Introduction to Optical/Thermal Remote Sensing

J. A. Sobrino, J. C. Jiménez-Muñoz
(University of Valencia, Spain)

sobrino@uv.es, jcjm@uv.es
OUTLINE

Basic radiometric magnitudes
Basic laws of radiation
Radiative transfer equation
Optical remote sensing: reflectivity
Thermal remote sensing: thermal properties
Atmospheric correction: solar & thermal
Measurements
## Spectral regions

<table>
<thead>
<tr>
<th>Spectral range (µm)</th>
<th>Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4-0.7</td>
<td>Visible (VIS)</td>
</tr>
<tr>
<td>0.7-1.5</td>
<td>Near Infrared (NIR)</td>
</tr>
<tr>
<td>1.5-2.5</td>
<td>Short-Wave Infrared (SWIR)</td>
</tr>
<tr>
<td>3-5</td>
<td>Mid-Infrared (MIR)</td>
</tr>
<tr>
<td>8-14</td>
<td>Thermal Infrared (TIR)</td>
</tr>
</tbody>
</table>

**VIS, NIR, SWIR:** dominated by reflected solar energy  
**TIR:** dominated by surface emission  
**MIR:** reflected solar energy + surface emission
RADIOMETRIC MAGNITUDES
Basic magnitudes

Radiative field: EM field of the wave propagating between the source and the detector.

Energy of the EM wave \( \rightarrow \text{Radiant energy: } Q \, [J] \)
Radiant energy/time: \( \text{Radiant flux } \phi = \frac{dQ}{dt} \, [W] \quad (W=J\cdot s) \)
\( (\phi: \text{flux of the Poynting vector}) \)

\( \phi \) Does not provide information about distribution/direction of radiation

Conservation of energy
\[ \phi_i = \phi_t + \phi_r + \phi_a \]
\( i: \text{incident} \)
\( t: \text{transmitted} \)
\( r: \text{reflected} \)
\( a: \text{absorbed} \)
Basic magnitudes

**Radiant flux density:** \( F = \frac{d\phi}{dS} \) [Wm\(^{-2}\)] (\( \phi \) through an element dS)

- **Irradiance (E):** \( F \) when the surface receives the radiation
- **Emittance (M):** \( F \) when radiation is emitted by a source

\( F \) does not include information about direction

**Radiant intensity** \( I = \frac{d\phi}{d\Omega} \) [Wsr\(^{-1}\)]: radiante flux in a given d\( \Omega \)

\( I \): used to characterize emission from point sources

**Radiance**

Radiant flux (\( \phi \)) in a given d\( \Omega \) through a perpendicular surface (dScos\( \theta \)) to the propagation direction.

\[
L = \frac{d^2\phi}{d\Omega dS \cos \theta} = \frac{dI}{dS \cos \theta} \quad [\text{Wm}^{-2}\text{sr}^{-1}]
\]
Basic magnitudes

\[ d\Omega = \frac{dA}{r^2} \Rightarrow \text{Sphere} \quad \Omega = 4\pi \ [\text{sr}] \]

Isotropic point source : \( I = \frac{\phi}{4\pi} \)

Lambertian surface:
\( L(\theta) = L(0^\circ) \Rightarrow I(\theta) = I(0^\circ) \cos \theta \) (cosine law)

Radiance/Emittance
\[ M = \int\int L(\theta, \phi) d\Omega \cos \theta = \int\int L(\theta, \phi) \cos \theta \sin \theta d\theta d\phi \]
Lambertian surface: \( : M = \pi L \)
Spectral magnitudes

The interaction mechanisms are dependent on $\lambda$

\[
\downarrow
\]

The previous magnitudes are spectral magnitudes!!!

$(Q_\lambda, \phi_\lambda, I_\lambda, E_\lambda, \text{etc})$

Spectral radiance:

\[ L_\lambda = \frac{dL}{d\lambda} \left[ \frac{W}{m^2 \text{sr} \mu\text{m}} \right] \]

(In practice spectral magnitudes are measured over a certain band width)
### Summary of radiometric magnitudes

<table>
<thead>
<tr>
<th>MAGNITUDE</th>
<th>SYMBOL</th>
<th>DEFINITION</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiant energy</td>
<td>Q</td>
<td>-</td>
<td>J</td>
</tr>
<tr>
<td>Radiant flux</td>
<td>( \phi )</td>
<td>( dQ/dt )</td>
<td>W</td>
</tr>
<tr>
<td>Emittance</td>
<td>M</td>
<td>( d\phi/dS )</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>Irradiance</td>
<td>E</td>
<td>( d\phi/dS )</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>Radiant intensity</td>
<td>I</td>
<td>( d\phi/d\Omega )</td>
<td>W sr(^{-1})</td>
</tr>
<tr>
<td>Radiance</td>
<td>L</td>
<td>( d^2\phi/(d\Omega dScos\theta) )</td>
<td>W m(^{-2}) sr(^{-1})</td>
</tr>
<tr>
<td>Spectral radiance</td>
<td>( L_\lambda )</td>
<td>( dL/d_\lambda )</td>
<td>W m(^{-2}) sr(^{-1}) (\mu m)^(-1)</td>
</tr>
</tbody>
</table>
Adimensional magnitudes

REFLECTIVITY:
Ratio between reflected and incident fluxes
\( \rho = \frac{f_r}{f_i} \)

ABSORTIVITY:
Ratio between absorbed and incident fluxes
\( \alpha = \frac{f_a}{f_i} \)

TRANSMISIVITY:
Ratio between transmitted and incident fluxes
\( \tau = \frac{f_t}{f_i} \)

EMISSIVITY
Ratio between the emittance of a body and the emittance of a blackbody at the same temperature
\( \varepsilon = \frac{M}{M_n} \)

Conservation of energy
\( f_i = f_t + f_r + f_a \Rightarrow \rho + \alpha + \tau = 1 \)

Spectral magnitudes
\( \rho_\lambda, \alpha_\lambda, \tau_\lambda, \varepsilon_\lambda \)
Basic laws of radiation
Planck law

Planck (1900) found a mathematical description for the spectra distribution of the radiance emitted by a blackbody:

\[ B_\lambda(T) = \frac{c_1 \lambda^{-5}}{\exp\left(\frac{c_2}{\lambda T}\right) - 1} \]

where:
- \( k \): Stefan-Boltzmann constant (1.38·10^{-23} \text{ J K}^{-1})
- \( c \): speed of light (2.9979·10^8 \text{ m s}^{-1})
- \( T \): absolute temperature (K)
- \( c_1, c_2 \): radiation constants
- \( c_1 = 2hc^2 = 1.19104·10^8 \text{ W } \mu\text{m}^4 \text{ m}^{-2} \text{ sr}^{-1} \); \( c_2 = hc/k = 14387.7·10^4 \text{ } \mu\text{m K} \)

