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Influence of Sky Radiance Distribution on the Ratio Technique for Estimating Bidirectional Reflectance

The error induced in the estimation of bidirectional reflectance factors using the standard ratio technique is less than five percent for zenith view and sun angles less than 55 degrees.

Abstract: *The technique of ratioing scene radiance to the radiance obtained from standard Lambertian reference panels in order to estimate bidirectional reflectance factors may depend on the angular distribution of the diffuse irradiance field as well as the direct solar irradiance. A simulation study was performed to estimate the magnitude of this effect for differing clear sky irradiance distributions for a variety of vegetated surfaces. For the seven surfaces and wavelengths analyzed, the error induced in the estimation of bidirectional reflectance factors using the standard ratio technique was less than 5 percent for zenith view and sun angles less than 55 degrees.*

Introduction

The bidirectional reflectance distribution function, BRDF, of a surface is an intrinsic property of the material and is independent of incident irradiance (Kriebel, 1976). In reality, one generally utilizes the average of the BRDF over finite solid angles of incidence and exitance. This average quantity is termed the (bidirectional) reflectance factor, *R*, and is also defined to be the ratio of the radiant flux reflected by the surface to that which similarly would be reflected by a Lambertian surface under the same viewing and illumination geometries (Robinson and Biehl, 1979). A commonly used measurement method to estimate (bidirectional) reflectance factors is to ratio the radiance of a target to the radiance of a standard Lambertian reference panel for varying view and sun angles.

Several authors have recently highlighted the potential errors induced in this method by a time varying irradiance field and have suggested potential improvements in the measurement procedures (Duggin, 1980; Duggin, 1981; Milton, 1981; Richardson, 1981). A second potential source of error is that induced by the diffuse sky radiance field. The interaction of the angular sky irradiance distribution with target reflectance anisotropies yields contributions to the target radiance in addition to that induced by the direct solar term. In order to yield a bidirectional reflectance factor corresponding to the solar incidence direction, these contributions of the sky radiance distribution are implicitly assumed to be negligible. For

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cloudy or partially cloudy conditions the sky radiance contributions can be significant and affect observed reflectance trends (Fuller, 1979; Gordon and Church, 1966; Kimes *et al.*, 1979). The purpose of this study was to examine the sky radiance contributions under clear sky conditions for a variety of vegetation canopies in order to determine at what view and solar angles these contributions may be significant to the radiation of the canopy.

Previous Work

Kriebel (1977) recognized the importance of understanding the effects of different irradiance distributions on final surface radiance. His approach to determining intrinsic surface reflectance properties was to obtain aircraft radiance measurements of the scene and measurements of the optical depth of the atmosphere. The latter were then used to calculate the irradiance by iterative solution of the atmosphere radiative transfer equation. The radiances were then used in a system of linear equations which were solved for the reflectance factors by inversion of the integral equation for radiance.

Bauer *et al.*, (1977) investigated the use of a subtractive technique to remove the effects of diffuse irradiance. By measuring the radiances of the shadowed target and shadowed reference panel, subtracting them from the corresponding measurements under normal sky illumination, and ratioing the results, a bidirectional reflectance factor related only to direct solar irradiance was obtained. However, they reported that the relative uncertainty associated with the measurement technique was greater than that of the standard ratio method.

Robinson and Biehl (1979) calculated the effect of sky radiance for a uniform overcast sky, an example anisotropic target bidirectional reflectance distribution function, and varying sun angles. However, only a nadir viewing geometry was simulated. Generally, they found the sky radiance contributions to the target reflectance factors to be less than three percent.

In this paper, we first extend the work of Robinson and Biehl by considering varying view angles as well as solar angles and by using two canopy reflectance models (Suits, 1972; Smith and Oliver, 1972) to generate a variety of theoretical canopy bidirectional reflectance distribution functions with known properties. We then also consider the more general clear sky distribution function of Pokrowski (1929).

