Lecture 03. Fundamentals of Lidar Remote Sensing (1)

- Introduction
- History from searchlight to modern lidar
- Various modern lidars
- Altitude and Range determination
- Summary

Introduction: Lidar

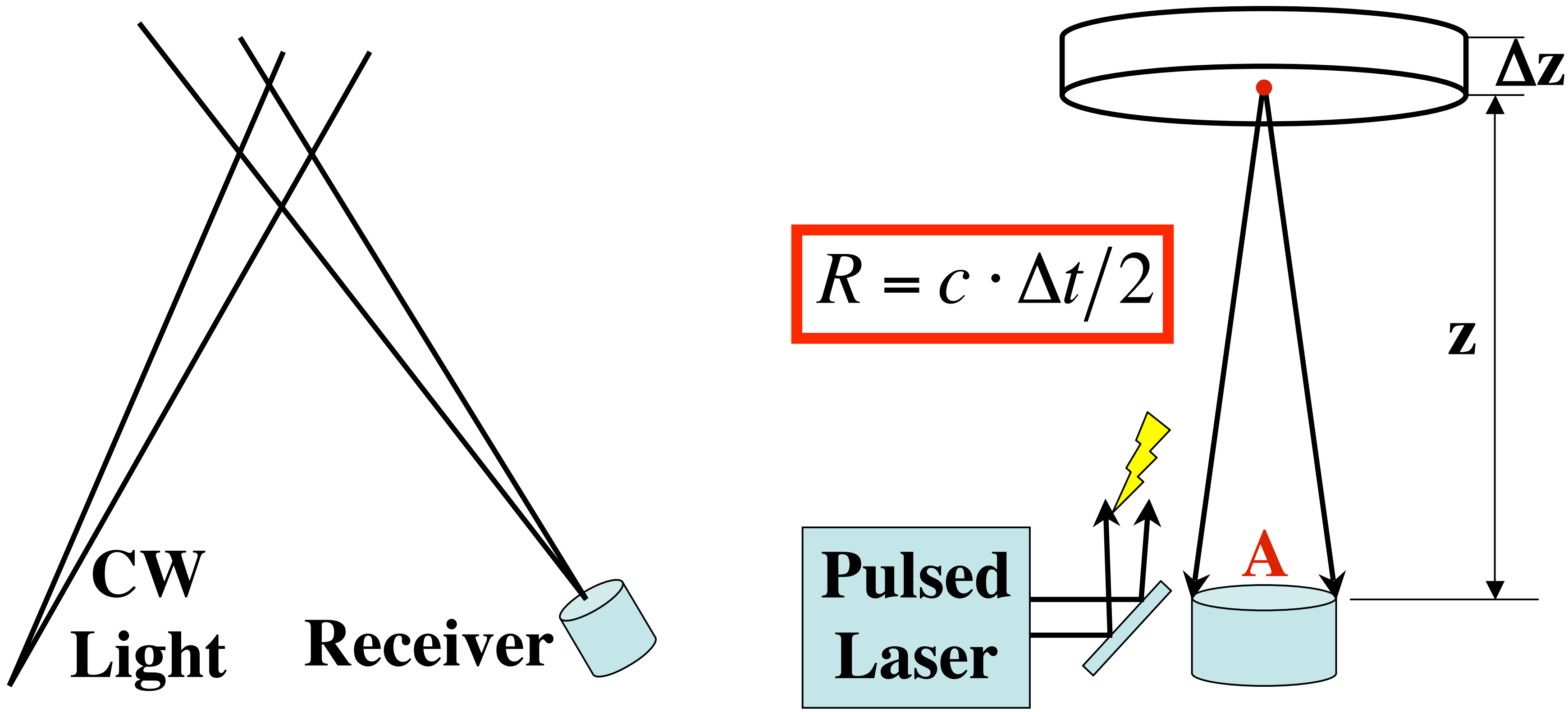
- LIDAR is the acronym of Light Detection And Ranging - a laser radar in light frequency range.

- 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.

