LARS Technical Report 073184
NASA-Johnson Space Center
Contract No. NAS9-16528

Variation in Spectral Response of Soybeans with Respect to Illumination, View and Canopy Geometry

by

K. J. Ranson
L. L. Biehl
M. E. Bauer

Laboratory for Applications of Remote Sensing

West Lafayette, Indiana 47906
USA

PURDUE, touching tomorrow today

LARS Technical Report 073184
NASA-Johnson Space Center
Contract No. NAS9-16528

(E85-10040 NASA-CR-171821) VARIATION IN SPECTRAL RESPONSE OF SOYBEANS WITH RESPECT TO ILLUMINATION, VIEW, AND CANOPY GEOMETRY (Purdue Univ.) 27 p HC A03/MF A01 CSCL 02C
N85-16241
Unclas
G3/43 00040

Variation in Spectral Response of Soybeans with Respect to Illumination, View and Canopy Geometry

by

K.J. Ranson
L.L. Biehl
M.E. Bauer

Laboratory for Applications of Remote Sensing

West Lafayette, Indiana 47906
USA

PURDUE,
touching
tomorrow
today

Star Information Form

1. Report No.	2. Government Accession No	3. Recipient's Catalog No.
4. Title and Subtitle Variation in Spectral Response of Soybeans With Respect to Illumination, View, and Canopy Geometry		5. Report Date 7/31/84
		6. Performing Organization Code
7. Author(s) K. Jon Ranson, Larry L. Biehl, and Marvin E. Bauer		8. Performing Organization Report No. 073184
9. Performing Organization Name and Address Laboratory for Applications of Remote Sensing Purdue University 1291 Cumberland Ave. West Lafayette, IN 47906-1399		10. Work Unit No.
		11. Contract or Grant No. NAS9-16528
12. Sponsoring Agency Name and Address NASA Johnson Space Center Houston, TX 77058		13. Type of Report and Period Covered Technical
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Comparisons of the spectral response for incomplete (well-defined row structure) and complete (overlapping row structure) canopies indicated a greater dependence on sun and view geometry for the incomplete canopies. This effect was more pronounced for the highly absorptive red (0.6-0.7μm) wavelength band than for the near-IR (0.8-1.1μm) based on relative reflectance factor changes.

Red and near-IR reflectance for the incomplete canopy decreased as solar zenith angle increased for a nadir view angle until the soil between the plant rows was completely shaded. Thereafter for increasing solar zenith angle, the red reflectance leveled off and the near-IR reflectance increased. A "hot spot" effect was evident for the red and near-IR reflectance factors, especially when the sun-sensor view directions were perpendicular to the rows. The "hot spot" effect was more pronounced for the red band based on relative reflectance value changes. The effect of sun angle was more pronounced for view angles perpendicular to the row direction.

An analysis of the ratios of off-nadir to nadir acquired data revealed that off-nadir red band reflectance factors more closely approximated straightdown measurements for time periods away from solar noon. Near-IR and greenness responses showed similar behavior. Normalized difference generally approximated straightdown measurements during the middle portion of the day. An exception occurred near solar noon when sunlit bare soil was present in the scene.

17. Key Words (Suggested by Author(s))		18. Distribution Statement	
Soybean (<u>Glycine max</u>), Sun Angle, View Angle, Reflectance Factor.			
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

LARS Technical Report 073184

VARIATION IN SPECTRAL RESPONSE OF SOYBEANS WITH RESPECT TO ILLUMINATION, VIEW, AND CANOPY GEOMETRY

K. Jon Ranson
Postdoctoral Research Associate, LARS

Larry L. Biehl
Research Engineer, LARS

Marvin E. Bauer
Formerly Senior Research Agronomist, LARS
Now Director, Remote Sensing Laboratory,
University of Minnesota

Laboratory for Applications of Remote Sensing
Purdue University
West Lafayette, IN 47906-1399, U.S.A.

July 1984

LARS Technical Report 073184

VARIATION IN SPECTRAL RESPONSE OF SOYBEANS WITH RESPECT TO ILLUMINATION, VIEW, AND CANOPY GEOMETRY

ABSTRACT

Comparisons of the spectral response for incomplete (well defined row structure) and complete (overlapping row structure) canopies indicated that there was a greater dependence on sun and view geometry for the incomplete canopies. This effect was more pronounced for the highly absorptive red (0.6-0.7μm) wavelength band than for the near-IR (0.8-1.1μm) based on relative reflectance factor changes.

Red and near-IR reflectance for the incomplete canopy decreased as solar zenith angle increased for a nadir view angle until the soil between the plant rows was completely shaded. Thereafter for increasing solar zenith angle the red reflectance leveled off and the near-IR reflectance increased. A "hot spot" effect was evident for the red and near-IR reflectance factors, especially when the sun-sensor view directions were perpendicular to the rows. The "hot spot" effect was more pronounced for the red band based on relative reflectance value changes. The effect of sun angle was more pronounced for view angles perpendicular to the row direction.

An analysis of the ratios of off-nadir to nadir acquired data revealed off-nadir red band reflectance factors more closely approximated straightdown measurements for time periods away from solar noon. Near-IR and greenness responses showed a similar behavior. Normalized difference generally approximated straight down measurements during the middle portion of the day. An exception occurred near solar noon when sunlit bare soil was present in the scene.

INTRODUCTION

An understanding of the reflectance characteristics of crop canopies is important if remotely sensed data is to be effectively used to monitor crop physiological and phenological status. Crops planted in rows present a complex scene consisting of vegetation and bare soil with the proportions of vegetation and soil viewed by a sensor varying seasonally as the crop grows. Further complicating the picture is the presence of shadows cast by the rows of plants across the soil surface or upon the adjacent rows. The amount and distribution of the shadows changes with the position of the sun. For a nadir viewing sensor, in the 0.6-0.7μm wavelength region, the reflectance of an incomplete soybean canopy decreases rapidly as solar zenith angle increases (Kollenkark et al., 1982). A study using potted soybean plants arranged in rows and rotated with respect to the solar azimuth showed that row direction is important when considering the variation in diurnal reflectance factors especially in the visible region (Vanderbilt et al., 1981).

The diurnal effect on nadir reflectance for incomplete canopies (i.e., row structure present) appears to be less in those wavelength bands where light absorption by vegetation is low. This is especially true in the highly reflective near-infrared region as demonstrated by Kollenkark et al. (1982). The insensitivity of the linear transformation "greenness" developed by Kauth and Thomas (1976) to sun angle variations for nadir viewing sensors prompted Kollenkark et al. (1982) to speculate that the near-infrared bands and transformations such as greenness would be most useful for inferring agronomic variables from remotely sensed data acquired over a wide range of solar illumination angles.

For remote sensing systems that are not restricted to nadir viewing, additional sources of variation in the measured reflectance are induced by the view direction. Large departures from the common assumption of Lambertian behavior have been noted. For example, Ranson et al. (1981) noted that off-nadir reflectance from incomplete and complete soybean canopies varied greatly with view zenith amd azimuth angles as well as sun angle. Studies of a cotton crop planted in rows by Kimes et al. (1983) yielded similar results. Methy et al., (1981) provided information on the non-Lambertian reflectance behavior of soybean canopies throughout the day and growing season. These researchers found that when the sensor viewed the canopy in the principal plane of the sun, reflectance increased for view zenith angles looking away from the sun and decreased for view zenith angles looking toward the sun's direction. On the other hand when the sensor viewed the canopy perpendicular to the sun's principal plane reflectance increased or decreased depending on the stage of growth.

The information content available with off-nadir reflectance data compared to that contained in nadir acquired data may be useful for estimating certain agronomic variables. Goel and Thompson (1984) reported that sun-sensor angle combinations best suited for inferring leaf area index and foliage geometry parameters of soy-beans exclude the nadir view direction. Jackson et al. (1979) developed a model of a sun, sensor, and row crop scene and demonstrated the potential of off-nadir reflectance measurements for inferring "radiometric" plant cover and crop height to width ratios.

