Lecture 39. Lidar Class Review (1)

- Concept of Lidar Remote Sensing
- Picture of Lidar Remote Sensing
- General Lidar Equation and Basic Assumptions
- Physical Processes Involved in Lidar
- Lidar Classification
- Lidar Equation in Different Forms
- Lidar Architecture
- Altitude and Range Determination

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 using 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.

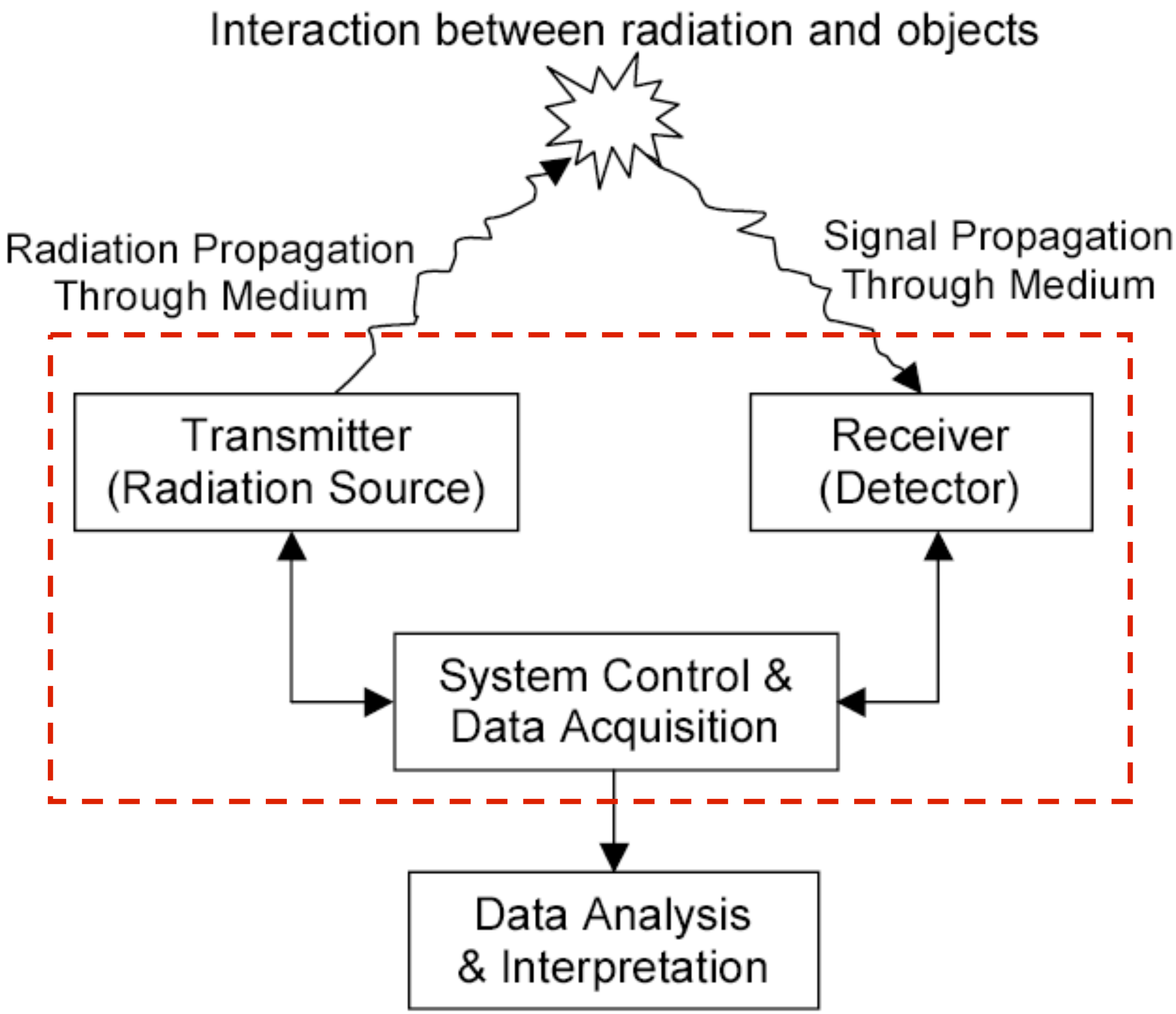
Concept of Lidar Remote Sensing

- Remote sensing has passive and active remote sensing, in optical, radio, and acoustic frequency ranges.
- LIDAR, RADAR, and SODAR are three main active remote sensing technologies.

- 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 other remote sensing.

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) with the transmitted laser photon numbers (or laser power), light transmission in atmosphere or medium, physical interaction between light and objects, and 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 relation. 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 our consideration.

