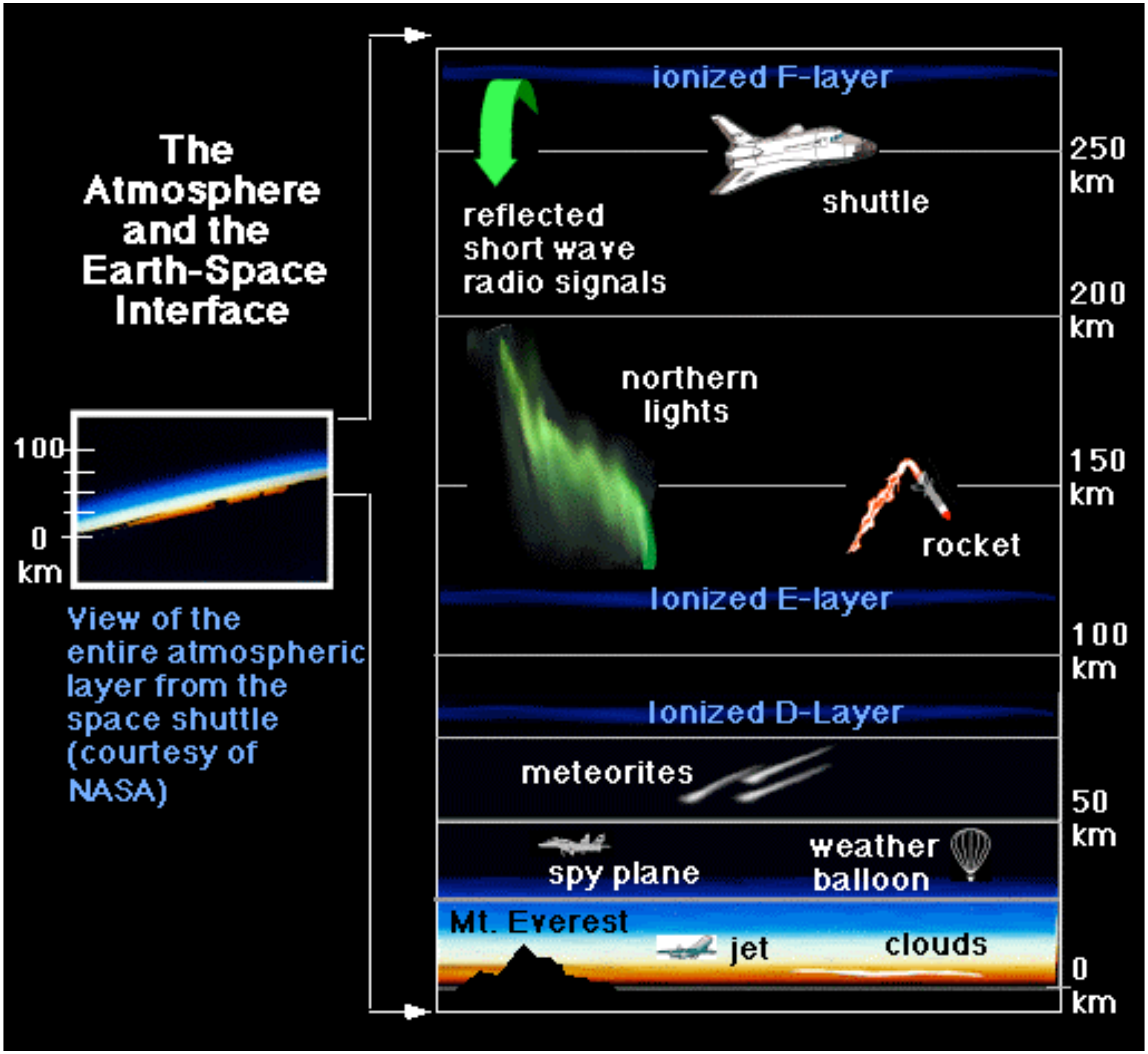
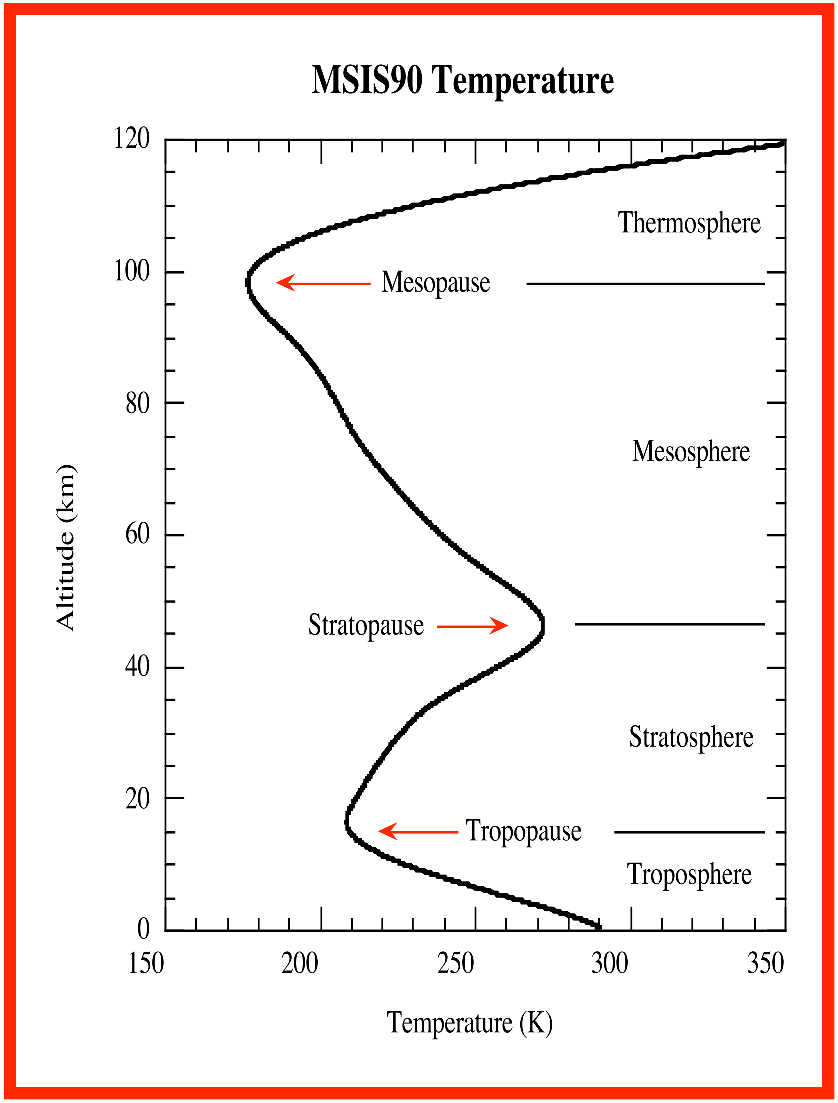
Lecture 2
Laser Remote Sensing Overview

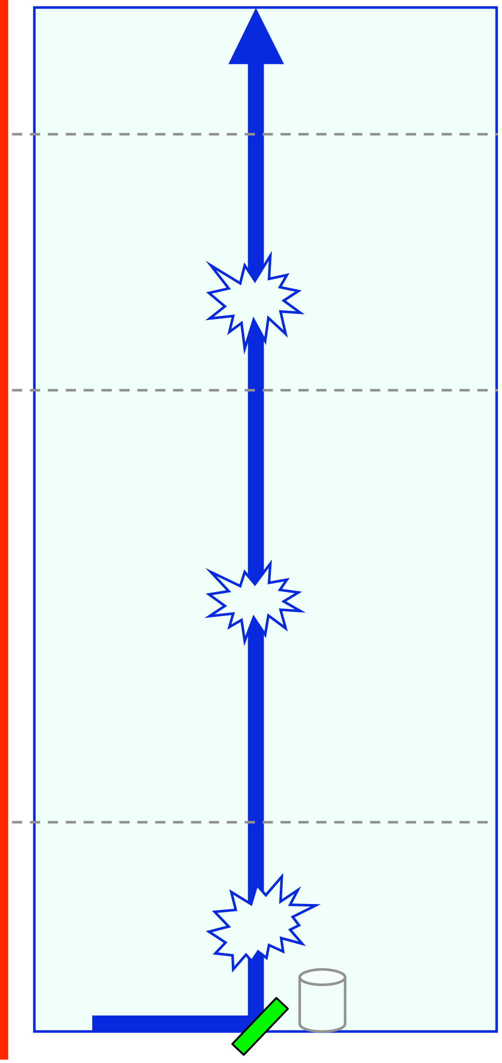
- History from searchlight to modern lidar
- Basic lidar architecture
- Basic lidar equation
- Classifications of lidars
- Summary

Earth Atmosphere and Space



Light Detection And Ranging (LIDAR)





Resonant Fluorescence From Metal Atoms

Rayleigh Scattering From Air Molecules

Mie Scattering From Aerosols

Range Determined From Time-of-Flight: $R = c \cdot \Delta t / 2$

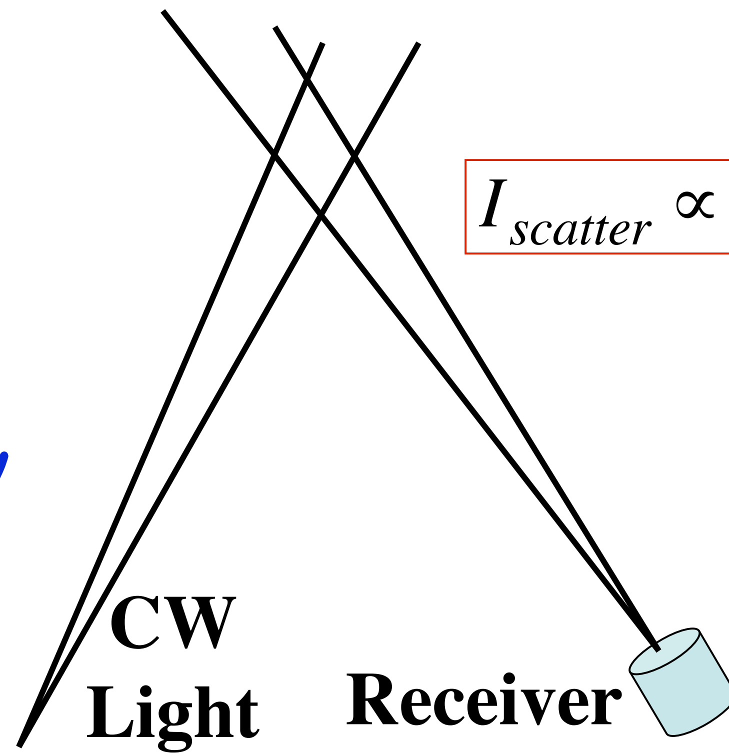
History: Searchlight → Modern Lidar

❑ Light Detection and Ranging (LIDAR) actually started with using the CW searchlights to measure stratospheric aerosols and molecular density in 1930s, well before the first (ruby) laser was invented in 1960.

Atmospheric aerosol and density measurements using searchlight tech.

