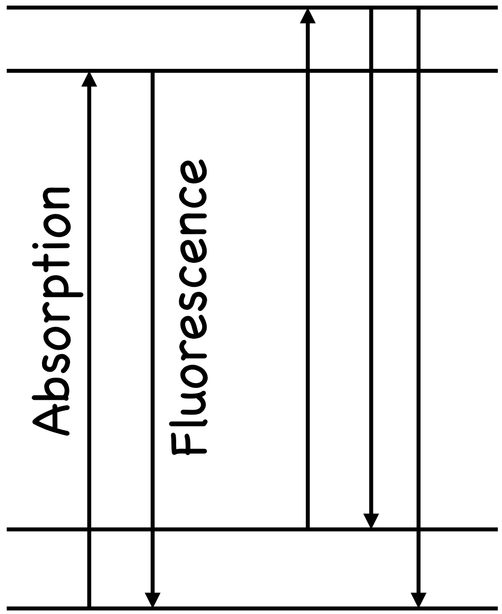
Extinction = Scattering + Absorption

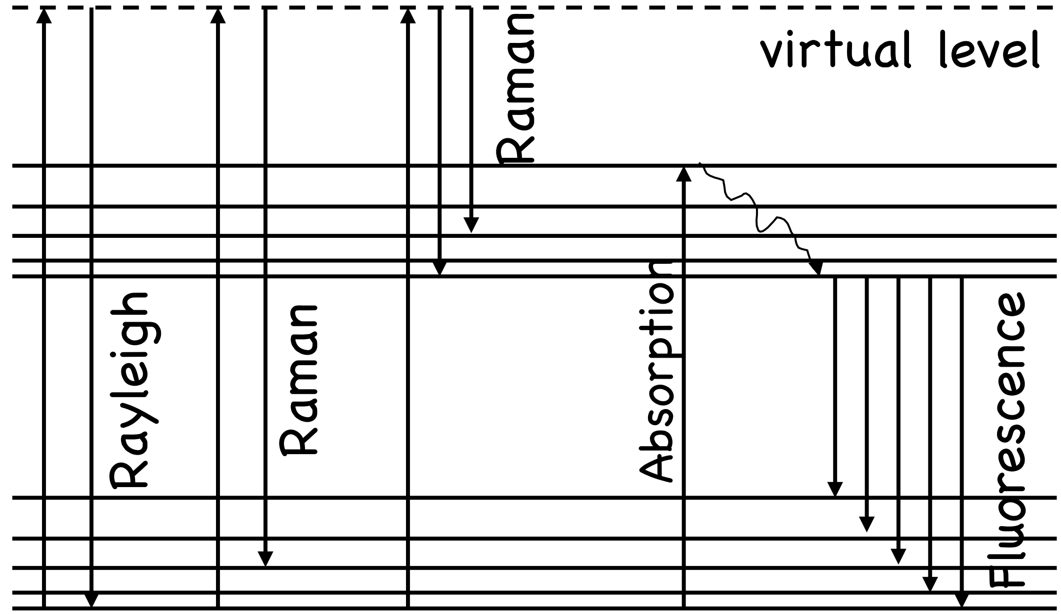
$$T(\lambda, R) = \exp\left[-\int_0^R \alpha(\lambda, r)\,dr\right]$$

$$\alpha(\lambda, R) = \sum_i \left[\sigma_{i,ext}(\lambda) n_i(R)\right]$$



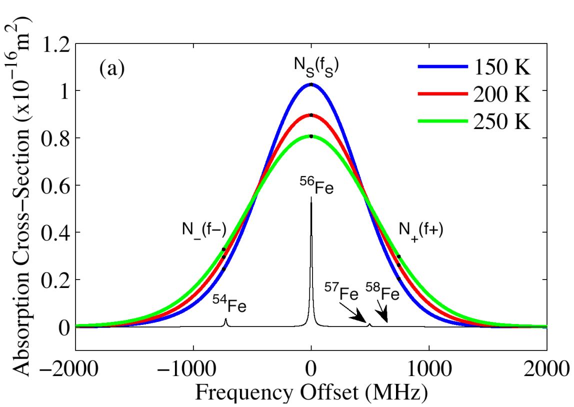
# Elastic and Inelastic Scattering

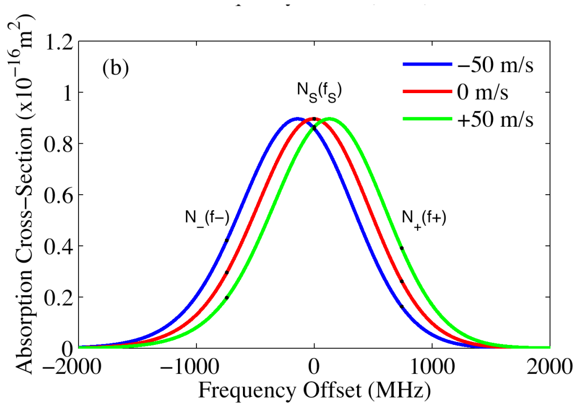


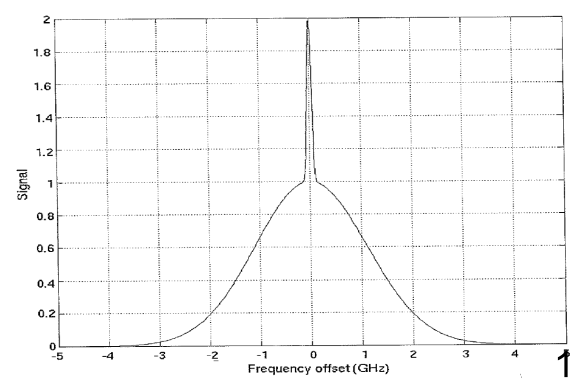




Atomic absorption & (resonance) fluorescence

Molecular elastic and inelastic scattering, absorption and fluorescence



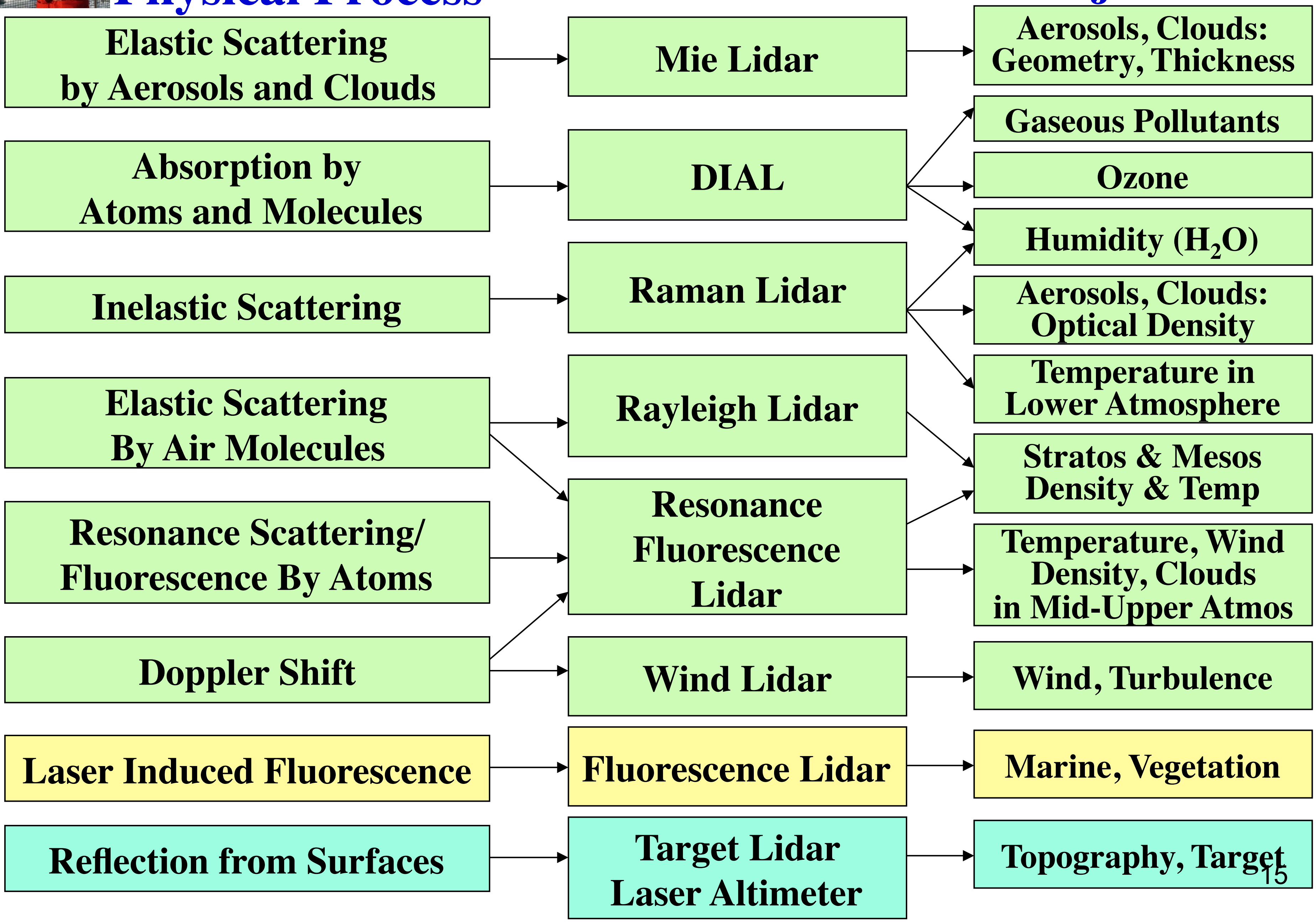


# Backscatter Cross-Section Comparison

| **Physical Process** | **Backscatter Cross-Section** | **Mechanism** |
|---|---|---|
| Mie (Aerosol) Scattering | $10^{-8}$ - $10^{-10}$ $cm^2sr^{-1}$ | Two-photon process<br>Elastic scattering, instantaneous |
| Atomic Absorption and Resonance Fluorescence | $10^{-13}$ $cm^2sr^{-1}$ | Two single-photon process (absorption and spontaneous emission)<br>Delayed (radiative lifetime) |
| Molecular Absorption | $10^{-19}$ $cm^2sr^{-1}$ | Single-photon process |
| Fluorescence From Molecule, Liquid, Solid | $10^{-19}$ $cm^2sr^{-1}$ | Two single-photon process<br>Inelastic scattering, delayed (lifetime) |
| Rayleigh Scattering<br>(Wavelength Dependent) | $10^{-27}$ $cm^2sr^{-1}$ | Two-photon process<br>Elastic scattering, instantaneous |
| Raman Scattering<br>(Wavelength Dependent) | $10^{-30}$ $cm^2sr^{-1}$ | Two-photon process<br>Inelastic scattering, instantaneous |



