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Radiative Transfer Modeling in Vegetation

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With collaborations of:

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Institute for Environment and Sustainability

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Outline

- Scientific Problems with Space Remote Sensing
- Radiative Transfer Equations
- Radiative Transfer Modeling for vegetation canopy
- RAMI
- Conclusion

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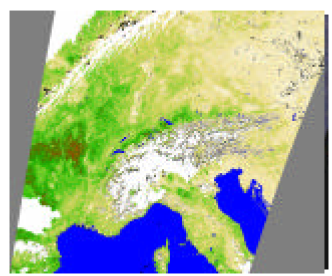
What is the main scientific issue in remote sensing?

- Remote sensing instruments on space platforms are sophisticated detectors recording the occurrence of elementary events (the absorption of photons or electromagnetic waves) as variations in electrical currents or voltages.

- Users, on the other hand, require information on events and processes occurring in the geophysical environment (e.g., atmospheric pollution, oceanic currents, terrestrial net productivity, etc.)



DEFORESTATION

Source: Goscinny & Uderzo,1971, Hachette

REFORESTATION

Source: Goscinny & Uderzo,1971, Hachette

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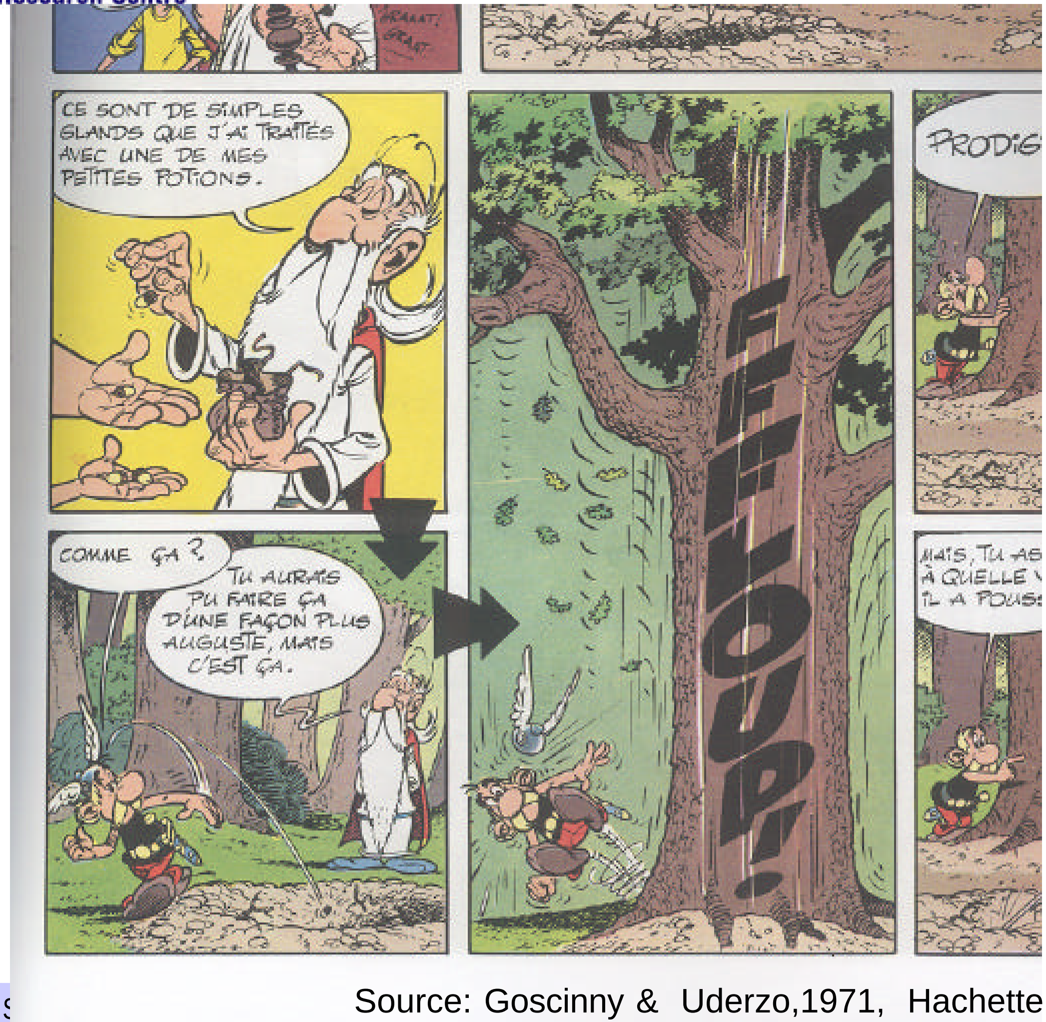

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- Extracting useful environmental information from data acquired in space is the main challenge facing remote sensing scientists.

How is remote sensing exploited?

- The signals detected by the sensors are immediately converted into digital numbers and transmitted to dedicated receiving stations, where these data are heavily processed.

- The effective exploitation of remote sensing data to reliably generate useful, pertinent information hinges on the availability and performance of specific tools and techniques of data analysis and interpretation.

- A variety of mathematical models can be used for this purpose; they are implemented as computer codes that read the data or intermediary products and ultimately lead to the generation of products and services usable in specific applications…. User is happy !

Why is remote sensing called an inverse problem?

- Since space borne instruments can only measure the properties of electromagnetic waves emitted or scattered by the Earth, scientists need first to understand where these waves originate from, how they interact with the environment, and how they propagate towards the sensor.

- To this effect, they develop models of radiation transfer, assuming that everything is known about the sources of radiation and the environment, and calculate the properties of the radiation field as the sensor should measure them. This is the so-called *direct problem*.

Why is remote sensing called an inverse problem?

- In practice, one does acquire the measurements from the satellite, and would like to know what is going on in the environment:

→ This is the *inverse problem*, which is much more complicated: Knowing the value of the electromagnetic measurements gathered in space, how can we derive the properties of the environment that were responsible for the radiation to reach the sensor?

Radiative Transfer Modeling

- In solar domain, radiation transfer models are tools to represent the scattering and absorption of radiation by scattering elements/centers. They should satisfy energy conservation.
- Spectral properties are depending on the geophysical medium: atmosphere, ocean, soil, or vegetation
- Monograph dealing with RT problems in geophysics (Chandrasekhar (1960), Van de Hulst (1957), Lenoble (1993), Hapke (1993), Liou (1980) etc…) mainly concentrate on mathematical issues related to solving equations.

- Rather than discussing the solving of approximate equations applicable to realistic geophysical situations, we will concentrate on exact and light mathematical treatment of a simplified physical system…

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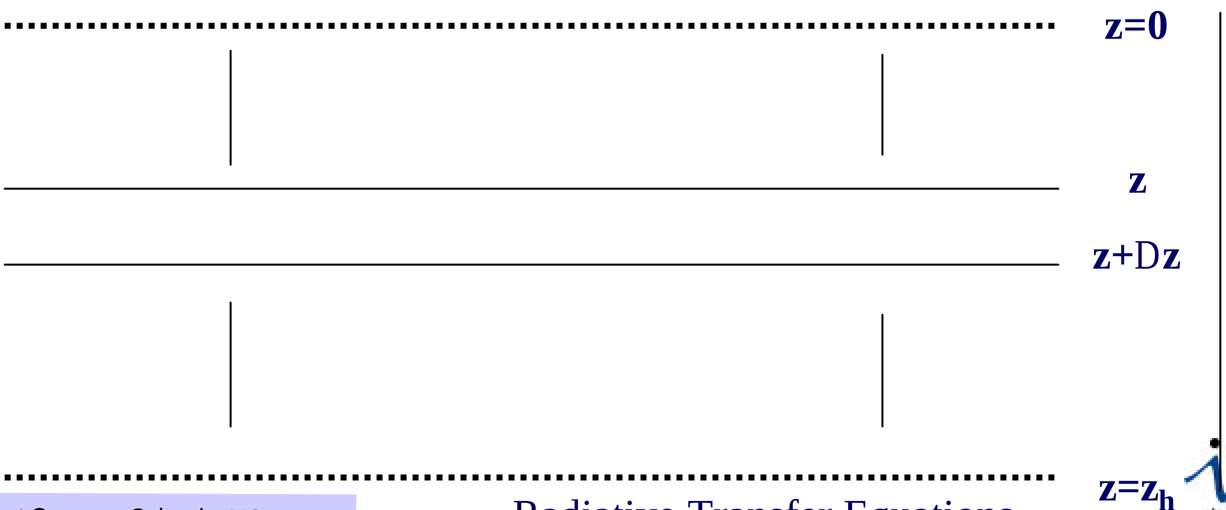
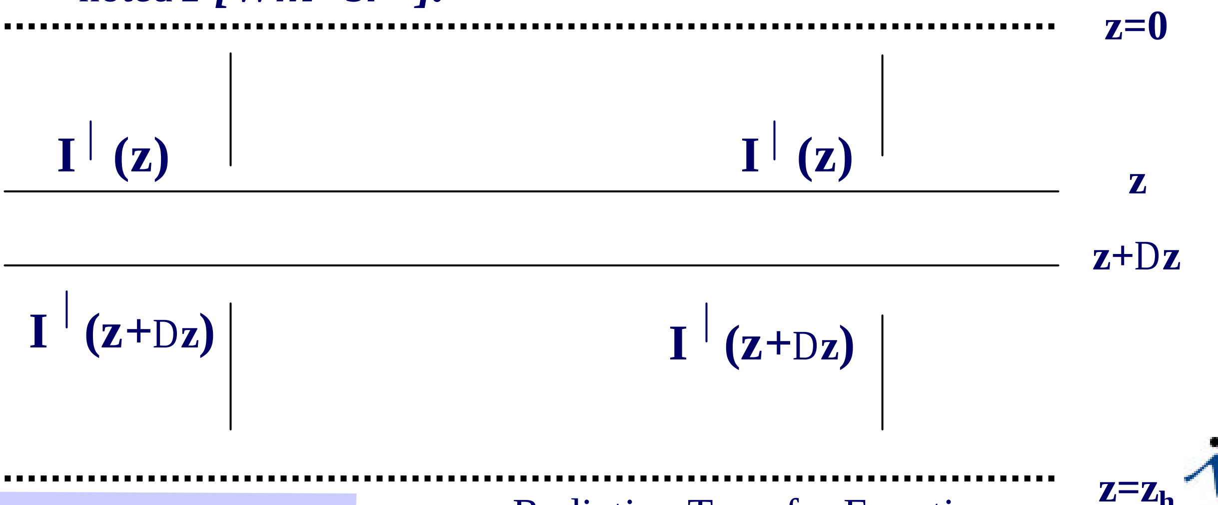
Radiative Transfer Equations (1)

- *Exact and light mathematical treatment of a simplified physical system*
- The system under consideration will have the following properties:
  - A continuous scattering-absorbing medium, infinite in lateral extent, bounded by two parallel planes, *i.e.* a plane-parallel medium.
  - Radiation can be scattered in only two directions, upward and downward.



