Lecture 25. Aerosol Lidar (1)

- Motivations to study aerosols and clouds
- Lidar detection of aerosol/cloud properties
- Single-channel vs multi-channel lidar

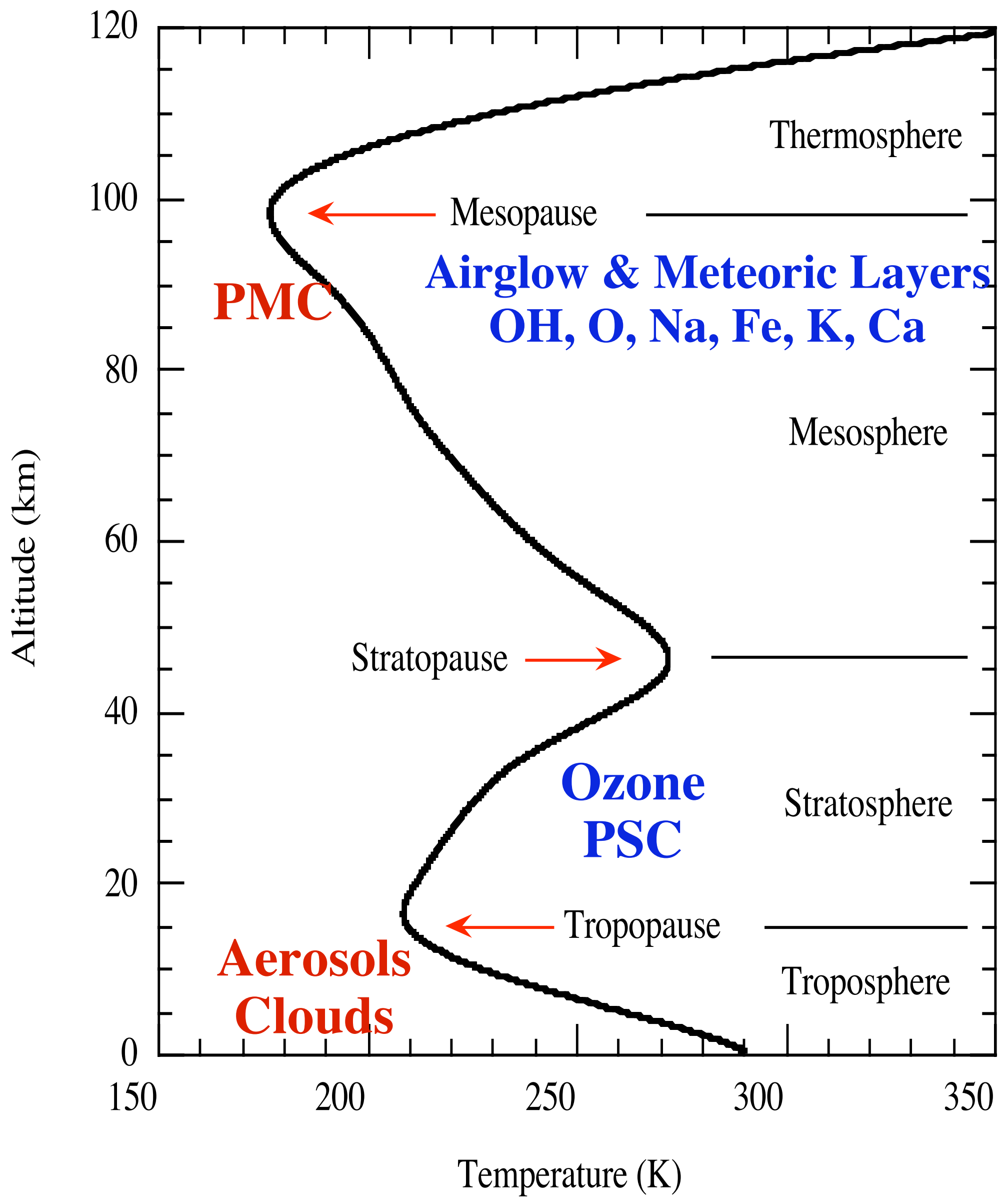
(Elastic-scattering lidar, Raman lidar, and HSRL)

- Polarization detection
- Multi-wavelength detection
- Summary

Motivations to Study Aerosols

- Atmospheric aerosols play an important role in many atmospheric processes. Although only a minor constituent of the atmosphere, they have appreciable influence on the Earth's radiation budget, air quality and visibility, clouds, precipitation, and chemical processes in the troposphere and stratosphere.
- The occurrence, residence time, physical properties, chemical composition, and corresponding complex-refractive-index characteristics of the particles , as well as the resulting climate-relevant optical properties are subject to large diversity especially in the troposphere because of widely different sources and meteorological processes.
- Therefore, vertically resolved measurements of physical and optical properties of particles such as the particle surface-area concentration, volume and mass concentrations, mean particle size, and the volume extinction coefficient are of great interest.
- Routine (long-term), range-resolved observations of these parameters can only be carried out with lidar.

