Lecture 11. Classification of Lidar by Topics

- Effective cross section for resonance fluorescence
- Various lidar classifications
- What are topical lidars and why?
- Temperature techniques
- Wind techniques
- Aerosol techniques
- Constituent techniques
- Target & altimeter techniques
- Summary

Resonance Fluorescence

- 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.

Atomic Absorption Cross-Section

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

$$\sigma_{abs}(\nu,\nu_0) = A_{ki}\frac{\lambda^2}{8\pi n^2}\frac{g_k}{g_i}g_A(\nu,\nu_0) \qquad (11.1)$$

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

$$g_A(\nu,\nu_0) = g_H(\nu,\nu_0) = \frac{\Delta\nu_H}{2\pi\left[(\nu-\nu_0)^2 + (\Delta\nu_H/2)^2\right]} \qquad (11.2)$$

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

$$\sigma_{abs}(\nu,\nu_o)=\sigma_o\exp\left(-\frac{\left[\nu(1-V_R/c)-\nu_o\right]^2}{2\sigma_D^2}\right) \qquad (11.3)$$

where $\sigma_o=\frac{1}{\sqrt{2\pi}\sigma_D}\frac{e^2}{4\varepsilon_o m_e c}f_{ik}$ (11.4) and $\sigma_D=\sqrt{\frac{k_B T}{M\lambda_0^2}}$

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

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

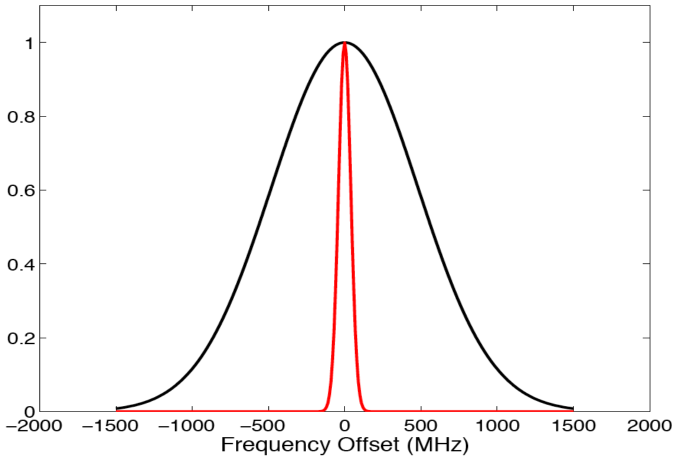
$$\int_0^{\infty} g_L(\nu,\nu_L)d\nu = 1 \qquad (11.5)$$

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

$$\sigma_{eff}(\nu_L,\nu_o) = \int_{-\infty}^{+\infty} \sigma_{abs}(\nu,\nu_o) g_L(\nu,\nu_L)d\nu \qquad (11.6)$$

- If the laser spectral lineshape is a Gaussian shape:

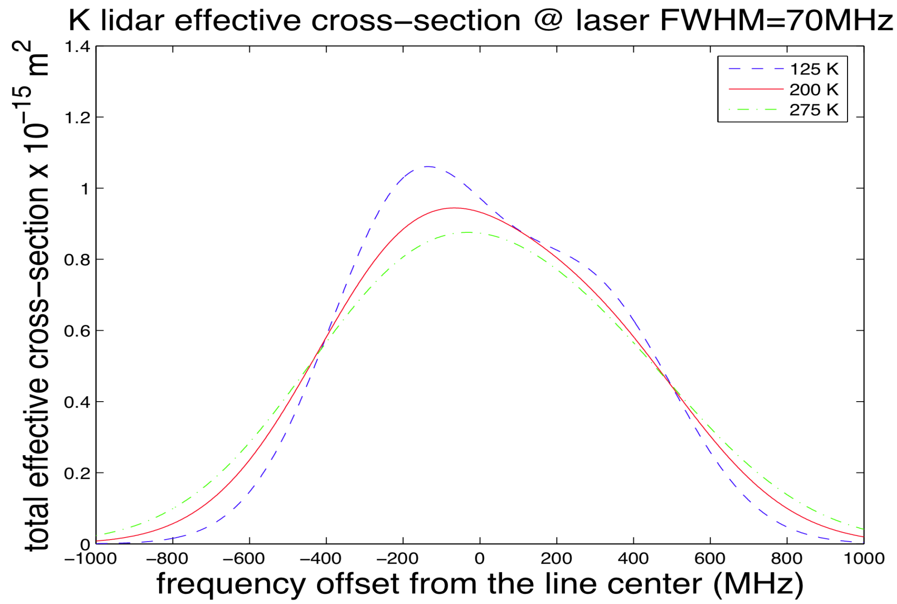
$$g_L(\nu,\nu_L) = \frac{1}{\sqrt{2\pi}\sigma_L}\exp\left(-\frac{(\nu-\nu_L)^2}{2\sigma_L^2}\right) \qquad (11.7)$$

