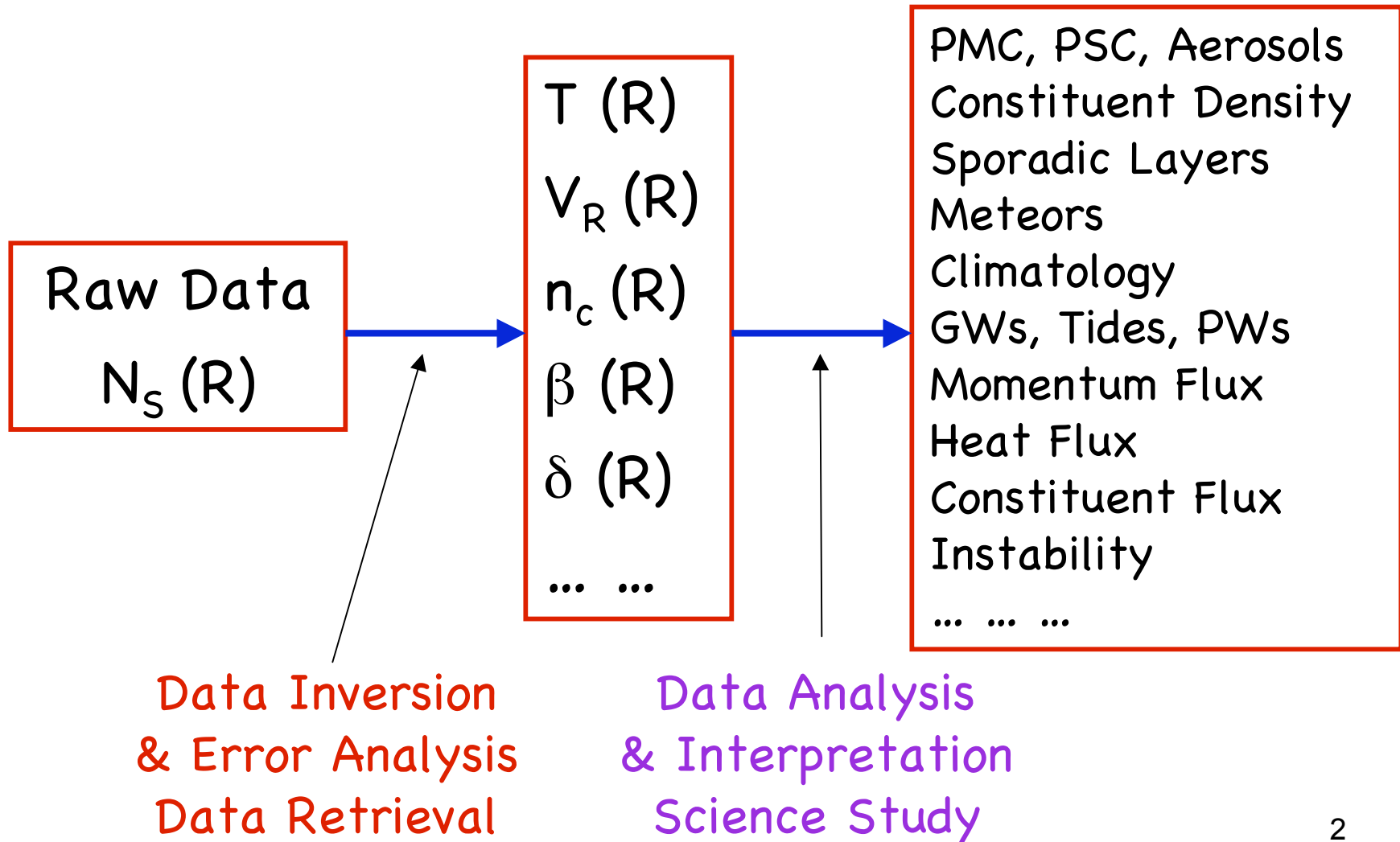


Lecture 13. Lidar Data Inversion (1)

- ❑ Introduction of data inversion
- ❑ Basic ideas (clues) for data inversion
- ❑ Preprocess
- ❑ Summary

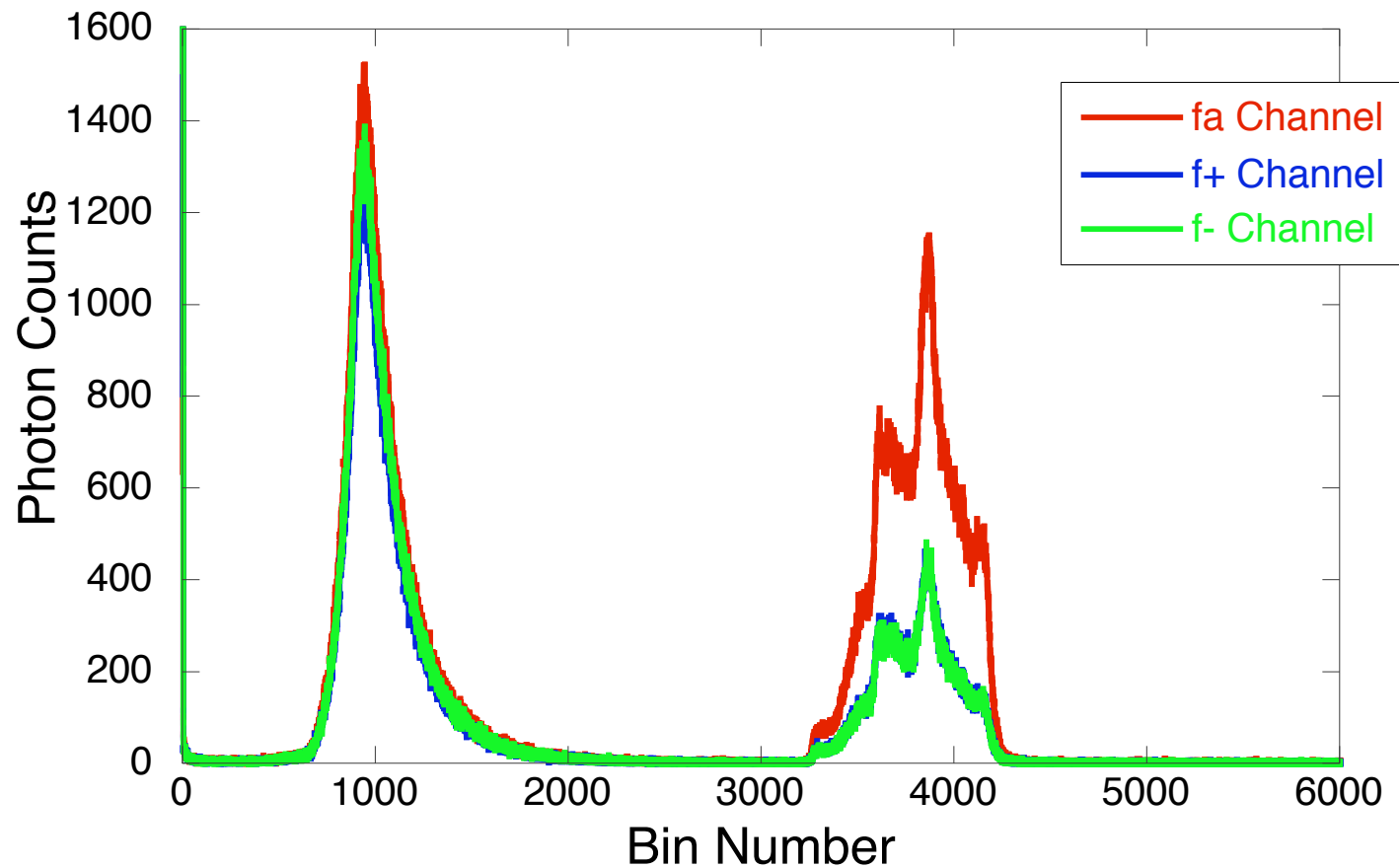
(By Chihoko Yamashita)

