Lecture 03. Lidar Remote Sensing Overview (1)

- Introduction
- History from searchlight to modern lidar
- Various modern lidars
- Altitude/Range determination
- Basic lidar architecture
- Summary

Introduction: Lidar

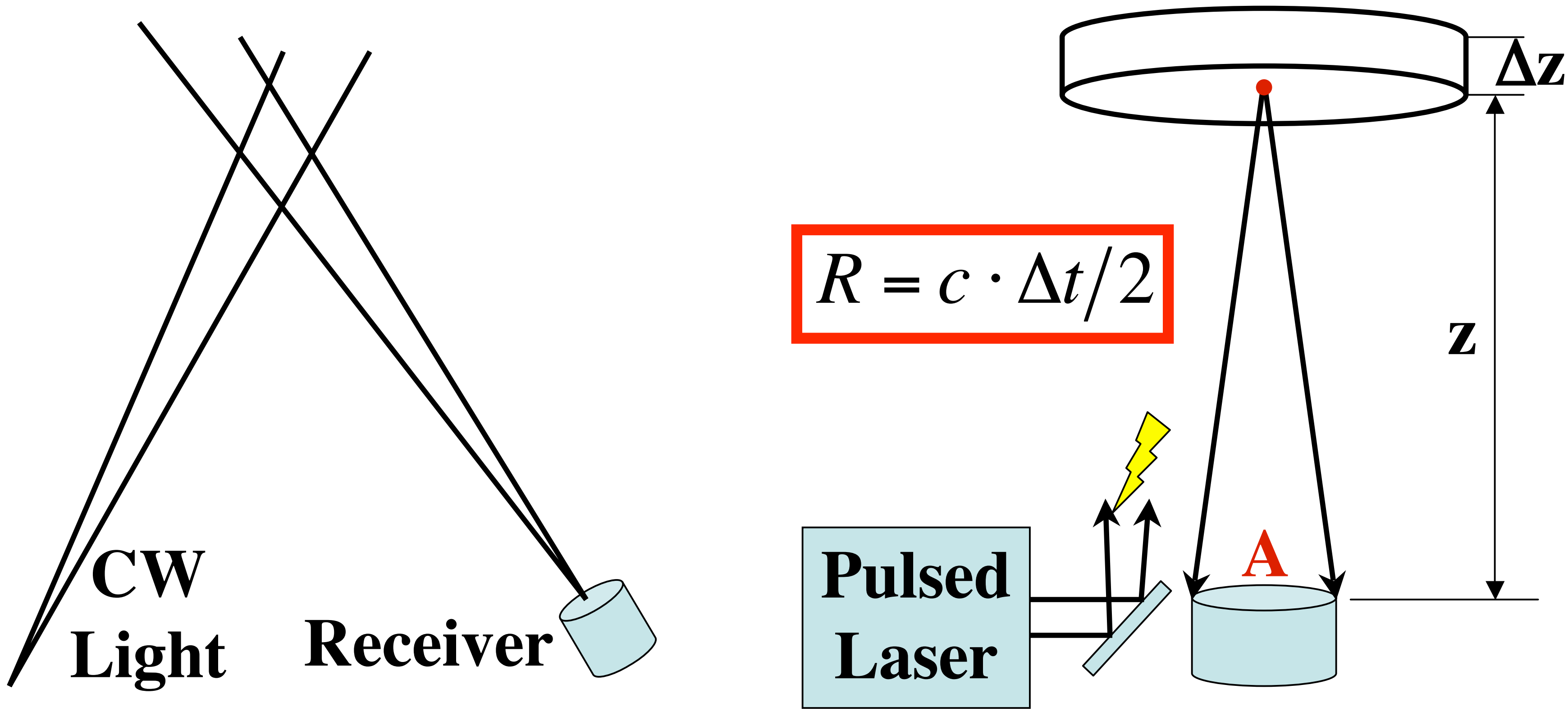
- LIDAR is the acronym of Light Detection And Ranging – a laser radar in light frequency range.

- Although lidar and radar share similar detection principles, large differences exist in the physical processes, the treatment approaches, and the system hardware, due to huge frequency difference of the radiation used in lidar and radar.

- Lidar uses the concept of photons, while radar uses the concept of electromagnetic waves.

- Lidar started in the pre-laser times in 1930s with searchlight beams, and then quickly evolved to modern lidars using nano-second laser pulses.

History: Searchlight → Modern Lidar



Bistatic Configuration **Monostatic Configuration**

CW searchlight → ns laser pulse

History: Searchlight Lidar

- 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.

