UCL

GEOGG141/ GEOG3051
Principles & Practice of Remote Sensing (PPRS)
Radiative Transfer Theory at optical wavelengths applied to vegetation canopies: part 2

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http://www2.geog.ucl.ac.uk/~mdisney/teaching/GEOGG141/GEOGG141.html
http://www2.geog.ucl.ac.uk/~mdisney/teaching/3051/GEOG3051.html

Notes adapted from Prof. P. Lewis plewis@geog.ucl.ac.uk

Reading

Full notes for these lectures

http://www2.geog.ucl.ac.uk/~mdisney/teaching/GEOGG141/rt_theory/rt_notes1.pdf

http://www2.geog.ucl.ac.uk/~mdisney/teaching/GEOGG141/rt_theory/rt_notes2.pdf

Books

Jensen, J. (2007) *Remote Sensing: an Earth Resources Perspective*, 2nd ed., Chapter 11 (355-408), 1st ed chapter 10.

Liang, S. (2004) *Quantitative Remote Sensing of Land Surfaces*, Wiley, Chapter 3 (76-142).

Monteith, J. L. and Unsworth, M. H. (1990) *Principles of Environmental Physics*, 2nd ed., ch 5 & 6.

Papers

Disney et al. (2000) Monte Carlo ray tracing in optical canopy reflectance modelling, Remote Sensing Reviews, 18, 163 – 196.

Feret, J-B. et al. (2008) PROSPECT-4 and 5: Advances in the leaf optical properties model separating photosynthetic pigments, RSE, 112, 3030-3043.

Jacquemoud. S. and Baret, F. (1990) PROSPECT: A model of leaf optical properties spectra, RSE, 34, 75-91.

Lewis, P. and Disney, M. I. (2007) Spectral invariants and scattering across multiple scale from within-leaf to canopy, RSE, 109, 196-206.

Nilson, T. and Kuusk, A. (1989) A canopy reflectance model for the homogeneous plant canopy and its inversion, RSE, 27, 157-167.

Price, J. (1990), On the information content of soil reflectance spectra RSE, 33, 113-121

Walthall, C. L. et al. (1985) Simple equation to approximate the bidirectional reflectance from vegetative canopies and bare soil surfaces, Applied Optics, 24(3), 383-387.

Radiative Transfer equation

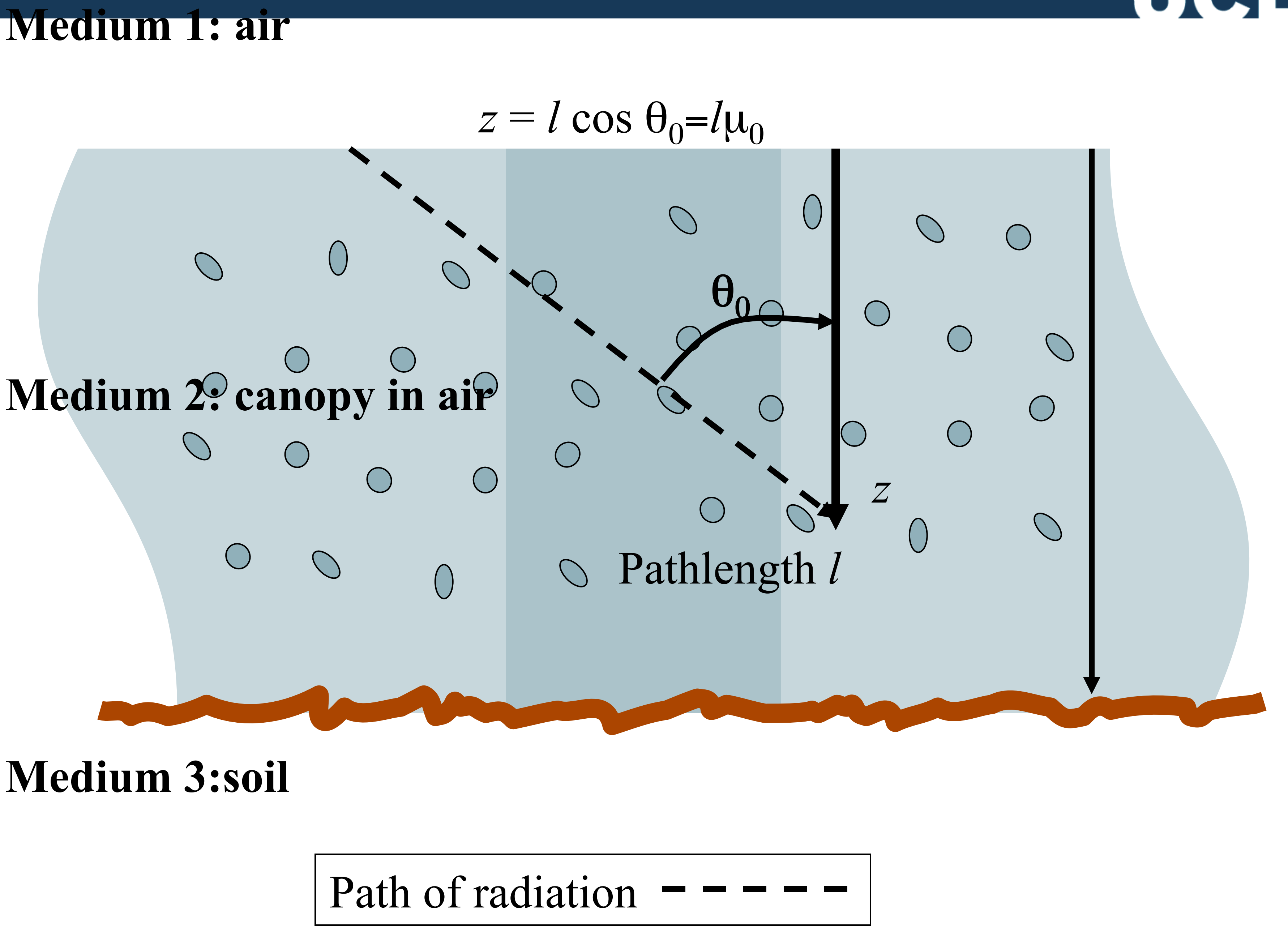
- Describe propagation of radiation through a medium under absorption, emission and scattering processes
- Origins
  - Schuster (1905), Schwarzchild (1906, 1914), Eddington (1916)….
  - Chandrasekhar (1950) – key developments in star formation, showed how to solve under variety of assumptions & cases
  - Applications in nuclear physics (neutron transport), astrophysics, climate, biology, ecology etc. etc.

