Lecture 10. Lidar Classification and Envelope Estimation

- ❑ Various Lidar Classifications
- ❑ Lidar Classification by Topics
  - ➢ Temperature lidar technologies
  - ➢ Wind lidar technologies
  - ➢ Constituent lidar technologies
  - ➢ Aerosol & cloud lidar technologies
  - ➢ Laser range finding and laser altimeter technologies
  - ➢ Target lidar technologies (Fluorescence, Raman, Brillouin)
- ❑ Effective Cross Section of Atoms
- ❑ Envelope Estimation -- Application of Lidar Equation
- ❑ Summary

Classifications of Lidar

There are several different classifications on lidars

e.g., based on the physical process;
(Mie, Rayleigh, Raman, DIAL, Res. Fluorescence, …)

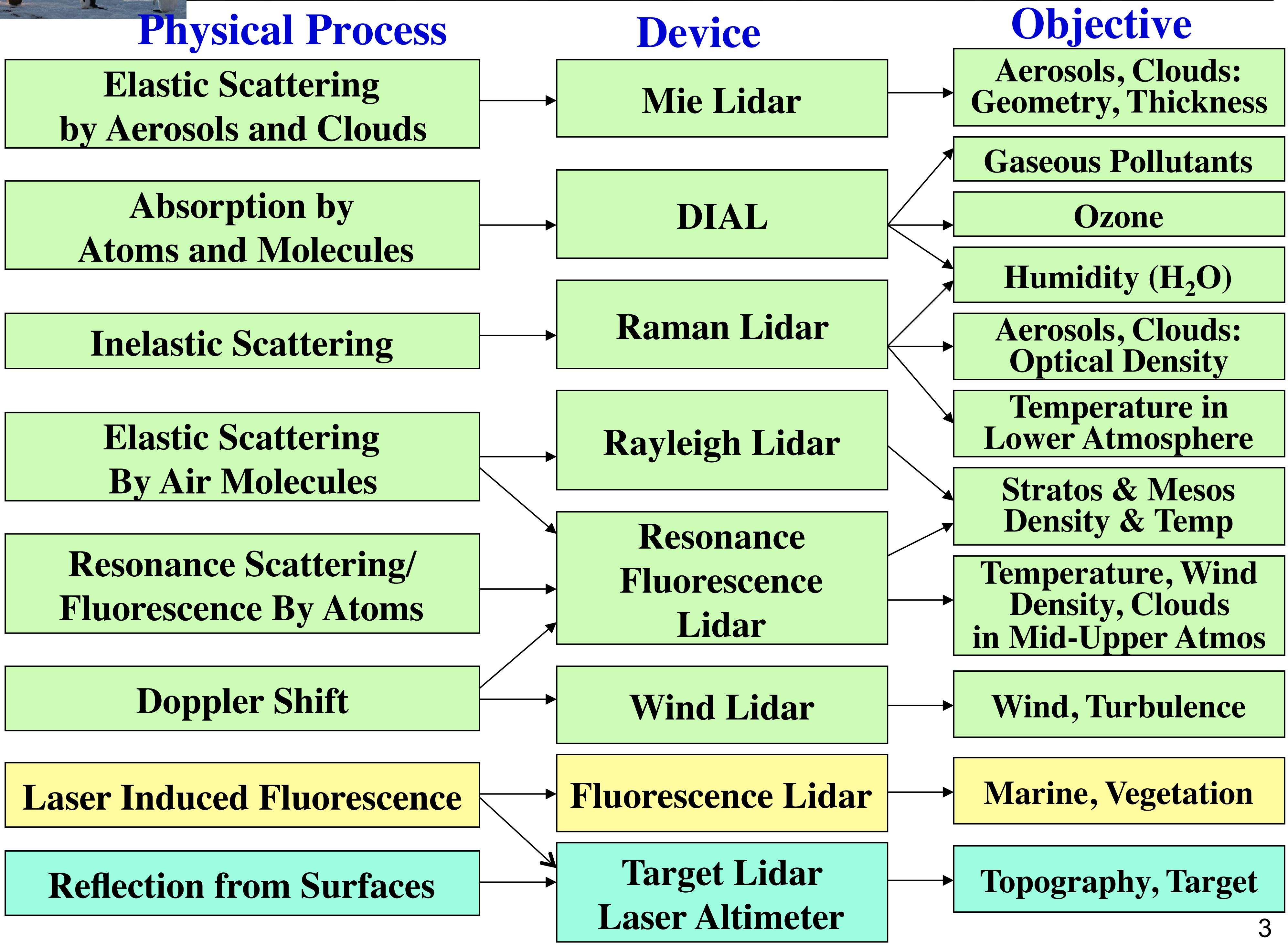
based on the platform;
(Groundbased, Airborne, Spaceborne, …)

based on the detection region;
(Atmosphere, Ocean, Solid Earth, Space, …)

based on the emphasis of signal type;
(Ranging, Scattering, …)

based on the topics to detect;
(Aerosol, Constituent, Temp, Wind, Target, …)

… …



Physical Process
Device
Objective
Elastic Scattering by Aerosols and Clouds
Mie Lidar
Aerosols, Clouds: Geometry, Thickness
Absorption by Atoms and Molecules
DIAL
Gaseous Pollutants
Ozone
Humidity (H_2O)
Inelastic Scattering
Raman Lidar
Aerosols, Clouds: Optical Density
Temperature in Lower Atmosphere
Elastic Scattering By Air Molecules
Rayleigh Lidar
Stratos & Mesos Density & Temp
Resonance Scattering/ Fluorescence By Atoms
Resonance Fluorescence Lidar
Temperature, Wind Density, Clouds in Mid-Upper Atmos
Doppler Shift
Wind Lidar
Wind, Turbulence
Laser Induced Fluorescence
Fluorescence Lidar
Marine, Vegetation
Reflection from Surfaces
Target Lidar Laser Altimeter
Topography, Target

Classification on Platform

Spaceborne lidar	Satellite, Rocket Space Shuttle. Space Station
Airborne lidar	Jet, Propeller Airplanes Unmanned Aerial Vehicle (UAV) Kite, Balloonborne
Groundbased lidar	Stationary on the ground Contanerized moving with truck
Shipborne lidar	Containerized onboard Icebreakers, Ships
Submarine lidar	Submarine

Detection Regions

Atmosphere lidar

Various types
From various platforms

Hydrosphere lidar

Various types
From various platforms

Solid Earth lidar

Airborne or Spaceborne
Laser altimeter

Non-Gas-Phase
Target lidar

Various type
With or without
Imaging function

Emphasis on Signal Type

Scattering Lidar

↓

Besides time delay, more interested in signal strength, spectra, etc

Ranging/Profiling Lidar

↓

Mainly concern Time delay between transmission and reception

Various Topics

- Temperature lidar
- Wind lidar
- Constituent lidar
- Aerosol/Cloud lidar
- Laser Range Finding
- Target lidar

… … … …

Topics to Be Covered

- 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, and its variations, etc.)

