# Lecture 17. Temperature Lidar (1)

- Introduction to Topical Lidars
- Motivations to Measure Temperature & Wind
- Techniques for Temperature Measurements (Temperature-Dependent Effects)
- Doppler Technique for T and W Measurements
- Resonance Fluorescence Na Doppler Lidar (Principle, Metrics, Calibration)
- Na Doppler Lidar Instrumentation
- Summary

# Introduction to Topical Lidars

- Topics we will discuss in this class are

1. Temperature (structure from ground to thermosphere, diurnal/seasonal/interannual variations, etc.)

2. Wind (structure from ground to upper atmosphere, its variations, etc.)

3. Constituents ($O_3$, $CO_2$, $H_2O$, $O_2$, $N_2^+$, He, metal atoms like Na, Fe, K, Ca, pollution, etc)

4. Aerosols and clouds (distribution, extinction, composition, size, shape, and variations spatially and temporally)

5. Solid target, altimetry (identification, accurate height & range determination, fish, vibration, etc.)

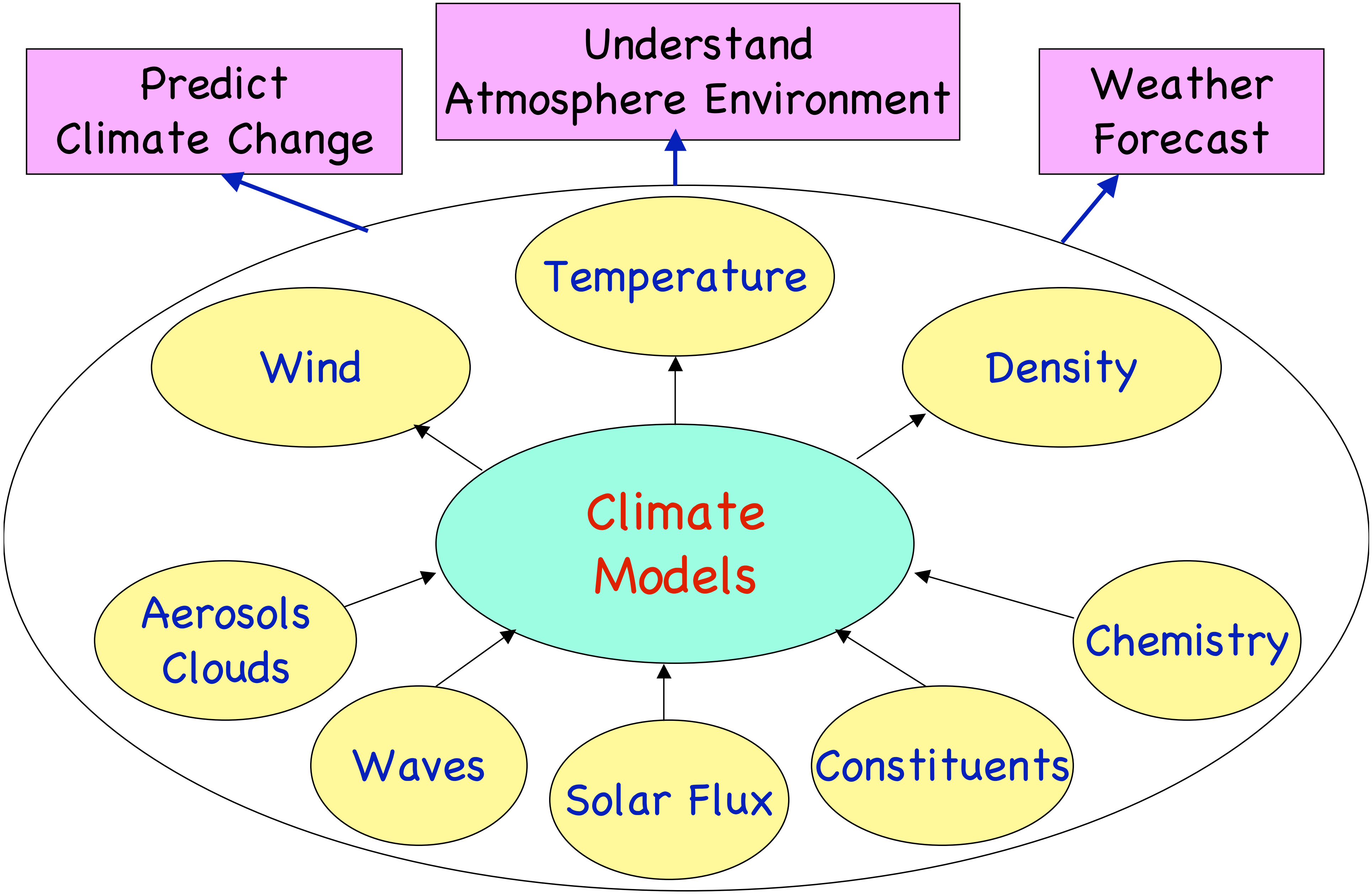
# Why Topical Lidars ?

- To compare different lidar techniques that address the same topic, e.g., how many ways to measure temperature, and what's the essential point among these different lidars?
- To illustrate the strengths and limitations of each different type of lidars, and give an insight of when and where to use what kind of lidars?
- To encourage students to explore new phenomena or effects to invent novel lidars / methods.

# Why These Five Topics ?

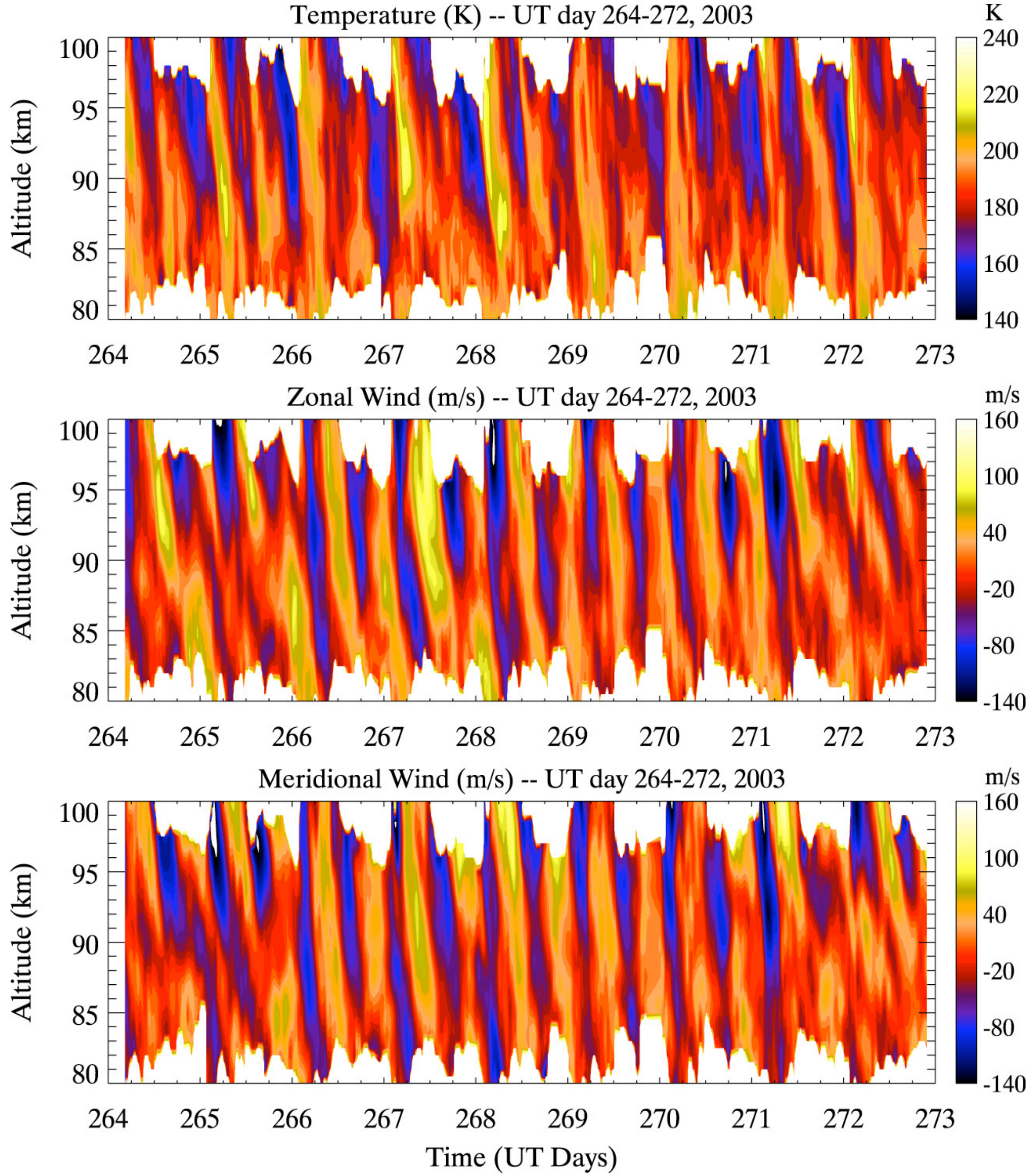
- These are five most interesting and hot topics in the atmospheric/space science, environmental research, and climate study.
- They also have wide applications in environmental monitoring, national defense, and industry applications.
- The lidar technologies used to address these five topics represent the key technology advancement in the past 20 years.
- There are also high potentials of future advancement in these aspects, so encouraging creative students to pursue technology innovation, development, implementation, as well as applying the existing and future technology to conduct novel science/environmental research.