Scattering light intensity is proportional to the atmosphere density in the aerosol free region

$$I_{scatter} \propto n_{atmos}$$



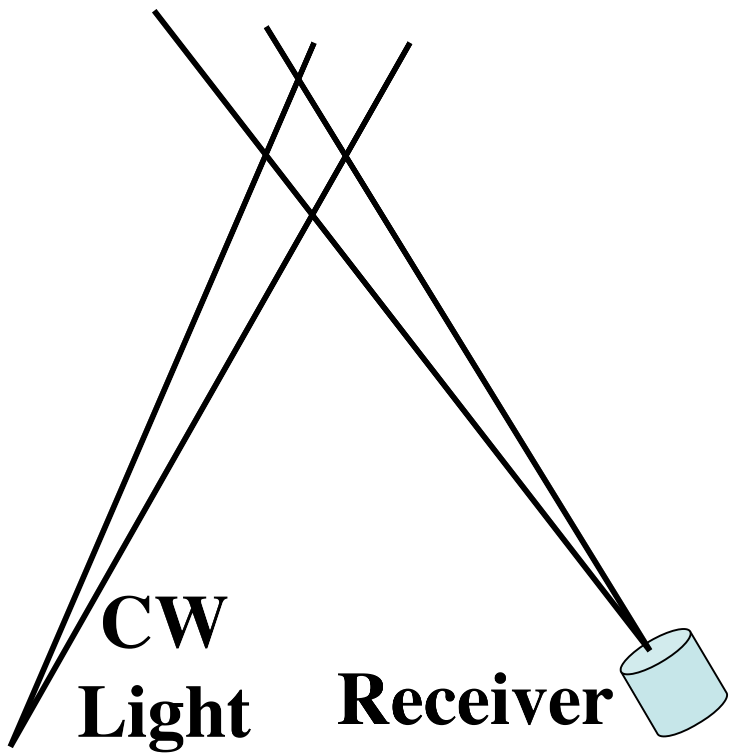
History: Searchlight

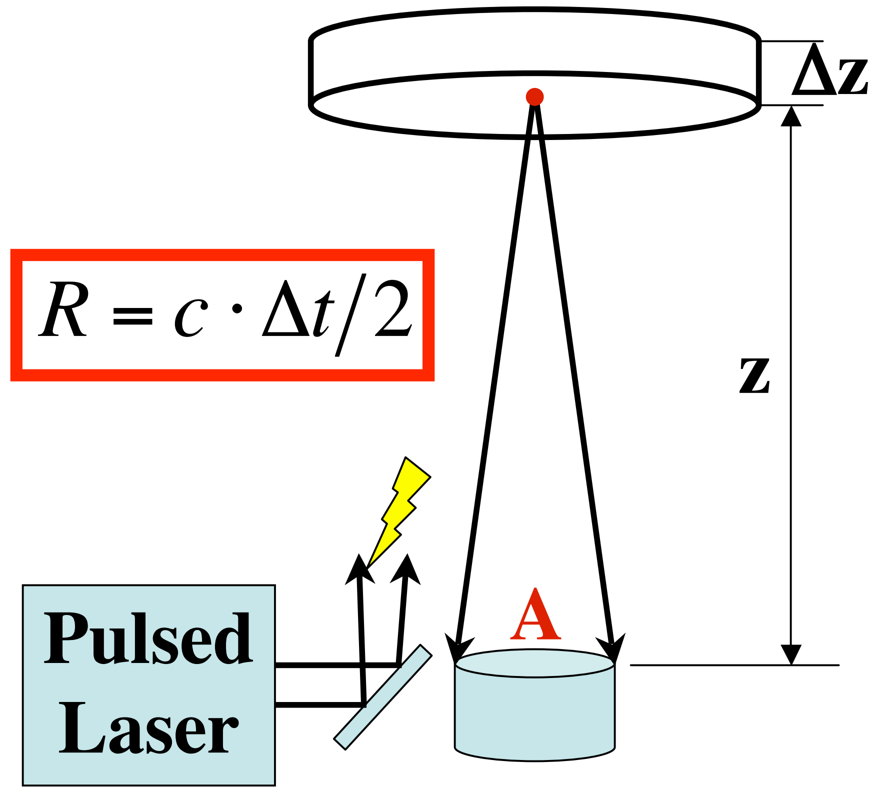
- Hulburt [1937] pioneered the aerosol measurements using the searchlight technique, who photographed the searchlight beam to 10 km.

- Johnson [1939] followed a proposal of Tuve et al. [1935] and modulated the searchlight beam with a mechanical shutter rotating at 10 cycles per second. Scattering to a height of 34 km was measured with good agreement between theory and experiment above 8 km.

- Elterman [1951, 1954, 1966] pushed the atmospheric study using searchlight to a high level and made practical devices.

Searchlight ➔ Laser Remote Sensing





Bistatic Configuration **Monostatic Configuration**

CW searchlight → ns laser pulse

History: Atmospheric Lidar

- The first laser - a ruby laser was invented in 1960 by Schawlow and Townes [1958] (fundamental work) and Maiman [1960] (construction).

- The first giant-pulse technique (Q-Switch) was invented by McClung and Hellwarth [1962].

- The first laser studies of the atmosphere were undertaken by Fiocco and Smullin [1963] for upper region and by Ligda [1963] for troposphere.

- Following this, great strides were made both in the development of lidar technologies/systems, and in the sophistication of their application.

Atmospheric Lidar

- The first application of laser radar was the detection of atmospheric aerosols and density. Basically, it is to know whether there are aerosols/density in the regions and how much. However, the composition of atmosphere cannot be told, because only the scattering intensity was detected but nothing about the spectroscopy.

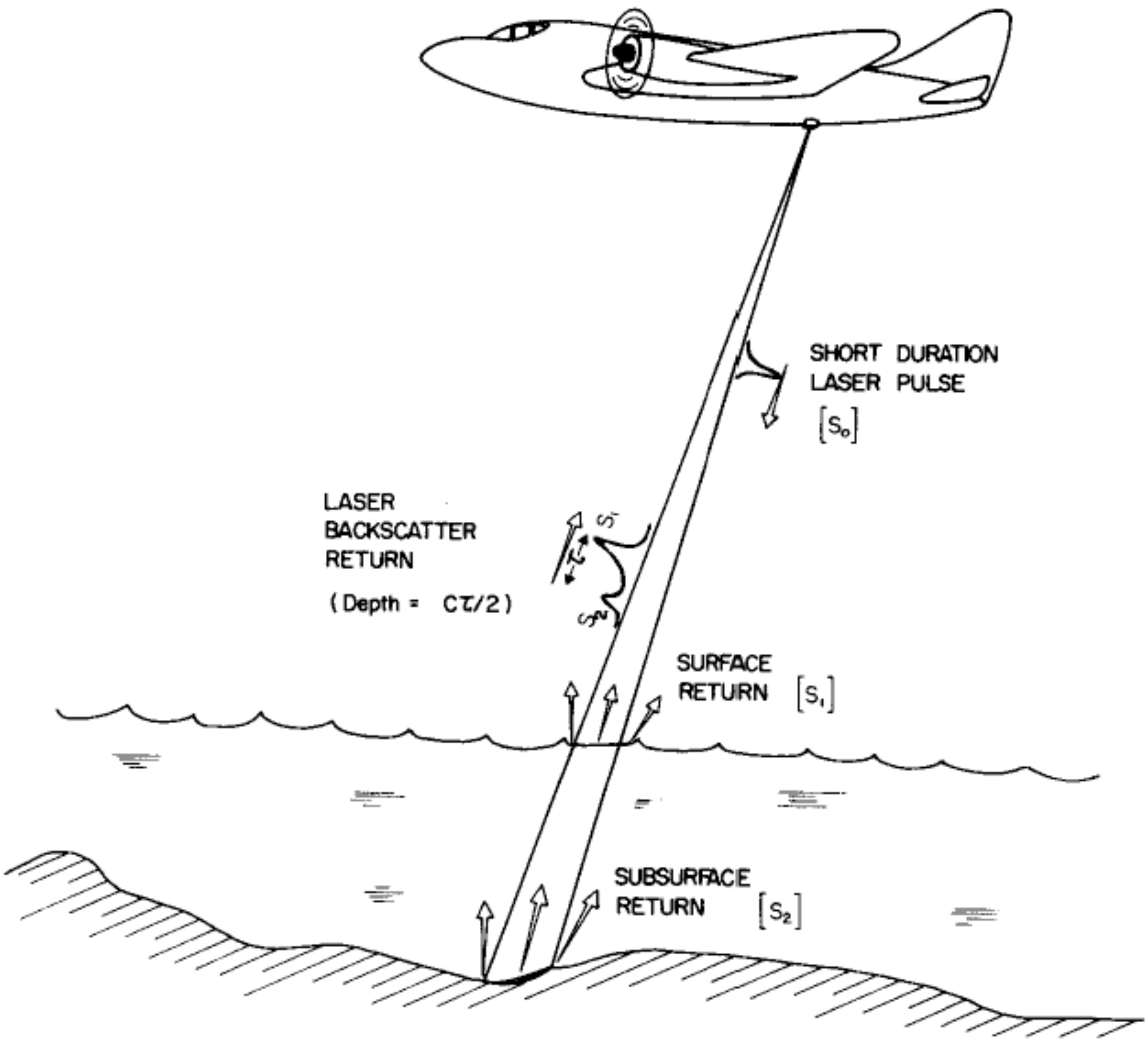
- An important advance in lidar was the recognition that the spectra of the detected radiation contained highly specific information related to the species, which could be used to determine the composition of the object region.

Atmospheric Lidar

- The broad selection of laser wavelengths became available and some lasers could be precisely tuned to specific frequencies. All these advancements enhanced the effective spectral analysis of the returned radiation from objects.

- This ability added a new dimension to remote sensing and made possible an extraordinary variety of applications, ranging from groundbased probing of the trace-constituent distribution in the tenuous outer reaches of the atmosphere, to airborne chlorophyll mapping of the oceans to establish rich fishing areas.

Hydrospheric Lidar



Hydrospheric Lidar

- Downward-pointing laser systems were operated in a mode where surface scattering and reflection represented the dominant form of interaction. Surface-wave studies and bathymetric measurements in coastal waters were the first topics to be given serious consideration. The studies of water turbidity grew naturally from latter work.