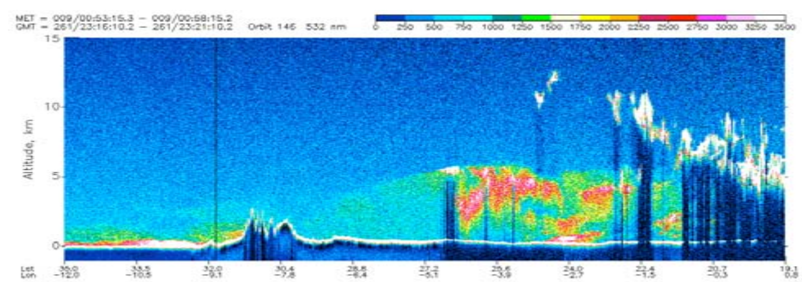
Aerosols and Clouds in Atmosphere



Polar mesospheric clouds (PMC) usually occur in polar summer

Polar stratospheric clouds (PSC) occur in polar winter and spring

Aerosols always present in troposphere with highly variable concentration and composition due to natural and anthropogenic sources



Nucleation mode: r < 0.1 μm
accumulation mode: 0.1 < r < 1 μm,
coarse mode: r > 1 μm

More Motivations

- Aerosol Properties – optical, microphysical, and chemical
- Cloud Properties – optical, microphysical, radiative for ice, water and mixed phase
- Aerosol-Cloud Interactions – aerosol act to seed clouds
- Air Quality and Pollutant Transport – Study long range transport, anthropogenic vs. natural sources, gas/aerosol interactions
- Direct and Indirect Aerosol Radiative Forcing – improve models
- Surface and Atmospheric Radiative effects
- Cloud – Radiation Dynamical Feedback Processes
- Properties of Mixed Phase Clouds
- Polar Stratospheric Clouds – distribution, properties and lifecycle
- Polar Mesospheric Clouds - indication of global climate change
- Aerosol influence is one of the major uncertainties in atmospheric models that are used to predict global climate change.
- All aerosols and clouds are also good tracers of atmosphere environment, so excellent natural indicator or laboratory.

Aerosol Properties vs Lidar Detection

- Physical Properties: Occurrence, Height, Residence Time, Vertical structure.
  - for any scattering lidar

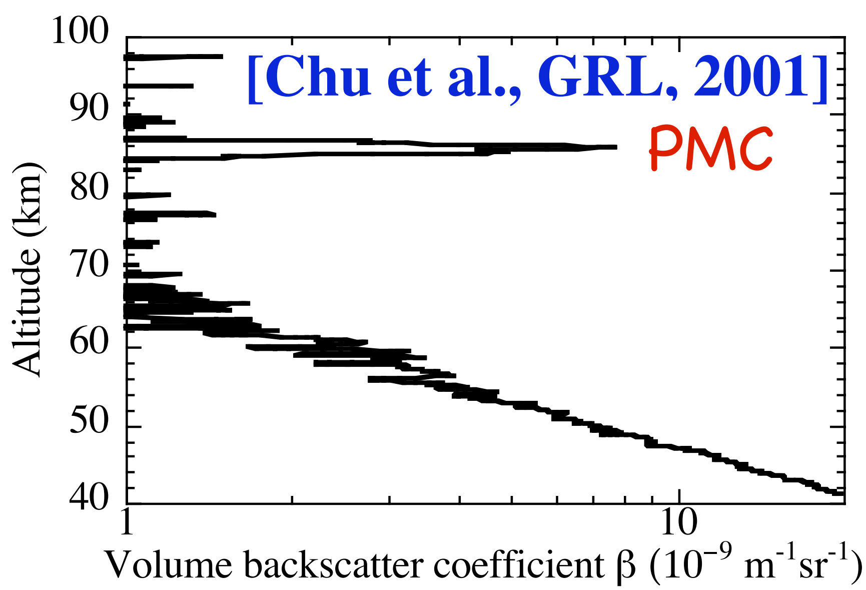
- Optical Properties: light backscatter, absorption, extinction, or albedo, complex-refraction-index
  - single-channel lidar versus multi-channel lidar

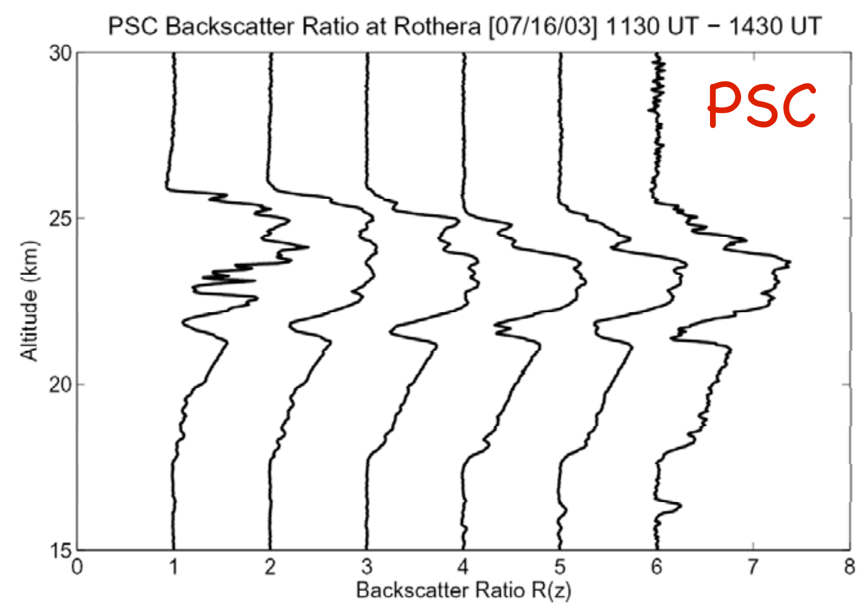
- Microphysical Properties: particle size, particle shape, number density, mass density, size distribution
  - multi-wavelength lidar and
  - polarization detection lidar

- Chemical Composition and Process in the Atmosphere
  - laser-induced-breakdown with spectroscopic lidar

