Remote Sensing Principles and Applications Part I

Daniela Viviana Vladutescu, Ph.D.
Assistant Professor of Electrical Engineering,
ETET Department, NYCCT/CUNY

Goal for this Lecture (2-hour course)

Introduce the field of remote sensing

- The electromagnetic spectrum
- Active sensors versus passive sensors

Part I

Introduce the fundamental of lidar remote sensing atmosphere including :

- Lidar technique and system
- Principle (physical process)
- Typical application (observation examples)

Part II Remote Sensing from Space

- Design considerations

Remote Sensing as an Information Source

Remote sensing has been defined as the science (and to some extent art) of acquiring information without actually being in contact with it. Applications of remote sensing information usually fall into one of the following categories:

1. Remote sensing is used as a tool to measure properties or conditions of the land, oceans, atmosphere or objects in space.
2. Images of remotely sensed information serve as base maps on which other information is overlaid for reference and enhanced interpretation.
3. Images of remotely sensed information are used to map and quantify the spatial distribution of features.
4. Multitemporal images can be compared to quantify changes in the area and spatial distribution of features.

Remote sensing advantages over traditional data sets

- it is unobtrusive;
- one can collect information simultaneously over a broad range of the electromagnetic spectrum;
- it is capable of making biophysical measurements; information can be acquired through clouds at long wavelengths;
- data can be collected in a very short timeframe with aircraft platforms and frequently with satellite platforms;
- data collection procedures are systematic thereby eliminating sampling bias introduced in some investigations;
- and analysis methods are relatively robust, objective, and repeatable.
- This is not to say that remotely sensed data necessarily replaces existing data sets, but in many cases it provides supplemental information that can lead to improved assessments.

Applications of Remote Sensing

- Astronomical (Hubble Telescope, Very Large Array)
- Climate Change (Environmental monitoring, see the Dept. of Environmental Conservation, NOAA, Environmental Protection Agency, Dept of Energy, etc)
- Medical (Xray, Ultrasounds, etc)
- Military (surveillance and target detection, see Dept. of Defense, NASA)
- Communication systems (free space optical communications, wireless)
- Geoscience (natural hazards, earthquake and volcano monitoring etc)
- Transportation systems (GIS and aerial photography)
- Archeology (satellite images and aerial photography)
- And many more

Electromagnetic Spectrum availability for Remote Sensing on Earth

Region Name	Wavelength	Comments
Gamma Ray	<0.03 nanometers	Entirely absorbed by the Earth's atmosphere and not available for remote sensing.
X-ray	0.03 to 30 nanometers	Entirely absorbed by the Earth's atmosphere and not available for remote sensing.
Ultraviolet	0.03 to 0.4 micrometers	Wavelengths from 0.03 to 0.3 micrometers absorbed by ozone in the Earth's atmosphere.
Photographic Ultraviolet	0.3 to 0.4 micrometers	Available for remote sensing the Earth. Can be imaged with cameras and sensors.
Visible	0.4 to 0.7 micrometers	Available for remote sensing the Earth. Can be imaged with cameras and sensors.
Near and Mid Infrared	0.7 to 3.0 micrometers	Available for remote sensing the Earth. Can be imaged with cameras and sensors.
Thermal Infrared	<0.7 to 3.0 micrometers (and other windows available in LWIR)	Available for remote sensing the Earth. This wavelength cannot be captured by film cameras. Sensors are used to image this wavelength band
Micowave or Radar	0.1 to 100 centimeters	Longer wavelengths of this band can pass through clouds, fog, and rain. Images using this band can be made with sensors that actively emit microwaves.
Radio	>100 centimeters	Not normally used for remote sensing the Earth.

Passive Sensors

Passive sensors include different types of radiometers and spectrometers. Most passive systems used in remote sensing applications operate in the visible, infrared, thermal infrared, and microwave portions of the electromagnetic spectrum. Examples of Passive remote sensors are:

- **Accelerometer**—An instrument that measures acceleration (change in velocity per unit time). There are two general types of accelerometers. One measures translational accelerations (changes in linear motions in one or more dimensions), and the other measures angular accelerations (changes in rotation rate per unit time). Translational accelerations are proportional to the sum of the forces acting through the center of mass of the instrument, and rotational accelerations are proportional to the total torque acting to change the rotation of the instrument around its center of mass.

- **Radiometer**—An instrument that quantitatively measures the intensity of electromagnetic radiation in some bands within the spectrum. Usually, a radiometer is further identified by the portion of the spectrum it covers; for example, visible, infrared, or microwave. Microwave sensors are able to penetrate clouds and most rain, making them all-weather sensors.

- **Imaging radiometer—**A radiometer that has a scanning capability to provide a two-dimensional array of pixels from which an image may be produced. Scanning can be performed mechanically or electronically by using an array of detectors.

- **Spectrometer**—A device that is designed to detect, measure, and analyze the spectral content of incident electromagnetic radiation. Conventional imaging spectrometers use gratings or prisms to disperse the radiation for spectral discrimination.

- **Spectroradiometer**—A radiometer that measures the intensity of radiation in multiple wavelength bands (i.e., multispectral). Many times the' bands are of high-spectral resolution, designed for remotely sensing specific parameters such as sea surface temperature, cloud characteristics, ocean color, vegetation, and trace chemical species in the atmosphere and in snow and sea ice data.

- **Hyperspectral radiometer**—An advanced multispectral sensor that detects hundreds of very narrow spectral bands throughout the visible, near-infrared, and mid-infrared portions of the electromagnetic spectrum. This sensor's very high-spectral resolution facilitates fine discrimination between different targets based on their spectral response in each of the narrow bands.

- **Sounder**—An instrument that measures vertical distributions of atmospheric parameters such as temperature, pressure, and composition from multispectral information.

- **Active Sensors**

The majority of active systems operate in the microwave portion of the electromagnetic spectrum, which makes them able to penetrate the atmosphere under most conditions. Examples of Active remote sensors are:

Ranging Instrument—A device that measures the distance between the instrument and a target object. Radars and altimeters work by determining the time a transmitted pulse (microwaves or light) takes to reflect from a target and return to the instrument. Another technique employs identical microwave instruments on a pair of platforms. Signals are transmitted from each instrument to the other, with the distance between the two determined for the differences between the received signal phase and transmitted (reference) phase. These are examples of active techniques. A passive technique views the target from either end of a baseline of known length. The change in apparent view direction (parallax) is related to the absolute distance between the instrument and target.

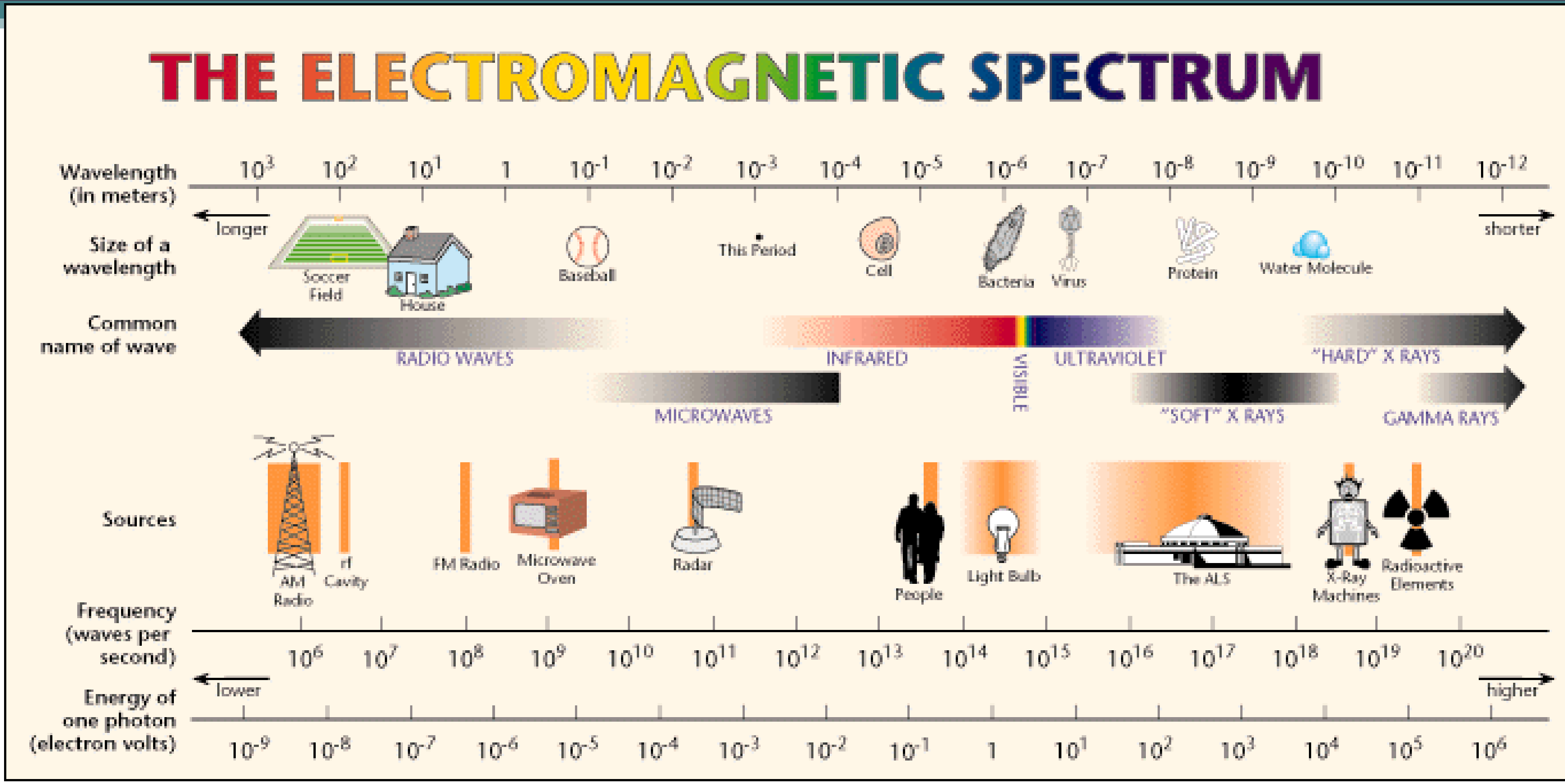
Radar—An active radio detection and ranging sensor that provides its own source of electromagnetic energy. An active radar sensor, whether airborne or space borne, emits microwave radiation in a series of pulses from an antenna. When the energy reaches the target, some of the energy is reflected back toward the sensor. This backscattered microwave radiation is detected, measured, and timed. The time required for the energy to travel to the target and return back to the sensor determines the distance or range to the target. By recording the range and magnitude of the energy reflected from all targets as the system passes by, a two-dimensional image of the surface can be produced. Because radar provides its own energy source, images can be acquired day or night. Also, microwave energy is able to penetrate clouds and most rain, making it an all-weather sensor.

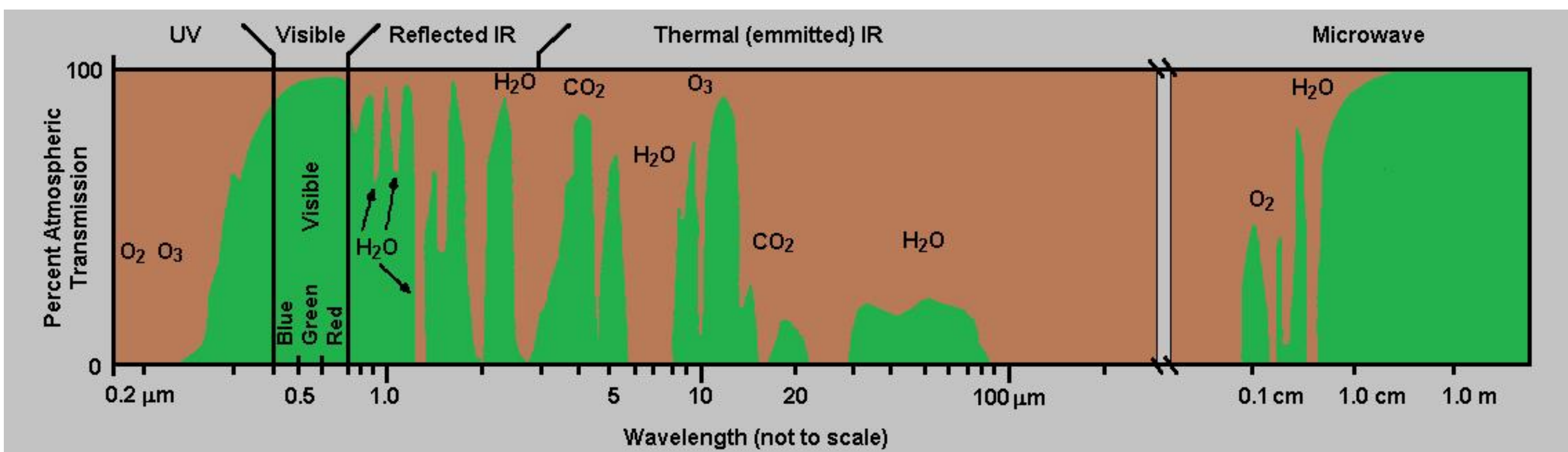
Scatterometer—A high-frequency microwave radar designed specifically to measure backscattered radiation. Over ocean surfaces, measurements of backscattered radiation in the microwave spectral region can be used to derive maps of surface wind speed and direction.

