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THE EXTENSION OF A UNIFORM CANOPY REFLECTANCE MODEL TO INCLUDE ROW EFFECTS

3. Gwynn H. Suits

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16. Abstract

The reflectance model for a uniform crop canopy is extended to include the effects of crops planted in rows. The effect of row structure is assumed to be caused by the variation in density of vegetation across rows rather than to a profile in canopy height. The calculation of crop reflectance using vegetation density modulation across rows follows a parallel procedure to that for a uniform canopy.

Predictions using the row model for wheat show that the effect of changes in sun to row azimuth are greatest in Landsat Band 5 (red band) and can result in underestimation of crop vigor.

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TECHNICAL REPORT

THE EXTENSION OF A UNIFORM CANOPY REFLECTANCE MODEL TO INCLUDE ROW EFFECTS

by

Gwynn H. Suits

This report describes results of research carried out in support of the Scene Simulation and Analysis Consortium of the Supporting Research Project.

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December 1981

PREFACE

The Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing program, AgRISTARS, is a six-year program of research, development, evaluation, and application of aerospace remote sensing for agricultural resources, which began in Fiscal Year 1980. This program is a cooperative effort of the National Aeronautics and Space Administration, the U.S. Agency for International Development, and the U.S. Departments of Agriculture, Commerce, and the Interior. AgRISTARS consists of eight individual projects.

The work reported herein was sponsored by the Supporting Research (SR) Project under the auspices of the National Aeronautics and Space Administration, NASA. Mr. Robert B. MacDonald, NASA Johnson Space Center, was the NASA Manager of the SR Project and Dr. Glen Houston was the Technical Coordinator for the reported effort.

The Environmental Research Institute of Michigan and the Space Sciences Laboratory of the University of California at Berkeley comprise a consortium having responsibility for development of corn/soybeans area estimation procedures applicable to South America within both the Supporting Research and Foreign Commodity Production Forecasting Projects of AgRISTARS.

This reported research, the extension of reflectance modeling to include row effects, was performed within the Environmental Research Institute of Michigan's Infrared and Optics Division, headed by Richard R. Legault, Vice-President of ERIM, under the technical direction of Robert Horvath, Program Manager, and Dr. William A. Malila, Task Leader.

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1.0
INTRODUCTION

The scattering and reflection of incident daylight by agricultural crops alters the direction and spectral composition of daylight radiation in a complex manner. A part of this altered radiation is detected by Landsat. From the detected part of the altered radiation, it is desired to infer the existence of important agronomic features of the crop which are the cause of the altered radiation.

A canopy reflectance model provides the logical connection between the botanical features of the canopy, the geometry of the radiometric interaction and the resulting alteration in the reflected radiation. Such a model allows one to understand the reasons for the alterations and to calculate the magnitude and trends of these alterations caused by the botanical features and the geometry of the interaction. The validity of inferences as to the existence of important agronomic features from the detected altered radiation may be tested on theoretical grounds.

Many crops are planted in rows by machinery. Upon emergence of the plants, the bare soil between rows is still the dominant feature which reflects incident daylight. As growth continues, the vegetation grows both higher and spreads out over the inter-row regions covering the bare soil. At some time during the growing season, the bare soil is covered enough that the bare soil between rows is no longer a dominant feature. The vegetation canopy becomes essentially laterally uniform in its radiation scattering properties. The alteration of incident daylight can be understood and calculated by a previously developed uniform canopy reflectance model [1] at this stage of growth.

However, for a considerable time during the early part of the growing season, the strips of bare soil between rows and the increasing density of vegetation along the rows become equally important in their contributions to canopy reflectance. One may intuitively understand that the direction of sunlight relative to the row direction will change the relative influence of vegetation and bare soil. When the sun is directed along the row direction, the bare soil is fully illuminated but, when the sun is directed across rows, the soil is largely in the shadow of the standing vegetation along the rows. Thus, Landsat can receive different alterations due only to the way the rows trend relative to sunlight. An inference that such altered radiation is due to a change in some important agronomic feature could be in error.

Field measurements of wheat [2] and soybeans [3] show that row direction relative to sunlight does change the character of the scattered and reflected radiation. The research presented in this report is the extension of the uniform canopy model so that it will also apply to the early season nonuniform row crop canopy so that this "row effect" may be understood and calculated.

Verhoef and Bunnik [4] developed a "row effect" model by assuming that the vegetation along rows formed a rectangular prism of plant material with bare soil between. The limitation of the model to a particular plant profile does not permit one to calculate intermediate amounts of soil cover between rows as the crop continues to grow. It is particularly desirable that any lateral distribution of vegetation should be allowed so that the model will apply to any crop at any time in the growing season.

The following text reviews the concepts, nomenclature, and symbols of the uniform canopy model in order to form the logical basis for its modification to incorporate the "row effect." The concept of density modulation is introduced to account for the row structure of a canopy and the manner of calculation using such a concept is described.

A comparison of the row effects predicted by the Verhoef-Bunnik rectangular prism model and the extended uniform canopy model is made for the extreme case of the rectangular prism row to show that the results are comparable in this case.

Finally, the extended model is applied to wheat where more realistic vegetation distributions are assumed. The results are similar to those of field measurements. The red band, Landsat band 5, is most sensitive to row direction because of the usual large contrast between vegetation and soil. Reflectance in this band may easily vary by a factor of two with changing row direction. The IR bands, Landsat 6 and 7, are least affected by row direction because of low contrast between soil and vegetation and because of the large amount of diffuse flux scattered to soil by the vegetation.

2.0
REVIEW OF THE UNIFORM CANOPY MODEL

The uniform canopy reflectance model consists of a number of infinitely extended horizontal layers or strata as illustrated in Figure 1. Within each layer, the plant components of the canopy are considered to be randomly distributed and homogeneously mixed. The plant components are the identifiable parts of the plant, such as, stems, leaves, branches, flowers and pods. Most vegetation has a morphology which is largely genetically controlled. As a consequence, agricultural vegetation tends to be stratified in such a way that particular plant components occur at different levels above the soil. For example, the heads of wheat are located at the top of the canopy and not at the bottom. The influence of the heads of wheat on the reflectance of a wheat field will be greater because the top layer receives full illumination and may be seen without obstruction. Lower layers lie in partial shadow and must be seen through the obstruction of the upper layers.

The location of layers are chosen in such a way as to quantize the vertical distribution of components. Each layer should contain uniformly some fraction of component types that is characteristic for that level above the soil.

Collimated radiation from the sun enters the top of the canopy. This collimated flow of radiation is called specular flux in the following text. That specular flux which is intercepted by a plant component is diffusely scattered and partially absorbed. The remaining specular flux, steadily diminished by such scattering, proceeds on to the soil making "sun flecks" upon the soil surface.

The diffuse flux created by scattering may be produced by reflection from a component or by transmission through a component. Some of the diffuse flux is scattered towards the top of the canopy; the remainder