Lidar Detection of Aerosols/Clouds

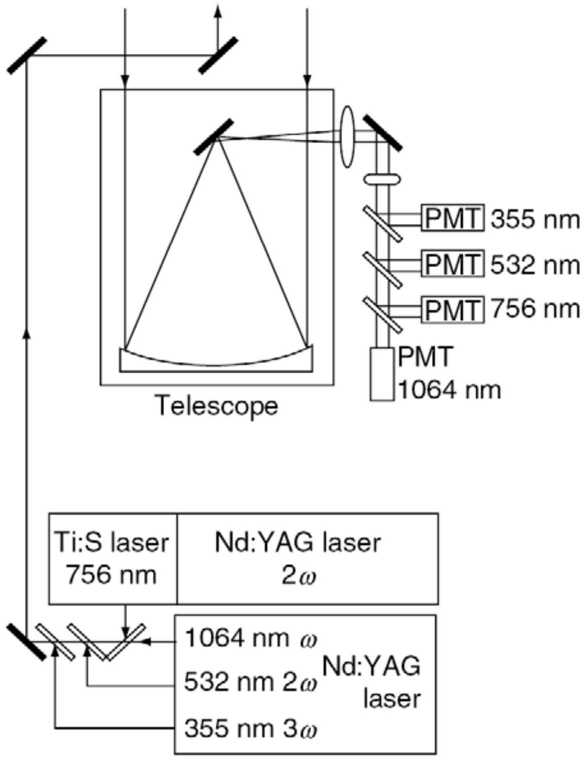
- Aerosols and clouds are shown as distinct peaks above the Rayleigh scattering background in range-resolved lidar profiles.
- The common way to detect aerosols and clouds is to use elastic scattering lidar with Rayleigh and Mie scattering detection capability.
- Virtually this can be done by any lidars that receive scattering signals, including resonance fluorescence, DIAL, Raman, Rayleigh, & Mie.
- The challenge is how to derive aerosol extinction when the aerosol layers are dense, i.e., to obtain extinction-corrected aerosol profiles.