From Raw Data to Physical Parameters



Example Lidar Raw Signal

Raw Data Profiles for 3-Frequency Na Doppler Lidar



Introduction: Lidar Data Inversion

- ❑ Lidar data inversion deals with the problems of how to derive meaningful physical parameters from raw photon counts.
- ❑ It is basically a reverse procedure to the development of lidar equation.
- ❑ It is necessary to understand the detailed physical procedure from light transmitting, to light propagation, to light interaction with objects, and to light detection, in order to conduct data inversion correctly.
- ❑ In this lecture we discuss the data inversion for Na Doppler lidar (K and Fe lidar would be similar).

Basic Clue: Lidar Equation & Solution

□ From lidar equation and its solution to derive preprocess procedure of lidar data inversion

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

+

$$N_S(\lambda, z_R) = \left(\frac{P_L(\lambda)\Delta t}{hc/\lambda} \right) \left[\sigma_R(\pi, \lambda)n_R(z_R) \right] \Delta z \left(\frac{A}{z_R^2} \right) T_a^2(\lambda, z_R) (\eta(\lambda)G(z_R)) + N_B$$

↓

$$N_{Norm}(\lambda, z) = \frac{N_{Na}(\lambda, z)}{N_R(\lambda, z_R)T_c^2(\lambda, z)} \frac{z^2}{z_R^2} = \frac{N_S(\lambda, z) - N_B - N_R(\lambda, z)}{[N_S(\lambda, z_R) - N_B]T_c^2(\lambda, z)} \frac{z^2}{z_R^2} \\ = \left[\frac{N_S(\lambda, z) - N_B}{N_S(\lambda, z_R) - N_B} \frac{z^2}{z_R^2} - \frac{n_R(z)}{n_R(z_R)} \right] \frac{1}{T_c^2(\lambda, z)}$$

Considerations in Data Inversion

□ How to obtain associated information like date, time, location, base altitude, operation conditions?

-- from data header and other info source

□ How to obtain range or altitude information?

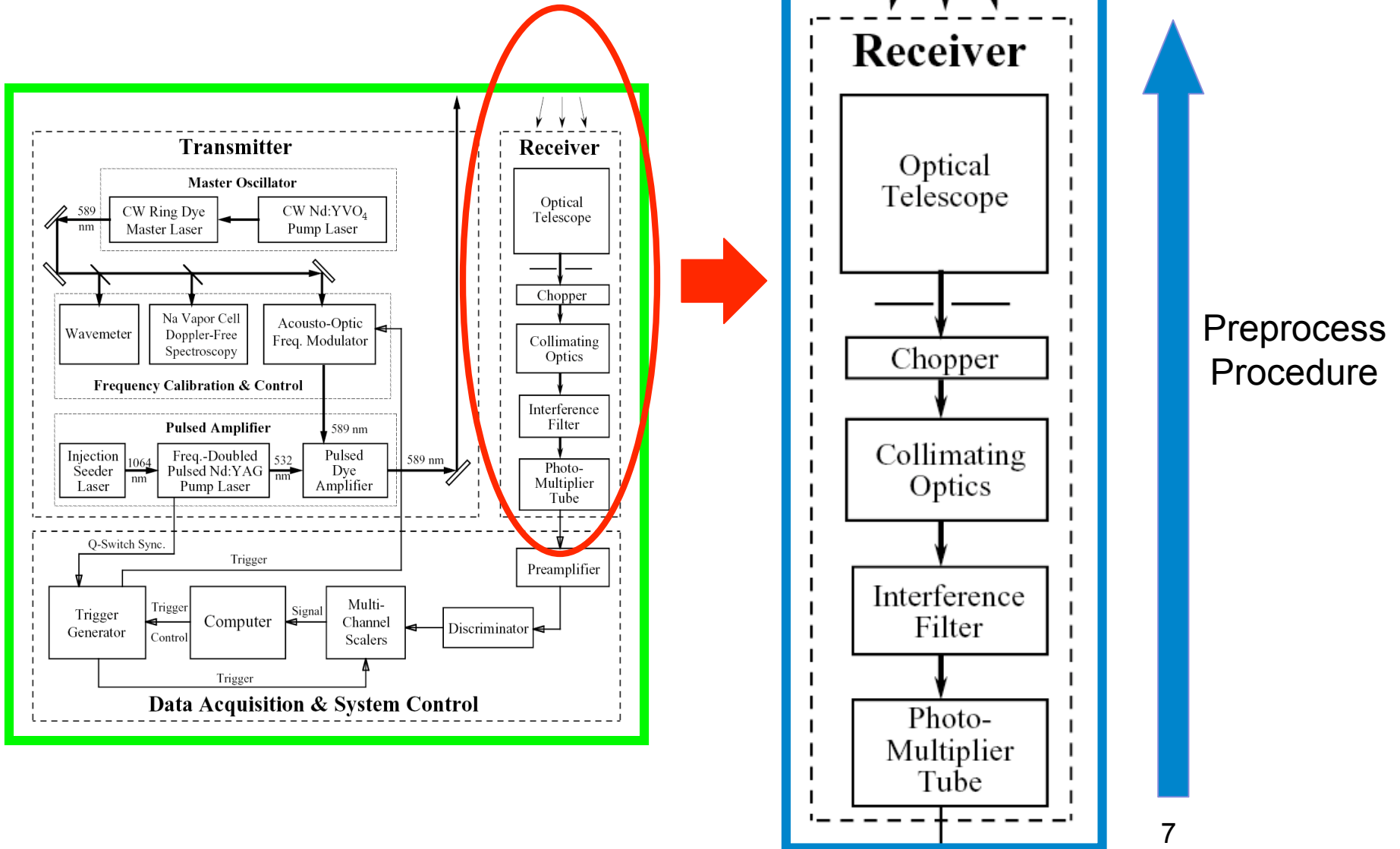
-- from bin number, data header and other source

