Optical: Basic Concepts

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OPTICAL THEORY – BASIC CONCEPTS

- Radiation laws: definitions and nomenclature
- Sources of radiation in natural environment in the optical domain
- Illumination and observation geometries
- Interaction of radiation with matter in the optical domain
- Radiative transfer in the optical domain
- General solutions for the radiation transfer in the coupled Earth-surface and through the atmosphere
- Derivation of surface reflectance from measured satellite radiances
- Spectral information: signatures of natural objects
- Spatial information: uniformity, textures and scales
- Temporal information: land surface dynamics at multiple scales
- Information retrieval: from spectral indices to model inversion
- Overview of applications
OPTICAL SYSTEMS

Spectral range: 400 - 2500 nm

Panchromatic / Broadband:
one single (broad) band (albedo)

<table>
<thead>
<tr>
<th>Multispectral</th>
<th>Superspectral</th>
<th>Hyperspectral</th>
<th>Ultraspectral</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ≤ N ≤ 10</td>
<td>10 ≤ N ≤ 100</td>
<td>100 ≤ N ≤ 1000</td>
<td>1000 ≤ N ≤ ?</td>
</tr>
<tr>
<td>Δλ ≈ 100 nm</td>
<td>Δλ ≈ 50 nm</td>
<td>Δλ ≈ 10 nm</td>
<td>Δλ ≈ 1 nm</td>
</tr>
</tbody>
</table>

Spectral range: 400 - 2500 nm
imaging in multiple spectral bands
Developments in new sensor technologies

RADIOMETRIC DEFINITIONS

solid angle

\[ d\Omega = \frac{(r \sin \vartheta \, d\varphi) \, (r \, d\vartheta)}{r^2} = \sin \vartheta \, d\vartheta \, d\varphi \]

In the particular case of azimuthal symmetry:

\[ d\Omega = 2\pi \, \sin \vartheta \, d\vartheta \]

Radiant energy \( Q_e \)
- The energy carried by electromagnetic radiation

Radiant flux \( \Phi \)
- Radiant energy transmitted per unit time

Radiant intensity \( I_e \)
- Radiant energy radiated from a point source per solid angle in a radial direction per unit time

Incidence \( I_0 \)
- Radiant energy incident on a unit area per unit time

Radiant emittance \( M_e \)
- Radiant energy radiated from a unit projected area per unit solid angle in a radial direction per unit time

Radiation \( Le \)
- Radiant energy radiated from a unit projected area per unit solid angle in a radial direction per unit time
### Nomenclature and Radiometric Units

<table>
<thead>
<tr>
<th>Term or quantity</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy content</strong></td>
<td></td>
</tr>
<tr>
<td>radiant energy</td>
<td>joule (J)</td>
</tr>
<tr>
<td>energy flow rate</td>
<td>J s⁻¹ or watt (W)</td>
</tr>
<tr>
<td>energy fluence</td>
<td>J m⁻²</td>
</tr>
<tr>
<td>energy fluence rate</td>
<td>W m⁻²</td>
</tr>
<tr>
<td><strong>Photon content</strong></td>
<td></td>
</tr>
<tr>
<td>number of photons (quanta)</td>
<td>dimensionless</td>
</tr>
<tr>
<td>Avogadro’s number of photons</td>
<td>mol</td>
</tr>
<tr>
<td>photon flow rate</td>
<td>s⁻¹ or mol s⁻¹</td>
</tr>
<tr>
<td>photon fluence</td>
<td>m² or mol m⁻²</td>
</tr>
<tr>
<td>photon fluence rate</td>
<td>m² s⁻¹ or mol m⁻² s⁻¹</td>
</tr>
</tbody>
</table>

#### RADIANCE

\[
L = \frac{d^2 \Phi}{d\Omega \, dS} = \frac{d^2 \Phi}{d\Omega \, dA \, \cos \phi} \\
W \, m^{-2} \, sr^{-1}
\]

\[
L = \frac{d^3 E}{dt \, d\Omega \, dA \, \cos \phi}
\]

