Lecture 30. Review of Lidar Class

- Concept and Picture of Lidar Remote Sensing
- General Lidar Equation and the ideas behind it
- Physical Processes involved in different lidars
- Lidar Architecture
- Altitude determination for different lidars
- Topical lidar technique summary

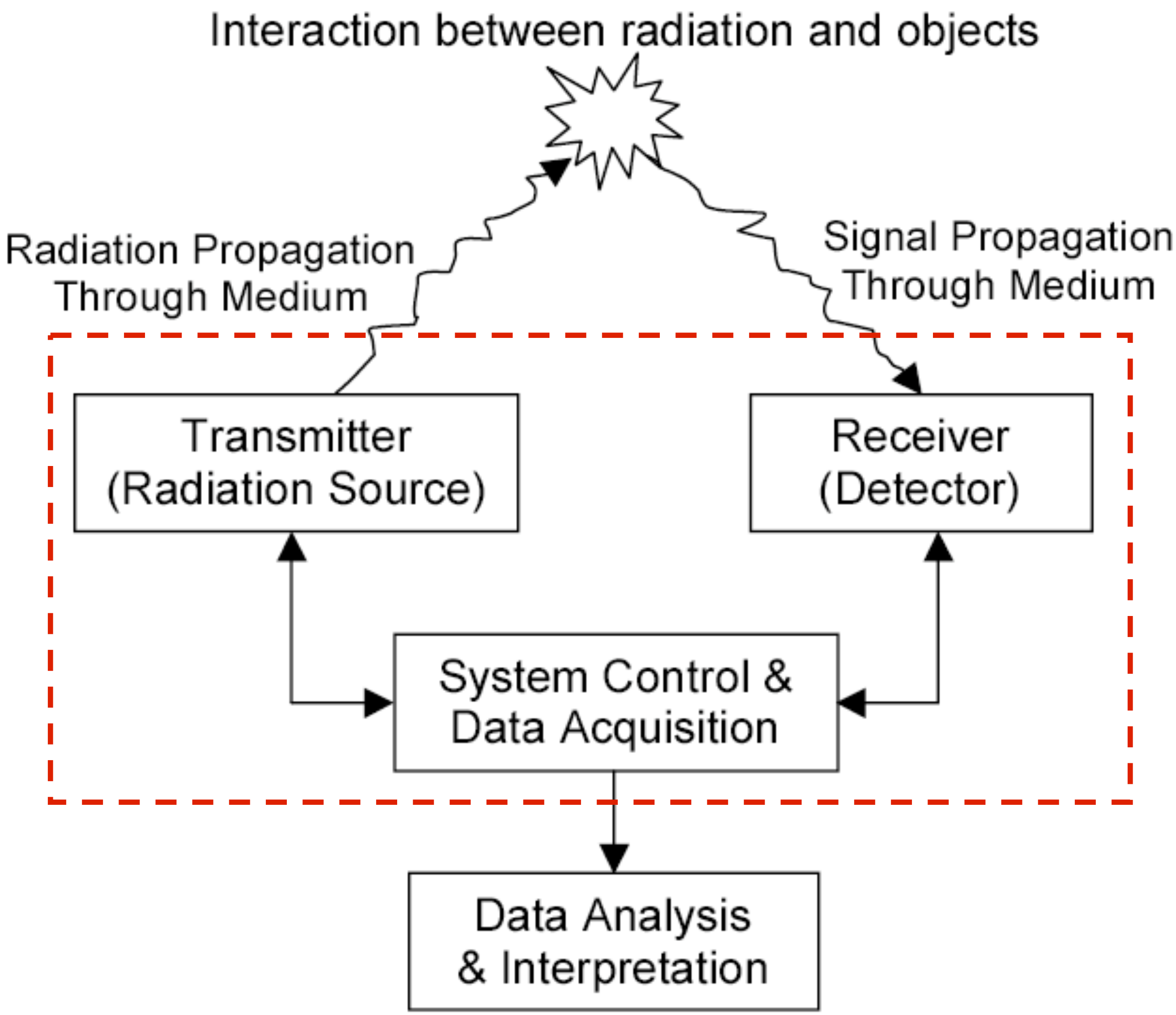
(Temp, Wind, Aerosol, Constituent, Target)

- Classifications of lidars
- Challenges in different categories of lidars
- Novel Lidar Technology and Application
- Outlook on Lidar Remote Sensing

Concept of Remote Sensing

- Remote Sensing is the science and technology of obtaining information about an object without having the sensor in direct physical-contact with the object.
- The nature of remote sensing is one kind of measurements, i.e., to obtain or acquire information of an object using experimental methods.
- There must be some interaction between the object and the instruments in order to acquire the information of the object. The interaction can be direct (local) or remote.
- For remote sensing, remote interaction must be introduced to carry away the object information so that the information can be acquired by the sensor remotely.
- The interaction between radiation and the object is the most common interaction used in modern remote sensing. The radiation includes electromagnetic radiation and acoustic waves.
- Remote sensing has passive and active remote sensing, in optical, radio, and acoustic frequency ranges.
- LIDAR, RADAR, and SODAR are three main active remote sensing technologies.

Physical Picture in LIDAR Remote Sensing



General LIDAR Equation

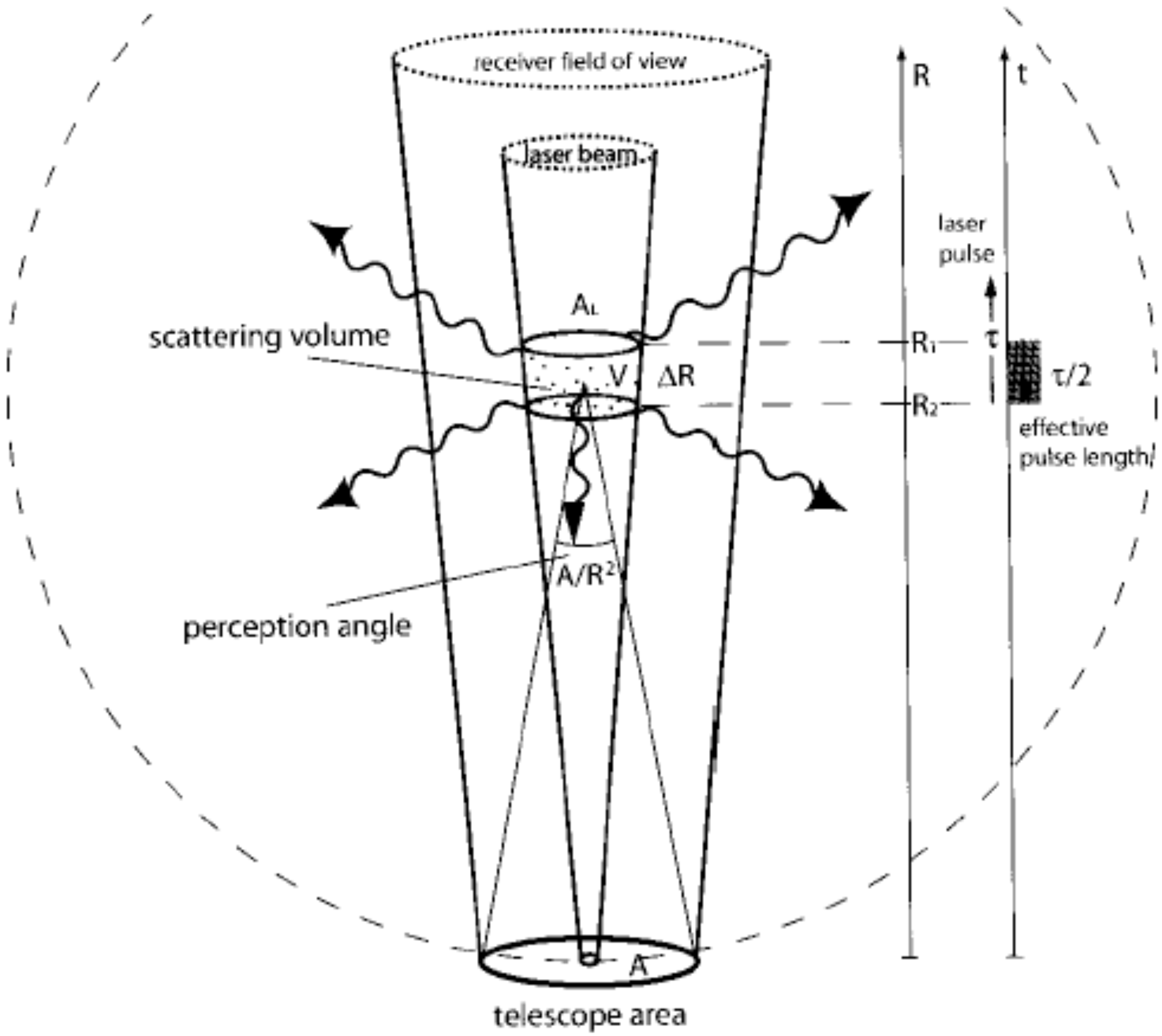
- Lidar equation is the fundamental equation in laser remote sensing field to relate the received photon counts (or light power) with the transmitted laser photon numbers (or laser power), light transmission in atmosphere or medium, physical interaction between light and objects, and lidar system efficiency and geometry, etc.

Basic Assumptions for Lidar Equation

Independent scattering & Single scattering

- Independent scattering: particles are separated adequately and undergo random motion so that the contribution to the total scattered energy by many particles have no phase relation. Thus, the total intensity is simply a sum of the intensity scattered from each particle.
- Single scattering: a photon is scattered only once. Multiple scatter is excluded in our consideration.

Illustration for LIDAR Equation



General Form of LIDAR Equation

$$N_S(\lambda,R) = N_L(\lambda_L)\cdot\left[\beta(\lambda,\lambda_L,\theta,R)\Delta R\right]\cdot\frac{A}{R^2}\cdot\left[T(\lambda_L,R)T(\lambda,R)\right]\cdot\left[\eta(\lambda,\lambda_L)G(R)\right]+N_B$$

$$P_S(\lambda,R) = P_L(\lambda_L)\cdot\left[\beta(\lambda,\lambda_L,\theta,R)\Delta R\right]\cdot\frac{A}{R^2}\cdot\left[T(\lambda_L,R)T(\lambda,R)\right]\cdot\left[\eta(\lambda,\lambda_L)G(R)\right]+P_B$$

General Lidar Equation in β and α

$$N_S(\lambda,R) = \left[\frac{P_L(\lambda_L)\Delta t}{hc/\lambda_L}\right]\left[\beta(\lambda,\lambda_L,R)\Delta z\right]\left(\frac{A}{R^2}\right)\exp\left[-2\int_0^R \alpha(\lambda,r')dr'\right]\left[\eta(\lambda,\lambda_L)G(R)\right]+N_B$$

Volume scatter coefficient $$\beta(\lambda,\lambda_L,R) = \sum_i\left[\frac{d\sigma_i(\lambda_L)}{d\Omega}n_i(R)p_i(\lambda)\right]$$

Transmission $$T(\lambda_L,R)T(\lambda,R) = \exp\left[-\left(\int_0^R \alpha(\lambda_L,r)dr + \int_0^R \alpha(\lambda,r)dr\right)\right]$$

