

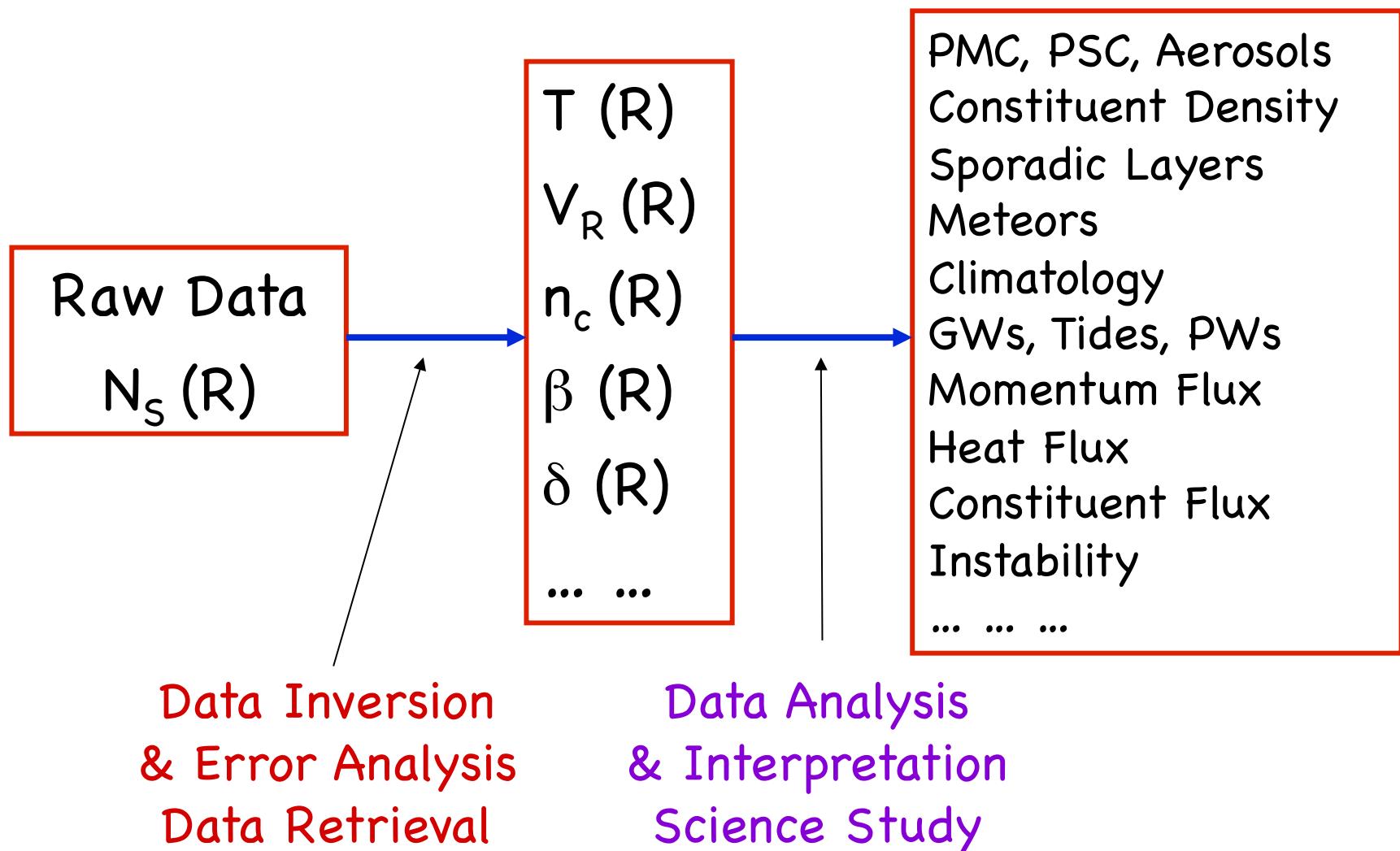


# Lecture 17. Lidar Data Inversion (1)

- ❑ Introduction of data inversion
- ❑ Basic ideas (clues) for lidar data inversion
- ❑ Preprocess
- ❑ Profile process
- ❑ Main process (next lecture)
- ❑ Summary

