Lecture 39. Lidar Class Review (1)

- 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

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
  - Topical Lidars: overview (x1), temperature (x6), wind (x5), aerosol (x2), constituent (x4), target (x2), and spaceborne (x2) lidars
  - Lidar Simulation and Error Analysis (x4) #8, 9, 27, and 28
  - Lidar Data Retrieval (x2) #13 and 14
  - Lidar Architecture and Lidar Design (x2) #37 and 38

- What are my expectations?
  - Give you a full and complete picture of lidar remote sensing.
  - All are based on the lidar fundamentals, especially the physical processed involved in the remote sensing procedure.
  - Hope you will gain a clear picture and good concepts, and then work out details through your projects and actual research work.

Concept of Remote Sensing

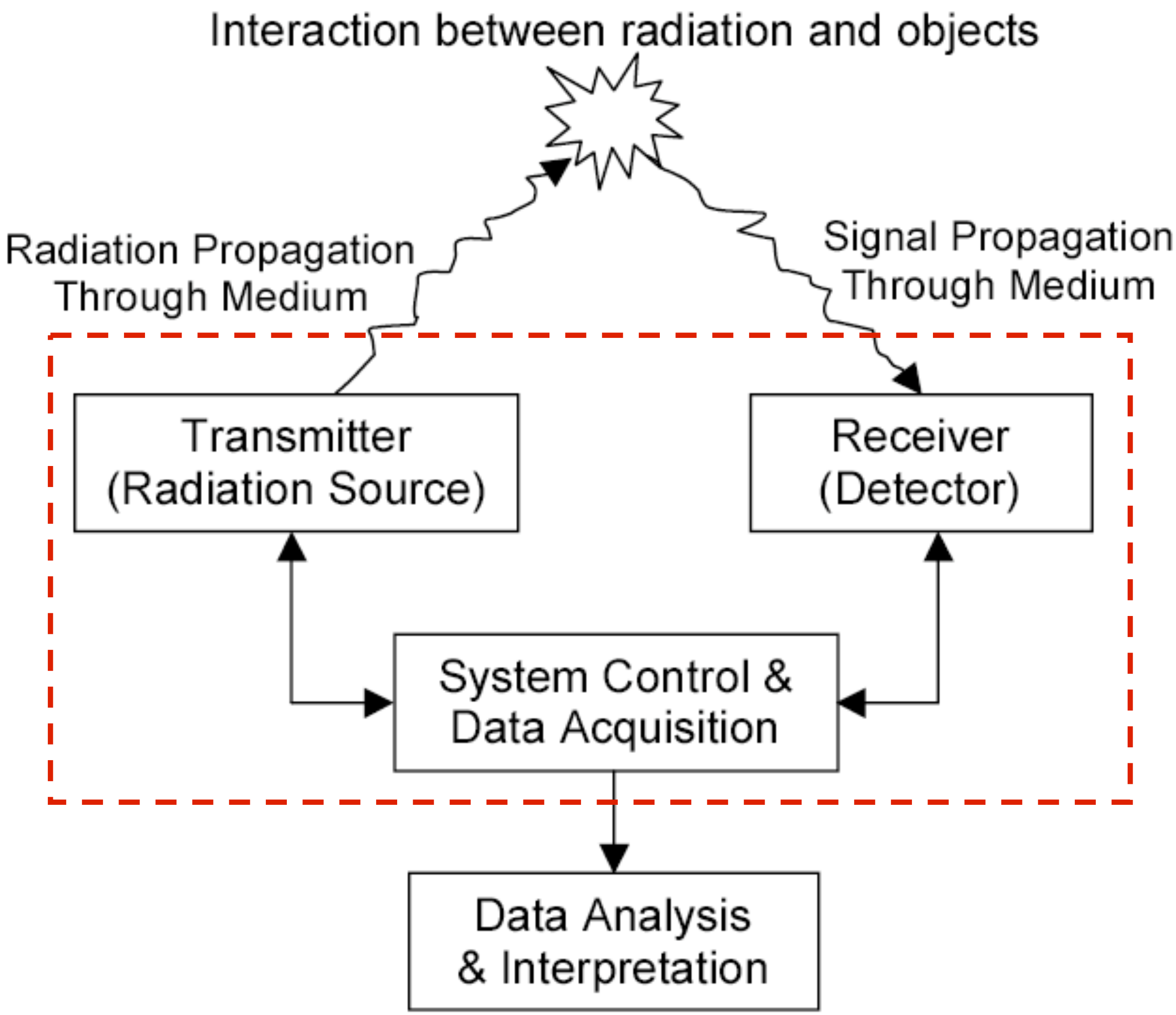
- Remote Sensing is the science and technology of obtaining information about an object without having the sensor in direct physical-contact with the object.
- The nature of remote sensing is one kind of measurements, i.e., to obtain or acquire information of an object through experimental methods.
- 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.