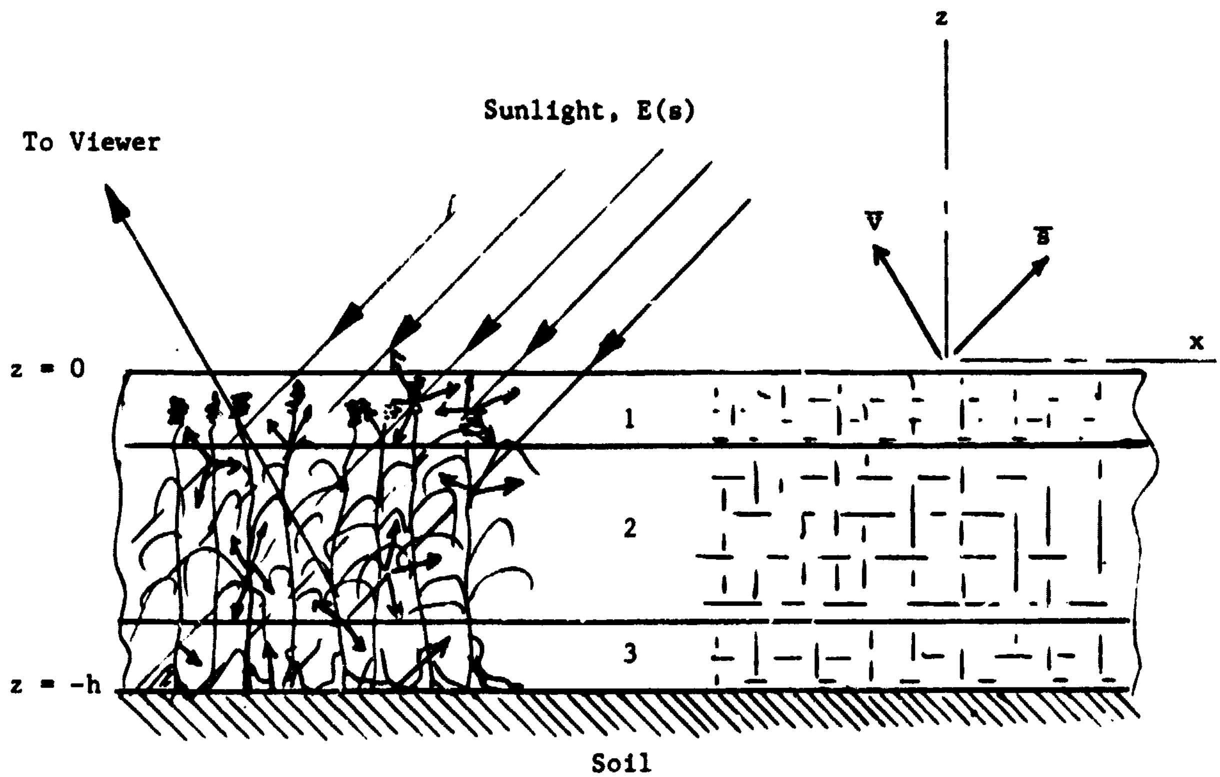

FIGURE 1. SCHEMATIC OF UNIFORM CANOPY MODEL. The actual plant components are illustrated on the left and the model equivalent components are shown on the right.

is scattered towards the soil. As the diffuse flux moves through the canopy, some of the diffuse flux will be intercepted and scattered again with some of the rescattered flux going up and some going down and so forth.

The lateral average flux density on a horizontal plane of specular flux, and upward and downward welling diffuse flux, varies with depth in the canopy. Allen, Gayle, and Richardson [5] showed by experiment that the flux densities could be derived using Duntley's differential equations for scattering in diffuse optical media. The scattering properties of any particular medium are specified by the values assigned to five independent parameters in these equations. These differential equations are shown in relations (1), (2), and (3),

$$dE(+d)/dz = -aE(+d) + bE(-d) + cE(s) \quad (1)$$

$$dE(-d)/dz = aE(-d) - bE(+d) - c'E(s) \quad (2)$$

$$dE(s)/dz = k(Es) \quad (3)$$

where $E(+d)$ = upward welling diffuse flux density,
$E(-d)$ = downward welling diffuse flux density,
$E(s)$ = specular flux density,
a = extinction coefficient for diffuse flux,
b = backscattering coefficient for diffuse flux,
c = backscattering coefficient for specular flux,
c' = forward scattering coefficient for specular flux,
k = extinction coefficient for specular flux.

The five parameters, a, b, c, c', and k for each layer plus the boundary conditions of soil reflection at the bottom and sunlight at the top are all that is needed to specify how much flux goes which way. What remains unknown is the relationship between these parameters and the plant components that are present within the canopy.

The uniform canopy model provides a systematic and logical method of calculating approximate values for these parameters given the number, orientation, and spectral properties of the plant components in a canopy. This method conceptually replaces a particular plant component with three plane orthogonal projections of that component. Each plane projection (hereafter called a model equivalent component) is assigned the same hemispherical spectral reflectance and transmittance as that of the actual plant component. The concept of projections is illustrated in Figure 2. The projection on the horizontal plane becomes the horizontal model equivalent component and the projections on vertical planes become the vertical model equivalent components. If the plant components were replaced by these model equivalent components, then collimated flux incident on model equivalent components in any of these three orthogonal directions would scatter flux in the same amount as would be scattered by the plant component itself. For other incident directions, the amount would only be approximately the same.

The five unknown parameters can now be calculated using model equivalent components. For one type of plant component,

$$a = \sigma_h n_h (1 - \tau) + \sigma_v n_v (1 - [\rho + \tau]/2), \quad (4)$$

$$b = \sigma_h n_h \rho + \sigma_v n_v (\rho/2 + \tau/2), \quad (5)$$

$$c = \sigma_h n_h \rho + (2/\pi) \sigma_v n_v (\rho/2 + \tau/2) \tan \theta_s, \quad (6)$$

$$c' = \sigma_h n_h \tau + (2/\pi) \sigma_v n_v (\rho/2 + \tau/2) \tan \theta_s, \quad (7)$$

$$k = \sigma_h n_h + (2/\pi) \sigma_v n_v \tan \theta_s, \quad (8)$$

where σ_h = mean horizontal model equivalent component area,

σ_v = mean vertical model equivalent component area,

n_h = number of horizontal components per unit volume,

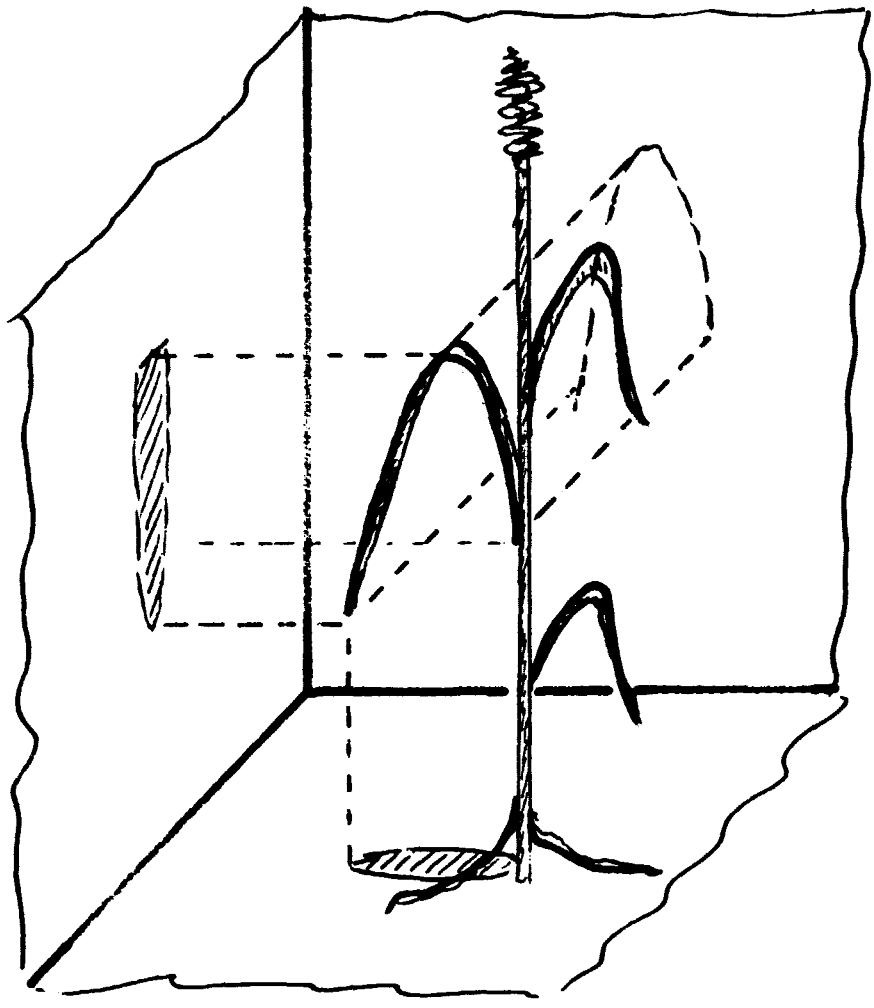

FIGURE 2. THE USE OF PROJECTIONS AS MODEL EQUIVALENT COMPONENTS. Three orthogonal projections of a leaf show the relationship between a plant component (leaf) and the model equivalent.

n_v = number of vertical components per unit volume,

τ = hemispherical transmittance of the plant component,

ρ = hemispherical reflectance of the plant component,

θ_s = polar angle of incident specular flux.

The mean values are taken over a field area the size of the instantaneous field of view (IFOV). The parameters for each type of plant component are determined in a similar manner. The parameter value for the ensemble of components within any given layer is simply the sum of the parameters for each type of component in that layer. Thus, for example,

$$a(\text{layer}) = a(\text{type } 1) + a(\text{type } 2) + a(\text{type } 3) + \ldots,$$

and similarly for the other parameters.