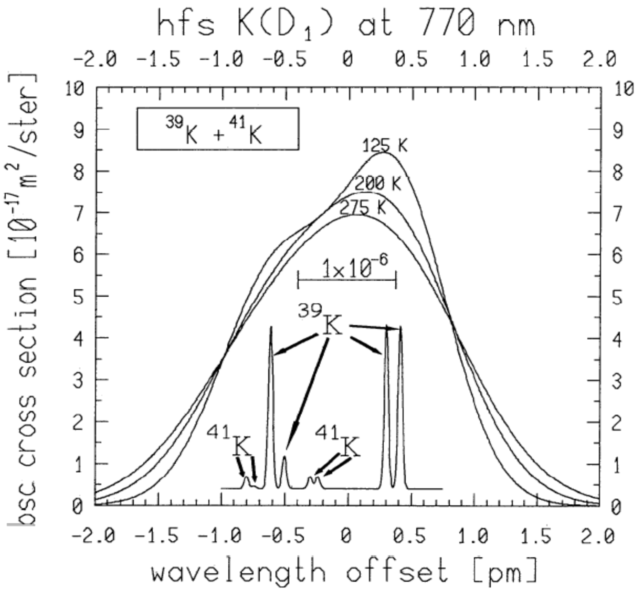


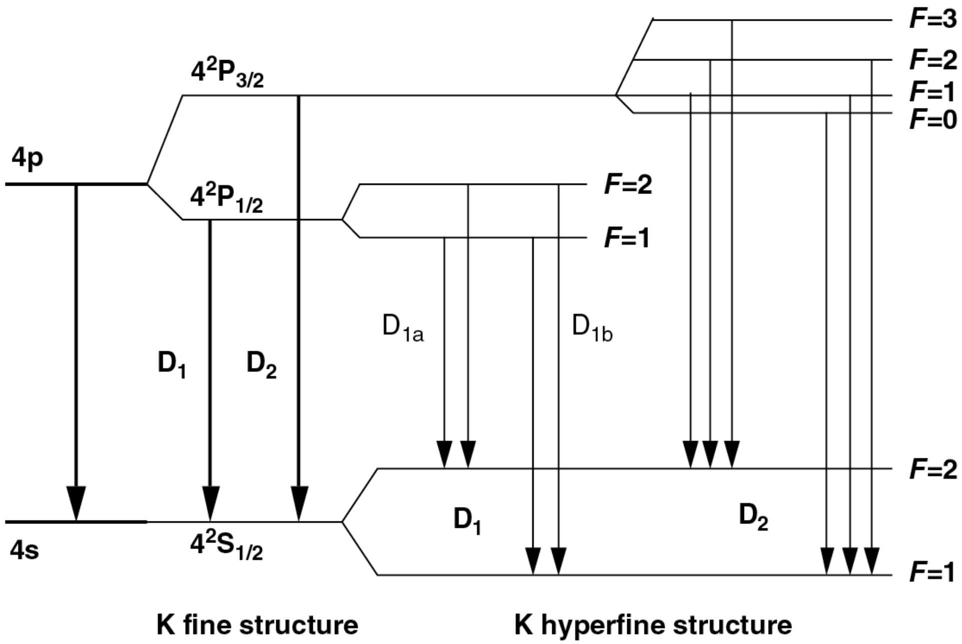
- then σ_{eff} can be written as

$$\sigma_{eff}(\nu_L,\nu_0) = \frac{\sigma_D\sigma_0}{\sqrt{\sigma_D^2+\sigma_L^2}}\exp\left(-\frac{\left[\nu_L(1-V_R/c)-\nu_0\right]^2}{2(\sigma_D^2+\sigma_L^2)}\right) \qquad (11.8)$$

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

Simulation of Resonance Fluorescence

- Besides common issues in lidar simulation, the main point in simulation of resonance fluorescence return is to correctly estimate the effective cross section and column abundance / density of these atomic species, e.g., K, Na, or Fe.
- Effective scattering cross section can be affected by laser central frequency, linewidth, saturation, optical pumping, branching ratio, isotopes, Hanle effect, etc.
- Correct estimate of this involves comprehensive understanding of the physical process and spectroscopy knowledge - This is why spectroscopy class is important!
- Column abundance and density of metal atoms in the upper atmosphere vary with season, latitude, and are also affected by waves etc. Usually we use a mean column abundance as a representative for envelope estimate.

Classifications of Lidar

There are several different classifications on lidars

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

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

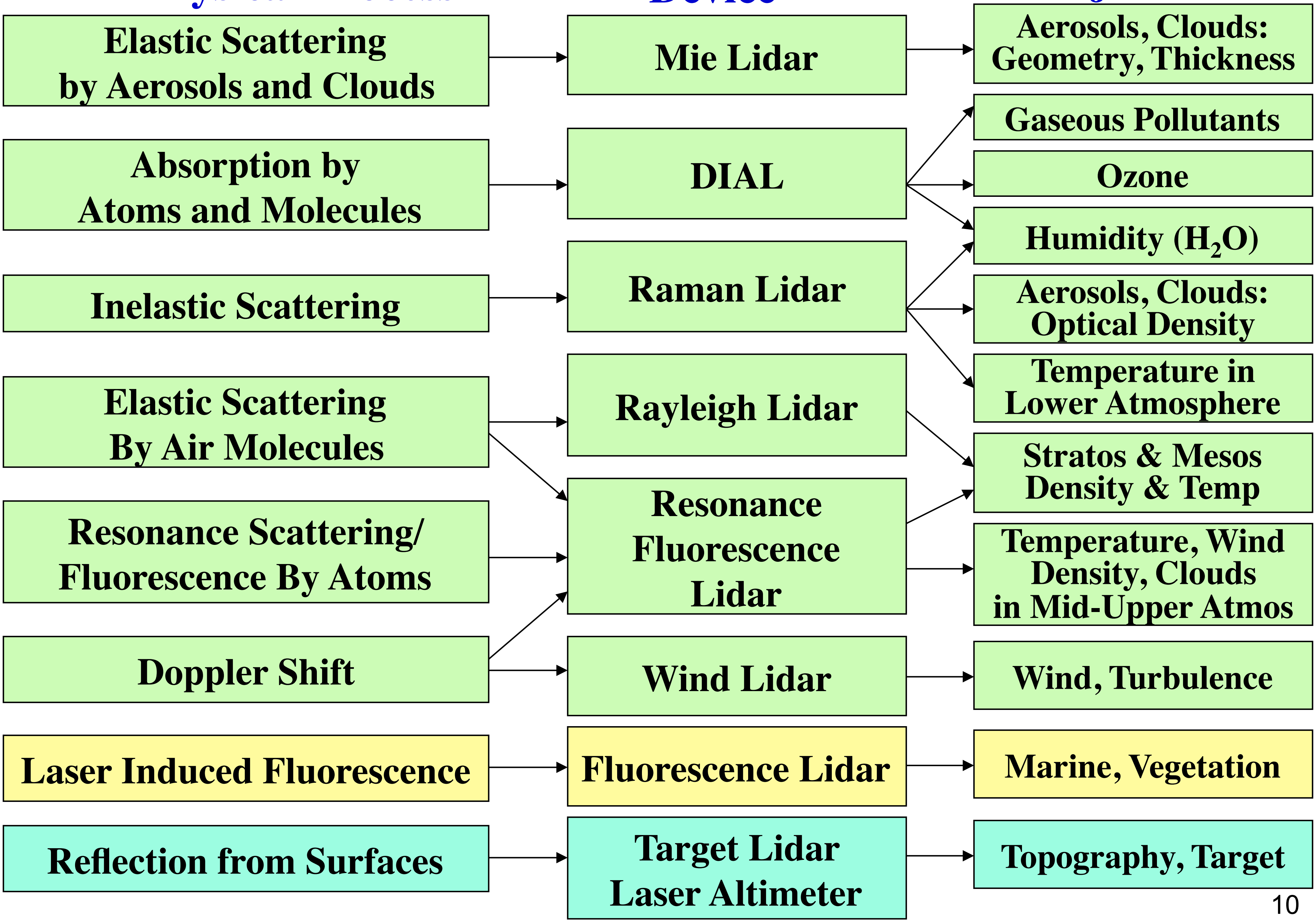
based on the detection region;
(Atmosphere, Ocean, Solid Earth, Space, ...)