**Lambertian case**

\[
M = \pi \, L
\]
**Planck's Law**

\[ L_\lambda(T) = \frac{2 \pi c^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \]

- \( c = 299792458 \text{ m s}^{-1} \)
- \( h = 6.62606876 \times 10^{-34} \text{ J s} \)
- \( k = 1.3806503 \times 10^{-23} \text{ J K}^{-1} \)

**Available Signal**

- Atmosphere
- Solar 1.0 Reflectance
- Earth 300 K, 1.0 Emissivity
Illumination and observation geometries

Solar and Satellite Orbital Geometry Components
Bidirectional Reflectance Distribution Function, BRDF

\[ f(\theta, \varphi, \theta', \varphi') = \frac{dL^\uparrow(\theta', \varphi')}{dE^\downarrow(\theta, \varphi)} \text{ sr}^{-1} \]

\[ f(\theta, \varphi, \theta', \varphi') = \frac{dL^\uparrow(\theta', \varphi')}{L^\downarrow(\theta, \varphi) \cos \theta \sin \theta d\theta d\varphi} \]

- Very difficult to measure experimentally
- Basic tool in computer graphics

Conical Reflectance

\[ dp(\theta, \varphi, \theta', \varphi') = \frac{dL^\uparrow(\theta', \varphi') \cos \theta' d\Omega'}{L^\downarrow(\theta, \varphi) \cos \theta d\Omega} \]

Hemispherical Reflectance

\[ \rho = \frac{d\phi_{\text{hemisf}}^\uparrow}{d\phi_{\text{hemisf}}} = \frac{M}{E} \frac{dS}{dS} = \frac{\pi L dS}{E dS} = \frac{\pi L}{E} \]

Bidirectional Reflectance Factor

\[ R(\theta, \varphi, \theta', \varphi') = \frac{dL^\uparrow}{dL_p} \]
nine types of reflectance measurements

<table>
<thead>
<tr>
<th>Reflected</th>
<th>Incident</th>
</tr>
</thead>
<tbody>
<tr>
<td>directional</td>
<td>directional</td>
</tr>
<tr>
<td>bidirectional</td>
<td>conical</td>
</tr>
<tr>
<td>conical</td>
<td>conical-directional</td>
</tr>
<tr>
<td>directional-hemispherical</td>
<td>hemispherical-directional</td>
</tr>
<tr>
<td>hemispherical</td>
<td>conical-hemispherical</td>
</tr>
<tr>
<td></td>
<td>bhemispherical</td>
</tr>
</tbody>
</table>

Red Near-Infrared reflectance (%)

<table>
<thead>
<tr>
<th>View Zenith Angle</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>View Azimuth Angle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

LAI = 4  
$\theta_{sun} = 35^\circ$  
$\varphi_{sun} = 180^\circ$
Optical properties of elementary constituents determine the spectral reflectance of land elements.
Radiative transfer in the optical domain

\[ \begin{align*}
\beta_a^{\text{ext}}(\mathbf{r}, \mathbf{\Omega}) \cdot \mathbf{T}(\mathbf{r}, \mathbf{\Omega}) \, dS &+ \beta_a^{\text{int}}(\mathbf{r}, \mathbf{\Omega}) \cdot \mathbf{J}_a(\mathbf{r}, \mathbf{\Omega}) \, dS \\
- \beta_s(\mathbf{r}, \mathbf{\Omega}) \cdot \mathbf{T}(\mathbf{r}, \mathbf{\Omega}) \, dS &+ \beta_s(\mathbf{r}, \mathbf{\Omega}) \cdot \mathbf{J}_s(\mathbf{r}, \mathbf{\Omega}) \, dS
\end{align*} \]

... this is most times too complex to be used in practice...