Radiative Transfer Equations (1)

- The system under consideration will have the following properties:
  - Radiation or “ensemble of photons” is emitted by sources outside the medium only.
  - The amount of mean monochromatic radiant energy traveling upward and downward that crosses a unit area per unit time is an intensity noted ***I [Wm^{-2}sr^{-1}].***



Basic Processes (1)

Scattering

"A physical process by which an ensemble of particles immerged into an electromagnetic radiation field remove energy from the incident waves to re-irradiate this energy into other directions"

Absorption

"A physical process by which an ensemble of particles immerged into an electromagnetic radiation field remove energy from the incident waves to convert this energy in a different form"

Extinction

"A physical process by which an ensemble of particles immerged into an electromagnetic radiation field remove energy from the incident waves to attenuate the energy of this incident wave"

Basic Processes (2)

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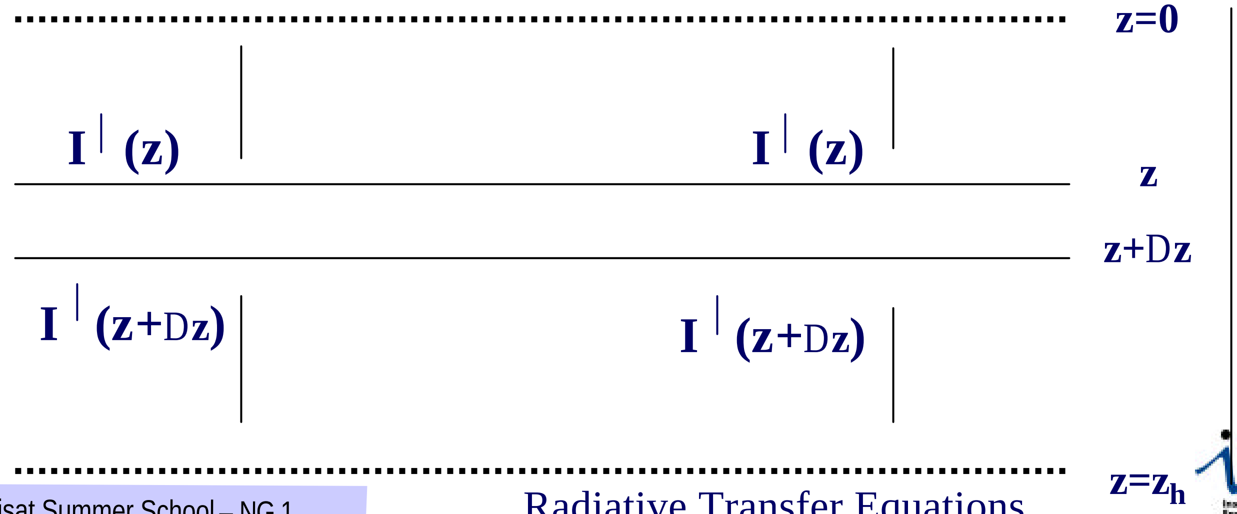
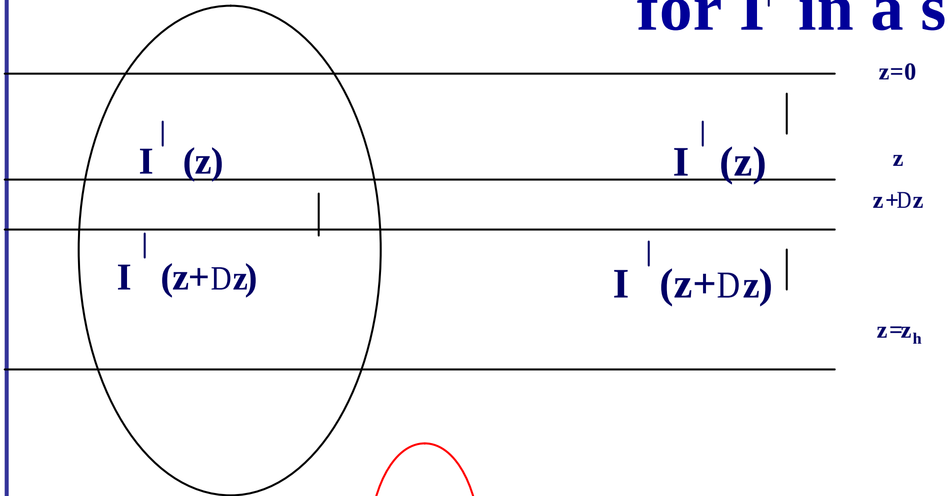
- The upward and downward intensities change along the vertical coordinate z in the medium according to the volumetric (individual cross-sections times the number per unit volume) coefficients of absorption, K (in m^{-1}) and scattering S (in m^{-1})

- Thus 1/S (1/K) have dimensions of length and may be interpreted as the absorption (scattering) mean free paths, i.e. the average distance between absorption (scattering) events.



Conservation of radiant energy for $I^{|}$ in a slab Dz (2)



$P^{||}$ is the probability that a photon directed upward is scattered downward

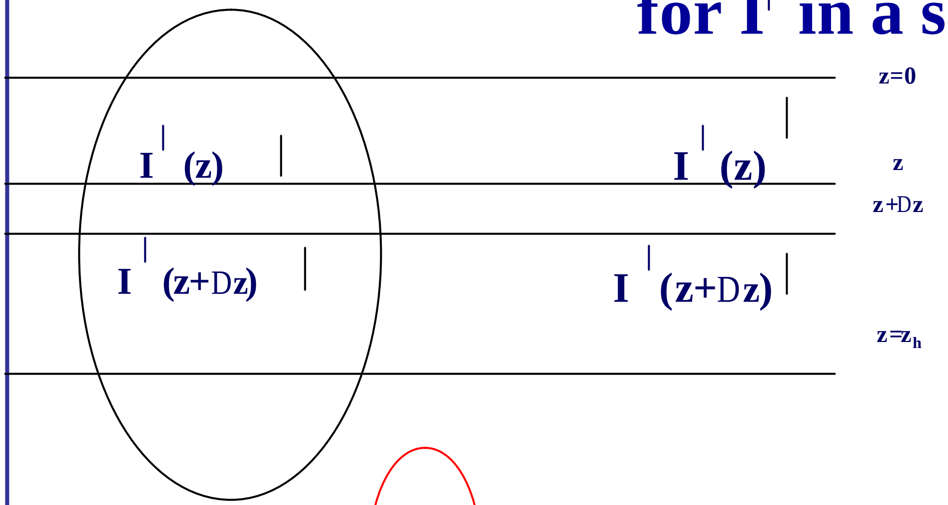
$P^{||}$ is the probability that a photon directed downward is scattered upward

$$\bar{I}^{-}(z) + S\Delta z \bar{P}^{-} I^{-}(z+\Delta z) =$$

$$K\Delta z \bar{I}(z) + S\Delta z \bar{P}^{-} \bar{I}(z) + \bar{I}(z+\Delta z)$$

coefficients of absorption, K (in m^{-1}) and scattering S (in m^{-1})

Conservation of radiant energy for I| in a slab Dz (2)



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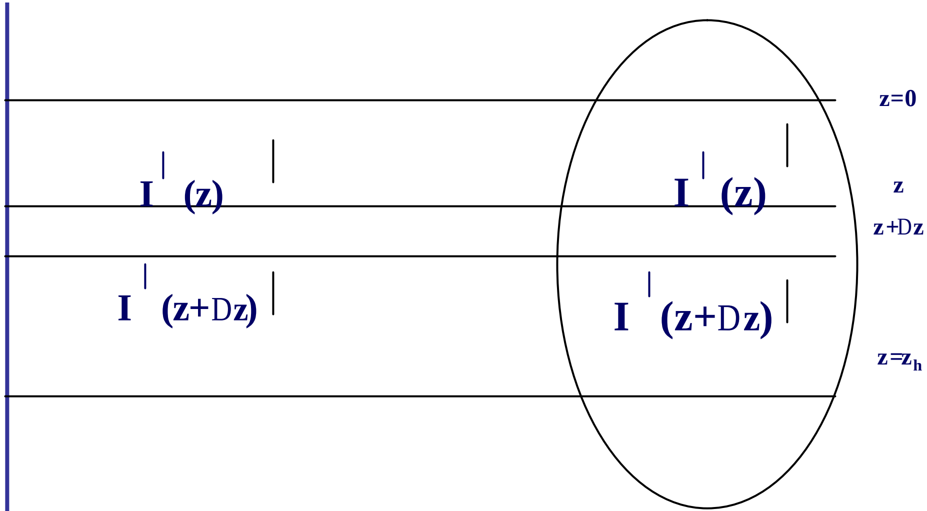


$$I^{-}(z+\Delta z)+S\Delta z P^{--}I^{-}(z)=$$

$$K\Delta z I^{-}(z+\Delta z)+S\Delta z P^{--}I^{-}(z+\Delta z)+I^{-}(z)$$

coefficients of absorption, K (in m^{-1}) and scattering S (in m^{-1})

Conservation of radiant energy in a slab Dz

Dividing both sides by Δz:

$$\frac{I^{\downarrow}(z+\Delta z)-I^{\downarrow}(z)}{\Delta z}=-KI^{\downarrow}(z)-SP^{\downarrow\uparrow}I^{\downarrow}(z)+SP^{\uparrow\downarrow}I^{\uparrow}(z)$$

…. taking the limit as Δz → 0 gives:

$$\frac{\partial I^{\downarrow}(z)}{\partial z}=-KI^{\downarrow}(z)-SP^{\downarrow\uparrow}I^{\downarrow}(z)+SP^{\uparrow\downarrow}I^{\uparrow}(z)$$

where I (z) decreases in the direction of increasing z

Conservation of radiant energy in a slab Δz

We obtain the two-stream equations

$$\frac{\partial I^{\downarrow}(z)}{\partial z} = -K I^{\downarrow}(z) - S P^{\downarrow\uparrow} I^{\downarrow}(z) + S P^{\uparrow\downarrow} I^{\uparrow}(z)$$

$$\frac{\partial I^{\uparrow}(z)}{\partial z} = +K I^{\uparrow}(z) + S P^{\uparrow\downarrow} I^{\uparrow}(z) - S P^{\downarrow\uparrow} I^{\downarrow}(z)$$

coefficients of absorption, K (in m^{-1}) and scattering S (in m^{-1})

Asymmetry factor for scattering processes

- We have for isotropic medium: $\mathbf{P}^{\uparrow\downarrow} = \mathbf{P}^{\downarrow\uparrow} \quad \mathbf{P}^{\downarrow\downarrow} = \mathbf{P}^{\uparrow\uparrow}$

$$P^{-\bar{}} + P^{--} = P^{\bar{}\,-} + P^{\bar{}\bar{}} = 1$$

- The asymmetry factor g is a single number, defined as *the mean cosine of the scattering angle* (-1 or +1 in our case):

$$g = (+1)P^{\bar{}\bar{}} + (-1)P^{\bar{}\,-}$$

- Typically: g = +1 for strict downward scattering,

g=-1 for strict upward scattering and,

g=0 for isotropic scattering.

- For the above set of equations, we have:

$$P^{-\bar{}} = P^{\bar{}\,-} = (1 - g)/2$$

$$P^{--} = P^{\bar{}\bar{}} = (1 + g)/2$$

Single scattering albedo

•Normalization of the radiation transport equations by the extinction factor E=S+K gives :

$$\frac{1}{E}\frac{\partial I^{-}(z)}{\partial z} = -\frac{K}{E} I^{-}(z) - \frac{S}{E} P^{--} I^{-}(z) + \frac{S}{E} P^{-} I^{-}(z)$$

which can be rewritten as:

$$\frac{1}{E}\frac{\partial I^{-}(z)}{\partial z} = -I^{-}(z) + \omega\frac{(1+g)}{2} I^{-}(z) + \omega\frac{(1-g)}{2} I^{-}(z)$$

$$\frac{1}{E}\frac{\partial I^{-}(z)}{\partial z} = +I^{-}(z) - \omega\frac{(1+g)}{2} I^{-}(z) - \omega\frac{(1-g)}{2} I^{-}(z)$$

where $\omega = \frac{S}{S+K} = \frac{S}{E}$ is called the single scattering albedo

expressing the probability for the photons to be scattered.

