A compendium of kernel & other (semi-)empirical BRDF Models

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Introduction

The BRDF Thread of the CSIRO EOC Tasks has a number of aims. One is the provide a basis for the correction of data which is being affected by BDRF effects and another is to interpret BRDF effects in terms of the nature and structure of the land surface.

As listed in the discussion paper by Jupp (1997) the fundamental questions we have to address are:

- Is there a consistent Typology of BRDF which relates to land cover structure?
- Is it representable by simple BRDF (eg Kernel) functions that can provide consistency & standards?
- can remote sensing consistently monitor changes in the coefficients of the functions or/or changes in functional form?
- Do the changes recorded key in to significant structural changes in the surface cover?

The above document (Jupp, 1997) follows on from a Discussion of the BRDF Thread for the EOC (Jupp and Strahler, 1996) and a discussion of the role of BRDF models in reflectance measurement (Jupp, 1996).

Jupp (1997) also investigates a limited range of kernel functions (semi-empirical BRDF models) in terms of their fit to some data recorded from an airborne scanner. The basis for a statistical comparison of BRDF models has been comprehensively discussed in the planning of research at the EOCby and tools have been developed to compare a range of candidate models against a range of data sets.

This document is a collection of the candidate models and their definition.

2 Kernel Models

These are (semi-)empirical models based on linear combinations of “kernels”.

$$\rho = f_{iso} + f_{geo}k_{geo} + f_{vol}k_{vol}$$

which represent surface reflectance (ρ) as a function of component reflectances (f_x) and the kernels (k_x) which are mathematical functions that depend on sun (or incident) and view (or observer) angles θ_i and θ_v. The subscripts “geo” and “vol” refer to the physical bases for some kernels in which there is an identification of a “geometric” or hotspot factor and a “volume” or path length and scattering factor.

By convention, kernel models are expressed in way is that when sun and observer are at zenith:

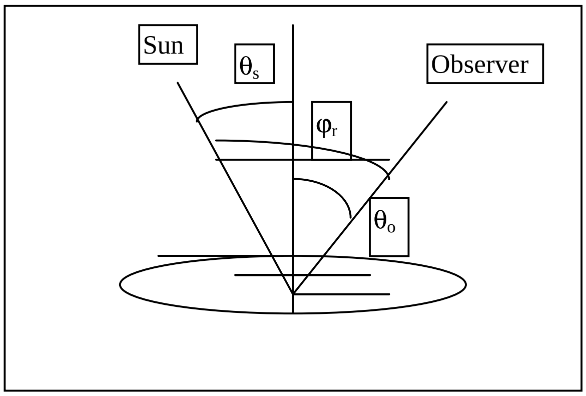
$$k_{geo}(0,0) = k_{vol}(0,0) = 0$$

so that $\rho(0,0) = f_{iso}$. Some published models do not enforce this convention but all can if needed.

To compute the kernel models, we need to specify which choice of the angular description is being used for sun and view directions. Sometimes this is ‘target based’ and sometimes it is ‘sensor based’. Relative to an airborne scanner, the position of the hotspot is dependent on flight direction, aircraft attitude, scan read-out order etc.

In an aircraft and scanner situation, the pointing vector for a pixel may be defined pointing “up” or “down” and there are important issues of whether the scanner scans left to right or right to left! In atmospheric correction routines, the conventions of the scanner and aircraft model frame must be very carefully specified. Any data on angles that came with images being investigated with kernel models must follow a single convention or be carefully and fully specified.

For the following, the consistent convention being used is the ‘target based’ one. That is, the geometry is as follows:



Where, θ_s (in the following θ_i) is the sun or incident ray zenith angle, θ_o (in the following θ_v) is the view or observed zenith angle and the azimuth (φ_r or ϕ) is relative to the sun position. This is the convention used by the MODIS MODLAND team in their product ATBD (Strahler *et al*., 1995, 1996) and in AVHRR pathfinder as well.

