Lecture 23

Lidar sensing of gases, aerosols, and clouds

1. The lidar equation

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

3. Lidars in space: LITE and CALIPSO

Required reading:

S: 8.4-8.5

Additional/advanced reading:

Weitkamp: Chapter 1

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

CALIPSO Data User's Guide:

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

Browse Image Tutorial:

http://www-calipso.larc.nasa.gov/resources/calipso_users_guide/browse/index.php

Winker, D. M., and Coauthors, 2010: The CALIPSO Mission: A Global 3D View of Aerosols and Clouds. Bull. Amer. Meteor. Soc., 91, 1211–1229.

Young, S. A., M. A. Vaughan, R. E. Kuehn, D. M. Winker, 2013: The Retrieval of Profiles of Particulate Extinction from Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) Data: Uncertainty and Error Sensitivity Analyses. J. Atmos. Oceanic Technol., 30, 395–428

1. 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

$$P_r(R) = \frac{C}{R^2}\frac{h}{2}\frac{k_b}{4\pi}\exp(-2\int_o^R k_e(r')dr') \qquad [23.1]$$

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.[23.1])

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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.[21.4] gives

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

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

$$\boldsymbol{k_b} = \boldsymbol{k_s P}\ (\Theta = 180) = 1.5\boldsymbol{k_s} = 1.5\boldsymbol{k_e} \qquad [23.2]$$

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

$$S(R) = \ln(R^2 P_r(R)) \qquad [23.3]$$

If S_o is the signal at the reference range R_0, from Eq.[23.1] 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

$$\boxed{\frac{dS}{dR} = \frac{1}{k_b(R)}\frac{dk_b(R)}{dR} - 2k_e(R)} \qquad [23.4]$$

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

$$\frac{dk_b(R)}{dR} \approx 0 \qquad [23.5]$$

Thus

$$\frac{dS}{dR} = -2k_e \qquad [23.6]$$

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

<u>Limitations</u>: applicable for a homogeneous path only.

<u>Techniques based on the extinction-to-backscattering ratio:</u>

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

$$k_b = bk_e^n \qquad [23.7]$$

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

Substituting Eq.[23.7] in Eq.[23.4], we have

$$\frac{dS}{dR} = \frac{n}{k_e(R)}\frac{dk_e(R)}{dR} - 2k_e(R) \qquad [23.8]$$

with a general solution at the range R

$$k_e = \frac{\exp\left(\frac{S - S_0}{n}\right)}{\frac{1}{k_{e,0}} - \frac{2}{n}\int_{R_o}^{R} \exp\left(\frac{S - S_0}{n}\right) dr} \qquad [23.9]$$

NOTE:

- Eq.[23.9] is derived ignoring the multiple scattering
- Eq.[23.9] requires the assumption on the extinction-to-backscattering ratio
- Eq.[23.9] 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)

2. 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)

$$k_e(\lambda) = k_{e,aer}(\lambda) + \rho_g k_{a,g} \qquad [23.10]$$

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

$$k_{e,aer}(\lambda_1) = k_{e,aer}(\lambda_2) \quad \text{and} \quad k_{b,aer}(\lambda_1) = k_{b,aer}(\lambda_2) \qquad [23.11]$$

Taking the logarithm of both sites of Eq.[23.1], we have (for each wavelength)

$$\ln(P_r(R)/P_t) = \ln(\frac{C}{R^2}\frac{h}{2}\frac{k_b}{4\pi}) - 2\int_o^R k_e(r')dr' \qquad [23.12]$$

Subtracting the measurements at two wavelengths, we have

$$\ln(P_1(R)/P_2(R)) = -2\int_o^R \rho_g(r')[k_{a,g,\lambda 1}(r') - k_{a,g,\lambda 2}(r')]dr' \qquad [23.13]$$

