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Vegetation Reflectance Measurements as a Function of Solar Zenith Angle

The wide variability in diurnal reflectance is caused by variations in anisotropic sky irradiance, canopy component geometry and optical properties, and type of reflectance measurement.

Introduction

An understanding of solar radiation interaction with vegetation canopies is necessary for accurately interpreting remotely sensed data. Broad- and narrow-band spectral reflectance measurements of vegetation canopies are often used to characterize this interaction. Measured reflectance, however, is a complex function of canopy constituent optical properties (Gates, 1970; Knipling, 1970), canopy geometry (Ross, 1976; Kimes *et al.*, 1979b) optical properties of the ground, atmospheric conditions (Kriebel, 1976; Ross, 1976), solar zenith angle (Smith *et al.*, 1974; Kriebel, 1975; Jarvis *et al.*, 1976), and sensor inclination and azimuthal view angles (Smith and Oliver, 1974; Kriebel, 1978; Smith *et al.*, 1979).

Understanding variations in canopy reflectance as a function of solar zenith angle is important for several remote sensing applications. For example, such knowledge can improve multitemporal vegetation classification by using sun-angle signature extension techniques (Smith *et al.*, 1975). At higher latitudes low sun-angles predominate and an understanding of the reflectance changes at low sun-angles would be beneficial. Diurnal reflectance trends are also important in photosynthetic and productivity studies (Kimes *et al.*, 1980).

To better understand these relationships, spectral reflectance measurements were obtained for several solar zenith angles for a lodgepole pine

Abstract: *An understanding of the behavior of vegetation canopy reflectance as a function of solar zenith angle is important to several remote sensing applications. Spectral hemispherical-conical reflectances of a nadir looking sensor were taken throughout the day of a lodgepole pine and two grass canopies. Mathematical simulations of both a spectral hemispherical-conical reflectance factor and a spectral bi-hemispherical reflectance were performed for two theoretical canopies of contrasting geometric structure. These results and results from literature studies showed a great amount of variability of vegetation canopy reflectances as a function of solar zenith angle. Explanations for this variability are discussed and recommendations for future measurements are proposed.*

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and two grass canopies. Mathematical simulations of the diurnal reflectance from theoretical vegetation canopies were performed. The instruments and methods used to obtain these data are described and the resulting trends presented and discussed. The results were compared to other field measurements of vegetation canopies reported in the literature, and variations of these results and sources of measurement error are discussed. Recommendations for future studies are made.

Reflectance Nomenclature

The two reflectance measurements which are most commonly reported in the literature for natural vegetation canopies are bi-hemispherical reflectance and hemispherical-conical reflectance factor. In this study a nadir looking sensor was used to measure the hemispherical-conical reflectance factor of vegetation canopies. The definitions of these reflectances are presented as follows. For clarity the standard nomenclature and symbolism for the basic radiometric quantities (e.g., radiance, irradiance, and exitance) as presented by Suits (1975) were used exclusively.

Bi-hemispherical reflectance (ρ^H) is defined as the ratio of the reflected exitance to the irradiance at the target surface. The hemispherical-conical reflectance factor (ρ^C) for a nadir looking sensor having a field of view of less than 2π steradians is measured as the ratio of the reflected flux of a surface in the direction of the sensor's field of view (FOV) to the reflected flux of a perfectly reflecting horizontal Lambertian surface in the direction of the sensor's FOV. Mathematical definitions of these reflectances are given by

$$\rho^H = \frac{\int_0^{2\pi} \int_0^{\pi/2} L_r(\theta_r, \phi_r)\, d\Omega_r}{\int_0^{2\pi} \int_0^{\pi/2} L_i(\theta_i, \phi_i)\, d\Omega_i} = \frac{M}{E} \tag{1}$$

where

θ_r, ϕ_r = the zenith and azimuth angles of the reflected sources respectively,
θ_i, ϕ_i = the zenith and azimuth angles of the incident sources, respectively,
L_r, L_i = the radiance values of the reflected and incident sources respectively as a function of θ and ϕ,
$d\Omega_i$ = $\cos\theta_i \sin\theta_i d\theta_i d\phi_i$,
$d\Omega_r$ = $\cos\theta_r \sin\theta_r d\theta_r d\phi_r$,
M = reflected exitance,
E = irradiance,

and

$$\rho^C = \frac{\int_{\phi_1}^{\phi_2} \int_{\theta_1}^{\theta_2} L_r(\theta_r, \phi_r)\, d\Omega_r}{\frac{E}{\pi} \int_{\phi_1}^{\phi_2} \int_{\theta_1}^{\theta_2} d\Omega_r} \tag{2}$$

where ϕ_1, ϕ_2, θ_1, θ_2 are the azimuth and zenith angle limits of the sensor's view. These two reflectances differ from those presented by Nicodemus *et al.* (1977) in that the incident radiance is treated as an anisotropic source rather than isotropic, since this is the situation which exists in the field.

