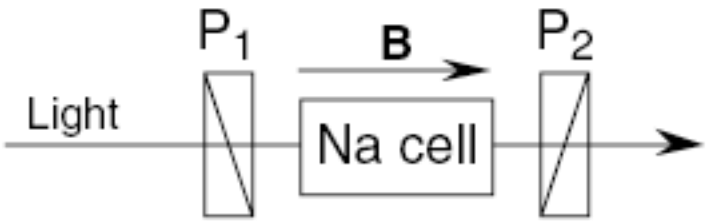
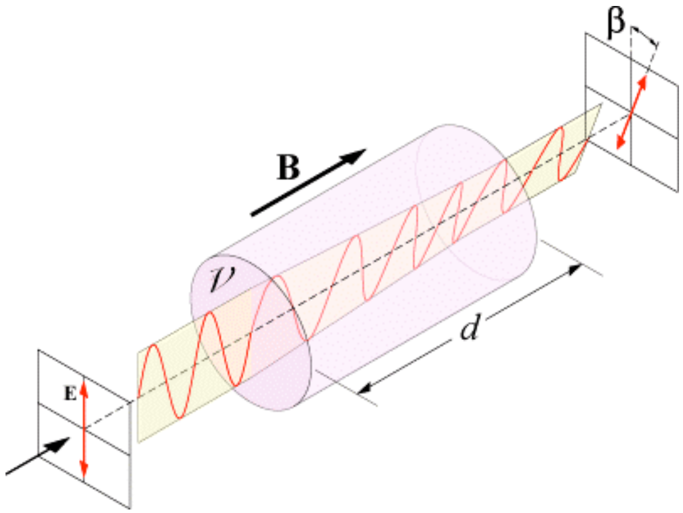
Lecture 13. Lidar Data Inversion

- ☐ Review Doppler lidar architecture
- ☐ Daytime capability of Na Doppler lidar
- ☐ Introduction
- ☐ Common raw data format
- ☐ Basic ideas (clues) for data inversion
- ☐ Preprocess
- ☐ Main process
- ☐ Summary

Daytime Capability: Faraday Filter

- Faraday effect is the rotation of light polarization by some media under magnetic field.





- Refraction index n of dilute Na vapor

$$n = \sqrt{1+\chi} \cong 1 + \frac{1}{2}\chi = 1 + \frac{1}{2}\chi' - \mathrm{i}\frac{1}{2}\chi'' \tag{5.74}$$

χ is the electric susceptibility of Na vapor

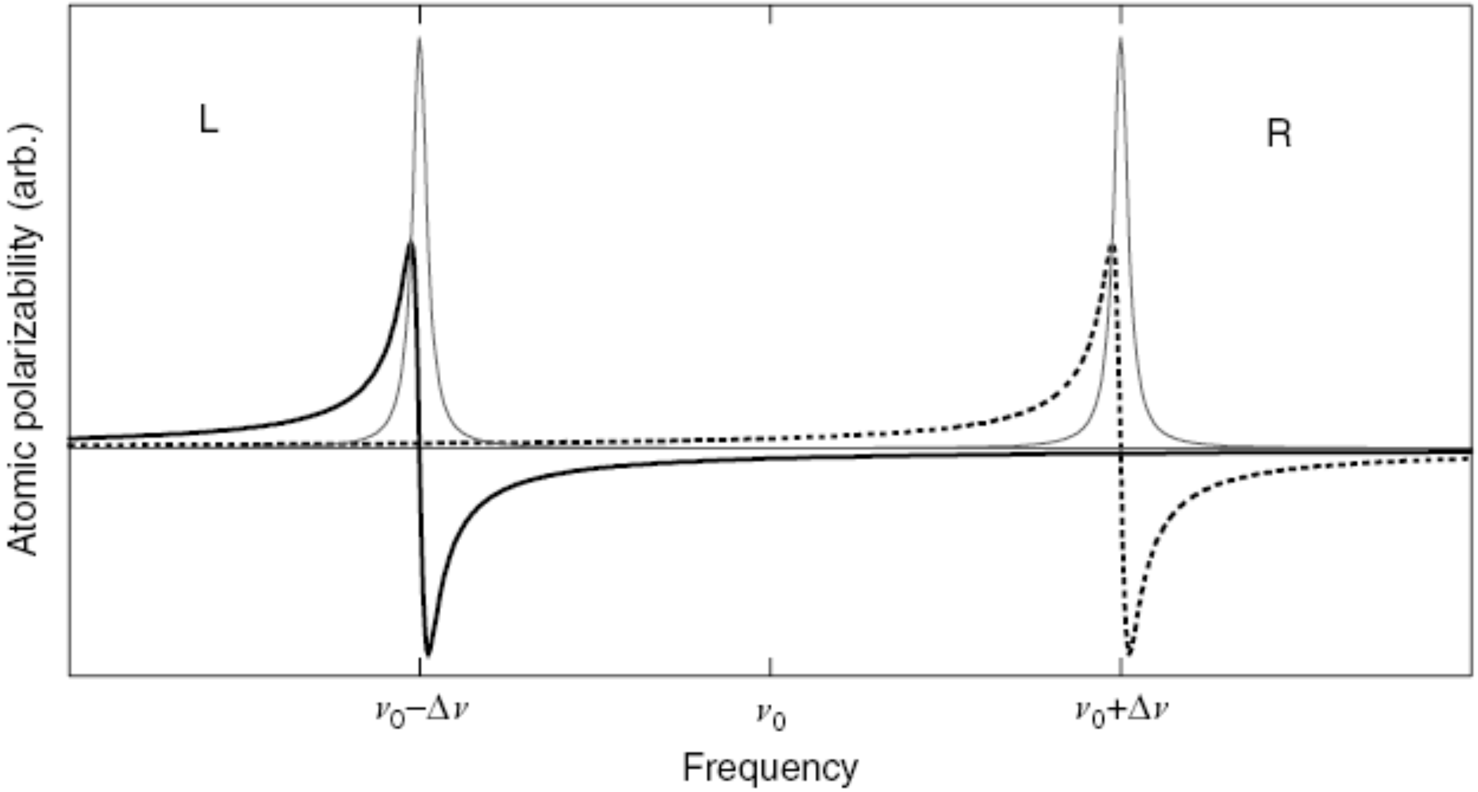
Faraday Filter

$$\chi' = \frac{Ne^2 f}{2m\omega\epsilon_0} \frac{\omega_0 - \omega}{(\omega_0 - \omega)^2 + (\gamma/2)^2}$$

Dispersion

$$\chi'' = \frac{Ne^2 f}{2m\omega\epsilon_0} \frac{\gamma/2}{(\omega_0 - \omega)^2 + (\gamma/2)^2}$$