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

Absorption by Atoms and Molecules

Inelastic Scattering

Elastic Scattering By Air Molecules

Resonance Scattering/ Fluorescence By Atoms

Doppler Shift

Laser Induced Fluorescence

Reflection from Surfaces

Mie Lidar

DIAL

Raman Lidar

Rayleigh Lidar

Resonance Fluorescence Lidar

Wind Lidar

Fluorescence Lidar

Target Lidar Laser Altimeter

Aerosols, Clouds: Geometry, Thickness

Gaseous Pollutants

Ozone

Humidity (H_2O)

Aerosols, Clouds: Optical Density

Temperature in Lower Atmosphere

Stratos & Mesos Density & Temp

Temperature, Wind Density, Clouds in Mid-Upper Atmos

Wind, Turbulence

Marine, Vegetation

Topography, Target

Classification on Platform

Spaceborne lidar	Satellite, Space Shuttle. Space Station
Airborne lidar	Jet, Propeller Airplanes Unmanned Aerial Vehicle (UAV) Kite
Groundbased lidar	Stationary Contanerized moved with truck
Shipborne lidar	Icebreaker, 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
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

Aerosol/Cloud lidar

Constituent lidar

Temperature lidar

Wind lidar

Target lidar

… … … …

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

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

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

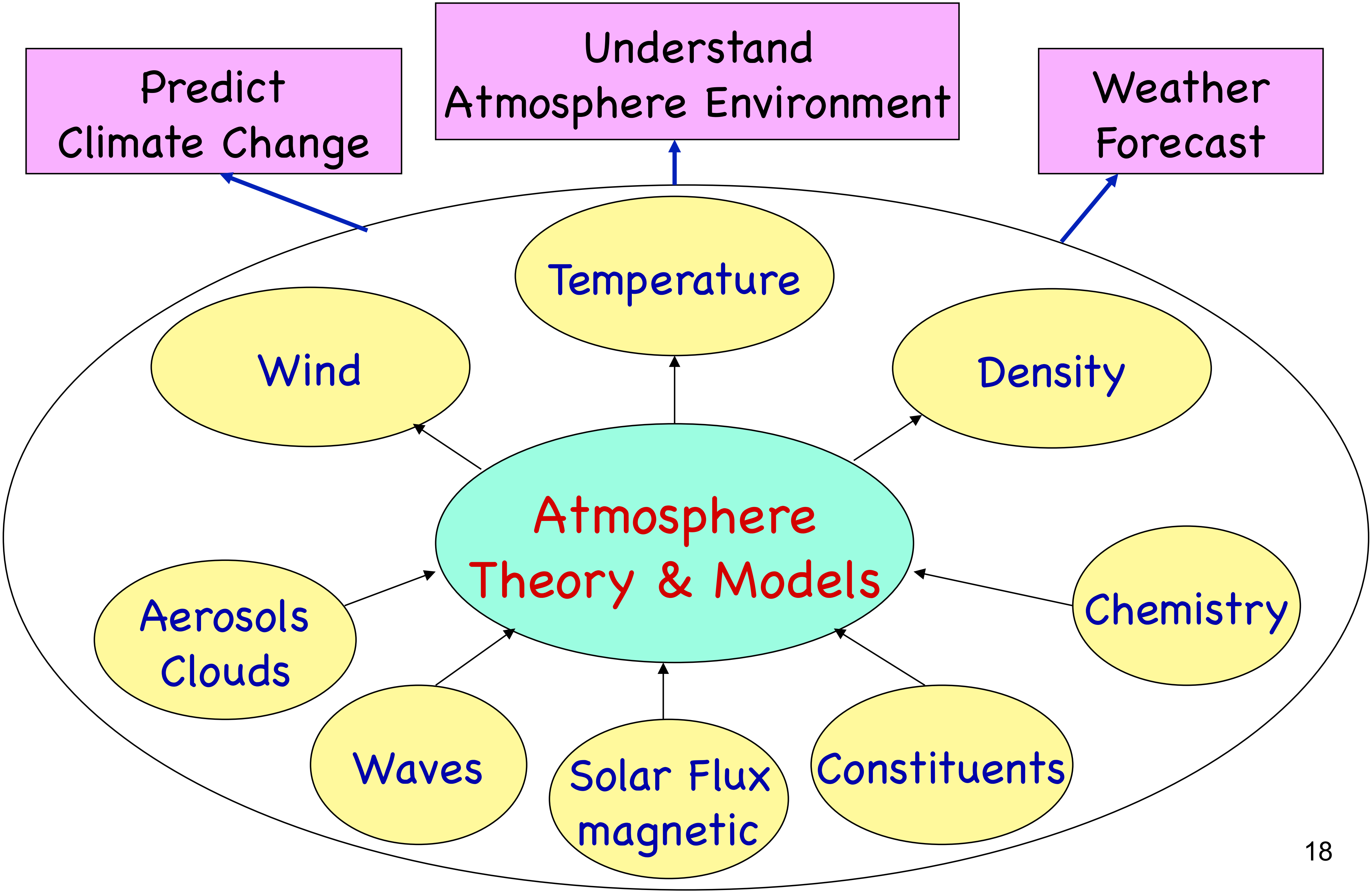
Why Topical Lidars ?