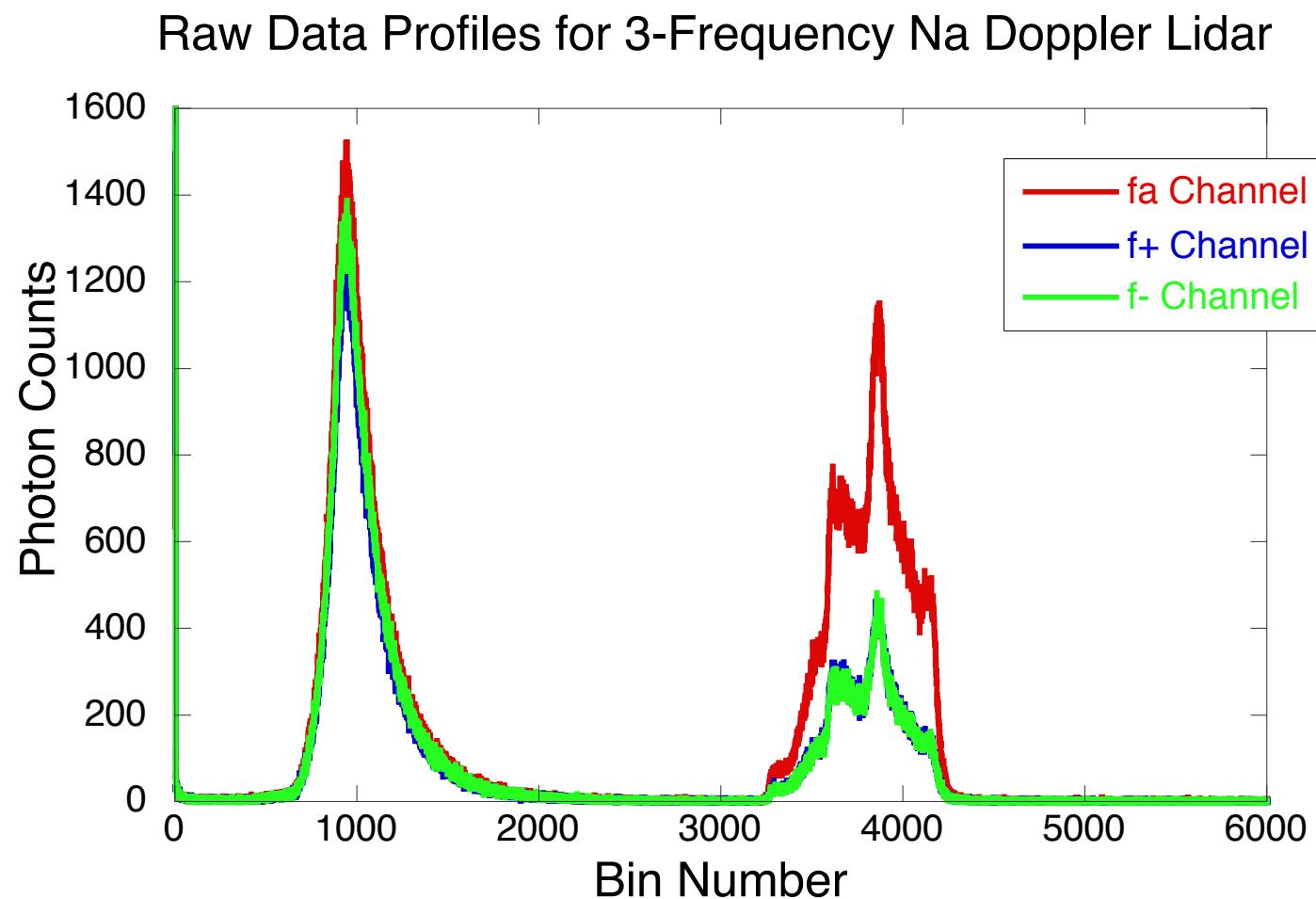


# From Raw Data to Physical Parameters





# Example Lidar Raw Signal





# Introduction: Lidar Data Inversion

- ❑ Lidar data inversion deals with the problems of how to derive meaningful physical parameters from raw data.
- ❑ Raw data are usually a column or a row of photon counts, where the positions of photon counts in the column or row mark their time bins, thus the ranges or heights.
- ❑ Data inversion 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

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

+

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



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



# Basic Clue: Ratio Computation

- From physics, we calculate the ratios of RT and RW as

$$R_T = \frac{\sigma_{eff}(f_+, z) + \sigma_{eff}(f_-, z)}{\sigma_{eff}(f_a, z)}$$

$$R_W = \frac{\sigma_{eff}(f_+, z) - \sigma_{eff}(f_-, z)}{\sigma_{eff}(f_a, z)}$$

- From actual photon counts, we calculate the ratios as

$$\begin{aligned} R_T &= \frac{N_{Norm}(f_+, z) + N_{Norm}(f_-, z)}{N_{Norm}(f_a, z)} \\ &= \frac{\left( \frac{N_S(f_+, z) - N_B}{N_S(f_+, z_R) - N_B} \frac{z^2}{z_R^2} \frac{1}{T_c^2(f_+, z)} - \frac{n_R(z)}{n_R(z_R)} \right) + \left( \frac{N_S(f_-, z) - N_B}{N_S(f_-, z_R) - N_B} \frac{z^2}{z_R^2} \frac{1}{T_c^2(f_-, z)} - \frac{n_R(z)}{n_R(z_R)} \right)}{\frac{N_S(f_a, z) - N_B}{N_S(f_a, z_R) - N_B} \frac{z^2}{z_R^2} \frac{1}{T_c^2(f_a, z)} - \frac{n_R(z)}{n_R(z_R)}} \end{aligned}$$

$$\begin{aligned} R_W &= \frac{N_{Norm}(f_+, z) - N_{Norm}(f_-, z)}{N_{Norm}(f_a, z)} \\ &= \frac{\left( \frac{N_S(f_+, z) - N_B}{N_S(f_+, z_R) - N_B} \frac{z^2}{z_R^2} \frac{1}{T_c^2(f_+, z)} - \frac{n_R(z)}{n_R(z_R)} \right) - \left( \frac{N_S(f_-, z) - N_B}{N_S(f_-, z_R) - N_B} \frac{z^2}{z_R^2} \frac{1}{T_c^2(f_-, z)} - \frac{n_R(z)}{n_R(z_R)} \right)}{\frac{N_S(f_a, z) - N_B}{N_S(f_a, z_R) - N_B} \frac{z^2}{z_R^2} \frac{1}{T_c^2(f_a, z)} - \frac{n_R(z)}{n_R(z_R)}} \end{aligned}$$



# Basic Clue: T, V<sub>R</sub>, n<sub>C</sub>, or β Derivation

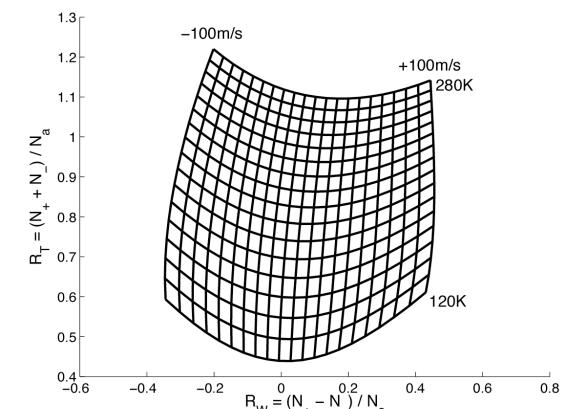
- ❑ Compute actual ratios RT and RW from photon counts, and then look up these two ratios on the calibration curves to infer the corresponding Temperature and Wind from isoline/isogram.
- ❑ If there is only RT ratio, then infer the temperature from the calibration curve, like the Fe Boltzmann lidar case.
- ❑ Constituent (e.g., Na) density can be inferred from the peak freq signal

$$n_{Na}(z) = \frac{N_{norm}(f_a, z)}{\sigma_a} 4\pi n_R(z_R) \sigma_R = \frac{N_{norm}(f_a, z)}{\sigma_a} 4\pi \times 2.938 \times 10^{-32} \frac{P(z_R)}{T(z_R)} \cdot \frac{1}{\lambda^{4.0117}}$$

- ❑ Volume backscatter coefficient can be derived as

$$\beta_{PMC}(z) = \left[ \frac{[N_S(z) - N_B] \cdot z^2}{[N_S(z_{RN}) - N_B] \cdot z_{RN}^2} - \frac{n_R(z)}{n_R(z_{RN})} \right] \cdot \beta_R(z_{RN})$$

where  $\beta_R(z_{RN}, \pi) = \frac{\beta}{4\pi} P(\pi) = 2.938 \times 10^{-32} \frac{P(z_{RN})}{T(z_{RN})} \cdot \frac{1}{\lambda^{4.0117}}$