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

Physical Picture in Lidar Equation

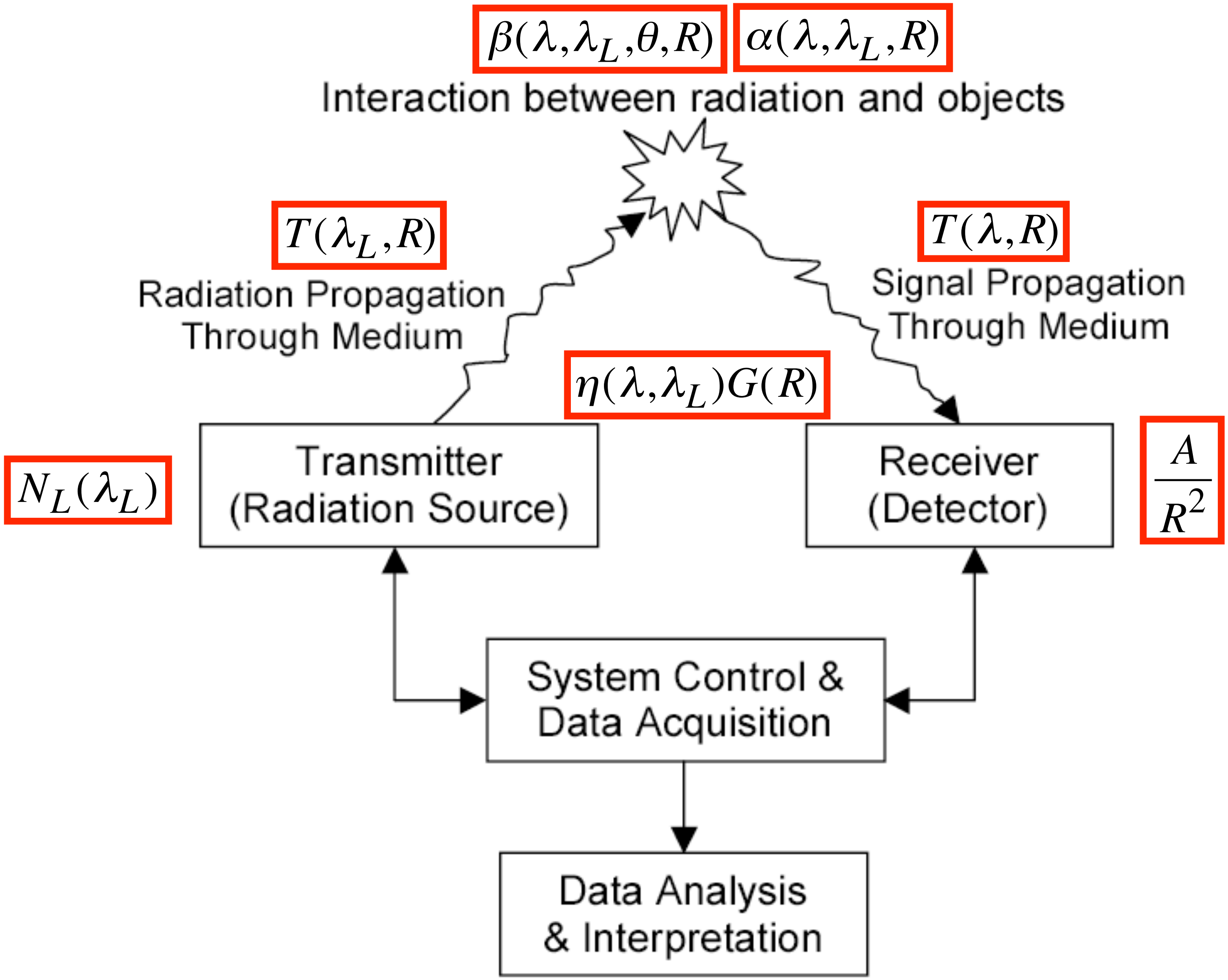
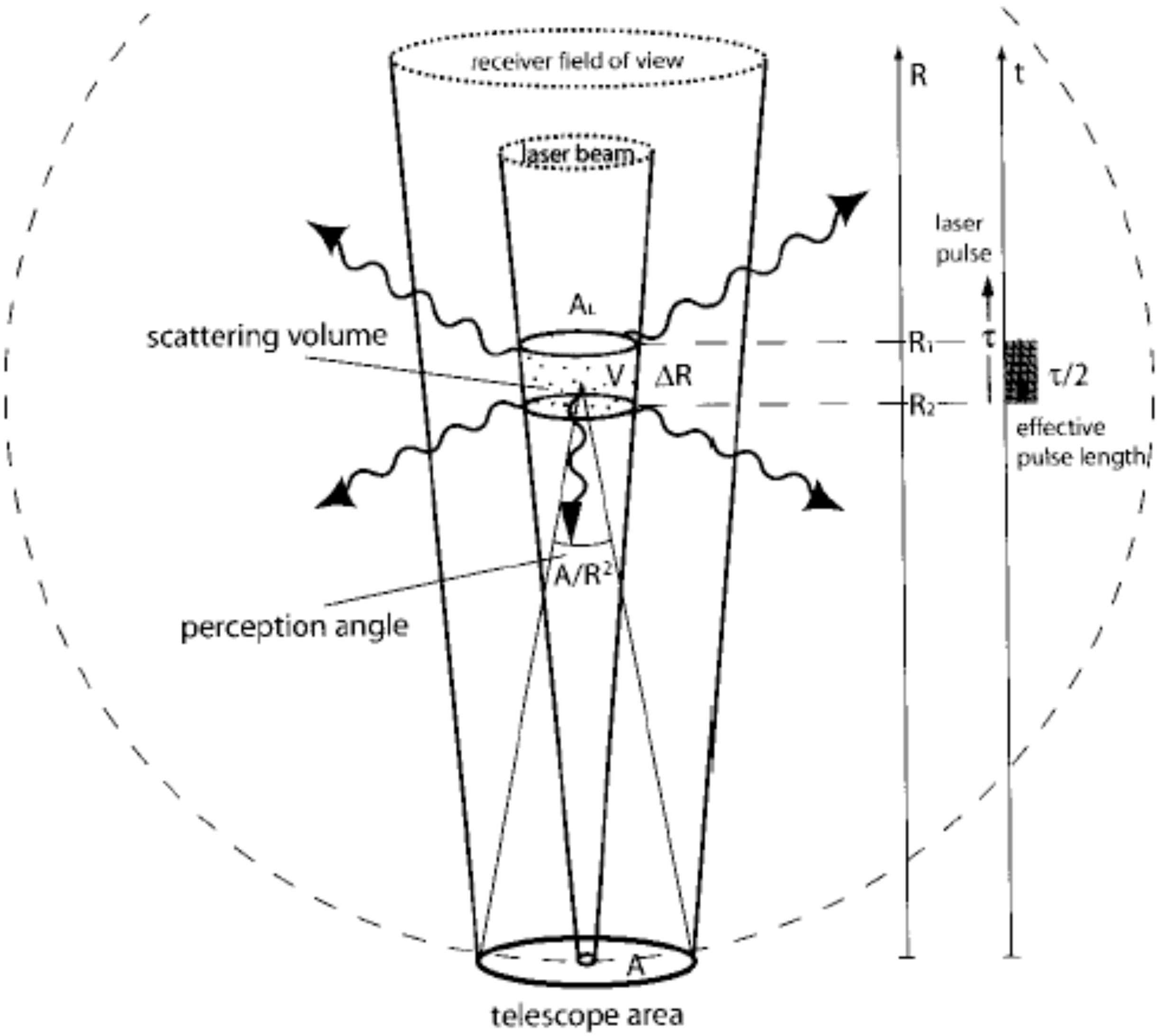