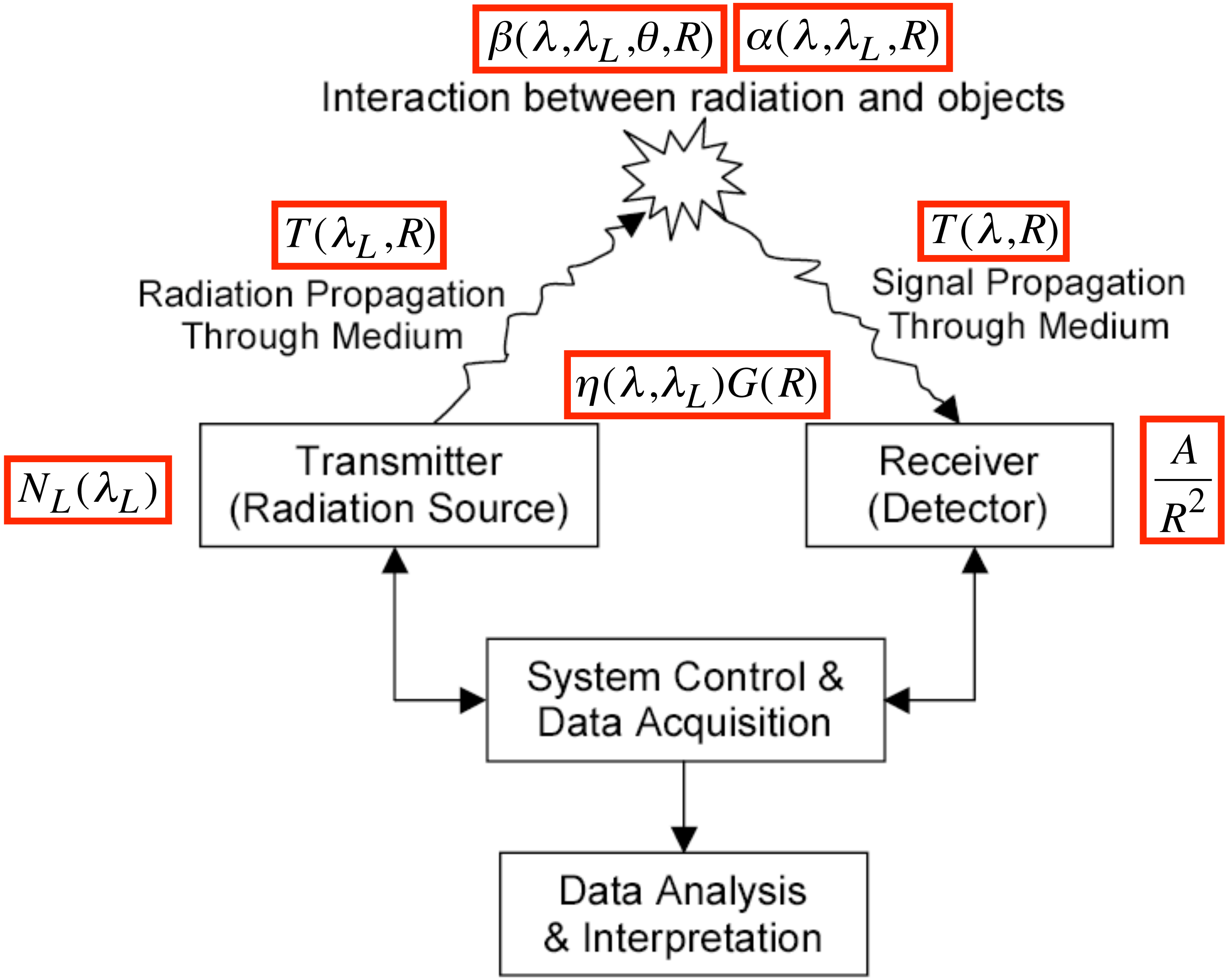
Basic Assumptions for Lidar Equation

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

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

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

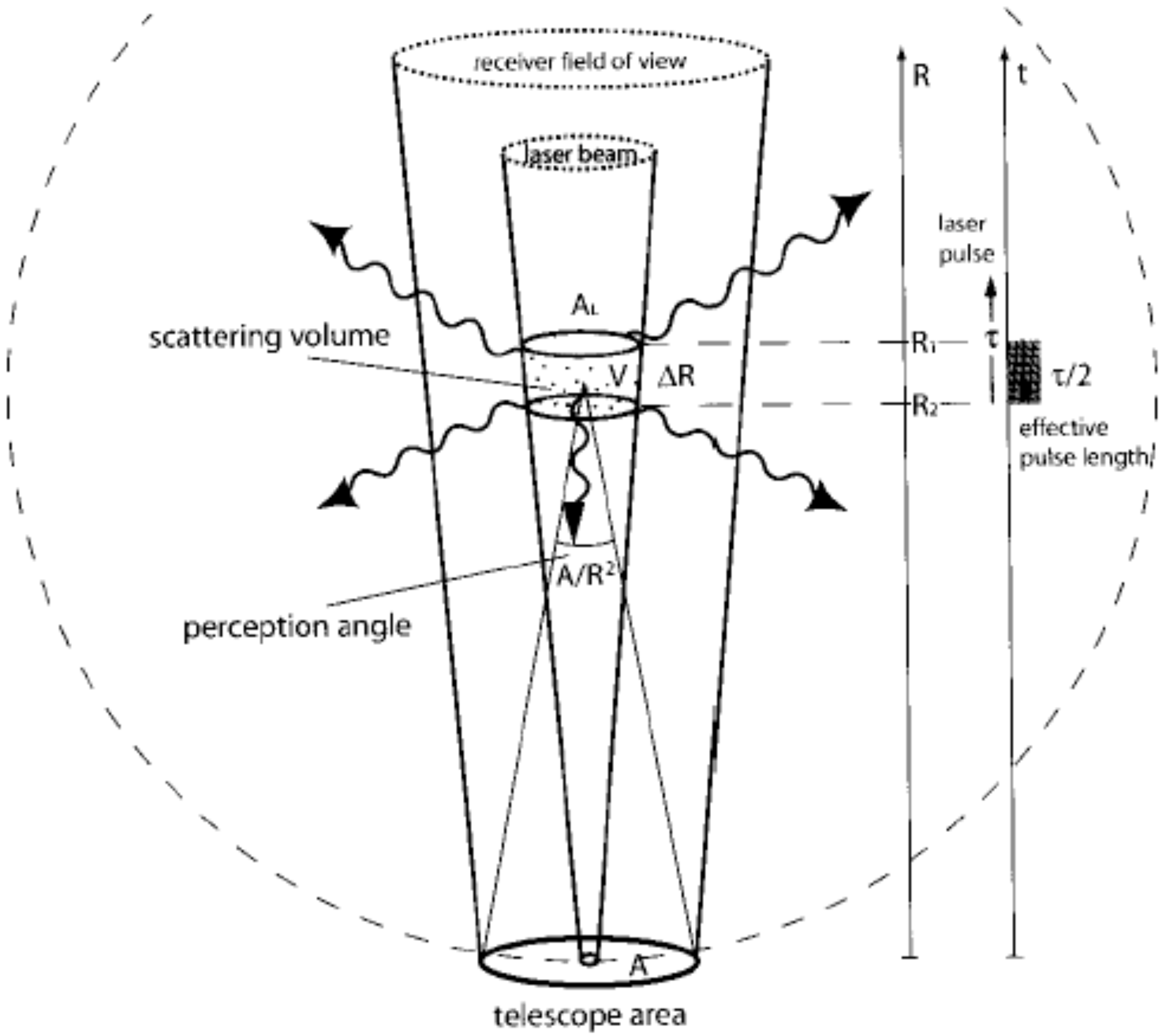
General Lidar Equation in β and α

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

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



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

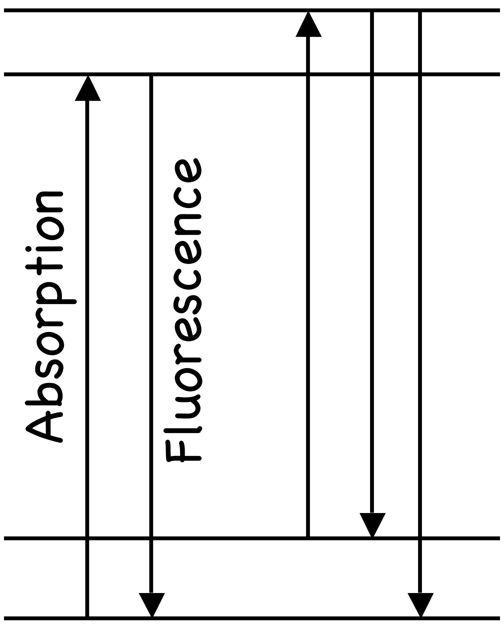
- Light propagation in atmosphere or medium: transmission vs extinction

