Physics of Remote Sensing

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Outline

• Major remote sensing configurations and remote sensing (RS) images.

• Sun radiation reflexion: - Radiometric variables & Components of TOA radiance
  - Hot spot, penumbra, 2D display of reflectance, albedo

• Thermal emission: Radiometric quantities and Components of TOA radiance

• Interpretation of VIS/IR/TIR satellite images: angular anisotropy, spectral wealth,...

• Hyperspectral remote sensing: mixels, end-members,...

• Satellite / airborne sensors with finite FOV

• LiDAR
Very often, analysis of RS signal without any physics understanding is dangerous...

**Approach:**
- To introduce physics with examples
  ⇒ simple questions not always so simple...
  ⇒ thank you for participating
- To illustrate RS physics with RS model (DART)
  (www.cesbio.ups-tlse.fr/dart)
  ⇒ DART input parameters represent major RS atmosphere / Earth surface parameters

**Objective:** to explain remote sensing signals with physics, and remote sensing models
Spectrum, atmosphere transmittance and Sun / Earth thermal emission

TOA irradiance (Kurucz)
Blackbody: 5900K and 6000K
(at sun distance)

BOA irradiance:
(Atmosphere US Standard - No aerosols)

O3, O2, H2O, H2O, H2O, CO2

Modtran - US Standard model

Total
H2O
CO2
O3

X-Rays | Ultraviolet | Near IR | Thermal IR | Far IR | Microwave | Radio
0.01µm | 0.1µm | 1µm | 10µm | 100µm | 1mm | 10mm | 100mm | 1m | Wavelength
10^{16} | 10^{15} | 10^{14} | 10^{13} | 10^{12} | 10^{11} | 10^{10} | 10^{9} | Frequency (Hz)

W/m²/µm
Remote sensing configurations in the optical domain ($\lambda \in [0.25\mu m \ 100\mu m]$)

Radiometer $L_{\lambda}(\Omega_s, \Omega_v)$

Lidar (WF, PC) $w_{\lambda}(\Omega_s, \Omega_v, t)$

$\rho_{\lambda}(\Omega_s, \Omega_v)$

$T_{B,\lambda}(\Omega_v)$

3D radiative budget

Any Earth landscape
**Orbits of Earth observation satellites**

- **Equatorial orbit**
- **Polar orbit**

**Nearly polar sun-synchronous orbit:** every 3 hours: MODIS, Landsat (500km-1500km)

**Non sun-synchronous orbit:** IceSat (LiDAR)  
**Geostationary orbit:** Meteosat, etc. (36 000km)
Remote sensing raster image

Multi-spectral image.

$\text{DN}_k(i,j)$ is the digital number of pixel $P_k(i,j)$

Images (i.e., DNs) are displayed with LUTs: grey/color tone = $f(\text{DN})$

High res commercial data galleries
- http://www.digitalglobe.com/
Cross track scanner: whiskbroom

Scan rate: $2 \times 10^{-2}$ s per scan line

IFOV: 1 mrad

Altitude 10 km

FOV 90°

X axis

Ground resolution cell 10 m x 10 m

20 km 2000 cells

Dwell time $\Rightarrow$ Signal to noise ratio (SNR)

$$\Delta t = \frac{\text{Scan rate per line}}{\text{Number cells per line}} = \frac{2 \times 10^{-2}}{2000 \text{ cells}} = 10^{-5} \text{s/cell}$$

$$\Delta t = \frac{\text{Cell dimension}}{\text{Velocity}} = \frac{10 \text{ m per cell}}{200 \text{ m/s}} = 5 \times 10^{-2} \text{s per cell}$$
What is the spatial resolution (GIFOV) of the sensor?
Remote sensing (RS) of Earth surfaces: **sensors that measure radiation**

### Variety of satellite / airborne sensors

- Passive sensors (multi/hyper spectral radiometers):
  - sun radiation reflected by Earth surfaces
  - radiation that is thermally emitted by Earth surfaces
- Active sensors: LiDARs and Radars (not considered here)

### Very diverse information

- Vegetation: biochemistry (Chl, H$_2$O, ...), spatial extent, ...
- Soil: humidity, temperature, chemistry, altitude, ...
- Water: temperature, salinity, roughness, ...

### Many applications:
- Biosphere functioning,
- Cartography & Topography,
- Agriculture (irrigation, crop forecast, ...),
- Oceanography,
- Forestry,
- Environment (fires, floods, ...), ...

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**Seasonal evolution of vegetation**

**Sea level trend:** 3.14 mm/year

**Disks:** crops + circular irrigation
Signatures of Earth surfaces vs. Resolutions in remote sensing images

Information about Earth surfaces to derive from remote sensing signals:

- **Spectral signature**: signal variation with wavelength ⇔ spectrometers
- **Angular signature**: signal variation with view (sun) direction ⇔ multi-view sensor,...
- **Spatial signature**: signal variation with space ⇔ high / mid spatial resolution
- **Temporal signature**: signal variation with time ⇔ sensor acquisition repetitivity
- **Architecture / distance signature**: backscattering of LiDAR pulse
- **Fluorescence emission** (specific spectral bands), **polarization**, etc.

