Advanced Optical 1

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• Radiative transfer modelling
  – General
  – Atmosphere
  – Leaves
  – Soils
  – Vegetation canopies

• Coupled and mixed modelling
  – 4-stream system, adding method
  – leaf colour gradient, clumping
What happens when a photon strikes a diffusing layer?

- It passes the layer uncollided (U),
- or it is scattered forward, transmitted (T),
- or it is absorbed inside the layer (A),
- or it is scattered backward, reflected (R).

Budget: $U + T + A + R = 1$
Scattering and the radiation budget

Radiation budget

- no absorption
- little absorption
- little scattering
- no scattering
Extinction = absorption + scattering

Extinction of specular flux (Beer’s law)

\[ \frac{dE_s}{dz} = -kE_s \]

solution: exponential function \[ E_s(z) = E_s(0) \exp(-kz) \]

It does not matter here how the radiation flux is lost, so \( k \) includes losses due to absorption as well as scattering.

Depth \( z \) = metrical depth in m; then the extinction coefficient \( k \) is in units of m\(^{-1}\).

One can write \( d\tau = kdz \), where \( \tau = \) optical depth.
A plane-parallel layer

\[ E_{s}^{o} = \text{specular irradiance on a plane perpendicular to the rays} \]

For randomly oriented or spherical particles (isotropic medium) interception coefficient \( \beta \) is constant, and extinction coefficient \( k \) depends on zenith angle as

\[ k = \frac{\beta}{\cos \theta} = \frac{\beta}{\mu} \]

due to longer path length

\[ E_{s}^{o}(z) = E_{s}^{o}(0) \exp(-\frac{\beta}{\mu} z) \]

Irradiance on horizontal plane = \[ E_{s}^{o}(z) \cos \theta = E_{s}^{o}(0) \mu \exp(-\frac{\beta}{\mu} z) \]
Direct flux as a function of the incidence angle for some optical thickness values, relative to $E_s^o$. 
How about scattered radiation? Suppose a small volume is illuminated from all sides, and the effect on the radiance in a certain direction is considered.

Radiance change in direction $o$ = gain due to scattering from all directions $i$, minus loss due to extinction in direction $o$. 

\[ \delta = \text{scattering angle} \]
The radiative transfer equation

\[ L_o(\tau + d\tau) - L_o(\tau) = \]

\[ \frac{d\tau}{\cos \theta_o} \left[ -L_o(\tau) + \frac{\omega}{4\pi} \int_{4\pi} p(\delta) L_i d\Omega_i \right] \]

\( \omega = \) single scattering albedo

\( p(\delta) = \) scattering phase function
More familiar radiative transfer equation:

\[ \mu_o \frac{dL_o}{d\tau} = -L_o(\tau) + \frac{\omega}{4\pi} \int p(\delta)L_i d\Omega_i \]

Optical depth and scattering phase function are suitable concepts to describe radiative transfer in isotropic media. In isotropic media:

- interception of flux is independent of the incidence direction
- directional scattering depends only on the scattering angle (the difference between incidence and scattering direction)

An isotropic medium requires random orientation of particles. Examples: the atmosphere, vegetation with a spherical leaf angle distribution.
Radiative transfer in non-isotropic media

\[
\mu_o \frac{dL_o}{dz} = -\beta(\mu_o) L_o + \gamma'(\mu_s, \mu_o, \psi) E_s^o + \int \gamma'(\mu_i, \mu_o, \varphi_i - \varphi_o) L_i d\Omega_i
\]

- extinction
- scattering of solar radiation
- scattering of diffuse radiation

Fundamental physical quantities here are:

- \( \beta(\mu_o) \) = interception coefficient in direction \( o \)
- \( \gamma'(\mu_s, \mu_o, \psi) \) = volume scattering phase function
Methods of solution