# Considerations in Data Inversion

- How to obtain related information like date, time, location, base altitude, operation conditions?
  - from data header and other info sources
- How to obtain range or altitude information?
  - from bin number, data header and other source

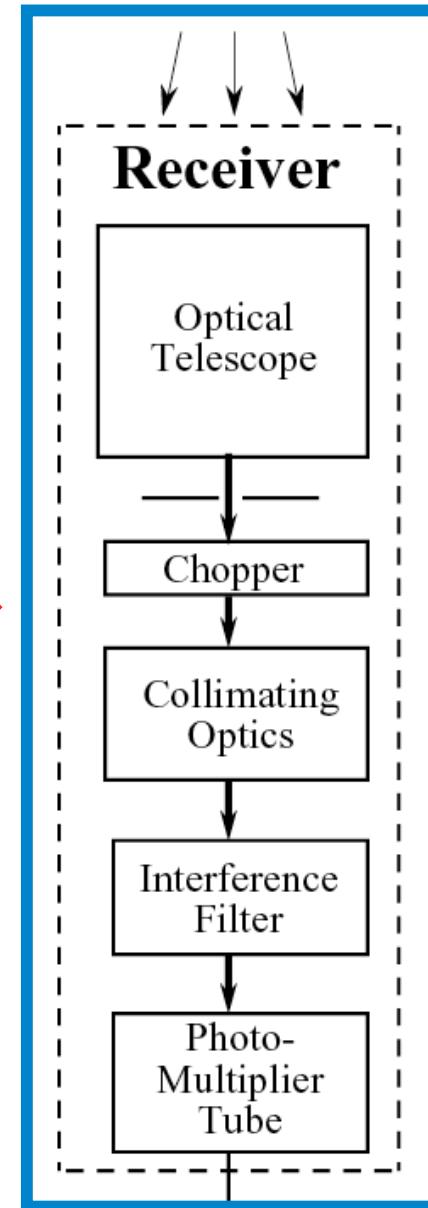
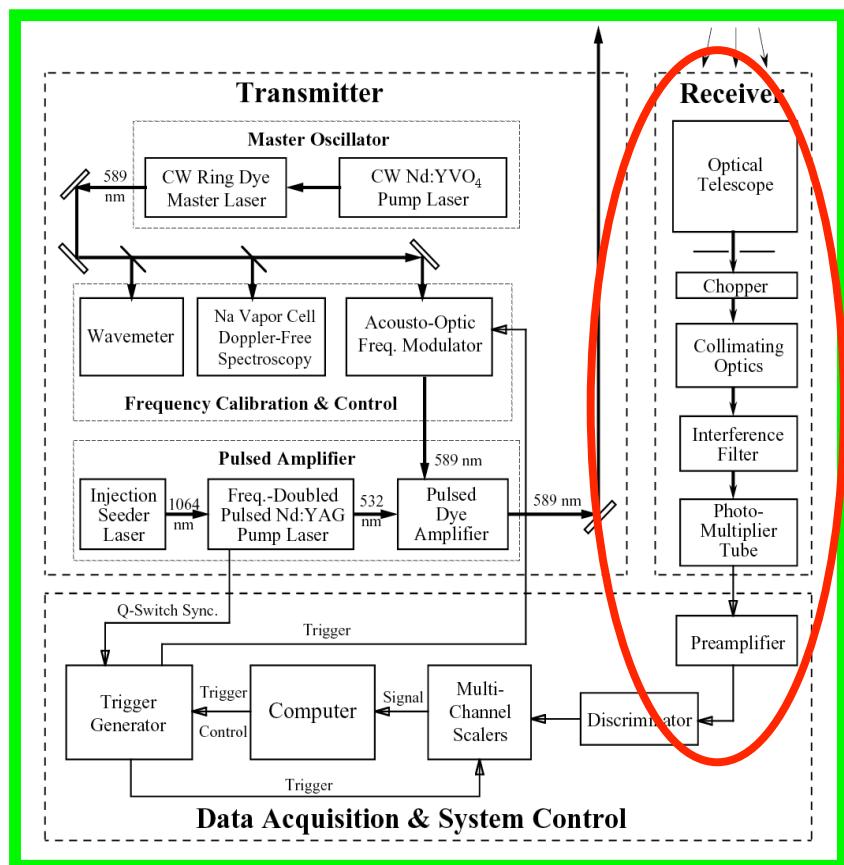
$$R = n_{bin} \cdot t_{bin} \cdot c / 2$$

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

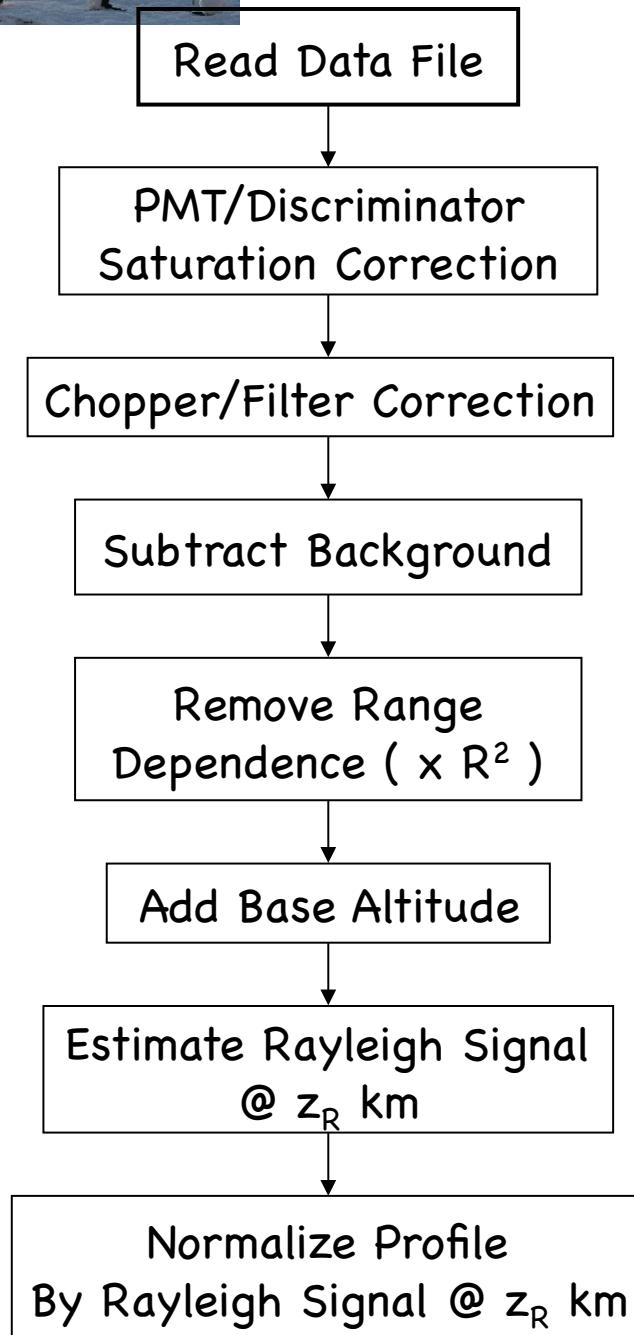
R is range,  $n_{bin}$  is bin number,  $t_{bin}$  is bin width in time, c is light speed, z is absolute altitude,  $\theta$  is off-zenith angle, and  $z_{base}$  is the base altitude relative to sea-level.