Lidar—A light detection and ranging sensor that uses a laser (light amplification by stimulated emission of radiation) to transmit a light pulse and a receiver with sensitive detectors to measure the backscattered or reflected light. Distance to the object is determined by recording the time between transmitted and backscattered pulses and by using the speed of light to calculate the distance traveled. Lidars can deter- . mine atmospheric profiles of aerosols, clouds, and other constituents of the atmosphere.

Laser altimeter—An instrument that uses a lidar to measure the height of the platform (spacecraft or aircraft) above the surface. The height of the platform with respect to the mean Earth's surface is used to determine the topography of the underlying surface.

Sounder—An instrument that measures vertical .distribution of precipitation and other atmospheric characteristics such as temperature, humidity, and cloud composition.


THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10^3 10^2 10^1 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12}
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Sources
AM Radio
rf Cavity
FM Radio
Microwave Oven
Radar
People
Light Bulb
The ALS
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}
lower
higher
Energy of one photon (electron volts)
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10^1 10^2 10^3 10^4 10^5 10^6


UV
Visible
Reflected IR
Thermal (emmitted) IR
Microwave
Percent Atmospheric Transmission
100
0
O_2 O_3
Visible
Blue
Green
Red
H_2O
H_2O
CO_2
O_3
H_2O
CO_2
H_2O
H_2O
O_2
0.2 µm
0.5
1.0
5
10
20
100 µm
0.1 cm
1.0 cm
1.0 m
Wavelength (not to scale)

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Part I Outline

1. **What is the lidar?**
2. **Lidar system and how it works**
3. **Principle of lidar remote sensing atmosphere (physical process)**
4. **Basic lidar returns equation**
5. **What can lidar measure in atmosphere?**
6. **Summary**

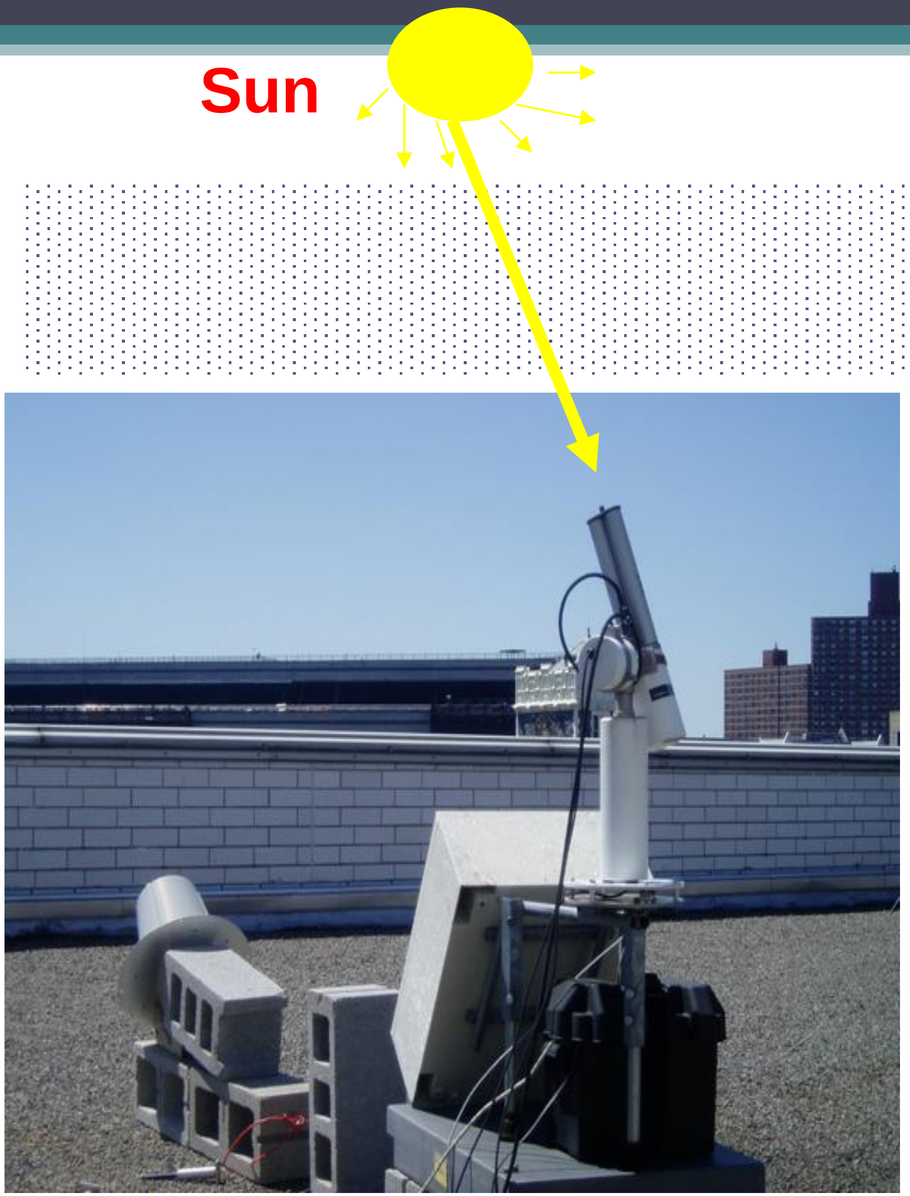
We only focus on atmospheric monitoring lidar.

1. What is the lidar?

- **LIDAR: Light Detection And Ranging,** or laser radar
  An optical remote sensing technology that measures properties of scattered light to find range and/or other information of a distant target.
  It uses the same principle as RADAR except that it uses a laser instead of radio waves.

- **Lidar VS. Radar** (different transmitting wavelength)
  Radar: microwaves, wavelength: 0.3-10 cm, detect big particles
  and target (> 0.1 mm) such as rain and clouds droplet
  Lidar: shorter wavelength: 0.25-1μm, detect small particles
  such as aerosol and molecule

- **Active VS. Passive**
  Active: instruments generate their own illumination/radiation source.
  such as RADAR, LIDAR, SODAR
  Passive: The source of energy is the environment: naturally occurring
  radiation from the sun and the Earth,
  such as radiometer or sun-photometer



Passive remote sensing:

Sun-photometer

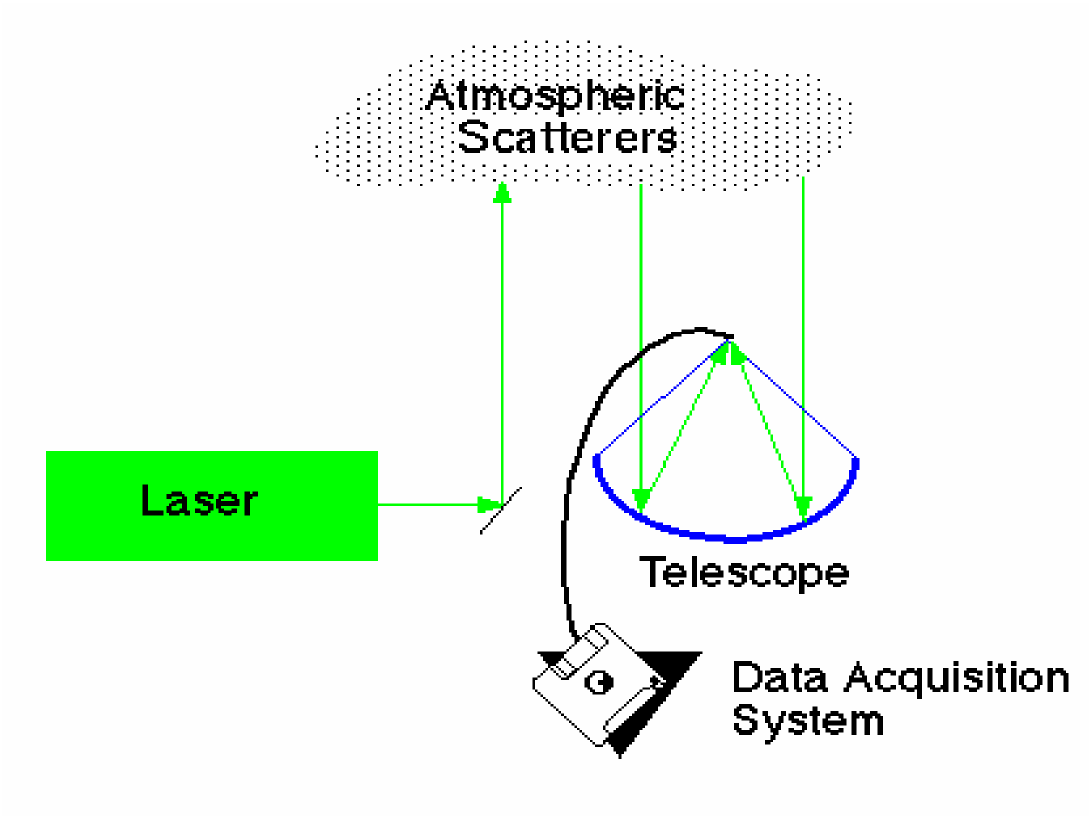
Measure the whole column information of atmosphere (aerosol and water vapor)

Light source: Sun

No range-resolved information

No work in the night and overcast sky

A simple schematic diagram for LIDAR



<u>The lidar's transmitter is a laser, while its receiver is an optical telescope.</u>

Advantage of lidar remote sensing

- Active remote sensing
- Range-resolved information
- Highly temporal and spatial resolution

The term ‘**aerosol in the atmosphere**’,

A suspension of small particles in a gas.

The particles may be solid or liquid or a mixture of both.