Several resolutions: - **Radiometric resolution**
  - **Spatial resolution** GIFOV (IFOV + altitude) ≠ pixel dimension
  - **Spectral resolution**
  - **Temporal resolution**
Importance of sensor characteristics and configuration

- Radiometric resolution
- Sun / Sensor configuration
- Spatial resolution,
- Spectral domain/resolution,
- Time resolution.

AVIRIS images: forest clearing fire (Cuiaba, Brazil, 25/08/1995)

- Fire signal low at 1µm and large at 2.5µm. Why?
- Earth surfaces: very low signal at 2.5µm. Why?
Perception vs. spectral domain: GOES 12 Sounder ⇒ Brightness temperature at several altitudes

- Signal is null in the visible band (0.65µm). Why?
- In thermal infrared (TIR) bands:
  - The low (-50C) and large (20C) signals (brightness temperature $T_B$) correspond to?
  - The atmosphere thermal emission changes with spectral band (*i.e.*, lower/higher $T_B$). Why?
Perception vs. spectral domain and passive vs. active sensor: G-LIHT images (NASA)

### Airborne G-LIHT sensor:

<table>
<thead>
<tr>
<th>Scanning lidar</th>
<th>387 m (60°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swath width/FOV</td>
<td>10 cm (0.3 mrad)</td>
</tr>
<tr>
<td>Footprint diameter</td>
<td>5 cm (2 σ)</td>
</tr>
<tr>
<td>Range precision</td>
<td>6 pulses m⁻²</td>
</tr>
<tr>
<td>Sampling density at surface</td>
<td>Max. returns per pulse</td>
</tr>
<tr>
<td>Acquis. rate</td>
<td>8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Irradiance spectrometer</th>
<th>hemispheric (180°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swath width/FOV</td>
<td>350 to 1,100 nm</td>
</tr>
<tr>
<td>Spectral range</td>
<td>1.5 and 1.5 nm</td>
</tr>
<tr>
<td>Sample/Band width</td>
<td>1 Hz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Imaging spectrometer</th>
<th>310 m (50°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swath width/FOV</td>
<td>1,004</td>
</tr>
<tr>
<td>Cross track pixels</td>
<td>420 to 950 nm</td>
</tr>
<tr>
<td>Sample/Band width</td>
<td>1.5 and 5.0 nm</td>
</tr>
<tr>
<td>Acquisition rate</td>
<td>50 Hz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thermal camera</th>
<th>173 m (30°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swath width/FOV</td>
<td>384 × 288</td>
</tr>
<tr>
<td>Imaging array size</td>
<td>8 to 14 μm</td>
</tr>
<tr>
<td>Sensitivity (NETD)</td>
<td>&gt;50 mK at 30°C</td>
</tr>
<tr>
<td>Acquisition rate</td>
<td>25 Hz</td>
</tr>
</tbody>
</table>

- Why brightness temperature is larger for grass than for trees?
- How 3D vegetation is obtained?
- What is LiDAR apparent $\rho$?
- What is the usefulness of the irradiance spectrometer?
- **Solid angle** $d\Omega$ of direction $\Omega(\theta,\phi)$: $d\Omega = \sin \theta \cdot \cos \phi \cdot d\theta \cdot d\phi$ with $\theta$ = zenith and $\phi$ = azimuth

- **Radiance** $L_\Sigma(\Omega)$ of $\Sigma$ along $(\Omega)$: $L_{\Sigma,\lambda}(\Omega)$ W/m²/sr/µm (/ effective m²!), $L_{\Sigma,\Delta\lambda}(\Omega)$: W/m²/sr

- **Irradiance** $E_\Sigma$ of $\Sigma$ (in flux): $E_{\Sigma,\lambda} = \int L_{\Sigma,\lambda}(\Omega) \cdot |\cos \theta| \cdot d\Omega$ W/m²/µm $E_{\Sigma,\Delta\lambda} = \int L_{\Sigma,\Delta\lambda}(\Omega) \cdot |\cos \theta| \cdot d\Omega$: W/m²

- **Exitance** $M_\Sigma$ of $\Sigma$ (out flux): $M_{\Sigma,\lambda} = \int L_{\Sigma,\lambda}(\Omega) \cdot \cos \theta \cdot d\Omega$ W/m²/µm $M_{\Sigma,\Delta\lambda} = \int L_{\Sigma,\Delta\lambda}(\Omega) \cdot \cos \theta \cdot d\Omega$: W/m²

- **Reflectance factor** $\rho_\Sigma(\Omega)$ of $\Sigma$ along $(\Omega)$: $\rho_{\Sigma,\lambda}(\Omega) = \frac{\pi \cdot L_{\Sigma,\lambda}(\Omega)}{E_{\Sigma,\lambda}}$ if $\Sigma$ is lambertian: $\rho_{\Sigma,\lambda}(\Omega) = \text{cst}$

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What is the physical quantity that is measured by a satellite radiometer?
Different reflectance factors (direct $d$, hemispherical $h$, conical $c$)

- **In or Out 'direct'** flux (index $d$): flux along a unique direction (i.e., $d\Omega=0$).