# Na Doppler Lidar Schematic



Preprocess  
Procedure



## Preprocess Procedure and Profile-Process Procedure for Na/Fe/K Doppler Lidar

- ❑ Read data: for each set, and calculate T, W, and n for each set
- ❑ PMT/Discriminator saturation correction
- ❑ Chopper/Filter 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
- ❑ Subtract Rayleigh signals from Na/Fe/K region



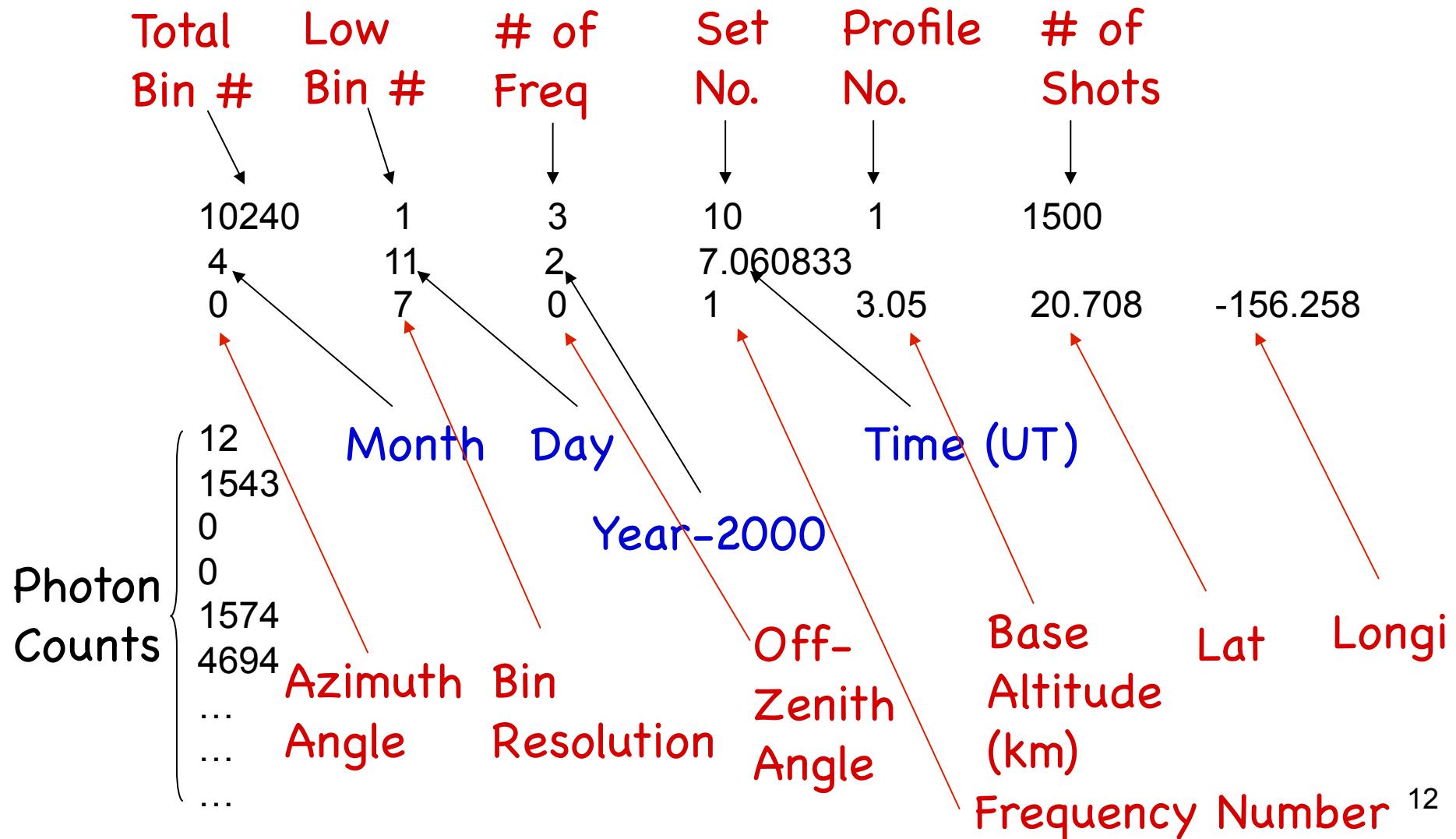
## Profile-Process Procedure

- ❑ Indicated from the lidar equation and its solution, the profile process 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 – preprocess procedure
  - PMT and discriminator saturation correction
  - Chopper or electronic gain correction



# Step1. Read Raw Data

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





## Another Example of Lidar Raw Data

Total Bin #	Low Bin #	# of Freq	Set No.	Profile No.	# of Shots
10240	1	3	11	2	1500
4	11	2	7.090278		
180	7	30	2	3.05	
12				20.708	-156.258
1532					
0					
0					
2400					
3771					
Azimuth Angle	Bin Resolution	Off-Zenith Angle	Base Altitude (km)	Lat	Longi
...	...	...	Frequency number		
...					