3. Constituents (O_3, CO_2, H_2O, NO_x, 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. Range finding and altimetry (accurate height & range determination)

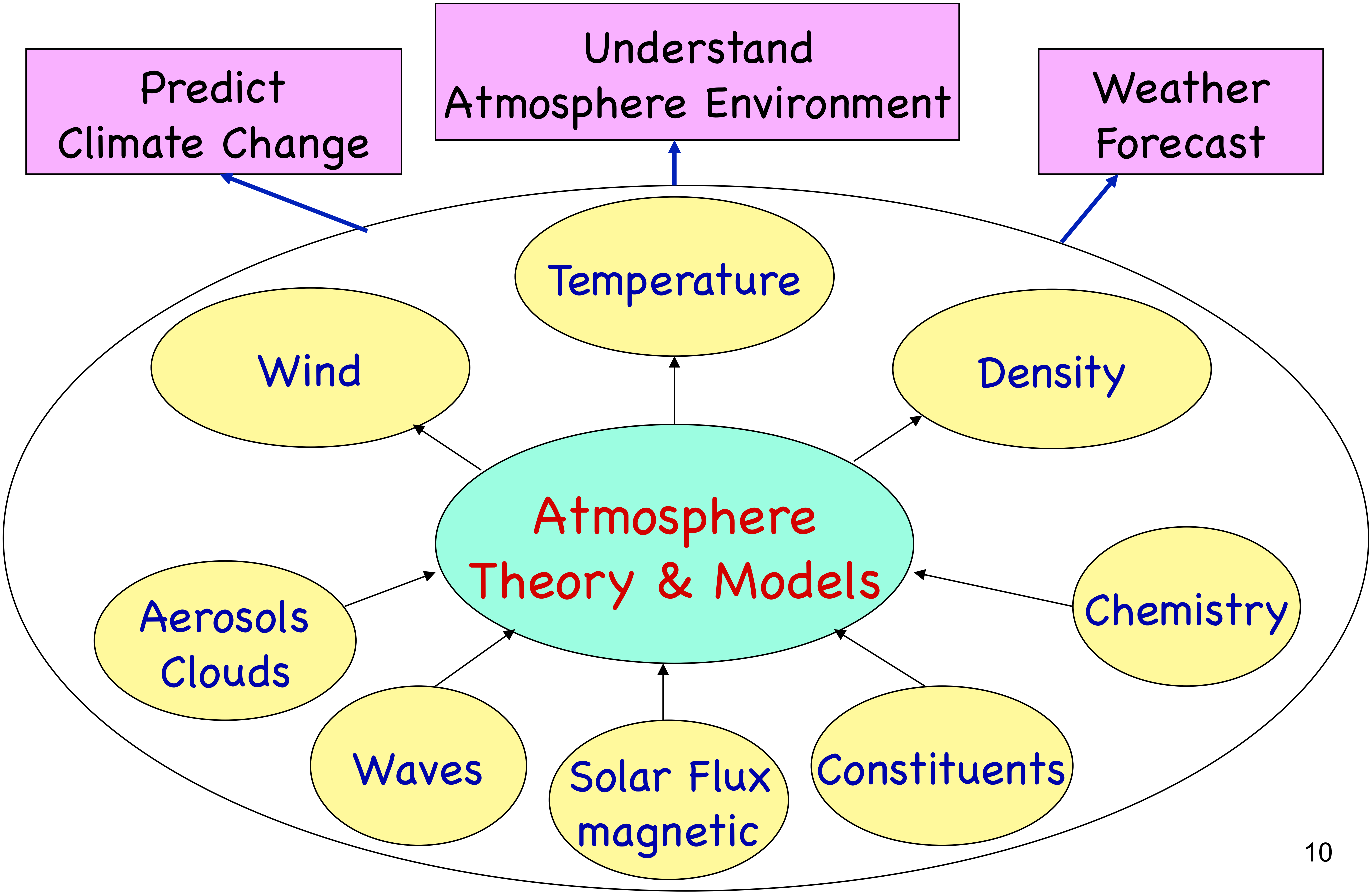
6. Target (identification, temperature measurements in waterbody, etc.)

Why Going by Topics?