$$R = n_{bin} \cdot t_{bin} \cdot c / 2$$

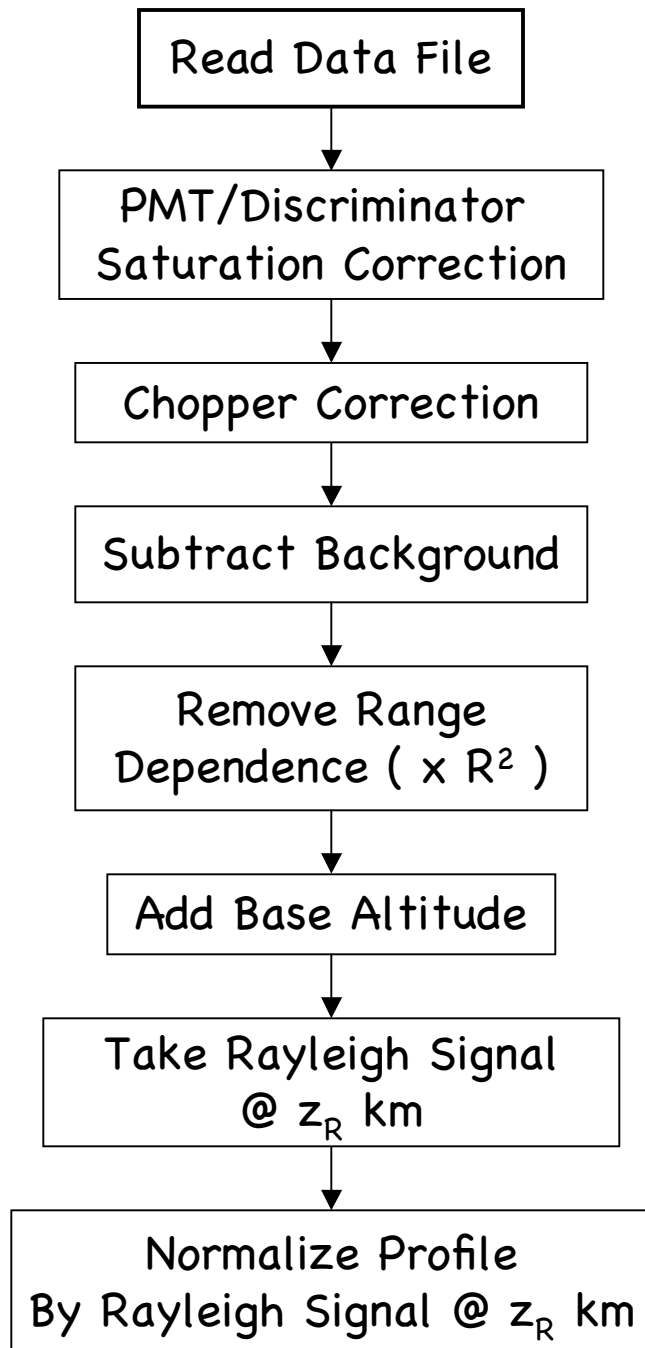
$$z = R \cdot \cos \theta + z_{base}$$

R is range, n_{bin} is bin number, t_{bin} is bin width in time, c is light speed, z is absolute altitude, θ is off-zenith angle, and z_{base} is the base altitude relative to sea-level.

Na Doppler Lidar Schematic



Preprocess Procedure for Na Doppler Lidar



- ❑ Read data: for each set, and calculate T, W, and n for each set
- ❑ PMT/Discriminator saturation correction
- ❑ Chopper correction
- ❑ Background estimate and subtraction
- ❑ Range-dependence removal (not altitude)
- ❑ Base altitude adjustment
- ❑ Take Rayleigh signal @ z_R (Rayleigh fit or Rayleigh sum)
- ❑ Rayleigh normalization

$$N_N(\lambda, z) = \frac{N_S(\lambda, z) - N_B \frac{z^2}{z_R^2}}{N_S(\lambda, z_R) - N_B \frac{z_R^2}{z_R^2}}$$

Preprocess Procedure

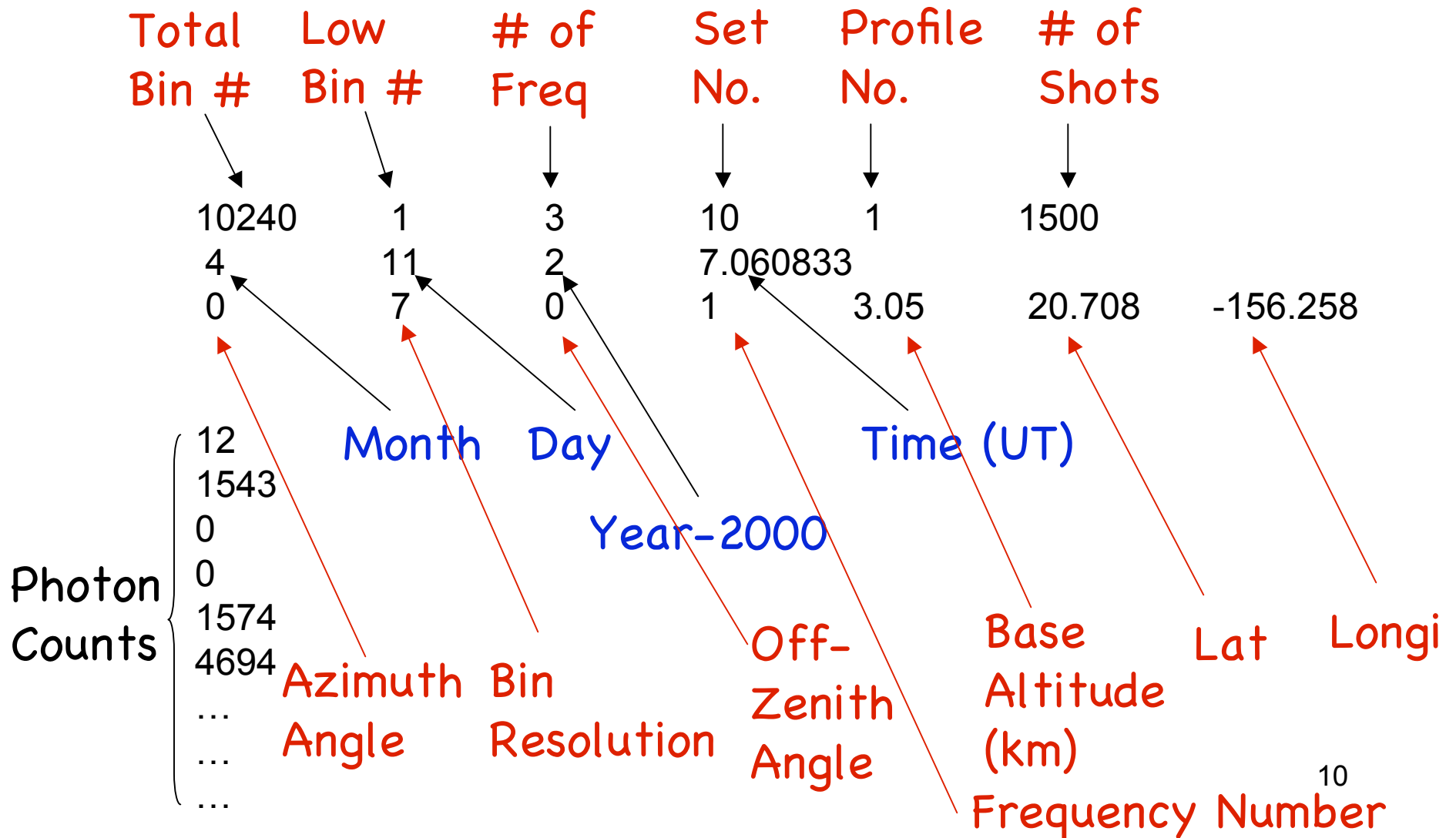
- ❑ Indicated from the lidar equation and its solution, the preprocess for Na Doppler lidar data is
 - Background estimation and subtraction ($- N_B$)
 - Range-dependence removal ($\times R^2$)
 - Rayleigh normalization [$1/(N_S(z_R)-N_B)$]
 - Rayleigh subtraction [$- n_R(z)/n_R(z_R)$]

- ❑ More considerations on lidar hardware and detection - extra preprocess procedure
 - PMT and discriminator saturation correction
 - Chopper or electronic gain correction