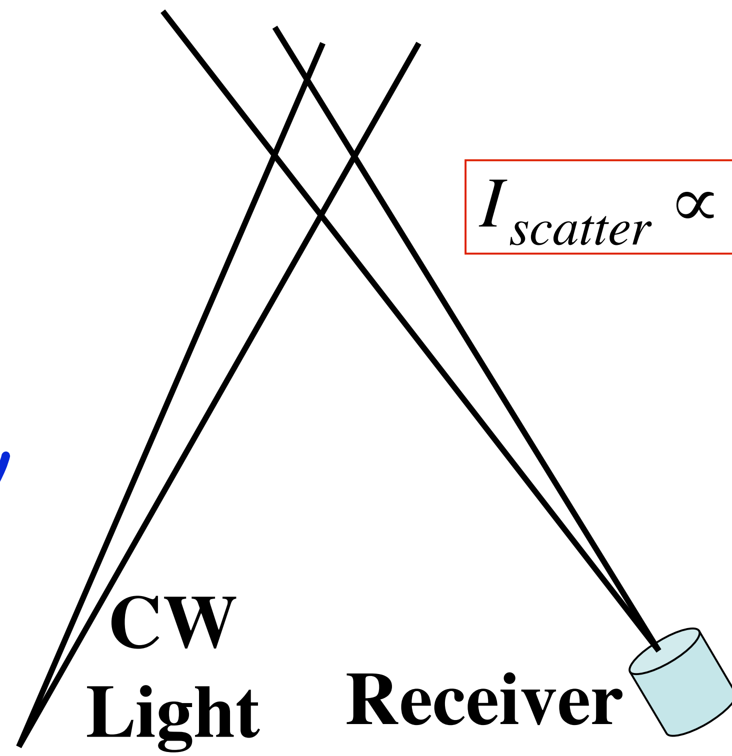
Lidar Started with Searchlight

- 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

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

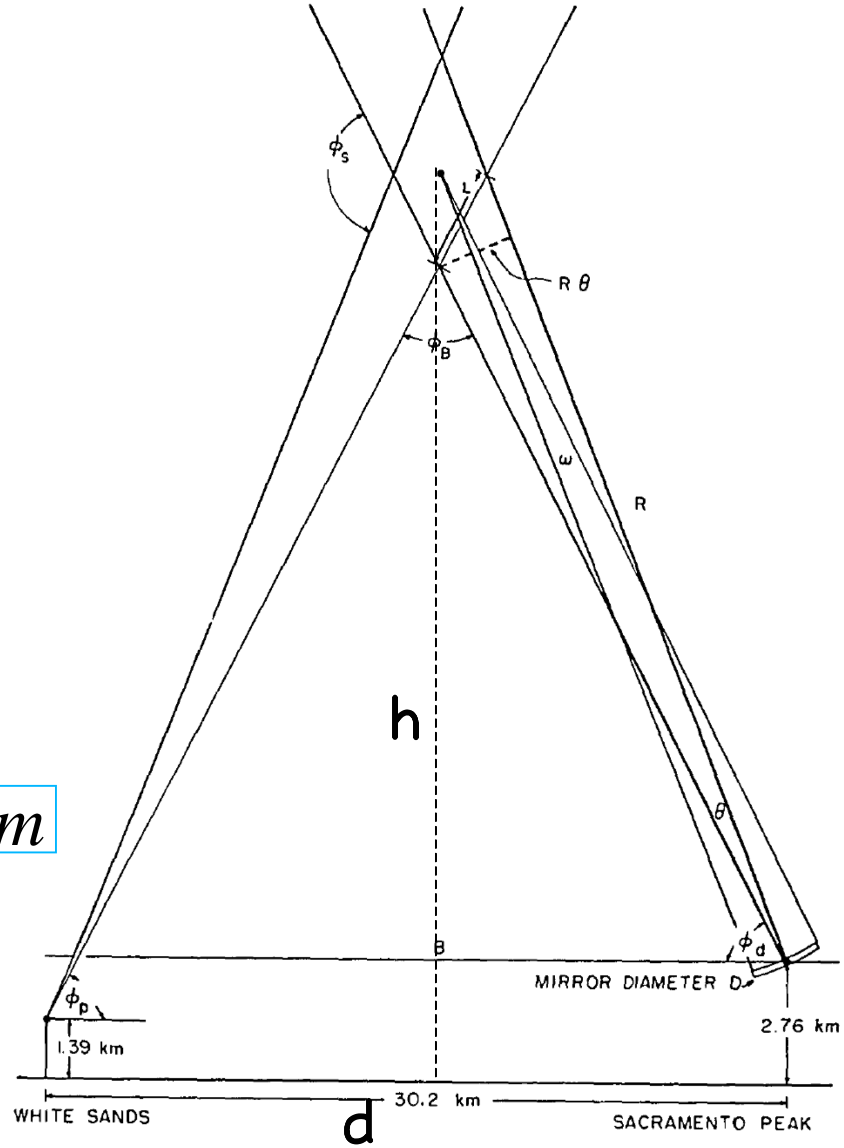


Searchlight

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

$$h = 2.76 km - 35.3 km$$

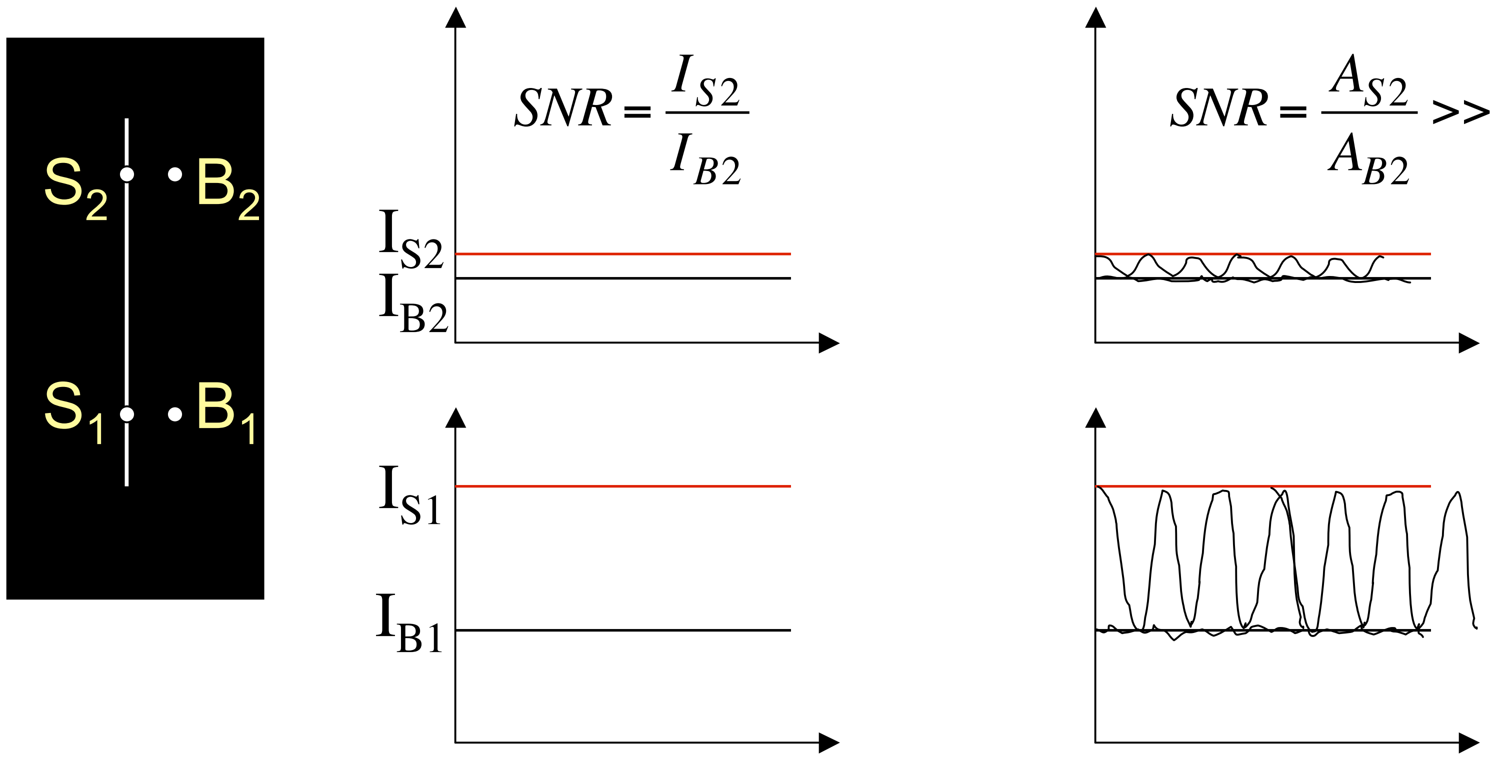
Transmitter (Projector) Angle fixed