Two important functions of the view and sun positions which are used often in the following are the angle between the sun and view vectors (ξ) and the related “distance” between the sun and view vectors (D) as defined by:

$$\cos\xi = \cos\theta_i \cos\theta_v + \sin\theta_i \sin\theta_v \cos\phi$$

and

$$D = \left[\tan^2\theta_i + \tan^2\theta_v - 2\tan\theta_i \tan\theta_v \cos\phi\right]^{1/2}$$

$\theta_i = \theta_v$ Clearly if the sun and view positions align ($\theta_v = \theta_i \ and \ \phi = 0$) then both ξ and D are zero. To see how they operate away from this “hotspot” point it is useful to consider the “Principal azimuth” (or almucantar) for which $\theta_v = \theta_i$. That is left to you.

3 Primary AMBRALS Kernel Models

The base components of the AMBRALS kernel models (Wanner *et al*., 1995) can either be used as individual kernels of combinations or as described in the section on the MODIS products. They are as follows:

3.1 Ross-thin (vol)

Derived in Wanner e*t al*., 1995 based on Ross, 1981

$$\cos\xi = \cos\theta_i \cos\theta_v + \sin\theta_i \sin\theta_v \cos\phi$$

$$k_{thin} = \frac{(\pi/2-\xi)\cos\xi + \sin\xi}{\cos\theta_i \cos\theta_v} - \frac{\pi}{2}$$

3.2 Ross-thick (vol)

Derived in Roujean *et al*., 1992 based on Ross, 1981

$$k_{thick} = \frac{(\pi/2-\xi)\cos\xi + \sin\xi}{\cos\theta_i + \cos\theta_v} - \frac{\pi}{4}$$

3.3 Roujean (geo)

Original Roujean model was “Roujean” + Ross-thick kernel model. Here “Roujean” refers to the geometric kernel

$$D = \left[\tan^2\theta_i + \tan^2\theta_v - 2\tan\theta_i \tan\theta_v \cos\phi\right]^{1/2}$$

$$k_{brick} = \frac{1}{2\pi}\left[(\pi-\phi)\cos\phi + \sin\phi\right]\tan\theta_i \tan\theta_v - \frac{1}{\pi}\left(\tan\theta_i + \tan\theta_v + D\right)$$

3.4 Li-sparse (geo)

The Li-sparse and Li-dense kernels are derived in Wanner *et al*. (1995). A detailed mathematical outline of the computation (the derivation is discussed later under the Li/Strahler/Jupp model) is as follows:

Sequence of steps for calculations:

$$\theta_i' = \tan^{-1}\left(\frac{b}{r}\tan\theta_i\right)$$

$$\theta_v' = \tan^{-1}\left(\frac{b}{r}\tan\theta_v\right)$$

$$\cos\xi' = \cos\theta_i'\cos\theta_v' + \sin\theta_i'\sin\theta_v'\cos\phi$$

$$D' = \left[\tan^2\theta_i' + \tan^2\theta_v' - 2\tan\theta_i'\tan\theta_v'\cos\phi\right]^{1/2}$$

$$\cos t = \min\left\{1, \frac{h}{b}\frac{\left[D'^2 + (\tan\theta_i'\tan\theta_v'\sin\phi)^2\right]^{1/2}}{\sec\theta_i' + \sec\theta_v'}\right\}$$

$$t = \cos^{-1}(\cos t)$$

$$O(b/r, h/b, \theta_i, \theta_v, \phi) = \frac{1}{\pi}(t - \sin t\cos t)(\sec\theta_i' + \sec\theta_v')$$

The Li-sparse kernel follows from these definitions as:

$$Li\_sp = O - \sec\theta_i' - \sec\theta_v' + \frac{1}{2}(1 + \cos\xi')\sec\theta_v'$$

3.5 Li-dense (geo)

The Li-dense approximation refers to dense vegetation canopies. Using the same definitions as for the Li-sparse kernel it is:

$$Li\_dn = \frac{(1 + \cos\xi')\sec\theta_v'}{\sec\theta_i' + \sec\theta_v' - O} - 2$$

3.6 Cox-Munk (geo)

Based on the Cox-Munk (1954) model for sun glint and presented in Strahler *et al.* (1996).