The relations (4) through (8) show how each plant component influences the radiant flux within the canopy. The influence increases as the size and concentration increases. If the plant component changes orientation with the vertical direction, the model equivalent components, which are projections, change size. The influence of plant morphology is accounted for in this simple manner.

Equipped with the values for the five parameters for each layer, one may solve relations (1), (2), and (3) for each layer and, hence, for the flux within the canopy. This flux is the illuminant for objects within the canopy which one can see from some direction of view. The final computation now is simply to determine the radiance, L, (radiometric brightness) of each component in the canopy and what fraction of these components can be seen without obstruction. The model equivalent components are again used to calculate the expected radiance of the components.

At any particular level within the canopy, the radiance per unit depth is*

$$dL/dz = \left(uE(+d) + vE(-d) + w'E(s)\right)/\pi, \tag{9}$$

where $u = \sigma_h n_h \tau + \sigma_v n_v (\rho/2 + \tau/2)(2/\pi) \tan \theta_v$,

$v = \sigma_h n_h \rho + \sigma_v n_v (\rho/2 + \tau/2)(2/\pi) \tan \theta_v$,

$w' = \sigma_h n_h \rho + \sigma_v n_v \tan \theta_s \tan \theta_v \left[(\sin \psi + (\pi - \psi) \cos \psi)\rho + (\sin \psi - \psi \cos \psi)\tau\right]/2\pi$,

ψ = azimuthal angle between sun and view directions,

θ_v = polar view direction.

The fraction, $p_v(\theta_v, z)$ of components that can be seen at depth, z, from view angle, θ_v, is given by

$$dp_v(\theta_v)/dz = Kp_v(\theta_v), \tag{10}$$

where $K = \sigma_h n_h + (2/\pi)\, \sigma_v n_v \tan \theta_v$.

Adding all contributions to radiance through the canopy and adding the soil radiance at the bottom of the canopy (z = -h), all in proportion to the fraction within clear view, one obtains the radiance that can be observed from the position of view,

$$L = \int_{-h}^{0} p_v(\theta_v, z)\left[uE(+d) + vE(-d) + w'E(s)\right] dz/\pi + p_v(\theta_v, -h)\left[\rho(\text{soil})(E(-d) + E(s))\right]/\pi. \tag{11}$$

*The relation for w' here differs from that in the original publication which was in error. The difference is due to a missing factor which was pointed out by Verhoef and Bunnik and confirmed by W. Malila.

The canopy reflectance for sunlight alone is,

$$\rho(\text{sun, canopy}) = \pi L/E(s). \tag{12}$$

The reflectance of the canopy for skylight alone is calculated in the same manner except that $E(s) = 0$ and the value of the downward welling diffuse flux, $E(-d)$, at the top ($z = 0$) of the canopy, instead of being set to zero, is set equal to the value of downward welling diffuse skylight, $E(\text{sky})$.

The canopy reflectance for skylight alone is,

$$\rho(\text{sky, canopy}) = \pi L/E(\text{sky}). \tag{13}$$

When both skylight and sunlight are incident upon the canopy together to produce global illumination, $E(\text{global})$, then the reflectance for global daylight is the weighted average of relations (12) and (13),

$$\rho(\text{global, canopy}) = [E(\text{sky})\rho(\text{sky, canopy}) + E(s)\rho(\text{sun, canopy})]/E(\text{global}) \tag{14}$$

3.0
EXTENSION TO INCLUDE ROW EFFECTS

The fundamental concepts, nomenclature, and procedures of the uniform canopy model will be used with certain modifications to incorporate the effects of a row structure in agricultural crops. These modifications are introduced in such a way as to reduce to the uniform canopy model as row structure disappears from the crop due to overgrowth of the area between rows by the natural growth of the crop during the growing season.

3.1 THE CONCEPT OF DENSITY MODULATION

In the uniform canopy, the density of components are the mean values for a patch of field the size of the instantaneous field of view (IFOV). Locally, the densities can be expected to vary due to the randomness of the distribution. Random distributions are expected to be clumpy but without any order as to where the clumps occur. One could consider any narrow strip of field and determine the mean density of components within that strip. The mean density would be the same as the IFOV mean,given sufficient strip length for any direction the strip might take over a uniform canopy.

However, in the case of a canopy with row structure, the strip mean will converge to a different mean density for strips parallel to the row direction depending upon the lateral displacement of the strip from the row center. The variation of strip means would be periodic for displacements of the strip in the across-row direction with large values on the row centers and small values between row centers. This variation in strip means relative to the IFOV mean is hereafter called density modulation. Density modulation is the evidence for the existence of row structure and is the measure of the amount of row structure.

To describe crop row structure by geometric shapes, such as, rectangular prisms, semicircular prisms, or other specialized prism shapes, is to utilize special cases of density modulation, where density modulation is different in lateral extent by layers where high density over row centers falls to zero between rows. The adoption of a profile or shape precludes the modeling of gradual and partial plant extension into the inter-row region. The point of view taken here is that the canopy is still represented by infinitely extended layers even if no plant components occupy parts of the layer. That is, a profile per se is not considered to be the feature causing the row effect in field reflectance but rather it is the density modulation which may or may not result in a profile.

In the following extension of the uniform canopy model, the density modulation will be the same for all layers so that a particular profile would not be evident to the eye as illustrated in Figure 3. The use of the same density modulation for all layers simplifies the calculations but should still lead to the essential features of the row effect on canopy reflectance.

3.2 ROW EFFECT LOGIC

Let the row modulation be defined by

$$M(\delta) = n(\delta)/n(IFOV) \tag{15}$$

where δ = across-row strip displacement,
$n(\delta)$ = mean strip density of components,
$n(IFOV)$ = mean value for the IFOV.

Since the modulation should be periodic and since the average of $n(\delta)$ across rows must converge to $n(IFOV)$, then,

$$M(\delta) = M(P + \delta) \geq 0, \tag{16}$$

$$\int_0^P M(\delta)\, d\delta = 1, \tag{17}$$

where P = the row spacing or period.