The bi-hemispherical (ρ^H) and hemispherical-conical (ρ^C) measurements are related to the bi-directional reflectance distribution function (ρ^B) as described by Nicodemus (1977) and Kriebel (1976). This function describes the most fundamental reflectance characteristics of a surface. The ρ^B function is

$$\rho^B(\theta_i, \phi_i; \theta_r, \phi_r) = \frac{d\, L_r(\theta_r, \phi_r)}{L_i(\theta_i, \phi_i)\, d\Omega_i} \tag{3}$$

As stated by Kriebel (1976) the function is defined as the relation of that part of the total spectral radiance $dL_r(\theta_r, \phi_r)$ reflected into the direction θ_r, ϕ_r which originates from the direction of incidence θ_i, ϕ_i, to the total spectral irradiance $L_i(\theta_i, \phi_i)\, d\Omega_i$ impinging on a surface from the direction θ_i, ϕ_i. This particular bi-directional reflectance function (ρ^B) is a unique characterization of a surface and is not dependent on the irradiance distribution as are a number of other bi-directional functions presented in the literature.

From Equation 3 it follows that

$$L_r(\theta_r, \phi_r) = \int_0^{2\pi} \int_0^{\pi/2} \rho^B(\theta_i, \phi_i; \theta_r, \phi_r)\, L_i(\theta_i, \phi_i)\, d\Omega_i \tag{4}$$

As a consequence, ρ^C and ρ^H are dependent on both the bi-directional reflectance function ρ^B and the solar irradiance distribution (Equations 1 and 2). From these equations it is important to note that hemispherical-conical reflectance factor (ρ^C) which is most commonly utilized in remote sensing research is not a physical parameter uniquely determined by a particular vegetation canopy but is dependent on the anisotropic distribution of sky irradiance. It is the bi-directional reflectance function together with information on the anisotropic distribution of sky irradiance which ultimately determines how vegetation canopy ρ^C and ρ^H reflectances will behave under various solar irradiance conditions. Bi-directional reflectance is a function of a number of geometric and optical characteristics of the canopy components as discussed by Oliver and Smith (1974) and Ross (1976). Kriebel (1977, 1978) presents spectral bidirectional reflectance values for four vegetation canopies.

A description of the above and other types of reflectance measurements is presented by Judd (1967) and Nicodemus (1977). The reflectance measurements can be distinguished as broad band (ρ^H, ρ^C, ρ^B) or spectral (ρ^H_λ, ρ^C_λ, ρ^B_λ) reflectance. The variability within and between these reflectance measurements is explored below. In addition, throughout this paper ρ^C_λ will refer to a nadir sensor angle.

Instrumentation and Methods

Both field and simulated data were obtained. In all field experiments a scene recording radiometer (SRR) as described by Berry *et al.* (1978) was used to obtain spectral hemispherical-conical measurements (ρ^C_λ) of vegetation canopies. The SRR was suspended on support cables attached to two 15-m towers, which allowed nadir looking measurements from above the canopy to be obtained. The instrument had a half-peak angular field of view of ±5.0 degrees. The instrument's optics consisted of a six narrow band interference filter wheel interfaced to a Hasselblad EL500 camera which provided a photographic record of the scene. All filtered spectral data were referenced to a horizontal barium sulfate panel to provide reflectance values. Filters used were centered at 4800, 5500, 6750, 7300, 8000, and 9600 Å and had a half width bandpass of 100 Å.

Four experiments were performed at two field sites to evaluate the spectral hemispherical-conical reflectance factors (ρ^C_λ) of various targets with changing solar zenith angle. The targets and date of measurements at site 1 were lodgepole pine with a grass understory (4 August, 1976) and open meadow (6 August, 1976). At site 2 a grass community was measured (20 April, 1978 and 18 May, 1978). In all experiments the sensor was nadir looking and a constant sensor position on the tower system was maintained. Target radiances and radiances of a sprayed barium sulfate panel were taken frequently throughout the day and the corresponding measurements were ratioed to obtain the ρ^C_λ values. In all cases the reference panel was positioned horizontally and supported directly below the nadir looking radiometer.

A description of the two study sites was as follows. Site 1 was located southeast of Leadville, Colorado, in the northeastern section of the Iron Hill area at an elevation of approximately 3,322m. The 45.7-m long transect defined by the tower system maintained a constant slope and aspect of 5 percent at 45°, respectively. The vegetation graded from a relatively dense lodgepole pine stand to an open, grass-covered clearing. Average height of the lodgepole pine stand was approximately 6.1 m. Canopy density was variable, ranging from 80 percent crown closure to the open meadow previously mentioned. The meadow was populated with rush (*Juncus sp.*) and sedge (*Carex sp.*). A more detailed description of the site was presented by Heimes and Smith (1977). A description of the geometric structure of the lodgepole pine canopy was presented by Kimes *et al.* (1979a).

Site 2 was located west of Fort Collins, Colorado, at an elevation of 1,570m at the Colorado State Forest Service Nursery. The towers at each end of the transect were 9-m high. Vegetation along the transect consisted of grasses which included fescue (*Festuca*), bluegrass (*Poa*), sedge (*Carex*), wheatgrass (*Agropyron*), and brome (*Bromus*). A more detailed description of the site was presented by Ranson *et al.* (1978).

The solar radiation vegetation canopy (SRVC) model was utilized to simulate the ρ^C_λ and ρ^H_λ reflectances for various theoretical vegetation canopies. The SRVC model is a Monte Carlo model which physically accounts for variations in direct/diffuse solar irradiance ratios, solar zenith angle, leaf angle geometry, leaf area indices (LAI), leaf spatial dispersion, and leaf and soil optical properties (Oliver and Smith, 1974). Several vegetation canopies were simulated with various geometric structures and LAI for a photosynthetically active spectral wavelength (0.68 μm). The entire procedure, parameters, and canopy absorption results are presented by Kimes *et al.* (1980). Two canopy geometries were simulated: an erectophile (mostly erect leaves) and planophile (mostly prostrate leaves) as described by DeWit (1965). These canopies were simulated for LAI of 1.0, 4.0, and 7.0. The simulated ρ^C_λ reflectance results are presented in this study.