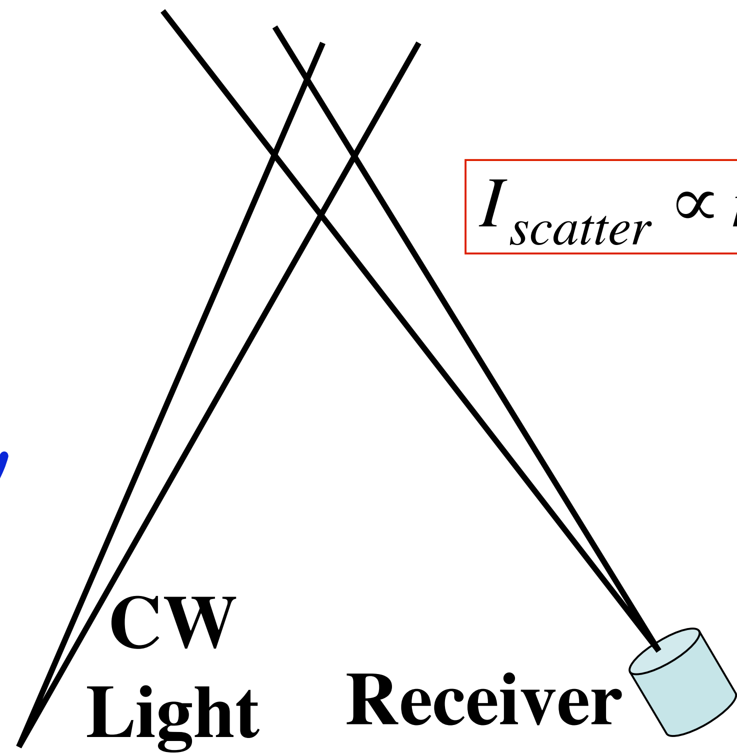
Lidar Started with Searchlight

- 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

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



Searchlight

$$\theta_T = 75^\circ$$

$$\theta_R = 0^\circ - 57^\circ$$

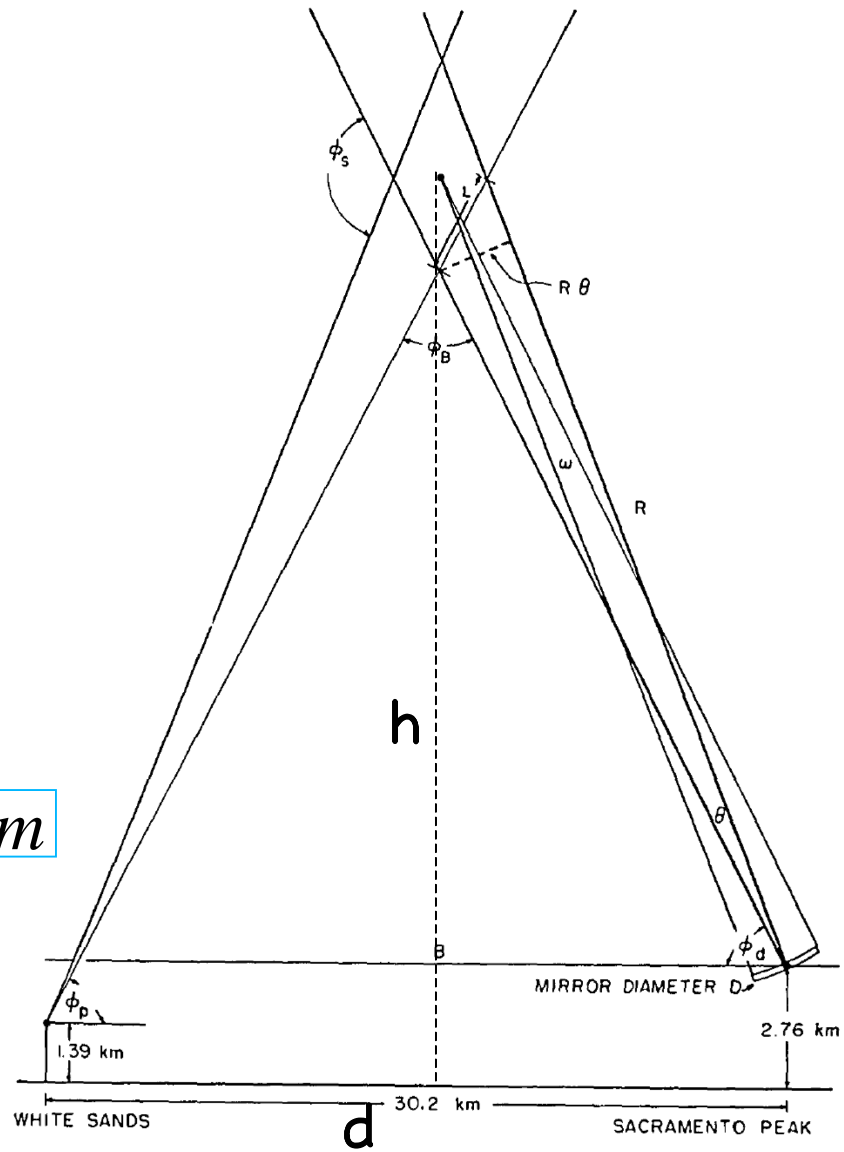
$$H_T = 1.39km$$

$$H_R = 2.76km$$

$$d = 30.2km$$

$$h = 2.76km - 35.3km$$

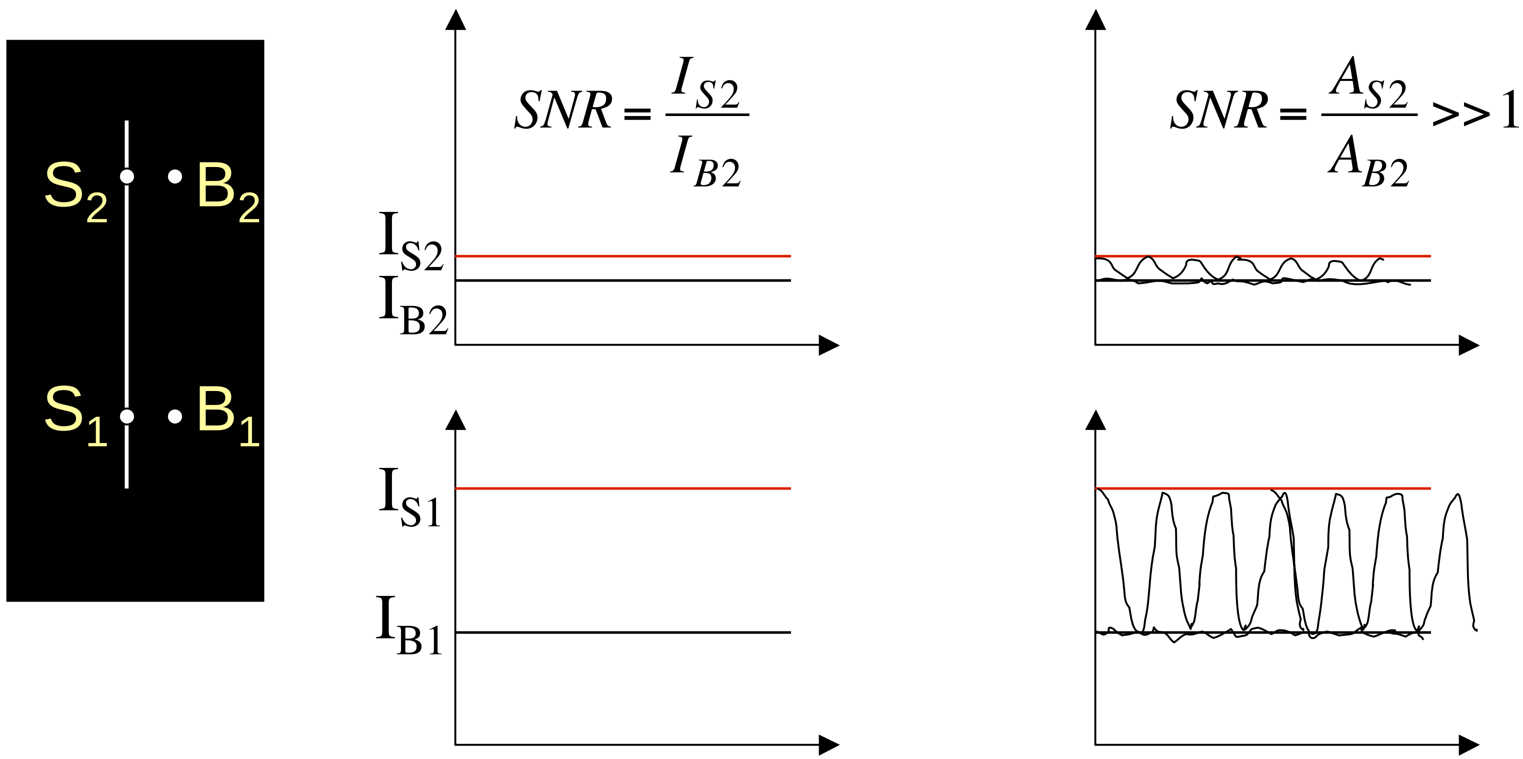
Transmitter
(Projector)
Angle fixed



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

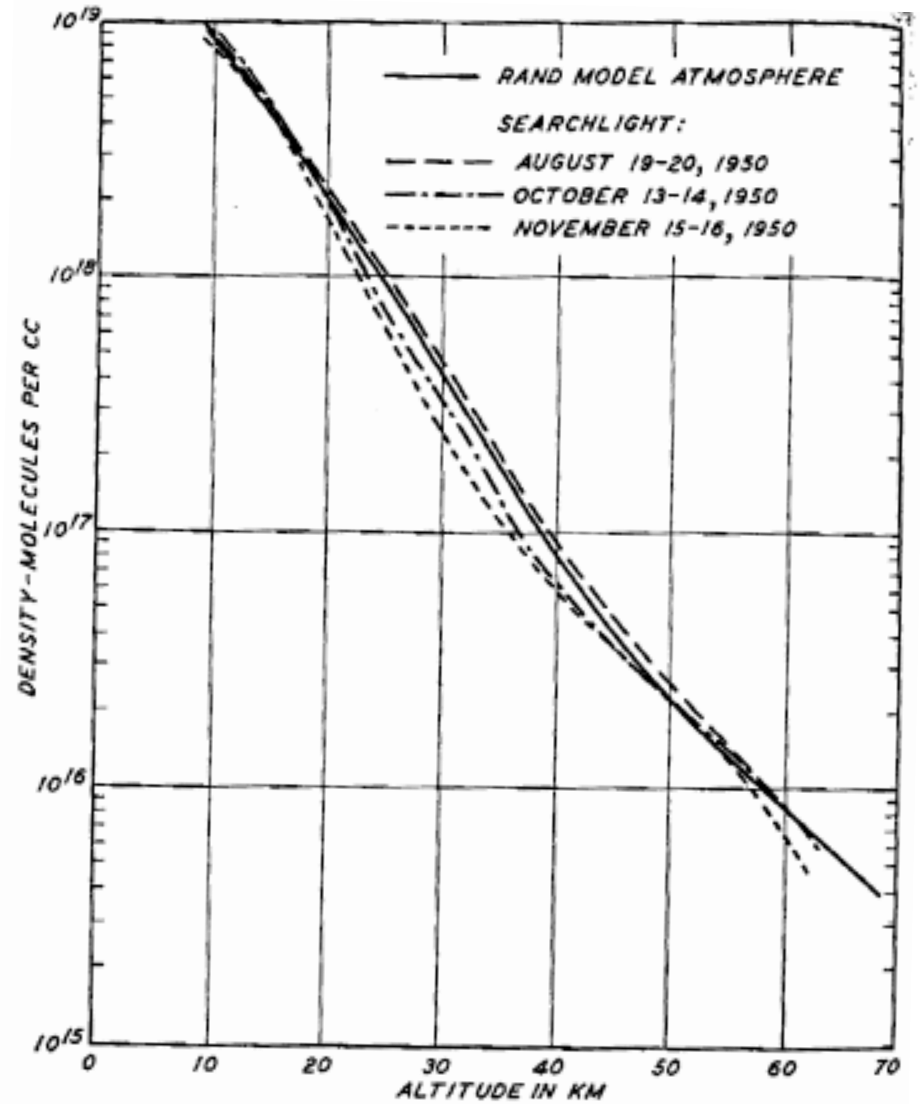
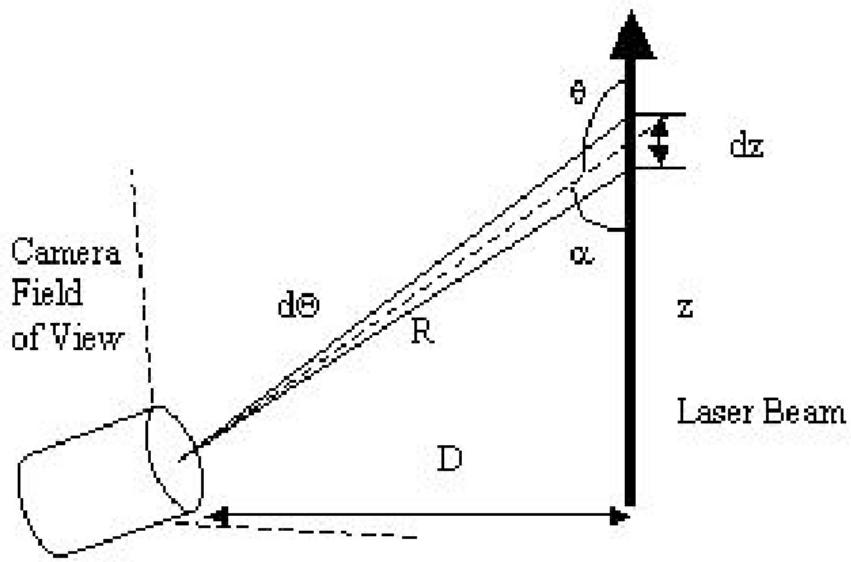