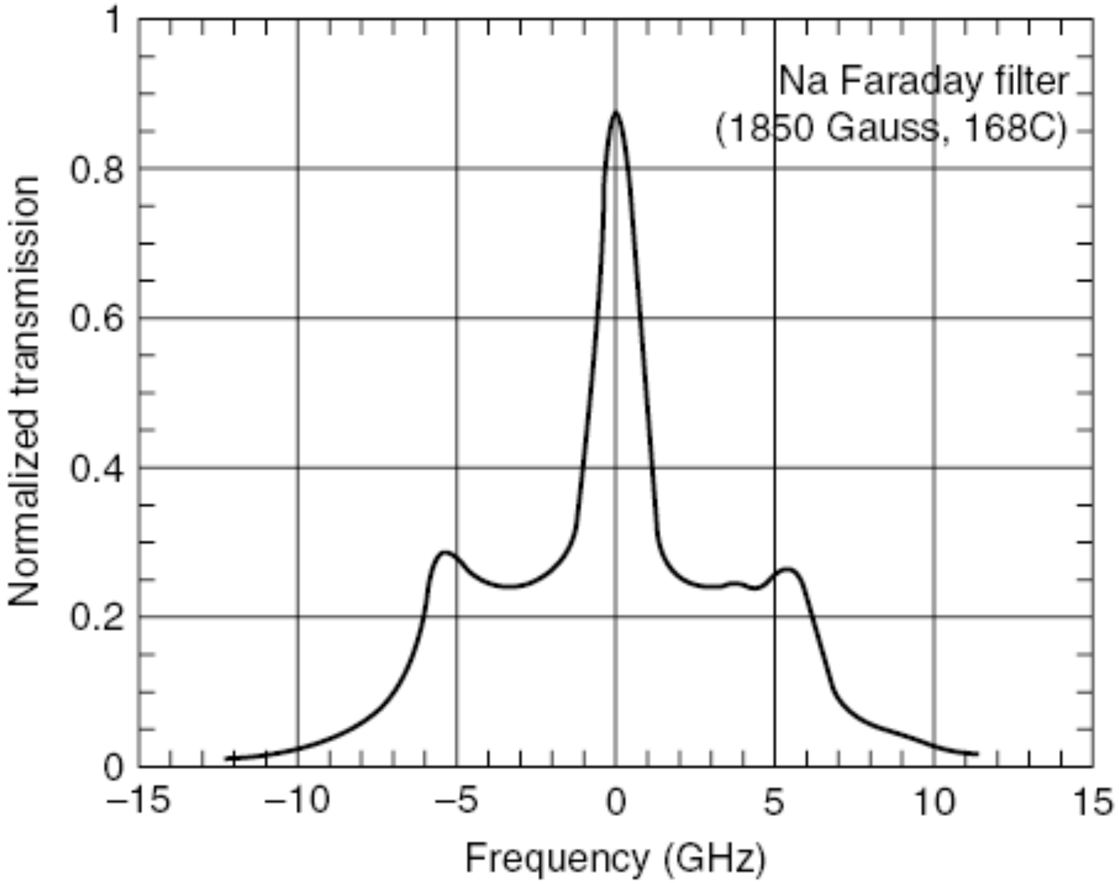
Resonance absorption



Faraday Filter

- Phase shift between two circular polarizations

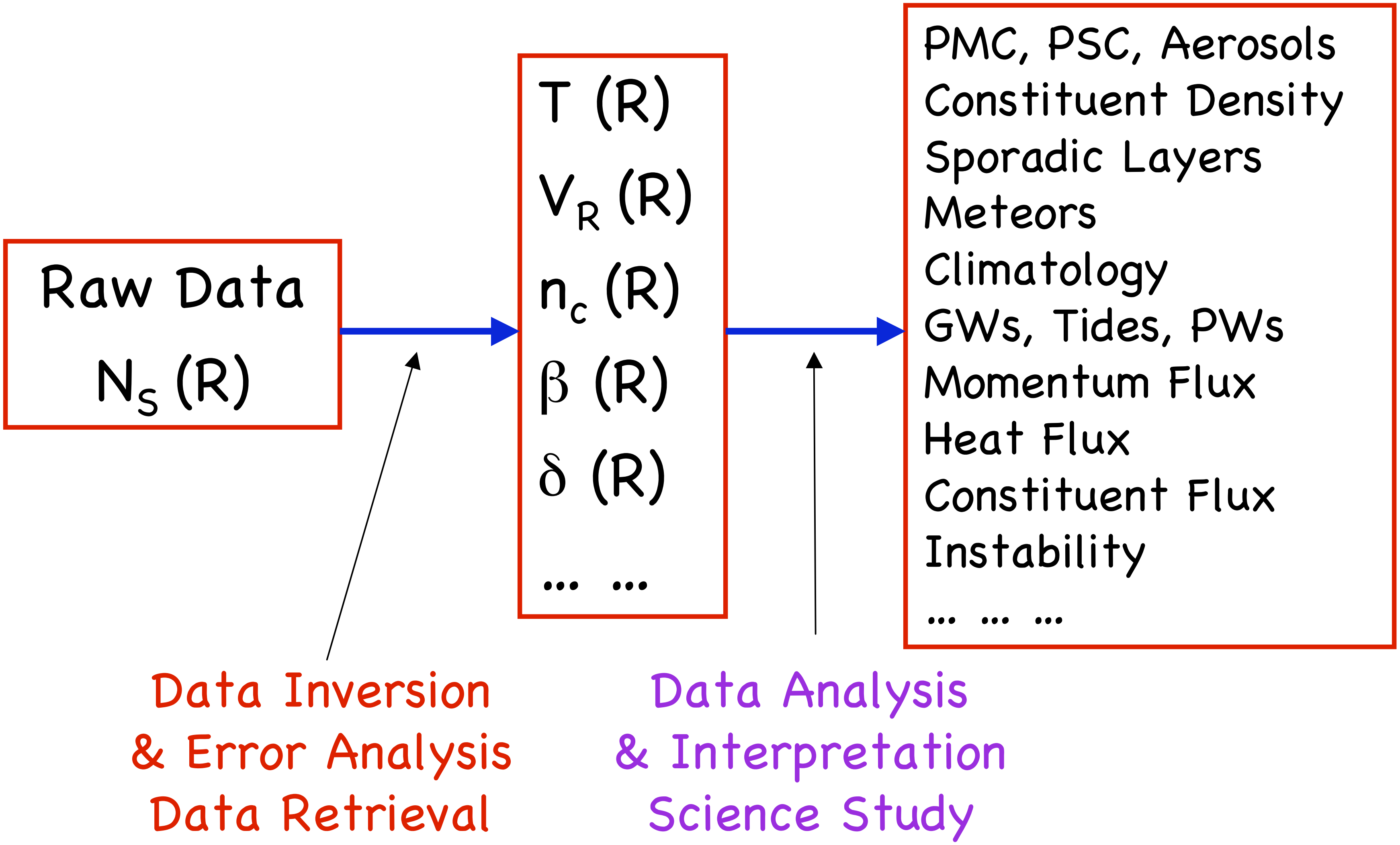
$$\Delta\varphi = 2\pi \frac{l\Delta n}{\lambda}$$



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).