**Physical Process** **Device** **Objective**





# Scattering Form of Lidar Equation

- Rayleigh, Mie, and Raman scattering processes are instantaneous scattering processes, so there are no finite relaxation effects involved, but infinitely short duration.
- For Rayleigh and Mie scattering, there is no frequency shift when the atmospheric particles are at rest, so

$$N_S(\lambda,R)=\left(\frac{P_L(\lambda)\Delta t}{hc/\lambda}\right)\left(\beta(\lambda,R)\Delta R\right)\left(\frac{A}{R^2}\right)T^2(\lambda,R)\left(\eta(\lambda)G(R)\right)+N_B$$

- For Raman scattering, there is large frequency shift, so

$$N_S(\lambda,R)=\left(\frac{P_L(\lambda_L)\Delta t}{hc/\lambda_L}\right)\left(\beta(\lambda,\lambda_L,R)\Delta z\right)\left(\frac{A}{R^2}\right)\left(T(\lambda_L,R)T(\lambda,R)\right)\left(\eta(\lambda,\lambda_L)G(R)\right)+N_B$$

where $\lambda \neq \lambda_L, \quad p_i(\lambda)\neq 1, \quad p_i(\lambda)<1$

$$T(\lambda_L,R)T(\lambda,R)=\exp\left\{-\int_0^R\left[\alpha(\lambda_L,r)+\alpha(\lambda,r)\right]dr\right\}$$



# Fluorescence Form of Lidar Equation

- Resonance fluorescence and laser-induced-fluorescence are NOT instantaneous processes, but have delays due to the radiative lifetime of the excited states.

$$N_S(\lambda,R) = \left(\frac{P_L(\lambda)\Delta t}{hc/\lambda}\right)\left(\sigma_{eff}(\lambda,R)n_c(z)R_B(\lambda)\Delta R\right)\left(\frac{A}{4\pi R^2}\right)\left(T_a^2(\lambda,R)T_c^2(\lambda,R)\right)\left(\eta(\lambda)G(R)\right) + N_B$$

- Here, $T_c(R)$ is the transmission caused by the constituent extinction.

$$T_c(R) = \exp\left(-\int_{R_{bottom}}^{R} \sigma_{eff}(\lambda,r')n_c(r')\,\mathrm{d}r'\right) = \exp\left(-\int_{R_{bottom}}^{R} \alpha_c(\lambda,r')\,\mathrm{d}r'\right)$$

- Here, $\alpha(\lambda,R)$ is the extinction coefficient mainly caused by the constituent absorption.

$$\alpha_c(\lambda,R) = \sigma_{eff}(\lambda,R)n_c(R)$$



# Differential Absorption/Scattering Form

- For the laser with wavelength $\lambda_{on}$ on the molecular absorption line

$$N_S(\lambda_{on},R) = N_L(\lambda_{on})\left[\beta_{scatter}(\lambda_{on},R)\Delta R\right]\left(\frac{A}{R^2}\right)\exp\left[-2\int_0^z \overline{\alpha}(\lambda_{on},r')dr'\right]$$
$$\times \exp\left[-2\int_0^z \sigma_{abs}(\lambda_{on},r')n_c(r')dr'\right]\left[\eta(\lambda_{on})G(R)\right] + N_B$$

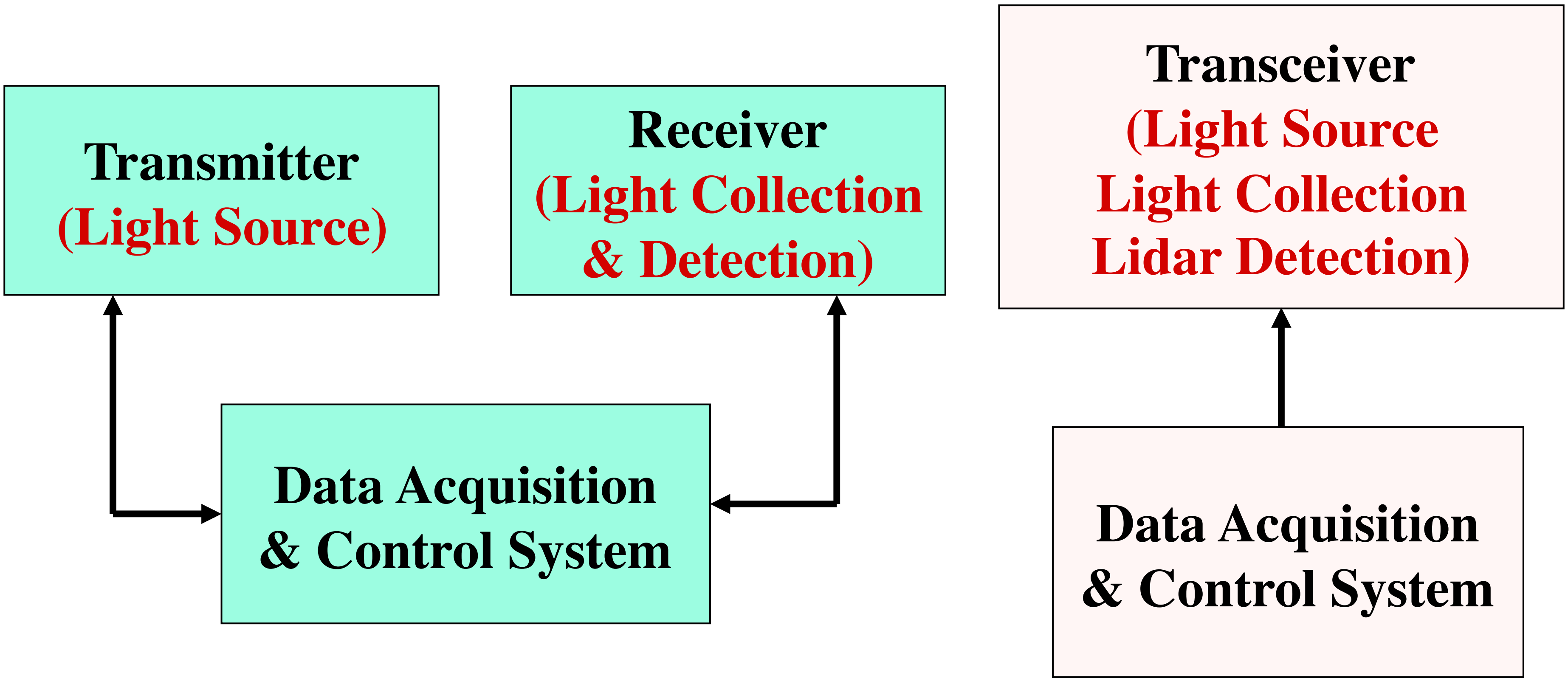
- For the laser with wavelength $\lambda_{off}$ off the molecular absorption line

$$N_S(\lambda_{off},R) = N_L(\lambda_{off})\left[\beta_{scatter}(\lambda_{off},R)\Delta R\right]\left(\frac{A}{R^2}\right)\exp\left[-2\int_0^z \overline{\alpha}(\lambda_{off},r')dr'\right]$$
$$\times \exp\left[-2\int_0^z \sigma_{abs}(\lambda_{off},r')n_c(r')dr'\right]\left[\eta(\lambda_{off})G(R)\right] + N_B$$

- Differential absorption cross-section

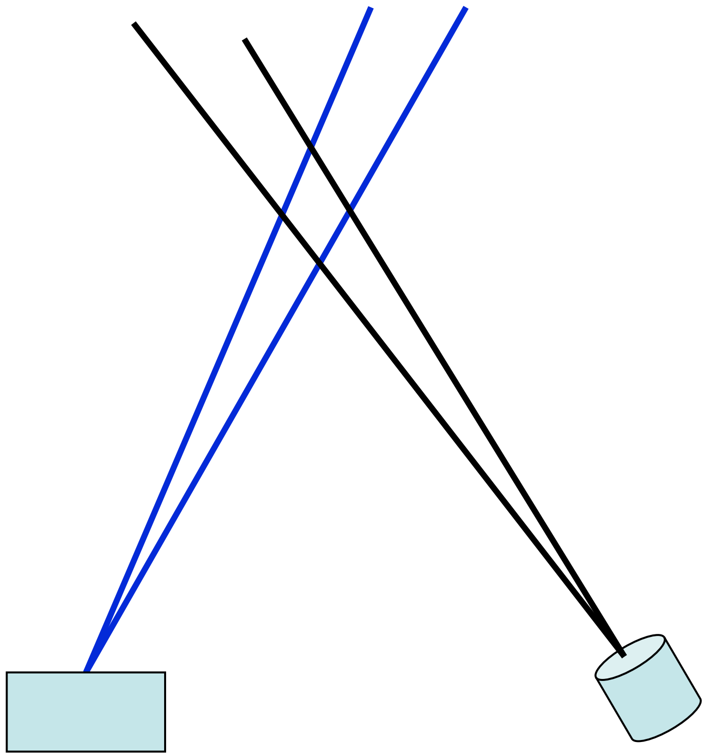
$$\Delta\sigma_{abs}(R) = \sigma_{abs}(\lambda_{ON},R) - \sigma_{abs}(\lambda_{OFF},R)$$

