Lecture 15.

Principles of active remote sensing: Lidar sensing of aerosols, gases and clouds.

1. Optical interactions of relevance to lasers.
2. General principles of lidars.
3. Lidar equation.
4. Examples of lidar sensing of aerosols, gases, and clouds.
5. Lidars in space: LITE and CALIPSO

Required reading:

S: 8.4.1, 8.4.2, 8.4.3, 8.4.4

Additional/advanced reading:

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

CALIPSO ALGORITHM THEORETICAL BASIS DOCUMENTS (ATBDs):

(4 large documents)

http://www-calipso.larc.nasa.gov/resources/project_documentation.php

1. Optical interactions of relevance to lasers.

- ✓ Laser is a key component of the lidar.

Lidar (LIght Detection And Ranging)

Laser (**L**ight **A**mplification by **S**timulated **E**mission of **R**adiation)

Basic principles of laser: stimulated emission in which atoms in an upper energy level can be triggered (or stimulated) in phase by an incoming photon of a specific energy. The emitted photons all possess the same wavelength and vibrate in phase with the incident photons (the light is said to be COHERENT).

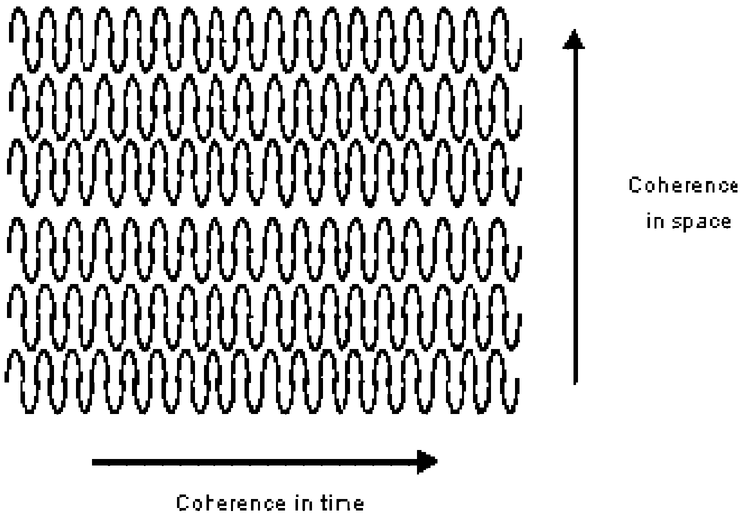
The emitted light is said to be INCOHERENT in time and space if

- ✓ the light is composed of many different wavelengths
- ✓ the light is emitted in random directions

- ✓ the light is emitted with different amplitudes
- ✓ there is no phase correspondence between any of the emitted photons

Properties of laser light:

- ✓ Monochromaticity
- ✓ Coherence



A TRAIN OF COHERENT PHOTONS

- ✓ Beam divergence:

  All photons travel in the same direction; the light is contained in a very narrow pencil (almost COLLIMATED), laser light is low in divergence (usually).

- ✓ High irradiance:

  Let's estimate the irradiance of a 1 mW laser beam with a diameter of 1 mm. The irradiance (power per unit area incident on a surface) is

$$F = P/S = 1\text{x}10^{-3}\ \text{W}/(\pi\ (1\text{x}10^{-3}\ \text{m})^2/4) = 1273\ \text{W/m}^2$$

- ✓ **Elastic scattering** is when the scattering frequency is the same as the frequency of the incident light (e.g., Rayleigh scattering and Mie scattering). **Inelastic scattering** is when there is a change in the frequency.

Optical interactions of relevance to laser environmental sensing

- Rayleigh scattering: laser radiation elastically scattered from atoms or molecules with no change of frequency
- Mie scattering: laser radiation elastically scattered from particulates (aerosols or clouds) of sizes comparable to the wavelengths of radiation with no change of frequency
- Raman Scattering: laser radiation inelastically scattered from molecules with a frequency shift characteristic of the molecule
- Resonance scattering: laser radiation matched in frequency to that of a specific atomic transition is scattered by a large cross section and observed with no change in frequency
- Fluorescence: laser radiation matched in frequency to a specific electronic transition of an atom or molecule is absorbed with subsequent emission at the lower frequency
- Absorption: attenuation of laser radiation when the frequency matched to the absorption band of given molecule

Types of laser relevant to atmospheric remote sensing :

- solid state lasers (e.g., ruby laser, 694.3 nm)
- gas lasers (e.g., CO_2, 9-11 μm)
- semiconductor lasers (GaAs, 820 nm)

2. General principles of lidars.

There are several main types of lidars:

Backscatter lidars measure backscattered radiation and polarization (often called the Mie lidar)

DIfferential Absorption Lidar (DIAL) is used to measure concentrations of chemical species (such as ozone, water vapor, pollutants) in the atmosphere.

Principles: A DIAL lidar uses two different laser wavelengths which are selected so that one of the wavelengths is absorbed by the molecule of interest while the other wavelength is not. The difference in intensity of the two return signals can be used to deduce the concentration of the molecule being investigated.

Raman (inelastic backscattering) Lidars: detect selected species by monitoring the wavelength-shifted molecular return produced by vibrational Raman scattering from the chosen molecules.

High Spectral Resolution Lidar (HSRL) measures optical properties of the atmosphere by separating the Doppler-broadened molecular backscatter return from the unbroadened aerosol return. The molecular signal is then used as a calibration target which is available at each point in the lidar profile. This calibration allows unambiguous measurements of aerosol scattering cross section, optical depth, and backscatter phase function (see S 8.4.3).

Doppler lidar is used to measure the velocity of a target. When the light transmitted from the lidar hits a target moving towards or away from the lidar, the wavelength of the light reflected/scattered off the target will be changed slightly. This is known as a Doppler shift - hence Doppler Lidar. If the target is moving away from the lidar, the return light will have a longer wavelength (sometimes referred to as a red shift), if moving towards the lidar the return light will be at a shorter wavelength (blue shifted). The target can be either a hard target or an atmospheric target - the atmosphere contains many microscopic dust and aerosol particles which are carried by the wind.