- **In or Out 'conical'** flux (index $c$): flux within a cone ($\Omega$, $d\Omega\neq 0$).

- **In or Out 'hemispherical'** flux (index $h$): flux within an hemisphere (i.e., $d\Omega=2\pi$).

Which reflectance is derived from the measurement of a satellite radiometer?
Which reflectance is used for computing the albedo of our planet?
Satellite image acquisition and display

Landscape: grass, house
Atmosphere
Sun (upward): $\theta_s = 30^\circ$, $\phi_s = 330^\circ$
Satellite: - nadir view direction
- 3 bands: B, G, R

Sun at nadir: what are the zenith and azimuth angles?

RGB Color Composite

DART simulations
**Satellite image acquisition and display**

Landscape: grass, house
Atmosphere
Sun: $\theta_s = 30^\circ$, $\phi_s = 330^\circ$
Satellite: - nadir view direction
- 3 bands: G, R, NIR

False Color Composite
Spatial resolution and radiometry

- 0.5m resolution
- 1m resolution
- 2m resolution
- 5m resolution
- 10m resolution

Red spectral band
- Spatial sampling
  ⇒ Change of DNs
TOA (Top of Atmosphere) and BOA (Bottom of Atmosphere) acquisitions

- Nadir view direction
- \((\theta_v=22^\circ, \phi_v=30^\circ)\) view direction
- \((\theta_v=22^\circ, \phi_v=330^\circ)\) view direction

Why TOA images are bluish?

- Atmosphere characteristics (atmosphere model), sun direction, etc.

Proportion of observed shadows can vary a lot with view direction
⇒ Anisotropy of RS signal
Satellite signal (TOA radiance) $L_{TOA,\lambda}(\Omega) - \text{short wavelengths}$

$L_{TOA,\lambda}(\Omega) = \text{"Radiance } L_{Earth,TOA,\lambda}(\Omega) \text{ due to scattering of sun flux by the Earth, only"}$

$+ \text{"Radiance } L_{atm,TOA,\lambda}(\Omega) \text{ due to scattering of sun flux by the Atmosphere, only"}$

$+ \text{"Radiance } L_{mult,TOA,\lambda}(\Omega) \text{ due to scattering of sun flux by \{Earth + Atmosphere\}"}$
The hot spot (backscattering effect): examples

Hot spot: sensor view direction = sun direction $\Rightarrow$ maximal reflectance

[Images of different landscapes with hot spot examples]

From Donald Deering
Reflectance of lambertian and natural surfaces

Lambertian surface: $\rho_{dd} = \rho_{dh} = \rho_{hd} = \rho_{hh} = \text{cst.}$

- White lambertian surface: $\rho = 1$
- Grey lambertian surface: $\rho = \text{cst} < 1$.

Natural surface: $\rho_{dd}(\Omega)$ varies with $(\Omega)$. Here, $\rho_{dd}$ is maximal for specular direction (water?) with local maximum (vegetation?) for sun direction (hot spot: the sensor does not see shadow)

How can there be hot spot? Indeed, a sensor with the sun behind it should see its own shadow...
Sun rays are not parallel
⇒ shadow is total at short distance and more and more partial as distance increases

100% shadow

Penumbra (partial shadow)

Why do not we see the shadows of satellites and planes on the Earth surfaces?

Actual sun rays: $\Delta \Omega_{\text{sun}} = 32'$

Parallel sun rays

DART simulation

Obstructing object (leaf,...)
For large view zenith angles $\theta_{\text{view}}$, vegetation reflectance increases in near infrared (top) and decreases in the visible (bottom). Which simple landscape (tree + bare ground) can explain it?
**Albedo** ($A_{dh}$ or $A_{hh}$): integral of reflectance $\rho_\lambda(\Omega_s, \Omega_v)$ weighted by incident flux $L_\lambda(\Omega_s)$ over scattering directions ($2\pi^+$) and all / part of the spectrum.

$$A_{dh}(\Delta\Omega_s=0, \Delta\lambda) = \frac{\text{Exitance: reflexion over } 2\pi^+}{\text{Irradiance (d) along } \Omega_s} = \frac{1}{\pi} \frac{\Delta\lambda}{\Delta\lambda} \int \hat{\rho}_{dd}(\Omega_s, \Omega_v, \lambda) \cdot \mu_v \cdot E_\lambda(\Omega_s) \cdot \mu_s \cdot d\Omega_v \cdot d\lambda$$

with $\Delta\lambda \approx [0.2 \ 4 \ \mu m]$

At the Earth surface, one uses often: 

$$A_{hh}(2\pi^+, \Delta\lambda) = \frac{\text{Exitance: reflexion over } 2\pi^+}{\text{Irradiance (h) along } 2\pi^+}$$