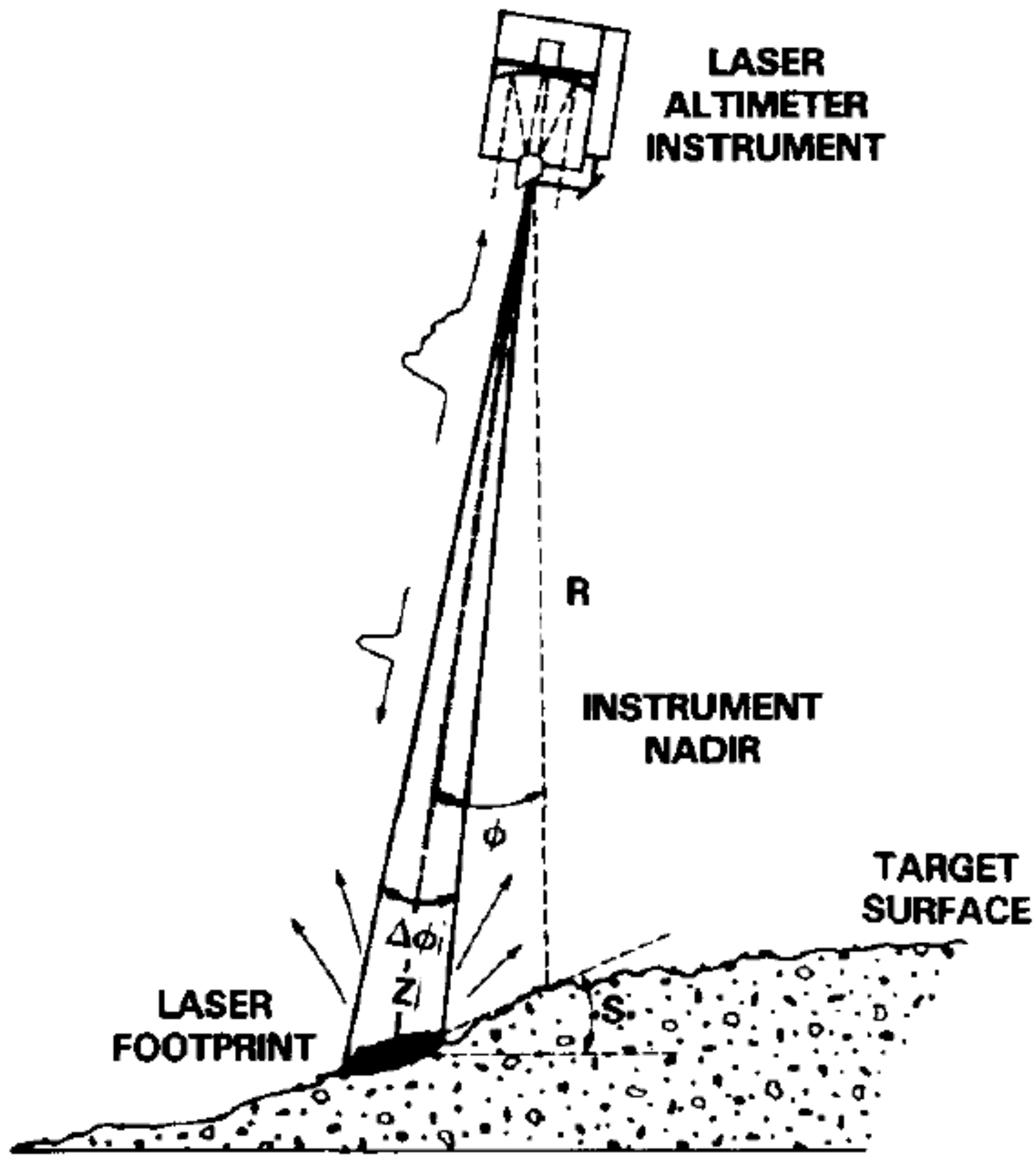
- A notable advance was made with the realization that use of a short-wavelength laser could broaden the spectrum of applications, as a result of laser-induced fluorescence, and led to the development of a new form of remote sensor "laser fluorosensor".

Hydrospheric Lidar

- The water fluorescence signal could indicate the presence of high organic contamination and enable the dispersion of various kinds of effluent plumes to be remotely mapped.

-

Solid Target lidar

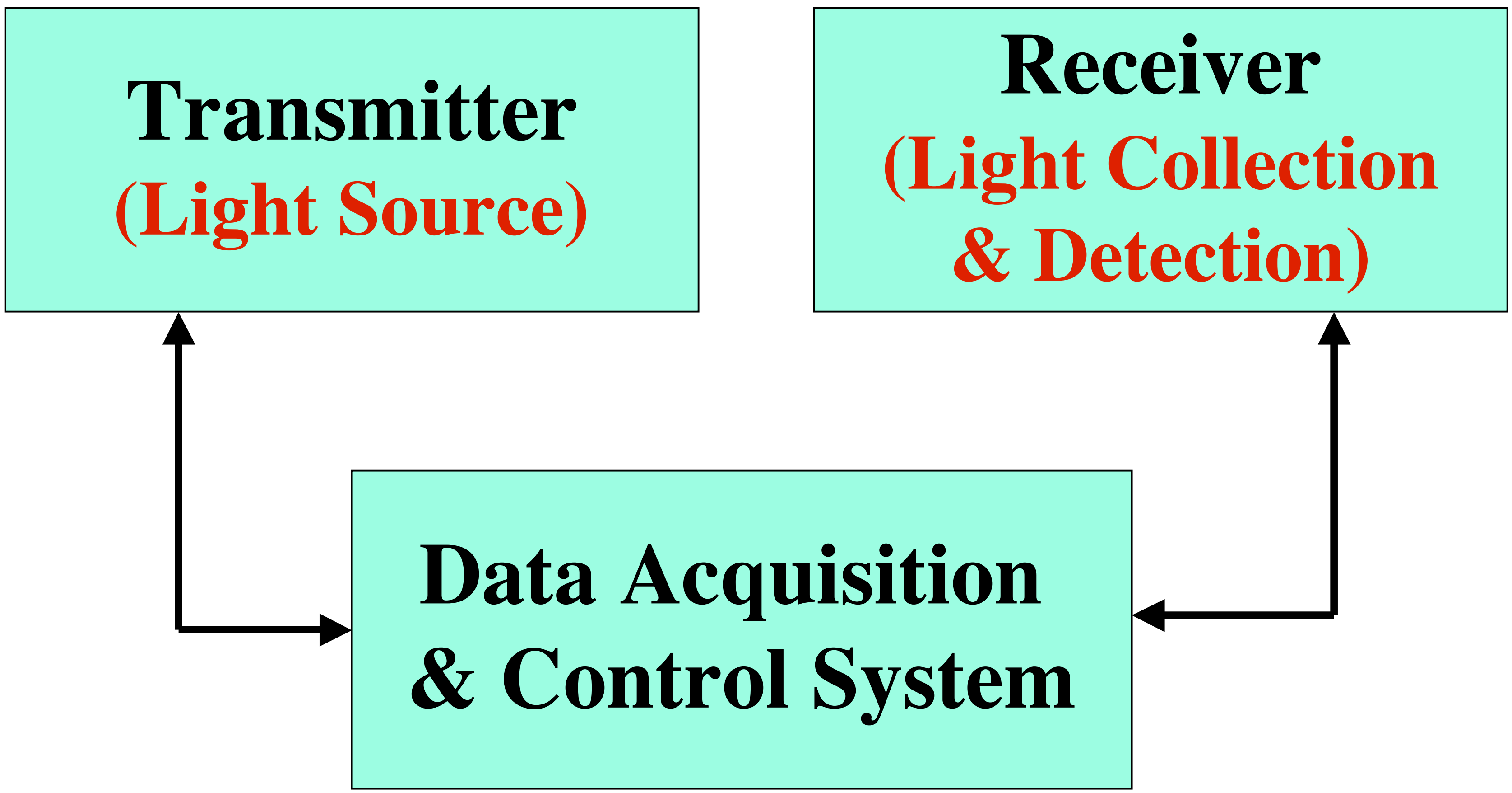


Solid Target Lidar: Laser Altimeter

- 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 with much higher resolution than the pulse duration time.

Basic Architecture of LIDAR



Function of Transmitter

- A transmitter is to provide laser pulses that meet certain requirements depending on application needs (e.g., wavelength, frequency accuracy, bandwidth, pulse duration time, pulse energy, repetition rate, divergence angle, etc).
- Usually, transmitter consists of lasers, collimating optics, diagnostic equipment, and wavelength control system.

Function of Receiver

- A receiver is to collect and detect returned photon signals while compressing background noise.
- Usually, it consists of telescopes, filters, collimating optics, photon detectors, discriminators, etc.
- The bandwidth of the filters determines whether the receiver can spectrally distinguish the returned photons.

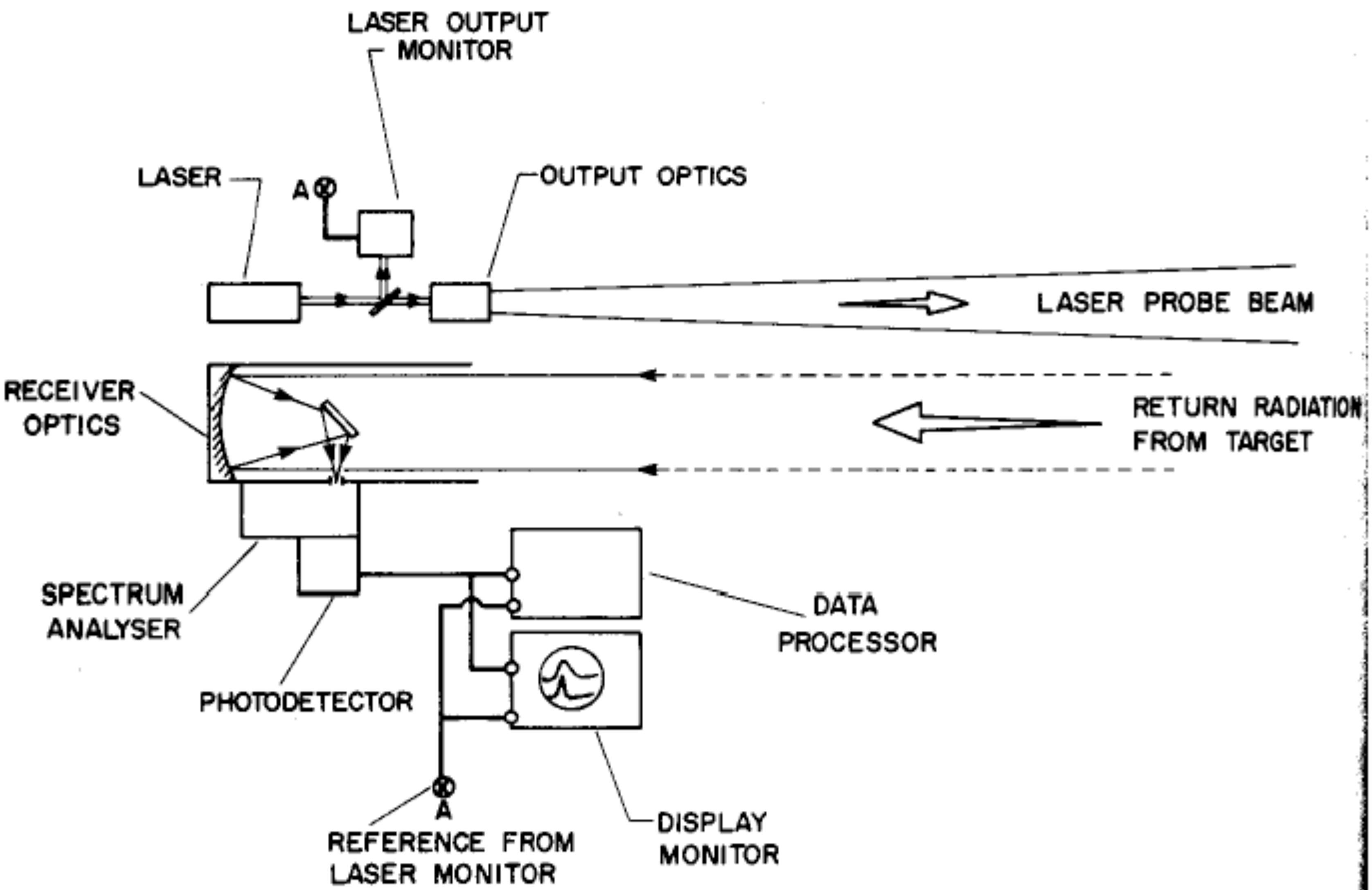
Function of Data Acquisition

- Data acquisition and control system are to record returned data and corresponding time-of-flight, provide system control and coordination to transmitter and receiver.
- Usually, it consists of multi-channel scaler which has very precise clock so can record time precisely, discriminator, computer and software.
- This part has become more and more important to modern lidars. Recording every single pulse return has been done by some group, but still challenging to the community.