- Used extensively for (optical) vegetation since 1960s (Ross, 1981)
- Used for microwave vegetation since 1980s

Radiative Transfer equation

- Consider energy balance across elemental volume

- Generally use scalar form (SRT) in optical
- Generally use vector form (VRT) for microwave


Medium 1: air
$z = l \cos \theta_0 = l\mu_0$
θ_0
Medium 2: canopy in air
z
Pathlength l
Medium 3:soil
Path of radiation

Scalar Radiative Transfer Equation

- 1-D scalar radiative transfer (SRT) equation
  - for a plane parallel medium (air) embedded with a low density of small scatterers
  - change in specific Intensity (Radiance) $I(z,\underline{\Omega})$ at depth z in direction $\underline{\Omega}$ wrt z:

$$\mu \frac{\partial I(z,\underline{\Omega})}{\partial z} = -\kappa_e I(\underline{\Omega},z) + J_s(\underline{\Omega},z)$$

  - Crucially, an integro-differential equation (i.e. hard to solve)

Scalar RT Equation

$$\mu \frac{\partial I(z,\underline{\Omega})}{\partial z} = -\kappa_e I(\underline{\Omega},z) + J_s(\underline{\Omega},z)$$

- Source Function:

$$J_S(\underline{\Omega},z) = \int_{4\pi} P(z,\underline{\Omega}' \to \underline{\Omega};) I(\underline{\Omega},\underline{\Omega}') d\underline{\Omega}'$$

- μ - cosine of the direction vector ($\underline{\Omega}$) with the local normal
  - accounts for path length through the canopy
- κ_e - volume extinction coefficient
- $P(z,\underline{\Omega}' \to \underline{\Omega})$ is the volume scattering phase function i.e. prob. of photon at depth z being scattered from illum direction $\underline{\Omega}$ to view direction $\underline{\Omega}$’

Extinction Coefficient and Beer’s Law

$$\kappa_e$$

- Volume extinction coefficient:
  - ‘total interaction cross section’
  - ‘extinction loss’
  - ‘number of interactions’ per unit length
- a measure of <u>attenuation</u> of radiation in a canopy (or other medium).

$$I(l) = I_0 e^{-\kappa_e l}$$

Beer’ s Law

Extinction Coefficient and Beers Law

$$I(l) = I_0 e^{-\kappa_e l}$$

$$\frac{dI}{dl} = -\kappa_e I_0 e^{-\kappa_e l}$$

$$= -\kappa_e I$$

No source version of SRT eqn $\mu \frac{\partial I(z, \underline{\Omega})}{\partial z} = -\kappa_e I(\underline{\Omega}, z) + J_s(\underline{\Omega}, z)$

Optical Extinction Coefficient for Oriented Leaves

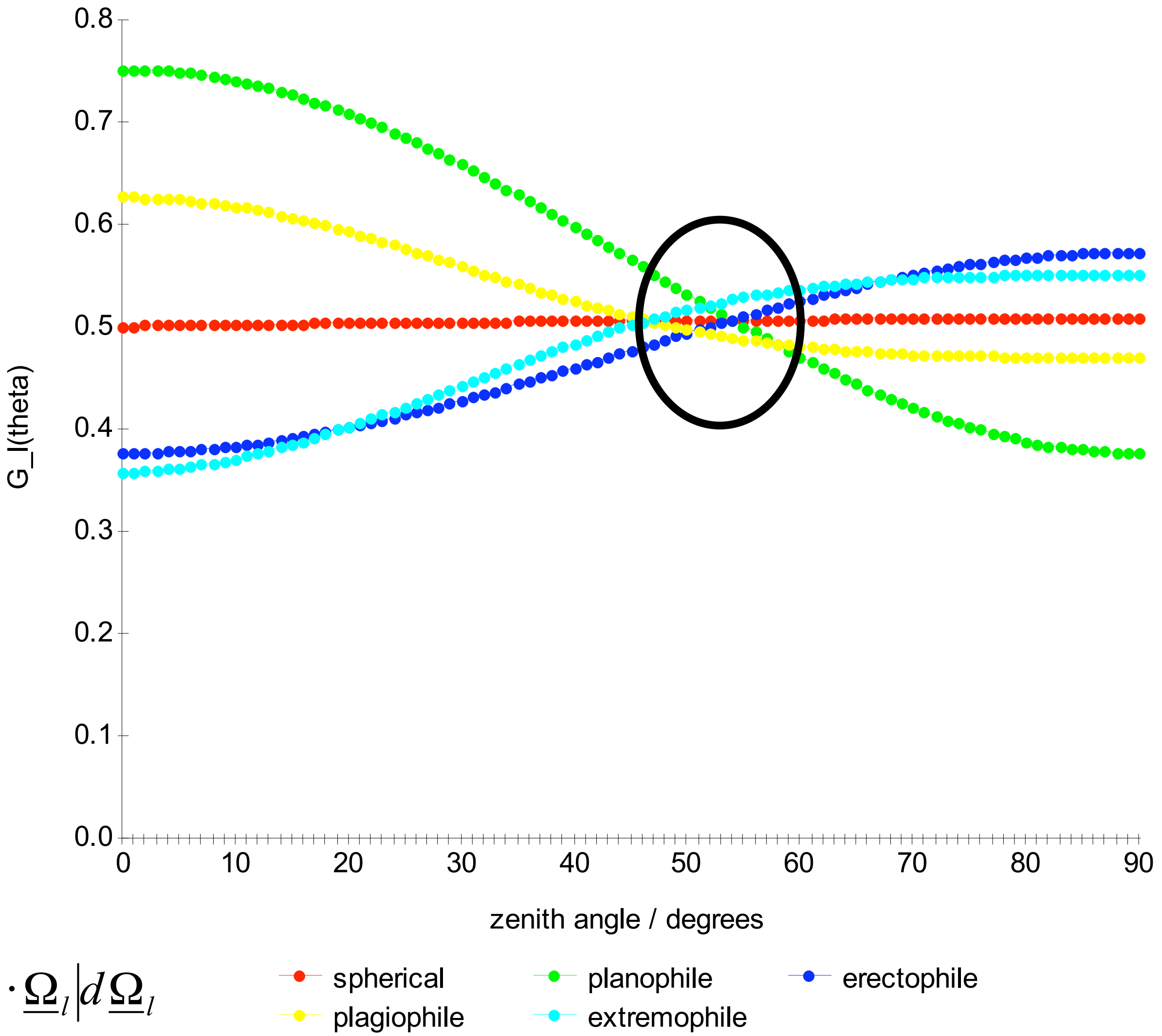
- Volume extinction coefficient:

$$\kappa_e\left(\underline{\Omega}\right) = u_l G_l\left(\underline{\Omega}\right)$$

