Optical Radiation Models

Reading: Chapter 2

- Energy Sources
- VSWIR Modeling
- MWIR-LWIR Modeling
Quantifying Radiation

- Radiant energy ($Q$ in joules) is a measure of the capacity of an EM wave to do work by moving an object, heating, or changing its state.

- Radiant flux ($\Phi$ in watts) is the time rate (flow) of energy passing through a certain location.

- Radiant flux density (watts/m$^2$) is the flux intercepted by a planar surface of unit area.
  - Irradiance ($E$) is flux density incident upon a surface.
  - Exitance ($M$) or emittance is flux density leaving a surface.

- The solid angle ($\Omega$ in steradians) subtended by an area $A$ on a spherical surface of radius $r$ is $A/r^2$.
  - Radiant intensity ($I$ in watts/sr) is the flux per unit solid angle in a given direction.
  - Radiance ($L$ in watts/m$^2$/sr) is the intensity per unit projected area.

- Radiance from source to object is conserved!

Spectral Radiant Exitance

- Spectral distribution of radiation flux

- Planck’s equation (Eq. 2-1) for perfect radiator (blackbody)

\[
M_{\lambda} = \frac{C_1}{\lambda^5 \exp(C_2/(\lambda T)) - 1} \left( W \cdot m^{-2} \cdot \mu m^{-1} \right)
\]

\[
C_1 = 3.74151 \times 10^8 \left( W \cdot m^{-2} \cdot \mu m^4 \right)
\]

\[
C_2 = 1.43879 \times 10^4 \left( \mu m \cdot K \right)
\]

- $T$ is the blackbody’s temperature in Kelvin (K), $T=5900K$ for sun, $300K$ for Earth.

- $M_{\lambda}$ is a function of both wavelength of radiation and temperature of the source
  - usually plotted as function of wavelength, for given temperature
THREE SPECTRAL REGIONS

- **VSWIR (Visible-ShortWave IR, 0.4 to 2.4 µm, 400 to 2400nm)**
  - Solar radiation dominates
- **MWIR (MidWave IR, 3 to 5 µm, 3000 to 5000nm)**
  - Mixture of solar and thermal radiation
- **LWIR (LongWave IR, 8 to 14 µm, 8000 to 14000nm)**
  - Thermal radiation dominates
  - Emitted by objects on Earth’s surface as a function of their temperature and emissivity

OPTICAL RADIATION MODELS

- Energy Sources
- **VSWIR Modeling**
- **MWIR-LWIR Modeling**
VSWIR Modeling

- Three components reach sensor
  - Direct component is unscattered from source
  - Skylight is scattered down onto the target (Why are shadows not black?)
  - Path radiance is scattered along path up into the sensor

Direct Component

- Related to the signal of interest, i.e. surface reflectance
- Top-Of-the-Atmosphere (TOA) irradiance $E^\text{TOA}_\lambda$ modified by atmospheric transmittance along solar path $\tau_s(\lambda)$

Earth surface irradiance $E_\lambda(x,y)$ depends on the angle of incidence, which in-turn, depends on solar angle and topography

\[ E_\lambda(x,y) = \tau_s(\lambda)E^\text{TOA}_\lambda \hat{n}(x,y) \cdot \hat{s} \]

\[ = \tau_s(\lambda)E^\text{TOA}_\lambda \cos[\Theta(x,y)] \quad (W \cdot m^{-2} \cdot \mu m^{-1}) \]
IRRADIANCE AT EARTH SURFACE

- Solar vector (to sun)
- View vector (to sensor)
- Surface normal vector
- Incidence irradiance
- View angle
- Solar elevation angle
- Flux density normal to solar path
- Flux density at earth surface

Example: Shaded Relief

- Solar incident angle
  - Solar elevation
  - Local topography (slope, aspect)
- Simulate incident angle effect on irradiance
  - Calculate \( \cos(\theta(x,y)) \)
  - For every pixel at \( (x,y) \) using solar elevation angle from TM image and DEM
  - “Shaded-relief” image
**Shadowing**

