

EE 445/645: Physical Models in Remote Sensing (Spring 2026)

Chapter 01-Part 03: Radiative Interactions – Notes (See C1-P3 PPTs)

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Overview of Radiative Interactions

This chapter explores the fundamental ways that electromagnetic radiation (photons) interacts with matter as it travels through different media. Understanding these interactions is crucial for remote sensing applications, as they determine how radiation from sources (like the sun or thermal emissions) is modified before reaching sensors.

The seven key concepts covered are:

1. Absorption Coefficient
 2. Scattering Coefficient
 3. Differential Scattering Coefficient
 4. Scattering Phase Functions
 5. Extinction Coefficient
 6. Single Scattering Albedo
 7. Emission Sources
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1. Radiative Interactions: The Three Main Mechanisms

When photons traverse a medium (such as the atmosphere, water, or vegetation), they encounter atoms and molecules that can alter their path or absorb them entirely. These interactions fall into three primary categories:

1.1 Absorption

Definition: Complete capture of a photon by an atom, where all the photon's energy is transferred to the atomic structure.

Mechanism:

- The photon's entire energy quantum is absorbed by an inner-shell electron
- This absorbed energy causes the electron to be ejected from the atom (photoelectric effect)
- The photon ceases to exist after this interaction
- The atom is left in an ionized state

Energy Regime: Dominant for low-energy photons, particularly in the visible light spectrum

Remote Sensing Significance:

- Determines which wavelengths are absorbed by atmospheric gases, water vapor, and surface materials
- Creates characteristic absorption features in spectral signatures
- Explains why certain wavelengths penetrate atmosphere while others are blocked
- Critical for understanding atmospheric windows used in satellite remote sensing

Examples in Remote Sensing:

- Water vapor absorption bands in the infrared
 - Chlorophyll absorption in red and blue wavelengths
 - Ozone absorption of UV radiation
 - CO₂ absorption in thermal infrared bands
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1.2 Coherent or Elastic Scattering

Definition: Deflection of a photon into a new direction without any energy loss.

Mechanism:

- The photon interacts with the atom as a unified whole or with the entire electron cloud
- No energy transfer occurs - the photon maintains its original frequency and wavelength
- Only the direction of propagation changes
- The interaction is "elastic" because kinetic energy is conserved

Energy Regime: Occurs primarily with low-energy photons

Rayleigh Scattering (Primary Example):

- Occurs when photon wavelength \gg particle size
- Interaction with atmospheric gases (N₂, O₂)
- Scattering intensity $\propto \lambda^{-4}$ (inversely proportional to the fourth power of wavelength)
- Explains why the sky appears blue (shorter wavelengths scatter more)
- Creates atmospheric haze in remote sensing images

Remote Sensing Implications:

- Atmospheric path radiance that must be corrected
- Limits contrast in imagery, especially at shorter wavelengths
- Stronger effect in blue wavelengths, requiring atmospheric correction
- Affects apparent brightness of dark targets
- Creates the "adjacency effect" where bright surfaces influence neighboring pixels

1.3 Inelastic Scattering

Definition: Photon interaction where direction changes AND energy is partially transferred, resulting in a lower-energy (longer wavelength) scattered photon.

Mechanism (Compton Scattering):

- Photon collides with an outer-shell electron
- Partial energy transfer occurs, ejecting the electron
- The photon continues traveling but with:
 - Lower frequency (red-shifted)
 - Longer wavelength
 - Reduced energy
- Both momentum and energy conservation apply

Energy Regime: Typical for mid-energy photons (like diagnostic X-rays)

Remote Sensing Relevance:

- Less common in optical remote sensing but important in some contexts
- Relevant for high-energy remote sensing applications
- Contributes to spectral shift phenomena
- Important in understanding energy degradation through media

Raman Scattering (Related Phenomenon):

- Molecular vibration causes small energy shifts
- Used in Raman lidar for atmospheric composition studies
- Provides information about molecular structure
- Creates weak signal but highly informative about chemical composition

2. Absorption Coefficient (σ_a)

Definition: A measure of how readily a medium absorbs photons per unit distance traveled.

