NASA CR-134243
ERIM 31650-78-T

INFORMAL TECHNICAL REPORT

OPTICAL MODELING OF AGRICULTURAL FIELDS AND ROUGH-TEXTURED ROCK AND MINERAL SURFACES

by

G. H. Suits
R. K Vincent
H. M Horwitz
J. D. Erickson
Infrared and Optics Division

ENVIRONMENTAL RESEARCH INSTITUTE OF MICHIGAN
FORMERLY WILLOW RUN LABORATORIES.
THE UNIVERSITY OF MICHIGAN

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NOVEMBER 1973

Johnson Space Center, Houston, Texas 77058
Earth Observations Division
Contract NAS9-9784

NOTICES

SPONSORSHIP. The work reported herein was conducted by the Environmental Research Institute of Michigan for the National Aeronautics and Space Administration, Johnson Spacecraft Center, under Contract NAS9-9784, Task B2.10. Dr. Andrew Potter (TF3) of the Earth Observations Division is Technical Monitor. Contracts and grants to the Institute for the support of sponsored research are administered through the Office of Contracts Administration.

DISCLAIMERS. This report was prepared as an account of Government-sponsored work. Neither the United States nor the National Aeronautics and Space Administration (NASA), nor any person acting on behalf of NASA:

(A) Makes any warranty or representation, expressed or implied with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

(B) Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method or process disclosed in this report.

As used above, "person acting on behalf of NASA" includes any employee or contractor of NASA, or employee of such contractor, to the extent that such employee or contractor of NASA or employee of such contractor prepares, disseminates, or provides access to any information pursuant to his employment or contract with NASA, or his employment with such contractor.

AVAILABILITY NOTICE. Requests for copies of this report should be referred to:

National Aeronautics and Space Administration
Scientific and Technical Information Facility
P.O. Box 33
College Park, Maryland 20740

FINAL DISPOSITION. After this document has served its purpose, it may be destroyed. Please do not return it to the Environmental Research Institute of Michigan.

INFORMAL TECHNICAL REPORT

OPTICAL MODELING OF AGRICULTURAL FIELDS AND ROUGH-TEXTURED ROCK AND MINERAL SURFACES

by

G. H. Suits
R. K. Vincent
H. M. Horwitz
J. D. Erickson

Infrared and Optics Division
Environmental Research Institute of Michigan

Prepared for

National Aeronautics & Space Administration

November 1973

NAS9-9784

FOREWORD

This report describes part of a comprehensive and continuing program of research into remote sensing of the environment from aircraft and satellites. The research is being carried out by the Environmental Research Institute of Michigan, for the Lyndon B. Johnson Space Center, Houston, Texas. The basic objective of this multidisciplinary program is to develop remote sensing as a practical tool to provide the planner and decision-maker with extensive information quickly and economically.

Timely information from remote sensing will be important to such people as the farmer, the city planner, the conservationist, and others concerned with a variety of resource problems such as crop yield and disease, urban land studies and development, air and water pollution, and forest and rangeland management. The scope of our program includes: (1) extending understanding of basic processes affecting the sensing systems; (2) better automatic data processing to extract information in a useful form; and (3) assisting in data collection, processing, and analysis, including laboratory and field material spectra and ground-truth verification.

The research described herein was performed under NAS9-9784, Task B 2.10, and covers the period 1 November 1971 through 31 January 1973. Dr. Andrew Potter was Technical Monitor. The program is directed by R.R. Legault, Associate Director of the Institute, and J.D. Erickson, Principal Investigator. The work was done under the management of the Earth Observations Division, Lyndon B. Johnson Space Center. The

Institute number for this report is 31650-78-T. Reports issued by the Infrared and Optics Division on related programs are listed in Appendix I.

ACKNOWLEDGEMENTS

The initial support for both selected models came from other sources. The agricultural/forestry model was conceived and begun by G. Suits under University of Michigan IST Director's funds, and the geological model is based on work initiated by R. Vincent while he was still a Captain in the U.S.A.F. at Air Force Cambridge Research Laboratories.