Physical Processes in LIDAR

- Interaction between light and objects

(1) Scattering (instantaneous elastic & inelastic): Mie, Rayleigh, Raman

(2) Resonance fluorescence

(3) Absorption and differential absorption

(4) Laser induced fluorescence

(5) Doppler shift and Doppler broadening

(6) Boltzmann distribution

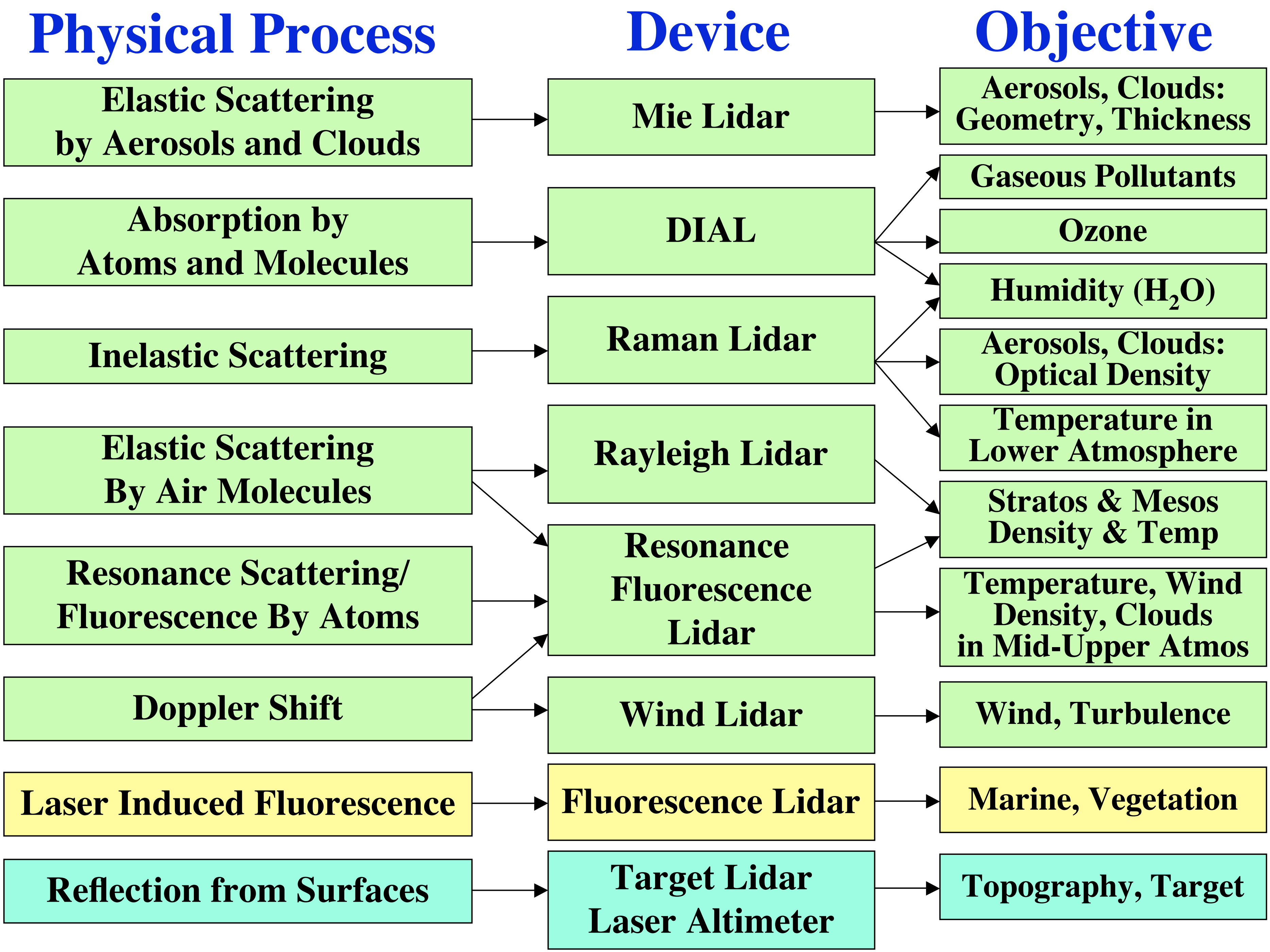
(7) Reflection from target or surface

- Light propagation in atmosphere or medium: transmission vs extinction

Extinction = Scattering + Absorption

$$\boxed{T(\lambda,R) = \exp\left[-\int_0^R \alpha(\lambda,r)\,dr\right]}$$

$$\boxed{\alpha(\lambda,R) = \sum_i \left[\sigma_{i,ext}(\lambda) n_i(R)\right]}$$


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

Backscatter Cross-Section Comparison

Physical Process	**Backscatter Cross-Section**	**Mechanism**
Mie (Aerosol) Scattering	10^{-8} - 10^{-10} cm^2sr^{-1}	Two-photon process Elastic scattering, instantaneous
Resonance Fluorescence	10^{-13} cm^2sr^{-1}	Two single-photon process (absorption and spontaneous emission) Delayed (radiative lifetime)
Molecular Absorption	10^{-19} cm^2sr^{-1}	Single-photon process
Fluorescence from molecule, liquid, solid	10^{-19} cm^2sr^{-1}	Two single-photon process Inelastic scattering, delayed (lifetime)
Rayleigh Scattering	10^{-27} cm^2sr^{-1}	Two-photon process Elastic scattering, instantaneous
Raman Scattering	10^{-30} cm^2sr^{-1}	Two-photon process Inelastic scattering, instantaneous

Scattering Form of Lidar Equation

$$\boxed{N_S(\lambda,R) = \left(\frac{P_L(\lambda)\Delta t}{hc/\lambda}\right)\left(\beta(\lambda,R)\Delta R\right)\left(\frac{A}{R^2}\right)T^2(\lambda,R)\left(\eta(\lambda)G(R)\right) + N_B}$$

- Rayleigh, Mie, and Raman scattering processes are instantaneous scattering processes, so there are no finite relaxation effects involved, but infinitely short duration. For Rayleigh and Mie scattering, there is no frequency shift when the atmospheric particles are at rest, so

$$\boxed{N_S(\lambda,R) = \left(\frac{P_L(\lambda_L)\Delta t}{hc/\lambda_L}\right)\left(\beta(\lambda,\lambda_L,R)\Delta z\right)\left(\frac{A}{R^2}\right)\left(T(\lambda_L,R)T(\lambda,R)\right)\left(\eta(\lambda,\lambda_L)G(R)\right) + N_B}$$

- For Raman scattering, there is large frequency shift and

$$\boxed{\lambda \neq \lambda_L, \quad p_i(\lambda) \neq 1, \quad p_i(\lambda) < 1}$$

$$\boxed{T(\lambda,R) = \exp\left[-\int_0^R \alpha(\lambda,r)\,dr\right]}$$

Fluorescence Form of Lidar Equation

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

- Here, $T_c(R)$ is the extinction coefficient caused by the absorption.

$$\boxed{T_c(R)\equiv E(R)=\exp\left(-\int_{R_{bottom}}^{R}\sigma_{eff}(\lambda,r')n_c(r')\,\mathrm{d}r'\right)=\exp\left(-\int_{R_{bottom}}^{R}\alpha_c(\lambda,r')\,\mathrm{d}r'\right)}$$

- Here, $\alpha(\lambda,R)$ is the extinction coefficient caused by the absorption.

$$\boxed{\alpha_c(\lambda,R)=\sigma_{eff}(\lambda,R)n_c(R)}$$

- Resonance fluorescence and laser-induced-fluorescence are NOT instantaneous processes, but have delays due to the radiative lifetime of the excited states.

Differential Absorption/Scattering Form

- For the laser with wavelength λ_{on} on the molecular absorption line

$$\boxed{\begin{aligned} N_S(\lambda_{on},R) = N_L(\lambda_{on})\left[\beta_{sca}(\lambda_{on},R)\Delta R\right]\left(\frac{A}{R^2}\right)\exp\left[-2\int_0^z \overline{\alpha}(\lambda_{on},r')dr'\right] \\ \times\exp\left[-2\int_0^z \sigma_{abs}(\lambda_{on},r')n_c(r')dr'\right]\left[\eta(\lambda_{on})G(R)\right]+N_B \end{aligned}}$$

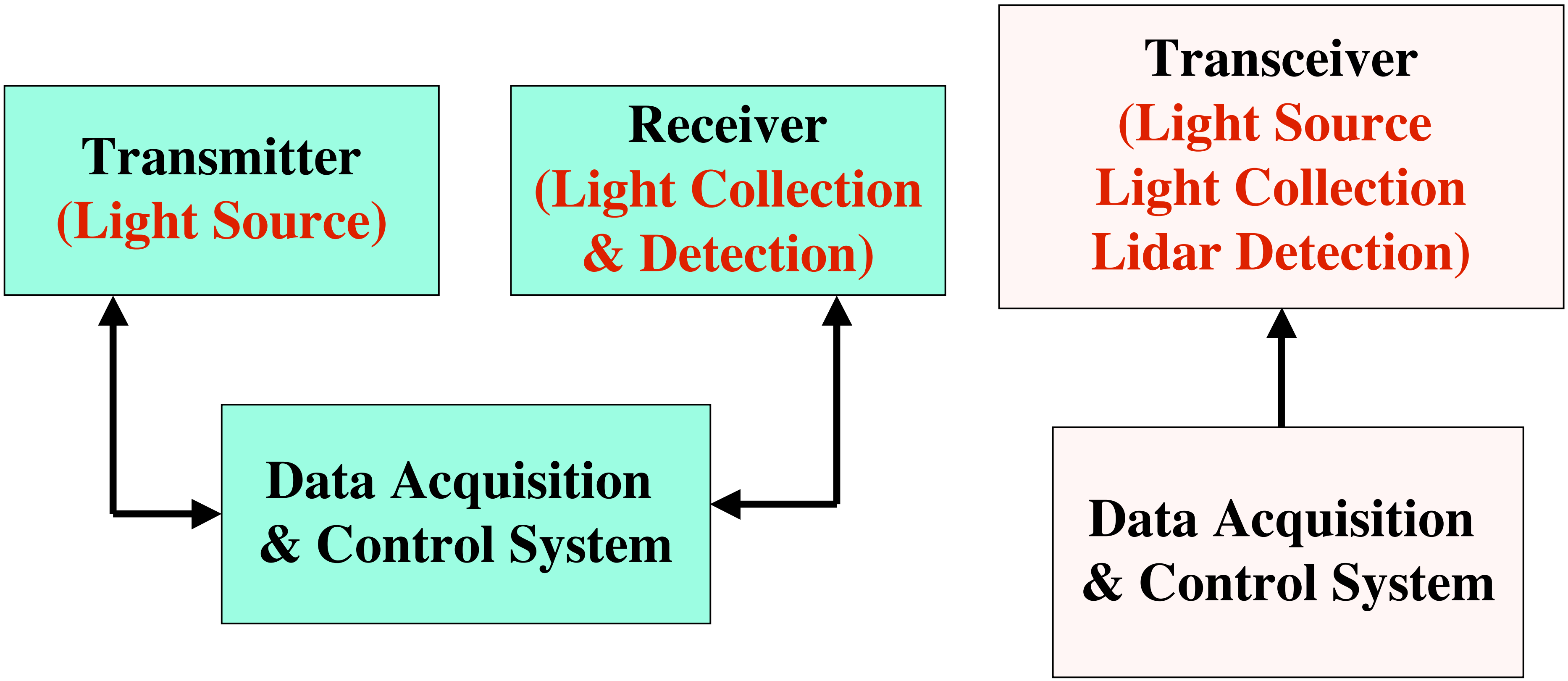
- For the laser with wavelength λ_{off} off the molecular absorption line

$$\boxed{\begin{aligned} N_S(\lambda_{off},R) = N_L(\lambda_{off})\left[\beta_{sca}(\lambda_{off},R)\Delta R\right]\left(\frac{A}{R^2}\right)\exp\left[-2\int_0^z \overline{\alpha}(\lambda_{off},r')dr'\right] \\ \times\exp\left[-2\int_0^z \sigma_{abs}(\lambda_{off},r')n_c(r')dr'\right]\left[\eta(\lambda_{off})G(R)\right]+N_B \end{aligned}}$$