# Observables in Climate Models

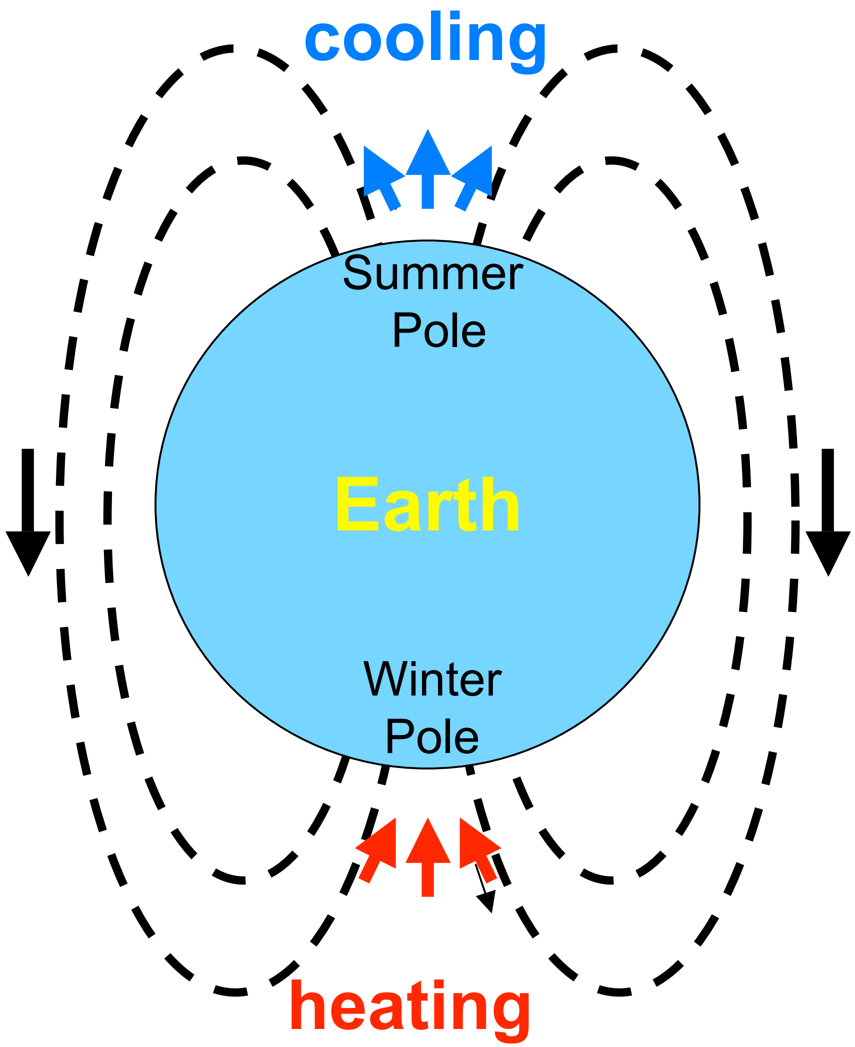


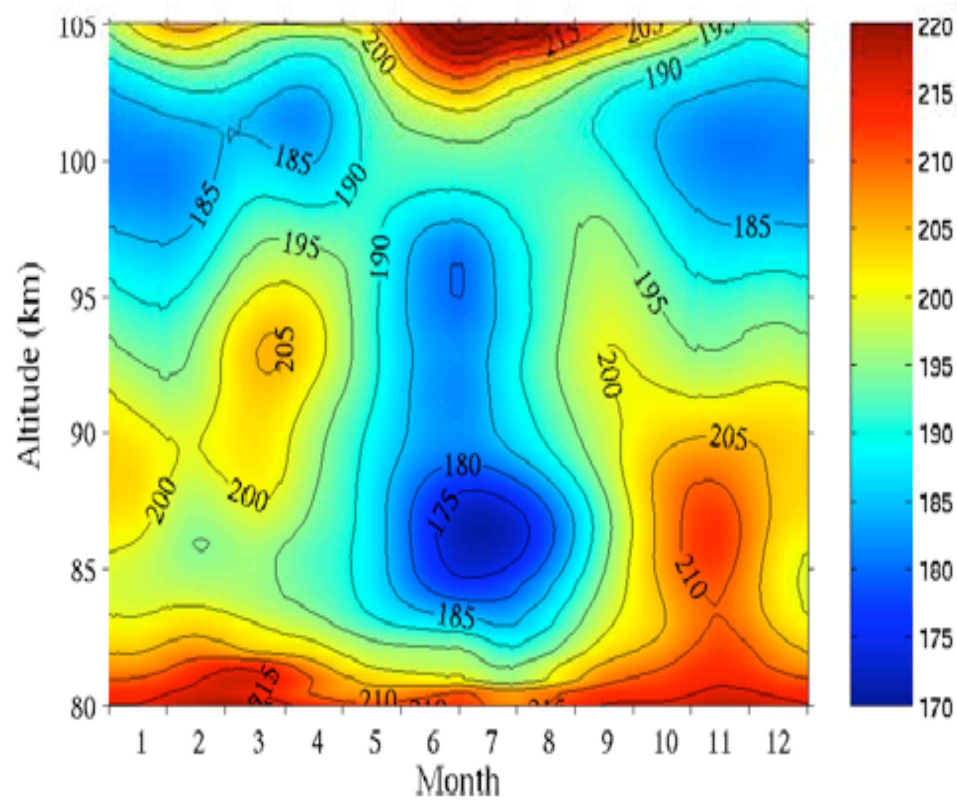
# Motivations For T/W Measurement

- Model validations
- Atmospheric dynamics study
- Global climate change monitoring
- Proxy to study gravity waves, tides, planetary waves, etc. dynamical processes



# General Circulation versus Global Thermal Structure



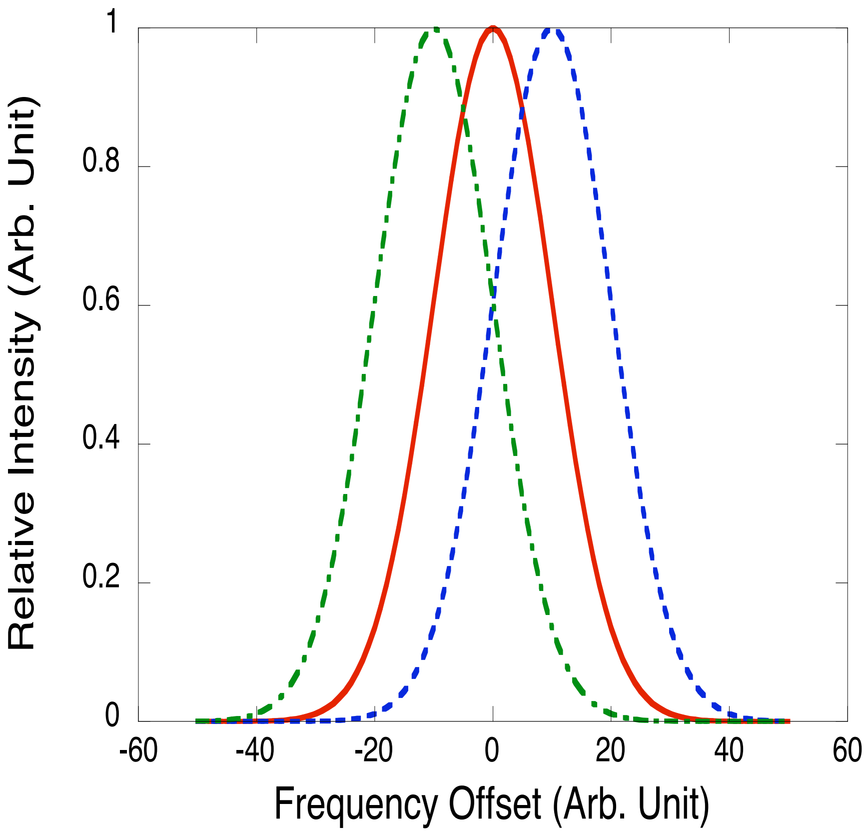

Lidar Temperature at Albuquerque, NM (35°N)

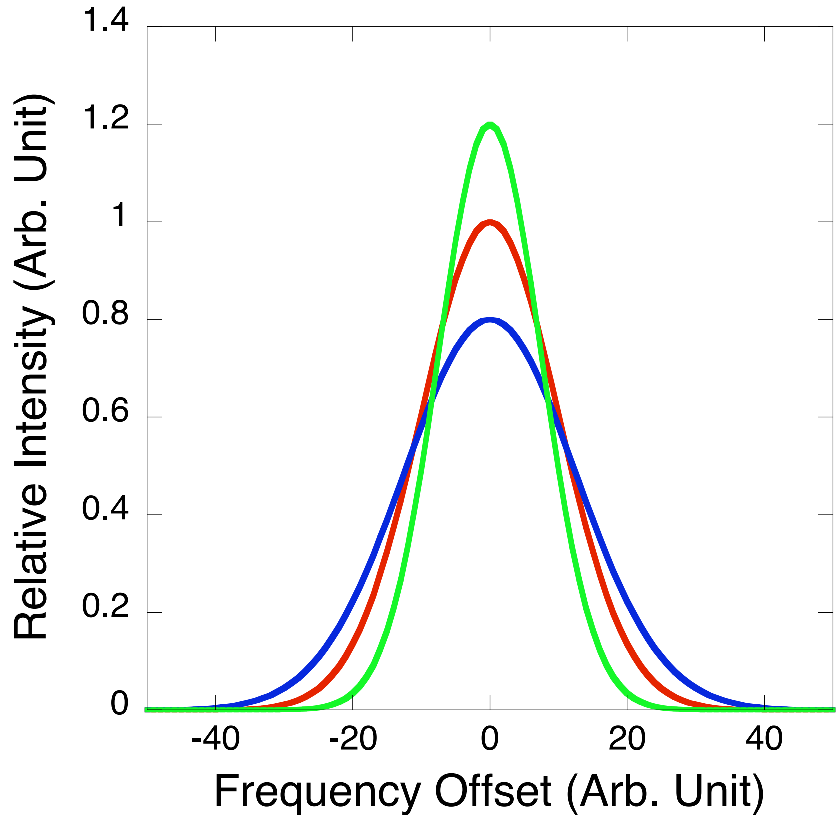
# How to Measure Temperature ?

## Use temperature-dependent effects or phenomena

- Doppler Technique – Doppler broadening (not only for Na, K, and Fe, but also for Rayleigh scattering, as long as Doppler broadening dominate and can be detected)
- Boltzmann Technique – population ratio (not only for Fe, but also for molecular spectroscopy in optical remote sensing and rotational Raman lidar)
- Rayleigh technique – integration lidar technique using ideal gas law and assuming hydrostatic equilibrium (not only for modern lidar, but also for cw searchlight and rocket falling sphere – something to measure atmos density)
- Rotational Raman technique – temperature dependence of population ratio, same as Boltzmann technique

# Doppler Technique



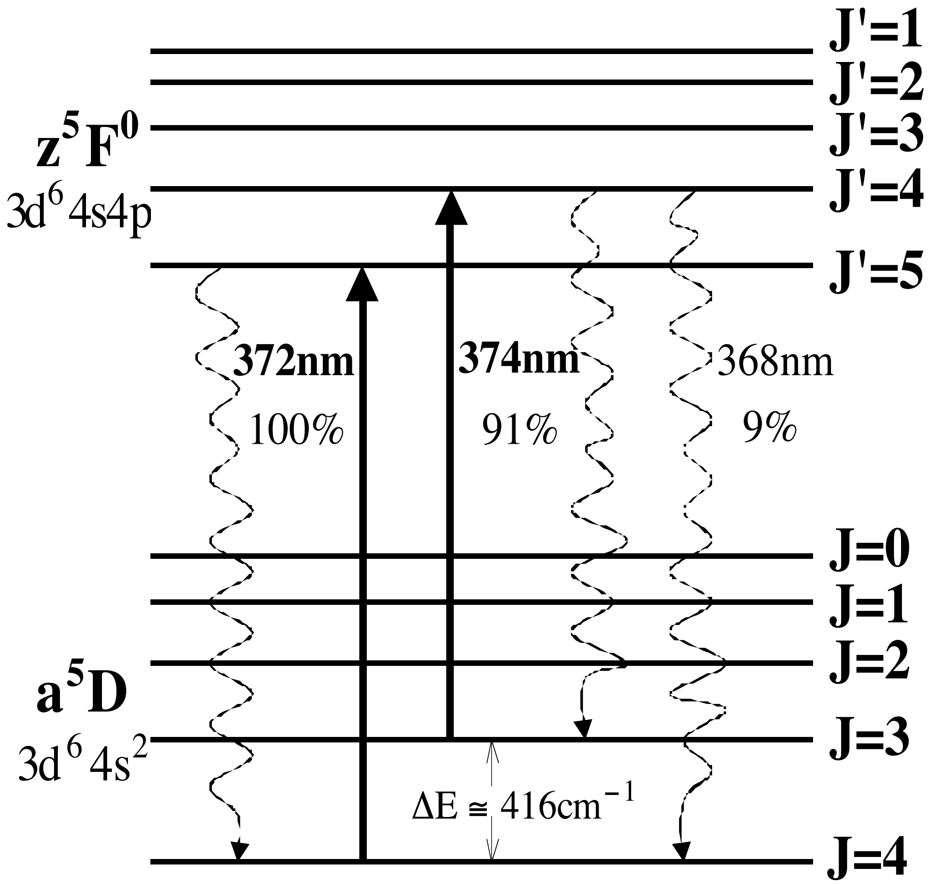




$$\nu' = \nu\left(1 - \frac{v_R}{c}\right)$$

$$\sigma_D = \sqrt{\frac{k_B T}{M\lambda_0^{\ 2}}}$$

**Doppler Spectrum (Width and Shift) ⇨ Temperature and Radial Wind**

# Boltzmann Technique




**Atomic Fe Energy Level**

**[Gelbwachs, 1994; Chu et al., 2002]**

**Maxwell-Boltzmann Distribution in Thermal-dynamic Equilibrium**

$$\frac{P_2(J=3)}{P_1(J=4)} = \frac{\rho_{Fe(374)}}{\rho_{Fe(372)}} = \frac{g_2}{g_1} exp(-\Delta E / k_B T)$$

$$T = \frac{\Delta E / k_B}{ln\left(\frac{g_2}{g_1} \cdot \frac{P_1}{P_2}\right)}$$