LIDAR Configurations: Bistatic vs. Monostatic

- Bistatic configuration involves a considerable separation of the transmitter and receiver to achieve spatial resolution in optical probing study.
- Monostatic configuration has the transmitter and receiver locating at the same location, so that in effect one has a single-ended system. The precise determination of range is enabled by the nanosecond pulsed lasers.
- A monostatic lidar can have either coaxial or biaxial arrangement.

Monostatic Configuration Example



Coaxial vs. Biaxial Arrangements

- In a coaxial system, the axis of the laser beam is coincident with the axis of the receiver optics.
- In the biaxial arrangement, the laser beam only enters the field of view of the receiver optics beyond some predetermined range.
- Biaxial arrangement helps avoiding near-field backscattered radiation saturating photo-detector.
- The near-field backscattering problem in a coaxial system can be overcome by either gating of the photo-detector or use of a fast shutter or chopper.

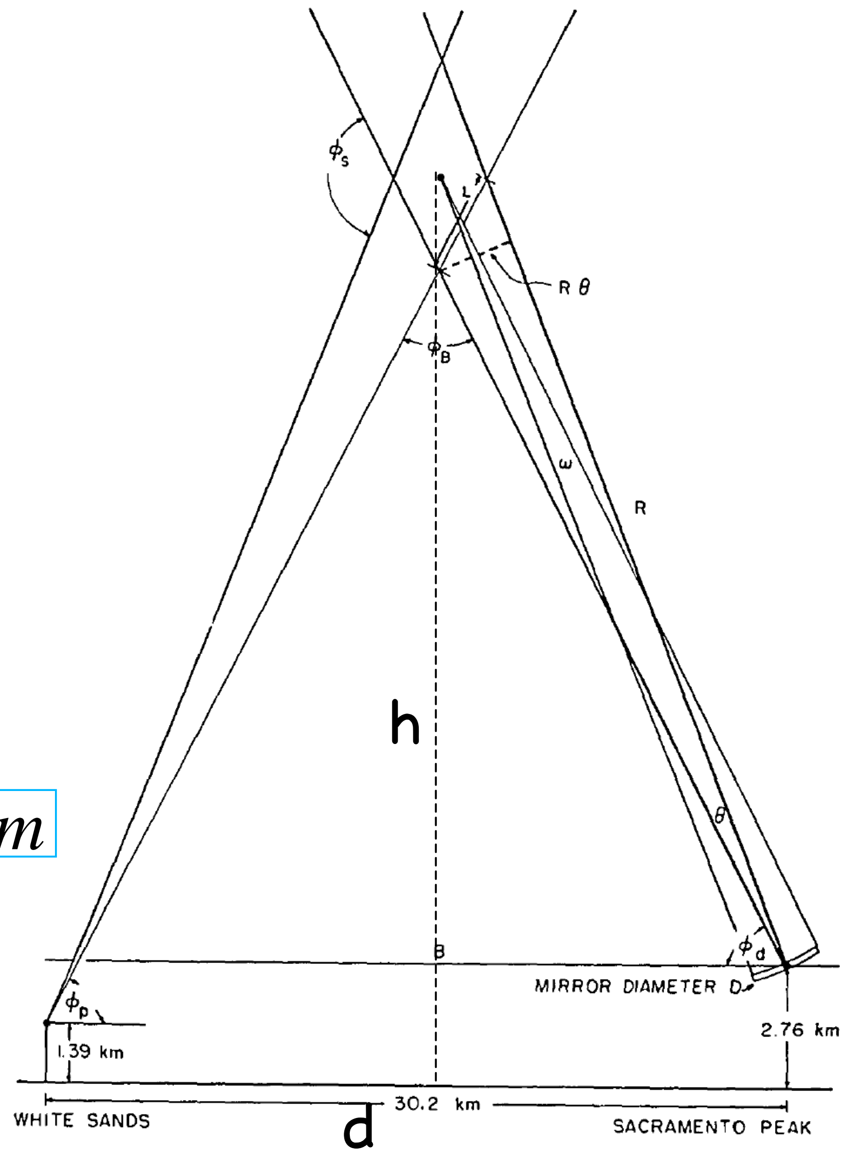
How does searchlight determine range ?

- Due to the CW light, it cannot be determined by the time-of-flight, but through the geometry calculation.
-

Searchlight

$$\theta_T = 75^\circ$$
$$\theta_R = 0^\circ - 57^\circ$$
$$H_T = 1.39km$$
$$H_R = 2.76km$$
$$d = 30.2km$$

$$h = 2.76km - 35.3km$$

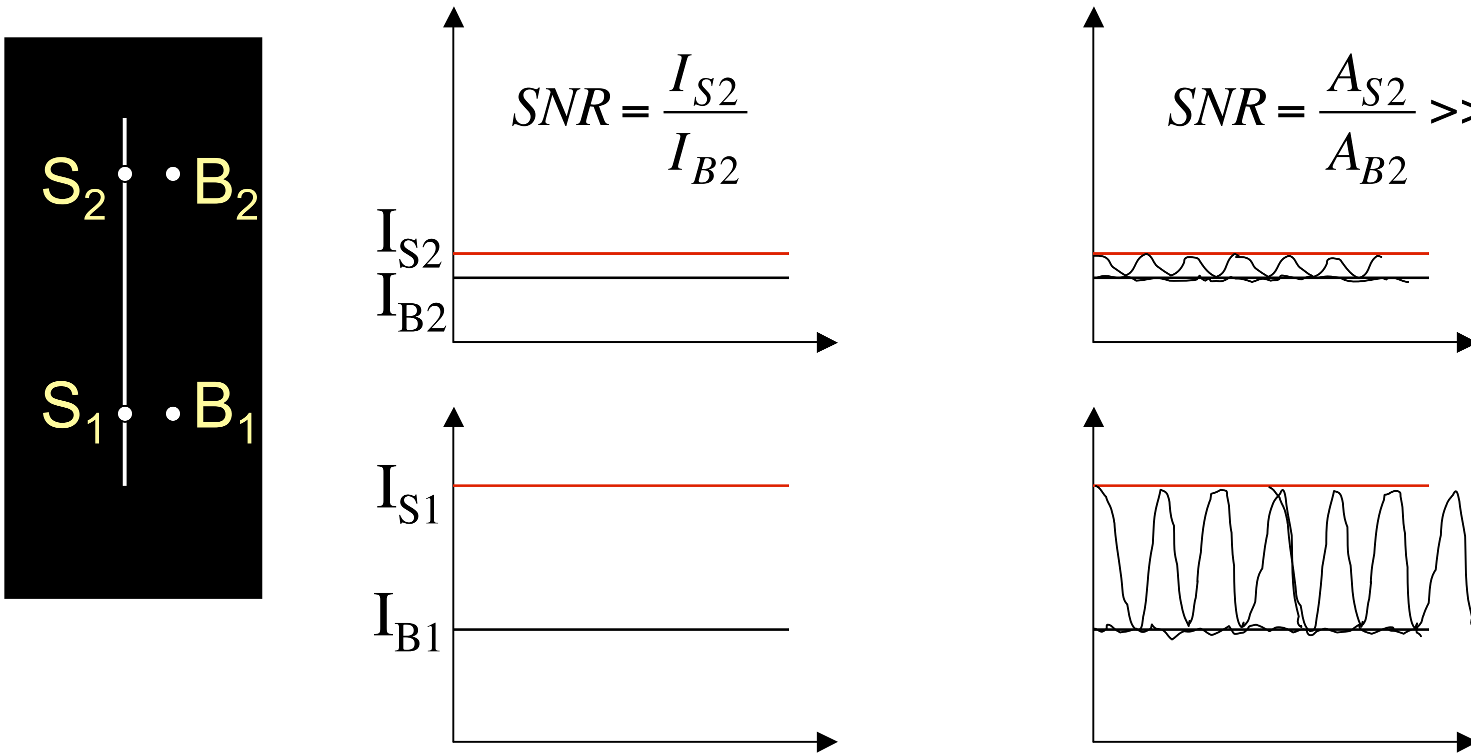


Transmitter
(Projector)
Angle fixed

Receiver
(Collector)
Angle
scanning

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

Photographing vs. Modulation
-- DC detection vs. AC detection



Although night-sky may still have quite strong background (DC), its AC component at the modulation frequency is very small, while the searchlight is much stronger at the modulation frequency. Therefore, the AC detection of modulated searchlight dramatically improves the SNR, resulting in higher detection range.