Single scattering albedo

$$\frac{1}{E}\frac{\partial I^{-}(z)}{\partial z} = -I^{-}(z) + \omega\frac{(1+g)}{2}I^{-}(z) + \omega\frac{(1-g)}{2}I^{-}(z)$$

$$\frac{1}{E}\frac{\partial I^{-}(z)}{\partial z} = +I^{-}(z) - \omega\frac{(1+g)}{2}I^{-}(z) - \omega\frac{(1-g)}{2}I^{-}(z)$$

$$\omega = \frac{S}{S+K} = \frac{S}{E}$$

- Single scattering albedo ω =0 for total absorption (no scattering)
- Single scattering albedo ω =1 for total or conservative scattering (no absorption)

Optical thickness

- The variable *physical depth* ∂z can be multiplied by the optical factor S+K=E to transform into an *optical thickness* $\partial \tau$

$$\tau = \int_0^z (S+K)\partial z$$

$$\frac{\partial I^{\uparrow}(z)}{\partial \tau} = -I^{\uparrow}(z) + \omega\frac{(1+g)}{2}I^{\uparrow}(z) + \omega\frac{(1-g)}{2}I^{\downarrow}(z) \qquad \textbf{(1)}$$

$$\frac{\partial I^{\downarrow}(z)}{\partial \tau} = +I^{\downarrow}(z) - \omega\frac{(1+g)}{2}I^{\downarrow}(z) - \omega\frac{(1-g)}{2}I^{\uparrow}(z) \qquad \textbf{(2)}$$

These last equations are typical two-stream equations for the system.

Two-stream equations

- In a more compact form [with (1) - (2) and (1)+(2)]:

$$\frac{\partial (I^{\uparrow} - I^{\downarrow})}{\partial \tau} = -(1-\omega)(I^{\uparrow} + I^{\downarrow})$$

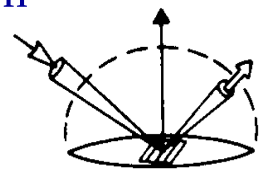
$$\frac{\partial (I^{\uparrow} + I^{\downarrow})}{\partial \tau} = -(1-\omega g)(I^{\uparrow} - I^{\downarrow})$$

Key variables to represent the radiative transfer processes are:

- ω : the single scattering albedo
- g : the asymmetry factor of the phase function
- τ : the optical thickness of the medium

Extension to N Flux (1)

• These equations can be extended to *N* flux to obtain *N* coupled differential equations including *N+1* terms on the right side.



•The first term represents the extinction and the N remaining terms represent all the possible ways in which radiation is scattering into one direction Ω from all other directions Ω'.

•In the limit when N goes to infinity, sums become integrals and the set of equations collapses into a single integro-differential equation:

$$-m\frac{\partial I(z,\Omega)}{\partial t}+\tilde{s}_e(z,\Omega)I(z,\Omega)=\int_{4\Pi}\tilde{s}_s(z,\Omega'\to\Omega)I(z,\Omega')d\Omega'$$

Extension to N Flux (2)

In the limit when N goes to infinity, sums become integrals and the set of equations collapses into a single integro-differential equation:

$$-\mu \frac{\partial I(z,\Omega)}{\partial \tau} + \tilde{\sigma}(z,\Omega) I(z,\Omega) = \int_{4\Pi} \tilde{\sigma}_s(z,\Omega' \rightarrow \Omega) I(z,\Omega') d\Omega'$$

$I(z, \Omega)$ represents the intensity ($W\, m^{-2} sr^{-1}$) at point z in the exiting direction Ω,

σ (m^{-1}) and σ_s ($m^{-1} sr^{-1}$) are the extinction and differential scattering coefficients, respectively, taken at the same point z along the direction Ω.

Vertical radiative coupling between geophysical media

Medium		Depth
Atmosphere	Upper limit (1) RTE Lower Limit (1)	Z_A
Vegetation	Upper limit (2) RTE Lower Limit (2)	Z_V
Soil	Upper limit (3) RTE Lower Limit (3)	Z_S

In each medium, the transfer of radiation may be represented by the following approximate equation:

$$[-m\frac{\partial}{\partial t}+\tilde{s}_e(z,\Omega,\Omega_O)]I(z,\Omega)=\int_{4\Pi}\tilde{s}_s(z,\Omega'\rightarrow\Omega)I(z,\Omega')d\Omega'$$

Extinction coefficient — **Differential scattering coefficient**

Vertical radiative coupling between geophysical media

Atmosphere	•Non oriented small scatterers •Infinite number of scatterers •Low density turbid medium
Vegetation	•Oriented finite-size scatterers •Finite number of scatterers •Dense discrete medium
Soil	•Oriented small-size scatterers •Infinite number of clustered scatterers •Compact semi-infinite medium

Vertical radiative coupling between geophysical media

The description of the interaction of a radiation field with a layered geophysical medium implies the solution of radiation transfer equations and the specification of appropriate boundary conditions

$$I^{\downarrow}(z_{ta},\Omega)=I_0 d(\Omega-\Omega_o) \qquad I^{\uparrow}(z_a,\Omega)$$

Atmosphere — Z_a

$$I^{\uparrow}(z_{ba},\Omega)=\frac{1}{\Pi}\int_{2\Pi} \boxed{g_v(z_{ba},\Omega,\Omega')} I^{\downarrow}(z_{ba},\Omega')\,|m'|\,d\Omega'$$

$$I^{\downarrow}(z_{tv},\Omega)=I^{\downarrow}(z_{ta},\Omega)\exp\left[\frac{-t_a}{|m_0|}\right]+I_d^{\downarrow}(z_{ba},\Omega)$$

Vegetation — Z_V

$$I^{\uparrow}(z_{bv},\Omega)=\frac{1}{\Pi}\int_{2\Pi} g_s(z_{bv},\Omega,\Omega')\boxed{I^{\downarrow}(z_{bv},\Omega')}\,|m'|\,d\Omega'$$

Soil — Z_S

$$I^{\uparrow}(z_{\infty},\Omega)=0$$

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Representation of vegetation canopy

‘Oriented’ scatterers elements in a finite volume

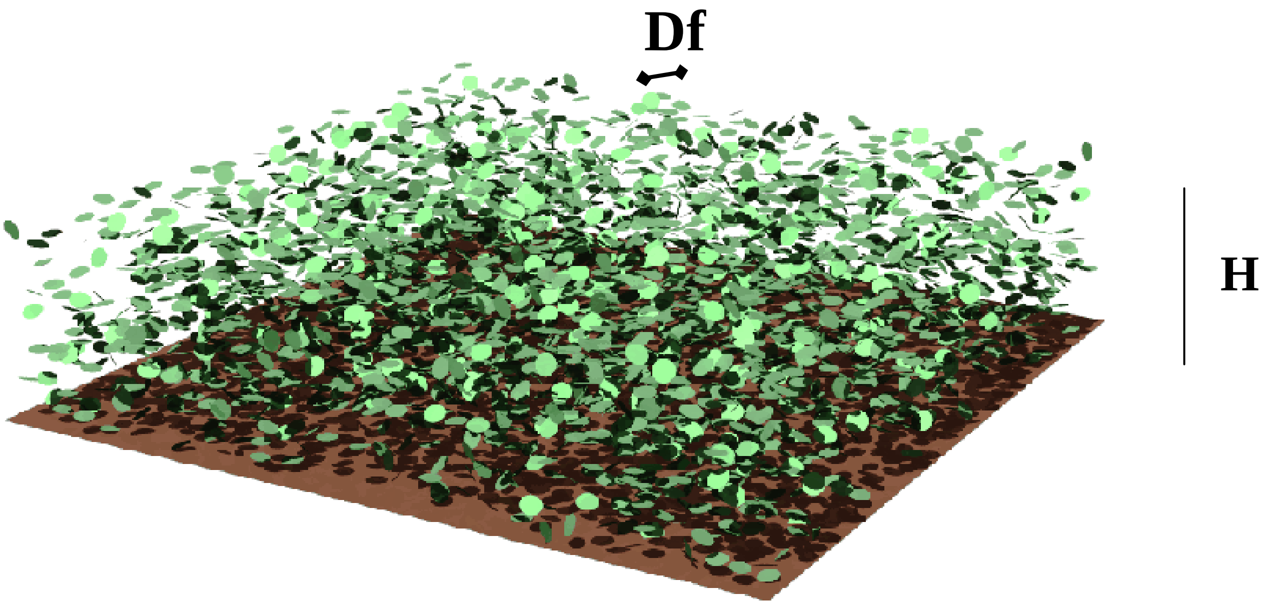
→ turbid medium

» Leaves are point-like scatterers

→ discrete medium

» Leaves are finited-size scatterers

Discrete canopy: 1D representation



Geometrical Parameters in 1D representation: Height of canopy, Size of a single leaf & Leaves orientation (leaf angle distribution)

Vegetation Optical Depth

- Leaf Area Index (LAI) is a quantitative measure of the amount of live green leaf material present in the canopy per unit ground surface.
- It is defined as the total one-sided area of all leaves in the canopy within a defined region.

$$LAI = \sum_{i=1}^{N} \lambda_i = \sum_{i=1}^{N} n_i a_i$$

N = # of layers

a_i = leaf surface

n_i = # leaves /m2

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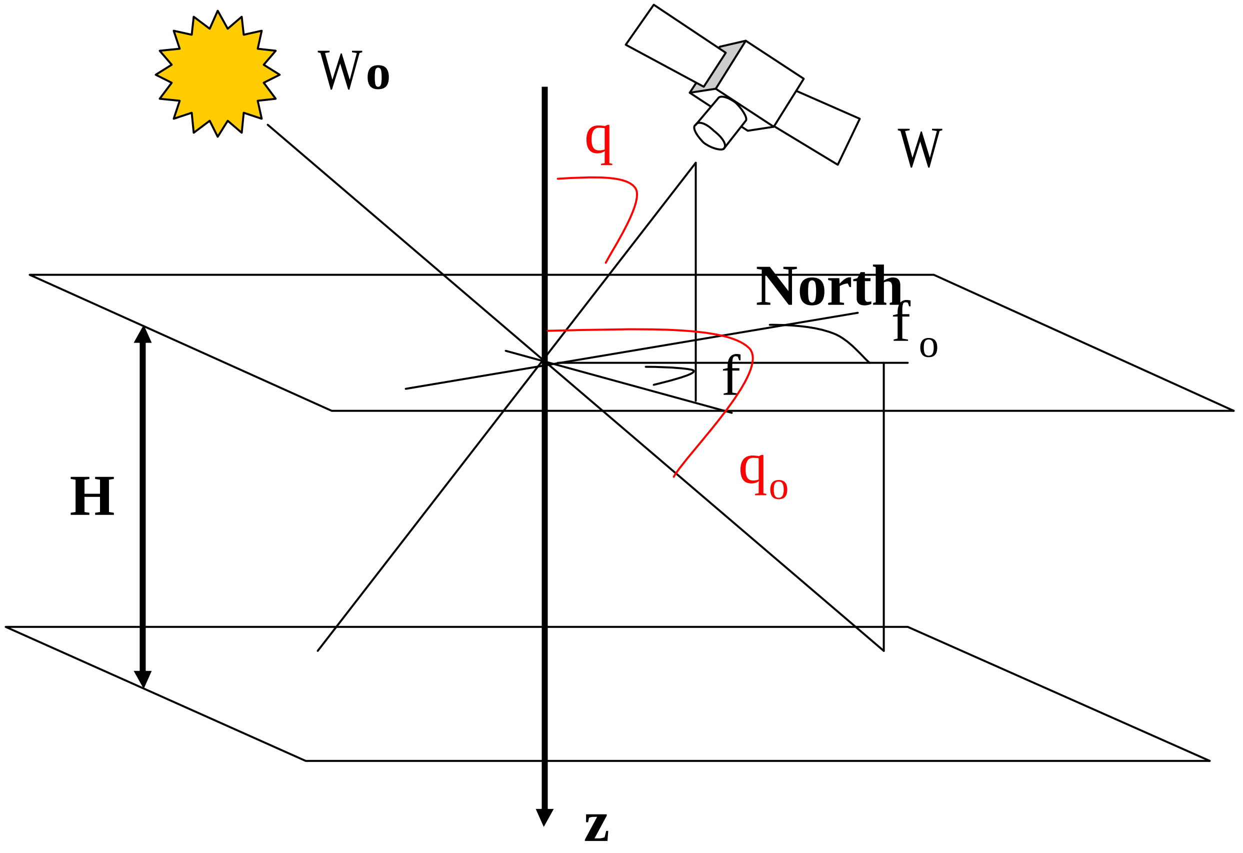
H : Height of canopy [m]