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

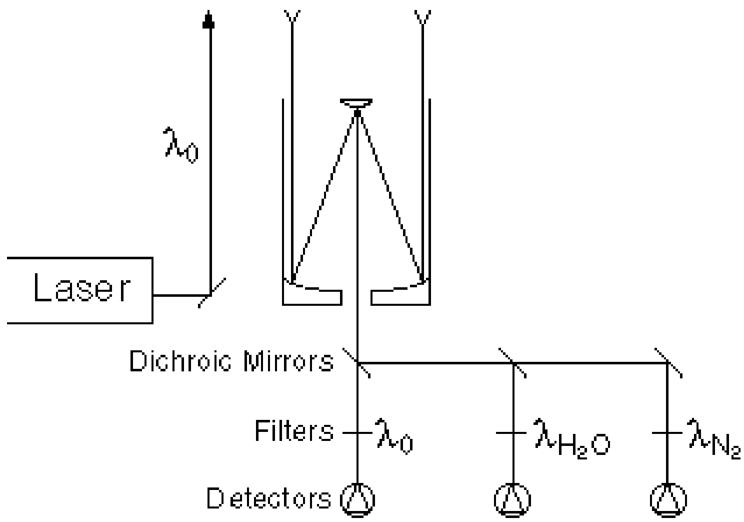
- ✓ Eq.[23.13] gives the density of the absorbing gas as a function of range.
- DIAL systems can measure the following gases: H_2O, O_3, CO_2, CH_4, NO_2, and SO_2

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

$$P_r(R,\lambda_L,\lambda_R) = \frac{C}{R^2}\frac{h}{2}\frac{k_b(R,\lambda_L,\lambda_R)}{4\pi}\exp\left(-\int_o^R [k_e(r',\lambda_L)+k_e(r',\lambda_R)]dr'\right) \qquad [23.14]$$

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

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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

<u>Example</u>: 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 $k_b(\lambda=355$ 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.

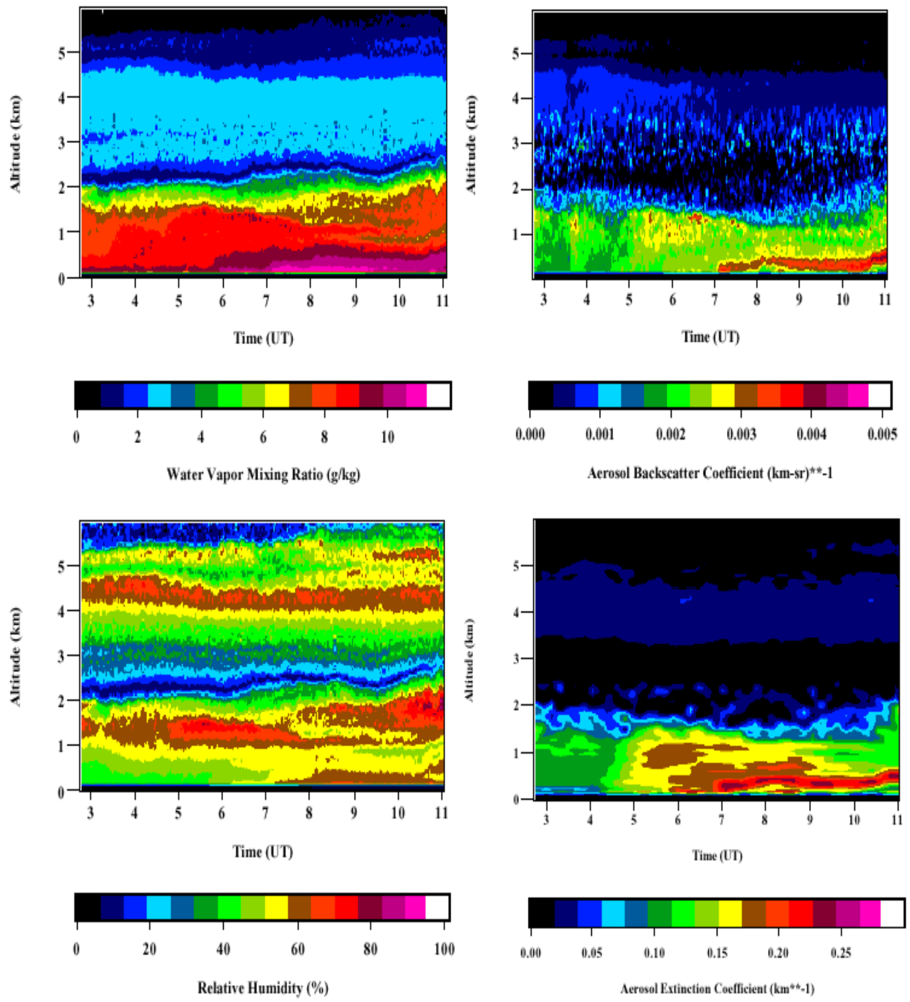

Figure 23.1 Examples of retrievals using the Raman lidar.