- u_l : leaf area density
  - Area of leaves per unit volume
- G_l : (Ross) projection function

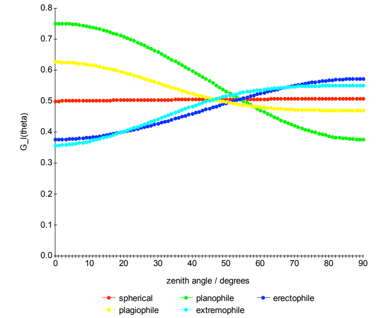
$$G_l\left(\underline{\Omega}\right) = \frac{1}{2\pi} \int_{2\pi+} g_l\left(\underline{\Omega}_l\right) \left|\underline{\Omega} \cdot \underline{\Omega}_l\right| d\underline{\Omega}_l$$

Optical Extinction Coefficient for Oriented Leaves



$$G_l(\underline{\Omega}) = \frac{1}{2\pi} \int_{2\pi+} g_l(\underline{\Omega}_l) \left| \underline{\Omega} \cdot \underline{\Omega}_l \right| d\underline{\Omega}_l$$

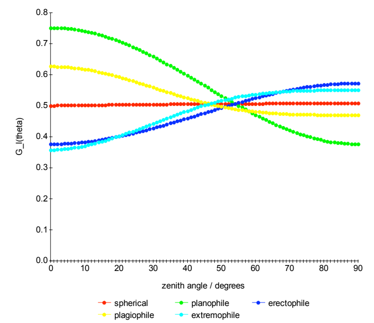
Optical Extinction Coefficient for Oriented Leaves



- range of G-functions small (0.3-0.8) and smoother than leaf inclination distributions;
- planophile canopies, G-function is high (>0.5) for low zenith and low (<0.5) for high zenith;
- converse true for erectophile canopies;
- G-function always close to 0.5 between 50^{o} and 60^{o}
- essentially invariant at 0.5 over different leaf angle distributions at 57.5^{o}.

Optical Extinction Coefficient for Oriented Leaves

$$\int_{z=0}^{z=-H} -\frac{u_l G(\underline{\Omega})}{\mu}\, dz = \frac{L G(\underline{\Omega})}{\mu}$$



- so, radiation at bottom of canopy for spherical:

$$I_0 e^{-\frac{L G(\underline{\Omega})}{\mu}} = I_0 e^{-\frac{0.5 L}{\mu}}$$

- for horizontal:

$$= I_0 e^{-L}$$

A Scalar Radiative Transfer Solution

- Attempt similar first Order Scattering solution
  - in optical, consider total number of interactions
    - with leaves + soil
- Already have extinction coefficient:

$$\kappa_e(\underline{\Omega}) = u_l G(\underline{\Omega})$$

SRT

- Phase function: $$P(\underline{\Omega}' \rightarrow \underline{\Omega}) = \frac{1}{\mu'} u_l \Gamma(\underline{\Omega}' \rightarrow \underline{\Omega})$$
- Probability of photon being scattered from incident (**Ω’**) to view (**Ω**)
- u_l - leaf area density;
- μ' - cosine of the incident zenith angle
- Γ - area scattering phase function.

SRT

- Area scattering phase function:

$$\Gamma\left(\underline{\Omega}' \to \underline{\Omega}\right) = \frac{1}{4\pi} \int_{4\pi} \omega_l g_l\left(\underline{\Omega}_l\right) \left|\underline{\Omega} \cdot \underline{\Omega}_l\right| \left|\underline{\Omega}' \cdot \underline{\Omega}_l\right| d\underline{\Omega}_l$$

- double projection, modulated by spectral terms
- ω_l : leaf single scattering albedo
  - Probability of radiation being scattered rather than absorbed at leaf level
  - Function of wavelength – low transmission, low fwd. scattering and vice versa

SRT

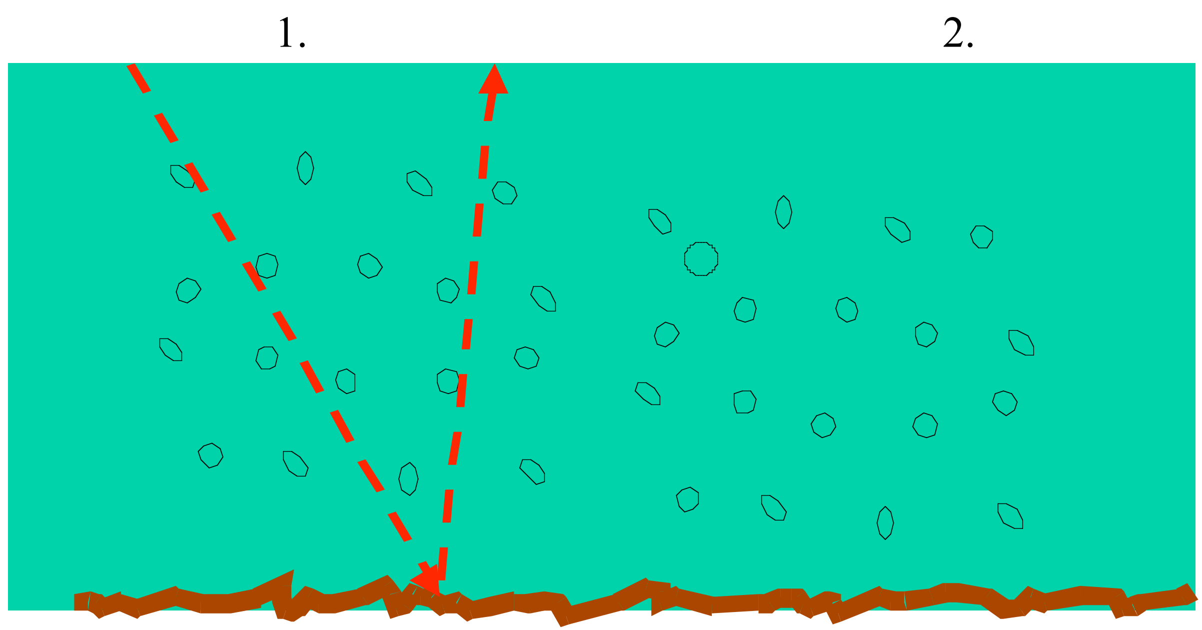
$$\underline{I}^{+}\left(\underline{\Omega}_s, z\right) = e^{-L\left(\frac{G\left(\underline{\Omega}_s\right)\mu_0 + G\left(\underline{\Omega}_0\right)\mu_s}{\mu_s \mu_0}\right)} \rho_{soil}\left(\underline{\Omega}_s, \underline{\Omega}_0\right) I_0 \delta\left(\underline{\Omega}_s - \underline{\Omega}_0\right) + \frac{I_0 \Gamma\left(\underline{\Omega}' \rightarrow \underline{\Omega}\right)}{G\left(\underline{\Omega}_s\right)\mu_0 + G\left(\underline{\Omega}_0\right)\mu_s} \left(1 - e^{-L\left(\frac{G\left(\underline{\Omega}_s\right)\mu_0 + G\left(\underline{\Omega}_0\right)\mu_s}{\mu_s \mu_0}\right)}\right)$$