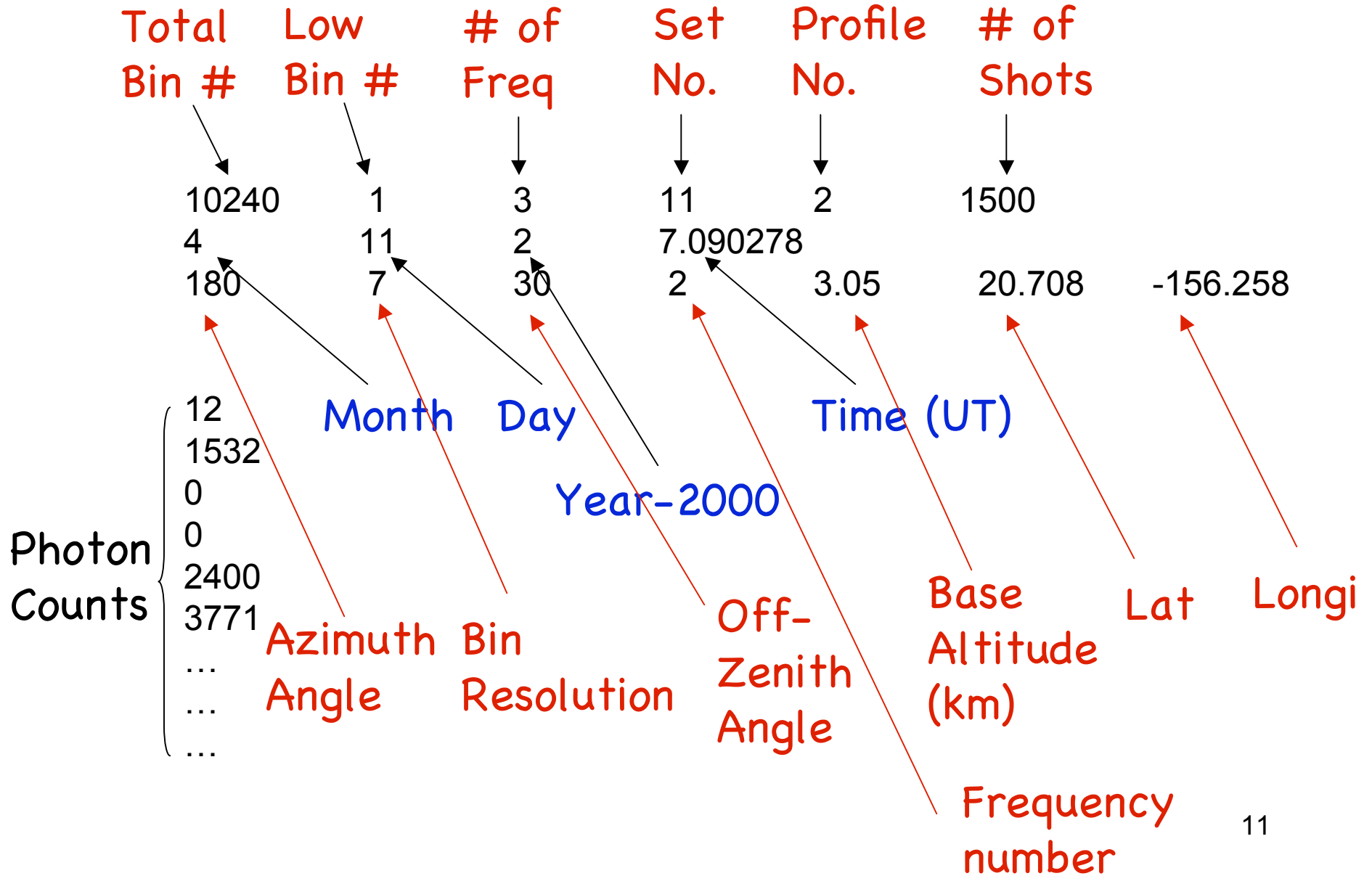
Step1. Read Raw Data

Common Raw Data Format of Lidar

☐ Headers + One Column Photon Counts (ASCII or Binary)



Another Example of Lidar Raw Data



Step2

Nonlinearity of PMT + Discriminator

For small input photon flux, PMT output photon counts are proportional to the input photon counts:

$$\lambda_{oP} = \lambda_S = \lambda_i \eta_{QE}$$

When the input photon flux is considerably large, the output photon counts are no longer linear with input photons. Nonlinearity of PMT occurs:

$$\lambda_{oP} = \lambda_S e^{-\lambda_S \tau_p}$$

A discriminator is used to judge real photon signals and also has a saturation effect, i.e., its output photon counts are smaller than input photon counts when input count rate is large:

$$\lambda_o = \frac{\lambda_{iD}}{1 + \lambda_{iD} \tau_d}$$

Nonlinearity of PMT + Discriminator

Since PMT output is the input of discriminator

$$\lambda_{iD} = \lambda_{oP}$$

we obtain

$$\lambda_o = \frac{\lambda_S e^{-\lambda_S \tau_p}}{1 + \lambda_S \tau_d e^{-\lambda_S \tau_p}} = \frac{\lambda_S e^{-\lambda_S \tau_p}}{1 + \lambda_S \tau_d e^{-\lambda_S \tau_p}}$$