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

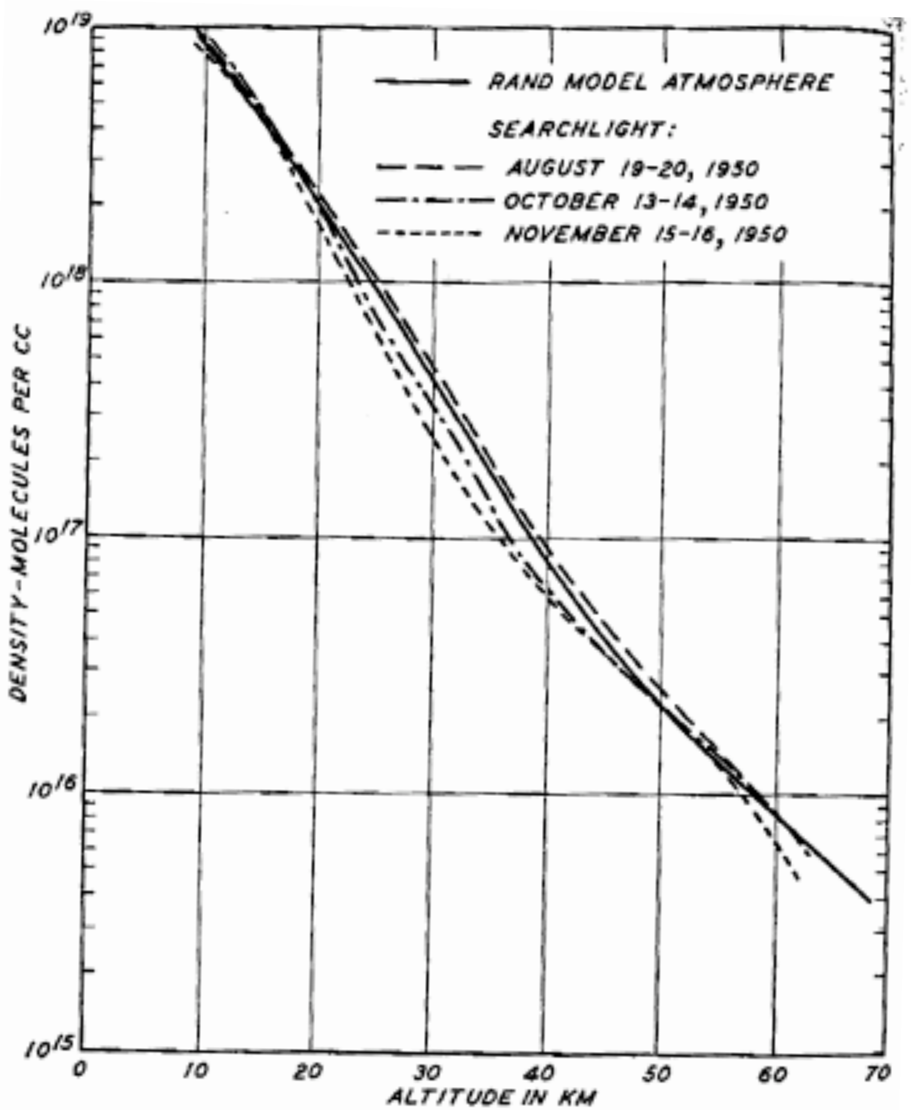


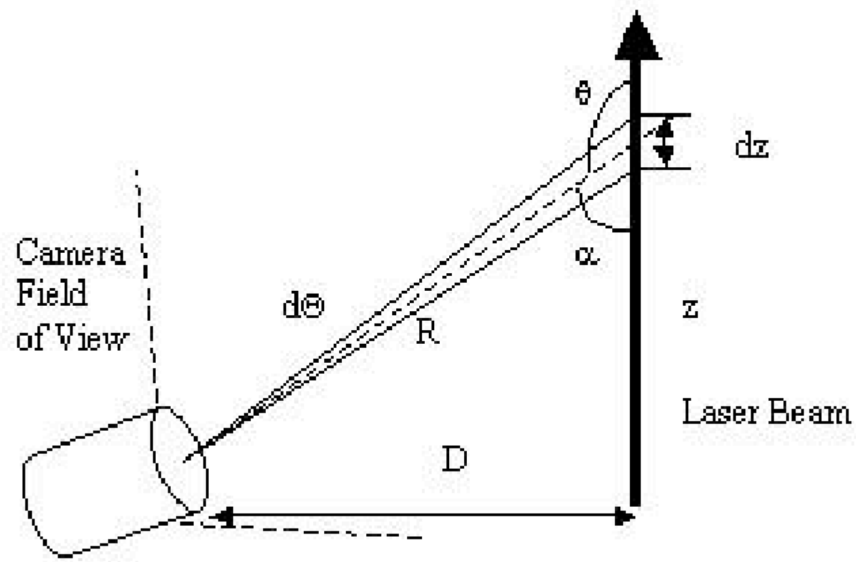
FIG. 4—DENSITY DISTRIBUTION FROM SEARCH-LIGHT DATA

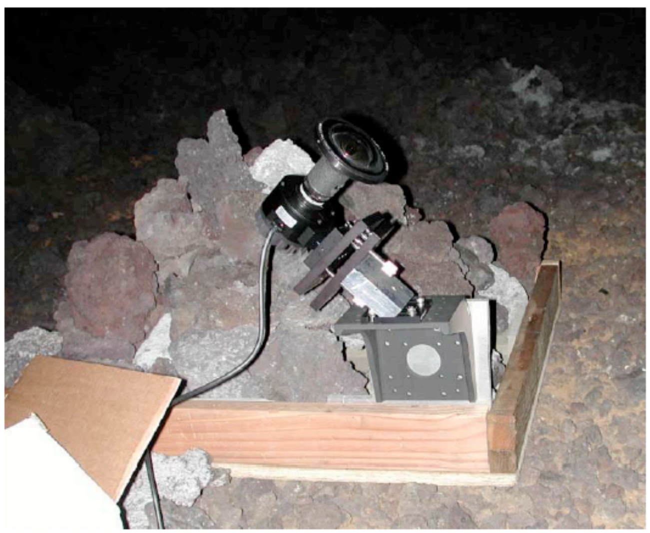
Elterman [1951]

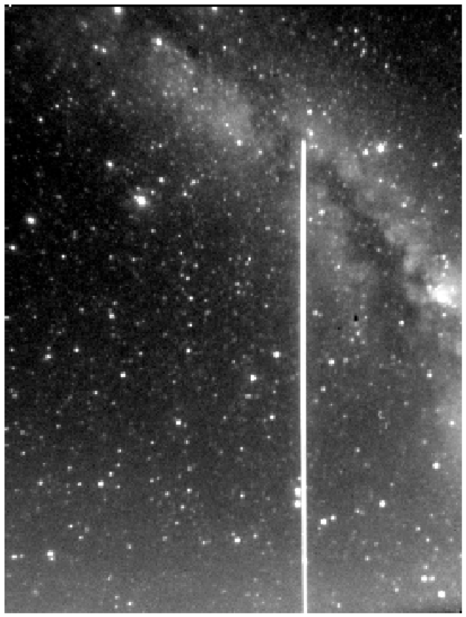
CCD-Imaging Lidar with Similar Idea

- 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.