Another important aspect of off-nadir reflectance measurements is the possibilty of obtaining repeat satellite observations at critical stages of crop development. The European "Systeme Probatoire d'Observation de la Terre" (SPOT) satellite scheduled for launch in 1985 was designed with off-nadir viewing capabilities (Chevrel et al., 1980). This feature will enable the satellite to acquire data of the same scene more frequently by changing the observation angle. This may provide the opportunity for repeat observations or the recovery of data lost due to clouds. In addition, the Advanced Very High Resolution Radiometer on board NOAA-6 and NOAA-7 satellites has an across track scan angle of $\pm 56°$. This sensor has been used to monitor the seasonal status of vegetation over large areas (Tucker et al., 1984). Other satellites with off-nadir viewing capabilities and increased spectral resolution have been proposed by NASA (Schnetzler and Thompson, 1979). It is therefore important to obtain a more complete understanding of the off-nadir reflectance of agricultural crops so these new data can be used to their fullest potential.

In this study, the variability of bidirectional reflectance factors of incomplete and complete soybean canopies is examined over a wide range of illumination and view directions. The objectives were (1) to document the trends of reflectance factors with changing sun angle, view angle and canopy structure; and (2) to identify sun-sensor geometries where the soybean canopies reflectance exhibit Lambertian behavior.

Materials and Methods

A commercial soybean field located approximately 13 km north-west of West Lafayette, Indiana was used for this study. The field was selected on the basis of uniformity in terms of slope, soil type, drainage and planting pattern. The field was planted to soybeans (Glycine max,(L.) Merr."Calahan 9250") at a seeding rate of 62 kg/ha in north-south oriented rows. The row spacing was 76 cm with a mean population density of 28 plants/m^2.

Agronomic and reflectance factor data were acquired on three dates during the summer of 1980. On the first two dates (July 17 and July 24) the soybean canopies were incomplete with well defined rows. By the third date (August 27) the canopy was completely closed and exhibited minimal row structure.

A complete set of agronomic measurements describing the canopies were acquired within one day of the spectral measurements. These data included leaf area index (LAI), total fresh phytomass, stage of development, percent canopy cover, canopy height, canopy width, leaf angle distribution and leaf spectral reflectance and transmittance as described by Ranson et al. (1981). These data sets are suitable for evaluating plant canopy reflectance models and have been used by several investigators (eg., Cooper et al., 1982; Kimes and Kirchner, 1982; Goel and Strebel, 1983).

A diagram of the relationship between sun and sensor geometry is presented in Figure 1. Spectral radiometric data for the soybean sun-view angle experiment were acquired with an Exotech Model 100 radiometer. The instrument has four spectral bands, 0.5-0.6μm, 0.6-0.7μm, 0.7-0.8μm, and 0.8-1.1μm, corresponding to the bands on the Landsat MSS. Field stops were used to restrict the half power angular field of view (FOV) to 10°. The instrument was attached to a mount capable of movement in the horizontal (azimuth) and vertical (zenith) planes. A truck with an extendable boom provided an aerial platform for the instrument at a nominal altitude of 10 m above the soil surface. Measurement hemispheres of radiometric data were acquired through all combinations of view zenith angles (θ_v) of 0, 7, 22, 30, 45, and 60° and view azimuth angles (ϕ_v) of 0, 45, 90, 135, 180, 225, 270, and 315° as described by Ranson et al. (1981). The instrument was also positioned over a plot of bare soil where reflectance at was measured. These data were acquired at hourly intervals through the day under a variety of solar zenith (θ_s) and solar azimuth (ϕ_s) angles as long as sky conditions permitted (i.e. no clouds) (Table 1).

Prior to and after each measurement hemisphere calibration measurements were acquired from a painted barium sulfate panel illuminated under the same conditions as the canopy to provide for calculation of reflectance factors (RF) (Robinson and Biehl, 1979). Calibration data were corrected to account for non-Lambertian reflectance properties of the panel at larger solar zenith angles. Shaded panel measurements were also made to estimate the percent skylight. Color photographs (35 mm) were taken at each canopy and soil view position to document the field of view.

Ancillary meteorological data were acquired during each day at the Purdue Agronomy Farm located about 3 km southeast of the test field. These data included relative humidity, air temperature, barometric pressure, wind direction, wind speed and global solar irradiance.

Two transformations of reflectance factors were used in this study. The spectral variable "greenness" was derived from the reflectance data using the transformation developed by Malila and Gleason (1977):

$$\text{greenness} = -0.48935(RF1) - 0.61249(RF2) + 0.17289(RF3) + 0.59538(RF4) \qquad (1)$$

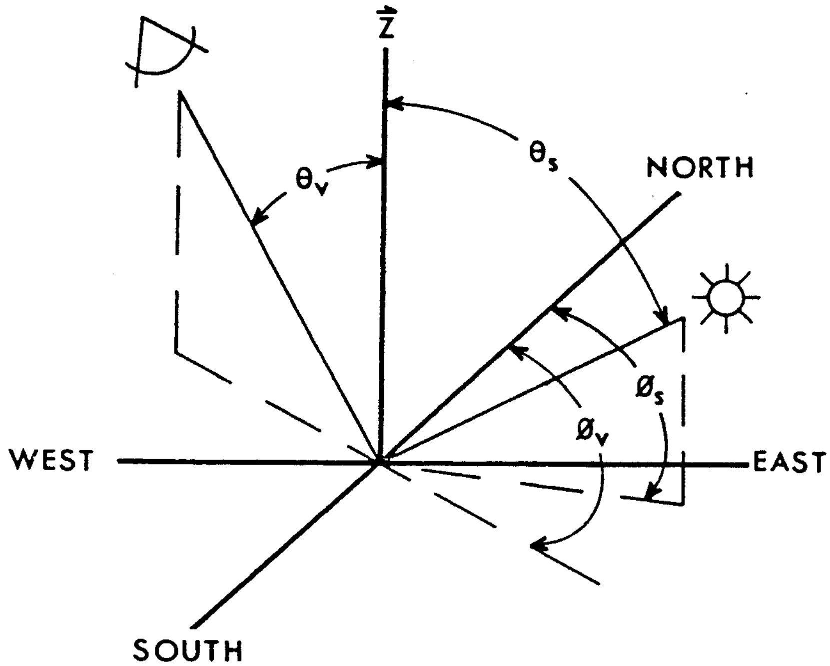

Figure 1. Diagram of sun and sensor geometry. θ_s = solar zenith angle, ϕ_s = solar azimuth angle, θ_v = view zenith angle and ϕ_v = view azimuth angle.

Table 1. Summary of Sun-view Angle Data Sets.

Date	Start Time	End Time	Solar Angle Range Zenith Max-Min-Max	Solar Angle Range Azimuth	Number of Sets	Cloud Cover
	CUT(hours)		------degrees-----			%
July 27	1759	2135	19-50	183-265	5	10-20
July 24	1514	1849	40-21-24	109-214	6	1-20
August 27	1515	1849	40-30-60	132-257	12	0

Table 2. Summary of agronomic measurements. Standard deviations are noted in parenthesis.

Date	Height	Width	Canopy Cover	Leaf Area Index	Total Fresh Biomass	Total Dry Biomass	Stage of Development†
	-----cm----		%		----g/m^2----		
July 17	69 (4)	55 (5)	72 (4)	3.0 (0.5)	1145 (226)	230 (40)	V13R3
July 24	84 (3)	69 (4)	83 (3)	3.9 (0.6)	1540 (199)	320 (51)	V14R3
August 27	102 (4)	104 (11)	99 (1)	2.9 (0.4)	2535 (476)	644 (95)	V20R6

† Fehr et al. (1971)