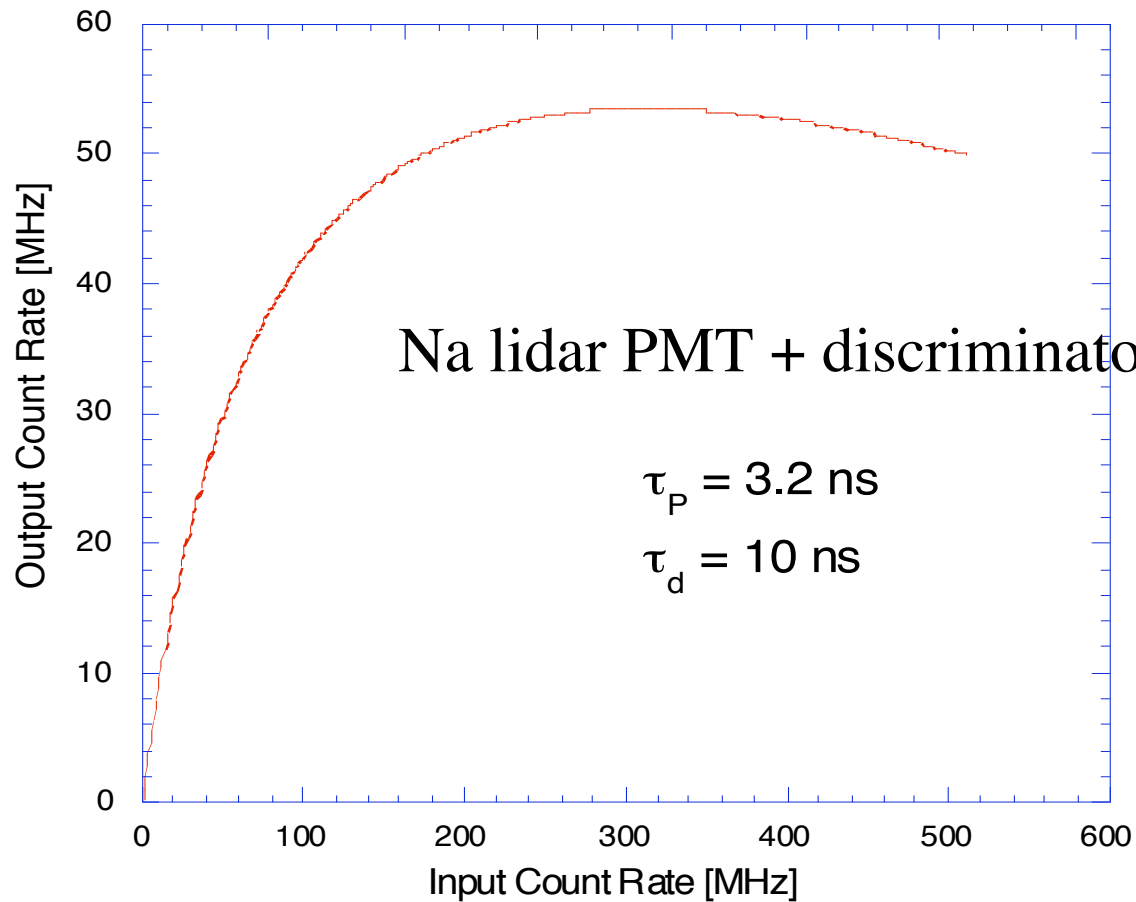
where

$$\lambda_S = \lambda_i \eta_{QE} \quad \eta_{QE} \text{ is the quantum efficiency of cathode}$$

Maximum output count rate is reached when $\lambda_S = 1/\tau_p$

$$\lambda_{o \max} = \frac{1}{\tau_p e + \tau_d} \quad \longrightarrow \quad \tau_p = \frac{\frac{1}{\lambda_{o \max}} - \tau_d}{e}$$

PMT+Discriminator Saturation Correction

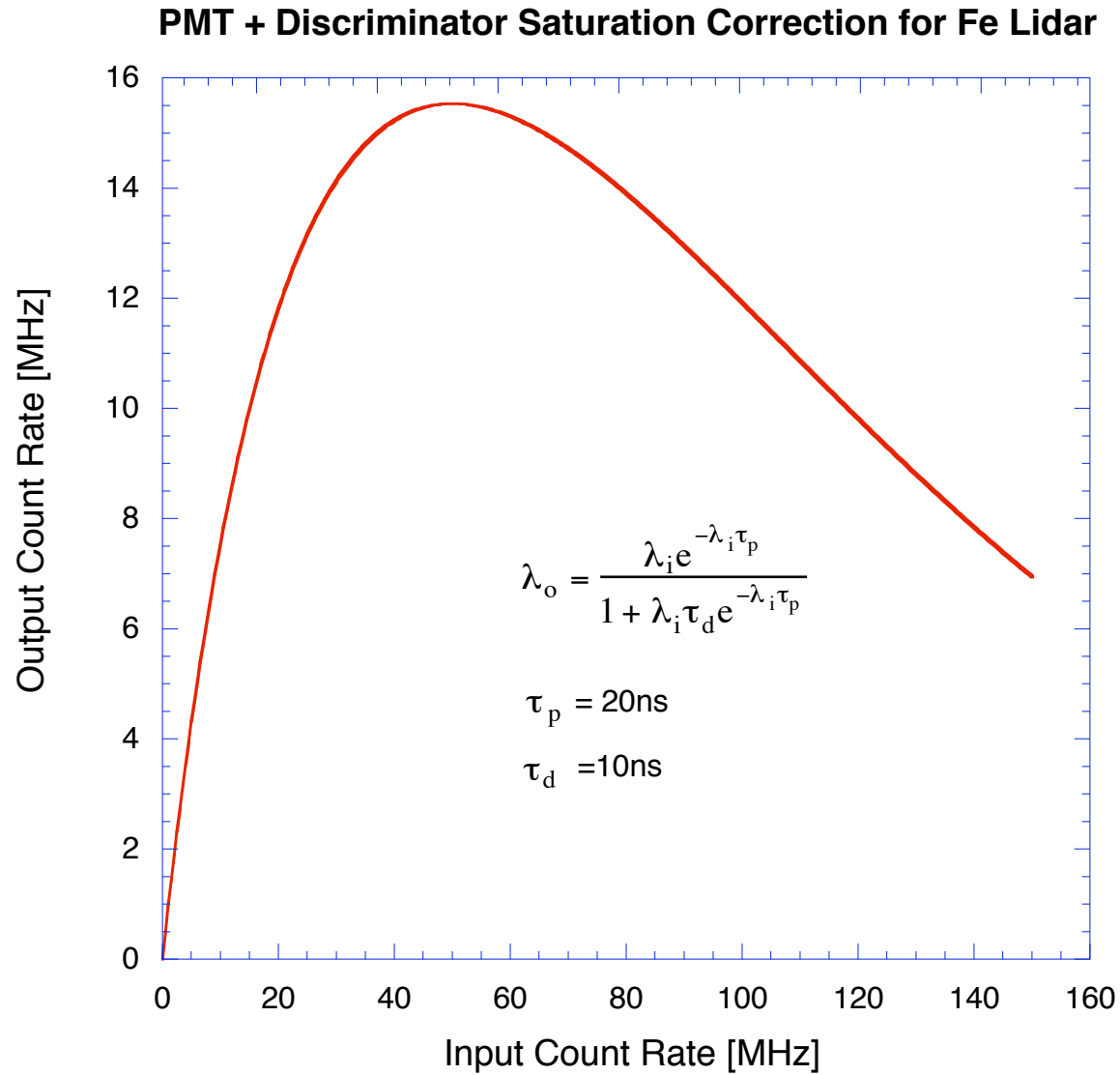


$$\lambda_o = \frac{\lambda_S e^{-\lambda_S \tau_p}}{1 + \lambda_S \tau_d e^{-\lambda_S \tau_p}}$$