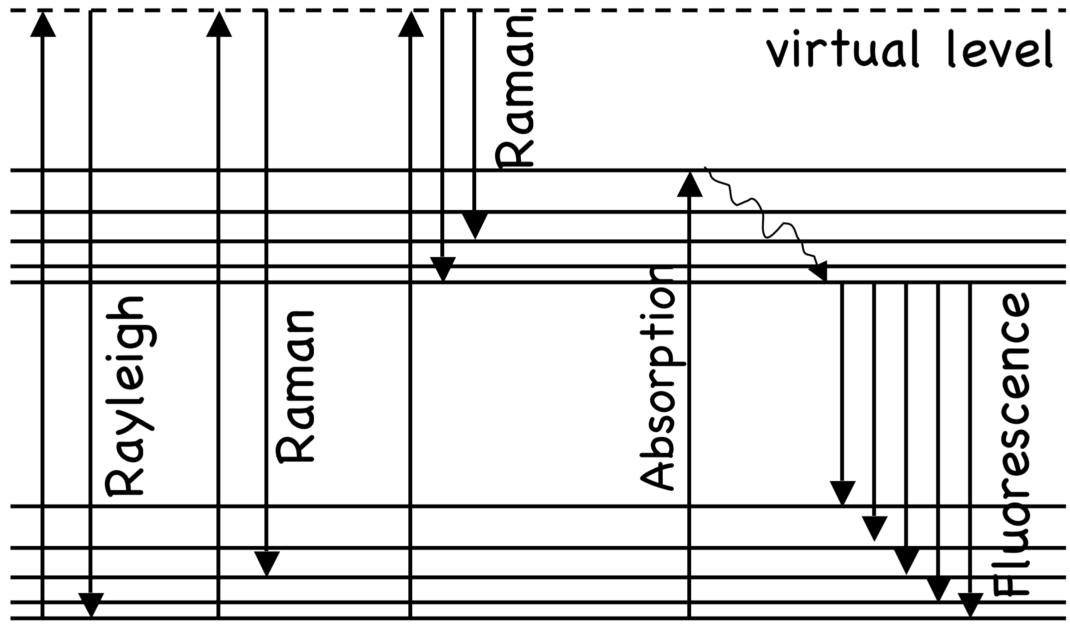
Extinction = Scattering + Absorption

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

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

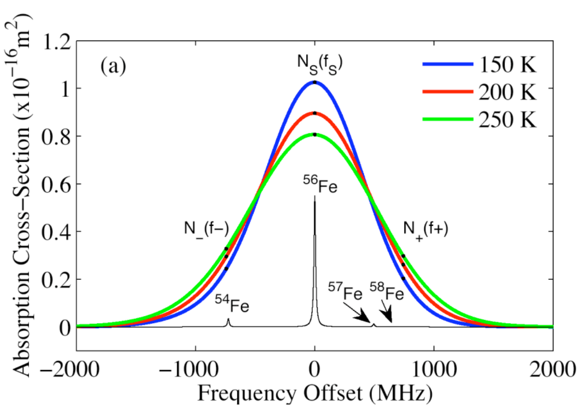
Elastic and Inelastic Scattering

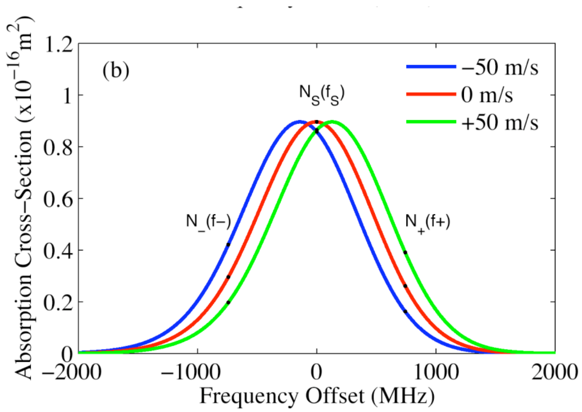


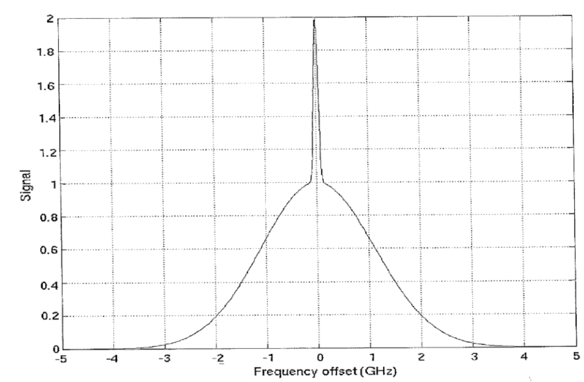


Atomic absorption & (resonance) fluorescence

Molecular elastic and inelastic scattering, absorption and fluorescence

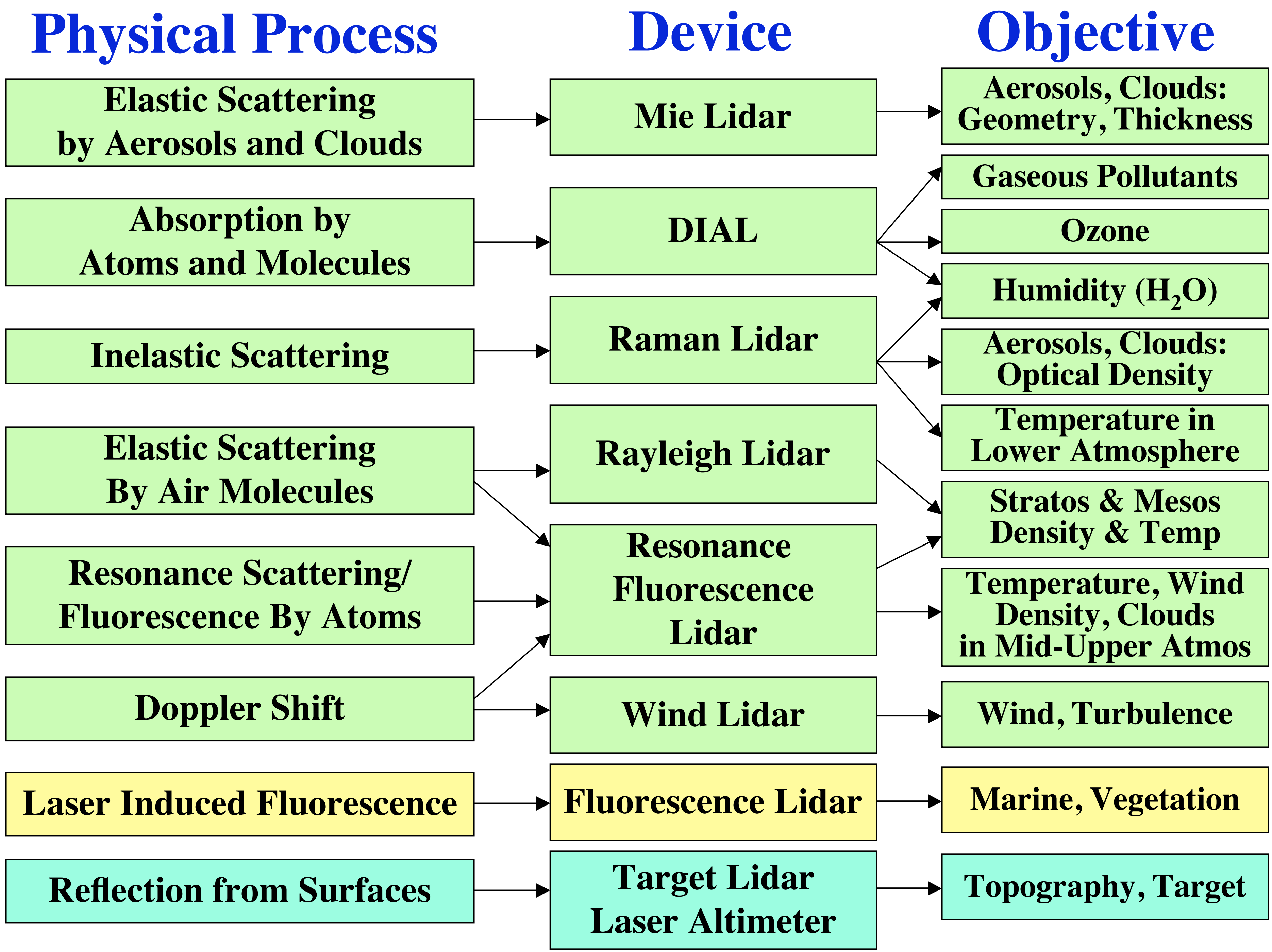






Backscatter Cross-Section Comparison

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


Physical Process
Device
Objective
Elastic Scattering by Aerosols and Clouds
Mie Lidar
Aerosols, Clouds: Geometry, Thickness
Absorption by Atoms and Molecules
DIAL
Gaseous Pollutants
Ozone
Humidity (H_2O)
Inelastic Scattering
Raman Lidar
Aerosols, Clouds: Optical Density
Temperature in Lower Atmosphere
Elastic Scattering By Air Molecules
Rayleigh Lidar
Stratos & Mesos Density & Temp
Resonance Scattering/ Fluorescence By Atoms
Resonance Fluorescence Lidar
Temperature, Wind Density, Clouds in Mid-Upper Atmos
Doppler Shift
Wind Lidar
Wind, Turbulence
Laser Induced Fluorescence
Fluorescence Lidar
Marine, Vegetation
Reflection from Surfaces
Target Lidar Laser Altimeter
Topography, Target