CO₂ 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)

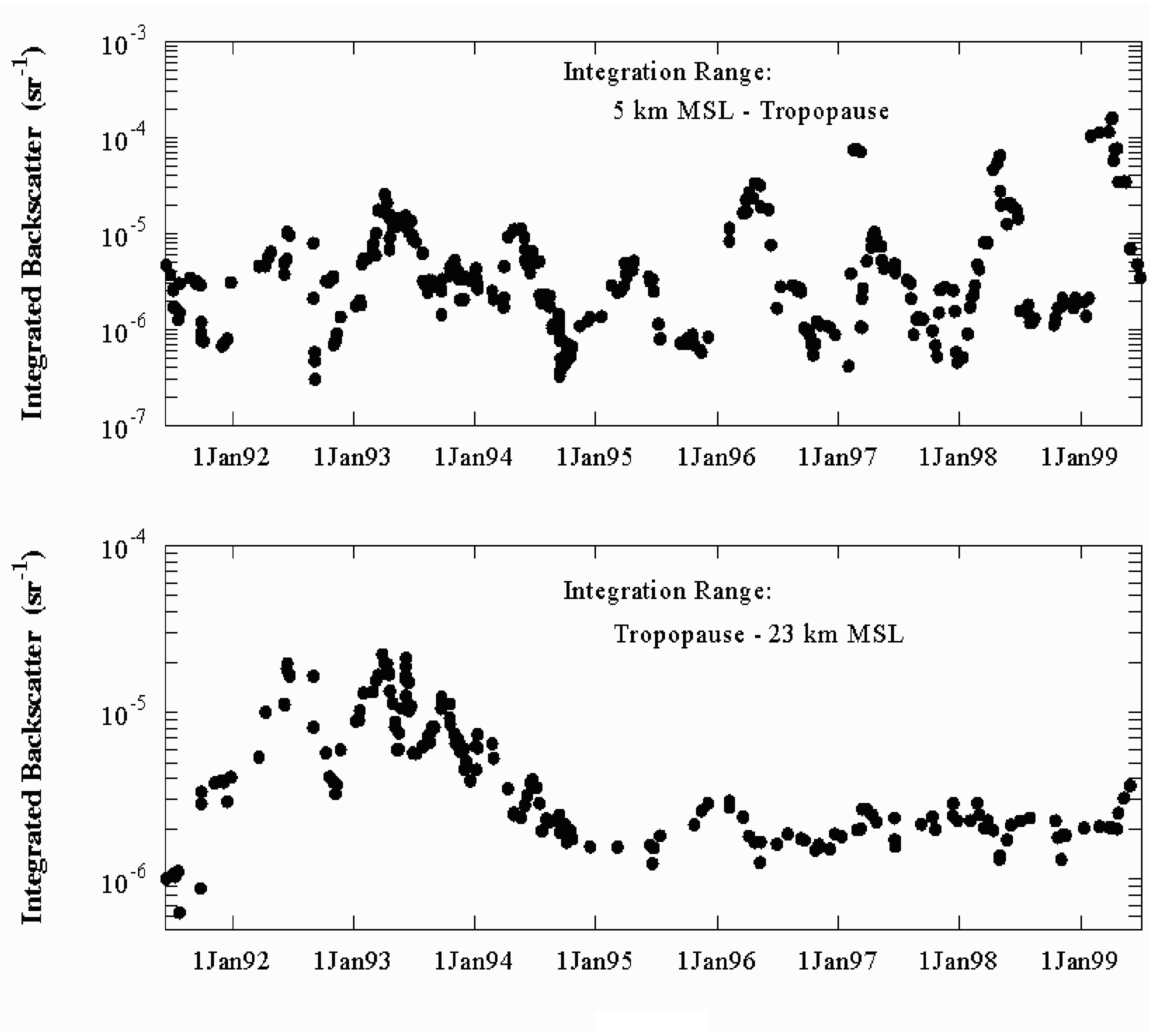

Figure 23.2. Integrated backscatter from the free troposphere (upper panel) and the lower stratosphere (lower panel) column above the JPL Pasadena site since the eruption of the Philippine volcano Mt. Pinatubo in June of 1991 (Tratt et al.)