<table>
<thead>
<tr>
<th>Material</th>
<th>Albedo (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Planet Earth</strong></td>
<td></td>
</tr>
<tr>
<td><em>Cloud (stratus)</em>:</td>
<td></td>
</tr>
<tr>
<td>- depth $&lt; 200 \ m$</td>
<td>$\approx 33 \ (\approx 36 \text{ for Visible domain})$</td>
</tr>
<tr>
<td>- depth $[200 \ 1000 \ m]$</td>
<td>$5 - 65$</td>
</tr>
<tr>
<td><em>Snow:</em> fresh and dry / old</td>
<td>$30 - 85$</td>
</tr>
<tr>
<td><em>Ground:</em> white sand</td>
<td>$75 - 90 / 45 - 70$</td>
</tr>
<tr>
<td>- dark moist / dry</td>
<td>$35 - 40$; increases from blue to red</td>
</tr>
<tr>
<td><em>Vegetation:</em> green crop / forest</td>
<td>$5 - 6 / 5 - 15$; increases from blue to red</td>
</tr>
<tr>
<td><em>Water:</em> sun zenith 0°/30°/60°/70°/80°/85°/&gt;87°</td>
<td>$5 - 15 / 10$; maximum in the green</td>
</tr>
<tr>
<td></td>
<td>$2 / 2.2 / 6 / 13.4 / 35.8 / \approx 60 / &gt;90$</td>
</tr>
</tbody>
</table>

*Very variable albedo /reflectancevalues*
Planck's law: \( L_{B,\lambda}(\Omega) = \frac{2hc}{\lambda^5} \left( e^{\frac{hc}{\lambda kT}} - 1 \right) \) (W/m\(^2\)/sr/m) with \( h = 6.63 \times 10^{-34} \) J.s, \( k = 1.3807 \times 10^{-23} \) J/K

Wien law: \( M(\lambda) \) is maximal for \( \lambda_m = \frac{a}{T} \) (a=2899 \( \mu \)m.K)

Stephan-Boltzmann law: \( M = \int_{0}^{\infty} \lambda B_{\lambda} d\lambda = \sigma T^4 \), with \( \sigma = 5.6704 \times 10^{-8} \) W/m\(^2\)/K\(^4\)

Emissivity \( \varepsilon(\lambda,T,\Omega) \): natural body \( \Rightarrow L_{\lambda}(T,\Omega) = \varepsilon(\lambda,T,\Omega) L_{B,\lambda}(T) \), with \( \varepsilon(\lambda,T,\Omega) = 1 - \rho_{hd}(\lambda,T,\Omega) \)

Brightness temperature \( T_B \): temperature of the blackbody that emits the measured radiance \( L_m \)

\[ L_{m,\lambda}(\Omega) = L_{B,\lambda}(T_B) \Rightarrow T_B = L_{B,\lambda}^{-1}(L_{m,\lambda}(\Omega)) = f(\lambda,T,\Omega) \]
Satellite signal (TOA radiance) $L_{\text{TOA,}\lambda}(\Omega)$ - long wavelengths

$\text{TOA: Top of the Atmosphere}$

$\text{BOA: Bottom of the Atmosphere}$

$L_{\text{TOA,}\lambda}(\Omega) =$ "Radiance $L_{\text{Earth,TOA,}\lambda}(\Omega)$ due to thermal emission by the Earth, only"

+ "Radiance $L_{\text{atm}^\uparrow,\text{TOA,}\lambda}(\Omega)$ due to thermal emission by the Atmosphere, only"

+ "Radiance $L_{\text{atm}^\downarrow,\text{TOA,}\lambda}(\Omega)$ due to Earth scattering of Atmosphere thermal emission"

+ "Radiance $L_{\text{sun},\text{TOA,}\lambda}(\Omega)$ due to {Earth, Atmosphere} scattering of sun radiation"

$(L_{\text{sun},\text{TOA,}\lambda}(\Omega) = 0$ at night, and usually neglected for $\lambda > 4\mu\text{m}$)
Why does the atmosphere emit radiation in spectral regions where its transmittance is small?
Why does the "apparent" (brightness temperature) of the Earth change with wavelength?
TOA and BOA sun spectral irradiance

-W/m²/µm

TOA irradiance (Kurucz)

- - - Blackbody: 5900K, 5800K

O₃, H₂O, O₂, O₃, H₂O absorption line

Sun absorption line

Atmosphere absorption line
Detector configurations: breaking up the spectrum

- **Discrete detectors and scanning mirrors**
  MSS, TM, ETM+, GOES, AMS, AVHRR, SeaWiFS, ATLAS

- **Linear Arrays**
  SPOT, IRS, IKONOS, ASTER, ORBIMAGE, Quickbird, MISR

- **Linear and area arrays**
  AVIRIS, CASI, MODIS, ALI, Hyperion, LAC
For which wavelengths can we consider that TOA radiance is mostly due to either Earth surface scattering or thermal emission?
How the influence of atmosphere does change with ($\theta_v, \theta_s, V$, etc.)?
For all surfaces, with $\lambda < 0.55\mu m$, $\rho_{TOA} > \rho_{BOA}$. Why?

