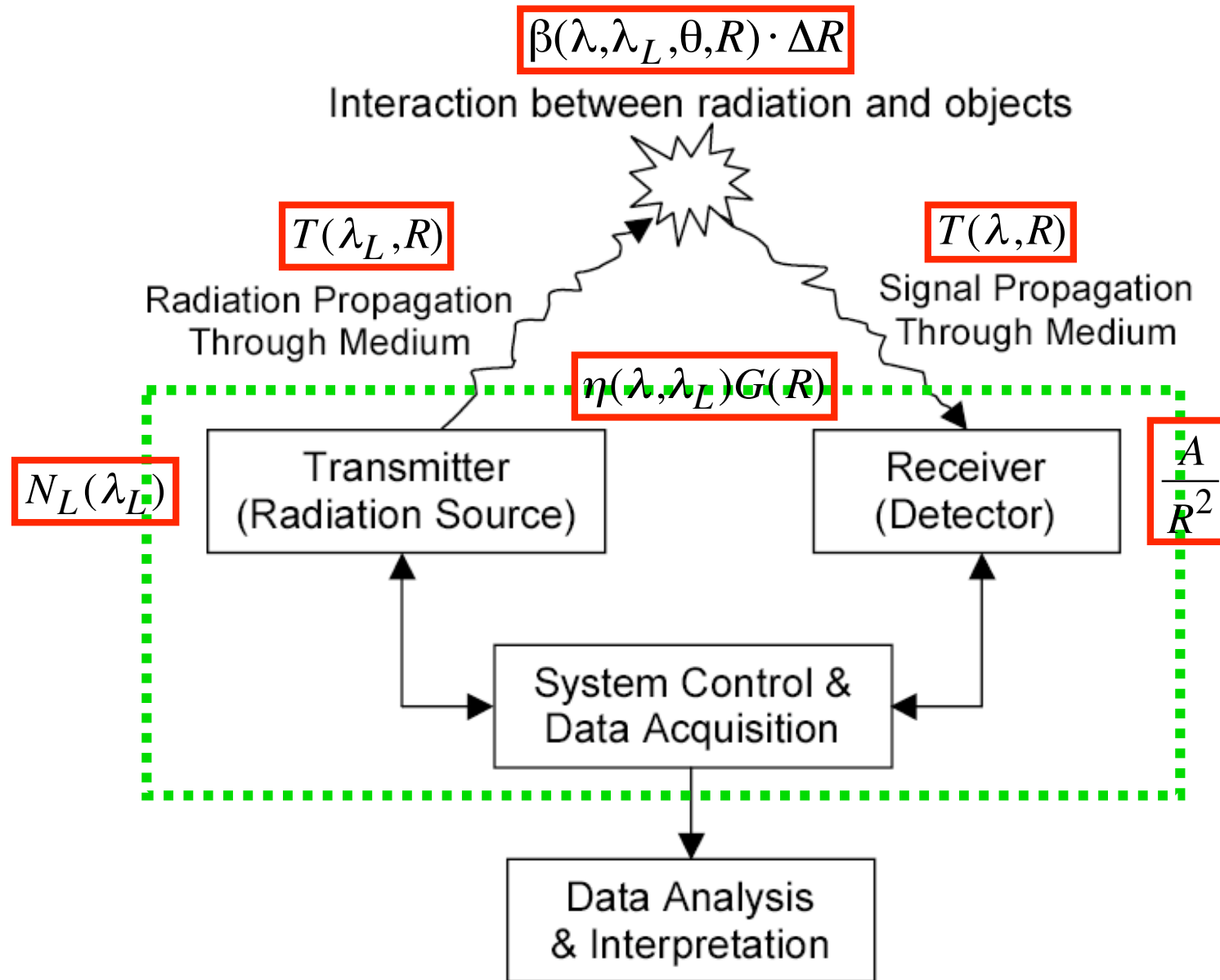


Lecture 08. Lidar Simulation - Application of Lidar Equation

- ❑ Review lidar fundamentals
- ❑ How to start lidar simulation?
- ❑ Lidar parameters and atmosphere parameters
- ❑ Simulation of resonance fluorescence return
- ❑ Simulation of Rayleigh scattering return
- ❑ K lidar signal estimate from lidar equation
- ❑ Summary