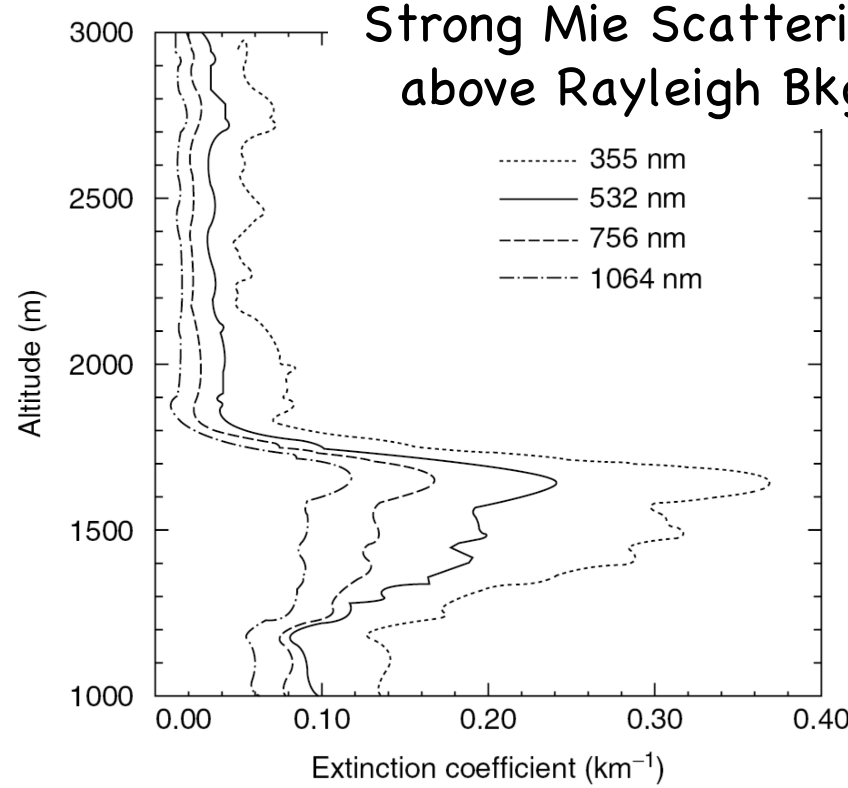
Lidar Detection of Aerosols

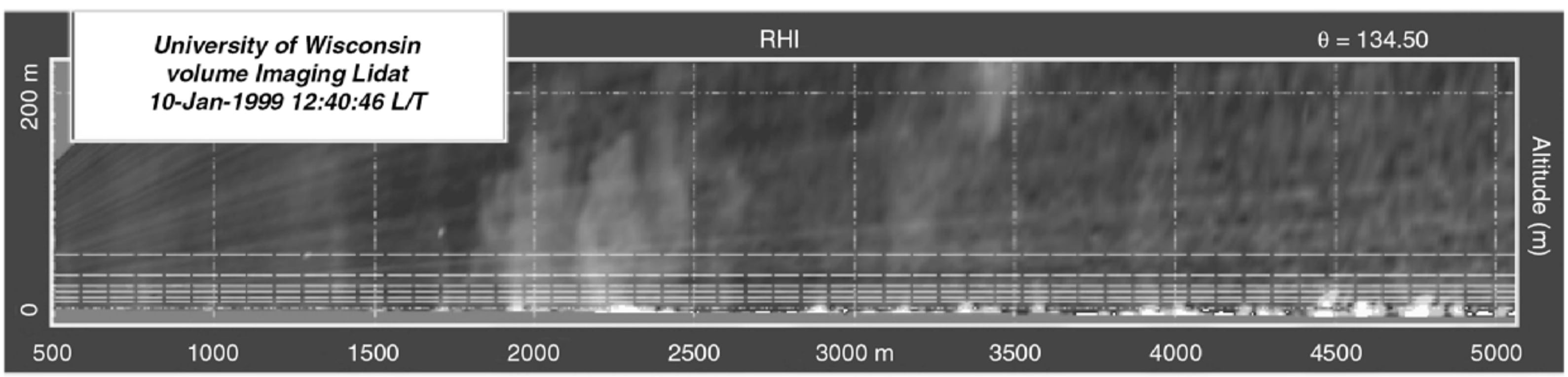
Co-axial Lidar



Block diagram of four-wavelength lidar.

Strong Mie Scattering above Rayleigh Bkg





Elastic-Scattering for Lower Atmos

- Lidar equation for elastic backscatter by air molecules and aerosols

$$P(R) = \frac{E_o \eta}{R^2} O(R) \beta(R) \exp\left[-2\int_0^R \alpha(r)dr\right]$$

O(R) - overlap between laser and FOV
β(R) - backscatter coefficient ($km^{-1}sr^{-1}$)
α(R) - extinction coefficient (km^{-1})

- Backscatter and extinction are contributed by aerosols and molecules

$$\beta(R) = \beta_{aer}(R) + \beta_{mol}(R)$$
$$\alpha(R) = \alpha_{aer}(R) + \alpha_{mol}(R)$$

Index aer refer to aerosol particles
Index mol refer to air molecules

- Combine above equation, we obtain

$$S(R) = P(R)R^2 = E_0 \eta_L \left[\beta_{aer}(R) + \beta_{mol}(R)\right] \exp\left[-2\int_o^R \left[\alpha_{aer}(r) + \alpha_{mol}(r)\right] dr\right]$$

Note: backscatter is local effect while extinction is integrated effect

- Recall the Rayleigh scattering from air molecules $\beta_{mol}(R)$ can be determined from atmosphere temperature and pressure

$$\beta_{mol}(\lambda, z_R) = 2.938 \times 10^{-32} \frac{P(z_R)}{T(z_R)} \cdot \frac{1}{\lambda^{4.0117}}$$

z_R is altitude for range R

Elastic-Scattering Cont'd

- Ignore the molecular absorption, then the extinction by air molecules is the integration of molecular angular scattering coefficient through the entire 4π solid angles. Rayleigh scattering is anisotropic

$$\beta(\theta) = \frac{\beta_T}{4\pi} P(\theta) = \frac{\beta_T}{4\pi} \times 0.7629 \times (1 + 0.9324\cos^2\theta)$$

$$\alpha_{mol}(R) = \beta_T = \frac{8\pi}{3} \cdot \beta(R,\pi)$$

- Define molecule extinction-to-backscatter ratio (lidar ratio) as

$$L_{mol} = \frac{\alpha_{mol}(R)}{\beta_{mol}(R)} = \frac{8\pi}{3} sr$$

The lidar ratio for molecule is range independent

- Thus, among the four parameters $\beta_{mol}(R)$, $\beta_{aer}(R)$, $\alpha_{mol}(R)$, $\alpha_{aer}(R)$, two are known, and the other two $\beta_{aer}(R)$ and $\alpha_{aer}(R)$ are unknown.

- Define the lidar ratio for aerosols (extinction-to-backscatter ratio)

$$L_{aer}(R) = \frac{\alpha_{aer}(R)}{\beta_{aer}(R)}$$

$$Y(R) = L_{aer}(R)\left[\beta_{aer}(R) + \beta_{mol}(R)\right]$$

Derive Aerosol Backscatter and Extinction in Lower Atmosphere

- Substitute lidar ratios and Y(R) into the lidar equation for S(R),

$$S(R)L_{aer}(R)\exp\left\{-2\int_o^R [L_{aer}(r)-L_{mol}]\beta_{mol}(r)dr\right\} = E_0\eta_L Y(R)\exp\left[-2\int_0^R Y(r)dr\right]$$

- Taking the logarithms of both sides of above equation and differentiating them with respect to R, we obtain

$$\frac{d\ln\left(S(R)L_{aer}(R)\exp\left\{-2\int_o^R [L_{aer}(r)-L_{mol}]\beta_{mol}(r)dr\right\}\right)}{dR} = \frac{1}{Y(R)}\frac{dY(R)}{dR} - 2Y(R)$$

- This is a Bernoulli equation, and can be solved for the following boundary condition

$$Y(R_0) = L_{aer}(R_0)\left[\beta_{aer}(R_0) + \beta_{mol}(R_0)\right]$$

Klett Method

- By solving the Bernoulli equation, we obtain the backscatter coefficient

$$\beta_{aer}(R)+\beta_{mol}(R)=\frac{S(R)\exp\left\{-2\int_{R_0}^{R}\left[L_{aer}(r)-L_{mol}\right]\beta_{mol}(r)dr\right\}}{\dfrac{S(R_0)}{\beta_{aer}(R_0)+\beta_{mol}(R_0)}-2\int_{R_0}^{R}L_{aer}(r)S(r)T(r,R_0)dr}$$

where

$$T(r,R_0)=\exp\left\{-2\int_{R_0}^{r}\left[L_{aer}(r')-L_{mol}\right]\beta_{mol}(r')dr'\right\}$$

- The aerosol extinction coefficient can be estimated by

$$\alpha_{aer}(R)=L_{aer}(R)\beta_{aer}(R)$$

- The solution for the Bernoulli equation can be integrated by starting from reference range R_0, which may be either the near end ($R > R_0$, forward integration), or the remote end ($R < R_0$, backward integration).
- Numerical stability is only given by the backward integration, which is called Klett method [1981].