<u>Lidars compared to radars:</u>

- Lidar uses laser radiation and a telescope/scanner similar to the way radar uses radio frequency emissions and a dish antenna.
- Optically thick cloud and precipitation can attenuate the lidar beam, but radar signals can penetrate heavy clouds (and precipitation).

- In optically clear air, radar return signals may be obtained from insects and birds, and from air refractive index variations due to humidity, temperature, or pressure fluctuations.
- Lidar beam divergence is two to three orders of magnitude smaller compared to conventional 5 and 10 cm wavelength radars.
- The combination of the short pulse (of the order of 10^{-8} s) and the small beam divergence (about 10^{-3} to 10^{-4} radiant) gives a small volume illuminated by a lidar (about a few m^3 at ranges of tens of km).

3. Lidar equation.

In general, the form of a lidar equation depends upon the kind of interaction invoked by the laser radiation.

Let's consider elastic scattering. Similar to the derivation of the radar equation, the lidar equation can be written as

$$P_r(R) = \frac{C}{R^2}\frac{h}{2}\frac{k_b}{4\pi}\exp\left(-2\int_o^R k_e(r')dr'\right) \qquad [15.1]$$

where C is the lidar constant (includes P_t, receiver cross-section and other instrument factors);

$\kappa_b/4\pi$ (in units of $km^{-1}sr^{-1}$) is called the **backscattering factor** or **lidar backscattering coefficient** or backscattering coefficient;

κ_e is the volume extinction coefficient; and t_p is the lidar pulse duration ($h=ct_p$)

- **Solutions of the lidar equation:**

In general, both the volume extinction coefficient κ_e and backscattering coefficient κ_b are unknown (see Eq.[15.1])

⇩

It is necessary to assume some kind of relation between κ_e and κ_b (called the extinction-to-backscattering ratio)

EXAMPLE: Consider Rayleigh scattering. Assuming no absorption at the lidar wavelength, the volume extinction coefficient is equal to the volume scattering coefficient

$$k_e = k_s$$

On the other hand, Eq.[14.22] gives

$$\boldsymbol{k_b} = \boldsymbol{k_s} \boldsymbol{P}(\Theta = 180^0)$$

Using the Rayleigh scattering phase function, we have

$$\boldsymbol{P}(\Theta = 180^0) = \frac{3}{4}(1 + \cos^2(180^0)) = 1.5$$

Thus, for Rayleigh scattering

$$\boldsymbol{k_b} = \boldsymbol{k_s} \boldsymbol{P} \ (\Theta = 180) = 1.5\boldsymbol{k_s} = 1.5\boldsymbol{k_e} \qquad [15.2]$$

To eliminate system constants, the **range-normalized signal variable, S,** can be defined as

$$S(R) = \ln(R^2 P_r(R)) \qquad [15.3]$$

If S_o is the signal at the reference range R_0, from Eq.[15.1] we have

$$S(R) - S(R_0) = \ln\left(\frac{k_b}{k_{b,o}}\right) - 2\int_{R_0}^{R} k_e(r)dr$$

or in the differential form

$$\boxed{\frac{dS}{dR} = \frac{1}{k_b(R)} \frac{dk_b(R)}{dR} - 2k_e(R)} \qquad [15.4]$$

<u>Solution of the lidar equation based on the slope method</u>**:** assumes that the scatterers are homogeneously distributed along the lidar path so

$$\frac{dk_b(R)}{dR} \approx 0 \qquad [15.5]$$

Thus

$$\frac{dS}{dR} = -2k_e \qquad [15.6]$$

and $\mathbf{k_e}$ is estimated from the slope of the plot S vs. R

Limitations: applicable for a homogeneous path only.

Techniques based on the extinction-to-backscattering ratio:

use *a priori* relationship between $\boldsymbol{k_e}$ and $\boldsymbol{k_b}$ typically in the form

$$k_b = bk_e^n \qquad [15.7]$$

where ***b*** and ***n*** are specified constants.

Substituting Eq.[15.7] in Eq.[15.4], we have

$$\frac{dS}{dR} = \frac{n}{k_e(R)}\frac{dk_e(R)}{dR} - 2k_e(R) \qquad [15.8]$$

with a general solution at the range R

$$\boxed{k_e = \frac{\exp\left(\frac{S - S_0}{n}\right)}{\frac{1}{k_{e,0}} - \frac{2}{n}\int_{R_o}^{R} \exp\left(\frac{S - S_0}{n}\right)dr}} \qquad [15.9]$$

NOTE:

- Eq.[15.9] is derived ignoring the multiple scattering
- Eq.[15.9] requires the assumption on the extinction-to-backscattering ratio
- Eq.[15.9] is instable with respect to $\boldsymbol{k}_e$ (some modifications were introduced to avoid this problem. For instance, use the reference point at the predetermined end range, R_m, so the solution is generated for $R< R_m$ instead of $R>R_o$)

4. Examples of lidar sensing of aerosols , gases, and clouds.

Retrieval of the gas density from DIAL measurements:

DIfferential Absorption Lidar (DIAL) uses two wavelengths: one is in the maximum of the absorption line of the gas of interest, and a second wavelength is in the region of low absorption.

For each wavelength, the total extinction coefficient is due to the aerosol extinction and the absorption by the gas (assumed that Rayleigh scattering is easy to correct for)

$$k_e(\lambda) = k_{e,aer}(\lambda) + \rho_g k_{a,g} \qquad [15.10]$$

where

$k_{e,aer}$ is the aerosol volume extinction coefficient; ρ_g is the density of the absorbing gas; and $k_{a,g}$ is the mass absorption coefficient of the absorbing gas.