# Basic Architecture of LIDAR



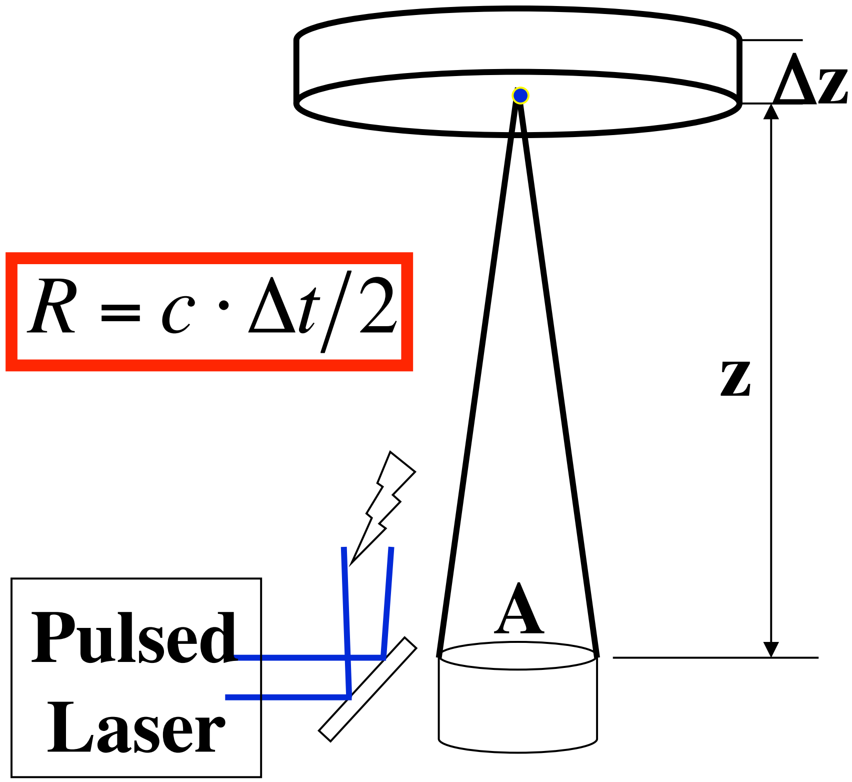


# Basic Configurations of LIDAR Bistatic and Monostatic




**Bistatic Configuration**

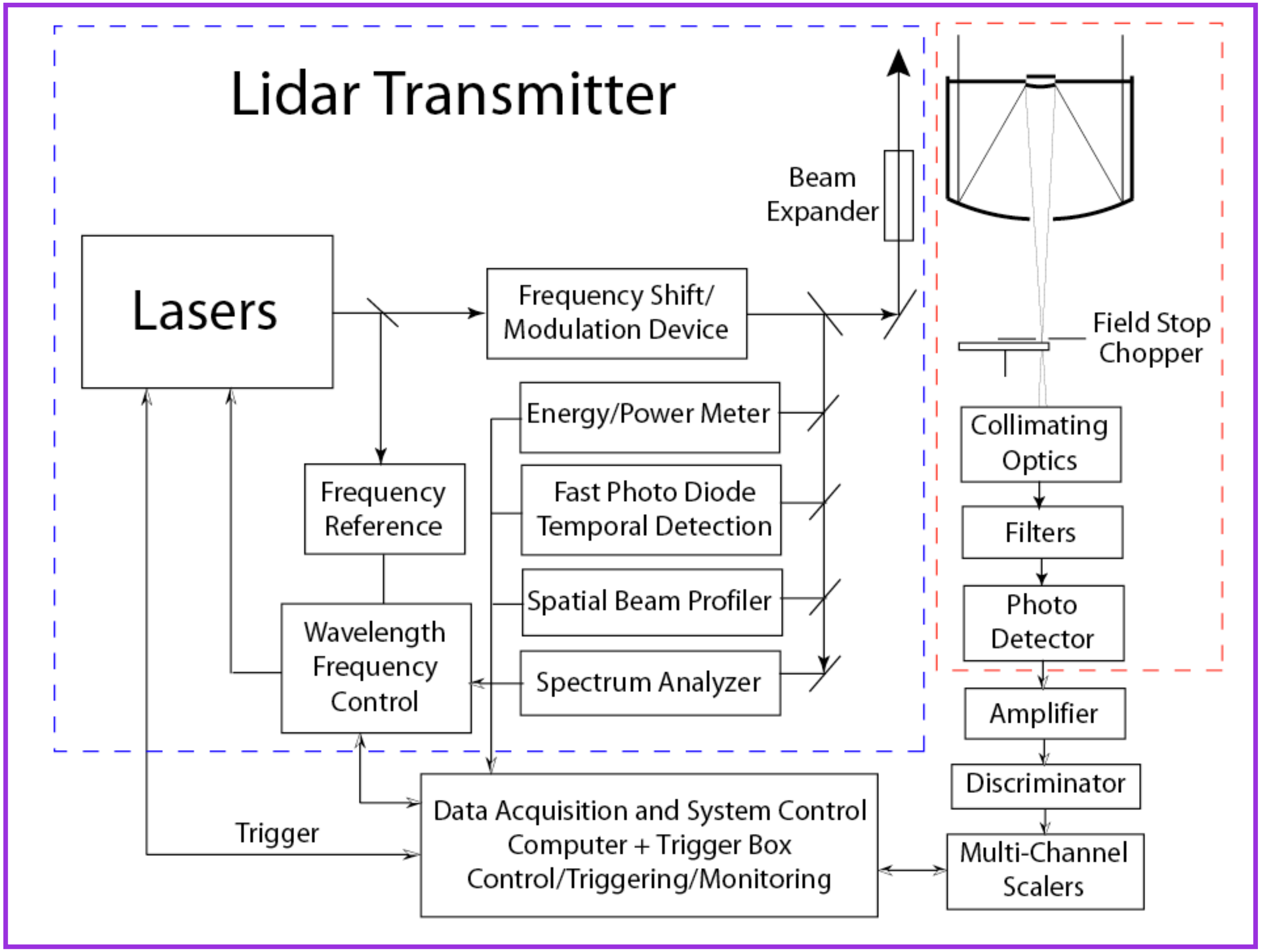
$$R = c \cdot \Delta t / 2$$



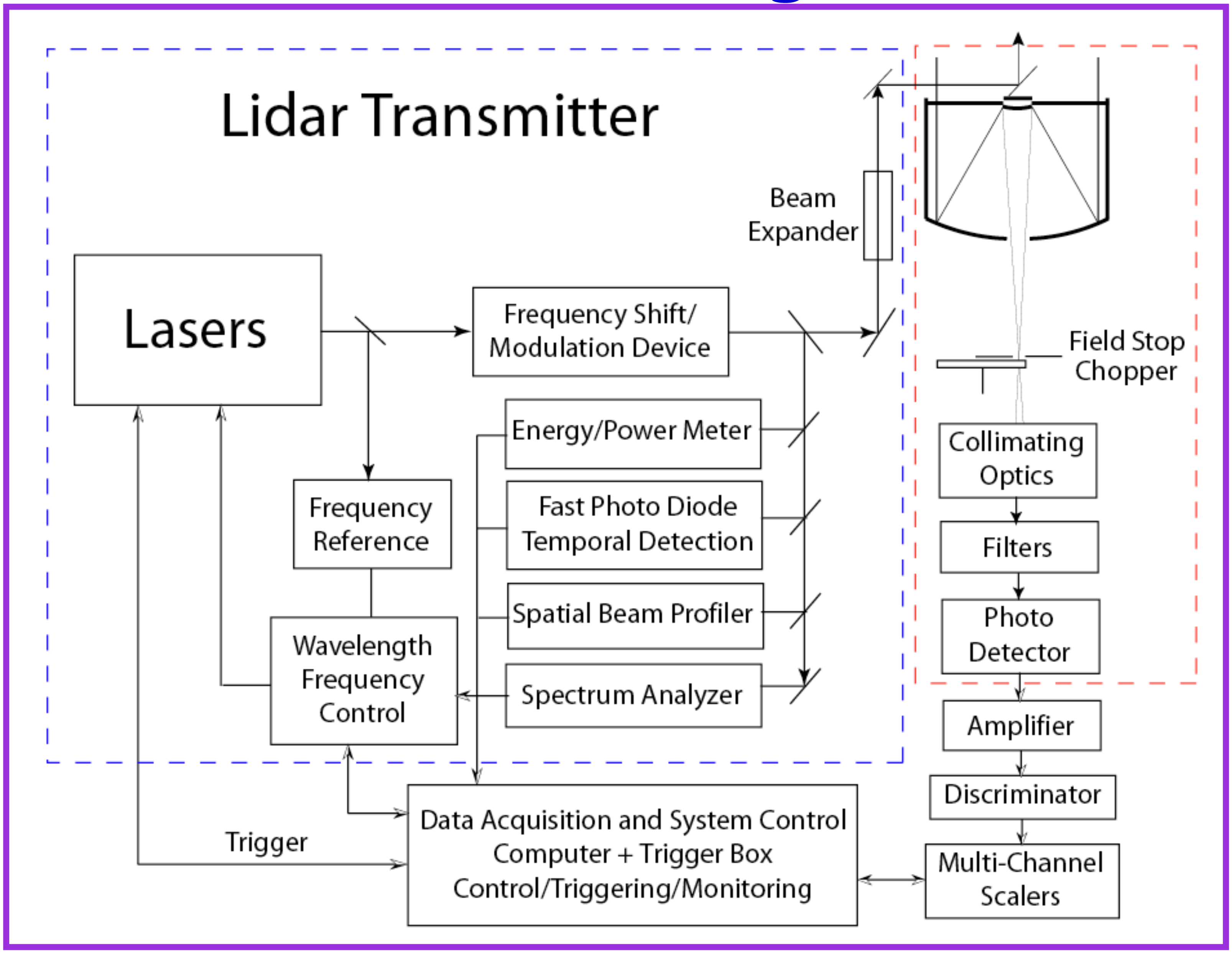

**Monostatic Configuration**



# Biaxial Arrangement



# Coaxial Arrangement

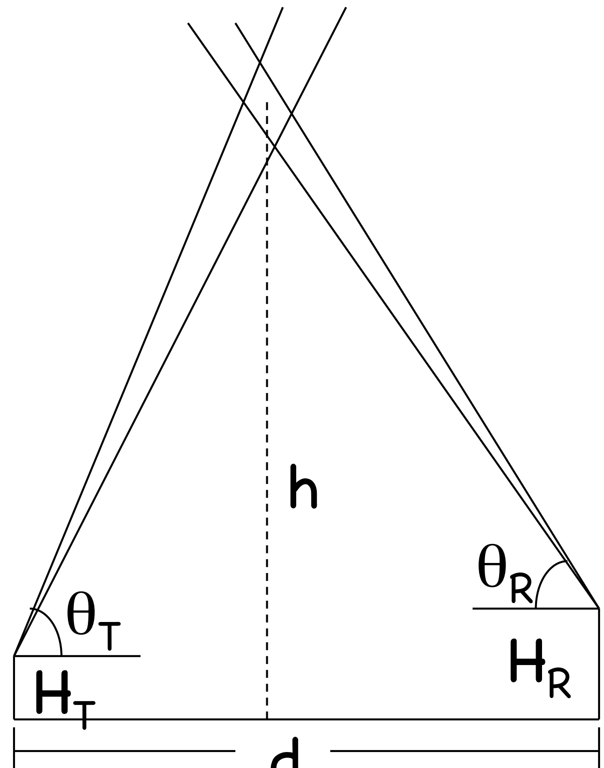




# Altitude Determination from Geometry

- Bistatic configuration involves a considerable separation of the transmitter and receiver to achieve spatial resolution in optical probing study.
- It originated from CW searchlight, and modulation was used to improve SNR.
- The range information is determined from geometry configuration, rather than the time-of-flight.

$$h = \frac{d \cdot \tan(\theta_T) \cdot \tan(\theta_R) + H_T \cdot \tan(\theta_R) + H_R \cdot \tan(\theta_T)}{\tan(\theta_T) + \tan(\theta_R)}$$



# Range Determination from TOF

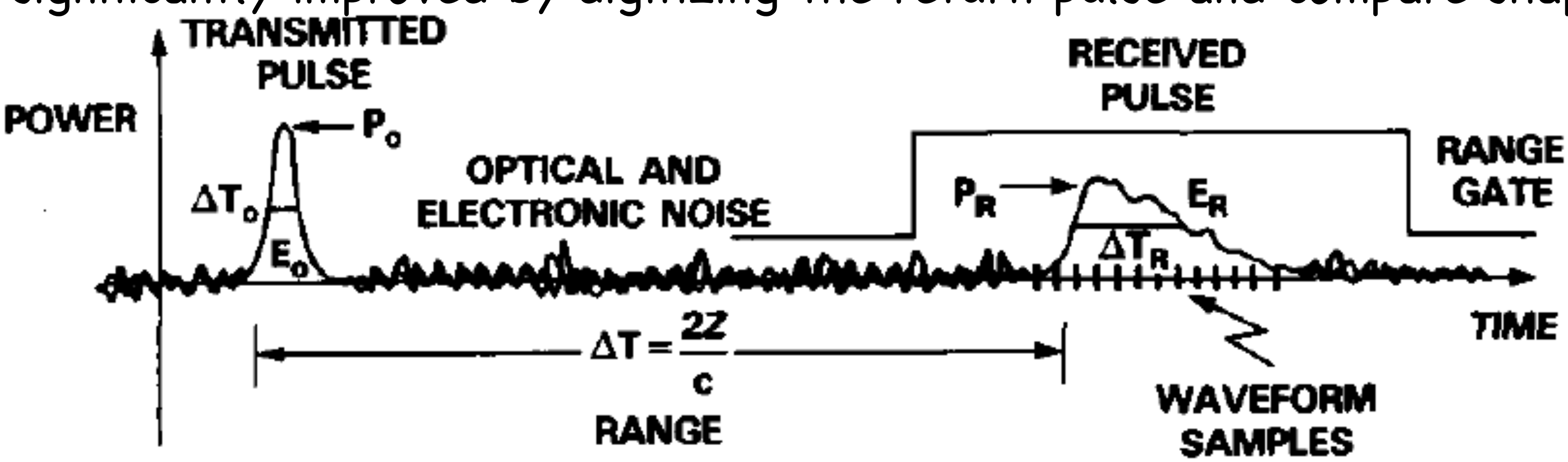
- For nanosecond pulsed-laser lidar, the range is determined by the time of flight of the photons propagating from lidar transmitter to the objects and returning to the lidar receiver.

- For atmospheric (scattering) lidar, the ultimate resolution is limited by the pulse duration time, as atmospheric scatters are distributed sources.

$$R = c \cdot t/2 \qquad \Delta R = c \cdot \Delta t/2$$

$\Delta t$ is pulse width

- For target lidar (e.g., laser altimeter), the distinct peak due to the strong reflection of light from surface or target, the range resolution can be significantly improved by digitizing the return pulse and compare shape.




Altitude = Platform Base Altitude - Range ± Interference of aerosols and clouds



# Lidar Calibration

- Understanding your lidar system and entire procedure is the key for all cases of lidar calibration, especially when we try to push technology or measurement envelope, because existing instruments have not been able to achieve what you design to achieve. You must fully understand every possible interaction or process involved, and do a thorough analysis on all possible measurement errors (accuracy, precision, resolution, and stability). A self-calibration must be made before cross-calibrations with others.