From Raw Data to Physical Parameters



Raw Data

N_S (R)

T (R)

V_R (R)

n_c (R)

β (R)

δ (R)

… …

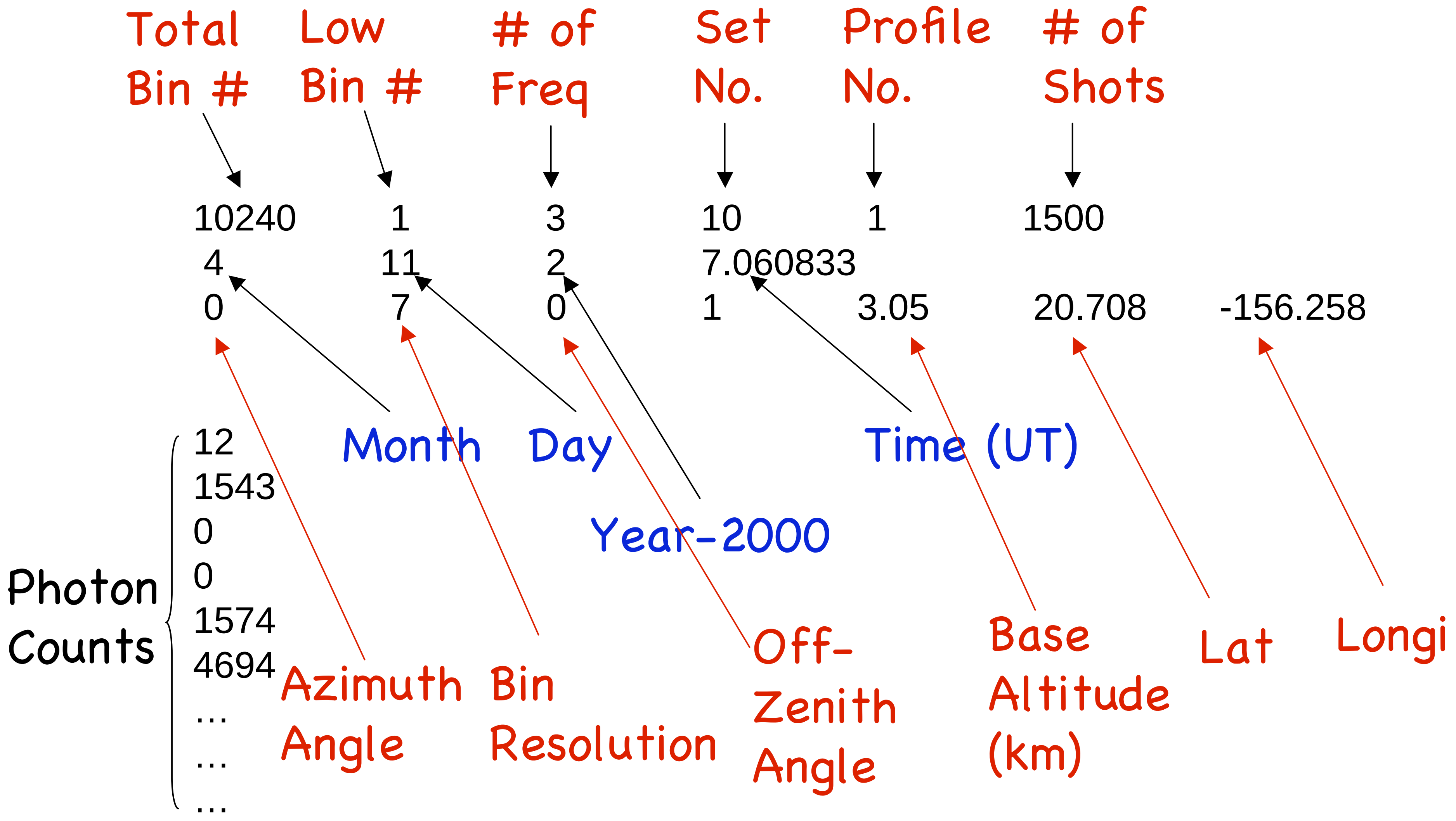
PMC, PSC, Aerosols
Constituent Density
Sporadic Layers
Meteors
Climatology
GWs, Tides, PWs
Momentum Flux
Heat Flux
Constituent Flux
Instability
… … …

Data Inversion
& Error Analysis
Data Retrieval

Data Analysis
& Interpretation
Science Study

Common Raw Data Format of Lidar

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



Total Bin #

Low Bin #

# of Freq

Set No.

Profile No.

# of Shots

```
10240     1     3     10           1       1500
4         11    2     7.060833
0         7     0     1            3.05    20.708    -156.258
```

Month

Day

Time (UT)

Year-2000

Azimuth Angle

Bin Resolution

Off-Zenith Angle

Base Altitude (km)

Lat

Longi

Photon Counts

```
12
1543
0
0
1574
4694
…
…
…
```

Considerations in Data Inversion

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

-- from data header and other info source

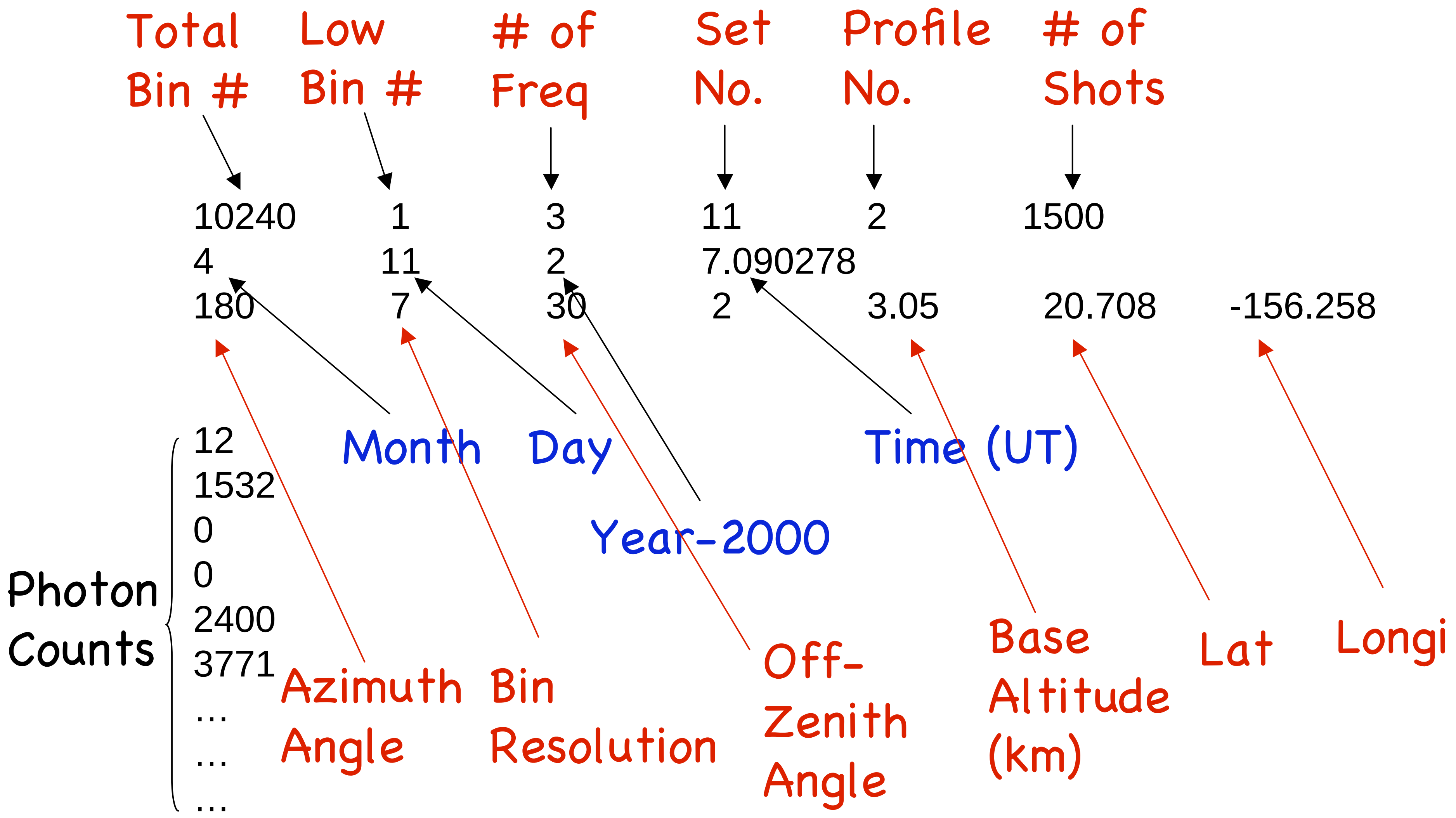
- ❑ How to obtain range or altitude information?

