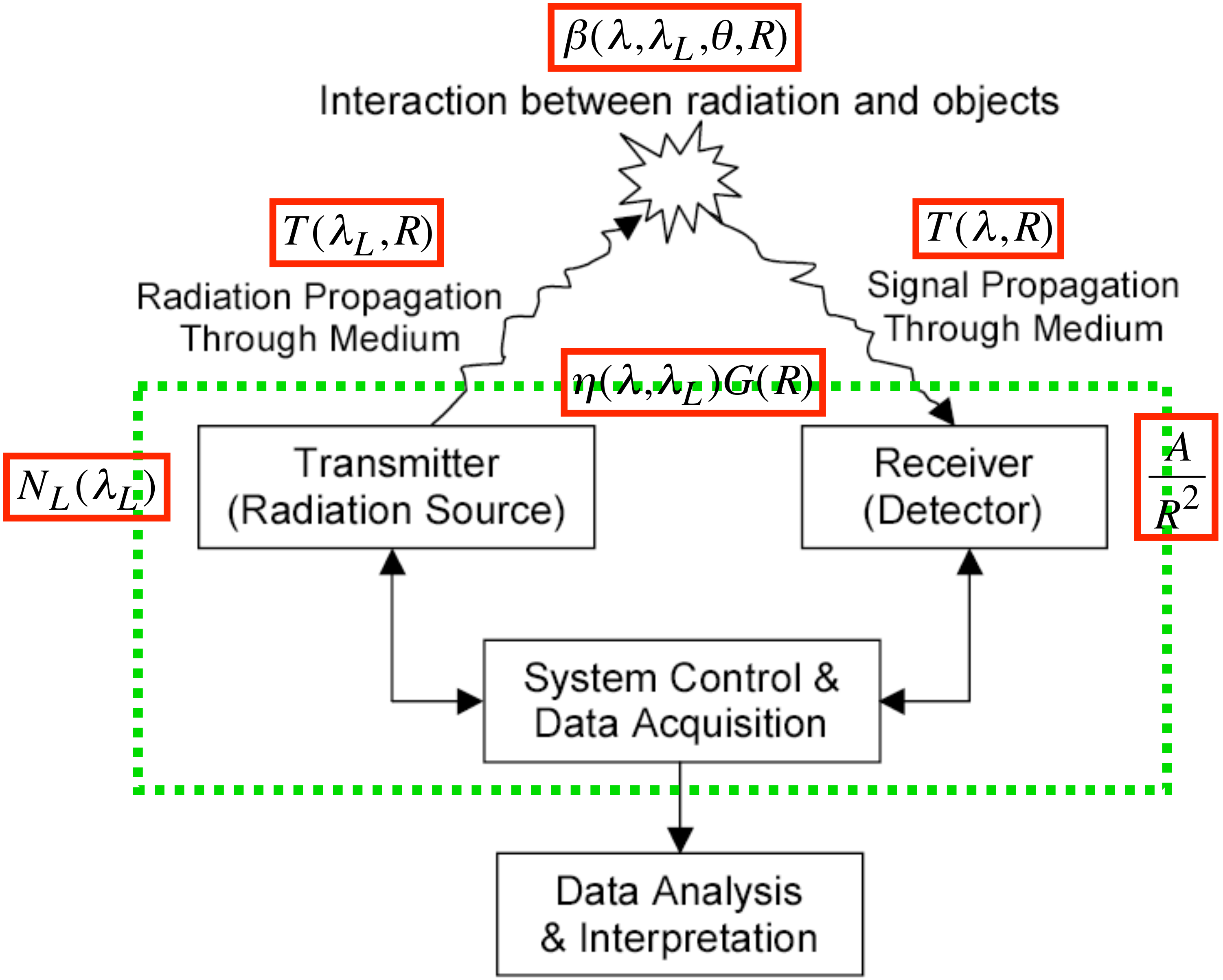
Lecture 05. First Example: A Real Lidar

- ☐ Brief review of lidar basics
- ☐ K Doppler lidar system architecture
- ☐ K lidar signal estimate from lidar equation
- ☐ Comparison of estimate to reality
- ☐ Summary