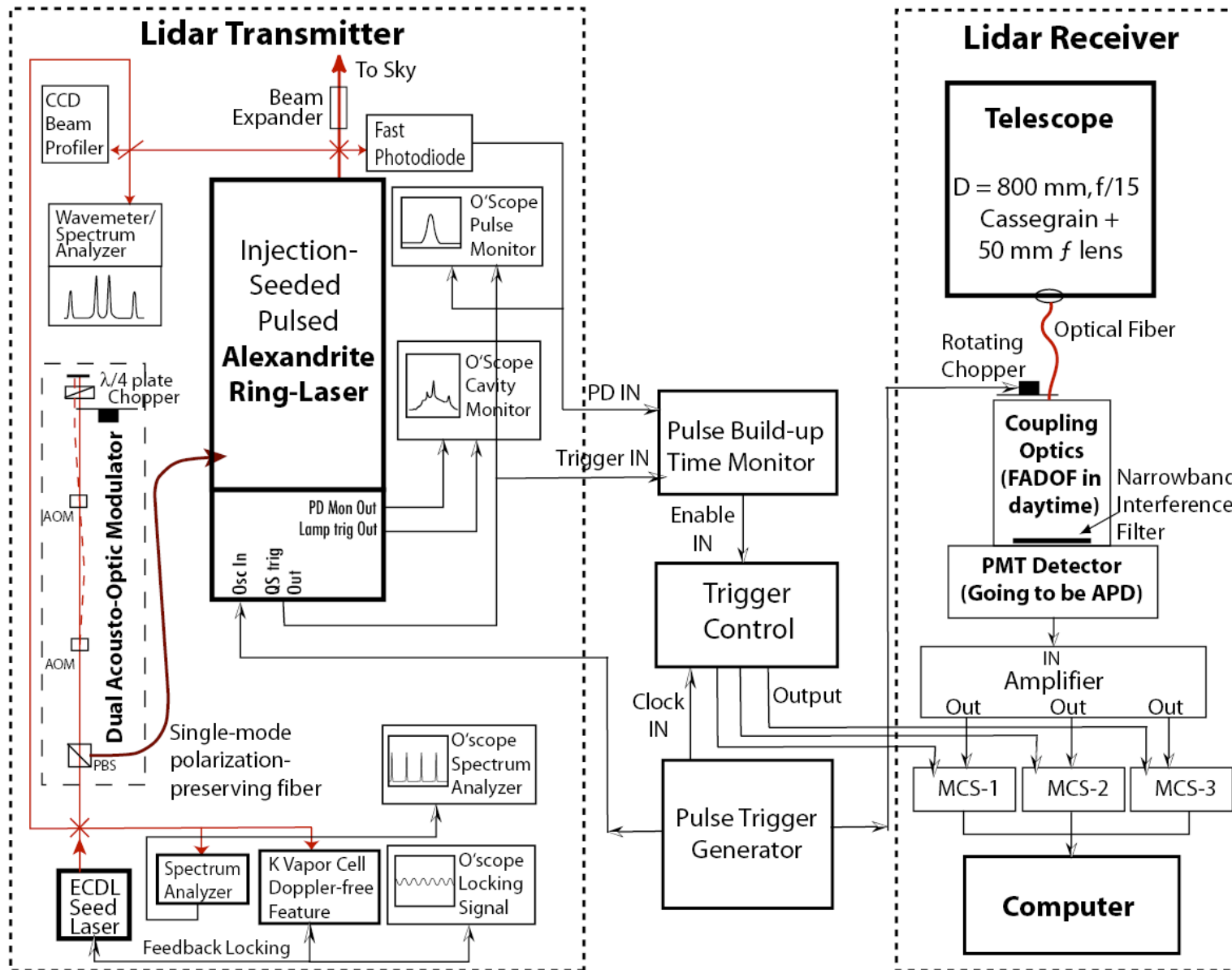
Review of Lidar Fundamentals



Review Lidar Architecture

- ❑ Basic architecture: three subsystems
 1. Lidar Transmitter
 2. Lidar Receiver
 3. Data Acquisition and Control System
- ❑ Basic function of each subsystem
- ❑ Major components for each subsystem
 - **Transmitter**: laser(s), collimating and steering mirrors, diagnostic equipment, wavelength control
 - **Receiver**: telescope(s), collimating optics, filters, photo-detectors
 - **DAQ and Control**: discriminator, multichannel scaler, DAQ card and code, computer, electronics for trigger control, timing control, etc.