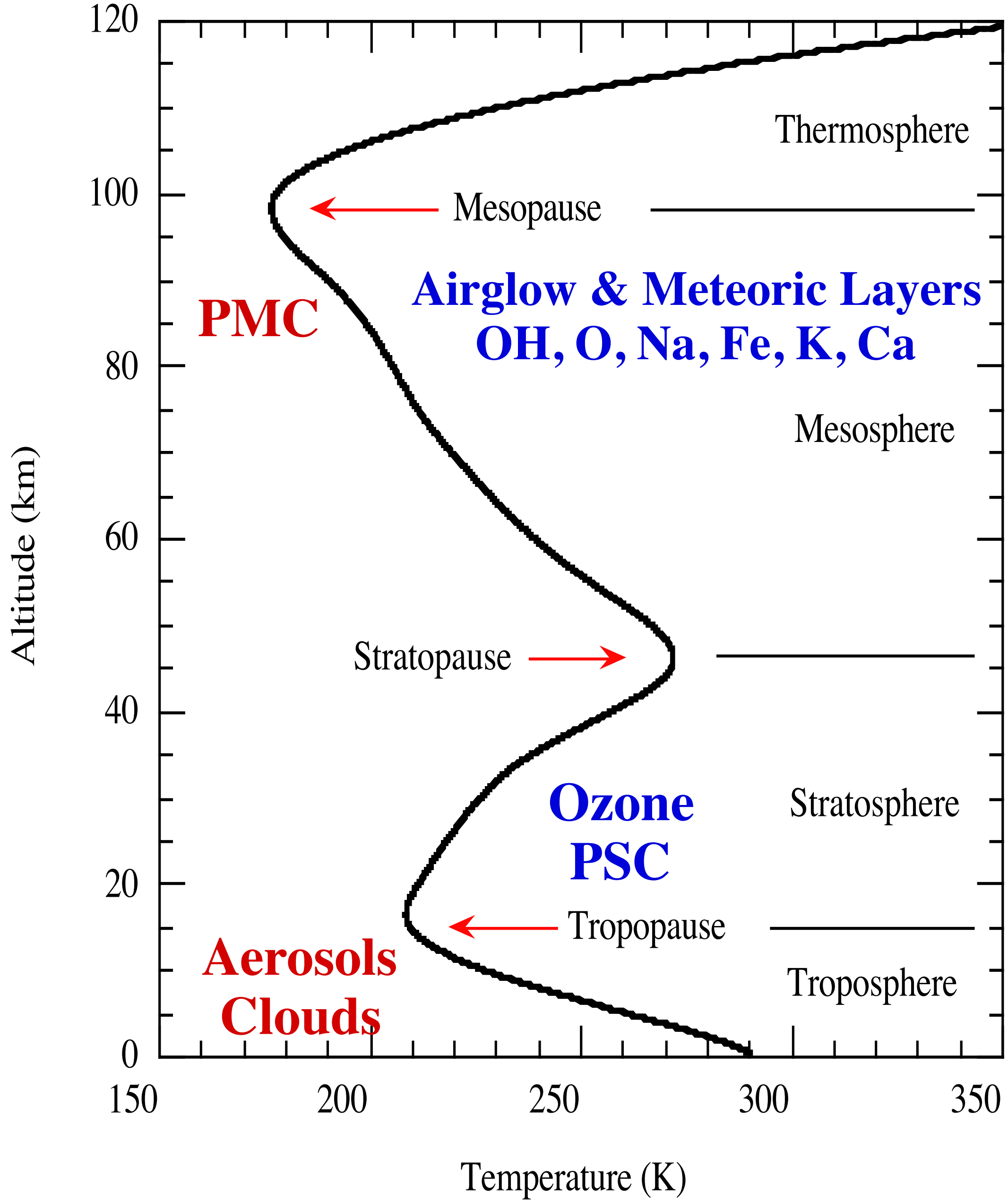
- To compare different lidar techniques that address the same topic, e.g., how many ways to measure temperature, and what is the essential point among these different lidars?
- To illustrate the strengths and limitations of each type of lidars, and give an insight of when and where to use what kind of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

- We choose 6 most interesting and hot topics in the atmosphere/space sciences, environmental research, and climate study. They have wide applications in environment, defense and industry.
- The lidar technologies used to address these six 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 technologies to conduct novel science and environmental research.