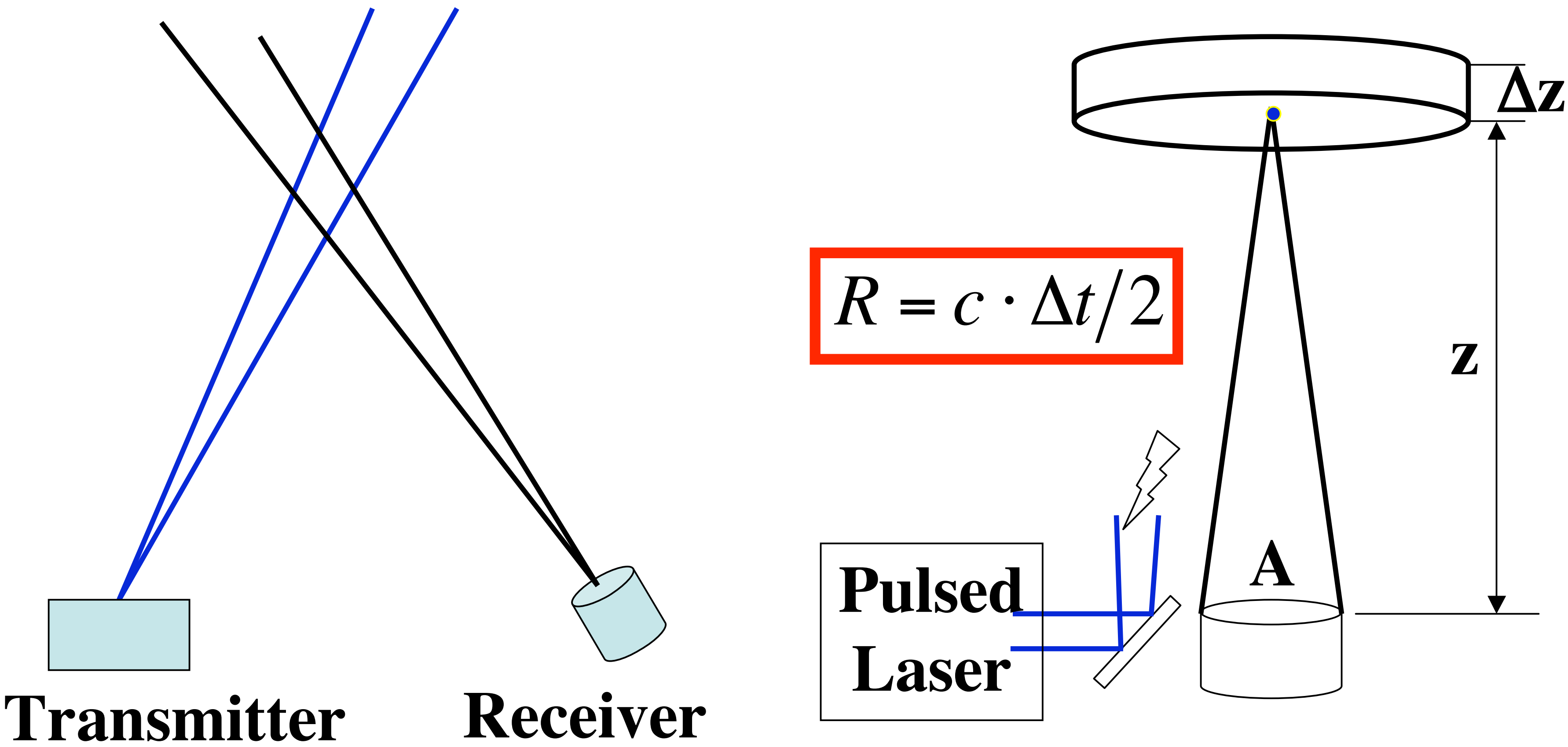
- Differential absorption cross-section

$$\boxed{\Delta\sigma_{abs}(R) = \sigma_{abs}(\lambda_{ON},R) - \sigma_{abs}(\lambda_{OFF},R)}$$

Basic Architecture of LIDAR



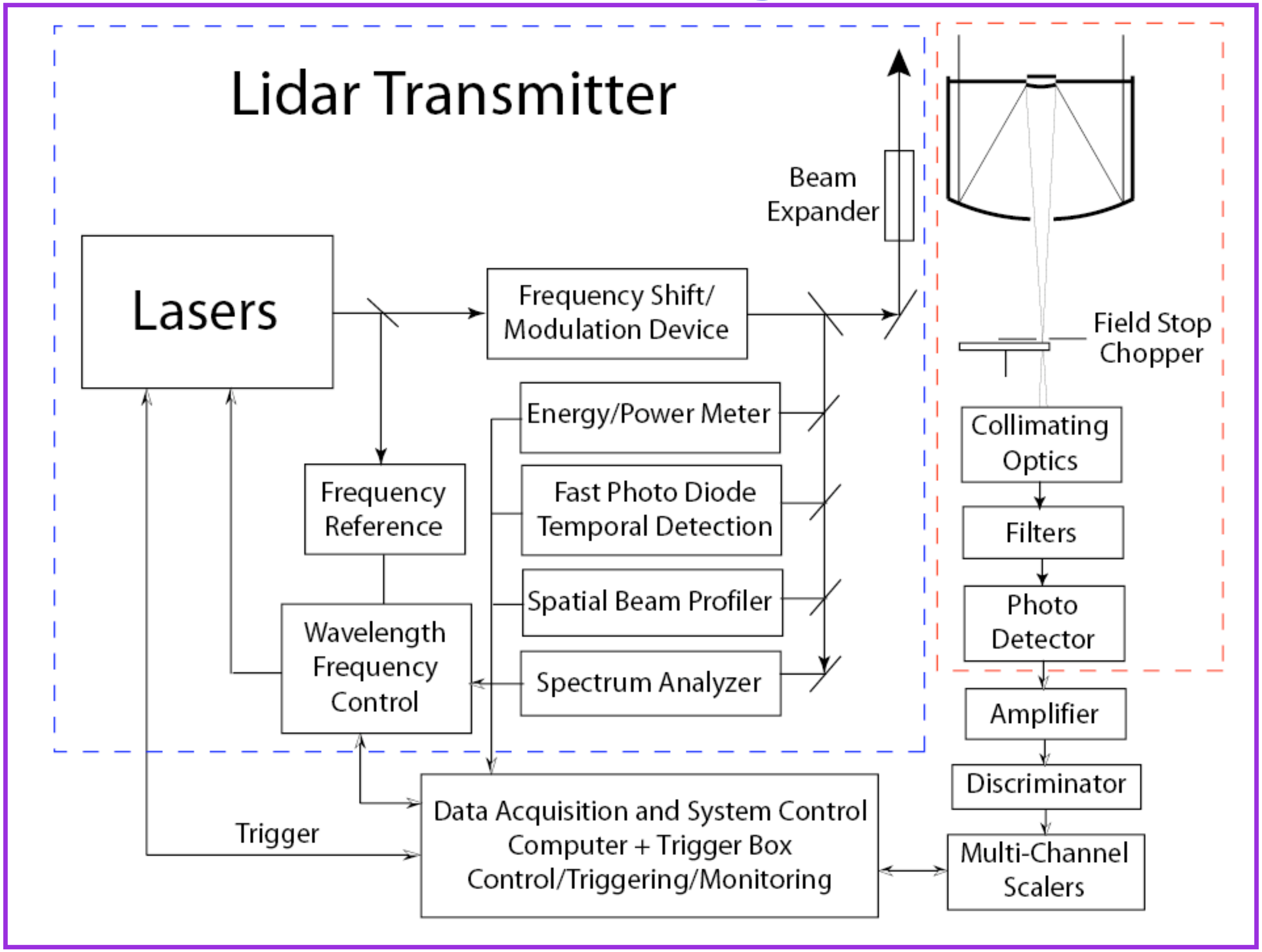
Basic Configurations of LIDAR
Bistatic and Monostatic



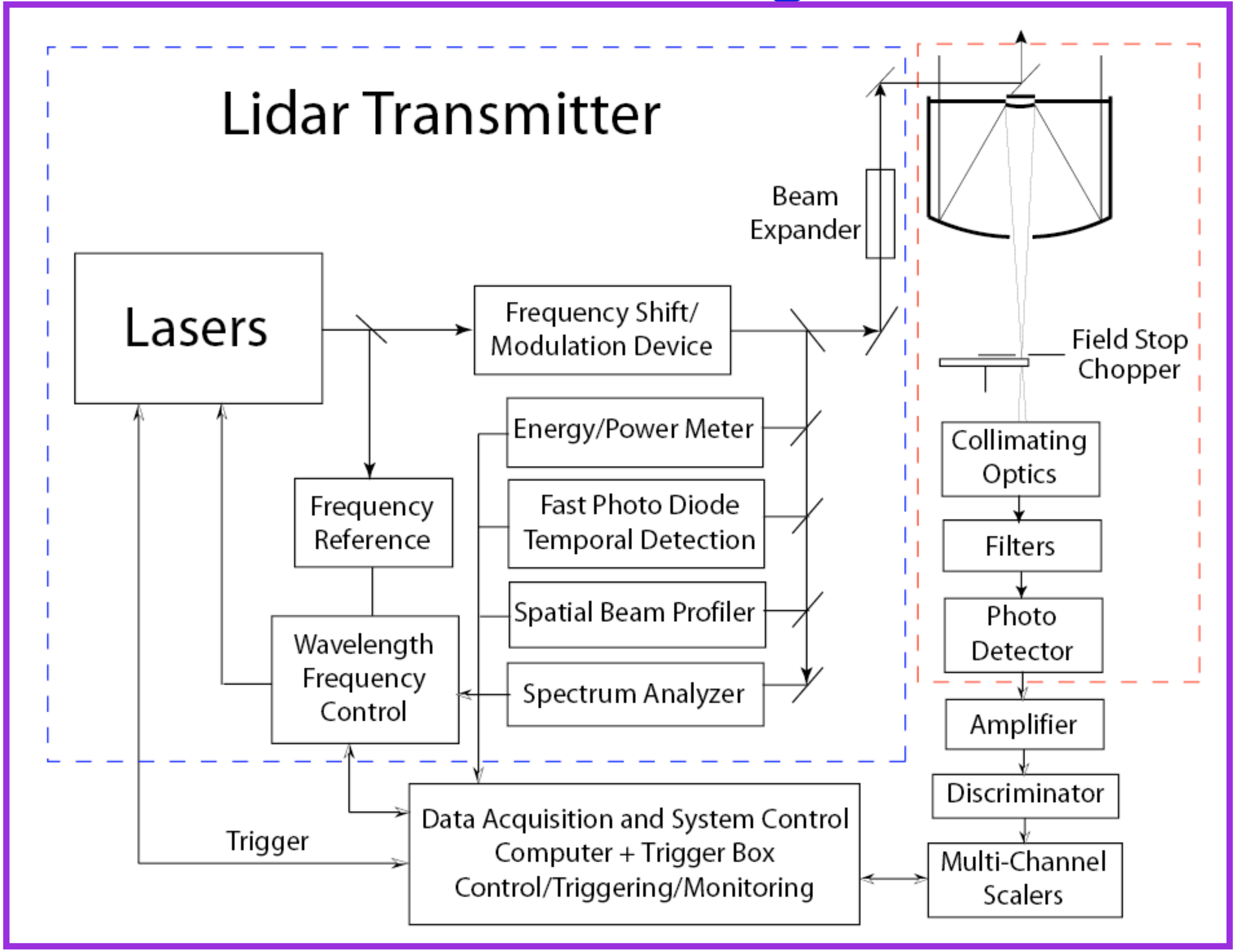
Bistatic Configuration

Monostatic Configuration

Biaxial Arrangement



Coaxial Arrangement



Considerations on Lidar Architecture

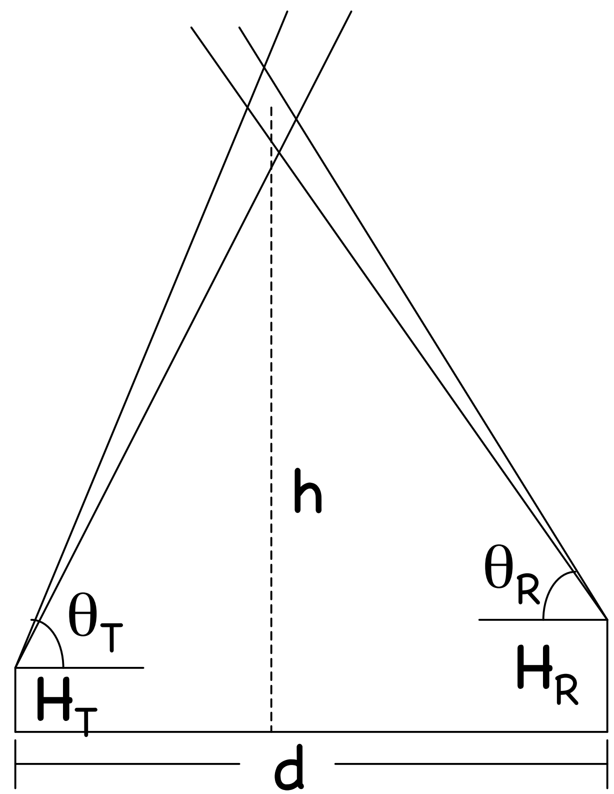
- Overall architecture - separate transmitter/receiever or transceiver?
- Configuration - bistatic or monostatic?
- Arrangement - biaxial or coaxial?
- Geometrical overlap
- Uplooking or downlooking?
- Care about radiation-matter interaction or only timing?
- Wavelength consideration and solar spectra
- Tunable or not?
- Bandwidth for transmitter and receiver
- Power/energy consideration
- Bin width - pulse duration time, repetition rate
- Nighttime or full diurnal capability?
- Volume, mass, cost, reliability, robustness, operation, etc?