ABSTRACT

To improve the ability to utilize laboratory spectra for predicting or interpreting airborne scanner data, a search was made for two theoretical models, one to calculate the reflectance of plant canopies and the other to assess the effect of textural variations on the spectral emittance or reflectance of natural rock surfaces. Several models were reviewed, from which it was possible to select the types of models best suited for these applications. The selected plant canopy model, an extension of the Allen-Gayle-Richardson model, can be used to predict the bidirectional reflectance of a field crop from known laboratory spectra of crop components and approximate plant geometry (planting density and average horizontal and vertical component cross-sections). It is applicable even to vegetative targets composed of multiple canopy layers. Bidirectional reflectances of two corn fields calculated from the canopy model were found to agree with laboratory data within an extremum error of 15% in $\frac{\Delta\rho}{\rho}$. The selected geological model which is to be developed later will permit calculation of spectral emittance spectra for different textured rock surfaces, even though the rock may contain randomly oriented birefringent crystals and may consist of several different minerals. The resulting emittance spectra for various particle diameters will be used to predict the effect of textural variations on an infrared ratio method used previously to image large compositional variations in silicate rocks with airborne or spaceborne multispectral scanner data. An adequate atmospheric radiative transfer model exists to calculate the atmospheric effects between such targets and remote spectral sensors.

TABLE OF CONTENTS

	Page
Foreword	iii
Acknowledgements	v
Abstract	vi
List of Figures	viii
Summary	ix
1. Introduction	1
2. Agricultural Models	2
2.1. Past Models	3
2.2. Selected Model for Plant Canopies	5
3. Geological Models	19
3.1. Past Models	21
3.2. Selected Model for Rock and Mineral Surfaces	27
4. Conclusions	31
References	34
Appendix I	36

LIST OF FIGURES

Page

Figure 1. SCHEMATIC OF A THREE LAYER CANOPY MODEL 7

The top of the canopy lies at x = 0. The canopy lies in the negative x region. The angle, Θ, is the polar angle for specular flux and the angle, Φ, is the polar angle of view. The canopy is isotropic in aziumth.

Figure 2. OPTICAL CROSS-SECTIONS BY PROJECTIONS 7

The horizontal panel area or cross-section, σ_h, of the leaf is shown in the horizontal plane. The vertical cross-section, σ_v, is the sum of the two projections on the vertical plane.

SUMMARY

Our purposes were to review past models for describing the reflectance and/or emittance properties of agricultural/forestry and geological targets, to select the best type of model for further development in each of the two categories, and to further develop the agricultural model. Multifaceted models were found to be unsuitable for both the agricultural and geological problems because of their use of specular reflectance facets which do not adequately characterize the properties of natural materials. Past models based on Kubelka-Munk equations are objectionable for both applications because they are not tied to enough of the intrinsic physical properties of plant canopies and do not account for both large and small particle diameters (compared with wavelength) in natural rock surfaces. The selected agricultural plant canopy model, an extension of the six-parameter Allen-Gayle-Richardson model, can be used to estimate the bidirectional reflectance of a field crop from known laboratory spectra of crop components and approximate plant geometry. The selected geological model is based on Mie theory and radiative transfer equations and, when completed, will assess the effect of textural variations on the spectral emittance of natural rock surfaces.

OPTICAL MODELING OF AGRICULTURAL FIELDS AND ROUGH-TEXTURED ROCK AND MINERAL SURFACES

1

INTRODUCTION

For the benefit of the remote sensing community, NASA has been compiling laboratory reflectance and emittance spectra of natural targets in the Earth Resources Spectral Information System (ERSIS) since 1970 [1, 2]. From the beginning, these data have been useful as qualitative aides to the scientific user in determining the optimum spectral regions for remotely acquiring the maximum information about particular natural targets. Until the recent development of a simplified infrared ratio technique [3] for scanner-data discrimination among certain rock-types, however, very few of these spectra were useful for quantitative remote sensing studies, primarily because there was not adequate theoretical models available that related laboratory spectra to radiance detected from a given target by an airborne or spaceborne scanner.

In this regard there are two specific problems which require solution. For vegetative targets some theoretical model which includes atmospheric radiative transfer is needed which correlates bidirectional reflectance of a plant canopy, as sensed by airborne and spaceborne scanners, and the laboratory reflectance spectra of the constituent plant components. For geological targets, a model is needed which will permit assessment and/or correlation of variations in texture of rock surfaces across the target

scene, with regard to the infrared ratio technique mentioned above. The purpose of this report is to review related theoretical models and to describe the two selected models which will be applied in following work to the solution of these specific problems.