- In all cases, try to find any possible existing measurements (even not as accurate or high-resolution as yours) and theoretical/model predictions, and then compare your measurements with them to figure out the similarity and differences. Analyze why so.
- Try to operate your lidars with an existing lidar or lidars or other instruments simultaneously and in common-volume, and then compare the measurement results. Be aware of the limitation of each instrument.

# More Considerations

- Before the full system calibration, you may want to calibrate each individual pieces, e.g., PMT, filter, laser, etc. Is your PMT or APD saturated? How is your filter function like and is it stable? How is your laser lineshape like and is it stable? Is there any component in your lidar having day-to-day variability?
- Design your measurements so that you can have some internal calibration or at least do some reality check. For example, temperature profile is usually stable but wind is highly variable. Simultaneous temperature and wind measurements can help determine whether the measurements make sense. If possible, compare with some in-situ measurements.
- Make sure your lidar system and data processing are human-error-free!
- For spaceborne or airborne lidars, it is necessary to set up some ground-based calibration points. Flight over-passes some ground-based lidar stations for simultaneous and common-volume measurements or over-pass some known objects for altimeter calibration.

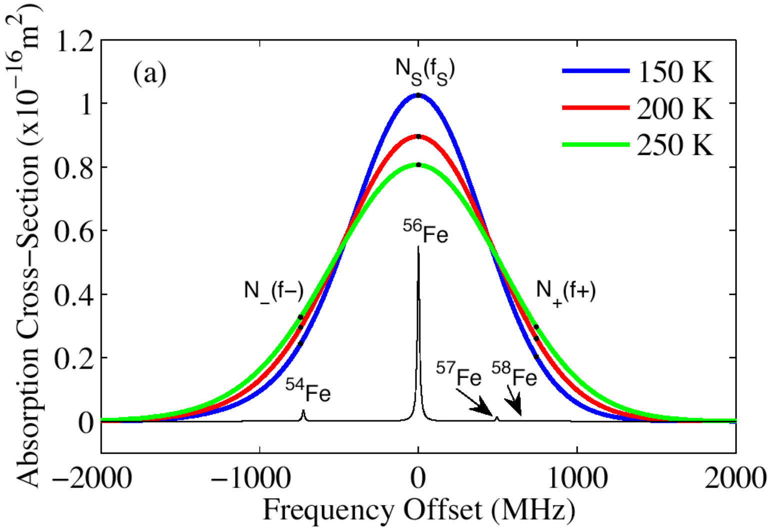


# Temperature Lidar Techniques

- 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)

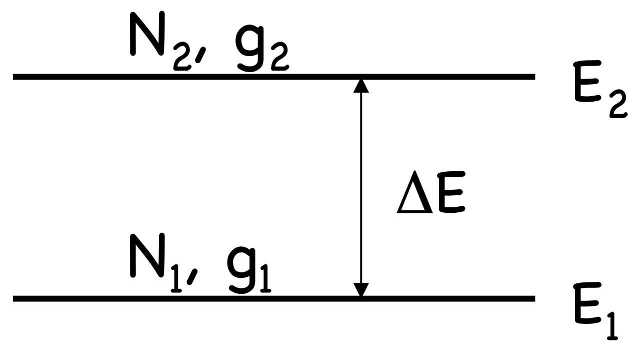
# Doppler & Boltzmann Techniques

- 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.