Why: - Ground: $\rho_{TOA,g} > \rho_{BOA,g}$ for $\lambda < 0.55\mu m$, and $\rho_{TOA,g} < \rho_{BOA,g}$ for $\lambda > 0.65\mu m$,
- Water: $\rho_{TOA,w} > \rho_{BOA,w}$ at all wavelengths.
Sky illumination: nadir image of a tropical forest (Sumatra, Indonesia) with 2 sky illuminations

\[ \text{Sky illumination: nadir image of a tropical forest (Sumatra, Indonesia) with 2 sky illuminations} \]

**DART simulations**

a) SKYL = 0, \( \theta_s = 35^\circ \). b) SKYL = 1. SKYL = \( \frac{\text{Atmosphere irradiance}}{\text{Total irradiance}} \). Simulations with DART model.

Does a SKYL increase, makes the reflectance of Earth surfaces larger, more anisotropic?
View direction: **POLDER** (Polarization and Directionality of Earth Reflectances) - **114° FOV, 6km**

The anisotropy of the Earth surfaces reflectance $\rho$ strongly affects TOA radiance. $\rho$: described by BRF or Bidirectional Reflectance Distribution Function (BRDF) BRF = function of sun direction $(\theta_s, \phi_s)$ & view direction $(\theta_v, \phi_v)$. In practice: $\rho(\theta_s, \theta_v, \phi_s-\phi_v)$

(E. Vermote, C. Justice and Breon, NASA supported Land LTDR Project)
Which elements do have the larger reflectance value (reddish tones)?

Why does reflectance change with view direction with a maximum in the forward direction?
For which configuration, a schematic landscape {bare ground + trees} has a strongly anisotropic reflectance with a maximum at nadir. Same, with minimum at nadir.
MODIS daily VIS / NIR surface reflectance: south Africa tropical savanna, 2000-2004

Not normalized reflectance

+ Near infrared
x Visible

Normalized reflectance
(using BRDF model calibrated with POLDER data)
⇒ Reflectance accuracy is much improved

Does the variability of Earth surface reflectance increase or decrease if satellite spatial resolution coarsens?

(E. Vermote, C. Justice and Breon, NASA supported Land LTDR Project)
Reflectance anisotropy with view direction: verification with RS model

**Old Black Spruce**

- **Dart Simulations: NIR**

Hot spot ($\rho_{\text{PIR}} \approx 0.287$, $\theta_v = 35^\circ$, $\phi_v = 0^\circ$)

Nadir ($\rho_{\text{PIR}} \approx 0.147$, $\theta_v = 0^\circ$)

纯净角度：$\theta_s = 35^\circ$, $\phi_s = 0^\circ$

Reflectance varies from 0.147 to 0.287!!!
Reflectance and albedo anisotropy with sun direction: verification with RS model

Nadir reflectance and albedo values can differ a lot. Hence, to approximate the Earth surface albedo as a directional reflectance value can be erroneous.
Spectral analysis: reflectance (ground, water, vegetation) and extinction coefficient (water)

Adapted from Szekielda (1988)
Hypotheses: same water in ocean & lagoon, vegetated islands.

Why:
- Ocean: dark tone in 3 images (darker in NIR image)?
- Island: dark tone in "green" & "red", and light tone in "NIR"?
- Foam: light tone in 3 images, conversely to water surfaces?
- Lagoon: light tone in "red" band, conversely to the ocean?
Foam scattering: large reflectance due to multiple scattering
**Objective**: to manipulate extinction coefficient $\alpha_e$ and Beer law $e^{-\alpha_e \Delta l}$ along path $\Delta l$

Total reflectance: $\rho = \rho_{\text{white surface}} \cdot e^{-\alpha_e \Delta l} = \rho_{\text{white surface}} \cdot e^{-\alpha_e 2H}$

<table>
<thead>
<tr>
<th>Depth H (µm)</th>
<th>0.5 - 0.6 µm</th>
<th>0.6 - 0.7 µm</th>
<th>0.7 - 0.8 µm</th>
<th>0.8 - 1.1 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 m</td>
<td>$\rho = 92%$</td>
<td>$\rho = 55%$</td>
<td>$\rho = 9%$</td>
<td>$\rho = 0.2%$</td>
</tr>
<tr>
<td>5 m</td>
<td>$\rho = 67%$</td>
<td>$\rho = 5%$</td>
<td>$\rho = 0%$</td>
<td>$\rho = 0%$</td>
</tr>
</tbody>
</table>