Theory

As a ratio of two quantities, reflectance cannot be directly measured. The measured quantity, radiance, is expressed mathematically by the following equation (Note: for convenience the wavelength subscript has been suppressed):

$$L(\theta_r,\phi_r) = \int\int f(\theta_i,\phi_i;\theta_r,\phi_r)\, L(\theta_i,\phi_i) \cos\theta_i \sin\theta_i \, d\theta_i \, d\phi_i \quad (1)$$

Here f represents the bidirectional reflectance distribution function, (θ_i,ϕ_i) is the direction of the incoming ray, (θ_r,ϕ_r) is the direction of the reflected ray, and the integral is taken over all sources of incident radiation throughout the hemisphere of the sky. The bidirectional reflectance distribution function (Nicodemus, 1970; Kasten and Raschke, 1974) is an intrinsic property of the surface which describes how incident radiation from any given (θ_i,ϕ_i) direction will be scattered or reflected into any given direction (θ_r,ϕ_r). It is independent of the irradiance and has units of sr^{-1}. As noted earlier, present techniques do not derive a true bidirectional reflectance distribution function which would describe the reflection properties of a surface for every idealized pair of incidence and exitance angles. Instead, reflectance factors, R, are calculated which describe the behavior over finite solid angles. These factors are dimensionless quantities equivalent to π times the bidirectional reflectance distribution function averaged over the solid angles of incidence, ω_i, and exitance ω_r:

$$R(\omega_i;\omega_r) = \frac{\pi\int \omega_r \int \omega_i f(\theta_i,\phi_i;\theta_r,\phi_r) \cos\theta_i \, d\omega_i \cos\theta_r \, d\omega_r}{\int \omega_r \int \omega_i \cos\theta_i \, d\omega_i \cos\theta_r \, d\omega_r} \quad (2)$$

Making use of these reflectance factors, Equation 1 can be approximated for any solid angle of reflection, ω_r, as

$$L(\omega_r) = (\pi)^{-1} \sum_{\omega_i} R(\omega_i;\omega_r)\, L(\omega_i) P_i$$

where $L(\omega_r)$ and $L(\omega_i)$ are the reflected and incident radiances in their respective solid angles ω_r and ω_i, P_i is equal to $\int \cos\theta_i \, d\omega_i$, and the summation is over all ω_i sources of incident radiation, ω_i.

The commonly used technique of ratioing the radiance of a target to that obtained from a standard Lambertian reference panel is one method of estimating bidirectional reflectance factors. In this case, the surface radiance as normally obtained in the field, L_s, is ratioed to the radiance of a standard Lambertian panel, L_w. Thus,

$$\hat{R}(\omega_r) = \frac{L_s(\omega_r)}{L_w(\omega_r)} = \frac{(\pi)^{-1} \sum R(\omega_i;\omega_r) L(\omega_i) P_i}{(\pi)^{-1} \sum 1 \cdot L(\omega_i) P_i} \quad (3)$$

The solid angle of incidence, ω_i, is the entire hemisphere of the sky and the solid angle of reflectance, ω_r, is the field of view of the observer's radiometer. The constant reflectance factor of a standard Lambertian panel has been taken to be one in the above expression on the assumption that it is a perfect, uniform reflector. The global irradiance, E, is represented in the above expression as

$$E = \sum_{\omega_i} L(\omega_i)P_i$$

This may be rewritten to emphasize that the global irradiance consists of terms arising from both direct, E_{sun}, and diffuse irradiance components:

$$E = E_{sun} + \sum_{\omega_i} L_{diffuse}(\omega_i)P_i$$

Similarly, the equation for radiance may be rewritten as

$$L(\omega_r) = (\pi)^{-1}R(\omega_{sun};\omega_r)E_{sun} + (\pi)^{-1} \sum_{\omega_i} R(\omega_i;\omega_r)L_{diffuse}(\omega_i)P_i$$

The implicit assumption made when ratioing field radiance measurements to estimate the reflectance factor is that the diffuse irradiance source is negligible. In this case, the incident source angle θ_i,ϕ_i becomes the solar zenith and azimuth and the ratio simplifies to

$$\hat{R}(\omega_r) = \frac{L_s}{L_w} = \frac{(\pi)^{-1}\, R(\omega_{sun};\omega_r)E_{sun}}{(\pi)^{-1}\, E_{sun}} = R(\omega_{sun};\omega_r) \tag{4}$$

In reality, the diffuse irradiance field is not zero and the correct expression for the ratio, Equation 3 is applicable. In this case, the ratio does not reduce to the simple bidirectional reflectance factor corresponding to a specific view angle and the solar direction. Rather, it represents a complex sum over all components of the bidirectional reflectance factor matrix.