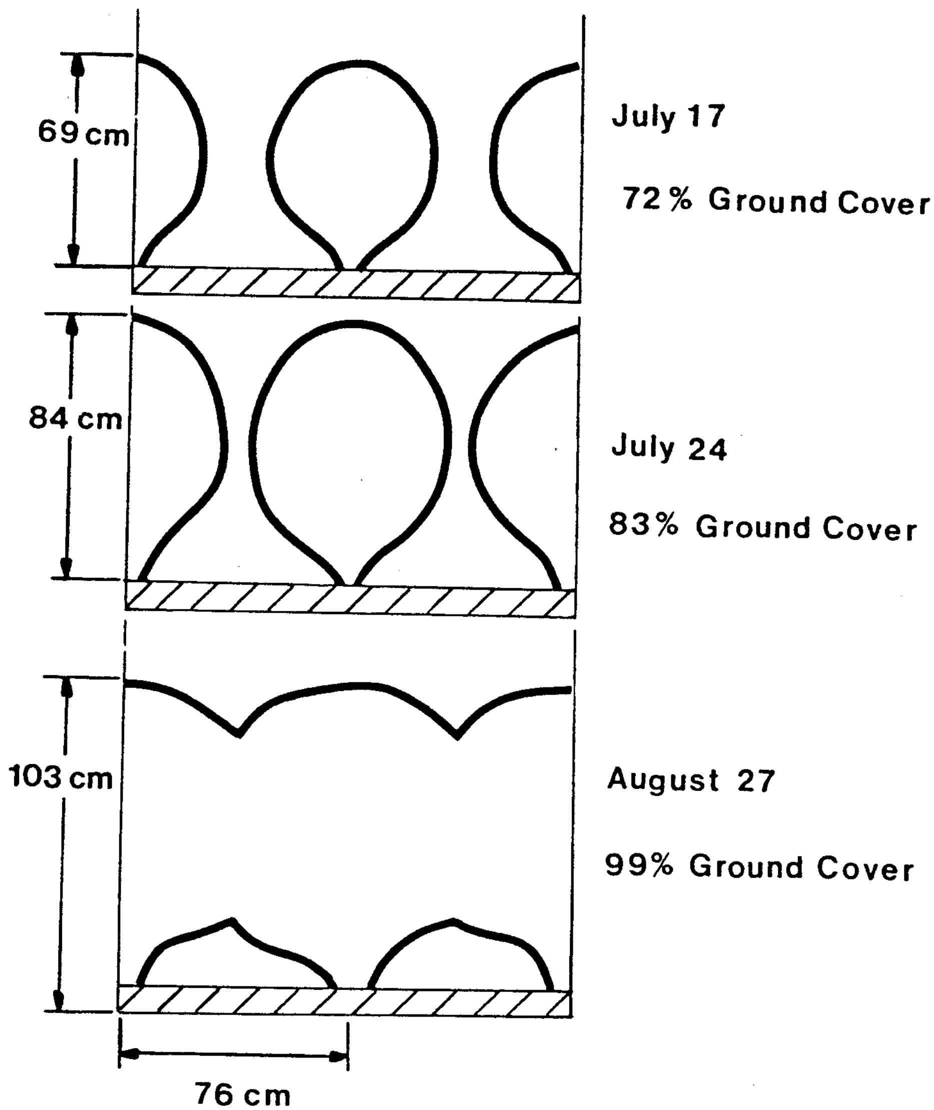

Figure 2. Idealized canopy profiles of the soybean field on the three measurement dates.

RF1 through RF4 are the reflectance factors acquired in the four Exotech Model 100 wavelength bands.

The normalized difference (ND) vegetation index commonly reported in the literature was calculated as:

$$ND = (RF4 - RF2)/(RF4+RF2) \qquad (2)$$

To facilitate comparisons of RF across dates solar zenith and azimuth angles were used to compute the projected solar angle (θ_{sp}) by;

$$\theta_{sp} = \tan^{-1}(\tan\theta_s \sin(\phi_s-\phi_r))|. \qquad (3)$$

The projected solar angle projects the sun angle into a plane perpendicular to a reference plane. Here the reference is defined to be a plane normal to the earth's surface and parallel to the row direction (ϕ_r).

Results and Discussion

The soybean field developed rapidly between the first and second dates with canopy cover increasing from 72 to 83%. By the last measurement date the canopy had attained nearly complete cover (99%) and was completely overlapping, although green LAI had decreased about 25% (Table 2). A comparison of the canopy cross sections or profiles is shown in Figure 2 to illustrate the change from well defined row structure on the first two dates to overlapping on the last date. Although the canopy is completely overlapping on August 27 there was a slight row structure present.

Sun and View Angle Effects

When a radiometer views a scene its response is dependent on the scattering properties and proportions of sunlit and shaded scene components within the FOV. For agricultural scenes such as a soybean field, the scene components are vegetation and bare soil. When the sensor looks straight down on a canopy with well defined row structure the effect of sunlit and shaded soil on the scene reflectance is maximized. As the view zenith angle increases proportionately more vegetation is viewed since the sensor FOV includes the sides of the plant rows.

Figure 3 illustrates the dependence of RF on view angle for two structurally different soybean canopies. The view azimuth angle was perpendicular to the rows and solar azimuth angle was parallel to the rows so shading of the soil surface was minimized. The RFs for each wavelength band are plotted against view zenith angle for an incomplete canopy in Figure 3a. The RFs in visible bands 1 and 2 (0.5-0.6µm, 0.6-0.7µm) decreased with view angle until about 30 and then leveled off. The corresponding photographs revealed that bare soil was no lon-

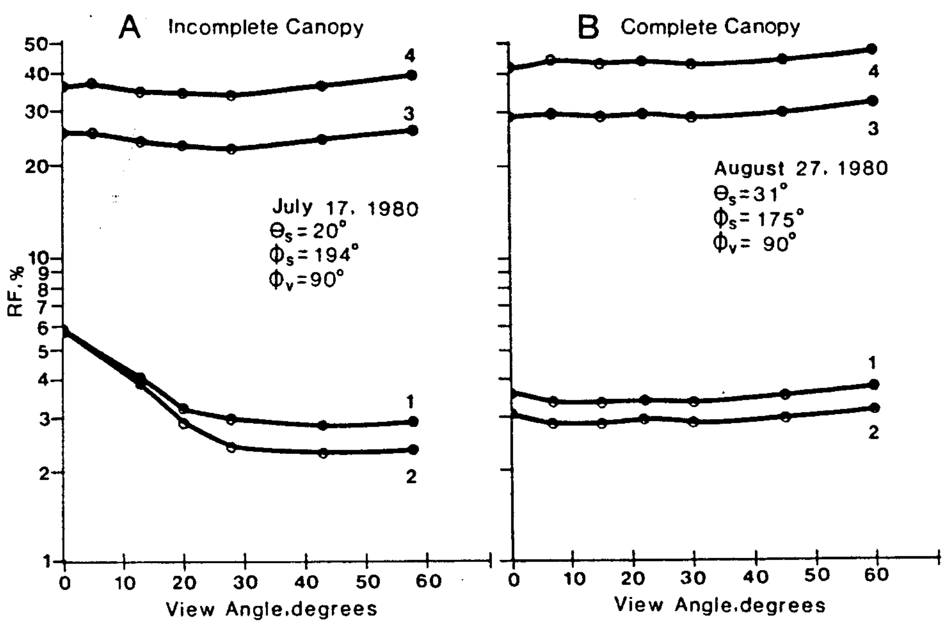

Figure 3. Relationship of reflectance factors and view zenith angle for an incomplete soybean canopy (A), and a complete soybean canopy (B). View azimuth angle = 90°. Numbers of curves indicate MSS band.

ger visible at view angles greater than about 30°. RF in near-IR bands 3 and 4 (0.7-0.8μm, 0.8-1.1μm) decreased initially and then increased. This is due in part to the relatively high reflectance of the soil (Figure 4) and the presence of multiply scattered light in these near-IR wavelength bands. The decreases in absolute reflectance up to view zenith angles of 30° were similar for the visible and near-IR bands. The relative changes, however, were much larger for the visible bands. Also, the reflectance of the soil in the visible is significantly greater than that for vegetation only (10-12% vs. <5%), whereas in the near-IR the soil reflectance is significantly less than that of the vegetation only (17-22% vs. 30-40%) (Figure 4). The complete soybean canopy reflectance in all four bands gradually increased (significant at α=0.05) as view angle increased (Figure 3b).

Through the day, the scene viewed by a sensor may change as the proportions of sunlit and shadowed vegetation and soil vary in response to changing sun zenith and azimuth angle. Comparisons of the diurnal trends for 0.6-0.7 μm and 0.8-1.1μm RF for two structurally different canopies with projected solar angle are presented in Figure 5 for a nadir view angle and Figure 6 for a series of off-nadir view angles, respectively.

In Figure 5, the effect of increased shadowing on the soil surface as θ_{sp} increased can be seen as a decrease of nearly 50% for the red RF. Red RF levels off after θ_{sp} of 38 which corresponds to the projected sun angle when the shadow reached across to the adjacent row. The rapid decrease in RF is not apparent for the near-IR band for the incomplete canopy. Greenness (not shown) behaved similarly to near-IR RF. The trends for the complete canopy are relatively level for all three spectral variables and in fact exhibit a slight but significant (α=0.05) increase with θ_{sp}.