Review of Lidar Basics



$\beta(\lambda, \lambda_L, \theta, R)$

Interaction between radiation and objects

$T(\lambda_L, R)$

Radiation Propagation Through Medium

$T(\lambda, R)$

Signal Propagation Through Medium

$\eta(\lambda, \lambda_L) G(R)$

$N_L(\lambda_L)$

Transmitter (Radiation Source)

Receiver (Detector)

$\frac{A}{R^2}$

System Control & Data Acquisition

Data Analysis & Interpretation

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.

Review Lidar Equation

☐ Keep in mind the big picture of a lidar system –

Radiation source

Radiation propagation in the medium

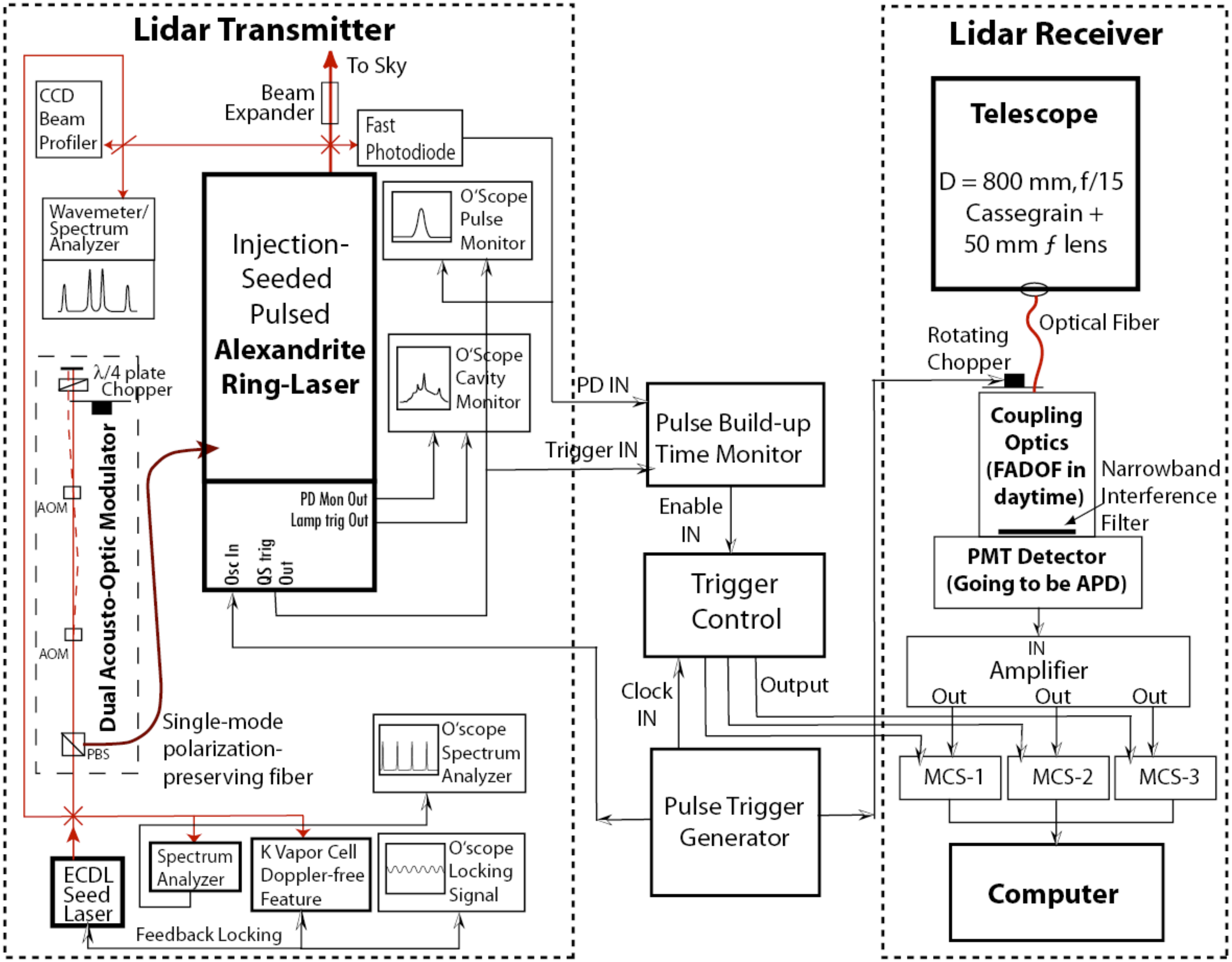
Interaction with the objects

Signal propagation in the medium

Photons are collected and detected

Can you derive a lidar equation by yourself?

Arecibo K Lidar Architecture



Lidar Transmitter

❑ A pulsed alexandrite ring laser
injection seeded by
an external cavity diode laser

❑ Seed laser frequency
is locked to K D1a Doppler-free feature

❑ Twin dual-pass acousto-optic modulators
shift seed laser to two wing frequencies

❑ Diagnostic equipment: CCD beam profiler, fast photo diode, spectrum analyzer, and oscilloscopes,
monitor the spatial, temporal, and spectral features of the lasers to ensure fidelity operation.

Lidar Receiver

- A Cassegrain optical telescope
  - 80-cm in diameter
- An optical fiber
  - couples signals to receiver chain
- A rotating chopper
  - blocks lower atmosphere return
    - to avoid saturating photo detector
- Coupling/collimating optics
- An interference filter and a Faraday filter
  - compress bkg while transmits signals
- A photomultiplier tube (PMT)
  - detects photons in photon counting mode

DAQ and Control System

- Amplifier
  - to amplify PMT signal
- Discriminator
  - to judge whether it is real photon signal
- Multichannel scaler
  - to record data along time bins
- Computer with DAQ card and code
  - to control system and record data
- Trigger control
  - to coordinate the entire system
- Pulse build-up time monitor
  - to preclude signals from bad pulses

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

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

- 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

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

- Arecibo K Doppler lidar parameters:
  Laser pulse energy: E_{pulse} = 100 mJ
  Laser central wavelength: λ_L = 770.1088 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

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

- Arecibo K Doppler lidar parameters:
  Transmitter mirrors: 3 mirrors @ R = 99.8%
  ⇨ $R_{tmirror} = (0.998)^3 = 0.994$
- 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)

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

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

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

- ☐ K layer column abundance:

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

- ☐ The scattering probability is given by:

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

- ☐ Therefore, the number of fluorescence photons

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

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

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

- 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

$$\boxed{N_{\mathrm{Pr}imary} = N_{Sphere} \cdot P_{collection} = N_{Sphere} \cdot \frac{A}{4\pi R^2}}$$

❑ Arecibo K lidar telescope: primary mirror diameter

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

❑ K layer centroid altitude:

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

❑ The collection probability is given by:

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

❑ Therefore, the number of photons reaching the primary mirror: $N_{\mathrm{Sphere}} = 730.8$

Lidar Estimate Procedure (6)