-- from bin number, data header and other source

$$\boxed{R = n_{bin} \cdot t_{bin} \cdot c/2} \qquad \boxed{z = R \cdot \cos\theta + z_{base}}$$

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.

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   20.708   -156.258

12
1532
0
0
2400
3771
…
…
…
```

Month

Day

Time (UT)

Year-2000

Photon Counts

Azimuth Angle

Bin Resolution

Off-Zenith Angle

Base Altitude (km)

Lat

Longi

Basic Clue: Lidar Equation & Solution

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

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

$$+$$

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

$$\Downarrow$$

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

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

Basic Clue: Ratio Computation

- From physics, we calculate the ratios of R_T and R_W as

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

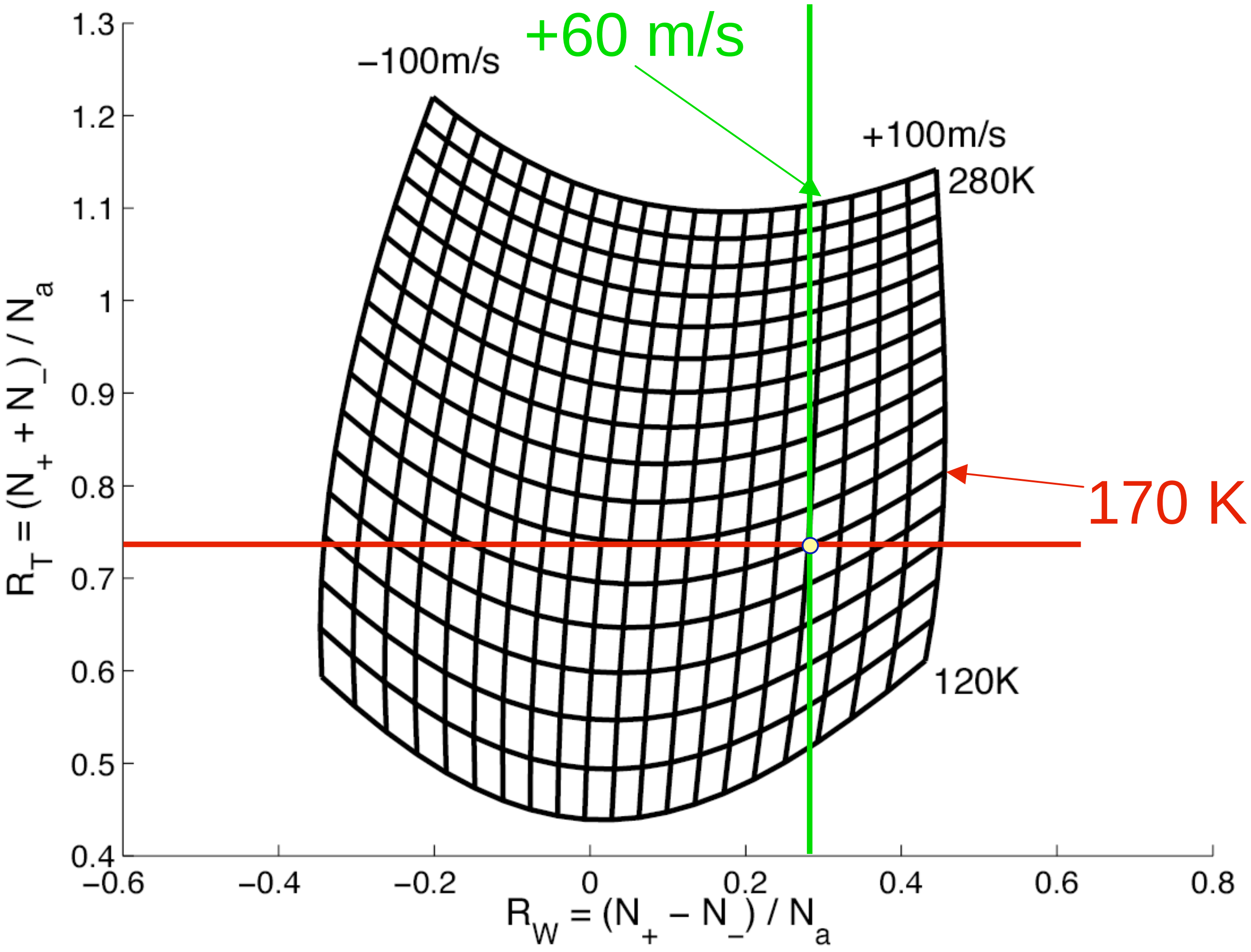
- From actual photon counts, we calculate the ratios as

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

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

Main Process Procedure

- ☐ Compute Doppler calibration curves from physics
- ☐ Look up these two ratios on the calibration curves to infer the corresponding Temperature and Wind from isoline/isogram.