Illustration for LIDAR Equation



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

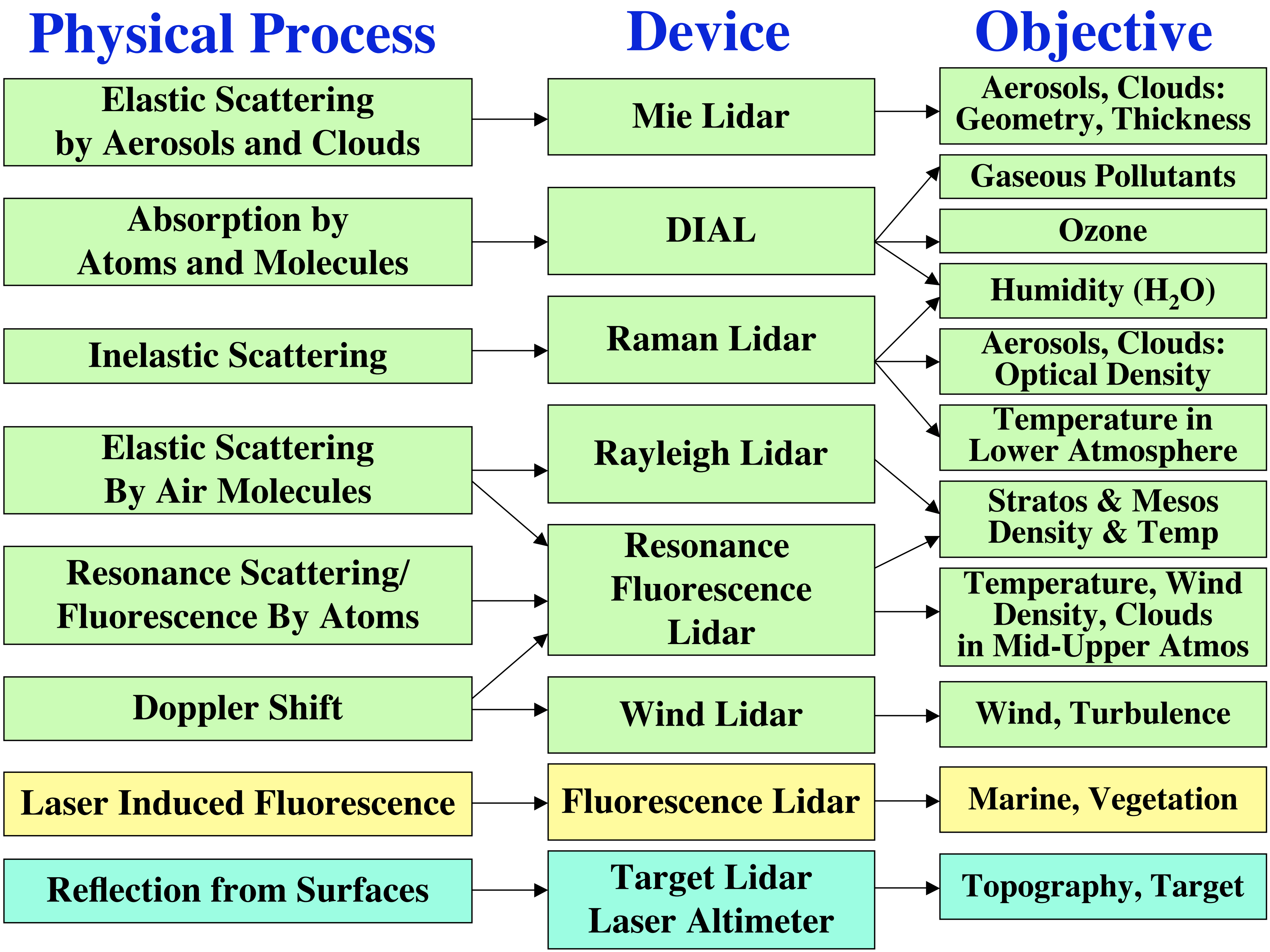
(7) Reflection from target or surface

- Light propagation in atmosphere or medium: transmission vs extinction

Extinction = Scattering + Absorption

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

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