SRT: 1st O mechanisms

$$e^{-L\left(\frac{G(\underline{\Omega}_s)\mu_0 + G(\underline{\Omega}_0)\mu_s}{\mu_s \mu_0}\right)} \rho_{soil}\left(\underline{\Omega}_s, \underline{\Omega}_0\right)$$

$$\underline{I}^+(\underline{\Omega}_s, z) = e^{-L\left(\frac{G(\underline{\Omega}_s)\mu_0 + G(\underline{\Omega}_0)\mu_s}{\mu_s \mu_0}\right)} \rho_{soil}\left(\underline{\Omega}_s, \underline{\Omega}_0\right) I_0 \delta\left(\underline{\Omega}_s - \underline{\Omega}_0\right) + \frac{I_0 \Gamma(\underline{\Omega}' \rightarrow \underline{\Omega})}{G(\underline{\Omega}_s)\mu_0 + G(\underline{\Omega}_0)\mu_s}\left(1 - e^{-L\left(\frac{G(\underline{\Omega}_s)\mu_0 + G(\underline{\Omega}_0)\mu_s}{\mu_s \mu_0}\right)}\right)$$

- through canopy, reflected from soil & back through canopy



SRT: 1st O mechanisms

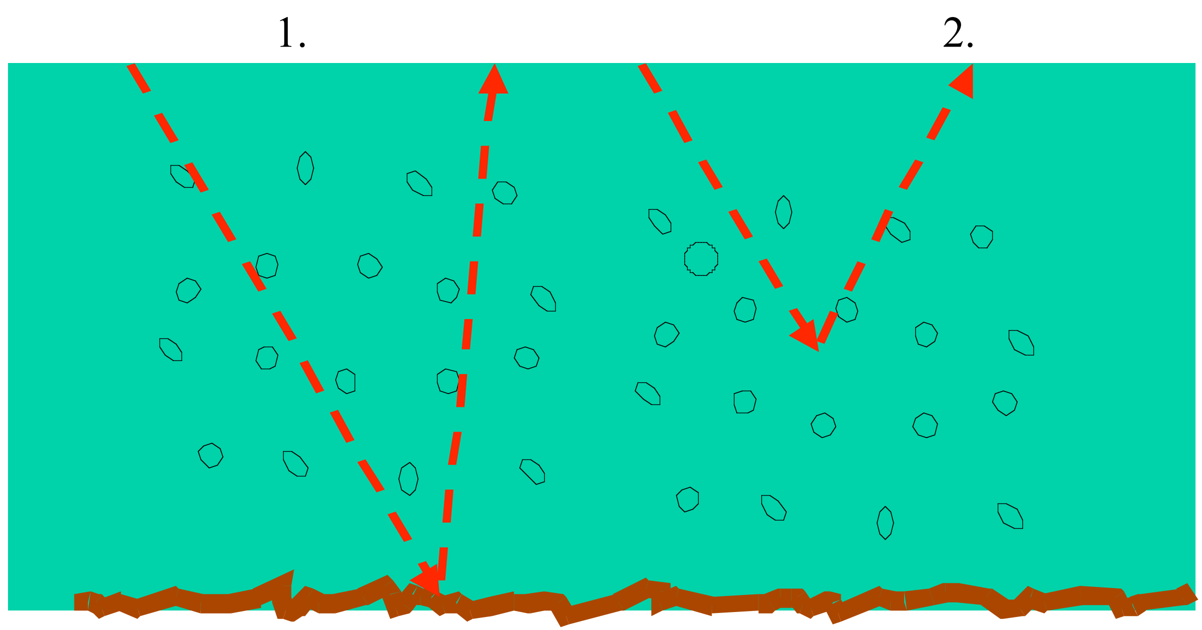
$$\frac{\Gamma\left(\underline{\Omega}' \rightarrow \underline{\Omega}\right)}{G\left(\underline{\Omega}_s\right)\mu_0 + G\left(\underline{\Omega}_0\right)\mu_s}\left(1 - e^{-L\left(\frac{G\left(\underline{\Omega}_s\right)\mu_0 + G\left(\underline{\Omega}_0\right)\mu_s}{\mu_s \mu_0}\right)}\right)$$

$$\underline{I}^{+}\left(\underline{\Omega}_s, z\right) = e^{-L\left(\frac{G\left(\underline{\Omega}_s\right)\mu_0 + G\left(\underline{\Omega}_0\right)\mu_s}{\mu_s \mu_0}\right)} \rho_{soil}\left(\underline{\Omega}_s, \underline{\Omega}_0\right) I_0 \delta\left(\underline{\Omega}_s - \underline{\Omega}_0\right) + \frac{I_0 \Gamma\left(\underline{\Omega}' \rightarrow \underline{\Omega}\right)}{G\left(\underline{\Omega}_s\right)\mu_0 + G\left(\underline{\Omega}_0\right)\mu_s}\left(1 - e^{-L\left(\frac{G\left(\underline{\Omega}_s\right)\mu_0 + G\left(\underline{\Omega}_0\right)\mu_s}{\mu_s \mu_0}\right)}\right)$$