The two wavelengths are selected so that the aerosol optical properties are the same at these wavelengths

$$k_{e,aer}(\lambda_1) = k_{e,aer}(\lambda_2) \quad \text{and} \quad k_{b,aer}(\lambda_1) = k_{b,aer}(\lambda_2) \qquad [15.11]$$

Taking the logarithm of both sites of Eq.[15.1], we have (for each wavelength)

$$\ln(P_r(R)/P_t) = \ln\left(\frac{C}{R^2}\frac{h}{2}\frac{k_b}{4\pi}\right) - 2\int_o^R k_e(r')dr' \qquad [15.12]$$

Subtracting the measurements at two wavelengths, we have

$$\ln(P_1(R)/P_2(R)) = -2\int_o^R \rho_g(r')[k_{a,g,\lambda 1}(r') - k_{a,g,\lambda 2}(r')]dr' \qquad [15.13]$$

where P_1(R) and P_2(R) are the normalized power received from the range R at two wavelengths.

- ✓ Eq.[15.13] gives the density of the absorbing gas as a function of range.

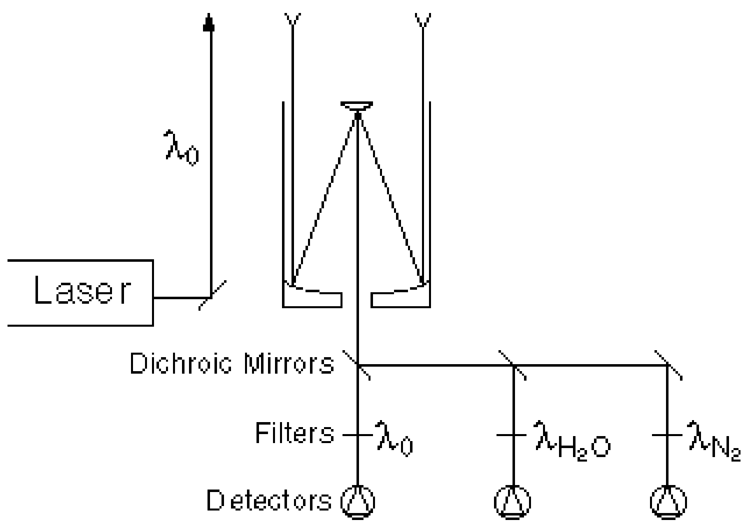
- DIAL systems can measure the following gases: H_2O, NO_2, SO_2 and O_3.

Elastic Mie Backscattering Lidars => gives aerosol extinction-to-backscatter ratio as a function of altitude (or the profile of k_e for an assumed relationship between k_e and k_b)

Example: MPL-Net is a worldwide network of ground-based micro-pulse lidars (MPLs) operated by NASA (http://mplnet.gsfc.nasa.gov/). MPL operates at the wavelength **0.523 µm.**

Raman (inelastic backscattering) Lidars => enable measurements of aerosol extinction and backscattering **independently**.

Principles: Raman lidar systems detect selected species by monitoring the wavelength-shifted molecular return produced by vibrational Raman scattering from the chosen molecule (or molecules)



- By taking the ratio of the signal at the water-vapor wavelength to the signal at the nitrogen wavelength, most of the range-dependent terms drop out, and one is left with a quantity that is almost directly proportional to the water-vapor mixing ratio.

The Raman lidar equation can be written as

$$P_r(R,\lambda_L,\lambda_R) = \frac{C}{R^2}\frac{h}{2}\frac{k_b(R,\lambda_L,\lambda_R)}{4\pi}\exp\left(-\int_o^R [k_e(r',\lambda_L)+k_e(r',\lambda_R)]dr'\right) \qquad [15.14]$$

where λ_L and λ_R are the lidar and Raman wavelengths, respectively; backscattering coefficient $\kappa_b(R, \lambda_L,\lambda_R)$ is linked to the differential Raman backscatter cross section of a gas and molecule number density, $\kappa_e(R, \lambda_L)$ and $\kappa_e(R, \lambda_R)$ are due to molecular (Rayleigh) scattering and aerosol extinction

$$\Downarrow$$

In Raman lidars, the inelastic Raman backscatter signal is affected by the aerosol attenuation but not by aerosol backscatter => aerosol extinction profile can be retrieved

Example: Raman lidar at DOE/ARM SGP site: Nd:YAG lidar (355 nm)

Receiving Wavelengths: Rayleigh/Aerosol (355 nm); Depolarization (355 nm), Raman water vapor (408 nm), Raman nitrogen (387 nm)

Aerosol characteristics retrieved from SGP Raman lidar:

- ***Aerosol Scattering Ratio*** (also called lidar scattering ratio)

is defined as the ratio of the total (aerosol+molecular) scattering to molecular scattering

$$[k_{b,m}(\lambda,z)+ k_{b,a}(\lambda,z))]/ k_{b,m}(\lambda,z)$$

- ***Aerosol Backscattering Coefficient***

Profiles of the aerosol volume backscattering coefficient $k_b(\lambda=355 \text{ nm}, z)$ are computed using the aerosol scattering ratio profiles derived from the SGP Raman Lidar data and profiles of the molecular backscattering coefficient. The molecular backscattering coefficient is obtained from the molecular density profile which is computed using radiosonde profiles of pressure and temperature from the balloon-borne sounding system (BBSS) and/or the Atmospheric Emitted Radiance Interferometer (AERI). No additional data and/or assumptions are required.

- ***Aerosol Extinction/Backscatter Ratio***

Profiles of the aerosol extinction/backscatter ratio are derived by dividing the aerosol extinction profiles by the aerosol backscattering profiles.

- ***Aerosol Optical Thickness***

Aerosol optical thickness is derived by integrating the aerosol extinction profiles with altitude.