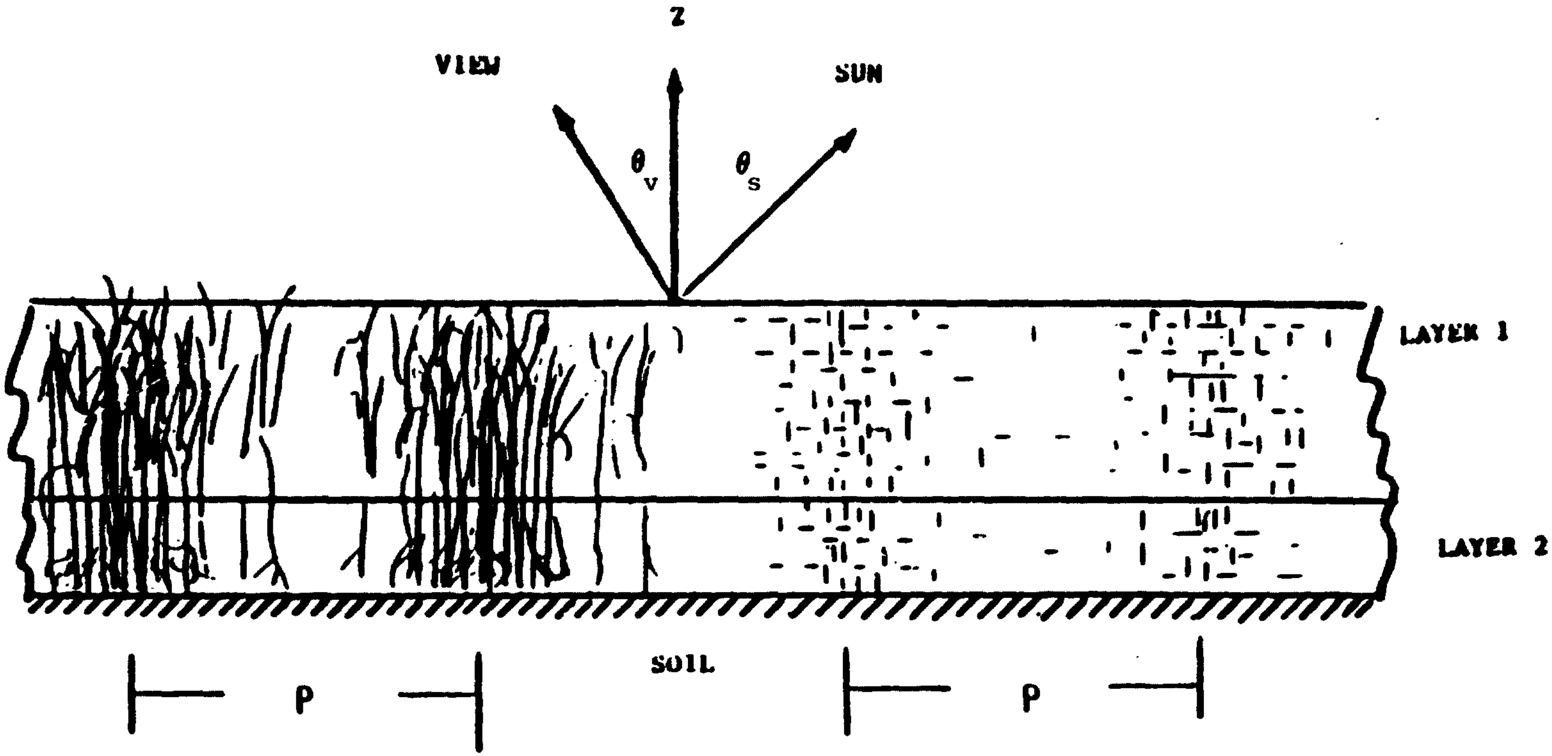

FIGURE 3. SCHEMATIC OF ROW CANOPY

Let the five parameters, a, b, c, c′ and k, be the IFOV mean values. Then the five parameters for strips required for row structure must be simply the IFOV means multiplied by the modulation, $M(\delta)$, since all parameters vary in direct proportion to component density.

Now, using the same differential equations as before but with the five parameters required for row structure, one obtains,

$$dE(+d)/dz = -M(\delta)\ aE(+d) + M(\delta)\ bE(-d) + M(\delta)\ cE(s), \tag{18}$$

$$dE(-d)/dz = M(\delta)\ aE(-d) - M(\delta)\ E(+d) - M(\delta)\ c'E(s), \tag{19}$$

$$dE(s)/dz = M(\delta)\ kE(s), \tag{20}$$

for each strip at level z in the canopy displaced from the row center by distance, δ.

The relations (18), (19), and (20) are to be solved and applied as in relation (11). Then the lateral average over all displacements, δ, must be calculated to find the average radiance in the direction of view. In relation (11), the values of u, v, and w′ are the IFOV means which must also be multipled by the density modulation to account for density variations. Thus, relation (11) will become,

$$L = (1/P) \int_0^P L(\delta)\ d\delta, \tag{21}$$

where

$$L(\delta) = \int_{-h}^{0} p_v(\theta_v,\ z,\ \delta)\ M(\delta)[uE(+d) + vE(-d) + w'E(s,\delta)]\ dz/\pi$$

$$+\ p_v(\theta_v,\ -h,\ \delta)[E(-d,\ -h) + E(s,\ \delta)]\ \rho(\text{soil})/\pi$$

The field reflectance is found as before.

The details of the solution to these equations and the determination of the average radiance are treated in Appendix A. In order to solve these equations, an important assumption is made that the upward and downward diffuse flux averaged along a strip is approximately uniform over all strip displacements. For small variations due to density modulation, this assumption is not different from the tacit assumption made in the uniform canopy model that the presence of random clumps will not result in significantly non-uniform lateral distributions of diffuse flux. The diffuse nature of this flux would tend to make the lateral distribution uniform in spite of local variations in concentration.

However, some important agricultural canopies, such as, soybeans, have density modulations with large values along row centers falling to zero between rows. Unless some modification is made in the logic, the upward diffuse flux will not even be approximately laterally uniform. Visualize, for example, an extreme case where a strip of dense vegetation occupies the row center and several meters of bare soil occupy the inter-row region. The upward diffuse flux at soil level below the dense vegetation is very small but the upward reflected diffuse flux over the exposed and fully illuminated soil between rows is very large. The upward diffuse flux cannot be considered uniform by any stretch of the imagination. But the overwhelming majority of the flux reflected from inter-row bare soil does not participate in the canopy scattering process which is controlled by relations (18) and (19). Sunlight is incident without scattering and is reflected largely towards outer space without coming close to any canopy components. Such flux is purely the result of a sun-soil interaction and would occur without any canopy at all.

In order to remove the excess, purely sun-soil upward diffuse flux from the lower boundary condition, an estimation formula is used to determine the amount of this excess and the excess is removed from the upward diffuse flux at the lower boundary. The remaining diffuse flux which does participate in the canopy scattering is uniform relative to the total diffuse flux involved in reflection from the IFOV. The contribution of the excess to IFOV radiance is accounted for in the second term of relation (21). With the above modification, the row effect calculation should apply to large, as well as small, variations in density.

4.0
COMPARISON OF RESULTS WITH THE VERHOEF-BUNNIK MODEL

The Verhoef-Bunnik rectangular prism profile model for calculating the row effect on crop reflectances is a special case of large density modulation where $M(\delta)$ varies between some constant value over the vegetation to zero over the bare inter-row soil. They calculated the variation of field reflectance with direction of view for a hypothetical field consisting only of green wheat leaves. Fortunately, they also published the necessary parameters by which a comparison calculation can be made using this model.

The results of a comparison calculation are shown in Figures 4, 5, and 6. The figures are polar plots of reflectance as a function of view azimuth. The row direction is north-south on the plot. In these figures, the rectangle points are the predictions of the uniform canopy model where vegetation is distributed randomly over the field. The "x" points are the predictions of the Verhoef-Bunnik rectangular prism model and the solid dots are the predictions of the new model. The closest agreement occurs when the view direction is close to the row direction. The variation in reflectance compares fairly well in other directions also except on the sunlit side of the canopy for 550 nm and 670 nm. Calculations for other sun directions yield similar results with some disagreement on the sunlit side. Because of the diversity in the methods of calculation in these two models, the cause of the disagreement on the sunlit side could not be traced. The validity of predictions will depend upon field tests.

Both models predict similar qualitative trends, however. In particular, both predict that row structure is most evident in the chlorophyll absorption band. This variation is primarily due to the large contrast between low green leaf reflectance and high soil reflectance that very often occurs at 670 nm.

POLAR SUN = 30°
POLAR VIEW = 45°
RECTANGLE = UNIFORM
X = VERHOEF AND BUNNIK ROW
SOLID DOT = SUITS ROW

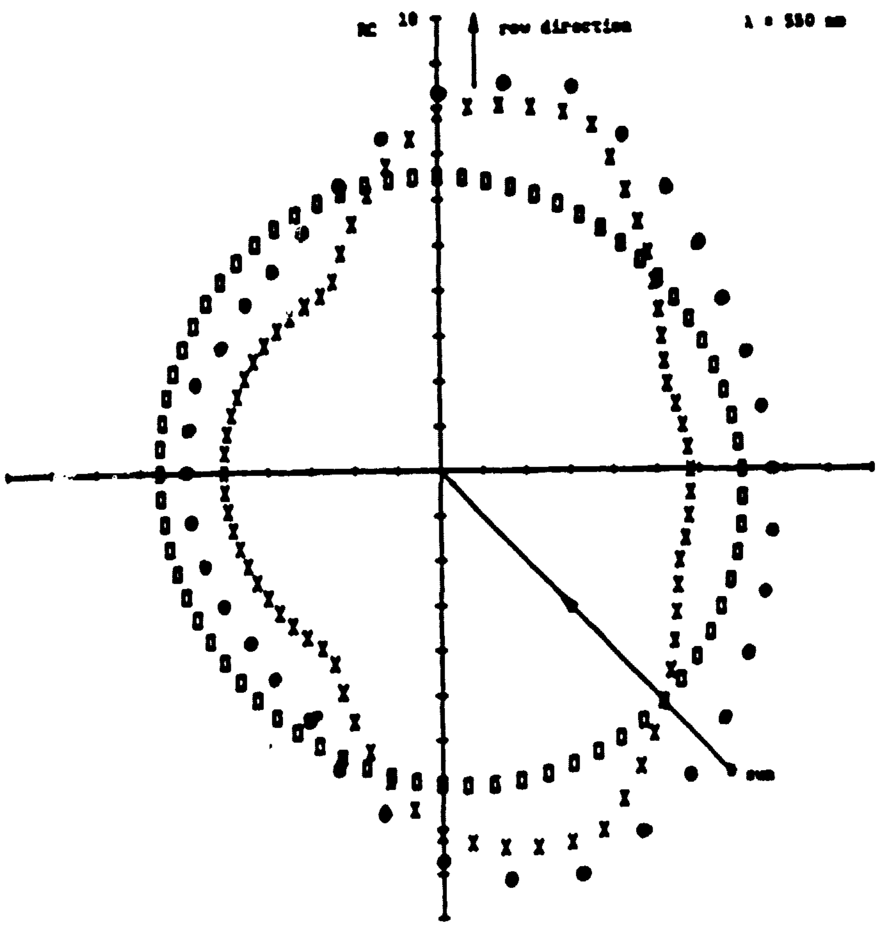

FIGURE 4. COMPARISON OF PREDICTIONS FOR 550 nm. The reflectance as a function of view azimuth shows the comparison between the Verhoef-Bunnik model and this row model for the rectangular prism profile wheat leaf canopy.