$$\lambda_S = \lambda_i \eta_{QE}$$

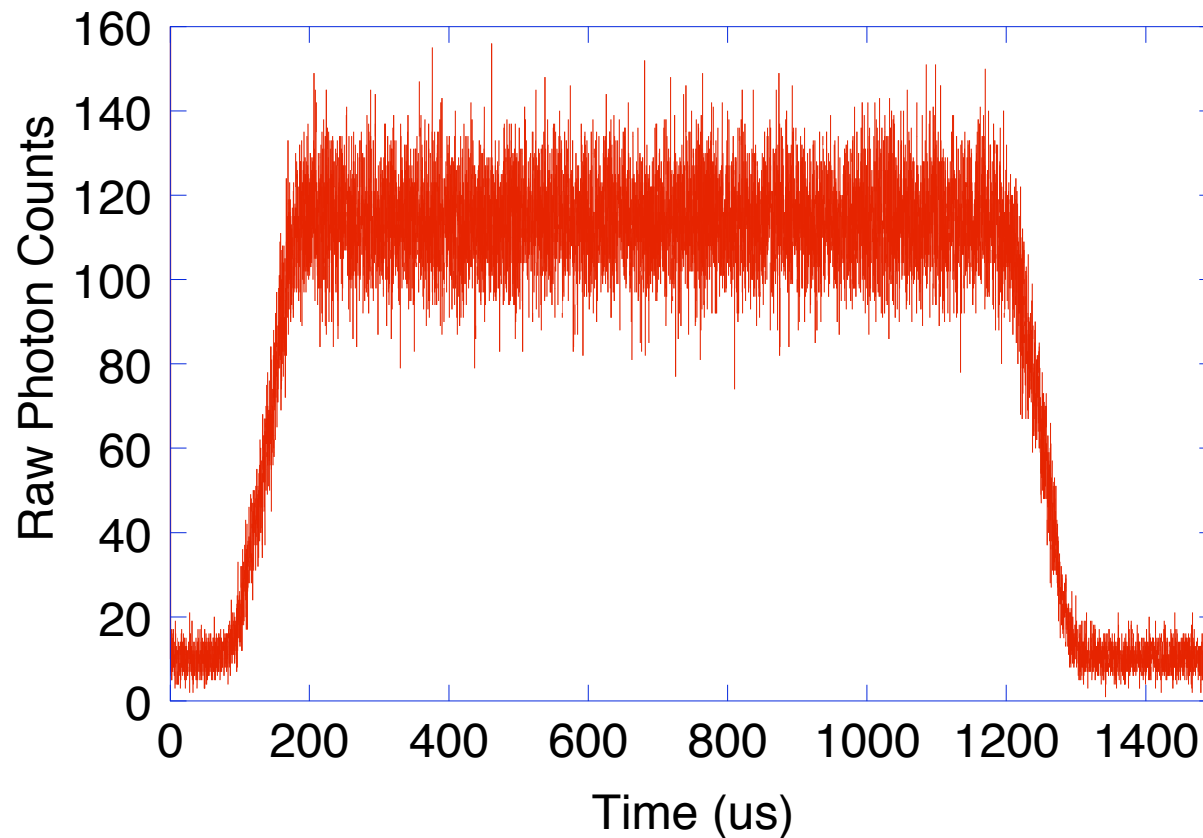
λ_S

Nonlinearity of PMT + Discriminator

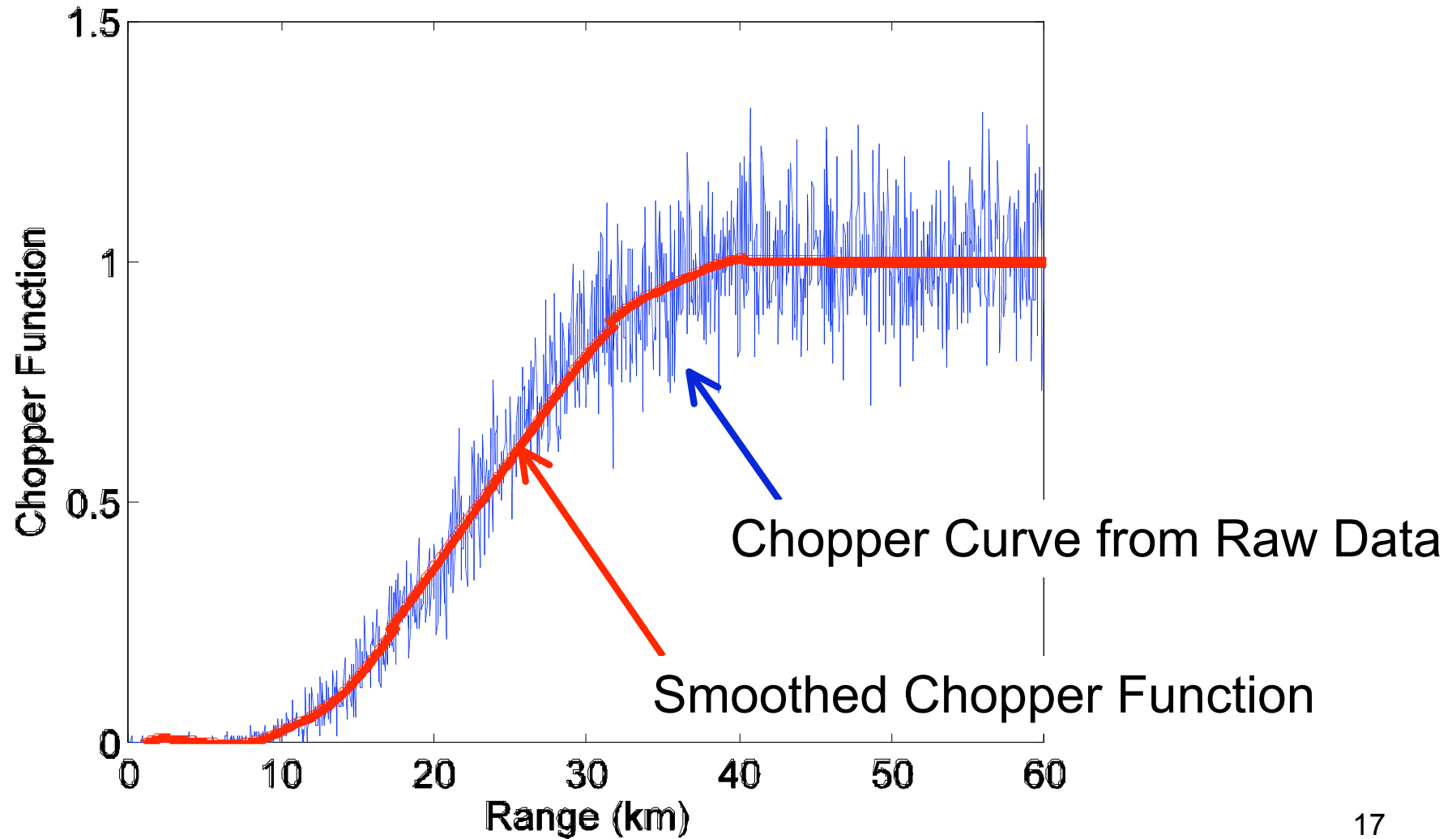


Step 3. Chopper Correction

- ❑ Chopper function is measured and then used to do chopper correction for lower atmosphere signals