Finally, literature studies on vegetation reflectance trends as a function of solar zenith angles were compared with the results of the above experiments.

Results and Discussion

Field and Simulation Results

Figures 1a and b present the 0.68 and 0.80 μm band hemispherical-conical reflectance factors (ρ^C_λ) as a function of solar zenith angle for the lodgepole pine and meadow at site 1. These data were acquired on 4 August, 1976, from 0657 to 1400 hours mountain daylight time (MDT) and 6 August, 1976, from 0815 to 1558 hours MDT, respectively. The arrows denote the sequence of data points from morning to afternoon. For both canopies ρ^C_λ increased with decreasing solar zenith

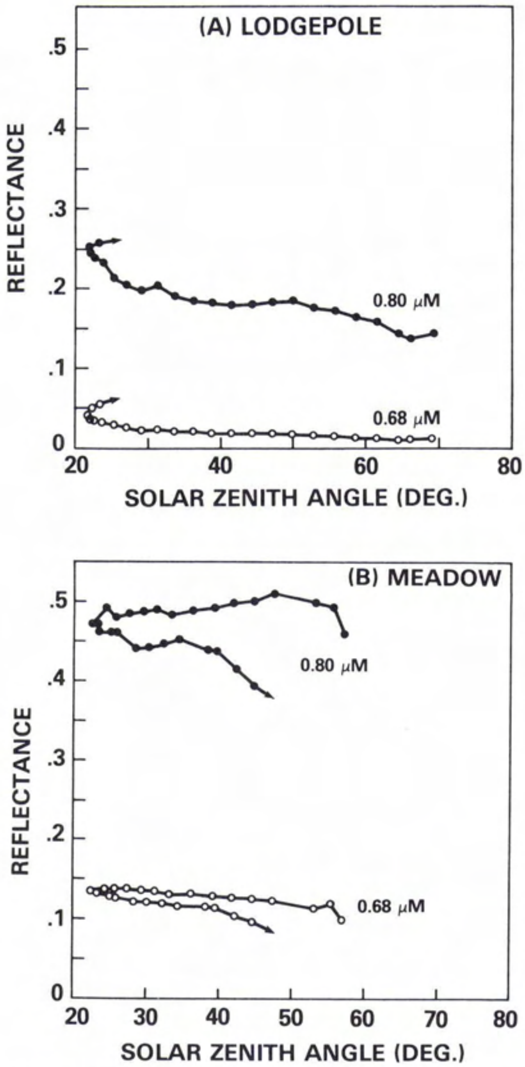

FIG. 1. Spectral hemispherical-conical reflectance factor ρ_λ^C versus solar zenith angle of lodgepole pine (A) and meadow (B) at site 1 for the 0.68 and 0.80 μm bands. Lodgepole and meadow data were collated 0657-1400 hours MDT 4 August, 1976 and 0815-1558 hours MDT 6 August, 1976.

angle except for the 0.80 μm band of the meadow in the morning. The meadow ρ_λ^C values were lower in the afternoon with respect to the morning and the opposite trend was apparent for lodgepole pine. All of the above ρ_λ^C measurements at site 1 were taken when the direct solar path was free of clouds. Consistently, there was a build up of cumulus clouds around noon which continued into the afternoon. The experiments were terminated when cloud cover did not permit a direct solar path free of clouds.

A disadvantage of all reflectance measurements which use a reference panel is that errors are introduced by the reflectance properties of the panel. For example, when using barium sulfate panels, there are minor errors caused by spectral deviations from a perfectly reflecting panel as discussed by Robinson and Biehl (1979). However, more important to this study are the errors introduced by the non-Lambertian behavior of barium sulfate. Robinson and Biehl (1979) reported that sprayed barium sulfate as used in this study differed no more than 5 percent from Lambertian for incident angles from 0° to 55° as measured from normal. This claim is corroborated by two studies. Spectral bi-directional measurements (0.633 μm) of a sprayed barium sulfate panel taken by Hsia and Richmond (1976) showed that the panel was a good diffuser at angles of incidence less than 50-60° from normal. However, at 77.5° from normal the specular reflection was quite pronounced. In addition, Viehmann (1978) has taken spectral bi-directional measurements (0.633 μm) of a sprayed barium sulfate panel. His results showed that the normal sensor response is underestimated (relative to a normal incident angle) by approximately 0, 16, 33, and 67 percent for incident angles of 40, 60, 70, and 80° from the normal, respectively. Thus, at incident angles greater than ~55° the response of a nadir or near nadir sensor looking at a barium sulfate panel is significantly less than the response from truly Lambertian panel. As a consequence, one can expect target reflectance errors in any study which uses barium sulfate panels past solar zenith angles on the order of 55°. Specifically, the measured ρ_λ^C results of this study, which were taken with solar zenith angles exceeding 55°, are biased toward higher values; the results from Viehmann (1978) give the order of magnitude of this error. In light of this error, the observed trends of decreasing ρ_λ^C with increasing solar zenith angle, as seen in Figure 1a and b, are actually more pronounced.