D **: Leaf Area Density [m^2/m^3]**

$$LAI = H.\Delta$$

Geometrical System



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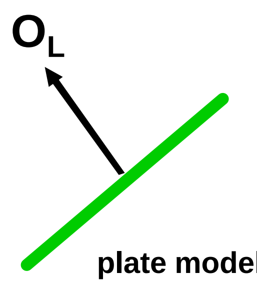
Extinction coefficient $\tilde{s}_e(z,\Omega,\Omega_O)$

$$[-m\frac{\partial}{\partial t} + \boxed{\tilde{s}_e(z,\Omega,\Omega_O)}]I(z,\Omega) = \int_{4\Pi} \tilde{s}_s(z,\Omega' \to \Omega)I(z,\Omega')d\Omega'$$

We assume that the canopy consists of **plane leaves with a leaf area density** l (**z**) defined to be the total one-sided leaf area per unit volume at depth z.
The probability that a leaf has a normal $O_\ell(?_\ell, j_\ell)$ directed away from the top surface, in a unit solid angle about O_ℓ is given by the leaf-normal distribution function $g_\ell(z,\Omega_\ell)$ which is normalized as

$$\frac{1}{2p}\int_{2p} df_\ell \int_0^1 dm_\ell\, g_\ell(z,\Omega_\ell) = 1$$



Extinction coefficient

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We now consider photons at a depth z travelling in direction Ω.
The **extinction coefficient** is then the probability, per unit path length, that the photon hits a leaf, i.e., the probability that a photon while traveling a distance ds along **Ω** is intercepted by a leaf divided by the distance ds.

$$s_e(z,\Omega) = G(z,\Omega)\, l_\ell(z)$$

Where the geometry factor G is the fraction of the total leaf area (per unit volume of the canopy) that is perpendicular to Ω

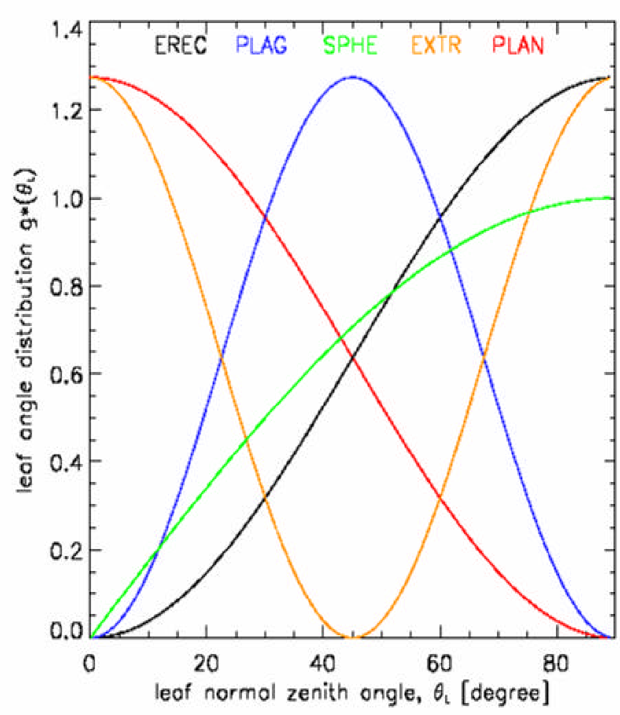
$$G(z,\Omega) = \frac{1}{2p} \int_{2p} g(\Omega_\ell)\, |\, \Omega_\ell \bullet \Omega \,|\, d\Omega_\ell$$

Ref: Ross (1981)

Leaf Orientations

Vegetation foliage features characteristic leaf-normal distributions, g($\mathbf{O}_L$) with preferred:

- azimuthal orientations, g(f $_L$)
- zenithal orientations, g(?$_L$):
  - erectophile (grass) (90^o)
  - planophile (water cress) (0^o)
  - plagiophile (45^o)
  - extremophile (0^o and 90^o)
  - uniform/spherical (all)
- time varying orientations:
  - heliotropism (sunflower)
  - para-heliotropism



Ref: Ross (1981)

Scattering properties of leaves

- Once the radiation is intercepted by the vegetation elements, it is scattered in directions determined by the leaf orientations and the leaf phase function

- Leaf reflection and transmission depend primarily on *wavelength*, plant species, growth condition, age and position in canopy.

- Directionality of leaf scattering depends on the leaf surface roughness, and the percentage of diffusely scattered photons from leaf interior.

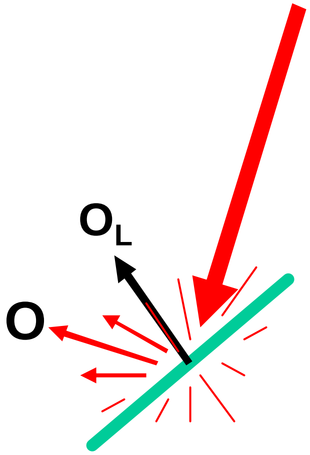


plate model

➢ Plate models often assume Bi-Lambertian scattering properties:
- radiation is scattered according to cosine law: $| \mathbf{O_L} \cdot \mathbf{O} |$
- magnitude depends on leaf reflection and transmission values

Ref: Ross (1981)

Leaf scattering properties

- Leaf scattering function for *classical plate scattering model*

$$f(\Omega' \text{ ® } \Omega, \Omega_\ell) = r_\ell \, |\Omega \cdot \Omega_\ell| / \pi \quad \text{if } (\Omega \cdot \Omega_\ell)(\Omega' \cdot \Omega_\ell) < 0$$

$$f(\Omega' \text{ ® } \Omega, \Omega_\ell) = t_\ell \, |\Omega \cdot \Omega_\ell| / \pi \quad \text{if } (\Omega \cdot \Omega_\ell)(\Omega' \cdot \Omega_\ell) > 0$$

Where r_l and t_l are the fraction of intercepted energy which are reflected (transmitted) following a simple cosine distribution law around the normal to the leaves.

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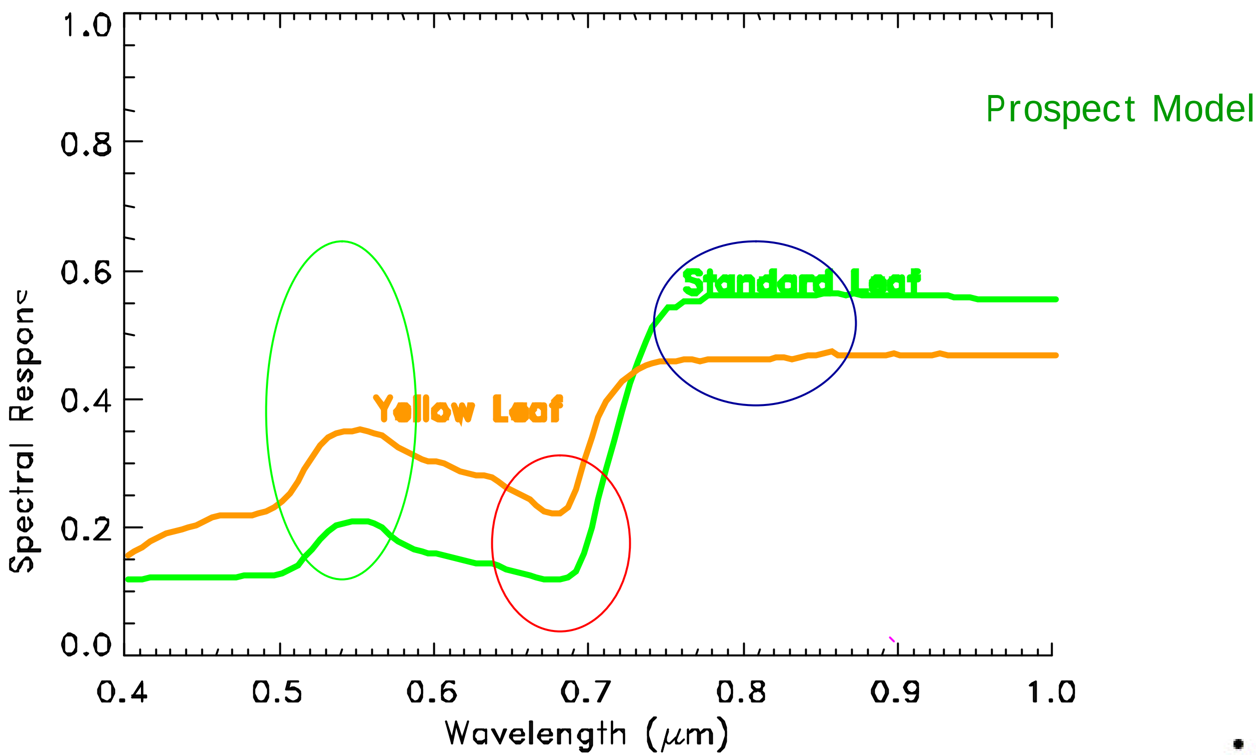
Spectral Leaves Profile



Ref: Jacquemoud and Baret (1990)

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Canopy scattering phase function

- Leaf properties are assumed to be the same throughout the canopy, we have

$$\frac{1}{\pi}\Gamma(z_k,\Omega' \rightarrow \Omega) \equiv \frac{1}{\pi}\Gamma(\Omega' \rightarrow \Omega)$$

$$\frac{1}{\pi}\Gamma(\Omega' \rightarrow \Omega) \equiv \frac{1}{2\pi}\int_{2\pi} g(\Omega_\ell)\,|\Omega' \cdot \Omega|\, f(\Omega' \rightarrow \Omega,\Omega_\ell)\,d\Omega_\ell$$

$g(\Omega_L)$ is the probability function for the leaf normal distribution Ω_L

f is the leaf phase function (when integrated over all exit photons directions, yields single scattering albedo ω).

Ref: Shultis & Myneni (1988) and Knyazihin *et. al.* (1992)

Specific Effects

•The presence of finite size scatterers implies that the radiation interception process by the leaves will not follow a continuous scheme, and in particular that radiation will be allowed to travel unimpeded within the free space between the scatterers.

•Since extinction occurs only at discrete locations, some of the radiation emerging from an arbitrary source, located inside or outside the canopy, any occasionally travel without any interaction in this canopy, depending on the shape and size of free space between these leaves.