2

AGRICULTURAL MODELS

The need for the identification of vegetative canopies and the detection of stresses in vegetative canopies by remote sensing techniques has continued to grow in economic importance. The management of natural resources, such as forests and wetlands, and the prediction of yields and assessment of pest damage of agricultural crops require both timely and economical survey techniques in order to supply the fundamental information for the formulation and execution of effective management strategies.

One of the most promising remote sensing techniques for rapid and economical mapping of vegetative canopy types is the multispectral optical mechanical scanner using automatic spectral pattern recognition summarized by Erickson [4]. This technique is capable of utilizing very subtle but systematic spectral reflectance differences for the mapping of vegetative canopy types.

The major weakness of this technique is the difficulty in relating subtle reflectance differences to the elemental causative factors which could be recognized and classified by botanists on the ground. Unless some

insight is achieved in connecting causative factors with detected effects, there is no foundation for claiming that a specific cause is uniquely coupled with a detected effect. Certain detected effects could be due to spurious causes which may be transient and be fundamentally unconnected with the condition of interest to the remote sensor user even though the occurrence of the detected effect appears to be associated with this condition at one time and location.

The next two sections will discuss what has been done and what approach we selected to develop a mathematical reflectance model of a canopy, which is based upon the spectral and geometric character of the individual pieces of the canopy, such that the model can connect the plant biological causes to a remotely sensed reflectance effect.

2.1 PAST MODELS

The construction of a mathematical model always requires compromises between realism and cogency. There is little doubt that a model which utilizes the exact spectroradiometric character and geometric placement of every individual canopy component will yield the measured spectral reflectance of the ensemble. However, the task of obtaining such data and making the computation is not feasible and does not lead to generalizations concerning the significance of overall canopy properties which are cogent.

Models which rely heavily on specular reflectance theory and require the description of many specular facets, such as the one described later in Section 3.1, are not suitable for describing plant canopy reflectance for two

reasons. First, describing many facets requires an inordinate amount of input data for all but the most regular crop fields. Secondly, plant leaves are relatively transparent in the reflective IR wavelength regions, which implies that a diffuse reflectance model is necessary to describe a plant canopy.

Most diffuse reflectance models are based on variations of the Kubelka-Munk (KM) equations, which in turn are a special case of the Schuster equations, published in 1905 [5] to explain the escape of radiation from the foggy, self-luminous atmosphere of a star. Schuster assumed that half the scattered flux in a scattering medium is directed forward, in the direction of incident radiation propagation, and half is directed backward. The same two-stream approximation was used by Kubelka and Munk [6], without the source term that Schuster found necessary for a self-luminous medium, to describe the visible diffuse reflectance of scattering media with relatively low intrinsic absorption coefficients, such as paper. The Schuster and/or KM equations describe the internal optical properties of a diffusing medium in terms of two parameters, a scattering coefficient and an absorption coefficient. As the KM theory was extended, Silberstein [7] increased the number of parameters to three, Ryde [8] to four, and Duntley [9] to six.

The first attempt to model the optical properties of a plant canopy were concentrated on determining the light transmittance of a canopy, with a one-parameter representation [10, 11, 12, 13]. For instance Monsi and Saeki [14] found that the relative irradiance at one height in a homogeneous canopy decreases exponentially with increasing leaf-area index. Whereas this

one-parameter approach was somewhat useful for transmittance calculations, it could not be used to calculate reflectances. In 1965, Allen and Brown [15] applied the two-parameter KM equations to radiation in a corn field (transmittance) and in 1968, Allen and Richardson [16] used the same equations to specify both reflectance and transmittance through a leaf canopy.

Then in 1970, Allen, Gayle, and Richardson [17] applied the six-parameter Duntley equations to the canopy problem to calculate reflectance and transmittance. This model, hereafter called the AGR model, requires at least 5 independent measurements of canopy irradiance to determine the six parameters inherent to the Duntley equations. None of these empirically determined parameters were related by the AGR model to physical properties of the plant canopy.

2.2 SELECTED MODEL FOR PLANT CANOPIES

The principal difficulty with all of the previously discussed plant canopy models is that they do not account for directional reflectance changes as a function of view angle, nor do they permit changes in reflectance of the canopy to be traceable to the specific causative factors of geometric and spectral changes in a particular class of components within the canopy. For these reasons, the Suits model [18] chosen for modeling of plant canopies is an extension of the AGR model, except that the one presented here will predict bidirectional reflectance properties of a canopy traceable to the geometric and spectral properties of identifiable canopy components.