Mathematical Expression:

- Units: m^{-1} (inverse meters) or cm^{-1}
- Represents the probability of absorption per unit path length

Physical Interpretation:

- High $\sigma_a \rightarrow$ Strong absorber, photons don't travel far
- Low $\sigma_a \rightarrow$ Weak absorber, photons penetrate deeply
- $\sigma_a = 0 \rightarrow$ Transparent medium (no absorption)

Factors Affecting Absorption Coefficient:

1. **Wavelength Dependence:** $\sigma_a(\lambda)$ varies strongly with wavelength
 - Creates absorption bands and transmission windows
 - Basis for spectral remote sensing
2. **Material Composition:** Different materials have unique absorption spectra
 - Water vs. vegetation vs. soil all have distinct $\sigma_a(\lambda)$
3. **Concentration:** Often proportional to absorber concentration (Beer's Law)
4. **Physical State:** Temperature, pressure affect molecular energy levels

Applications in Remote Sensing:

- **Atmospheric Correction:** Quantifying atmospheric absorption for correction algorithms
 - **Water Quality:** Absorption by dissolved organic matter, phytoplankton
 - **Vegetation Studies:** Chlorophyll absorption drives photosynthesis indices
 - **Mineral Identification:** Diagnostic absorption features identify minerals
 - **Thermal Remote Sensing:** Atmospheric absorption affects thermal band radiance
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3. Scattering Coefficient (σ_s')

Definition: Measure of the total scattering probability per unit distance, integrating over all possible scattering directions.

Mathematical Expression:

- Units: m^{-1} (inverse meters)
- Represents probability of scattering (into any direction) per unit path length
- $\sigma_s' = \int \sigma_s(\Omega \rightarrow \Omega') d\Omega'$ (integral of differential scattering over all directions)

Physical Meaning:

- Quantifies how much a photon beam is depleted by scattering
- Does not specify the direction of scattered photons
- High σ_s' \rightarrow highly scattering medium (like clouds, fog)
- Low σ_s' \rightarrow relatively transparent medium

Types of Scattering Regimes:

1. **Rayleigh Scattering** (particle \ll wavelength):
 - Molecular scattering in clear atmosphere
 - $\sigma_s' \propto \lambda^{-4}$ (strong wavelength dependence)
2. **Mie Scattering** (particle \approx wavelength):
 - Aerosols, cloud droplets, dust particles
 - Complex angular dependence
 - Less wavelength dependent than Rayleigh

3. Geometric Scattering (particle \gg wavelength):

- Large particles like rain drops, hail
- Wavelength independent
- Follows geometric optics principles

Remote Sensing Applications:

- **Cloud Detection:** High scattering creates bright cloud signatures
 - **Aerosol Monitoring:** Scattering coefficient relates to aerosol optical depth
 - **Visibility Estimation:** Scattering reduces contrast and limits visibility
 - **Vegetation Structure:** Multiple scattering in canopy affects reflectance
 - **Ocean Color:** Scattering by particles affects water-leaving radiance
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4. Differential Scattering Coefficient (σ_s)

Definition: Describes the probability of scattering from one specific direction to another specific direction per unit path length and per unit solid angle.

Mathematical Expression:

- $\sigma_s(\Omega \rightarrow \Omega')$ where Ω is incident direction, Ω' is scattered direction
- Units: $\text{m}^{-1} \text{sr}^{-1}$ (inverse meters per steradian)
- More detailed than total scattering coefficient

Physical Significance:

- Provides directional information about scattering
- Essential for calculating radiance in specific viewing geometries
- Accounts for anisotropic scattering (direction-dependent)
- Forms the basis for radiative transfer modeling

Relationship to Total Scattering:

- Total scattering coefficient: $\sigma_s' = \int_{4\pi} \sigma_s(\Omega \rightarrow \Omega') d\Omega'$
- Integration over all possible scattered directions (4π steradians)

Importance in Remote Sensing:

- **Bidirectional Effects:** Explains why surfaces appear different from different viewing angles
- **Radiative Transfer Models:** Required for accurate atmospheric correction
- **BRDF Models:** Basis for bidirectional reflectance distribution function
- **Multiple Scattering:** Determines photon path through turbid media

5. Downscattering vs. Upscattering

Understanding energy transfer during scattering is crucial for comprehending radiative processes.