POLAR SUN = 30°
POLAR VIEW = 45°
RECTANGLE = UNIFORM
X = VERHOEF AND BUNNIK ROW
SOLID DOT = SUITS ROW

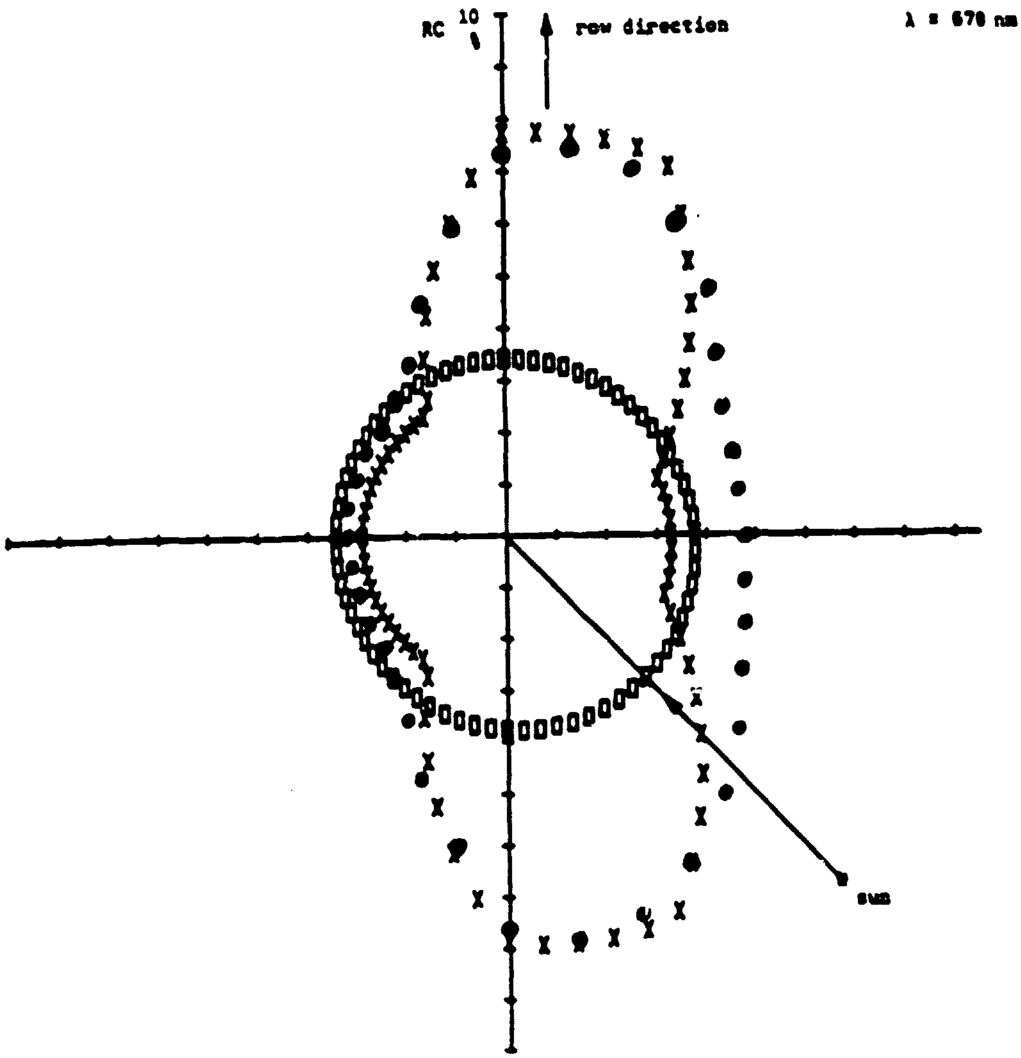

FIGURE 5. COMPARISON OF PREDICTIONS FOR 670 nm. The reflectance as a function of view azimuth shows the comparison between the Verhoef-Bunnik model and this row model for the rectangular prism profile wheat leaf canopy.

POLAR SUN = 30°
POLAR VIEW = 45°
RECTANGLE = UNIFORM
X = VERHOEF AND BUNNIK ROW
SOLID DOT = SUITS ROW

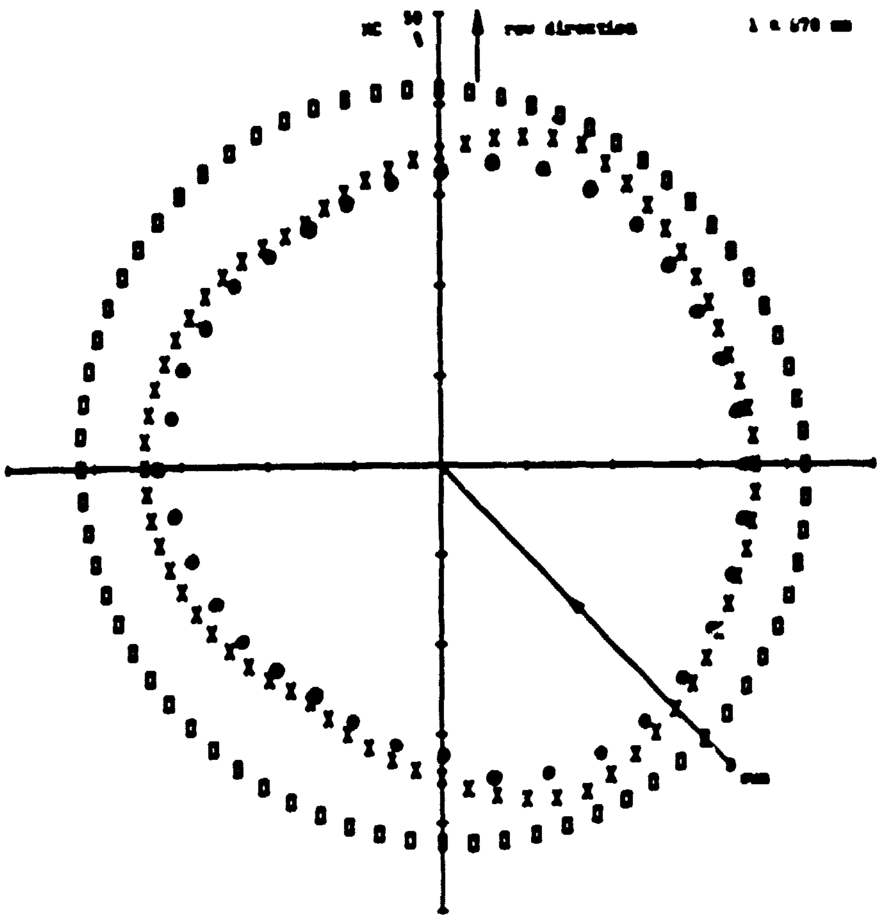

FIGURE 6. COMPARISON OF PREDICTIONS FOR 870 nm. The reflectance as a function of view azimuth shows the comparison between the Verhoef-Bunnik model and this row model for the rectangular prism profile wheat leaf canopy.

Both predict very little effect due to row structure at 870 nm. The minor variation is due to the low soil to leaf contrast, as well as the high value of diffuse flux which tends to produce uniform illumination in spite of row structure.