Observables in Atmosphere Models

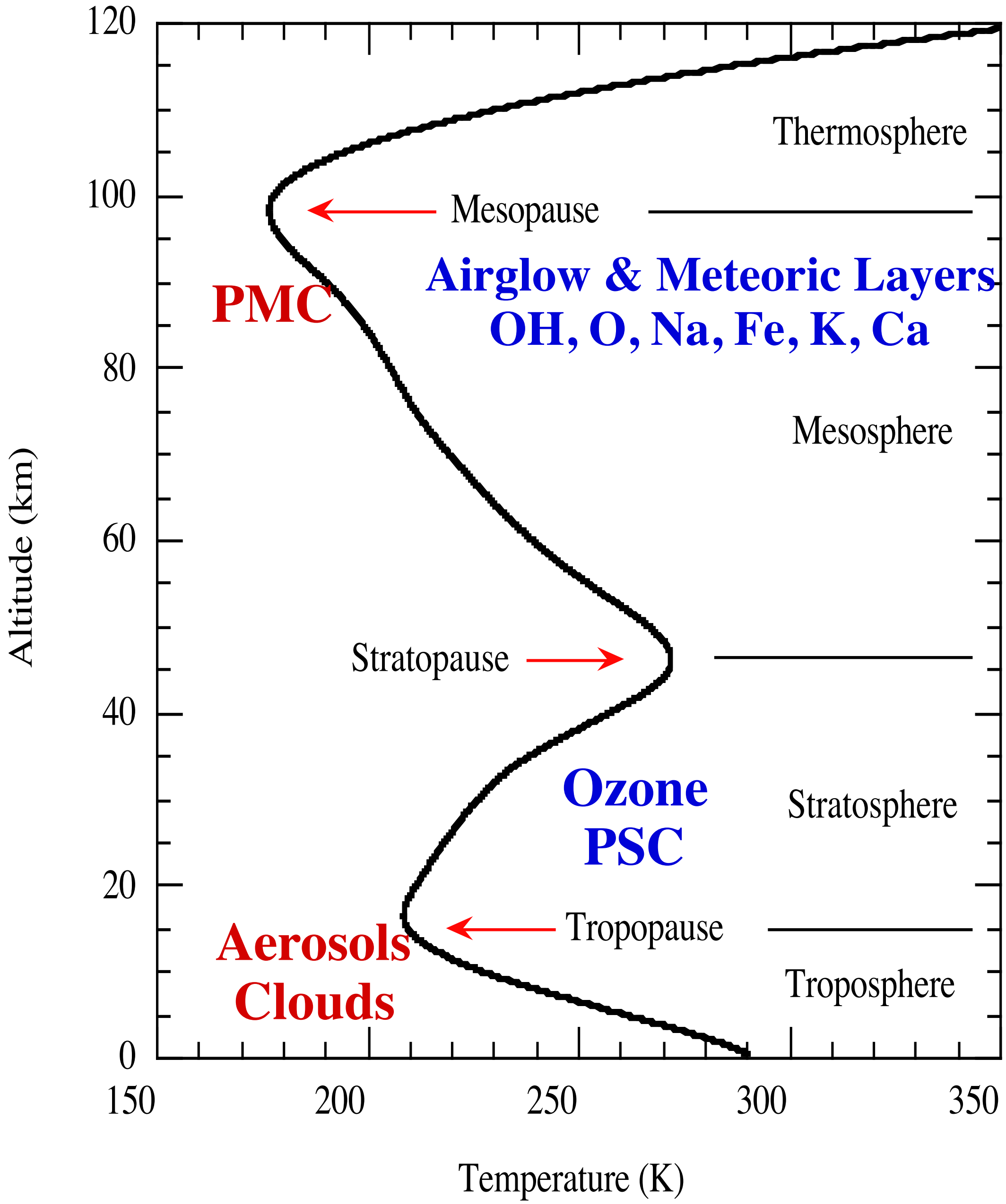


Temperature Lidars



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

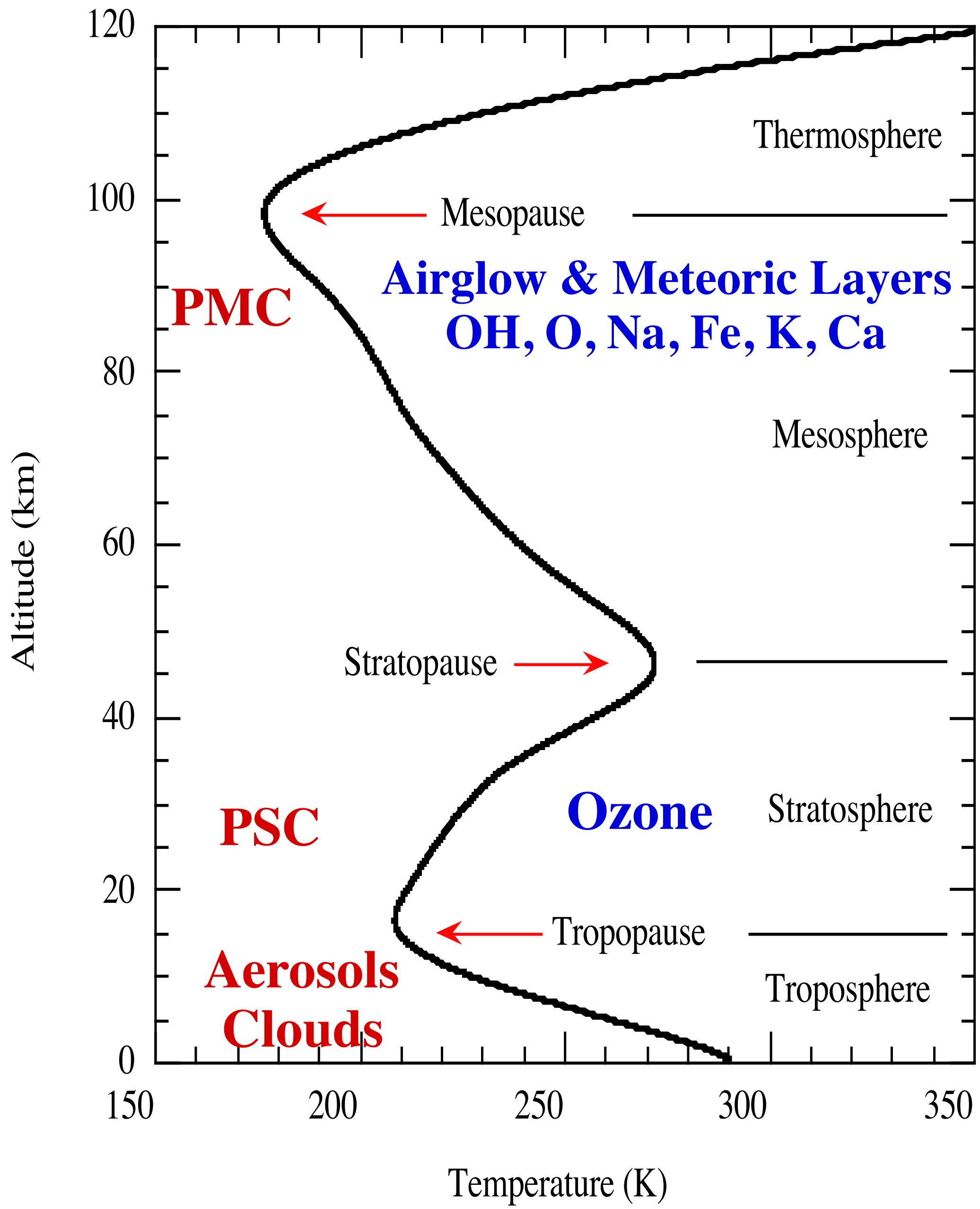
Wind Lidars vs. Altitude



- 75-120km: resonance fluorescence (Na, K, Fe) Doppler technique (DDL)
- FPI: Fabry-Perot Interferometer
- Below 60km: Rayleigh Doppler technique (DDL)
- Below 30 km: Direct Detection Doppler technique
- In troposphere:

Coherent Detection Doppler tech, Direct Detection Doppler tech, Direct motion Detection tech (tracking aerosols, LDV, LTV)

Aerosol Lidar Comparison



- Aerosols in mesosphere (Mesospheric Clouds ~ 85 km): Rayleigh/Mie lidar, resonance fluorescence lidar (detuned)
- Aerosols in upper stratosphere (Polar Stratospheric Clouds ~ 20 km): Rayleigh/Mie lidar, resonance fluorescence lidar
- Aerosols in lower stratosphere and troposphere: Rayleigh/Mie elastic-scattering lidar, Raman scattering lidar, High-Spectral-Resolution Lidar (HSRL)

- In all altitude range, polarization & multi-wavelength detections help reveal aerosol microphysical properties

HSRL

- High-Spectral-Resolution-Lidar (HSRL) is to measure the molecule scattering separately from the aerosol scattering, utilizing the different spectral distribution of the Rayleigh and Mie scattering.