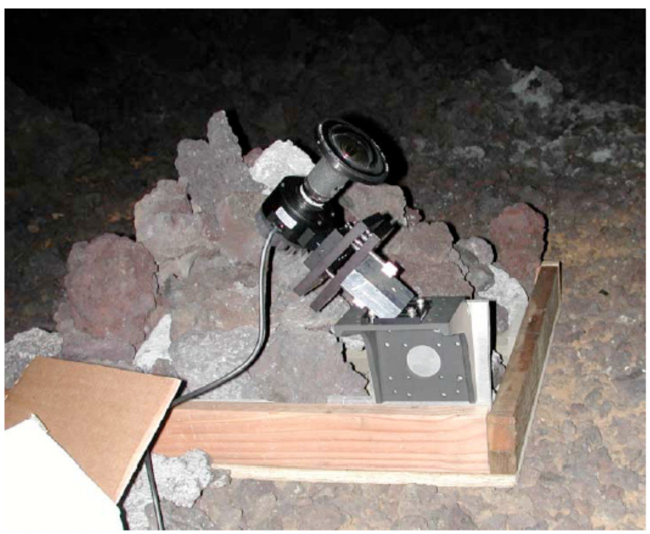
FIG. 4—DENSITY DISTRIBUTION FROM SEARCH-LIGHT DATA

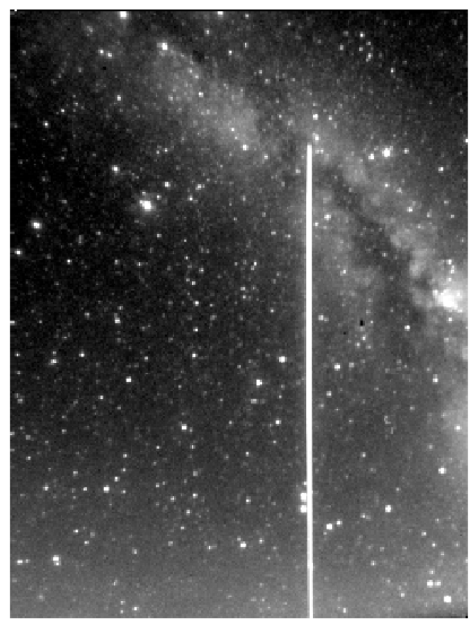
CCD-Imaging Lidar with Similar Idea

- Modern CCD-imaging lidar utilizes an similar idea as the searchlight lidar.

- The bistatic lidar seems to have better near-field detection.







History: Modern 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 applications.

Modern Lidar: Atmosphere Lidar

- The first application of lidar 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 spectra.

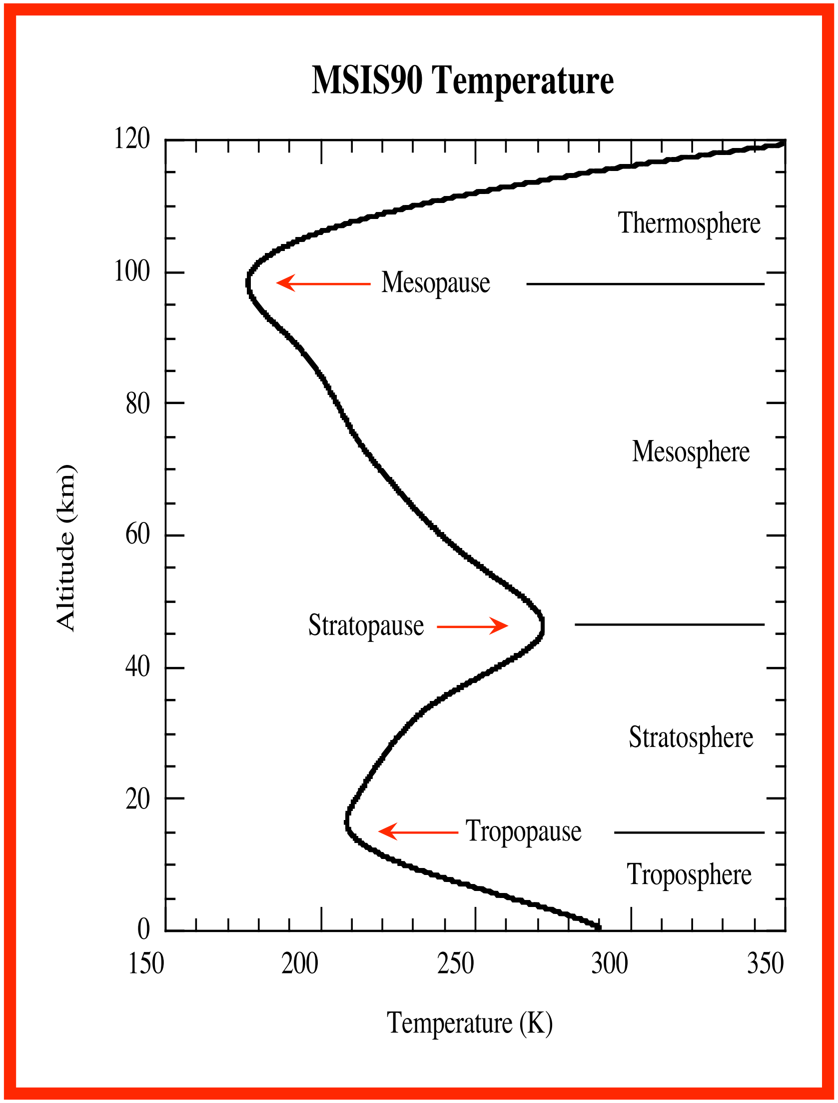
- An important advance in lidar was the recognition that the spectra of the detected radiation contained highly specific information related to the species, which could be used to determine the composition of the object region.

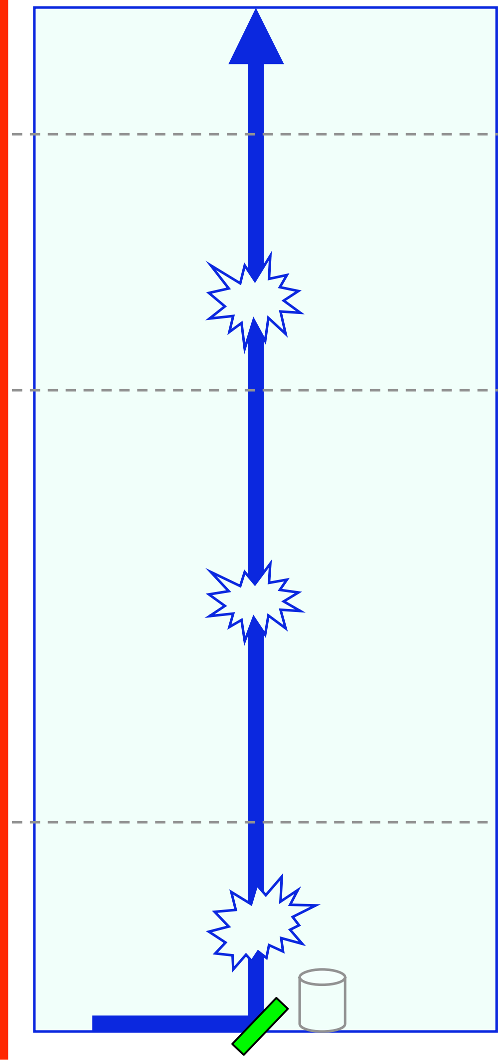
Modern Lidar Advancement

- 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 (upper atmosphere lidar), to lower atmosphere constituents (differential absorption lidar), to airborne chlorophyll mapping of the oceans to establish rich fishing areas (fluorescence lidar).

