CHAPTER 2: Electromagnetic Radiation Principles

REFERENCE: Remote Sensing of the Environment
John R. Jensen (2007)
Second Edition
Pearson Prentice Hall
DETECTING THE REMOTE SIGNAL
Energy recorded by remote sensing systems undergoes fundamental *interactions* that should be understood to properly interpret the remotely sensed data. For example, if the energy being remotely sensed comes from the Sun, the energy:

- is radiated by atomic particles at the source (the Sun),
- propagates through the vacuum of space at the speed of light,
- interacts with the Earth's atmosphere,
- interacts with the Earth's surface,
- interacts with the Earth's atmosphere once again, and
- finally reaches the remote sensor where it interacts with various optical systems, filters, emulsions, or detectors.
Solar and Heliospheric Observatory (SOHO)
Image of the Sun Obtained on September 14, 1999
SOURCE OF THE SUN'S ENERGY

**Fusion process:** Nuclear reactions where lightweight chemical elements (like hydrogen) form heavier elements (such as helium and carbon). This process converts matter (i.e. mass of an atom) to energy.

Albert Einstein in 1905 showed that: $E = mc^2$

Where,
- $E$ = Energy
- $m$ = mass
- $c$ = speed of light in a vacuum ($3.0 \times 10^8$ m/s)

The Sun produces its energy by two fusion reactions:
1. Proton-Proton (PP) – 88%
2. Carbon-Nitrogen-Oxygen (CNO) – 12%
How is Energy Transferred?

Energy may be transferred in three ways: **conduction, convection, and radiation**.

a) Energy may be *conducted* directly from one object to another as when a pan is in direct physical contact with a hot burner.

b) The Sun bathes the Earth’s surface with radiant energy causing the air near the ground to increase in temperature. The less dense air rises, creating *convectional* currents in the atmosphere.

c) Electromagnetic energy in the form of *electromagnetic* waves may be transmitted through the vacuum of space from the Sun to the Earth.
Electromagnetic Radiation Models

To understand how electromagnetic radiation is created, how it propagates through space, and how it interacts with other matter, it is useful to describe the processes using two different models:

- the wave model
- the particle model

![Electromagnetic Radiation Models Diagram]
Wave Model of Electromagnetic Radiation

In the 1860s, James Clerk Maxwell (1831–1879) conceptualized electromagnetic radiation (EMR) as an electromagnetic wave that travels through space at the speed of light, \( c \), which is \( 3 \times 10^8 \) meters per second (hereafter referred to as \( \text{m s}^{-1} \)) or 186,282.03 miles \( \text{s}^{-1} \). A useful relation for quick calculations is that light travels about 1 ft per nanosecond (10\(^{-9}\) s).

The electromagnetic wave consists of two fluctuating fields—one electric and the other magnetic. The two vectors are at right angles (orthogonal) to one another, and both are perpendicular to the direction of travel.
ELECTROMAGNETIC RADIATION

Wavelength ($\lambda$): The distance between two successive crests.

Frequency ($\nu$): The number of crests (or cycles) that pass a given point each second.

Speed ($c$): The distance traveled by a crest in time.

Therefore:

$$c = \lambda \cdot \nu$$

$$\nu = \frac{c}{\lambda} \quad \lambda = \frac{c}{\nu}$$
Wave Model of Electromagnetic Energy

This cross-section of an electromagnetic wave illustrates the inverse relationship between wavelength ($\lambda$) and frequency ($\nu$).

The longer the wavelength the lower the frequency; the shorter the wavelength, the higher the frequency.

The amplitude of an electromagnetic wave is the height of the wave crest above the undisturbed position. Successive wave crests are numbered 1, 2, 3, and 4. An observer at the position of the clock records the number of crests that pass by in a second. This frequency is measured in cycles per second, or hertz.
Using the wave model, it is possible to characterize the energy of the Sun which represents the initial source of most of the electromagnetic energy recorded by remote sensing systems (except radar). We may think of the Sun as a 6,000 K blackbody (a theoretical construct that absorbs and radiates energy at the maximum possible rate per unit area at each wavelength for a given temperature). The total emitted radiation \( (M_\lambda) \) from a blackbody is proportional to the fourth power of its absolute temperature.