Altitude Determination from Geometry

- Bistatic configuration involves a considerable separation of the transmitter and receiver to achieve spatial resolution in optical probing study.
- It originated from CW searchlight, and modulation was used to improve SNR.

- The range information is determined from geometry configuration, rather than the time-of-flight.

$$h = \frac{d \cdot \tan(\theta_T) \cdot \tan(\theta_R) + H_T \cdot \tan(\theta_R) + H_R \cdot \tan(\theta_T)}{\tan(\theta_T) + \tan(\theta_R)}$$



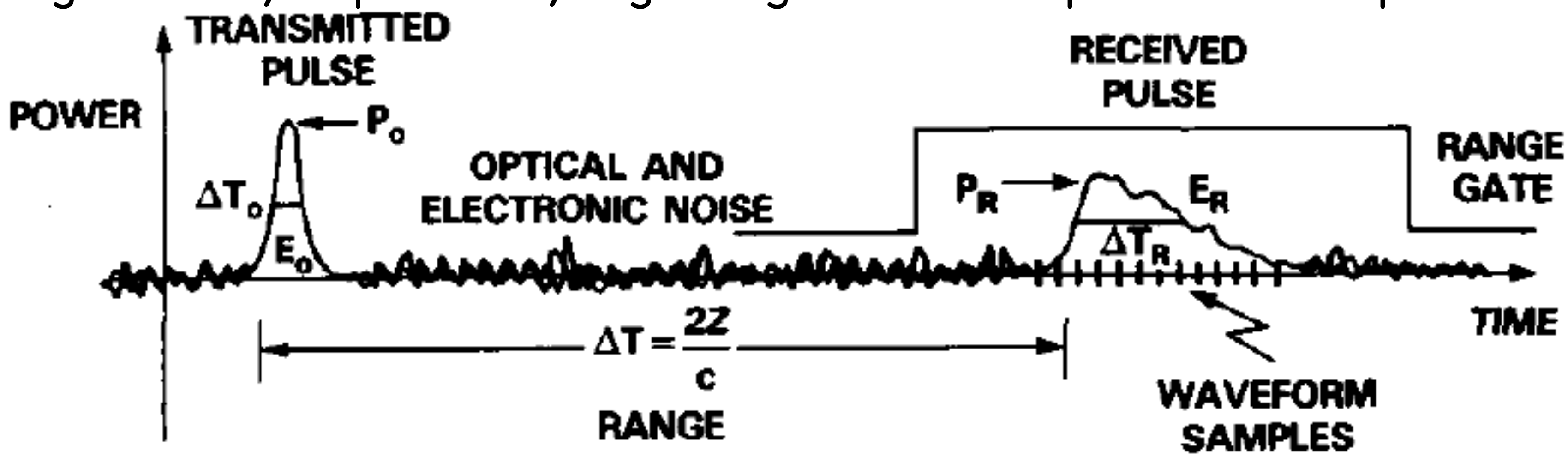
Altitude Determination from TOF

- For nanosecond pulsed-laser lidar, the range is determined by the time of flight of the photons propagating from lidar transmitter to the objects and returning to the lidar receiver.
- For atmospheric (scattering) lidar, the ultimate resolution is limited by the pulse duration time, as atmospheric scattering has no distinct peak.

$$\boxed{R = c \cdot t/2} \qquad \boxed{\Delta R = c \cdot \Delta t/2}$$

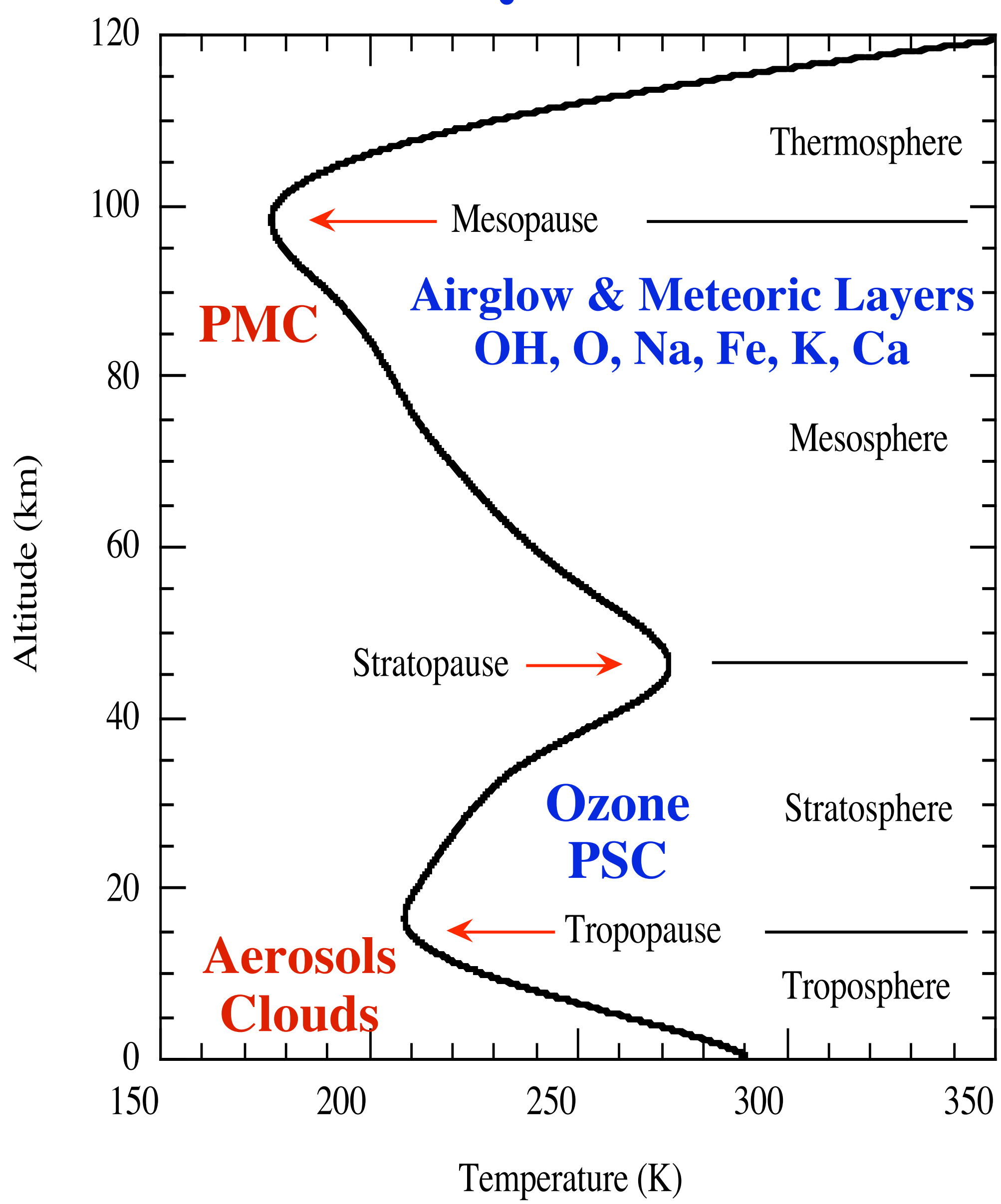
Δt is pulse width

- For target lidar (e.g., laser altimeter), the distinct peak due to the strong reflection of light from surface or target, the range resolution can be significantly improved by digitizing the return pulse and compare shape.



Altitude = Platform Base Altitude – Range ± Interference of aerosols and clouds

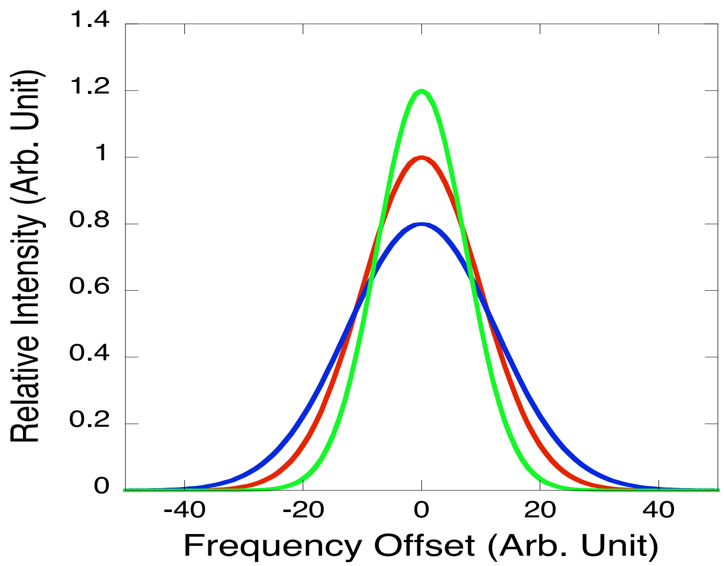
Temperature Techniques



- 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

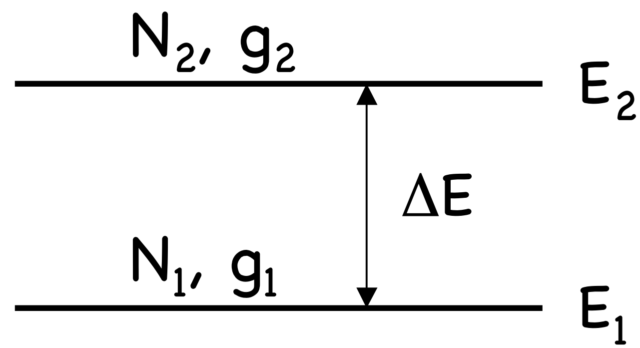
Review of Doppler & Boltzmann

- Doppler effect and Boltzmann distribution are two effects that are directly temperature-dependent. The Doppler technique and Boltzmann technique are “straight-forward” in the sense of deriving temperature or wind. However, the lidar architecture is usually complicated and sophisticated, due to the high demands on frequency accuracy, linewidth, and power combination.



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

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



$$\frac{N_2}{N_1} = \frac{g_2}{g_1}\exp\left\{-\left(E_2 - E_1\right)/k_B T\right\}$$

$$T = \frac{\Delta E / k_B}{\ln\left(\frac{g_2}{g_1}\cdot\frac{N_1}{N_2}\right)}$$

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 population on different initial energy states	Troposphere and stratosphere temperature
Integration Technique: hydrostatic equilibrium and ideal gas law	Rayleigh Integration Temperature Lidar: atmospheric density ratio to temperature, integration from upper level	Stratosphere and mesosphere temperature (30-90 km)
DIAL	Differential Absorption Lidar: Temp-dependence of line strength and lineshape	Boundary layer temperature

Techniques for Wind Measurements

Use wind-dependent effects or use definition of wind

- **Direct Motion Detection Technique:**

(using the definition of velocity)

$$\boxed{\vec{v} = \frac{d\vec{r}(t)}{dt}}$$

(1) Tracking aerosol/cloud motions
(2) Laser Time-of-Flight Velocimetry
(3) Laser Doppler Velocimetry

- **Doppler (Shift) Wind Technique:** $\boxed{\Delta\omega = -\vec{k}\cdot\vec{v}}$ or $\boxed{\Delta\omega = -2\vec{k}\cdot\vec{v}}$