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

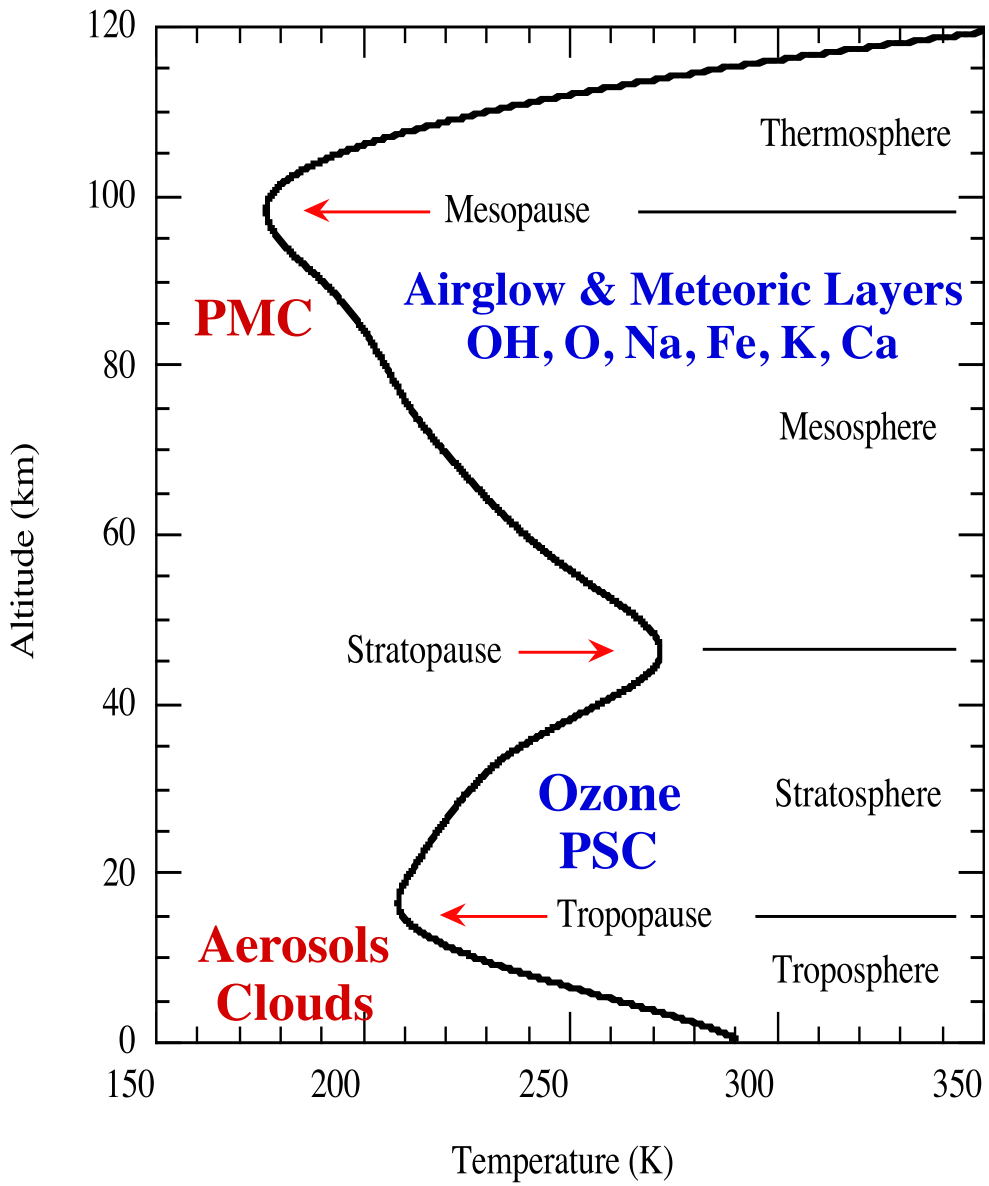
$$\sigma_{rms} = \frac{\omega_0}{c}\sqrt{\frac{k_B T}{M}} = \frac{1}{\lambda_0}\sqrt{\frac{k_B T}{M}}$$




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

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

# 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)<br>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)<br>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 $\Delta\omega = -2\vec{k} \cdot \vec{v}$

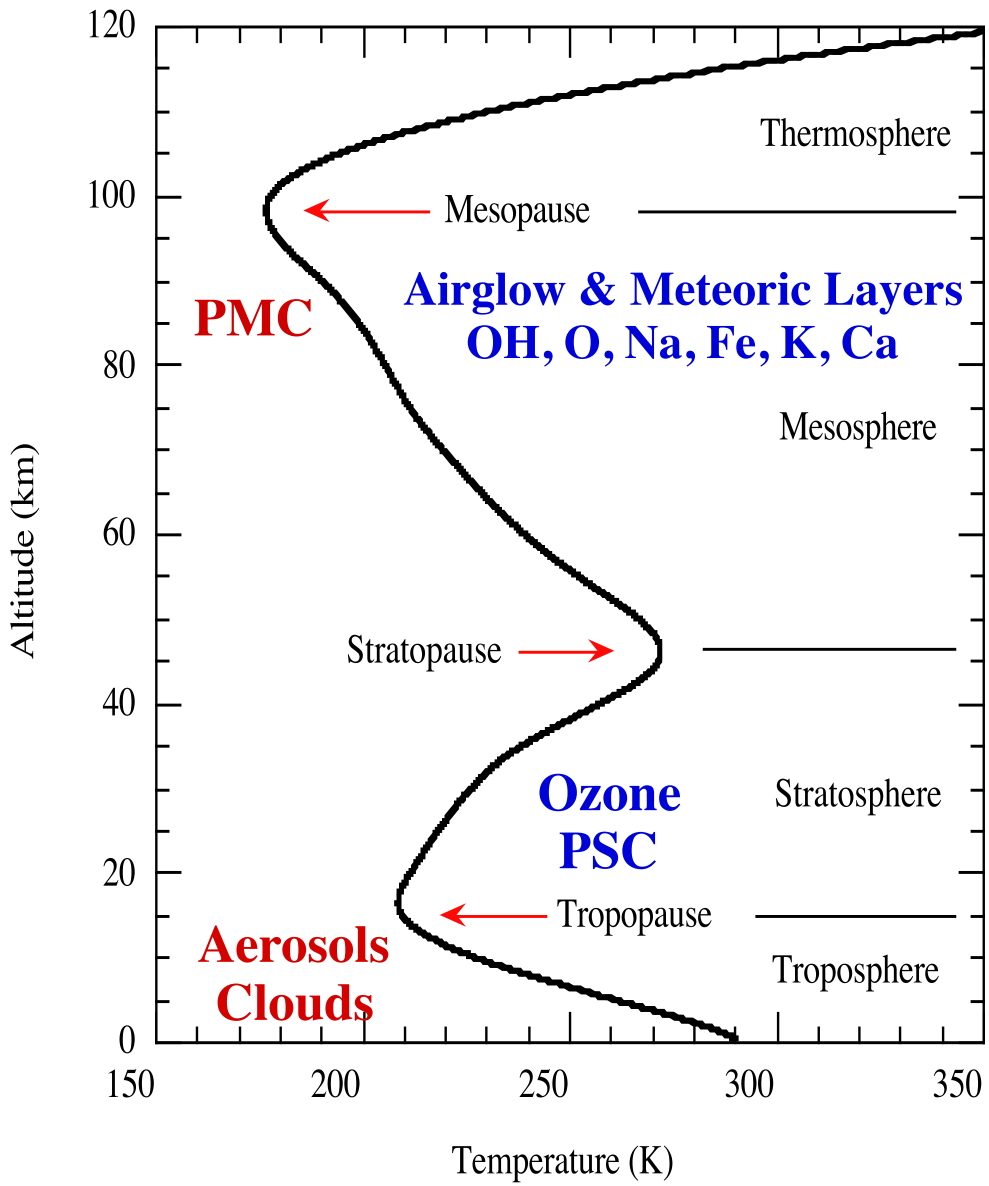
(1) Coherent (Heterodyne) Detection Doppler Wind Lidar

(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 |



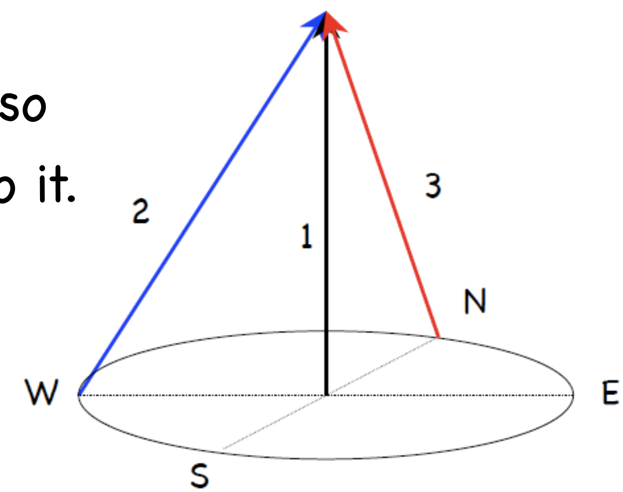
# Vector Wind Velocity Determination

- 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:

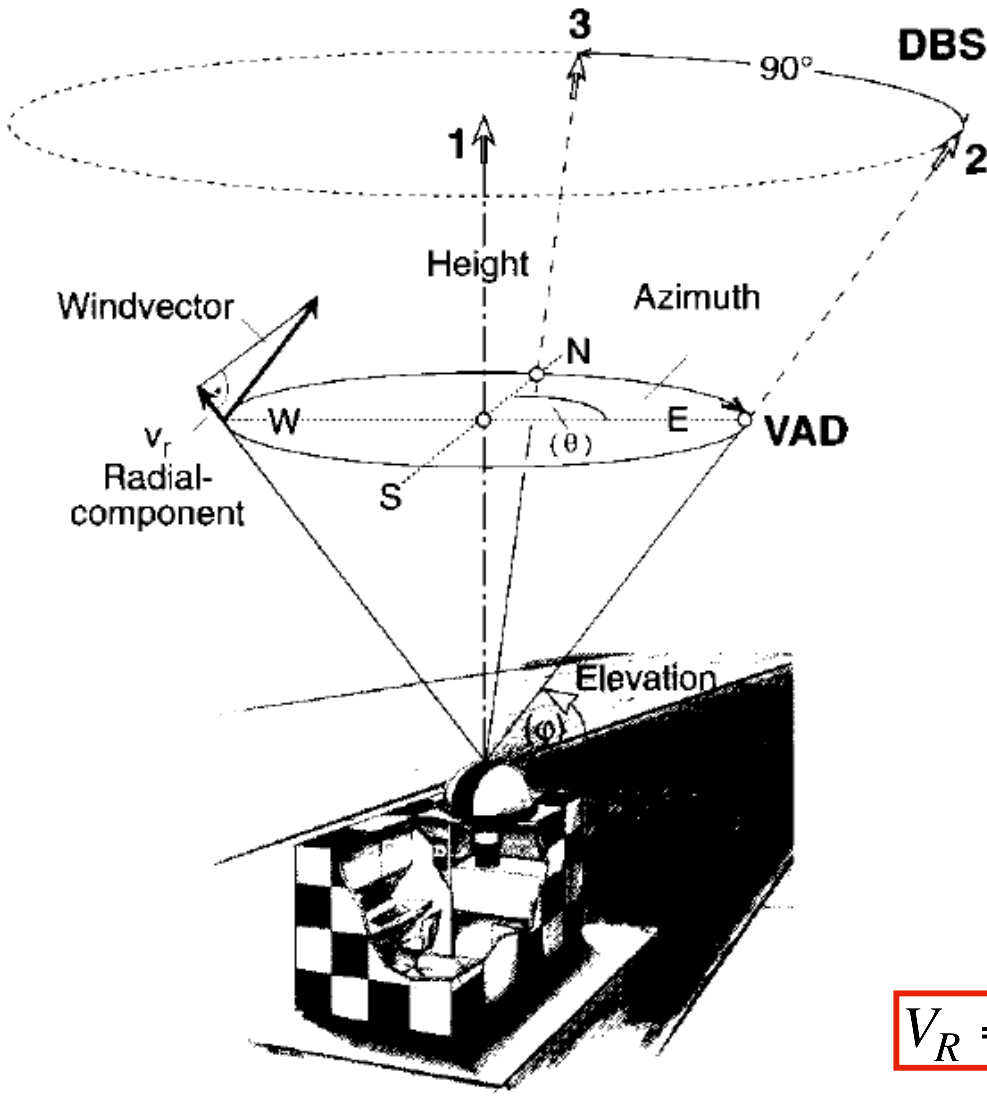
-- conical scan lidar beam at a fixed elevation angle

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

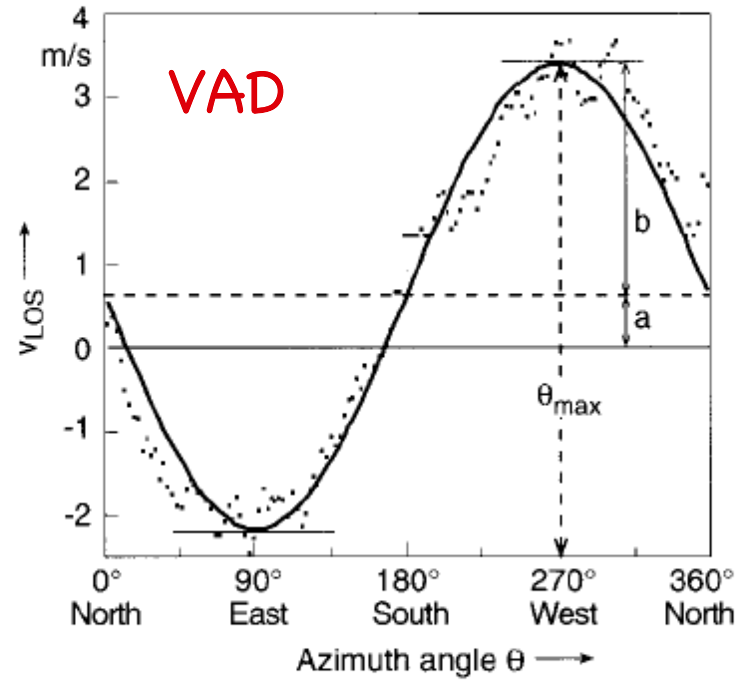
-- pointing lidar beam to vertical, tilted east, and tilted north



# VAD and DBS Techniques









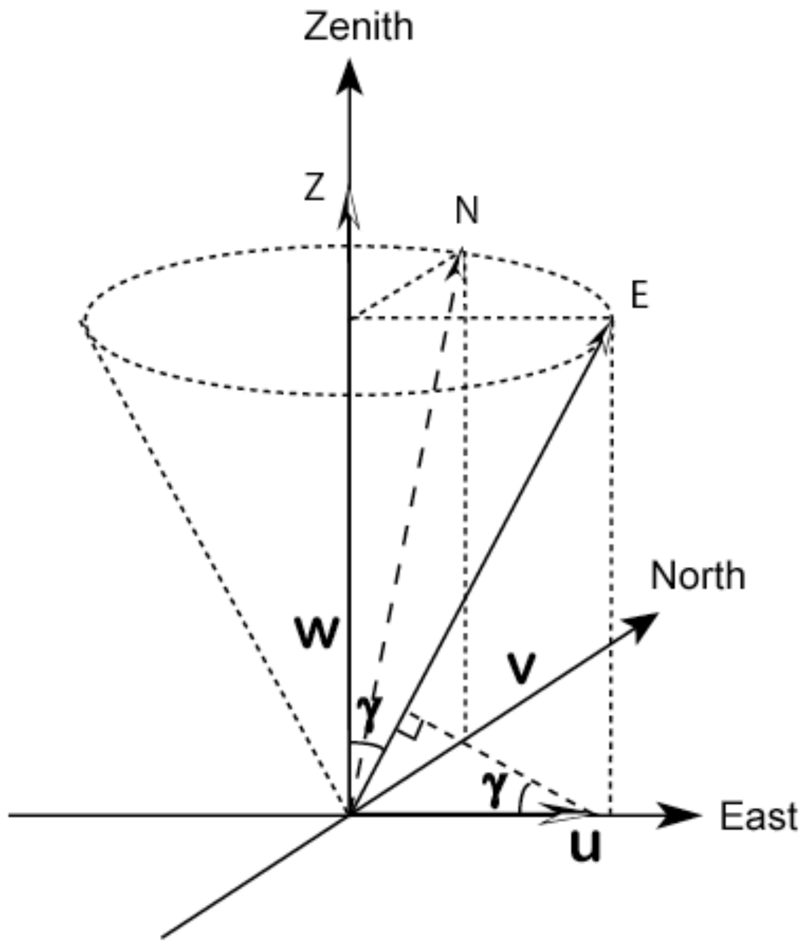
$$V_R = u\sin\theta\cos\varphi + v\cos\theta\cos\varphi + w\sin\varphi$$

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



# DBS Techniques for Vector Wind

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




$\gamma$ is the off-zenith angle

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

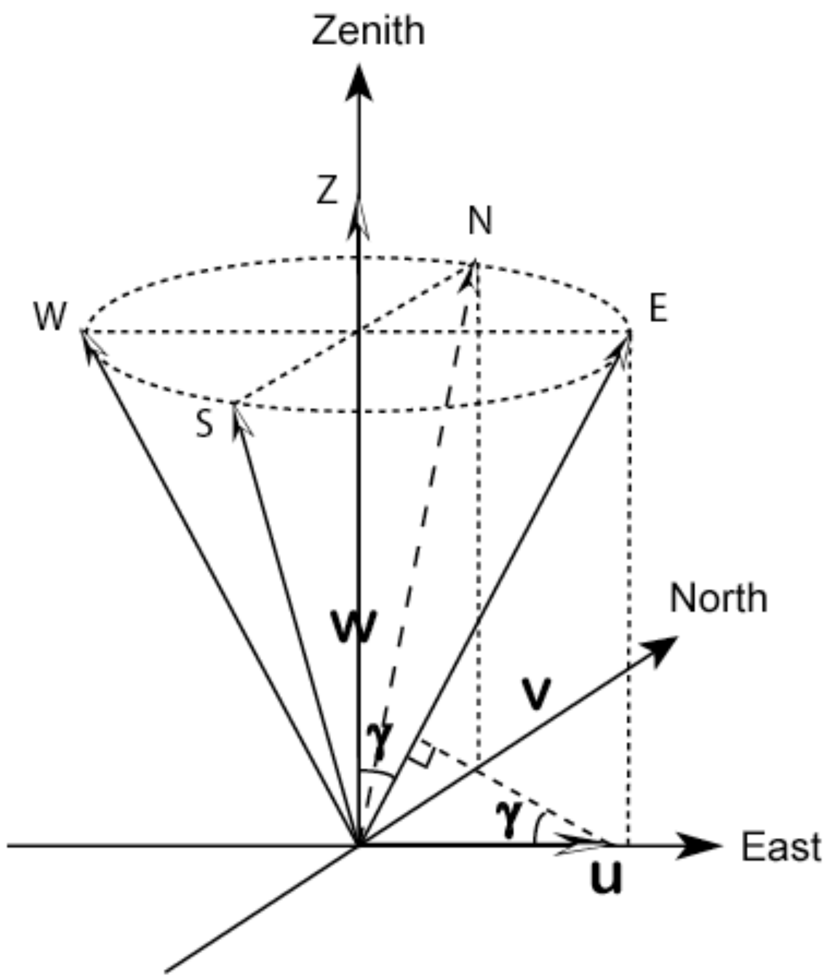
$$u = (V_{RE} - V_{RZ}\cos\gamma)/\sin\gamma$$
$$v = (V_{RN} - V_{RZ}\cos\gamma)/\sin\gamma$$
$$w = V_{RZ}$$

$V_{RZ}$, $V_{RE}$, $V_{RN}$ 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).