5.0
ROW MODEL PREDICTIONS FOR WHEAT

One of the purposes of canopy reflectance modeling is to assess the effect· ᶠ canopy structure upon received signals. The crop which is considered here to assess row structure effects is wheat. The spectral properties of plant components and soil were those for Kansas wheat and soil obtained under previous NASA contracts. The model equivalent component sizes were obtained from Ray Jackson's field data for wheat as a function of Feekes scale.

Two wheat stages were modeled: Feekes 5 and Feekes 8. The row modulation was taken to be the rectangular prism modulation of Verhoef and Bunnik which might be suitable at Feekes 5 but probably is not accurate for Feekes 8. Figures 7, 8, and 9 show polar plots of reflectance for three band centers — 550, 650, and 750 nm. Row direction is north-south in the plot and the direction of view is the nadir in all cases. Because of the symmetry due to the nadir view, only one sun azimuth quadrant for each band center is necessary to illustrate all of the important variations. Along with solar azimuthal variations shown on the polar plot, three different polar sun angles were used. The solid polar plot is for a 25° polar angle, the long dash plot is for a 45° polar angle, and the short dash is for a 60° polar angle. The scale for the 750 nm band is different from the scale for the 550 and 650 nm bands.

Figure 7 shows the results for Feekes 5 wheat. One may observe for variable sun angle similar qualitative features as in the Verhoef-Bunnik calculation for variable view angles. The greatest effect is in the 650 nm band and the effect becomes more significant as the polar sun angle increases while the infrared 750 nm band is only moderately affected. One can see that the infrared to red ratio, which is often used as a crop vigor measure, will be significantly altered merely by sun-to-row

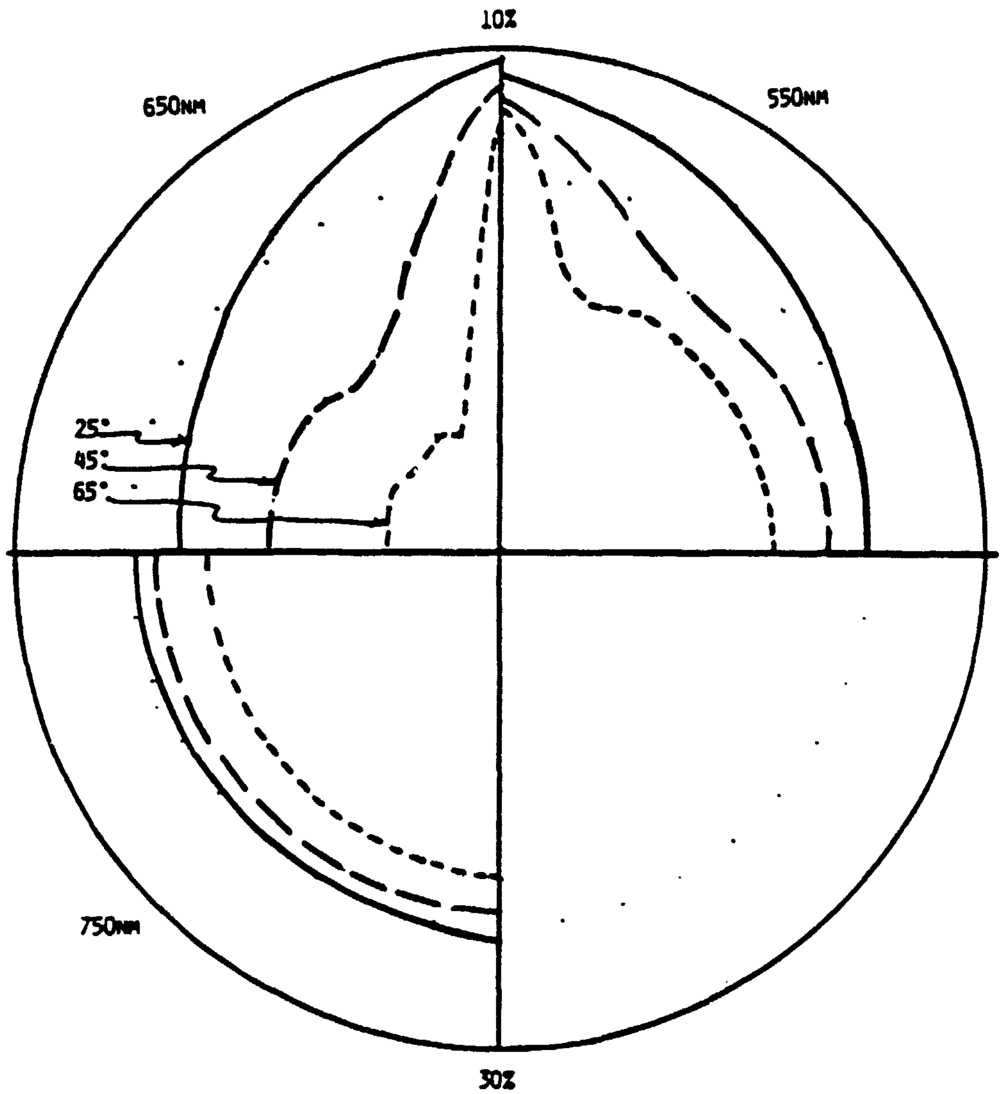

FIGURE 7. RECTANGULAR ROW WHEAT, FEEKES 5. Rows are north-south and the view direction is the nadir. Reflectance in three bands is shown in a polar plot as a function of sun azimuth for three polar sun angles: solar line = 25°, long dash = 45°, short dash = 65°. No sky light.

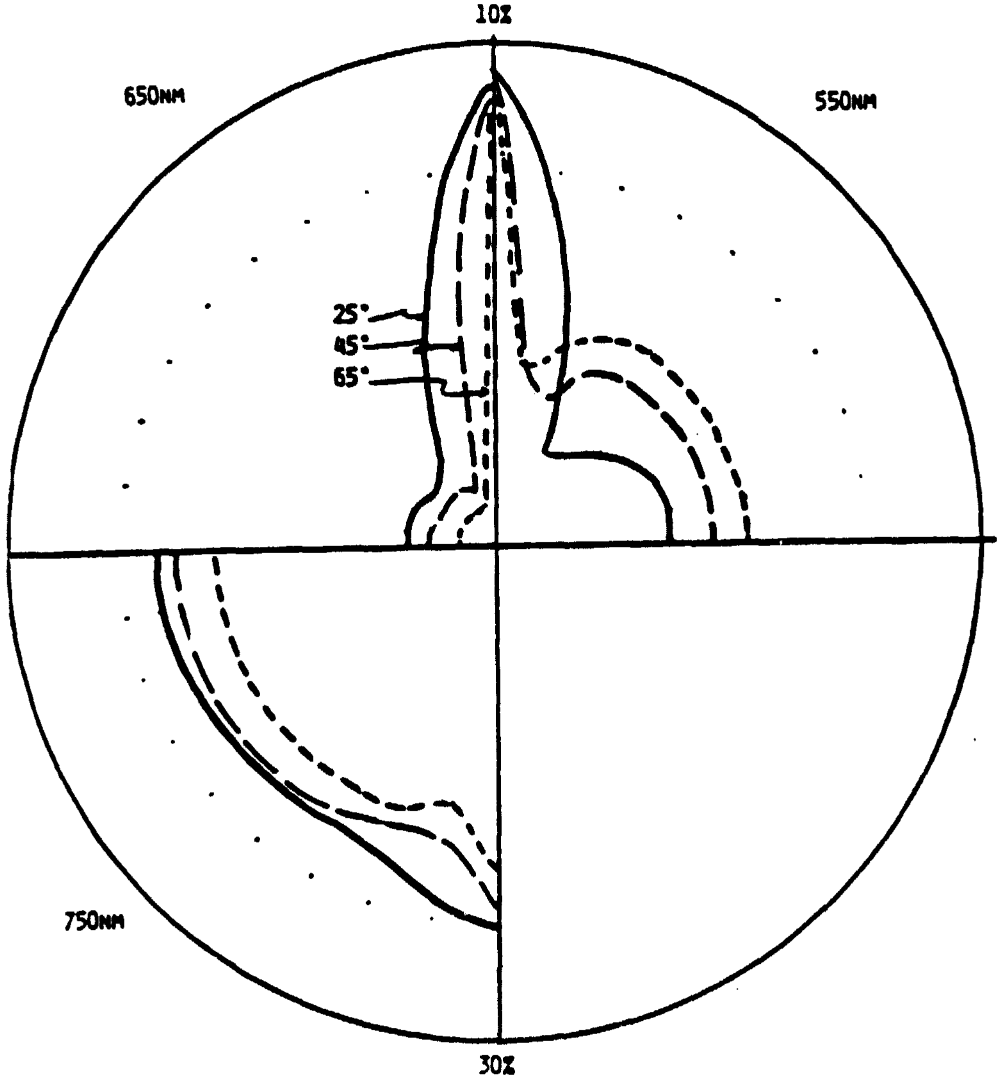

FIGURE 8. RECTANGULAR ROW WHEAT, FEEKES 8. Rows are north-south and the view direction is the nadir. Reflectance in three bands is shown in a polar plot as a function of sun azimuth for three polar sun angles: solid line = 25°, long dash = 45°, short dash = 65°. No sky light.

