Session 3: Aerosol remote sensing using ground-based instruments (e.g., Pandora, AERONET)

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Ground Remote Sensing Lab.
AOT vs. microphysical property retrieval

• AOT measurements (total amounts) from ground-based instruments (DIRECT SUN) are simple and straightforward, thus have relatively smaller uncertainty.

• However, direct-Sun measurement does not provide sufficient information for deriving detailed aerosol properties (particle size, absorption and scattering properties).

• Detailed information on aerosols is important to understand air quality, climate forcing, and other terrestrial retrievals.

→ We need more information by taking additional measurements
Deriving Terrestrial Information from Spectroradiometric Instruments

**Measurements**
- Solar reflectance or earth’s emission by Passive sensor
- Backscattered laser by Active sensor

**Forward model**
(simulate light reaching to a sensor using atmosphere/surface condition)

**Inversion**
(estimate terrestrial states from light measured by a sensor)

**What we want to know**
- Atmosphere (Clouds, Aerosols, Gases)
- Land (Vegetation, Fire count, …)
- Ocean (Salinity, Plankton, Colored Dissolved Organic Matter, …)
- Cryosphere (Glaciers, Snow, …)
Guess target object from the shadow
Advantages
- Provides terrestrial information over broader coverage
- Quality of data are relatively uniform over the domain.

Limitations
- May have larger uncertainty due to the interferences with other parameters
- Some parameters may have low measurement sensitivity

→ Requires sufficient validation using reliable data
More information from...

**Multi-spectral**

- X-ray
- Visible
- Infrared

**Polarization**

- Breon and Goloub (1998)
- Chipman (MSPI brochure)

**Multi-angle**

- Additional Angles

(By Julian Wolkenstein)
Radiative Transfer in the Earth System

Atmosphere (e.g., Spurr, 2014)

Snow and Ice (e.g., He and Flanner, 2020)

Vegetation (e.g., Quan et al., 2017)

Ocean (e.g., Xiao et al., 2020)
Solar almucantar scan: proven to have optimum information on aerosols since it takes measurements of forward and backward scattering of aerosols. Limitations: are not available from low solar zenith angles.

Aerosol size, refractive indices
From sun/sky scan measurements
For here, Almucantar scan
(VZA = SZA, RAA = 3-180°)

Jeong et al. (2020; 2022)

Total amount of aerosols from attenuated direct solar light

Jeong et al. (2018)
Fitting example of the SMART-s aerosol algorithm to measured Sun/sky radiances of the AERONET at Kanpur, India, at 04:54 UTC on 2 January 2016. (a–g) Solar almucantar sky radiances from 380 to 1,640 nm and (h) spectral $\tau_{aer}$. Solid lines with brighter orange color represent simulated radiances of lower iteration steps and darker colors indicate those of higher-order iterations. The red circles are measured sky radiances (a–g) and $\tau_{aer}$ (h) from the AERONET.
Aerosol Inversion parameters

**Measurement Vector**
- Spectral AOT from direct-Sun measurements
- Diffuse-sky measurements (Almucantar or Hybrid scan)
- Measurement error covariance from calibration record

**State Vector** *(Retrieval parameter)*
- Spectral complex refractive indices
- Particle size distribution
- Single-scattering albedo
- Surface reflectance

**Inversion Method**
- Forward model

**Additional constraints**
- Climatology
- Smoothness
- Etc.
Retrieval methods of atmospheric trace gases and aerosols from the hyperspectral measurements

- TOMS\textsuperscript{*1} method (Bhartia, 2002): $O_3$

- DOAS\textsuperscript{*2} & BOAS\textsuperscript{*3} technique (Platt and Stutz, 2008; Chance, 2002): $O_3$, $NO_2$, $SO_2$, HCHO, ...

- Optimal Estimation Method (Rodgers, 2000; Liu et al., 2006): $O_3$, $CO_2$, Aerosols, and many

- Near UV method and Multi-wavelength method (Torres et al., 2007; Veihelmann et al., 2007): Aerosols

- Combined method

Different channel, inversion scheme and equations are optimized for each target species. But, the performance of the retrieval method depends on not only the retrieval method but also feature of the instrument.