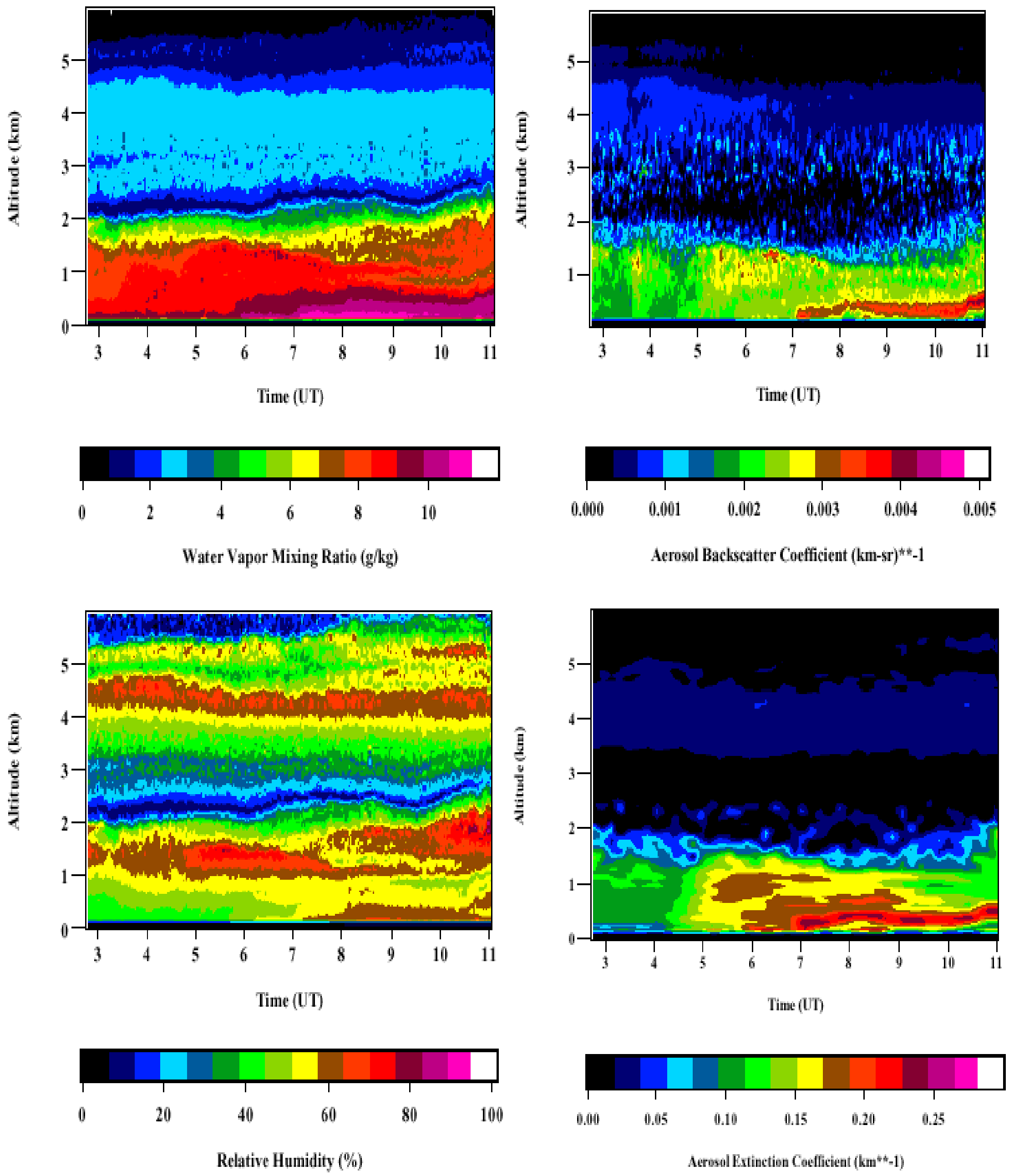


Figure 15.1 Examples of retrievals using the Raman lidar.

CO_2 lidar at 9.25 μm and 10.6 μm: measures the backscattering coefficient

Example: Jet Propulsion Lab (JPL) CO2 lidar (almost continuous operation since 1984): vertical resolution is about 200 m throughout the troposphere and lower stratosphere (up to about 30km)