$\alpha_e$ (m$^{-1}$) | 0.04 | 0.30 | 1.2 | 3.1 |

Compute reflectance $\rho$ for a sun direction with a zenith angle equal to 60°

$\theta_s = 60°$

<table>
<thead>
<tr>
<th>Depth H (µm)</th>
<th>0.5 - 0.6 µm</th>
<th>0.6 - 0.7 µm</th>
<th>0.7 - 0.8 µm</th>
<th>0.8 - 1.1 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 m</td>
<td>$\rho = 89%$</td>
<td>$\rho = 68%$</td>
<td>$\rho = 28%$</td>
<td>$\rho = 4%$</td>
</tr>
<tr>
<td>5 m</td>
<td>$\rho = 55%$</td>
<td>$\rho = 15%$</td>
<td>$\rho = 0.17%$</td>
<td>$\rho = 1E-07%$</td>
</tr>
</tbody>
</table>

$\rho = \rho_{\text{white surface}} \cdot e^{-\alpha_e H} \cdot e^{-\alpha_e \frac{H}{\cos(60°)}}$
Why:
- Sumatra has dark tones in the VIS image and light tones in the NIR image?
- Clouds have light tones in the VIS image and dark tones in the "3-4µm" image
- In the VIS image, the bright spot below South Sumatra is not a cloud. What is it?
**Hyperspectral sensor**: simultaneous acquisition of spatially co-registered images, in many spectrally contiguous bands, measured in calibrated radiance units, from a remotely operated platform (Schaepman *et al.* 2006)

Many contiguous narrow spectral bands are necessary for sampling correctly landscape spectral features of interest, typically absorption bands.

Conceptual imaging spectrometer data cube: 2 spatial \((x, y)\) and 1 spectral \((\lambda)\) domains. Typically acquired by a whiskbroom scanning system.  
- a) The data cube.  
- b) 1 scan line.  
- c) 1 pixel.  
- d) Pixel, spectral image and scan line.  
- e) Actual data cube.
Future hyperspectral satellite sensors: HYSPIRI, ENMAP, HypXIM, etc.

Typical spectra with absorption bands.

a) Vegetation at different growth stages.

b) Minerals.
Spectral analysis: Optical properties of Earth surface elements

- **Different acquisition configurations:**
  - **Illumination & view:** $\rho_{dd}(\lambda)$, $\rho_{hd}(\lambda)$, ...
  - **State of material:** grinded/dried ground, stack of leaves, etc.
Absorption spectra of foliar pigments
GOME-2

HyspIRI

EnMAP

HYPXIM

ASD

≈ 5km

≈ 60m

≈ 30m

≈ 10m

≈ 1m
Future hyperspectral satellite sensors: HYSPIRI, ENMAP, HypXIM, etc.

**Hyspiri (2019?)**

- **Imaging Spectrometer (VSWIR)**
  - 380 to 2500nm in ≤10nm bands
  - 60 m spatial sampling*
  - 19 days revisit*
  - Global land and shallow water

- **Thermal Infrared (TIR):**
  - 7 bands in 7.5-12µm + 1 band in 3-5µm
  - 60 m spatial sampling
  - 5 days revisit; day/night
  - 3-5 µm band saturates at 1400K
  - 7.5-12 µm bands saturate at 400K

**EnMap (2018?)**

Pointing range: 30° from nadir
IFOV: 7.45” (30m x 30m au nadir);
FOV: ±1.06° (30km)
Waveband: - VNIR: 420 - 1030 nm (96 bands)
  - SWIR: 950 – 2450 nm (122 bands)
Spectral sampling: - VNIR: 5 nm to 10 nm
  - SWIR: 10 nm
Noise equivalent variance (mW/cm²/sr/µm):
  - 420 - 1030nm : 0.005
  - 900-1760nm: 0.003
  - 1950-2450nm: 0.001

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<thead>
<tr>
<th>Domain</th>
<th>Spectral range</th>
<th>Spectral resolution</th>
<th>Pixel size</th>
<th>SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIS</td>
<td>400nm – 700nm</td>
<td>10nm</td>
<td>8m</td>
<td>≥250</td>
</tr>
<tr>
<td>VNIR</td>
<td>700nm – 1100nm</td>
<td>10nm</td>
<td>8m</td>
<td>≥200</td>
</tr>
<tr>
<td>SWIR</td>
<td>1100nm – 2500nm</td>
<td>10nm</td>
<td>8m</td>
<td>≥100</td>
</tr>
<tr>
<td>PAN</td>
<td>400nm – 800nm</td>
<td>400nm</td>
<td>2m</td>
<td>≥90</td>
</tr>
</tbody>
</table>
How to detect the absorption features in an hyperspectral pixel spectrum $\alpha(\lambda)$?

The continuum removal technique breaks down $\alpha(\lambda)$ into smooth spectrum $\beta$ (continuum: lines joining local reflectance maxima) and narrow band features $\gamma = \alpha - \beta$.

Then, a spectral matching technique can compare $\gamma(\lambda)$ to standard feature spectra.