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 λ_{on} on the molecular absorption line

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

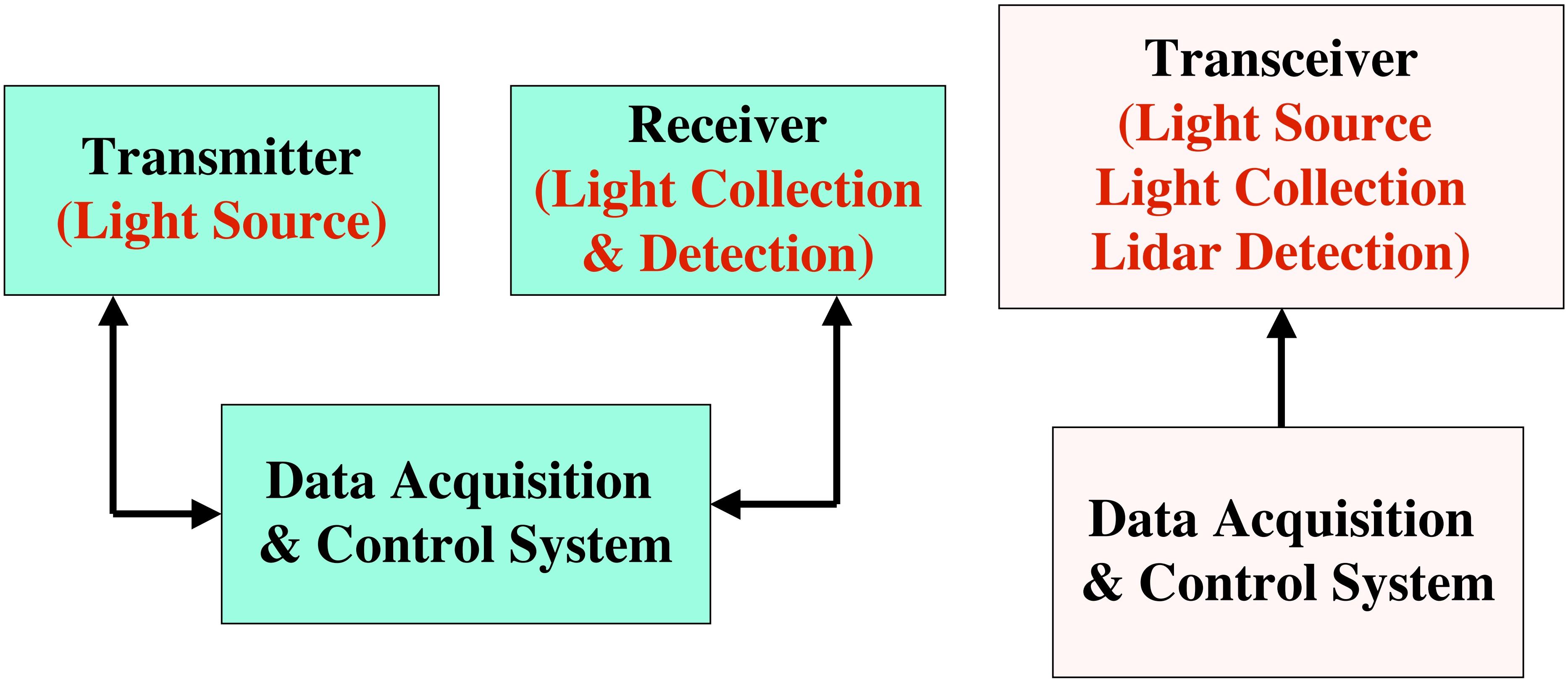
- For the laser with wavelength λ_{off} off the molecular absorption line