**$P_1$, $P_2$ -- Fe populations**
**$g_1$, $g_2$ -- Degeneracy**
**$k_B$ -- Boltzmann constant**
**T -- Temperature**

**Population Ratio ⇨ Temperature**

# Rayleigh Integration Technique

Hydrostatic Equation

$$dP = -\rho g dz$$

+

Ideal Gas Law

$$P = \rho R T$$

$$T(z) = T(z_o)\frac{\rho(z_o)}{\rho(z)} + \frac{1}{R}\int_{z}^{z_o} g(r)\,dr\,\frac{\rho(r)}{\rho(z)}$$

Seeding Temperature

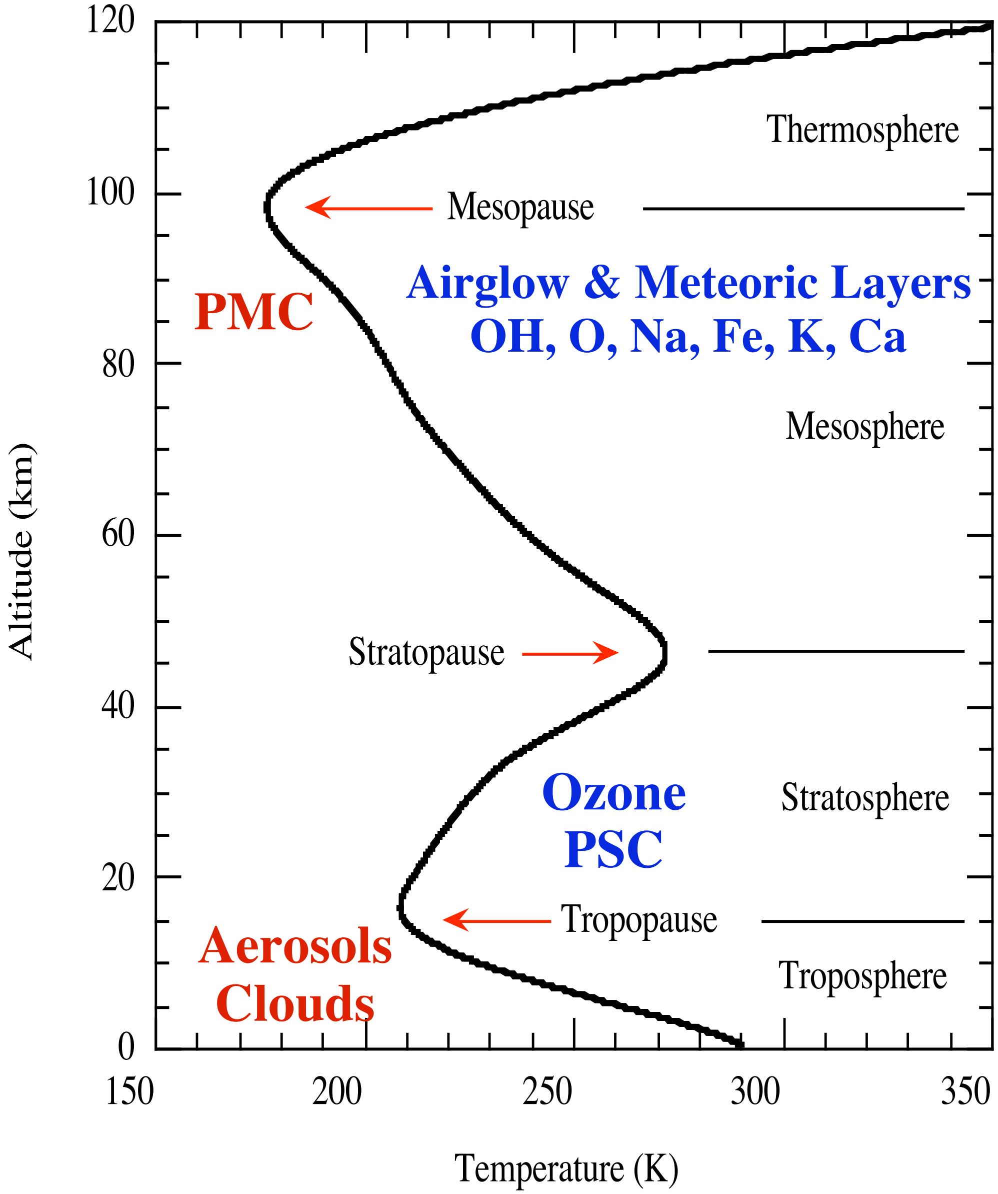
Relative Density

**$T(z_0)$ - Seeding Temperature;** **ρ - number density**

**R - gas constant for dry air;** **g - gravitational acceleration**

**Lidar Backscatter Ratio ⇨ Relative Density ⇨ Temperature**
**(at different altitudes)** **(Rayleigh)**

# Temperature Techniques




- 75-120km: resonance fluorescence Doppler technique (Na, K, Fe) & Boltzmann technique (Fe, OH, $O_2$)
- 30-90km: Rayleigh integration technique & Rayleigh Doppler technique
- Below 30 km: scattering Doppler technique and rotation Raman (Boltzmann) technique
- Boundary layer: DIAL, HSRL, Rotational Raman

# Doppler Technique to Measure Temperature and Wind

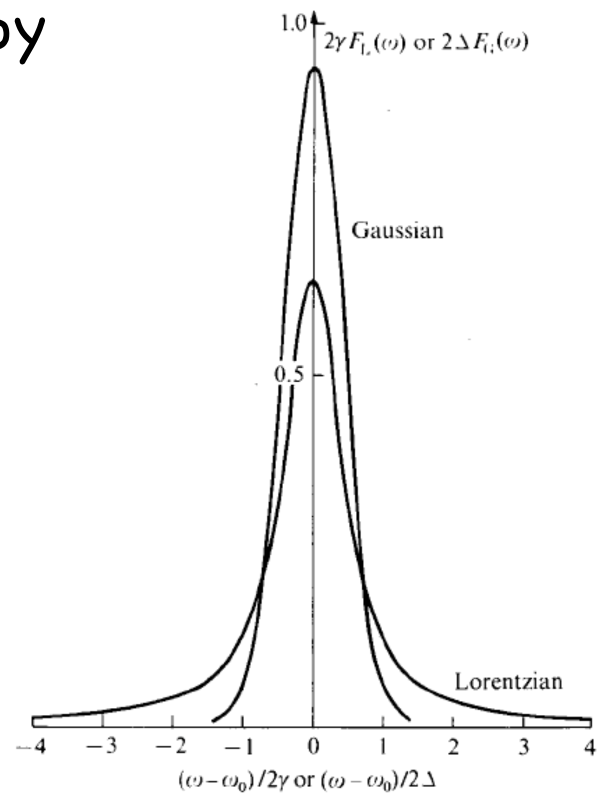
- Doppler effect is commonly experienced by moving particles, such as atoms, molecules, and aerosols. It is the apparent frequency change of radiation or wave that is perceived by the particles moving relative to the source of the radiation or wave. This is called Doppler shift.
- Doppler frequency shift is proportional to the radial velocity along the line of sight (LOS) of the radiation –

$$\boxed{\omega = \omega_0 - \vec{k} \cdot \vec{v}} \Longrightarrow \boxed{\Delta\omega = \omega - \omega_0 = -\vec{k} \cdot \vec{v} = -\omega_0 \frac{v \cos\theta}{c}}$$

where $\omega_0$ is the radiation frequency at rest, $\omega$ is the shifted frequency, k is the wave vector of the radiation ($k=2\pi/\lambda$), and v is the particle velocity.

# Doppler Technique to Measure Temperature and Wind

- Due to particles' thermal motions in the atmosphere, the distribution of perceived frequencies for all particles mirrors their velocity distribution. According to the Maxwellian velocity distribution, the perceived frequencies by moving particles has a Gaussian lineshape, given by



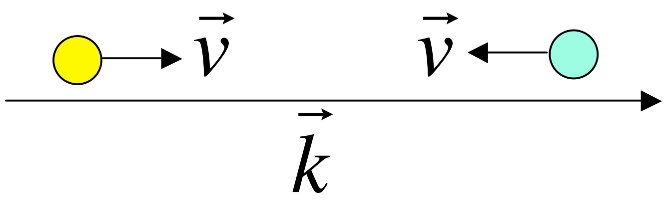

$$\boxed{\exp\left(-\frac{Mv_z^2}{2k_BT}\right)dv_z = \exp\left\{-\frac{Mc^2(\omega-\omega_0)^2}{2\omega_0^2k_BT}\right\}\frac{c}{\omega_0}d\omega}$$

- The peak is at $\omega = \omega_0$ and the rms width is give by

$$\boxed{\sigma_{rms} = \frac{\omega_0}{c}\sqrt{\frac{k_BT}{M}} = \frac{1}{\lambda_0}\sqrt{\frac{k_BT}{M}}}$$

# Doppler Shift For Wind Measurement

$$\boxed{\Delta\omega = \omega - \omega_0 = -\vec{k}\cdot\vec{v} = -\omega_0 \frac{v\cos\theta}{c}}$$