• 2-stream / 4-stream approximation
• Multistream methods
• DISORT (discrete ordinates radiative transfer)
• SOSA (successive orders of scattering)
• Doubling / Adding
• Monte Carlo / Ray tracing
• Radiosity
4-stream radiative transfer

Solar incident flux

Diffuse downward flux

Diffuse upward flux

Observed radiance

Canopy layer

Soil
4-stream system

Four-stream approximation of the RT equation

\[
\begin{align*}
\frac{d}{d\tau} \begin{pmatrix} E_s \\ E^- \\ E^+ \\ E_o \end{pmatrix} &= \begin{pmatrix} -k & -\kappa & \kappa \\ -\kappa & -s & -s' \\ \kappa & -\sigma & -\sigma' \\ K & -\sigma' & -\sigma' \end{pmatrix} \begin{pmatrix} E_s \\ E^- \\ E^+ \\ E_o \end{pmatrix} \\
&\quad + \begin{pmatrix} s' & \sigma' & \sigma \\ -s & -\sigma & -\sigma' \\ -w & -v & -v' \end{pmatrix} \begin{pmatrix} E_s \\ E^- \\ E^+ \\ E_o \end{pmatrix}
\end{align*}
\]

This approximation is applied in the SAIL canopy reflectance models
Four-stream interactions for:

- **a layer**
  - $\tau_{ss}$
  - $\tau_{sd}$
  - $\rho_{sd}$
  - $\rho_{so}$
  - $\tau_{dd}$
  - $\rho_{dd}$
  - $\rho_{do}$
  - $\tau_{do}$
  - $\rho_{dd}$
  - $\tau_{oo}$

- **a surface**
  - $r_{sd}$
  - $r_{so}$
  - $r_{dd}$
  - $r_{do}$
Adding canopy and soil

Adding mechanism

\[ E_s (b) = \tau_{ss} E_s (t) \]
\[ E^- (b) = \tau_{sd} E_s (t) + \tau_{dd} E^- (t) + \rho_{dd} E^+ (b) \]
\[ E^+ (t) = \rho_{sd} E_s (t) + \rho_{dd} E^- (t) + \tau_{dd} E^+ (b) \]
\[ E_o (t) = \rho_{so} E_s (t) + \rho_{do} E^- (t) + \tau_{do} E^+ (b) + \tau_{oo} E_o (b) \]

\[ E^+ (b) = r_{sd} E_s (b) + r_{dd} E^- (b) \]
\[ E_o (b) = r_{so} E_s (b) + r_{do} E^- (b) \]
Four-stream adding equations

\[ r_{so}^* = \rho_{so} + \tau_{ssoo} r_{so} + \frac{(\tau_{sd} + \tau_{ss} r_{sd} \rho_{dd}) r_{do} \tau_{oo} + (\tau_{sd} r_{dd} + \tau_{ss} r_{sd}) \tau_{do}}{1 - r_{dd} \rho_{dd}} \]

\[ r_{do}^* = \rho_{do} + \frac{\tau_{dd} (r_{do} \tau_{oo} + r_{dd} \tau_{do})}{1 - r_{dd} \rho_{dd}} \]

\[ r_{sd}^* = \rho_{sd} + \frac{(\tau_{ss} r_{sd} + \tau_{sd} r_{dd}) \tau_{dd}}{1 - r_{dd} \rho_{dd}} \]

\[ r_{dd}^* = \rho_{dd} + \frac{\tau_{dd} r_{dd} \tau_{dd}}{1 - r_{dd} \rho_{dd}} \]

\( \tau_{ssoo} = \) bi-directional gap fraction for vegetation canopies

\( \tau_{ssoo} = \tau_{ss} \tau_{oo} \) for the atmosphere

These are employed to couple soil and canopy, and next to couple the surface with the atmosphere
Media

- Atmosphere
  - Absorption spectra of gases
  - Isotropic medium (interception of radiation independent of direction)
  - Forward scattering of aerosols
  - Polarisation
• Water

