ON CANOPY SPECTRAL INVARIANTS AND HYPERSPECTRAL RAY TRACING

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ABSTRACT

In this paper we present a method for the efficient simulation of canopy hyperspectral reflectance using Monte Carlo Ray Tracing. The method essentially describes the scattered radiation in terms of spectral invariants that gives an expression as a series of powers of leaf single scattering albedo. This can then be post-processed to describe the scattering regime for arbitrary leaf spectral functions. The spectral invariant expression is explored to interpret some of its features. Some practical uses of this include the use of truncated ray tracing methods that can be adjusted for unsampled scattering orders by consideration of energy conservation.

Index Terms— Spectral Invariants, Radiative Transfer, Monte Carlo Ray Tracing, Hyperspectral Simulation, Vegetation.

1. INTRODUCTION

1.1. Canopy Spectral Invariants

Information extraction from hyperspectral remote sensing signals over vegetation is often aimed at monitoring leaf biochemistry. This information is not directly available from such data so some model must be used in interpretation. We can phrase this model in several ways, but the traditional view in building radiative transfer models is to first develop a relationship between leaf biochemical concentrations C_x and leaf reflectance ρ_l and transmittance τ_l. These latter terms vary with wavelength and are functions of C_x and leaf internal and surface structure. Given such a model and a set of specific absorption spectra k_x, structural terms and C_x can be inferred from hyperspectral measurements of ρ_l and τ_l. Since remote sensing monitoring is generally aimed at canopies rather than leaves an additional function maps the leaf scattering properties to canopy reflectance ρ_c and transmittance τ_c. This signal is also conditioned by the scattering materials on the canopy lower boundary (i.e. soil, snow etc.), which we may term ρ_s. Atmospheric properties impact the directional and spectral nature of the incident irradiance at the top of the canopy, but we will ignore the details of this in this paper.

At optical wavelengths, the scattering objects (leaves, stems etc.) are large compared to the wavelength of radiation so we can use geometric optics principles. We can therefore express the upward scattering of a vegetation canopy ρ_c as infinite series of powers of leaf total scattering, $\omega_l = \rho_l + \tau_l$:

$$\rho_c = i_0 \sum_{i=1}^{i=\infty} r_i \omega_l^i \qquad [1]$$

where i_0 is the probability of radiation from the upper boundary intercepting the canopy, and terms r_i are the compound probabilities of radiation escaping the canopy at scattering order i given initial interception and unit single scattering albedo at all scattering orders for some given value of leaf asymmetry $\left(\zeta_l = \tau_l / \omega_l\right)$ (typically 0.5). The terms r_i are purely geometric terms (not functions of wavelength, other than the dependency on ζ_l which shall be considered later) and so can be called spectral invariants. These can also be expressed as:

$$r_i = i_0 e_{r\,i} \prod_{j=1}^{j=i} p_j \qquad [2]$$

where p_j is the recollision probability at scattering order j, and $e_{r\,i}$ is the escape probability at scattering order i and $p_1 \equiv 1$. Clearly similar expressions exist for and direction of escape, including downward travel (canopy transmittance). This escape probability depends on the distribution of radiation within the canopy at the preceding scattering order and so varies with scattering order. The integral of $e_{r\,i}$ over 4π sr, the integral escape probability for that scattering order is equal to $1 - p_i$.

1.2. Hyperspectral Monte Carlo Ray Tracing

Monte Carlo ray tracing (MCRT) has become one of the main benchmark techniques for simulating the radiative regime of vegetation canopies [1,2]. This is because simulations can be achieved that make relatively few prior assumptions regarding the nature of the radiation regime and scattering within complex structured media, such as those encountered in vegetation canopies, can be readily simulated. There are two main options for simulation:

forward ray tracing, where sample ray trajectories are followed from some illumination source through interactions with the scattering and absorbing medium, providing a simulation of scattered radiation in all directions from the mean of the samples; and reverse ray tracing in which radiation is followed from some imaging device, again through the scattering and absorbing medium, but with targeted light sources (such as solar illumination) considered by extra samples along the ray path. In the former, the radiation regime is generally simulated by applying some probability of absorption at each interaction event. Thus sample ray trajectories terminate either on absorption or on escaping the canopy. In reverse ray tracing, it is more typical that the absorption modeling is achieved by attenuating the ray intensity along the path, so that (in theory) all ray paths continue (from sensor to illumination). In practice, ray paths are generally terminated after some pre-defined number of scattering orders when the radiation level is assumed small, although this can clearly lead to bias and also break energy conservation laws.