\textsuperscript{*1}Total Ozone Mapping Spectrometer
\textsuperscript{*2}Differential Optical Absorption Spectroscopy
\textsuperscript{*3}Basic Optical Absorption Spectroscopy
Example Retrievals of the SMART-s and AERONET
- Seven Southeast Asian Studies (7SEAS) campaign
- 9 March – 2 May in 2019 (pre-monsoon)
- Rooftop of the Fang hospital, Fang, Thailand

Collocated AERONT and SMART-s instruments
Details are at Jeong et al. (2022, ACP)
Temporal variations of total columns of (a) aerosol extinction at 500 nm, (b) nitrogen dioxide, (c) precipitable water vapor, and (d) ozone at Fang, Thailand in 2019. The blue circles are from SMART–s retrievals, and the grey circles in panels (a) and (c) show those from the AERONET. In panel (a), the red circles indicate aerosol optical thickness at 550 nm from VIIRS Deep Blue (DB), while those in panel (d) depict total column ozone retrievals from OMI (TOMS Version 8.5). The correlation coefficient (R), root-mean-squared-error (RMSE), and mean-bias-error (MBE) at panels (a), (c), and (d) are between collocated SMART–s and AERONET/OMI data in black, and those of red color in panel (a) are between SMART–s and VIIRS DB retrievals.

From Direct-Sun measurements (based on the Langley method)
Volume-size distribution from the SMART-s and AERONET

Dominated by fine-mode particles (e.g., biomass-burning) and minor fraction of coarse mode (dust particles)

→ From the inversion method, hereafter
- Strong spectral absorption features in the UV by carbonaceous particles.

- The UV radiances are sensitive to aerosol absorption and vertical distribution, thus used to retrieve these parameters.

- Current AERONET algorithm provides from 440 nm, thus many of satellite algorithm assumes the UV optical properties.

- AERONET will provide aerosol properties in 380 nm soon.
Refractive index measurements from previous literatures

Recent advanced instruments, for in situ and/or laboratory environments, enable precision measurements of spectral-refractive-indices of various aerosol species (e.g., Washenfelder et al., 2013; Flores, et al., 2014, Shepherd et al. 2018)

Refractive index of the aerosols is a highly variable parameter depending on chemical composition, aging and mixing state, etc.

→ Measurements of the aerosol refractive index can provide valuable information on them.

Figure 4. Refractive index dispersions for urban, remote, and woodsmoke atmospheric aerosol extracts and humic acid aerosol, compared to refractive index values from the literature. A sample of literature studies investigated aerosols from (1) remote locations (e.g. b: Virkkula et al., 2006); (2) biomass burning (e.g. a: Hoffet et al., 2006; c: Guyon et al., 2003; i: Yamase et al., 1998; n: Chakrabarty et al., 2010; and o: Dinar et al., 2008); and (3) organic aerosols (e.g. d: Kim and Paulson, 2013; e: Nakayama et al., 2013; h: Lambe et al., 2013; j: Spindler et al., 2007; k: Kim et al., 2010; l: Yu et al., 2008; m: Flores et al., 2014a; n: Chakrabarty et al., 2010; and p: Trainic et al., 2011).
- Real refractive index ($n$) depends on chemical compounds, aging state, and etc.

- The $n$ affects scattering phase function of particles.

- The $n$ of the hygroscopically grown particles becomes to be close to that of water (1.33 in the UV-NIR).

- Imaginary refractive index ($k$) also depends on chemical compounds and aging state, etc.

- The $k$ affects absorption (higher $k$ results in stronger light-absorption).

- The $k$ of the hygroscopically grown particles also becomes to be close to that of water (0.0 in the UV-NIR), thus less absorbing (higher single-scattering albedo).
- Higher amount of the water vapor (H$_2$O) results in active hygroscopic growth of the carbonaceous aerosols.