Arecibo K Lidar Architecture



Review Lidar Equation

- Lidar equation is to link the expected lidar returns (N_R) to the lidar parameters (both transmitter and receiver), transmission through medium, physical interactions between light and objects, and background/noise conditions, etc.
- Keep in mind the big picture of a lidar system -
 - Radiation source
 - Radiation propagation in the medium
 - Interaction with the objects
 - Signal propagation in the medium
 - Photons are collected and detected

Can you derive a lidar equation by yourself?

Various Forms of Lidar Equations

- General lidar equation with angular scattering coefficient

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

- General lidar equation with total scattering coefficient

$$N_S(\lambda, R) = N_L(\lambda_L) \cdot [\beta_T(\lambda, \lambda_L, R) \Delta R] \cdot \frac{A}{4\pi R^2} \cdot [T(\lambda_L, R) T(\lambda, R)] \cdot [\eta(\lambda, \lambda_L) G(R)] + N_B$$

- Lidar equation for Rayleigh lidar

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

- Lidar equation for resonance fluorescence lidar

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

How to Start Lidar Simulation?

- ❑ Lidar simulation of return signals is a direct application of lidar equation involving physical processes.
- ❑ Let us start with the Arecibo K Doppler lidar as an example.
- ❑ 1st, write down all fundamental constants used in lidar.
- ❑ 2nd, gather lidar, atomic/molecular & atmosphere parameters.
- ❑ 3rd, start with the laser source of transmitter and follow the lidar picture from transmitted photons, through atmosphere transmission, backscatter probability, collection probability, and receiver efficiency, to detected photon numbers.
- ❑ 4th, understand the physical process of light interaction with objects to calculate the backscatter probability.
- ❑ 5th, background estimate considering many factors (both atmosphere conditions and lidar parameters like filter, FOV, ...)
- ❑ 6th, get the final results and verify them with reality.

Fundamental Constants in Lidar

- ❑ Fundamental constants for lidar simulation
- 1) Light speed in vacuum c
- 2) Planck constant h
- 3) Boltzmann constant k_B
- 4) Elementary charge e
- 5) Electron mass m_e
- 6) Proton mass m_p
- 7) Electric constant ϵ_0
- 8) Magnetic constant μ_0
- 9) Avogadro constant N_A
- 10)

Lidar Parameters

- ❑ Lidar parameters for lidar simulation
 - 1) Laser pulse energy, repetition rate, pulse duration,
 - 2) Laser central wavelength, linewidth, chirp
 - 3) Laser divergence angle
 - 4) Transmitter mirror reflectivity
 - 5) Telescope primary mirror diameter and reflectivity
 - 6) Telescope/receiver field-of-view (FOV)
 - 7) Receiver mirrors' transmission,
 - 8) Fiber coupling efficiency, transmission
 - 9) Filter peak transmission, bandwidth, out-of-band rejection
 - 10) Detector quantum efficiency and maximum count rate
 - 11)

Atomic or Molecular Parameters

- Atomic and molecular parameters for lidar simulation
 - 1) Atomic energy level structure, degeneracy
 - 2) Spontaneous transition rate A_{ki} , oscillator strength f
 - 3) Atomic mass or molecular weight
 - 4) Resonance frequency or wavelength
 - 5) Isotope shift, abundance, line strength
 - 6)

Atmosphere Parameters

- ❑ Atmosphere parameters for lidar simulation
 - 1) Lower atmosphere transmission
 - 2) Atmosphere number density
 - 3) Atmosphere pressure and temperature
 - 4) Species number density or column abundance
 - 5) Background sky radiance, solar angle, base altitude, etc.
 - 6)

Simulation of Resonance Fluorescence

- ❑ Besides common issues in lidar simulation, the main point in simulation of resonance fluorescence return is to correctly estimate the effective cross section and column abundance / density of these atomic species, e.g., K.
- ❑ Effective scattering cross section can be affected by laser central frequency, linewidth, saturation, optical pumping, branching ratio, Hanle effect, etc.
- ❑ Correct estimate of this involves comprehensive understanding of the physical process and spectroscopy knowledge - This is why spectroscopy class is important!
- ❑ Column abundance and density vary with season, latitude, and are also affected by waves etc. Usually we use a mean column abundance as a representative.