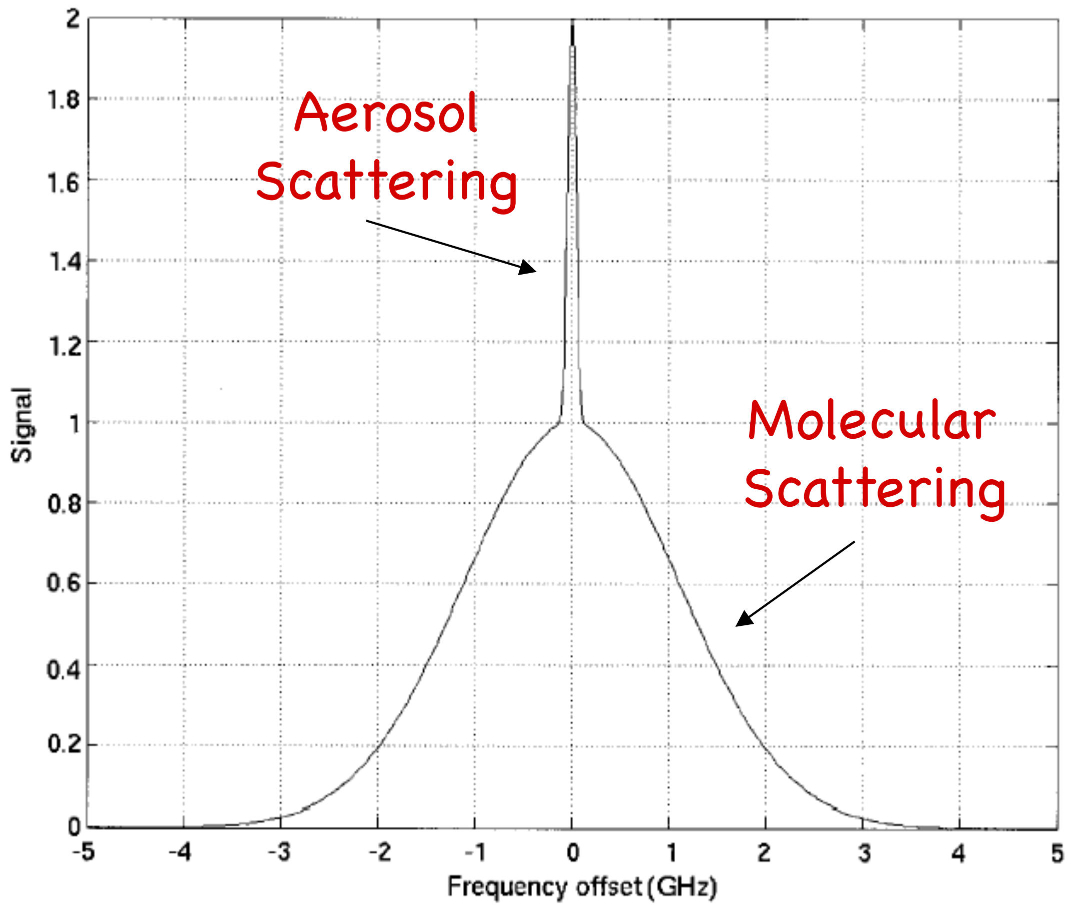
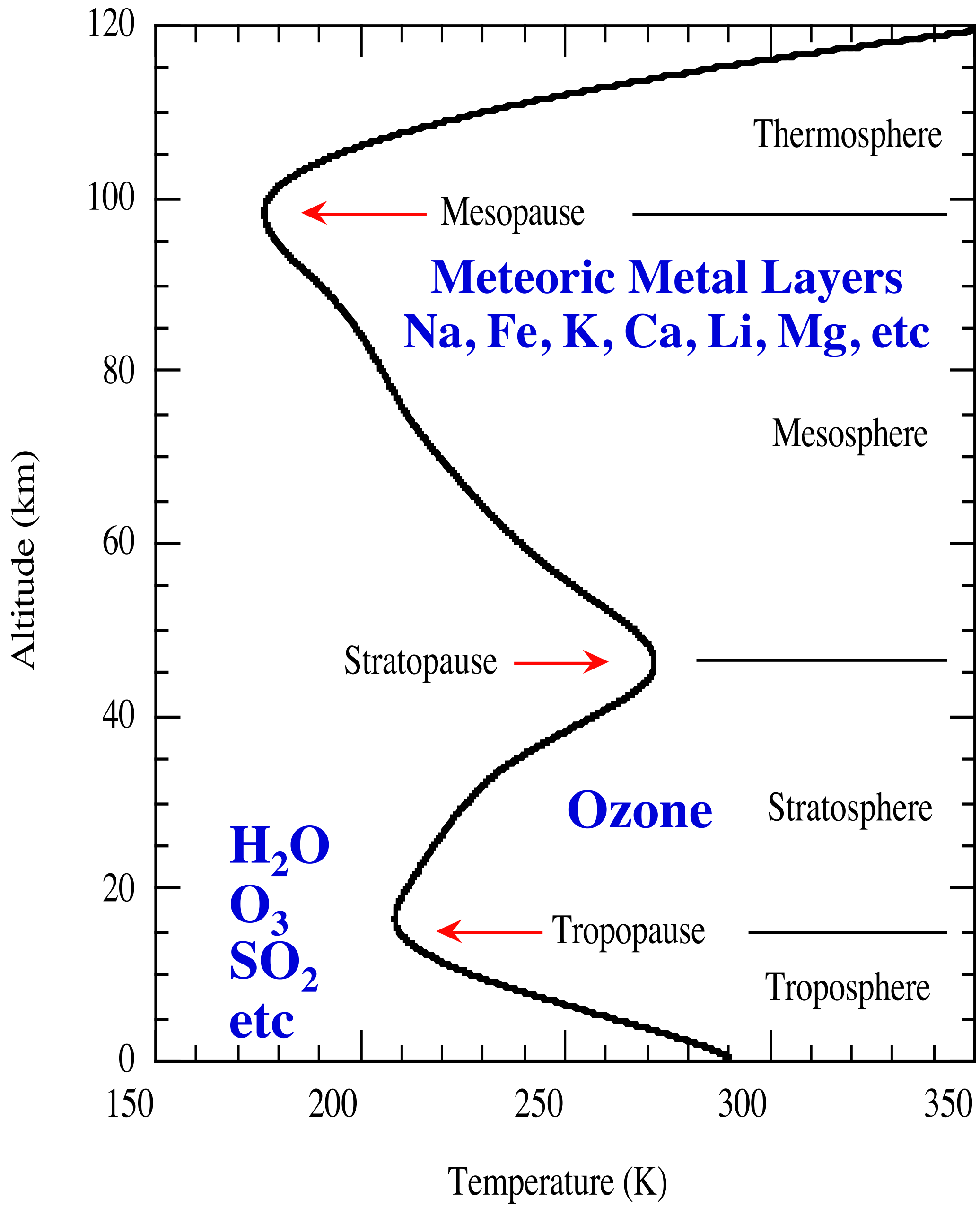


Fig. 5.1. Spectral profile of backscattering from a mixture of molecules and aerosols for a temperature of 300 K. The spectral width of the narrow aerosol return is normally determined by the line width of the transmitting laser.