- The values of H$_2$O gradually increased when approaching the monsoon season.
The retrieved $\omega_0$ and weighted-mean-radius of fine-mode aerosols from the SMART–s showed positive correlations with the H$_2$O ($R = 0.81$ for $\omega_0$ at 330 nm and 0.56 for volume-weighted-mean-radius), whereas the real-part of the refractive-index of fine-mode aerosol ($n_f$) showed negative correlations ($R = -0.61$ at 330 nm), which suggest that aerosol aging processes including hygroscopic growth (e.g., humidification and cloud processing) can be a major factor affecting temporal trends of aerosol optical properties.

Details are at Jeong et al., 2022
Example of application: Provides UV aerosol model for satellite algorithm

ASHE: Aerosol Single-scattering albedo and Height Estimation (Lee et al., 2021 and references therein)
Example of application: satellite products comparison/validation in the UV
Example of application: evaluation of the UV aerosol model for satellite algorithm

(a)

AAE

- 340 – 550 nm: $2.04 \pm 0.27$
- 378 – 550 nm: $1.94 \pm 0.33$
- 340 – 412 nm: $2.69 \pm 0.35$

(b)

$\frac{k_r(354 \text{ nm})}{k_r(388 \text{ nm})}$

- $1.17 \pm 0.05$

Mar 21 Mar 26 Mar 31 Apr 05 Apr 10 Apr 15 Apr 20 Apr 25 Apr 30
Example of application: aerosol over snow

Operational Deep blue product

Extended Deep blue product
Variabilities of the aerosol properties over globe?

Preliminary (from low AOT)
AERONET Inversion data handling (https://aeronet.gsfc.nasa.gov/)

AEROSOL INVERSIONS (V3)
+ Data Display
+ Download Tool
+ Download All Sites
+ Web Service
Level 1.5:
The following data are cloud cleared and quality controls have been applied but these data may not have final calibration applied. These data may change.


To zoom the map click on it.
Back to World Map

Sites: ☐ Permanent ☐ Campaigns
Total Data (Years): ☐ All ☐ >0.5 ☐ >1 ☐ >2 ☐ >3 ☐ >5 ☐ >10 ☐ >15
Sky Scan Scenario: ☐ Almucantar ☐ Hybrid
Inversion Level ☐ Level 1.5 ☐ Level 2.0
Hybrid scan

![Image showing hybrid scan results with different SZA angles (75°, 50°, 30°, 15°).] 

New hybrid sky radiance scans – only possible with the new Model-t cimel instrument.

This allows for significantly larger scattering angle measurements at smaller SZA.

Black: 0 <= angle < 6.5
Red: 6.5 <= angle < 31
Blue: 31 <= angle < 81
Green: angle >= 81

These ranges are similar to the scattering angle bin ranges used for V2 level 2.0 inversion criteria:

Minimum binned scattering angle requirements for each λ:
- ≥3.2 to 6.0: at least 2 in range
- ≥6.0 to 30.0: at least 5 in range
- ≥30.0 to 80: at least 4 in range
- ≥80.0: at least 3 in range
AERONET Download Site

Notice to users:

The public domain data you are about to download are contributed by the International AERONET Federation. Each site has a Principal Investigator(s) (PI), responsible for deployment, maintenance and data collection. The PI has priority use of the data collected at the site. The PI is entitled to be informed of any other use of that site data.

The Principal Investigator(s) of 'Bangkok' is (are): Brent Holben. If you intend to use the following data please consult with him/her/them via e-mail(s):

brent@aeronet.gsfc.nasa.gov

Recommended guidelines for data use and publication:

Although journal paper authorship and acknowledgement is the domain of the senior author and no policy is universally applicable, the AERONET contributors ask that every practical attempt be made to honor the following general guidelines.

Using AERONET data:
Please consult with the PI(s) and Co-I(s) of the data to be used.

Referencing:
Always cite the appropriate key AERONET papers for any publications as well as cite relevant manuscripts pertaining to previously published site data.