- 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 Atmosphere Models



Predict Climate Change

Understand Atmosphere Environment

Weather Forecast

Temperature

Wind

Density

Atmosphere Theory & Models

Aerosols Clouds

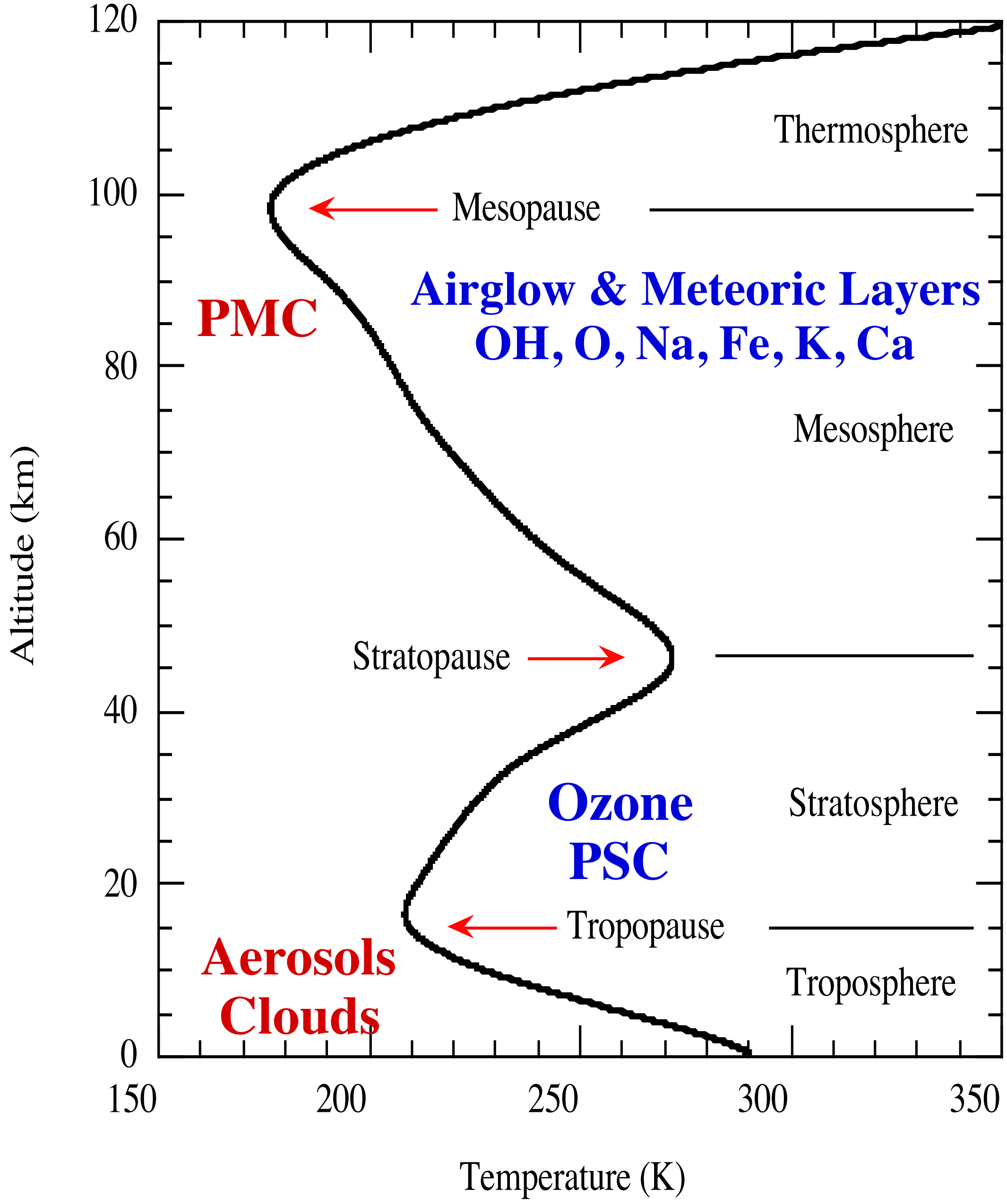
Chemistry

Waves

Solar Flux magnetic

Constituents

Temperature Techniques

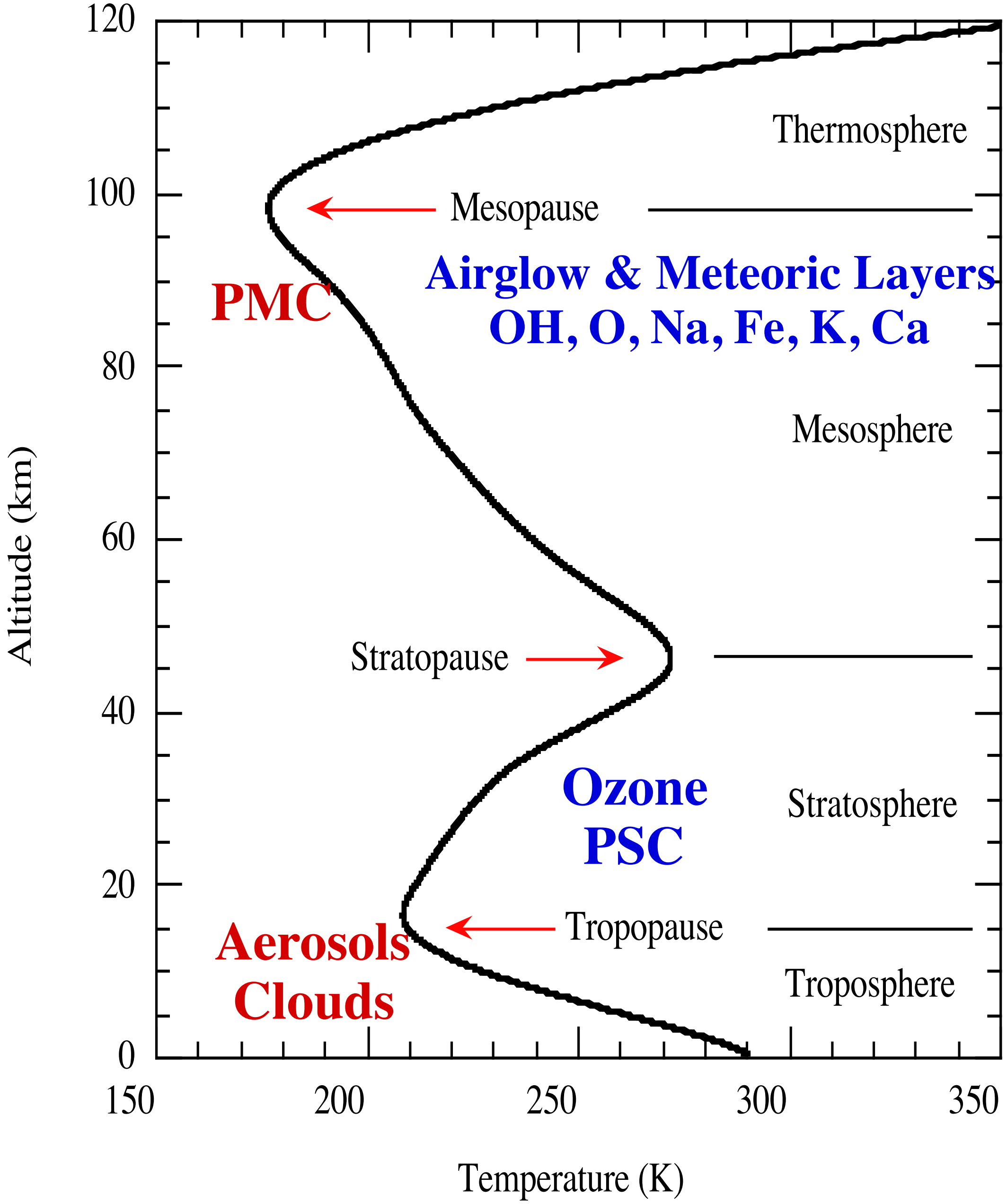


- ☐ 75-120 km: resonance fluorescence Doppler technique (Na, K, Fe) & Boltzmann technique (Fe, OH, O_2)
- ☐ 30-90 km: Rayleigh integration technique & Rayleigh Doppler technique
- ☐ Below 30 km: scattering Doppler technique and Raman technique (Boltzmann and integration)
- ☐ Boundary layer: DIAL, HSRL,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

Comparison of Temperature Technique

Technique	Lidars	Applications
Doppler Technique: temperature dependence of Doppler broadening (1 time Doppler shift and Doppler broadening for single absorption or emission process) (2 times Doppler shift and Doppler broadening for Rayleigh scattering)	Resonance fluorescence Doppler Lidar: Doppler broadening and Doppler shift of resonance fluorescence absorption cross-section (scan and ratio techs)	Mesosphere and Lower Thermosphere temperature and wind (75-120 km)