\( \lambda \) in \( \mu\text{m} \), then Planck’s function in \( \text{W m}^{-2} \mu\text{m}^{-1} \text{ sr}^{-1} \)

\[ c = \lambda \nu \Rightarrow d\nu = -\left(\frac{c}{\lambda^2}\right)d\lambda \]

\[ B_\nu(T) = \frac{2h\nu^{-3}c^{-2}}{\exp\left(\frac{h\nu}{kT}\right) - 1} \]
Blackbody is lambertian

\[ M(T) = \pi L(T) \]

### Earth: 300 K

\[ M_{n,\lambda} = \frac{2\pi \hbar c^2}{\lambda^5 \left\{ \exp \left( \frac{\hbar c}{\lambda kT} \right) - 1 \right\}} \]
Planck’s law is fundamental in thermal remote sensing. It related emitted radiance with body temperature. From the measured radiance in a given sensor bands, we can obtain the radiant temperature

\[
T = \frac{c_2}{\lambda \ln \left( \frac{c_1}{\lambda^5 B_\lambda} + 1 \right)}
\]
**Stefan-Boltzmann law**

Total emissive power of a blackbody (no consideration of the spectral distribution) is a function of $T^4$

$$L(T) = \int L_\lambda(T) d\lambda = \frac{\sigma T^4}{\pi}$$  
$$M(T) = \sigma T^4$$

*Stefan-Boltzmann constant* ($\sigma$)

Example: emittance for 300 K (Earth) and 6000 K (Sun).
The figure includes the bands of the NOAA/AVHRR sensor.
Wien’s displacement law

For an object at a constant kinetic temperature, the radiant energy (flux) varies as a function of wavelength (see Planck’s law).

The radiant energy peak ($\lambda_{\text{max}}$) is the wavelength at which the maximum amount of energy is radiated.

As temperature increases, the radiant energy peak shifts to shorter wavelengths. This shift is described by Wien’s displacement law:

$$\left( \frac{dB(T)}{d\lambda} \right)_{\lambda=\lambda_{\text{max}}} = 0 \Rightarrow \lambda_{\text{max}} T = 2.8975 \cdot 10^{-3} \text{m} \cdot \text{K}$$

When $\lambda=\lambda_{\text{max}}$:

$$\frac{B_{\lambda_{\text{max}}}}{T^5} = 4.7961 \cdot 10^{-6} \text{ (Wm}^{-3}\text{sr}^{-1}\text{K}^{-5})$$
Wien’s displacement law

Sun (6000 K): $\lambda_{\text{max}}=0.5$ μm (VIS)

Earth (300 K): $\lambda_{\text{max}}=9.7$ μm (TIR)
Radiation laws need to be corrected for the emissivity, since real materials are not perfect blackbodies:

\[ B(T) \rightarrow \varepsilon B(T) \]
Approximations (Planck’s law)

**Wien’s radiation law**

\[
\frac{c^2}{\lambda T} \gg 1 \ (\lambda \text{ cortas}) \Rightarrow \lambda T < 5000 \mu \text{m} \cdot \text{K} \Rightarrow \exp \left( \frac{c^2}{\lambda T} \right) - 1 \approx \exp \left( \frac{c^2}{\lambda T} \right)
\]

**Rayleigh-Jeans’ law**

\[
\frac{c^2}{\lambda T} \ll 1 \ (\lambda \text{ largas}) \Rightarrow \lambda T > 10^5 \mu \text{m} \cdot \text{K} \Rightarrow \exp \left( \frac{c^2}{\lambda T} \right) - 1 \approx \frac{c^2}{\lambda T}
\]

(In this case, blackbody radiance and temperature show a linear relationship)

\[
T = 1000 \text{ K} \rightarrow \begin{cases} 
\lambda < 5 \mu \text{m} \ & \text{Wien} \\
\lambda > 100 \mu \text{m} \ & \text{R–J}
\end{cases}
\]

**Examples:**

\[
T = 300 \text{ K} \rightarrow \begin{cases} 
\lambda < 16.6 \mu \text{m} \ & \text{Wien} \\
\lambda > 333.3 \mu \text{m} \ & \text{R–J}
\end{cases}
\]
Kirchhoff’s law

When a radiation source is surrounded by other radiation sources, it emits radiation but also absorbs radiation.

The temperature will depend on the balance between emitted and absorbed energy.

Radiation equilibrium: emitted energy = absorbed energy (all \( \lambda \))

\[
L_{\text{absorbida}}^\lambda = \alpha^\lambda B^\lambda(T) = L_{\text{emitida}}^\lambda = \varepsilon^\lambda B^\lambda(T) \Rightarrow \alpha^\lambda = \varepsilon^\lambda
\]

*Kirchhoff’s law:* for a given \( \lambda \), the absorptivity of the surface equals the emissivity of the surface, at the same temperature.

Opaque surfaces \( (\tau^\lambda = 0) \) \( \Rightarrow \varepsilon^\lambda = 1 - \rho^\lambda \)

Fundamental approach in radiometry, since emissivity values can be obtained from reflectivity measurements.
Radiative transfer

It describes the processes involved in the propagation of the radiation from the surface to the sensor (or sun-to-sensor) through the atmosphere

⇒ RADIATIVE TRANSFER EQUATION (RTE)

RTE allows to perform atmospheric corrections and also forward simulations

“CLASSIC” THEORY OF RADIATIVE TRANSFER:
RTE is obtained from an energy balance (conservation of energy) (Chandrasekhar, 1960; Lenoble, 1993)

“MODERN” THEORY OF RADIATIVE TRANSFER:
RTE obtained from wave theory (Maxwell Eqs. + statistical considerations) (Apresyan y Kravtsov, 1996).
Radiative Processes

Absorption:
\[ \frac{dL}{dn} = -\sigma_a L \]

Scattering:
\[ \frac{dL}{dn} = -\sigma_s L \]

Absorption + Scattering:
\[ \frac{dL}{dn} = -(\sigma_a + \sigma_s) L = -\sigma_e L \]

Absorption + Scattering + Sources:
\[ \frac{dL}{dn} = -\sigma_e (L - J) \]

Source function:
\[ J = J^{sc} + J^{em} \]
Absorption

\[ dL = -\sigma_a \ L \ dx \]

Volumetric absorption coefficient \((m^{-1})\)

\[ \delta_a = \int_{x_1}^{x_2} \sigma_a(x) \ dx \]

Optical depth (absorption)

Homogeneous media: \(\sigma_a \cdot \Delta x\)

Beer-Lambert-Bouguer law

\[ L(x_2) = L(x_1) \ \exp(-\delta_a) \]

Transmissivity

\[ \tau = \frac{L(x_2)}{L(x_1)} = \exp(-\delta_a) \]

\[ \delta_a = -\ln \tau = \ln \frac{L(x_1)}{L(x_2)} \]