$$k_{spec} = \begin{cases} \frac{1}{\cos\theta_i}\left(1 - \frac{\tan^2\theta_n}{\sigma^2}\right) - 1 & if\ \frac{\tan^2\theta_n}{\sigma^2} \le 1 \\ -1 & else \end{cases}$$

where σ^2 is the wave slope variance (nonlinear parameter):

$$\sigma^2 = 0.003 + 0.00512\ w$$

w is the wind speed and the parameter θ_n is defined as:

$$\cos^2\theta_n = \frac{1}{2}\left(\frac{(\cos\theta_i + \cos\theta_v)^2}{1+\cos\phi}\right)$$

3.7 Walthall (vol)

This empirical model (also called the "limacon" function) was due to Walthall *et al*. (1985) and improved by Nilson and Kuusk (1989) to include reciprocity. It has 4 linear parameters:

$$\rho(\theta_i,\theta_v,\phi) = p_0(\theta_i^2 + \theta_v^2) + p_1\theta_i^2\theta_v^2 + p_2\theta_i\theta_v\cos\phi + p_3$$

3.8 MODIS Products

Best fitting model from a selection of kernels (AMBRALS)

Ross-thin + Li-sparse
Ross thin + Li-dense
Ross-thick + Li-sparse
Ross-thick + Li-dense
Cox-Munk + Li-sparse
Walthall

The first 4 of these have parameters that can be converted to "physical" parameters.

4 Extensions and Alternatives

4.1 Reciprocal Li models

[Modified for varying sun as well as observer position so that they are "reciprocal"]

4.2 RPV Model

[Rahman, Pinty & Verstraete model]. Derived in Rahman *et al*. (1993).

$$\rho(\theta_i,\theta_v,\phi) = \rho_0\ M(\theta_i,\theta_v,k)\ P(g,\xi)\ H(\rho_0,D)$$

$$M(\theta_i,\theta_v,k) = \frac{\cos^{k-1}\theta_i\cos^{k-1}\theta_v}{(\cos\theta_i + \cos\theta_v)^{1-k}}$$

$$P(g,\xi) = \frac{1-g^2}{\left[1+g^2-2g\cos(\pi-\xi)\right]^{1.5}}$$

$$H(\rho_0, D) = 1 + \frac{1-\rho_0}{\delta + D}$$

where the linear parameter is ρ_0 and g, k [and δ] are nonlinear parameters (generally δ≈1). M is the Minnaert model, P is the Henyey Greenstein phase function and H is the hotspot function.

4.3 MRPV model

[MISR version of RPV model as suggested by J.V. Martonchik.]

$$P(g,\xi) = P_M(\xi) = e^{-b_M \cos\xi}$$
$$H(\bar{\rho}, D) = 1 + \frac{1-\bar{\rho}}{1+D}$$

where $\bar{\rho}$ is an average reflectance assumed known if the algorithm is "linearised" by taking logs. Otherwise a simple nonlinear iteration can be used.

4.4 Staylor & Suttles

(as given in Cosnefroy, *et al*., 1996 following Staylor and Suttles, 1986)

$$\rho(\theta_i, \theta_v, \phi) = \frac{1}{\cos\theta_i \cos\theta_v}\left[Y_0 + Y_1\left(\frac{\cos\theta_i \cos\theta_v}{\cos\theta_i + \cos\theta_v}\right)^N\right] \times \frac{1 + C_{sw}\cos^2\xi}{1 + C_{sw}\left[\cos^2\theta_i \cos^2\theta_v + (\sin^2\theta_i \sin^2\theta_v)/2\right]}$$

where Y_0 and Y_1 are two linear parameters and C_{sw} and N are two nonlinear parameters. This model is very flexible and quite useful. The nonlinear parameters seem to converge quite quickly.