In this study we used simulation techniques as discussed in the following sections to calculate both target reflectance factors, $R(\omega_i;\omega_r)$, and incident radiance distribution fields, $L(\omega_i)$, in order to evaluate Equation 3 for various sun and view angles, the results were then compared to the inferred reflectance factors, Equation 4.

Calculation of Reflectance Factor Matrices

Two distinct canopy reflectance models were used to calculate representative reflectance factor matrices, Equation 2. The first was the Monte Carlo SRVC Model (Smith and Oliver, 1972), originally developed for grasslands, then extended to wheat canopies (Smith *et al.*, 1978), and further extended to lodgepole pine canopies (Kimes *et al.*, 1978). The second model used was the Suits Model (Suits, 1972), based on the Duntley equations.

Seven different canopies were simulated at the different wavelengths. The two wavelengths chosen were at 0.68μm, where reflectance is typically low due to absorption of the radiation by chlorophyll, and at 0.80μm in the near infrared region of the electromagnetic spectrum where healthy vegetation characteristically exhibits a high reflectance.

The seven canopies simulated included a lodgepole pine canopy with a measured leaf-area-index of 5.1 and a grass canopy with a measured leaf-area-index of 1.2, and a measured spherical leaf-slope distribution. Five additional theoretical canopies were simulated corresponding to a grass canopy also with spherical leaf slope distribution, but leaf-area-index equal to 0.5 and 4.0 and a grass canopy with a Planophile leaf slope distribution and leaf-area-index equal to 0.5, 1.2, and 4.0 (Kirchner, 1980). For the cases simulated, azimuthal isotrophy of reflectance was assumed. Consequently, each reflectance factor matrix described the reflection properties of the target surfaces at nine zenith view angles and nine source angles at equally spaced intervals centered at 5 to 85 degrees.

Irradiance Distributions

The second function required to evaluate Equation 3 is a specification for the irradiance field, $L(\omega_i)$, which includes both the direct solar term and the skylight distribution. We selected two broad types of skylight distribution functions for this study. The first was to assume that $L(\omega_i)$ was a constant, independent of ω_i, except for the solar term. We then allowed $L(\omega_i)$ to vary over the hemisphere.

As mentioned previously, the uniform sky distribution case has been addressed by Robinson and Biehl (1979). In their paper they show how Equation 3 may be reduced to the following expression for $L(\omega_i)$ constant and a vertical view, i.e., $\omega_r = 0$:

$$\hat{R}(\omega_r) = R(\omega_{sun};0)\left[1 + K_1(\omega_{sun})\, K_2(\omega_{sun})\right]$$

where $K_1(\omega_{sun})$ is the fractional amount by which the target reflectance factor differs from a Lambertian surface with the same hemispherical reflectance, and $K_2(\omega_{sun})$ is the ratio of the constant diffuse field to the total irradiance (diffuse plus solar). They then used the above expression to evaluate the difference between $\hat{R}(\omega_r)$ and $R(\omega_{sun};0)$ for a variety of solar angles, ω_{sun}, and a vertical view.

The above expression generalizes to the following equation when off-nadir views are included:

$$\hat{R}(\omega_r) = R(\omega_{sun};\omega_r)\left[1 + K_1(\omega_{sun};\omega_r)K_2(\omega_{sun})\right] \tag{3'}$$

where K_1 is now a matrix of deviations for each sun angle and view angle considered and K_2 is again the variation in the hemispherical sky radiance with sun angle.

The four theoretical canopies simulated with the Suits and SRVC models corresponding to sparse (LAI = 0.5) and dense (LAI = 4.0) grass canopies with both sperical and planophile leaf-slope-distributions were used to derive $K_1(\omega_{sun};\omega_r)$

for sun and view angles between 5 degrees and 75 degrees in 10-degree increments. The data for $K_2(\omega_{sun})$ are extracted from Figure 7 in Oliver *et al.* (1975).