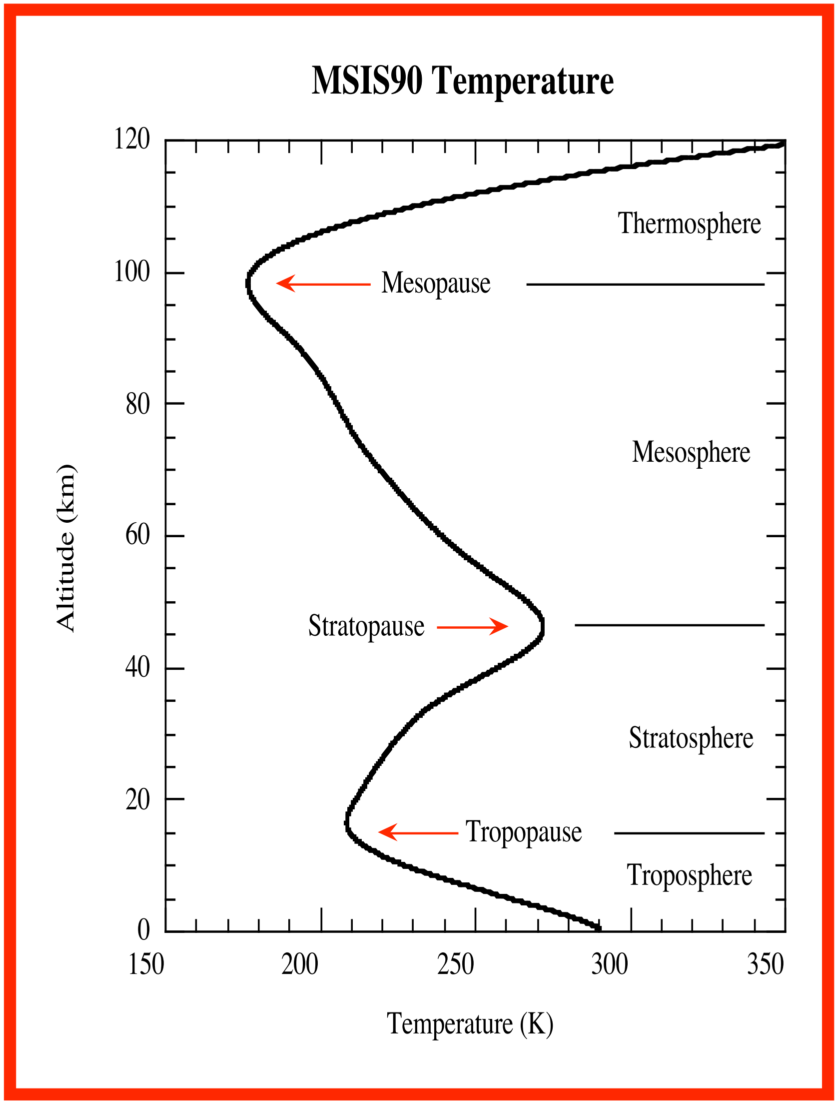
- An important advance in lidar was the recognition that the spectra of the detected radiation contained highly specific information related to the species, which could be used to determine the composition of the object region.

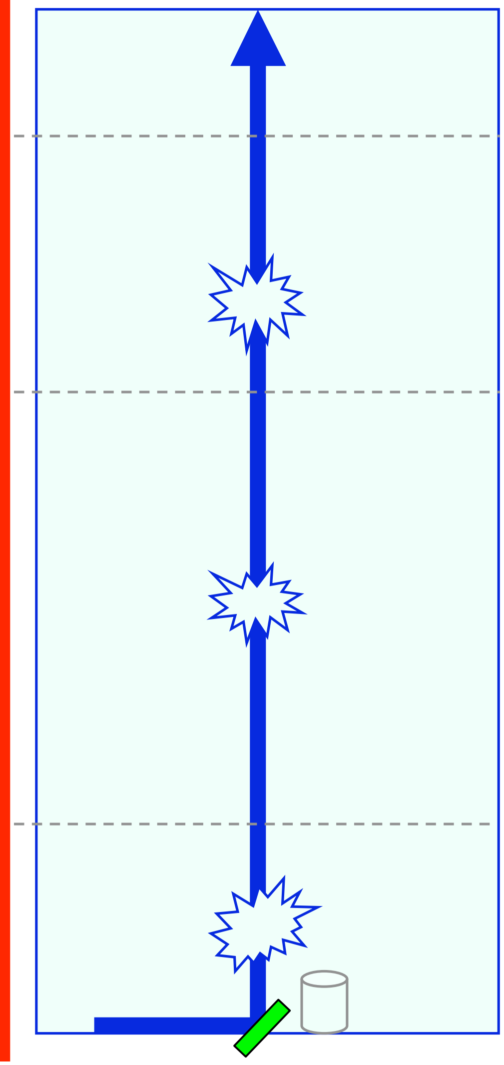
Modern Lidar Advancement

- 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).