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

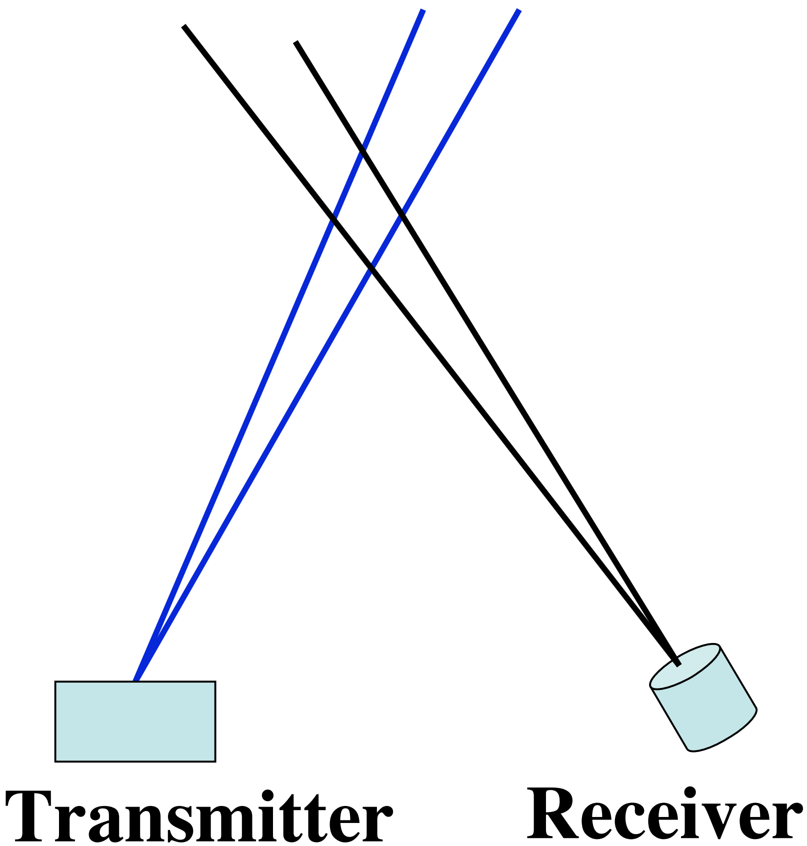
- Differential absorption cross-section

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

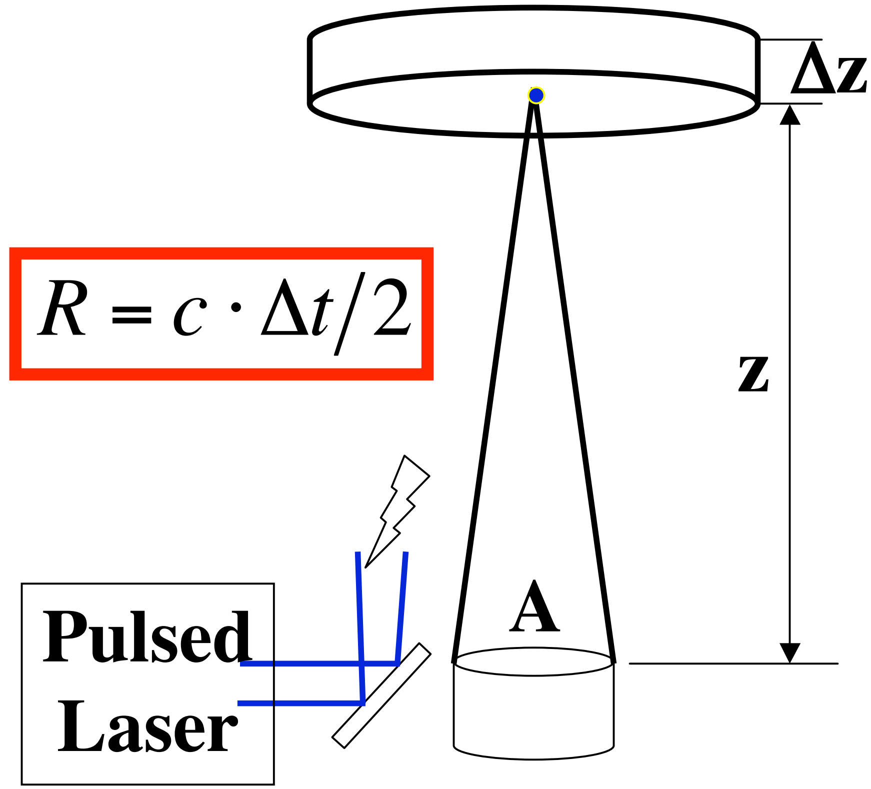
Basic Architecture of LIDAR



Basic Configurations of LIDAR
Bistatic and Monostatic