Density measured by searchlight

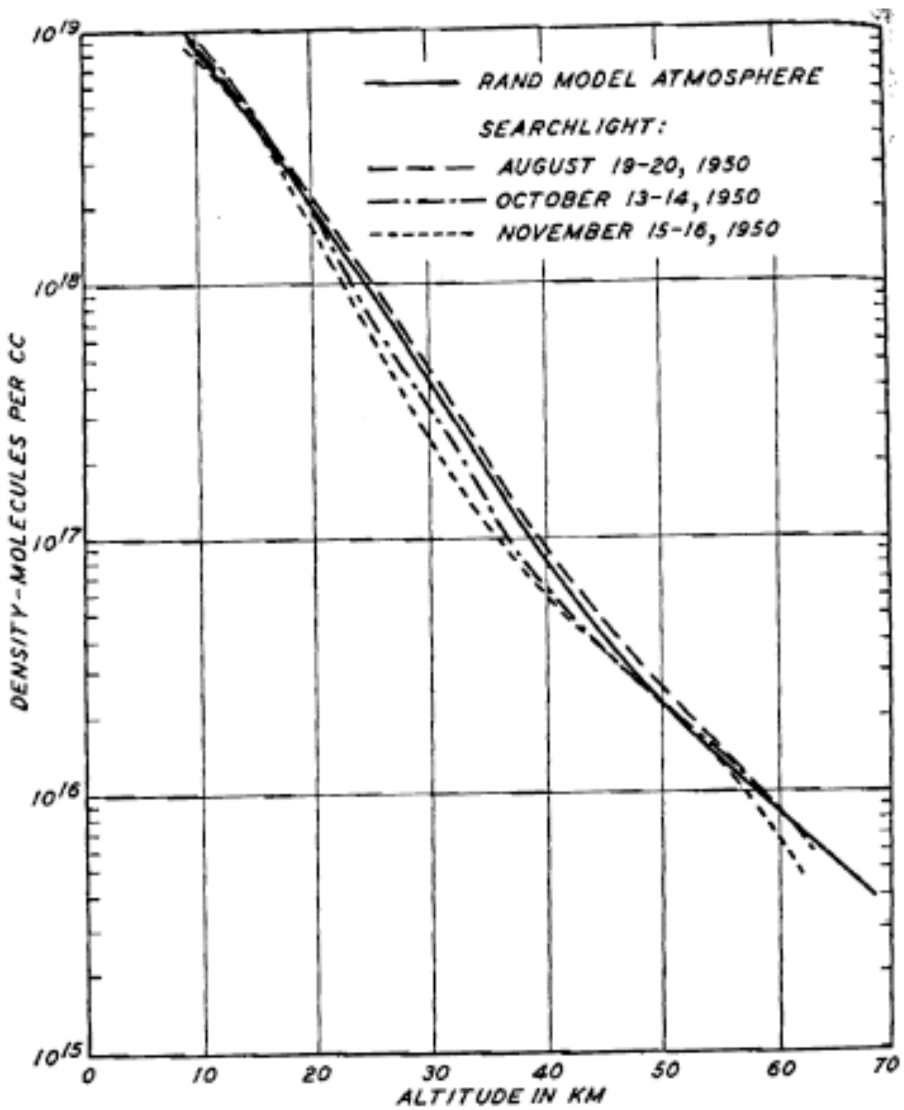
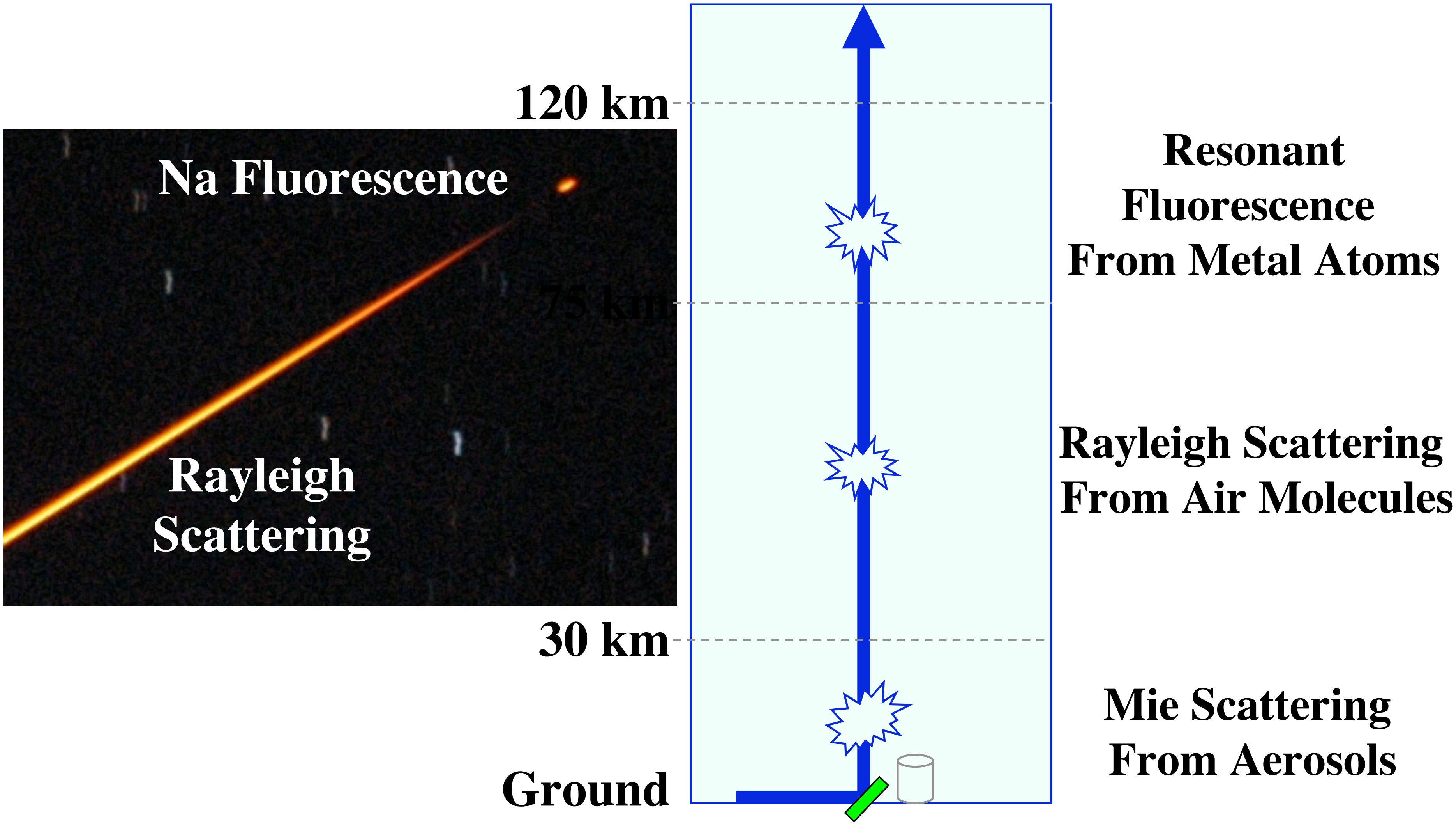


FIG. 4—DENSITY DISTRIBUTION FROM SEARCH-LIGHT DATA

How does atmospheric lidar determines range ?

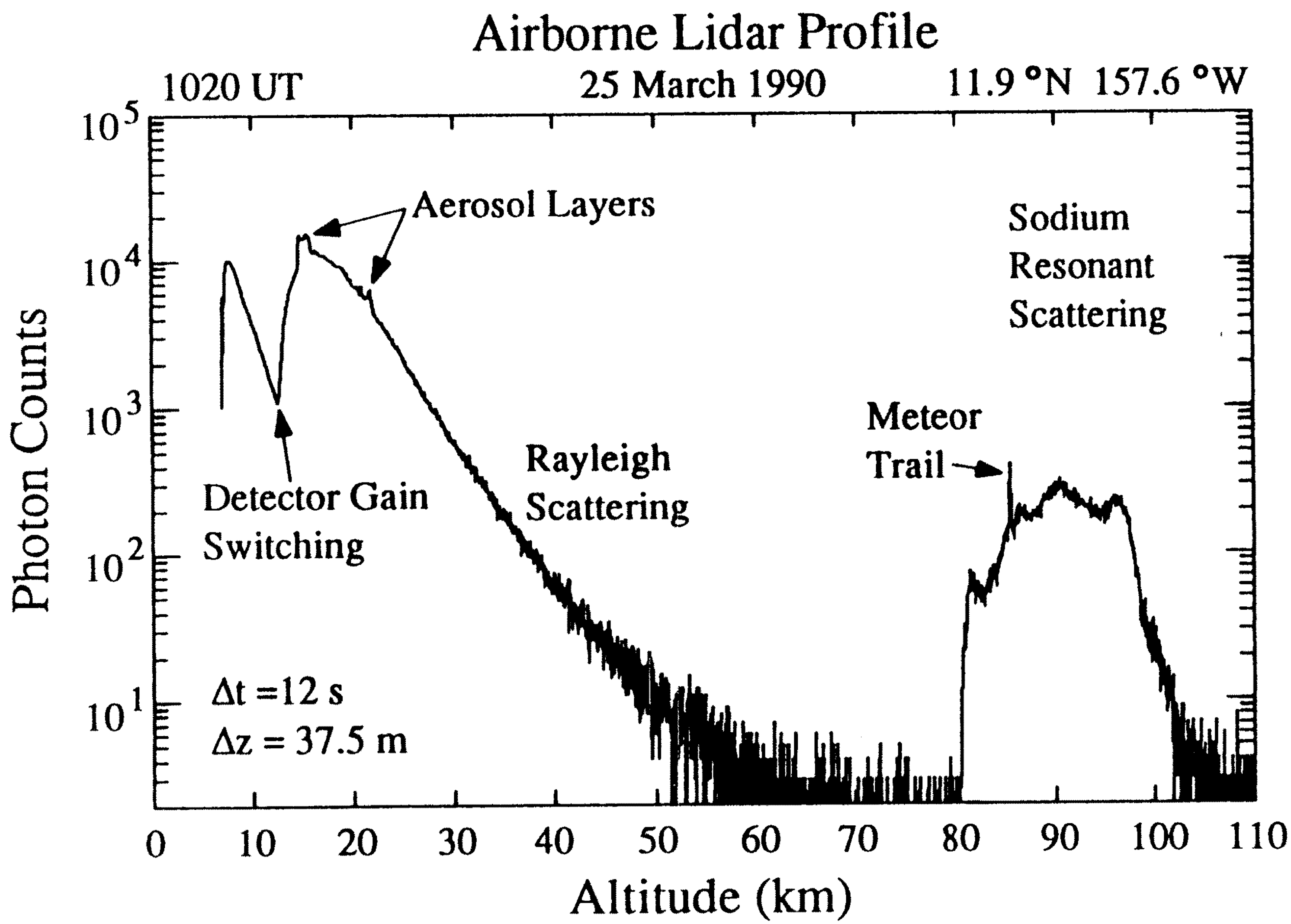
- Due to the use of nanosecond pulse lasers, the range can be determined by the time-of-flight through equation $R = C \cdot t/2$, where C is the light speed in the medium, t is the time-of-flight, and 2 for the round-trip of the photons traveled.
- The ultimate resolution of range determination is limited by the pulse duration time. For example, a 5-ns pulse gives 75 cm as the highest resolution for an atmospheric lidar where signals are continuous.
- Ultimate resolution: $\Delta R = C \Delta t/2$

Light Detection And Ranging (LIDAR)