Figures 2a and b present the measured ρ_λ^C results as a function of solar zenith angle for the grass community at site 2 on 20 April, 1978 and 18 May, 1978. The April and May data were collected from 0856-1715 MDT and 1015-1947 MDT, respectively. Data for both the 0.68 μm and 0.80 μm bands are presented. Both of these experiments were executed under rapidly changing sky conditions. Cumulus clouds partially or totally obscured the sun at various times throughout the measurement periods. Accordingly, there was a relatively large amount of variability in the data. No dominating ρ_λ^C trends occurred as a function of solar zenith angle with exception of the 0.68 μm band on 18 May, which showed a slight increase in reflectance with decreasing solar zenith angle. Corrections for the non-Lambertian behavior of the reference panel cannot easily be approximated under such rapidly changing irradiance conditions

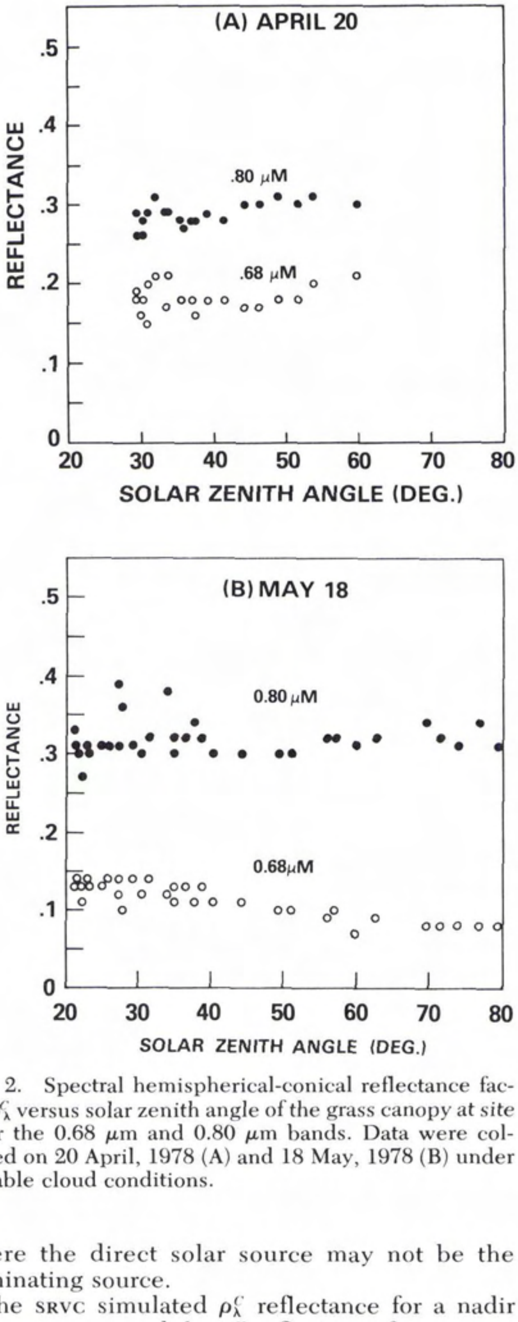

FIG. 2. Spectral hemispherical-conical reflectance factor ρ^C_λ versus solar zenith angle of the grass canopy at site 2 for the 0.68 μm and 0.80 μm bands. Data were collected on 20 April, 1978 (A) and 18 May, 1978 (B) under variable cloud conditions.

where the direct solar source may not be the dominating source.

The SRVC simulated ρ^C_λ reflectance for a nadir looking sensor and the ρ^H_λ reflectance for an erectophile and planophile canopy of three LAI values are shown in Figure 3a, b, c, and d. These results showed that, for LAI of 1.0 and 4.0 of the erectophile canopy, the ρ^C_λ decreased with increasing solar zenith angle (Figure 3a). However, the ρ^H_λ for all three LAI values tended to increase with increasing solar zenith angle (Figure 3b). These differences arose from anisotropic scattering by the vegetation canopy into off-nadir view angles. The effect can be correctly quantified by the bidirectional reflectance function as presented by Kriebel (1976, 1978) and discussed below. In contrast, the ρ^C_λ for the erectophile canopy of an 7.0 LAI increased with increasing solar zenith angle (Figure 3a). Subtle geometric and optical effects of the soil and canopy accounted for this discrepancy as will be discussed later.

Grass canopies such as measured in this study tend to assume erectophile geometries (Oliver and Smith, 1974). The measured results of the meadow (Figure 1b) showed ρ^C_λ both increasing and decreasing with increasing solar zenith angle. The geometry of lodgepole pine was intermediate between a planophile and erectophile canopy as measured by Kimes *et al.* (1979a). Kimes *et al.* (1979b) have used the SRVC model to simulate ρ^C_λ as a function of solar zenith angle for the specific geometric and optical properties of the lodgepole pine canopy at site 1; simulated ρ^C_λ decreased slightly as solar zenith angle increased as was shown by the measured data (Figure 1a).

The simulated results of the planophile canopies were much less variable than the erectophile canopy (Figure 3c, d).

VARIABILITY OF REFLECTANCE TRENDS

The diurnal reflectance results from this study were compared to previous studies. These comparisons showed a great deal of variability in diurnal reflectance trends. This variability and explanations for it will be presented under the headings of ρ^C, ρ^H, and ρ^B reflectance.