Na Density Derivation

- The Na density can be inferred from the peak freq signal

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

- The Na density can be inferred from a weighted average of all three frequency signals.
- The weighted effective cross-section is

$$\sigma_{eff\_wgt} = \sigma_a + \alpha\sigma_+ + \beta\sigma_-$$

where α and β are chosen so that

$$\frac{\partial \sigma_{eff\_wgt}}{\partial T} = 0; \qquad \frac{\partial \sigma_{eff\_wgt}}{\partial \nu_R} = 0$$

- The Na density is then calculated by

$$n_{Na}(z) = 4\pi n_R(z_R)\sigma_R \frac{N_{norm}(f_a,z) + \alpha N_{norm}(f_+,z) + \beta N_{norm}(f_-,z)}{\sigma_a + \alpha\sigma_+ + \beta\sigma_-}$$

Main Ideas to Derive Na T and W

- In the ratio technique, Na number density is cancelled out. So we have two ratios R_T and R_W that are independent of Na density but both dependent on T and W.

- The idea is to derive temperature and radial wind from these two ratios first, and then derive Na number density using computed temperature and wind at each altitude bin.

- To derive T and W from R_T and R_W, the basic idea is to use look-up table or iteration methods to derive them: (1) compute R_T and R_W from physics point-of-view to generate the table or calibration