	Rayleigh Doppler Lidar : Doppler broadening of molecular scattering	Lower mesosphere, stratosphere and troposphere temperature and wind (up to 60 km)
	High-Spectral-Resolution Lidar: Doppler broadening of molecular scattering, ratio of two signals	Stratosphere and troposphere temperature and wind (up to 30 km)
Boltzmann Technique: temperature dependence of population ratio	Resonance fluorescence Boltzmann Temperature Lidar: population ratio on the lowest two ground states	Mesosphere and Lower Thermosphere temperature (75-120 km)
	Rotation Raman Temperature Lidar: ratio of two Raman line intensities and populations on initial energy states	Troposphere and stratosphere temperature
Integration Technique: hydrostatic equilibrium and ideal gas law	Rayleigh or Raman Integration Temp Lidar: atmospheric density ratio to temperature, integration from upper level	Stratosphere and mesosphere temperature (30-90 km) Troposphere temperature
DIAL	Differential Absorption Lidar: Temp-dependence of line strength and lineshape	Boundary layer temperature

Wind Techniques vs Altitude



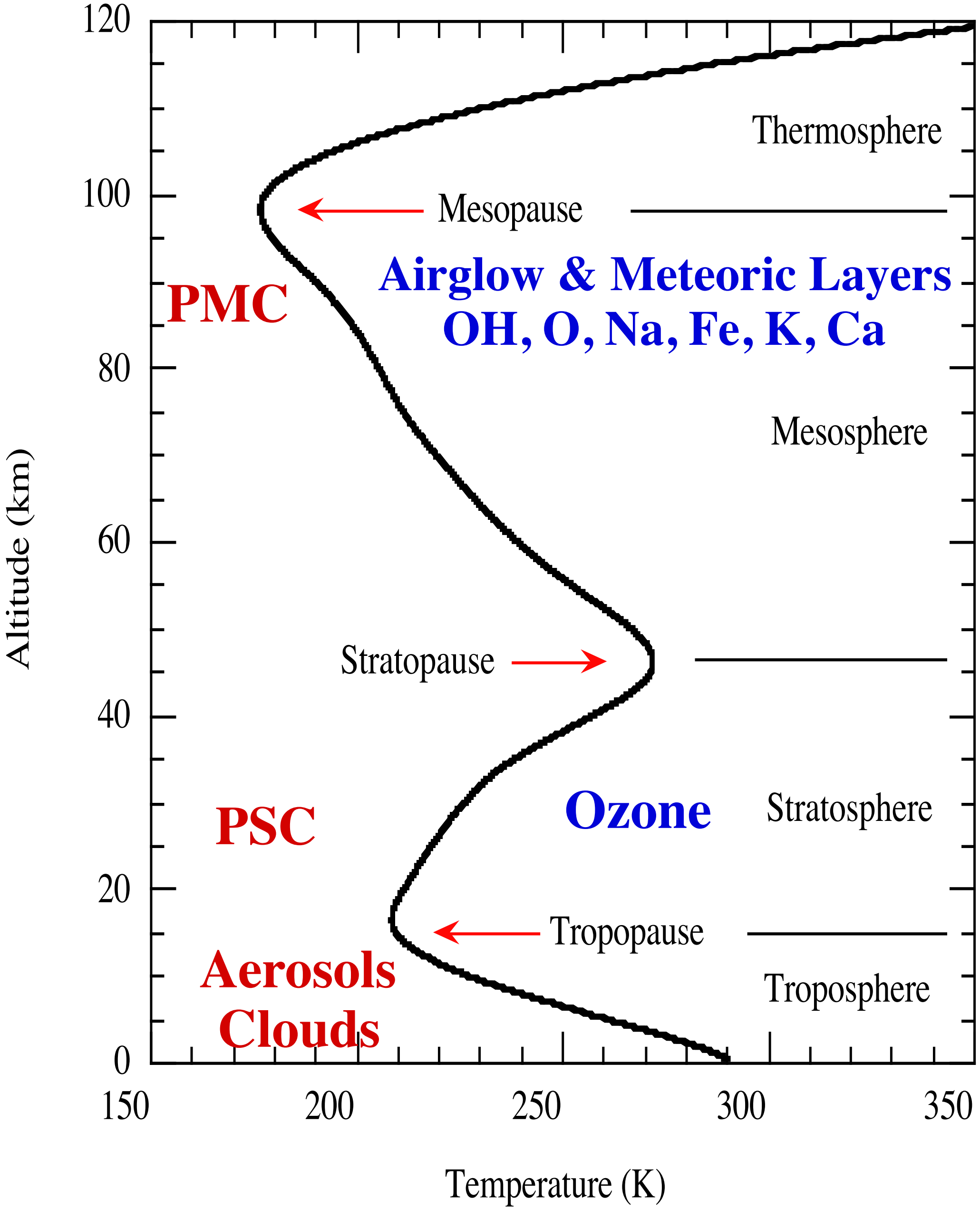
- ☐ 75-120km: resonance fluorescence (Na, K, Fe) Doppler technique (DDL)
- ☐ FPI: Fabry-Perot Interferometer
- ☐ Below 60km: Rayleigh Doppler technique (DDL)
- ☐ Below 30 km: Direct Detection Doppler technique
- ☐ In troposphere:

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

Comparison of Wind Techniques

Technique	Lidars	Applications
Doppler Wind Technique (Direct Detection or Coherent Detection): wind dependence of Doppler frequency shift (1 time Doppler shift for single absorption or emission process) (2 times Doppler shift for Mie and Rayleigh scattering)	Resonance Fluorescence Doppler Lidar: Doppler frequency shift and broadening of resonance fluorescence absorption cross-section (scan and ratio techniques)	Mesosphere and Lower Thermosphere temperature and wind (75-120 km)
	Rayleigh/Mie Doppler Lidar : Doppler frequency shift of molecular and aerosol scattering using edge filters and/or fringe imaging	Lower mesosphere, stratosphere and troposphere wind (up to 50-60 km)
	Coherent Detection Doppler Lidar: Doppler frequency shift of aerosol scattering using heterodyne detection tech	Troposphere wind, especially in boundary layers (up to 15 km), where aerosols are abundant
Direct Motion Detection Technique: derivative of displacement (the definition of velocity) (direct application of velocity definition or cross-correlation coefficient)	High-Spectral-Resolution Lidar: tracking aerosol / cloud motion through time	Troposphere wind, where aerosols and clouds are abundant
	(Scanning) Aerosol Lidar: tracking aerosol motion through time	Troposphere wind, where aerosols and clouds are abundant
	Laser Time-of-Flight Velocimeter: measuring time-of-flight of aerosol across two focused and parallel laser beams	Within the first km range, laboratory, machine shop, etc.
	Laser Doppler Velocimeter: measuring the frequency of aerosol scattering across the interference fringes of two crossed laser beams	Within the boundary layers, wind tunnel, production facility, machine shop, laboratory, etc

Aerosol Lidar Technique 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.

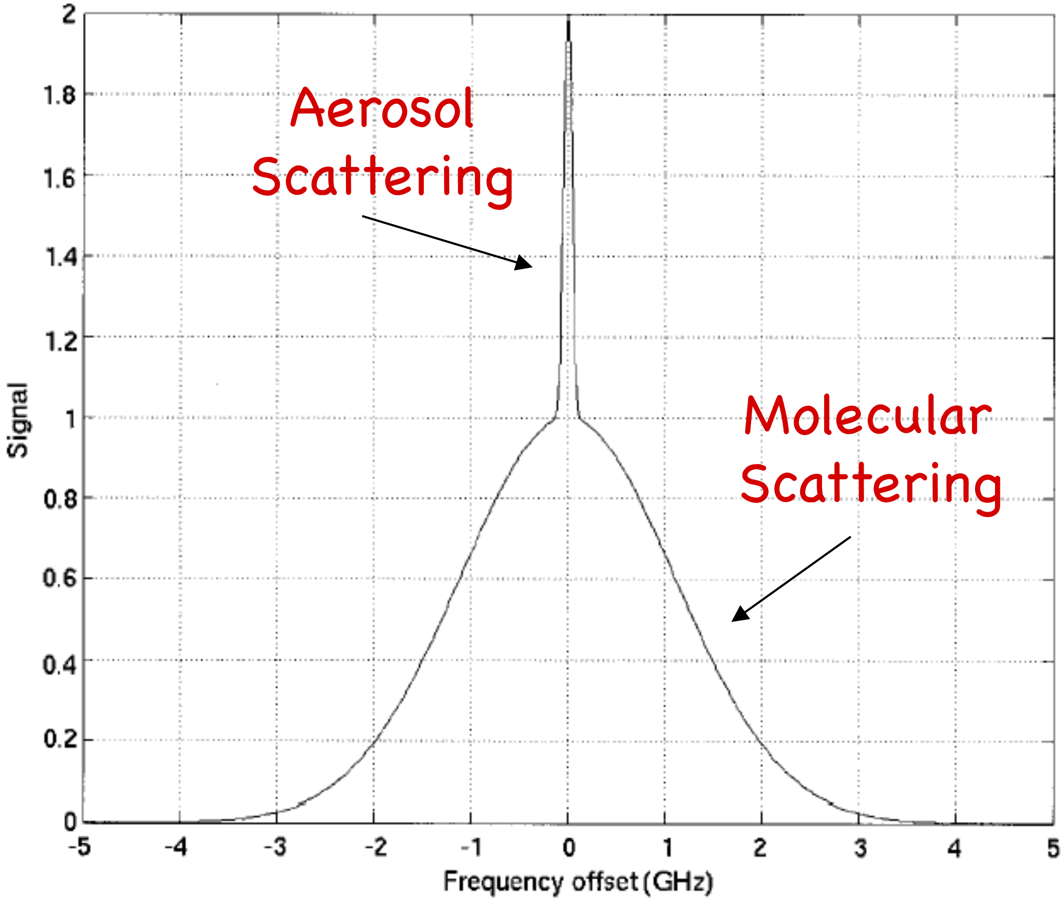
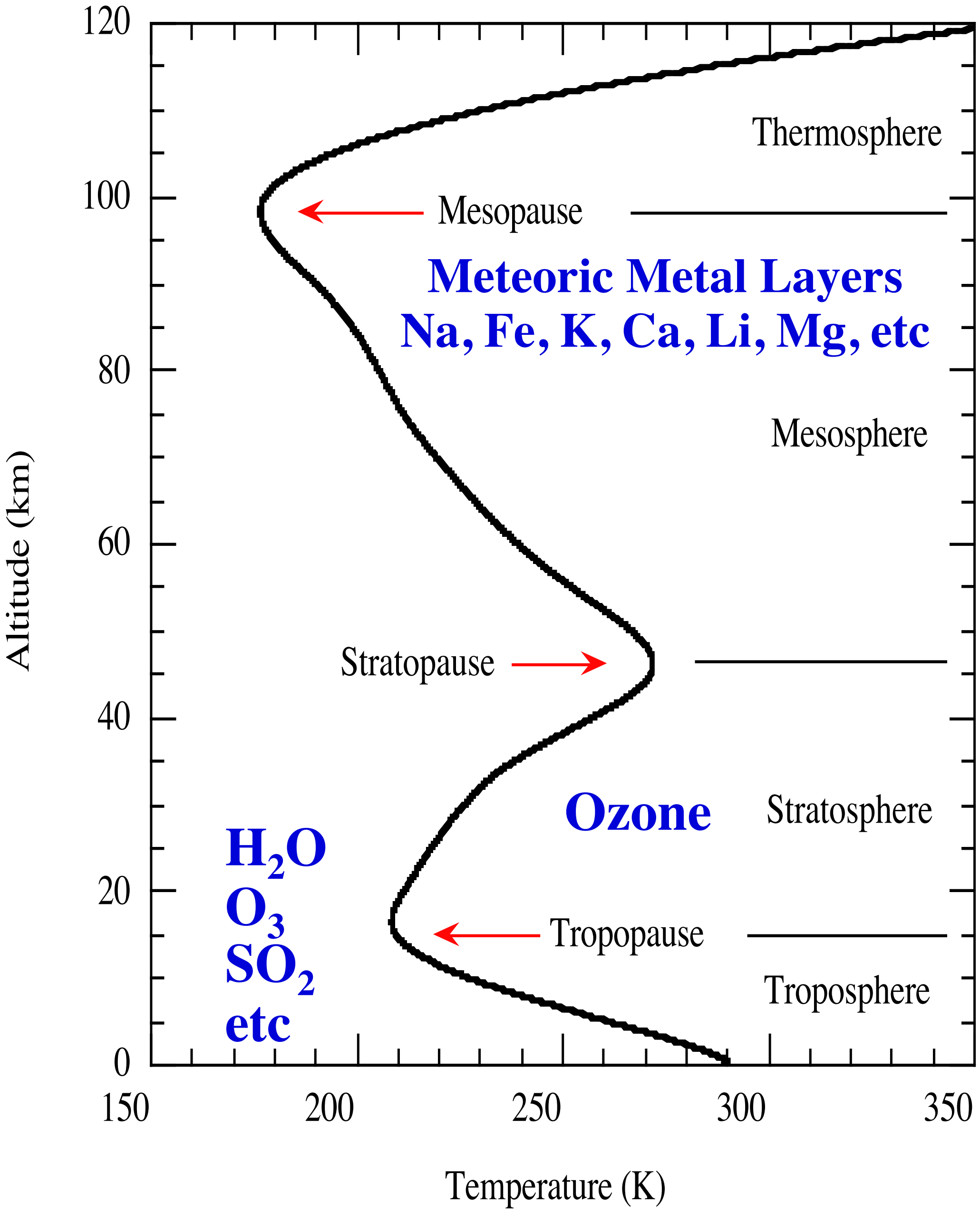