General 5D ([3+2]D) vector radiative transfer equation

\[ \begin{align*}
\mathbf{dT}(\mathbf{r}, \mathbf{\Omega}) &= - \beta_a^{\text{ext}}(\mathbf{r}, \mathbf{\Omega}) \cdot \mathbf{T}(\mathbf{r}, \mathbf{\Omega}) \, dS - \beta_s(\mathbf{r}, \mathbf{\Omega}) \cdot \mathbf{T}(\mathbf{r}, \mathbf{\Omega}) \, dS + \\
&+ \beta_a^{\text{int}}(\mathbf{r}, \mathbf{\Omega}) \cdot \mathbf{J}_a(\mathbf{r}, \mathbf{\Omega}) \, dS + \beta_s(\mathbf{r}, \mathbf{\Omega}) \cdot \mathbf{J}_s(\mathbf{r}, \mathbf{\Omega}) \, dS
\end{align*} \]

\[ \begin{align*}
\mathbf{J}_s(\mathbf{r}, \mathbf{\Omega}) &= \frac{1}{4\pi} \int \mathbf{d\Omega'} \left[ \Psi_s(\mathbf{r}, \mathbf{\Omega}, \mathbf{\Omega}') \cdot \mathbf{T}(\mathbf{r}, \mathbf{\Omega}') \right] \\
\mathbf{\beta}_s(\mathbf{r}, \mathbf{\Omega}) &= \frac{1}{4\pi} \int \mathbf{d\Omega'} \Psi_s(\mathbf{r}, \mathbf{\Omega}, \mathbf{\Omega}')
\end{align*} \]

... this is most times too complex to be used in practice...
\[
\frac{\partial}{\partial s} = (\hat{\Omega} \cdot \vec{V})
\]

\[
\frac{1}{\beta_s(r, \Omega)} \frac{\partial}{\partial s} \bar{I}(r, \Omega) = - \bar{I}(r, \Omega) + \\
+ \frac{\omega_0(r, \Omega)}{4\pi} \int \frac{d\Omega'}{4\pi} \left[ \hat{P}(r, \Omega, \Omega') \cdot \bar{I}(r, \Omega') \right] + \\
+ \bar{J}(r, \Omega)
\]

\[d\tau \equiv - \beta_s(r, \Omega) \; dz\]

\[d\tau = - \beta_s(r, \Omega) \cos \theta \; ds\]

\[ds = \frac{dz}{\cos \theta}\]

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Signal modelling by multiple contributions

\[\rho_{sat} = \rho_{atm} + \]
\[+ T^{\uparrow} \rho_s T^{\uparrow} + \]
\[+ T^{\uparrow} \rho_s S \rho_s T^{\uparrow} + \]
\[+ T^{\uparrow} \rho_s S \rho_s S \rho_s T^{\uparrow} + \]
\[+ T^{\uparrow} \rho_s S \rho_s S \rho_s S \rho_s T^{\uparrow} + \]
\[+ \cdots \]

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14
This approximate solution is very useful in practice !!!
SATELLITE SIGNAL MODELLING

\[ p' (\theta_x, \theta_y, \phi_z) = t_g (\theta_x, \theta_y) \cdot \rho_a (\theta_x, \theta_y, \phi_z) + \frac{\tau (\theta_y)}{1 - \rho (M)} \cdot \rho_c (M) e^{-\tau (\mu_z)} + \rho (M) \cdot t_d (\theta_y) \]
RADIOMETRIC CALIBRATION

- Pre-launch radiometric calibration to traceable standard (accepted reference)
- Post launch calibration campaigns to maintain/monitoring in flight calibration (vicarious)
- On-board calibration (both radiometric and spectral)

CLOUD SCREENING

- Very dependent on the available spectral information
- Many different algorithms (from simple thresholds up to sophisticated techniques)
The atmosphere modifies the radiation measured by optical sensors:

- Aerosols and gases present optical activity at VIS/NIR/SWIR.
- Reflectance increases/decreases depending on the wavelength.
- Image loses contrast.