This is known as the Stefan-Boltzmann law and is expressed as:

\[
M_\lambda = \sigma T^4
\]

where \( \sigma \) is the Stefan-Boltzmann constant, \( 5.6697 \times 10^{-8} \) W m\(^{-2}\) K\(^{-4}\).

Thus, the amount of energy emitted by an object such as the Sun or the Earth is a function of its temperature.
The Sun produces a continuous spectrum of energy from gamma rays to radio waves that continually bathe the Earth in energy. The visible portion of the spectrum may be measured using wavelength (measured in micrometers or nanometers, i.e., mm or nm) or electron volts (eV). All units are interchangeable.
Wein’s Displacement Law

In addition to computing the total amount of energy exiting a theoretical blackbody such as the Sun, we can determine its dominant wavelength ($\lambda_{\text{max}}$) based on the \textit{Wein's displacement law}:

$$\lambda_{\text{max}} = \frac{k}{T}$$

where $k$ is a constant equaling 2898 $\mu$m K, and $T$ is the absolute temperature in kelvin. Therefore, as the Sun approximates a 6000 K blackbody, its dominant wavelength ($\lambda_{\text{max}}$) is:

$$\lambda_{\text{max}} = \frac{2898 \ \mu m \ K}{6000 \ K} = 0.483 \ \mu m$$
Blackbody Radiation Curves

Blackbody radiation curves for several objects including the Sun and the Earth which approximate 6,000 K and 300 K blackbodies, respectively.

The area under each curve may be summed to compute the total radiant energy \((M_l)\) exiting each object. Thus, the Sun produces more radiant exitance than the Earth because its temperature is greater. As the temperature of an object increases, its dominant wavelength \((\lambda_{\text{max}})\) shifts toward the shorter wavelengths of the spectrum.
Particle Model of Electromagnetic Energy

For a 100 years before 1905, light was thought of as a smooth and continuous wave as discussed. Then, Albert Einstein (1879-1955) found that when light interacts with electrons, it has a different character.

He found that when light interacts with matter, it behaves as though it is composed of many individual bodies called photons, which carry such particle-like properties as energy and momentum.

Thus, we sometimes describe electromagnetic energy in terms of its wave-like properties. But, when the energy interacts with matter it is useful to describe it as discrete packets of energy or quanta.
Particle Model of Electromagnetic Energy

This radiation can be described equally well in terms of waves or in terms of packets of radiant energy called **quanta** or **photons**.

The relationship between these two "forms" of electromagnetic radiation is:

\[ Q = h \nu \]

Where,

- \( Q \) = Energy of a photon (joules)
- \( h \) = Planck's constant (joules * s) = 6.626 x 10^{-34} \text{ J*s}
- \( \nu \) = frequency (hertz)
  
1 hertz = cycle/second

**Remember!**

\[ \nu = \frac{c}{\lambda} \quad \lambda = \frac{c}{\nu} \]

**How \( Q \) relates with \( \lambda \) and \( \nu \) ?**

Therefore, the energy of a photon is directly proportional to the frequency but indirectly proportional to the wavelength.
A photon of electromagnetic energy is emitted when an electron in an atom or molecule drops from a higher-energy state to a lower-energy state. The light emitted (i.e., its wavelength) is a function of the changes in the energy levels of the outer, valence electron. For example, yellow light may be produced from a sodium vapor lamp. The intense heat at the surface of the Sun produces a continuous spectrum in this manner.
Creation of Light from Atomic Particles in a Sodium Vapor Lamp

Atom's energy loss is 2.1 eV when an excited electron falls back to an orbit closer to the nucleus. Energy change in electron volts (eV)

Sodium atom

Emits a photon of yellow light (2.1 eV)

Creation of Light

Creation of light from atomic particles in a sodium vapor lamp. After being energized by several thousand volts of electricity, the outermost electron in each energized atom of sodium vapor climbs to a high rung on the energy ladder and then returns down the ladder in a predictable fashion. The last two rungs in the descent are 2.1 eV apart. This produces a photon of yellow light, which has 2.1 eV of energy.
Energy of Quanta (Photons)

The energy of quanta (photons) ranging from gamma rays to radio waves in the electromagnetic spectrum.