Simulation of Rayleigh Return

- ❑ This is relatively simpler compared to resonance fluorescence, because the Rayleigh scatter is straightforward.
- ❑ The key is to correctly estimate the Rayleigh backscatter cross section and atmosphere number density.
- ❑ Usually atmosphere number density can be taken from standard US atmosphere or MSIS model. MSIS number density varies with season and location.
- ❑ Estimate of atmosphere transmission or extinction is also very important. If going to lower atmosphere, it could be tricky as scattering from aerosols may interfere the lidar return signals.

Rayleigh Backscatter Cross Section

□ It is common in lidar field to calculate the Rayleigh backscatter cross section using the following equation

$$\frac{d\sigma_m(\lambda)}{d\Omega} = 5.45 \cdot \left(\frac{550}{\lambda}\right)^4 \times 10^{-32} \left(m^2 sr^{-1}\right)$$

where λ is the wavelength in nm.

□ The Rayleigh backscatter cross section can also be estimated from the Rayleigh backscatter coefficient

$$\beta_{Rayleigh}(\lambda, z, \theta = \pi) = 2.938 \times 10^{-32} \frac{P(z)}{T(z)} \cdot \frac{1}{\lambda^{4.0117}} \left(m^{-1} sr^{-1}\right)$$

where λ is the wavelength in meter, P in mbar, T in Kelvin.

$$\therefore \frac{d\sigma_m(\lambda)}{d\Omega} = \frac{\beta_{Rayleigh}(\lambda, z, \pi)}{n_{atmos}(z)} \left(m^2 sr^{-1}\right)$$

Arecibo K Lidar Estimate

- We want to use the fundamental lidar equation to estimate the detected photon counts of return K signals using the Arecibo K lidar parameters.
- This is the first step for lidar simulations to assess a lidar potential and system performance.
- Let us start with the general lidar equation

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

- Resonance fluorescence lidar uses the lidar equation

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

Lidar Estimate Procedure (1)

- First, estimate the transmitted laser photon numbers for single lidar pulse

$$N_L(\lambda_L) = \frac{P_L(\lambda_L)\Delta t}{hc/\lambda_L} = \frac{E_{pulse}}{hc/\lambda_L}$$

- Arecibo K Doppler lidar parameters:

Laser pulse energy: $E_{pulse} = 100 \text{ mJ}$

Laser central wavelength: $\lambda_L = 770.1088 \text{ nm}$

- h is Planck constant and c is light speed

- Therefore, a single lidar pulse sends out photons of

$$N_L = 3.88 \times 10^{17}$$

Lidar Estimate Procedure (2)

- Second, consider the transmitter steering mirror reflectivity and atmosphere transmission, and estimate the number of laser photons that reach K layers

$$N_{Trans} = N_L \cdot R_{Tmirror} \cdot T_{atmos}$$

- Arecibo K Doppler lidar parameters:

Transmitter mirrors: 3 mirrors @ R = 99.8%

$$\Rightarrow R_{tmirror} = (0.998)^3 = 0.994$$

- Lower atmosphere transmission at 770 nm:

$$T_{atmos} = 80\%$$

- Therefore, the number of photons reaching K layers

$$N_{Trans} = 3.08 \times 10^{17}$$

Lidar Estimate Procedure (3)

- Third, consider the absorption and spontaneous emission procedure, estimate scattering probability and estimate the number of resonance fluorescence photons produced by entire K layers (ignoring extinction in K)

$$N_{Fluorescence} = N_{Trans} \cdot P_{scattering} = N_{Trans} \cdot \sigma_{eff} \cdot KAbdn$$