Removing the atmospheric influence from remote sensing data is necessary before the data exploitation.
Surface reflectance retrieval

- TOA radiance modeled assuming Lambertian reflectance for the target:

\[ L_{\text{TOA}} = L_0 + \frac{1}{\pi} \rho_s (E_{\text{dir}} t_{\text{il}} + E_{\text{dif}}) T_{\parallel} T_{\perp} \]

- Analytically invertible to retrieve \( \rho_s \):

\[ \rho_s = \frac{L_{\text{TOA}} - L_0}{[(E_{\text{dir}} t_{\text{il}} + E_{\text{dif}}) T_{\parallel} T_{\perp} + S(L_{\text{TOA}} - L_0)]} \]

- Removal of adjacency effects

INVERSION OF SURFACE REFLECTANCE

Flat Lambertian areas:

\[ \rho' = A + \frac{B \rho_c + C <\rho>}{1 - S <\rho>} \]

\[ \rho_c = \frac{(\rho' - A)}{B} + C + \frac{<\rho'> - A}{B + C} \]

Non-Lambertian areas with topographic structure:
- no analytic inversion under approximations
- decoupling ‘effective’ reflectances and ‘effective’ geometric terms required for environment
- multistep numerical procedure required for inversion
- multiple reflection terms only significant for high reflectance surroundings
### Permanent Constituents

<table>
<thead>
<tr>
<th>Constituent</th>
<th>% by volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen (N₂)</td>
<td>78.084</td>
</tr>
<tr>
<td>Oxygen (O₂)</td>
<td>20.948</td>
</tr>
<tr>
<td>Argon (Ar)</td>
<td>0.934</td>
</tr>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>0.033</td>
</tr>
<tr>
<td>Neon (Ne)</td>
<td>1.88 x 10⁻⁴</td>
</tr>
<tr>
<td>Helium (He)</td>
<td>1.24 x 10⁻⁴</td>
</tr>
<tr>
<td>Krypton (Kr)</td>
<td>1.24 x 10⁻⁴</td>
</tr>
<tr>
<td>Xenon (Xe)</td>
<td>0.89 x 10⁻⁴</td>
</tr>
<tr>
<td>Hydrogen (H₂)</td>
<td>0.8 x 10⁻⁴</td>
</tr>
<tr>
<td>Methane (CH₄)</td>
<td>1.3 x 10⁻⁴</td>
</tr>
<tr>
<td>Nitrous Oxide (N₂O)</td>
<td>2.7 x 10⁻⁴</td>
</tr>
<tr>
<td>Carbon Monoxide (CO)</td>
<td>0.19 x 10⁻⁴</td>
</tr>
</tbody>
</table>

### Variable Constituents

<table>
<thead>
<tr>
<th>Constituent</th>
<th>% by volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Vapor (H₂O)</td>
<td>0.04</td>
</tr>
<tr>
<td>Ozone (O₃)</td>
<td>12 x 10⁻⁶</td>
</tr>
<tr>
<td>Sulfur dioxide (SO₂)</td>
<td>0.001 x 10⁻⁶</td>
</tr>
<tr>
<td>Ammonia (NH₃)</td>
<td>0.001 x 10⁻⁶</td>
</tr>
<tr>
<td>Nitric acid vapor</td>
<td>trace</td>
</tr>
<tr>
<td>Nitric oxide (NO)</td>
<td>0.0005 x 10⁻⁶</td>
</tr>
<tr>
<td>Nitric oxide (NO₂)</td>
<td>0.0005 x 10⁻⁶</td>
</tr>
<tr>
<td>Sulfur dioxide (SO₃)</td>
<td>0.0005 x 10⁻⁶</td>
</tr>
</tbody>
</table>

* 4th ADVANCED TRAINING COURSE IN LAND REMOTE SENSING
1–5 July 2011 | Harokopio University | Athens, Greece
**Surface reflectance retrieval**

**Atmospheric correction:** Removal of the atmospheric effects from the measured at-sensor radiance, leading to the derivation of surface reflectance images.