Absorptivity

\[ \alpha = \frac{L(x_1) - L(x_2)}{L(x_1)} = 1 - \tau \]

(with reflection: \(\rho + \sigma + \tau = 1\))
Scattering

(similar to absorption, more complex because of the scattering function)

\[ dL = -\sigma_s \ L \ dx \]

\[ \delta_s = \int_{x_1}^{x_2} \sigma_s(x) \, dx \]

Let us to consider a volume element \( dv \). The incident ray is characterized by its irradiance \( E \) over \( dv \). The scattered radiant flux by \( dv \) in a given direction \( n \) and angle \( \theta \) inside a solid angle \( d\Omega \) is given by

\[ d^2\phi = f(\theta) \ E \ dv \ d\Omega \]

\( f(\theta) \) (m\(^{-1}\)sr\(^{-1}\)): scattering function

(charactersizes the angular distribution of scattered photons)
Total flux lost in the scattering (integration over all the space):

$$d\phi = -Edv \int \int_{espacio} f(\theta) d\Omega$$

For a given volume ($dV (dv = dS dx)$, the incident flux is given by $\phi = E dS$

$$d\phi = -\sigma_s \phi \ dx = -\sigma_s \ E \ dv$$

**Normalized phase function**

$$p(\theta) = \frac{4\pi}{\sigma_s} f(\theta) \quad \Rightarrow \quad \int \int_{espacio} p(\theta) d\Omega = 4\pi \quad ; \quad \int_0^\pi p(\theta) \ sen\theta d\theta = \int_{-1}^{+1} p(\mu) d\mu = 2$$
General case: Absorption + Scattering

Similar to the previous cases

**Extinction coefficient** \((\sigma_e)\) and **Total optical depth** \((\delta)\)

\[
\sigma_e = \sigma_a + \sigma_s \\
\delta = \delta_a + \delta_s
\]

**Single-scattering albedo**
(ratio between absorption and scattering processes)

\[
\omega = \frac{\sigma_s}{\sigma_e} \\
\sigma_s = \omega \sigma_e \\
\sigma_a = (1 - \omega) \sigma_e
\]

Conservative case: single-scat. albedo = 1 \(\Rightarrow\) No loss of radiative energy
(no absorption)
Radiative Transfer Equation

“CLASSIC” THEORY OF RADIATIVE TRANSFER:

- Phenomenological considerations
- Based on the conservation of energy

-Radiance is an energetic variable. Energy balance:

\[
\text{Variation of } L(R,n) \quad \text{along the direction } \mathbf{n} \quad = \quad \text{Loss of energetic flux} \quad \text{because of absorption and scattering from direction } \mathbf{n} \text{ to direction } \mathbf{n}' \quad + \quad \text{Increase of energy flux in the direction } \mathbf{n} \text{ because of scattering from other directions } \mathbf{n}' \quad + \quad \text{Increase in the flux because of the sources}
\]
\[ \frac{dL_\lambda(R,n)}{dn} = -\sigma_{e\lambda}(R) \left[ L_\lambda(R,n) - J_\lambda(R,n) \right] \]
OPTICAL REMOTE SENSING

REFLECTIVITY
Definitions of reflectivity

\[ \rho = \frac{d\phi_r}{d\phi_i} \]

Adimensional magnitude. Ratio between reflected and incident fluxes

a) lambertian
(perfectly diffuse)

b) non-lambertian
(directional or diffuse)

c) Specular

d) Hot spot
Hemispherical reflectance

\[
\begin{align*}
\text{Hemispherical reflectance} & \quad h = \frac{d_h}{d_i} \\
\frac{d^2}{d} & = \frac{dA}{r^2} = \frac{\text{rsen} \ (\text{rd})d}{r^2} \\
\Rightarrow d & = \int_0^2 d \int_0^2 LdS \cos \text{sen} \ d \\
\Rightarrow d_i & = E dS \Rightarrow \left( \begin{array}{c} h \end{array} \right) = \frac{1}{E} \int_0^2 d \int_0^2 LdS \cos \text{sen} \ d \\
\text{Lambertian surface} & \quad d_h = LdS \int_0^2 d \int_0^2 \cos \text{sen} \ d = LdS \Rightarrow h = \frac{L}{E} = \frac{M}{E} \\
\text{Reflectividad hemisferica espectral} : & \quad h_r, = \frac{M}{E}
\end{align*}
\]

(Ratio between emittance and irradiance)
BIDIRECTIONAL REFLECTANCE DISTRIBUTION FACTOR: BRDF

NATURAL SURFACES ARE NOT LAMBERTIAN ➔ distribution of radiance shows a significant angular dependence

\[
\begin{align*}
\mathbf{f}_r (\theta_i, \phi_i, \theta_r, \phi_r) &\equiv \frac{dL_r (\theta_i, \phi_i, \theta_r, \phi_r, E_i)}{dE_i (\theta_i, \phi_i)} \\
&\equiv \frac{dL_r (\theta_i, \phi_i, \theta_r, \phi_r, E_i)}{L_i (\theta_i, \phi_i) \cos \theta_i d\omega_i} [\text{sr}^{-1}]
\end{align*}
\]

Nicodemus et al. (1977):
Definition of reflectivity from BRDF:

\[
\rho(\theta_i, \phi_i; \theta_r, \phi_r; L_i) = \frac{d\phi_r}{d\phi_i} = \\
\int \int f_r(\theta_i, \phi_i; \theta_r, \phi_r) L_i(\theta_i, \phi_i) d\Omega_i d\Omega_r
\]

= \frac{\omega_r \omega_i}{\omega_i} \int L_i(\theta_i, \phi_i) d\Omega_i

Bidirectional Reflectance Factor (BRF):

\[
\text{BRF} = \frac{d\phi_r}{d\phi_{r,id}}
\]

Ratio between reflected flux and reflected flux of a perfectly diffuse (ideal) surface
Different definitions of reflectivity (Sobrino, 2000)