curves, (2) compute R_T and R_W from actual photon counts, (3) check the table or calibration curves to find the corresponding T and W. (4) If R_T and R_W are out of range, then set to nominal T and W.

- However, because the Na extinction coefficient is involved, the upper bins are related to lower bins, and extinction coefficient is related to Na density and effective cross-section. The solution is to start from the bottom of the Na layer.

Preprocess Procedure

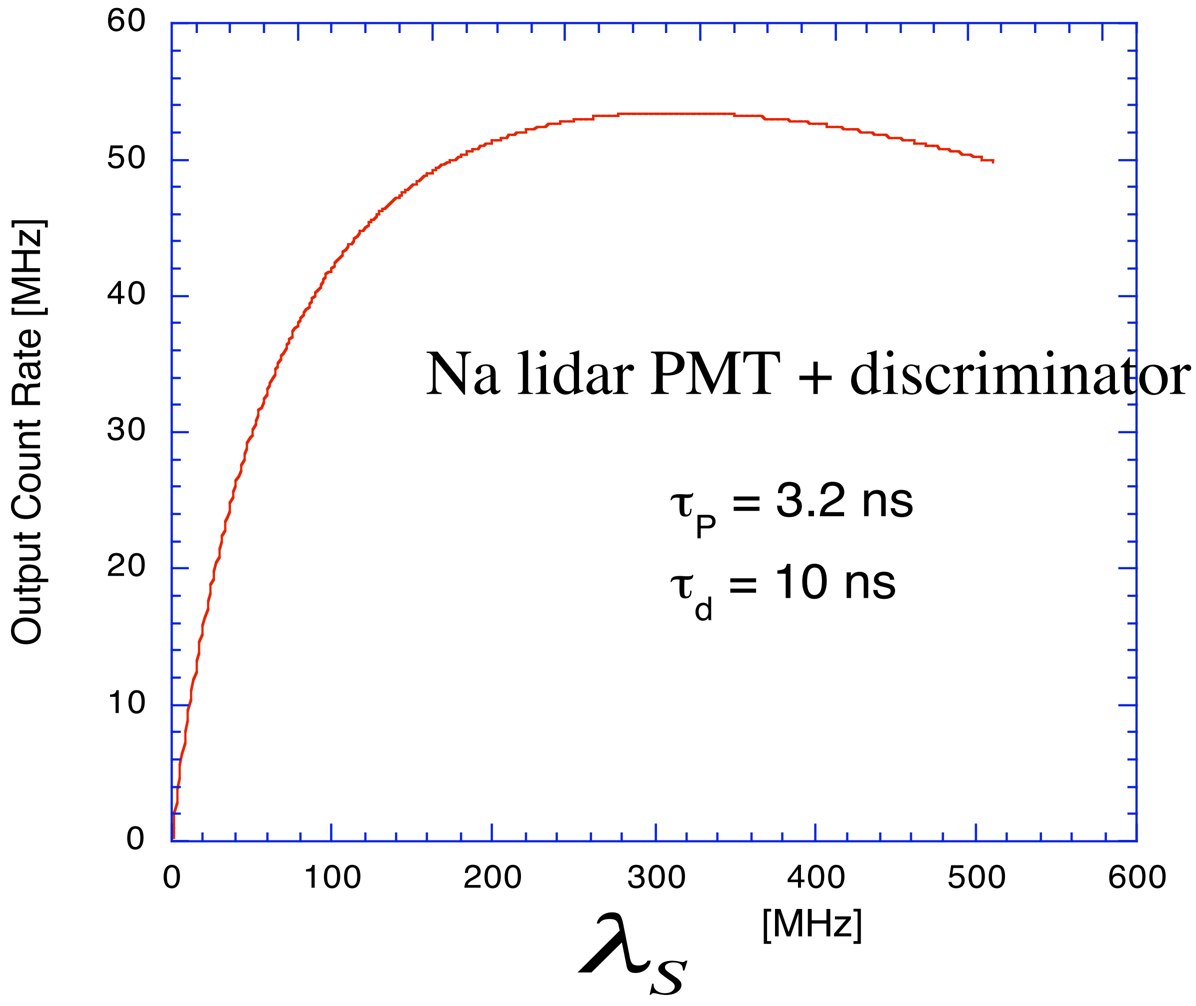
❑ Indicated from the lidar equation and its solution, the preprocess for Na Doppler lidar data is

- Background estimation and subtraction ($- N_B$)
- Range-dependence removal ($\times z^2$)
- 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

PMT+Discriminator Saturation Correction

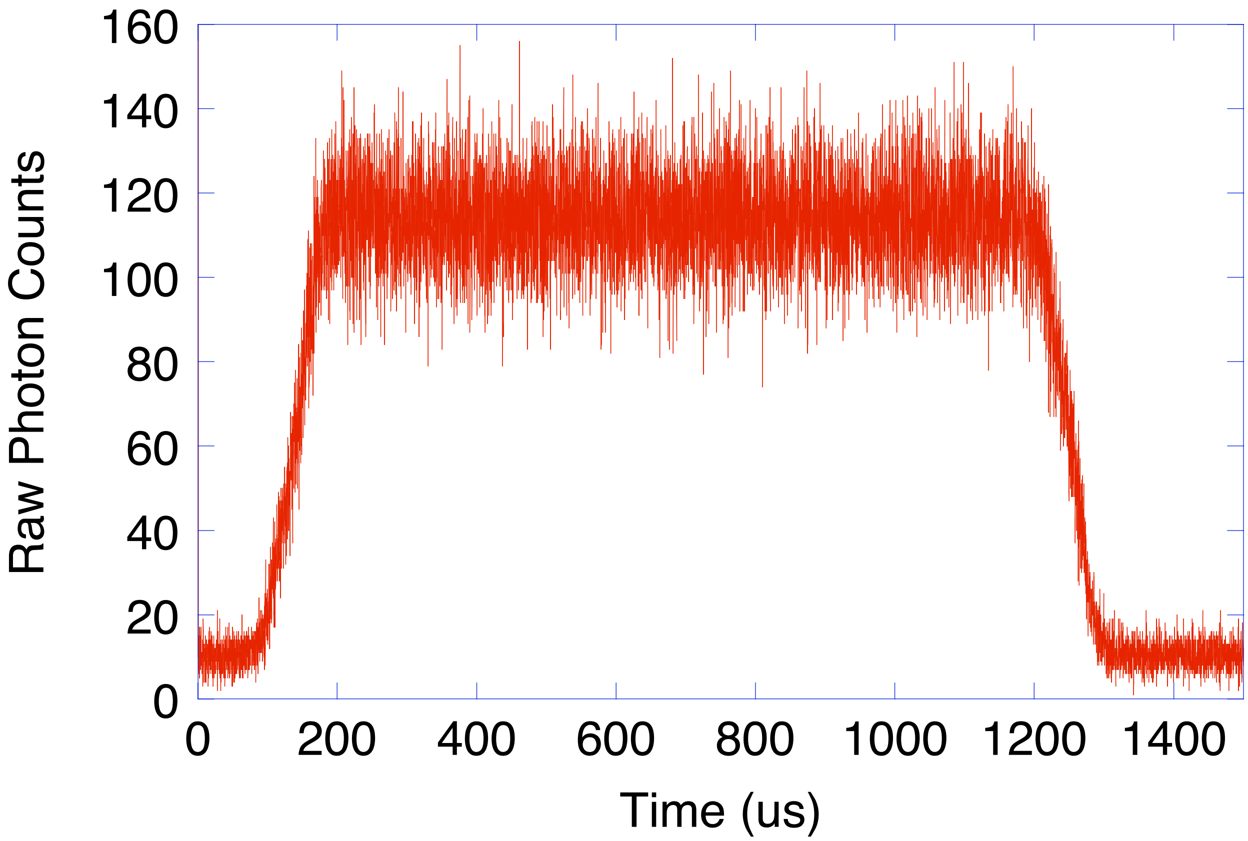


$$\lambda_o = \frac{\lambda_S e^{-\lambda_S \tau_p}}{1 + \lambda_S \tau_d e^{-\lambda_S \tau_p}}$$

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

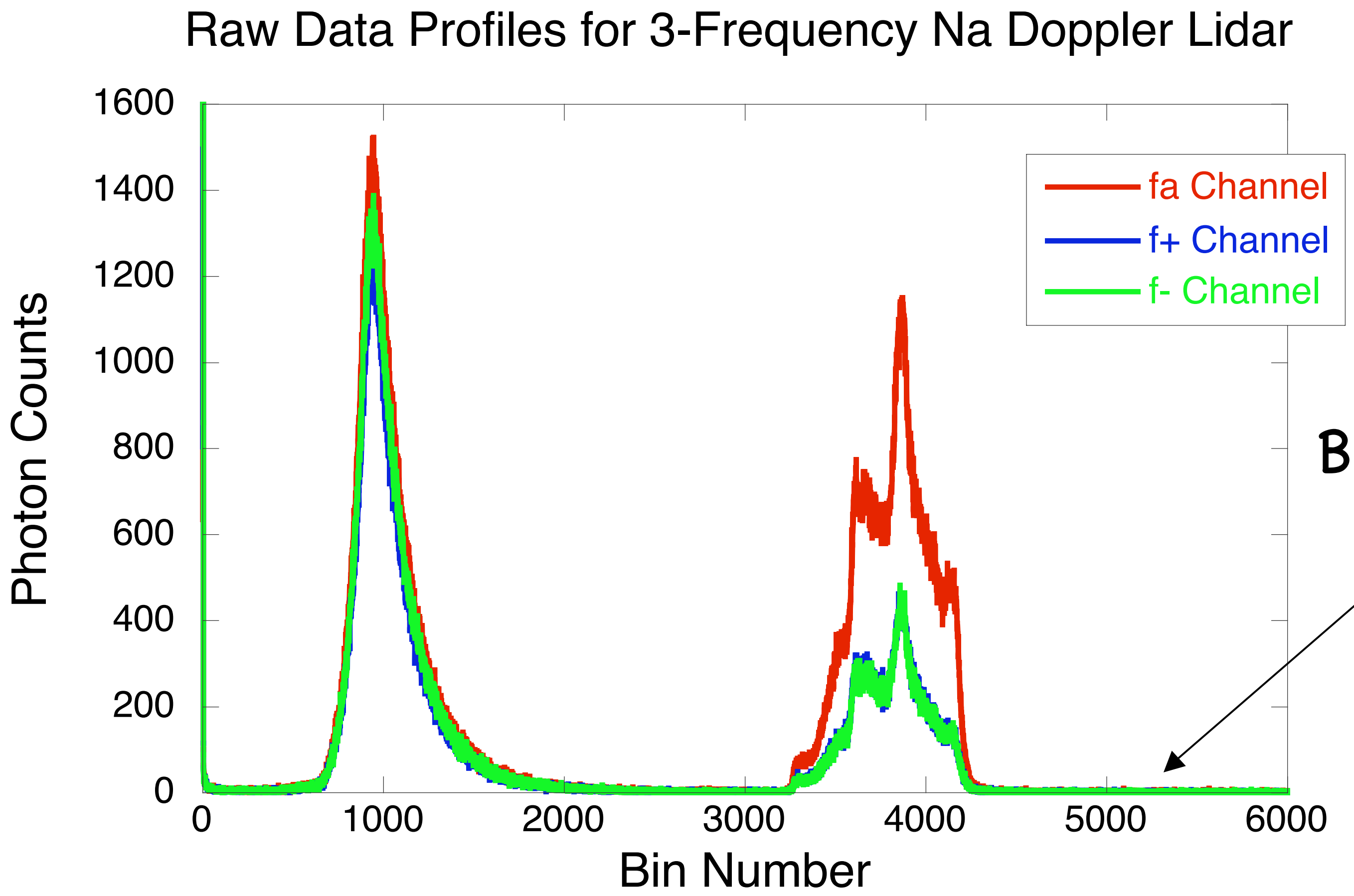
Chopper Correction

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



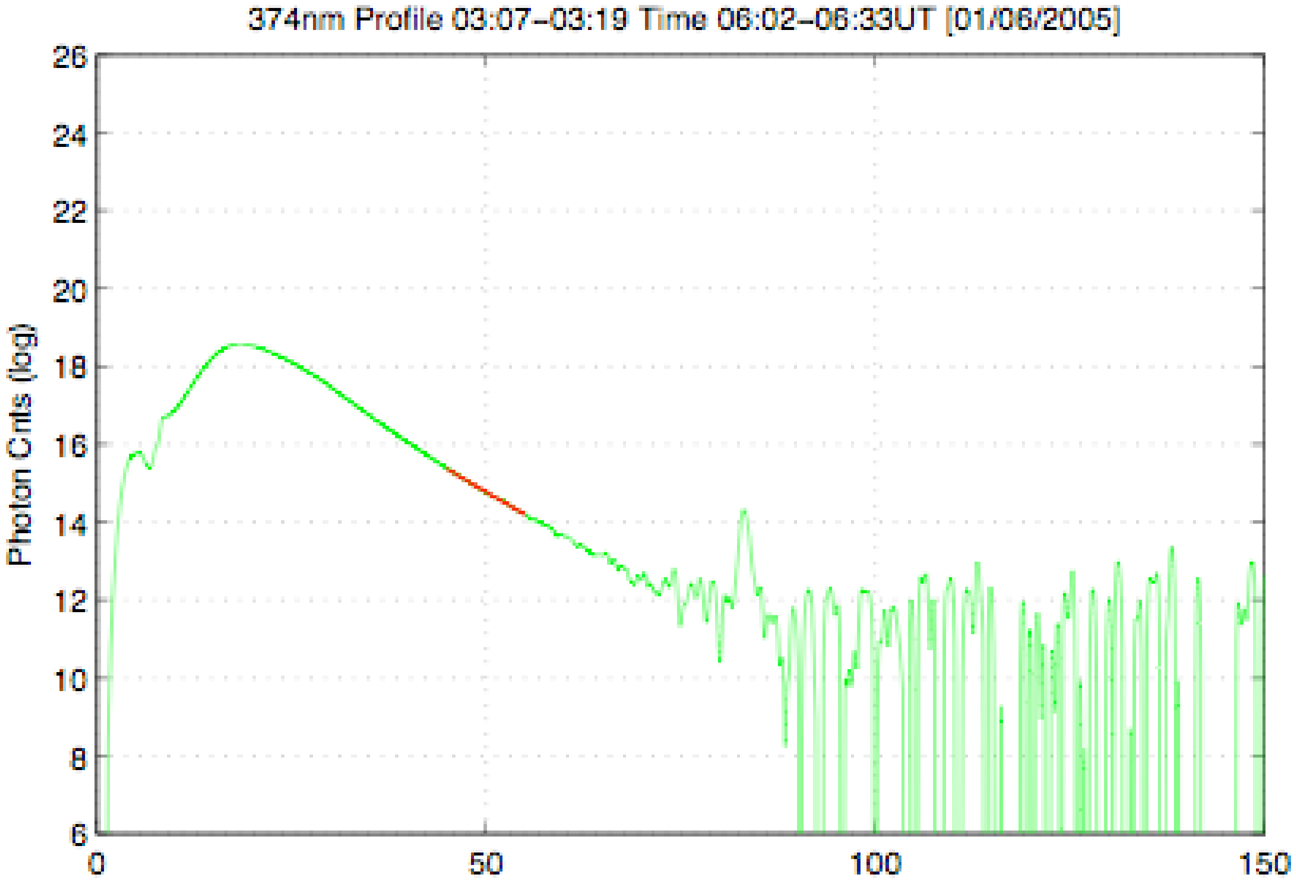
Background Estimate

- Background is estimated from high altitude signal

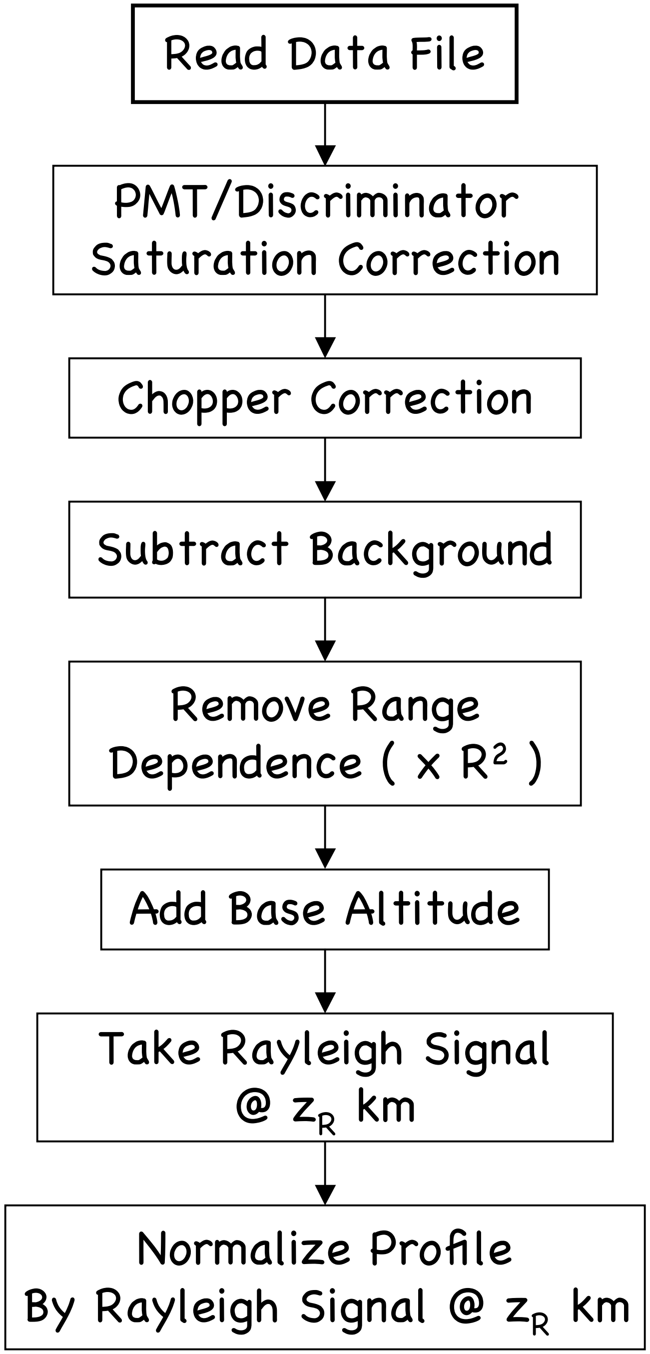