4.5 Shibayama & Weigand

Developed in Shibayama and Weigand (1985) and used in Qi *et al*. (19??)

$$\rho(\theta_i, \theta_v, \phi) = \rho_0 (1 + \left[\beta_0 + \beta_1 \sin(\phi/2) + \beta_2 (1/\cos\theta_i)\right]\sin\theta_v)$$

4.6 Dymond & Qi

Derived by Dymond and Qi (in press).

$$S(\theta_i, \theta_v) = \frac{\cos\theta_i}{\cos\theta_i + (\sigma_{\theta_i}/\sigma_{\theta_v})\cos\theta_v}$$

$$H(\xi,\theta_i)=\begin{cases}2\,e^{-\tan(\xi/2)/h\theta_i} & \xi<\pi/2\\ 2\,e^{-\tan(\pi/4)/h\theta_i} & \xi\geq\pi/2\end{cases}$$

$$B(\xi)=\frac{4\rho_0}{3\pi^2}\left(\sin\xi+(\pi/2-\xi)\cos\xi\right)$$

$$\rho(\theta_i,\theta_v,\xi)=S(\theta_i,\theta_v)\;H(\xi,\theta_i)\;B(\xi)$$

Parameters are one linear (ρ_0) and two nonlinear (h and R) where $R=\sigma_i/\sigma_v$

4.7 Chen modification to Roujean

In Chen and Cihlar (In Press) a modification of the Roujean model is proposed based on a simplification of Chen's more complex canopy model. The simple model reduces to:

$$\rho(\theta_i,\theta_v,\phi)=(\,f_{iso}+\,f_{geo}k_{brick}+\,f_{vol}k_{thick})(1+C_1e^{-C_2\frac{\xi}{\pi}})$$

where the constants C1 and C2 must be determined from the data. This added flexibility allows the Roujean model to approximate the hotspot effect much more successfully than before. Perhaps choosing a better model would be even better!

The Chen modification could, of course, be applied to any of the Kernel models to "sharpen" the hotspot. However, there are two extra parameters to estimate.

4.8 Liang modification to Walthall.

In a similar way to the modification of the Roujean model by Chen to improve modelling of the hotspot, Liang (1994) modified the Walthall model to include a hotspot effect. He increased the number of parameters from 4 to 6 by proposing a linear sum of the two models in the form:

$$\rho(\theta_i,\theta_v,\phi)=\rho_1(\theta_i,\theta_v,\phi)+\rho_2(\theta_i,\theta_v,\phi)$$

where the first is the Walthall model described above and:

$$\rho_2(\theta_i,\theta_v,\phi)=C_1\;e^{-C_2\tan(\pi-\xi)}$$

where, as above, C_1 and C_2 are adjustable parameters. In this case, one is non-linear and the hotspot shape is added rather than used multiplicatively.

Jupp (1997) described how a Walthall model plus a Li-sparse kernel could also effectively model a woodland BRDF with the Walthall accommodating the volume effect and the Li-sparse modelling the hotspot.

4.9 Pickup & Chewings Model

Pickup *et al*. (1995a,b) developed and extended an approach similar to one originally reported by Royer *et al*. (1985) to correct Video images for BRDF and other angular effects.

A simple linear "kernel" model of the form:

$$\rho(\theta_i, \theta_v, \phi) = p_0 + p_1\xi + p_2\xi^2 + p_3 \cos^4 \theta_v$$

Was fitted to a line of Video data frames and then used to normalise the individual frames in the line. The cos^4 term was introduced to account for lens effects but can also model a volume effect. The authors claim the power is insensitive to choices between 2 and 4.

5 Slightly more Complex models - not in "kernel" form

5.1 Otterman Model

Used in Deering *et al*. (1990). Based on previous work by Otterman (eg Otterman and Weiss, 1984) where the geometry is based on thin vertical cylinders.

$$\rho = R_g e^{-s(\tan\theta_i + \tan\theta_v)} + R_p(1 - e^{-s(\tan\theta_i + \tan\theta_v)})$$

$$R_g = (1-f)\frac{r(\sin\phi - \phi\cos\phi) + t((\phi-\pi)\cos(\phi-\pi) - \sin(\phi-\pi))}{4(\cot\theta_i + \cot\theta_v)} + fr_0$$

$$R_p = \frac{r_p(\sin\phi - \phi\cos\phi)}{4(\cot\theta_i + \cot\theta_v)}$$

where the parameters to be modelled are:

s or "cylinder area index"
r_p or plant reflectance
and three soil reflectance parameters:

$$L = fr_0$$
$$B = (1-f)r$$
$$T = (1-f)t$$

where:

f is the lambertian fraction
r_0 is the lambertian reflectance
r is facet reflectance
t is facet transmittance

That is, five parameters in all. Four of the parameters are linear but *s* is nonlinear.