Fig. 5.1. Spectral profile of backscattering from a mixture of molecules and aerosols for a temperature of 300 K. The spectral width of the narrow aerosol return is normally determined by the line width of the transmitting laser.

Constituent Lidar Techniques



- ☐ 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.

Comparison of Constituent Lidar Tech

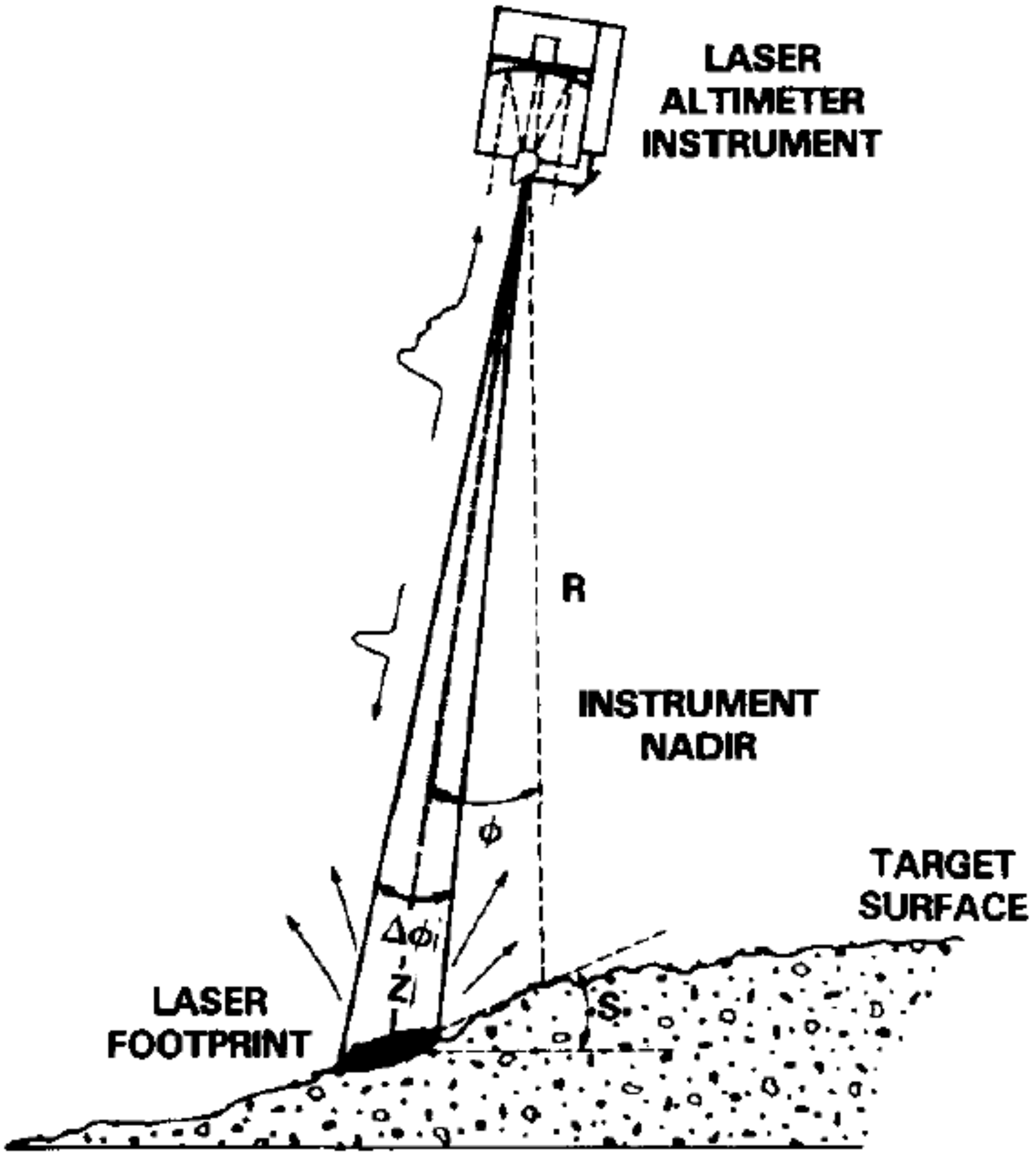
Technique	Signal Source & Trace Gas		Interests
Resonance Fluorescence Lidar	Resonance fluorescence from metal atoms in middle and upper atmosphere		Temp, Wind, Density, Wave
Resonance Fluorescence Lidar	Resonance fluorescence from He, N_2^+, O in thermosphere		Density, Temp Wind, etc
Conventional DIAL	Elastic-scattering from air molecules and aerosols	Trace gas absorption in the extinction terms	Species, Density
Raman Lidar	Inelastic Raman scattering from trace gas and reference N_2 or O_2	Trace gas scattering in the backscatter terms (no aerosol scattering)	Species, Density, Mixing ratio
Raman DIAL	Inelastic Raman scattering from N_2 or O_2	Trace gas absorption in the extinction terms	Species, Density
RVR Raman DIAL	Pure rotational Raman scattering and Vibrational-Rotational Raman scattering	Trace gas absorption in the extinction terms	Species, Density
Multiwavelength DIAL	Elastic scattering from air molecules and aerosols	Trace gas absorption in the extinction terms	Species, Density