Photon Counts {

Month Day Year-2000 Time (UT)



## Step 2. 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

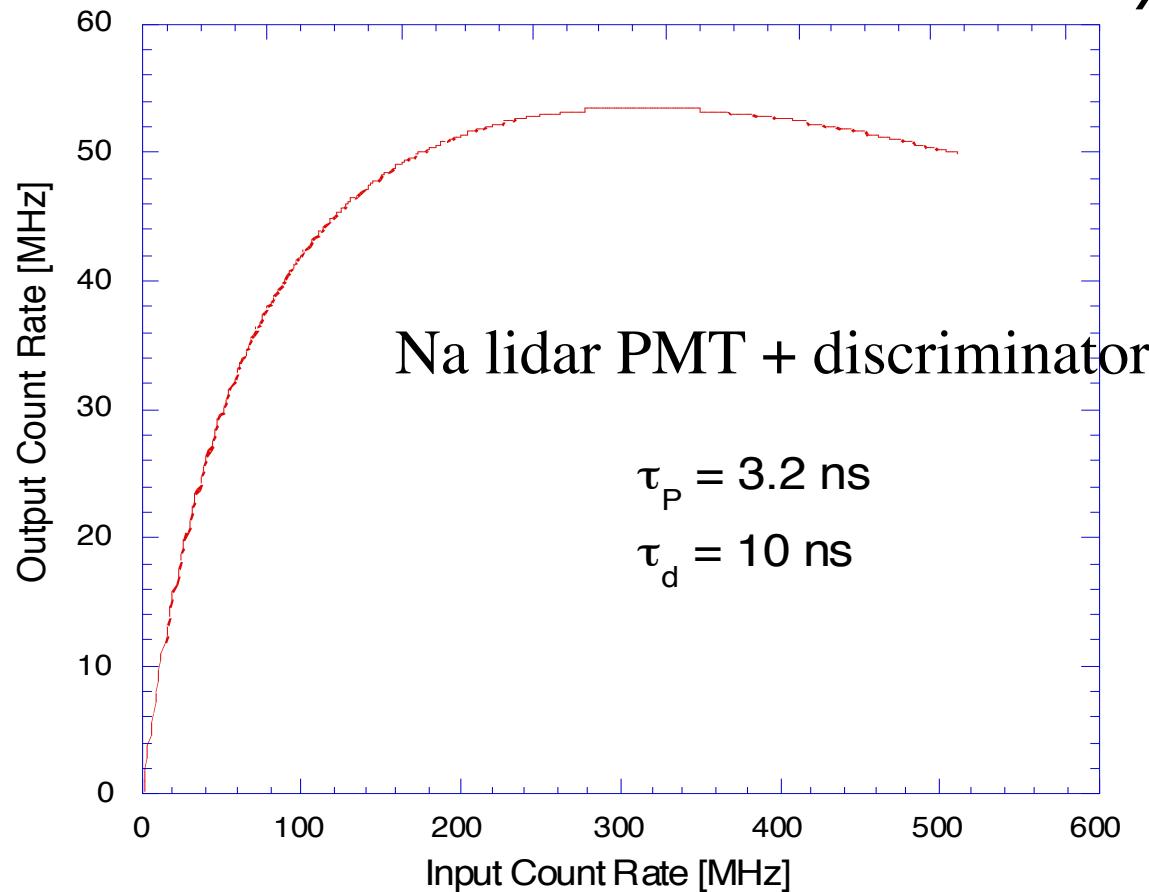
$\lambda_S = \lambda_i \eta_{QE}$   $\eta_{QE}$  is the quantum efficiency of cathode

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

$$\lambda_{o \max} = \frac{1}{\tau_p e + \tau_d} \quad \xrightarrow{\text{red arrow}} \quad \tau_p = \frac{\frac{1}{\lambda_{o \max}} - \tau_d}{e}$$



# PMT+Discriminator Saturation Correction



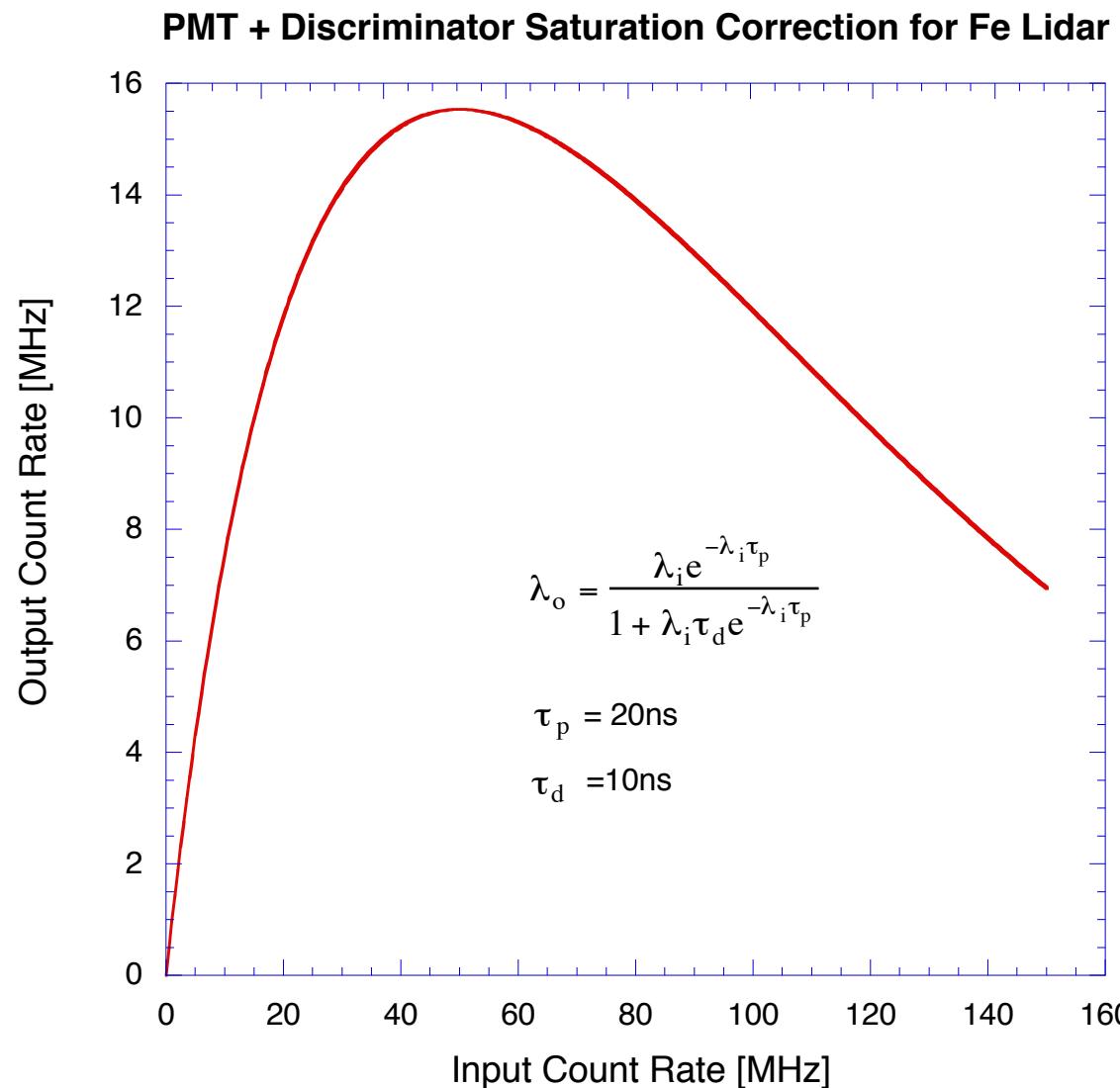
$$\lambda_o = \frac{\lambda_S e^{-\lambda_S \tau_p}}{1 + \lambda_S \tau_d e^{-\lambda_S \tau_p}}$$