How it works

LIDAR: Light Detection And Ranging

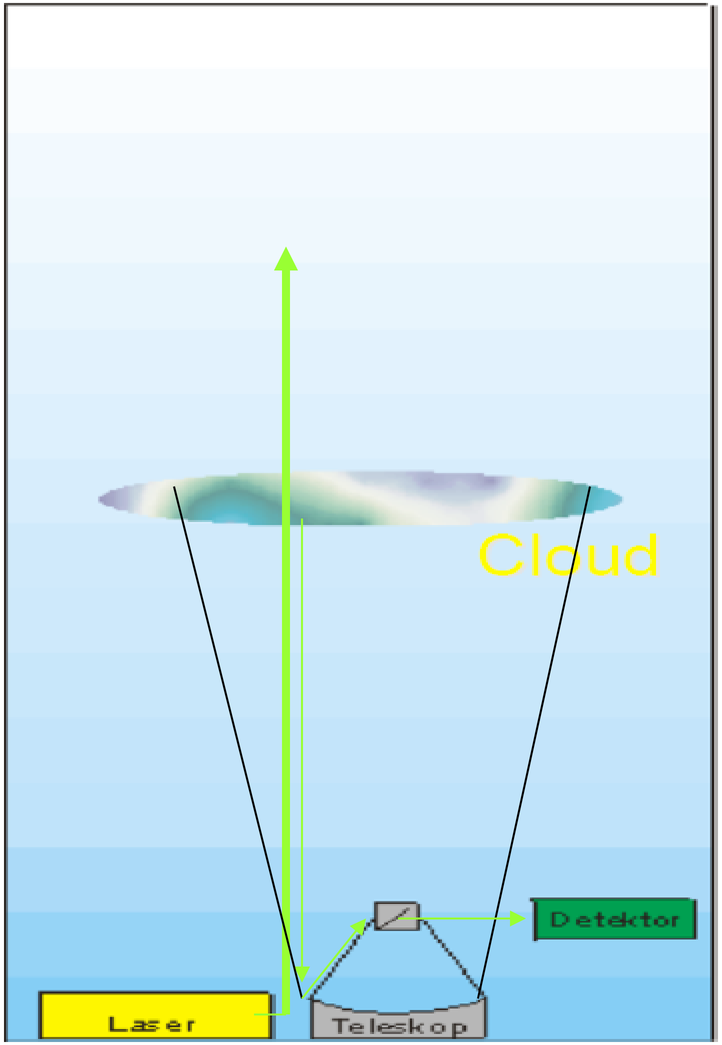
- Send light to the atmosphere

- Record light scattered by the atmosphere as function of time

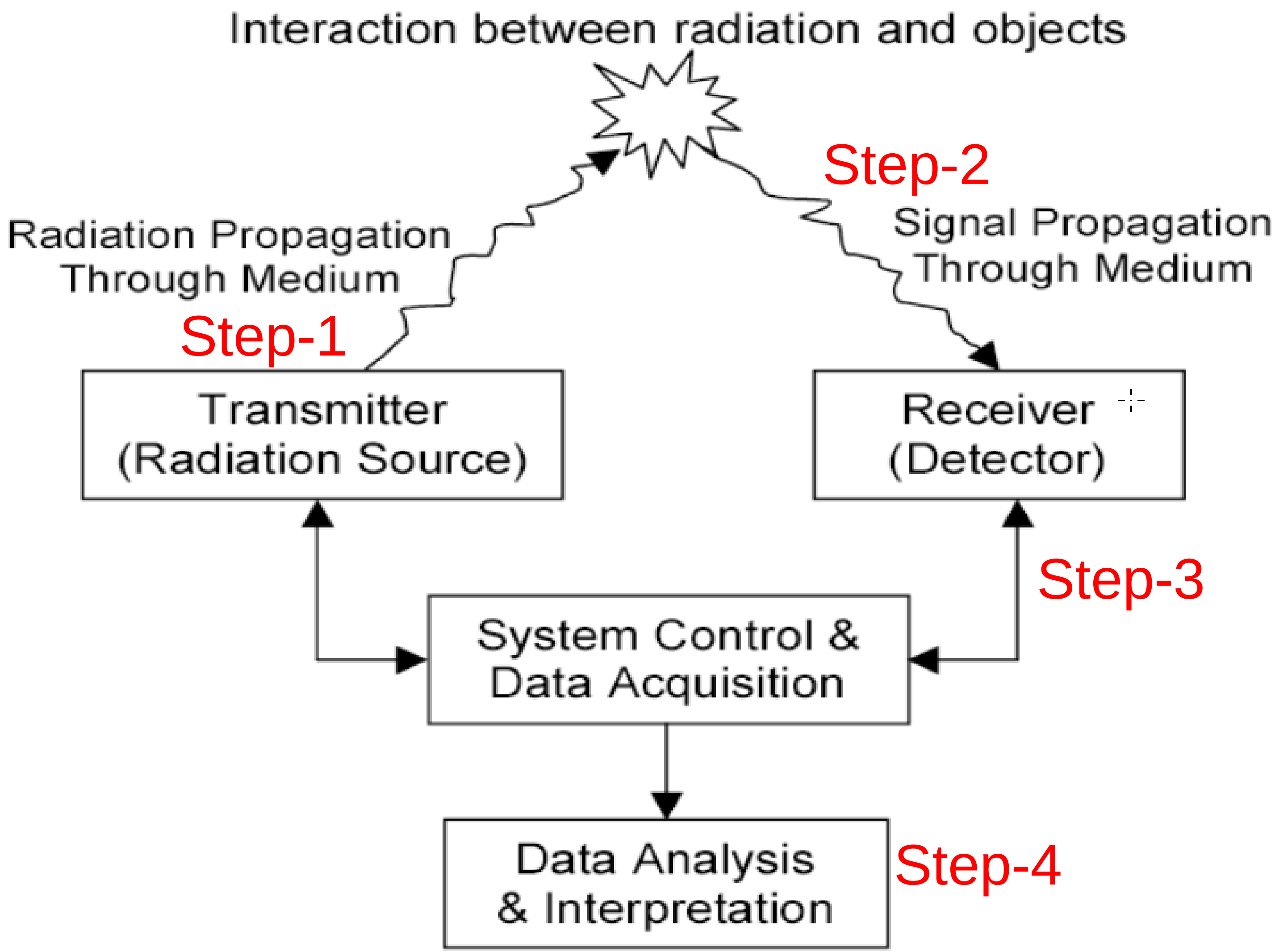
- Convert time of flight to distance
  (1 ms ~ 150 km)

$R = c \bullet \Delta t/2$,

C: light speed, 3×10^8 m/s



Active Remote Sensing



HOW IT WORKS:

1. Laser transmits beams to atmosphere
   A Photo-diode detects the start-time when laser beams go out,
   then make the trigger pulses to detector, data acquisition system
   Time-range relationship: $Z=C \bullet t/2$,
   c is light speed, $3.0*10^8$ m/s
   $t=1\ \mu s$, $z=150$ m; $t=1$ ms, $z=150$ km
2. Receiver telescope collects the atmospheric return signals,
   separate the different wavelength optical signals by delay-optics
   send them to detectors
3. Data acquisition samples the electrical signals from detectors output,
   then store data in computer
   Range resolution VS sampling rate: $\Delta Z=C\bullet \Delta t/2$,
   10MHz---10^{-7} sec=100 ns=0.1 μs; 10MHz----- 15 meter
   40MHz---3.75 meter
4. Analyze data for atmospheric research

2. Lidar system and main components

- **Laser transmitter: laser and steering mirrors**
  (Wavelength, pulse energy, repetition rate, divergence angle, pulse- width etc)

- **Optical receiver: telescope and delay-optics**
  (Newtonian/Cassegrain, diameter, Field-of-View)
  (narrrowband filter, beam-splitter, collimator lens)

- **Signal detection**
  Detector PMT or APD (Avalanche photodiode) and pre-amplifier
  (spectral sensitivity, quantum efficiency, gain, dark-current)

- **Data acquisition and control**
  A/DC: Analogue to digital converter (8~32-bits, sampling rate)
  Photon-counter (count rate, dead time)
  Control: scanner, synchronizer and computer

Key component: **Laser (light source) ---1**

- Acronym for *Light Amplification by Stimulated Emission of Radiation*
- Narrow, low-divergencemonochromatic beam with a well-defined wavelength, high power/energy
- Main specifications:
  - wavelength, UV,visible, infrared
  - power, μJ~J (joule) (issue: eye-safe)
  - repetition rate (1~KHz)
  - pulse width: ns
  - divergence angle: mrad

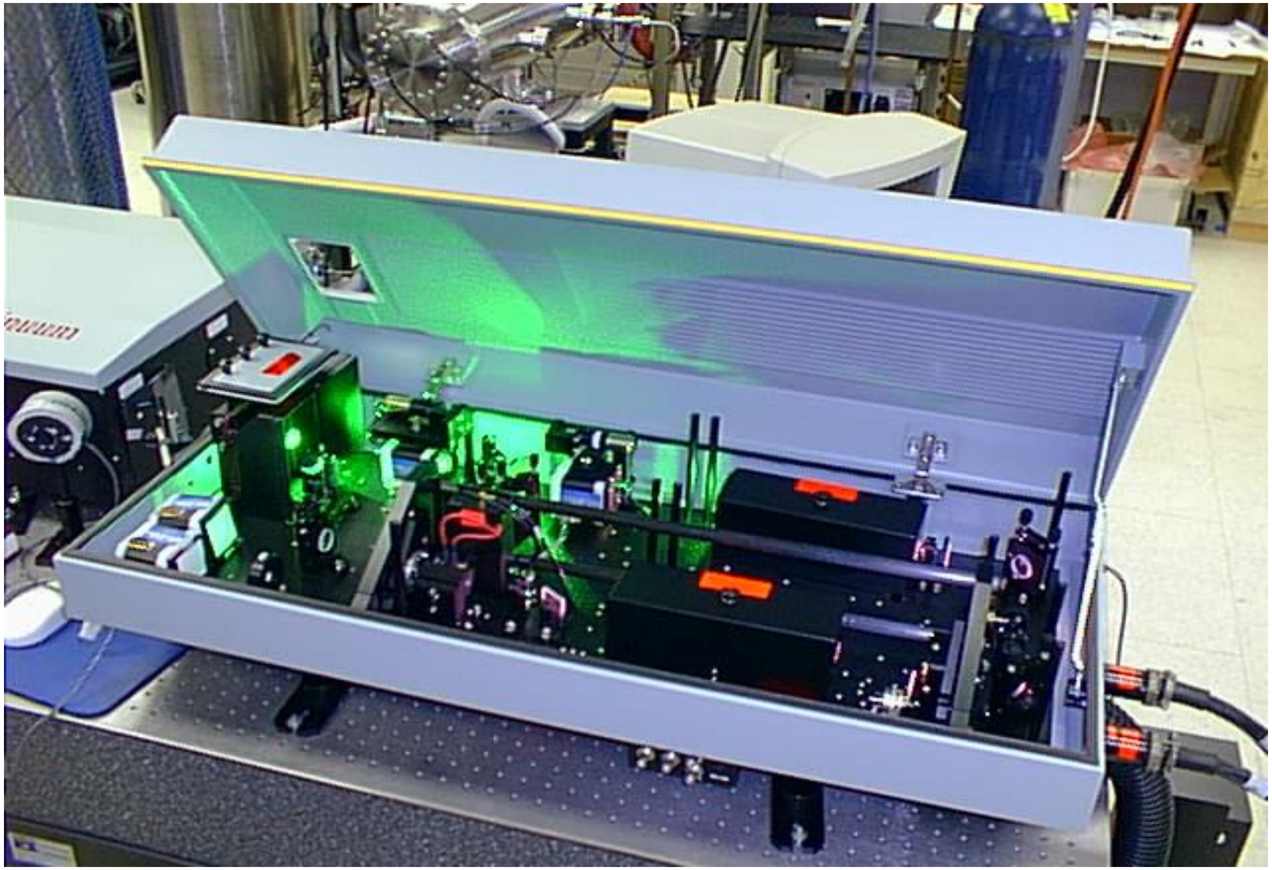


Fig. Powerlite Nd:YAG

Key component: **Interference filter ---2 (suppress sky-light noise)**

Main specifications:

- Center wavelength:
- Bandwidth (1.0~0.2 nm)
- Peak transmittance %: >30%
- Block ratio: 1e-7