The nadir red response for the incomplete canopy can be explained simply in terms of the shaded soil component resulting from shadows cast by the plant rows. A model described by Egbert (1977) explained 85% of the variation in bidirectional reflectance in terms of the shadow cast by solid objects. Healthy, green leaves absorb over 90% of the intercepted sunlight in the red region of the spectrum resulting in distinct shadows being cast on the soil surface. Analysis of photographs indicated that sunflecks on the soil surface were minimal for the incomplete canopy so it is reasonable to expect that the primary factor responsible for the trends is variation in the proportion of shaded soil in the FOV.

The near-IR wavelengths are characterized by a very small absorption coefficient and high reflectance and transmittance coefficients for green vegetation. In this case there is a tendency for the light intercepted by the canopy to be multiply scattered onto the soil surface thus reducing the dependence on θ_{sp} in this wave-length region.

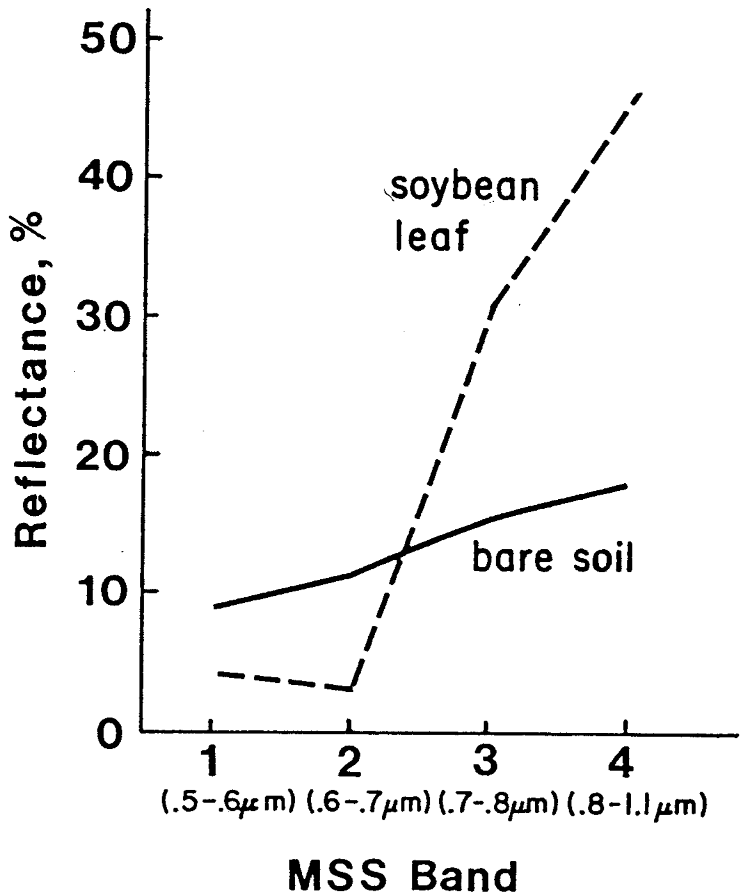

Figure 4. Bare soil reflectance factor and soybean leaf hemispherical reflectance for Landsat MSS bands.

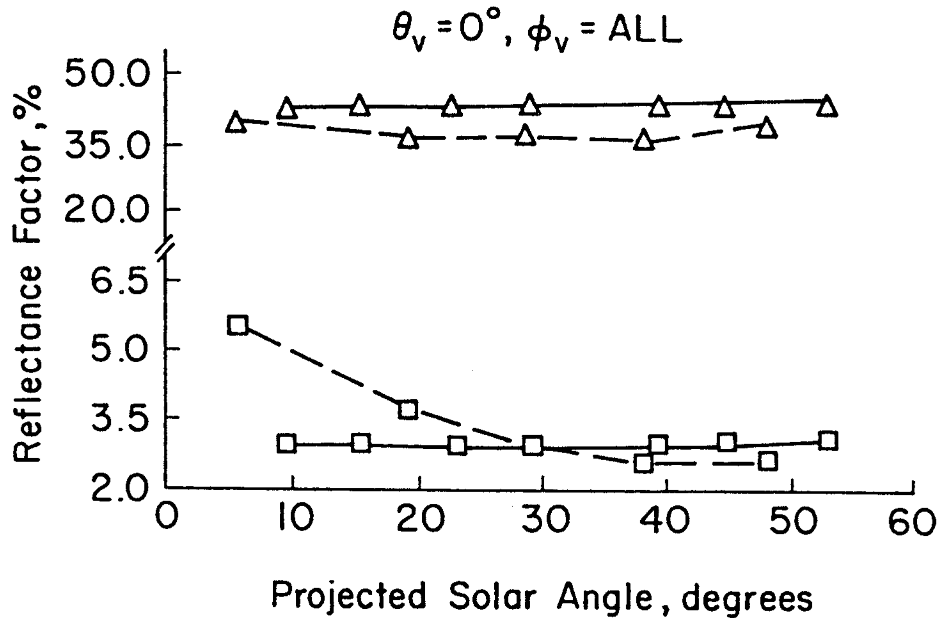

Figure 5. Relationship of nadir acquired reflectance factors with projected solar angle for incomplete and complete soybean canopies. Dashed and solid lines represent incomplete and complete canopies, respectively. Triangles and squares indicate 0.6-0.7 μm and 0.8-1.1 μm wavelength bands, respectively. Standard deviations were less than or equal to symbol height.

After the soybean rows grow together and overlap, row structure is minimized as is the proportion of bare soil in the FOV. The nadir looking sensor views mainly the sunlit upper stratum of the canopy. Shadows present within the FOV are be caused by mutual shading within the canopy. This effect would be most important in the red band for reasons discussed above. The data for the complete canopy indicate that this effect is minimal since the response does not vary with θ_{sp} in either spectral band.

As the sensor is moved off-nadir the relationship between the sun and sensor positions becomes increasingly important. Figure 6 presents a series of graphs showing the spectral reflectance with θ_{sp} for view zenith angles (ϕ_v) of 15, 30, 45 and 60° for two view azimuth angles (ϕ_v). The left and right sides of Figure 6 show data acquired at ϕ_v of 90° (sun generally behind the sensor) and ϕ_v of 270° (sun generally in front of sensor), respectively. In both cases the view direction is perpendicular to the row orientation. Examining Figure 6a-d it is apparent that a maximum response in the red band occurs for the incomplete canopy when θ_v approaches θ_{sp}. For θ_v of 15 and 30° the sensor FOV includes some bare soil and the tops and sides of the soybean rows. At larger θ_v the FOV consists mainly of vegetation. There is a general increase in the near-IR response with θ_v for the incomplete canopy. In addition, there is an indication of a local maximum in near-IR response with when θ_v approaches θ_{sp} for $\theta_v > 15°$.

With the view zenith angle at 60° and the view azimuth perpendicular to the rows (Figure 6d), reflectance factors increased with solar zenith angle for both canopies. The increase for the 90° view azimuth was nearly 85% of value for the red RF from solar noon ($\theta_{sp} = 0°$) to a θ_{sp} of 45°. Near-IR RF increased by more than 70% for the incomplete canopy. In all cases the changes in RF of complete canopy, a function of projected solar angle, were less than those for the incomplete canopies.

For the opposing ϕ_v (Figure 6e-h), spectral RF is generally lower than that noted for $\phi_v = 90°$, but tends to increase with θ_{sp} for both wavelength bands and canopy types. The effect of sunlit bare soil is evident only at $\theta_v = 15°$ and $\theta_{sp} = 10°$ for the incomplete canopy. The complete canopy response increased gradually with θ_v and was maximized at the largest sun angle.

With the sensor looking across the rows in a direction generally toward the sun ($\phi_v = 270°$), the FOV will include a greater proportion of shadows at a given θ_{sp} than for the opposite view direction. This difference in shadowing accounts for the lower spectral response noted in Figure 6e-h. This can not, however, explain the gradual increase in response with θ_{sp} . If the canopies scattered light as perfectly diffusing surfaces, then reflectance should decrease with θ_{sp} in response to increased shading. The increased reflectance as θ_{sp} increases may be due in part to a forward scattered specular component as suggested by the work of Vanderbilt and Grant (1983).