In the Suits model the canopy is divided into a number of infinitely extended horizontal canopy layers. Within each layer, the components of the canopy are considered to be randomly distributed and homogeneously mixed. Figure 1 illustrates the geometry of the model.

Many vegetative canopies have a distinct layer structure. Wheat, for example, produces the grain at the top layer of the canopy, while the stalk and leaves occupy a second layer. In a mature corn field, corn tassels occupy the top layer while leaves and ears occupy a second layer. A leaf slough-off layer may occur as a lower third layer. Forests frequently exhibit a layered structure with the components of different species occupying different layers. The order and content of these layers will affect the canopy directional reflectance. The lowest layer is always bounded by the soil.

Each component of the canopy, such as a leaf or stalk, is idealized as a combination of vertically oriented and horizontally oriented flat diffusely reflecting and transmitting panels. The size and spectral properties of the panels are obtained from physical measurements of the canopy components. In general, the objective is to determine the size of panels which would intercept the same amount of radiant flux as would the component. The projections of a component on horizontal and vertical planes define panel areas which are fairly close to meeting this criterion while retaining geometric simplicity for the model. Component projections are used to calculate optical cross sections in this model as illustrated in Figure 2. The laboratory hemispherical spectral transmittance and reflectance of the

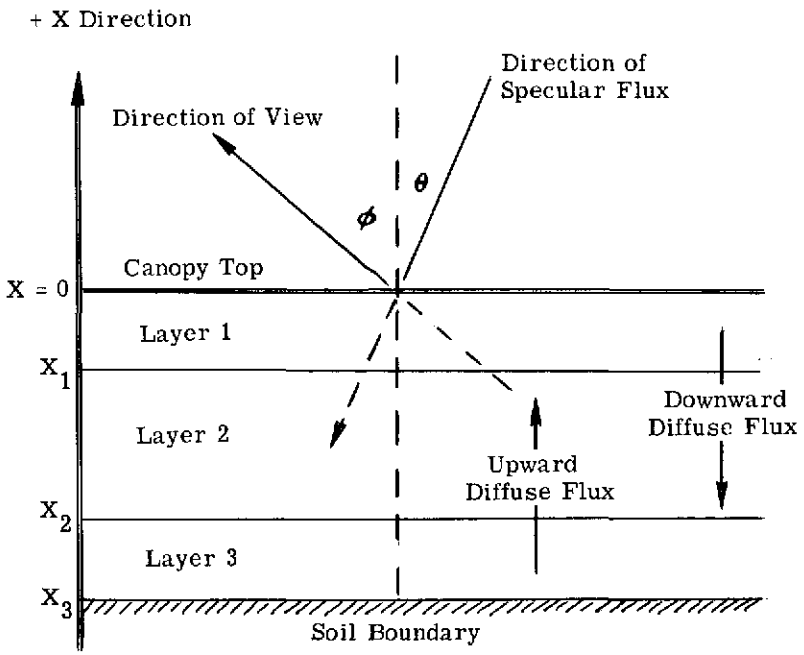

FIGURE 1. IDEALIZED LAYER STRUCTURE OF A CANOPY

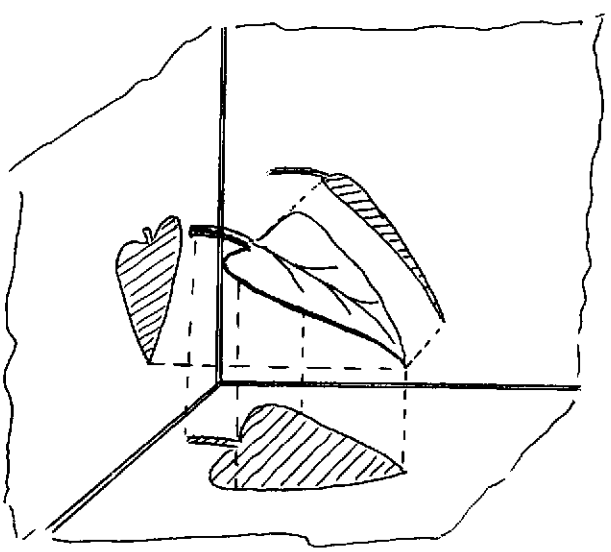

FIGURE 2. OPTICAL CROSS-SECTIONS BY PROJECTIONS

component are taken to be those of the radiatively equivalent panels of the model.