ρ^C Reflectance. In general the measured and simulated ρ^C_λ results for the vegetation canopies supported a trend of decreasing ρ^C_λ with increasing solar zenith angle for clear conditions. There were exceptions, however, as noted above.

Previous studies have shown a great deal of variability in ρ^C_λ reflectance trends. For example, a number of investigators have measured wheat which tends to approximate an erectophile canopy. Smith *et al.* (1975) have shown that spectral canopy reflectance can increase or decrease as a function of increasing solar zenith angle, depending on the growth stage of the wheat. Duggin (1977) reported that the effect of solar zenith angle on spectral reflectance differed significantly among seven wheat varieties of the same growth stage. Finally, Jackson *et al.* (1979) observed that the effect of solar zenith angle on spectral reflectance were quite different for various crop configurations (row orientation, row spacing, plant height, canopy cover, etc.) for a single wheat variety. Spectral reflectance for specific canopies changed by as much as a factor of 2.3 between solar zenith angles of 57° and 28°. In addition, both increasing and decreasing reflectance trends with an increase in solar zenith angle were observed depending on the crop configuration. In each of

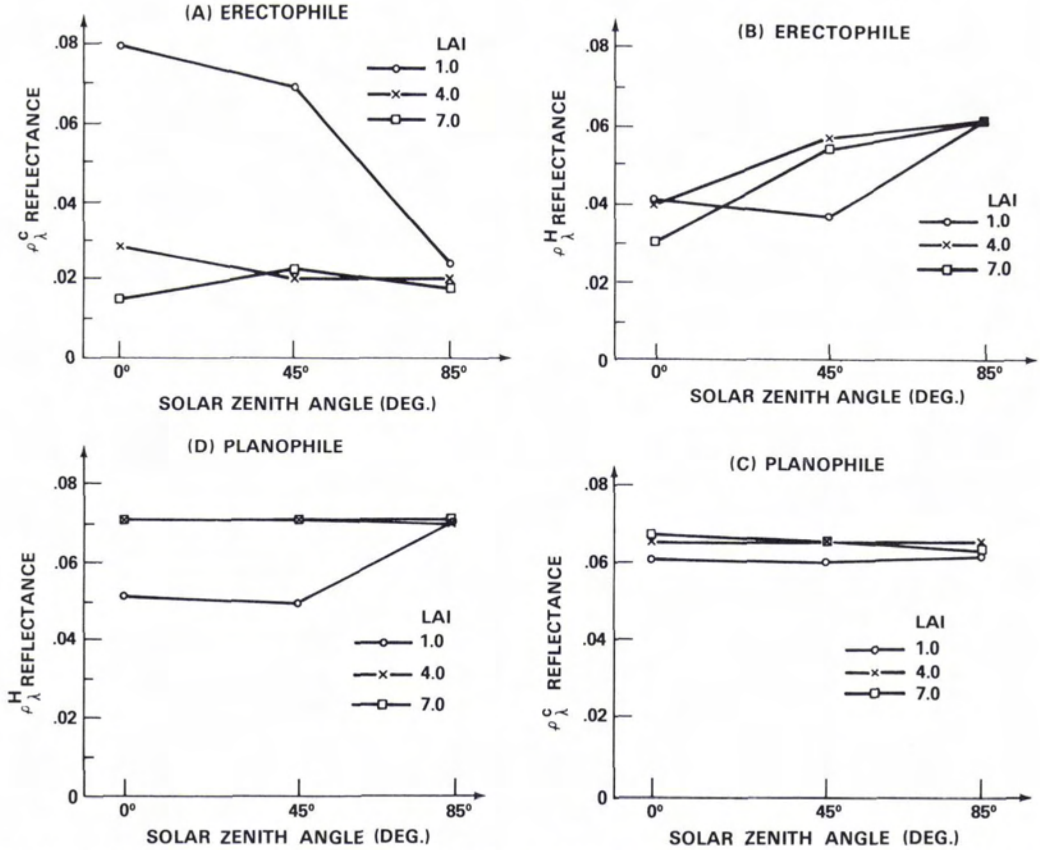

FIG. 3. SRVC simulated spectral hemispherical-conical reflectance factor ρ^C_λ and bi-hemispherical reflectance ρ^H_λ as a function of solar zenith angle for theoretical erectophile and planophile canopies. A photosynthetically active wavelength (0.68 μm) was simulated for various leaf area indicies (LAI).

these studies, many of the trajectories did not have any clear increasing or decreasing trends as a function of solar zenith angle.