<table>
<thead>
<tr>
<th>Reflectividad</th>
<th>Notación</th>
<th>Formulación</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bidireccional</td>
<td>$d\rho (\theta_i,\phi_i;\theta_r,\phi_r)$</td>
<td>$= f_r (\theta_i,\phi_i;\theta_r,\phi_r). d\Omega_i$</td>
</tr>
<tr>
<td>Direccional-cónica</td>
<td>$\rho (\theta_i,\phi_i;\omega_r)$</td>
<td>$= \int_{\omega_r} f_r (\theta_i,\phi_i;\theta_r,\phi_r). d\Omega_r$</td>
</tr>
<tr>
<td>Direccional-hemisférica</td>
<td>$\rho (\theta_i,\phi_i;2\pi)$</td>
<td>$= \int_{2\pi} f_r (\theta_i,\phi_i;\theta_r,\phi_r). d\Omega_r$</td>
</tr>
<tr>
<td>Cónica-direccional</td>
<td>$d\rho (\omega_i;\theta_r,\phi_r)$</td>
<td>$= (d\Omega_r/d\Omega_i) \int_{\omega_i} f_r (\theta_i,\phi_i;\theta_r,\phi_r). d\Omega_i$</td>
</tr>
<tr>
<td>Bicónica</td>
<td>$\rho (\omega_i;\omega_r)$</td>
<td>$= (1/\Omega_i) \int_{\omega_i} \int_{\omega_r} f_r (\theta_i,\phi_i;\theta_r,\phi_r). d\Omega_r . d\Omega_i$</td>
</tr>
<tr>
<td>Cónica-hemisférica</td>
<td>$\rho (\omega_i;2\pi)$</td>
<td>$= (1/\Omega_i) \int_{\omega_i} \int_{2\pi} f_r (\theta_i,\phi_i;\theta_r,\phi_r). d\Omega_r . d\Omega_i$</td>
</tr>
<tr>
<td>Hemisférica-direccional</td>
<td>$d\rho (2\pi;\theta_r,\phi_r)$</td>
<td>$= (d\Omega_r/\pi) \int_{2\pi} f_r (\theta_i,\phi_i;\theta_r,\phi_r). d\Omega_i$</td>
</tr>
<tr>
<td>Hemisférica-cónica</td>
<td>$\rho (2\pi;\omega_r)$</td>
<td>$= (1/\pi) \int_{2\pi} \int_{\omega_i} f_r (\theta_i,\phi_i;\theta_r,\phi_r). d\Omega_r . d\Omega_i$</td>
</tr>
<tr>
<td>Bihemisférica</td>
<td>$\rho (2\pi;2\pi)$</td>
<td>$= (1/\pi) \int_{2\pi} \int_{2\pi} f_r (\theta_i,\phi_i;\theta_r,\phi_r). d\Omega_r . d\Omega_i$</td>
</tr>
</tbody>
</table>
Reflectivity of natural surfaces

Soils

Reflectivity increases with increasing wavelength

Depends on:
- texture
- water content
- organic matter
- iron oxides
- roughness

**Figura 4.3.** Espectro representativo de cinco suelos minerales (adaptado de Ben-Dor et al., 1994; Camacho-de Coca, 2000). a) Alto contenido en materia orgánica y fina textura, b) bajo contenido en materia orgánica y bajo contenido en hierro, c) bajo contenido en materia orgánica, contenido medio en hierro, d) alto contenido orgánico, grado de textura medio, e) alto contenido en hierro, textura fina.
Reflectivity of natural surfaces

**Water and Snow**

*Water: low reflectivity*

Depends on:
- depth
- chlorophyll, nutrients...
- roughness

*Snow: high reflectivity $\lambda<0.8\ \mu m$, low reflectivity $\lambda>1.5\ \mu m$*

Decreases with the snow age

*Fresh snow > frozen snow*
Reflectivity of natural surfaces

Green Vegetation (Leaves)
THERMAL REMOTE SENSING

Thermal properties & Emissivity
Thermal Remote Sensing

Less attention has been given (in comparison to VNIR-SWIR data exploitation)

Necessary for a better understanding of land surface processes and land-atmosphere interactions (most of the fluxes at the surface/atmosphere interface can only be parameterized through the use of TIR data).

Key parameters:
- LAND SURFACE TEMPERATURE (LST)
- LAND SURFACE EMISSIVITY (LSE, $\varepsilon$) – spectral magnitude!

Low Resolution:
- LST: climatology, land cover change, SST
- LSE: not exploited. Used as input to LST algorithms.

High Resolution:
- LST: energy balance (heat fluxes => ET => water management)
- LSE: geology (mineral mapping), identification of characteristic features in the spectrum... and also land cover change
Thermal Remote Sensing

Heat energy is transferred from one place to another by 3 means: 
*Conduction, Convection and Radiation*

Materials at the surface of the earth receive thermal energy primarily in the form of radiation from the sun.

All matter radiates energy at thermal IR wavelengths (around 3 to 15 mm) both day and night (VNIR data only available at day!).

Kinetic heat: energy of particles of matter in a random motion, which causes particles to collide, resulting in changes of energy state and the emission of electromagnetic radiation form the surface of materials (radiant energy).

Kinetic temperature: concentration of kinetic heat of a material. Measured with a thermometer (direct contact).

Radiant temperature: concentration of radiant flux of a body. Measured *remotely* by radiometers.
Reflectivity, absorptivity, transmissivity

Radiante energy striking the surface of a material is partly reflected, partly absorbed, and partly transmitted (conservation of energy)

\[ \text{reflectivity} + \text{absorptivity} + \text{transmissivity} = 1 \]

Spectral magnitudes determined by properties of matter

Opaque materials:

\[ \text{reflectivity} + \text{absorptivity} = 1 \]
Blackbody. Emissivity.

The concept of blackbody is fundamental to understanding heat radiation.

**Blackbody:** theoretical material that absorbs all the radiant energy that strikes it (absorptivity=1). It also radiates all of its energy in a wavelength distribution pattern that is dependent only on the kinetic temperature.

A blackbody is a physical abstraction: no material has an absorptivity of 1 and no material radiates the full amount of energy.

Real materials: a property called **emissivity** is introduced, defined as the ratio between the real radiant flux and the radiant flux from a blackbody. It is a spectral magnitude.

**Table 5-1** Emissivity of materials measured at wavelengths of 8 to 12 μm

<table>
<thead>
<tr>
<th>Material</th>
<th>Emissivity (ε)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granite, typical</td>
<td>0.815</td>
</tr>
<tr>
<td>Dunite</td>
<td>0.856</td>
</tr>
<tr>
<td>Obsidian</td>
<td>0.862</td>
</tr>
<tr>
<td>Feldspar</td>
<td>0.870</td>
</tr>
<tr>
<td>Granite, rough</td>
<td>0.898</td>
</tr>
<tr>
<td>Silicon sandstone, polished</td>
<td>0.909</td>
</tr>
<tr>
<td>Sand, quartz, large-grain</td>
<td>0.914</td>
</tr>
<tr>
<td>Dolomite, polished</td>
<td>0.929</td>
</tr>
<tr>
<td>Basalt, rough</td>
<td>0.934</td>
</tr>
<tr>
<td>Dolomite, rough</td>
<td>0.958</td>
</tr>
<tr>
<td>Asphalt paving</td>
<td>0.959</td>
</tr>
<tr>
<td>Concrete walkway</td>
<td>0.966</td>
</tr>
<tr>
<td>Water, with a thin film of petroleum</td>
<td>0.972</td>
</tr>
<tr>
<td>Water, pure</td>
<td>0.993</td>
</tr>
</tbody>
</table>

Effect of emissivity on measured radiant temperature:

“Real” temperature: 10 °C

Radiometer 1: Emis=0.06. T= -133 °C

Radiometer 2: Emis=0.97. T=8 °C

The difference for the radiometer 1 is more than 140 °C!!!