5.2 Verstraete, Pinty & Dickinson (VPD) model

Derived in Verstraete *et al*. (1990) and Pinty *et al*. (1990). This is a more complex form of the RPV model given above.

$$\rho(\theta_i,\theta_v,\phi)=\frac{\omega}{4}\frac{\kappa_i}{\kappa_i\mu_v+\kappa_v\mu_i}\left[P_\upsilon(D)P(g,\xi)+H\left(\frac{\mu_i}{\kappa_i},\omega\right)H\left(\frac{\mu_v}{\kappa_v},\omega\right)-1\right]$$

where:

$$\mu_i=cos\theta_i$$
$$\mu_v=cos\theta_v$$

Following Dickinson *et al*. (1990) after Goudriaan (1977):

$$\kappa_x=\Psi_1+\Psi_2\mu_x$$
$$\Psi_1=0.5-0.489\chi_l-0.33\chi_l^2$$
$$\Psi_2=1-2\Psi_1$$

where χ_l is a function of the leaf angle distribution of the canopy and varies from -0.4 for an erectophile canopy to 0.6 for a planophile canopy. Random orientation is zero.

$$P_\upsilon(D)=\frac{1}{1+V_P(D)}$$
$$V_P(D)=4\left(1-\frac{4}{3\pi}\right)\frac{D}{2r\Lambda}\frac{\mu_v}{\kappa_v}$$

$$P(g,\xi)=1 \qquad \textit{Isotropic}$$
$$=\frac{1-g^2}{\left[1+g^2-2g\cos(\pi-\xi)\right]^{1.5}} \qquad \textit{Henyey and Greenstein}$$
$$=1+g\cos\xi+\frac{L_2}{2}(3\cos^2\xi-1) \qquad \textit{Legendre}$$

$$H(x,\omega)=\frac{1+x}{1+x\sqrt{(1-\omega)}}$$

The parameters for this model that need to be fitted in inversion or supplied for a given land surface are:

ω the single scattering albedo

g the asymmetry of the phase function (and L_2 if Legendre)
χ_l the scatterer orientation parameter (used to obtain κ_i and κ_v)
$2r\Lambda$ the structural parameter (r is the sunfleck radius and Λ is the scatterer area density)

[NOTE: There are discrepancies between this (which basically comes from Rahman *et al*., 1993 and the 6S Manual. Need to check original Verstraete *et al*. (1990).)

5.3 *Strahler & Jupp simple model*

(Derived as in Strahler and Jupp (1991) but here using overlap function derived for the Li kernels above.)

In this model, there are four kinds of ground cover "visible" from a given direction. These are referred to as scene components and consist of sunlit canopy (symbol *C*), shaded canopy (*T*), sunlit background (*G*), and shaded background (*Z*). Each component is assumed to have a characteristic reflectance and the reflectance of a pixel is modelled as the area weighted combination (or linear mixture) of the characteristic component reflectances. That is, the observed reflectance of a single pixel is modelled as:

$$\rho(\theta_i,\theta_v,\phi) = k_C R_C + k_T R_T + k_G R_G + k_Z R_Z$$

where *C*, *T*, *G*, and *Z* indicate the reflectances of the four components as named above, R_X represents the (mean) radiance of component "*x*" and *k* indicates the sensed proportion of each component within the pixel from the given view direction.

Obviously, with these definitions:

$$k_x \geq 0$$
$$\sum_{x=C,T,G,Z} k_x = 1$$

If the proportions are replaced by their expectations then the various components can be derived from the equations:

$$k_G = e^{-\lambda\bar{A}(\sec\theta_i' + \sec\theta_v' - O)}$$
$$k_C + k_T = 1 - e^{-\lambda\bar{A}\sec\theta_v'}$$

which, given the closure above means there is one extra condition to complete the model. This was done one way in Strahler and Jupp (1991) and in a second way in Li and Strahler (1992).