5.1 Downscattering (Energy Loss)

Definition: Scattering process where the scattered photon emerges with LOWER energy than the incident photon.

Mechanism - Compton Scattering:

- High-energy photon encounters a free or loosely-bound electron
- Photon transfers part of its energy to the electron
- Photon continues with reduced frequency (increased wavelength)
- Energy conservation: $E_{\text{photon,initial}} = E_{\text{photon,final}} + E_{\text{electron}} + \text{binding_energy}$

Key Characteristics:

- Photon gives energy to matter
- Drives physical and chemical processes in the medium
- Results in "red-shift" of scattered radiation
- More probable at higher photon energies

Example: Fluorescence

- Chlorophyll absorbs blue/red light (high energy)
- Re-emits in red/near-infrared (lower energy)
- Indicator of photosynthetic activity in vegetation
- Used in solar-induced fluorescence (SIF) remote sensing

Remote Sensing Applications:

- **Vegetation Health Monitoring:** Fluorescence as stress indicator
- **Phytoplankton Detection:** Ocean color fluorescence
- **Atmospheric Chemistry:** Energy transfer drives photochemical reactions
- **Thermal Processes:** Photon energy converts to heat

Process Significance:

- Energy input from radiation field to matter
- Drives biological processes (photosynthesis)
- Causes heating of surfaces and atmosphere
- Results in spectral shift that can be detected

5.2 Upscattering (Energy Gain)

Definition: Scattering process where the scattered photon emerges with HIGHER energy than the incident photon.

Mechanism - Inverse Compton Scattering:

- Low-energy photon encounters a high-energy (relativistic) electron
- Photon gains energy from the electron's kinetic energy
- Photon continues with increased frequency (decreased wavelength)
- Energy conservation: $E_{\text{photon,final}} = E_{\text{photon,initial}} + \Delta E_{\text{from_electron}}$

Key Characteristics:

- Matter gives energy to photon
- "Heats" the radiation field
- Results in "blue-shift" of scattered radiation
- Requires high-energy electrons (rare in most remote sensing contexts)

Astrophysical Context:

- Cosmic microwave background photons upscattered by hot electrons in galaxy clusters
- Critical for understanding high-energy astrophysical phenomena
- Sunyaev-Zel'dovich effect in cosmology
- X-ray production in accretion disks

Remote Sensing Relevance:

- **Generally Rare:** Not common in Earth observation remote sensing
- **Plasma Environments:** May occur in ionospheric studies
- **High-Energy Events:** Lightning, aurora
- **Theoretical Importance:** Completes understanding of scattering physics

Conceptual Importance:

- Demonstrates energy can flow from matter to radiation
 - Shows reciprocal nature of radiation-matter interaction
 - Relevant for extreme environments
 - Completes the theoretical framework
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6. Scattering Phase Function (P(θ))

Definition: A normalized angular distribution function that describes the probability of photons being scattered into different directions.

Mathematical Properties:

- Dimensionless function
- Normalized: $(1/4\pi) \int_{4\pi} P(\theta) d\Omega = 1$
- Depends on scattering angle θ (angle between incident and scattered directions)
- Range: $P(\theta) \geq 0$ for all angles

Physical Meaning:

- $P(\theta) = 1 \rightarrow$ isotropic scattering (equal probability in all directions)
- $P(\theta) > 1 \rightarrow$ preferential scattering in that direction
- $P(\theta) < 1 \rightarrow$ reduced scattering in that direction

Relationship to Differential Scattering:

- $\sigma_s(\Omega \rightarrow \Omega') = (\sigma_s' / 4\pi) \times P(\theta)$
- Separates magnitude (σ_s') from angular pattern ($P(\theta)$)

Common Scattering Regimes:

1. **Rayleigh Scattering:** $P(\theta) = (3/4)(1 + \cos^2\theta)$
 - Symmetric forward-backward scattering
 - Zero at 90° relative to polarization
2. **Forward-Peaked:** $P(\theta)$ large for small θ
 - Mie scattering from particles
 - Increases with particle size/wavelength ratio
3. **Isotropic:** $P(\theta) = 1$ (constant)
 - Very small particles
 - Simplified models

6.1 Henyey-Greenstein Phase Function

Definition: An analytical approximation widely used to model phase functions with a single asymmetry parameter.

Mathematical Form: $P(\theta) = (1 - g^2) / [4\pi(1 + g^2 - 2g \cos \theta)^{3/2}]$

Where:

- θ = scattering angle
- g = asymmetry parameter ($-1 \leq g \leq 1$)

Asymmetry Parameter (g):

- $g = \langle \cos \theta \rangle$ = average cosine of scattering angle
- $g = 0$: Isotropic scattering (symmetric)
- $g > 0$: Forward scattering dominates ($0 < g < 1$)
- $g < 0$: Backward scattering dominates ($-1 < g < 0$)

- $g = 1$: Complete forward scattering
- $g = -1$: Complete backward scattering

Physical Interpretation:

- $g \approx 0$: Small particles (Rayleigh regime), symmetric scattering
- $g = 0.7-0.85$: Typical for atmospheric aerosols, cloud droplets
- $g = 0.9-0.95$: Large particles, strong forward peak
- $g > 0.95$: Very large particles (rain, hail)

Advantages:

1. Simple analytical form
2. Single parameter (g) captures essential behavior
3. Computationally efficient
4. Physically intuitive
5. Good approximation for many natural media

Limitations:

1. Cannot represent complex multi-modal distributions
2. May not accurately capture backscattering for some particles
3. Asymmetric assumption may not hold for all materials

Remote Sensing Applications:

- **Radiative Transfer Models:** Essential input parameter
- **Cloud Retrievals:** Characterizing cloud particle properties
- **Aerosol Studies:** Describing scattering by pollution, dust
- **Vegetation Modeling:** Leaf and canopy scattering
- **Atmospheric Correction:** Accounting for path radiance

7. Example Scattering Phase Functions

Understanding real-world phase functions helps interpret remote sensing observations:

Molecular (Rayleigh) Scattering:

- **Pattern:** Symmetric forward-backward lobes
- $g \approx 0$: Nearly isotropic
- **Context:** Clean atmosphere, clear sky
- **Impact:** Blue sky, atmospheric haze

Small Aerosols:

- **Pattern:** Slight forward preference
- $g \approx 0.3-0.5$: Mild asymmetry
- **Context:** Urban pollution, fine dust

- **Impact:** Reduced contrast, whitish haze

Large Aerosols / Small Cloud Droplets:

- **Pattern:** Strong forward peak
- **$g \approx 0.75-0.85$:** Significant asymmetry
- **Context:** Coarse dust, maritime aerosols
- **Impact:** Strong forward scattering, glory effects

Cloud Droplets:

- **Pattern:** Very strong forward peak with rainbow/glory features
- **$g \approx 0.85-0.90$:** High asymmetry
- **Context:** Water clouds, fog
- **Impact:** High reflectance, rainbows, halos

Vegetation:

- **Pattern:** Complex, wavelength-dependent
- **$g \approx 0.5-0.7$:** Moderate asymmetry
- **Context:** Leaves, canopy elements
- **Impact:** Hot spot effect, BRDF patterns

8. Extinction Coefficient (σ)

Definition: The total rate at which photons are removed from a beam per unit distance, combining both absorption and scattering.