(1) Coherent (Heterodyne) Detection Doppler Wind Lidar

(2) Direct Detection Doppler Wind Lidar

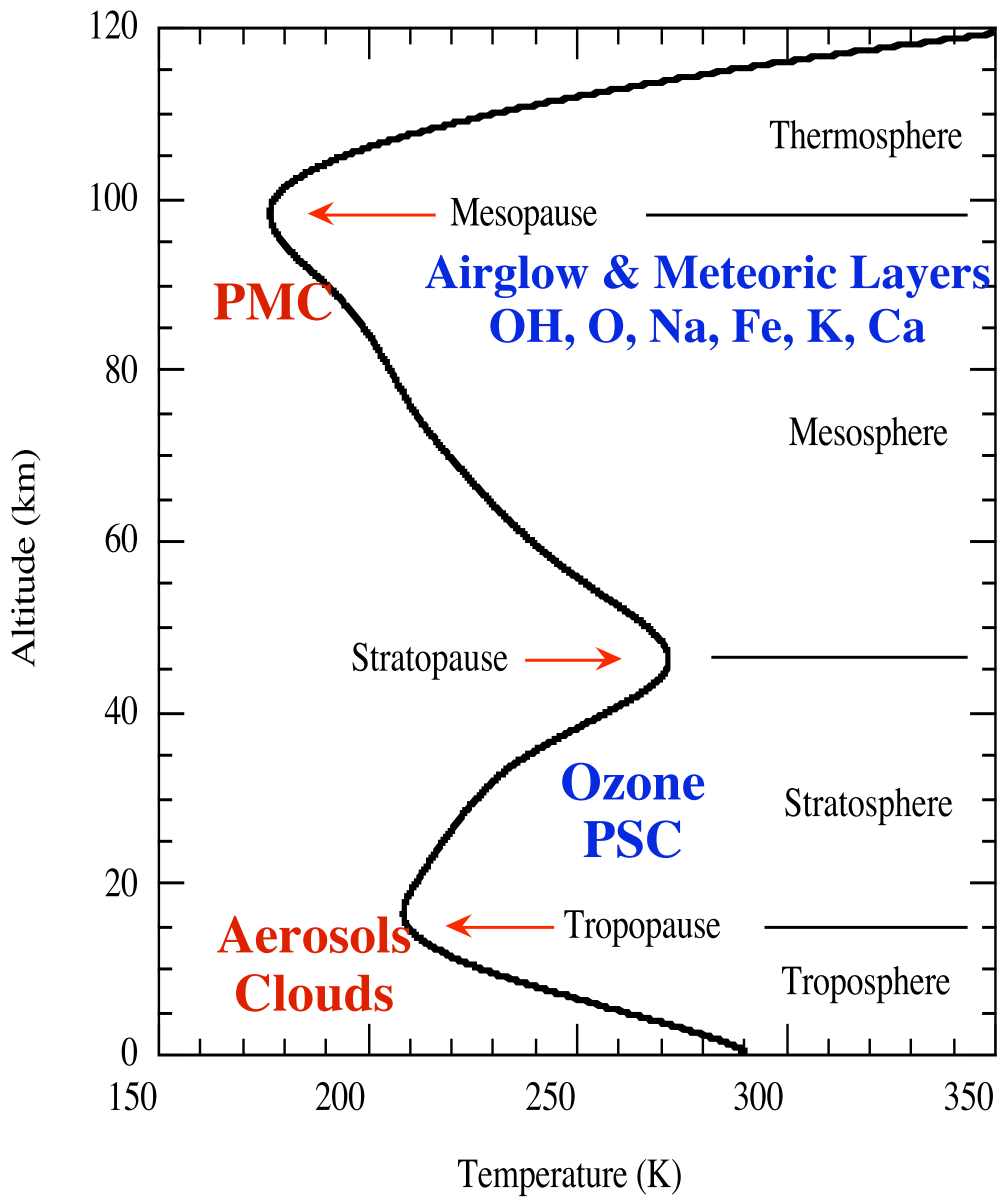
- **Geostrophic wind detection:**

Temperature ⇨ Pressure Gradients ⇨ Geostrophic Wind

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

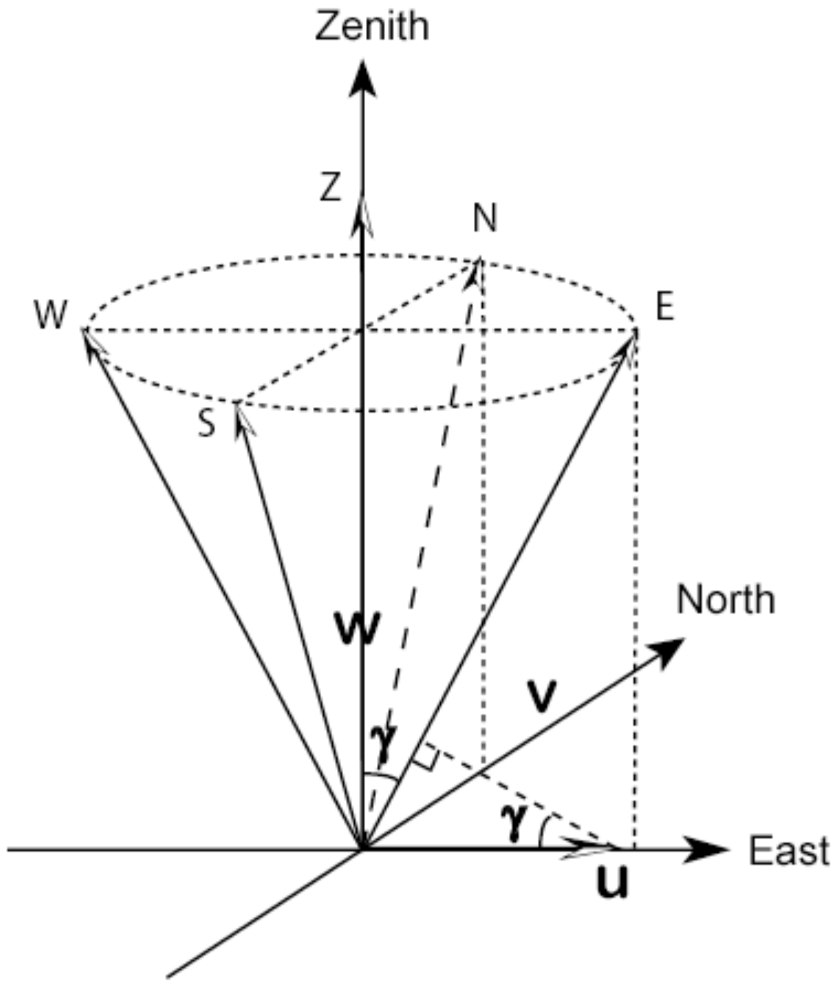
Wind Techniques vs Altitude



- ❑ 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)

Modified DBS Technique

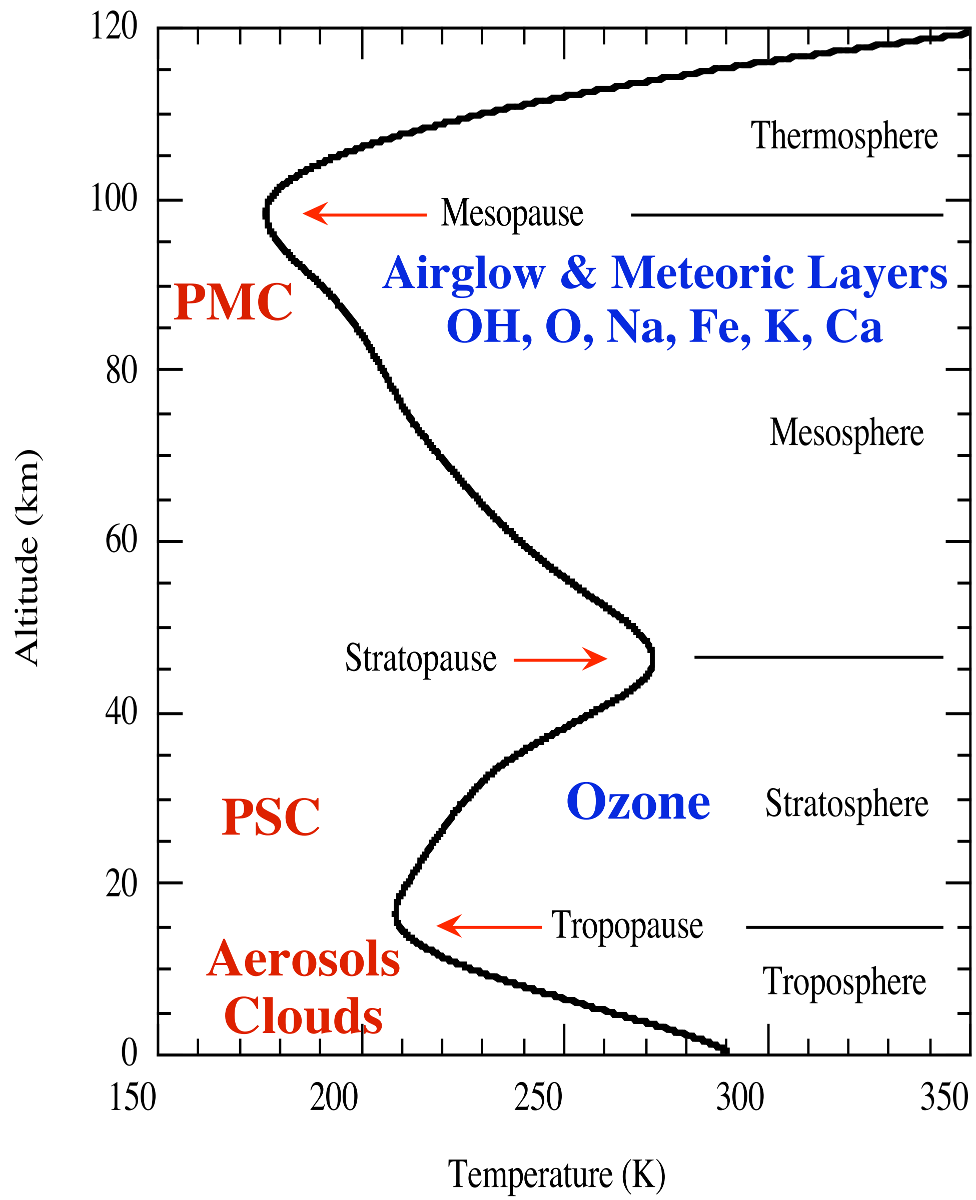


$$V_{RE} = u\sin\gamma + w\cos\gamma$$
$$V_{RW} = -u\sin\gamma + w\cos\gamma$$
$$V_{RN} = v\sin\gamma + w\cos\gamma$$
$$V_{RS} = -v\sin\gamma + w\cos\gamma$$
$$V_{RZ} = w$$

$$u = (V_{RE} - V_{RZ}\cos\gamma)/\sin\gamma$$
$$u = -(V_{RW} - V_{RZ}\cos\gamma)/\sin\gamma$$
$$v = (V_{RN} - V_{RZ}\cos\gamma)/\sin\gamma$$
$$v = -(V_{RS} - V_{RZ}\cos\gamma)/\sin\gamma$$
$$w = V_{RZ}$$

$V_R > 0$, $w > 0$, $u > 0$, $v > 0$ for wind towards away, upward, east, and north

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.

