Lecture 8: Rayleigh lidar for observations of middle atmospheric temperature
Rayleigh lidar equation

\[ N_{Ray}(z, \lambda_L) = N_L(\lambda_L) \frac{A_L}{(z - z_L)^2} T^2 \left( \beta_{Ray}(z, \lambda_L) + \beta_{Mie}(z, \lambda_L) \right) \Delta z \]

\[ T^2 = \exp \left( -2 \int_{z'=z_L}^{z} \alpha_{Ray}(z', \lambda_L) dz' - 2 \int_{z'=z_L}^{z} \alpha_{Mie}(z', \lambda_L) dz' - \sum_{i} 2 \int \sigma_i(z', \lambda_L) N_i(z') dz' \right) \]

- \( N_{Ray} \) is the number of photons received per laser shot at wavelength \( \lambda_R = \lambda_L \)
- \( N_L \) is the number of photons emitted per laser shot at wavelength \( \lambda_L \)
- \( z \) is the altitude of the \( \Delta z \)-thick back-scattering layer
- \( A_L \) is the area of the receiving telescope
- \( z_L \) is the altitude of the emitting/receiving system
- \( \beta_{Ray} \) is the Rayleigh backscatter coefficient: \( \beta_{Ray}(z, \lambda_L) = \frac{3}{8\pi} \sigma_{Ray}(\lambda_L) N_{Air}(z) \)
- \( \beta_{Mie} \) is the Mie back-scattering coefficient of the atmospheric aerosols particles
- \( \alpha_{Ray} \) is the air Rayleigh extinction coefficient: \( \alpha_{Ray}(z, \lambda_L) = \sigma_{Ray}(\lambda_L) N_{Air}(z) \)
- \( \alpha_{Mie} \) is the Mie extinction coefficient of the atmospheric aerosols particles
- \( \sigma_{Ray} \) is the Rayleigh extinction cross-section of the air molecules
- \( N_{Air} \) is the air number density at altitude \( z \)
- \( i \) denotes all the atmospheric absorbers (ozone, water vapor, etc.)
- \( \sigma_i \) is the absorption cross-section of the constituent \( i \)
- \( N_i \) is the number density of the constituent \( i \).
Density and temperature derivation

hydrostatic equilibrium: \[ dp(z) = -\rho(z)g(z)\,dz \]

Ideal gas law:
\[ p(z) = \rho(z) \frac{R}{M(z)} T(z) \]

\[ \rho(z) = \frac{C (z - z_L)^2 N_{Ray}(z)}{T_{Ray}^2 T_{O_3}^2} \]

\[ T_{Ray}^2 = \exp \left( - \int_{z' = z_L}^{z} \left( \sigma_{Ray}(\lambda_L) + \sigma_{Ray}(\lambda_R) \right) \frac{M(z') k_B}{R} \rho(z') \,dz' \right) \]

\[ T_{O_3}^2 = \exp \left( - \int_{z' = z_L}^{z} \left( \sigma_{O_3}(z', \lambda_L) + \sigma_{O_3}(z', \lambda_R) \right) N_{O_3 i}(z') \,dz' \right) \]

Only consider ozone observation, an \textit{a priori} ozone profile is also necessary
Density and temperature derivation

\[ S^C_{\lambda_R}(z) = \frac{(z - z_L)^2 N_{Ray}(z)}{T^2_{Ray} T^2_{O_3}} = \frac{\rho(z)}{C} \]

Using an external source (from a model or from external measurements) of temperature information \( T_0 \) at the top of the profile (integration downward, uncertainty converge)

\[
T(z) = \frac{1}{S^C_{\lambda_R}(z)} \left( T_0(z_{TOP}) S^C_{\lambda_R}(z_{TOP}) + \frac{M(z)}{R} \int_{z'=z}^{z_{TOP}} S^C_{\lambda_R}(z') g(z') \delta z' \right)
\]

\[
p(z) = \rho(z) \frac{R}{M(z)} T(z) = \frac{RT(z)}{K_N M(z)} S^C_{\lambda_R}(z)
\]
Error analysis

The uncertainty is determined by the photon noise and upper altitude temperature $T(z_0)$. The variance of derived temperature is given by

$$\text{var}[T(z)] \approx \frac{T^2(z)}{N_R(z)} + \left\{ \text{var}[T(z_0)] + \frac{T^2(z_0)}{N_R(z_0)} \right\} \exp\left[-\frac{2(z_0 - z)}{H}\right]$$

After 1-2 scale height (10-15 km), the error introduced by $T(z_0)$ is not important anymore. So the temperature error is primarily due to the photon noise.
Error analysis

**Figure 7.** Deviation between original and MLO retrieved profiles for a simulated profile 15 K warmer than the standard CIRA profile.