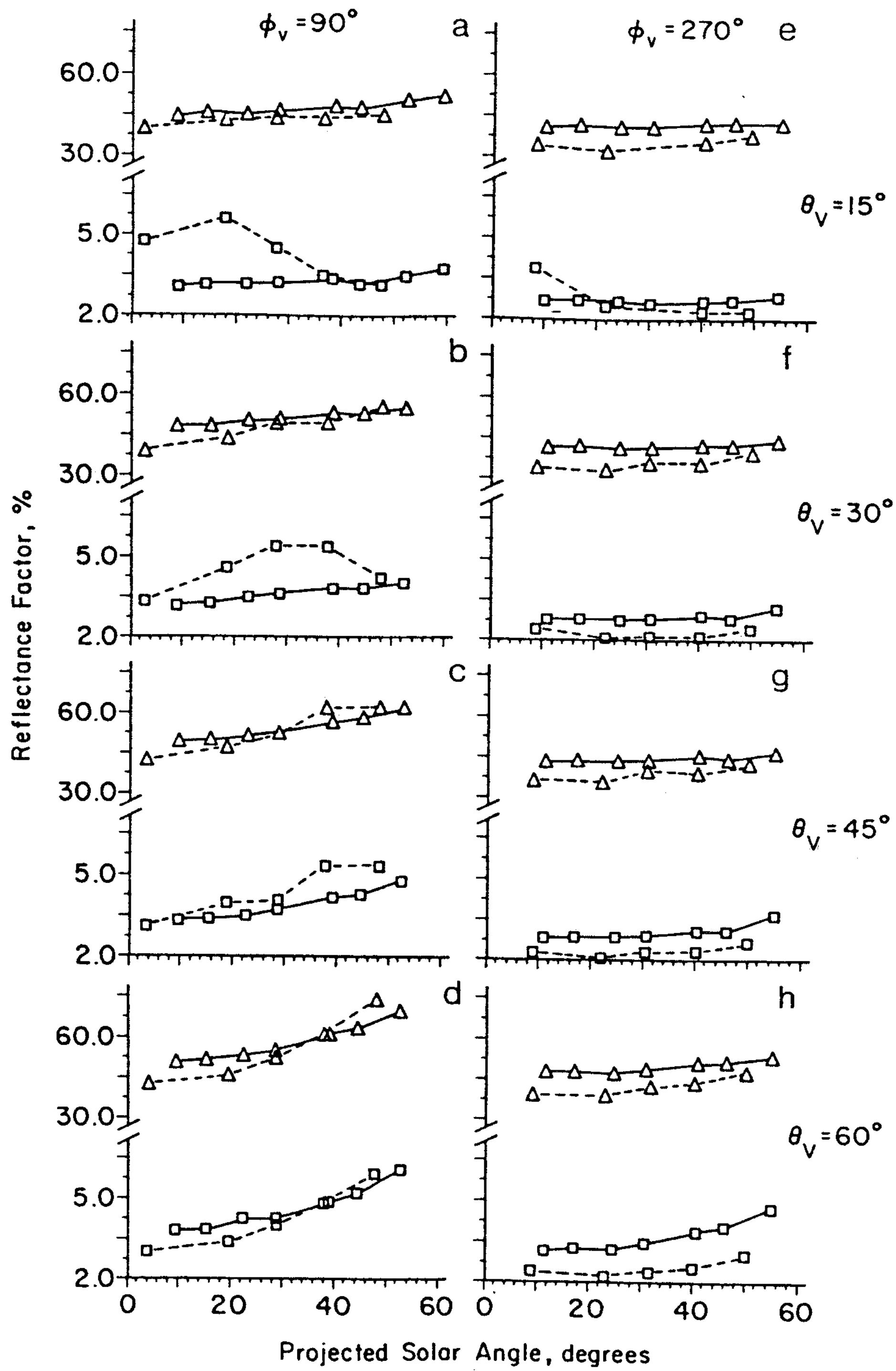

Figure 6. Relationship of off-nadir acquired reflectance factors with projected solar angle for incomplete and complete soybean canopies. Dashed and solid lines represent incomplete and complete canopies, respectively. Triangles and squares indicate 0.6-0.7 μm and 0.8-1.1 μm wavelength bands, respectively.

Lambertian Analysis

Although the differences in reflectance distributions undoubtedly contain additional useful information about the observed canopies, it is pertinent to approach the problem from a different perspective for some applications. That is, are there sun and view angle combinations where the reflectance is essentially constant? This information is useful if we are to relate off-nadir measurements of canopies to those acquired from nadir or straight down. This question is directly applicable to data acquired with airborne multispectral scanners and will increase in importance with the launch of satellites with off-nadir pointing capabilities. To examine this question, off-nadir visible, near-IR reflectance factors greenness and normalized difference data were ratioed with nadir data acquired under similar sun angle conditions. For a surface to be considered "Lambertian" then the reflectance is isotropic under the conditions that the scene is uniformly illuminated and fully occupies the field of view. A ratio of 1.0 indicates that the Lambertian assumption is satisfied at least for that off-nadir view angle. The differences between ratios for incomplete and complete soybean canopies with changing view and illumination angles were examined with response surface plots.

Figures 7, 8, and 9 present the data for both incomplete and complete canopies collected in the morning, near solar noon, and afternoon, respectively. The solar azimuth angles for the morning and afternoon are generally perpendicular to the row direction and for the solar noon data the solar azimuth is parallel to the row direction.

The red and near-IR band ratios for the incomplete canopies have a peak value near the hot spot where the sun and view positions coincide near θ_v=40° and ϕ_v=270° for morning data (Figure 7) and θ_v=60° and θ_v=90° for afternoon data (Figure 9). There is a secondary peak at $_v$=90°, 180° in view azimuth from the maximum, and corresponds to the forward scattering direction. The magnitude of the near-IR and greenness ratios are smaller than those for the red band. ND response was essentially level across view angle, but analysis showed a slight decrease near the hot spot. The red, near-IR and greenness response surfaces for the complete canopy were maximized along the view direction corresponding to the sun's azimuth, but were relatively flat compared to the incomplete case. Again ND exhibited essentially no change in response across view angle.

At a solar azimuth angle of about 195° (near solar noon), the red band response surface peaked between view zenith angles of 15 and 22° along view azimuth directions more or less in line with the sun for the incomplete canopy (Figure 8). There was another peak between 45 and 60° zenith along the azimuth in the principal plane of the sun, but looking towards the sun. Ratio values dropped off sharply for larger θ_v away from the solar azimuth. In the near-IR, these peaks were less pronounced. ND ratios showed a dependence on view angle for this mea-