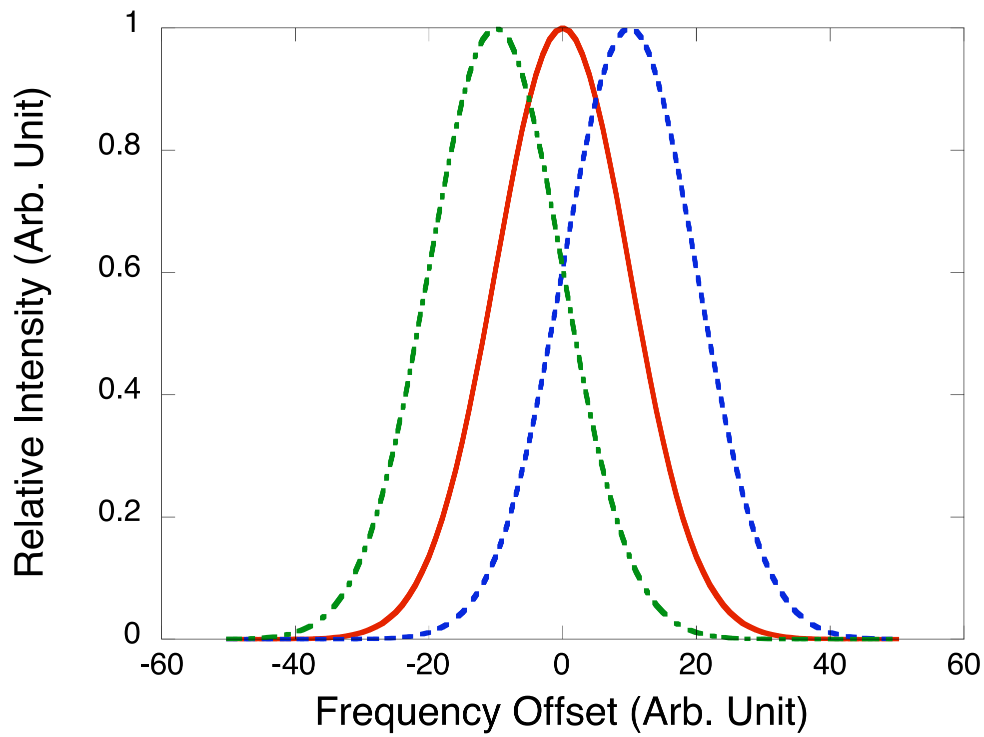



Same direction

- red shift

Opposite direction

- blue shift



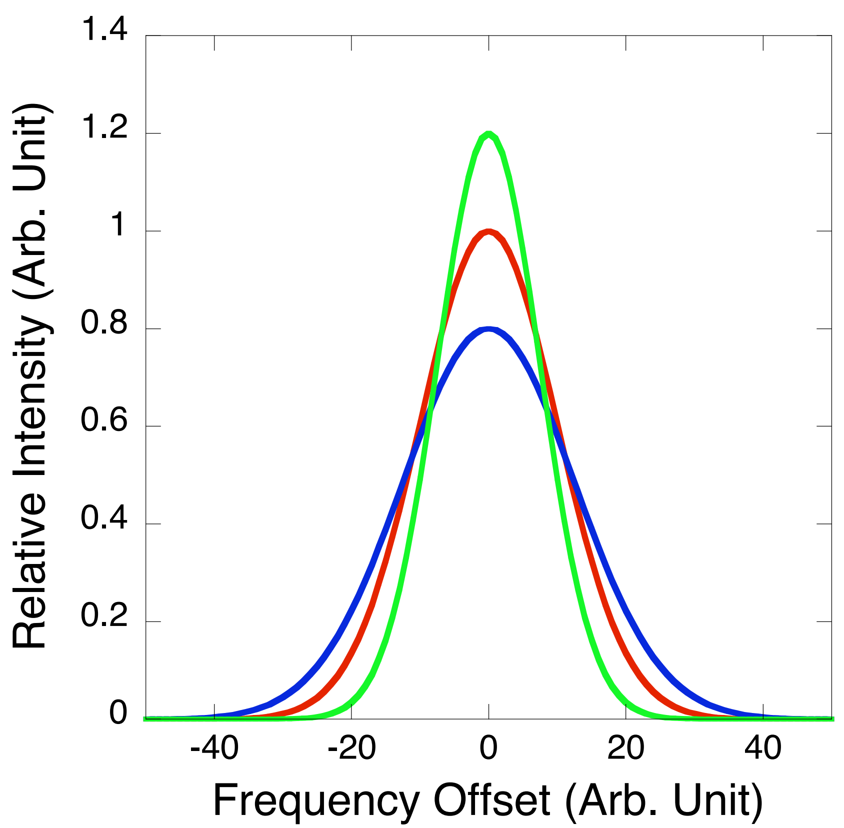

❑ The velocity measurements of lidar, radar, and sodar all base on the Doppler shift principle !

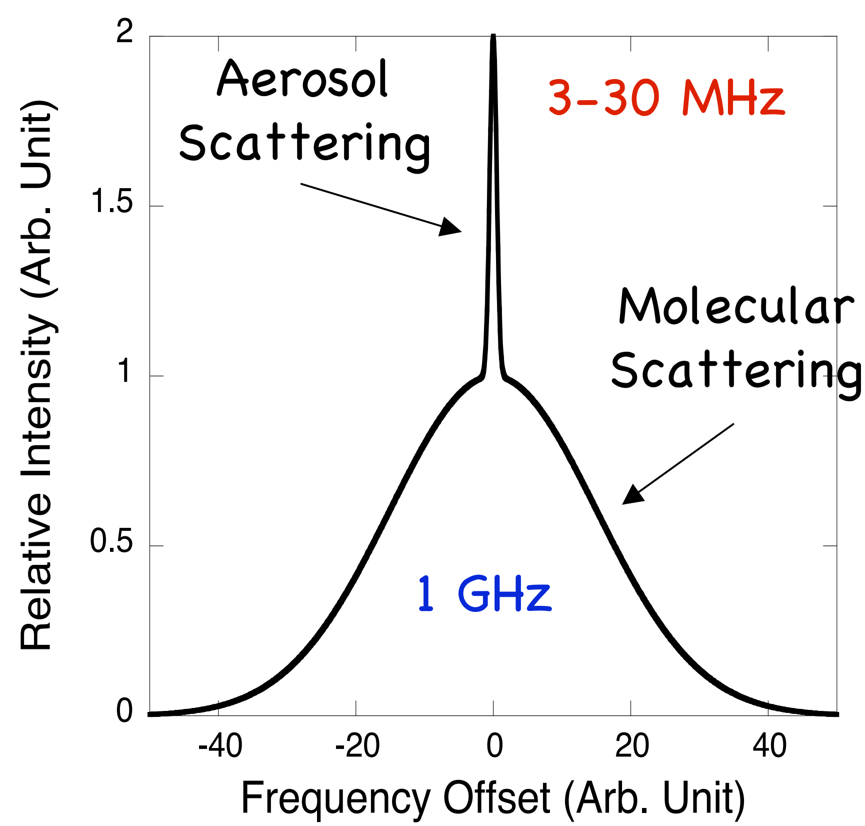
# Doppler Broadening For Temperature

$$\boxed{\sigma_{rms} = \frac{\omega_0}{c}\sqrt{\frac{k_B T}{M}} = \frac{1}{\lambda_0}\sqrt{\frac{k_B T}{M}}}$$

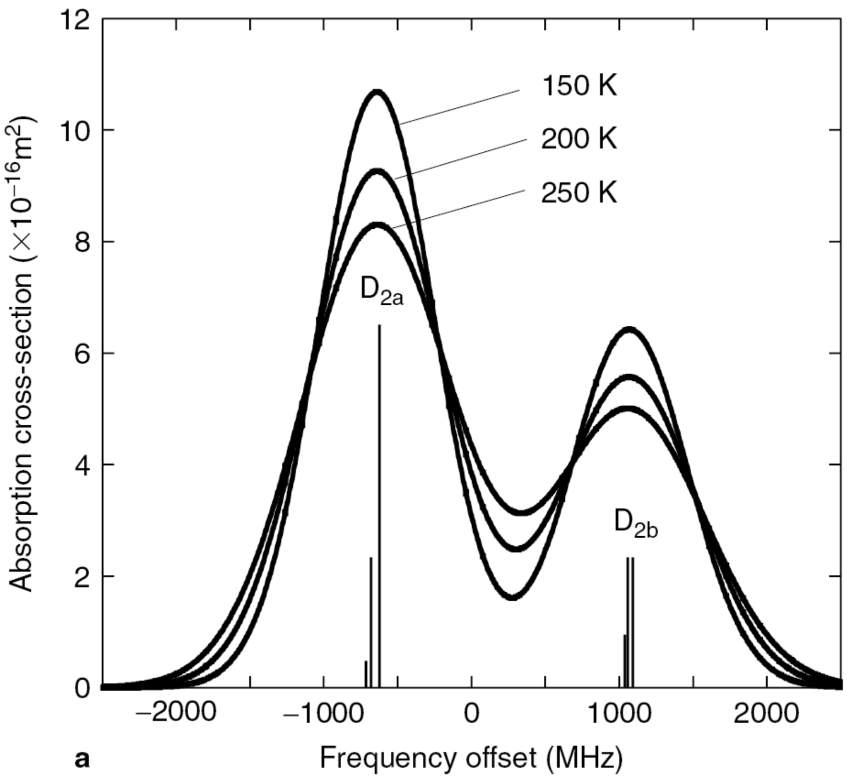
$T \nearrow \;\Rightarrow\; \sigma_{rms} \nearrow$

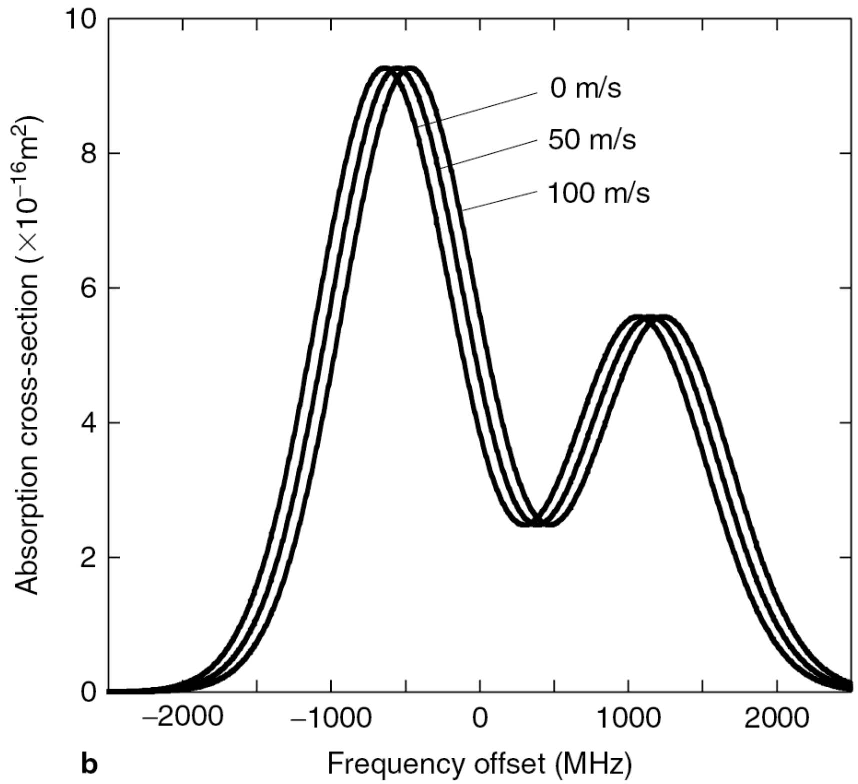
$M \nearrow \;\Rightarrow\; \sigma_{rms} \searrow$