How Reliable is Single-Channel Lidar?

- The above method is basically using one lidar equation to determine two unknown parameters. Its accuracy critically relies on the input parameter $L_{aer}(R)$ - lidar ratio for aerosol.
- However, this quantity depends on the microphysical, chemical and morphological properties of the particles, and varies strongly with height, especially when marine, anthropogenic (urban, biomass burning), and desert dust particles or mixtures of these are present in layers above each other. Even in the well-mixed layer, the lidar ratio is not constant with height because relative humidity increases with height.

Aerosol type	Lidar ratio
Marine particles	20-35 sr
Saharan dust	50-80 sr
Less absorbing urban particles	35-70 sr
Absorbing particles from biomass burning	70-100 sr

- Variations between 20-100 sr make it practically impossible to estimate trustworthy extinction profiles from single-channel data in lower atmos.

Multi-Channel Lidar for Aerosols

- To infer aerosol extinction more trustworthy, the key is to add additional channel to provide addition information. At least, two channels of lidar profiles are needed. Raman lidar and HSRL are two major solutions to this problem.

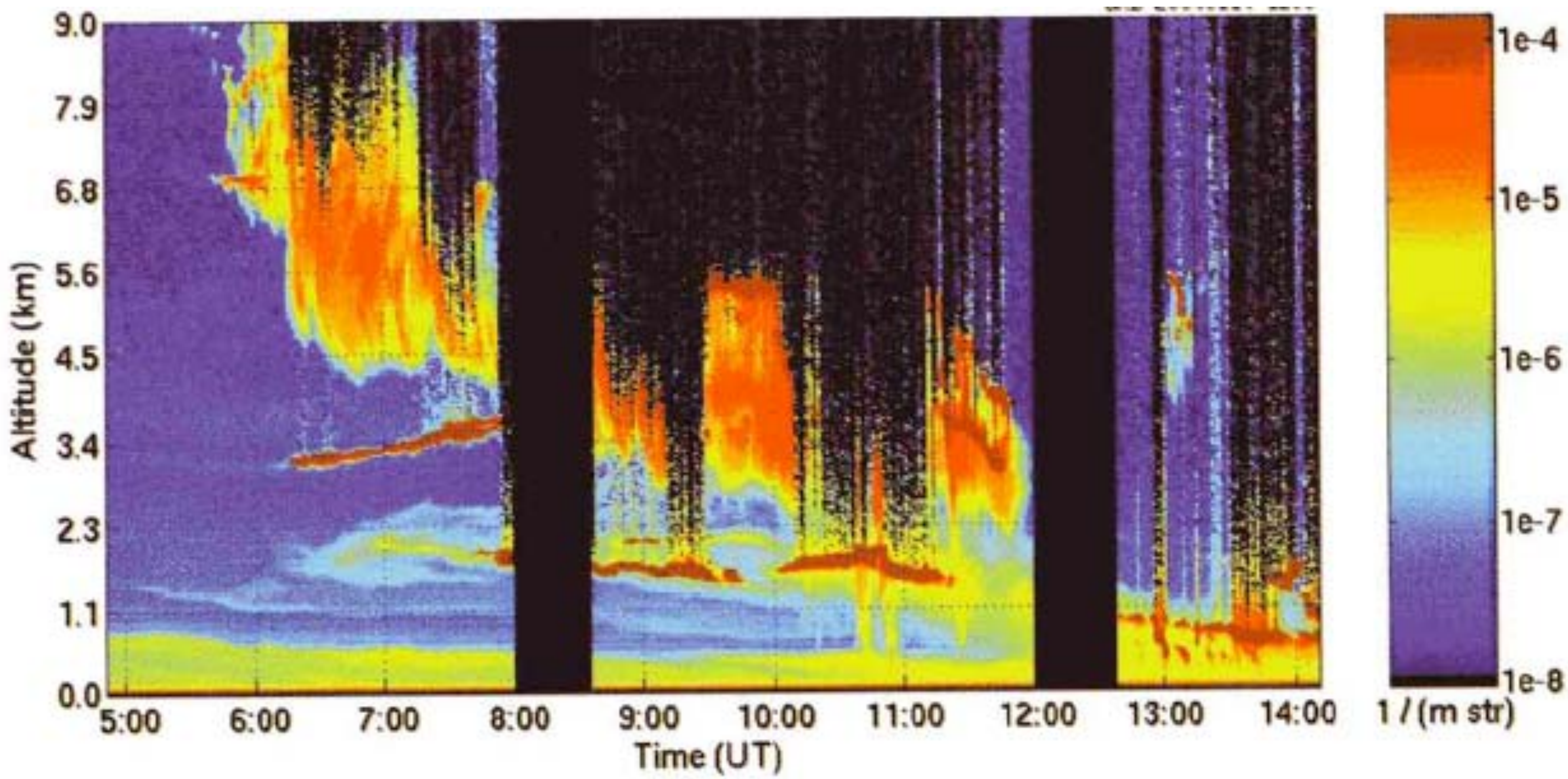
- One method is the measurement of two lidar profiles in one of which the aerosol scattering is zero $\beta_{aer} = 0$. This is the case in Raman lidar. Only molecules, not aerosols, contribute to the inelastic Raman backscatter profile produced by molecular nitrogen or oxygen.