- Another incident geometry effect

  - Self-shadowed pixels
  - Projected shadows

  total shadowed area = union(self-shadowed area, projected shadow area)

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**Temporal Changes**

- Shading and shadowing 5 months apart
- Landsat MSS image of Grand Canyon, AZ

  - June 11, 1981
  - October 20, 1980
View Path

• Incident irradiance reflects at Earth surface to become surface radiance \( L_\lambda(x, y) \)

\[
L_\lambda(x, y) = \rho(x, y, \lambda) \frac{E_\lambda(x, y)}{\pi} \quad (W \cdot m^{-2} \cdot \mu m^{-1})
\]

Earth surface:

\[
L_\lambda(x, y) = \rho(x, y, \lambda) \frac{E_\lambda}{\pi} \cos[\Theta(x, y)]
\]

• Surface radiance modified by atmospheric transmittance along sensor view path to become at-sensor radiance

\[
L_{\text{at}}^\text{nu} = \tau_\nu(\lambda)L_\lambda(x, y) \quad (W \cdot m^{-2} \cdot \mu m^{-1})
\]

At-sensor:

\[
L_{\text{at}}^\text{nu} = \rho(x, y, \lambda) \frac{\tau_\nu(\lambda)E_\nu}{\pi} \cos[\Theta(x, y)]
\]

Angle Dependency

• Atmospheric transmittance varies with view angle (and solar angle)
  - particularly important for wide-FOV sensors, such as AVHRR and MODIS
Direct Component Summary

\[ E_{\lambda}(x, y) = \tau_0(\lambda)E^0_{\lambda} \cos[\theta(x, y)] \]

\[ L^s_\lambda = \rho(x, y, \lambda) \tau_0(\lambda)E^0_{\lambda} \frac{\cos[\theta(x, y)]}{\pi} \]

Indirect Components

- Skylight component
  - secondary signal component
    \[ L^{ed}_{\lambda} = F(x, y)\rho(x, y, \lambda) \tau_0(\lambda)E^d_{\lambda} \frac{\cos[\theta(x, y)]}{\pi} (W \cdot m^{-2} \cdot \mu m^{-1}) \]
    - where \( F \) is the fraction of sky visible at a given earth surface point

- Path radiance component
  - assumed independent of \((x, y)\) here
  - atmospheric scattering (“haze”)
    - Rayleigh scattering for a clear atmosphere (molecules only)
    - Mie scattering for an atmosphere with aerosols (water vapor) or particulates (dust, smoke)
    - real atmospheres exhibit both Rayleigh and Mie scattering
  
  \[ L^p_{\lambda} (W \cdot m^{-2} \cdot \mu m^{-1}) \]
**Total At-Sensor Radiance**

\[
I_{\lambda}(x, y) = I_{\lambda}^{aw}(x, y) + I_{\lambda}^{ad}(x, y) + L_{\lambda}^{up}
\]

\[
= \rho(x, y, \lambda) \frac{\tau_{e}(\lambda) \tau_{a}(\lambda) E_{\lambda}^{s}}{\pi} \cos[\theta(x, y)] + F(x, y) \rho(x, y, \lambda) \frac{\tau_{a}(\lambda) E_{\lambda}^{s}}{\pi} + L_{\lambda}^{up}
\]

\[
= \rho(x, y, \lambda) \frac{\tau_{e}(\lambda) \tau_{a}(\lambda) E_{\lambda}^{s}}{\pi} \cos[\theta(x, y)] + F(x, y) \rho(x, y, \lambda) \tau_{a}(\lambda) E_{\lambda}^{s} + L_{\lambda}^{up}
\]

