Lecture 04. Lidar Remote Sensing Overview (2)

- Introduction
- Basic Lidar equation
- Different forms of lidar equation
- Classifications of lidars
- Different challenges in various lidars
- Summary

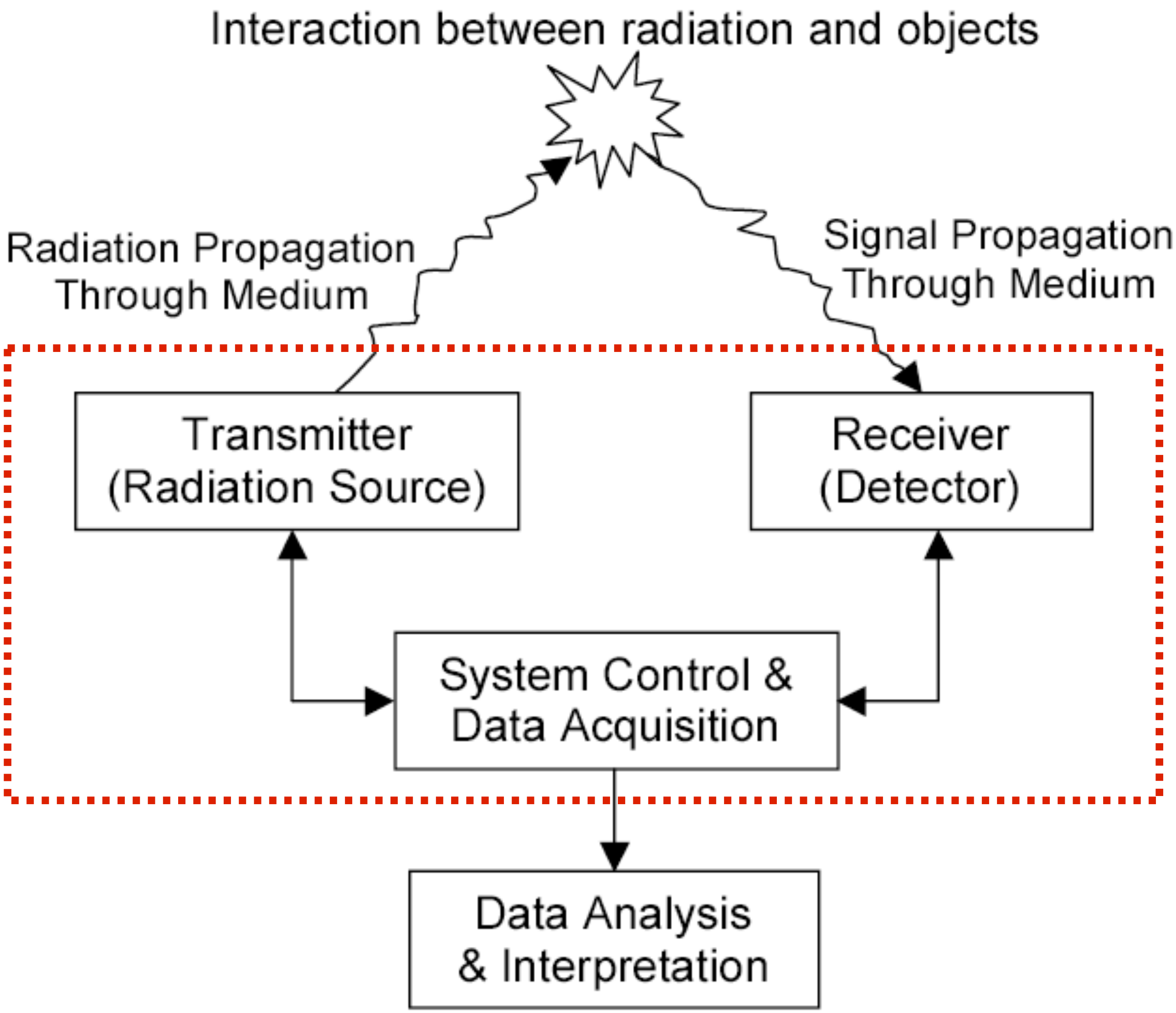
Introduction

- Lidar equation is the fundamental equation in laser remote sensing field to relate the received photon counts (or light power) with 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.