γ is the off-zenith angle

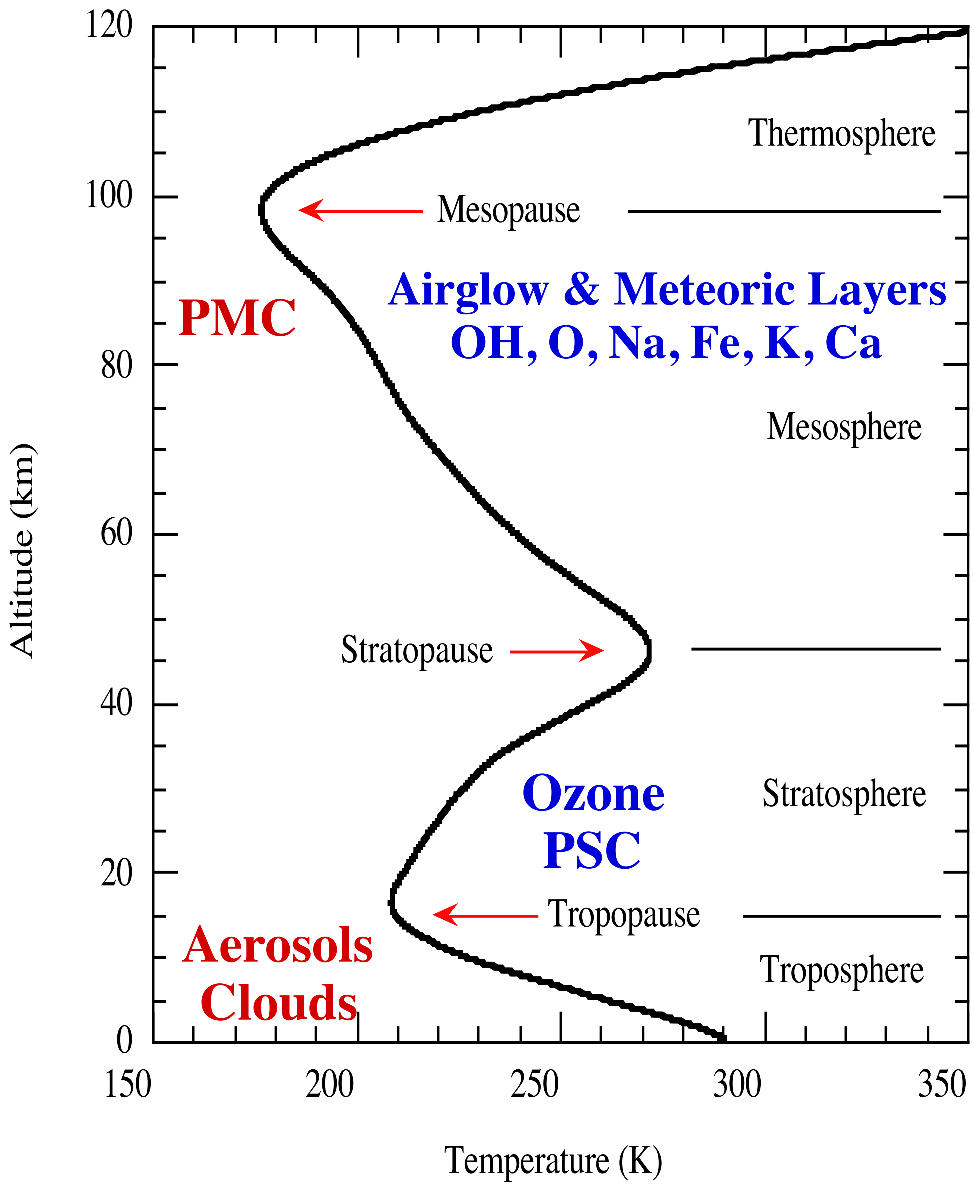
$$V_{RE} = u\sin\gamma + w\cos\gamma$$
$$V_{RW} = -u\sin\gamma + w\cos\gamma$$
$$V_{RN} = v\sin\gamma + w\cos\gamma$$
$$V_{RS} = -v\sin\gamma + w\cos\gamma$$
$$V_{RZ} = w$$

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

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

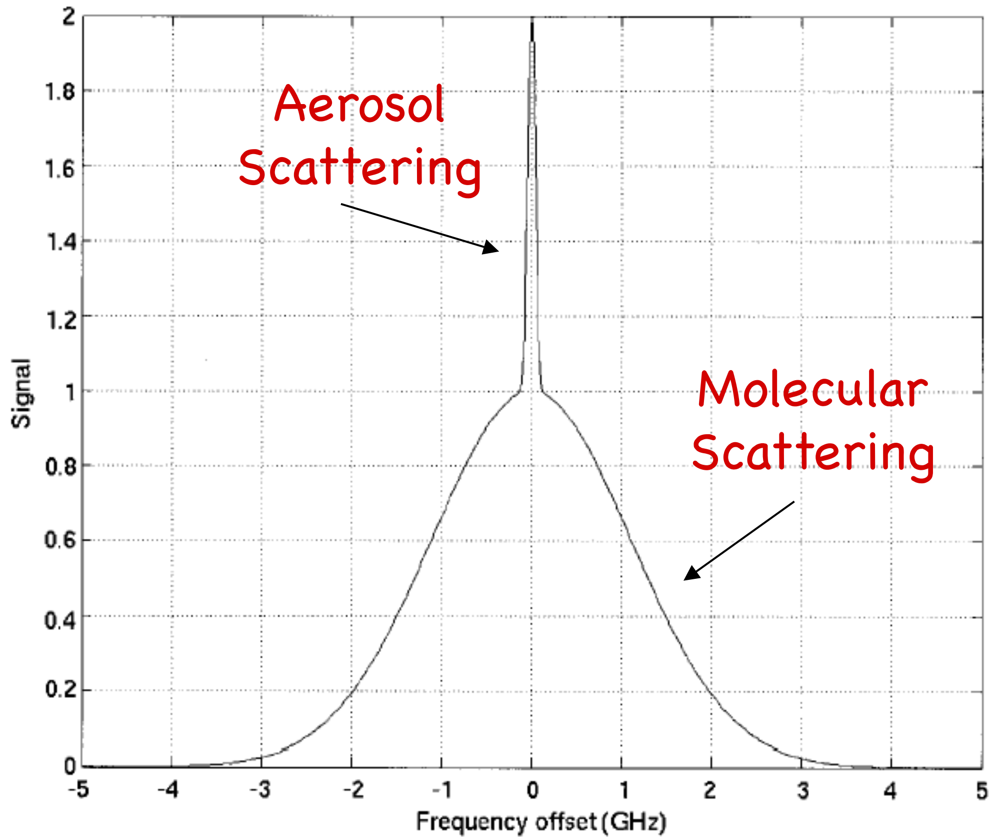
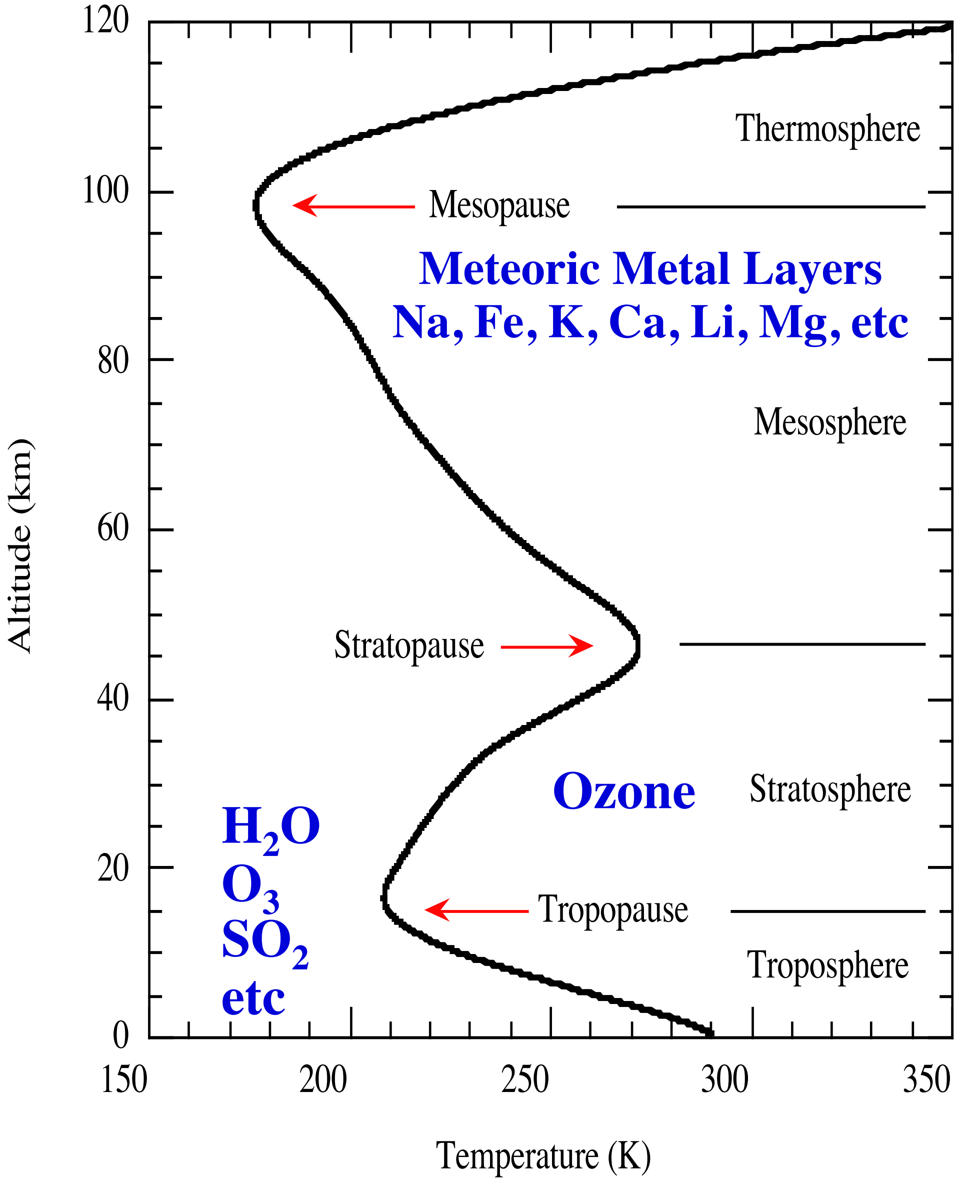



**Fig. 5.1.** Spectral profile of backscattering from a mixture of molecules and aerosols for a temperature of 300 K. The spectral width of the narrow aerosol return is normally determined by the line width of the transmitting laser.