\[\rho(x, y, \lambda) : \text{surface diffuse reflectance (unitless)}\]
\[\tau_{e}(\lambda) : \text{view path atmospheric transmittance (unitless)}\]
\[\tau_{a}(\lambda) : \text{solar path atmospheric transmittance (unitless)}\]
\[E_{\lambda}^{s} : \text{incident, exo-atmospheric spectral irradiance (W-m}^{-2}\cdot\text{µm}^{-1})\]
\[\cos[\theta(x, y)] : \text{cosine of angle between solar vector and surface normal}\]
\[F(x, y) : \text{fraction of sky hemisphere visible from surface point}\]
\[E_{\lambda}^{d} : \text{downwelling atmospheric spectral irradiance (W-m}^{-2}\cdot\text{µm}^{-1})\]
\[L_{\lambda}^{up} : \text{upwelling atmospheric path spectral radiance (W-m}^{-2}\cdot\text{µm}^{-1}\cdot\text{sr}^{-1})\]

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**MODTRAN Simulation**

![MODTRAN Simulation Graph](image-url)
**Optical Radiation Models**

- Energy Sources
- VSWIR Modeling
- MWIR-LWIR Modeling

**Broad Radiation Regime**

- 2.4 to 14 µm (2400 to 14000 nm)
- Solar and thermal radiation mixed in MWIR
- Thermal radiation in LWIR
- Measured geophysical variables:
  - reflectance
  - spectral emissivity (thermal analogy to reflectance)
  - temperature

![Graph showing solar irradiance and earth emission over wavelength (µm)]
**Thermal Radiation**

- **Perfect radiator**
  - "blackbody"
  - emissivity = 1 (ratio of spectral radiant exittance of given object to that of a blackbody at the same temperature)
  - obeys Planck’s Law
- **Imperfect radiator**
  - “graybody”
  - emissivity ≤ 1 (radiates less efficiently than a blackbody)
  - obeys scaled Planck’s Law
- **Need to separate emissivity effects (surface property) from temperature effects (bulk property) - not easy!**
  - usually assume one or the other is constant for all objects in the scene

**LWIR Radiation Components**

MWIR:

\[ L^m_{\lambda} = L^e_{\lambda} + L^d_{\lambda} + L^{ep}_{\lambda} \]

LWIR:

\[
L^x_{\lambda}(x, y) = L^e_{\lambda}(x, y) + L^d_{\lambda}(x, y) + L^{ep}_{\lambda}
\]

\[
e(x, y, \lambda) = \epsilon(x, y, \lambda) \frac{\tau_{\lambda}(T)}{\pi} (a_{\lambda} T(x, y) + b_{\lambda}) + F(x, y, \lambda) \rho(x, y, \lambda) \frac{\tau_{\lambda}(T) M^e_{\lambda}}{\pi} + L^{ep}_{\lambda}
\]

- \( \epsilon(x, y, \lambda) \): spectral emissivity (unitless)
- \( M^e_{\lambda} \): downwelling atmospheric-emitted spectral radiance (W·m\(^{-2}\)·\(\mu\)m\(^{-1}\)·sr\(^{-1}\))
- \( L^{ep}_{\lambda} \): upwelling atmospheric-emitted path spectral radiance (W·m\(^{-2}\)·\(\mu\)m\(^{-1}\)·sr\(^{-1}\))
- \([a_{\lambda} T(x, y) + b_{\lambda}]\): linear approximation to spectral radiance for blackbody temperature \( T \) (W·m\(^{-2}\)·\(\mu\)m\(^{-1}\)·sr\(^{-1}\))
**THERMAL EXAMPLES**

Clouds and their shadows (Fig. 2–19)

- Cloud shadow
- Clouds

**THERMAL EXAMPLES (CONT.)**

Lake used to cool nuclear power plant (Fig. 2–20)

- MSS band 4
- Nuclear power plant
- Cooling ponds
- HCMM LWIR
New Orleans, LA, an example of a urban “heat island”(Fig. 2-21)