Range Determined From Time-of-Flight: $R = c \cdot \Delta t / 2$

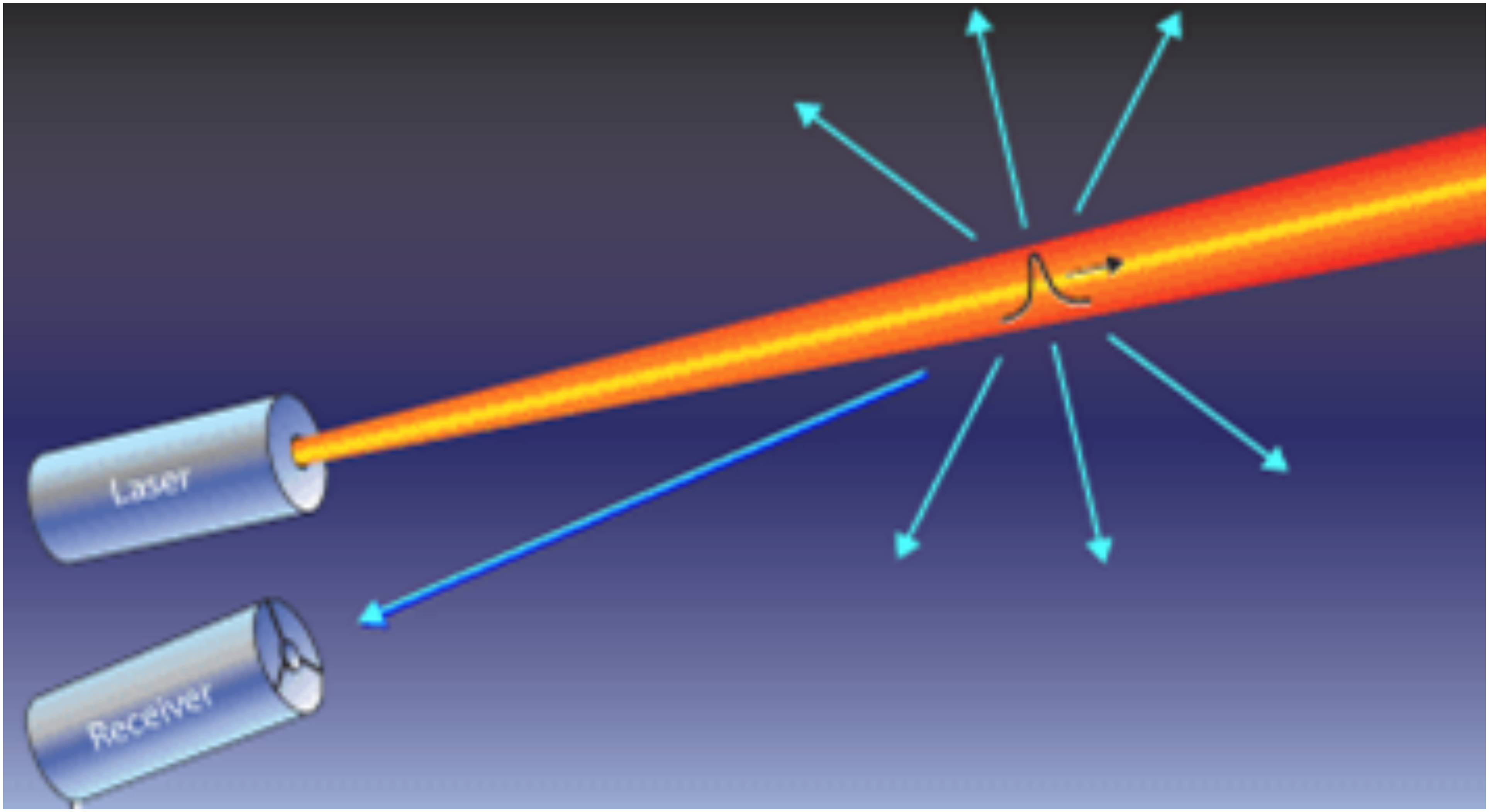
Typical LIDAR Profile



How does solid target lidar determines range more precisely ?

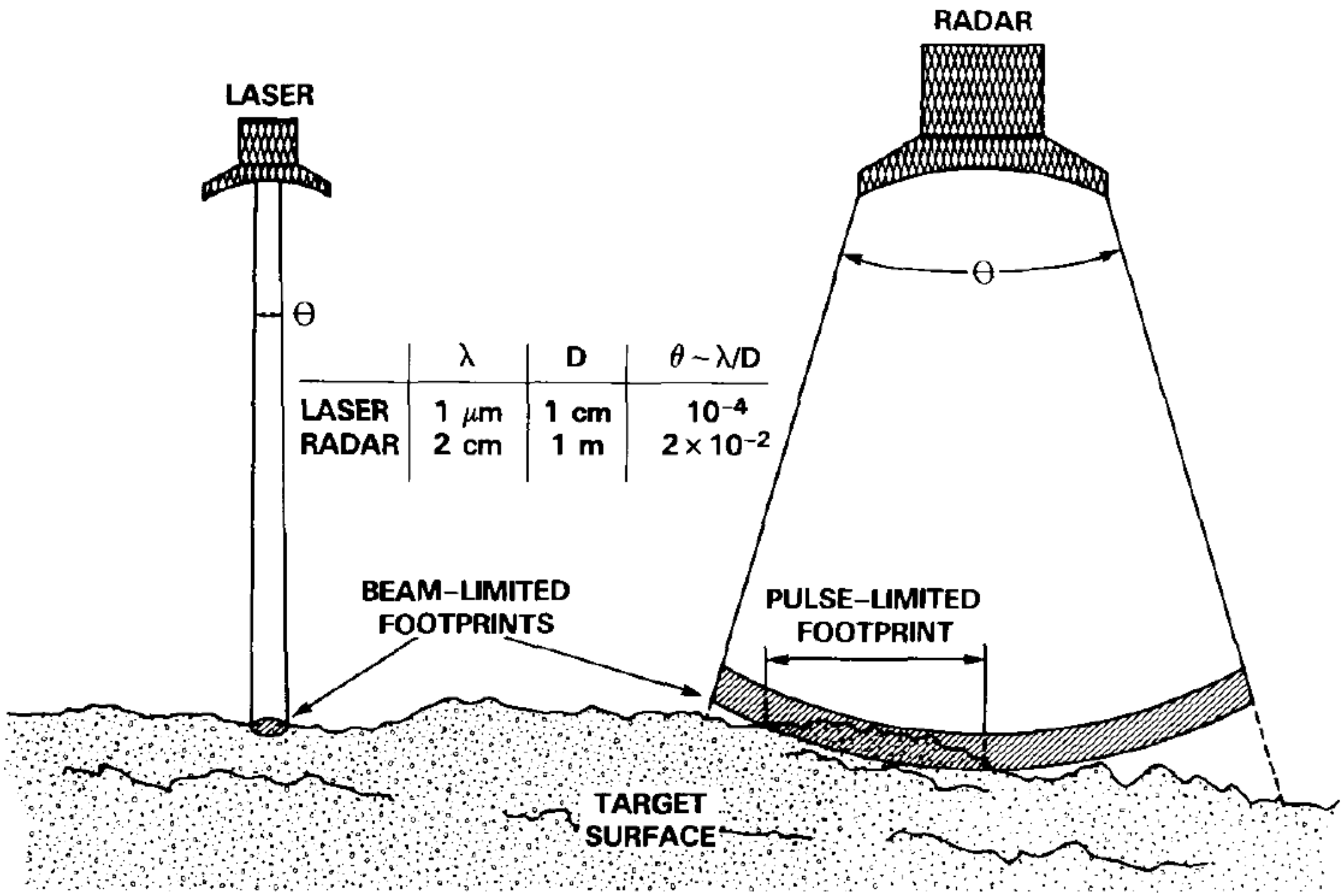
- Distinct peak coming from the reflection of surfaces allows a more precise measurement of the time-of-flight through rising edge or peak comparison, thus enabling higher resolution than the pulse duration limitation.
- For example, a laser altimeter using 5-ns pulse duration can have better than 5 cm resolution and accuracy.