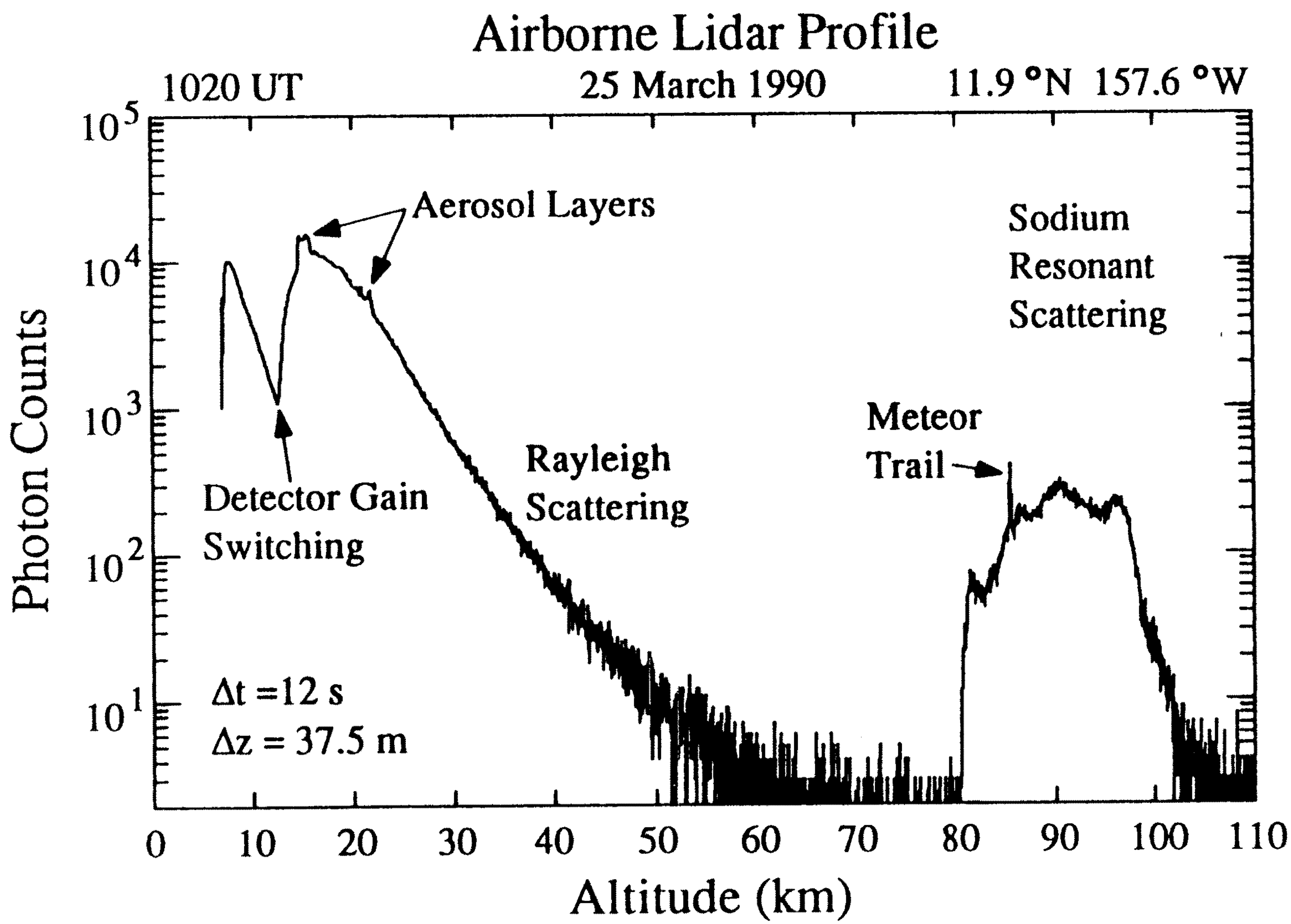
Atmosphere Lidar





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

Typical Atmosphere Lidar Profile



Modern Lidar: Target Lidar

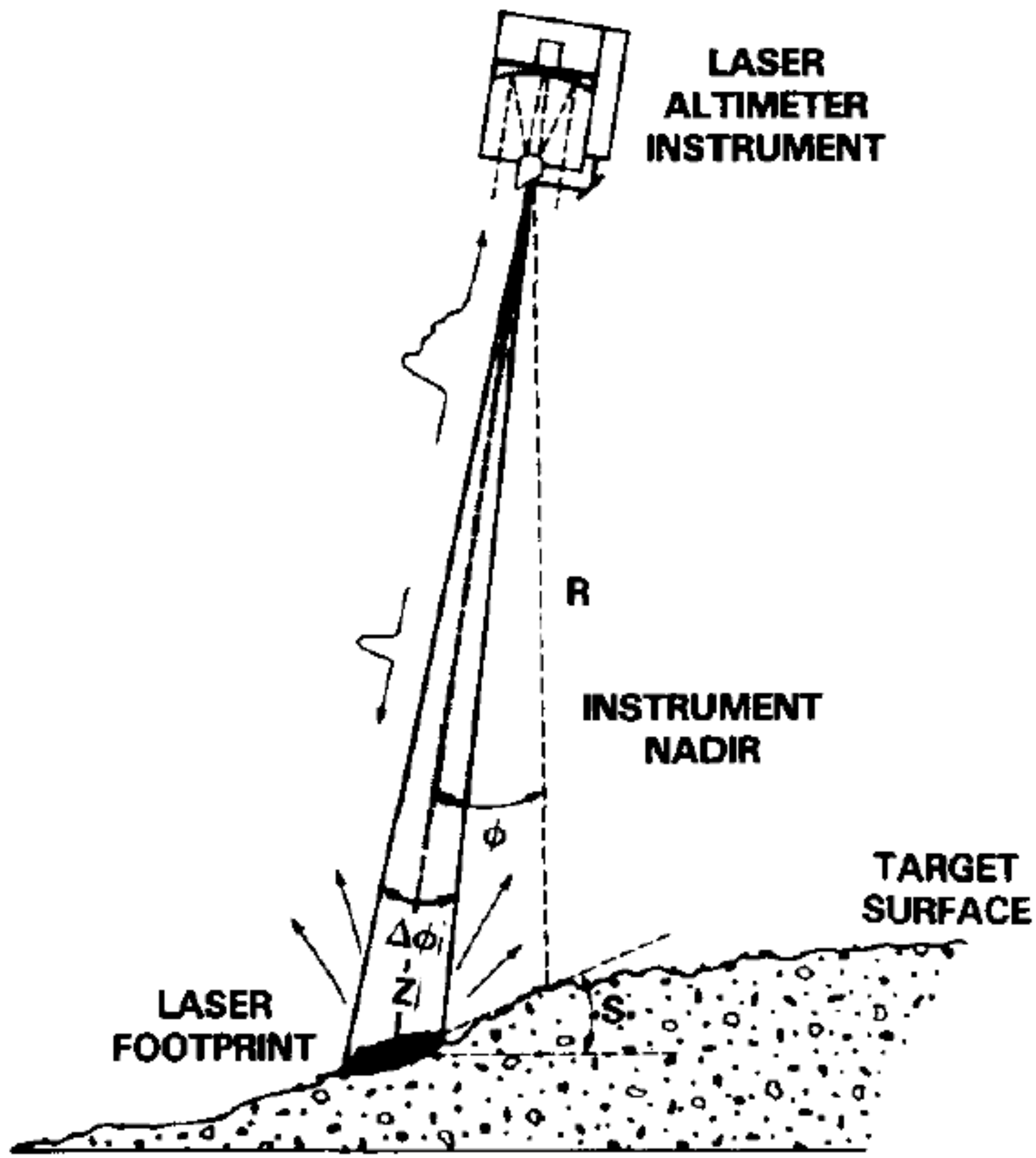
- Besides atmosphere, our environment includes many other things, like the solid earth, cryosphere, hydrosphere, and non-gas-phase objects on the earth, in the ocean, and in the air (e.g., plants, oil, buildings) etc. Study of our environment demands good measurement technology and approach for measurements 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).