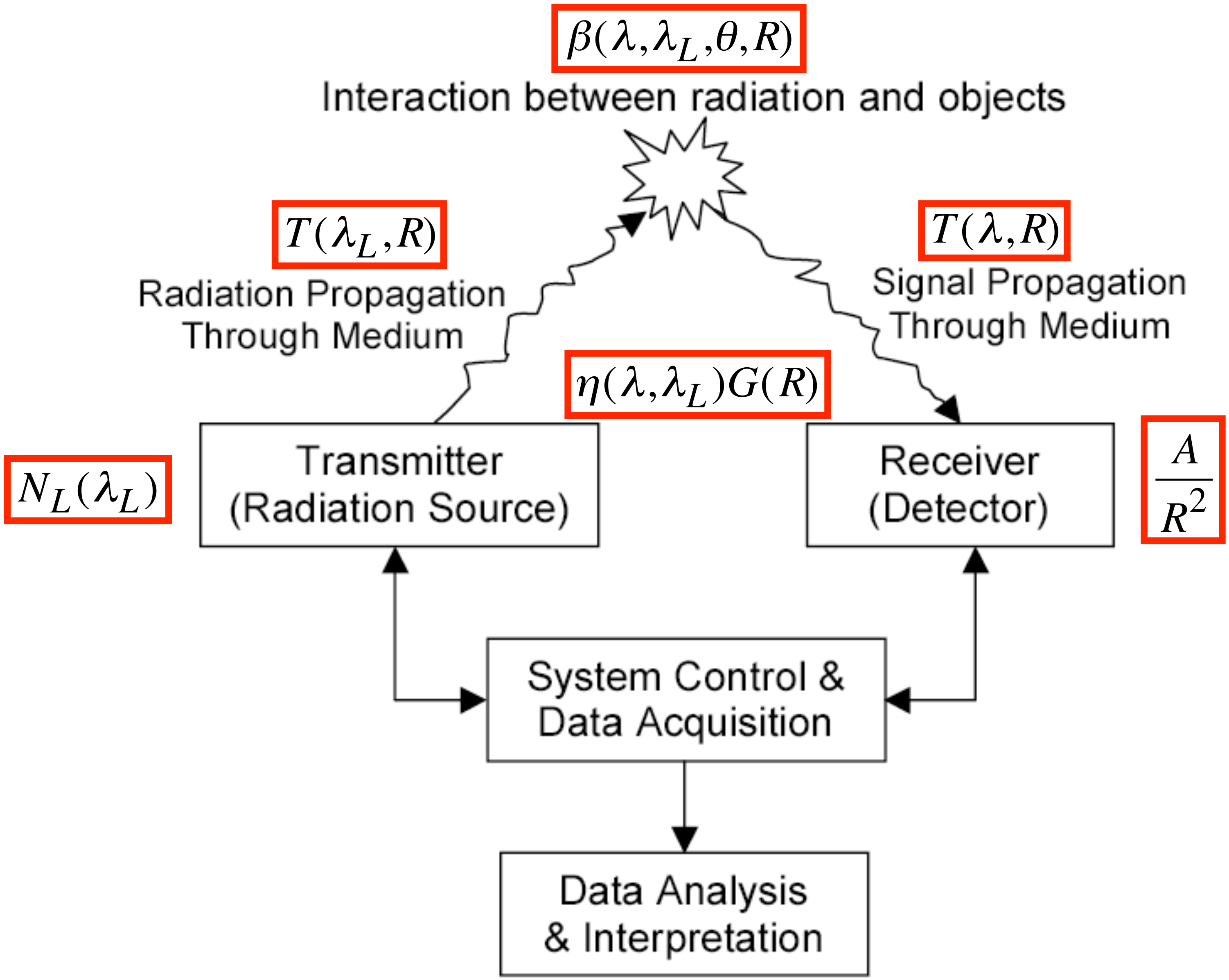
- The lidar equation is based on the physical picture of lidar remote sensing, and derived under two assumptions: independent and single scattering.

- Different lidars may use different forms of the lidar equation, but all come from the same picture.