# 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



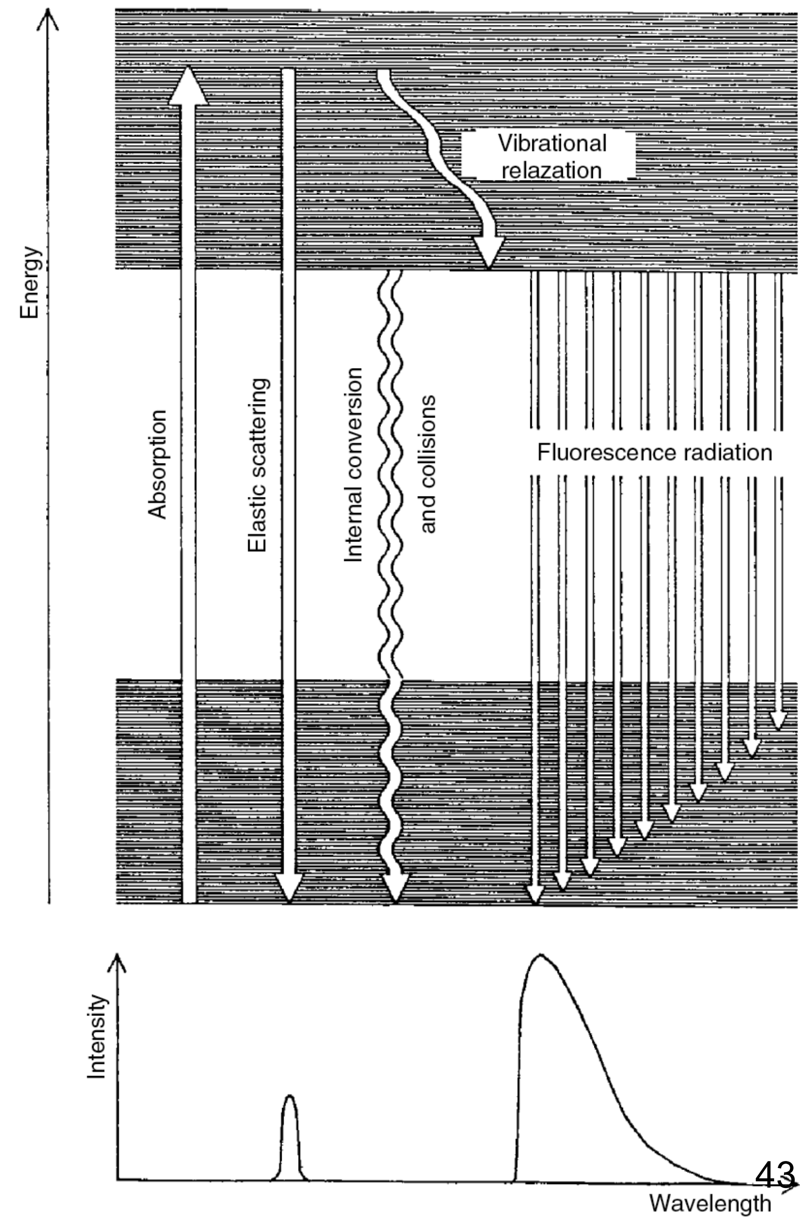
# Target Lidar Techniques

- 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 Rangefinder

❑ Rangefinding Principles and Techniques

1) Time of Flight; 2) Geometry-based

3) Interferometry / Diffraction ranging

❑ Time of Flight Techniques

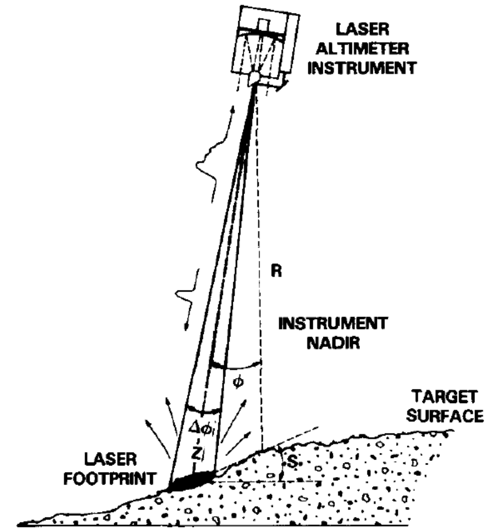
1) Pulsed laser rangefinding,

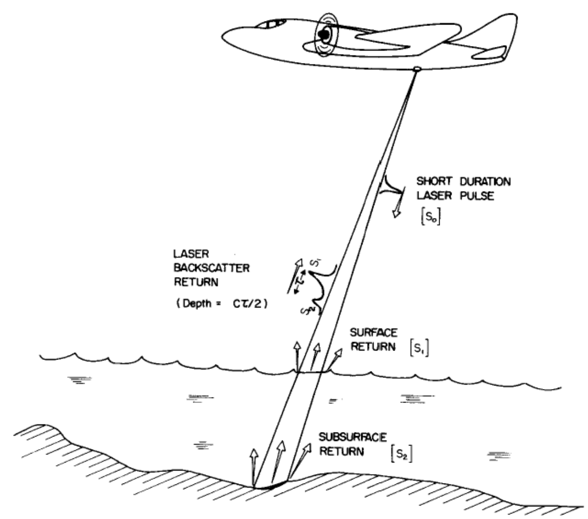
2) CW laser amplitude modulation,

3) CW laser chirp / Chirp pulse compression

❑ 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 & 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

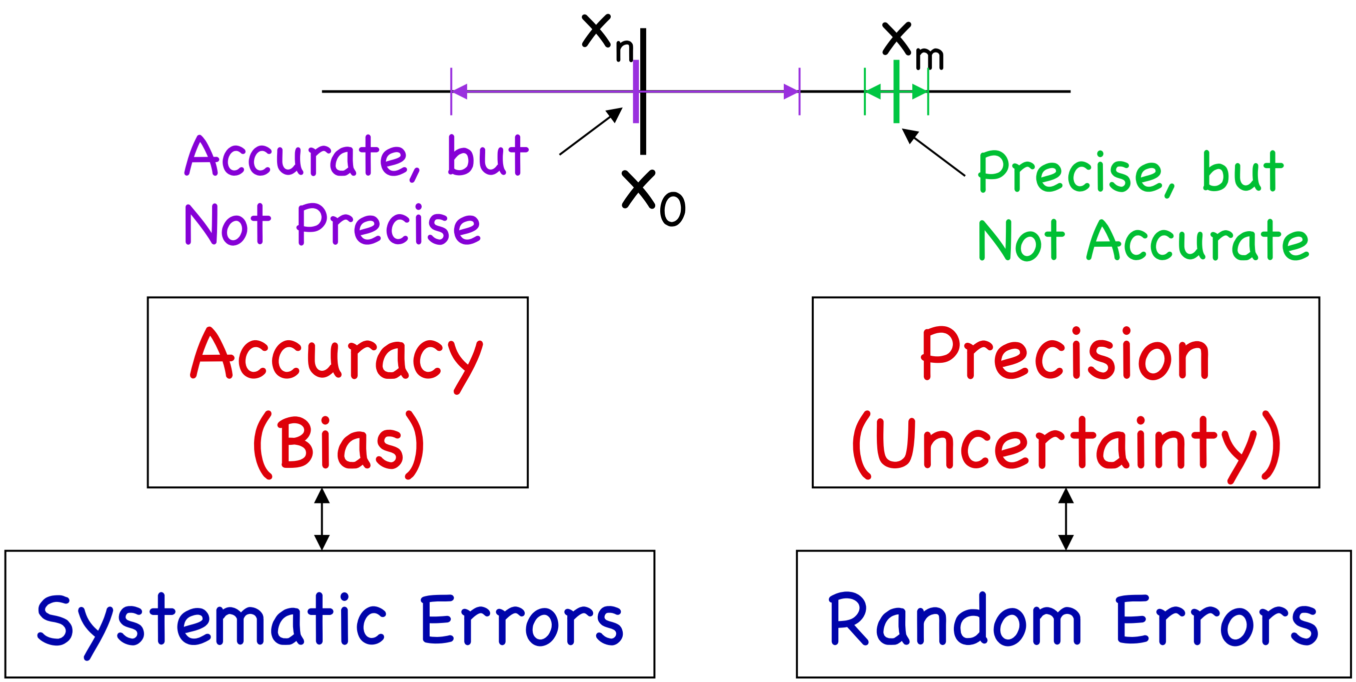
- Simulation of range-resolved lidar returns should include different scattering processes for all or different altitudes:

(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

(5) Spaceborne lidars for global probing and for other sky object detection

- 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.