The difference for the radiometer 2 is only 2 °C because emissivity is near to 1 (blackbody).
Other thermal properties

**Thermal conductivity:** rate at which heat will pass through a material. Rocks and soils are relatively poor conductors of heat.

**Thermal capacity:** ability of a material to store heat. Water has a high value of thermal capacity.

**Thermal inertia:** measure of the thermal response of a material to temperature changes. It depends on thermal conductivity, density and thermal capacity. Materials with a high thermal inertia (sandstone, basalt) strongly resist temperature changes and have low $\Delta T$ (maximum-minimum $T$ in the daily cycle).

**Apparent Thermal Inertia:** it can be measured from remote sensing methods, and depends on $\Delta T$ and albedo (measurements of thermal inertia require contact methods).

**Thermal diffusivity:** rate at which temperature changes within a substance.
<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity (K), cal·cm⁻¹·sec⁻¹·°C⁻¹</th>
<th>Density (ρ), g·cm⁻³</th>
<th>Thermal capacity (c), cal·g⁻¹·°C⁻¹</th>
<th>Thermal diffusivity (k), cm²·sec⁻¹</th>
<th>Thermal inertia (P), cal·cm⁻²·sec⁻¹/²·°C⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Basalt</td>
<td>0.0050</td>
<td>2.8</td>
<td>0.20</td>
<td>0.009</td>
<td>0.053</td>
</tr>
<tr>
<td>2. Clay soil, moist</td>
<td>0.0030</td>
<td>1.7</td>
<td>0.35</td>
<td>0.005</td>
<td>0.042</td>
</tr>
<tr>
<td>3. Dolomite</td>
<td>0.012</td>
<td>2.6</td>
<td>0.18</td>
<td>0.026</td>
<td>0.075</td>
</tr>
<tr>
<td>4. Gabbro</td>
<td>0.0060</td>
<td>3.0</td>
<td>0.17</td>
<td>0.012</td>
<td>0.055</td>
</tr>
<tr>
<td>5. Granite</td>
<td>0.0075</td>
<td>2.6</td>
<td>0.16</td>
<td>0.016</td>
<td>0.056</td>
</tr>
<tr>
<td>6. Gravel</td>
<td>0.0030</td>
<td>2.0</td>
<td>0.18</td>
<td>0.008</td>
<td>0.033</td>
</tr>
<tr>
<td>7. Limestone</td>
<td>0.0048</td>
<td>2.5</td>
<td>0.17</td>
<td>0.011</td>
<td>0.045</td>
</tr>
<tr>
<td>8. Marble</td>
<td>0.0055</td>
<td>2.7</td>
<td>0.21</td>
<td>0.010</td>
<td>0.056</td>
</tr>
<tr>
<td>9. Obsidian</td>
<td>0.0030</td>
<td>2.4</td>
<td>0.17</td>
<td>0.007</td>
<td>0.035</td>
</tr>
<tr>
<td>10. Peridotite</td>
<td>0.011</td>
<td>3.2</td>
<td>0.20</td>
<td>0.017</td>
<td>0.084</td>
</tr>
<tr>
<td>11. Pumice, loose, dry</td>
<td>0.0006</td>
<td>1.0</td>
<td>0.16</td>
<td>0.004</td>
<td>0.009</td>
</tr>
<tr>
<td>12. Quartzzite</td>
<td>0.012</td>
<td>2.7</td>
<td>0.17</td>
<td>0.026</td>
<td>0.074</td>
</tr>
<tr>
<td>13. Rhyolite</td>
<td>0.0055</td>
<td>2.5</td>
<td>0.16</td>
<td>0.014</td>
<td>0.047</td>
</tr>
<tr>
<td>14. Sandy gravel</td>
<td>0.0060</td>
<td>2.1</td>
<td>0.20</td>
<td>0.014</td>
<td>0.050</td>
</tr>
<tr>
<td>15. Sandy soil</td>
<td>0.0014</td>
<td>1.8</td>
<td>0.24</td>
<td>0.003</td>
<td>0.024</td>
</tr>
<tr>
<td>16. Sandstone, quartz</td>
<td>0.0120</td>
<td>2.5</td>
<td>0.19</td>
<td>0.013</td>
<td>0.075</td>
</tr>
<tr>
<td>17. Serpentinite</td>
<td>0.0063</td>
<td>2.4</td>
<td>0.23</td>
<td>0.013</td>
<td>0.059</td>
</tr>
<tr>
<td>18. Shale</td>
<td>0.0042</td>
<td>2.3</td>
<td>0.17</td>
<td>0.008</td>
<td>0.041</td>
</tr>
<tr>
<td>19. Slate</td>
<td>0.0050</td>
<td>2.8</td>
<td>0.17</td>
<td>0.011</td>
<td>0.049</td>
</tr>
<tr>
<td>20. Syenite</td>
<td>0.0077</td>
<td>2.2</td>
<td>0.23</td>
<td>0.009</td>
<td>0.062</td>
</tr>
<tr>
<td>21. Tuff, welded</td>
<td>0.0028</td>
<td>1.8</td>
<td>0.20</td>
<td>0.008</td>
<td>0.032</td>
</tr>
<tr>
<td>22. Water</td>
<td>0.0013</td>
<td>1.0</td>
<td>1.01</td>
<td>0.001</td>
<td>0.036</td>
</tr>
</tbody>
</table>

*Source: Janza and others (1975, Table 4-1).*
Emissivity spectra of natural surfaces

Surface emissivity is a key variable in thermal remote sensing. Accurate retrievals of LST from remote sensing techniques rely on accurate estimations of surface emissivity.

Natural (and manmade) surfaces are not perfect blackbodies. The emissivity spectra needs to be characterized.

Spectral libraries include several emissivity spectra measured in the laboratory for different surfaces. These spectra are useful for simulation purposes.

MODIS Emissivity Library
http://www.ices.ucsb.edu/modis/EMIS/html/em.html

ASTER Spectral Library
http://speclib.jpl.nasa.gov/
Natural surfaces: Rocks
Natural surfaces: Water and Vegetation

![Graph showing the emisividad for different surfaces as a function of the wavelength (µm). The graph includes lines for water, dry grass, and green grass, with the y-axis representing emisividad and the x-axis representing wavelength.](image-url)
Spectral features

A sample and the medium in which it is embedded for the purpose of taking and infrared spectrum will always having differing dispersions, although their indices of refraction may match at a center frequency of interest. In general, there will therefore be a wavelength at which the sample+medium have a maximum transparency.

Christiansen frequency: the frequency of maximum transparency.