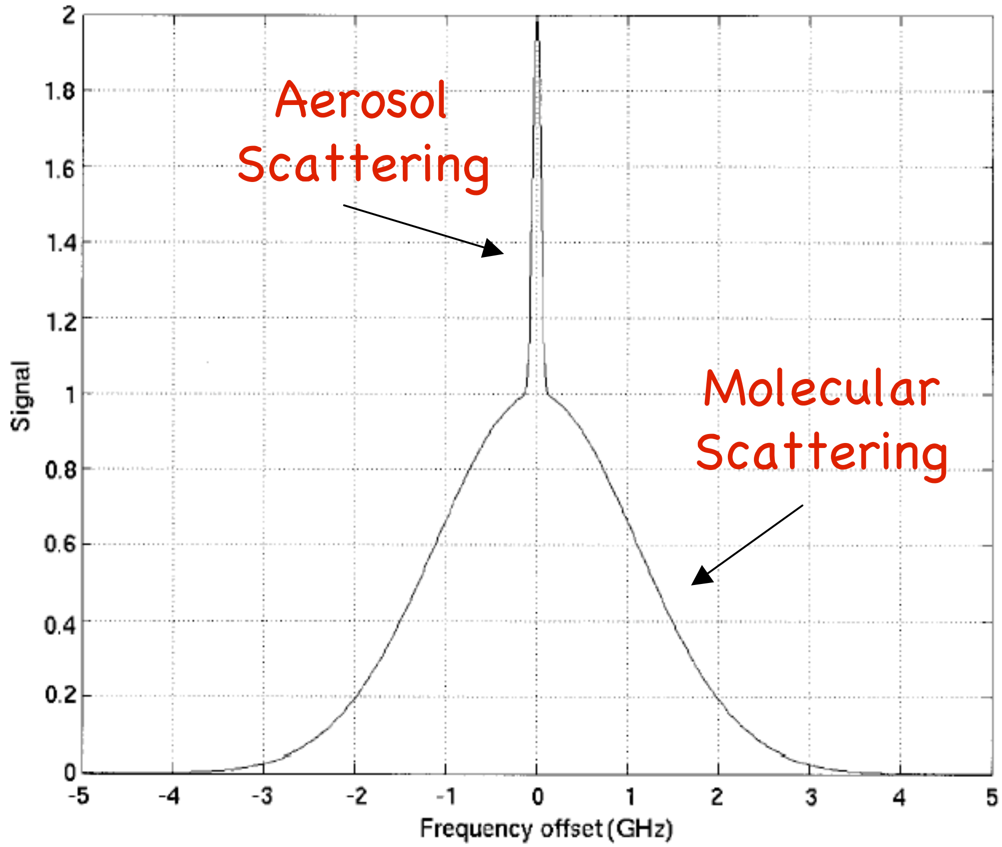
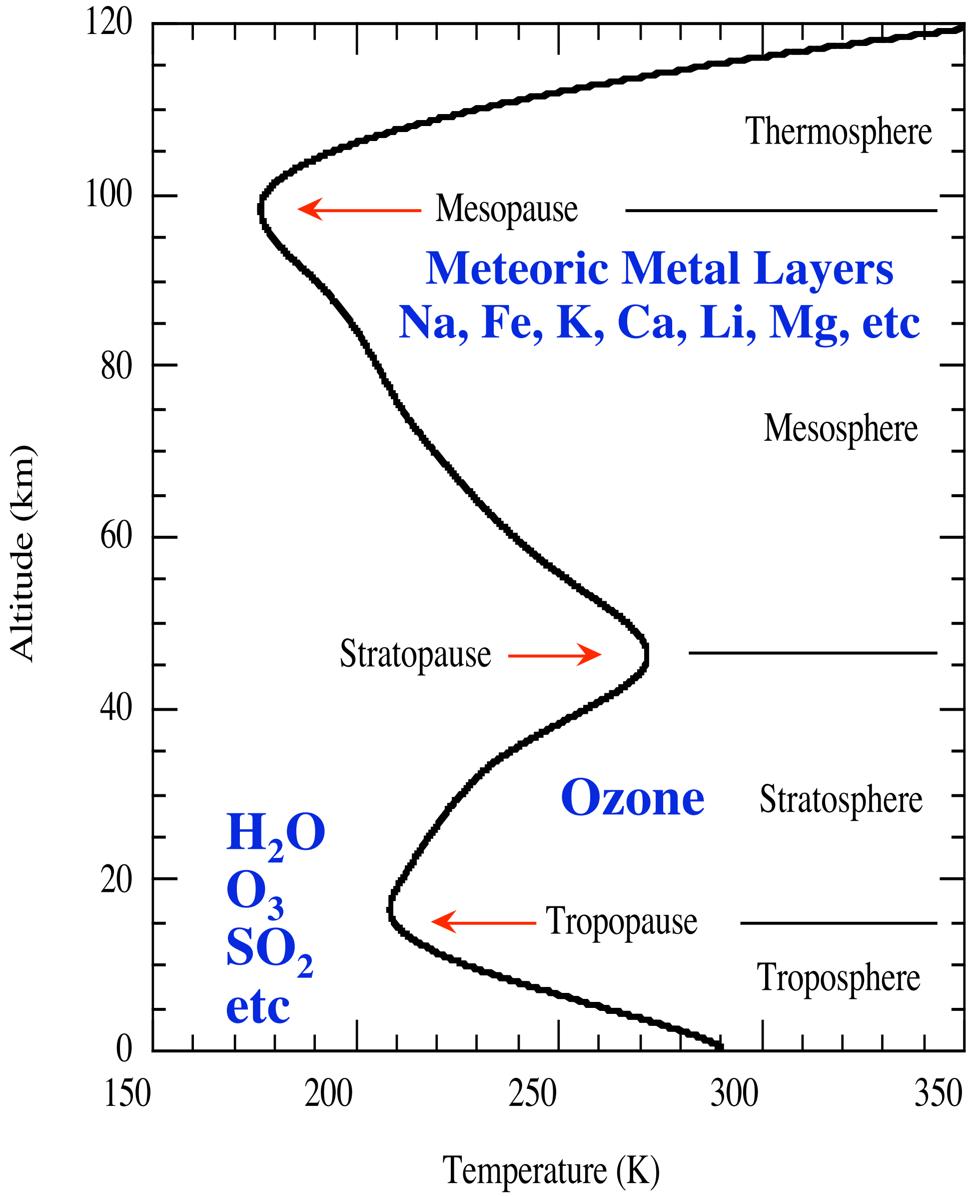


Fig. 5.1. Spectral profile of backscattering from a mixture of molecules and aerosols for a temperature of 300 K. The spectral width of the narrow aerosol return is normally determined by the line width of the transmitting laser.

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

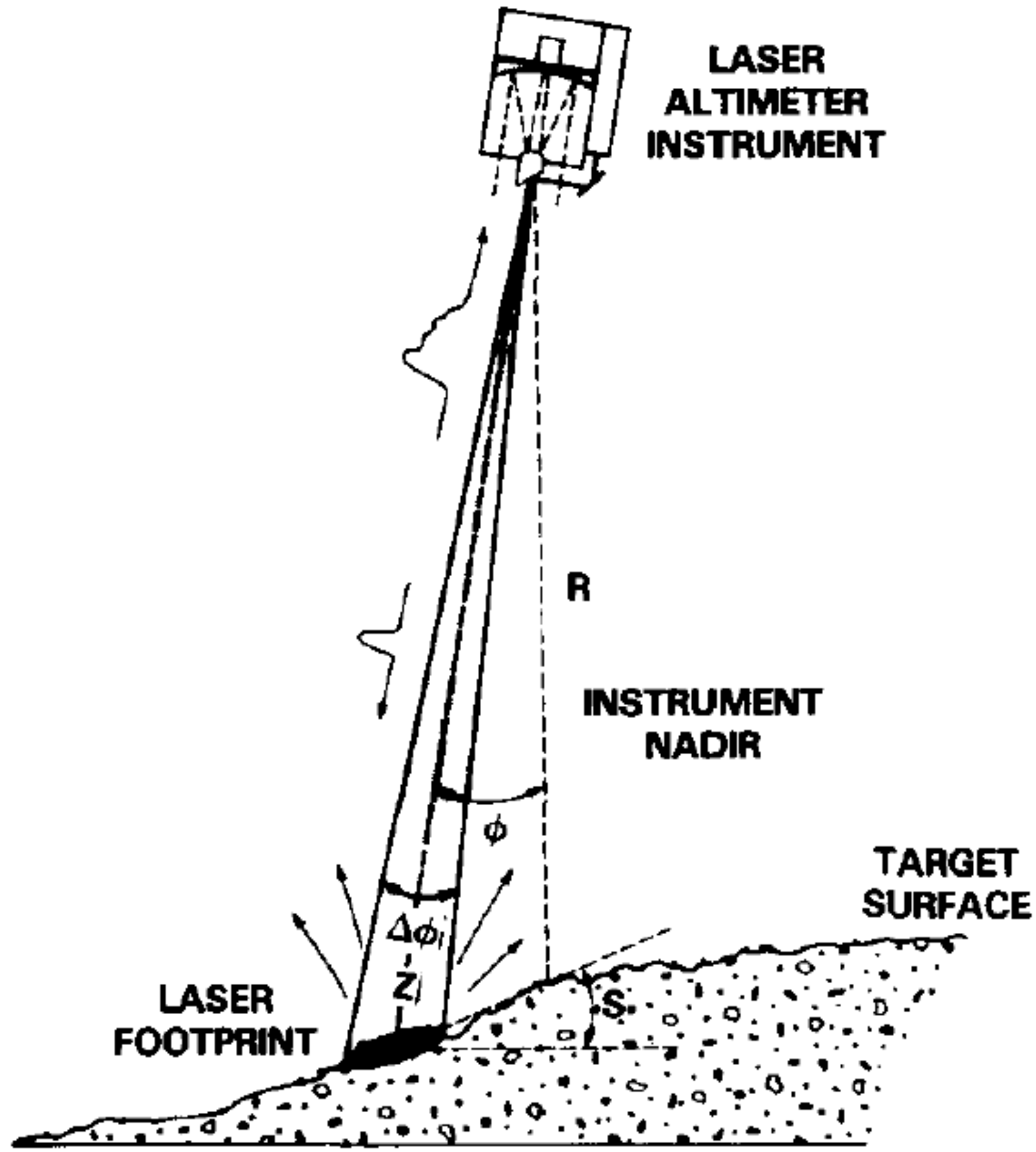
Technique	Signal Source & Trace Gas		Interests
Resonance Fluorescence Lidar	Resonance fluorescence from metal atoms in middle and upper atmosphere		Temp, Wind, Density, Wave
Resonance Fluorescence Lidar	Resonance fluorescence from He, N_2^+, O in thermosphere		Density, Temp Wind, etc
Conventional DIAL	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)

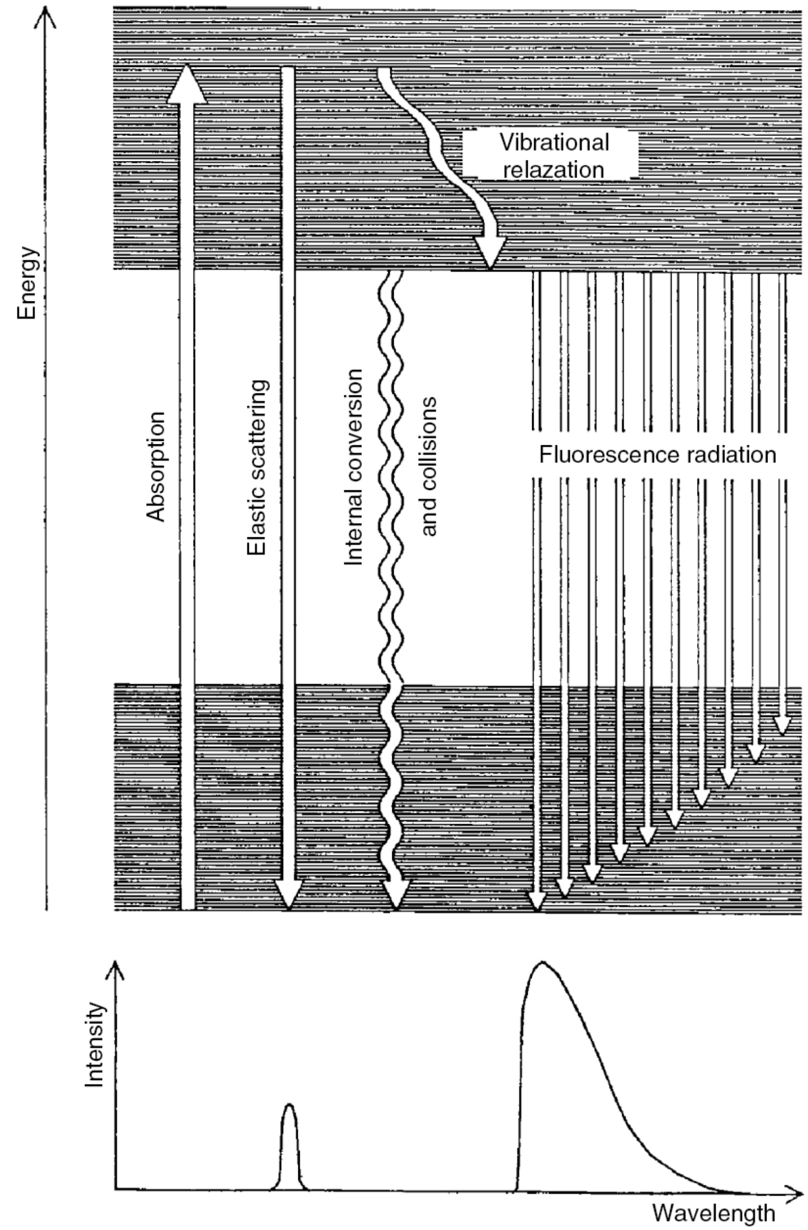
- The time-of-flight information from a lidar system can be used for laser altimetry from airborne or spaceborne platforms to measure the heights of surfaces with high resolution and accuracy.