Atmosphere Lidar





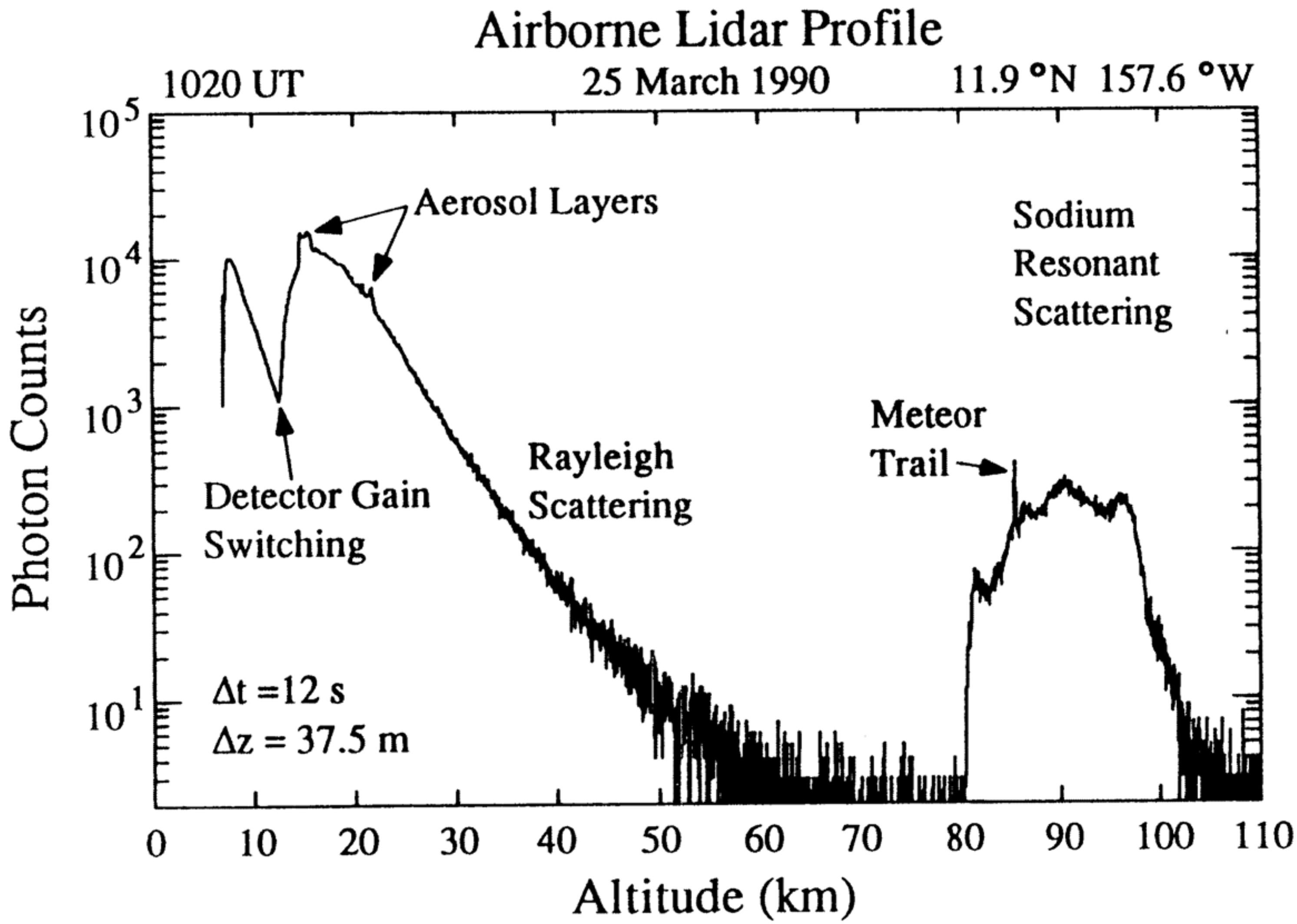
Resonant Fluorescence From Metal Atoms

Rayleigh Scattering From Air Molecules

Mie Scattering From Aerosols

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

Typical Atmosphere Lidar Profile



Modern Lidar: Target Lidar

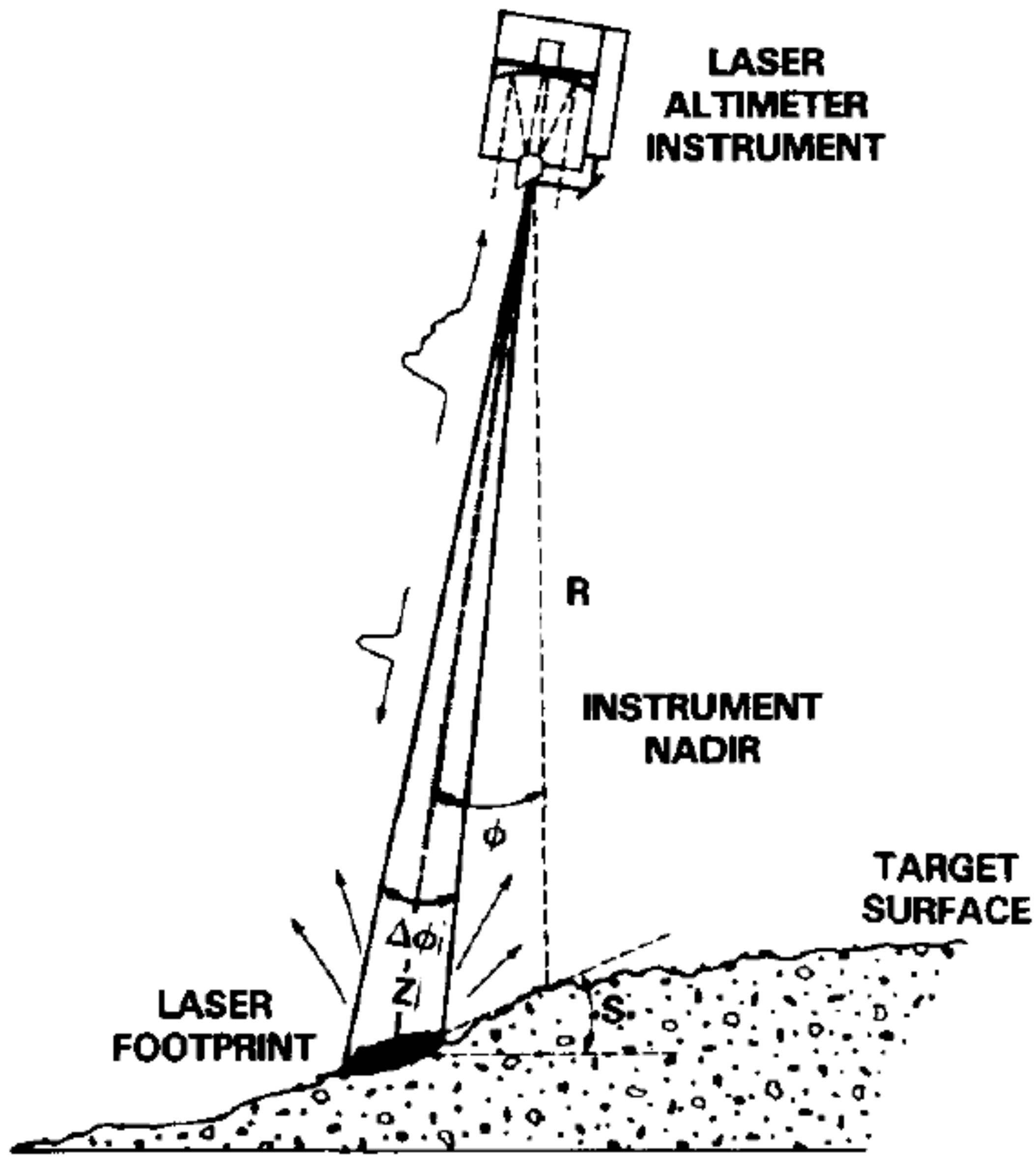
- Besides atmosphere, our environment includes many other things, like the solid earth, cryosphere, hydrosphere, and non-gas-phase objects on the earth, in the ocean, and in the air (e.g., plants, oil, buildings) etc. Study of our environment demands good measurement technology and approach for measurements in all sorts of occasions. Therefore, lidar technology for target (anything other than gas phase objects) detection is essential and highly demanded.

- Two main categories for target lidars: (1) lidars for ranging (laser altimeter) and (2) lidars for species identification (fluorescence lidar).