(1) The elastic lidar return is affected by both aerosol extinction α_{aer} and aerosol backscatter β_{aer}.

(2) But Raman lidar return is only affected by aerosol extinction α_{aer} alone, as aerosol scattering β_{aer} is at a different wavelength than the Raman return wavelength, so won't be received by the Raman channel.

- Another method is the high-spectral-resolution lidar (HSRL) that has two channels - one to measure pure molecular scattering, and another to measure the combination of aerosol and molecular scattering.

Example of Aerosol Results



High-Spectral-Resolution Lidar Measurements
Courtesy of Dr. Ed Eloranta, University of Wisconsin

Multi-Wavelength Lidar Detection

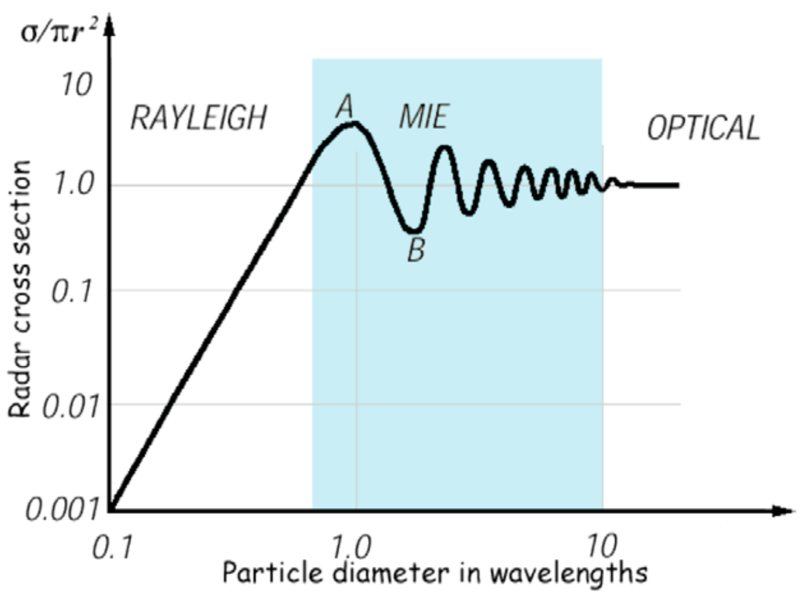
- From the name, multi-wavelength lidar is to detect the common-volume aerosols using several different wavelengths that are significant apart from each other, e.g., 1064, 532, 355 nm (fundamental, doubled, and tripled Nd:YAG laser wavelengths).
- By taking the color ratio of aerosol scattering, plus some assumptions of particle shape and size distribution, e.g., spherical particles and lognormal distribution, the multi-wavelength lidar measurements of aerosol can be used to determine the particle size (e.g., radius, width) and particle number density.
- This is based on the dependence of backscatter cross section versus the ratio of particle size/wavelength. When particle is small compared to laser wavelength, it is pure Rayleigh scattering with λ^{-4} relationship (e.g., air molecules). When particle size increases, the scattering slowly goes from Rayleigh to Mie scattering, and could experience "oscillation" with particle size/wavelength (shown in next slide).

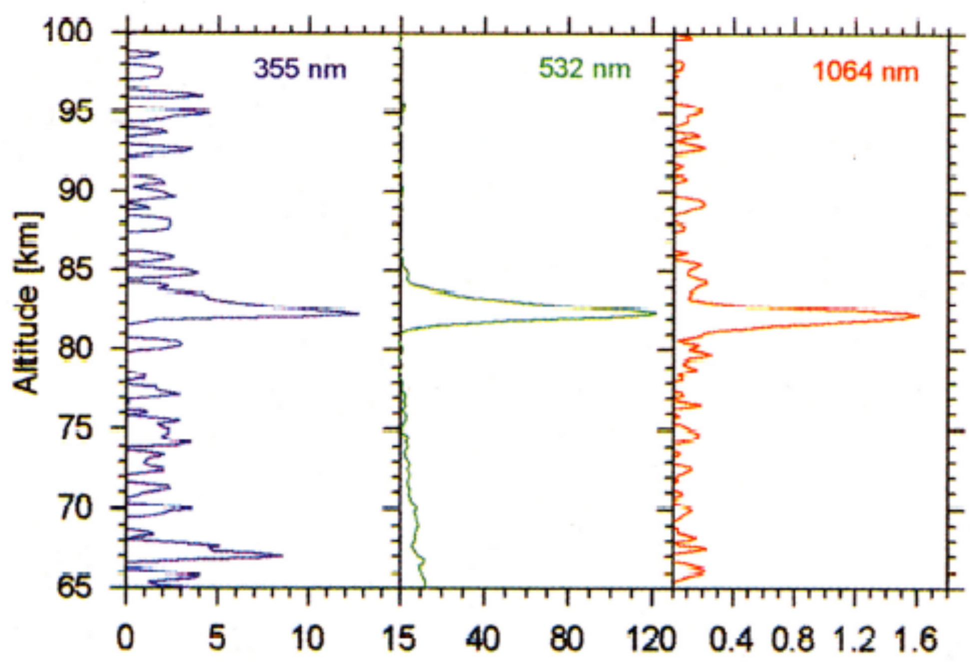
Multi-Wavelength Lidar Detection

- Lognormal Distribution of Spherical particles

$$\frac{dn_{NLC}(r)}{dr} = \frac{N_{NLC}}{\sqrt{2\pi} \cdot r \cdot \ln \sigma} \cdot \exp\left(- \frac{\ln^2(r/r_{med})}{2\ \ln^2\sigma} \right) \quad (4)$$