- Peak effective cross-section of K D_{1a} line:

$$\sigma_{eff} = 10 \times 10^{-16} \text{ m}^2$$

- K layer column abundance:

$$KAbdn = 6 \times 10^7 \text{ cm}^{-2} = 6 \times 10^{11} \text{ m}^{-2}$$

- The scattering probability is given by:

$$P_{scattering} = \sigma_{eff} \times KAbdn = 6 \times 10^{-4}$$

- Therefore, the number of fluorescence photons

$$N_{Fluorescence} = 1.85 \times 10^{14}$$

Lidar Estimate Procedure (4)

- Fourth, consider the atmosphere transmission for return signals and estimate the number of fluorescence photons that reach the sphere surface at receiver range

$$N_{Sphere} = N_{Fluorescence} \cdot T_{atmos}$$

- Lower atmosphere transmission at 770 nm:

$$T_{atmos} = 80\%$$

- Note: we ignore the extinction caused by K layers

- Thus, the number of photons reaching the sphere

$$N_{Sphere} = 1.48 \times 10^{14}$$

Lidar Estimate Procedure (5)

□ Fifth, consider the telescope primary mirror area, estimate the collection probability, and estimate the number of photons reaching the primary mirror

$$N_{\text{Primary}} = N_{\text{Sphere}} \cdot P_{\text{collection}} = N_{\text{Sphere}} \cdot \frac{A}{4\pi R^2}$$

□ Arecibo K lidar telescope: primary mirror diameter

$$D = 80 \text{ cm} \Rightarrow A = 0.50 \text{ m}^2$$

□ K layer centroid altitude:

$$R = 90 \text{ km} = 9 \times 10^4 \text{ m}$$

□ The collection probability is given by:

$$P_{\text{collection}} = A/(4\pi R^2) = 4.94 \times 10^{-12}$$

□ Therefore, the number of photons reaching the

primary mirror: $N_{\text{Sphere}} = 730.8$

Lidar Estimate Procedure (6)

- Sixth, estimate the receiver efficiency considering primary mirror reflectivity, collimating optics transmission, filter transmission, and PMT QE

$$\eta_{receiver} = R_{primary} \cdot \eta_{fiber} \cdot T_{Rmirror} \cdot T_{IF} \cdot QE$$

- Arecibo K lidar receiver parameters:

primary mirror reflectivity

$$R_{primary} = 91\%$$

Fiber coupling efficiency

$$\eta_{fiber} = 75\%$$

receiver mirror transmittance

$$T_{Rmirror} = 74\%$$

Interference filter peak transmission

$$T_{IF} = 80\%$$

PMT quantum efficiency

$$QE = 15\%$$

- Therefore, the receiver efficiency is

$$\eta_{receiver} = 6.06\%$$

Lidar Estimate Procedure (7)

- Seventh, consider the receiver efficiency and estimate the number of photons detected by PMT

$$N_{S(K)} = N_{primary} \cdot \eta_{receiver}$$

- Using the results from steps 5th and 6th,

$$N_{S(K)} = 730.8 \times 6.06\% = 44.3$$

- Therefore, the number of photons detected by PMT, (i.e., the K lidar return signal counts), for each single lidar pulse from the entire K layers are

$$N_{S(K)} = 44.3$$

- Note: these photon counts originate from 3.88×10^{17} laser photons!!!

Comparison to Actual Lidar Return

- ❑ Typical lidar return signals of the Arecibo K Doppler lidar are about 10–50 counts per shot from the entire K layers, depending on seasons and atmosphere conditions.
- ❑ Our estimate is surprisingly close to the actual situation – K lidar people have tried their best to measure the system efficiencies precisely.
- ❑ From this estimate, how do you feel about the upper atmosphere lidar: What is the major killer of the signal strength?

Long range - weak signal !

Summary

- ❑ Lidar simulation is a direct application of lidar equation to practical problems.
- ❑ Our first step demonstrated in this lecture is to estimate the expected lidar returns from lidar parameter, transmittance through medium, physical interaction, etc. More functions of lidar simulation will be discussed in later lectures.
- ❑ The major difficulty in upper atmosphere lidar is the tiny collection efficiency (10^{-12}) caused by the long range (A/R^2) \Rightarrow weak signals.
- ❑ Receiver efficiency is another important factor that must be given careful considerations.

HWK Project #1 Assignment - Estimate of lidar returns
Due on Friday, September 19, 2008