**Topic 2a: Radiative Transfer - Atmosphere**

(Peering through the haze)

Looking horizontally through the atmosphere is analogous to looking down through the atmosphere.

Reflectance from trees in the foreground is basically the same as that from trees in the background. The apparent difference in color is due to radiance scattered by the intervening atmosphere.

1) The background is brighter than the foreground ➔ the atmosphere is adding light.

2) The background is bluer than the foreground ➔ either the added light is rich in blue, or the atmosphere is also absorbing red light.

In fact, the atmosphere both adds (scatters) and subtracts (absorbs) radiation along the viewing path.

Note that the greatest part of the scattering is from the lowest portion of the atmosphere ➔ atmospheric correction may be necessary even for low-altitude systems.

1) Atmospheric correction will be helpful, but not essential for spatial interpretation (e.g., roads, buildings, fields, etc.)

2) Atmospheric correction will be essential for extracting quantitative color information (e.g., material properties).

**Atmospheric Effects**

Who cares?

- *Atmospheric correction* will be critical if quantitative spectral (color) information is required

- *Atmospheric normalization* will be necessary in order to effectively compare images taken under different atmospheric conditions.

- It may not be necessary to account for atmospheric effects for purely spatial interpretations.

Mosaic of 5 ASTER images over Iran prior to radiometric normalization, RGB color composite equalization stretch: band 1 (blue), band 2 (green), band 3N (red)

**Spectral Reflectance:** If the atmosphere is uniform over the scene, imagery may not appear very different after atmospheric correction, but the spectra of individual targets will usually be very different.

AVIRIS image f960705t01p02_r05_s04 collected on July 5, 1996 (area West of Pocomoke City, MD, USA)

**Radiance**

uncorrected image
(with automated stretch for viewing)

uncorrected spectra
(radiance)

**Reflectance**

corrected image
(with automated stretch for viewing)

corrected spectra
(reflectance)

Red: soil; White: vegetation

White: water
Illumination and viewing **directions** are also an issue.

- The greater the angle with respect to the local vertical, the longer the atmospheric path.
- The longer the path, the greater the opportunity for scattering and absorption along the path.

**Observations:**

**From the ground:** the sun appears red when near the horizon because more blue light from the sun has been scattered out of the path.

**From above:** An object viewed at an oblique angle appears bluer (and brighter) than the same object viewed at nadir because more blue light has been scattered into the viewing path.

Illumination and viewing directions also affect the apparent reflectance of objects, even **without** atmospheric effects.

**Example:**

- Fixed viewing direction
- Varying orientation to the sun

The roofs are made of the same material (slate), but differ both in brightness and in apparent color.

Note that roofs in direct sunlight have a more homogeneous appearance than the shaded roofs.

**Atmospheric Correction**

\[
E_d(x, y) = \text{illumination (irradiance) at the earth's surface due to sunlight and skylight (includes losses due to scattering and absorption).}
\]

\[
R_{RS}(x, y) = \text{Remote Sensing Reflectance of the earth's surface}
\]

\[
\tau_v(x, y) = \text{transmission from the ground to the imaging system}
\]

\[
L_s(x, y) = \text{path radiance (atmospheric scattering)}
\]

\[
L_i(x, y) = \tau_v(x, y) E_d(x, y) R_{RS}(x, y) + L_s(x, y) \quad \text{Radiance at the imaging system}
\]
**Illumination**

**Solar constant:** Solar irradiance reaching the earth, but still outside Earth's atmosphere, is nearly constant throughout the year.

The solar constant has a value of \(1366 \pm 1 \text{ W m}^{-2}\) (varies seasonally by \(\pm 50 \text{ Wm}^{-2}\))

[https://www.ngdc.noaa.gov/stp/solar/solarirrad.html](https://www.ngdc.noaa.gov/stp/solar/solarirrad.html)

**Solar Irradiance inside the atmosphere**

Solar irradiance is attenuated due to scattering and absorption as it passes through the Earth's atmosphere.