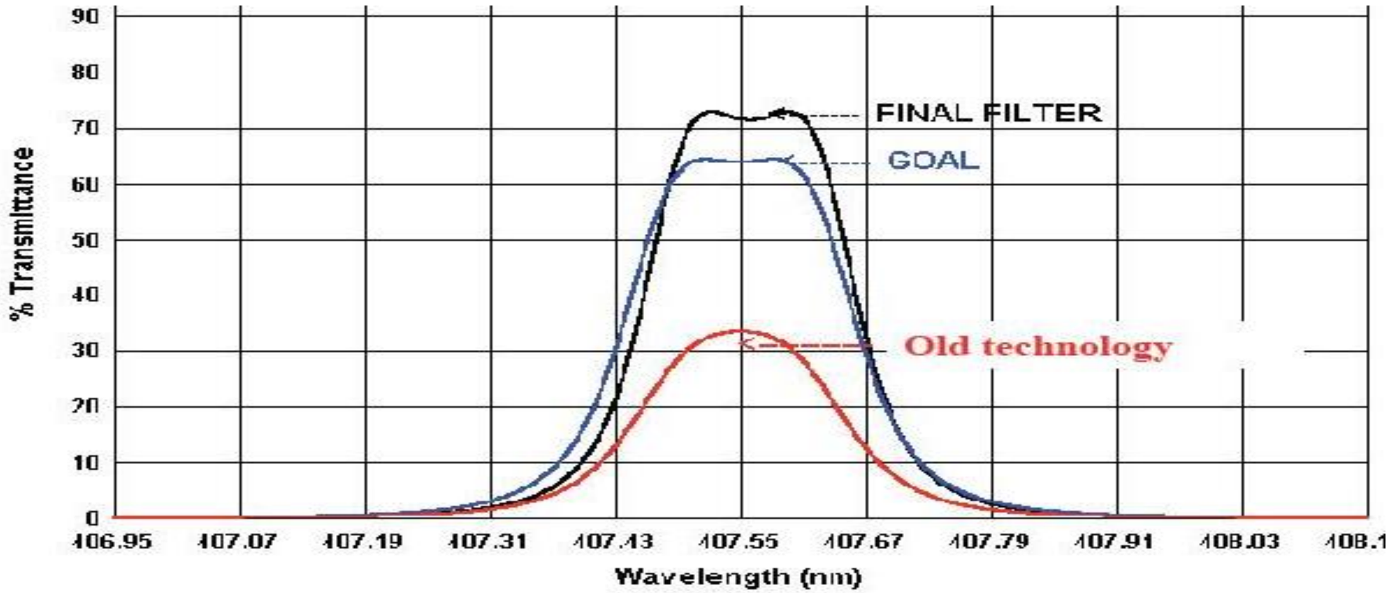


Figure- Lidar system prototype

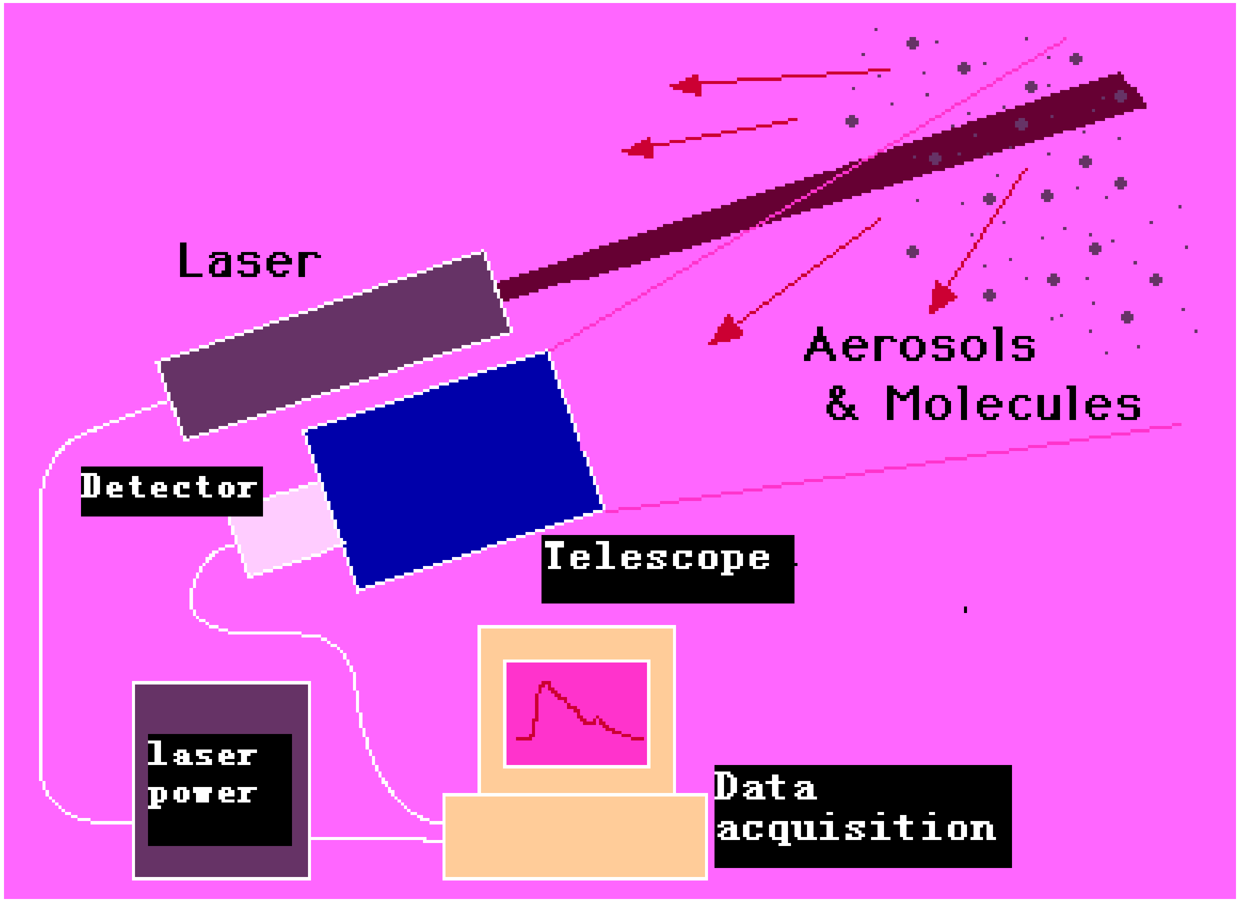


Figure- Micropulse lidar (commercial product)

1.ND:YLF Laser (523.5-nm)
semiconductor laser,
Output Energy 10 μj
Pulse Repetition Frequency 2500 Hz

2. **Transceiver: diameter** 20 cm
Beam Divergence 50 μrad
Field-of-View 100 μrad

3.Detector: Si:APD

4.Data acquisition:
photon-counter
Vertical Resolution 30 m - 300 m

5.Detection objective:
aerosol, cloud and PBL

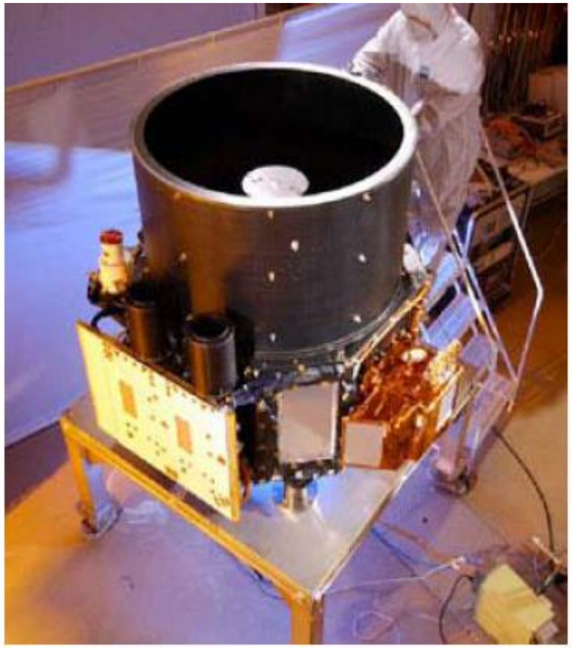
6. Working mode: 24-hr/7
No operator

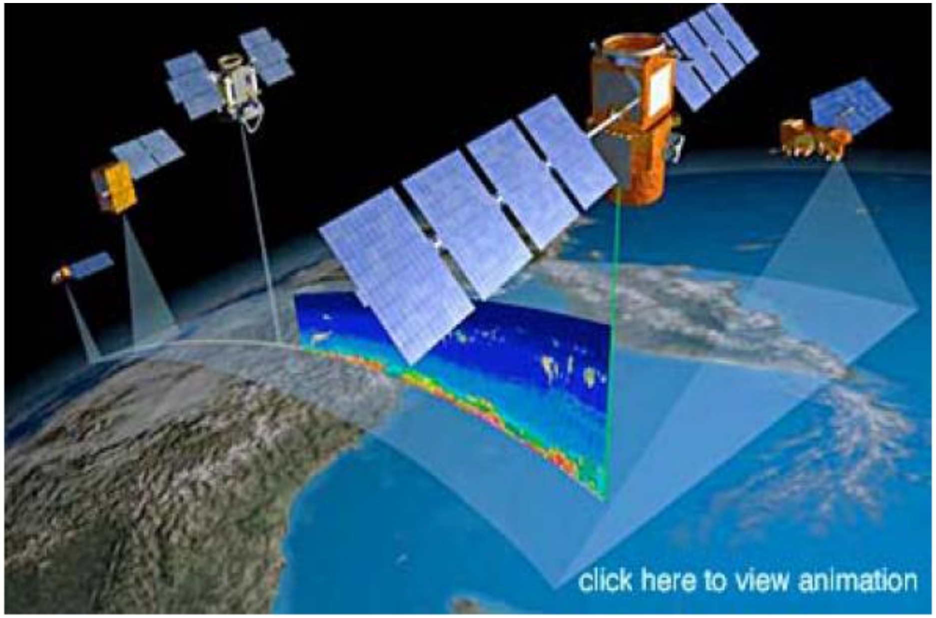
http://www.sigmaspace.com/sigma/micropulseLidar.php

Figure- Satellite-borne lidar CALIPSO

(launched in April 2006 by NASA to be part of the A-Train constellation at an altitude of 690 km**) .**

Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO)





http://www-calipso.larc.nasa.gov/

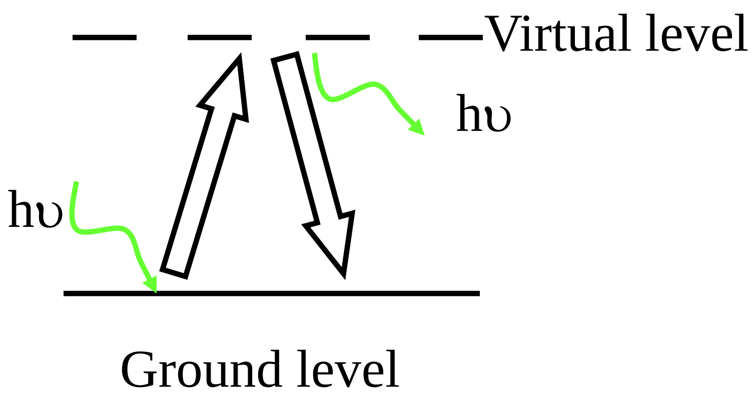
3. Principle of lidar remote sensing atmosphere

Physical process of laser and atmosphere

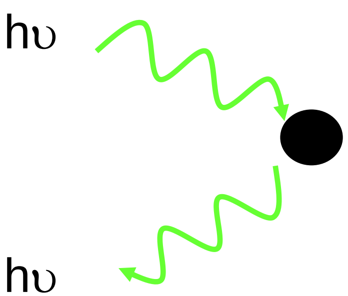
- Elastic-scattering of molecule and particle (Rayleigh-Mie scattering)
- Raman-scattering (Water vapor, CH_4, N_2, O_2)
- Absorption of trace gas (Ozone, SO_2, NO_2 etc.)
- Fluorescent scattering (Na^+, Ca^+)
- Doppler shift

Lidar Interaction Elastic-scattering Mechanisms

- Rayleigh Scattering relevant for molecular gases including N_2,O_2 where $d \ll \lambda$
  - "Laser radiation elastically scattered from atoms or molecules is observed with no change of frequency"

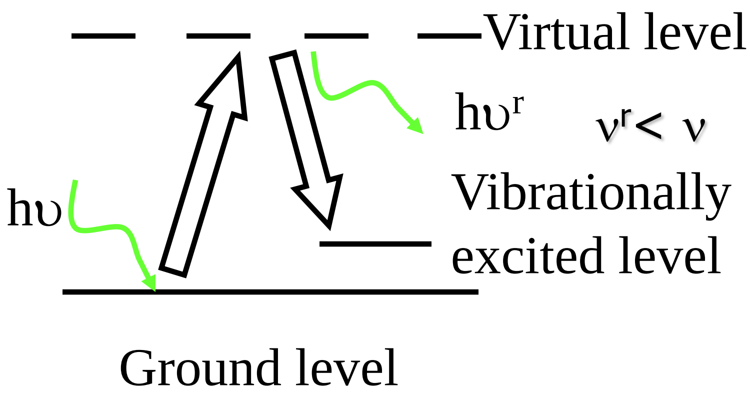


- Mie Scattering for particulates (spherical) where $d \sim \lambda$
  - "Laser radiation elastically scattered from small particulates or aerosols (of size comparable to wavelength of radiation) is observed with no change in frequency"



No wavelength Change in either mechanism

Lidar Interaction Inelastic-scattering Mechanisms



$\nu^r < \nu \longrightarrow \lambda^r > \lambda$

Raman Transition radiation generated at longer wavelength from excitation

- Raman Scattering
  - "Laser radiation inelastically scattered from molecules is observed with a frequency shift characteristic of the molecule ($h\nu$ - $h\nu^r$ = E)"

$$\lambda = 355 \text{ excitation} \quad \begin{array}{l} \nearrow \lambda_R^{N_2} = 387, \\ \searrow \lambda_R^{H_2O} = 407, \end{array}$$

Physical process between laser-beam and atmospheric medium

(λ_t incident laser wavelength (WL)，λ_r receiving wavelength）

Physical-process	Medium	WL	Cross-section (cm^2)	Detection objective
Rayleigh-scat	molecule	$\lambda t = \lambda r$	10^{-27}	Air density， temperature
Mie-	aerosol	$\lambda t = \lambda r$	$10^{-8} \sim 10^{-27}$	Aerosol, cloud
Raman-	molecule	$\lambda t \neq \lambda r$	10^{-30}	Trace-gas (H2O,SO2,CH4)
Resonance-	atom &mol	$\lambda t = \lambda r$	$10^{-14} \sim 10^{-23}$	Metal atom and iron Na^+, K^+,Ca^+, Li
Fluorescence	molecule	$\lambda t \neq \lambda r$	$10^{-16} \sim 10^{-25}$	
Absorption	atom & mol	$\lambda t = \lambda r$	$10^{-14} \sim 10^{-21}$	Trace-gas(O3， SO2,NO2 etc)
Doppler-shift	atom & mol	$\lambda t \neq \lambda r$		Wind-speed,direction

Common types of Lidar & their application

1.Mie-scattering lidar: aerosol, clouds

2.Raman-Lidar: Vibrational and rotation-Raman lidar
Aerosol, Cloud, Water vapor, Ozone, CH_4 and temperature

3.DIAL(DIAL): trace-gas, Ozone, Water vapor, SO_2, NO_2 , etc

4.High-Spectral Resolution Lidar (HSRL):
Separate molecular and aerosol scattering, aerosol & cloud

5.Rayleigh-Lidar: stratosphere-mesosphere temperature

6.Resonance-fluorescence lidar: metal atom Na, Fe, Ca

7. Doppler-Lidar: wind field

4. Elastic-scattering lidar returns equation

The reflected power from the atmosphere, P_r , as a function of range, R and wavelength λ, C (Callibration Constant:Includes Detector Area and Efficiencies, Field of View of Telescope etc.)

$\alpha_T = \alpha_M + \alpha_A$: total atmospheric (molecular + aerosol) extinction including Absorption + Scattering coefficient (m^{-1}) (it is a function of object scattering or absorption properties and concentration)

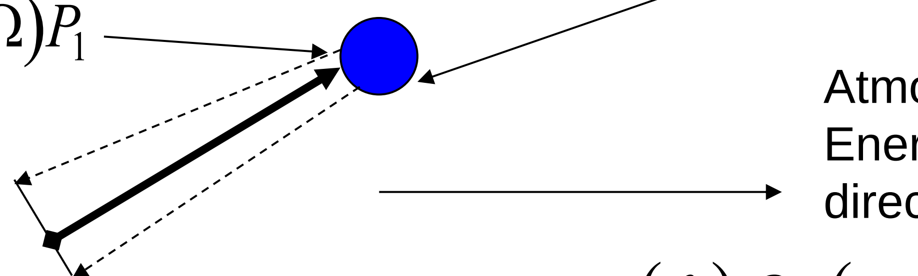
P_0= transmitted peak power (W).