# Doppler Effect in Na $D_2$ Line Resonance Fluorescence

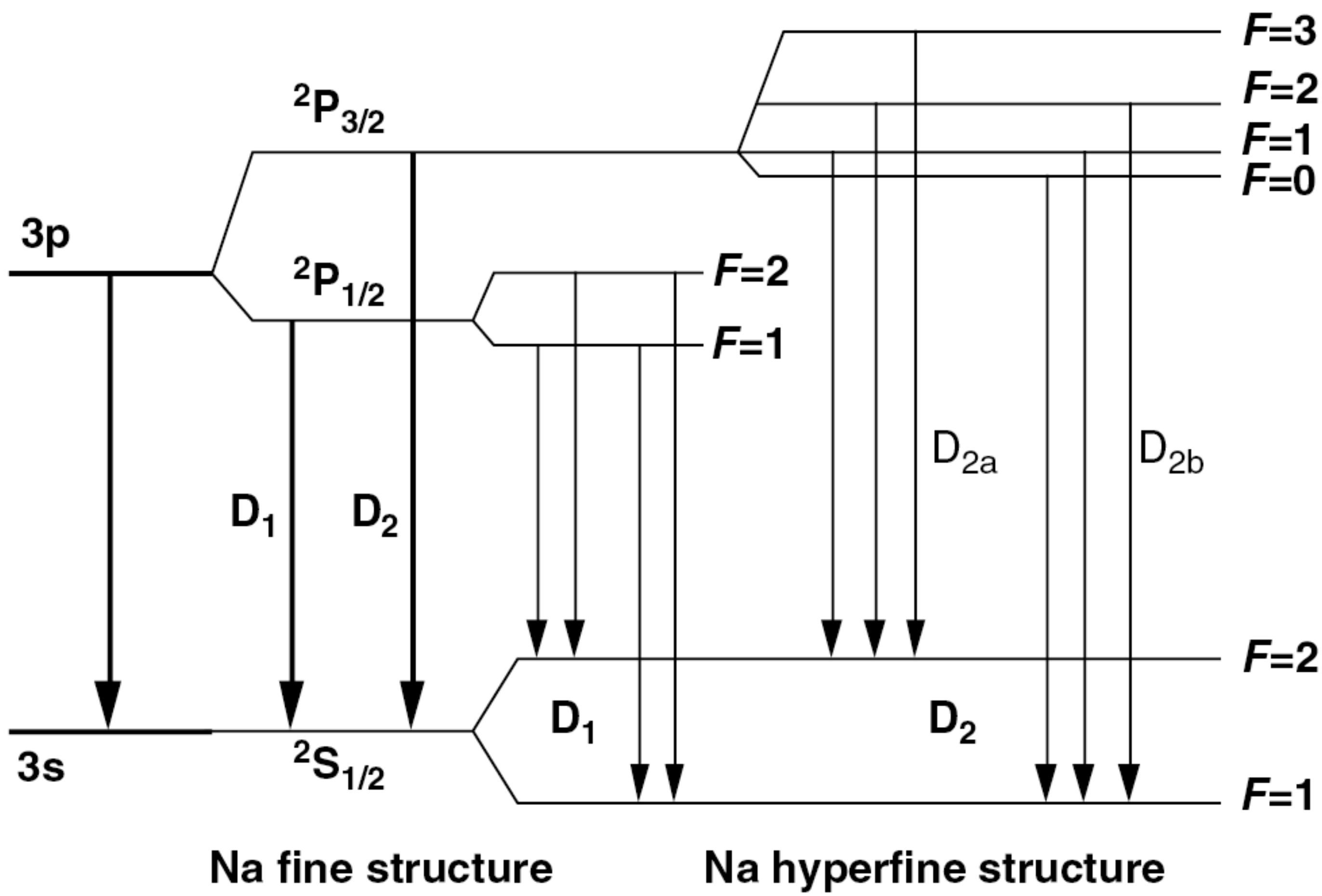



Na $D_2$ absorption linewidth is temperature dependent

Na $D_2$ absorption peak freq is wind dependent

# Na Atomic Energy Levels



# Na Atomic Parameters

**Table 5.1** Parameters of the Na $D_1$ and $D_2$ Transition Lines

| Transition Line | Central Wavelength (nm) | Transition Probability ($10^8\ s^{-1}$) | Radiative Lifetime (nsec) | Oscillator Strength $f_{ik}$ |
|---|---|---|---|---|
| $D_1$ ($^2P_{1/2} \rightarrow {}^2S_{1/2}$) | 589.7558 | 0.614 | 16.29 | 0.320 |
| $D_2$ ($^2P_{3/2} \rightarrow {}^2S_{1/2}$) | 589.1583 | 0.616 | 16.23 | 0.641 |

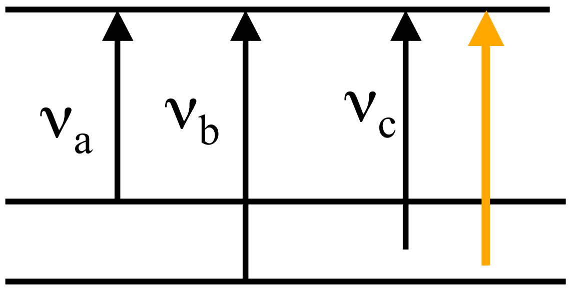
| Group | $^2S_{1/2}$ | $^2P_{3/2}$ | Offset (GHz) | Relative Line Strength[a] |
|---|---|---|---|---|
| $D_{2b}$ | $F=1$ | $F=2$ | 1.0911 | 5/32 |
| | | $F=1$ | 1.0566 | 5/32 |
| | | $F=0$ | 1.0408 | 2/32 |
| $D_{2a}$ | $F=2$ | $F=3$ | −0.6216 | 14/32 |
| | | $F=2$ | −0.6806 | 5/32 |
| | | $F=1$ | −0.7150 | 1/32 |

Doppler-Free Saturation–Absorption Features of the Na $D_2$ Line

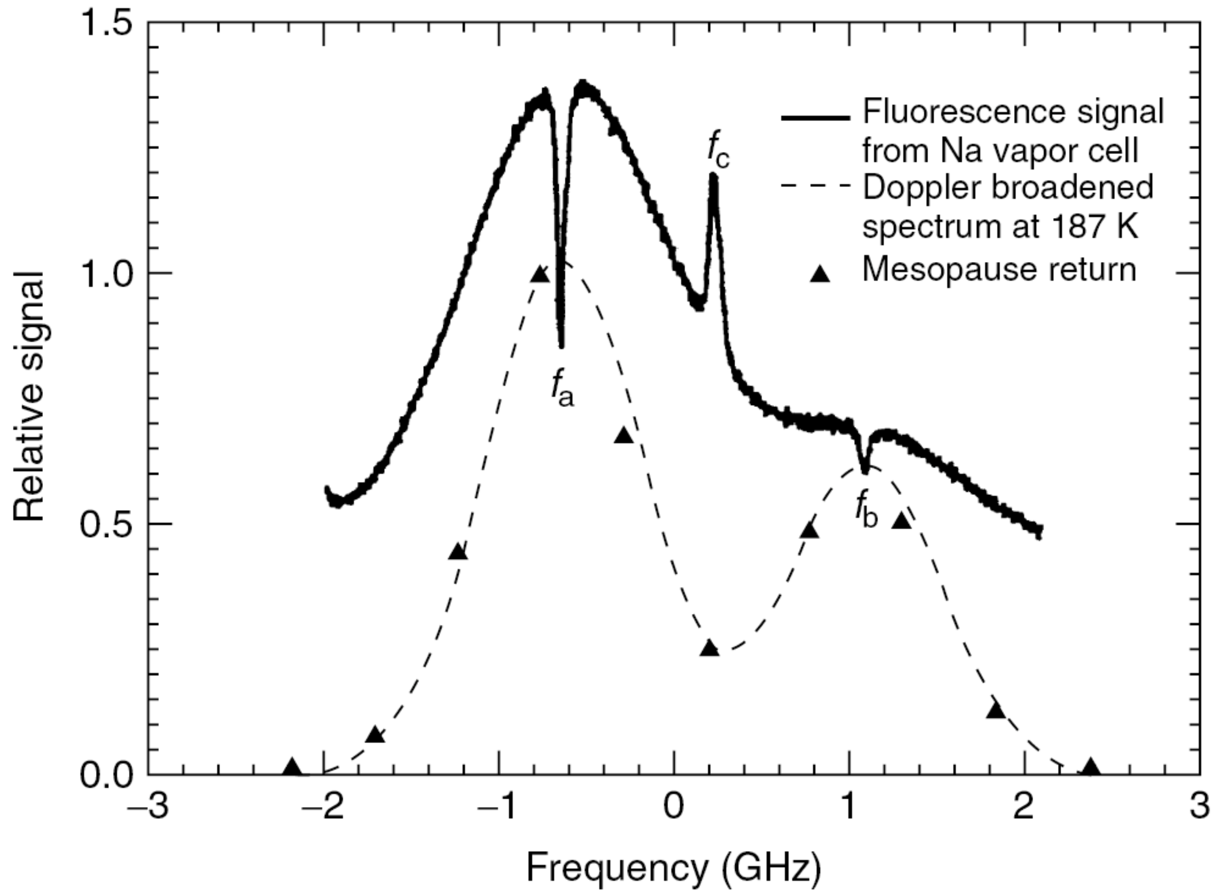
| $f_a$ (MHz) | $f_c$ (MHz) | $f_b$ (MHz) | $f_+$ (MHz) | $f_-$ (MHz) |
|---|---|---|---|---|
| −651.4 | 187.8 | 1067.8 | −21.4 | −1281.4 |

[a]Relative line strengths are in the absence of a magnetic field or the spatial average. When Hanle effect is considered in the atmosphere, the relative line strengths will be modified depending on the geomagnetic field and the laser polarization.

# Na Spectroscopy




$$\nu_c = (\nu_a + \nu_b)/2$$




$$\sigma_{\mathrm{eff}}(\nu) = \frac{1}{\sqrt{2\pi}\sigma_{\mathrm{e}}} \frac{e^2 f}{4\epsilon_0 m_{\mathrm{e}} c} \sum_{n=1}^{6} A_n \exp\left( - \frac{\left[\nu_n - \nu\left(1 - \frac{v_{\mathrm{R}}}{c}\right)\right]^2}{2\sigma_{\mathrm{e}}^2} \right)$$