Canopy only scattering

Direct function of ω

Function of g_l, L, anc



1st O SRT

- Special case of spherical leaf angle:

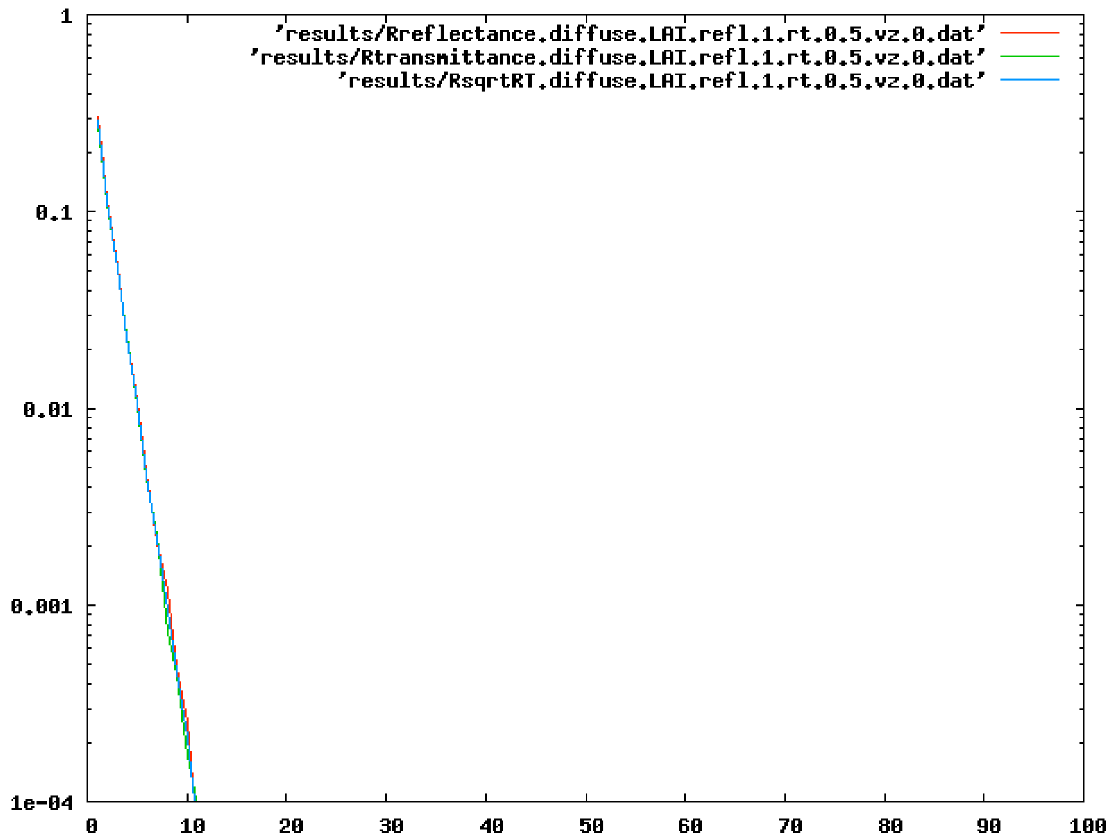
$$G(\underline{\Omega}) = 0.5$$

$$\Gamma(\underline{\Omega'} \rightarrow \underline{\Omega}) = \frac{\rho_l + \tau_l}{3\pi}(\sin\gamma - \gamma\cos\gamma) + \frac{\rho_l}{3}\cos\gamma$$