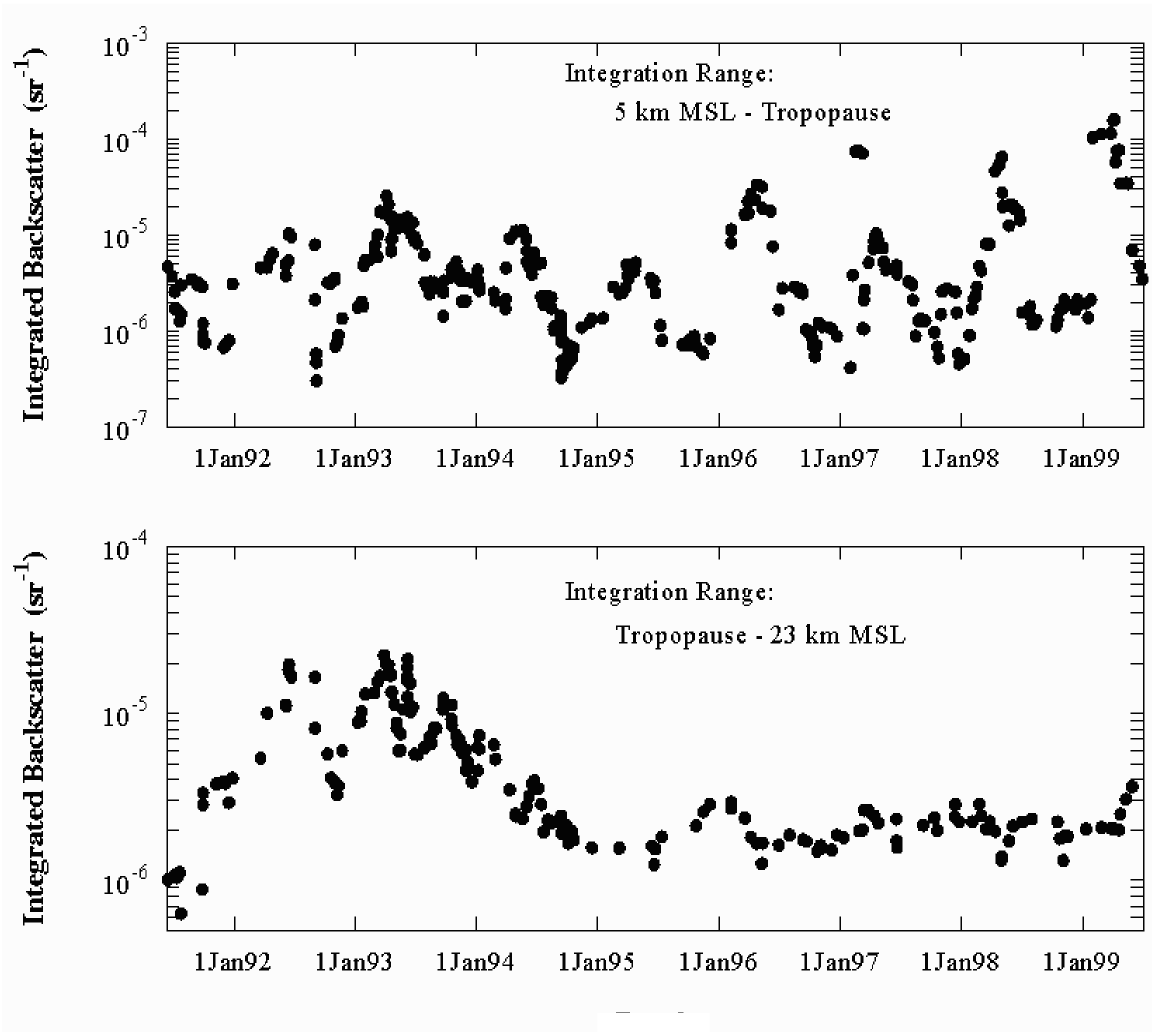


Figure 15.2. Integrated backscatter from the free troposphere (upper panel) and the lower stratosphere (lower panel) column above the JPL Pasadena site since the eruption of the Philippine volcano Mt. Pinatubo in June of 1991 (Tratt et al.)

➢ **Lidar sensing of clouds.**

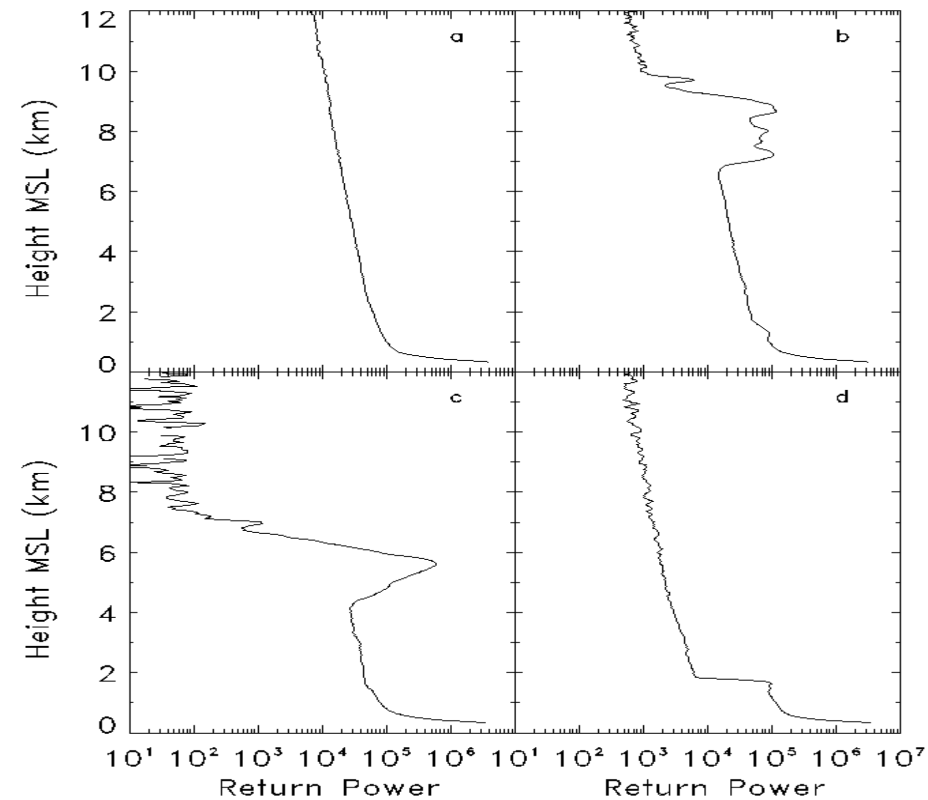


Figure 15.3. Four typical examples of range corrected lidar backscatter versus altitude (ARM Raman lidar, 10 min average, Sassen et al.). Fig. 15.3a illustrates a clear sky backscatter, which decrease with altitude due to the decrease in molecular density. Fig. 15.3b shows a backscatter from cirrus, which has a strong increase in backscatter above cloud base, and air return above cloud top. Backscatter, which is totally attenuated in clouds, is shown in Fig. 15.3c. Compare with clear sky case (Fig. 15.3a), we can find a very strong increase in lidar backscatter form clouds (Fig. 15.3b-c), but it is not always observable (Fig. 15.3d). The other common feature for cloud signal is there is a fast decrease region in cloud backscatter due to strong attenuation of clouds or transition form cloud to clear region. So strong negative and strong positive slopes in lidar backscatter signal are observable in the presence of clouds.

Cloud boundary detection: there is no universal algorithm

Common approach: analysis of dP/dR (i.e., retuned power vs. the range)

6. Lidars in space: LITE and CALIPSO

LITE (**Lidar In-space Technology Experiment)** (http://www-lite.larc.nasa.gov/)

- **LITE** flew on Discovery in September 1994
- **LITE** was operated for 53 hours, resulting in over 40 GBytes of data covering 1.4 million kilometers of ground track;
- YAG lasers which emit simultaneously at the three harmonically related wavelengths of 1064 nm (infrared), 532 nm (visible green), and 355 nm (ultraviolet). The two-laser system provides redundancy in case one laser fails. Only one laser operates at a time.