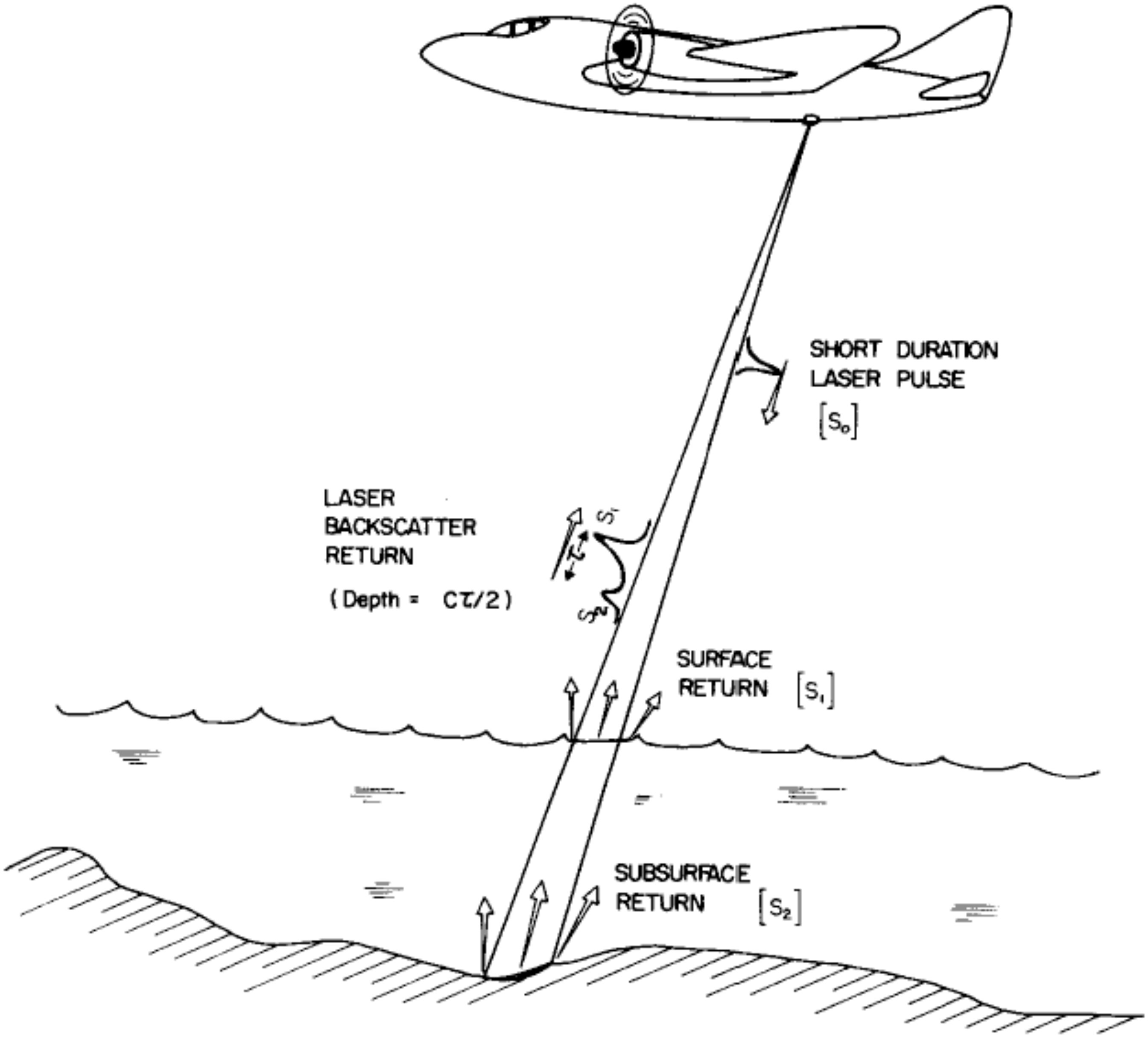
Laser Altimeter

- 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.