Laser Altimeter and Ranging



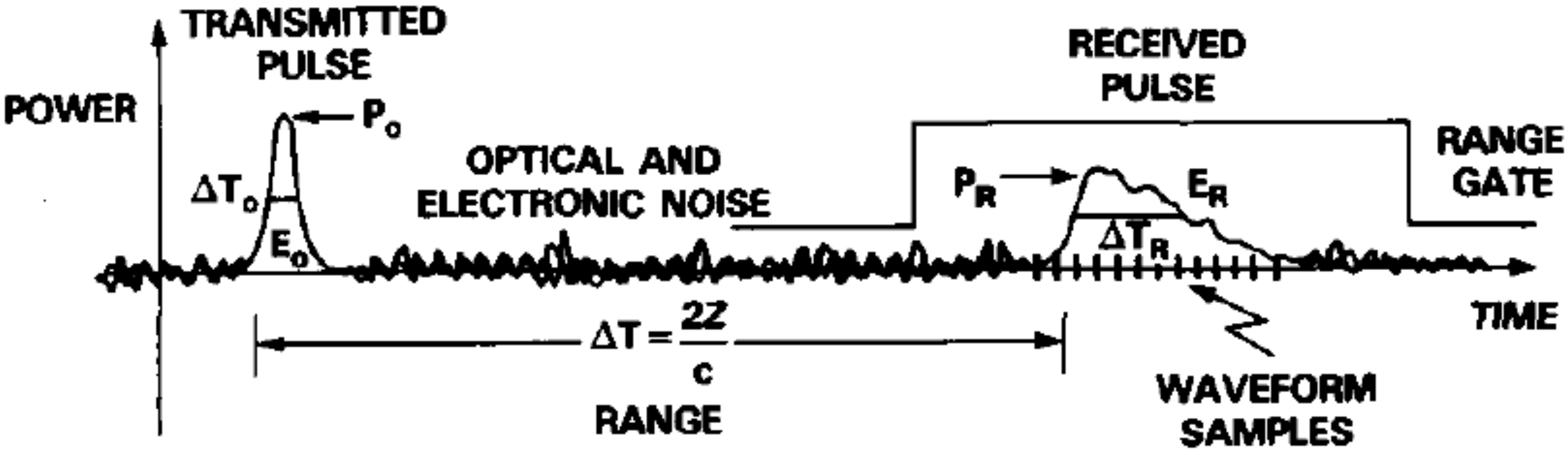
Lidar on solid target: time of flight

Laser Altimeter



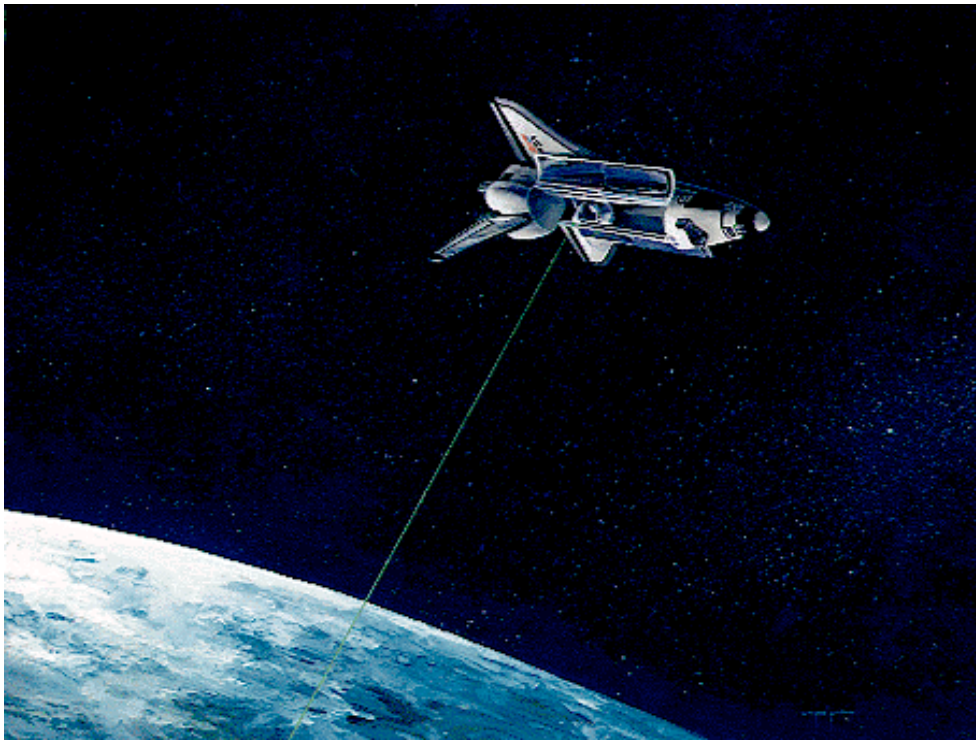
Lidar on solid target: time of flight

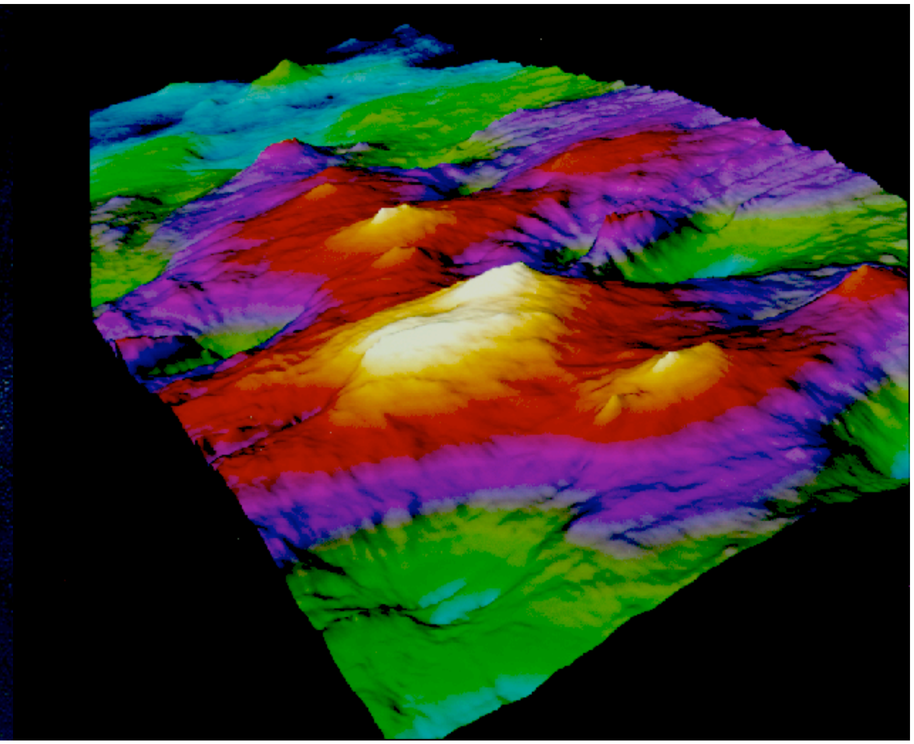
Laser Altimeter and Ranging



- The resolution is now determined by the resolution of the timer for recording pulses, instead of the pulse duration width.

Spaceborne Laser Altimeter





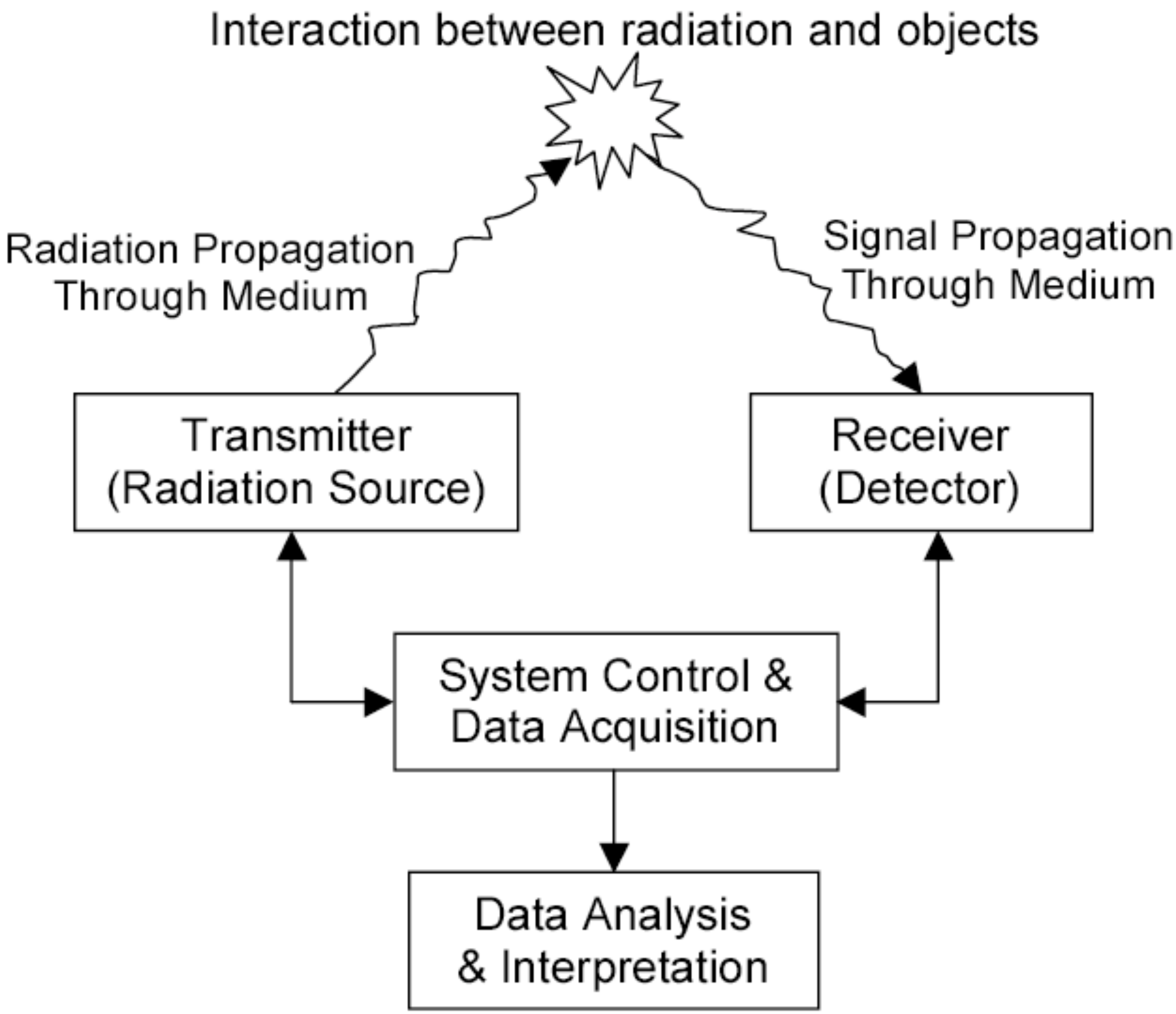
Basic Principle - LIDAR Equation

- The lidar equation is the basic equation in the field of lidar remote sensing, which relates the received photon number (power) coming from a scattering region or object to the emitted laser photon number (power), the concentration of the scatterer, the interaction between the light radiation and the scatterer, and the lidar system efficiency.

Photon Counting $\boxed{N_R = f(N_{Trans}, n_{scatter}, \sigma_{eff}, T, \eta)}$

Analog Detection $\boxed{P_R = f(P_{Trans}, n_{scatter}, \sigma_{eff}, T, \eta)}$

Active Remote Sensing



LIDAR Equation

- The lidar equation is developed under two assumptions: the scattering processes are independent, and only single scattering occurs.
- Independent scattering means that 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 implies that a photon is scattered only once. Multiple scatter is excluded in our consideration.

LIDAR Equation

- In general, the interaction between the light photons and the particles is a scattering process.
- The expected received photon number is equal to the product of

the number of transmitted photons,

the probability that a transmitted photon is scattered,

the probability that a scattered photon is collected/received,

and the system efficiency.

LIDAR Equation

Assumptions: independent and single scattering

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

- **N_S -- expected photon counts detected at λ and z**
- **1st term -- the number of transmitted laser photons;**
- **2nd term -- the probability that a transmitted photon is backscattered by the scatters into a unit solid angle;**
- **3rd term -- the probability that a scatter photon is collected by the receiving telescope;**
- **4th term -- the overall system efficiency;**
- **N_B -- background and detector noise**

1st Term: Transmitted Photon Number

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

$$\frac{\text{Laser Power x time bin length}}{\text{Planck constant x Laser frequency}}$$

$$=\frac{\text{Transmitted laser energy within time bin}}{\text{Single laser photon energy}}$$

= Transmitted laser photon number within time bin length

2nd Term: Probability to be Scattered

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

Angular scattering probability - the probability that a transmitted photon is backscattered by scatters into a unit solid angle.

Angular scattering probability =
volume backscatter coefficient x scattering layer thickness

Volume backscatter coefficient β is the probability per unit distance travel that a photon is scattered into wavelength λ in unit solid angle at angle $\theta = \pi$.

2nd Term: Probability to be Scattered

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

Volume backscatter coefficient β is equal to

$$\boxed{\beta(\lambda,\lambda_L,z) = \sum_i \left[\frac{d\sigma_i(\lambda_L)}{d\Omega} n_i(z) p_i(\lambda)\right]}$$

$\frac{d\sigma_i(\lambda_L)}{d\Omega}$ Is the differential backscatter cross-section of single particle

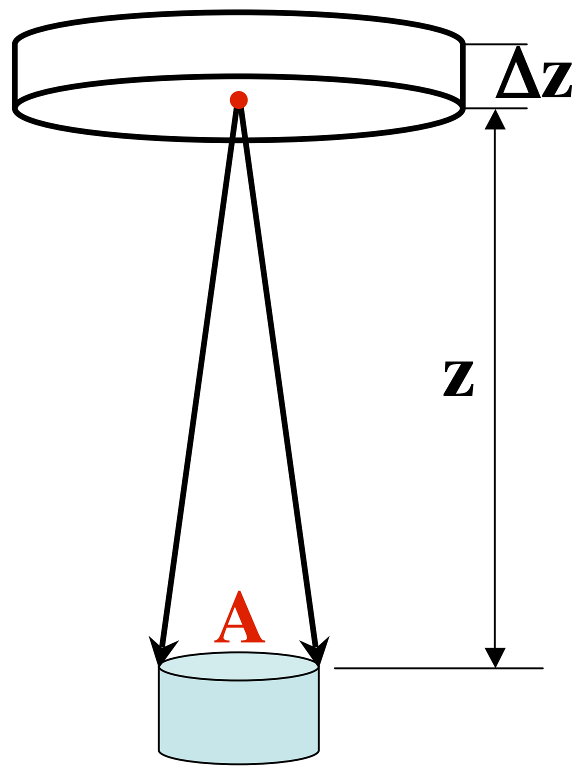
$n_i(z)$ Is the number density of scatter species i

$p_i(\lambda)$ Is the probability of the scattered photons falling into the wavelength λ.

3rd Term: Probability to be Collected

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

The probability that a scatter photon is collected by the receiving telescope, i.e., the solid angle subtended by the receiver aperture to the scatterer



4th Term: Overall Efficiency

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

$\boxed{\eta(\lambda,\lambda_L) = \eta_T(\lambda_L)\cdot\eta_R(\lambda)}$ is the lidar hardware optical efficiency

e.g., mirrors, lens, filters, detectors, etc

$\boxed{T(\lambda_L,z)T(\lambda,z)}$ is the atmospheric transmittance at outgoing wavelength λ_L and return wavelength λ

$\boxed{G(z)}$ is the geometrical form factor, mainly concerning the overlap of the area of laser irradiation with the field of view of the receiver optics

5th Term: Background Noise

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

$\boxed{N_B}$ is the expected photon counts per range bin per unit time, due to background noise (e.g., solar scattering) and detector/circuit shot noise.