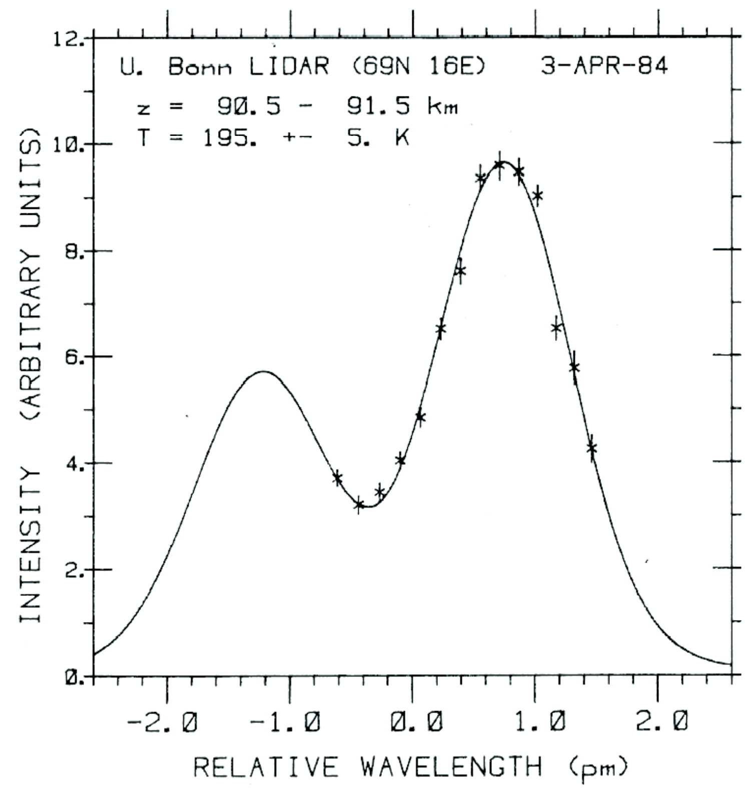
# Metrics: Scanning Technique

$$N_{Na}(\lambda,z)=\left(\frac{P_L(\lambda)\Delta t}{hc/\lambda}\right)\left(\sigma_{eff}(\lambda)n_{Na}(z)\Delta z\right)\left(\frac{A}{4\pi z^2}\right)\left(\eta(\lambda)T_a^{\,2}(\lambda)E^2(\lambda,z)G(z)\right)$$

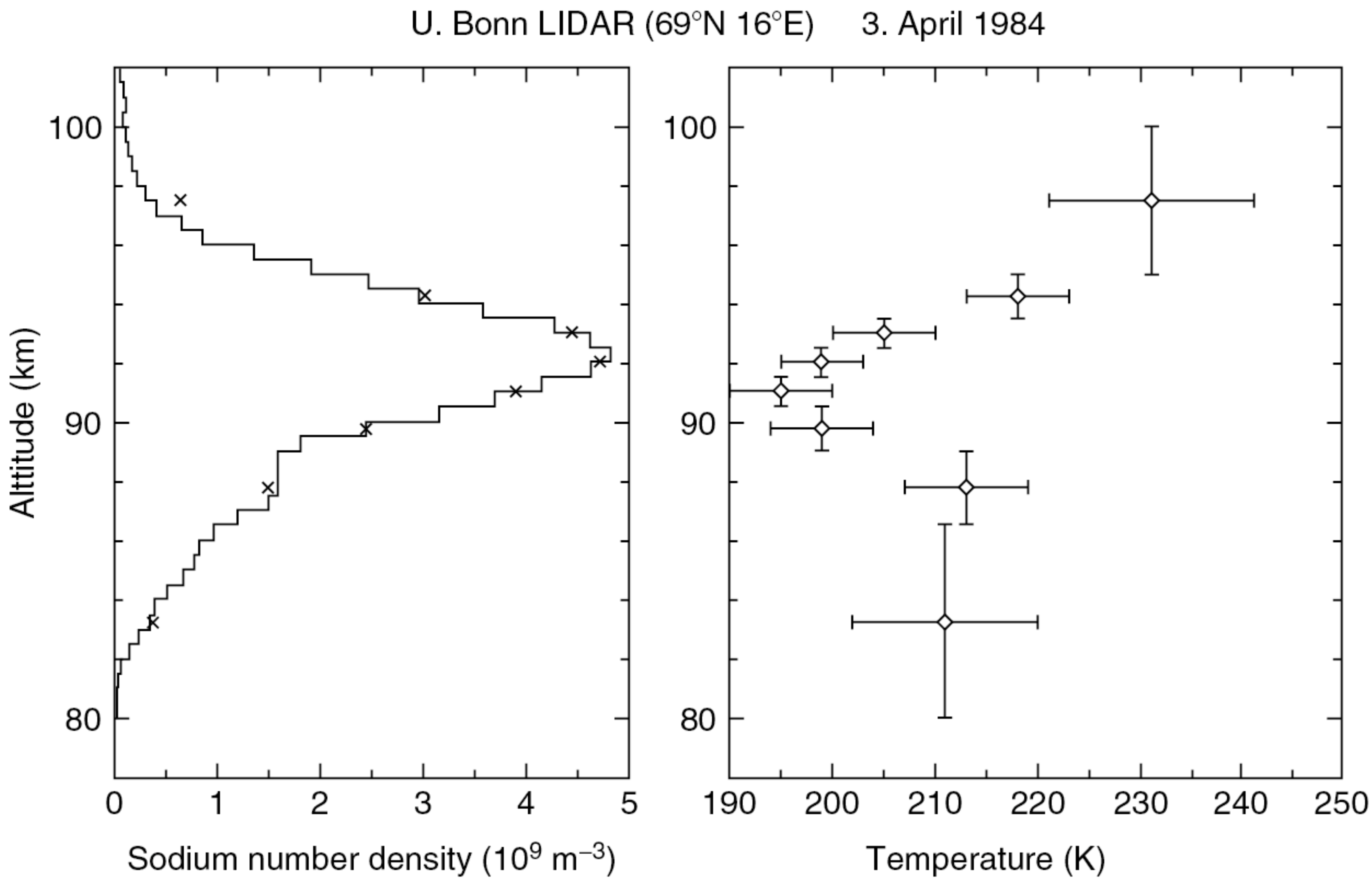
$$N_R(\lambda,z_R)=\left(\frac{P_L(\lambda)\Delta t}{hc/\lambda}\right)\left(\sigma_R(\pi,\lambda)n_R(z_R)\Delta z\right)\left(\frac{A}{z_R^{\,2}}\right)\left(\eta(\lambda)T_a^{\,2}(\lambda,z_R)G(z_R)\right)$$

$$\sigma_{eff}(\lambda,z)=\frac{C(z)}{E^2(\lambda,z)}\frac{N_{Na}(\lambda,z)}{N_R(\lambda,z_R)}$$

where $C(z)=\dfrac{\sigma_R(\pi,\lambda)n_R(z_R)}{n_{Na}(z)}\dfrac{4\pi z^2}{z_R^{\,2}}$

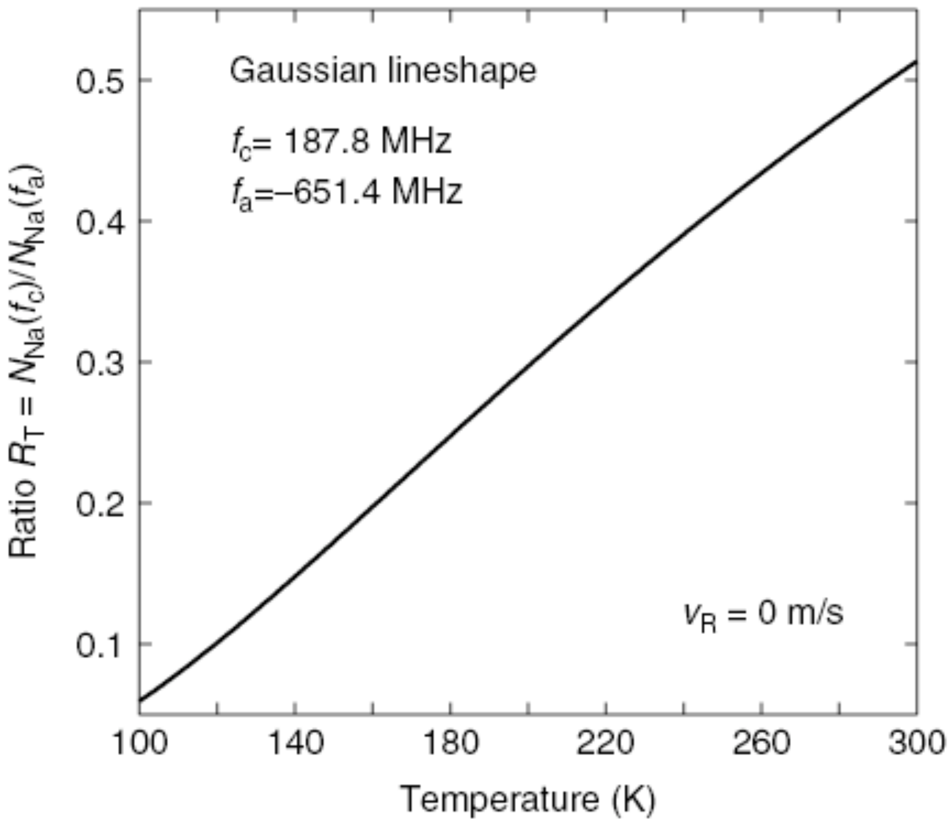


# Scanning Na Lidar Results



# Metrics: 2-Frequency Technique

$$R_{\mathrm{T}}(z) = \frac{N_{\mathrm{norm}}(f_{\mathrm{c}}, z, t_1)}{N_{\mathrm{norm}}(f_{\mathrm{a}}, z, t_2)} = \frac{\sigma_{\mathrm{eff}}(f_{\mathrm{c}}, z) n_{\mathrm{Na}}(z, t_1)}{\sigma_{\mathrm{eff}}(f_{\mathrm{a}}, z) n_{\mathrm{Na}}(z, t_2)} \approx \frac{\sigma_{\mathrm{eff}}(f_{\mathrm{c}}, z)}{\sigma_{\mathrm{eff}}(f_{\mathrm{a}}, z)}$$



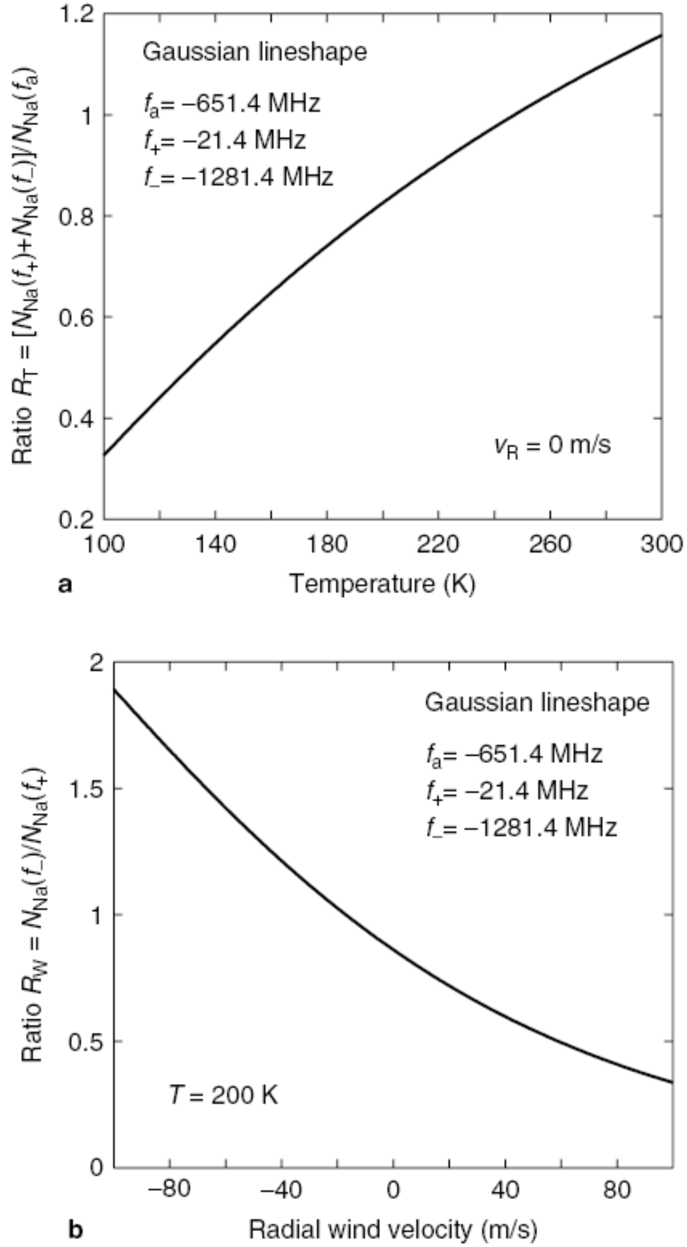

$$N_{\mathrm{norm}}(f, z, t) = \frac{N_{\mathrm{Na}}(f, z, t)}{N_{\mathrm{R}}(f, z, t) E^2(f, z)}$$

$$N_{\mathrm{norm}}(f, z, t) = \frac{\sigma_{\mathrm{eff}}(f) n_{\mathrm{Na}}(z)}{\sigma_{\mathrm{R}}(\pi, f) n_{\mathrm{R}}(z_{\mathrm{R}})} \frac{z_{\mathrm{R}}^2}{4\pi z^2}$$