- 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 of Target Lidar

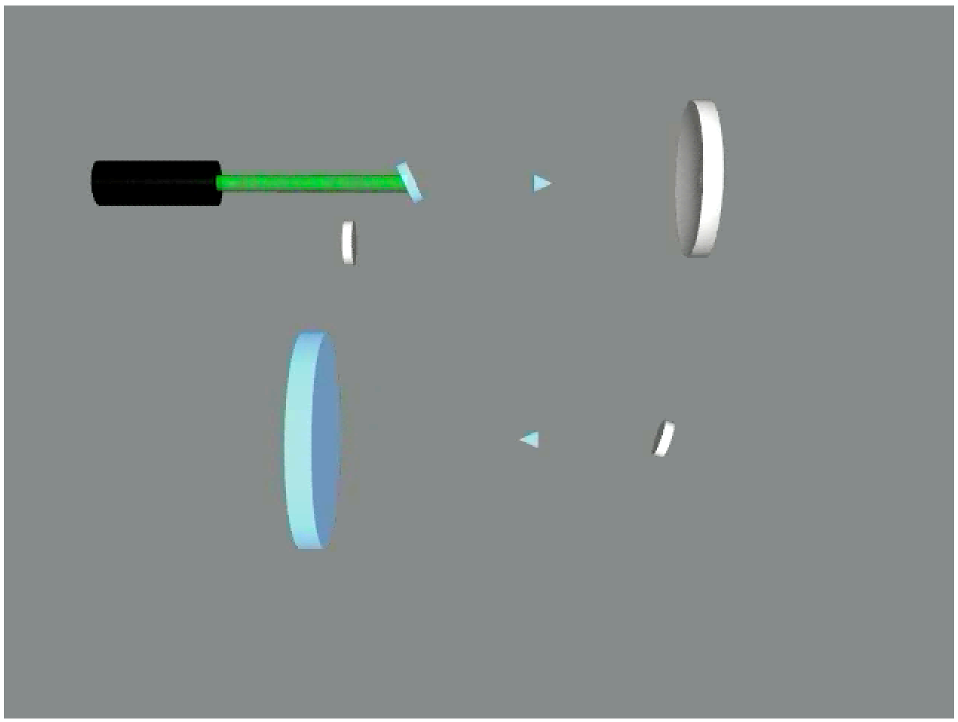
- Target lidars, including laser altimeter, hydrosphere lidar, fluorescence lidar, ladar, fish lidar, vibration detection lidar, etc, are an variant of atmospheric lidars. They share some of the same techniques used in atmospheric lidars.
- Laser altimeter and ladar use time-of-flight to determine the range of objects or surface. Many factors are involved.
- Fluorescence is used to measure organic materials, plants.
- Raman scattering by water is used to normalize the lidar returns.
- Target lidars face some different challenges and difficulties than atmospheric lidars. These challenges and difficulties also determines the growing points in this field.
- Target lidars have been deployed on different platforms for various applications. More efficient and compact target lidars on platforms like UAV, promise more applications.

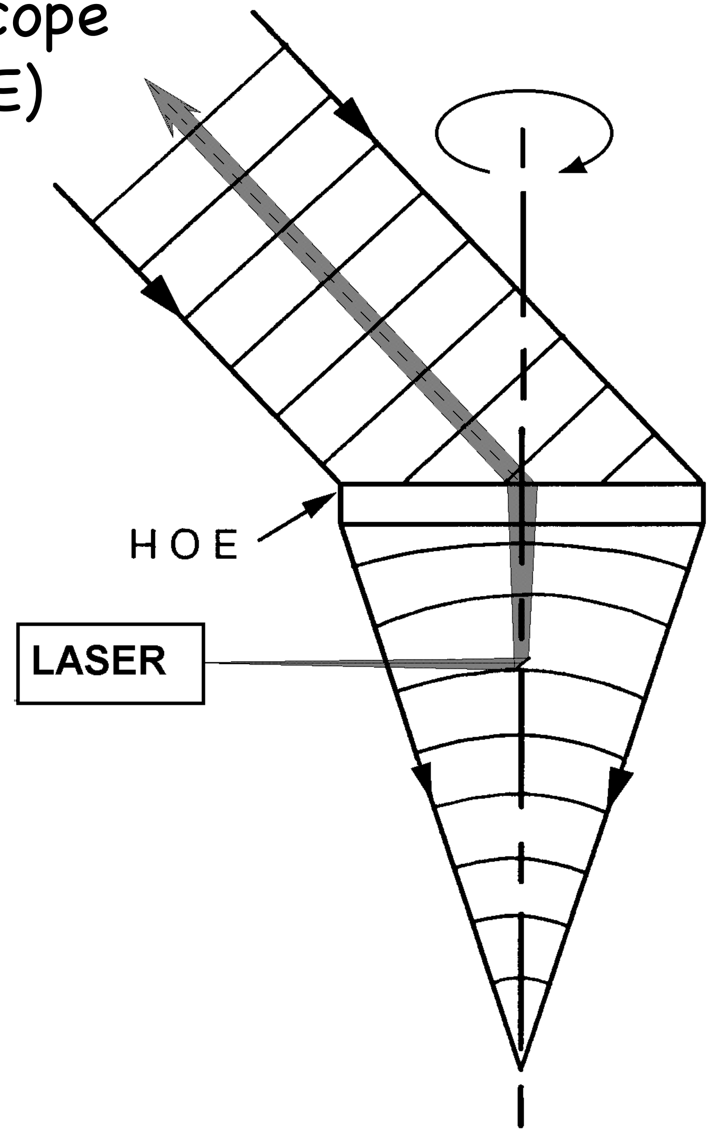
Lidar Classifications on Challenge

Middle and Upper Atmosphere Lidar	Long range - weak signal Accurate knowledge about atoms Accurate knowledge of transmitter Accurate knowledge of receiver Demanding requirements on lasers
Lower Atmosphere Lidar	Many factors involved together Aerosols play a key role, also add the difficulty to lower atmosphere
Target lidar	Precise determination of altitude is a great challenge, as many factors are involved.

Novel Lidar Technology

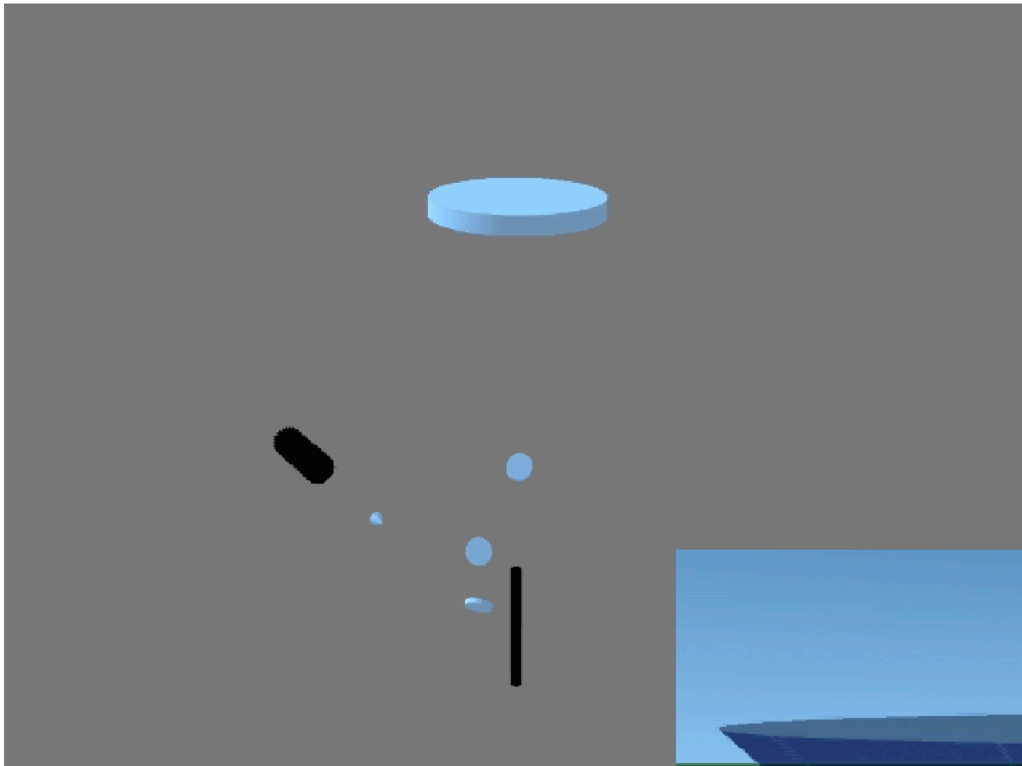
Holographic Conical Scanning Telescope
Holographic Optical Element (HOE)