Raw Data Profiles for 3-Frequency Na Doppler Lidar

Background Estimate

Estimate of Rayleigh Normalization Signal - Rayleigh Fit or Sum



Preprocess Procedure for Na Doppler Lidar



Read Data File

PMT/Discriminator Saturation Correction

Chopper Correction

Subtract Background

Remove Range Dependence (x R^2)

Add Base Altitude

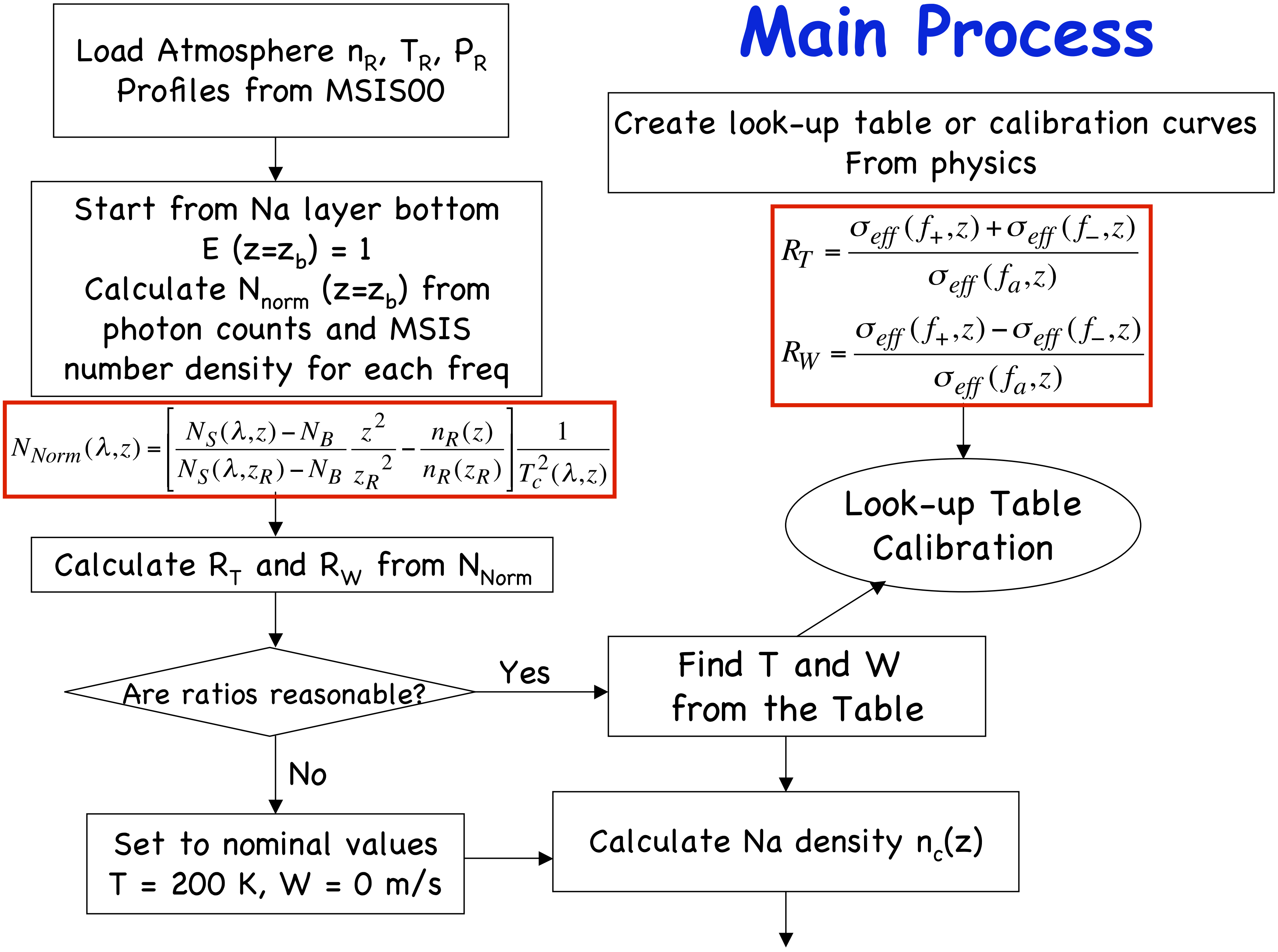
Take Rayleigh Signal @ z_R km

Normalize Profile By Rayleigh Signal @ z_R km

- 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

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

Main Process



Load Atmosphere n_R, T_R, P_R Profiles from MSIS00

Start from Na layer bottom
E $(z=z_b) = 1$
Calculate N_{norm} $(z=z_b)$ from photon counts and MSIS number density for each freq

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

Calculate R_T and R_W from N_{Norm}

Are ratios reasonable?

Yes

No

Set to nominal values
T = 200 K, W = 0 m/s

Create look-up table or calibration curves
From physics

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

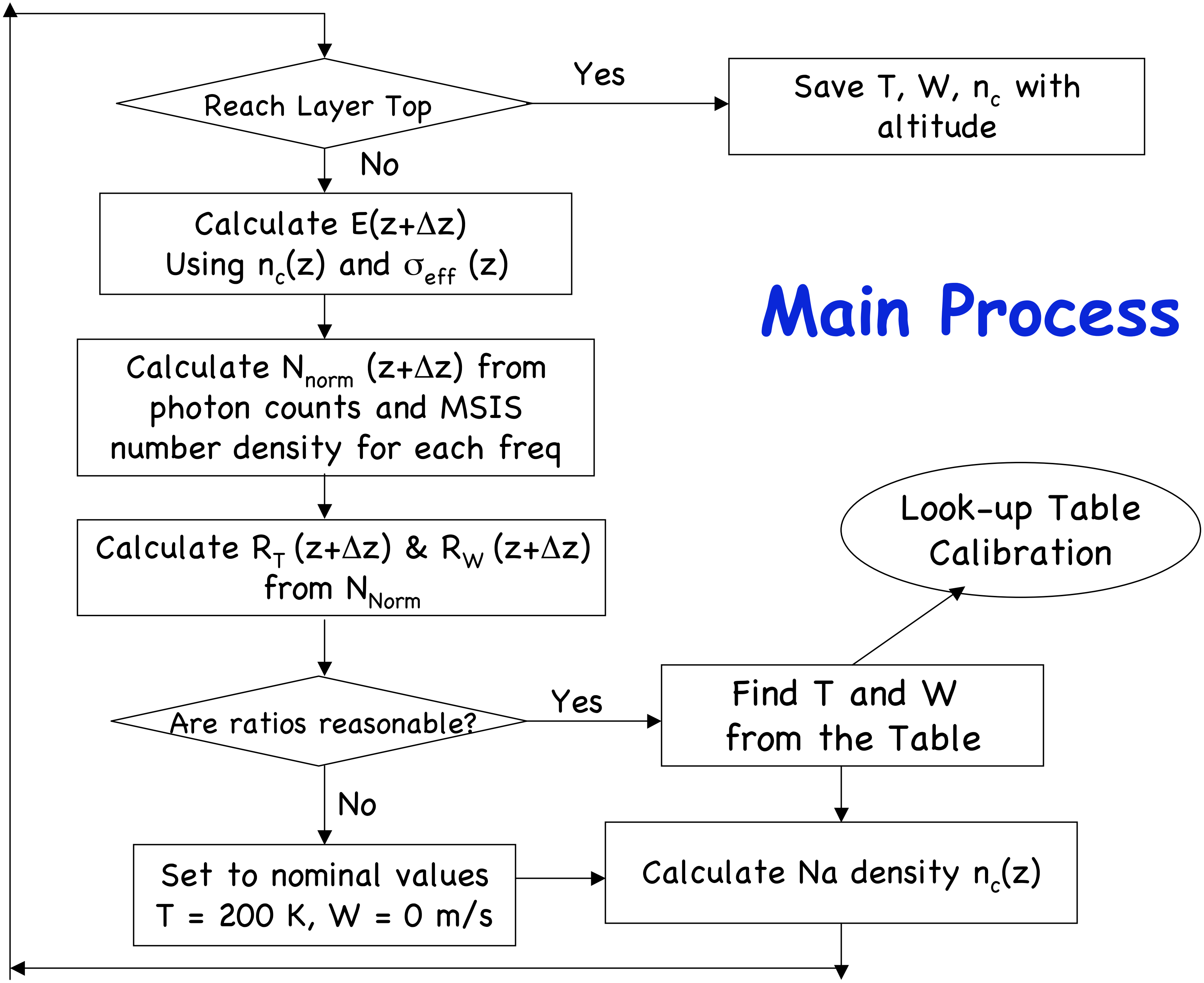
$$R_W = \frac{\sigma_{eff}(f_+,z)-\sigma_{eff}(f_-,z)}{\sigma_{eff}(f_a,z)}$$

Look-up Table Calibration

Find T and W from the Table

Calculate Na density $n_c(z)$

Main Process



Reach Layer Top

Yes

Save T, W, n_c with altitude

No

Calculate $E(z+\Delta z)$ Using $n_c(z)$ and $\sigma_{eff}(z)$

Calculate $N_{norm}(z+\Delta z)$ from photon counts and MSIS number density for each freq

Calculate $R_T(z+\Delta z)$ & $R_W(z+\Delta z)$ from N_{Norm}

Are ratios reasonable?

Yes

Find T and W from the Table

Look-up Table Calibration

No

Set to nominal values T = 200 K, W = 0 m/s

Calculate Na density $n_c(z)$

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.
- The data inversion procedure consists of three main processes: (1) preprocess, (2) process of T and V_R, (3) process of n_c and β, etc.

Summary

- ☐ The preprocess is to convert the raw photon counts to corrected and normalized photon counts in consideration of hardware properties and limitations.
- ☐ The process of T and V_R is to convert the normalized photon counts to T and V_R through integration, iteration or looking-up table methods.
- ☐ The process of n_c is to convert the normalized photon counts to meaningful number density, in combination with prior acquired knowledge or model knowledge of certain atmosphere information or atomic/molecular spectroscopy.
- ☐ These processes sometimes involve considerable binning, smoothing, or temporal integration in order to improve the signal-to-noise ratio (SNR) to result in meaningful results.