Classifications of Lidar

There are several different classifications on lidars

e.g., based on the physical process;

(Mie, Rayleigh, Raman, Fluorescence, …)

based on the platform;

(Groundbased, Airborne, Spaceborne, …)

based on the detection region;

(Atmosphere, Ocean, Solid Target, …)

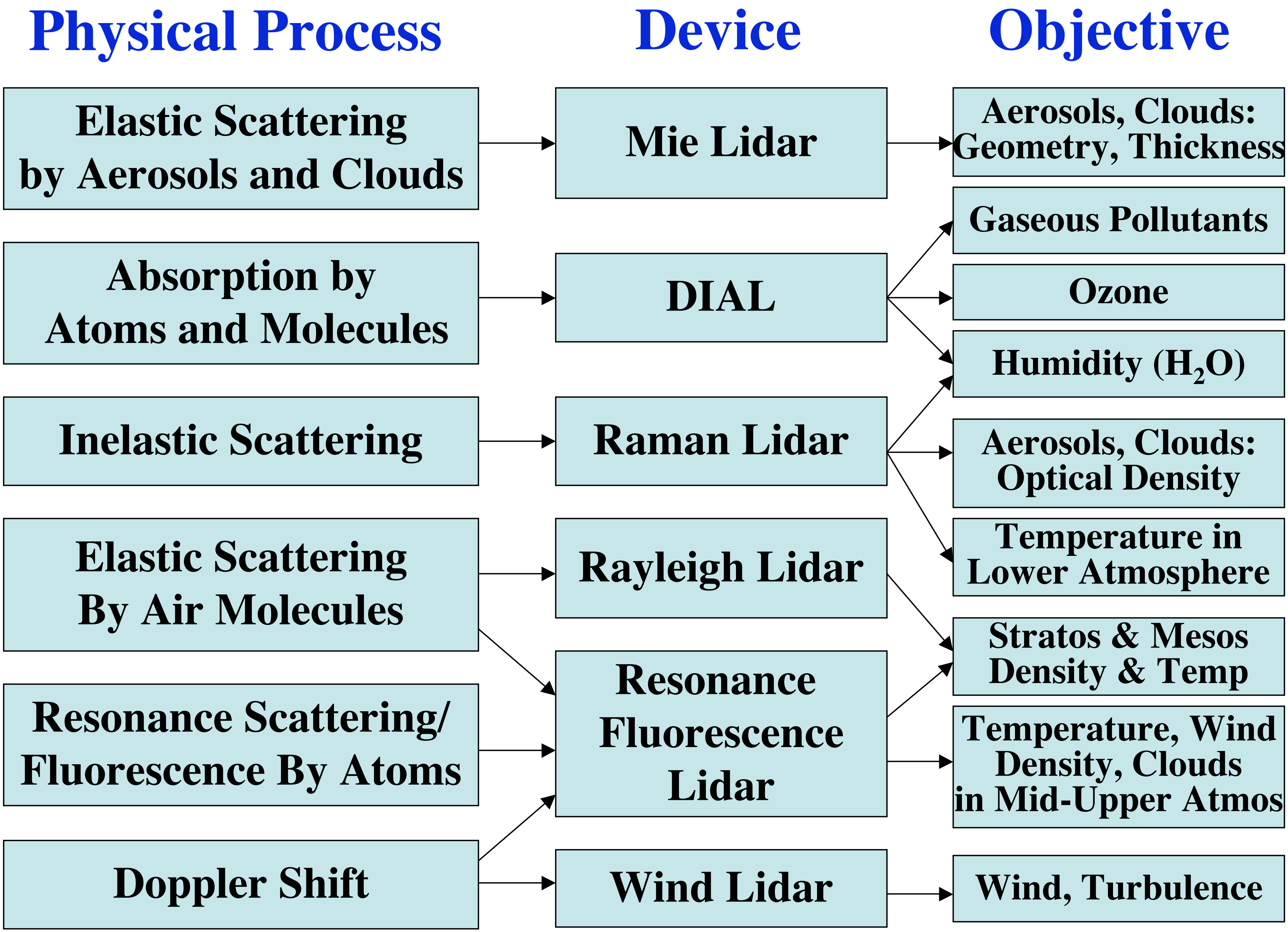
based on the emphasis of signal type;

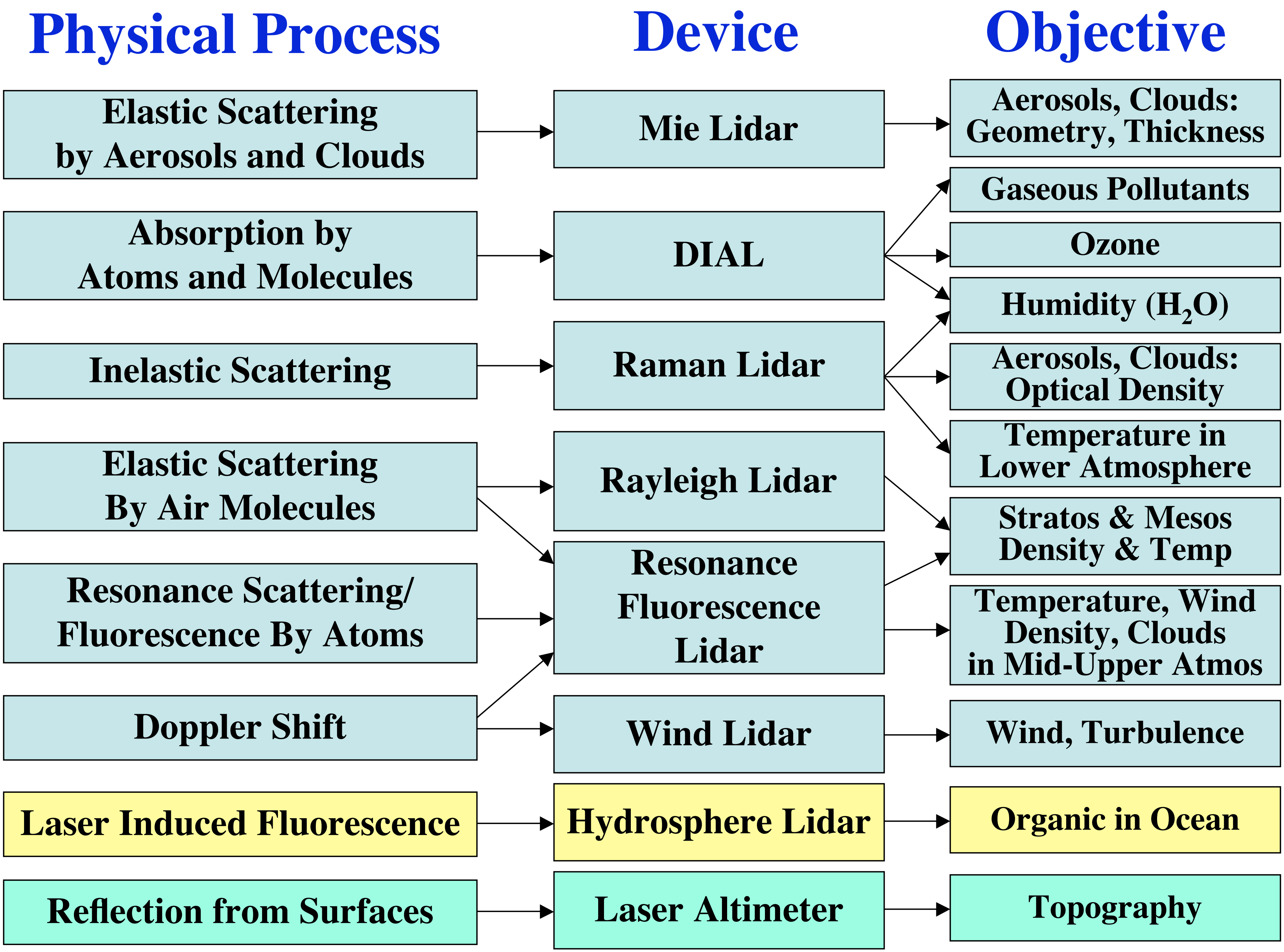
(Ranging, Scattering, …)

based on the topics to detect;

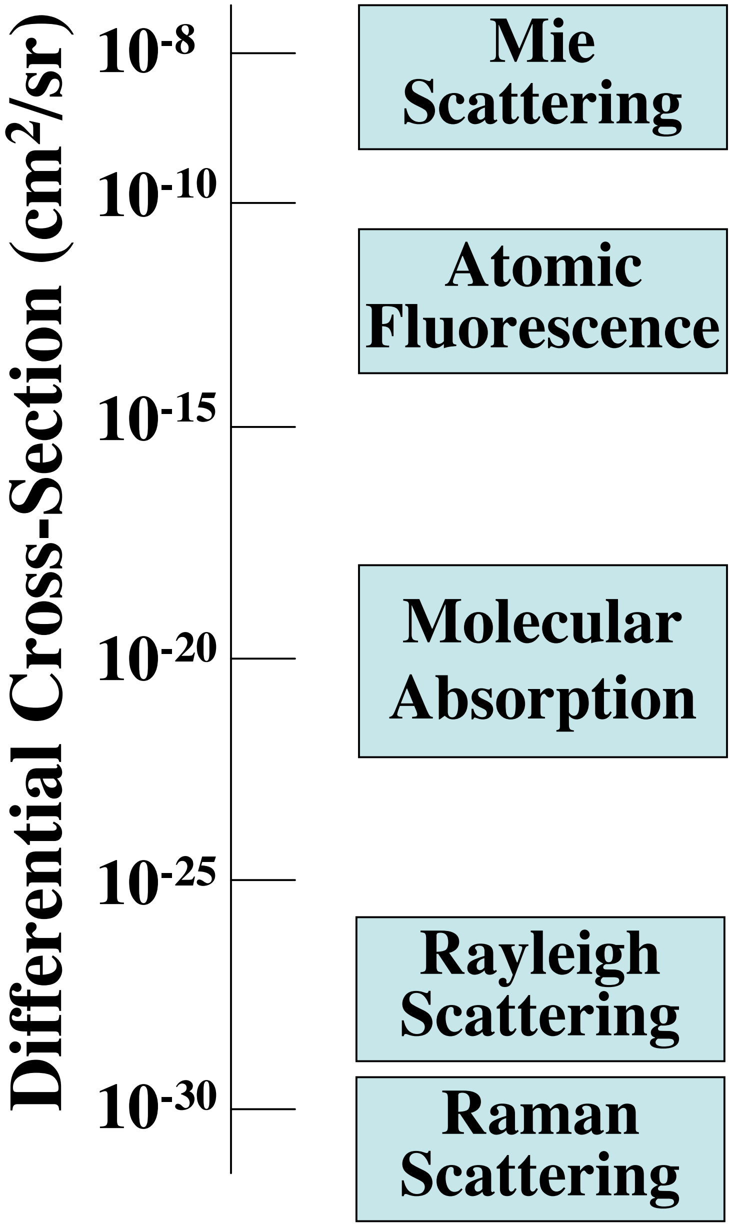
(Aerosol, Density, Temperature, Wind, …)

… …


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


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
Hydrosphere 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
Organic in Ocean
Topography

Comparison of Scattering



$$\beta(\lambda, \lambda_L, z) = \sum_i \left[\frac{\mathrm{d}\sigma_i(\lambda_L)}{\mathrm{d}\Omega} n_i(z) p_i(\lambda) \right]$$

Rayleigh

$$\frac{d\sigma}{d\Omega} = \sigma_R \propto \frac{1}{\lambda^4}$$

Resonance Fluorescence

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_{eff}}{4\pi} = \frac{\int_{-\infty}^{+\infty} \sigma_{abs}(\nu, \nu_0) \cdot g_L(\nu, \nu_L)\, \mathrm{d}\nu}{4\pi}$$

Platform Classification

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
Solid 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

Topography lidar

Fish lidar

... ...

Summary For Lecture 2

- History from searchlight to modern lidar
- Basic lidar architecture
- Basic lidar equation
- Classifications of lidars