$\beta_T = \beta_M + \beta_A$: Total Backscatter (m^{-1} sr^{-1})

$$P_1(R) = P_0 e^{-\int_0^R [\alpha_T(r)]dr}$$

$$d\Omega = \frac{A}{R^2}$$

$$P_2 = \left(\beta_T(R)\, d\Omega\right) P_1$$



Atmospheric Extinction takes Energy out of the beam in both directions

Standard Lidar Equation

$$P_r(R,\lambda) = \frac{C P_0(\lambda)\beta_T(R,\lambda)}{R^2} e^{-2\int_0^R [\alpha_T(R,\lambda)]dr}$$

Elastic-scattering lidar returns equation

1. Lidar returns (basic lidar equation, single scattering)

$$P(\lambda,z) = EC\left[\beta_m(\lambda,z) + \boldsymbol{\beta}_\mathbf{P}(\lambda,z)\right]T_m{}^2(\lambda,z)\mathrm{T}_\mathrm{P}{}^2(\lambda,z)/z^2 + P_{noise}$$

P(λ,z): Lidar return signals intensity.

E: Laser pulse energy

C: System constant

$$C(\lambda) = \eta_{trans.opt}(\lambda)\times A(\lambda)\times\eta_{rec.opt}(\lambda)\times\eta_{electron}(\lambda)$$

$\beta_{m,p}$: backscatter coefficient, m-molecule, p-particle or aerosol

$T^2_{m,p}$: two-way transmittance

$$T^2{}_{m,p}(\lambda,z) = \exp(-2\int_{z_0}^{z}\alpha_{m,p}(\lambda,z)dz)$$

Two unknown parameters: backscatter and transmittance (extinction)

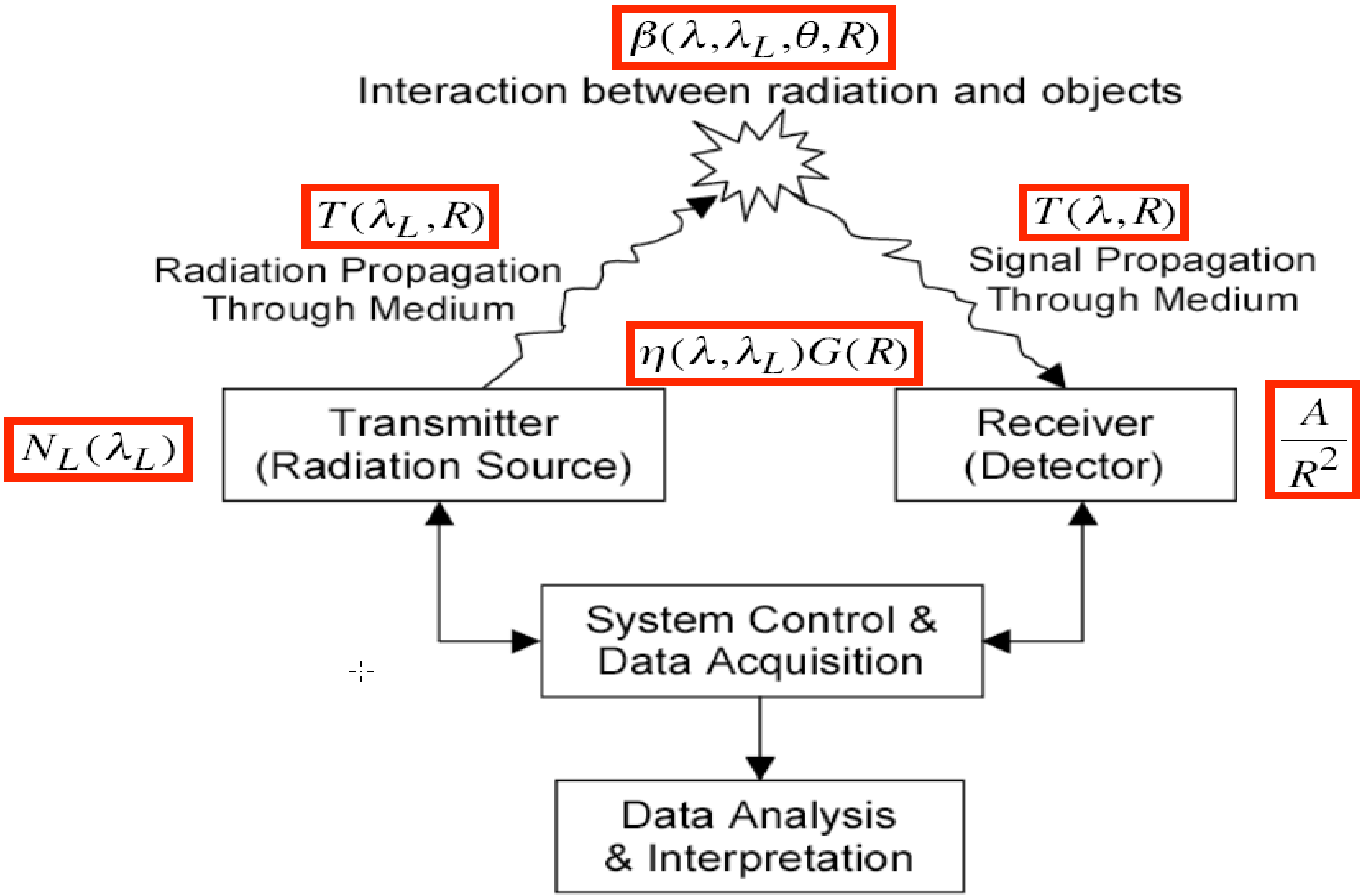
P_{noise}: background and detector noise

$P_{noise}=P_{sky}+P_{d\text{-}dark}+P_{d\text{-}thermo}$

Main factors to influence Signal-to-Noise Ratio (SNR):

Laser energy, telescope effective area, optical -electronic efficiency, species contents

Each physical item in Lidar equation



N2-Raman (inelastic)-scattering lidar equation

$$P(\lambda_n, z) = EC\left[\beta_n(\lambda_n, z)\right] T_m(\lambda_0, \lambda_n, z) \mathrm{T}_\mathrm{P}(\lambda_0, \lambda_n, z) / z^2 + P_{noise}$$

β_n: N2-Raman backscatter coefficient, no aerosol

$T_{m,p}$: One-way transmittance from both molecule and aerosol

Advantage:
Only extinction coefficient is unknown, easy solution

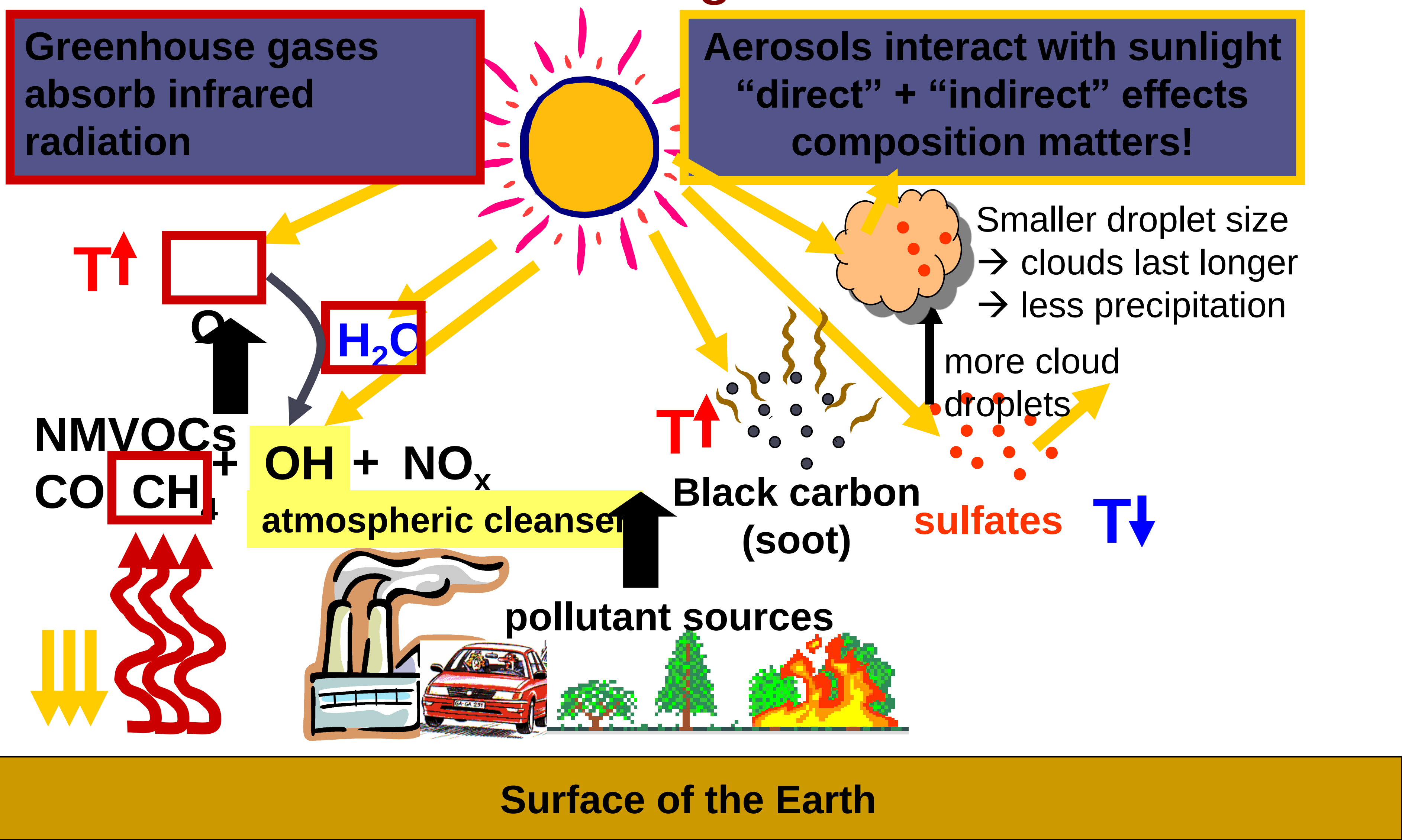
Disadvantage: weak signals

5. What can lidar measure?

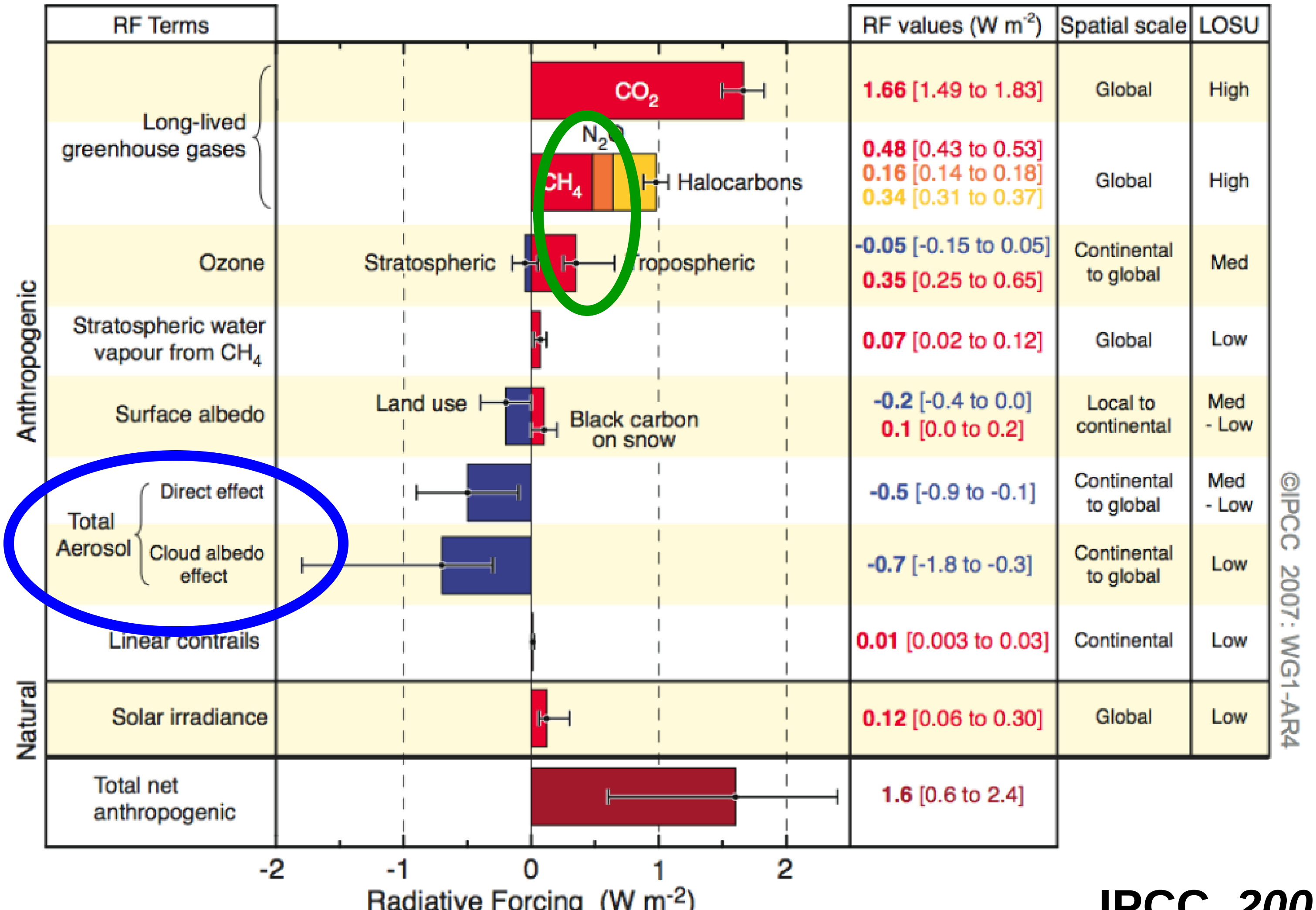
Application in atmospheric remote sensing: observation examples