Publishing AERONET data from a 'few' sites:
Please consider authorship for the PI(s) and Co-I(s) and/or the following acknowledgement:

We thank the (Project/PI(s)/Co-I(s)) for (its/their) effort in establishing and maintaining (site name(s)) sites.

Publishing data from 'many' sites:
A general acknowledgement is typically sufficient and may read:

We thank the (PI(s) and Co-I(s)) and their staff for establishing and maintaining the (#)sites used in this investigation.

However if the AERONET data are a principal component of the paper then co-authorship to PI and Co-I(s) should be offered.

If you accept the above conditions, please click the "Accept" button below to download the ZIP file. If you do not agree with the above conditions, click "Do Not Accept" to return to the data plots.

[Accept] or [Do Not Accept]

Close Window
Prep. For tomorrow’s training session

• Make sure that the python is installed and properly set up

• If have any technical issues, let me know.

• If have any preferred language, please feel free to use it.
(For typical ground-based instruments, data is easy to handle)

• In the beginning of the session, you all will have a chance to introduce yourself and your research interest area, and your plan to use the data

- Tomorrow’s Goal -

   How many AERONET and Pandoras are under operation? Get and plot the AERONET and Pandora data in your country (or nearby), and think bout how to utilize them for your research or Task.
Mie solution

- Rigorous solution of Maxwell’s equations applied to the scattering of plane waves from a sphere

- Valid for any value of particle diameter (relative to scattered light wavelengths) and particle refractive index

- No simple analytical expressions. Need to solve numerically with computers.

Gustav Adolf Feodor Wilhelm Ludwig Mie (German: [miː]; 29 September 1868 – 13 February 1957) was a German physicist.
Mie solution

\[ \nabla \cdot \mathbf{D} = \rho \]
\[ \nabla \cdot \mathbf{B} = 0 \]
\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]
\[ \nabla \times \mathbf{B} = \epsilon_0 \mu_0 \frac{\partial \mathbf{E}}{\partial t} \]

Perturbation of a uniform electric field by a homogeneous sphere. The field within the sphere is uniform.

(1) The normal component of \( \mathbf{B} \) is continuous.
\[ (\mathbf{B}_2 - \mathbf{B}_1) \cdot \mathbf{n} = 0 \]

(2) There is a discontinuity in the normal component of \( \mathbf{D} \) equivalent to \( \mathbf{K} \), the surface charge density.
\[ (\mathbf{D}_2 - \mathbf{D}_1) \cdot \mathbf{n} = \mathbf{K} \]

(3) The tangential component of \( \mathbf{E} \) is continuous
\[ (\mathbf{E}_2 - \mathbf{E}_1) \times \mathbf{n} = 0 \]

(4) There is a discontinuity in the tangential component of \( \mathbf{H} \) equal to \( \mathbf{L} \), the surface current density.
\[ (\mathbf{H}_2 - \mathbf{H}_1) \times \mathbf{n} = \mathbf{L} \]
Geometry for Mie theory

\[ \mathbf{E}_i = E_{||i} \hat{e}_{||i} + E_{\perp i} \hat{e}_{\perp i} \]

\[ \mathbf{E}_i = \mathbf{E}_0 e^{-i(k \cdot r - \omega t)} \]
Amplitude scattering matrix (Jones matrix)

\[
\begin{pmatrix}
E_{s\|} \\
E_{s\perp}
\end{pmatrix} = \frac{e^{-i(k\cdot r - \omega t)}}{ikr}
\begin{pmatrix}
S_2 & S_3 \\
S_4 & S_1
\end{pmatrix}
\begin{pmatrix}
E_{i\|} \\
E_{i\perp}
\end{pmatrix}
\]

- **Spherical wave**
- **Incident E-field amplitudes** (complex)
- **Scattered E-field amplitudes** (complex)