In fact, either of the 'absorption probability' or 'attenuation' methods can be applied to both forward and reverse ray tracing, so that should not be considered the fundamental distinction in technique. The largest computational cost involved in MCRT remains that of calculating which geometric primitives the rays interact with. This suggests that efficient use must be made of what samples are available without biasing the results. This in turn implies that sample paths should be used for simulating scattering from however many wavelengths are being simulated. This concept was implemented in the MCRT tool *Ararat* [3], which in turn became *drat* and is now implemented as a library of ray tracing functions in *librat*, http://www2.geog.ucl.ac.uk/~plewis/bpms/src/lib/configure. In this software, the default behaviour is that the radiation intensity is scaled at each scattering order by the probability of scattering from the incident angle to the scattered angle (in so-called 'ray bundles'), which means that hyperspectral simulation can be achieved at a similar cost to monochromatic simulation. Recently, a new mode of operation has been defined for the tool, whereby a set of canopy spectral invariants is the main result (assuming for the present diffuse interactions at each scattering primitive). This can in turn be post-processed to achieve a simulation for arbitrary scattering properties, so that changing e.g. the leaf reflectance and transmittance spectral functions requires no further ray tracing. Further, the spectral invariant terms themselves provide scientifically interesting output, as they explain the impact of the geometric arrangement of the canopy on the radiation regime and provide insights into scattering processes.

1.3. Spectral Invariant Ray Tracing

We may call this then 'spectral invariant ray tracing'. If we suppose there are three different types of spectral material behaviour in the scene (e.g. soil reflectance, leaf reflectance and leaf transmittance), then we can write canopy reflectance ρ_c as:

$$\rho_c = \sum_{i,j,k} r_{ijk} \rho_l^i \tau_l^j \rho_s^k \qquad [3]$$

where the summation is performed over all values of i,j,k in the simulation and r_{ijk} is the spectral invariant term associated with i scattering events involving leaf reflectance, j events involving leaf transmittance and k events involving soil reflectance. The scattering order for this sample would be $i+j+k$. Thus for example $r_{001}\rho_s$ is the first order scattering from the soil only, with no canopy interactions, $\omega_l\left[r_{100} + \zeta\left(r_{010} - r_{100}\right)\right]$ is the first order scattering from the canopy with no soil interactions. There are some downsides and limitations to this form of output. First, there is a danger of numerical issues if care is not taken to output the spectral invariants with sufficient precision. Second, the number of terms that must be stored can grow rather large if the number of different material types considered in the canopy is too large (which has a significant impact on computer memory usage). With current computing facilities, it is generally reasonable to simulate up to around 5 types of spectral material behaviour in a simulation of up to 100 scattering orders.

2. EXAMPLES OF SPECTRAL INVARIANTS

2.1. Simulations

To demonstrate the concepts behind this spectral invariant ray tracing, we use a geometric scene from the RAMI exercises [1,2] (HET01_DIS_UNI), which consists of fifteen spheres of LAI 5.0 radius 10 units with bi-Lambertian scattering discs of radius 0.1 units, giving a fractional coverage for the spheres of 0.471. Figure 1 shows a representation of the scene for direct illumination at a zenith angle of 50° for a viewing zenith angle of 9°. Simulations for the following examples were performed with 450×10^3 primary rays, simulating interactions up to 100 orders of scattering. Figure 2 shows a simulation of canopy reflectance performed with the spectral invariant solution for the scenario illustrated in Figure 1.

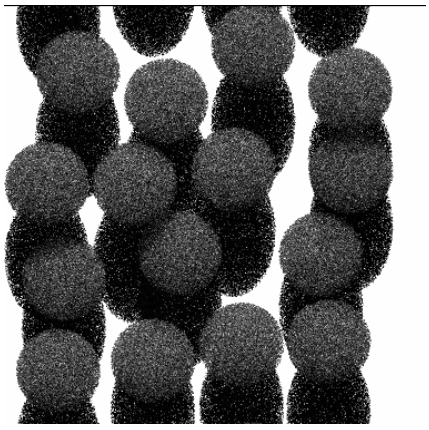

Figure 1. Visualisation of HET01_DIS_UNI scene.