Mathematical Expression: $\sigma = \sigma_a + \sigma_s'$

Where:

- σ_a = absorption coefficient
- σ_s' = scattering coefficient
- σ = total extinction coefficient

Units: m^{-1} or cm^{-1}

Mean Free Path:

- $\lambda_{\text{mfp}} = 1/\sigma$
- Average distance a photon travels before a collision (absorption or scattering)
- Inverse relationship: high $\sigma \rightarrow$ short mean free path (opaque medium)
- Low $\sigma \rightarrow$ long mean free path (transparent medium)

Physical Interpretation:

- Measures total attenuation of radiation
- Combines both loss mechanisms
- Critical for radiative transfer calculations
- Determines optical depth: $\tau = \int \sigma(s) ds$

Directional Dependence: The extinction coefficient can depend on the direction of photon propagation: $\sigma(\Omega)$

Why Direction Matters:

1. **Anisotropic Media:** Non-uniform structure
2. **Oriented Particles:** Aligned crystals, leaves
3. **Vegetation Canopies:** Vertical structure creates directional variation

Vegetation Example:

- Horizontal photons: must traverse many leaf layers (high σ)
- Vertical photons: gaps between leaves (lower σ)
- Creates angular dependence in canopy transmission
- Explains bidirectional reflectance patterns

Remote Sensing Applications:

- **Atmospheric Optical Depth:** Column-integrated extinction
- **Beer's Law Transmission:** $I = I_0 \exp(-\sigma z)$ for uniform medium
- **Visibility Estimation:** σ determines visual range
- **Canopy Architecture:** Directional extinction reveals structure
- **Water Clarity:** Extinction coefficient indicates water quality

Measurement Techniques:

- Direct beam transmission experiments
- Lidar returns (aerosol extinction)
- Sun photometry (atmospheric extinction)
- In situ sensors (water extinction)

9. Single Scattering Albedo (ω)

Definition: The probability that a photon, upon collision with matter, will scatter rather than be absorbed.

Mathematical Expression: $\omega = \sigma_s' / \sigma = \sigma_s / (\sigma_a + \sigma_s')$

Range: $0 \leq \omega \leq 1$ (dimensionless)

Physical Interpretation:

1. $\omega = 0$ (Pure Absorption - "Black Medium")
 - o All collisions result in absorption
 - o No scattering occurs
 - o Example: Perfect blackbody, highly absorbing materials
 - o $\sigma_s' = 0$, only σ_a contributes
2. $\omega = 1$ (Conservative Scattering - "White Medium")
 - o All collisions result in scattering
 - o No absorption occurs
 - o Example: Clean ice, pure molecular scattering
 - o $\sigma_a = 0$, only σ_s' contributes
3. $0 < \omega < 1$ (Mixed Medium - Most Common)
 - o Both processes occur with respective probabilities
 - o Realistic materials
 - o Example: Vegetation ($\omega \approx 0.4-0.9$ depending on wavelength)

Typical Values in Remote Sensing:

Medium/Material	Wavelength	Typical ω	Character
Snow/Ice	Visible	0.98-1.0	Highly scattering
Clouds	Visible	0.99+	Nearly conservative
Vegetation	NIR	0.85-0.95	High scattering
Vegetation	Red	0.40-0.60	Moderate scattering/absorption
Soil	Visible	0.50-0.70	Mixed
Water	Blue	0.40-0.60	Moderate
Aerosols	Visible	0.80-0.95	Generally high scattering
Smoke	Visible	0.70-0.90	Varies with composition

Wavelength Dependence:

- $\omega(\lambda)$ varies significantly with wavelength
- Chlorophyll absorption \rightarrow low ω in red, high ω in NIR
- Creates spectral signatures useful for classification

Impact on Radiation Field:

- **High ω :** Bright surfaces, multiple scattering, diffuse radiation
- **Low ω :** Dark surfaces, radiation absorbed, heating
- **Radiative Transfer:** ω determines surface brightness and photon escape probability

Climate and Energy Balance:

- High ω aerosols: cooling effect (reflect sunlight)
- Low ω aerosols: warming effect (absorb sunlight)
- Snow albedo feedback: ω changes affect climate
- Surface energy partitioning depends on ω

Measurement and Retrieval:

- Can be retrieved from satellite observations
 - Requires separation of absorption and scattering
 - Often derived from multi-angle or polarimetric measurements
 - Critical parameter in climate models
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10. Emission Sources

Context: While previous sections focused on photon attenuation (removal from beam), emission represents photon **generation** within the medium.