Reststrahlen bands: reflectance phenomenon in which EM radiation within a narrow energy cannot propagate within a given medium due to a change in refractive index concurrent with the specific absorbance band of the medium. Normally-inciden Reststrahlen band radiation experiences strong-reflection or total-reflection from that medium.

Reststrahlen bands manifest as a minima in emissivity.
quartz

Christiansen bands for quartz

“a” shows a strong minimum at 9.67 μm, related to the Reststrhalen bands
REFLECTIVITY (VNIR) VS EMISIVITY (TIR)

Green vegetation

Rock (quartz)
Emissivity/Temperature

What happens if measurements are not corrected for emissivity?

\[
\frac{\Delta T}{T} = \frac{1}{5} \frac{\Delta \varepsilon}{\varepsilon}
\]

\[
T = 300K \Rightarrow \Delta T = 60 \left( \frac{\Delta \varepsilon}{\varepsilon} \right)
\]

\[
\frac{\Delta \varepsilon}{\varepsilon} = 1\% \Rightarrow \Delta T = 0.6K
\]

<table>
<thead>
<tr>
<th>Sample</th>
<th>(\varepsilon) (8-14 \text{ (\mu)m})</th>
<th>(\Delta T) ((\varepsilon=1))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>0.8-0.9</td>
<td>15-6</td>
</tr>
<tr>
<td>Clay</td>
<td>0.94-0.98</td>
<td>4-1</td>
</tr>
<tr>
<td>Water, Vegetation</td>
<td>0.97-0.99</td>
<td>2-0.6</td>
</tr>
<tr>
<td>Snow</td>
<td>0.99</td>
<td>0.6</td>
</tr>
</tbody>
</table>
Emissivity correction

Surfaces are not blackbodies: \( \varepsilon \neq 1 \) y \( \varepsilon = f(\lambda) \)

Some natural surfaces behave as black/grey-bodies (e.g. water, vegetation)
Atmospheric Correction
The atmosphere mainly absorbs the thermal radiation emitted by the surface, and also scatter in the VNIR (solar) range. This loss of radiation needs to be compensated to recover the at-surface signal (Atmospheric Correction).
**ATMOSPHERIC CORRECTION IN THE SOLAR RANGE: SIMPLIFIED APPROACH**

\[
L_{\lambda}^{\text{TOA}} = L_{\lambda}^{\text{SUN}} \tau_{\lambda} \rho_{\lambda}^{\text{sur}} + L_{\lambda}^{\text{path}}
\]

\[
L_{\lambda}^{\text{SOL}} = \frac{\cos \theta_z}{d^2} E_{0,\lambda}
\]

- **L_{\lambda}^{\text{TOA}}**: At-sensor registered radiance (TOA, Top Of Atmosphere).
- **L_{\lambda}^{\text{SOL}}**: Extraterrestrial solar irradiance (corrected for eccentricity and zenithal solar angle).
- **\tau**: Total atmospheric transmissivity: Sun-to-target (\(\tau^\downarrow\)), target-to-sensor (\(\tau^\uparrow\)) \(\Rightarrow\) \(\tau = \tau^\downarrow \cdot \tau^\uparrow\).
- **\rho_{\lambda}^{\text{sur}}**: at-surface reflectivity.
- **L_{\lambda}^{\text{path}}**: path radiance.
ATMOSPHERIC CORRECTION FROM A SIMPLIFIED APPROACH OF THE R.T.E.

At-surface reflectance is obtained after compensation of path radiance and atmospheric transmissivity

\[
\rho_{\lambda}^{\text{sup}} = \frac{L_{\lambda}^{\text{TOA}} - L_{\lambda}^{\text{camino}}}{L_{\lambda}^{\text{SOL}} \tau_{\lambda}}
\]

In terms of reflectivity the R.T.E. can be expressed as:

\[
\rho_{\lambda}^{\text{TOA}} = \tau_{\lambda} \rho_{\lambda}^{\text{sur}} + \rho_{\lambda}^{\text{path}}
\]
ATMOSPHERIC CORRECTION IN THE THERMAL INFRARED

Atmospheric Windows in the TIR

8-9.4 µm

10-12.5 µm

Transmissivity vs. Wavelength (µm)

O₃
THERMAL INFRARED - TIR (8-14 μm)

\[ L_{sen}^{\lambda} = \left[ \varepsilon_{\lambda} B_{\lambda}(T_{s}) + (1 - \varepsilon_{\lambda})L_{atm}^{\lambda \downarrow} \right] \tau_{\lambda} + L_{atm}^{\lambda \uparrow} \]

\(\lambda \rightarrow i\)

Brightness temperature: \(L_{sen}^{\lambda} \equiv B(T_{sen})\)

LST: \(T_s\)

Physical basis: classical radiative transfer

B: Planck’s law

\[ L_{sen}^{\lambda} = \left[ \varepsilon_{\lambda} B_{\lambda}(T_{s}) + (1 - \varepsilon_{\lambda})L_{atm}^{\lambda \downarrow} \right] \tau_{\lambda} + L_{atm}^{\lambda \uparrow} \]
Atmospheric Correction:
The signal measured by the sensor is not the radiance coming from the surface because of the perturbation of the atmosphere.

\[
L_{\text{sen}}^{\lambda} = \left[ \varepsilon_{\lambda} B_{\lambda}(T_s) + (1 - \varepsilon_{\lambda})L_{\text{atm}}^{\lambda\downarrow} \right] \tau_{\lambda} + L_{\text{atm}}^{\lambda\uparrow}
\]

\[
L_{\lambda}^{\text{superficie}} = \varepsilon_{\lambda} B_{\lambda}(T_s) + (1 - \varepsilon_{\lambda})L_{\text{atm}}^{\lambda\downarrow}
\]

Atmospheric Correction (TIR)

\[
L_{\lambda}^{\text{sup}} = \frac{L_{\lambda}^{\text{sen}} - L_{\lambda}^{\text{atm}\uparrow}}{\tau_{\lambda}}
\]
LST RETRIEVAL

LST retrievals from remote sensing data require an atmospheric correction and also a previous estimation of the surface emissivity (we need to solve the coupling between LST & $\varepsilon$)

Rigorous algorithms are based in the Radiative Transfer Equation. Algorithms depend mainly on the spectral characteristics of the TIR sensor

METHODS FOR LST RETRIEVAL:

1 BAND: Single-channel (mono-window)
2 BANDS: Two-channel or split-window
1 BANDS and 2 VIEW ANGLES: Bi-angular (dual-angle)
≥3 BANDS (multispectral): TES algorithm

Other Methods: TISI, day/night combinations, tri-channel, etc…
LST: TWO-CHANNEL ALGORITHMS (2 BANDS)

Based on the “differential absorption” concept, also known as “split-window”

\[
\text{Differential absorption} \Rightarrow \text{Atmospheric correction } \propto (T_i - T_j)
\]

Mathematical structure of the algorithm (Sobrino et al. 1996; Sobrino & Raissouni, 2000)

\[
\text{LST} = T_i + c_1(T_i-T_j) + c_2(T_i-T_j)^2 + c_0 + (c_3+c_4 W)(1-\varepsilon) + (c_5+c_6 W)\Delta\varepsilon
\]

\[
\varepsilon = 0.5 (\varepsilon_i - \varepsilon_j) \\
\Delta\varepsilon = \varepsilon_i - \varepsilon_j \\
T_i, T_j \text{ in K} \\
W \text{ in g/cm2}
\]

DUAL-ANGLE ALGORITHMS

Same as split-window, but using two different view angles:

\[
T_i \Rightarrow T_n \text{ (nadir)} \quad T_j \Rightarrow T_f \text{ (forward)}
\]
Emissivities are obtained from VNIR data, and not from TIR data! This avoids the undetermined problem.