<table>
<thead>
<tr>
<th>Energy (J)</th>
<th>Frequency (Hz)</th>
<th>Wavelength (λ)</th>
<th>Type of radiation</th>
<th>Absorption by atmosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-30}$</td>
<td>$10^3$</td>
<td>$1000$ km</td>
<td>Long radio waves</td>
<td>Radio window</td>
</tr>
<tr>
<td>$10^{-29}$</td>
<td>$10^4$</td>
<td>$100$ km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^{-28}$</td>
<td>$10^5$</td>
<td>$10$ km</td>
<td>Radio broadcast</td>
<td></td>
</tr>
<tr>
<td>$10^{-27}$</td>
<td>$10^6$</td>
<td>$1$ km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^{-26}$</td>
<td>$10^7$</td>
<td>$100$ m</td>
<td>FM, TV broadcast</td>
<td></td>
</tr>
<tr>
<td>$10^{-25}$</td>
<td>$10^8$</td>
<td>$10$ m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^{-24}$</td>
<td>$10^9$</td>
<td>$1$ m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^{-23}$</td>
<td>$10^{10}$</td>
<td>$10$ cm</td>
<td>Shortwave radio</td>
<td></td>
</tr>
<tr>
<td>$10^{-22}$</td>
<td>$10^{11}$</td>
<td>$1$ mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^{-21}$</td>
<td>$10^{12}$</td>
<td>$10^{-1}$ mm</td>
<td>Infared</td>
<td></td>
</tr>
<tr>
<td>$10^{-20}$</td>
<td>$10^{13}$</td>
<td>$10^{-2}$ mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^{-19}$</td>
<td>$10^{14}$</td>
<td>$10^{-3}$ mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^{-18}$</td>
<td>$10^{15}$</td>
<td>$10^{-4}$ mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^{-17}$</td>
<td>$10^{16}$</td>
<td>$10^{-5}$ mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^{-16}$</td>
<td>$10^{17}$</td>
<td>$10^{-6}$ mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^{-15}$</td>
<td>$10^{18}$</td>
<td>$10^{-7}$ mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^{-14}$</td>
<td>$10^{19}$</td>
<td>$10^{-8}$ mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^{-13}$</td>
<td>$10^{20}$</td>
<td>$10^{-9}$ mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
What is the energy of a photon with a wavelength of 400 nm?

1. Get wavelength (λ) in meters:
   
   $$1\text{ nm} = 10^{-9}\text{ m}$$
   
   $$400\text{ nm} = 4 \times 10^{-7}\text{ m}$$

2. Get the frequency: $$\nu = \frac{c}{\lambda}$$
   
   $$= \frac{3 \times 10^8\text{ m/s}}{4 \times 10^{-7}\text{ m}} = 7.5 \times 10^{14}\text{ cycles/second (or Hz)}$$

3. Get the energy: $$Q = h\nu$$
   
   $$= (6.63 \times 10^{-34}\text{ J}\cdot\text{s}) (7.5 \times 10^{14} /\text{s})$$
   
   $$= 4.97 \times 10^{-19}\text{ J}$$
What is the energy of a photon with a wavelength of 500 nm?

1. Get wavelength (\( \lambda \)) in meters:
   \[
   1 \text{ nm} = 10^{-9} \text{ meters}
   \]
   \[
   ? \text{ meters} = 500 \text{ nm} \left( \frac{10^{-9} \text{ m}}{1 \text{ nm}} \right) = 5 \times 10^{-7} \text{ meters}
   \]

2. Get the frequency: \( \nu = c/\lambda \)
   \[
   = \frac{3 \times 10^8 \text{ m/s}}{5 \times 10^{-7} \text{ m}} = 6 \times 10^{14} \text{ cycles/second (or Hz)}
   \]

3. Get the energy: \( Q = h\nu \)
   \[
   = (6.63 \times 10^{-34} \text{ J*s}) \left( 6 \times 10^{14} /\text{s} \right)
   \]
   \[
   = 3.98 \times 10^{-19} \text{ J}
   \]
What is the energy of a photon with a wavelength of 700 nm?