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

Backscatter Cross-Section Comparison

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

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

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

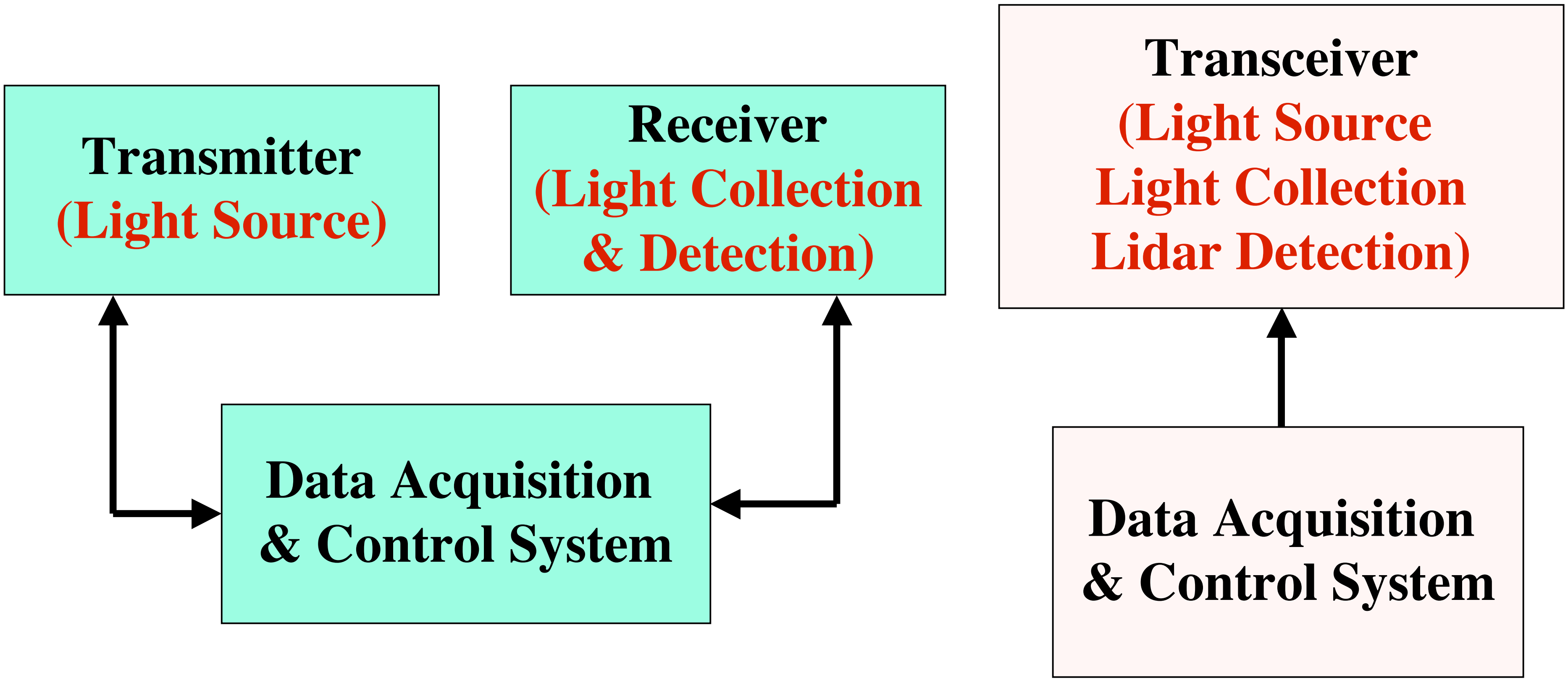
- For the laser with wavelength λ_{off} off the molecular absorption line