_Leblanc et al., 1998_
ARCtic Lidar Technology (ARCLITE) system
System Specifications

Transmitter: **Spectra-Physics GCR5-30 Nd:YAG**
- Wavelength: 532nm
- Pulse width: 7 ns
- Pulse repetition rate: 30 Hz
- Pulse energy: 560 mJ
- Average power: 17 W
- Seeded linewidth: 105 MHz
- Beam divergence (X4): 0.1 mrad

Receiver: **Newtonian Telescope**

**Configuration**
- Telescope diameter: 92 cm
- Focal length: 203 cm
- Field of view: 0.5 mrad
- Number of channels: 2
- Filter bandwidth:
  - Nighttime: 10 Å
  - Daytime: 0.8 Å

Signal Processing:

**Photon Counting Data Acquisition System**
- Data system SR430
- Maximum count rate: 100 MHz
- Range bin size: 192 m
- Number of range bins: 1024
- On-line integration: 1 min
- Computer system: PC 486-33
- PMTs (2) EMI 9863B/100
ARCLITE lidar observations

Temperature
ARCLITE lidar observations
Noctilucent clouds
(Polar Mesospheric Clouds, or PMC)
Inter-comparisons of middle atmospheric temperature observed by lidars and NASA EOS Aura MLS satellite
The Lidar stations

**JPL TMF lidar station:**
- 50 miles NE of Los Angeles
- Latitude: 34.4°N
- Longitude: 117.7°W
- Elevation: 2285 m (7500 ft)

**JPL MLO Lidar station:**
- Near center of Big Island of Hawaii
- Latitude: 19.5°N
- Longitude: 204.4°W
- Elevation: 3400 m (12,000 ft)

**France OHP lidar station:**
- southeast France
- Latitude: 44°N
- Longitude: 6°W
- Elevation: 679m

**Ny-Alesund lidar station:**
- west coast of Spitsbergen, Norway
- Latitude: 78.9°N
- Longitude: 11.9°E
- Elevation: 11m

**Germany HOH Lidar station**
- Hohenpeissenberg, Germany
- Latitude: 47.8°N
- Longitude: 11°E
- Elevation: 1000m
Comparisons MLS – TMF and MLO lidars (temperature profiles)

Temperature comparison MLS-TMF, 04/16/2005
Temperature comparison MLS-MLO, 04/12/2005
Comparisons MLS – TMF (34.4°N, 117.7°W) lidar (temperature)

Blue: MLS  Green: MLS-lidar (individual)  Red and blue solid: Standard deviations
Red: lidar  Black: MLS-lidar (mean)  Red and blue dotted: Precisions

MLS-TMF, 2004-2006 (138 coincidences)

MLS-TMF, 2004-2006

MLS-TMF, 2004-2006
Comparisons MLS - TMF lidar (temperature)
Comparisons MLS - TMF NDSC Model (temperature)

Blue: MLS  Green: MLS-lidar (individual)  Red and blue solid: Standard deviations
Red: NDSC  Black: MLS-lidar (mean)  Red and blue dotted: Precisions
Comparisons MLS - TMF NCEP Model (temperature)

Blue: MLS  Green: MLS-lidar (individual)  Red and blue solid: Standard deviations
Red: NCEP  Black: MLS-lidar (mean)  Red and blue dotted: Precisions
Comparisons MLS – MLO (19.5°N, 204.4°W) lidar (temperature)

Blue: MLS
Green: MLS-lidar (individual)
Red: lidar
Black: MLS-lidar (mean)
Red and blue dotted: Precisions
Red and blue solid: Standard deviations

MLS-MLO, 2004-2006 (96 coincidences)

ML5-MLO, 2004-2006

ML5-MLO, 2004-2006
Comparisons MLS - MLO lidar (temperature)
Comparisons MLS - MLO NDSC Model (temperature)

Blue: MLS  Green: MLS-lidar (individual)  Red and blue solid: Standard deviations
Red: NDSC  Black: MLS-lidar (mean)  Red and blue dotted: Precisions
Comparisons MLS - MLO NCEP Model (temperature)

Blue: MLS  Green: MLS-lidar (individual)  Red and blue solid: Standard deviations
Red: NCEP  Black: MLS-lidar (mean)  Red and blue dotted: Precisions
Comparisons MLS - MLO Radiosonde (temperature)

- Blue: MLS
- Green: MLS-lidar (individual)
- Red: RadioSonde
- Black: MLS-lidar (mean)
- Red and blue solid: Standard deviations
- Red and blue dotted: Precisions

MLS-MLO(RAOB), 2004-2006 (94 coincidences)
Comparisons MLS - OHP (44ºN, 6ºE) lidar (temperature)

Blue: MLS  Green: MLS-lidar (individual)  Red and blue solid: Standard deviations
Red: lidar  Black: MLS-lidar (mean)  Red and blue dotted: Precisions
Comparisons MLS - HOH (47.8°N, 11°E) lidar (temperature)

Blue: MLS  Green: MLS-lidar (individual)  Red and blue solid: Standard deviations
Red: lidar  Black: MLS-lidar (mean)  Red and blue dotted: Precisions
Comparisons MLS - NYA (78.9°N, 11.9°E) lidar (temperature)

Blue: MLS  Green: MLS-lidar (individual)  Red and blue solid: Standard deviations
Red: lidar  Black: MLS-lidar (mean)  Red and blue dotted: Precisions