  – Air-water interface (Fresnel reflection)
  – Forward scattering by particles
  – Main constituents sediment, chlorophyll (algae), dissolved organic matter (DOM)
  – Sea-bottom influence
Soils

- Semi-infinite medium
- Semi-empirical models (Hapke-model)
- Smooth spectra, with water absorption features
- Mineral detection by hyperspectral sensing (SWIR region)
• Plant leaves

  – Reflectance & Transmittance
  – Absorption by chlorophyll and water
  – Scattering by cell walls and intercellar spaces
  – Some spectral influence of dry matter (cellulose, lignin), and other pigments
• Vegetation canopies
  – Leaves, stems, heads, flowers, twigs, branches, etc.
  – Interception dependent on incidence direction (non-spherical medium)
  – 3-D structure gives rise to “hot spot” effect
  – Mixture of spectral and structural properties
Mixing models

• Remote sensing data may contain contributions from several objects

• 1) Horizontal mixing: e.g. trees, bare soil, mixed pixel effect

• 2) Vertical mixing: e.g. sea bottom, water body, atmosphere (lower media are partly covered by higher media)
Analogy to a pile of glass plates, including absorption inside the plates. Scattering simulated from glass-air interfaces.
PROSPECT parameters

- Cab = leaf chlorophyll concentration in $\mu$g/cm$^2$
- Cw = water content in g/cm$^2$ or cm EWT
- Cd = dry matter content in g/cm$^2$
- Cs = senescent material concentration (brown pigments) in arbitrary units
- N = leaf structure parameters (# of ‘glass plates’, or ~leaf thickness)

- Output: leaf reflectance $\rho$, transmittance $\tau$
PROSPECT spectra for green leaf

Reflectance / transmittance (%)

Wavelength (nm)

Cab_green 70.0
Cw_green 0.008
Cdm_green 0.003
Cs_green 0.05
N_green 1.500
PROSPECT spectra for brown leaf

Reflectance, transmittance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Cab_brown</td>
<td>5.0</td>
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<tr>
<td>Cw_brown</td>
<td>0.001</td>
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<tr>
<td>Cdm_brown</td>
<td>0.005</td>
</tr>
<tr>
<td>Cs_brown</td>
<td>1.00</td>
</tr>
<tr>
<td>N_brown</td>
<td>2.000</td>
</tr>
</tbody>
</table>
• Suits / SAIL and descendants
• INFORM (see lectures Martin Schlerf)
• 5-Scale (Canada)
• DART (France)
• 3D ray-tracing models
• RAMI (JRC, Ispra) numerical experiments
SAIL model

- scattering from arbitrarily inclined leaves
- canopy reflectance model (1981)
- refinement of Suits model (H and V leaves)
- solved by boundary condition method
- parameters $\rho, \tau, r_s, \text{LAI}, \text{LIDF}, \theta_s, \theta_o, \psi, f_{\text{sky}}$
Assumptions

- Homogeneous canopy layer, of infinite horizontal extension (1D-model)
- Leaves have Lambertian reflection and transmission
- Leaf azimuth distribution uniform (random)
- Lambertian soil background
- 4-stream approximation
4-stream RT equation

Generic four-stream RT equation (for any media)

\[
\frac{d}{d\tau} \begin{pmatrix}
E_s \\
E^- \\
E^+ \\
E_o
\end{pmatrix} = \begin{pmatrix}
-k & -\kappa & \kappa & K \\
\kappa & E^- & E^+ \\
E^- & E^+ & E_o \\
\kappa & K & E_o
\end{pmatrix} + \begin{pmatrix}
s' & \sigma' & \sigma & 0 \\
-s & -\sigma & -\sigma' & 0 \\
-w & -v & -v' & 0 \\
-w & -v & -v' & K
\end{pmatrix} \begin{pmatrix}
E_s \\
E^- \\
E^+ \\
E_o
\end{pmatrix} = \begin{pmatrix}
-k & -a & \sigma & 0 \\
s' & -a & \sigma & 0 \\
-s & -\sigma & a & 0 \\
-w & -v & -v' & K
\end{pmatrix} \begin{pmatrix}
E_s \\
E^- \\
E^+ \\
E_o
\end{pmatrix}
\]