- **Aerosol-cloud (particle) detection**
- **Planetary Boundary Layer detection**
- **Water vapor distribution**
- Meteorological visibility
- Ozone and SO_2 detection
- Temperature profiles

Air pollutants affect climate by absorbing or scattering radiation



Radiative forcing of climate (1750 to present): Important contributions from air pollutants

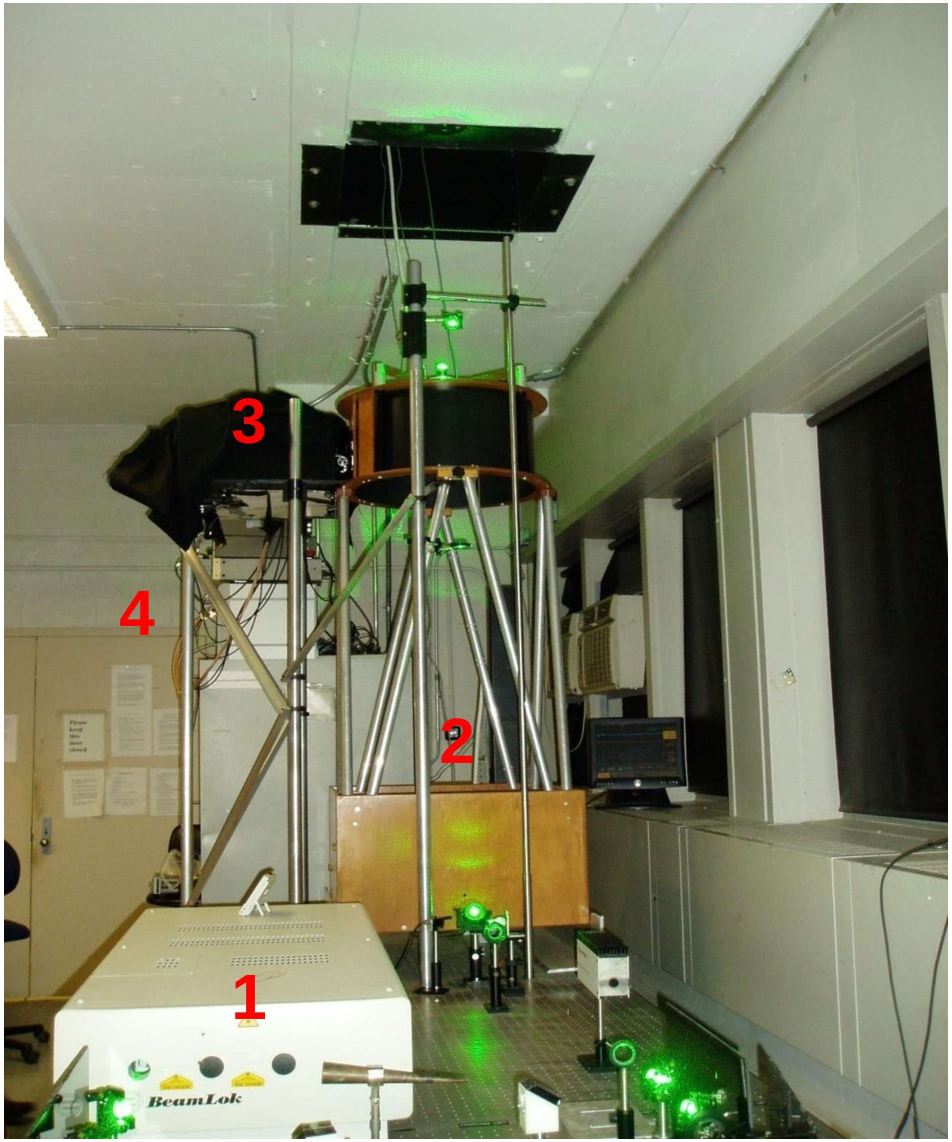


IPCC, *2007*

Aerosol effects on Health

- Aerosols have been also linked to both cardiovascular and respiratory illness
  - PM2.5 (particulate matter less than 2.5 um diameter) is particularly a problem requiring **Environmental Protection Agency** health Standards to be set
  - New York City Metropolitan area has the largest frequency of problematic air-quality episodes and it is therefore extremely important to monitor, determine sources and predict air-quality

Figure- CCNY multiwavelength elastic-inelastic lidar



1.ND:YAG Laser (1064-532-355nm)

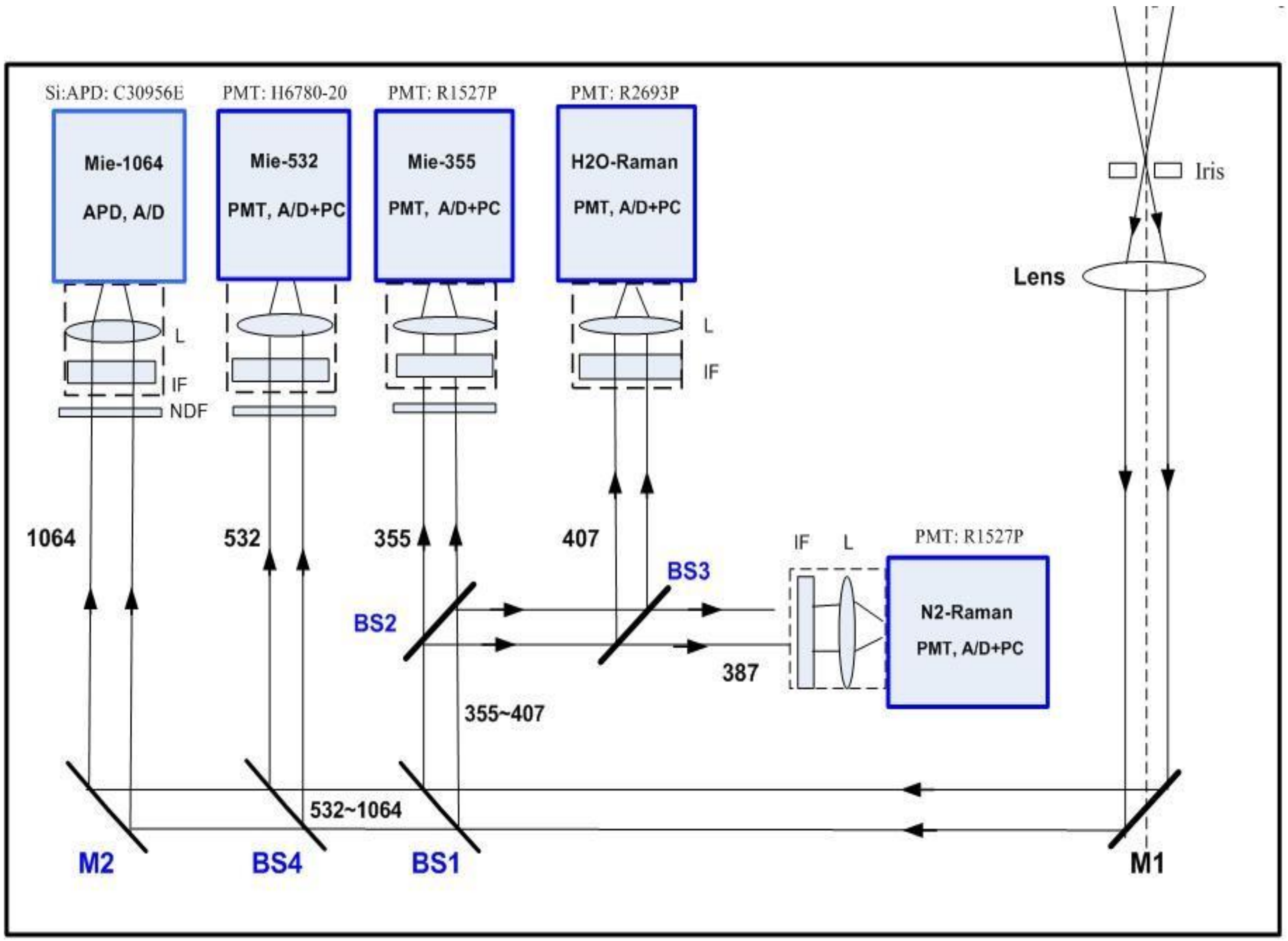
2.Telescope: diameter 500-mm

3.Detector: PMTs and Si-APD

4.Data acquisition:
12-bit ADC and Photon-counting

5.Detection range and objective:
~10 km altitude
aerosol, cloud, water vapor, PBL

6.Working mode:
Only vertical pointing in the lab
Anciliary Radar for airplane
(not eye-safe)

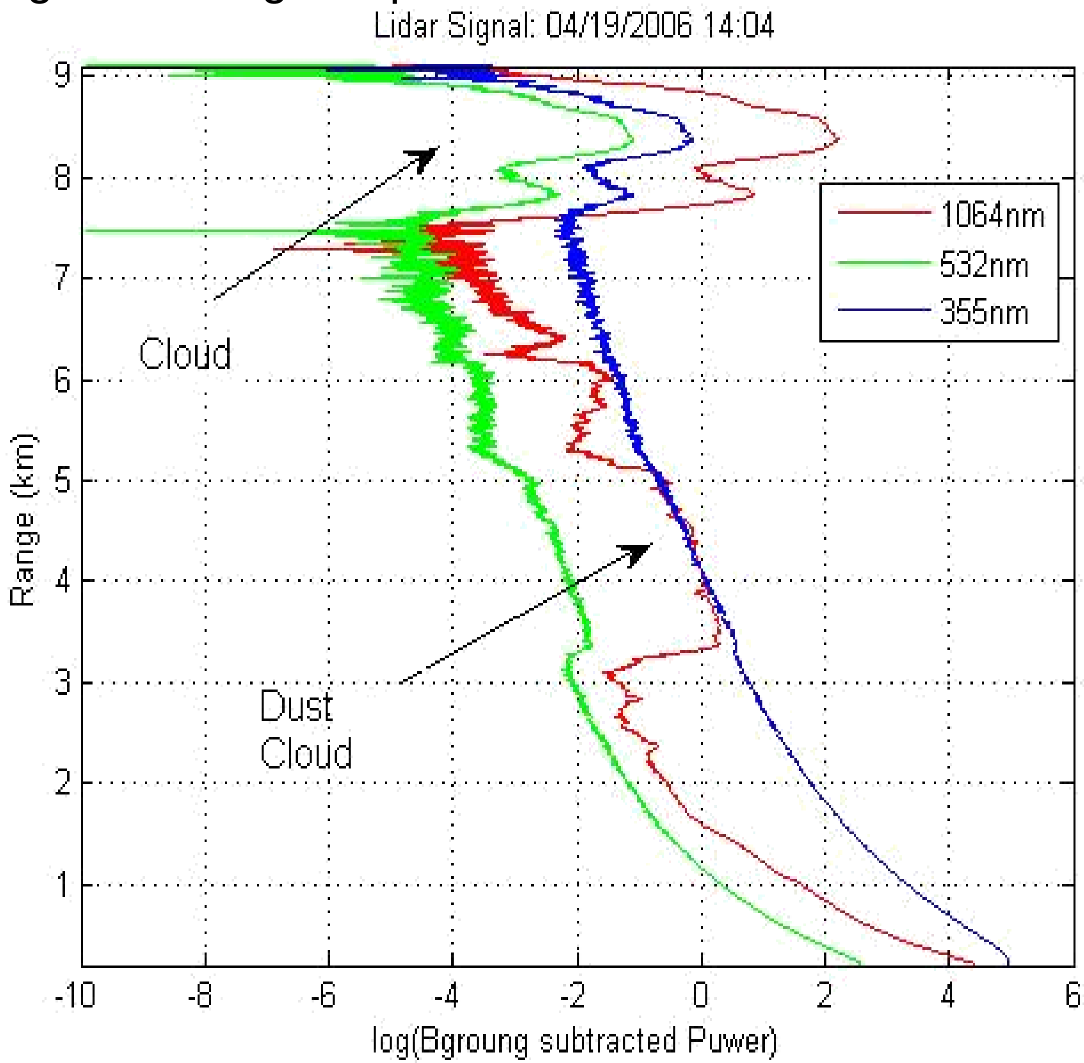


L = Lens – focus light
IF = Interference Filter – select the wavelength
NDF = Nurture Density Filter – attenuate the signal