1. Get wavelength (\( \lambda \)) in meters:
   
   \[
   1 \text{ nm} = 10^{-9} \text{ meters}
   \]
   
   \[
   ? \text{ meters} = 700 \text{ nm} \times \frac{10^{-9} \text{ m}}{1 \text{ nm}} = 7 \times 10^{-7} \text{ meters}
   \]

2. Get the frequency: \( \nu = c/\lambda \)

   \[
   = \frac{3 \times 10^8 \text{ m/s}}{7 \times 10^{-7} \text{ m}} = 4.28 \times 10^{14} \text{ cycles/second (or Hz)}
   \]

3. Get the energy: \( Q = h\nu \)

   \[
   = (6.63 \times 10^{-34} \text{ J*seconds}) \times (6 \times 10^{14} /\text{s})
   \]

   \[
   = 2.84 \times 10^{-19} \text{ J}
   \]
ELECTROMAGNETIC SPECTRUM

Wavelength (nm)

Gamma Ray  X-Ray  UV Visible  Infrared  Microwave (Radar)  Radio

At 400 nm
Q=4.97 \times 10^{-19} \text{ J}

At 500 nm
Q=3.98 \times 10^{-19} \text{ J}

At 700 nm
Q=2.84 \times 10^{-19} \text{ J}
PROCESSES RELATED WITH ELECTROMAGNETIC RADIATION
Refraction is the bending of a wave when it enters a medium where it's speed is different. The refraction of light when it passes from a fast medium to a slow medium bends the light ray toward the normal to the boundary between the two media. The amount of bending depends on the indices of refraction of the two media and is described quantitatively by Snell’s Law.

\[
\frac{n_1}{n_2} = \frac{\sin \theta_2}{\sin \theta_1}
\]
Once electromagnetic radiation is generated, it is propagated through the earth's atmosphere almost at the speed of light in a vacuum.

Unlike a vacuum in which nothing happens, however, the atmosphere may affect not only the speed of radiation but also its wavelength, intensity, spectral distribution, and/or direction.

Major subdivisions of the atmosphere and the types of molecules and aerosols found in each layer.
Atmospheric Scattering

Type of scattering is a function of:

1. the \textit{wavelength} of the incident radiant energy, and
2. the \textit{size} of the gas molecule, dust particle, and/or water vapor droplet encountered.

\textit{Scattering} differs from \textit{reflection} in that the direction associated with scattering is \textit{un}predictable, whereas the direction of reflection is predictable. There are essentially three types of scattering:

a. Rayleigh,

b. Mie, and

c. Non-selective.

Type of scattering is a function of:

1. the \textit{wavelength} of the incident radiant energy, and
2. the \textit{size} of the gas molecule, dust particle, and/or water vapor droplet encountered.
RAYLEIGH SCATTERING

This is the most common scattering produced by atmospheric gases.

Occurs when the diameter of the matter (usually air molecules) are many times smaller than the wavelength of the incident electromagnetic radiation. 
(a <<\lambda)

It depends of the wavelength and is proportional to \(1/\lambda^4\).

Responsible for the blue sky. Blue light (400 nm) is scattered 16 times more than near-infrared light (800 nm).
Rayleigh scattering is responsible for the blue sky. The short violet and blue wavelengths are more efficiently scattered than the longer orange and red wavelengths. When we look up on cloudless day and admire the blue sky, we witness the preferential scattering of the short wavelength sunlight.