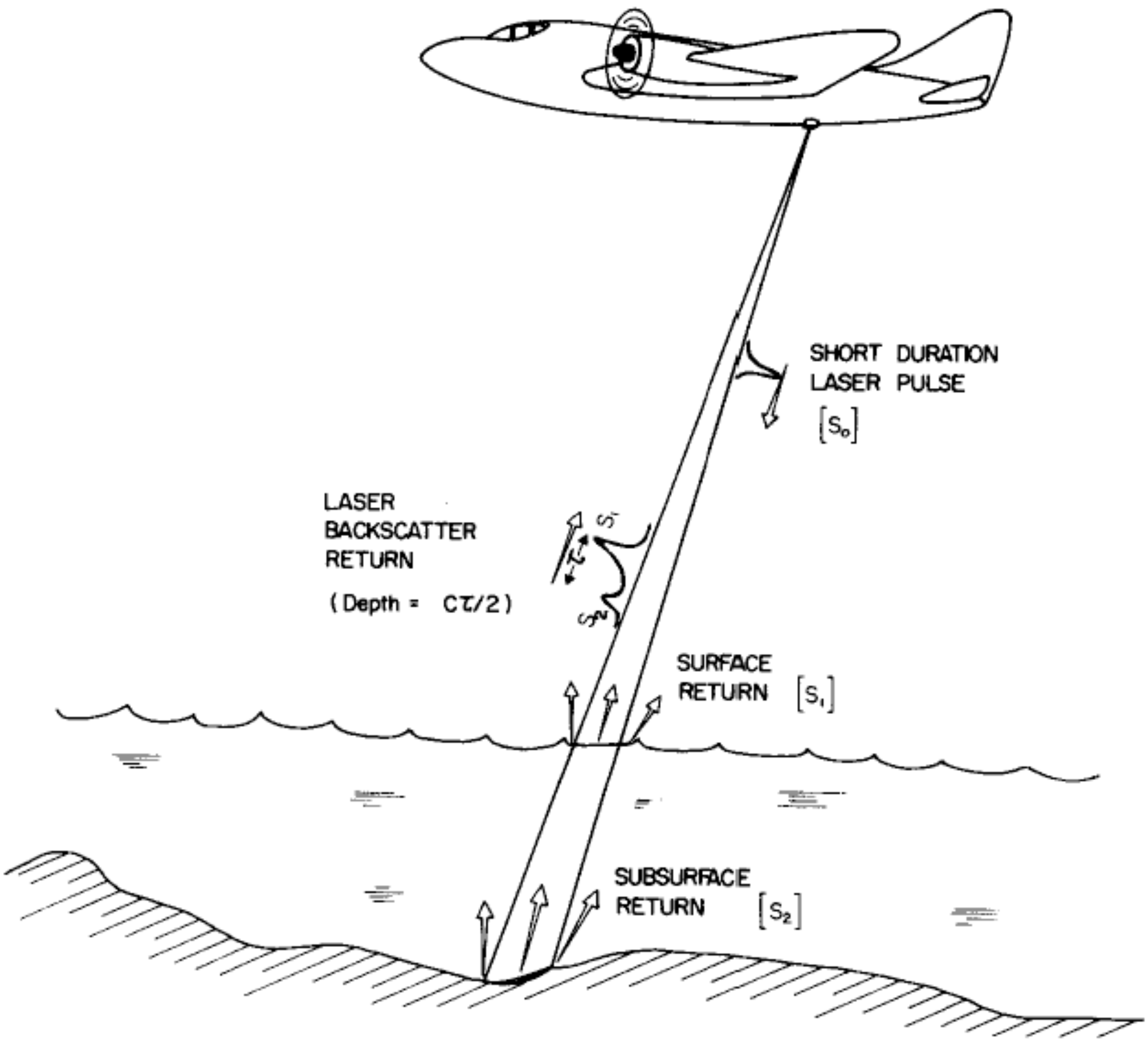
Laser Altimeter

- The time-of-flight information from a lidar system can be used for laser ranging and laser altimetry from airborne or spaceborne platforms to measure the heights of surfaces with high resolution and accuracy.
- Downward-pointing laser systems were operated in a mode where surface scattering and reflection represented the dominant form of interaction.
- 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.

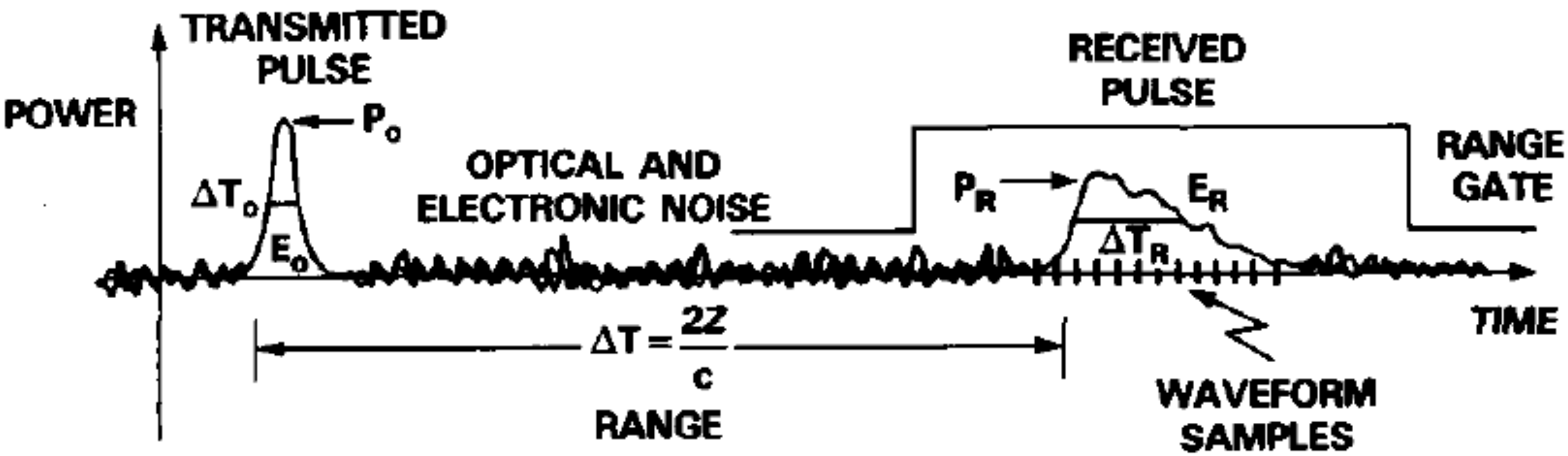
Laser Altimeter



Lidar for Hydrosphere

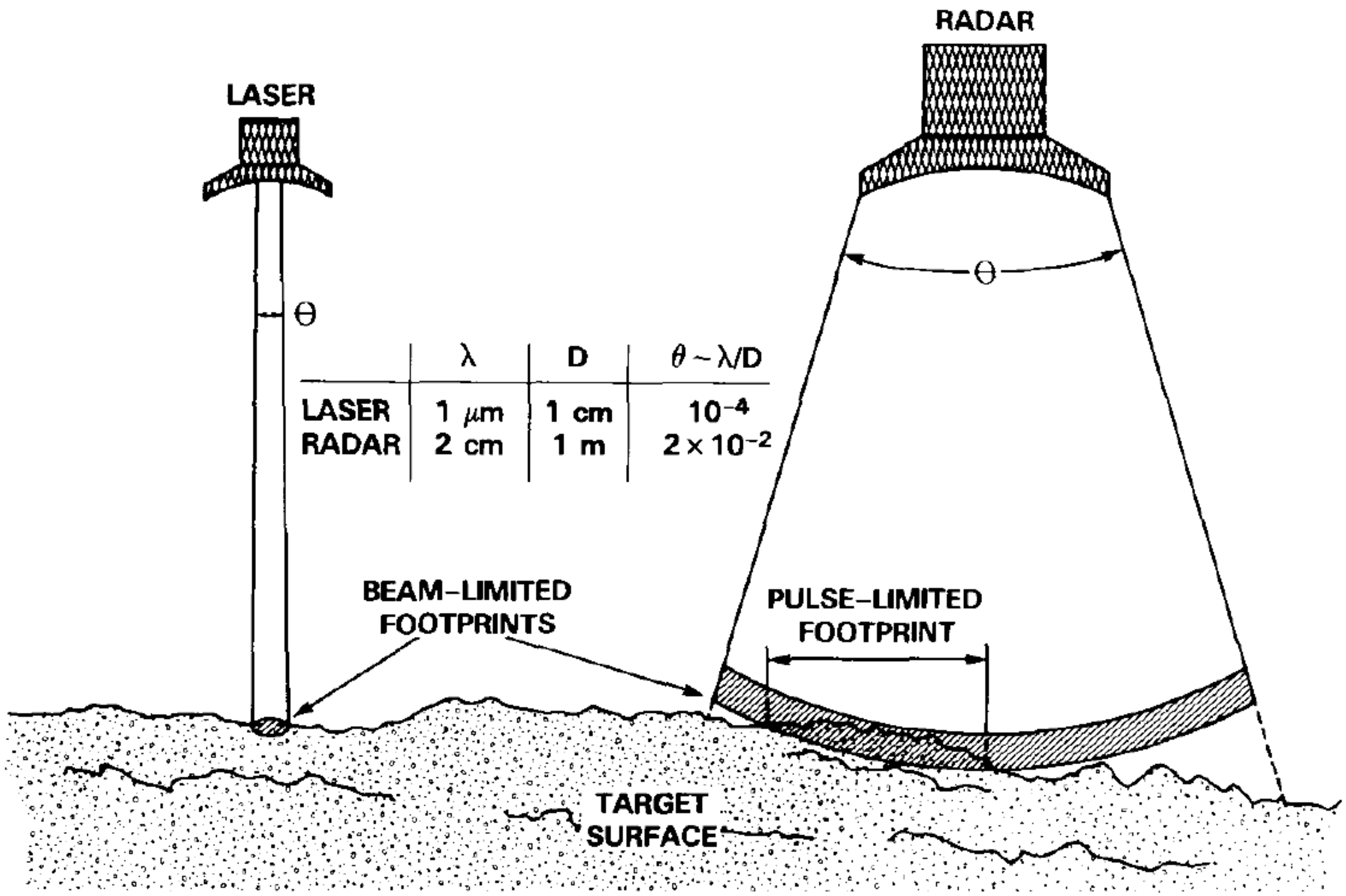


Laser Altimeter and Ranging



- The resolution is now determined by the resolution of the timer for recording pulses, instead of the pulse duration width.
- By computing the centroid, the resolution can be further improved.