N_{NLC}	total number density of aerosols
r_{med} , σ	median radius and width parameter of the lognormal size distribution, respectively





Multi-Wavelength Lidar Detection

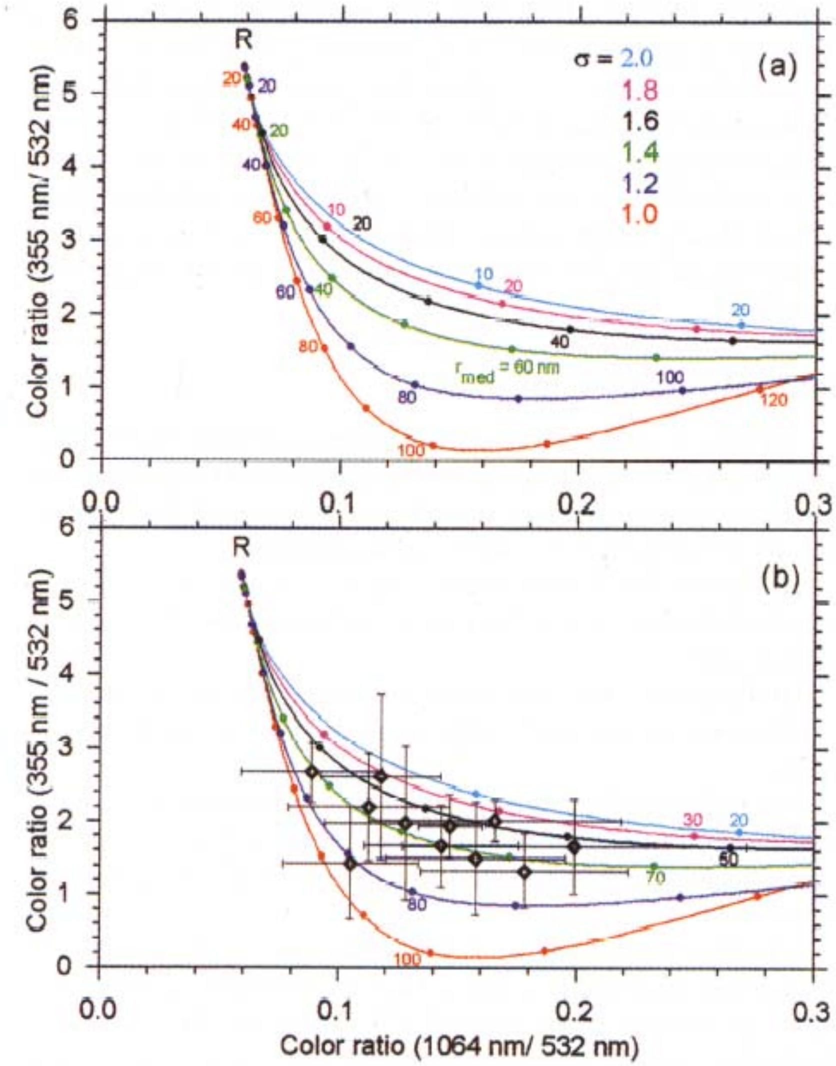


Figure 1. Panel (a) shows as a result of Mie calculations for the color ratios *CR* of used laser wavelengths a set of color coded curves for constant σ and r_{med}. In panel (b) the derived color ratios of the 11 NLC events are plotted in the field of the modelled color ratios.

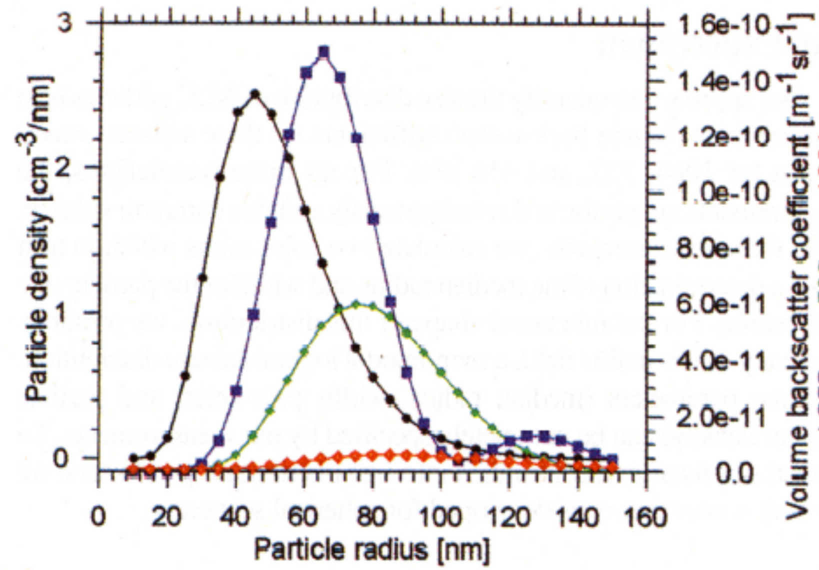


Figure 3. Properties of a lognormal size distribution with $r_{med} = 50$ nm, $\sigma = 1.4$, and $N_{NLC} = 100$ cm^{-3}: Contributions of particles in 5 nm-wide size classes to the particle density (black line) and volume backscatter coefficients (colored lines) as function of the radius and three wavelengths.