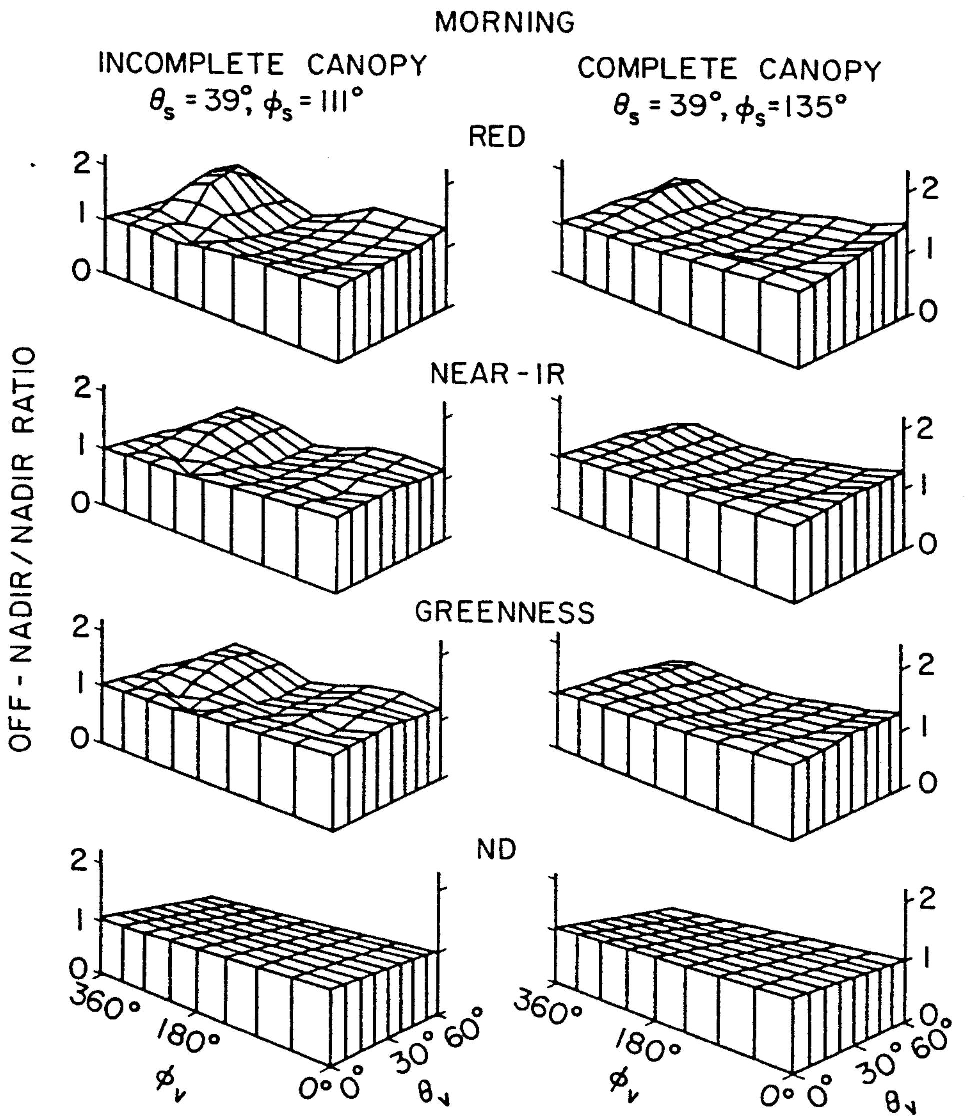

Figure 7. Response surface plots of ratios of off-nadir to nadir reflectance for incomplete and complete soybean canopies with view zenith (θ_v) and azimuth angle (ϕ_v). Data acquired during mid-morning.

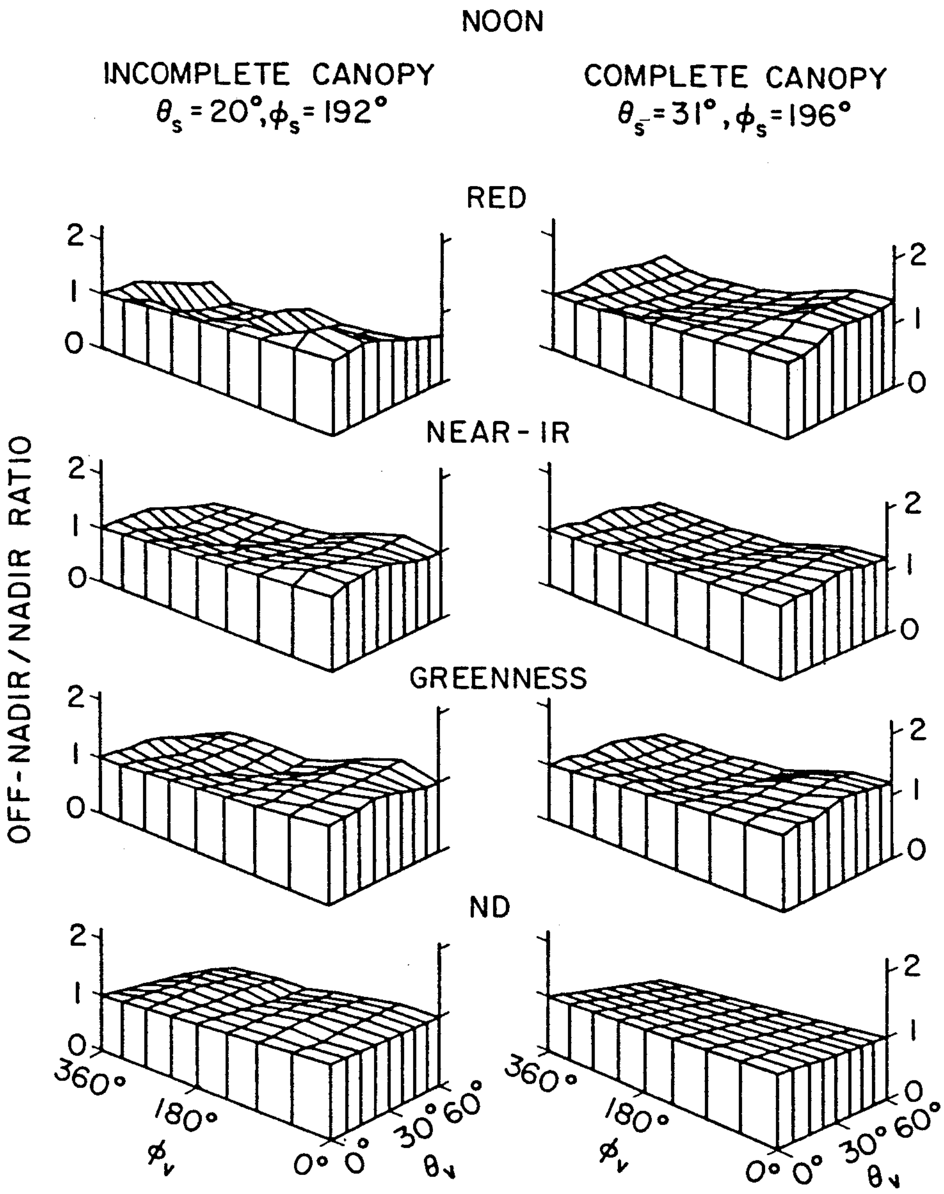

Figure 8. Same as Figure 7 but, data acquired shortly after solar noon.

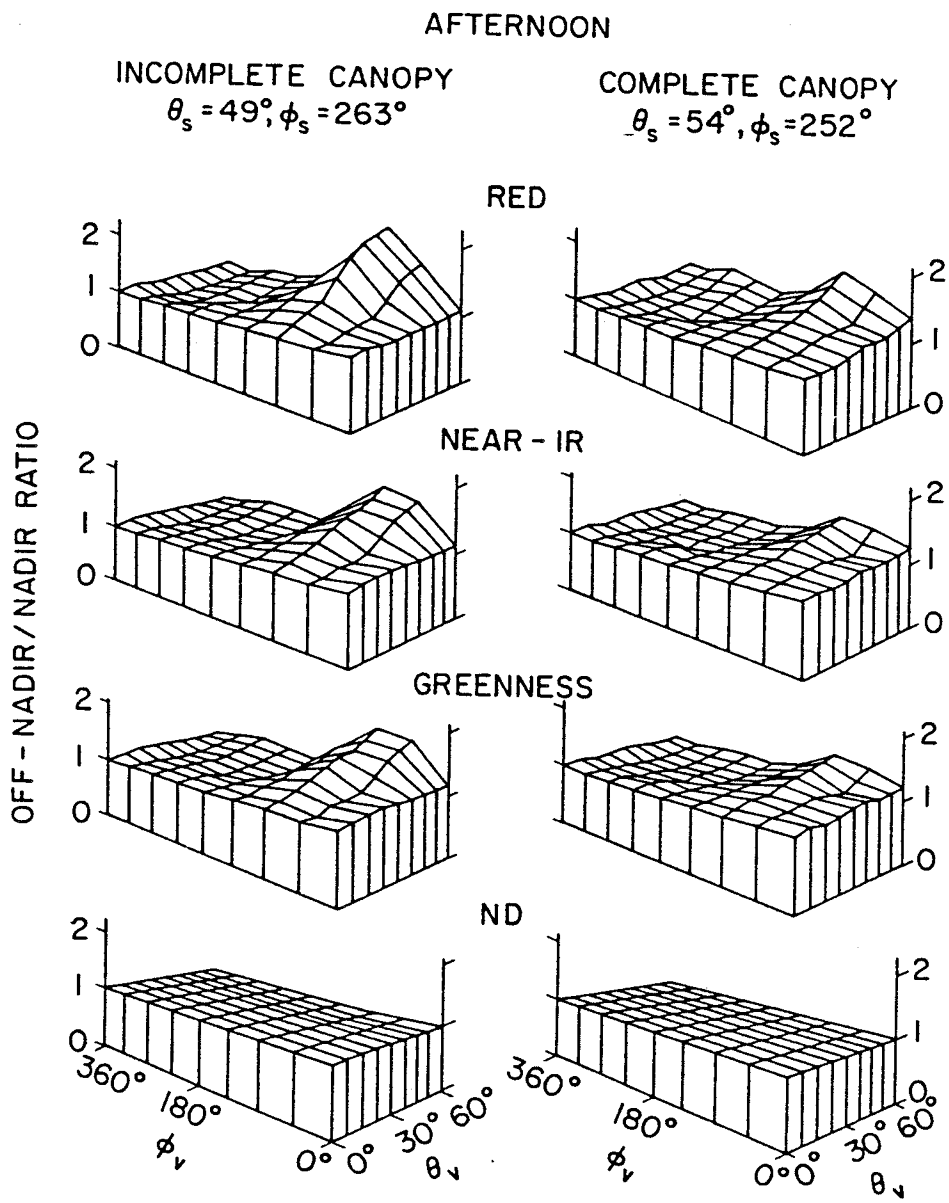

Figure 9. Same as Figure 7, but data acquired in late afternoon.

surement period mainly in response to the presence of sunlit soil. The response of the complete canopy was maximized along the view direction generally away from the sun (back scattered direction), but the surface was overall more level than that of the incomplete canopy. Near-IR and greeness ratios exhibit similar trends.