Laser Altimeter vs Radar Altimeter



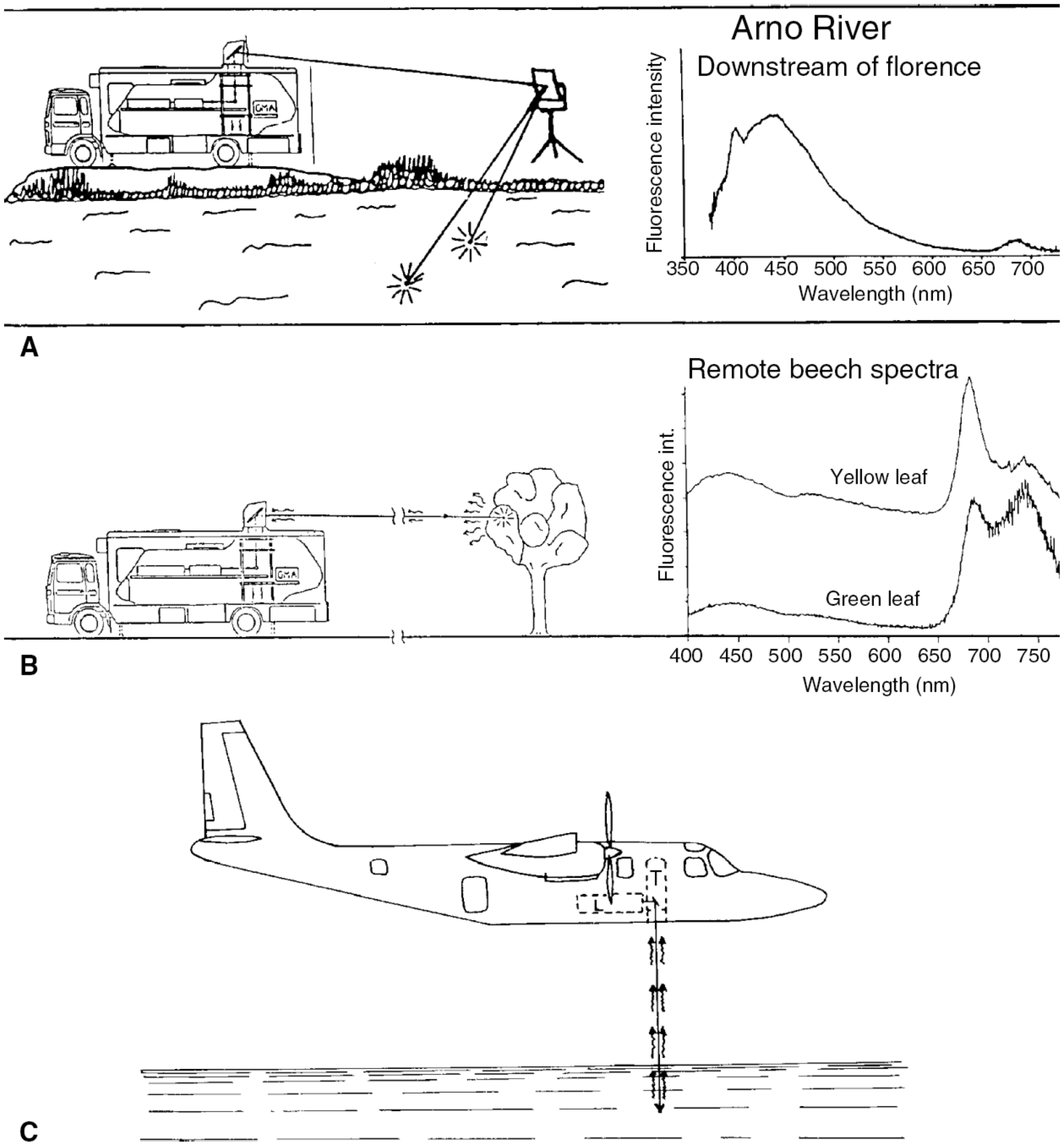
	λ	D	$\theta \sim \lambda/D$
LASER	1 μm	1 cm	10^{-4}
RADAR	2 cm	1 m	2×10^{-2}

Much better resolution and precision

Fluorescence Lidar

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

Scenarios for Fluorescence Lidar



Aquatic monitoring
Via folding mirror

Vegetation
Monitoring

Airborne
Fluorescence

Detection of Historic Monument

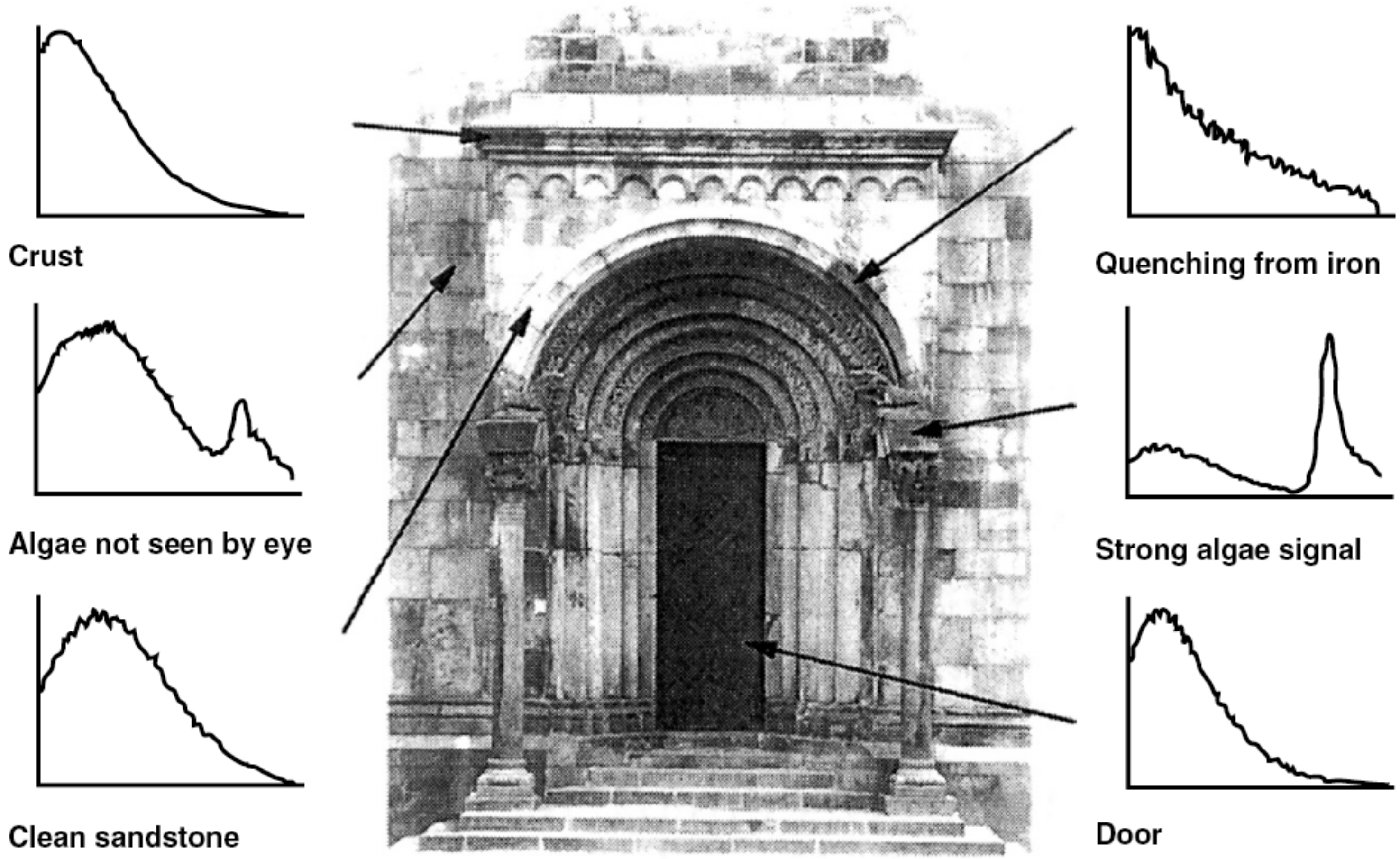
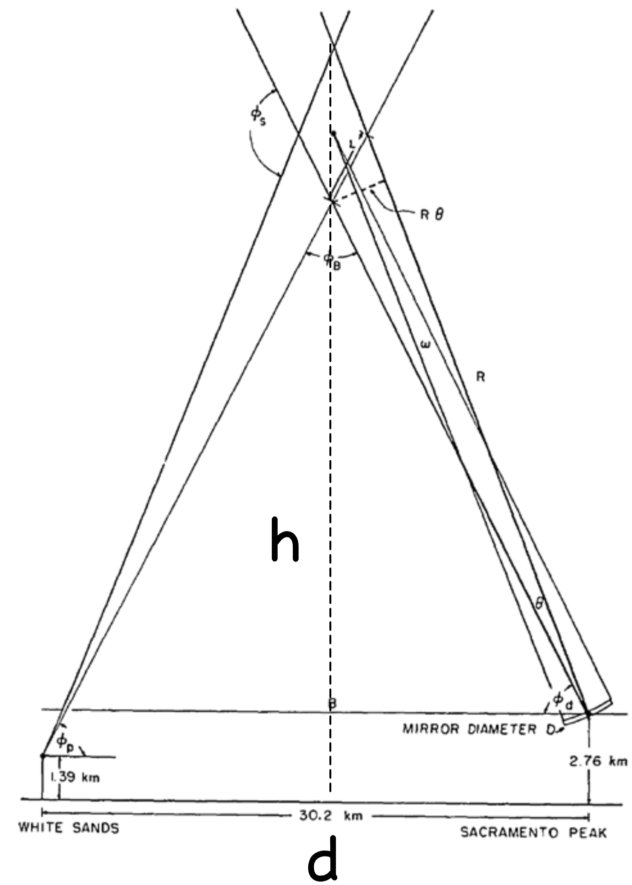


Figure 6.13 Photograph of the northern gate of the Lund Cathedral and six remotely recorded fluorescence spectra. (From Weibring, P. et al., *Appl. Opt.*, 40, 6111, 2001. With permission.)