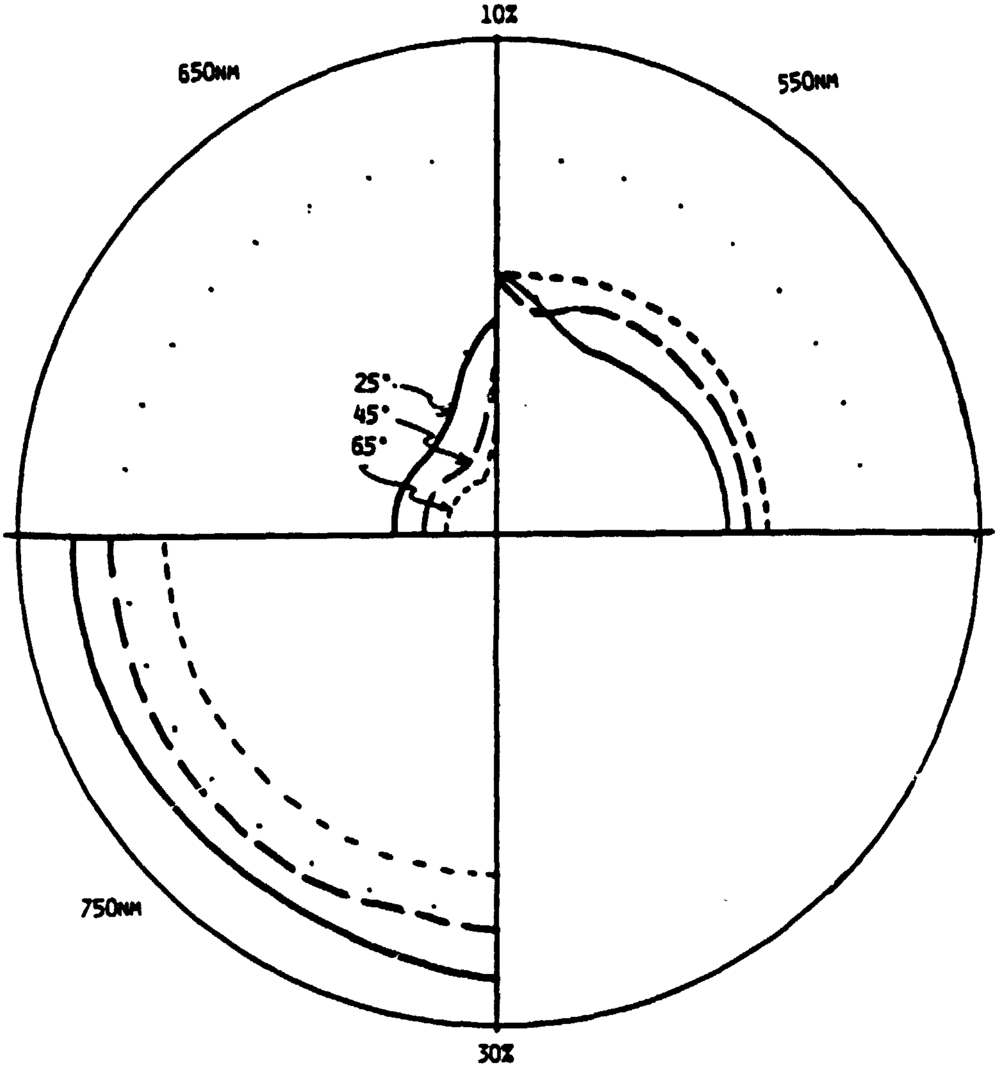

FIGURE 9. MODIFIED ROW WHEAT, FEEKES 8.
Rows are north-south and the view direction is the nadir. Reflectance in three bands is shown in a polar plot as a function of sun azimuth for three polar sun angles: solid line = 25°, long dash = 45°, short dash = 65°. No sky light.

angle conditions. These calculations are for direct sunlight alone. The addition of skylight will tend to reduce the extreme variations for the setting sun.

The case for Feekes 8 wheat for sunlight alone is shown in Figure 8 for an extreme rectangular prism type of row structure which would almost surely require artificial restraints to hold the vegetation away from the inter-row region. The row effect is also extreme. Figure 9 shows the same wheat where the row structure allows only 5% of the peak on-row concentration to appear at mid-row. Notice that the row effect is still significant but is much more subdued. It does not take much more vegetation in the inter-row region to reduce the row effect to negligible proportions.

The impact of row direction on Landsat signals from the latter field was estimated for a 45° sun angle and a nominal amount of path radiance. The resulting MSS7/MSS5 ratio and Greenness measures are shown in Table I for sun down-row and sun across-row directions.

TABLE I. ESTIMATED LANDSAT RESULTS

	ACROSS-ROW	DOWN-ROW
MSS7/MSS5	2.0	1.33
GREENNESS	47.5	42.1

The down-row direction gives an indication of a much less vigorous field. An underestimation of crop vigor and biomass could result purely from a chance row-sun relation. However, the cross-row direction does not lead to a serious overestimation. The reflectance for the cross-row direction is not greatly different from that of the uniform canopy.

REFERENCES

1. Suits, G. H., "The Calculation of the Directional Reflectance of a Vegetative Canopy," and "The Cause of Azimuthal Variations in Directional Reflectance of Vegetative Canopies," Remote Sensing of Environment, 2, (p. 117 and p. 175), 1972.

2. Jackson, R. D., et al., "Wheat Spectral Reflectance: Interactions Between Crop Configuration, Sun Elevation, and Azimuth Angle," Applied Optics, 18, p. 3730, 1979.

3. Vanderbilt, C. V., et al., "Diurnal Changes in Reflectance Factor due to Sun-Row Direction Interactions," Purdue University LARS Technical Report, SR-P1-04140, 1981.

4. Verhoef, W., and N.J.J. Bunnik, "The Spectral Directional Reflectance of Row Crops," NIWARS publication number 35, 1976.

5. Allen, W., et al., "Plant Canopy Irradiance Specified by the Duntley Equations," JOSA, 60, p. 372, 1970.

APPENDIX A

CALCULATION DETAILS FOR ROW CANOPY

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The first step in calculating the canopy reflectance is to solve relations (18), (19), and (20) to determine the diffuse and specular flux at any level, z, within the canopy. Relation (20) for specular flux is solved first and substituted into relations (18) and (19).

SOLVING FOR SPECULAR FLUX

In order to solve for specular flux, one must recognize that the density modulation for slant rays through the canopy will also be a function of z. Consider a coordinate system with z = 0 at the top of the canopy, x = 0 at a position, δ, in the direction across rows, and the y axis along the row direction as shown in Figure 1A. A unit vector directed at the sun, $\bar{s}$, will be given by,

$$\bar{s} = (\sin\theta_s \sin\psi_s,\ \sin\theta_s \cos\psi_s,\ \cos\theta_s) \tag{1A}$$

where θ_s = polar sun angle,

ψ_s = sun azimuth relative to row direction or y axis (positive clockwise).

The density modulation along the incoming ray of sunlight will be $M(\delta + x_r)$ but from relation (1A) the lateral distance, x_r, along a ray is given by,

$$x_r = (z_r - z) \tan\theta_s \sin\psi_s \tag{2A}$$

or

$$x_r = \alpha_s(z_r - z)$$

where $\alpha_s = \tan\theta_s \sin\psi_s$,

x_r = x coordinate along the ray,

z_r = z coordinate along the ray.