$$\cos\gamma = \left|\underline{\Omega} \cdot \underline{\Omega'}\right|$$

Multiple Scattering

Contributions to reflectance and transmittance

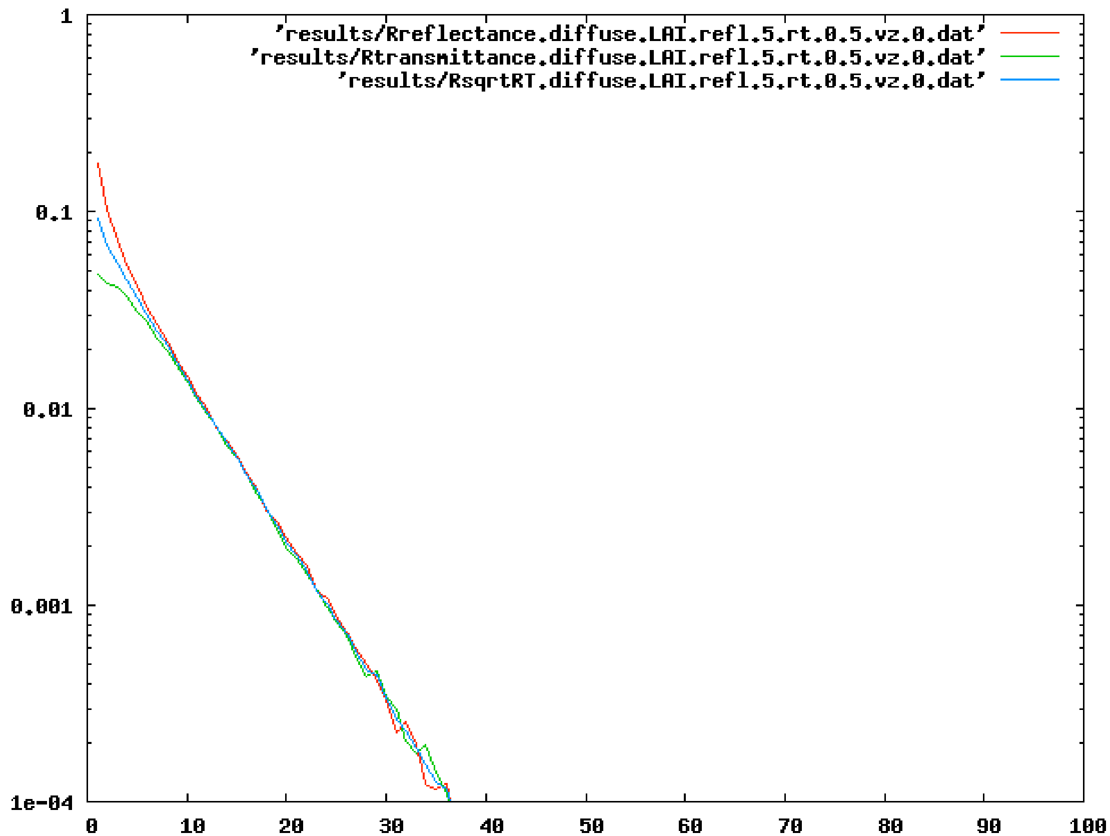


Scattering order

LAI 1

Multiple Scattering

Contributions to reflectance and transmittance

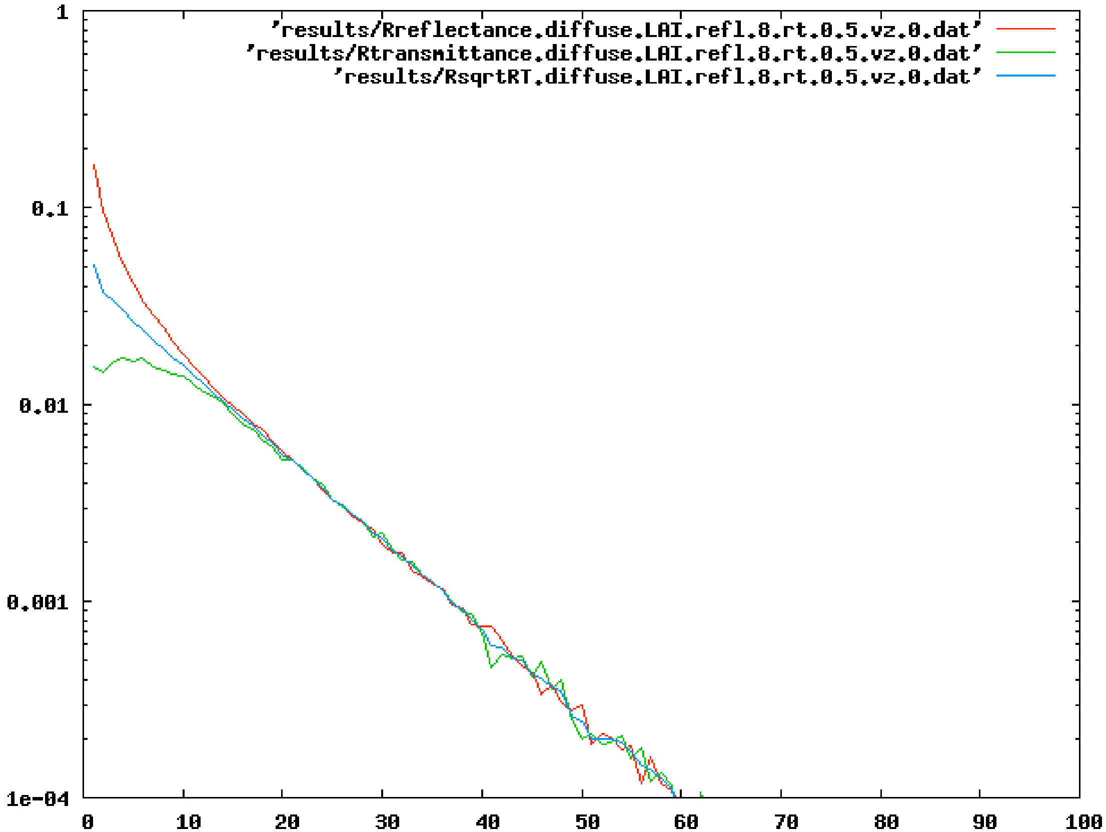


Scattering order

LAI 5

Multiple Scattering

Contributions to reflectance and transmittance

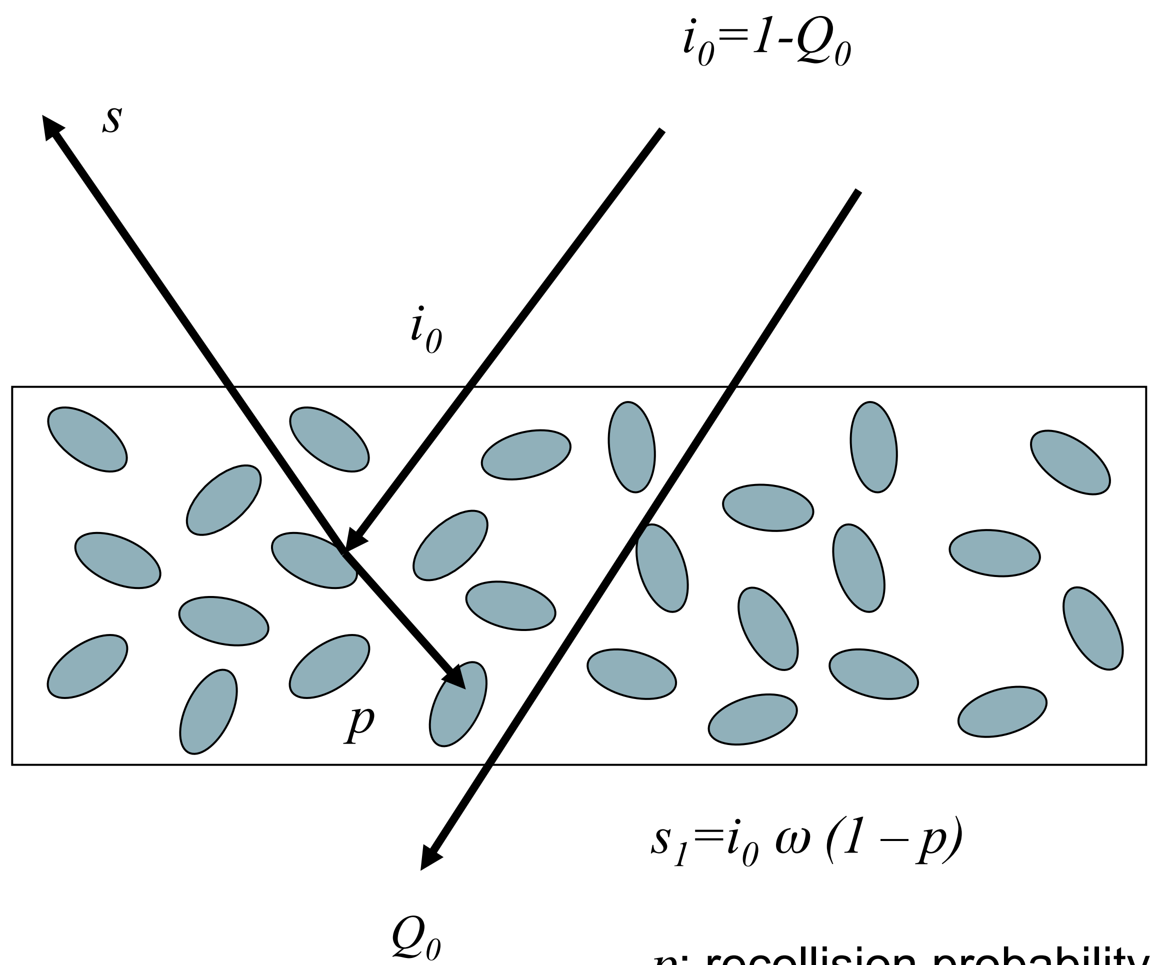


Scattering order

LAI 8

Multiple Scattering

- range of approximate solutions available
  - Successive orders of scattering (SOSA)
  - 2 & 4 stream approaches etc. etc.
  - Monte Carlo ray tracing (MCRT)
- Recent advances using concept of recollision probability, p
  - Huang et al. 2007

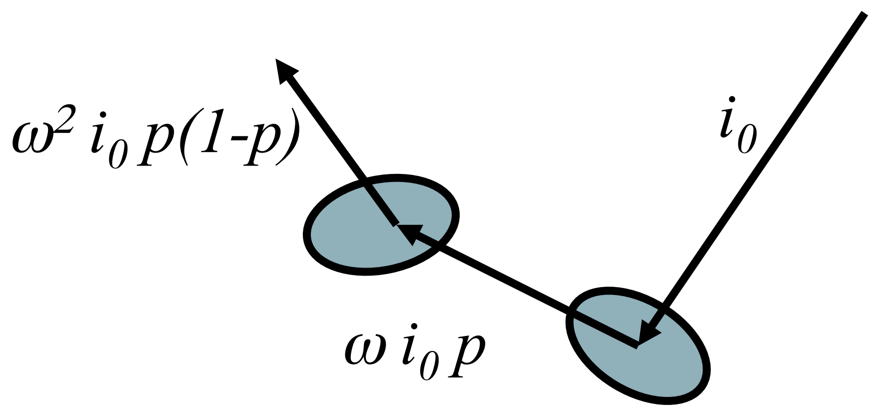


p: recollision probability
ω: single scattering albedo of leaf

i_0 = intercepted (incoming)
Q_0 = transmitted (uncollided)