Explanations for this variability are as follows. Kriebel (1978) has shown that the bi-directional reflectance functions for vegetation canopies were generally non-isotropic in nature. As a consequence, ρ^C_λ variations arise from variations in the anisotropic irradiance field and the bi-directional reflectance function since the observed ρ^C_λ is an integration of the bi-directional reflectance values (ρ^B_λ) for the near nadir reflectance angles and all incident radiation angles (Equations 2 and 4). Each of these ρ^B_λ values must be weighted by the distribution of the incoming solar irradiance field. This weighting phenomenon may account for the wide variability in measured ρ^C_λ seen on partly cloudy days (Figures 2a, and b). It is precisely this effect that is responsible for the changing ρ^C_λ as a function of solar zenith angle on clear days. Specifically, the data from Kriebel (1978) indicate non-Lambertian behavior for the four vegetated surfaces: savannah, bog, pasture land, and coniferous forest. Assuming that the sun is the primary radiant source on a clear day, the ρ^C_λ is approximately proportional to ρ^B_λ $(\theta_s, \phi_s; \theta_o, \phi_o)$ where θ_s, ϕ_s denote the solar zenith and azimuth angles respectively and θ_o and ϕ_o denote the viewing angle of a nadir sensor (Equation 3). The ρ^B_λ $(\theta_s, \phi_s; \theta_o, \phi_o)$ values for the four vegetation types did not follow any consistent trend with increasing solar zenith angle. One would expect the bi-directional reflectance function to differ substantially among various geometrical structures of plant canopies (vegetation type, growth stage, row structure, density, etc.). Thus, from the results of this study and the cited literature, one may expect ρ^C_λ trajectories of vegetation as a function of solar zenith angle to be relatively variable due to the different bi-directional functions of plant canopies and variation in atmospheric conditions throughout the day.

There was a significant deviation between morning and afternoon reflectances. In some instances the morning ρ^C_λ were higher than those in the afternoon (meadow, Figure 1b) and in other instances the opposite is true (lodgepole, Figure

1a). Such an effect was not explored using the SVRC model because azimuthal symmetry is mathematically assumed. Ripley and Redmann (1976) found for a grassland canopy that the reflectance was considerably higher during the afternoons than in the morning for the same solar zenith angle. They propose that a portion of the observed variation is caused by canopy geometry in which preferential azimuthal orientation of the leaves was assumed due to a preferential wind direction. The authors also suggested that plant water content, leaf rolling, and atmospheric conditions may also be involved. In some cases the effects of morning dew may cause an asymmetry about solar noon. Smith *et al.* (1975), Duggin (1977), and Jackson *et al.* (1979) have shown a variety of asymmetric reflectance trajectories about solar noon for wheat canopies of various geometric structures. If such variations in canopy geometry caused the above phenomena, the variations in canopy geometry due to species, planting, temporal, spatial, stress, and wind variations may also account for the contrasting diurnal reflectance trajectories seen in this study and others.

Variations in reflectance trajectories can be caused by subtle geometric effects. For example, the simulated SRVC ρ_λ^C results of an erectophile canopy showed that for LAI values of 1.0 and 4.0 ρ_λ^C decreased with increasing solar zenith angle (Figure 3a). However, the opposite trend was observed for an LAI of 7.0. The radiation transfer within vegetation canopies for highly absorptive wavelengths such as the simulated wavelength used in this study (0.68 μm) is largely controlled by the probability of gap (PGAP) in the canopy as a function of source angle. Thus, the above variability can be explained as follows. At low LAI the PGAP to the ground varies greatly as a function of view angle. This variation for high LAI is small (Table 1). The spectral reflection (ρ_λ) and transmission (τ_λ) for the canopy components and ground were $\rho_\lambda = 0.8$, $\tau_\lambda = 0.4$, and $\rho_\lambda = 0.11$, $\tau_\lambda = 0.00$, respectively (Kimes *et al.* 1980). Thus, ground reflectance was significantly higher than the canopy components. The PGAP for a small zenith angle and a LAI of 1.0 was high. As a consequence, the observed ρ_λ^C for small solar zenith angles should be high due to the relatively high contribution of ground reflectance. At large solar zenith angles the PGAP to the ground was small and the observed ρ_λ^C is low due to the relatively small contribution of ground reflectance. For an LAI of 7.0 the PGAP was relatively constant with zenith angle and this geometric effect was not dominating.

ρ^H *Reflectance*. Although ρ^H reflectances were not measured in this study, a large amount of data has been collected for vegetation canopies by other researchers. These reflectance measurements are compared with the results of this study. It is important to understand the inherent differences between ρ^H and ρ^C measurements.

The simulated results within this study showed that the ρ_λ^C and ρ_λ^H for the erectophile canopy as a function of increasing solar zenith angle decreased and increased, respectively. These differences were explained by the anisotropic bi-directional reflectance function of the simulated vegetation canopy. Equations 1, 2, and 4 show the ρ^H and ρ^C dependence on the bi-directional reflectance function. According to measurements from Coulson (1966) and Kriebel (1978) and simulated results from Oliver and Smith (1974), the nadir spectral reflectance was generally lower than all off-nadir spectral reflectances for any given source direction. As a consequence, one would expect the nadir ρ_λ^C to be lower than the corresponding ρ_λ^H reflectance. Such information is important for several applications. For example, accurate estimation of ρ^H for global surfaces is important in calculating the planetary heat budget. Eaton and Dirmhirn (1979) have developed coefficients to estimate bi-hemispherical measurements from hemispherical-conical measurements for several target types. The purpose of these coefficients was to improve the prediction of ρ^H from the conical radiance values from space platforms.

Coulson and Reynolds (1971) have measured ρ_λ^H as a function of solar zenith angle of six vegetation canopies for six discrete wavelengths in the visible and near infrared regions. The authors found that the reflectances of most surfaces reached a maximum at solar zenith angles of 80-70° and in general ρ_λ^H decreased with decreasing solar zenith angle. The authors suggested that these trends are a result of the effects of both canopy structure and the changing ratio of direct to diffuse light throughout the day. The magnitude of these independent effects on ρ_λ^H is not known.