Constituent Lidars



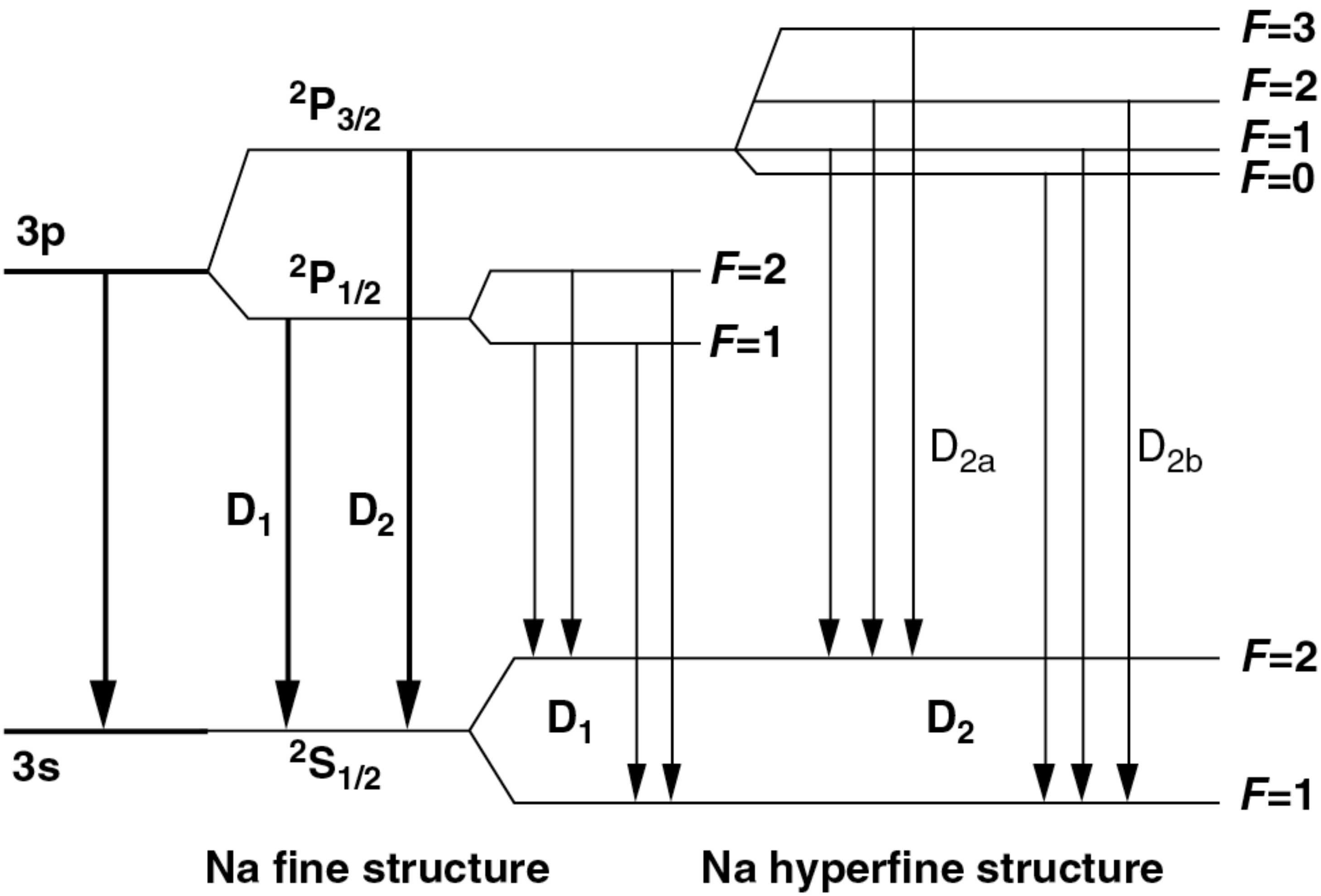
- He and N_2^+ in thermosphere: resonance fluorescence lidar
- O in thermosphere: resonance fluorescence lidar or DIAL from space
- Metal atoms in 75-120km: resonance fluorescence lidar (broadband or narrowband transmitter)
- Molecular species in lower stratosphere & troposphere: Differential absorption lidar (DIAL), Raman scattering lidar, Raman DIAL, RVR Raman DIAL, Multiwavelength DIAL

- The key is to use spectroscopic detection for distinguish species.

Resonance Fluorescence Lidar: Effective Cross Section

- Refer to the textbook Section 5.2.1.3.1 for effective cross section σ_{eff}
- Resonance fluorescence contains two single-photon processes: Absorption of a photon by an atom, and spontaneous emission of another photon by the atom.
- Because resonance fluorescence is isotropic, the differential backscatter cross-section $d\sigma/d\Omega$ can be replaced by the total effective scattering cross-section σ_{eff} divided by 4π.
- The total effective scattering cross-section σ_{eff} is defined as the ratio of the average photon number scattered by an individual atoms (in all directions) to the total incident photon number per unit area.
- The σ_{eff} is determined by the convolution of the atomic absorption cross-section σ_{abs} and the laser spectral lineshape $g_L(\nu)$.
- The absorption cross-section σ_{abs} is defined as the ratio of the average absorbed single-frequency photons per atom to the total incident photons per unit area.

Na Atomic Energy Levels



Atomic Absorption Cross-Section

- σ_{abs} is proportional to the probability of a single-frequency photon being absorbed by an atom:

$$\sigma_{abs}(\nu,\nu_0) = A_{ki}\frac{\lambda^2}{8\pi n^2}\frac{g_k}{g_i}g_A(\nu,\nu_0) \qquad (10.1)$$

where A_{ki} is the spontaneous transition probability per unit time, i.e., the Einstein A coefficient; g_k and g_i are the degeneracy factors for the upper and lower energy levels k and i, respectively; λ is the wavelength; n is the refraction index, and g_A is the absorption lineshape. ν and ν_o are the laser frequency and the central frequency of the atomic absorption line, respectively.

- For single atom, the absorption lineshape g_A is determined by natural linewidth and collisional broadening, which has Lorentzian shape

$$g_A(\nu,\nu_0) = g_H(\nu,\nu_0) = \frac{\Delta\nu_H}{2\pi\left[(\nu-\nu_0)^2 + (\Delta\nu_H/2)^2\right]} \qquad (10.2)$$

where $\Delta\nu_H$ is the homogeneous broadened linewidth.

Refer to our textbook Chapter 5 and references therein

Absorption Cross Section Under Doppler Effects

- For many atoms in thermal equilibrium, the Doppler broadening dominates the lineshape. The statically averaged absorption cross section for each atomic transition line is then given by

$$\sigma_{abs}(\nu,\nu_o) = \sigma_o \exp\left(-\frac{\left[\nu(1-V_R/c)-\nu_o\right]^2}{2\sigma_D^2}\right) \qquad (10.3)$$

where $\sigma_o = \frac{1}{\sqrt{2\pi}\sigma_D}\frac{e^2}{4\varepsilon_o m_e c} f_{ik}$ (10.4) and $\sigma_D = \sqrt{\frac{k_B T}{M\lambda_0^2}}$ (10.5)

σ_o – peak absorption cross section (m^2 or cm^2)
e – charge of electron; m_e – mass of electron
ε_o – electric constant; c – speed of light
f_{ik} – absorption oscillator strength; V_R – radial velocity

σ_D – Doppler broadened line width
k_B – Boltzmann constant; T – temperature
M – mass of atom; λ_o – wavelength

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.