- 2nd Order scattering:

$$\frac{s_1}{i_0} = \omega\left(1 - p\right)$$



$$\frac{s_2}{i_0} = \frac{s_1}{i_0}\omega p$$

$$\frac{s}{i_0} = \omega\left(1 - p\right) + \omega^2\left(1 - p\right)p + \omega^3\left(1 - p\right)p^2 + \cdots$$

$$\frac{s}{i_0} = \omega(1-p) + \omega^2(1-p)p + \omega^3(1-p)p^2 + \cdots$$

$$\frac{s}{i_0} = \omega(1-p)\left[1 + \omega p + \omega^2 p^2 + \cdots\right]$$

$$\frac{s}{i_0} = \frac{\omega(1-p)}{1-p\omega}$$

'single scattering albedo' of canopy

$$\frac{s}{i_0} = \frac{\omega(1-p)}{1-p\omega}$$

p: recollision probability

$$n_s(\lambda) = \frac{1}{1-p\omega(\lambda)}$$

Average number of photon interactions:
The degree of multiple scattering

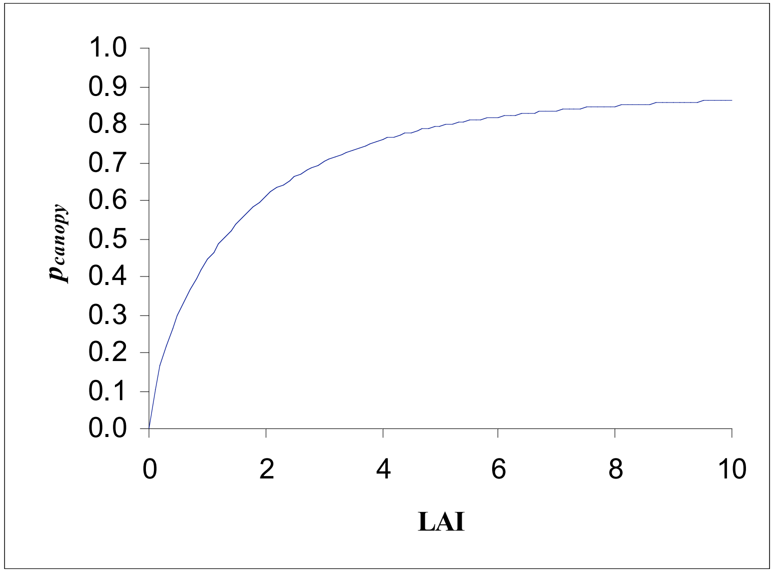
$$\alpha(\lambda) = \frac{1-\omega(\lambda)}{1-p\omega(\lambda)}$$

Absorptance

Knyazikhin et al. (1998): p is eigenvalue of RT equation
Depends on ***structure*** only