A pixel can include several materials (e.g., A, B). Then, it has a mixed spectrum $\rho_p(\lambda)$. An usual objective is to assess the material spectra ($\rho_A(\lambda), \rho_B(\lambda),...$) and fractions. Components that correspond to spectra $\rho_A(\lambda), \rho_B(\lambda),...$ are called "end members".

The approach is called: "unmixing", possibly linear ($\rho_p(\lambda) = \sum_{i=1}^{I} a_i \cdot \rho_i(\lambda)$) or not.
Photosynthesis and Fluorescence

Photosynthesis:
- Plants use sunlight, water, nutrients and CO₂ to produce energy-rich biomolecules
- The mechanism for plant growth / productivity, and, thus, energy / mass exchange.
- Light is absorbed by plant photosynthetic pigments (Chl, Ca) in photosystems I & II
- The efficiency (≈3-6%) with which absorbed light is converted into biochemical energy and energy-rich carbohydrates is an indicator of the plant functional status.
- Water deficit, temperature,... perturb the operation of the 2 photosystems.

![Chemical Energy + Carbon Dioxide = Sugar](image-url)
Non photochemical energy is dissipated by heat transfer and fluorescence. It depends on plant stress.

Theoretical fluorescence of photosystems I and II.

Measured fluorescence of 2 vegetation covers. Valencia University.
Under optimal conditions, ≈86% of absorbed radiation is used for carbon assimilation (photochemistry). Remaining energy is lost as heat and dissipated as fluorescence.

Energy dissipation with fluorescence is directly related to plant stress

⇒ Fluorescence = indicator of plant health
⇒ Valuable tool for surveying / managing vegetation (crops, etc.).
⇒ Next FLEX satellite mission of ESA

Canopy fluorescence differs from leaf fluorescence

⇒ Need of RS model to simulate "leaf fluorescence" + "vegetation 3D architecture"

RS signal = Fluorescence signal + Sun reflected radiation.

In order to assess fluorescence, one considers the ratio of narrow spectral bands inside and on the edge of very narrow absorption bands of the atmosphere ($O_2$-A: 760nm, $O_2$-B: 688.4nm,...) or of the sun corona (Fraunhofer lines).

⇒ Fluorescence detection requires hyperspectral sensors.
Physical bases about radiation: Radiative transfer and landscape models

Classical equation to track radiation in 3D media: the Radiative Transfer Equation (RTE)

$$\bar{\Omega}.\bar{\nabla}L(r, \Omega) = -\alpha(r, \Omega).L(r, \Omega) + \int_{4\pi} L(r, \Omega').\alpha_d(r, \Omega' \rightarrow \Omega).d\Omega' + \xi_{emis}(r, \Omega)$$

3D media: no analytic solution of RTE $\Rightarrow$ **Numeric solution**

$\Rightarrow$ **Simplified implementation of RTE**: 2 fluxes, 4 fluxes, ..., N fluxes, ...

$\Rightarrow$ **Simplified landscape simulation**: horizontal turbid layer, ...,
3D objects with many triangles are unmanageable ⇒ Transformation turbid 3D objects

Example: Transformation of a "triangle" tree (left) into a "turbid" tree with 2 spatial resolutions: $\Delta x = \Delta y = \Delta z = 0.5\text{m}$ (center) and $\Delta x = \Delta y = \Delta z = 0.05\text{m}$ (right)
Dual approach (turbid + "triangle") for simulating Earth surface elements

Triangle trees

Turbid trees derived from triangle trees can give realistic images

Turbid trees

DART RGB color composite (turbid trees)
Presentation of DART: Facets or turbid?

Triangles trees

Turbid trees from triangle trees ($\Delta r = 0.125m$)

Image with turbid trees can be very similar to images with triangle trees
DART presentation: To simulate a landscape with which spatial resolution?

2D plots of directional reflectance

- Turbide: ΔX = 0.125
  - RMSE = 0.00225
- Turbide: ΔX = 0.25
  - RMSE = 0.00207
- Turbide: ΔX = 0.5
  - RMSE = 0.00304
- Turbide: ΔX = 1
  - RMSE = 0.00519
- Turbide: ΔX = 5
  - RMSE = 0.01189
- Turbide: ΔX = 10
  - RMSE = 0.01267
Simulation of scenes: Example of DART images (scene = simulated + imported objects)

1 DART simulation ⇒ camera / scanner (satellite, plane, ground) images for all defined view directions

DART Earth scene: tree, car, plane, house

Oblique image: sensor frame

Nadir image

Ortho-image

$L_{x,y,ortho} = 0$: unseen for oblique direction
Simulating images of radiometers with finite FOV (perspective projection)

Sensor at infinite distance:
parallel projection ⇒ $\Phi_{\text{crown}} = \Phi_{\text{shadow}}$

Camera: perspective proj ⇒ $\Phi_{\text{crown}} > \Phi_{\text{shadow}}$

Pushbroom/scanner: parallel + perspective projection
Example of geometric distortion: Basilica St-Sernin (Toulouse, France)

Identical objects in a simulated landscape appear differently, depending on view configuration (distance, view angle)

Toulouse urban data base    -   DART scene

DART simulated images

Parallel projection (satellite, $\theta_v=50^\circ$, $\phi_v=0^\circ$)    Perspective projection (UAV camera, $z_s=140m$)
The DART model: dual approach (turbid + "triangle") for simulating Earth surface elements

Oblique image of St Sernin district, Toulouse, France (RGB color)
Radiance variability due to geometry: fish eye camera VIS/TIR images (Toulouse)

Why does radiance change with view direction in the VIS/NIR? In the TIR?