Thus, every physical part of a plant yields two kinds of model components - vertical and horizontal - the sizes and number of which can be found from physical measurements of representative plants. If a plant canopy is stressed by some pathogen, or environmental condition, the changes in plant component geometry due to the stress leads to a corresponding change in the sizes of model panels in a cogent fashion. For instance, moisture stress causes leaves, which are normally horizontal, to droop. The vertical components of the model increase in area at the expense of horizontal components of the model to correspond to the geometric change in orientation of the leaves. If all other factors governing canopy reflectance are considered fixed, the calculated change in canopy reflectance can be attributed to the drooping of the leaves alone.

As in the AGR model, the radiant flux that interacts with the canopy is divided into two kinds, specular and diffuse. The specular flux is that flux which arrives from a part of the sky or the sun and flows into the canopy in a straight line without interception by any canopy component or the soil. The diffuse flux is that flux which has been intercepted at least once. As specular flux enters the canopy and is intercepted by a component, the flux leaves the specular category permanently. It is either absorbed or contributes to the diffuse flux of the canopy.

In the following calculations, the spectral flux density is symbolized by $E_\lambda(s)$ for specular flow and $E_\lambda(d)$ for diffuse flow. The diffuse flux

density is again divided into upward and downward flow and is symbolized by $E_\lambda(+d)$ and $E_\lambda(-d)$ respectively. Since the canopy consists of different layers each with its own properties, the specification of the layer must be included in the nomenclature. Thus, for instance, $E_\lambda(+d, i, x)$ represents the upward directed flux in the i^{th} layer at level, x.

The calculation to determine $E_\lambda(+d, i, x)$ in each layer is the same as in the AGR layer model using the equations

$$\frac{dE\ (+d, i, x)}{dx} = -a_i E_\lambda(+d, i, x) + b_i E_\lambda(-d, i, x) + c_i E_\lambda(s, i, x), \quad (1)$$

$$\frac{dE\ (-d, i, x)}{dx} = a_i E_\lambda(-d, i, x) - b_i E_\lambda(-d, i, x) - c_i' E_\lambda(s, i, x) \quad (2)$$

$$\frac{dE\ (s, i, x)}{dx} = k_i E_\lambda(s, i, x) \quad (3)$$

The constants a_i, b_i, c_i, c_i', and k_i are derived from measurements of canopy components of the i^{th} layer. If only one type of component occupies the i^{th} layer, then

$$a_i = [\sigma_h n_h\ (1 - \tau) + \sigma_v n_v\ (1 - \frac{\rho + \tau}{2})], \quad (4)$$

$$b_i = [\sigma_h n_h\ \rho + \sigma_v n_v\ \frac{\rho + \tau}{2}], \quad (5)$$

$$c_i = [\sigma_h n_h\ \rho + \frac{2}{\pi}\ \sigma_v n_v\ \frac{\rho + \tau}{2}\ \tan\theta], \quad (6)$$

$$c_i' = [\sigma_h n_h + \frac{2}{\pi} \sigma_v n_v \frac{\rho + \tau}{2} \tan \theta], \quad (7)$$

and

$$k_i = [\sigma_h n_h + \frac{2}{\pi} \sigma_v n_v \tan \theta]. \quad (8)$$

where σ_h is the average area of the projection of the canopy component on a horizontal plane,

σ_v is the average area of the projection of the canopy component on two orthogonal vertical planes,

n_h is the number of horizontal projections per unit volume,

n_v is the number of vertical projections per unit volume.

The angle, θ, is the polar angle for incident specular flux.

The spectral transmittance, τ, and the spectral reflectance, ρ, are the hemispherical reflectance values obtained from measurements of component samples in the laboratory. The factor $(2/\pi)$ associated with the tangent of the specular angle in equations (6), (7), and (8) is the average value of the cosine of the azimuthal angle. The vertical projection is averaged for random, azimuthal orientations.