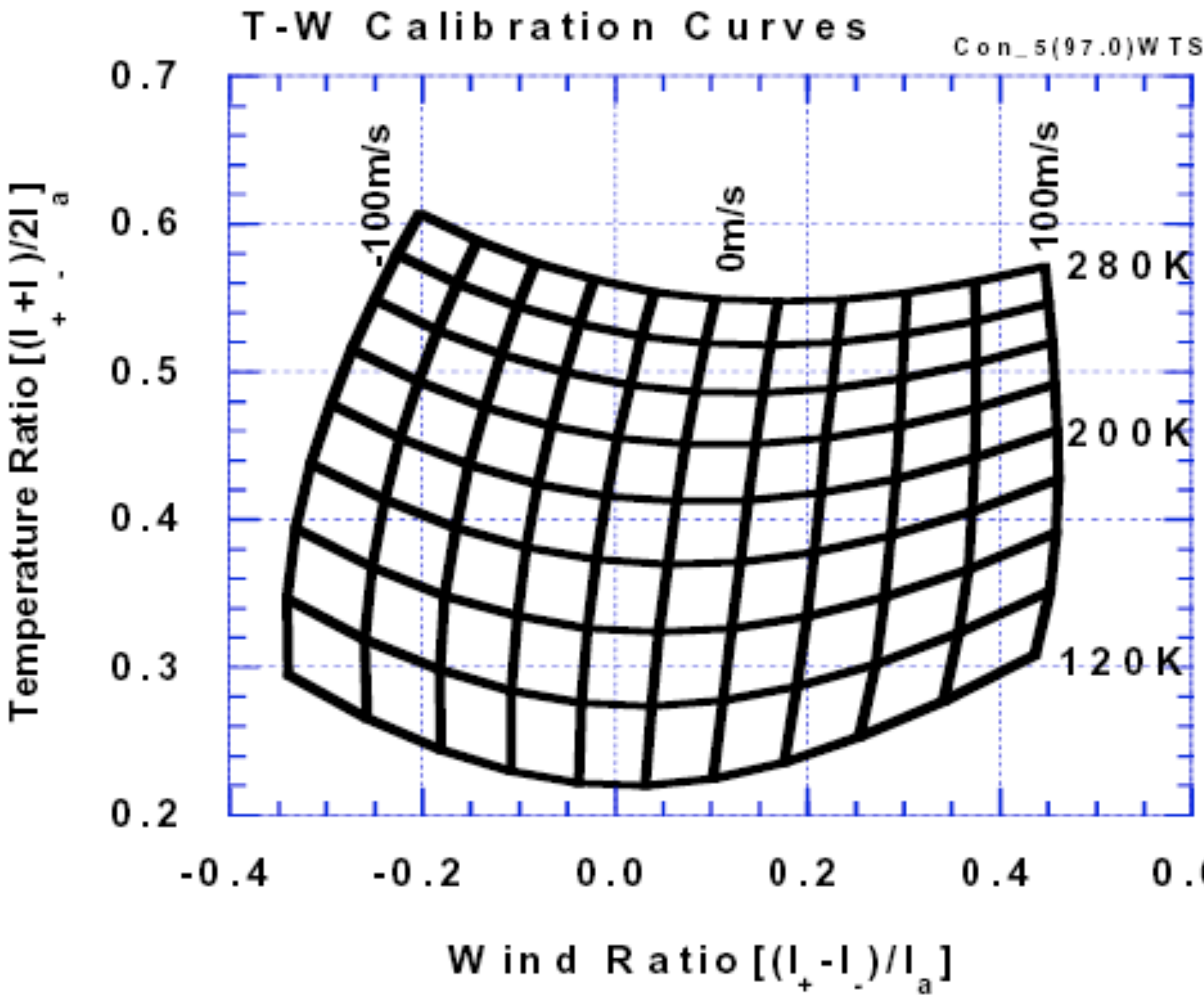
# Metrics: 3-Frequency Technique

$$R_{\mathrm{T}}(z) = \frac{N_{\mathrm{norm}}(f_+, z, t_1) + N_{\mathrm{norm}}(f_-, z, t_2)}{N_{\mathrm{norm}}(f_{\mathrm{a}}, z, t_3)} \approx \frac{\sigma_{\mathrm{eff}}(f_+, z) + \sigma_{\mathrm{eff}}(f_-, z)}{\sigma_{\mathrm{eff}}(f_{\mathrm{a}}, z)}$$

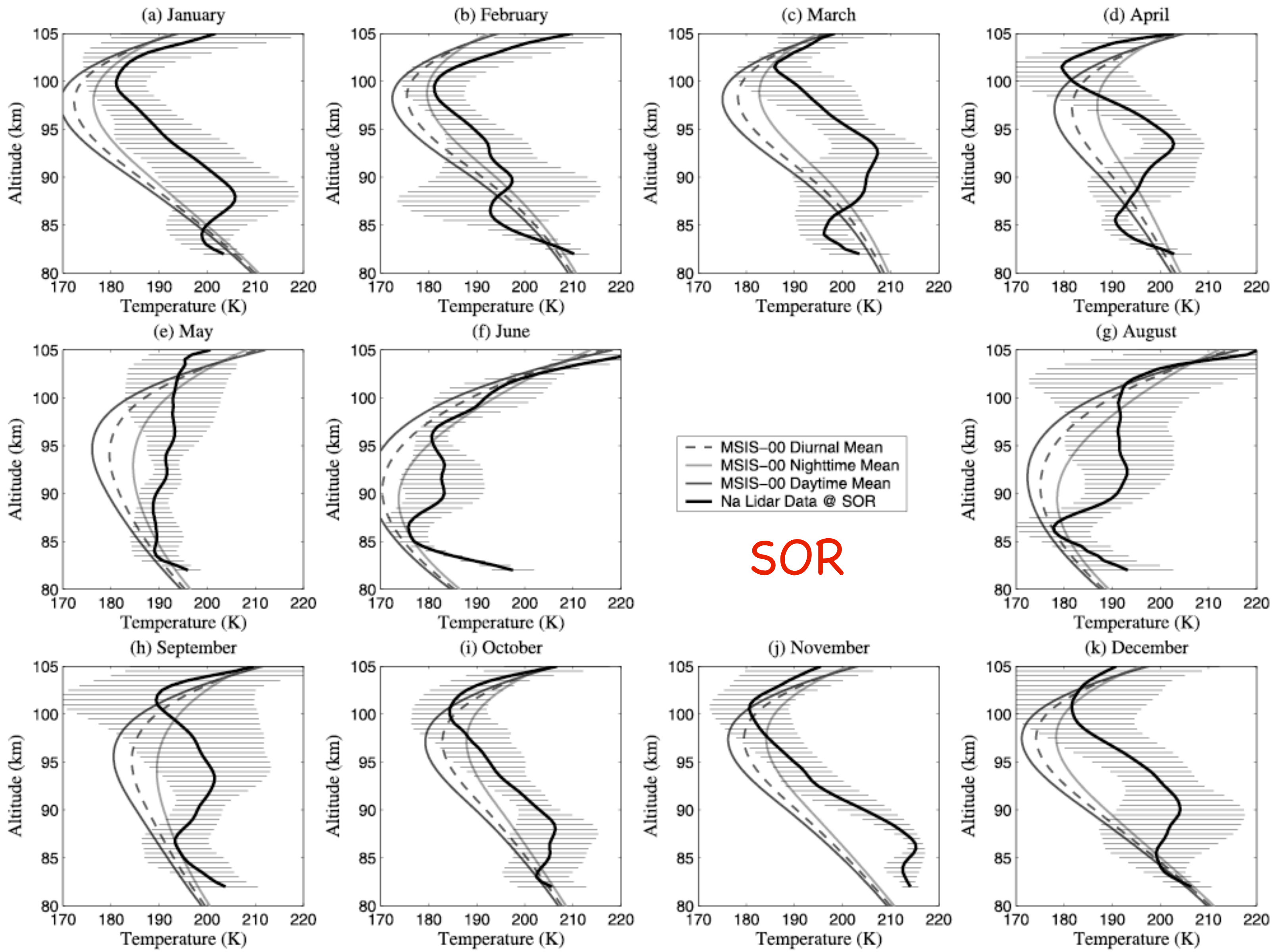
$$R_{\mathrm{W}}(z) = \frac{N_{\mathrm{norm}}(f_-, z, t_2)}{N_{\mathrm{norm}}(f_+, z, t_1)} \approx \frac{\sigma_{\mathrm{eff}}(f_-, z)}{\sigma_{\mathrm{eff}}(f_+, z)}$$