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

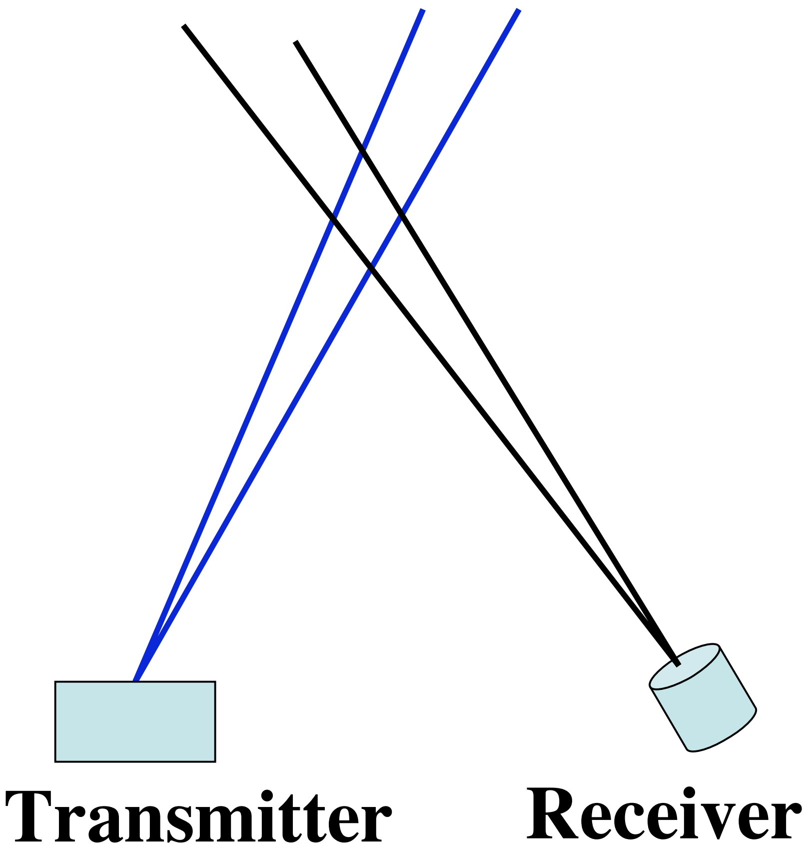
- Differential absorption cross-section

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

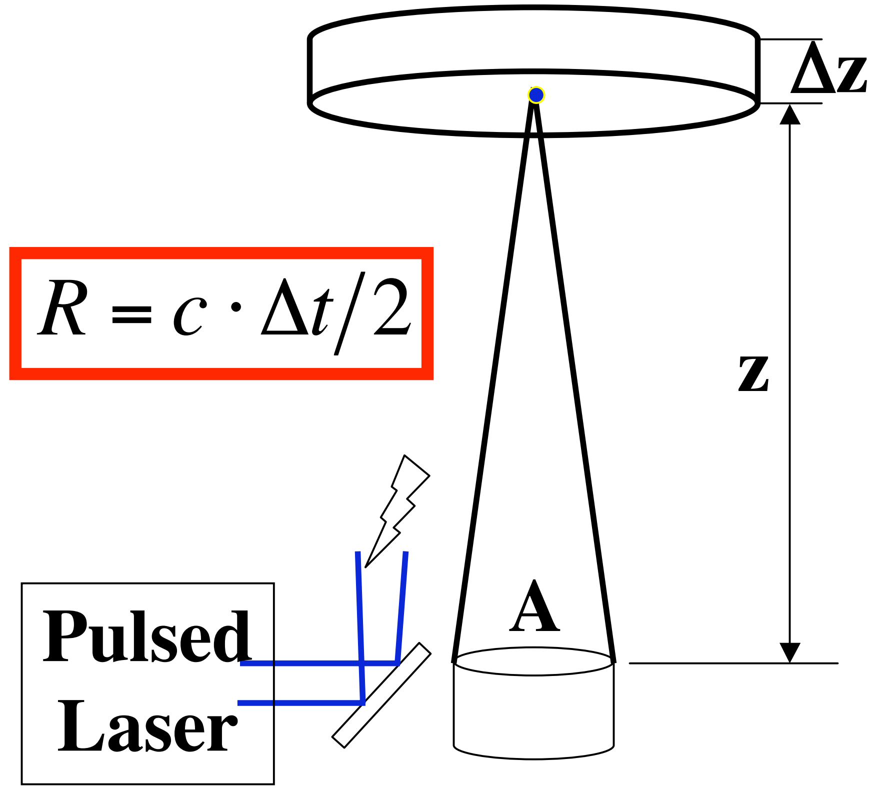
Basic Architecture of LIDAR



Basic Configurations of LIDAR
Bistatic and Monostatic

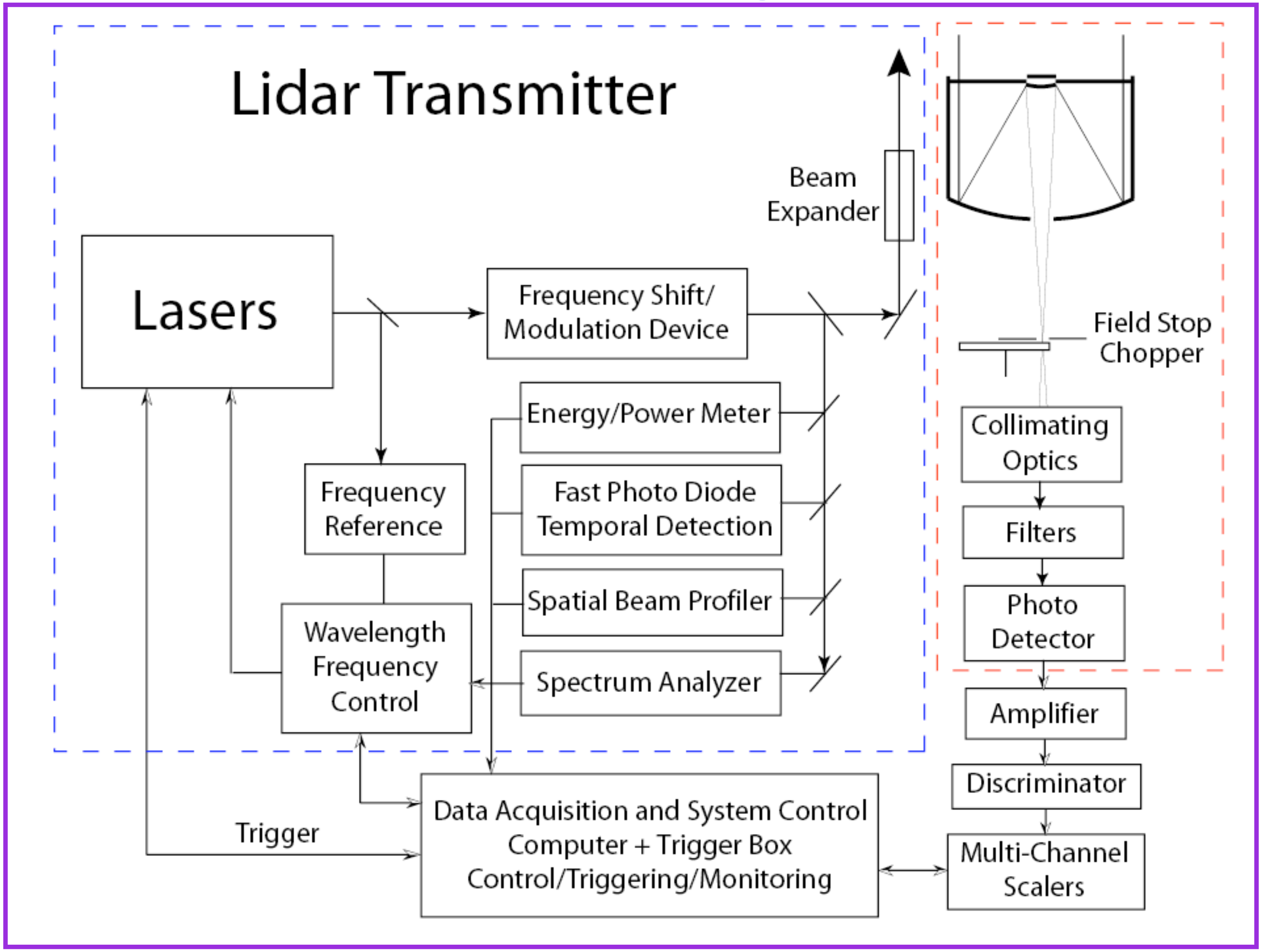