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

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

- 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

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

- ❑ 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

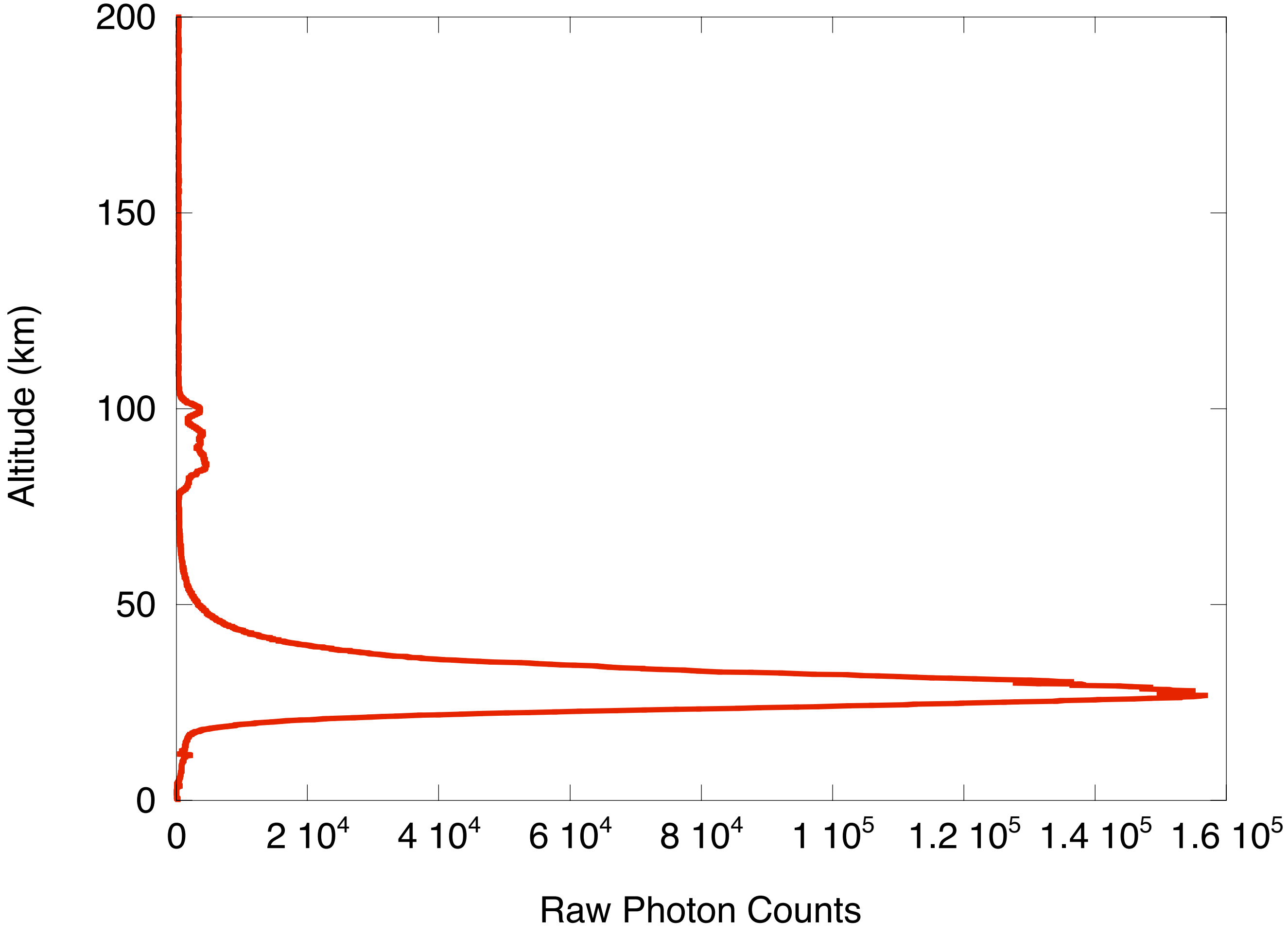
- Typical lidar return signals of the Arecibo K Doppler lidar are about 10-50 counts per shot from the entire K layers, depending on seasons and atmosphere conditions.

- Our estimate is surprisingly close to the actual situation – K lidar people have tried their best to measure the system efficiencies precisely.