LITE provided the first highly detailed global view of the vertical structure of clouds and aerosols

- **CALIPSO (**Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) satellite has been launched in April 2006 (http://www-calipso.larc.nasa.gov/)

CALIPSO has three instruments: Cloud-Aerosol Lidar with Orthogonal Polarization (**CALIOP**); Three-channel Imaging Infrared Radiometer (IIR); Wide Field Camera (WFC)

CALIOP is a two-wavelength (532 nm and 1064 nm) polarization-sensitive lidar that provides high-resolution vertical profiles of aerosols and clouds. It has three receiver channels: one measuring the 1064-nm backscattered intensity, and two channels measuring orthogonally polarized components (parallel and perpendicular to the polarization plane of the transmitted beam) of the 532-nm backscattered signal. It has a footprint at the Earth's surface (from a 705-km orbit) of about 90 meters and vertical resolution of 30 meters.

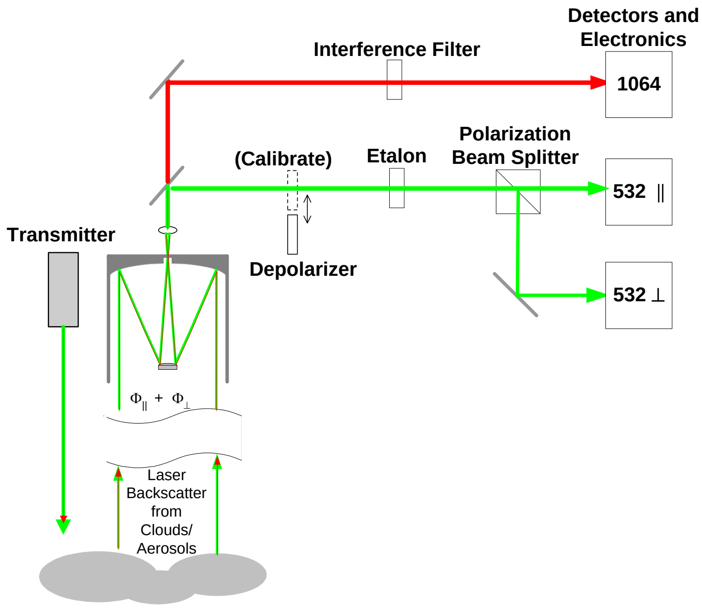


Figure 15.4 Functional block diagram of CALIOP (from CALIPSO ATBD).

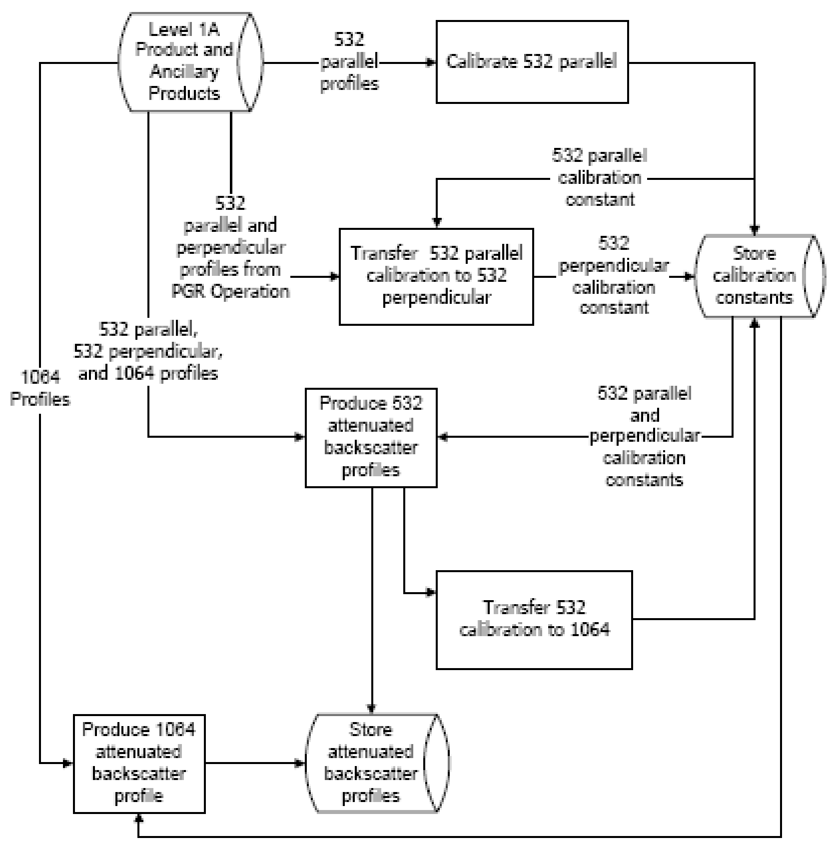
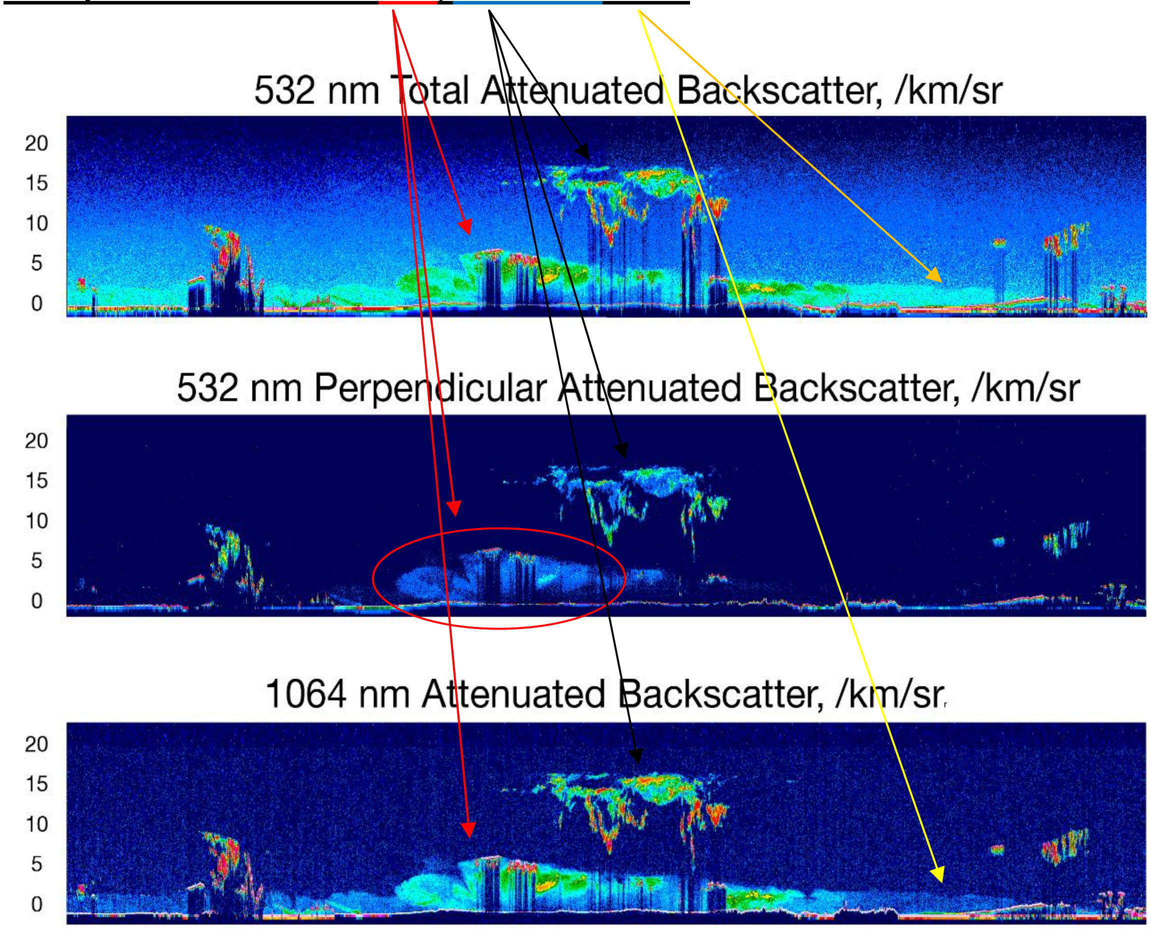
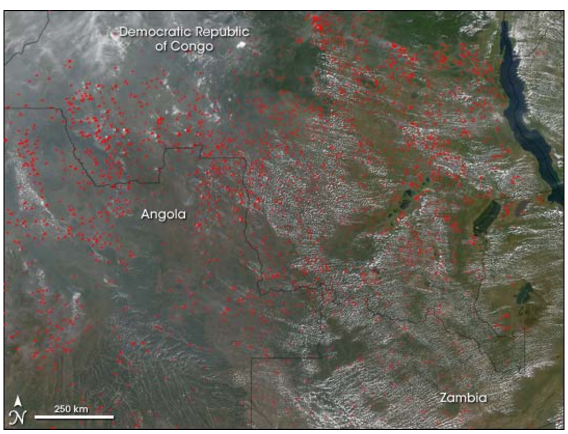


