Lecture 8.

Applications of passive remote sensing using extinction and scattering:

Aerosol retrievals. Ocean color.

Objectives:
1. Reflection from surfaces.
2. The principle of interaction.
4. Application example: ocean color characterization.

Required reading:
S: pp. 177-180; 6.3, 6.5.1

Additional reading:
ATBD for aerosol from MODIS: collection 5
http://modis.gsfc.nasa.gov/data/atbd/atbd_mod02.pdf

Ocean color:
MODIS ocean color: http://oceancolor.gsfc.nasa.gov/


1. Reflection from surfaces.

Bi-directional reflectance distribution function (BRDF) is introduced to characterize the angular dependence in the surface reflection and defined as the ratio of the reflected intensity (radiance) to the radiation flux (irradiance) in the incident beam:

\[
R(\mu_r, \varphi_r, \mu_i, \varphi_i) = \frac{\pi dI^\uparrow(\mu_r, \varphi_r)}{I^\downarrow(\mu_i, \varphi_i) \mu_i d\Omega_i}
\]  

[8.1]

where \(\mu_i = \cos(\theta_i)\) and \(\theta_i\) is the incident zenith angle, \(\varphi_i\) is the incident azimuthal angle, and \(\mu_r = \cos(\theta_r)\) and \(\theta_r\) is the viewing zenith angle, \(\varphi_r\) is the viewing azimuthal angle.
Two extreme types of the surface reflection:

specular reflectance and diffuse reflectance.

Specular reflectance is the reflectance from a perfectly smooth surface (e.g., a mirror):
Angle of incidence = Angle of reflectance

- Reflection is generally specular when the "roughness" of the surface is smaller than the wavelength used. In the solar spectrum (about 0.4 to 2 µm), reflection is therefore specular on smooth surfaces such as polished metal, still water or mirrors.
- Practically all real surfaces are not smooth and the surface reflection depends on the incident angle and the angle of reflection. Reflectance from such surfaces is referred to as diffuse reflectance.
Special case of diffuse reflection: Lambertian reflection.

A surface called the Lambert surface if it obeys the Lambert’s Law which states that the diffusely reflected light is isotropic and unpolarized (i.e., natural light) independently of the state of polarization and the angle of the incidence light.

**Reflection from the Lambertian surface is isotropic:**

\[ R(\mu, \varphi, \mu_i, \varphi_i) = R_L \]  \[8.2\]

where \( R_L \) is the Lambert reflectance (also called surface albedo), which, in general, depends on the wavelength.

**In general, the surface reflectance is a function of wavelength.**

Examples of the surface albedo at \( ~550 \text{ nm} \): fresh snow/ice =0.8-0.9; desert=0.3, soils=0.1-0.25; ocean=0.05.

![Figure 8.1 Typical spectral reflectances (albedo) of various surfaces.](image-url)
NOTE: Each surface type has a specific spectral fingerprint that is the surface reflection has a specific dependence of the wavelength. This plays a central role in the remote sensing of planetary surfaces.

2. The principle of interaction.

Consider an atmospheric layer that can reflect and transmit the incident radiation.

**Reflection** $R(\tilde{\Omega}, \tilde{\Omega}')$ and **transmission** $T(\tilde{\Omega}, \tilde{\Omega}')$ functions of diffuse radiation are defined as

$$I_{\text{reflected}}(\tilde{\Omega}, \tilde{\Omega}') = R(\tilde{\Omega}, \tilde{\Omega}')I(\tilde{\Omega}')d\Omega' \quad [8.3]$$

$$I_{\text{transmittal}}(\tilde{\Omega}, \tilde{\Omega}') = T(\tilde{\Omega}, \tilde{\Omega}')I(\tilde{\Omega}')d\Omega' \quad [8.4]$$

where $I_{\lambda}(\tilde{\Omega}')$ is the incident intensity in the direction $\tilde{\Omega}'(\mu', \phi')$.

If the atmosphere layer illuminated by many sources of radiation from below and above with $I_{\lambda}(\tilde{\Omega}'_k)$ of the $k$-th source below and $I_{\lambda}(\tilde{\Omega}'_j)$ of the $j$-th source above, then the intensity emerging from the layer in the direction $\tilde{\Omega}$ is

$$I(\tilde{\Omega}) = \sum_j R(\tilde{\Omega}, \tilde{\Omega}'_j)I(\tilde{\Omega}'_j)d\Omega'_j + \sum_k T(\tilde{\Omega}, \tilde{\Omega}'_k)I(\tilde{\Omega}'_k)d\Omega'_k \quad [8.5]$$
Principle of interaction:
The resulting intensity emerging from the surface of the layer is a superposition of reflected and transmitted intensities.