Doppler-Limited Na Spectroscopy

- Doppler-broadened Na absorption cross-section is approximated as a Gaussian with rms width σ_D

$$\sigma_{abs}(\nu) = \frac{1}{\sqrt{2\pi}\sigma_D} \frac{e^2 f}{4\varepsilon_0 m_e c} \sum_{n=1}^{6} A_n \exp\left(-\frac{[\nu_n - \nu(1 - V_R/c)]^2}{2\sigma_D^2} \right) \quad (10.6)$$

- Assume the laser lineshape is a Gaussian with rms width σ_L
- The effective cross-section is the convolution of the atomic absorption cross-section and the laser lineshape

$$\sigma_{eff}(\nu) = \frac{1}{\sqrt{2\pi}\sigma_e} \frac{e^2 f}{4\varepsilon_0 m_e c} \sum_{n=1}^{6} A_n \exp\left(-\frac{[\nu_n - \nu(1 - V_R/c)]^2}{2\sigma_e^2} \right) \quad (10.7)$$

where $\sigma_e = \sqrt{\sigma_D^2 + \sigma_L^2}$ (10.8) and $\sigma_D = \sqrt{\frac{k_B T}{M\lambda_0^2}}$ (10.5)

Effective Cross-Section

- The effective cross section is a convolution of the atomic absorption cross section and the laser line shape. When the laser has finite spectral linewidth with lineshape (its intensity distribution along frequency) of

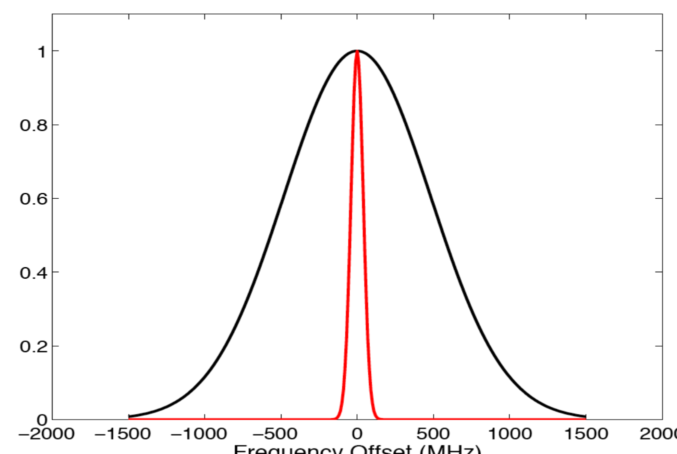
$$\int_0^\infty g_L(\nu,\nu_L)d\nu = 1 \qquad (10.9)$$

- The effective cross-section σ_{eff} is given by the convolution of σ_{abs} with the laser lineshape g_L:

$$\sigma_{eff}(\nu_L,\nu_o) = \int_{-\infty}^{+\infty}\sigma_{abs}(\nu,\nu_o)g_L(\nu,\nu_L)d\nu \qquad (10.10)$$

- If the laser spectral lineshape is a Gaussian shape:

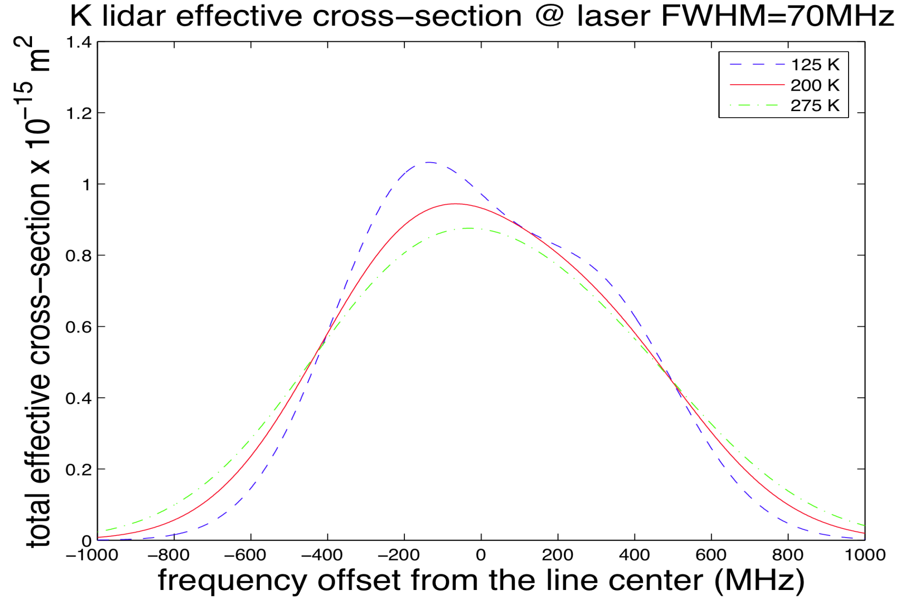
$$g_L(\nu,\nu_L) = \frac{1}{\sqrt{2\pi}\sigma_L}\exp\left(-\frac{(\nu-\nu_L)^2}{2\sigma_L^2}\right) \qquad (10.11)$$