Range-Resolved spatial & temporal distribution of these species, density, temp, wind and waves

Laser Altimeter (Laser Ranging)

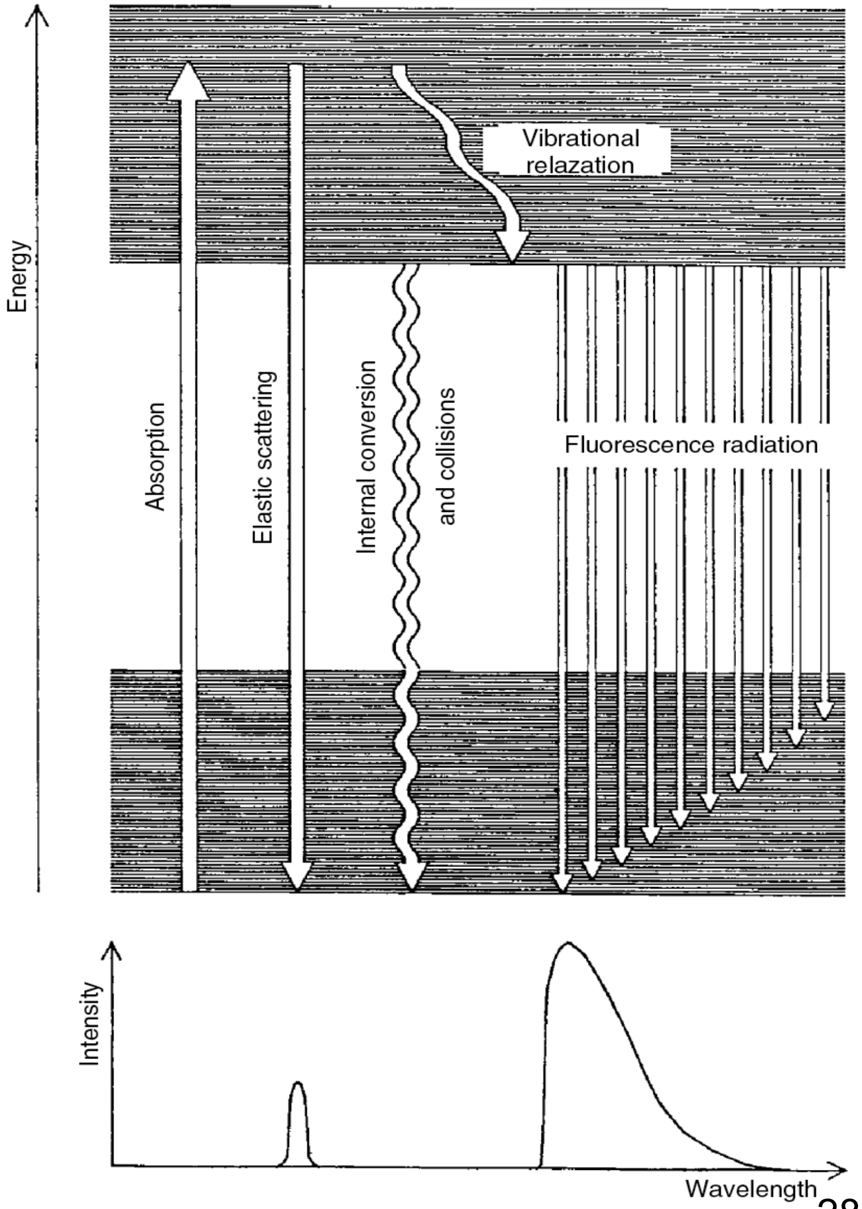
- The time-of-flight information from a lidar system can be used for laser altimetry from airborne or spaceborne platforms to measure the heights of surfaces with high resolution and accuracy.

- The reflected pulses from the solid surface (earth ground, ice sheet, etc) dominant the return signals, which allow a determination of the time-of-flight to much higher resolution than the pulse duration time.



Fluorescence from Liquids and Solids

- In contrast to free atoms and molecules, solids and liquids exhibit broad absorption and emission spectra because of the strong intermolecular interactions.
- A fixed frequency laser can be used for the excitation due to the broad absorption.
- Following the excitation, there is a very fast (ps) radiationless relaxation down to the lowest sub-level of the excited state, where the molecules remain for a typical excited-state fluorescence lifetime.
- The decay then occurs to different sub-levels of the ground state giving rise to a distribution of fluorescence light, which reflect the lower-state level distribution.
- Fixing the excitation wavelength, we can obtain fluorescence spectra. While fixing the detection channel and varying the excitation wavelength, an excitation spectrum can be recorded.



Summary

- Five major topics are chosen for reviewing lidar measurement principles and technologies: temperature, wind, aerosol, constituent, and target/altimeter.

- 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.