- For canopy:

$$p_{canopy} = p_{\max}\left(1 - \exp\left(-kLAI^{b}\right)\right)$$



Spherical leaf angle distribution

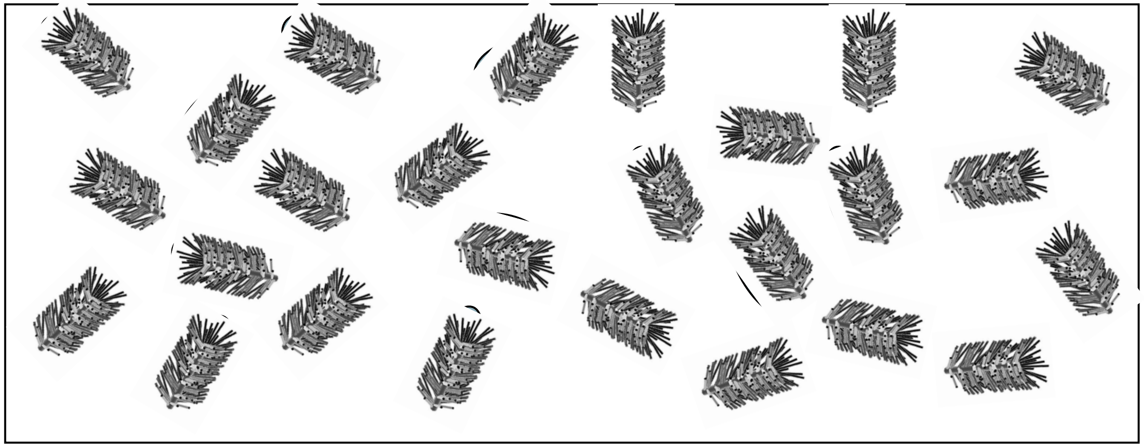
p_{max}=0.88, k=0.7, b=0.75

Smolander & Stenberg RSE 2005

Clumping: aggregation across scales?

Canopy with 'shoots' as fundamental scattering objects:

$$\left(\frac{s}{i_0}\right)_{canopy} = \omega_{canopy} = \frac{\left(1 - p_{canopy}\right)\omega_{shoot}}{1 - p_{canopy}\omega_{shoot}}$$



Canopy with 'shoots' as fundamental scattering objects:

$$\left(\frac{s}{i_0}\right)_{canopy} = \omega_{canopy} = \frac{(1 - p_{canopy})\omega_{shoot}}{1 - p_{canopy}\omega_{shoot}}$$

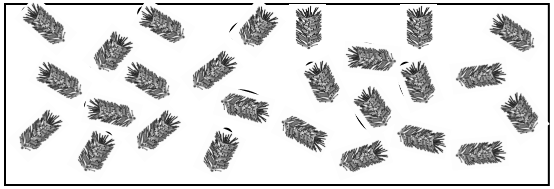
$$\left(\frac{s}{i_0}\right)_{shoot} = \omega_{shoot} = \frac{(1 - p_{shoot})\omega_{needle}}{1 - p_{shoot}\omega_{needle}}$$

$$\left(\frac{s}{i_0}\right)_{canopy} = \omega_{canopy} = \frac{(1 - p_2)\omega_{needle}}{1 - p_2\omega_{needle}}$$

$$p_2 = p_{canopy} + (1 - p_{canopy})p_{shoot}$$

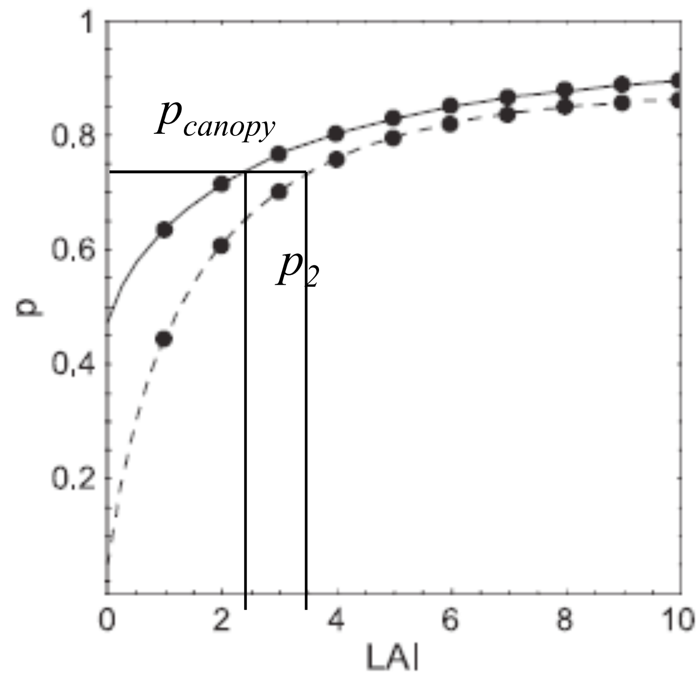
i.e. can use approach across nested scales

Lewis and Disney, 2007



- p_{shoot}=0.47 (scots pine)
- $p_2 < p_{canopy}$

- Shoot-scale clumping reduces apparent LAI



Smolander & Stenberg RSE 2005

Other RT Modifications

- Hot Spot
  - joint gap probabilty: *Q*
  - For far-field objects, treat incident & exitant gap probabilities independently

$$Q(\underline{\Omega}' \rightarrow \underline{\Omega}) = e^{-L\frac{G(\underline{\Omega})\mu' + G(\underline{\Omega}')\mu}{\mu\,\mu'}}$$

  - product of two Beer's Law terms

RT Modifications

- Consider retro-reflection direction:
  - assuming independent:

$$Q(\underline{\Omega} \rightarrow \underline{\Omega}) = e^{-\frac{2LG(\Omega)}{\mu}}$$

  - But *should* be:

$$Q(\underline{\Omega} \rightarrow \underline{\Omega}) = e^{-\frac{LG(\Omega)}{\mu}}$$

RT Modifications

- Consider retro-reflection direction:
  - But *should* be:

$$Q(\underline{\Omega} \rightarrow \underline{\Omega}) = e^{-\frac{L\,G(\underline{\Omega})}{\mu}}$$

  - as 'have already travelled path'
  - so need to apply corrections for Q in RT
    - e.g. $Q(\underline{\Omega}' \rightarrow \underline{\Omega}) = P(\underline{\Omega}')\,P(\underline{\Omega})\,C(\underline{\Omega}',\underline{\Omega})$

RT Modifications

- As result of finite object size, hot spot has angular width
  - depends on 'roughness'
    - leaf size / canopy height (Kuusk)
    - similar for soils
- Also consider shadowing/shadow hiding

Summary

- SRT formulation
  - extinction
  - scattering (source function)
- Beer's Law
  - exponential attenuation
  - rate - extinction coefficient
    - LAI x G-function for optical

Summary

- SRT 1st O solution
  - use area scattering phase function
  - simple solution for spherical leaf angle
  - 2 scattering mechanisms
- Multiple scattering
  - Recollison probability
- Modification to SRT:
  - hot spot at optical