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

 $\lambda_S$



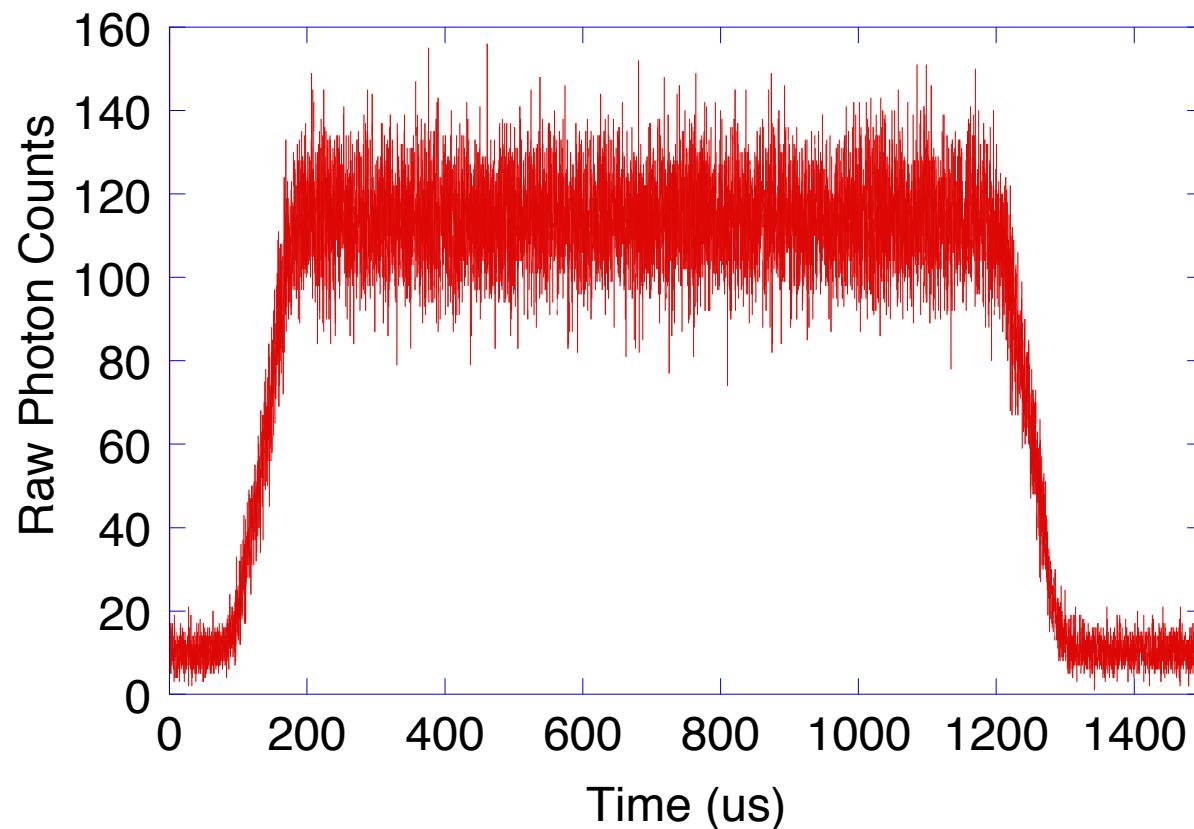
# Nonlinearity of PMT + Discriminator





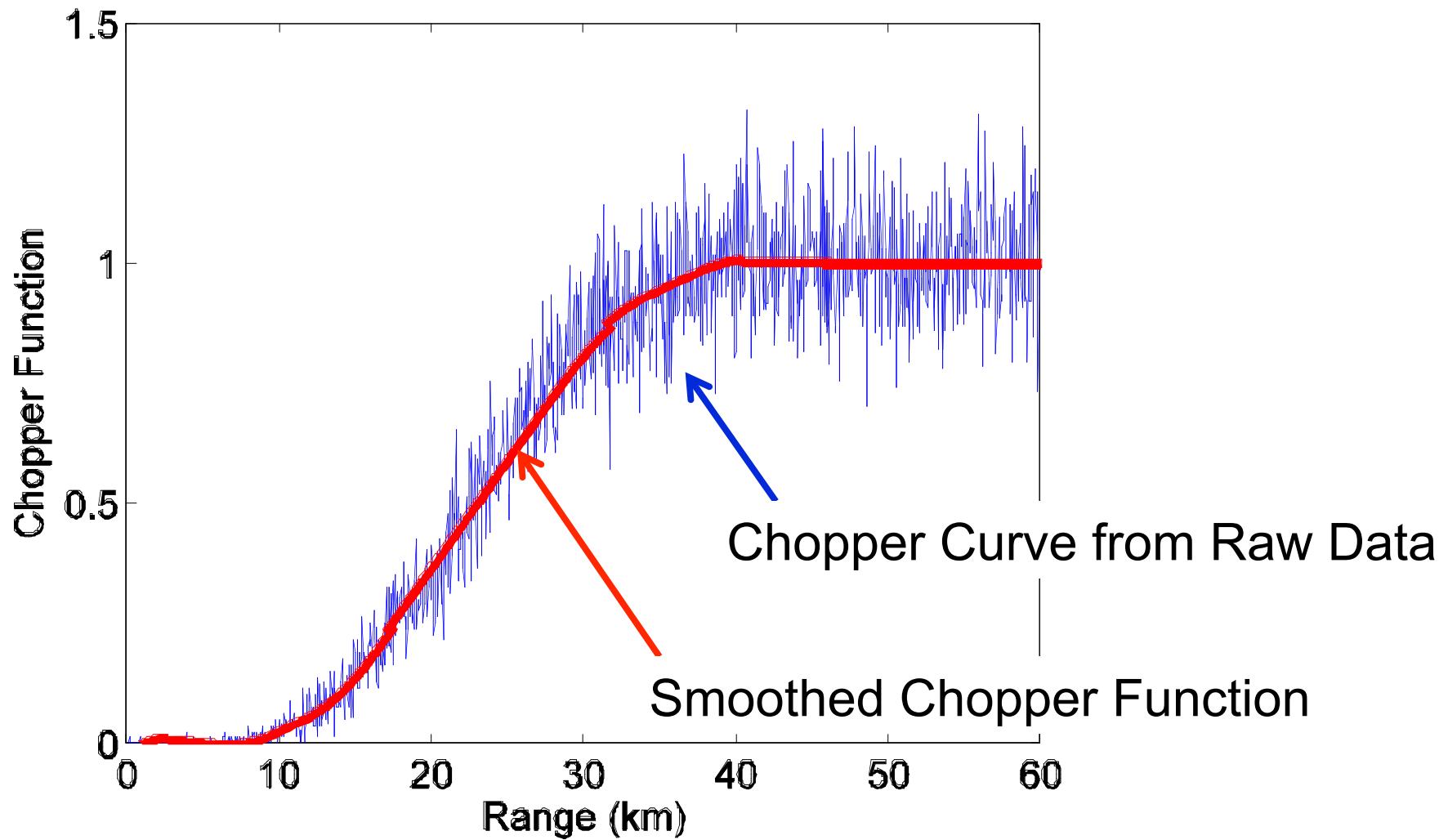
## Step 3. Chopper Correction

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





# Chopper Correction





## Step 4. Subtract Background $N_B$

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