Chopper Correction



Step4. Subtract Background N_B

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

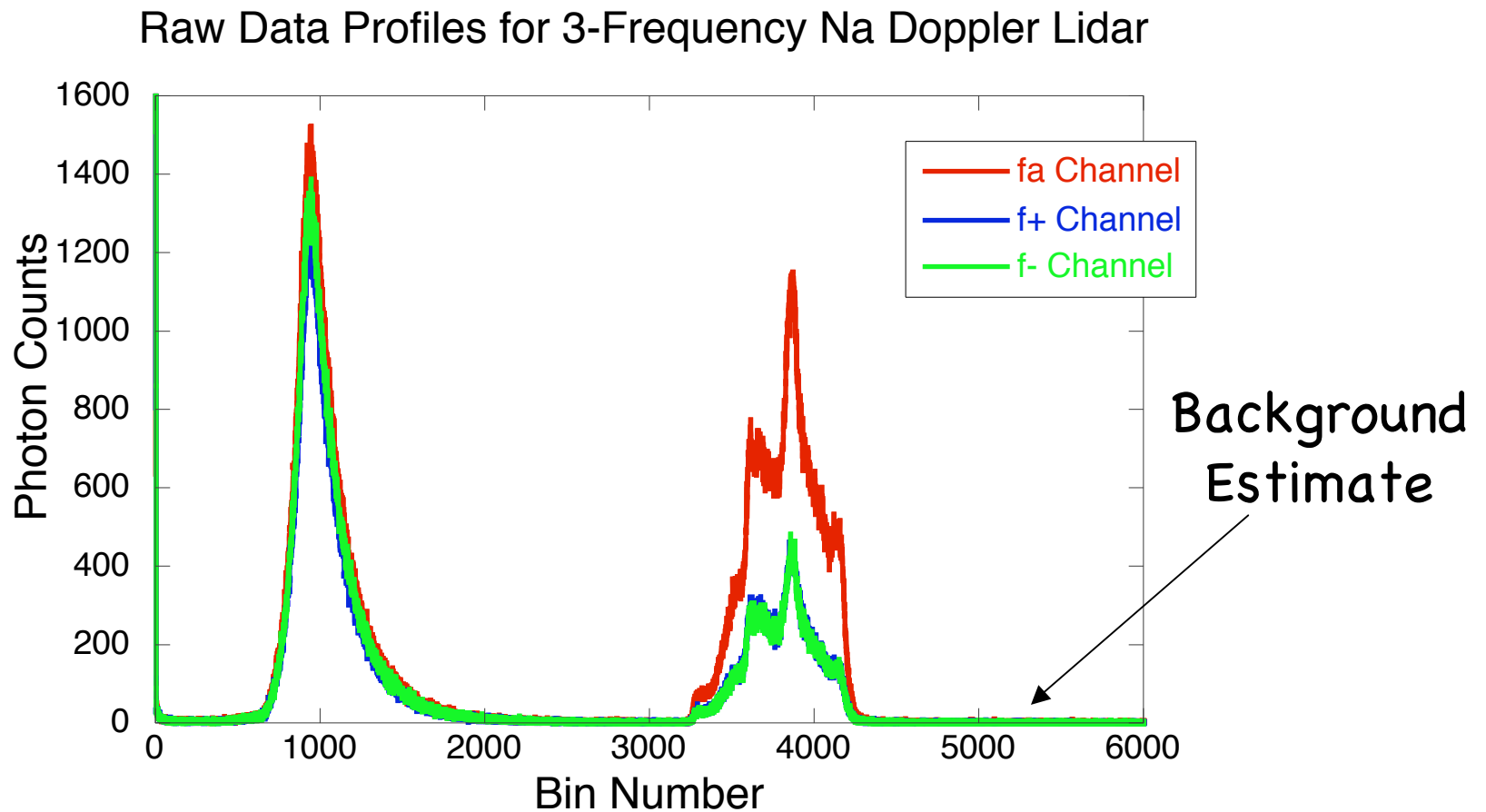
$$N_S(\lambda, z_R) = \left(\frac{P_L(\lambda)\Delta t}{hc/\lambda} \right) \left[\sigma_R(\pi, \lambda)n_R(z_R) \right] \Delta z \left(\frac{A}{z_R^2} \right) T_a^2(\lambda, z_R) (\eta(\lambda)G(z_R)) + N_B$$



$$N_S(\lambda, z_R) - N_B = \left(\frac{P_L(\lambda)\Delta t}{hc/\lambda} \right) \left[\sigma_R(\pi, \lambda)n_R(z_R) \right] \Delta z \left(\frac{A}{z_R^2} \right) T_a^2(\lambda, z_R) (\eta(\lambda)G(z_R))$$

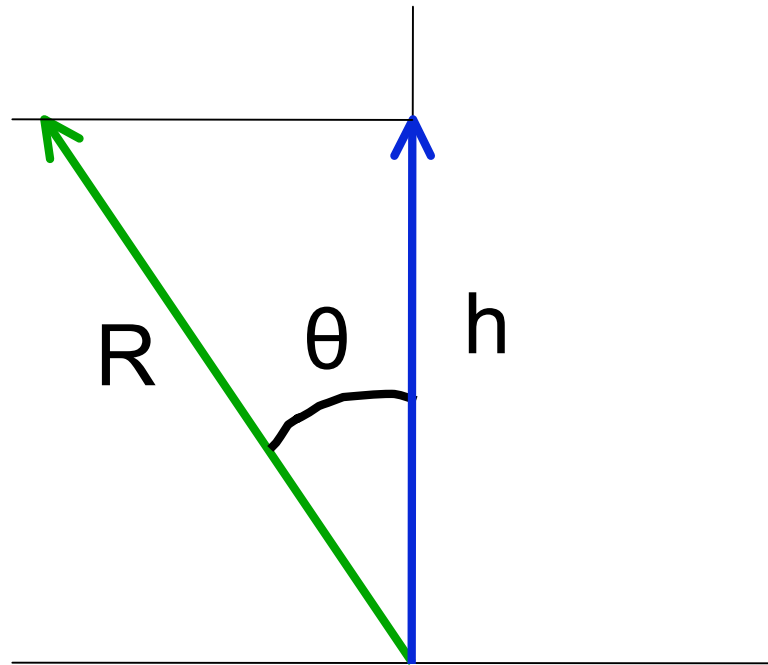
Background Estimate

- Background is estimated from high altitude signal



Step 5. Remove Range Dependence

$$\left[N_S(\lambda, z_R) - N_B \right] R^2 = \left(\frac{P_L(\lambda) \Delta t}{hc/\lambda} \right) \left[\sigma_R(\pi, \lambda) n_R(z_R) \right] \Delta R(A) I_a^2(\lambda, z_R) (\eta(\lambda) G(z_R))$$