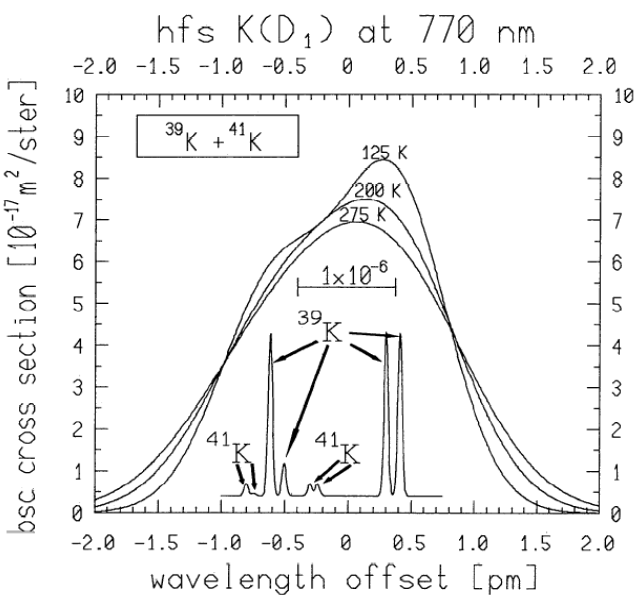


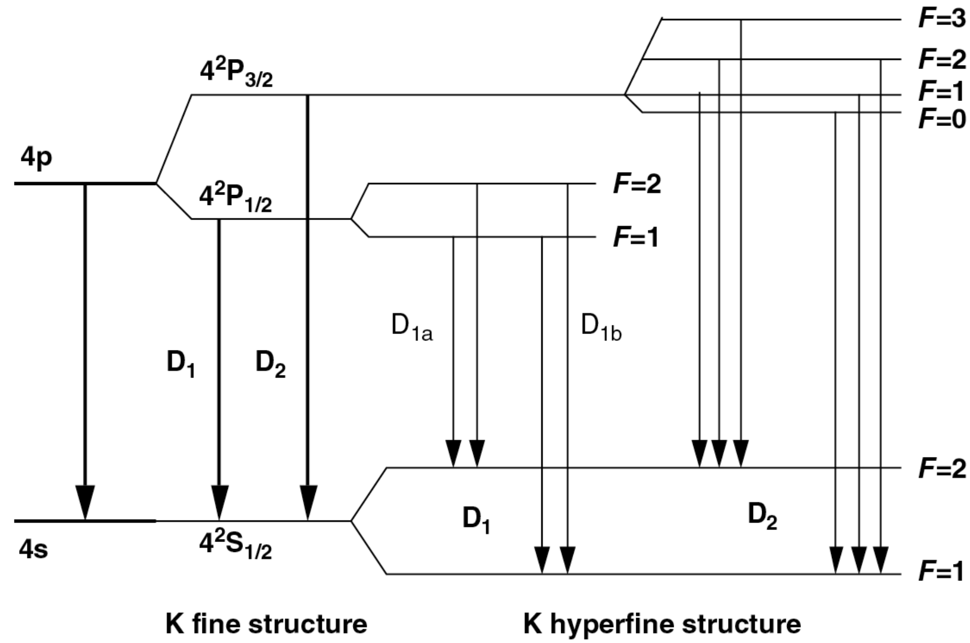
- then σ_{eff} can be written as

$$\sigma_{eff}(\nu_L,\nu_0) = \frac{\sigma_D\sigma_0}{\sqrt{\sigma_D^2+\sigma_L^2}}\exp\left(-\frac{[\nu_L(1-V_R/c)-\nu_0]^2}{2(\sigma_D^2+\sigma_L^2)}\right) \qquad (10.12)$$

Effective Cross-Section for K Atoms







Atomic K energy levels

Reference our textbook Chapter 5

Effective Cross-Section for K Atoms

- Absorption cross section of K atom's D1 line is given by

$$\sigma_{abs}(\nu) = \sum_{A=39}^{41} \left\{ IsotopeAbdn(A) \frac{1}{\sqrt{2\pi}\sigma_D} \frac{e^2 f}{4\varepsilon_0 m_e c} \sum_{n=1}^{4} A_n \exp\left(-\frac{[\nu_n - \nu(1 - V_R/c)]^2}{2\sigma_D^2} \right) \right\} \quad (11.9)$$

Isotope abundance: 93.2581% (^{39}K), 0.0117% (^{40}K), 6.7302% (^{41}K)
Line strength: An = 5/16, 1/16, 5/16, 5/16
Oscillator strength: f, Doppler broadening: σ_D

- The effective total scattering cross section of K atom's D1 line is the convolution of the absorption cross section and the laser lineshape. Under the assumption of Gaussian lineshape of the laser, it is given by

$$\sigma_{eff}(\nu) = \sum_{A=39}^{41} \left\{ IsotopeAbdn(A) \frac{1}{\sqrt{2\pi}\sigma_e} \frac{e^2 f}{4\varepsilon_0 m_e c} \sum_{n=1}^{4} A_n \exp\left(-\frac{[\nu_n - \nu(1 - V_R/c)]^2}{2\sigma_e^2} \right) \right\} \quad (11.10)$$

where $\sigma_e = \sqrt{\sigma_D^2 + \sigma_L^2}$ (11.11) and $\sigma_D = \sqrt{\frac{k_B T}{M\lambda_0^2}}$ (11.12)

Refer to our textbook Chapter 5 and references therein

Lidar Envelope Estimation

- This is to estimate the return photon counts from the entire metal layers using lidar equation and lidar/atomic/atmospheric parameters. It is useful to anticipate expected signal levels.
- 1st, write down all fundamental constants used in lidar.
- 2nd, gather lidar, atomic/molecular & atmosphere parameters.
- 3rd, start with the laser source of transmitter and follow the lidar picture from transmitted photons, through atmosphere transmission, backscatter probability, collection probability, and receiver efficiency, to detected photon numbers.
- 4th, understand the physical process of light interaction with objects to calculate the backscatter probability.
- 5th, background estimate considering many factors (both atmosphere conditions and lidar parameters like filter, FOV, ...)
- 6th, get the final results and verify them with reality.

Envelope Estimate

(use parameters on page 25 of Lecture 4)

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

5.81×10^{17} 6×10^{-4} 4.94×10^{-12} 0.64 0.336

The scattering probability is given by: $P_{scattering} = \sigma_{eff} \times \text{Kabdn} = 6 \times 10^{-4}$

Transmitter efficiency $\eta_{transmitter} = (0.99)^5 = 0.95$
Receiver efficiency $\eta_{receiver} = 0.91 \times 0.9 \times 0.9 \times 0.8 \times 0.6 = 0.35$
Overall lidar efficiency $\eta = 0.336$

- The overall lidar return from the entire K layer is

$N_S = 5.81\times10^{17} \times 6\times10^{-4} \times 4.94\times10^{-12} \times 0.64 \times 0.35 =$ 370 counts/shot

- These returns originate from 5.8×10^{17} laser photons!!!

Envelope Estimate Procedure

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

$N_L = 5.81 \times 10^{17}$

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

$N_{Trans} = 4.42 \times 10^{17}$

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

$N_{Fluorescene} = 2.65 \times 10^{14}$

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

$N_{Sphere} = 2.12 \times 10^{14}$

$$N_{Primary} = N_{Sphere} \cdot P_{collection} = N_{Sphere} \cdot \frac{A}{4\pi R^2}$$

$N_{Sphere} = 1048.2$

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

$\eta_{receiver} = 35.38\%$

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

$N_{S(K)} = 370.8$

Comparison to reality: 50-175 count/shot

Summary

- Six major topics are chosen for reviewing lidar measurement principles and technologies: temperature, wind, constituent, aerosol, altimetry and target.
- For each topic, various technologies will be compared to reveal the key ideas behind the lidar technologies.
- Real lidar data for some of the topics will be given for students to perform data inversion, i.e., from raw photon counts to meaningful physical parameters.
- Data inversion principles and procedures will be explained along the way.