We utilized the following clear sky radiance distribution function developed by Pokrowski (1929) to generate anisotropic sky radiance distributions, $L(\omega_i)$:

$$L_{\Theta,\alpha} = B(1 - e^{-P \text{ cosec}\Theta})\ (1 + \cos^2\alpha)/(1 - \cos\alpha) \quad (5)$$

Here $L_{\Theta,\alpha}$ is the radiance at a point an angle θ above the horizon and an angle α from the sun, P is a scattering coefficient whose value was given by Walsh (1961) as 0.32, and B is the radiance at the two points on the horizon at angular distances of 90° from the sun.

This distribution is similar to actual conditions as reported by Kimball and Hand (1921). Furthermore, the angular radiance distribution varies with sun angle. Thus, in this study the effect of eight different clear sky distribution functions was evaluated corresponding to zenith sun angles between 5 and 75 degrees.

Integration of the above equation over the hemisphere and over each sector to determine $L(\omega_i)$ values is somewhat cumbersome because of the dependence of α on θ and on the difference in azimuth between the sun and observed point. In order to perform the necessary integrations, a bicubic spline interpolation routine from the International Mathematical and Statistical Library (IMSL) was used. Complete details are given in Kirchner (1980).

For the analyses using the more general expression for sky radiance, Equation 5, the number of theoretical canopies studied was extended to include grass canopies of intermediate denseness, LAI equal to 1.2, and a forest canopy, lodgepole pine, with LAI equal to 5.1.

Results and Conclusions

To facilitate the comparison of the measured reflectance factors, Equation 3 or Equation 3′ with the inferred reflectance factors, Equation 4, the percent differences between them were calculated for all of the cases simulated. The information was organized into tables for each target surface as a function of wavelength and of view angle and solar angle, between 5 and 75 degrees. These tables were then systematically examined to determine the maximum zenith view and sun angles where the difference exceeded five percent.

Table 1 shows the results for the uniform sky distribution; Table 2 for the more general clear sky distributions. Generally, both tables indicated that the error induced in the estimation of bidirectional reflectance factors using the standard ratio technique is less than five percent for zenith view and sun angles less than 55 degrees.

While the results of this study have strongly indicated the negligible contribution of the sky radiance distribution to target reflectance factors, there are two potential limitations to the analyses performed.

First, target reflectance isotropy in the azimuthal direction was assumed. Azimuthal reflectance asymmetry could have an effect; however, essentially no effect was observed for very strong target reflectance asymmetries in the polar directions. Thus, we do not believe this to be an important factor.

The second potential limitation is more serious, and further theoretical analyses are recommended. This is the potential effect of strong angular anisotropies in the sky radiance distribution caused by scattered cloud patterns. In effect, such patterns could behave as secondary direct sources. As mentioned in the Introduction, there is experimental evidence for significant sky radiance contributions for cloudy or partly cloudy conditions. Theoretical analyses similar to those performed here could define the magnitude of such effects.

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Table 1. *Uniform Sky Results:* The Table Indicates the Zenith View Angle, θ_o, and Solar Angle, θ_s, where the Diffuse Sky-Light Contribution Causes the Measured Reflectance Factor to Differ by More than Five Percent from the Inferred Reflectance Factor Corresponding to the Angles θ_o and θ_s. Results are given for Theoretical Surfaces Simulated According to Both the Suits and SRVC Models for the Wavelengths 0.68 and 0.8 Micrometers.

		Suits				SRVC			
		0.68		0.80		0.68		0.80	
Surface	LAI	θ_o	θ_s	θ_o	θ_s	θ_o	θ_s	θ_o	θ_s
Grass Spherical	0.5	75	65	65	75	75	75	75	75
	4.0	55	65	65	75	75	75	75	75
Grass Planophile	0.5	75	75	75	75	75	65	75	75
	4.0	75	65	75	75	75	75	75	75

TABLE 2. CLEAR SKY DISTRIBUTION RESULTS

		Suits				SRVC			
		0.68		0.80		0.68		0.80	
Surface	LAI	θ_o	θ_s	θ_o	θ_s	θ_o	θ_s	θ_o	θ_s
Lodgepole Pine	5.10	55	55	45	55	75	65	75	75
Grass Spherical	0.5	75	65	65	75	75	75	75	75
	1.20	65	45	45	65	75	75	75	75
	4.00	55	65	65	75	75	65	75	75
Grass Planophile	0.5	75	75	75	75	75	65	75	75
	1.20	75	65	75	75	75	55	75	55
	4.00	75	65	75	75	75	75	75	75

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