The spectral response from soybean canopies varies greatly with solar zenith, solar azimuth, view zenith, view azimuth angles and canopy structure. For a given sun position that the maximum reflectance is obtained in the vicinity of the hot spot for both visible and near-IR reflectance factors. A reflectance minimum is located at an opposite view azimuth near view zenith angles equal to the solar zenith angle. It is apparent that the red band (0.6–0.7μm) off-nadir ratios exhibit the greatest departures from nadir, especially for view azimuth angles perpendicular to the rows. There is a strong peak in the ratios for the perpendicular view azimuths that appears to occur at view angles less than the solar zenith angle. The ratio decreased as the solar azimuth angle approaches 180° and then increased later in the day. The red band ratios for the complete canopy do not show the strong peaks characteristic of the incomplete canopy, but depart from nadir response at the steeper view zenith and solar zenith angles. Over-all, the view azimuth angles parallel to the row more closely agreed with straight down measurements for both incomplete and complete canopies. The near-IR and greenness ratios approximated straight down measurements for smaller view zenith angles, but departed from nadir response at the larger view angles, especially for large solar zenith angles.

An additional analysis was performed with the objective of determining sun-view angle combinations where the reflectance measured at an off-nadir angle is similar to reflectance measured from nadir. A test was devised to determine if the RF for a given off nadir view angle was within two standard deviations of the mean RF for nadir measurements acquired under similar sun angle conditions. If so, the RF for that view angle was considered equivalent to nadir RF and a test value (V) of 1 was assigned. If the RF of the off-nadir angle was either greater or less than two standard deviations, then V = 0 was assigned.

The test results for all measurement hemispheres on all three dates were combined to determine if there were any view angles that satisfied the nadir response criteria for the wide range of canopy and illumination geometry conditions. No single view angle satisfied the test criteria.

To determine under what sun angle conditions the reflectance hemispheres for each canopy exhibit more or less Lambertian behavior a quantity termed the Relative Lambertian Coefficient (RLC) was devised:

$$RLC = \sum_{j=1}^{8} \sum_{i=1}^{6} V_{ij} / 48 \qquad (4)$$

where

V_{ij} is the test value determined as above for the i = 1-6 off-nadir view zenith angles and j = 1-8 view azimuth angles.

RLC is a measure of how well off-nadir spectral measurements approximate straight down measurements. An RLC of 1 implies an isotropic surface whereas RLC values of less than 1 indicates that the canopy exhibits anisotropic scattering.

The results for the three measurement dates representing canopies of different structure are illustrated in Figure 10 for the red, near IR, greenness, and ND spectral variables. For the red band, RLCs are highest for incomplete canopies at times corresponding to larger solar zenith angles in the morning and afternoon. The minimum RLCs are found near solar noon (1745 hours) when, for our north-south rows, sunlit soil was maximized. The RLC values for the complete canopy are relatively stable across the middle of the day, but are lower early and late in the day.

Near-IR and greenness RLC values (Figure 10) tend to be greater for times away from solar noon for all three canopies and were lowest near solar noon.

The ND RLC peaked around 1630 hours in the morning for the incomplete canopy and then decreased sharply near noon. The complete canopy RLC values remained high through the middle portions of the day.

These results indicate that the anisotropic behavior from the soybean canopies is, in part, due to the amount of sunlit bare soil in the sensor FOV. They also suggest that certain times of the day may be better for relating off-nadir measurements to nadir acquired data. It should be cautioned here that for incomplete canopies, row direction will affect these results by shifting the maximum RLC values away from times when the sun's direction is parallel with the rows.

Atmospheric effects also become important when satellite or high altitude aircraft mounted sensors are considered. However, these effects were not addressed in this paper.

Summary and Conclusions

In this study the effects of sun and view angles on reflectance factors and spectral transformations for incomplete and complete soybean canopies were evaluated. Spectral data were acquired at many view angles over a range of sun angles for two incomplete canopies with well defined row structure and one completely overlapping canopy.

The spectral responses of the incomplete canopies depended greatly on sun and view geometry This effect was more pronounced for the highly absorptive red (0.6-0.7μm) wavelength band than for the near-IR (0.8-1.1μm) using relative change in reflectance as the criterion.

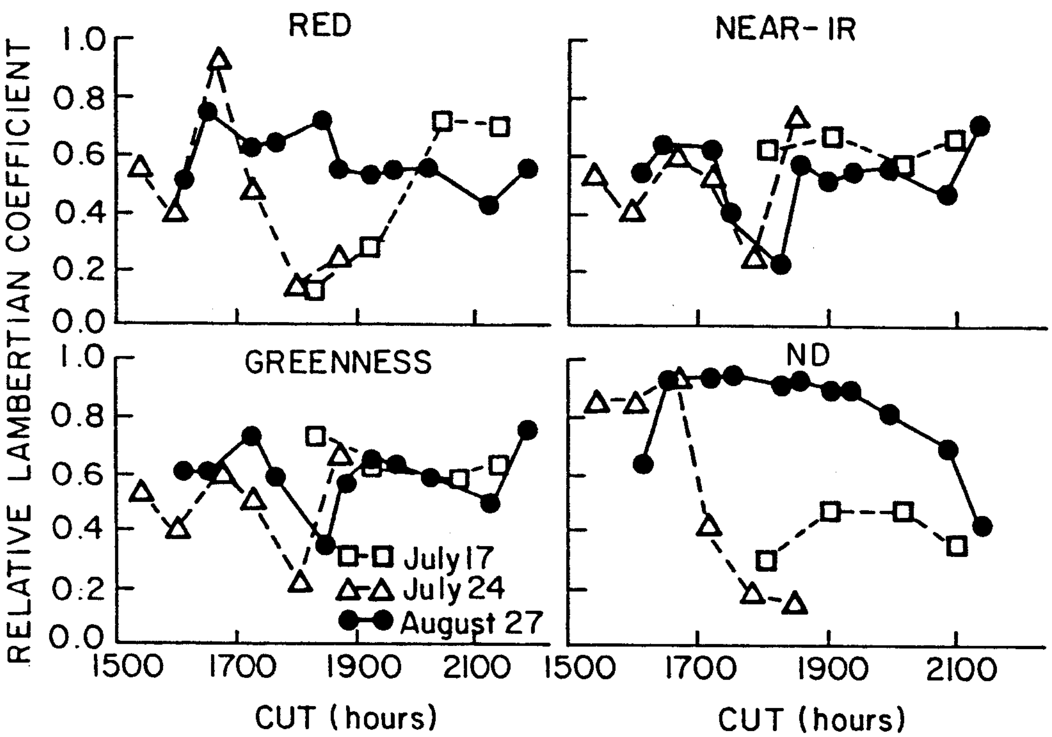

Figure 10. Variation of Relative Lambertian Coefficient (RLC) for spectral variables over Coordinated Universal Time (CUT) of measurement hemispheres for different soybean canopies.

Red reflectance tended to decrease as solar zenith angle increased for a nadir view angle for the incomplete canopy. This decline was maintained until the soil between the plant rows was completely shaded and the reflectance leveled off or increased slightly. A pronounced "hot spot" effect was evident for the red band reflectances, especially when both sun and sensor view directions were perpendicular to the rows.