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

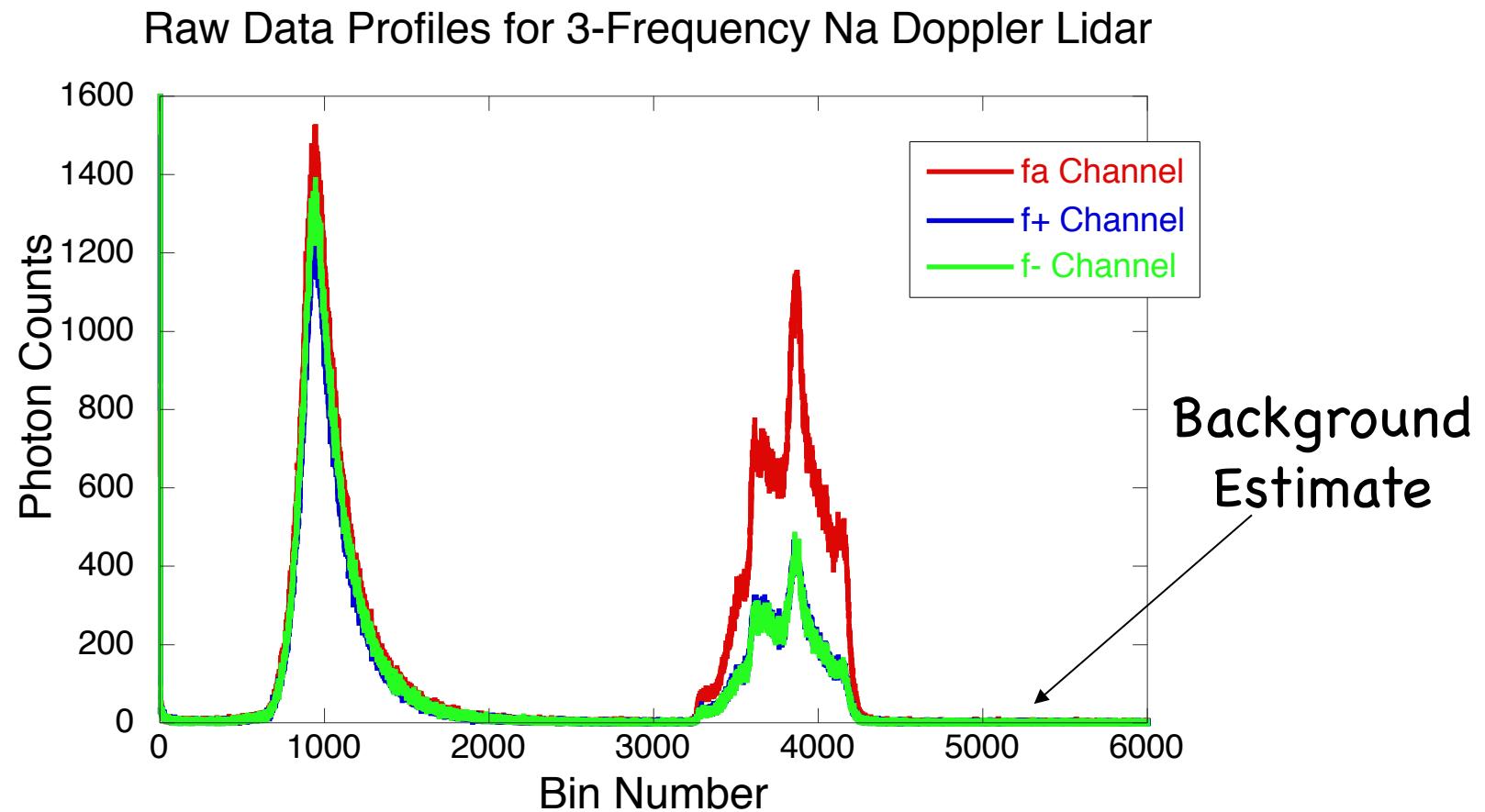


$$N_S(\lambda, z_R) - N_B = \left( \frac{P_L(\lambda)\Delta t}{hc/\lambda} \right) \left[ \sigma_R(\pi, \lambda)n_R(z_R) \right] \Delta z \left( \frac{A}{z_R^2} \right) T_a^2(\lambda, z_R) (\eta(\lambda)G(z_R))$$