NOTE: Eqs.[7.18]-[7.19] for the first order scattering were derived for non-reflecting surfaces (called black surfaces). The principle of interaction enables the incorporation of radiances reflected from the surfaces.

NOTE: See an example for the case of two layers in S 6.5.1

The bottom line: To detect an aerosol plume, it must be brighter than the background => problems with remote sensing of aerosol over bright surfaces.

Algorithm Theoretical Basic Document (ATBD) gives the detailed description of the aerosol models and procedure used in the retrievals. Each sensor has its own ATBD.

Example: MODIS aerosol ATBD

<table>
<thead>
<tr>
<th>F</th>
<th>$\lambda_{=0.47-0.86\mu m}$</th>
<th>$\lambda_{=1.24\mu m}$</th>
<th>$\lambda_{=1.64\mu m}$</th>
<th>$\lambda_{=2.12\mu m}$</th>
<th>$\tau_g$</th>
<th>$\sigma$</th>
<th>$r_{eff}$</th>
<th>Comments</th>
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<tbody>
<tr>
<td>1</td>
<td>1.45-0.0035i</td>
<td>1.45-0.0035i</td>
<td>1.43-0.01i</td>
<td>1.46-0.005i</td>
<td>0.07</td>
<td>0.40</td>
<td>0.10</td>
<td>Water Soluble</td>
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<tr>
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<td>1.45-0.0035i</td>
<td>1.43-0.01i</td>
<td>1.46-0.005i</td>
<td>0.06</td>
<td>0.60</td>
<td>0.15</td>
<td>Water Soluble</td>
</tr>
<tr>
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<td>1.40-0.0020i</td>
<td>1.39-0.005i</td>
<td>1.36-0.003i</td>
<td>0.08</td>
<td>0.60</td>
<td>0.20</td>
<td>Water Soluble with humidity</td>
</tr>
<tr>
<td>4</td>
<td>1.40-0.0020i</td>
<td>1.40-0.0020i</td>
<td>1.39-0.005i</td>
<td>1.36-0.003i</td>
<td>0.10</td>
<td>0.60</td>
<td>0.25</td>
<td>Water Soluble with humidity</td>
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<table>
<thead>
<tr>
<th>C</th>
<th>$\lambda_{=0.47-0.86\mu m}$</th>
<th>$\lambda_{=1.24\mu m}$</th>
<th>$\lambda_{=1.64\mu m}$</th>
<th>$\lambda_{=2.12\mu m}$</th>
<th>$\tau_g$</th>
<th>$\sigma$</th>
<th>$r_{eff}$</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
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<td>1.35-0.001i</td>
<td>1.35-0.001i</td>
<td>1.35-0.001i</td>
<td>1.35-0.001i</td>
<td>0.40</td>
<td>0.60</td>
<td>0.98</td>
<td>Wet sea salt type</td>
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<tr>
<td>6</td>
<td>1.35-0.001i</td>
<td>1.35-0.001i</td>
<td>1.35-0.001i</td>
<td>1.35-0.001i</td>
<td>0.60</td>
<td>0.60</td>
<td>1.48</td>
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<tr>
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<td>1.35-0.001i</td>
<td>1.35-0.001i</td>
<td>1.35-0.001i</td>
<td>0.80</td>
<td>0.60</td>
<td>1.98</td>
<td>Wet sea salt type</td>
</tr>
<tr>
<td>8</td>
<td>1.53-0.003i: (0.47)</td>
<td>1.53-0.001i: (0.55)</td>
<td>1.53-0.000i: (0.66)</td>
<td>1.53-0.000i: (0.86)</td>
<td>1.46-0.000i: (0.47)</td>
<td>1.46-0.000i: (0.55)</td>
<td>1.46-0.000i: (0.66)</td>
<td>Dust-like type</td>
</tr>
<tr>
<td>9</td>
<td>1.53-0.003i: (0.47)</td>
<td>1.53-0.001i: (0.55)</td>
<td>1.53-0.000i: (0.66)</td>
<td>1.53-0.000i: (0.86)</td>
<td>1.46-0.000i: (0.47)</td>
<td>1.46-0.000i: (0.55)</td>
<td>1.46-0.000i: (0.66)</td>
<td>Dust-like type</td>
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</table>
Figure 8.2. Flow diagram for retrieval of aerosols (and other atmospheric parameters) from MODIS.
4. Ocean color characterization.