Bistatic Configuration

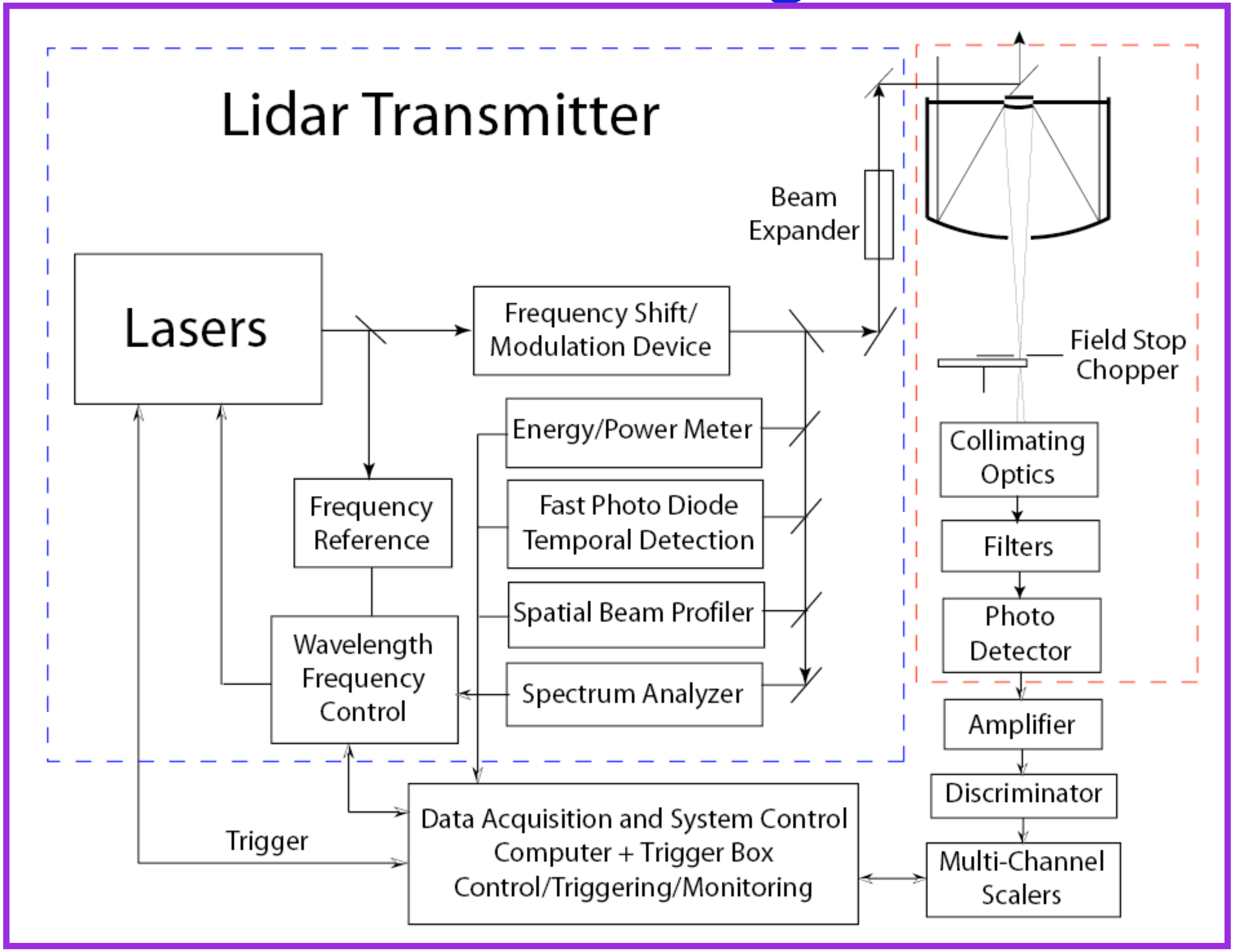


Monostatic Configuration

Biaxial Arrangement



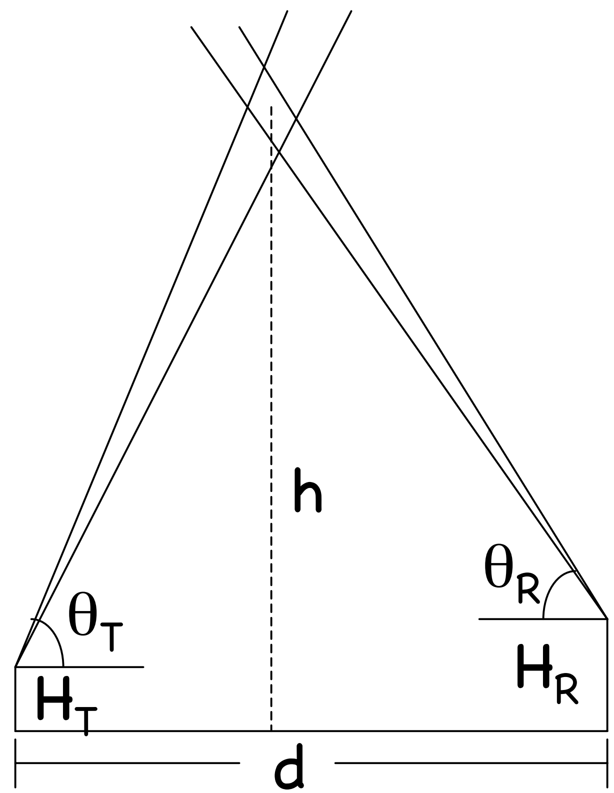
Coaxial Arrangement



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

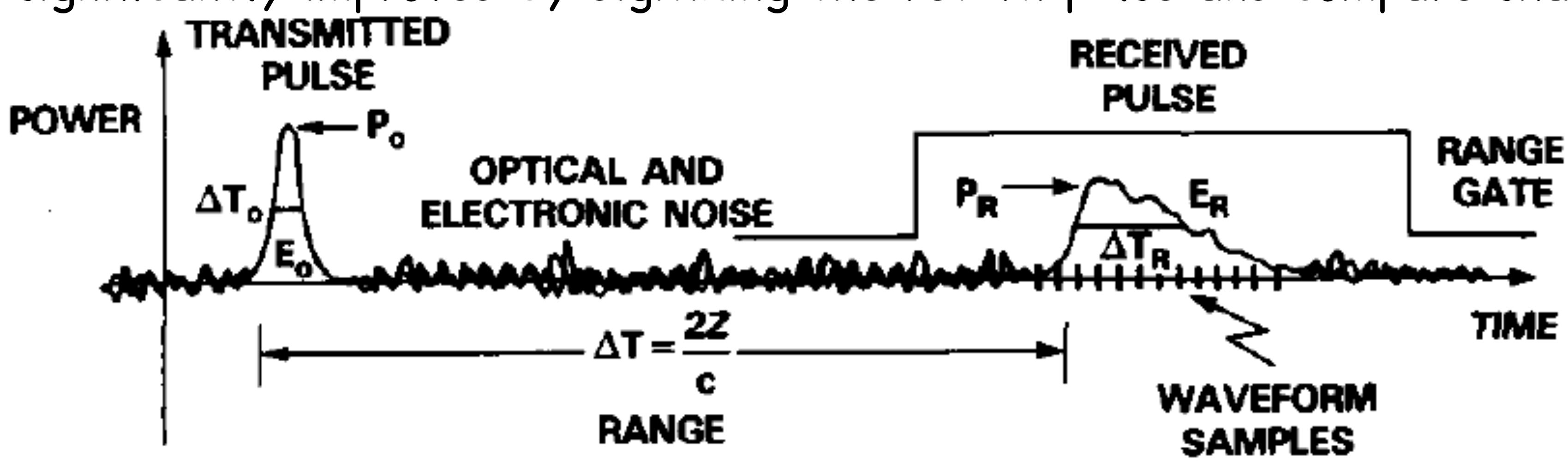
- For nanosecond pulsed-laser lidar, the range is determined by the time of flight of the photons propagating from lidar transmitter to the objects and returning to the lidar receiver.

- For atmospheric (scattering) lidar, the ultimate resolution is limited by the pulse duration time, as atmospheric scattering has no distinct peak.

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

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