Ref: Verstraete et. al. (1990) Ref: Gobron et al. (1997)

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Hot-spot Effects

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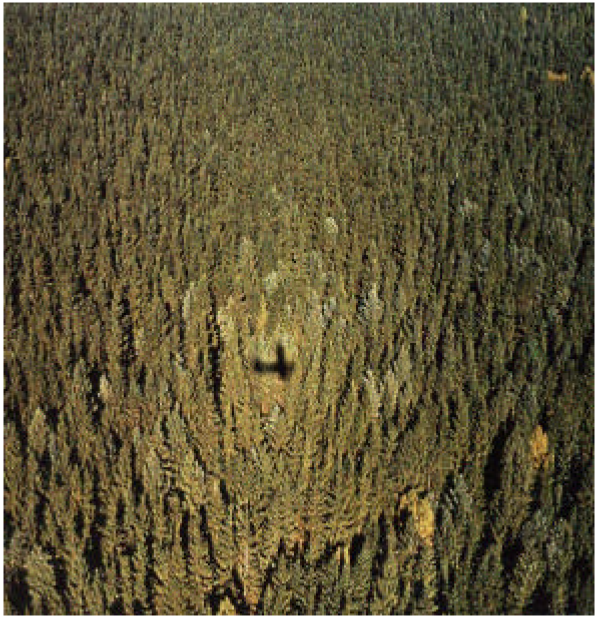
•When the radiation is scattered back in the direction from which it originates, the probability of further interaction with the canopy is lower than in other scattering directions.

•In case of RS measurements outside the canopy, this give rise to a relative increase in the value in the backscattering direction which is knows as the hot-spot phenomenon.



Ref: Verstraete et. al. (1990)

Ref: Gobron et al. (1997)

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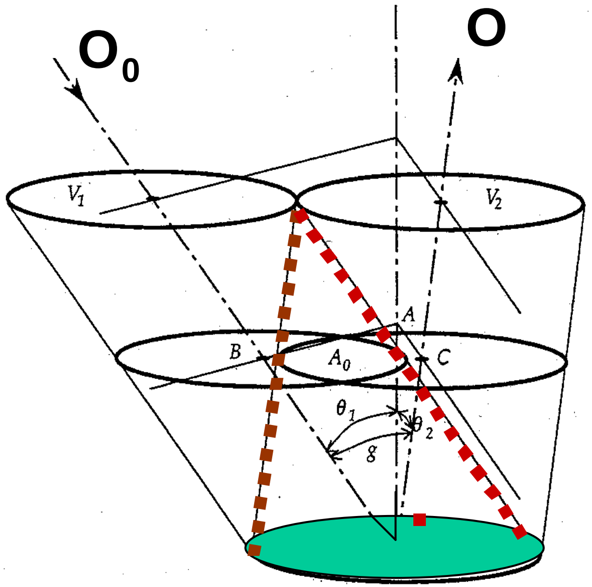
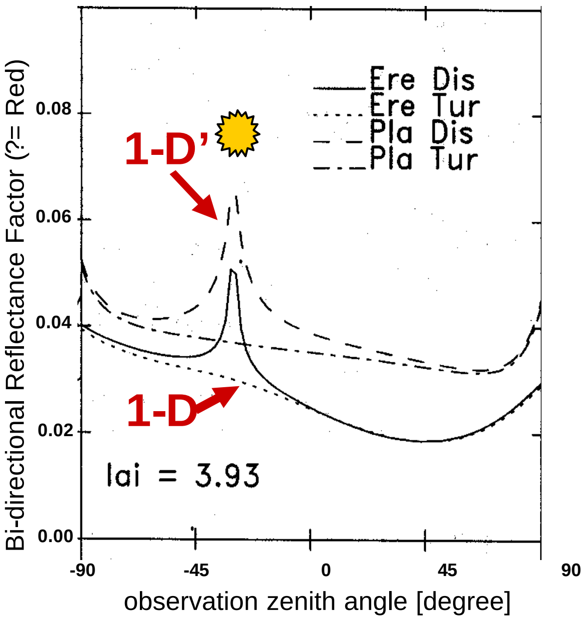
Hot-spot Effects

Extinction coefficient is modified adding hot-spot scale factor:

$s_e(z, O, O_0) = ?(z) \cdot G(O) \cdot O(z, O, O_0$





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Separation of Scattering Order

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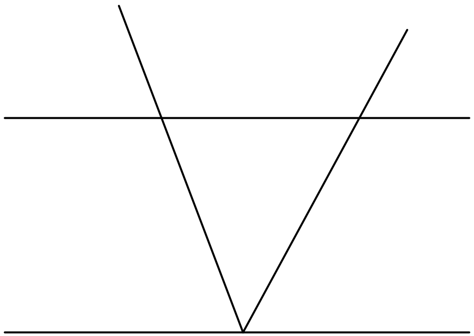
$$\rho(z_0,\Omega,\Omega_0) = \rho_0(z_0,\Omega,\Omega_0)$$

- Uncollided intensity



Ref: Gobron et al. (1997)

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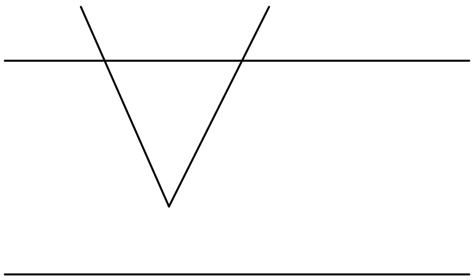
Separation of Scattering Order

$$\rho(z_0,\Omega,\Omega_0) = \rho_0(z_0,\Omega,\Omega_0) + \rho_1(z_0,\Omega,\Omega_0)$$

- Uncollided intensity
- Single Collided intensity

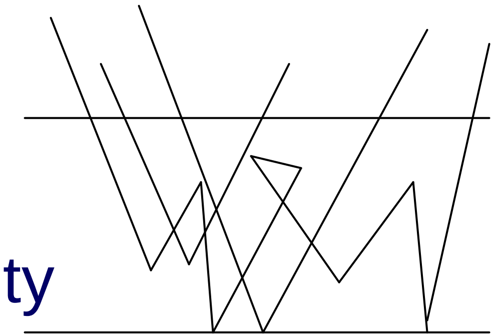


Ref: Gobron et al. (1997)

Separation of Scattering Order

$$\rho(z_0,\Omega,\Omega_0) = \rho_0(z_0,\Omega,\Omega_0) + \rho_1(z_0,\Omega,\Omega_0) + \rho_M(z_0,\Omega,\Omega_0)$$

- Uncollided intensity
- Single Collided intensity
- Multiple scattering intensity



Ref: Gobron et al. (1997)

Uncollided intensity (1)

Downward uncollided intensity at level z_k

$$I_{-}^{0}(z_k, \Omega_0) = I_s \left[1 - \lambda \frac{G(\Omega_0)}{|\mu_0|} \right]^k$$

Where $I_s = I^0(z_0, \Omega_0)\delta(\Omega - \Omega_0)$ is the incoming collimated beam at the top of canopy

Probability that a light ray within this beam is transmitted downward in the same direction through the first k layers

Ref: Gobron et al. (1997)

Uncollided intensity (2)

The radiation scattered by the soil, which provides the lower radiative boundary condition of the canopy system, for uncollided radiation is given by:

$$I_{-}^{0}(H,\Omega,\Omega_0) = \frac{1}{\pi}\gamma_s(H,\Omega,\Omega_0)\,|\mu_0|\,I_s\left[1 - \lambda\frac{G(\Omega_0)}{|\mu_0|}\right]^{K}$$

Where $\gamma_s(H,\Omega,\Omega_0)$ denotes the bidirectional reflectance factor of the soil at the bottom of canopy.

$$I_{-}^{0}(z_k,\Omega,\Omega_0) = \frac{1}{\pi}\gamma_s(H,\Omega,\Omega_0)\,|\mu_0|\,I_s\left[1 - \lambda\frac{G(\Omega_0)}{|\mu_0|}\right]^{K}\prod_{j=K}^{k+1}\left[1 - \lambda_K^{'}\frac{G(\Omega)}{\mu}\right]$$

Ref: Gobron et al. (1997)

Uncollided BRF

Applying last equation at the top of canopy and normalized by the intensity of the source of incoming direct solar radiation as well as by the reflectance of a Lambertian surface illuminated and observed under identical conditions ($|\mu_0|/\pi$) yields the contribution to the bidirectional reflectance factor due to this uncollided radiation, namely:

$$\rho_0(z_0,\Omega,\Omega_0) = \gamma_s(H,\Omega,\Omega_0)\left[1 - \lambda\frac{G(\Omega_0)}{|\mu_0|}\right]^K \left[1 - \lambda'_K\frac{G(\Omega)}{\mu}\right]^K$$

Ref: Gobron et al. (1997)

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Uncollided BRF in Principal Plan

Solar Zenith Angle: 20 [deg]

Solar Azimuth Angle: 0 [deg]

Radius: 0.05 [m]

Leaf Area Index: 3.0 [m2/m2]

Height of the canopy: 2.0 [m]

Normal Distribution: Erectophile

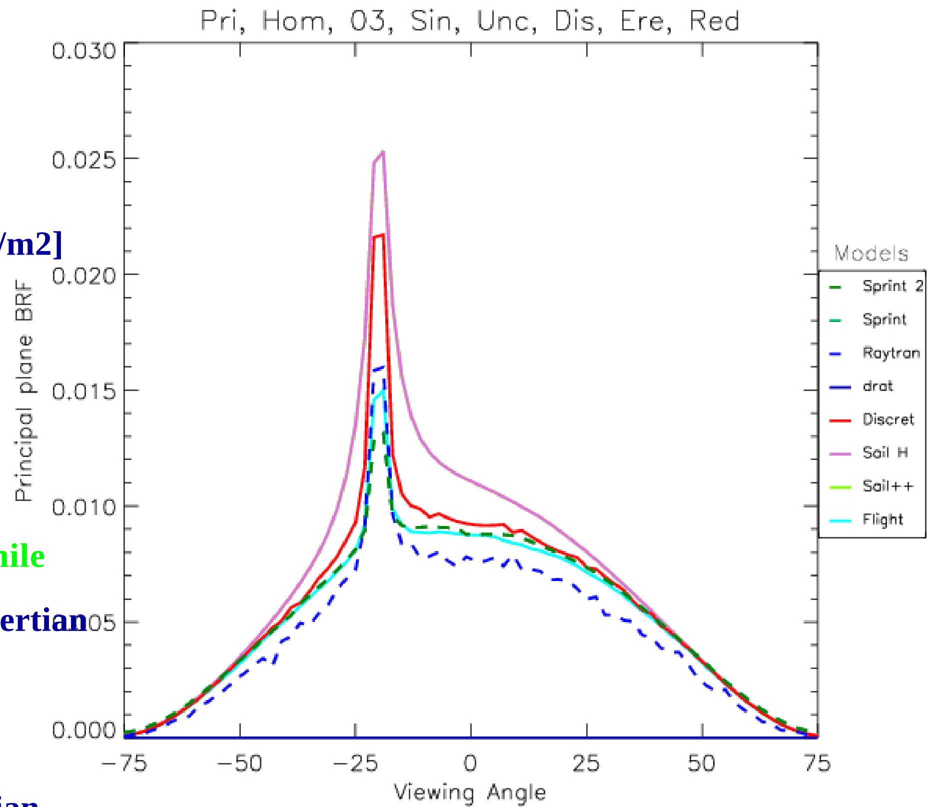
Leaf scattering law: Bi-Lambertian

Leaf reflectance: 0.0546

Leaf transmittance: 0.0149

Soil scattering law: Lambertian

Soil reflectance: 0.127



Source: www.rami.jrc.it

Uncollided BRF in Principal Plan

Solar Zenith Angle: 20 [deg]

Solar Azimuth Angle: 0 [deg]

Radius: 0.05 [m]