If more than one type of component exists in a canopy layer, then the values of a, b, c, c', and k are obtained for each type separately and added together to obtain the value for the layer. For instance, with three types of components in the i^{th} layer, a_i for that layer is

$$a_i = a_i(\text{type 1}) + a_i(\text{type 2}) + a_i(\text{type 3}).$$

The solutions to equations (1), (2), and (3) are of the form

$$E_\lambda(+d, i, x) = A_i(1 - f_i)\exp(g_i x) + B_i(1 + f_i)\exp(-g_i x) + C_i \exp(k_i x), \tag{9}$$

$$E_\lambda(-d, i, x) = A_i(1 + f_i)\exp(g_i x) + B_k(1 - f_i)\exp(-g_i x) + D_i \exp(k_i x), \tag{10}$$

and

$$E_\lambda(s, i, x) = E_\lambda(s, i - 1, x_{i-1})\exp(k_i x) \tag{11}$$

where A_i and B_i are to be determined by the boundary conditions; C_i, D_i, g_i and f_i are determined by substitution of relations (9) and (10) into relations (1) and (2). Substitution yields

$$C_i = \frac{c_i(k_i - a_i) - c_i' b_i}{k_i^2 - g_i^2} E_\lambda(s, i - 1, x_{i-1}),$$

$$D_i = \frac{c_1'(k_i + a_i) + c_i b_i}{k_i^2 - g_i^2} E_\lambda(s, i - 1, x_{i-1}),$$

$$g_i = \sqrt{a_i^2 - b_i^2},$$

$$f_i = \sqrt{(a_i - b_i)/(a_i + b_i)}$$

The quantity $E_\lambda(s, i-1, x_{i-1})$ is the value of the specular irradiance at the bottom of the $(i-1)^{th}$ layer, $x = x_{i-1}$.

The boundary conditions require that at the top of the first layer (at $x = 0$) the only downward directed flux is specular flux, $E_\lambda(s, 1, x = 0)$. Thus, downward diffuse flux is zero at that boundary,

$$E_\lambda(-d, 1, x = 0) = 0 \tag{12}$$

The boundary conditions between layers are merely that the upward and downward directed flux is continuous across the layer boundaries. At the soil level, the boundary conditions require that downward directed specular and diffuse flux at the soil level is reflected by the soil to produce only upward directed diffuse flux. The specular and diffuse flux within the canopy become fully determined. The boundary conditions for a one layer canopy are simply

$$E_\lambda(-d, 1, 0) = 0$$

$$E_\lambda(+d, 1, x_1) = \rho(\text{soil})[E_\lambda(-d, 1, x_1) + E_\lambda(s, 1, x_1)].$$

These relations are solved for A_1 and B_1. It is clear that the reflectance of the soil enters into the evaluation of these constants as long as there is any downward flux left at the bottom of the canopy.

However, for a very deep and opaque canopy, the characteristics of the soil will be inconsequential to the canopy reflectance. For the infinitely deep canopy, the boundary conditions are

$$E_\lambda(-d,\ 1,\ 0) = 0$$

$$E_\lambda(+d,\ 1,\ x_1 \to -\infty) = 0,$$

so that

$$B_1 \to 0 \text{ and } A_1 = -D_1/(1 + f_1).$$

For the infinitely deep canopy, one can see more easily the influence of the specular flux angle on the diffuse flow. The angular dependence enters through the value of D_1 which is a function of the θ dependent parameters, c, c', and k. In these parameters, tan θ multiplies the areas of the vertical canopy components. Therefore, it is the vertical structures in the canopy which are primarily responsible for the variations of flow field with sun angle just as common sense would indicate.

The only two alterations of the AGR model thus far have been the introduction of scattering terms which are directly related to identifiable components properties that can be physically measured and the introduction of a number of canopy layers.

The next logical step in the calculation of the directional reflectance of a vegetative canopy employs the concept of the self-consistent field. The flux field within the canopy consists of a specular and a diffuse field.

The calculation of these fields using the above relations implies that the diffuse field is Lambertian in character at all levels in the canopy. Since common experience indicates that the reflectance of canopies are generally not Lambertian, the calculated flux fields may be considered as merely the first approximation to the actual field, which is somewhat non-Lambertian in character.

If this approximate Lambertian flux field is considered to be the source of illumination for each infinitesimal layer, then the directional reflectance properties of the infinitesimal layers will yield a non-Lambertian flux distribution more closely approximating the real flux field. It is then possible to calculate a more realistic value of the directional flux field at any point in the canopy by integrating the contributions of directional flux from each infinitesimal layer. This new directional flux field may in turn be considered to be a more realistic illumination for each infinitesimal layer, again inter-acting with the directional reflectance properties of each infinitesimal layer, whereby a still more realistic directional flux distribution may be calculated by integration. The procedure is an iteration process which could be carried on many times until the directional properties of the last calculated flux field do not differ from the directional properties of the next to last calculated directional flux field. The flux field is then self-consistent with the directional reflectance properties of the components which cause the field.