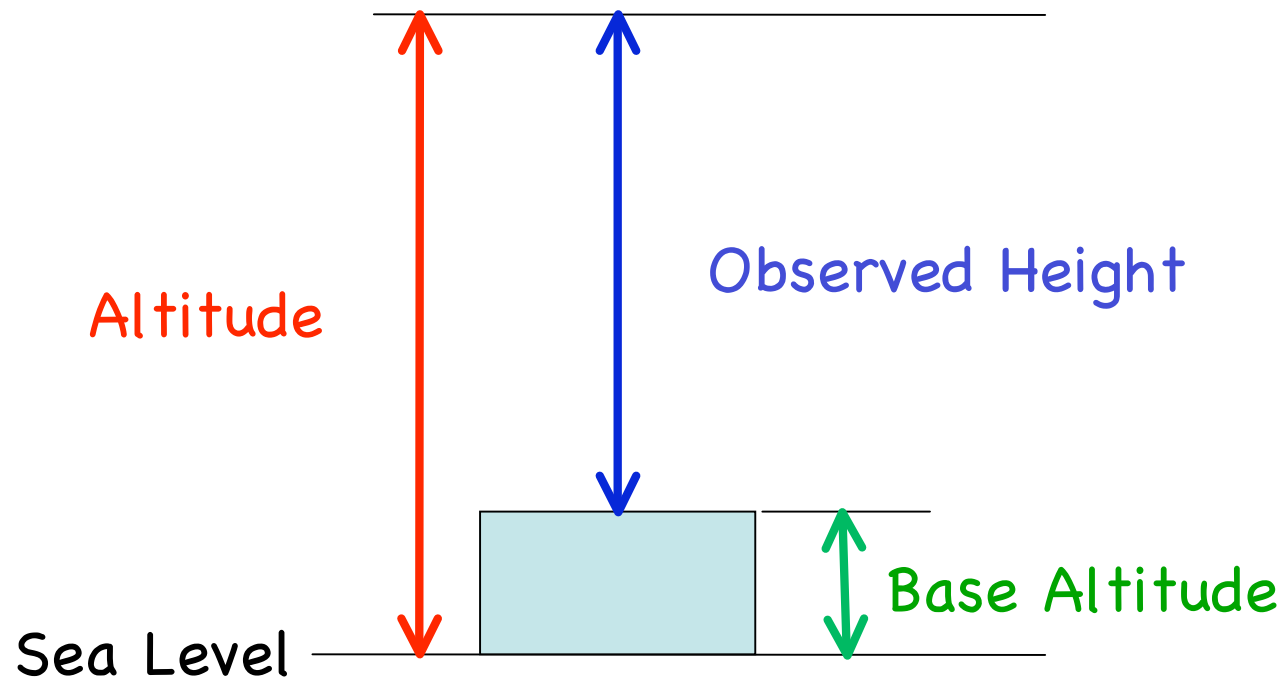


$$h = R \cos \theta$$

Step 6. Add Base Altitude

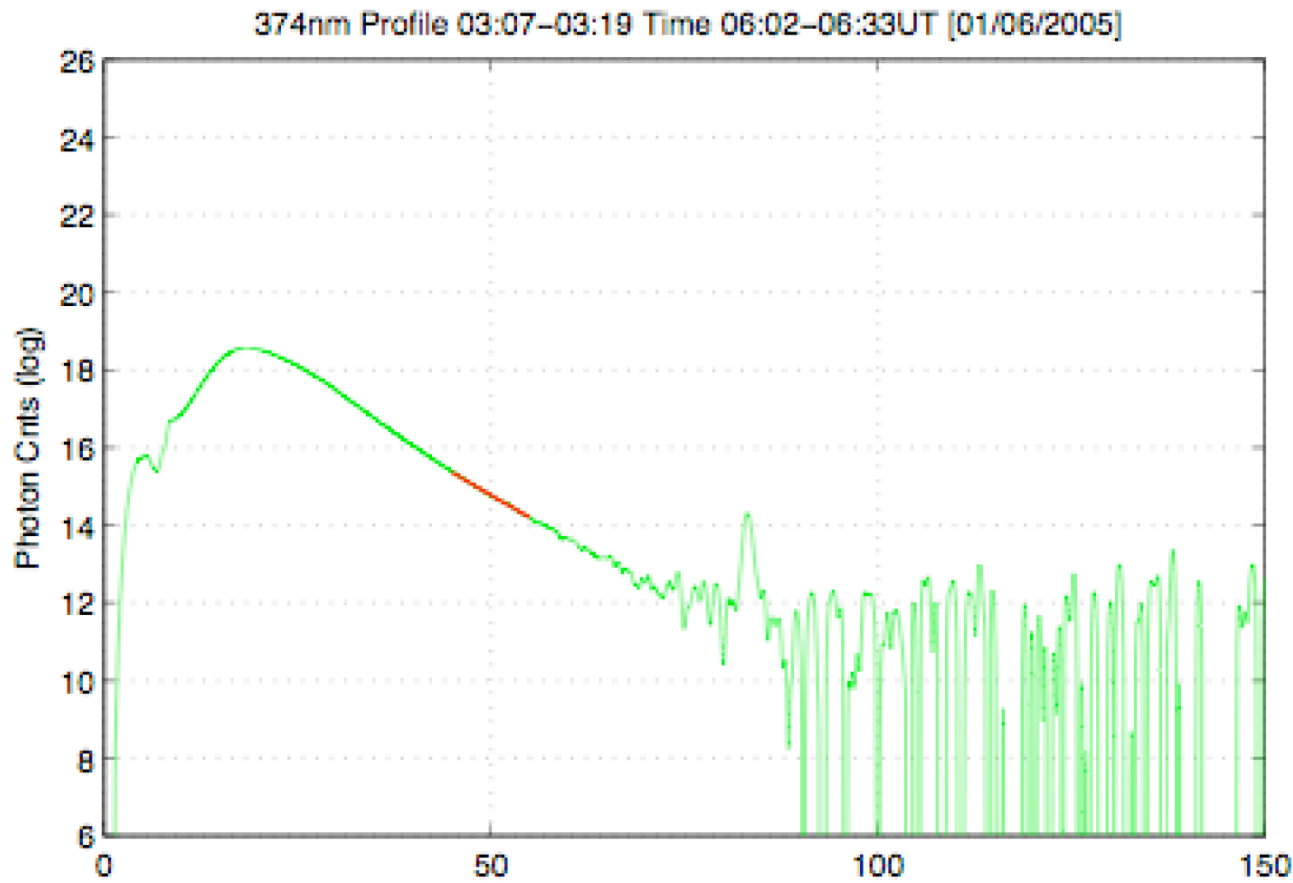
Altitude (relative to sea level)
= Observed Height + Base Altitude

$$z = h + z_{base} = R \cos \theta + z_{base}$$



Step 7. Rayleigh Normalization

- Estimate of Rayleigh Normalization Signal - Rayleigh Fit or Sum

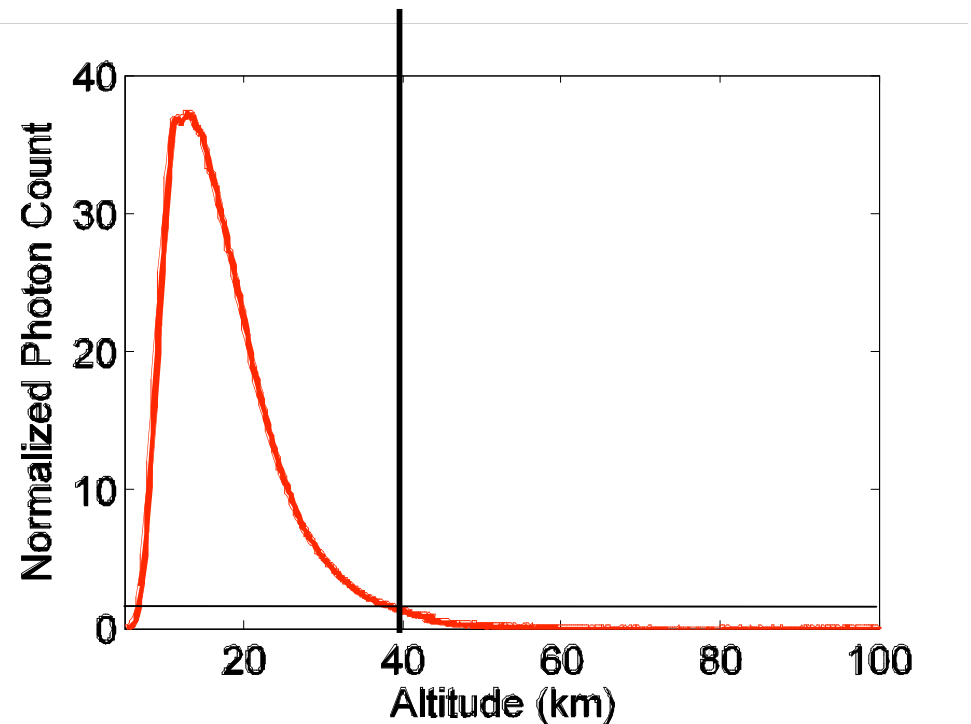


Rayleigh Normalization

$$N_{\text{Normalization}}(\lambda, z) = \frac{N_S(\lambda, z) - N_B \frac{z^2}{z_R^2}}{N_S(\lambda, z_R) - N_B \frac{z_R^2}{z_R^2}}$$

Photon Counts at Rayleigh
Normalization Altitude
(~30-50 km)

Normalization Altitude (40 km)



Summary

- ❑ Lidar data inversion is to convert raw photon counts to meaningful physical parameters like temperature, wind, number density, and volume backscatter coefficient. It is a key step in the process of using lidar to study science.
- ❑ The basic procedure of data inversion originates from solutions of lidar equations, in combination with detailed considerations of hardware properties and limitations as well as detailed considerations of light propagation and interaction processes.
- ❑ Output of the preprocess is Normalized Photon Count.