Leaf Area Index: 3.0 [m2/m2]

Height of the canopy: 2.0 [m]

Normal Distribution: Erectophile

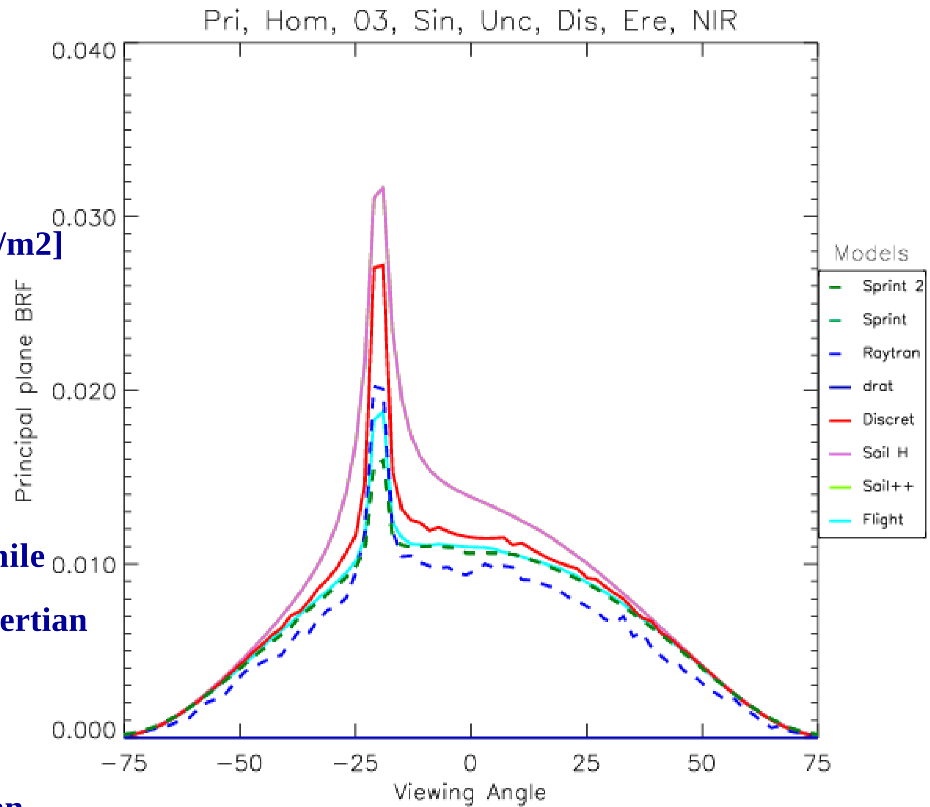
Leaf scattering law: Bi-Lambertian

Leaf reflectance 0.4957

Leaf transmittance 0.4409

Soil scattering law Lambertian

Soil reflectance 0.159



Source: www.rami.jrc.it

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Uncollided BRF in Cross Plan

Solar Zenith Angle: 20 [deg]

Solar Azimuth Angle: 0 [deg]

Radius: 0.05 [m]

Leaf Area Index: 3.0 [m2/m2]

Height of the canopy: 2.0 [m]

Normal Distribution: Erectophile

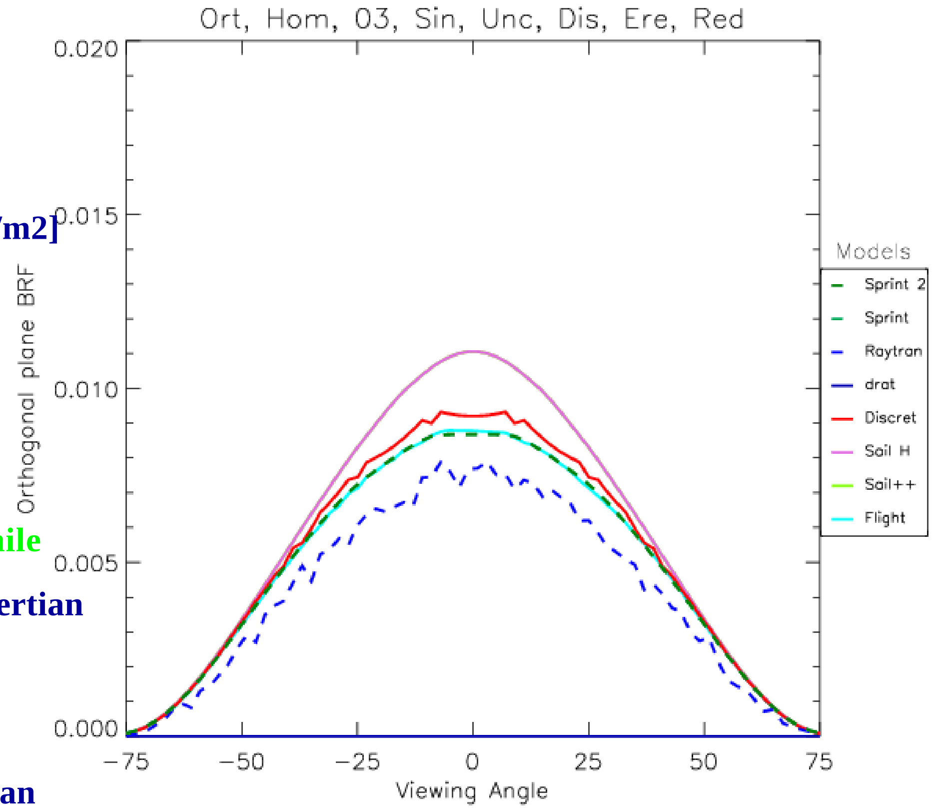
Leaf scattering law: Bi-Lambertian

Leaf reflectance: 0.0546

Leaf transmittance: 0.0149

Soil scattering law: Lambertian

Soil reflectance: 0.127



Source: www.rami.jrc.it

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Uncollided BRF in Cross Plan

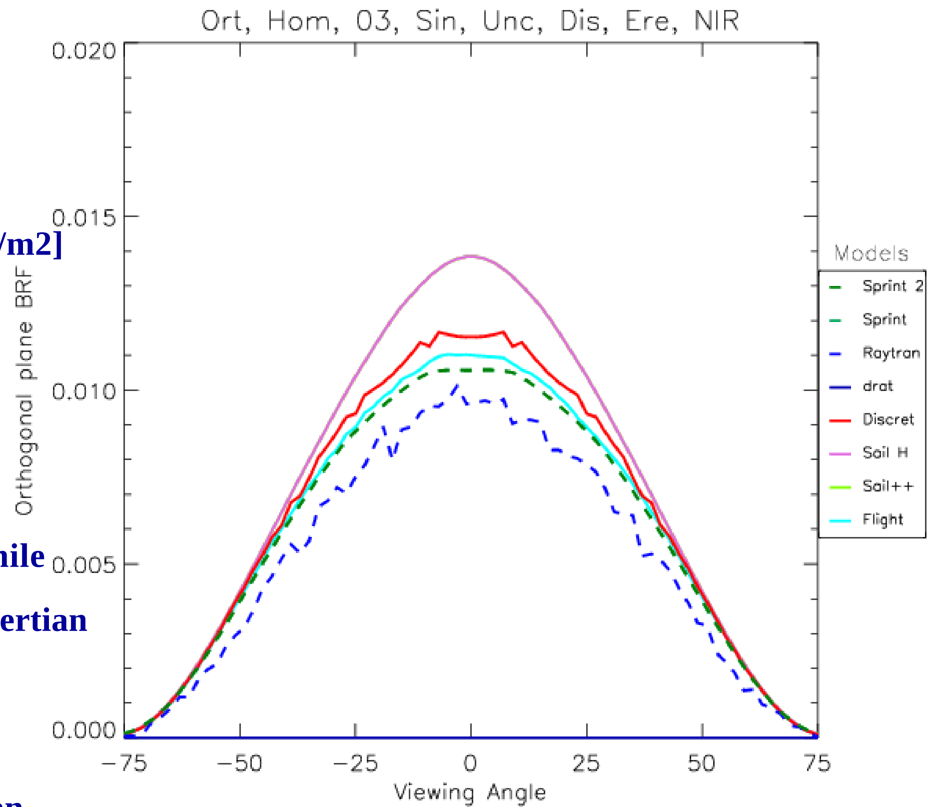
Solar Zenith Angle: 20 [deg]

Solar Azimuth Angle: 0 [deg]

Radius: 0.05 [m]

Leaf Area Index: 3.0 [m2/m2]

Height of the canopy: 2.0 [m]



Normal Distribution: Erectophile

Leaf scattering law: Bi-Lambertian

Leaf reflectance 0.4957

Leaf transmittance 0.4409

Soil scattering law Lambertian

Soil reflectance 0.159

Source: www.rami.jrc.it

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First collided Intensity (1)

The first collided intensity in downward direction Ω corresponds to the radiation scattered only once by leaves, but which has not interacted with the soil.

•Downward source coming from the direct intensity, attenuated through the first k layers, and scattered by the leaves according to their optical properties in layer k:

$$Q_{-}^{0}(z_k,\Omega,\Omega_0)=\frac{1}{\pi}\Gamma(\Omega_0\rightarrow\Omega)I_s\left[1-\lambda\frac{G(\Omega_0)}{|\mu_0|}\right]^{k}$$

•Downward intensity

$$I_{-}^{1}(z_k,\Omega,\Omega_0)=\frac{1}{\mu}\sum_{i=1}^{k}Q_{-}^{0}(z_i,\Omega,\Omega_0)\lambda\left[1-\lambda\frac{G(\Omega)}{|\mu|}\right]^{k-i}$$

Ref: Gobron et al. (1997)

First collided Intensity (2)

The first collided intensity in downward direction Ω corresponds to the radiation scattered only once by leaves, but which has not interacted with the soil.

•Downward intensity

$$I_-^1(z_k,\Omega,\Omega_0) = \frac{1}{\mu}\sum_{i=1}^{k} Q_-^0(z_i,\Omega,\Omega_0)\lambda\left[1-\lambda\frac{G(\Omega)}{|\mu|}\right]^{k-i}$$

•Upward intensity

$$I_-^1(z_k,\Omega,\Omega_0) = \frac{1}{\mu}\sum_{i=K}^{k+1}\left\{Q_-^0(z_i,\Omega,\Omega_0)\lambda \times \prod_{j=i}^{k+1}\left[1-\lambda'_i\frac{G(\Omega)}{|\mu|}\right]\right\}$$

Ref: Gobron et al. (1997)

Single collided BRF

The contribution to the bidirectional reflectance factor due to the first collided intensity is obtained after normalizing the upward intensity $I_{\uparrow}^{1}(z_0, \Omega, \Omega_0)$ by the incoming directional source of radiation at the top of canopy:

$$r_1(z_0, \Omega, \Omega_0) = \frac{\Gamma(\Omega \to \Omega_0)}{m \, | m_0 |} \sum_{i=K}^{1} l \left[1 - l \frac{G(\Omega_0)}{| m_0 |} \right]^i \left[1 - l'_K \frac{G(\Omega)}{m} \right]^i$$

Ref: Gobron et al. (1997)