**Simplified approach**

Emissivity as an average of soil and vegetation emissivities according to the Fractional Vegetation Cover (FVC).

\[ \varepsilon_{\lambda} = \varepsilon_{s,\lambda} (1 - FVC) + \varepsilon_{v,\lambda} FVC \]

**NDVI Thresholds Method (Sobrino & Raissouni, IJRS, 2000)**

Pixels are classified into bare pixels, mixed pixels and fully-vegetated pixels. Cavity effect is estimated from a geometric model.

\[ FVC = \left[ \frac{NDVI - NDVI_s}{NDVI_v - NDVI_s} \right]^2 \]

\[ \varepsilon_{\lambda} = \begin{cases} 
\varepsilon_{s,\lambda} (1 - FVC) + \varepsilon_{v,\lambda} FVC + C_{\lambda} & NDVI < NDVI_s \\
0.985 + 0.005 & NDVI_s < NDVI < NDVI_v \\
NDVI_v & NDVI_v
\end{cases} \]

\[ C_i = (1 - \varepsilon_{si}) \varepsilon_{vi} F'(1 - P_v) \]

\[ F' = \left(1 + \frac{H}{S}\right) - \sqrt{1 + \left(\frac{H}{S}\right)^2} \]
5th ESA ADVANCED TRAINING COURSE ON LAND REMOTE SENSING

MEASUREMENTS
REFLECTANCE MEASUREMENTS

(GER, ASD, etc.)

REFERENCE WHITE PANEL:

Spectralon, highly reflectant and diffuse (hemispherical reflectance > 99%)
Broadband radiometers (8-14 μm)

**RAYTEK ST8**
-30 to 100 °C
±0.5 °C
FOV: 8°

**RAYTEK MID**
-40 to 600 °C
±0.5 °C
FOV: 20°

**EVEREST 3000**
-40 to 100 °C
±0.5 °C
FOV: 4°

**Apogee IR-120 (Campbell)**
-25 to 60 °C
±0.2 °C
FOV: 20°
### Multiband: CIMEL

<table>
<thead>
<tr>
<th>MODEL</th>
<th>BANDS</th>
<th>RANGE</th>
<th>ACCURACY</th>
<th>FOV</th>
</tr>
</thead>
</table>
| CIMEL 312-1| 8-13 \(\mu\)m  
8.2-9.2 \(\mu\)m  
10.3-11.3 \(\mu\)m  
11.5-12.5 \(\mu\)m | -80 a 60 °C | 0.1 °C   | 10°  |
| CIMEL 312-2| 8-13 \(\mu\)m  
11-11.7 \(\mu\)m  
10.3-11 \(\mu\)m  
8.9-9.3 \(\mu\)m  
8.5-8.9 \(\mu\)m  
8.1-8.5 \(\mu\)m | -80 a 60 °C | 0.1 °C   | 10°  |

[Graphs showing spectral response for each band]
The box method: emissivity measurements

(Buettner y Kern, 1965; Dana, 1969; Sobrino y Caselles, 1989; Nerry et al. 1990)

The box method was designed to measure the surface emissivity.

It removes the surrounding (or sky) irradiance using a closed lambertian box. It can be used both at the field (outdoors) or in the laboratory (indoors).
The box method
Formulation

Si suponemos que las paredes laterales interiores de la caja son perfectamente reflectantes y lambiqueanas y consideramos que el techo y el fondo de la misma son dos planos paralelos infinitos, la radiancia medida por el sensor \( L_i \) vendrá dada por:

\[
L_i = \varepsilon_i B(T_i) + (1 - \varepsilon_i)L_i
\]  \hspace{1cm} (3.1)

donde \( \varepsilon_i \) es la emisividad de la muestra, \( T_i \) su temperatura y \( L_i \) la radiancia que proviene del techo y donde la dependencia espectral de las magnitudes se ha omitido por simplicidad en la notación. Análogamente, para el techo tendremos:

\[
L_i = \varepsilon_i B(T_i) + (1 - \varepsilon_i)L_i
\]  \hspace{1cm} (3.2)

siendo en este caso \( \varepsilon_i \) la emisividad del techo, \( T_i \) su temperatura y \( L_i \) la radiancia que proviene de la superficie o muestra. Si sustituimos ahora la expresión para \( L_i \) dada por la Ecuación (3.2) en la Ecuación (3.1) y aplicamos la expresión resultante a dos techos distintos (1 y 2) obtendremos el siguiente sistema de dos ecuaciones:

\[
\begin{align*}
L_1 &= \varepsilon_1 B(T_1) + (1 - \varepsilon_1) \left[ \varepsilon_1 B(T_1) + (1 - \varepsilon_1) L_1 \right] \\
L_2 &= \varepsilon_2 B(T_2) + (1 - \varepsilon_2) \left[ \varepsilon_2 B(T_2) + (1 - \varepsilon_2) L_2 \right]
\end{align*}
\]  \hspace{1cm} (3.3)

Restando ambas ecuaciones y despejando \( \varepsilon_i \) se obtiene finalmente la expresión dada por Buettner y Kern (1965):

\[
\varepsilon_i = 1 - \frac{L_2 - L_1}{\varepsilon_1 B(T_1) - \varepsilon_2 B(T_2) + (1 - \varepsilon_1)L_1 - (1 - \varepsilon_2)L_2}
\]  \hspace{1cm} (3.5)

De esta forma se consigue eliminar la dependencia en \( T_i \), que es un parámetro difícil de medir en campo si un conocimiento a priori de la emisividad.
Ideal case:

- t1: blackbody ($\varepsilon = 1$ y $\rho = 0$)
- t2: perfect reflector ($\rho = 1$ y $\varepsilon = 0$)