TABLE 1. PROBABILITY OF GAP (PGAP) THROUGH A THEORETICAL ERECTOPHILE CANOPY OF LEAF AREA INDEX (LAI) EQUAL TO 1.0, 4.0, AND 7.0

	Inclination View Angle Interval								
LAI	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90
1.0	0.00	0.00	0.00	0.21	0.39	0.52	0.61	0.68	0.72
4.0	0.00	0.00	0.00	0.00	0.02	0.07	0.14	0.21	0.26
7.0	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.10

There are a large number of studies which showed a decreasing broad band bi-hemispherical reflectance (ρ^H) with decreasing solar zenith angle for vegetation canopies (Rijks, 1967; Davies and Buttimor, 1969; Idso *et al.*, 1969; Proctor *et al.*, 1972; Ripley and Redmann, 1976; among others). These studies used sensors sensitive to the visible and/or near IR regions. A typical curve such as presented by Proctor *et al* (1972) may increase by a factor of 0.8 from small to large solar zenith angles. As previously discussed, the changing ρ_λ^C as a function of solar zenith angle was largely due to the non-Lambertian nature of the bi-directional reflectance function, the changing solar irradiance field, and the directional field of view of the sensor. However, these relationships of ρ^H reflectance as a function of solar zenith angle cannot be explained by the above directional considerations since ρ^H is a hemispherical measurement integrating over all view angles. Other geometric effects must be operating.

One explanation which is often presented is that the probability of a gap through the vegetation components in the upper layers is generally lowest at the larger solar zenith angles. As a consequence, less radiant flux will be attenuated and absorbed by the soil and lower layers of the canopy and a greater bi-hemispherical reflectance will occur at the larger solar zenith angles. This is a simplified explanation of some very complex radiation transfers within vegetation canopies particularly in the near infrared region where strong multiple scattering occurs.

Secondly, studies which measured broad band ρ^H may introduce several sources of error. For example, one source of error which is commonly not considered when measuring broad band reflectance values is the effects of variations in the spectral quality of solar irradiance as a function of solar zenith angle and atmospheric conditions. When this variation is systematic in nature as a function of solar zenith angle, false reflectance trends can occur. As presented in the Appendix, simulated results showed that, for a particular theoretical vegetation canopy, the calculated bi-hemispherical reflectance (ρ^H) may increase as much as a factor of 0.4 from small to large solar zenith angles due to variations in the spectral quality of the solar irradiance.

Instrumentation error can also introduce systematic errors which cause false reflectance curves as a function of solar zenith angle. For example, using an Eppley pyranometer on an alfalfa canopy, Brown *et al.* (1970) showed particularly that at greater solar zenith angles extraneous light (outside the normal 2π steradians) reached the sensor. The absolute reflectance error between a shaded sensor which reduced this extraneous light and an unshaded sensor is shown in Figure 4. This error

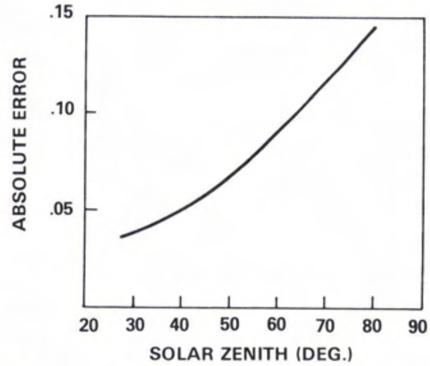

FIG. 4. Absolute error of the unshaded minus shaded Eppley pyranometer for measurements of shortwave bi-hemispherical reflectance ρ^H of an alfalfa canopy (derived from Brown *et al.*, 1970).

can clearly introduce erroneous ρ^H trends as a function of solar zenith angle.

ρ^B Reflectance. In this article a specific ρ^B function as presented by Kriebel (1976) has been emphasized because the function was independent of the anisotropic irradiance field. However, there are a number of studies which have made other types of bi-directional measurements on a variety of material types, for example, Egbert and Ulaby (1972), Eaton and Dirmhirn (1979), and Rao *et al.* (1979), among others.

The trends and magnitudes of these studies suggested that these functions are highly variable and dependent on target types, geometric structure of targets, and the solar irradiance field. These studies attempted to explain some of the variability in terms of the optical and geometric characteristics of the vegetation canopies. However, to date there has been a lack of general understanding of the nature of the physical radiant interactions which take place in vegetation canopies in terms of the bi-directional function ρ_λ^B which is independent of the solar irradiance field.

Conclusions and Recommendations

The wide variability seen in diurnal reflectance trends is caused by variations in anisotropic sky irradiance, canopy component geometry and optical properties, and type of reflectance measurement. In addition, systematic errors in instrumentation, spectral integration, and reference panels can cause false diurnal reflectance trends. In most cases there is a lack of information concerning the effect of these variables on the magnitude of observed reflectance.

Considering the large number of possible permutations of variables affecting diurnal reflectance trends, we believe that future studies should be designed to relate observed diurnal reflectance trends to the physical characteristics of the canopy and irradiance field. Collecting reflectance data only would be undesirable. Further decoupling the effects of the anisotropic irradiance and the anisotropic reflectance of the canopy on canopy reflectance measurements must be accomplished before a more complete and quantitative understanding of diurnal reflectance trends can be obtained.

It is unlikely that the variations in diurnal reflectances of vegetation canopies will be clearly understood until bi-directional measurements such as suggested by Kriebel (1978) are more commonly derived and related to the geometric structure and optical properties of the canopy constituents.