Picture of Lidar Remote Sensing



Physical Picture in Lidar Equation



Factors in Lidar Equation

The received photon counts N_S are related to the factors

$$N_S(\lambda, R) \propto N_L(\lambda_L)$$ Transmitted laser photon number

$$T(\lambda_L, R)$$ Laser photon transmission through medium

$$\beta(\lambda, \lambda_L, \theta, R)$$ Probability of a transmitted photon to be scattered

$$T(\lambda, R)$$ Signal photon transmission through medium

$$\frac{A}{R^2}$$ Probability of a scattered photon to be collected

$$\eta(\lambda, \lambda_L) G(R)$$ Lidar system efficiency and geometry factor

Considerations for Lidar Equation

- In general, the interaction between the light photons and the particles is a scattering process.
- The expected photon counts are proportional to the product of the

(1) transmitted laser photon number,

(2) probability that a transmitted photon is scattered,

(3) probability that a scattered photon is collected,

(4) light transmission through medium, and

(5) overall system efficiency.

- Background photon counts and detector noise also contribute to the expected photon counts.

Fundamental Lidar Equation

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

- **N_S -- expected photon counts detected at λ and R**
- **1st term -- the transmitted laser photon number;**
- **2nd term -- the probability of a transmitted photon to be scattered by the objects into a unit solid angle;**
- **3rd term -- the probability of a scatter photon to be collected by the receiving telescope;**
- **4th term -- the light transmission through medium for the transmitted laser and return signal photons;**
- **5th term -- the overall system efficiency;**
- **6th term N_B -- background and detector noise counts.**

Basic Assumptions in Lidar Equation

- The lidar equation is developed under two assumptions: the scattering processes are independent, and only single scattering occurs.
- Independent scattering means that 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 implies that a photon is scattered only once. Multiple scatter is excluded in our consideration.

1st Term: Transmitted Photon Number

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

$$N_L(\lambda_L) = \left(\frac{P_L(\lambda_L)\Delta t}{hc/\lambda_L}\right)$$

$$\frac{\text{Laser Power x time bin length}}{\text{Planck constant x Laser frequency}}$$

$$= \frac{\text{Transmitted laser energy within time bin}}{\text{Single laser photon energy}}$$

= Transmitted laser photon number within time bin length

2nd Term: Probability to be Scattered

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

Angular scattering probability – the probability that a transmitted photon is scattered by scatters into a unit solid angle.

Angular scattering probability =
volume scatter coefficient β
x scattering layer thickness ΔR

Volume Scatter Coefficient β

Volume scatter coefficient β is equal to

$$\beta(\lambda,\lambda_L,R) = \sum_i \left[\frac{d\sigma_i(\lambda_L,\theta)}{d\Omega} n_i(R) p_i(\lambda) \right] \quad (m^{-1}sr^{-1})$$

$\frac{d\sigma_i(\lambda_L)}{d\Omega}$ is the differential scatter cross-section of single particle in species i at scattering angle θ ($m^2 sr^{-1}$)

$n_i(R)$ is the number density of scatter species i (m^{-3})

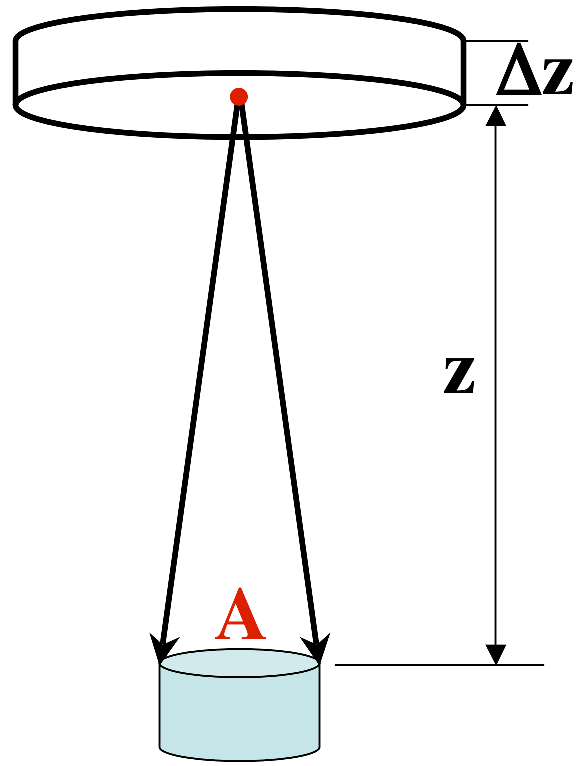
$p_i(\lambda)$ is the probability of the scattered photons falling into the wavelength λ.

Volume scatter coefficient β is the probability per unit distance travel that a photon is scattered into wavelength λ in unit solid angle at angle θ.