If we define the attenuation coefficient, \(c\), to be the rate per unit distance at which the irradiance is reduced then, the irradiance reaching a point after traversing a distance, \(r\), in the atmosphere is given by:

\[
E_r = E_{\text{sun}} e^{-cr}
\]

**Note:** In reality \(c\) is a function of position, \(r\), since the atmosphere is not uniform vertically. A more accurate formula would be:

\[
E_r = E_{\text{sun}} e^{-\int_0^r c(r) \, dr}
\]

**Absorption.** A photon interacts with a particle by imparting its energy to an electron which moves to a higher orbit. Absorption is very wavelength dependent and can often provide a characteristic signature for a particular substance. Absorption in the atmosphere is primarily due to oxygen (\(O_2\)), carbon dioxide (\(CO_2\)), ozone (\(O_3\)), and water (\(H_2O\)).
Scattering describes any process by which radiation changes direction. The process is essentially instantaneous, occurring on time scales of ~10^{-14} seconds.

Elastic scattering is scattering in which there is no change in wavelength and is generally characterized as either Rayleigh or Mie scattering, depending on the size of the scattering particles relative to the wavelength.

Rayleigh (molecular) scattering results from interaction of radiation with particles which are much smaller than the scattered wavelength, \( \lambda \), and the amount of scattering is proportional to \( 1/\lambda^4 \). For visible radiation, Rayleigh scattering is predominantly due to molecules (N2, O2, etc.) and blue light is much more likely to be scattered than red light. Rayleigh scattering of sunlight is, of course, the origin of the blue sky on a clear day.

\[
E \propto E_0 \frac{1 - \cos^2 \theta}{\lambda^4}
\]

Mie (particle) scattering results from interaction of radiation with particles which are larger than the scattered wavelength, \( \lambda \). When the particle size, \( \alpha \), is much larger than the wavelength (\( \alpha \gg \lambda \)) the amount of scattering is independent of wavelength.

The specific wavelength dependence will depend on the particle size distribution.

- Scattering \( \propto 1/\lambda^4 \) when \( r \ll \lambda \) (Rayleigh limit)
- Scattering \( \propto 1/\lambda^2 \) when \( r \approx \lambda \)
- Scattering \( \propto 1/\lambda \) when \( r \approx 3\lambda / 2 \)
- Scattering independent of \( \lambda \) when \( r \gg \lambda \)
Solar Irradiance at the Earth's surface

In the absence of clouds, it is common to treat the earth's atmosphere as if it consisted of plane, parallel slabs, each of which is optically uniform—this is a reasonable assumption for near-nadir observations.

Radiative Transfer (RT) Model

$E_{\text{sun}} = \text{solar constant (solar irradiance outside the earth's atmosphere): 1,366 W/m}^2$

$\tau_{\text{sun}} = \text{atmospheric transmission along the solar path (accounts for absorption and scattering)}.$

$\theta_{\text{sun}} = \text{solar zenith angle}$

$E_{\text{sky}} = \text{Irradiance at the earth's surface due to skylight}$

$E_d = \text{total irradiance at the earth's surface}$

$E_d = \tau_{\text{sun}} E_{\text{sun}} \cos \theta_{\text{sun}} + E_{\text{sky}}$

$L_t = L(\theta_v) = \text{Radiance at the ground target in the direction of the satellite}$

$\theta_v = \text{observation angle}$

$L_t = R_{rs}(\theta_v)E_d = R_{rs}(\theta_v)\left(\tau_{\text{sun}} E_{\text{sun}} \cos \theta_{\text{sun}} + E_{\text{sky}}\right)$

$L* = \text{Path radiance}$

$L_{\text{sat}} = \tau_v L_t + L*$

$L_t = \tau_v \left[\tau_{\text{sun}} E_{\text{sun}} \cos \theta_{\text{sun}} + E_{\text{sky}}\right] R_{rs}(\theta_v) + L*$
There are two general categories of atmospheric correction:

- **In-scene techniques** *(always requires assumption of uniform atmosphere)*
  - Dark object subtraction (DOS) *(path radiance only)*
  - RATIOing (not a true correction)
  - Shadow technique
  - Empirical Line Method (ELM)

- **Radiative propagation/transfer models**
  - LOWTRAN *(LOW Resolution TRANsmission code)*
  - MODTRAN *(MODerate Resolution TRANsmission code)*
  - ACORN *(Atmospheric CORrection Now)*
  - FLAASH *(Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes)*
  - FASCODE *(Fast Atmospheric Signature CODE)*
  - 6S *(Second Simulation of Satellite Signal in the Solar Spectrum)*
  - ATREM *(ATmospheric REMoval) now TAFKAA*
  - APDA *(Atmospheric Precorrected Differential Absorption)*

**Approximate atmospheric "corrections"**

**Dark Object Subtraction**

- Justification: Path radiance is the largest component of atmospheric error.
  