If the real diffuse flux field were Lambertian in directional properties,

then no iteration would be necessary at all. If the real flux field did not differ from Lambertian excessively, then only a few iterations would be needed. One could expect that the iteration process would rapidly converge to the realistic flux field. Experience indicates that vegetative canopies are not Lambertian but are approximately so. Therefore, the convergence of the iteration process should be very rapid. Consequently, the approximate flux field as calculated above is used as the illuminant to determine the more accurate directional flux field, the integrated effect of which is observed remotely by sensors above the canopy. A second iteration is assumed to be unnecessary.

On each infinitesimal layer in the canopy, two kinds of flux fields form the illumination - the approximate diffuse flux and the undeviated specular flux which has reached that level. The undeviated specular flux at any level in the canopy is proportional to the probability of line-of-sight to that level in the direction of the specular flux. With these two flux fields as the illumination and the directional reflectance properties of the infinitesimal layer, the radiance of the layer is calculated. The radiance is not Lambertian but exhibits both polar angle variations as well as azimuthal variations relative to the solar azimuth. Details of the calculation of this azimuthal variation are given in reference [18]. Some fraction of each layer is viewed by the sensor outside the canopy. The total contribution is the integrated contribution to the radiance of each infinitesimal layer which can be seen by line-of-sight in the direction of

view. The probability of line-of-sight for viewing will be similar in form to that for specular flux, but usually an independent part of the canopy obstructs the line-of-sight for viewing. The radiance contribution outside of the canopy of an infinitesimal layer will be proportional to the probability of line-of-sight to that layer in the direction of view for components illuminated by both specular and diffuse flux. However, if the direction of view coincides with the direction of specular flux, the probability of achieving line-of-sight for viewing to those components which are illuminated by specular flux becomes unity. Every component which specular flux reaches must necessarily be in line-of-sight for viewing. The probability of line-of-sight for specular flux and for viewing are not independent in this case. The joint probability for both reaching a given level in the canopy by specular flux and viewing the consequential reflection due to specular flux is just the probability of specular flux reaching that level.

The condition where the viewing direction coincides with the specular flux direction is called the "hot-spot" condition. The dependence of line-of-sight probabilities are taken into account in integrating the contributions to the radiance of reflected specular flux in that direction. The hot-spot condition is the condition which eliminates all geometric shadows from view. It is that condition which is normally avoided for aerial photography where the presence of geometric shadows for photo-interpretation of shapes are needed. In aerial photographs the hot-spot

condition occurs at most in only one location in the photograph and therefore cannot be useful for large area mapping.

On the other hand, an airborne scanning laser system utilizes the hot-spot condition at all times. It is not easily avoided. There is an important difference between hot-spot and normal detection in that the hot-spot direction provides the best communication with the lower levels of the canopy. Many plant diseases attack first the lower levels of the canopy. These levels consist of older leaves and are generally in a high humidity region near the soil encouraging the propagation of fungal diseases in this level. A system which does not function by shape recognition but by the spectral character of the reflected radiation can make good use of the hot-spot condition.

Verification of the Model

One of the important aspects of any model is how well the model can represent that which it was designed to represent. Every model contains simplifying assumptions for the sake of cogency. These assumptions must be shown to be reasonable by demonstrating that the essential features which are predicted by the model are experimentally verified.

In reference [19] the verification of the model was demonstrated for two different corn fields, each with two different view angles, for wave-lengths in the visible and near infrared spectral ranges. The method of verification required the measurement of three or more corn plants per field with a meter stick in order to determine the horizontal and vertical leaf area indices

of each component type. A weighted average of the measurements in each field were used to characterize the field. Component spectra were taken in the laboratory with a Beckman photometer. From these data, the directional spectral reflectances of the fields were calculated. Finally, the directional spectral reflectances of the fields were measured using the Instrument Specialties Company field spectro-radiometer and the results were compared with the predictions. The maximum deviation between calculated and field-measured bidirectional reflectances was approximately 20% in $\frac{\Delta\rho}{\rho}$.