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Appendix

When broad band bi-hemispherical reflectance (ρ^H) measurements are taken as a function of view angle, error is introduced due to the varying spectral quality of the solar irradiance. When this variation is systematic in nature as a function of solar zenith angle, false diurnal reflectance trends can occur. The following simulation was performed as an example.

First, a basic distinction between broad band (e.g., entire solar spectrum) and discrete wavelength diurnal bi-hemispherical reflectance should be made. For very small discrete wavelength bands and ignoring path radiance and atmospheric transmission between the sensor and the target, the following ratio is measured:

$$\rho_\lambda^H = \frac{\rho_\lambda^H \cdot E_\lambda \cdot R_\lambda \cdot \Omega}{E_\lambda \cdot R_\lambda \cdot \Omega}$$

where

ρ_λ^H = bi-hemispherical spectral reflectance of target,
E_λ = hemispherical spectral irradiance,
R_λ = spectral responsivity of detector, and
Ω = sensor related parameters.

However, when using a broad band (e.g., total solar spectrum) such as used by Proctor *et al.* (1972) and Idso et al. (1978), one measures

$$\rho^H = \frac{\int_{\lambda_1}^{\lambda_2} (\rho_\lambda^H \cdot E_\lambda \cdot R_\lambda \cdot \Omega)\, d\lambda}{\int_{\lambda_1}^{\lambda_2} (E_\lambda \cdot R_\lambda \cdot \Omega)\, d\lambda} \quad \text{(A.1)}$$

where

λ_1, λ_2 = spectral limits of the effective detection of the sensor, and
ρ^H = measured broad band bi-hemispherical reflectance for the (λ_1, λ_2) interval.

For any given measurement period one wishes to measure a reflectance value for the entire spectral limits of the detector. However, it is clear that this measured value is dependent on the sensor's spectral responsivity R_λ and the solar irradiance E_λ. Indeed, the E_λ is not a constant function but varies as a function of path length through the atmosphere and atmospheric conditions. Thus, it was hypothesized that diurnal reflectance trends as measured by broad solar band sensors may in some instances be only artifacts of the measurement procedure as reflected in Equation A.1.

The above hypothesis was examined in the following manner. Initially it was assumed that an ideal detector was being used with $R_\lambda = 1.0$ units $\lambda \epsilon (\lambda_1, \lambda_2)$. In addition, for convenience the spectral solar irradiance was introduced as the product of the normalized spectral irradiance and the total irradiance. Thus, after the above transformations, Equation A.1 becomes

$$\rho^H = \frac{\int_{\lambda_1}^{\lambda_2} (\rho_\lambda^H \cdot E_\lambda^n \cdot E^t)\, d\lambda}{\int_{\lambda_1}^{\lambda_2} (E_\lambda^n \cdot E^t)\, d\lambda}$$

where

E^n = normalized solar irradiance function

$$\int_{\lambda_1}^{\lambda_2} E_\lambda^n \, d\lambda = 1.0$$

E^t = total solar irradiance in the (λ_1, λ_2) interval.

The above equation can be further reduced.

$$\rho^H = \int_{\lambda_1}^{\lambda_2} (\rho_\lambda^H \cdot E_\lambda^n)\, d\lambda \qquad \text{(A.2)}$$

Theoretical E^n functions were derived for several atmospheric path lengths as a function of solar zenith angle from data for a clear and dry atmosphere presented by Kondrat'yev (1965). The resulting curves are presented by Kimes *et al.* (1979b). In addition, a typical reflectance curve of vegetation was utilized for ρ_λ^H as reported by Kimes *et al.* (1979b). This ρ_λ^H curve was held constant with changing solar zenith angle; thus, isotropic reflectance of the canopy was assumed. Equation A.2 was then numerically integrated over 34 discrete wavelengths. The results for several solar zenith angles are presented in Figure A.1.

Note in Figure A.1 that with a constant ρ_λ^H function we obtained an increase in total ρ^H due to a changing E^n function throughout the day. The shifts in the E^n function throughout a theoretical clear day weighted different portions of the ρ_λ^H function, thus causing a changing total ρ^H. Different responsivity functions (R_λ) of the detector could in some cases increase this effect.

Such an artifact as discussed above can mask true reflectance changes of vegetational canopies.

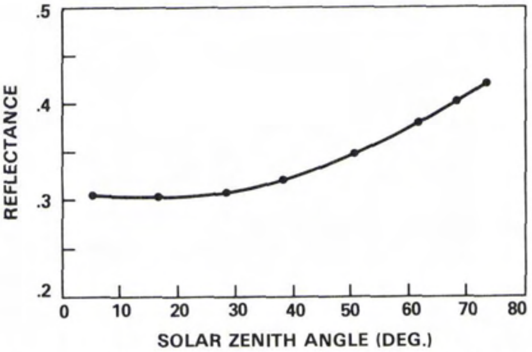

FIG. A.1 Simulated bi-hemispherical reflectance ρ^H from a theoretical vegetation canopy as a function of solar zenith angle.

Gates *et al.* (1965) have reported similar effects for individual leaf reflectance under clear and cloudy sky conditions. Although one may criticize the validity of the particular sky irradiance and plant reflectance curves utilized in this study, the above simulation does demonstrate that such effects can feasibly occur. The same effect can theoretically occur for broad band hemispherical-conical reflectance (ρ^C) measurements.

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