Types of Emission:

10.1 Thermal Emission

Mechanism: All matter with $T > 0$ K emits electromagnetic radiation

- **Planck's Law:** Spectral distribution of blackbody radiation
- **Wien's Law:** Peak wavelength $\lambda_{\text{max}} = 2898/T$ (μm , K)
- **Stefan-Boltzmann:** Total emission $\propto T^4$

Applications:

- Thermal infrared remote sensing (8-14 μm)
- Sea surface temperature
- Land surface temperature
- Fire detection
- Night-time observations

Emission Coefficient (ϵ):

- Related to absorption: Kirchhoff's Law $\epsilon = \alpha$ (emissivity = absorptivity)
- Good absorbers are good emitters
- $\epsilon < 1$ for real materials (non-blackbodies)

10.2 Fluorescence

Mechanism: Absorption followed by re-emission at longer wavelength

- Chlorophyll fluorescence: absorbed blue/red \rightarrow emitted red/NIR
- Quantum yield: photons emitted / photons absorbed
- Indicator of photosynthetic efficiency

Applications:

- Solar-induced chlorophyll fluorescence (SIF)
- Vegetation stress detection

- Photosynthetic activity monitoring
- Ocean color (phytoplankton fluorescence)

10.3 Luminescence

Other Forms:

- **Chemiluminescence:** Chemical reactions produce light
- **Bioluminescence:** Biological light production (marine organisms)
- **Phosphorescence:** Delayed re-emission after excitation

Remote Sensing Relevance:

- Night-time imagery
- Marine biology studies
- Some specialized applications

Summary of Key Relationships

Fundamental Equations:

1. **Extinction:** $\sigma = \sigma_a + \sigma_s'$
2. **Single Scattering Albedo:** $\omega = \sigma_s' / \sigma$
3. **Scattering Integration:** $\sigma_s' = \int_{4\pi} \sigma_s(\Omega \rightarrow \Omega') d\Omega'$
4. **Phase Function:** $\sigma_s(\Omega \rightarrow \Omega') = (\sigma_s' / 4\pi) \times P(\theta)$
5. **Mean Free Path:** $\lambda_{\text{mfp}} = 1 / \sigma$
6. **Optical Depth:** $\tau = \int \sigma ds$

Physical Insights:

- Absorption removes photons permanently (converts to other energy)
- Scattering redirects photons without energy loss (elastic) or with energy change (inelastic)
- Phase function describes angular pattern of scattering
- Single scattering albedo partitions between scattering and absorption
- Extinction combines both loss mechanisms
- Emission adds photons to the radiation field

Remote Sensing Implications:

- These parameters determine what sensors measure
- Wavelength dependence creates spectral signatures
- Angular dependence creates bidirectional effects
- Understanding these processes enables quantitative retrieval of surface and atmospheric properties
- Accurate modeling requires knowledge of all these coefficients

Conclusion

Understanding radiative interactions is fundamental to remote sensing science. These seven concepts—absorption coefficient, scattering coefficient, differential scattering coefficient, phase functions, extinction coefficient, single scattering albedo, and emission sources—form the theoretical foundation for:

1. Interpreting satellite and airborne observations
2. Developing atmospheric correction algorithms
3. Retrieving surface and atmospheric properties
4. Understanding bidirectional reflectance effects
5. Modeling radiative transfer in complex media
6. Advancing quantitative remote sensing applications

The physical models described here bridge the gap between raw sensor measurements and the geophysical quantities we seek to understand, enabling the transformation of remote sensing from qualitative imagery to quantitative Earth observation.