Scientific Motivation:
Remote sensing of ocean color provides information on the abundance of phytoplankton and the concentration of dissolved and particulate material in surface ocean waters.

Importance:
- biological productivity in the oceans (the oceans take up about 1/3 of CO2, two major mechanism: solubility pump and biological pump, the latter is controlled by phytoplankton biomass)
- marine optical properties,
- the interaction of winds and currents with ocean biology (see Figure 9.2)
- effects of human activities on the oceanic environment.

Ocean color is referred to the wavelength dependence of the water-leaving radiances at the ocean surface. Ocean color is the result of scattering and absorption by chlorophyll pigments, as well as dissolved and particulate matter in the surface ocean water.

Principles of ocean color retrievals:
Phytoplankton has a specific absorbing spectrum => its concentration can be retrieved if the spectral water-leaving radiances are measured.

Need for accurate atmospheric correction:
Water-leaving radiances can be as low as a few percent of the TOA (top-of-the-atmosphere) radiances => it is critical to quantify and correctly remove the contribution from the atmosphere to the TOA radiances.

SENSORS:
CZCS (Coastal Zone Color Scanner, flown on the NIMBUS-7 satellite): data for 1978 - 1986
SeaWiFS (Sea-viewing Wide Field-of-View Scanner, launched onboard Orbview-2 satellite): data from 1997
MODIS (Moderate Resolution Imaging Spectroradiometer, launched on Terra satellite): data from 1999

Figure 8.3 MODIS wavelength bands and the water leaving radiance in high and low chlorophyll waters without the atmospheric signal (lower curves) and with the atmospheric signal (upper curves).

Table 8.1 MODIS, SeaWiFS, and CZCS channels and their central wavelengths used for ocean color retrievals.

<table>
<thead>
<tr>
<th>Band</th>
<th>$\lambda$ (nm)</th>
<th>MODIS</th>
<th>SeaWiFS</th>
<th>CZCS</th>
</tr>
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<tr>
<td>8</td>
<td>412</td>
<td>+</td>
<td>+</td>
<td>-</td>
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<tr>
<td>9</td>
<td>443</td>
<td>+</td>
<td>+</td>
<td>+</td>
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<tr>
<td>10</td>
<td>490</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>530</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
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<td>12</td>
<td>550</td>
<td>+</td>
<td>+</td>
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<tr>
<td>15</td>
<td>750</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>16</td>
<td>865</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>
Ocean color retrieval algorithm (retrieval of the chlorophyll concentration):
CZCS, SeaWiFS and MODIS algorithms use the normalized water-leaving radiance \([I_w]_N\)
defined as
\[
I_w(\lambda) = [I_w(\lambda)]_N T(\lambda)
\]  
where
\(T(\lambda)\) is the diffuse transmittance (see Eq.[8.9]);
\(I_w(\lambda)\) is the radiance backscattered out of the water.

- The normalized water-leaving radiance is approximately the radiance that would exit the ocean in the absence of the atmosphere with the sun in the zenith.

Assuming the Lambertian surface, reflectance associated with the radiance \([I_w]_N\) can be defined as
\[
[R_w(\lambda)]_N = \frac{\pi}{F_0} [I_w(\lambda)]_N
\]
and Eq. [8.6] becomes
\[
R_w(\lambda) = [R_w(\lambda)]_N T(\lambda)
\]

Figure 8.4 Normalized water-leaving reflectance ratio as a function of pigment concentration (Gordon et al. 1988)
If the ratio $\left[ R_w (443) \right]_N / \left[ R_w (550) \right]_N$ is known, the pigment concentration $C$ can be approximated as

$$\log_{10}(3.33C) = -1.2 \log_{10} r + 0.5(\log_{10} r)^2 - 2.8(\log_{10} r)^3$$

where $r = 0.5 \left[ R_w (443) \right]_N / \left[ R_w (550) \right]_N$

Need to correct for the atmospheric contribution to the TOA radiances measured by the sensor to retrieve the normalized water-leaving radiance and then retrieve the pigment concentrations.