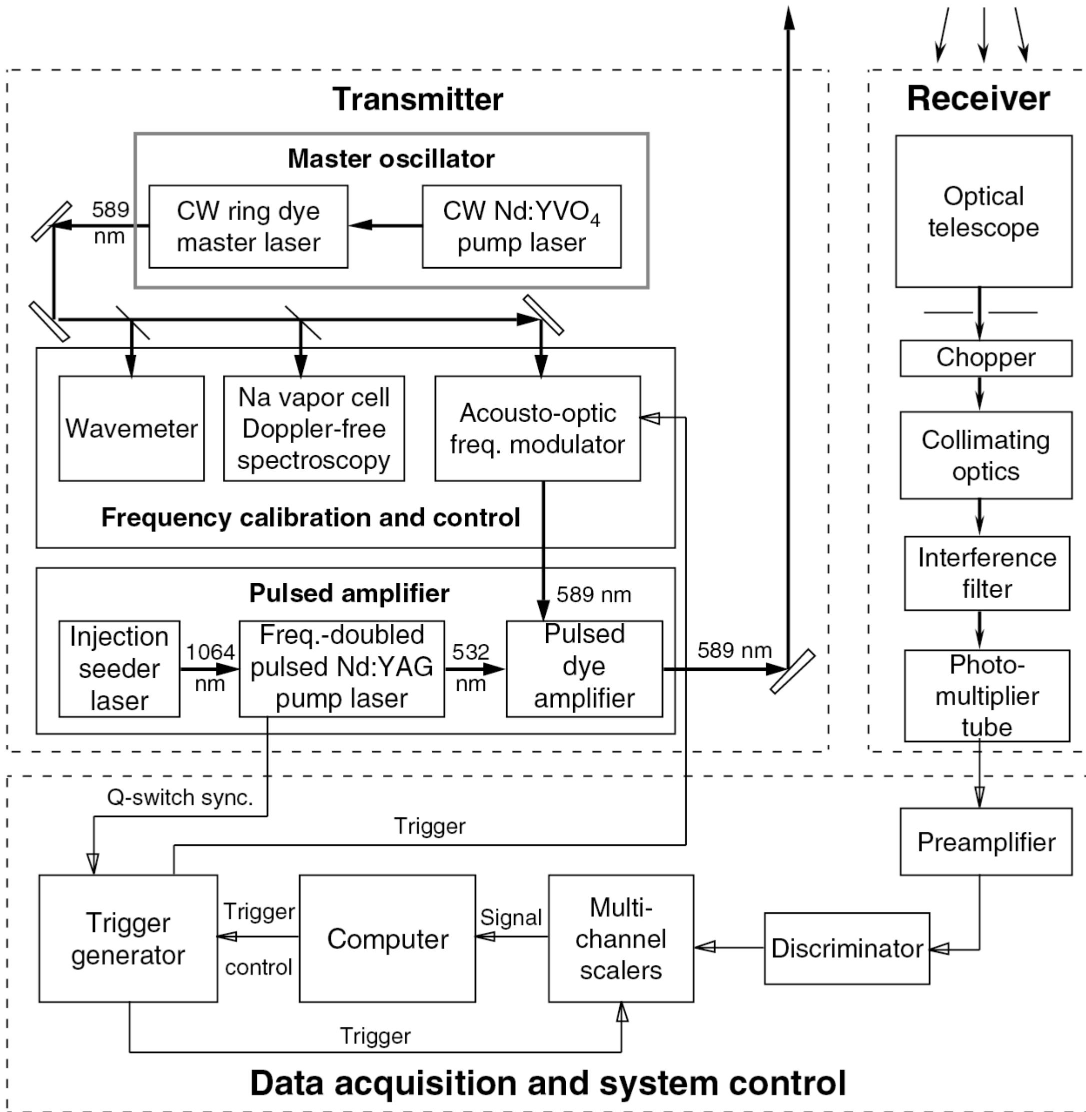
# Na Doppler Lidar Calibration



# 3-Frequency Results

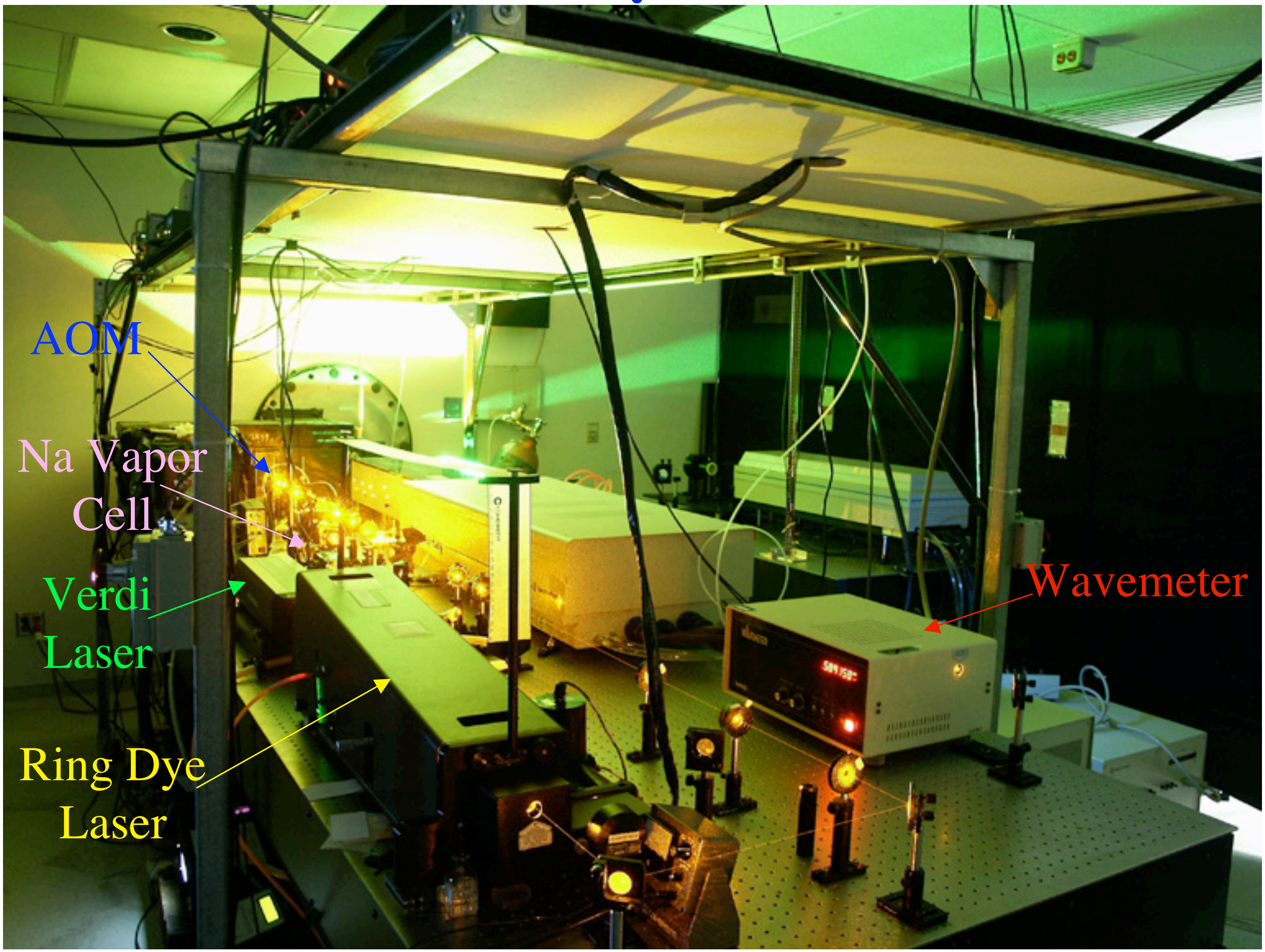


# Na Lidar Instrumentation

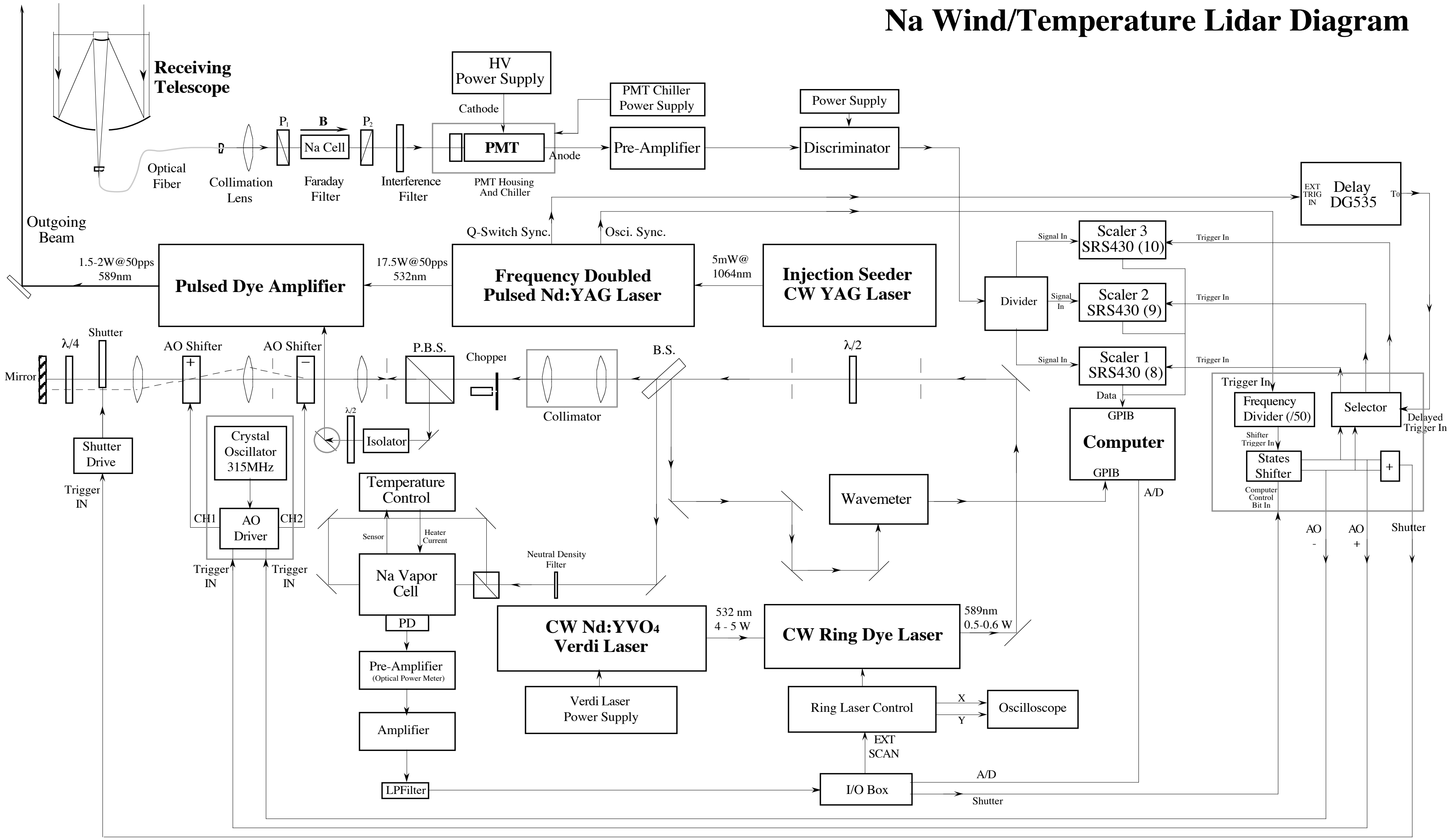



Na Wind/Temperature Lidar System

# Na Wind/Temperature Lidar



# Na Wind/Temperature Lidar



# Summary

- The key point to measure temperature and wind is to find and use temperature-dependent and wind-dependent effects and phenomena to make measurements.
- Doppler technique utilizes the Doppler effect (frequency shift and linewidth broadening) by moving particles to infer wind and temperature information.
- It is widely applied in lidar, radar and sodar technique as well as passive optical remote sensing.
- Resonance fluorescence Doppler lidar technique applies scanning or ratio technique to infer the temperature and wind from the Doppler spectroscopy, while the Doppler spectroscopy is inferred from intensity ratio at different frequencies.

# HW Project #2

- Derive temperature and wind from Maui Na wind/temperature lidar on April 11, 2002.
- The first step is to derive the T-W calibration curve. Let's use the simple metrics of 3-frequency technique

$$R_T = \frac{N_+ + N_-}{N_a} \qquad R_W = \frac{N_-}{N_+}$$

- Also note: $f_\pm = f_a \pm 630$ MHz
- Then draw a flowchart of the procedure. We will compare yours with routine flowchart in next lecture.
- Update your code to derive temperature, wind and density from the AR1102 data.