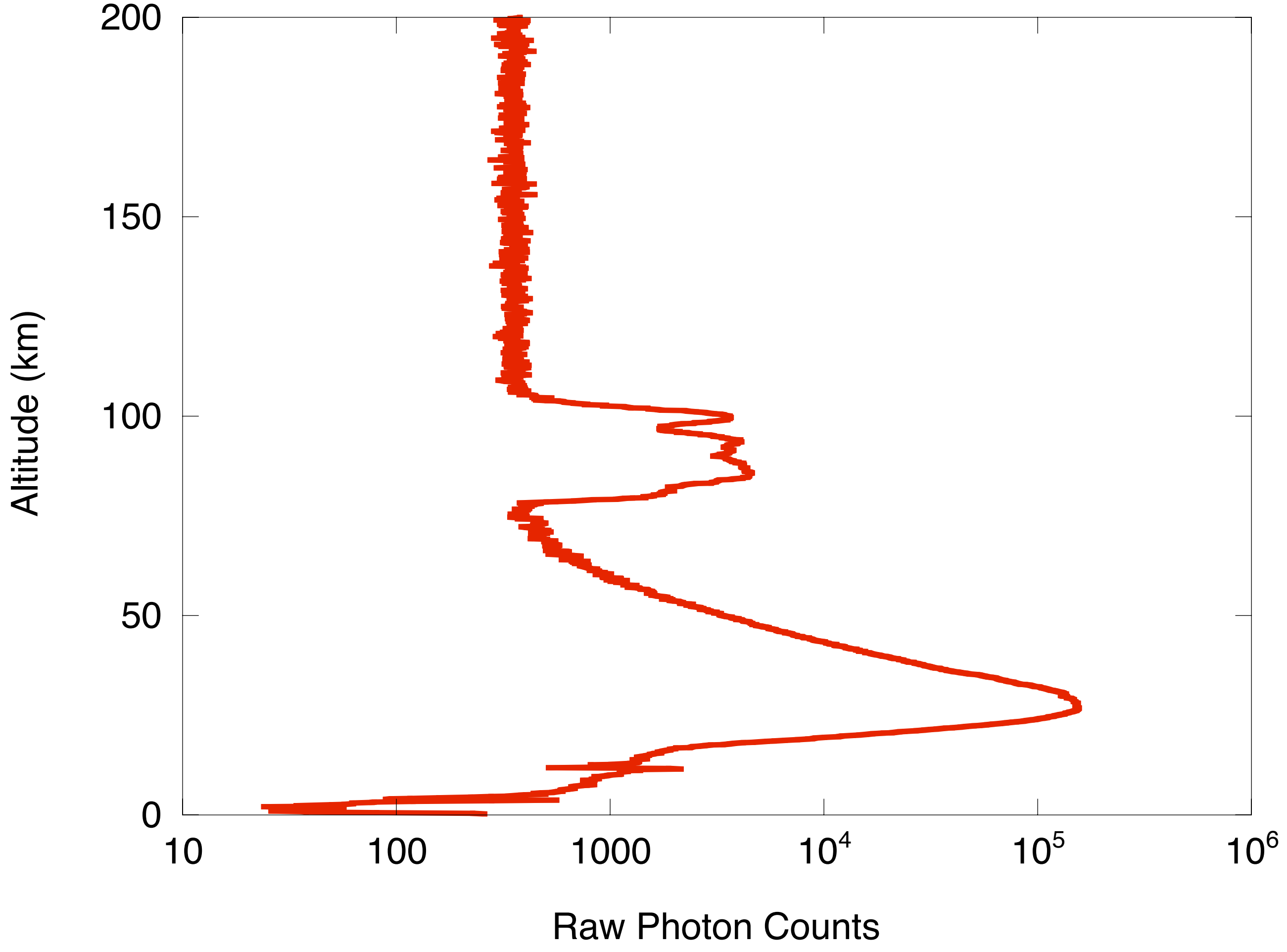
- From this estimate, how do you feel about the upper atmosphere lidar: What is the major killer of the signal strength?

Long range - weak signal !

Rawdata Profile of K Lidar



Rawdata Profile: Log Scale



Summary

- We use a real lidar - the Arecibo K Doppler lidar - as an example to examine the basic concepts of lidar picture, lidar architecture, and lidar equation.

- High level lidar systems are sophisticated, mainly on the transmitter (laser) aspect. But receiver and DAQ also strongly affect system performance.

- The major difficulty in upper atmosphere lidar is the tiny collection efficiency (10^{-12}) caused by the long range (A/R^2) ⇨ weak signals.

- Receiver efficiency is another important factor that must be given careful considerations.