Altitude and Range Determination

- Searchlight lidar and CCD-imaging lidar: determine altitude through the geometry calculation.

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



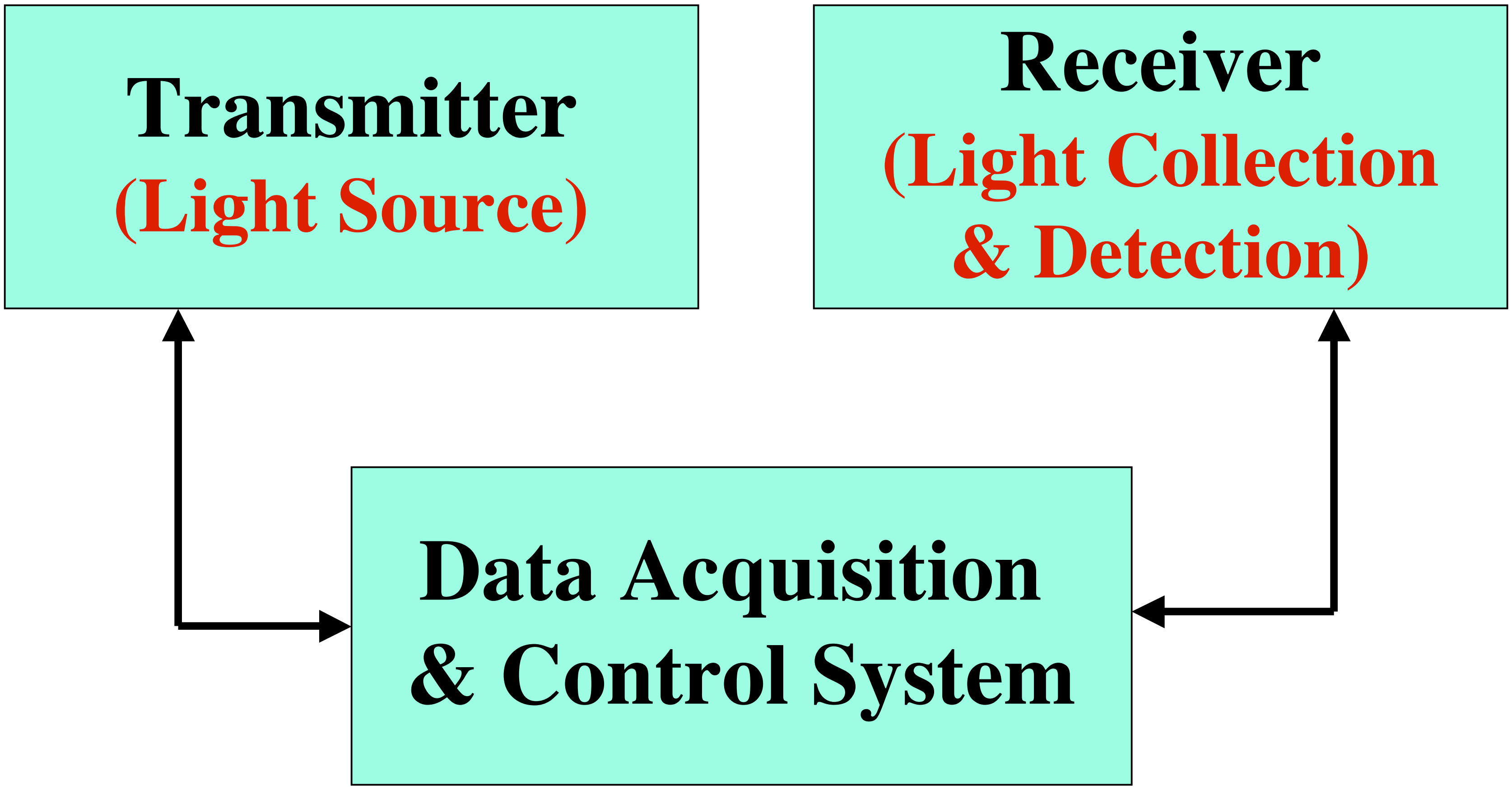
Altitude and Range Determination

- Modern atmosphere lidars: 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: $\Delta R = C \Delta t/2$

Altitude and Range Determination

- Target lidar - laser altimeter: 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.

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.

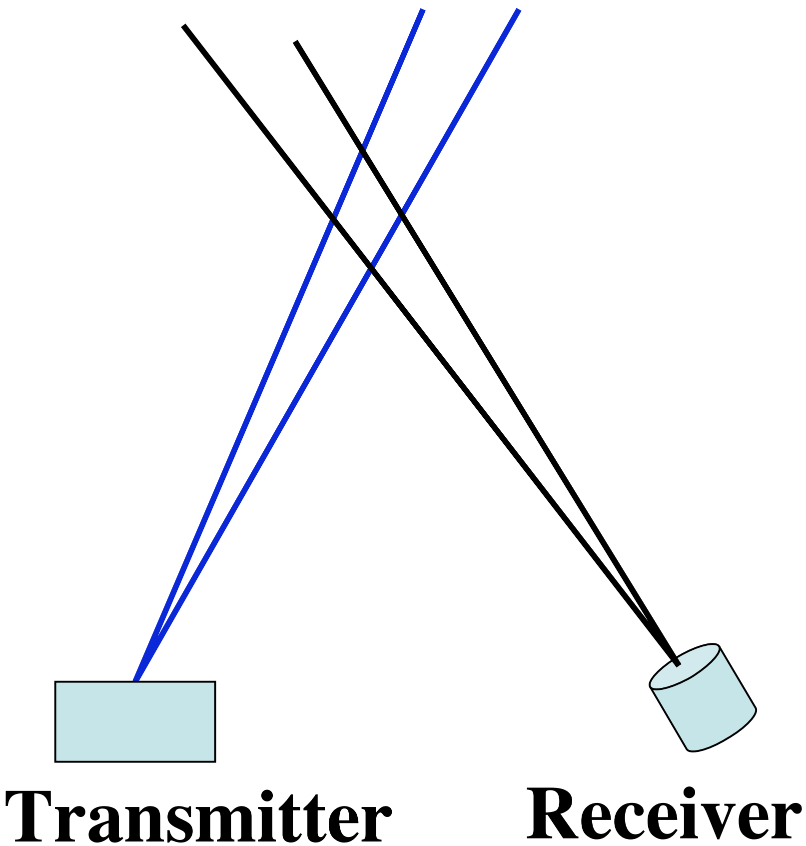
Function of Data Acquisition

- 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 several groups, enabling various data acquisition modes.

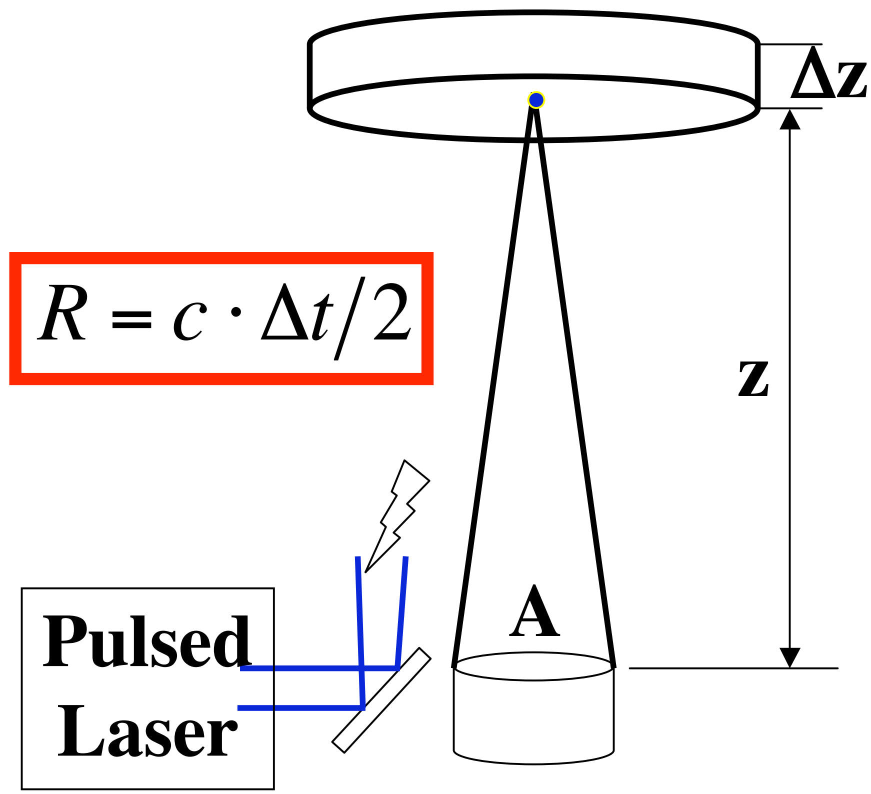
LIDAR Configurations: Bistatic vs. Monostatic

- 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.