Rayleigh scattering is responsible for red sunsets. Since the atmosphere is a thin shell of gravitationally bound gas surrounding the solid Earth, sunlight must pass through a longer slant path of air at sunset (or sunrise) than at noon. Since the violet and blue wavelengths are scattered even more during their now-longer path through the air than when the Sun is overhead, what we see when we look toward the Sun is the residue - the wavelengths of sunlight that are hardly scattered away at all, especially the oranges and reds (Sagan, 1994).
MIE SCATTERING

It takes place when there are essentially spherical particles present in the atmosphere with diameters approximately equal to the wavelength of radiation being considered.

It is mainly produced by aerosols (large particles) like water vapor, smoke, and dust.

Mie scattering increases when the atmosphere is partly cloudy. This is mainly a forward scattering.

Pollution also contributes to beautiful sunsets and sunrises. The greater the amount of smoke and dust particles in the atmospheric column, the more violet and blue light will be scattered away and only the longer orange and red wavelength light will reach our eyes.

The size of the particles is similar to the wavelength. ($a \approx \lambda$)
Rayleigh Scattering

Mie Scattering

From overhead, the Rayleigh scattering is dominant, the Mie scattered intensity being projected forward. Since Rayleigh scattering strongly favors short wavelengths, we see a blue sky.

When there is large particulate matter in the air, the forward lobe of Mie scattering is dominant. Since it is not very wavelength dependent, we see a white glow around the sun.
Non-selective Scattering

Non-selective scattering is produced when there are particles in the atmosphere several times the diameter of the radiation being transmitted. ($a \gg \lambda$)

This type of scattering is non-selective, i.e. all wavelengths of light are scattered, not just blue, green, or red. Thus, water droplets, which make up clouds and fog banks, scatter all wavelengths of visible light equally well, causing the cloud to appear white (a mixture of all colors of light in approximately equal quantities produces white).

Scattering can severely reduce the information content of remotely sensed data to the point that the imagery loses contrast and it is difficult to differentiate one object from another.
SCATTERING OF PHOTONS

Non-Selective

Rayleigh Scattering

Mie Scattering
Absorption

Absorption is the process by which radiant energy is absorbed and converted into other forms of energy.

Absorption occurs when energy of the same frequency as the resonant frequency of an atom or molecule is absorbed, producing an excited state. If, instead of re-radiating a photon of the same wavelength, the energy is transformed into heat motion and is reradiated at a longer wavelength, absorption occurs.
Absorption

An *absorption band* is a range of wavelengths (or frequencies) in the electromagnetic spectrum within which radiant energy is absorbed by substances such as water (H₂O), carbon dioxide (CO₂), oxygen (O₂), ozone (O₃), and nitrous oxide (N₂O).

The cumulative effect of the absorption by the various constituents can cause the atmosphere to *close down* in certain regions of the spectrum. This is bad for remote sensing because no energy is available to be sensed.
Absorption of the Sun’s Incident Electromagnetic Energy in the Region from 0.1 to 30 μm by Various Atmospheric Gases
The combined effects of atmospheric absorption, scattering, and reflectance reduce the amount of solar irradiance reaching the Earth’s surface at sea level.
Spectral Windows

- U.V. Visible
- Infrared
- Solar Radiation

Atomsphere

λ μm

Transparency

% 0 50 100
Most remote sensors have bands in the Visible, IR, and Microwaves.
REFLECTION

Light is said to be reflected when the angle at which light initially strikes a surface is equal to the angle at which light bounces off the same surface.

Reflectance is the process whereby radiation “bounces off” an object like a cloud or the terrain.
REFLECTION OF COLORS
REFLECTION OF COLORS

B
BLUE

G
GREEN

R
RED

WHITE

YELLOW

CYAN

MAGENTA

BLACK

0.4 0.5 0.6 0.7 \mu m

UV

VISIBLE

IR
Spectral Reflectance Curves for Selected Materials

- Grass
- Concrete
- Sandy loam soil
- Shingles
- Fallow field
- Asphalt
- Artificial turf
- Clear water

Reflectance (%) vs. Wavelength, μm
DETECTING THE REMOTE SIGNAL