  $L_{sat} = t_v \left[ (t_{sun}E_{sun}cos(\theta_{sun}) + E_{sky}) \right] R_{rs}(\theta_v) + L_*$

- Assumptions
  - assumes that the atmosphere is **horizontally uniform** over the image
  - atmospheric correction limited to removal of **path radiance** effects.
  - not a true atmospheric correction, only an "adjustment"

- Requires at least 1 in-scene "black" target for each spectral
  - A single target should be dark in ALL bands
  - Multiple targets need only be dark over a selected range
  - Calibration panels

- Techniques include
  - Histogram Minimum Method (HMM)
  - Automated (treats the minimum DN as a zero reflectance target)
  - Regression Intersection Method (RIM)
  - Uses the intersection of the best-fit lines of two classes as the zero point
  - Covariance Matrix Method (CMM)

**The Simple RT Model revisited**

$L_i(x,y) = M(x,y) R(x,y) + A(x,y)$

$E_d(x,y) = \text{illumination (irradiance) at the earth's surface due to sunlight and skylight.}$

$R_{rs}(x,y) = \text{reflectance of the earth's surface}$

$L*(x,y) = \text{path radiance (atmospheric scattering)}$

- If the atmosphere is uniform over the scene then $[L_(x,y) = L_*]$, **and**
- If a black (zero reflectance) object exists in the scene
  - then one may correct the image for path radiance by subtracting the gray value of the dark object pixel from the gray value of every other pixel in the image:

  $L_i(x,y) - L_* = E_d(x,y) R_{rs}(x,y)$
**Dark Object Subtraction requires 1 in-scene "black" target**

A single target must be dark in ALL bands.

More realistically, choose different targets for each band (or range of bands).

- water (presumably clear, deep water) is frequently chosen as the dark target. This is reasonable for wavelengths > 0.8 μ (as long as one avoids glint from the water surface), but it is frequently not true for wavelengths < 0.8 μ.

- dense vegetation is often darker in the visible – particularly in the red – than most other in-scene objects.

- calibration panels can be used, but must be uniform and large enough to span several pixels.

**Problems:**

- does not account for spatial variation in the atmosphere (full-scene correction).
- truly "dark" pixels are rare and dark pixels in all spectral bands are rarer.

**Ratioing**

Suppose that the illumination and atmosphere are both spatially variable, but differ from band to band only by a constant factor, c, then:

\[ E_{d2}(x, y) = c \ E_{d1}(x, y) \]

(number subscripts refer to spectral bands)

then dividing (pixel by pixel) the first band by the second yields a new image:

\[ L_{rat}(x, y) = \frac{L_{i1}(x, y)}{L_{i2}(x, y)} = \frac{R_{RS1}(x, y) + L_{s1}(x, y)}{c R_{RS2}(x, y) + L_{s2}(x, y)} \]

If the path radiance is negligible \( [L_{s1}(x, y) = L_{s2}(x, y) \to 0] \) or can be removed by another method then

\[ L_{rat}(x, y) = \frac{L_{i1}(x, y)}{L_{i2}(x, y)} = \frac{R_{RS1}(x, y)}{c R_{RS2}(x, y)} \]

and the new image will be insensitive to variations in illumination and atmosphere.

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**1995 AVIRIS image of Cuprite, Nevada**

\[
Blue = \frac{B_{183}(2.101\mu m)}{B_{199}(2.201\mu m)} \quad Green = \frac{B_{183}(2.101\mu m)}{B_{207}(2.201\mu m)} \quad Red = \frac{B_{193}(2.101\mu m)}{B_{207}(2.201\mu m)}
\]