Radiance/Temperature approach:
(Slater, 1980): $L = aT^b$

$$\varepsilon_s = \frac{L_{t1} - L_s^1}{L_{t1} - L_s^2}$$

$$\varepsilon_s = \frac{(T_{t1})^b - (T_s^1)^b}{(T_{t1})^b - (T_s^2)^b}$$

<table>
<thead>
<tr>
<th>Banda (μm)</th>
<th>a (W m⁻² K⁻ᵇ)</th>
<th>b</th>
<th>DT (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-14</td>
<td>3'0783 10⁻⁹</td>
<td>4'3400</td>
<td>0'16</td>
</tr>
<tr>
<td>10'5-12'5</td>
<td>6'5850 10⁻⁹</td>
<td>4'0161</td>
<td>0'17</td>
</tr>
<tr>
<td>10'5-11'5</td>
<td>1'4159 10⁻⁹</td>
<td>4'1697</td>
<td>0'17</td>
</tr>
<tr>
<td>11'5-12'5</td>
<td>8'2751 10⁻⁹</td>
<td>3'8486</td>
<td>0'17</td>
</tr>
</tbody>
</table>
Accuracy of the box method

\[ D\varepsilon = 6 \delta DT \]

DT es la precisión del radiómetro, y para (8-14 μm)

\[ \delta = \frac{(T_2)^{3.34}}{(T_3)^{4.34} - (T_2)^{4.34}} \]

T_3=320 K y T_2=300 K, Dε = 0.06 DT

Radiómetro de campo, DT=0.1°C, Dε = 0.6%

The box is not perfect, so a correction factor is added:

\[ \varepsilon_s = \varepsilon_0 + \delta \varepsilon \]

\( \delta \varepsilon \): depends on the box geometry, temperature and emissivity of the lids
RADIOMETRIA PASIVA

1.-MÉTODO DE LA RADIANCIA ATMOSFÉRICA

Utiliza una superficie reflectante cerrada y lambertiana (Caja) 3 medidas para obtener la emisividad

1) Radiometro observa muestra a través orificio practicado en la caja

\[ L_{BB}^{caja} = \varepsilon_s B(T_s) + (1-\varepsilon_s) B(T_s) = B(T_s) \]

Supone emisividad caja=0

2) Medida muestra sin caja

\[ L_{BB} = \varepsilon_s B(T_s) + (1-\varepsilon_s) L_a \]

3) Medida de la Radiancia de los alrededores, La

La temperatura del suelo no debe cambiar durante el proceso de medida

Combinando 1) y 2) \[ L_{BB} = \varepsilon_s (L_{BB}^{caja}-L_a) + L_a \]

FINAL EXPRESSION

\[ \varepsilon_s \lambda = \frac{L_{BB}-L_a}{L_{BB}^{caja}-L_a} \]

Método adecuado cuando alrededor=atmosfera
RECOMMENDATIONS FOR IN-SITU MEASUREMENTS USING THE BOX METHOD

1 LID: clear-sky, or totally cloudy

2 LIDS: T for the “hot” lid should be higher than the sample T

- Buettner & Kern (1965): hot water flows
- Nerry (1988): Electrical resistances
- Sobrino (1989): Heating by sunlight

Measurements should be performed around midday.

Our experience shows a reproducibility better than 1% for temperature differences between the lids of around 20 °C.

Measurements in short periods of time with low wind speed.

1 LID: first measurement with box, second measurement without the box, and third measurement the atmospheric contribution

2 LIDS: i) box with the “cold” lid, ii) box with the “hot” lid, and iii) T of the “hot” lid
Box with 2 lids

\[ \varepsilon_s = \frac{L_{t1} - L_{1s}^1}{L_{t1} - L_{2s}^2} \]

- \( L_{t1} \): radiance from the “hot” lid
- \( L_{1s}^1 \): radiance from the sample with the “cold” lid
- \( L_{2s}^2 \): radiance from the sample with the “hot” lid
Angular Variations

Surface emissivity depends on different factors:

- Composition of the body and spectral range
- Temperature of the body (negligible for ambient temperatures)
- Soil moisture (increases with SM)
- Direction of emission (angular effects)
Absolute directional emissivity:

\[
\varepsilon_\theta = \frac{\exp\left(-\alpha / T_{rad}\right) - 1,3 \exp\left(-\alpha / T_{atm0}\right)}{\exp\left(-\alpha / T_S\right) - 1,3 \exp\left(-\alpha / T_{atm0}\right)}
\]

Relative directional emissivity:

\[
\varepsilon_{r,\theta} = \frac{\exp\left(-\alpha / T_{rad}\right) - 1,3 \exp\left(-\alpha / T_{atm0}\right)}{\exp\left(-\alpha / T_{rad0}\right) - 1,3 \exp\left(-\alpha / T_{atm0}\right)}
\]

(Factor 1.3: depends on the radiometer)
EXPERIMENTAL RESULTS

Semicircular goniometer with R=1.5 m

Radiometer Omega OS86 (8-14 μm) with $\sigma=0.1$ K and IFOV=2º

Thermopar (water measurements): TES 1310 Type K ($\sigma=0.1$ K)

Thermistor calibrated in the laboratory with a Hg thermometer (Siebert&Kuhn, $\sigma=0.05$K)

Samples: sand, clay, lime, gravel, water, grass

Measurement steps: 5º (t< 2 min, thermal stability)
Samples

- Grass
- Gravel
- Sand
HOMOGENEOUS SAMPLES (8-14 μm)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Decrease in relative emissivity (%)</th>
<th>Decrease in absolute emissivity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>3,3</td>
<td>3,3</td>
</tr>
<tr>
<td>sand</td>
<td>2,0</td>
<td>1,9</td>
</tr>
<tr>
<td>clay</td>
<td>0,5</td>
<td>0,5</td>
</tr>
<tr>
<td>slime</td>
<td>0,9</td>
<td>0,9</td>
</tr>
<tr>
<td>gravel</td>
<td>1,2</td>
<td>1,2</td>
</tr>
<tr>
<td>grass</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
HOMOGENEOUS SAMPLES (CIMEL BANDS)

(Cuenca & Sobrino, 2004, Applied Optics)
RESULTS FOR A WATER SAMPLE

agua: canal 1

![Graph for agua: canal 1](image)

águlo (°)

Masuda et al.
trabajo presente

agua: canal 2

![Graph for agua: canal 2](image)

águlo (°)

Masuda et al.
trabajo presente

agua: canal 3

![Graph for agua: canal 3](image)

águlo (°)

Masuda et al.
trabajo presente

agua: canal 4

![Graph for agua: canal 4](image)

águlo (°)

Masuda et al.
trabajo presente
Automatic Goniometer
Angular measurements over different natural (agricultural) surfaces

Bare soil  Green grass  Wheat
Angular variations on Brightness Temperatures (LSBT: Land Surface Brightness Temperature)

\[ \Delta \text{LSBT}(\theta_i) = \text{LSBT}(\theta_i) - \frac{1}{n} \sum_{i=1}^{n} \text{LSBT}(\theta_i) \]

Bare soil