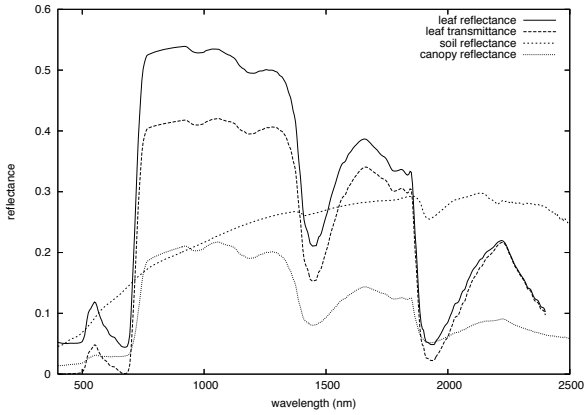

Figure 2. Canopy spectral reflectance and component terms.

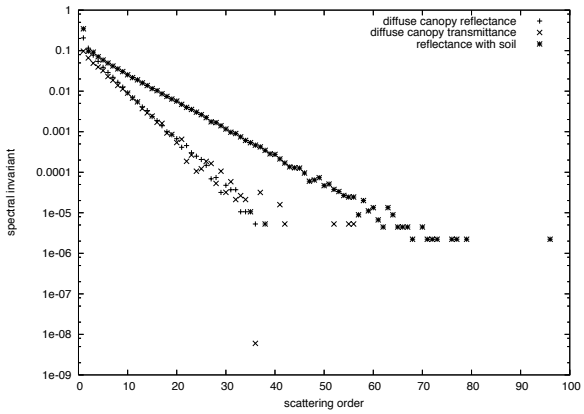

Figure 3. Spectral invariants for canopy for SZA 9^o.

2.2 Truncated ray series

Figure 3 shows spectral invariant terms for the canopy illuminated by a directional source at 9^o as a function of scattering order. The plot shows the spectral invariants for the directional-hemispherical integral of reflectance and transmittance (diffuse reflectance/transmittance) (relative to canopy interception) for equal leaf reflectance and transmittance ($\zeta = 0.5$) and those for the combined soil/canopy scattering, for $\rho_s = 1.0$.

The figure illustrates some of the important features of spectral invariance plots. First, examining the components involving canopy scattering only, we observe that although reflectance is greater than transmittance for the first few scattering orders, it converges (within about 2 x LAI scattering orders) to a point where the reflectance and transmittance contributions are equal. This represents the point at which the canopy radiation becomes 'well-mixed', i.e. where the escape probabilities in the upward and downward directions become equal. This then is also the point at which the recollision probability effectively becomes constant, although there is evidence to suggest that this term converges more rapidly than the escape probabilities. We note that the Monte Carlo simulations become rather noisy, at around 20 orders of scattering in this case. With the particular sampling here then, we cannot accurately represent scattering orders beyond this. From the data alone, and cannot in turn guarantee energy conservation. However, because this is past the point where the escape probabilities become effectively constant, we can write:

$$\begin{aligned} \rho_c &= i_0\left[\sum_{i=1}^{i=20} r_i\omega_l^i + \frac{r_{20}p_\infty\omega^{21}}{(1-p_\infty\omega)}\right] \\ \tau_c &= (1-i_0) + i_0\left[\sum_{i=1}^{i=20} t_i\omega_l^i + \frac{r_{20}p_\infty\omega^{21}}{(1-p_\infty\omega)}\right] \end{aligned} \qquad [4]$$

where p_∞ is the recollision probability [4] for high orders of scattering. This term is an intrinsic property of the canopy (for a given value of ζ) and will hold for both direct and diffuse cases. We can estimate its value from diffuse flux simulations and energy conservation:

$$p_\infty = \frac{\left[1-\sum_{i=1}^{i=20}(r_i+t_i)\right]}{\left\{r_{20}+\left[1-\sum_{i=1}^{i=20}(r_i+t_i)\right]\right\}} \qquad [5]$$

For the case shown in figure 3, a value of $p_\infty = 0.874$ is obtained. This is potentially very important for speeding up MCRT simulations: so long as we simulate up to interaction orders where the escape probabilities become approximately equal, we can accurately simulate scattering impacts beyond that point from an estimate of p_∞ provided simply by energy conservation.