In SAIL models we use \(x = \) relative optical height, and \(L = \) leaf area index
\(L = \) total one-sided leaf area per unit ground area

\[
\frac{d}{Ldx} \begin{pmatrix}
E_s \\
E^- \\
E^+ \\
E_o
\end{pmatrix} = \begin{pmatrix}
k & -s' & a & -\sigma \\
-s' & a & -\sigma & 0 \\
s & \sigma & -a & 0 \\
w & v & v' & -K
\end{pmatrix} \begin{pmatrix}
E_s \\
E^- \\
E^+ \\
E_o
\end{pmatrix}
\]

\[x = 0\]

\[x = -1\]

Coefficients are dimensionless and depend only on geometry and leaf properties
For arbitrarily inclined Lambertian leaves and random leaf azimuth:

\[ k = f(\text{LIDF}, \theta_s) \]
\[ K = f(\text{LIDF}, \theta_o) \]
\[ a, \sigma = f(\text{LIDF}, \rho, \tau) \]
\[ s, s' = f(\text{LIDF}, \rho, \tau, \theta_s) \]
\[ v, v' = f(\text{LIDF}, \rho, \tau, \theta_o) \]
\[ w = f(\text{LIDF}, \rho, \tau, \theta_s, \theta_o, \psi) \]

LIDF = leaf inclination distribution function
\[ \rho \] = leaf reflectance
\[ \tau \] = leaf transmittance
Illustration of SAIL coefficients
Leaf inclination and azimuth

\[ \theta_\ell \]

\[ \varphi_\ell \]
Hemispherical diffuse interactions

\[ \kappa = 1 \]

\[ \sigma = \frac{\rho + \tau}{2} + \frac{\rho - \tau}{2} \cos^2 \theta_{\ell} \]

\[ \sigma' = \frac{\rho + \tau}{2} - \frac{\rho - \tau}{2} \cos^2 \theta_{\ell} \]

\[ a = \kappa - \sigma' \]
(Bi)-directional interactions

\[
\cos \delta_s = \cos \theta_s \cos \theta_\ell + \sin \theta_s \sin \theta_\ell \cos (\varphi_s - \varphi_\ell) \\
\cos \delta_o = \cos \theta_o \cos \theta_\ell + \sin \theta_o \sin \theta_\ell \cos (\varphi_o - \varphi_\ell) \\
|\varphi_s - \varphi_o| = \psi
\]

\[
f_s = \frac{\cos \delta_s}{\cos \theta_s} \quad ; \quad f_o = \frac{\cos \delta_o}{\cos \theta_o}
\]

\[
k = |f_s| \\
s = |f_s| \frac{\rho + \tau}{2} + f_s \frac{\rho - \tau}{2} \cos \theta_\ell \\
s' = |f_s| \frac{\rho + \tau}{2} - f_s \frac{\rho - \tau}{2} \cos \theta_\ell \\
v = |f_o| \frac{\rho + \tau}{2} + f_o \frac{\rho - \tau}{2} \cos \theta_\ell \\
v' = |f_o| \frac{\rho + \tau}{2} - f_o \frac{\rho - \tau}{2} \cos \theta_\ell \\
w = |f_s f_o| \frac{\rho + \tau}{2} + f_s f_o \frac{\rho - \tau}{2}
\]
Leaf inclination distribution functions (LIDFs)

- **planophile**: horizontal leaves are most frequent
- **erectophile**: vertical leaves are most frequent
- **plagiophile**: oblique leaves are most frequent
- **extremophile**: oblique leaves are least frequent
- **uniform**: all leaf inclinations are equally frequent
- **spherical**: all 3D-orientations are equally frequent (equal to distribution of surface elements on a sphere)

Parameterisation used in SAIL models:

- $a$ controls **average** leaf inclination
- $b$ controls **bimodality** of distribution
Cumulative LIDFs generated with \((a,b)\) parameters.