Single Collided BRF in Principal Plan

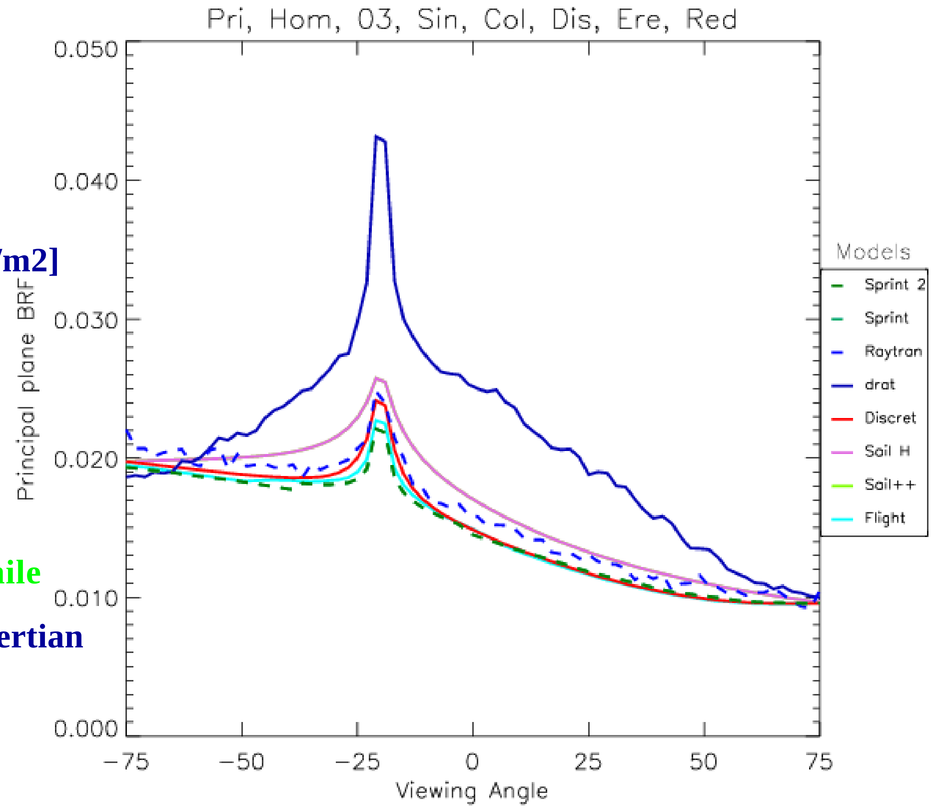
Solar Zenith Angle: 20 [deg]

Solar Azimuth Angle: 0 [deg]

Radius: 0.05 [m]

Leaf Area Index: 3.0 [m2/m2]

Height of the canopy: 2.0 [m]



Normal Distribution: Erectophile

Leaf scattering law: Bi-Lambertian

Leaf reflectance: 0.0546

Leaf transmittance: 0.0149

Soil scattering law: Lambertian

Soil reflectance: 0.127

Source: www.rami.jrc.it

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Single Collided BRF in Cross Plan

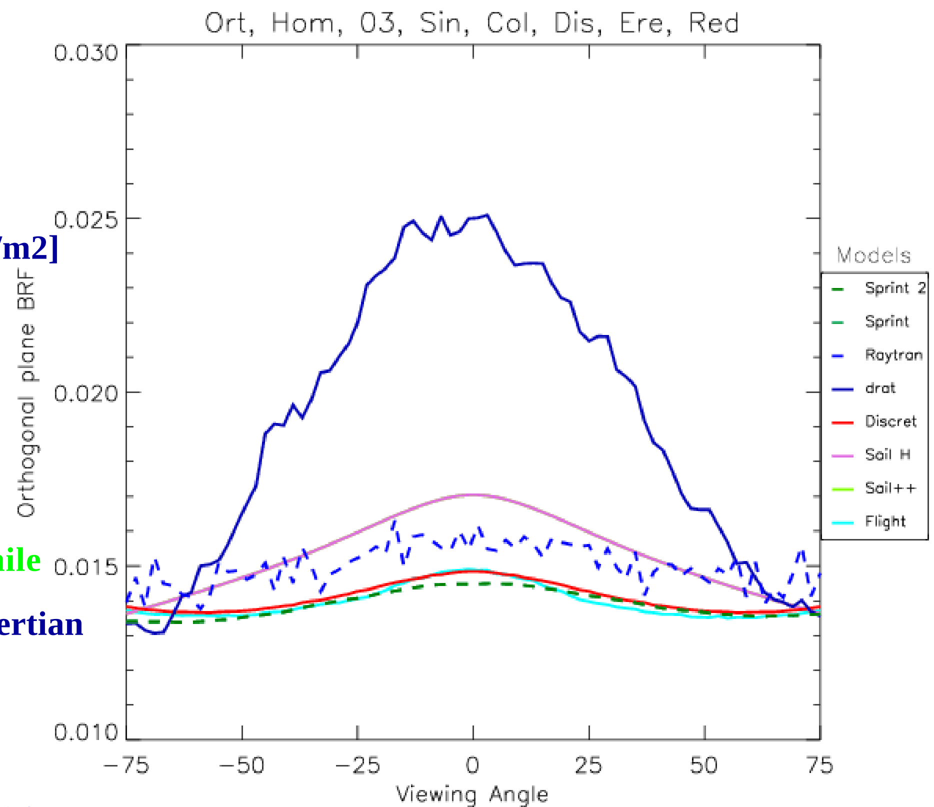
Solar Zenith Angle: 20 [deg]

Solar Azimuth Angle: 0 [deg]

Radius: 0.05 [m]

Leaf Area Index: 3.0 [m2/m2]

Height of the canopy: 2.0 [m]



Normal Distribution: Erectophile

Leaf scattering law: Bi-Lambertian

Leaf reflectance: 0.0546

Leaf transmittance: 0.0149

Soil scattering law: Lambertian

Soil reflectance: 0.127

Source: www.rami.jrc.it

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Single collided BRF in Principal Plan

Solar Zenith Angle: 20 [deg]

Solar Azimuth Angle: 0 [deg]

Radius: 0.05 [m]

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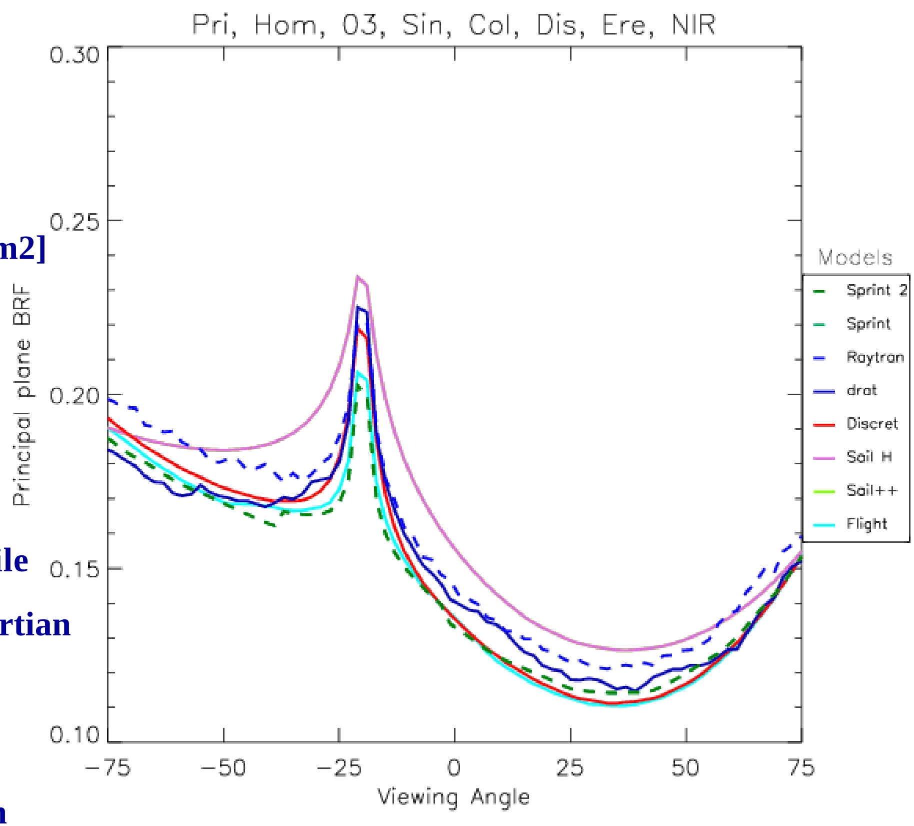
Height of the canopy: 2.0 [m]



Normal Distribution: Erectophile

Leaf scattering law: Bi-Lambertian

Leaf reflectance 0.4957

Leaf transmittance 0.4409

Soil scattering law Lambertian

Soil reflectance 0.159

Source: www.rami.jrc.it

Multiple Scattering

$$\Omega \bullet \nabla I_l(x,\Omega) + G(x,\Omega) u_L(x) I_l(x,\Omega) = \frac{u_L(x)}{p} \int_{4p} \Gamma_l(x,\Omega \rightarrow \Omega') I_l(x,\Omega') d\Omega'$$

Multiple scattering intensities are computed solving RT equations using various numerical tools, like:

- **Discrete Ordinate Methods**
- d-**Eddington method**
- **Adding-doubling**
- **Two-streams**

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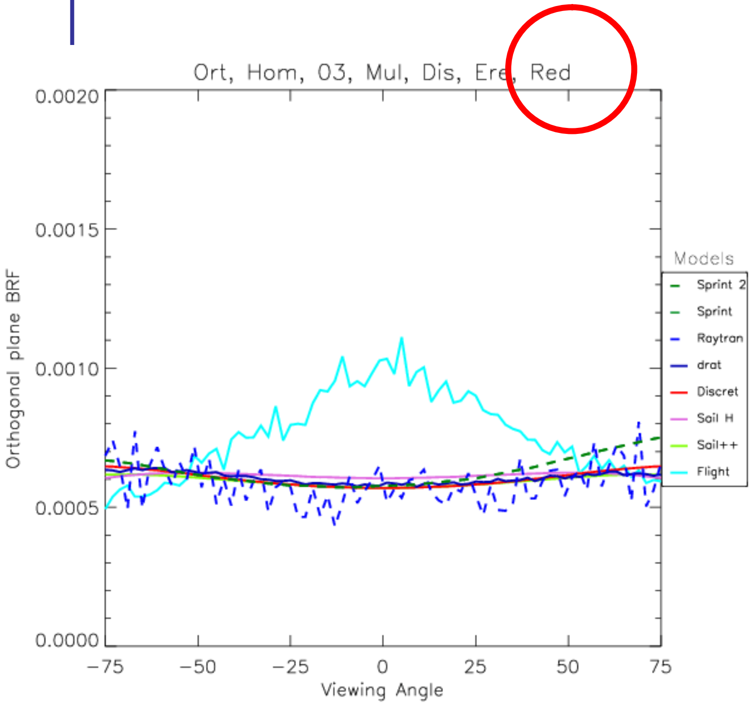
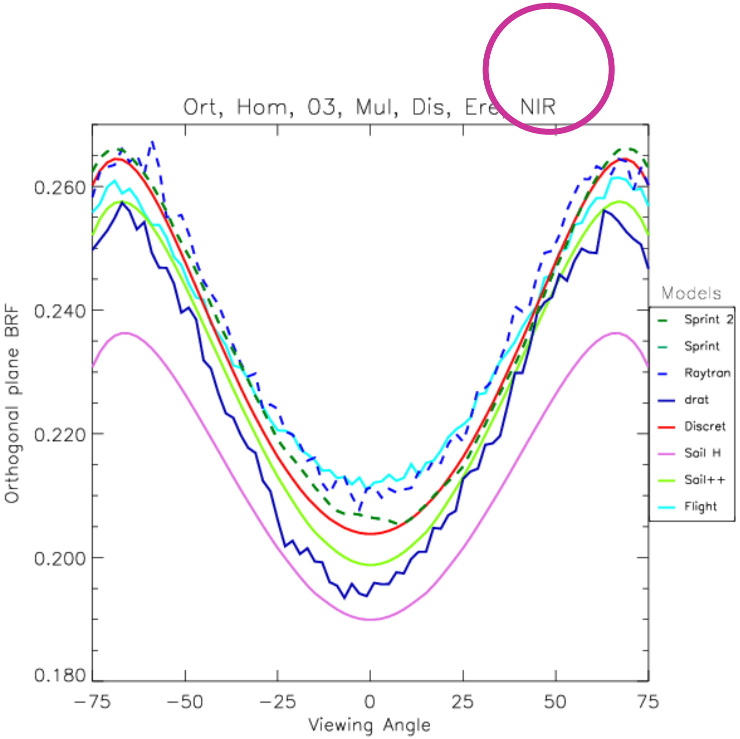
Multiple Scattering





3-Dimensional problem

where the plan-parallel concept may be inappropriate

Examples of Scenes

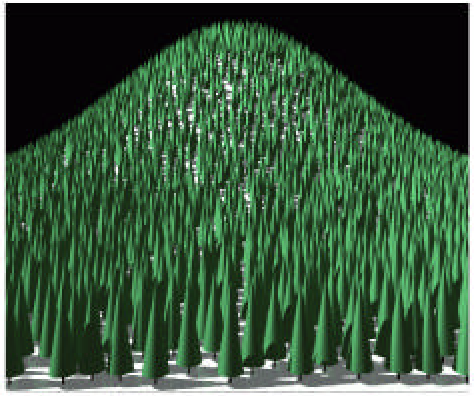
Clumping of leaves into floating spheres

100 x 100 x 30 m

Structurally heterogeneous trees at various res.