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**ATMOSPHERIC INFORMATION**

**In-situ radiosoundings**

- Temperature
- Relative Humidity (%)
- Total Optical Depth
- Ozone

**In-situ spectral irradiance**

- Solar radiation (W m⁻² nm⁻¹)
- Relative Humidity (%)
- Temperature (°C)
- Ozone (ppb)
- Height (gpm)

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Topographic effects

$$L_{\text{TOA}} = L_0 + \frac{1}{\pi} \frac{\rho_b (E_{\text{dir}} \mu_{\text{dir}} + E_{\text{diff}}) T \uparrow}{1 - 8 \rho_b}$$

$$\mu_{\text{dir}} = n \cdot S \rightarrow \text{Cosine correction}$$

$$E'_{\text{diff}}(x, y, z) = E_{\text{diff}}(z) \left[ t_{\text{dir}}(z) \mu_{\text{dir}}(x, y) + \left| 1 - t_{\text{dir}}(z) \mu_{s} \right| \frac{1 + \mu_{s}(x, y)}{2} \right]$$

$$\rightarrow \text{Hay’s model}$$
SOIL REFLECTANCE

- dry soil
- wet soil

Reflectance vs. wavelength (μm)

- green vegetation (alfalfa)
- senescent vegetation (barley)
MERIS Terrestrial Chlorophyll Index (MTCI)

\[ MTCI = \frac{R_{\text{Band 10}} - R_{\text{Band 9}}}{R_{\text{Band 9}} - R_{\text{Band 8}}} \]
Optimized spectral indices

**Leaf chlorophyll**

\[ y = 3.1431x + 857, \quad R^2 = 0.5797 \]

![HYMAP data](image)

**Canopy water**

\[ y = 0.0359x + 0.347, \quad R^2 = 0.3789 \]


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Merit function:

Incorporation of the uncertainties in the inversion process

\[ \chi^2 = \left[ R_{\text{mes}} - R_{\text{mod}}(V) \right]^t W^{-1} \left[ R_{\text{mes}} - R_{\text{mod}}(V) \right] + \left[ V - V_p \right]^t C^{-1} \left[ V - V_p \right] \]

Use of constrained minimization procedures that guarantee the minimal variation of model variables to produce the same output, and a robust initialization procedure of such variables (consistency even if model has global bias).
Neural network methods

Training becomes the critical issue
Spatial information in the images
- Textures
- Higher order statistics

Multiresolution data
VIS/NIR/SWIR Colour Composite
Thermal data
1.25 m
3.75 m
12.0 m
QuickBird

counting individual trees by using Quickbird very high resolution imagery
Time series: Coupling canopy functioning and radiative transfer models for remote sensing data assimilation

MERIS and Landsat both provide time series at different spatial and temporal scales.
Stable calibration, adequate cloud screening and precise atmospheric corrections are needed for time series analysis.

ISSUES ABOUT VALIDATION OF RETRIEVALS

- Statistical representativity of measurements used for validation
- Strategy for spatial and temporal sampling
- Validation methodology versus retrieval technique
- Statistical extrapolation of results (sample versus population)
- Adaptation of different methodology for each biophysical parameter
- Examination of results in view of the expected limitations
- Adaptability to the application
- Critical review of actual achievements
Usage of the derived information:

- Tendency: from proxies to quantitative information
- Multi-resolution spatial inputs and time series

- **First approach**: Land cover mapping, classification and tables of biophysical variables assigned to each class
- **Second approach**: Retrievals of biophysical variables as direct inputs to models
- **Third approach**: direct assimilation of radiances/reflectances into models

REMOTE SENSING OF LAND SURFACE PROCESSES

- **Mapping Applications**
  - cartography
  - thematic mapping

- **Monitoring Applications**
  - ecosystems dynamics
  - natural hazards (fires, floods, desertification)