Figure : A schematic of the optical receiver

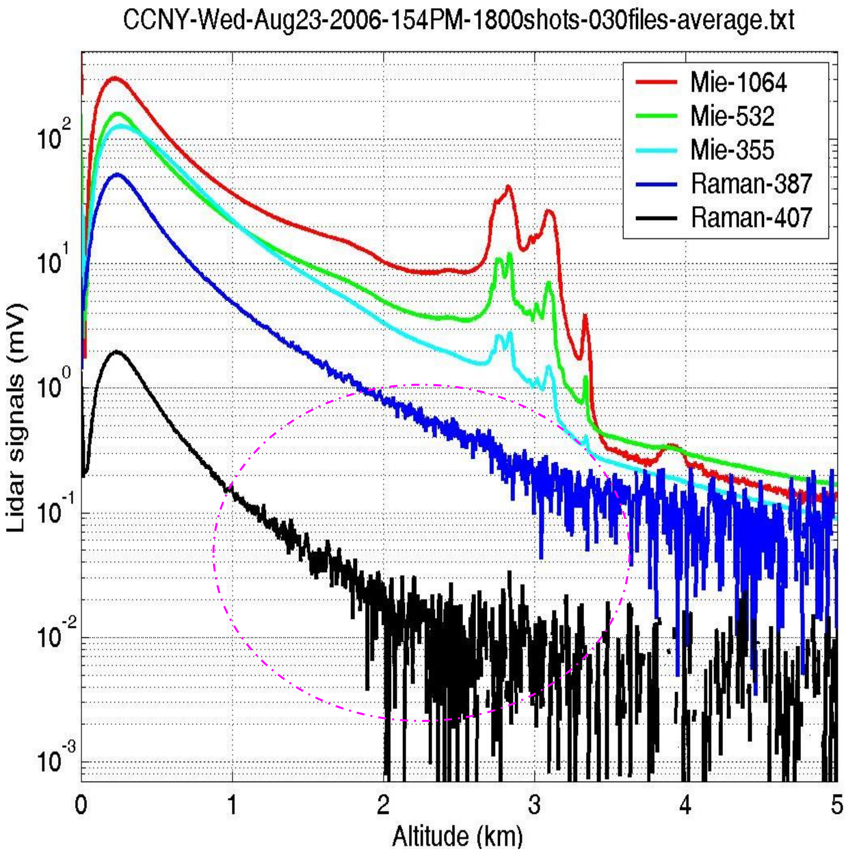
Some typical observation examples

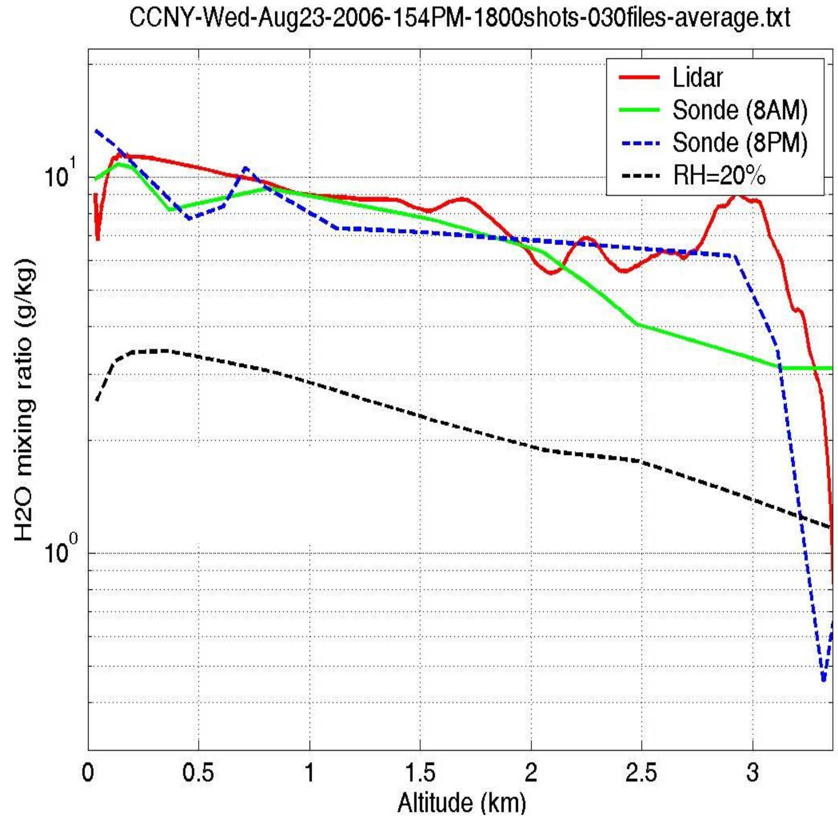
1-min average Lidar signals profiles



Case- Date=2006-08-23

- Raman signals (black & blue) are much smaller than elastic signals
- No strong cloud returns in Raman-channel
- Consistent H2O profile with radiosonde observation

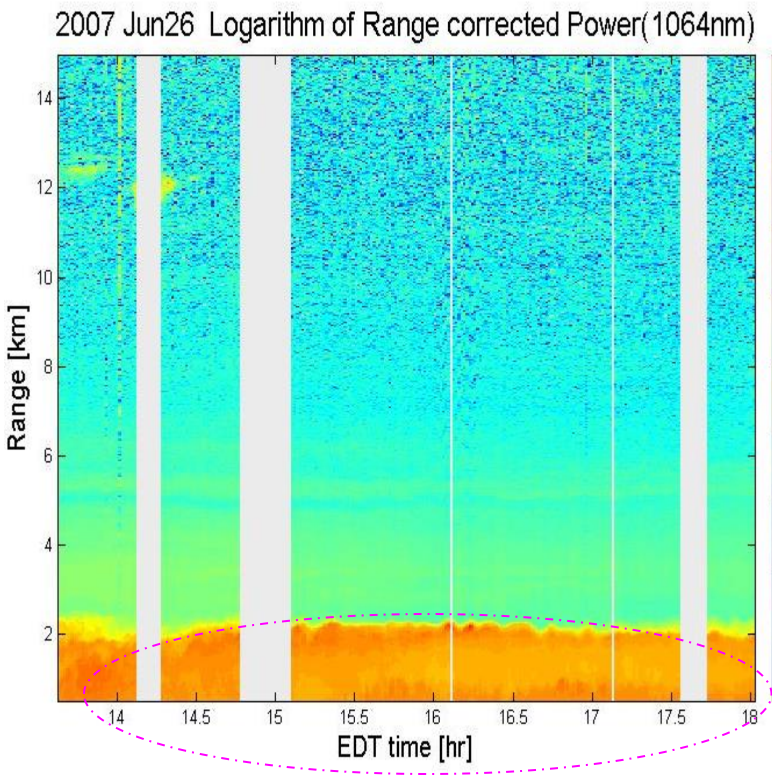




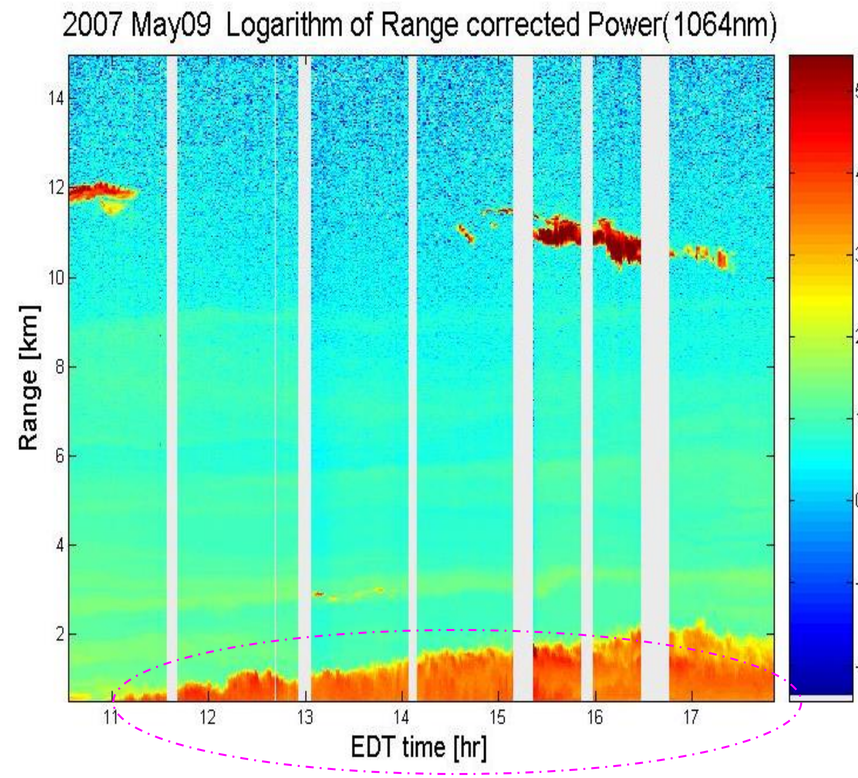
5.1 PBL variation (planetary boundary layer)

or known as the **atmospheric boundary layer (ABL) , is the lowest part of the atmosphere and its behavior is directly influenced by its contact with a planetary surface.**

(**Roles in air pollution, moisture and weather process etc.)**



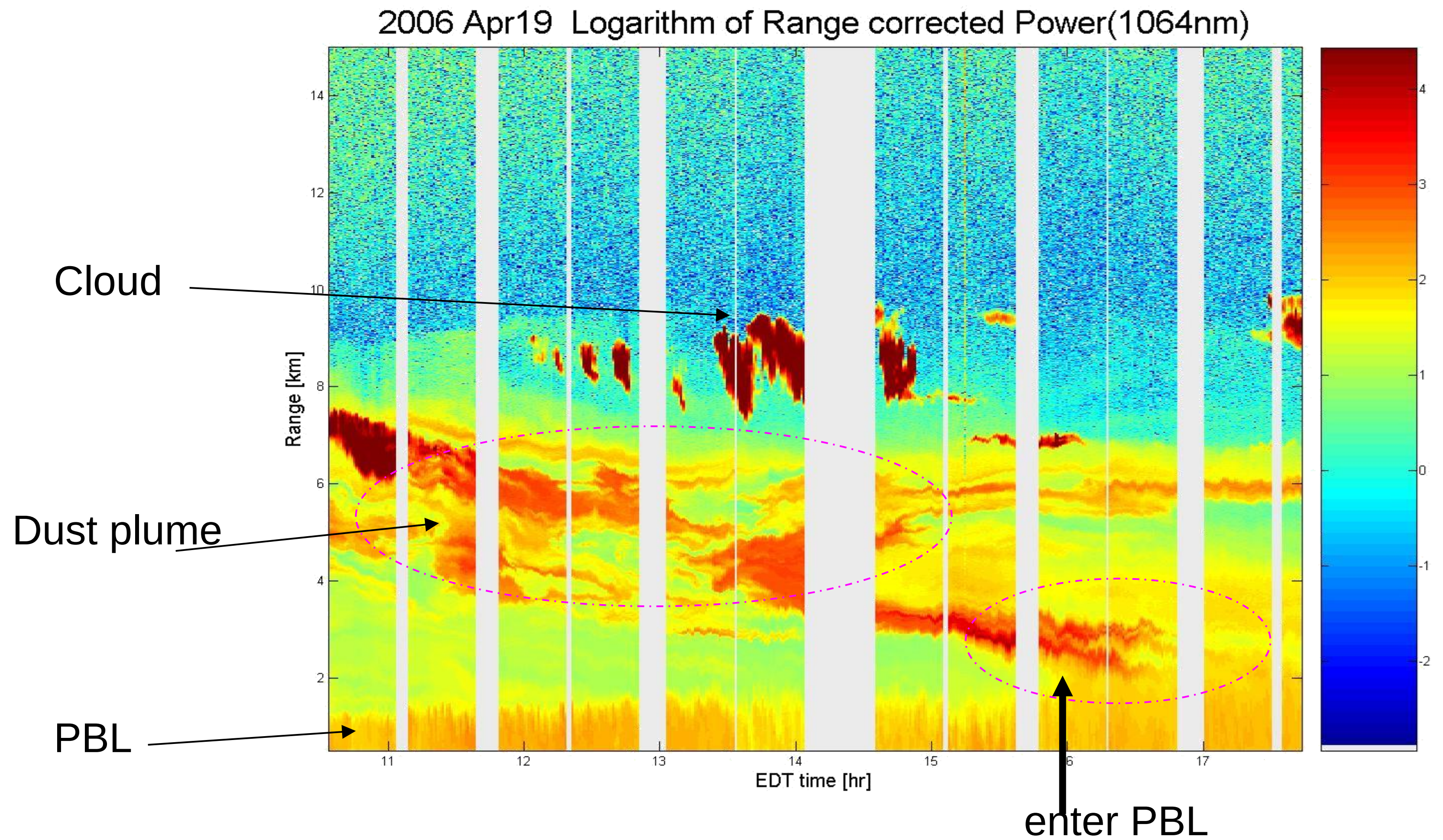
Stable PBL



Large variation with time
(atmospheric process change)