- **Lidar sensing of clouds.**

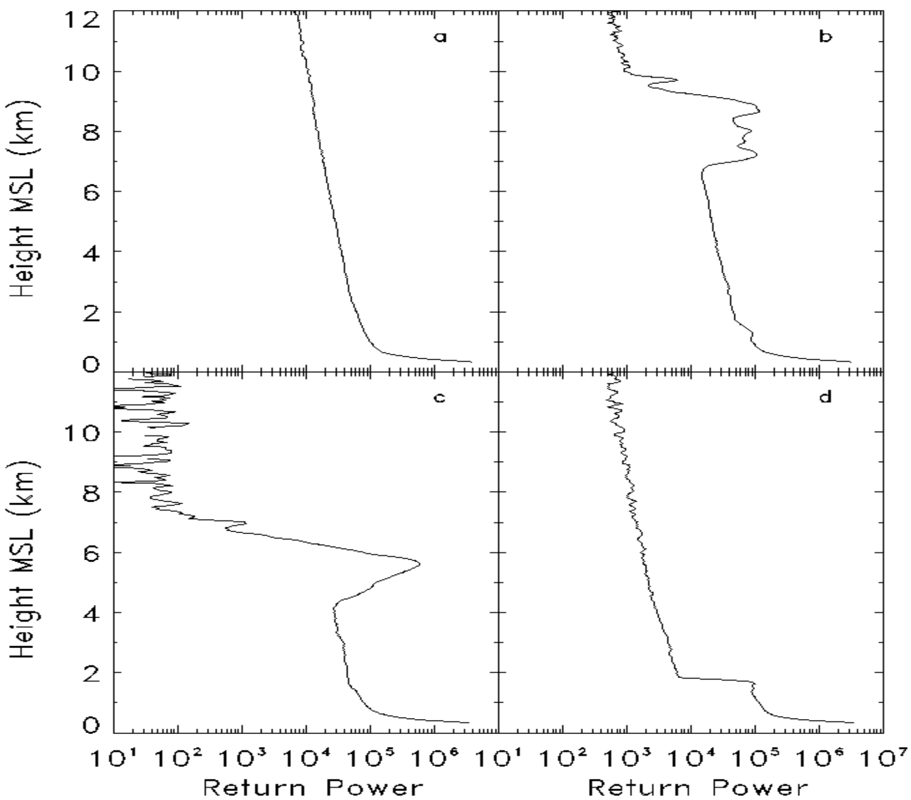

Figure 23.3. Four typical examples of range corrected lidar backscatter versus altitude (ARM Raman lidar, 10 min average, Sassen et al.). Fig. 23.3a illustrates a clear sky backscatter, which decrease with altitude due to the decrease in molecular density. Fig. 23.3b shows a backscatter from cirrus, 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. 23.3c. Compare with clear sky case (Fig. 23.3a), we can find a very strong increase in lidar backscatter form clouds (Fig. 23.3b-c), but it is not always observable (Fig. 23.3d). 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)

3. 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.

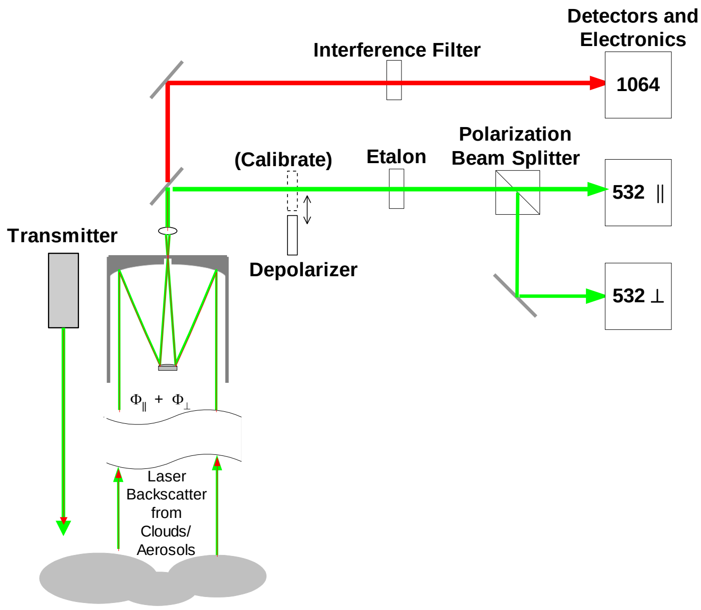

Figure 23.4 Functional block diagram of CALIOP (from CALIPSO ATBD).