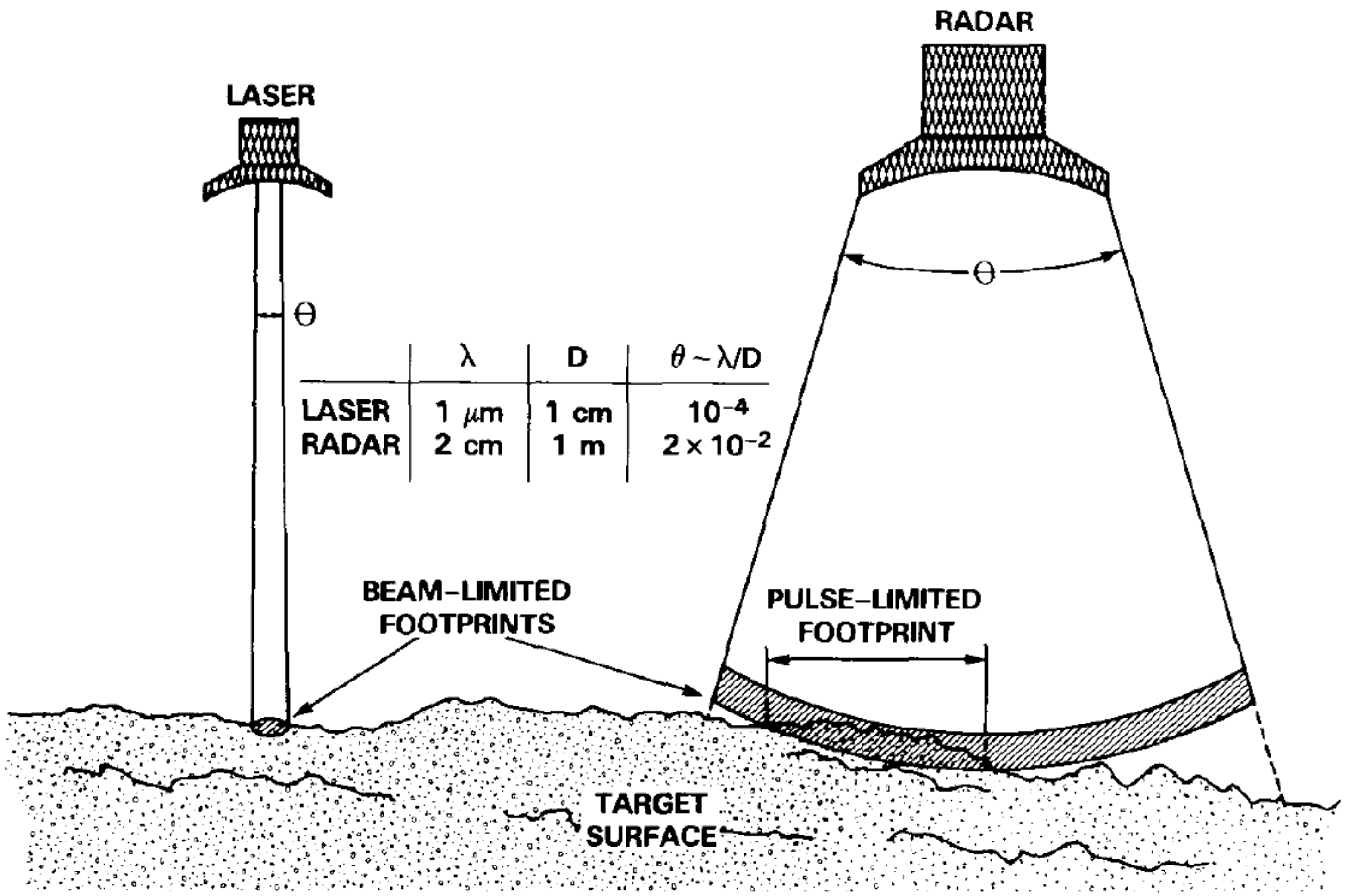
Laser Altimeter



Lidar for Hydrosphere



Laser Altimeter vs Radar Altimeter



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

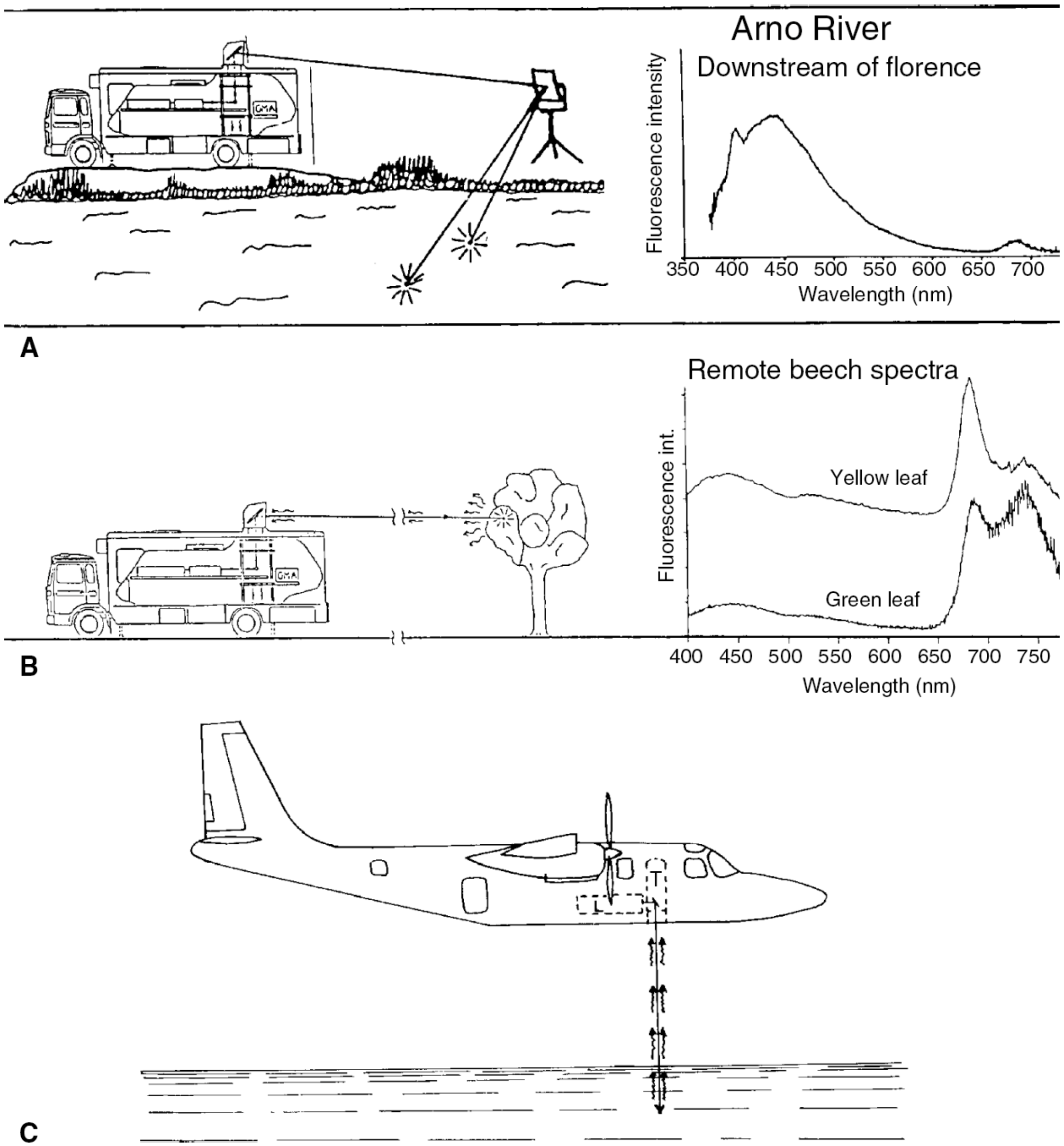
Much better resolution and precision

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

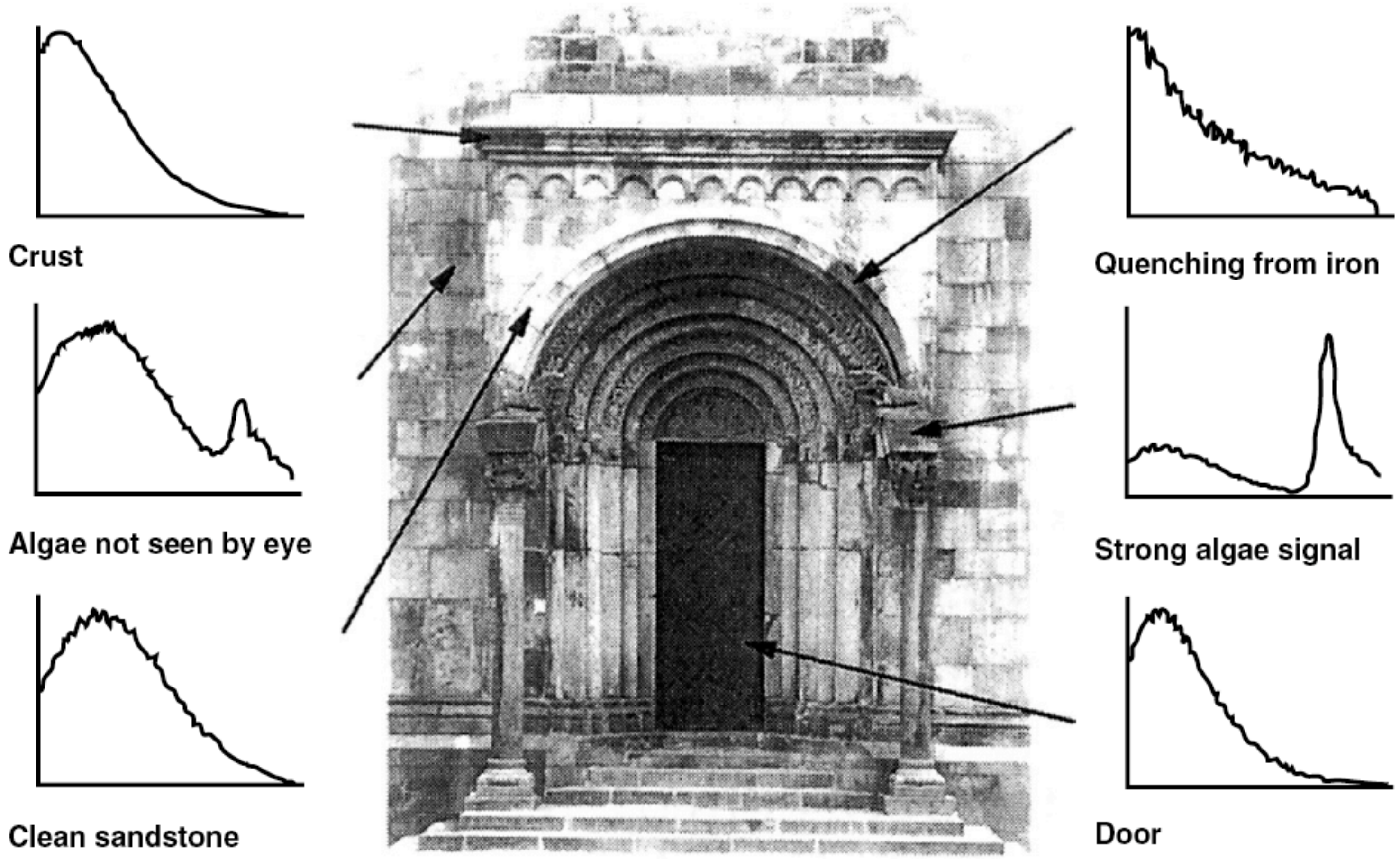
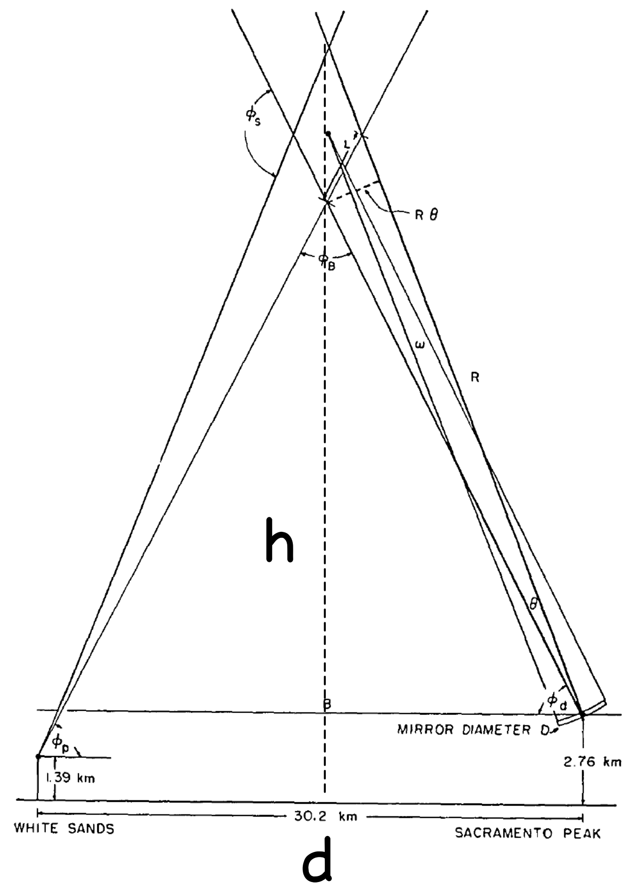


Figure 6.13 Photograph of the northern gate of the Lund Cathedral and six remotely recorded fluorescence spectra. (From Weibring, P. et al., *Appl. Opt.*, 40, 6111, 2001. With permission.)

Altitude and Range Determination

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

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



Range Determination from TOF

- 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: $\Delta R = C \Delta t/2$