**Jones matrix**
- Complex elements, given by Mie Theory (function of wavelengths, size, refractive index)
- For sphere, \( S_3 = S_4 = 0 \)
The resulting field components can be written at once in the form:

\[
E_\theta = H_\varphi = -\frac{i}{kr} e^{-ikr+i\omega t} \cos \varphi S_2(\theta)
\]

\[
-E_\varphi = H_\theta = -\frac{i}{kr} e^{-ikr+i\omega t} \sin \varphi S_1(\theta)
\]

\[
S_1(\theta) = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \{a_n \pi_n(\cos \theta) + b_n \tau_n(\cos \theta)\}
\]

\[
S_2(\theta) = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \{b_n \pi_n(\cos \theta) + a_n \tau_n(\cos \theta)\}
\]

These are the \(S_1\) and \(S_2\) terms from the Jones matrix. The heart of Mie theory is the numerical evaluation of these terms, as a function of various optical parameters (wavelength, polarization, relative refractive index, sphere diameter, scattering polar angle).

The \(S_1\) and \(S_2\) give the amplitudes of the scattered electric fields

\[
I_s \propto |S_1|^2 \text{ and } |S_2|^2
\]

Where \(I_s\) is the scattered light intensity.
Mie Scattering Calculator

by Scott Prail

Just what you've been waiting for! Web based Mie scattering calculations!

<table>
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<th>Sphere diameter</th>
<th>1.0</th>
<th>microns</th>
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<tbody>
<tr>
<td>Wavelength in Vacuum</td>
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<td>microns</td>
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<tr>
<td>Index of Refraction in Medium</td>
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<td></td>
</tr>
<tr>
<td>Real Index of Sphere</td>
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</tr>
<tr>
<td>Imag Index of Refraction (negative)</td>
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<td></td>
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<tr>
<td>Number of angles</td>
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<tr>
<td>Concentration</td>
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<td>spheres per cubic micron</td>
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</table>

[Calculate]

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## Input Parameters

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<th>Value</th>
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<tr>
<td>Refractive Index of Medium</td>
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<tr>
<td>Real Refractive Index of Sphere</td>
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</tr>
<tr>
<td>Imaginary Refractive Index of Sphere</td>
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<tr>
<td>Wavelength in Vacuum</td>
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<tr>
<td>Concentration</td>
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## Calculated results

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<td>Extinction Efficiency</td>
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<td>Backscattering Efficiency</td>
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<td>Scattering Cross Section</td>
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<tr>
<td>Extinction Cross Section</td>
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<tr>
<td>Backscattering Cross Section</td>
<td>1.5259 micron²</td>
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<tr>
<td>Scattering Coefficient</td>
<td>306 mm⁻¹</td>
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<tr>
<td>Total Attenuation Coefficient</td>
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</table>
MiePlot

A computer program for scattering of light from a sphere using Mie theory & the Debye series

Click here to download MiePlot v4.6

MiePlot was originally designed to provide a simple interface (for PCs using Microsoft Windows) to the classic BHMIE algorithm for Mie scattering from a sphere - as published by Bohren and Huffman in "Absorption and scattering of light by small particles" (ISBN 0-471-29340-7).

In addition to calculations of Mie scattering for single wavelengths, MiePlot offers calculations for scattering of sunlight - and simulations of atmospheric optical effects (such as rainbows, coronas and glories). These simulations can be superimposed on digital images of actual optical effects - as shown elsewhere on this web site. Click here to see some examples.

MiePlot also offers the option of calculations using the Debye series. Although Mie theory provides an exact mathematical solution to the problem of scattering of electromagnetic waves from an homogeneous sphere, it does not provide any insight into the physical processes involved in scattering. The Debye series is essentially a reformulation of Mie theory allowing the separation of contributions due to specific ray paths.

![Graph showing scattering of unpolarised light of wavelength λ = 0.65 μm by a spherical water drop of radius r = 100 μm](image)

Fig. 1 Scattering of unpolarised light of wavelength λ = 0.65 μm by a spherical water drop of radius r = 100 μm
Fig. 3 $Q_{ext}$ versus size parameter $x$ for different values of refractive index $n$