The term involving soil interactions (labeled 'reflectance with soil' in Figure 1) clearly also is well behaved for higher scattering orders. Since both the leaf single scattering albedo and soil reflectance are unity in the formation of these spectral invariants, this is another case in which energy conservation can be applied. Thus, we could estimate a new value of p_∞ for the compound canopy-soil case using equation 5, but this would not directly allow solution of total canopy reflectance for arbitrary soil and leaf reflectance values. One option is to use a modeling construct such as adding/doubling to consider the joint impacts of the soil and canopy. This could be written as:

$$\rho_{c,s} - \rho_c = \sum_{i=1}^{i=\infty} R_i \rho_s^i \qquad [6]$$

where it is usual to assume in doubling that $R_{i+1} = \tau_c^2 \rho_c^i$, i.e.:

$$\rho_{c,s} = \rho_c + \frac{\tau_c^2 \rho_s}{1 - \rho_c \rho_s} \qquad [7]$$

However, with the MCRT output, we can analyse these terms in more detail. The output described above can be filtered to obtain only values associated with n soil interactions, directly giving access to R_n.

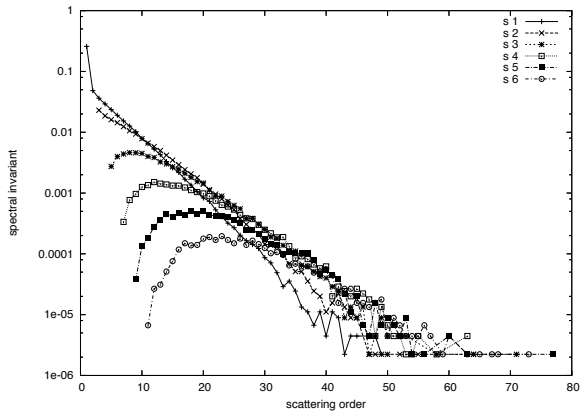

Figure 4. Spectral invariant terms for varying numbers of soil interactions

Figure 4 shows plots of R_n for n from 1 to 6. The first order soil interaction has rather different behaviour to the subsequent terms. For *n=2+*, the plots asymptotically approach the *n=2* curve. This suggests that the extension of curve s 1 for scattering orders higher than those sampled should be treated separately from that of higher scattering orders. For most practical applications however, equation 7 could simply be used.

3. DISCUSSION

This paper presents a method whereby MCRT methods, truncated at some fixed scattering order, can be used to express the spectral invariant behaviour of a canopy. Such analyses are important because the provide insights into the fundamental scattering properties in vegetation-soil complexes, which in turn affects (and limits) the information that can be estimated from remote sensing data. Hyperspectral ray tracing (scene simulation) can be readily achieved if weighting mechanisms are used in the simulator so that ray-object intersections need only be calculated once per waveband. Further, if the number of scattering materials considered in the simulation is relatively small, it is advantageous to describe the canopy in terms of spectral invariants, so that new simulations for arbitrary scene scattering properties can be performed with no further ray tracing. It is shown that truncated MCRT simulations can be extended to infinite scattering order by estimating the term p_∞ for the canopy from energy conservation in simulations of diffuse fluxes. This same term can be used to extend the scattering series for bidirectional fluxes as it is an intrinsic property of the canopy.

4. ACKNOWLEDGEMENTS

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5. REFERENCES

[1] J-L. Widlowski, M. et al. (2007), The third RAdiation transfer Model Intercomparison (RAMI) exercise: Documenting progress in canopy reflectance models, Journal of Geophysical Research, 112, D09111, doi:10.1029/2006JD007821.

[2] J.-L. Widlowski, et al. (2008) The RAMI On-line model checker (ROMC): A web-based benchmarking facility for canopy reflectance models, Remote Sensing of Environment, 112(3), 1144-1150.

[3] P. Lewis , (1999) Three-dimensional plant modelling for remote sensing simulation studies using the Botanical Plant Modelling System .Agronomie: Agriculture and Environment Vol.19, No.3-4, pp.185-210

[4] D. Huang, et al (2007), Canopy spectral invariants for remote sensing and model applications, Remote Sensing of Environment, 106, 106-122.