Basic Configurations of LIDAR
Bistatic and Monostatic



Bistatic Configuration

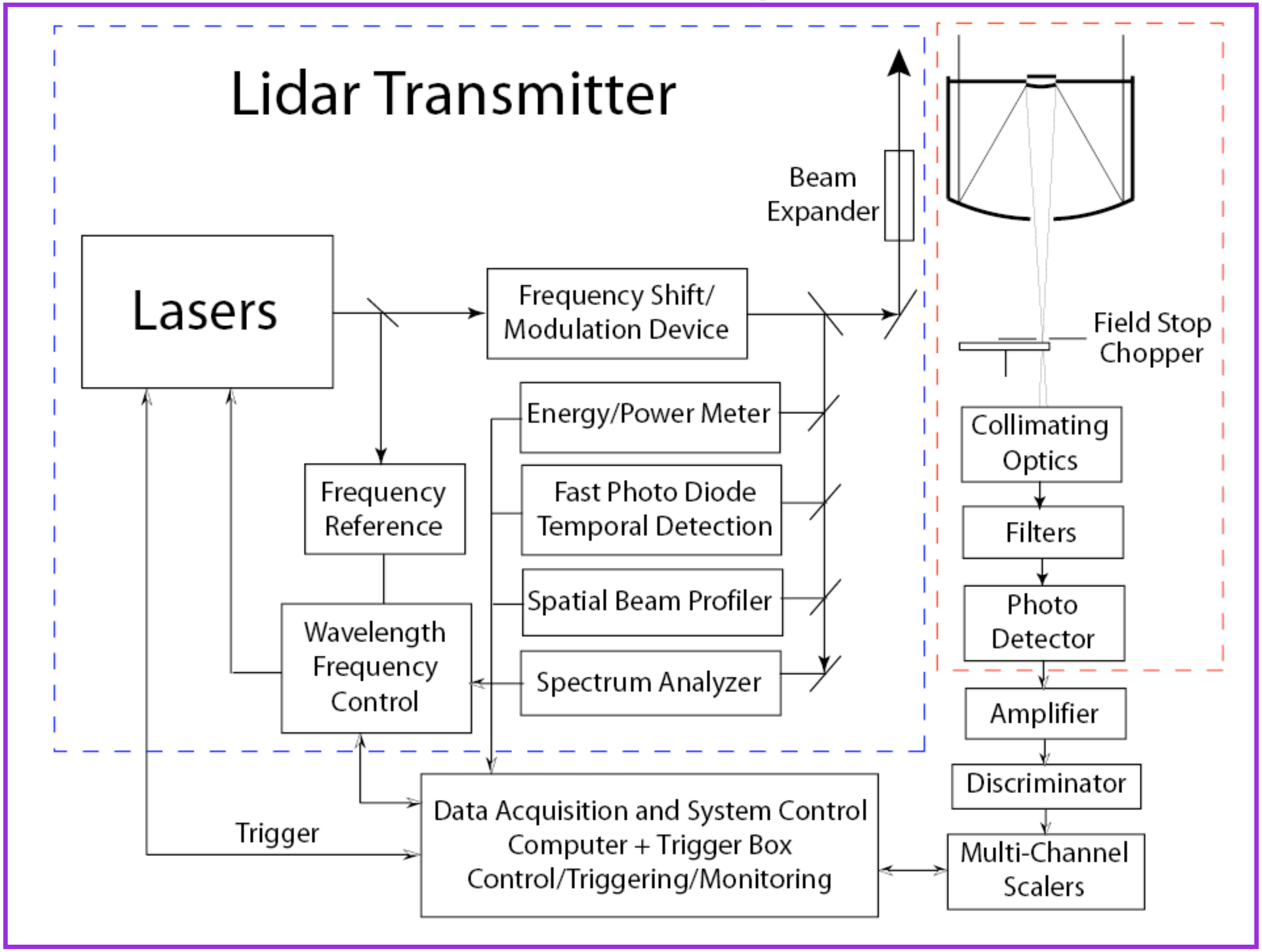


Monostatic Configuration

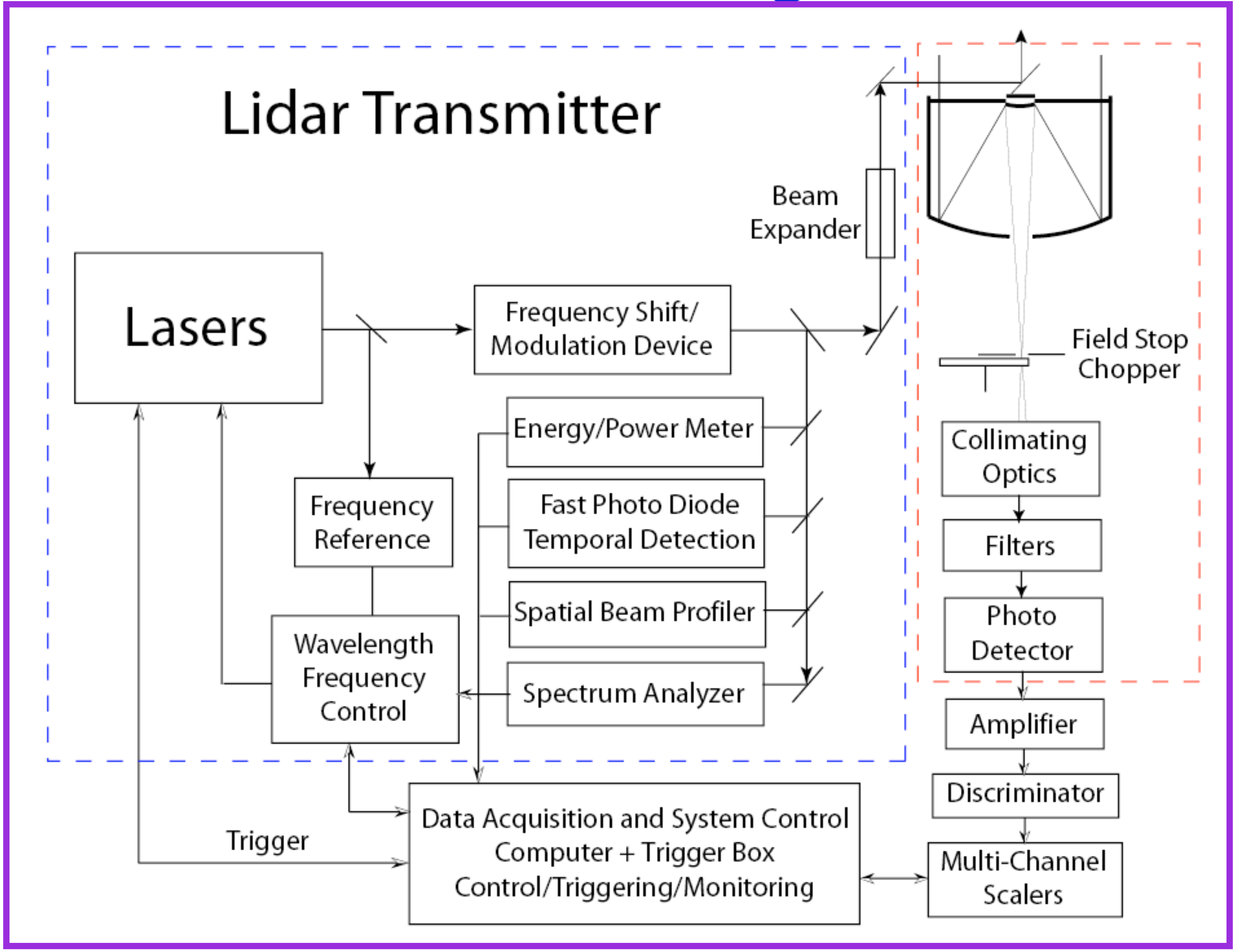
Coaxial vs. Biaxial Arrangements

- 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.

Biaxial Arrangement



Coaxial Arrangement



Summary

- LIDAR actually started with CW searchlight using geometry to determine altitude. The invention of lasers pushed lidar to a whole new level - modern laser remote sensing. The time-of-flight of a short pulse is used to precisely determine range and altitude.

- Modern lidars have various formats and utilize different ways to determine altitude and range precisely.

- Basic lidar architecture includes transmitter, receiver and data acquisition/control system. Each has special functions. There are bistatic and monostatic configurations, and coaxial and biaxial arrangements.