In Strahler and Jupp (1991) it was assumed that the proportion of visible sunlit tree was the same as for a single tree. That is:

$$\frac{k_C}{k_C + k_T} = \frac{1}{2}(1+\cos\xi')$$

This model is the basis for the simplified Li-sparse formulation. In the full model, the four signatures must be determined as well as the ratios b/r and h/b and the vertical projected "crown area index", or cover, λA.

There are some simplifications. For example, in cases where the background is bright and trees dark it is possible to write:

$$\rho(\theta_i,\theta_v,\phi) \approx R_X + k_G(R_G - R_X)$$

where X refers to a composite of tree plus shade which is assumed dark. Obviously,

$$R_X = \frac{k_C R_C + k_T R_T + k_Z R_Z}{1 - k_G}$$

This simple two-component model can often do a very good job. If, however, the variation is dependent on the differences between sunlit and shaded tree then the model will not do so well. It is often better just to assume that shaded tree and shaded background have the same colour. This reduces the number of parameters and is usually a reasonable assumption.

In the Li-sparse kernel given above and derived in Wanner *et al*. (1995), it is assumed that R_T=R_Z=0 and R_C=R_G. Then:

$$\begin{aligned}\rho(\theta_i,\theta_v,\phi) &\approx (k_G + k_C)R_C \\ &= R_C\left[\frac{1}{2}(1+\cos\xi')(1-e^{-\lambda\bar{A}\sec\theta_v'}) + e^{-\lambda\bar{A}(\sec\theta_i'+\sec\theta_v'-O)}\right] \\ &\approx R_C\lambda\bar{A}\left[O - \sec\theta_i' - \sec\theta' + \frac{1}{2}(1+\cos\xi')\sec\theta_v'\right] + R_C \\ &= c_1 k_{sparse} + c_2\end{aligned}$$

which is the form previously given.

5.4 *Li's "Top easy seen" modification*

Li and Strahler (1992) modified the simple model to take account of the fact that when the density of trees increases then the shaded crown tends to be "hidden" and the view becomes dominated by the sunlit crown tops.

Of a number of choices, the one used for the simple dense canopy models assumes that:

$$f = \frac{k_C}{1 - k_G} = F$$

where F is the ratio for a single crown or rather the very dense case. It follows that:

$$F = \frac{\frac{1}{2}(1+\cos\xi')\sec\theta'_v}{\sec\theta'_v + \sec\theta'_i - O}$$

The model may now be resolved and even inverted as it stands or it may be approximated in various ways with simpler forms. This model is used in dense vegetation and the previous one in sparse vegetation.

Note that this is equivalent to:

$$\begin{aligned}\frac{k_c}{k_c+k_t} &= F\,\frac{1-k_g}{k_c+k_t} \\ &= \frac{\frac{1}{2}(1+\cos\xi')\sec\theta'_v}{\sec\theta'_v+\sec\theta'_i-O}\,\frac{1-e^{-\lambda\bar{A}(\sec\theta'_v+\sec\theta'_i-O)}}{1-e^{-\lambda\bar{A}\sec\theta'_v}}\end{aligned}$$

which asymptotes to the same result as before when the density is low ($1-e^{-x}\approx x$).

To derive the Li-dense kernel (Wanner *et al*., 1995), suppose R_G is neglected since there is so little sunlit soil showing in dense vegetation and also the forest floor may be dark material. Assume all shadow and R_G is zero. Then:

$$\begin{aligned}\rho(\theta_i,\theta_v,\phi) &= k_C R_C \\ &\approx f\ R_C \\ &= \left[\frac{(1+\cos\xi')\sec\theta'_v}{\sec\theta'_v+\sec\theta'_i-O}-2\right]\frac{R_C}{2}+R_C \\ &= c_1 k_{dense}+c_2\end{aligned}$$

which is again in the form of the Li-dense kernel approximation. But again, it is possible also to solve the complete model or a model with some less restrictive assumptions if the linear kernel structure is not enforced.