CALIOP image tutorial :

http://www-calipso.larc.nasa.gov/resources/calipso_users_guide/browse/index.php

How to "read" lidar backscattering: an example

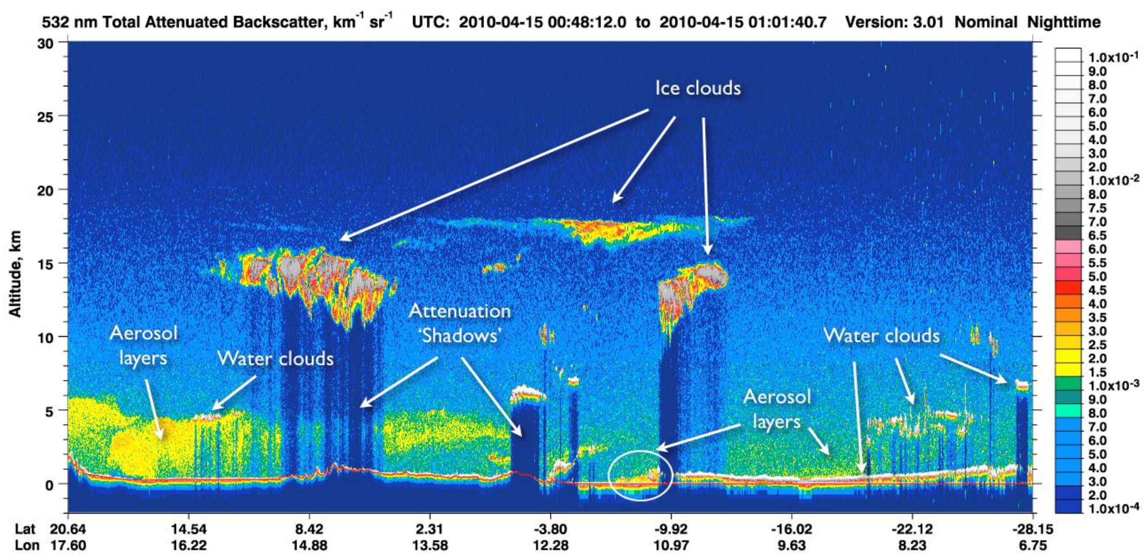

Table 23.1 CALIPSO lidar Level 2 aerosol and clouds products

Data Product	Measurement Capabilities and Uncertainties	Data Product Resolution	
		Horizontal	Vertical
Aerosols			
Height, Thickness	For layers with $\beta > 2.5 \times 10^{-4}\ km^{-1}\ sr^{-1}$	5 km	60 m
Optical depth, τ	40% *	5 km	N/A
Backscatter, $\beta_a(z)$	20 - 30%	40 km 40 km	Z < 20 km 120 m Z ≥ 20 km: 360 m
Extinction, σ_a	40% *	40 km 40 km	Z < 20 km 120 m Z ≥ 20 km: 360 m
Clouds			
Height	For layers with $\beta > 1 \times 10^{-3}\ km^{-1}\ sr^{-1}$	1/3, 1, 5 km	30, 60 m
Thickness	For layers with $\tau < 5$	1/3, 1, 5 km	60 m
Optical depth, τ	within a factor of 2 for $\tau < 5$	5 km	N/A
Backscatter, $\beta_c(z)$	20 - 30%	5 km	60 m
Extinction, σ_c	within a factor of 2 for $\tau < 5$	5 km	60 m
Ice/water phase	Layer by layer	5 km	60 m
Ice cloud emissivity, ε	±0.03	1 km	N/A
Ice particle size	±50% for $\varepsilon > 0.2$	1 km	N/A

NOTE: Notations used in Table for backscattering coefficient and extinction coefficient differ from those used in lecture