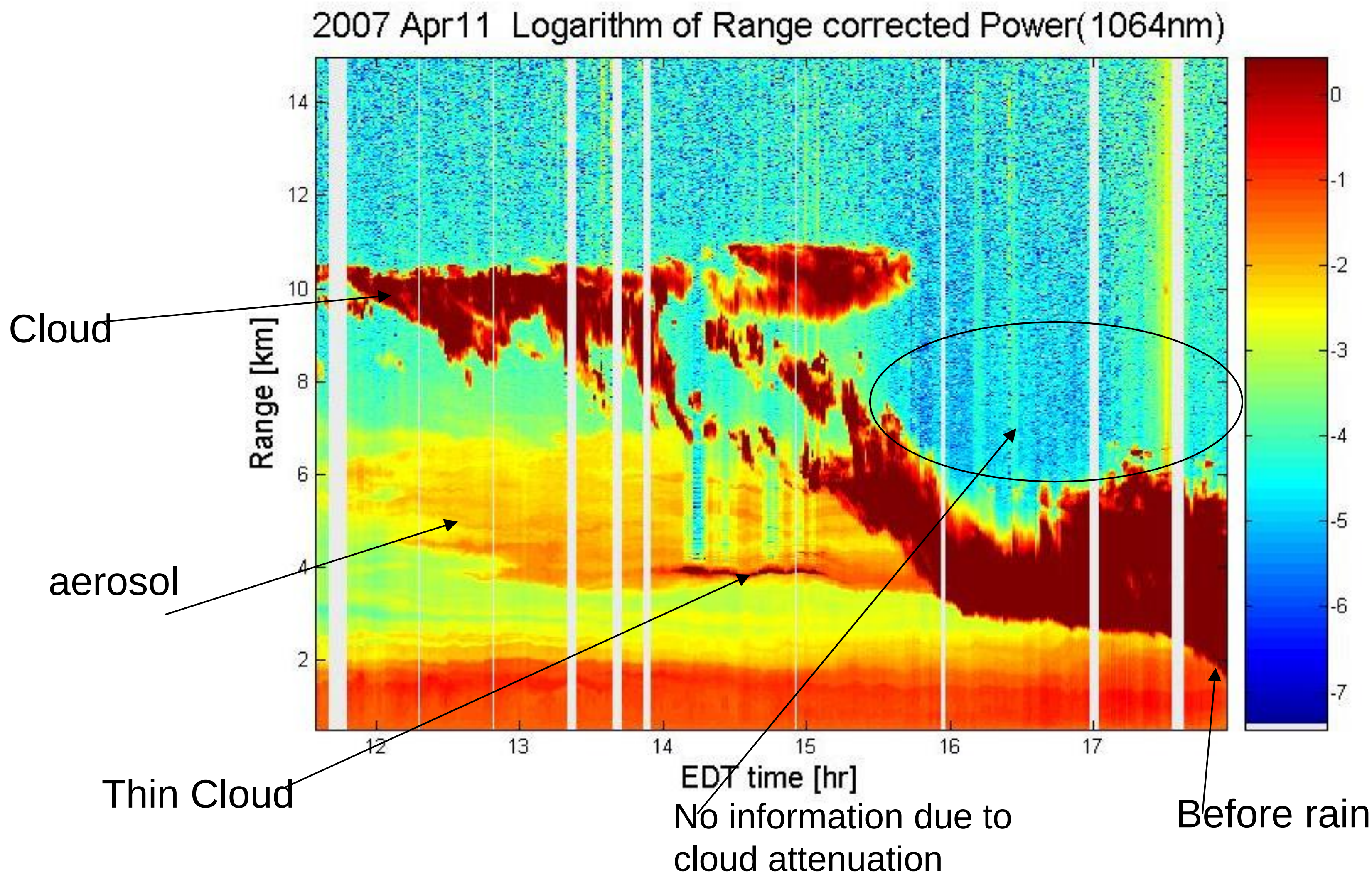
5.2 Aerosol-plume

Asian dust or smoke-plume
Important to Air pollution & Climate Radiative Change



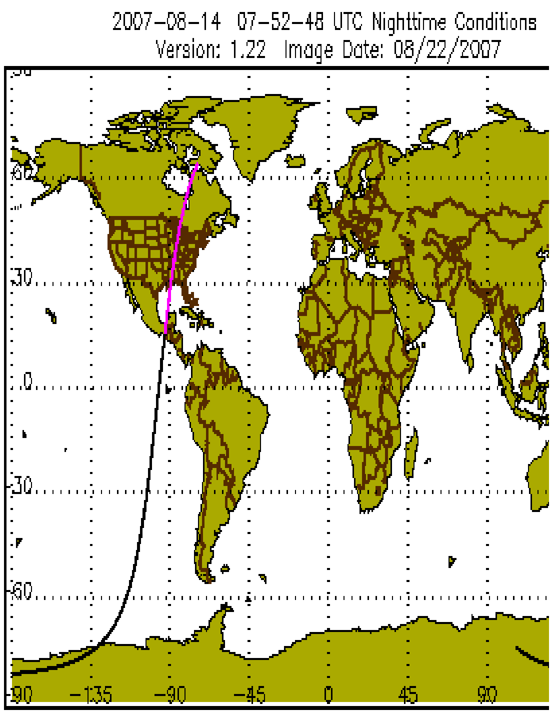
5.3 Cloud-aerosol

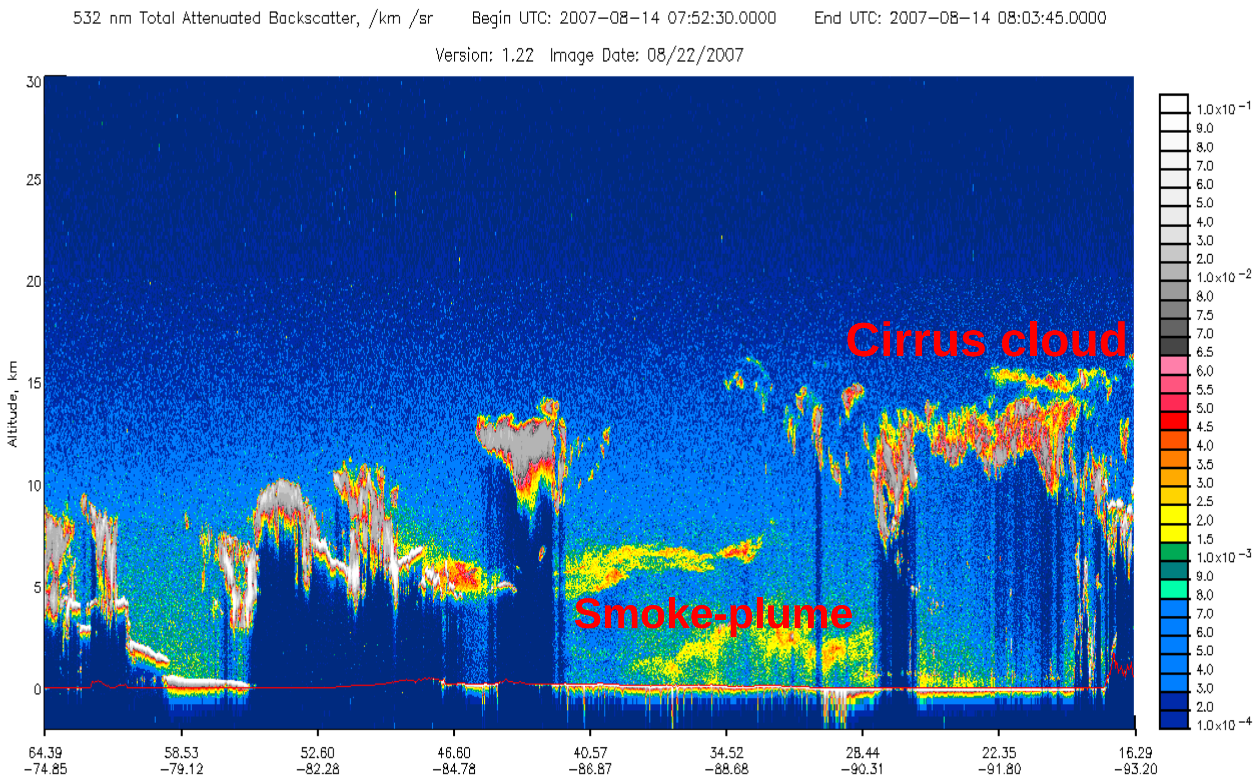
Aerosol-cloud interaction at same level



CALIPSO- Spaceborne lidar (Mie-scattering+polarization lidar):

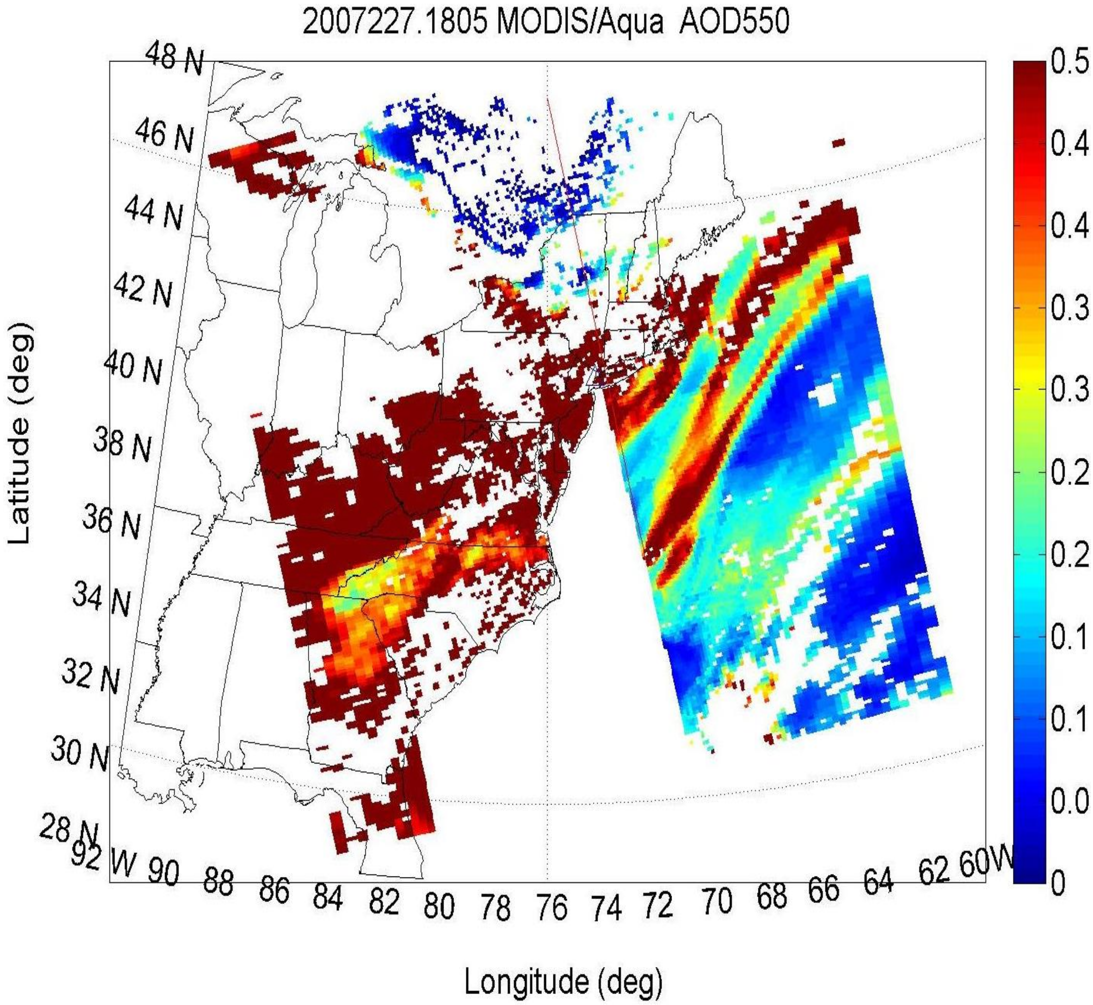
- Global-scale **vertical distribution** of aerosol and clouds
- **Aerosol types**: 2-wavelength channel
- **Cloud-phase**: water or ice clouds





http://www-calipso.larc.nasa.gov/products/

Passive Satellite remote sensing Aerosol



Column aerosol only

No altitude-information

No retrievals in cloudy-region

Influence by surface influence