5.5 Hapke BRDF Model for soils

Hapke (1981) derived a model for dimensionless particles which has principally been applied to Soil data and is used also in the RPV and VPD models. The model was:

$$\rho(\theta_i,\theta_v,\phi)=\frac{\omega}{4}\frac{1}{\mu_v+\mu_i}\left[\left[1+B(\xi)\right]P(g,\xi)+H\left(\mu_i,\omega\right)H\left(\mu_v,\omega\right)-1\right]$$

where:

[NOTE: Soil Reflectance Chapter in Asrar has:

$$\rho(\theta_i,\theta_v,\phi)=\frac{\omega}{4}\frac{\mu_v}{\mu_v+\mu_i}\left[\left[1+B(\xi)\right]P(g,\xi)+H\left(\mu_i,\omega\right)H\left(\mu_v,\omega\right)-1\right]\ ]$$

$$\mu_i = cos\theta_i$$
$$\mu_v = cos\theta_v$$

B(ξ) is a backscattering function that accounts for the hotspot effect:

$$B(\xi)=\frac{S(0)}{\omega\ P(g,0)}\frac{1}{\left[1+(1/h)\tan(\xi/2)\right]}$$

Where *S(0)* defines the magnitude of the "hotspot" and *h* defines the width.

P(g,ξ) is the phase function for the particle collection with assymetry *g*:

$$P(g,\xi)=\frac{1-g^2}{\left[1+g^2-2g\cos(\pi-\xi)\right]^{1.5}} \quad \textit{Henyey and Greenstein}$$
$$=1+g\cos\xi+\frac{L_2}{2}(3\cos^2\xi-1)\ \ \textit{Legendre}$$

In the Legendre case there is an extra parameter L_2.

H(x,ω) is a function to account for multiple scattering:

$$H(x,\omega)=\frac{1+2x}{1+2x\sqrt{(1-\omega)}}$$

The parameters for this model that need to be fitted in inversion or supplied for a given land surface are:

ω the single scattering albedo
g the asymmetry of the phase function [plus L_2 for the Legendre phase function]
S(0) is a parameter defining the height of the hotspot function at the hotspot
h a parameter that controls the width of the hotspot function.

5.6 Ross' Simplified vegetation canopy formula

The "turbid medium" formula by Ross (1981) which was used by Roujean *et al*. (1992) to derive a volume kernel (the Ross-Thick) and by Wanner *et al*. (1995) to derive another (the Ross-Thin) kernel was simplified by both groups of writers to the following form as an initial step in their formulation:

$$\rho(\theta_i,\theta_v,\phi)=\frac{4\rho_L}{3\pi}\frac{(\pi/2-\xi)\cos\xi+\sin\xi}{\cos\theta_i+\cos\theta_v}\left(1-e^{-\frac{LAI}{2}(\sec\theta_i+\sec\theta_v)}\right)+\rho_s e^{-\frac{LAI}{2}(\sec\theta_i+\sec\theta_v)}$$

where:

ρ_L is the reflectance of a single leaf
ρ_s is the background soil reflectance and
LAI is Leaf Area Index

If these three parameters are estimated subject to the reflectances being in the range (0,1) and LAI>0 then this provides a model that includes both the Ross-thin and the Ross-thick (Wanner *et al*., 1995). As with all these non-kernel models, however, the fit will need to be nonlinear. However, this often presents little problem.

5.7 Minnaert's Original Model

Minnaert (1941) proposed a model that has been used for modelling topographic shading and has been used a s a component in a number of semi-empirical models. Its form is:

$$\rho(\theta_i,\theta_v)=\rho_L\,\frac{k+1}{2}\mu_i^{k-1}\mu_v^{k-1}$$

This function is a reciprocal "volume" scattering kernel in its behaviour with k=1 being Lambertian, k=0 being a "bowl" with highest reflectances away from nadir and k=2 being an inverted "bowl" with darkening away from nadir.

Parameters to estimate are ρ_L and *k*.

6 References

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