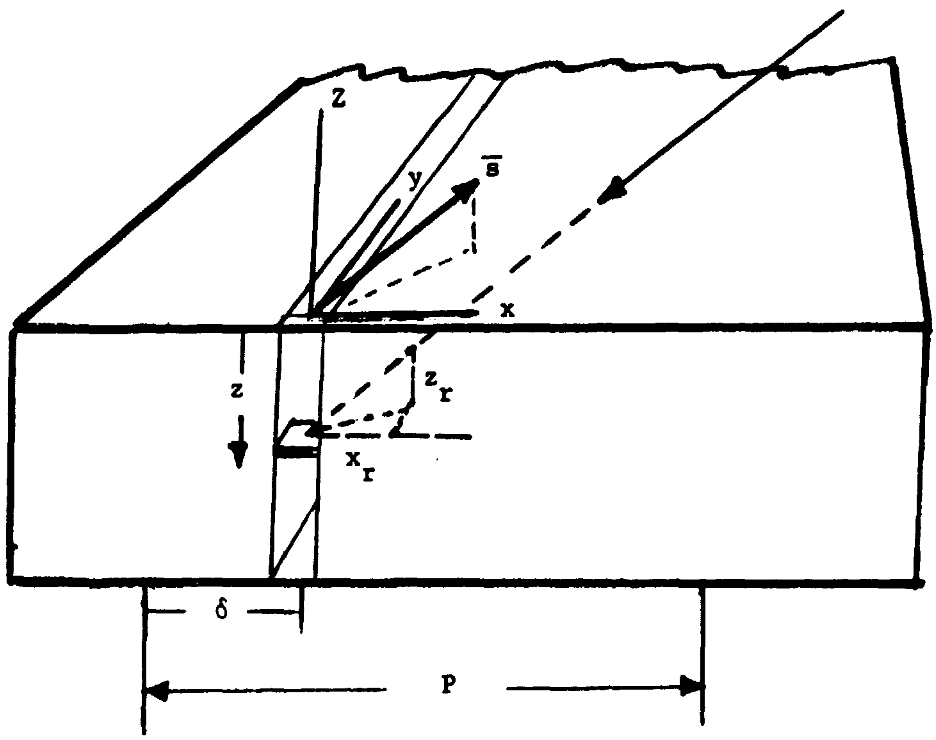

FIGURE 1A. RAY GEOMETRY THROUGH DENSITY MODULATED CANOPY

Consequently, the density modulation along a ray is $M(\delta + \alpha_s(z_r - z))$. Relation (20) may be written as,

$$E_o \, dp_s(\delta, z)/dz_r = kM(\delta + \alpha_s(z_r - z)) \, p_s(\delta, z) \, E_o \tag{3A}$$

where $p_s(\delta, z)$ = probability of line of sight to level z in the direction, $\overline{r}$,

E_o = specular irradiance at the top of the canopy.

The integration of (3A) is then,

$$p_s(\delta, z) = \exp\left(k\int_z^o M(\delta + \alpha_s(z_r - z)) \, dz_r\right) \tag{4A}$$

and

$$E(s) = E_o p_s(\delta, z). \tag{5A}$$

Numerical methods will be needed for the integration indicated in relation (4A) since any density modulation may be considered.

It should also be evident that the probability of line of sight, $p_v(\delta, z)$, in the direction of view will be obtained in like manner but with the unit vector pointing towards the viewer with $\alpha_v = \tan\theta_v \sin\psi_v$ and with extinction coefficient, K.

The next step is to substitute E(s) into relations (18) and (19) and solve. The assumption is made that E(+d) and E(−d), because of their diffuse nature, are approximately laterally uniform even with density modulation. The diffuse flux is controlled by the lateral average of diffuse extinction, diffuse scattering, and specular flux scattering. Thus relations (18) and (19) become,

$$dE(+d)/dz = -aE(+d) + bE(-d) + cE_o \overline{M(\delta) \, p_s(\delta, z)}, \tag{6A}$$

$$dE(-d)/dz = aE(-d) - bE(+d) - c'E_o \overline{M(\delta) \, p_s(\delta, z)}, \tag{7A}$$

where the bar indicates the lateral average over δ.

Again, numerical methods are required for the indicated integration for the average.

The solution to (6A) and (7A) are now found by standard procedures. The diffuse flux variables are separated by use of differential operators and the resulting equations are solved by finding the solution to the homogeneous equations and adding a special solution using Lagrange's method of variation of parameters (also known as variation of constants).

In solving for the upward and downward welling diffuse flux, the lower boundary condition normally requires that,

$$E(+d, -h) = \rho(\text{soil})(E(-d, -h) + E_o\overline{p_s(\delta, -h)}). \tag{8A}$$

However, part of the contribution from $E_o\overline{p_s(\delta, -h)}$ represents excess sun-soil interaction and does not contribute to the upward diffuse flux within the canopy. An estimation of the amount of the excess is made by,

$$E_x(\text{sun}) = \rho(\text{soil})\, E_o\left[\overline{p_s(-h, \delta)\tau(\delta)} - p_s(-h, \text{uniform})\tau(\text{uniform})\right] \tag{9A}$$

where

$p_s(-h, \delta)$ = fraction of direct sunlight on the soil at lateral position, δ

$\tau(\delta)$ = diffuse transmittance of the canopy if the entire canopy had the modulation density above position, δ, with all components black and opaque.

$p_s(-h, \text{uniform})$ = fraction of sunlight on the soil for a uniform canopy with IFOV average.

$\tau(\text{uniform})$ = the diffuse transmittance of the uniform canopy with all components black and opaque.

The bar indicates the lateral average as before.

One may observe that the excess is zero for a uniform canopy. The two terms in relation (9A) represent the estimated amount of direct sunlight which both reaches the soil and also is able to escape as diffuse flux without participation in canopy scattering. The second term estimates the normal amount of escape and the first term estimates the amount escaping due to row structure.

The adjusted lower boundary condition becomes,

$$E(+d, -h) = \rho(\text{soil}) \left[E(-d, -h) + E_o \overline{p_s(\delta, -h)} \right] - E_x(\text{sun}) \qquad (10A)$$

The final step is the calculation of the lateral average of observed radiance using relation (21). Reversing the order of integration, one obtains,

$$L = \int_{-h}^{o} \overline{M(\delta)\ p_v(\delta, z)}\,[uE(+d) + vE(-d)]\ dz/\pi$$

$$+ \int_{-h}^{o} w' E_o\ \overline{M(\delta)\ p_v(\delta, z)\ p_s(\delta, z)}\ dz/\pi$$

$$+ \rho(\text{soil}) \left[\overline{p_v(\delta, -h)}\ E(-d, -h) + E_o\ \overline{p_s(\delta, -h)\ p_v(\delta, -h)} \right] / \pi \qquad (11A)$$

Numerical methods must be used since $M(\delta)$ may have any periodic variation desired.

For skylight alone, $E_o = 0$, and the lower boundary condition is,

$$E(-d, o) = E(\text{sky}). \qquad (12A)$$

But some fractional part of the diffuse flux at soil level is only sky-soil interaction due to row structure. The remaining diffuse flux is spectrally modified by canopy scattering. The excess fraction of spectrally unmodified skylight at soil level is estimated by,

$$E_x(\text{sky}) = \left(\overline{\tau^2(\delta)} - \tau^2(\text{uniform}) \right) E(\text{sky}) \qquad (13A)$$

Thus, the radiance contribution of soil illuminated by diffuse flux is,

$$L(\text{soil}) = \rho(\text{soil})\left[E(-d, -h)\left\{1 - \left[\overline{\tau^2(\delta)} - \tau^2(\text{uniform})\right]\right\} + \left[\overline{\tau^2(\delta)} - \tau^2(\text{uniform})\right]E(\text{sky})\right]\Big/\pi \tag{14A}$$

Both of the estimation formulas for direct and diffuse excess due to row structure are not mathematically derivable but are chosen on the basis of reasonableness in order to extend the scope of the model to include extreme row structure circumstances where diffuse flux flow is actually no longer a one dimensional flow as assumed.

Since numerical integration is required in a number of steps, computer programming of the calculation is necessary All numerical integrations that are independent of wavelength should be performed first and stored in computer memory as look-up tables to be used for the spectrally dependent calculations.

The program is complex but it will easily fit on a personal computer with 12K of available RAM and run in BASIC.