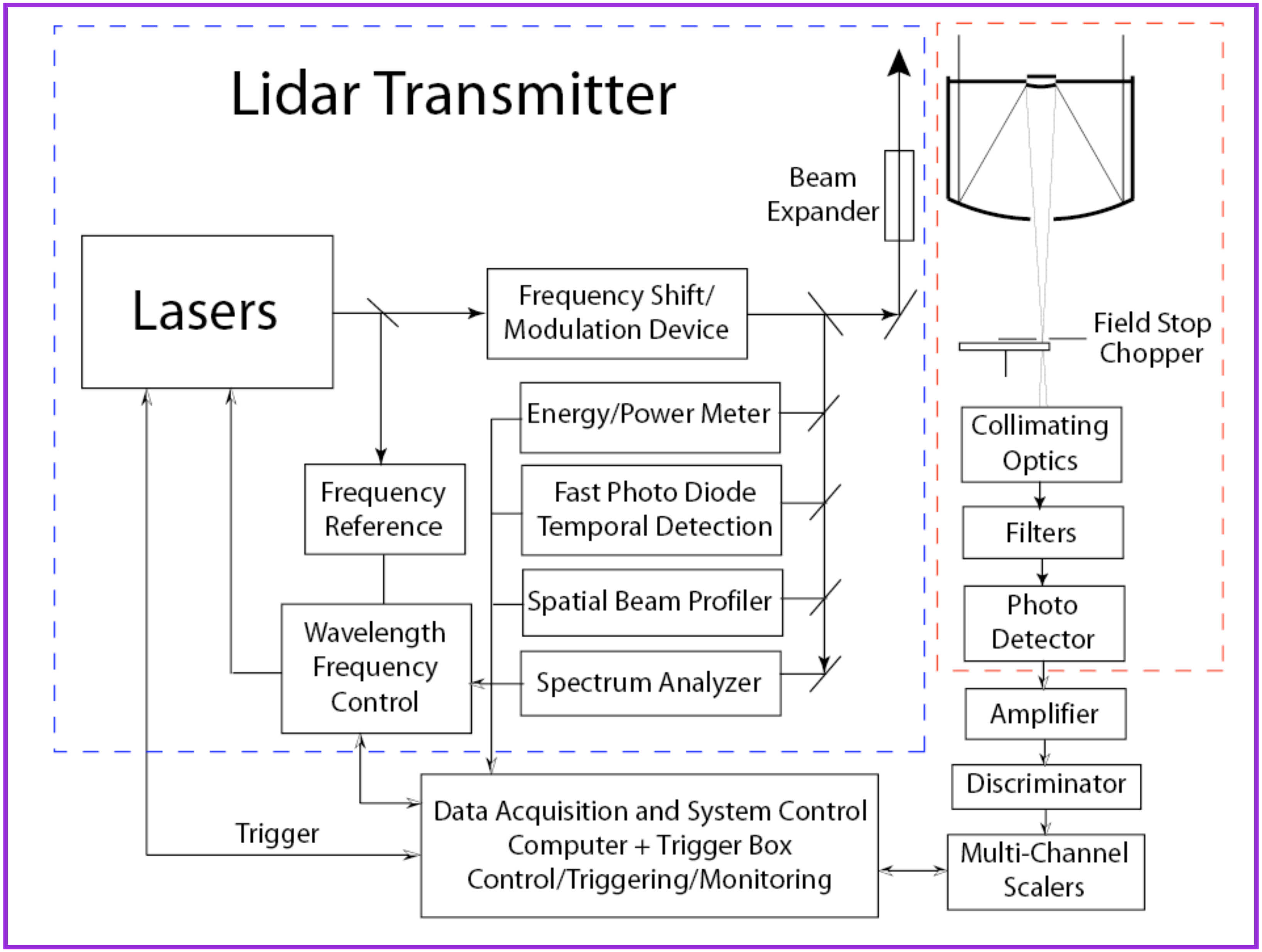


Bistatic Configuration

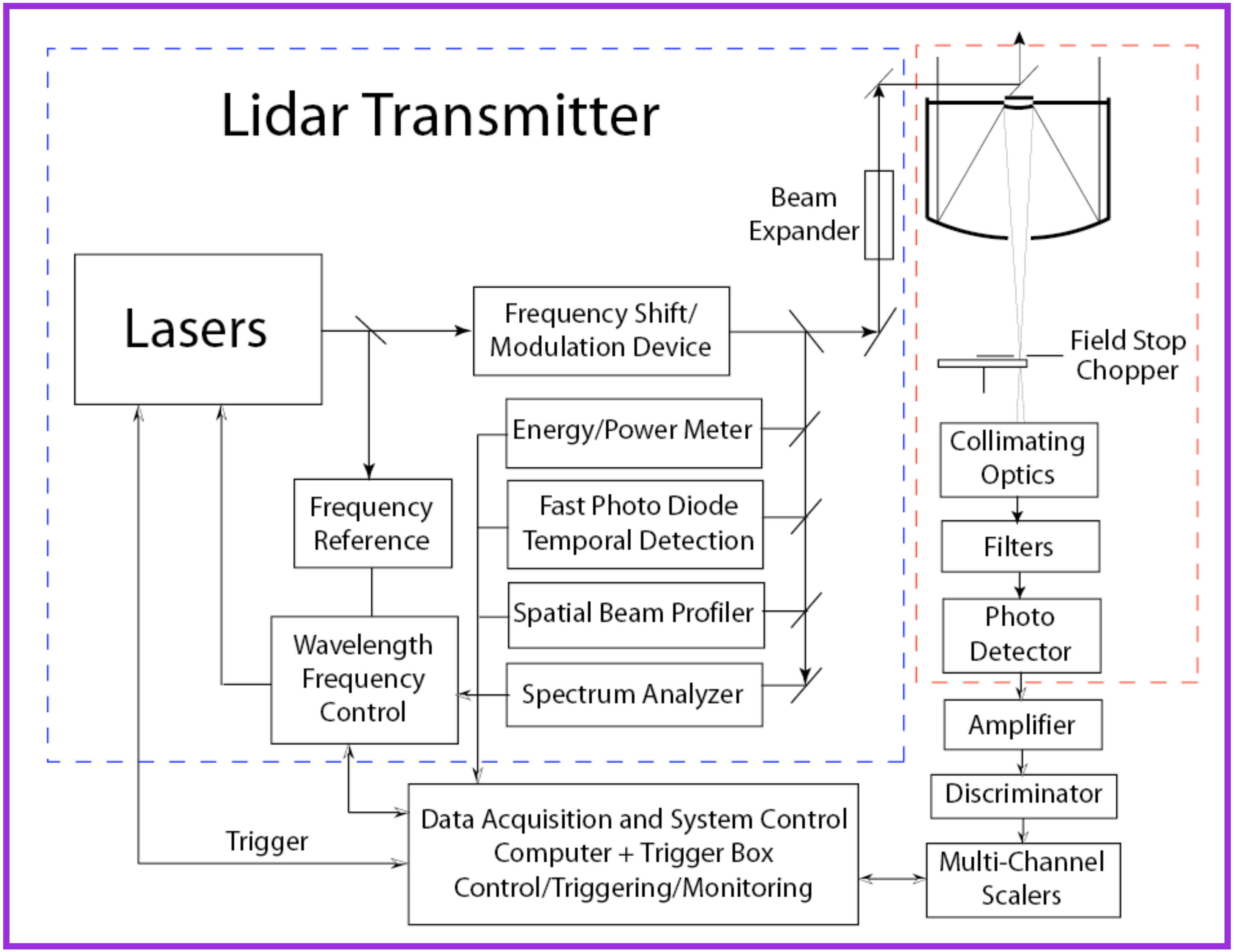


Monostatic Configuration

Biaxial Arrangement



Coaxial Arrangement

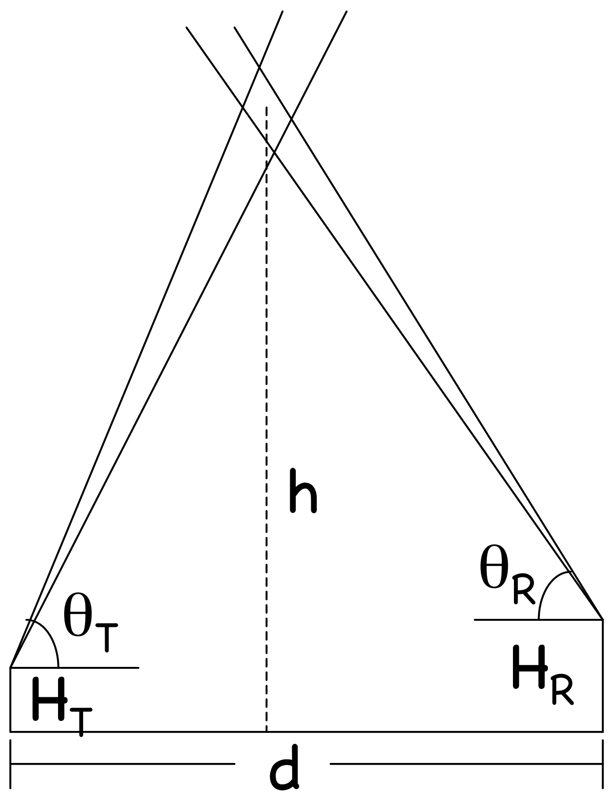


Altitude Determination from Geometry

- 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.