Polarization in Scattering

- According to Mie theory, backscattering from spherical particles does not change the polarization state of the radiation. The backscattered light has polarization parallel to that of the transmitted beam (usually linearly polarized).
- As long as the particles are small compared to the wavelength, the actual particle shape does not play a major role for the scattering properties as theories for non-spherical scatters show.
- Large non-spherical particles lead to a depolarization of backscattered radiation, i.e., partial backscattered light has polarization perpendicular to that of the transmitted beam.
- The range-resolved linear depolarization ratio is

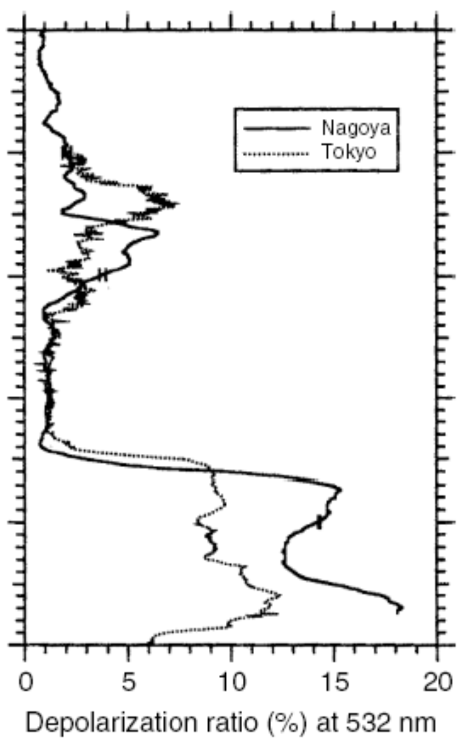
$$\delta(R) = \left[\beta_{\perp}(R) / \beta_{||}(R)\right] \exp\left(T_{||} - T_{\perp}\right)$$

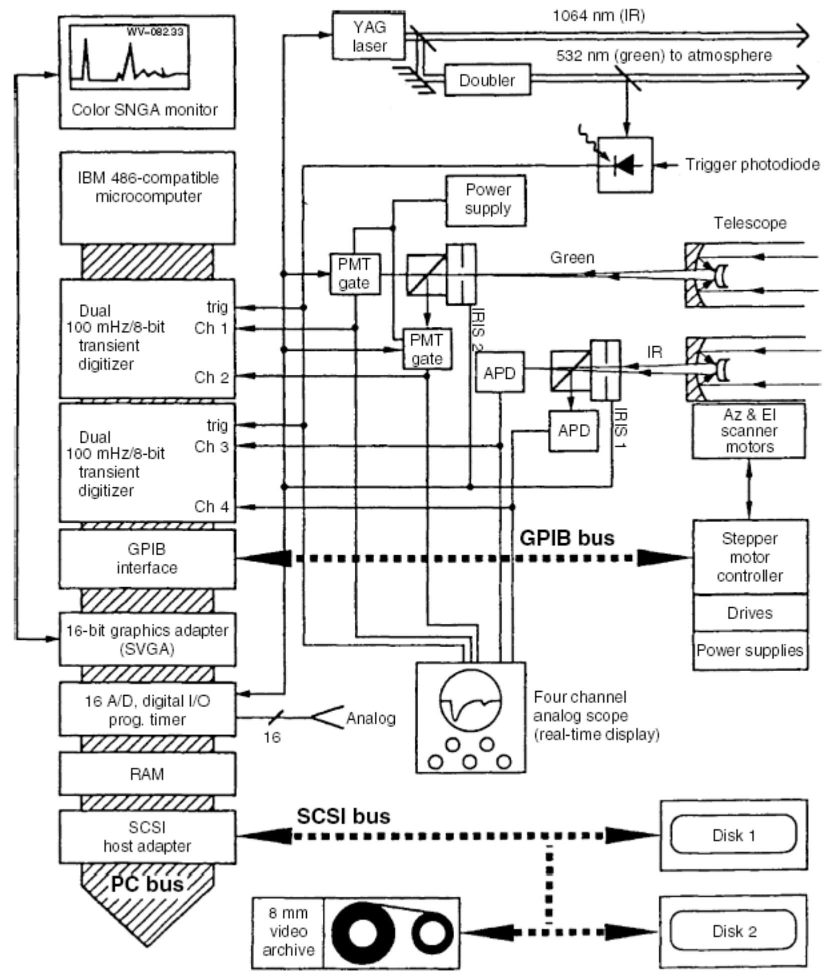
Polarization Lidar Detection

- Backscattering from a spherical particle does not change the polarization, but the non-spherical particle changes the polarization. Thus, by monitoring the polarization status of the scattered light, information on the shape of the aerosol particles can be obtained.

- Depolarization is defined by

$$\delta = I_{\perp} / I_{\parallel}$$





Summary

- Aerosol is an important topic in atmospheric science and environmental research. It can be measured/monitored by hot lidar technologies.
- Conventional single-channel elastic-scattering lidar can beautifully address PMC and PSC backscatter problems, and monitor the occurrence, height, vertical structure, etc. However, it is unreliable to derive aerosol extinction.
- Raman lidar and HSRL provide addition information by adding Raman channel or separate molecular scattering from aerosol scattering. Both can measure aerosol backscatter and extinction nicely. However, HSRL is more desirable as Rayleigh scattering is much stronger than Raman scattering.
- Polarization detection and multi-wavelength detection can help identify aerosol shape, size, distribution, and number density.
- Aerosol study is growing, and awaiting for more smart lidar ideas.