# Background Estimate

- ☐ Background is estimated from high altitude signal

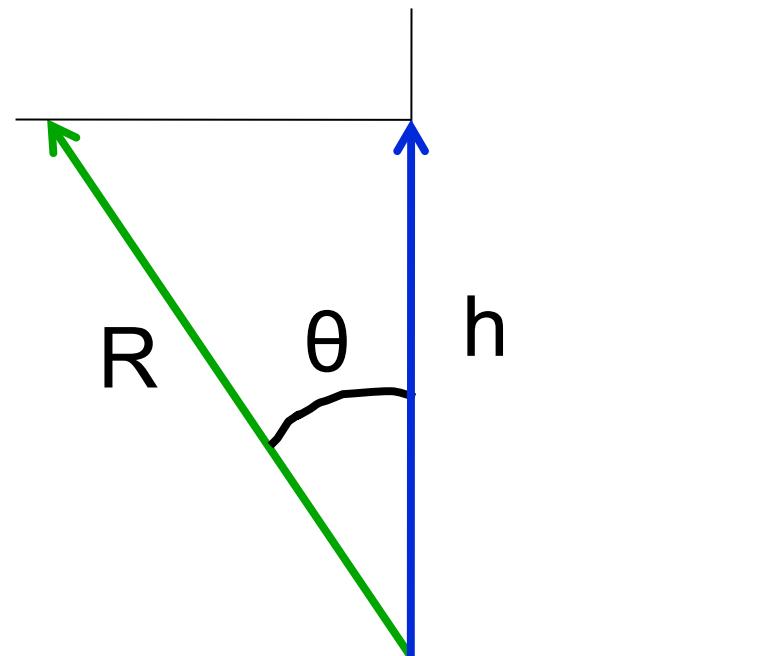


There could be tilted background due to PMT saturation



## Step 5. Remove Range Dependence

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



$$h = R \cos \theta$$

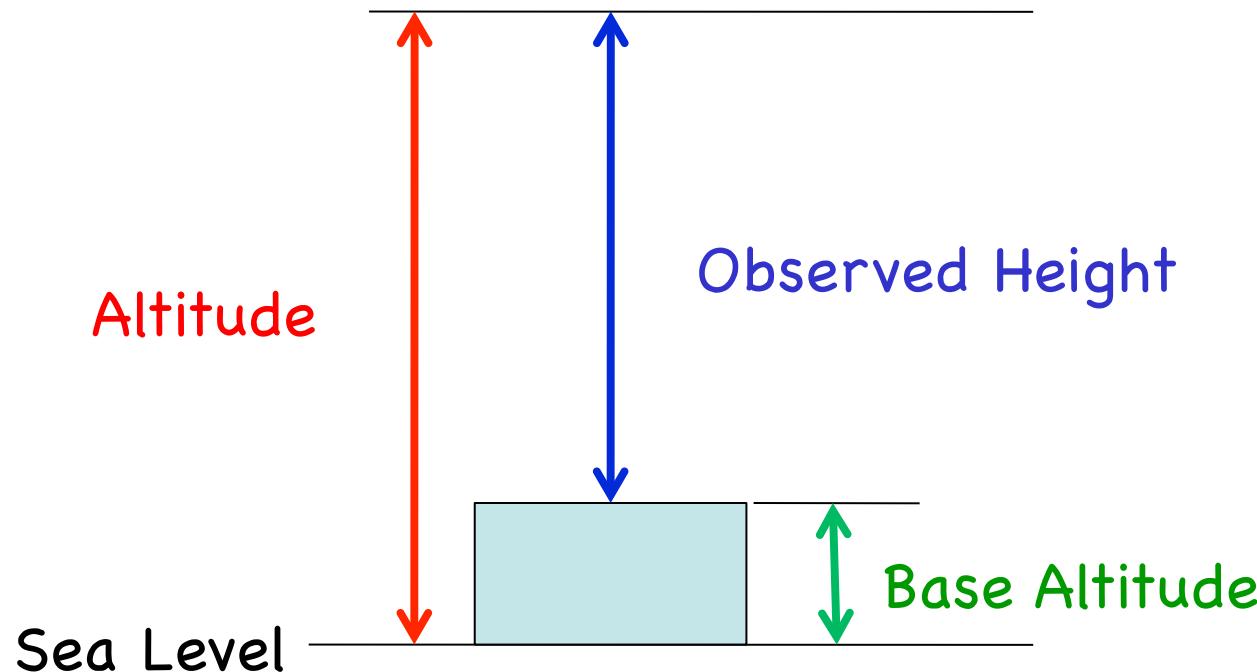


## Step 6. Add Base Altitude

Altitude (relative to mean sea level)

$$= \text{Observed Height} + \text{Base Altitude}$$

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





## Step 7. Rayleigh Normalization

- ☐ Estimate of Rayleigh Normalization Signal - Rayleigh Fit or Sum



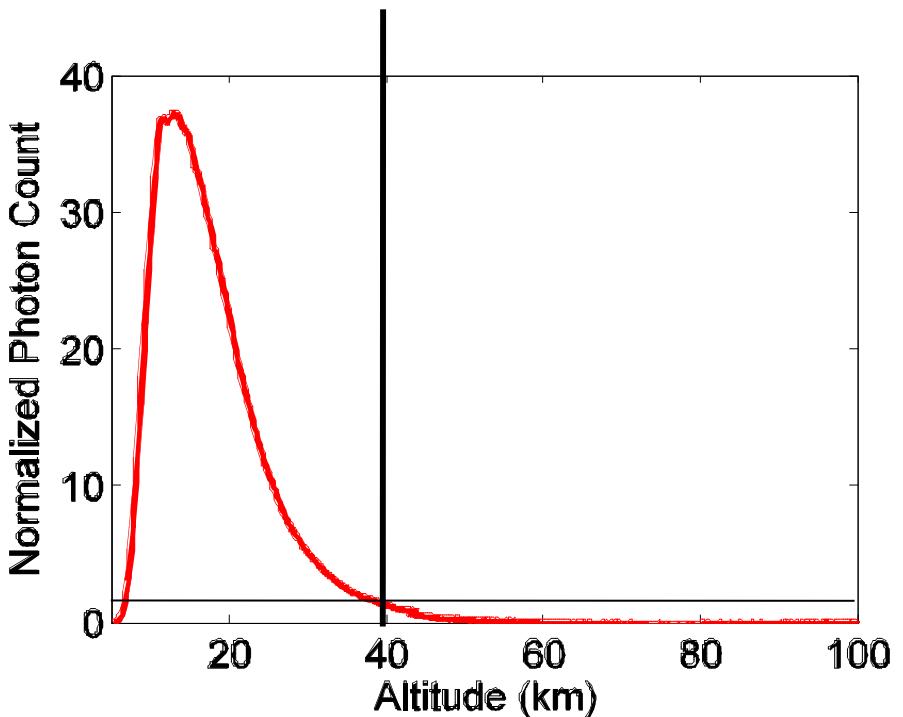


# Rayleigh Normalization

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

Photon Counts at Rayleigh  
Normalization Altitude  
(30-55 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 and profile process is Normalized Photon Count, which is a preparation for the main process to derive temperature, wind, density, or backscatter coefficient, etc.