- **planophile**
- **erectophile**
- **extremophile**
- **plagiophile**
- **uniform**
- **approx. spherical**
- **spherical**
Fractions of green and brown leaves and a layer dissociation factor $D$, as used in the 2-layer models GeoSAIL and 4SAIL2

$D = 1$ means complete dissociation, e.g. all green leaves in the top layer, and all brown leaves in the bottom layer.

$D = 0$ means a perfect homogeneous mixture.
Clumping

Projection of a tree crown onto the background surface from two directions, sun and view.

Overlap between projections is estimated from spatial correlation function, as in FLIM (Rosema et al., 1992)

Clumping parameters considered:

- \( C_v \) = vertical crown coverage
- \( \zeta \) = ratio crown diameter / crown height

\[ \zeta = \frac{d}{h} \]
Order of adding components in the SLC model

- Atmosphere
- Top canopy layer
- Bottom canopy layer
- Crown clumping
- Soil background
Canopy structure input parameters of 4SAIL2 model

- **LAI**  leaf area index
- **LIDF\textsubscript{a}**  controls average leaf inclination
- **LIDF\textsubscript{b}**  controls bimodality of distribution
- **hot**  hot spot size parameter, $\sim$ leaf width / canopy height
- **f\textsubscript{B}**  fraction brown leaves
- **D**  layer dissociation factor
- **Cv**  vertical crown cover
- **zeta**  tree shape factor
Fluxes considered
1. Direct solar flux
2. Diffuse downward flux
3. Diffuse upward flux
4. Direct observed flux (radiance)

Solar zenith angle sza
Viewing zenith angle vza
Relative azimuth angle raa

Parameters of SLC model
- Leaf Area Index LAI
- LIDF leaf slope parameter a
- LIDF bimodality parameter b
- Hot spot parameter hot
- Fraction brown leaf area fB
- Layer dissociation factor D
- Crown coverage Cv
- Tree shape factor zeta

Dry soil reflectance spectrum
Soil moisture SM
Soil BRDF Parameters (b, c, B0, h)
Chlorophyll Cab
Water Cw
Dry matter Cdm
Senescent material Cs
Mesophyll structure N

Four-stream RT modelling
- Fluxes considered
- Parameters of SLC model
SLC demo Visual Basic program (control window)
### SLC demo Visual Basic program

#### Table:

<table>
<thead>
<tr>
<th>Soil</th>
<th>Leaf</th>
<th>Canopy</th>
<th>Angles</th>
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</thead>
<tbody>
<tr>
<td>LAI</td>
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<td>0.15</td>
<td>Plot spectra</td>
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<tr>
<td>LidF a</td>
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<tr>
<td>LidF b</td>
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<tr>
<td>Hot</td>
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<td>zeta</td>
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</tr>
</tbody>
</table>

*Plot canopy absorption for red and red*

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#### Graphs:

- **Green leaf spectra (PROSPECT model)**
- **Brown leaf spectra (PROSPECT model)**
- **Single scattering albedo**

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Application path: C:\Wout\O\Projects\41 BV\Solanely\Software\SLC\VB

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ESA ADVANCED TRAINING COURSE ON LAND REMOTE SENSING 28 June-3 July 2009 | Prague (Czech Republic)
Soil moisture effect according to model of Bach & Mauser (1994)

Modelling the effects of
- refraction index
- water absorption spectrum
BRDFs in the principal plane simulated with SLC (3 hot spots)

- Hot spot of bare soil (Hapke model)
- Hot spot of tree crowns
- Hot spot of foliage

Cv = vertical crown cover %
Crown LAI = 4