3rd Term: Probability to be Collected

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

The probability that a scatter photon is collected by the receiving telescope,
i.e., the solid angle subtended by the receiver aperture to the scatterer.



4th Term: Light Transmission

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

The atmospheric transmission of laser light at outgoing wavelength λ_L and return signal at wavelength λ

Transmission for laser light →

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

Transmission for return signal →

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

Where $\alpha(\lambda_L, R)$ and $\alpha(\lambda, R)$ are extinction coefficients (m^{-1})

Extinction Coefficient α

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

$\sigma_{i,ext}(\lambda)$ is the extinction cross-section of species i

$n_i(R)$ is the number density of species i

Extinction = Absorption + Scattering (Integrated)

$$\sigma_{i,ext}(\lambda) = \sigma_{i,abs}(\lambda) + \sigma_{i,sca}(\lambda)$$

Total Extinction = Aerosol Extinction + Molecule Extinction

$$\alpha(\lambda, R) = \alpha_{aer,abs}(\lambda, R) + \alpha_{aer,sca}(\lambda, R) + \alpha_{mol,abs}(\lambda, R) + \alpha_{mol,sca}(\lambda, R)$$

5th Term: Overall Efficiency

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

$\eta(\lambda,\lambda_L) = \eta_T(\lambda_L)\cdot\eta_R(\lambda)$ is the lidar hardware optical efficiency

e.g., mirrors, lens, filters, detectors, etc

$G(R)$ is the geometrical form factor, mainly concerning the overlap of the area of laser irradiation with the field of view of the receiver optics

6th Term: Background Noise

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

N_B is the expected photon counts due to background noise (e.g., solar scattering) and detector and circuit shot noise.

Different Forms of Lidar Equation

- The main difference between upper and lower atmosphere lidars lies in the treatment of backscatter coefficient and atmosphere transmission (extinction).
- Upper atmosphere lidar cares about the backscatter coefficient more than anything else, because (1) the lower atmosphere transmission is cancelled out during Rayleigh normalization, and (2) the extinction caused by atomic absorption can be precisely calculated, thus, extinction is not an issue to upper atmosphere lidar.
- Lower atmosphere lidar relies on both backscatter coefficient and atmospheric extinction, as these are what they care about or something that cannot be cancelled out.

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

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

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

Fluorescence Form of Lidar Equation

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

- Here, $T_c(R)$ is the extinction coefficient caused by the absorption.