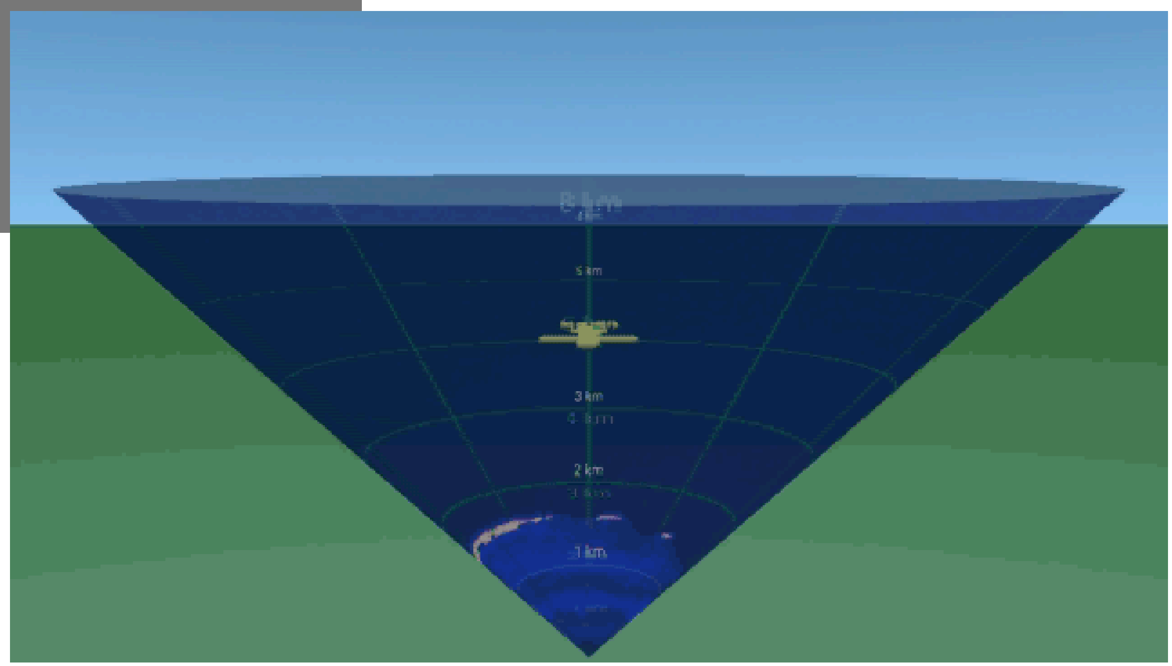




Courtesy of Geary Schwemmer

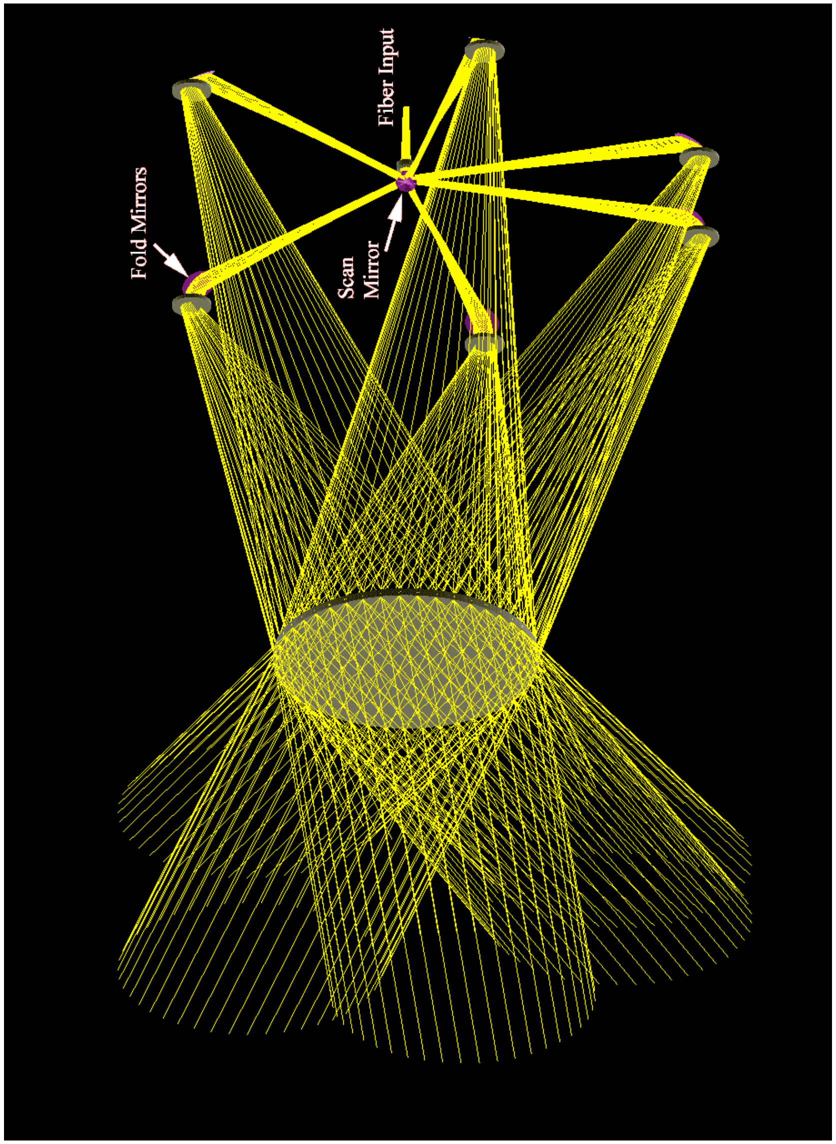
Lidar with Holographic Scanner





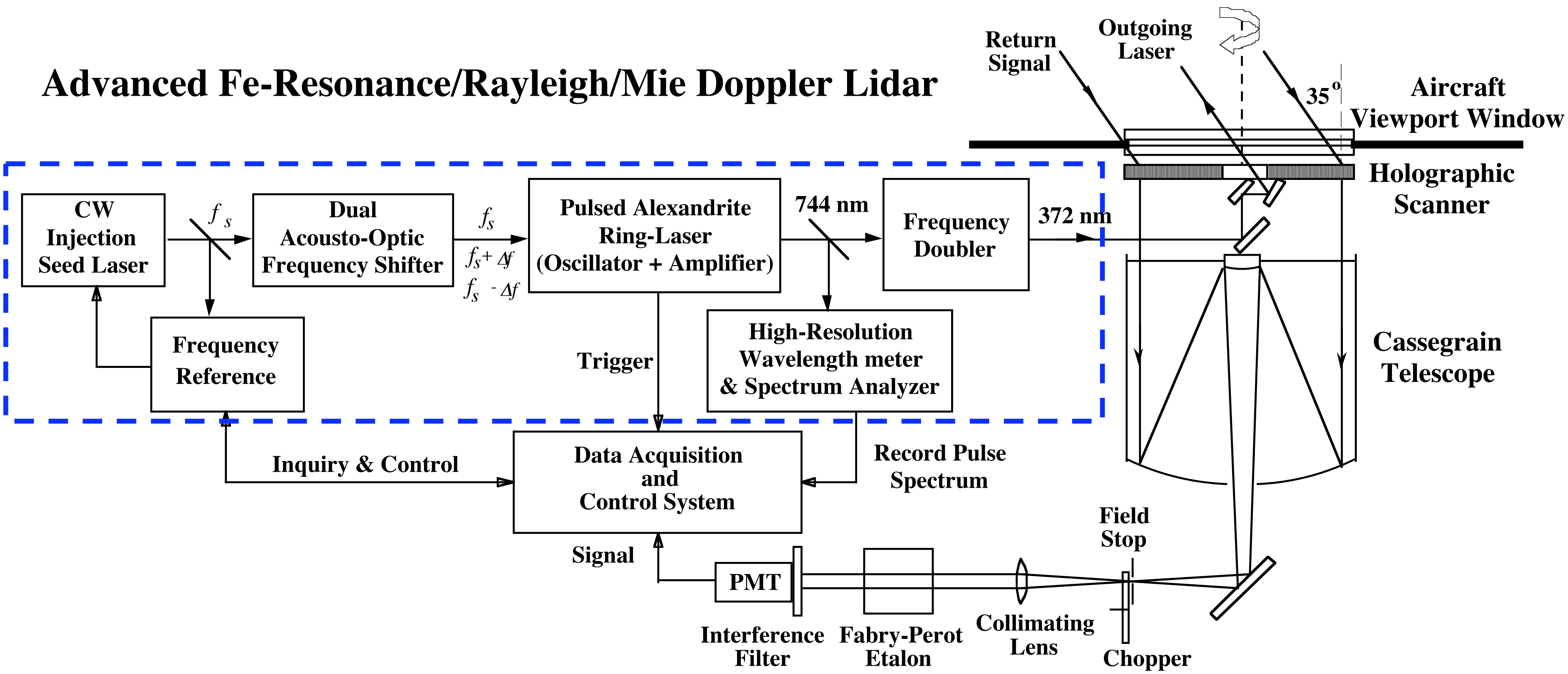
Courtesy of
Geary Schwemmer

Angle multiplexed HOEs

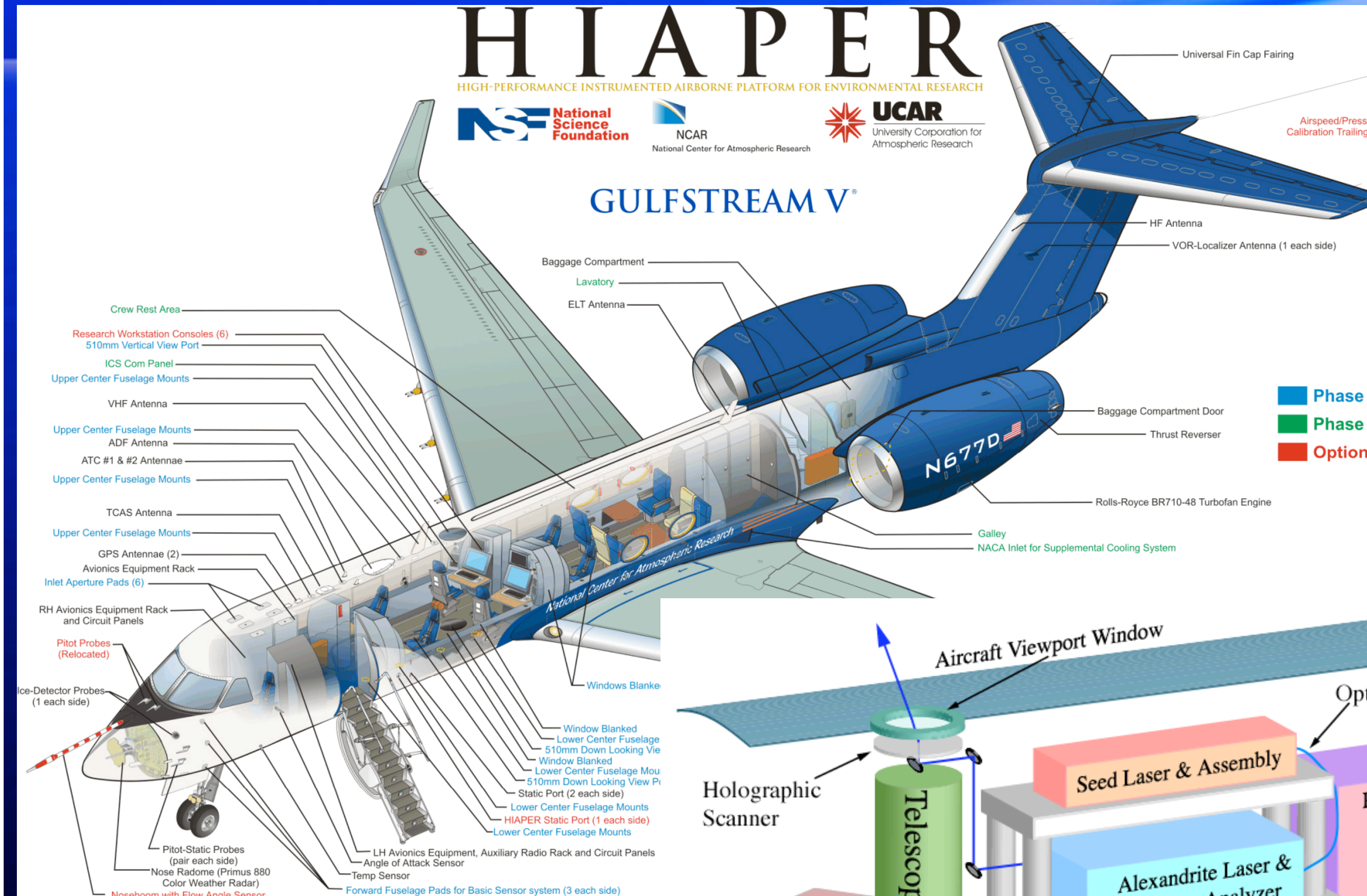


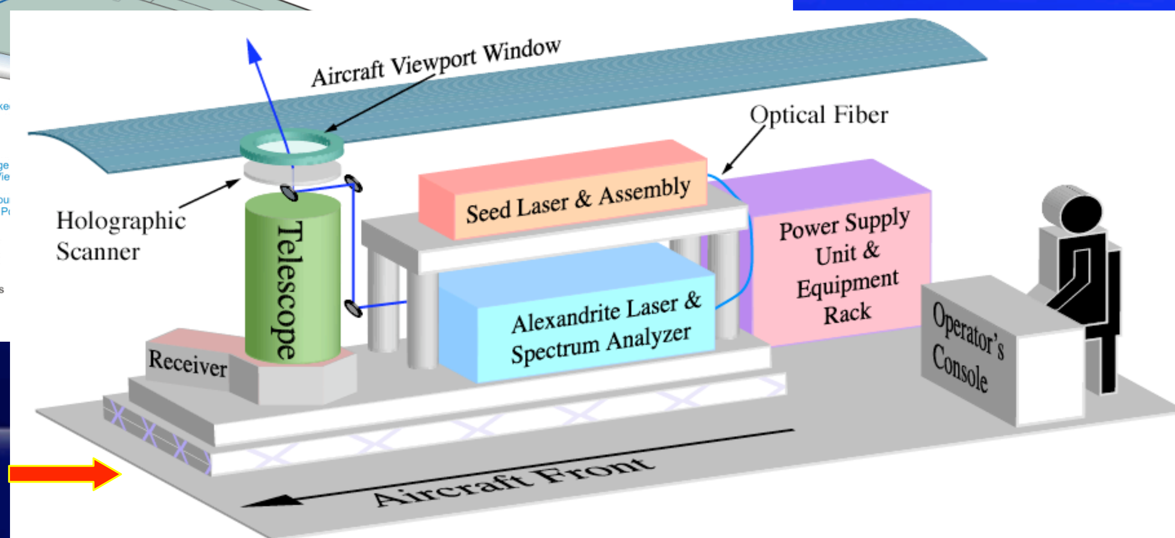
**Courtesy of
Geary Schwemmer**

Future LIDAR: Mobile Fe Doppler Lidar



High-performance Instrumented Airborne Platform for Environmental Research (HIAPER)





Proposed Doppler Lidar

Outlook for Lidar Remote Sensing

- Laser remote sensing (LIDAR) is an advanced technology that is not only replacing conventional sensors in science study, environmental research, and industry application, but also creating new methods with unique properties that could not be achieved before.
- Lidar technology has been advanced dramatically in the past 20 years, owing to the new availability of lasers, detectors, creative people involved, and the demanding needs from various aspects.
- Potential growing points at this stage include

(1) Solid-state resonance fluorescence lidar for mobile deployment globally

(2) Extend measurement range into thermosphere and lower mesosphere

(3) Doppler, DIAL, HSRL, and Raman lidar for lower atmosphere research

(4) Target lidar for novel applications

- Always keep eyes open for new potentials: principles, phenomena, effects to be applied in lidar and optical remote sensing.
- The exciting and growing lidar field is anxious for new "blood" - the creative, intelligent, diligent, and passionate young researchers.