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



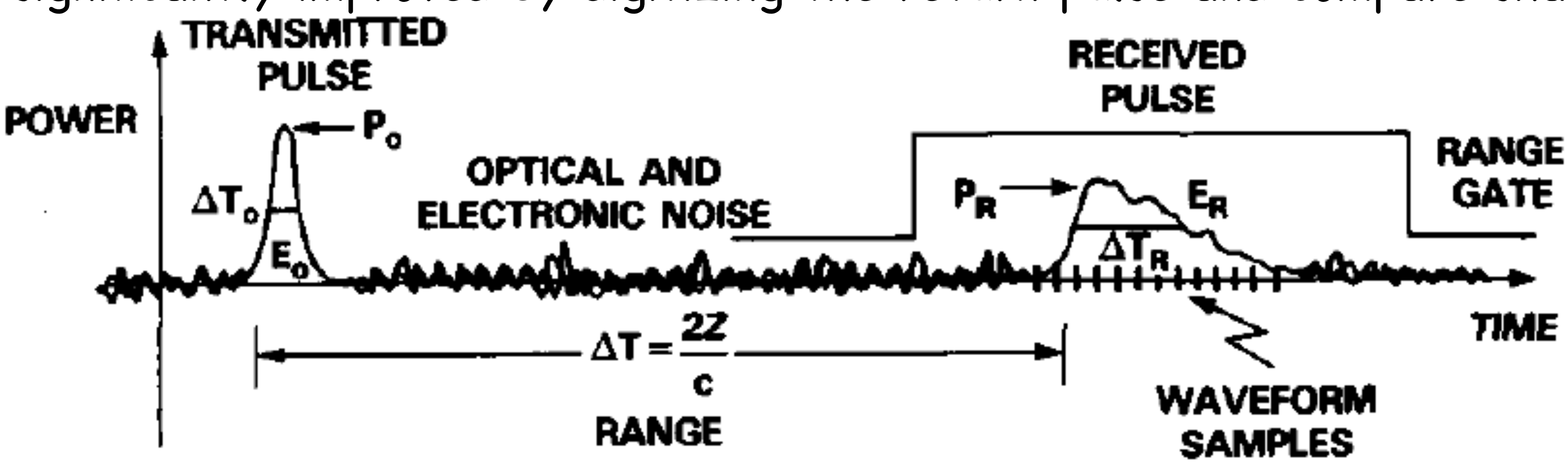
Range Determination from TOF

- 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.

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

Δt 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

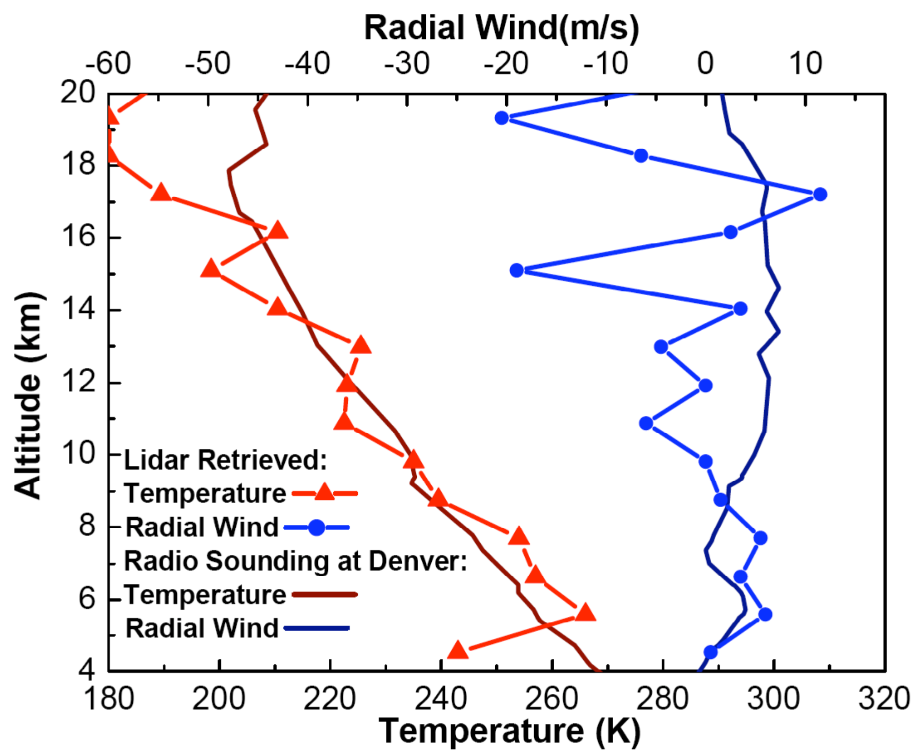
- Understanding your lidar system and entire procedure is the key for all cases of lidar calibration, especially when we try to push technology or measurement envelope, because existing instruments have not been able to achieve what you design to achieve. You must fully understand every possible interaction 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.
- 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?

More Considerations

- 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.



Na-DEMOF initial results