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

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

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

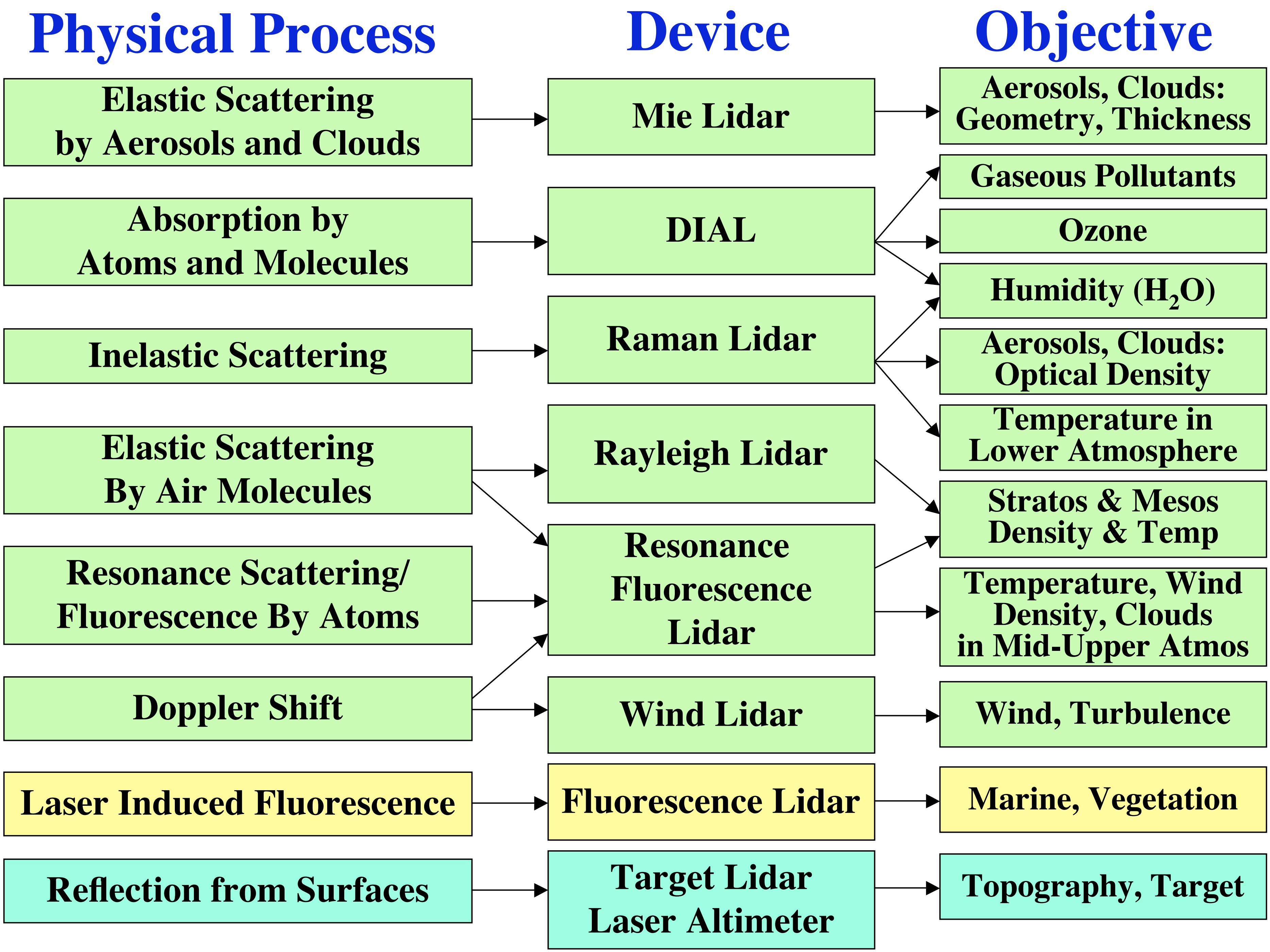
- Resonance fluorescence and laser-induced-fluorescence are NOT instantaneous processes, but have delays due to the radiative lifetime of the excited states.

Classifications of Lidar

There are several different classifications on lidars

e.g., based on the physical process;
(Mie, Rayleigh, Raman, Res. Fluorescence, …)
based on the platform;
(Groundbased, Airborne, Spaceborne, …)
based on the detection region;
(Atmosphere, Ocean, Solid Earth, Space, …)
based on the emphasis of signal type;
(Ranging, Scattering, …)
based on the topics to detect;
(Aerosol, Constituent, Temp, Wind, Target, …)

… …


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

Classification on Platform

Spaceborne lidar	Satellite, Space Shuttle. Space Station
Airborne lidar	Jet, Propeller Airplanes Unmanned Aerial Vehicle (UAV) Kite
Groundbased lidar	Stationary Contanerized moved with truck
Shipborne lidar	Icebreaker, Ships
Submarine lidar	Submarine

Detection Regions

Atmosphere lidar	Various types From various platforms
Hydrosphere lidar	Various types From various platforms
Solid Earth lidar	Airborne or Spaceborne Laser altimeter
Target lidar	Various type With or without Imaging function

Emphasis on Signal Type

Scattering Lidar → Besides time delay, more interested in signal strength, spectra, etc

Ranging/Profiling Lidar → Mainly concern Time delay between transmission and reception

Various Topics

Aerosol/Cloud lidar

Constituent lidar

Temperature lidar

Wind lidar

Target lidar

… … … …

Lidar Classifications on Challenge

Middle and Upper Atmosphere Lidar

Long range - weak signal
Accurate knowledge about atoms
Accurate knowledge of transmitter
Accurate knowledge of receiver
Demanding requirements on lasers

Lower Atmosphere Lidar

Many factors involved together
Aerosols play a key role, also add the difficulty to lower atmosphere

Target lidar

Precise determination of altitude is a great challenge, as many factors are involved.

Summary

- Lidar equation is the fundamental equation governing the lidar remote sensing field.
- Lidar equation relates the received photon counts to the transmitted laser photon numbers, light transmission through medium, probability of a transmitted photon to be scattered, properties of scatters, probability of a scattered photon to be collected, and lidar system efficiency and geometry factors.
- Different lidars may use different forms of the lidar equation, depending on the needs and emphasis.
- Classifications of lidars can have different categories.