Near-IR reflectances decreased initially as solar zenith angle increased for nadir data and then increased for the incomplete canopies. Beyond the sun angle at which the soil surface was completely shaded, the responses increased sharply and then leveled off. There was a slight increase in near-IR response in the vicinity of the hot spot angle. General trends for the completely overlapping canopy showed increased red and near-IR reflectance. The effect of sun angle was more pronounced for view angles perpendicular to the row direction.

An analysis of the angular reflectance data was conducted to determine at what sun-view angle combinations the soybean canopies could be considered isotropic. Off-nadir red band reflectance factors more closely approximated straightdown measurements for time periods away from solar noon. Near-IR and greenness responses showed a similar behavior. Normalized difference results generally approximated straight down measurements during the middle portion of the day except for incomplete canopies near solar noon when shadowing of the soil between the rows was minimized.

The spectral data and corresponding agronomic measurements of the soybean canopies have been compiled and documented (Ranson and Biehl, 1984). These data are well suited for validating light interaction canopy models and have been distributed to a number of interested organizations.

Acknowledgements

This study was sponsored by the U.S. National Aeronautics and Space Administration, Johnson Space Center, under contract number NAS9-16528. The authors appreciate the helpful comments of Dr. C.S.T. Daughtry, LARS, regarding the manuscript.

REFERENCES

Chevrel, M., M. Courtois and G. Weill. 1980. The SPOT satellite remote sensing mission. Photogramm. Eng. Rem. Sens. 47(8):1163-1171.

Cooper, K., J. Smith and D. Pitts. 1982. Reflectance of a vegetation canopy using the adding method. Applied Optics. 21:4112-4118.

Egbert, D.D. 1977. A practical method for correcting bidirectional reflectance variations. Proc. Symp. Machine Processing Remotely Sensed Data. Purdue Univ., W. Lafayette, IN, 47906-1399, June 21-23. pp. 178-188.

Fehr, W.R., C.E. Caviness, D.T. Burmood and J.S Pennington. 1971. Stage of development descriptions for soybeans, Glycine max (L.) Merrill. Crop Sci. 11:929-931.

Goel, N.S. and D.E. Strebel. 1983. Inversion of vegetation canopy reflectance models for estimating agronomic variables. I. Problem definition and initial results using the Suits model. Remote Sens. Environ. 13:487-507.

Goel, N.S. and R.L. Thompson. 1984. Accuracy of estimation of leaf area index and leaf angle distribution from the bidirectional reflectance data:Optimal solar/viewing directions. Int. J. Remote Sensing. (submitted).

Jackson, R.D., R.J. Reginato, P.J. Pinter, Jr. and S.B Idso. 1979. Plant canopy information extraction from composite scene reflectance of row crops. Appl. Opt. 18(22):3775-3782.

Kauth, R.J. and G.S. Thomas. 1976. The tasselled cap -- a graphic description of spectral temporal development of agricultural crops as seen by Landsat. Proc. Symp. Machine Processing Remotely Sensed Data Purdue Univ., W. Lafayette, IN. 47906-1399, June 29-July 1. pp. 4B/41-51.

Kimes, D.S. and J.A Kirchner. 1982. Radiative transfer model for heterogeneous 3-D scenes. Applied Optics. 21:4119-4129.

Kimes, D.S., W.W Newcomb, J.B. Schutt, P.J. Pinter and R.D. Jackson. 1984. Directional reflectance factor distributions of a cotton row crop. Int. J. Remote Sensing (accepted).

Kollenkark, J.C., V.C. Vanderbilt, C.S.T. Daughtry and M.E. Bauer. 1982. Influence of solar illumination angle on soybean canopy reflectance. Applied Optics. 21:1179-1184. LARS Technical Report 021681.

Malila, W.A. and J.M Gleason. 1977. Investigations of spectral separabilty of small grains, early season wheat detection, and multicrop inventory planning. Report 122700-34-F, Environmental Research Institute of Michigan, Ann Arbor, MI.

Methy, M., B. Lacaze and J. Dauzant. 1981. Cinetiques journaliere et saisonniere des facteurs spectraux de reflectance directionelle d'une culture de soja, et implications pour l'utilisation des donnees du satellite SPOT. In Proc. International Colloquium on Spectral Signatures of Objects in Remote Sensing. Avignon, France. Sept 8-11, 1980, pp. 591-599.

Ranson, K.J., V.C. Vanderbilt, L.L. Biehl, B.F. Robinson and M.E. Bauer. 1981. Soybean canopy reflectance as a function of view and illumination geometry. Proc. 15th Int. Symp. Rem. Sens. Environ., ERIM, Ann Arbor, MI. 48107. pp. 853-856. LARS Technical Report 042182.

Ranson, K.J. and L.L. Biehl. 1984. Soybean canopy reflectance modeling data set. Laboratory for Applications of Remote Sensing, Purdue Univ., W. Lafayette, IN, 47906. 25 pp. LARS Technical Report 071584.

Robinson, B.F. and L.L. Biehl. 1979. Calibration procedures for measurement of reflectance factor in remote sensing field research. Proc. Soc. Photo-Optical Instrumentation Engr. 23rd Annual Tech. Symp. on Measurements of Optical Radiation, Bellingham, WA, pp. 16-26. LARS Technical Report 082679.

Schnetzler, C.C. and L.L. Thompson. 1979. Multiple resource sampler:an experimental satellite sensor for the mid-1980s. Proc. SPIE Tech. Symp., Vol. 183, Huntsville, AL. 11 pp.

Tucker, C.J., Gatlin, J.A. and S.R. Schneider. 1984. Monitoring vegetation in the Nile Delta with NOAA-6 and NOAA-7 AVHRR imagery. Photogramm. Engin. Remote Sensing 50:53-62.

Vanderbilt, V.C., J.C. Kollenkark, L.L. Biehl, B.F. Robinson, M.E. Bauer and K.J. Ranson. 1981. Diurnal changes in reflectance factor due to sun-row direction interactions. AgRISTARS Tech. Rep. SR-P1-04140. Laboratory for Applications of Remote Sensing, Purdue University, W. Lafayette, IN, 47906-1399. 10pp. LARS Technical Report 090881.

Vanderbilt, V.C and L. Grant. 1983. Light polarization measurements a method to determine specular and diffuse light scattering properties of both leaves and plant canopies, Laboratory for Applications of Remote Sensing, Purdue University, W. Lafayette, IN, 47906-1399. 11pp. LARS Technical Report 091683.

DISTRIBUTION

NASA Johnson Space Center
- SA2: R. MacDonald
- SC1: J. Erickson
- SC2: I. Browne (6)
- SC3: F. Hall
  - G. Badhwar
  - K. Henderson
  - G. Houston
  - D. Pitts
- SC4: J. Dragg
  - R. Heydorn
  - D. Thompson
- SC5: R. Hill
- SC6: R. Musgrove
- BB63: Carol Homan
- JM6: Technical Library (4)
- AT3: Technology Utilization Ofc.
- AP: Public Affairs Office

NASA Headquarters
- EL4: H. Hogg
  - R. Murphy

NASA Goddard Space Flight Center
- 920: V. Salomonson
- 923: B. Holben
  - D. Kimes
  - C. Tucker

NASA Ames Research Center
- D. Peterson

NASA Earth Resources Lab.
- S. Wu

Jet Propulsion Laboratory
- J. Paris

USDA/Agricultural Research Service
- G. Boatwright
- H. Gausman
- J. Hatfield
- R. Jackson
- J. Musick
- C. Wiegand

USDA Soil Conservation Service
- R. Gilbert

ASTER Consulting
- N. Goel

CIMMYT
- P. Hobbs

Canada Centre for Remote Sensing
- P. Teillet

Colorado State University
- J. Smith

Environmental Research Inst. Mich.
- W. Malila

Kansas State University
- G. Asrar
- E. Kanemasu

Oregon State University
- M. Hall
- B. Schrumpf

Pan American University
- J. Chance
- E. LeMaster

Purdue University
- M. Baumgardner
- B. Baumgardt
- D. Landgrebe
- M. Phillips
- T. Phillips

Texas A&M University
- J. Heilman

Univ. California - Santa Barbara
- D. Botkin
- K. Woods

University of Michigan
- G. Suits
- F. Ulaby

University of Minnesota
- M. Bauer

University of Nebraska
- B. Blad
- J. Norman