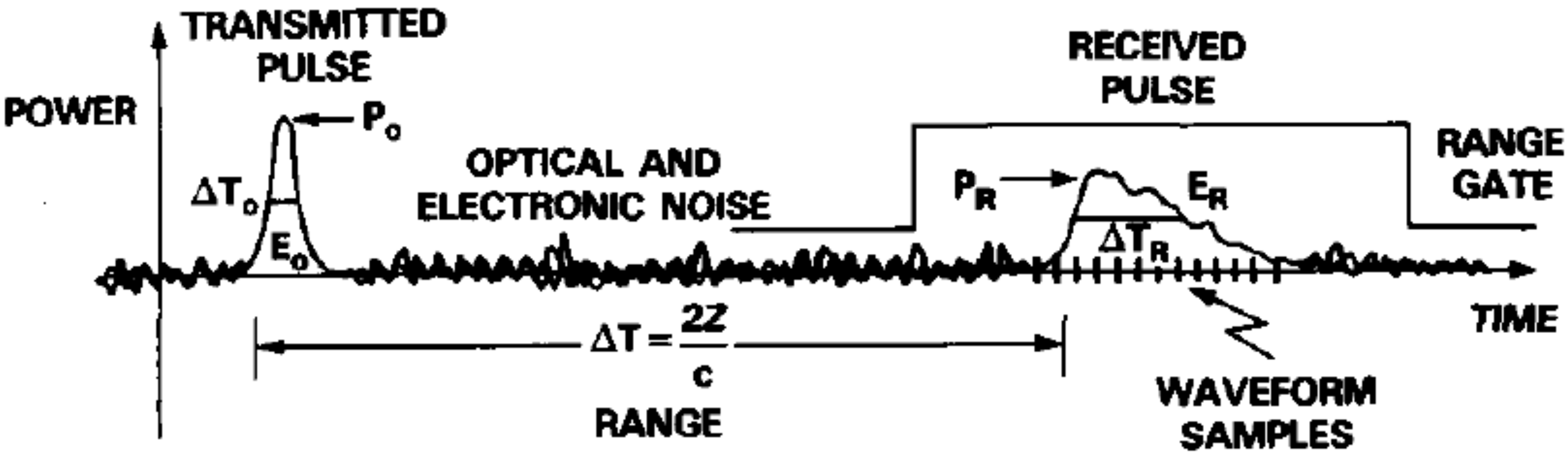
Range Determination from TOF

- 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.

Laser Altimeter and Ranging

- 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.



- 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.

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

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 from numerous atmosphere lidars to target lidars.

- Modern lidars utilize different approaches to determine altitude and range precisely: (1) geometry for searchlight or cw lidar; (2) the time of flight for ns pulse atmosphere lidar; (3) the time of flight and digitized pulse shape comparison for laser altimeter.

Chapter 1 of "Laser Remote Sensing" textbook
Chapter 5. Sections 5.1 and 5.2.1 textbook