270 x 270 x 15 m

Coniferous trees onto a Gaussian shaped topography



500 x 500 x 114 m

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Scene Visualization

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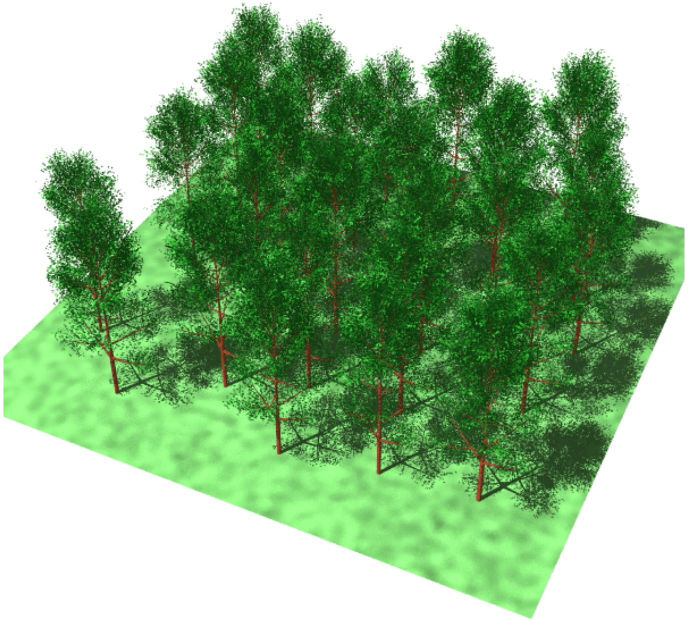
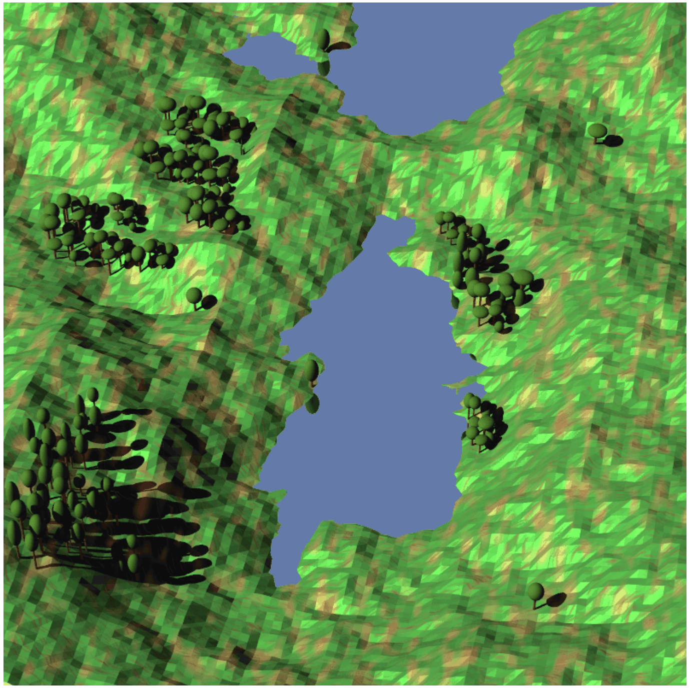


Local Scale



Regional Scale

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3-Dimensional problem

where the plan-parallel concept may be inappropriate:

- **Document the errors due to an oversimplification of the full 3-D situation, *i.e.* deviations from the 1D case.**
- **Explore new ways and techniques for representing, at limited costs, the 3D nature of the medium which basically require almost an infinity of parameters!**
- **Address the application issues for geophysical modeling, e.g. the definition of new "equivalent variables", and satellite data interpretation, e.g. the non-uniqueness of the inverse problem.**

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3-D Radiative Transfer Equations

$$\Omega \bullet \nabla I_l(x,\Omega) + G(x,\Omega)u_L(x)I_l(x,\Omega) = \frac{u_L(x)}{p}\int_{4p}\Gamma_l(x,\Omega \rightarrow \Omega')I_l(x,\Omega')d\Omega'$$

3-D Models

- **Ray tracing models**
- **Geometrical models**
- **Hybrid models**

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Outline

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- Scientific Problems with Space Remote Sensing
- Radiative Transfer Equations
- Radiative Transfer Modeling for vegetation canopy
- RAMI
- Conclusion

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RAMI

RADIATIVE TRANSFER MODEL INTERCOMPARISON

RAdiation transfer Model Intercomparison (RAMI)

This is the official site of the radiation transfer model intercomparison (RAMI) initiative. RAMI proposes a mechanism to benchmark spectral bidirectional reflectance models designed to simulate the transfer of radiation at or near the Earth's terrestrial surface, i.e., in plant canopies and over soil surfaces. As an on-going activity RAMI operates in succesive phases, each one aiming at re-assessing the capability, performance and agreement of the latest generation of radiation transfer (RT) models. This in turn, will lead to model enhancements and further development that benefit the RT modelling community as a whole.

Participation in the RAMI initiative is open to everyone willing to run a previously published RT model against an ensemble of prescribed test cases. Obviously the number and complexity of the scenes that have to be simulated is determined by the dimensionality of RT model (1-D versus 3-D). The first two RAMI phases have not only lead to improved computer codes, but also to publications in the refereed scientific literature. However, for referencing purposes only previously published models may feature in future RAMI activites. For more information please consult the FAQs and our privacy and data-usage policy via the DISCLAIMER link.

Phase	Active Period	Participating Models	First Conference Presentation	Scientific Publication
RAMI-1	Mar - Aug 1999	1-D models: 3 3-D models: 5	Sep 1999: IWMMM-2, Ispra, Italy	JGR, Vol 106, No. D11, p. 11,937-11,956, June 2001
RAMI-2	Feb - Jun 2002	1-D models: 3 3-D models: 10	Jun 2002: IWMMM-3, Steamboat Springs, USA	JGR, Vol 109, No. D6210, 2004

This site is maintained by the Science and Technology for Applied Remote Sensing (STARS) group of the Global Vegetation Monitoring (GVM) unit in the Institute for Environment and Sustainability (IES) of the EC Joint Research Centre (JRC).

CONTACT: RAMI.WEBADMIN@JRC.IT
LAST UPDATED: JULY 01, 2004
ACKNOWLEDGEMENTS

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RAMI
RADIATIVE TRANSFER MODEL INTERCOMPARISON

EXPERIMENTS RESULTS MODELS PARTICIPANTS

RAMI2

MODELS LIST

The following is the list of RT models that participated in the second phase of the RAMI initiative.

- DART
- Drat
- FRT
- Flight
- GORT
- LIM
- RGM
- Raytran
- SAIL++
- SAILH
- SGORT
- SPRINT-2
- Semi-discrete

Contact: rami.webadmin@jrc.it
Last Updated: May 07, 2004
Acknowledgements

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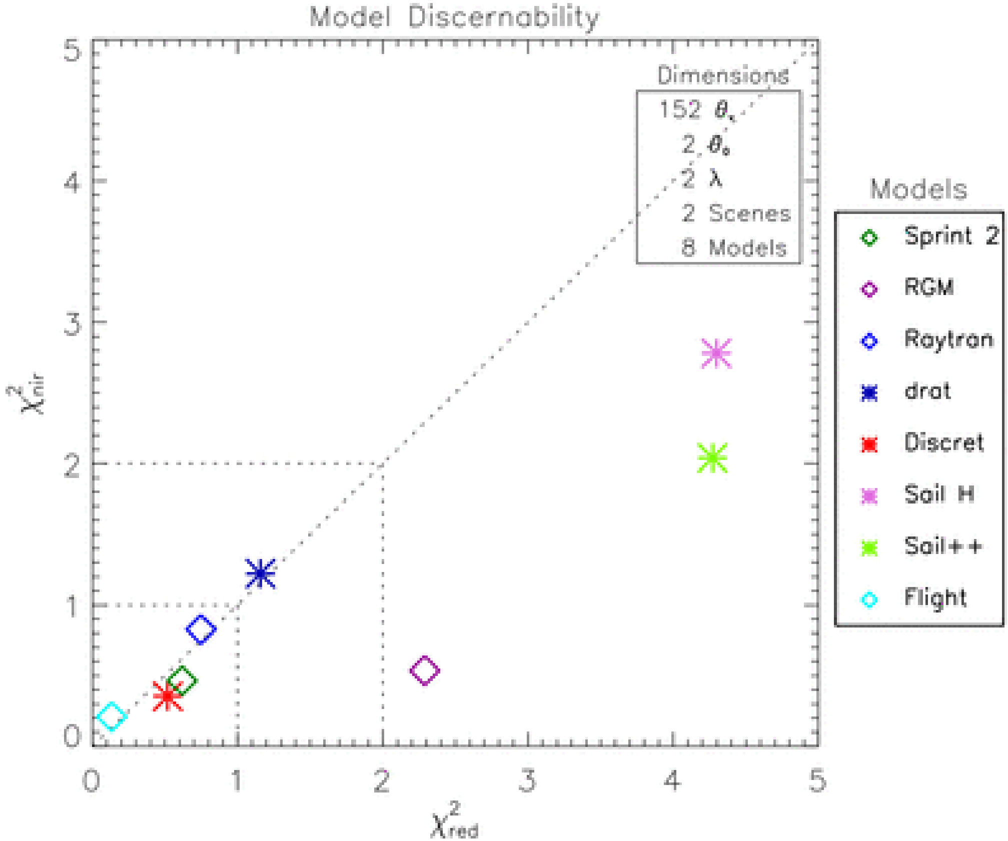
Model Benchmarking



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Outline

- Scientific Problems with Space Remote Sensing
- Radiative Transfer Equations
- Radiative Transfer Modeling for vegetation canopy
- 3D models
- RAMI
- Conclusion

Conclusion

- RT modeling in vegetation: two-stream RT equations, 1D turbid canopy, 1D' discrete model & *3D heterogeneous canopy model*

- All models require spectral scattering and absorption canopies properties

  … *and assumptions*

- RAMI exercise for direct mode comparison and validation

- The fun with RT models with space remote sensing data comes with the inversion mode … tomorrow !