RGB color composite - Thermal infrared camera image
  (DART simulated images)
Pushbroom hot spot effect at different altitudes

Sun direction:
$\theta_s = 36.6^\circ$, $\phi_s = 299.06^\circ$

Platform path dir

$\theta_{vp}$

$z_S = 0.1 km$

$z_S = 0.5 km$

$z_S = 1 km$

$z_S = 5 km$

$z_S = 50 km$

$z_S = 500 km$
Satellite / airborne sensor with finite FOV (perspective projection) - Järvselja pine stand, Estonia

Direction oversampling within camera FOV

Identical objects (trees,...) appear with different radiance values due to sensor FOV (angular effects)

UAV camera ($\theta_v = 50^\circ$, $z_s = 140m$)
LiDAR emits laser pulse, and uses the time-of-flight technique for measuring distance and amplitude of return energy. Satellite, airborne and terrestrial systems

Various types: discrete-return, waveform and photon counting LiDARs.
Light Detection And Ranging (LiDAR)

Application: DEM/DSM, vegetation / urban architecture & dimensions, atmosphere,...

1st order LiDAR models: Geo-optical models with hot spot configuration.
Multiple order models: Monte-Carlo ray tracing (Flight, DELiS,...), DART (quasi-MC),...
Small footprint waveform simulation: Linden tree from RAMI-4 ($\lambda = 1064\text{nm}, \text{H} = 10\text{km}$)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbols</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor area</td>
<td>$A_t$</td>
<td>0.1$m^2$</td>
</tr>
<tr>
<td>Time step per bin</td>
<td>$\delta t_{bin}$</td>
<td>1 ns</td>
</tr>
<tr>
<td>Footprint divergence half angle</td>
<td>$\beta_{fp}$</td>
<td>0.25 mrad</td>
</tr>
<tr>
<td>FOV divergence half angle</td>
<td>$\beta_{FOV}$</td>
<td>0.4 mrad</td>
</tr>
</tbody>
</table>

*Figure showing the simulation setup with parameters and a graph depicting the acquisition time relative to ground vs. distance relative to ground.*
ALS simulation: LiDAR of CAO AtoMS system over Järvselja pine stand (RAMI-4)

Number of pulses: 167478 (309 scans × 542 pulses per scan)

Pulse density: 14.35 /m²

5000 SPs per pulse → 0.78 seconds / pulse / thread ⇒ 110 minutes with 20 threads
ALS simulation: LiDAR of CAO AtoMS system over Järvselja pine stand (RAMI-4)

Display of DART simulations with SpDLib code (color = altitude)

$\theta_L = 45^\circ$ at the center of swath
Thank you

Questions?
**DART: 3D radiative transfer model**

**Principles:**
- Landscape: - Turbid medium (fluid, veg., atm.) + Facets
  - Repetitive or isolated
  - Imported: $B_{\text{atm}}, \text{L.C.}, 3D$ objects,
- Discrete ordinates (space, directions)
- Earth / Atmosphere radiative coupling
- Iterative XS flux tracking (radiometer) or photon (Lidar)
- Parallel / projective projection $\Rightarrow$ camera, pushbroom,...

**Operating modes**
- Reflectance (R), Thermal (T) and (R+T)
- Lidar (RayCarlo: flux tracking + M. C.)
- Sequence of simulations $\forall$ parameter ($\text{LAI}, \Omega_s,...$)

**Products**
- Images $\rho_\lambda(\Omega_s,\Omega_v)$, $T_B(\Omega_s,\Omega_v)$, $L_\lambda(\Omega_s,\Omega_v)$ $\forall \Omega_s,\Omega_v$
- Lidar waveform and photon counting
- 3D Radiative budget of Earth landscapes
- Atmosphere terms $\rho_{\text{atm},\lambda}$, $T_{B,\text{atm},\lambda}$, $L_{\text{atm},\lambda}$

**Image Elements:**
- Direct sun irradiance
- Per pixel
- High atmosphere
- Mid atmosphere
- BOA: Bottom of atmosphere
- TOA: Top of atmosphere
- Airborne sensor
- Satellite sensor
- Tree (facets)
- Smoke
- Topography
- Grass (turbid)
- Water
- Pavement
- Infinite scene
Camera hot spot effect at different altitudes

$z_s = 0.1km$

$z_s = 0.5km$

$z_s = 1km$

$z_s = 5km$

$z_s = 50km$

$z_s = 500km$