- **Research about Land Surface Processes**
  - heat and mass exchange at Land/Atmosphere interface
  - photosynthesis and net primary production
  - hydrologic processes
  - Land/Atmosphere exchange of biochemicals
HEAT, MASS AND MOMENTUM TRANSFER

- photosynthesis
- temperature

ECOSYSTEM DYNAMICS
- CO₂ fluxes
- NPP
- vegetation dynamics
- growth
- regeneration
- mortality

HYDROLOGICAL PROCESSES
- interception
- throughfall/surface flow
- snow hydrology
- infiltration/surface runoff
- soil water redistribution
- capillary rise/drainage
- irrigation
- lateral inflow

ECOSYSTEM PROCESSES
- soil processes
- decomposition
- mineralization

<1 - 300 meters
- Local site
- Global sampling

10 km to global

SPATIAL SCALES TO BE RESOLVED

1. LSM model
- radiative transfer
- sensible/lateral heat
- snowmelt
- temperature

2. Biophysical fluxes
- photosynthesis, temperature

3. Hydrological processes
- lateral inflow
- surface/sub-surface transport
- river flow
- lake/wetland/glacier dynamics

4. Ecosystem dynamics
- CO₂ fluxes
- NPP
- vegetation dynamics
- growth
- regeneration
- mortality

5. Chemical exchanges
- CO₂
- CH₄
- NMHC
- H₂O

6. Bioschemical fluxes
- maintenance respiration
- growth respiration
- microbial respiration
- net primary production

7. Local site
- Global sampling
- 10 km to global
- 1 - 300 meters

8. Spatial scales to be resolved

- 10 km to global
- 1 - 300 meters

- Local site
- Global sampling

- 4th Advanced Training Course in Land Remote Sensing
- 1-5 July 2013 | Harokopio University | Athens, Greece
3 - 10 days

TIME SCALES TO BE RESOLVED

> 3 years

Process modeled

- Photosynthesis and leaf respiration
- Growth respiration and stem and root maintenance respiration
- Allocation
- Phenology
- Nitrogen cycle
- Competition between plant functional types (PFTs)

Extent to which vegetation acts as a dynamic component

- Stomata respond to variability in environmental conditions and CO₂ concentration when coupling between photosynthesis and stomatal conductance is explicitly modeled
- Estimating respiration allows us to model NPP
- Biomass allocated to leaves determines LAI. LAI thus varies with changes in climate conditions from year to year, and the seasonal cycle of LAI can be simulated rather than being prescribed
- The timing of leaf onset and offset is modeled rather than prescribed
- Explicitly modeling N cycle and plant N uptake implies that if availability does not have to be assumed constant. The effect of variability in N availability on plant productivity can thus be modeled
- Vegetation reacts to long-term changes in climate, and PFTs, which are best suited for a given region and climate, succeed

Timesteps at which processes are modeled

- Minutes to months
- Minutes to months
- Daily to annual
- Daily to monthly
- Monthly to annual
- Decades to centuries

Requires very large time series

EO Applications

- Calibration & Validation
- Vegetation monitoring
- Agriculture
- Forestry
- Water quality
- Climate change
- Damage Assessment
- Cartography

Methods

- Physical models
- Instrument design
- Image processing and analysis
- Automatic classification
- Analysis of time series
- Biophysical parameter estimation
- Data fusion
NEW GENERATION OF SENSORS

- Well calibrated (more suitable for multitemporal studies)
- Increased spatial resolution (0.5 m PAN now available)
- Increased spatial coverage (global mapping in high spatial resolution (as ESA GMES/Sentinel-2))
- New type of information (i.e., vegetation fluorescence)
- Time series: gap filling using multi-sensor data, better temporal resolution with high spatial resolution
- Integration of multi-resolution data with diverse spectral information in common temporal databases