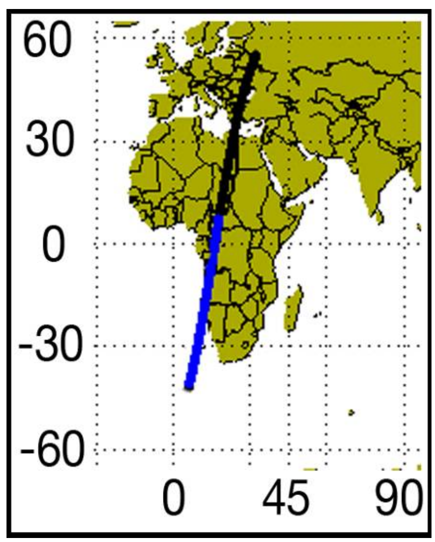
Figure 15.5 Block diagram of calibration and Level 1 data products.

Example of CALIOP data: dust, cirrus and smoke





Fire locations (MODIS) 06/10/2006

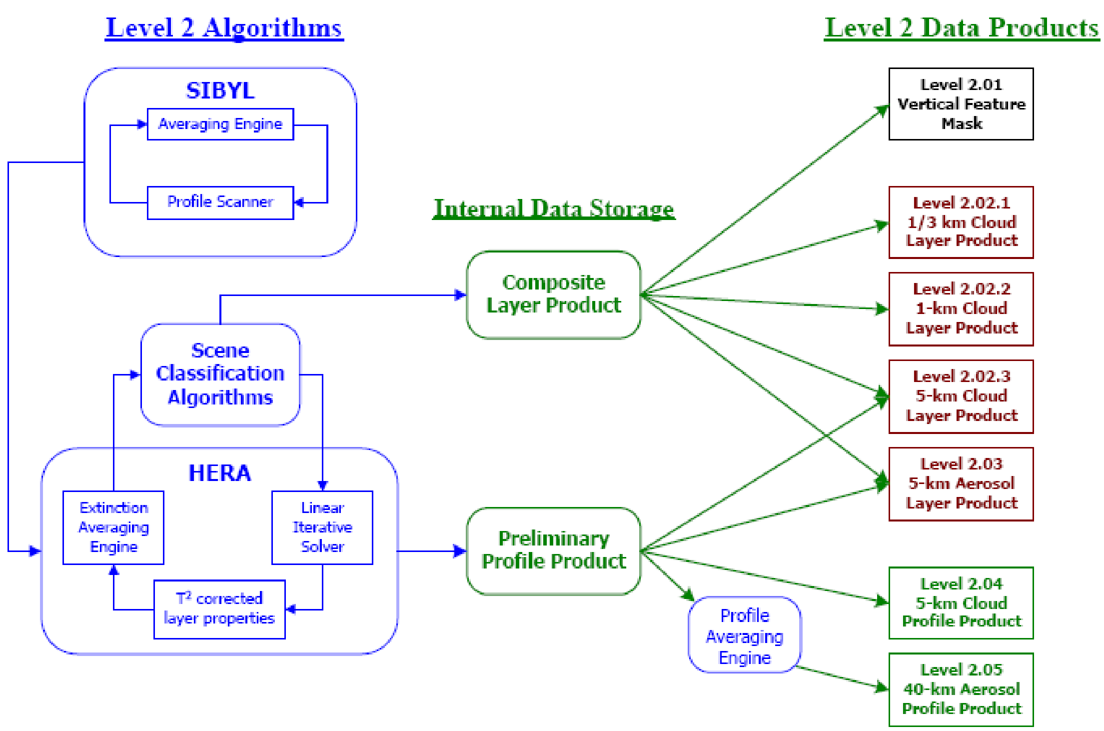


CALIPSO track

CALIPSO Level 2 Aerosol and Cloud Products:

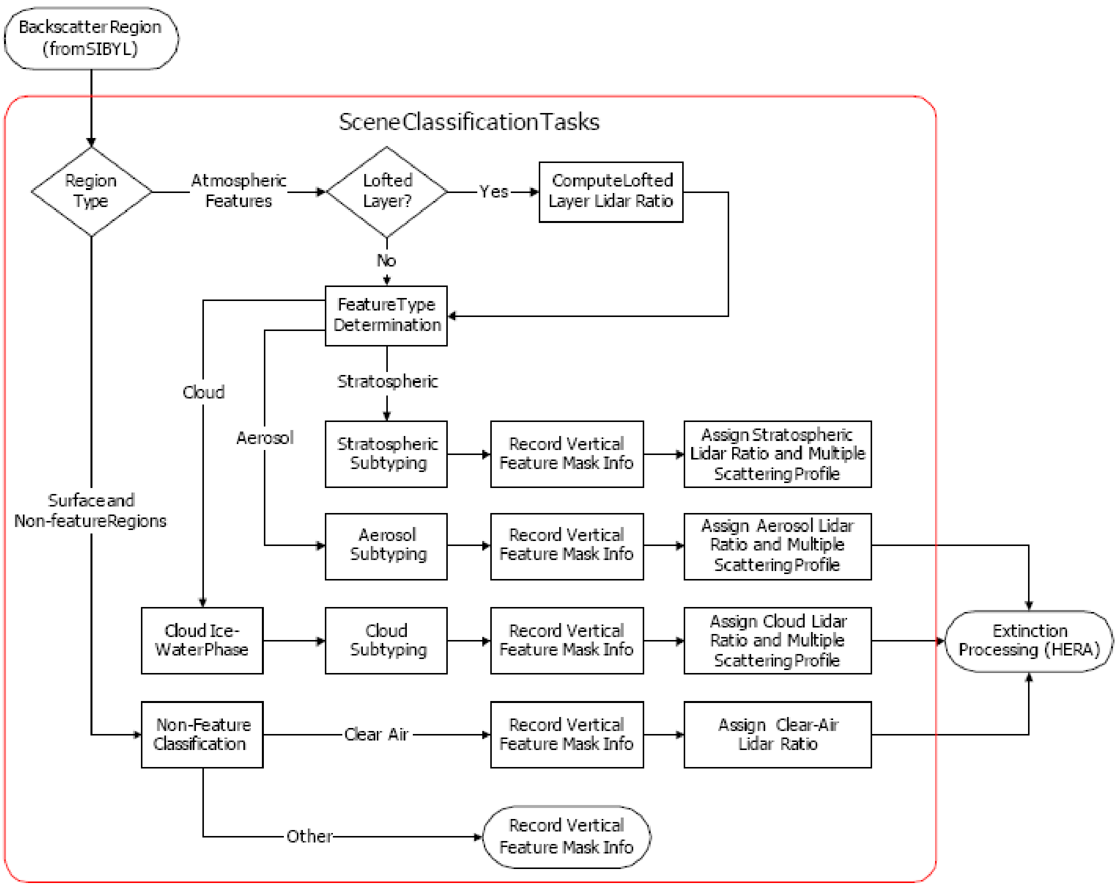
- ✓ layer heights and descriptive properties (e.g., integrated attenuated backscatter, layer integrated depolarization ratio, etc.);
- ✓ layer identification and typing (i.e., cloud vs. aerosol, ice cloud vs. water cloud, etc.); and
- ✓ profiles of cloud and aerosol backscatter and extinction coefficients.

Before the retrieval of extinction coefficients can be performed, clouds must be located and discriminated from aerosol, and water clouds must be discriminated from ice clouds. In the Level 2 algorithms, the Selective Iterated BoundarY Locator (SIBYL) detects layers, the Scene Classification Algorithm (SCA) classifies these layers, and the Hybrid Extinction Retrieval Algorithms (HERA) perform extinction retrievals. Although the location of cloud and aerosol layers and the determination of cloud ice/water phase are necessary precursors to extinction retrieval.



Schematic of the Scene Classification Algorithm (SCA):

A schematic of the scene classification tasks is shown below. The SCA first identifies layers as either cloud or aerosol, based primarily on scattering strength and the spectral dependence of backscattering. The SCA computes the depolarization profile within layers using the (Level 1) 532 nm parallel and perpendicular profiles. Cloud layers are then classified as ice or water, primarily using the depolarization signal and the temperature profile supplied as part of the ancillary data. Aerosol layers are similarly distinguished according to type using indicators such as depolarization, geophysical location, and backscatter intensity. Based on this classification according to type, the SCA then estimates values of the lidar ratio, S, for clouds and aerosols, and selects the appropriate range-dependent multiple scattering correction function for the layer.



NOTE: That CALIPSO extinction (optical depth) retrievals are strongly depend on the assumed aerosol (or cloud) lidar ratio (pre-defied based on the type of aerosol and clouds).

<u>Example of data analysis</u>: Dust storm in Central Asia (Choi&Sokolik)