The calculations presented in reference [20] incorporate a minor integration error in the second layer of both canopies. The error was discovered by Mr. R. E. Stokes of JSC, NASA. A second calculation was made for these two fields with the correct integration, to assure that the verification was still valid. The correct integration reduced the maximum deviation in $\frac{\Delta\rho}{\rho}$ from 20% to 15% for the field where agreement was poorest. The calculation for the other field was not significantly changed.

Further verification attempts are underway for certain grass canopies [21]. Agreement between calculated and measured reflectances are not as good as for corn. There is growing evidence that the model concepts are valid for grasses, also, but that the extension of the measurement technique for leaf area indices using meter sticks is so difficult when applied to small blades of grass that serious errors in leaf area index values result. The results of the meter stick method of obtaining leaf area indices disagree with leaf area indices obtained from a simple photogrammetric technique

by almost a factor of two in some cases. Hence, verification of the model for grasses awaits the evaluation of better techniques for measuring leaf area indices.

This model has recently been further modified and extended to apply to submarine vegetative canopies by incorporating the radiative influence of the aquatic medium. Near-shore sea weed growths may be indicative of water quality. The aquatic model could be used to predict the detectability of submerged canopies as a function of water depth and turbidity as well as to assess the potentiality of remotely measuring phytoplankton and mineral particulate concentrations suspended in water.

Although the calculations using the aquatic canopy model predict reasonable spectral reflectances when hypothetical water conditions are assumed, the accuracy of the model has not been verified due to the lack of the combination of ground ("water") truth combined with reliable field reflectance measurements.

3

GEOLOGICAL MODELS

The problems encountered in geological remote sensing are different in several aspects from agricultural problems. First, temporal effects are much slower for geological than for vegetative targets. Secondly, for rock-type identification the spectral emittance or reflectance variations are

much more important than geometrical variations (shapes, shadows, observation angle, etc.) across the scene, whereas both are relatively important for the identification of vegetative targets. Thirdly, the thermal IR spectral region contains more chemically diagnostic information about rocks than the visible-reflective IR wavelength regions, whereas the converse is true for vegetative targets.

Rocks and minerals present a special problem in the thermal IR region not normally encountered in the lower wavelength regions. Thermal IR wavelengths ($\lambda \tilde{\sim} 10\mu m$) approach in size the particle diameters of some of the grains in fine-textured rock surfaces, which produces some complex optical phenomena related to surface roughness. For instance, it has been noted by R. J. P. Lyon [22] and other investigators that the spectral emittance within the major reststrahlen bands (interatomic vibration modes in this case) of silicate rocks and minerals tends to increase with decreasing particle size. Later work [23] has shown that in spectral regions of moderate to small complex refractive index, outside the reststrahlen bands (high complex refractive index), the emittance can either increase or decrease with decreasing particle size.

The spectral emittance dependence on particle size is an important factor in geological remote sensing, because textural variations from rock to rock may mask differences in chemical composition and vice versa. It is necessary, therefore, to separate textural and chemical effects on the spectral emittance, as much as possible. To do this, a model of rough rock and mineral surfaces is sought which can at least qualitatively explain the effect of

textural variations on the IR spectrum of those surfaces. The resulting calculated spectral emittances are specifically needed to assess what effects textural variations have on an infrared ratio method developed over the past two years [3].

3.1 PAST MODELS

There are several approaches to such a model. One is the attempt to explain a rough surface as a multitude of planar, Fresnel-type facets. A model of this type has been developed at ERIM (formerly the Willow Run Laboratories of The University of Michigan) [24]. That multifaceted target model requires as input the spectral emittance of the facets involved and a geometrical description of the target, which is approximated by a collection of planar facets. The facets are further decomposed into facet-elements for the purpose of considering shadowing and obscuration that occurs with complex-shaped targets. The facets and facet-elements are described by the three dimensional coordinates of their vertices or corners. If the spectral emittance of type of facet is unknown, the spectral emittance and reflectance (related by Kirchhoff's law, $E_\lambda = 1 - R_\lambda$) of each facet are calculated from a reflectance model that linearly combines specular and Lambertian reflectance characteristics. The specular part is calculated from Fresnel's reflectivity equations, with an input of complex refractive indices of the facet material. The Lambertian part is determined from a measurement of the cross-polarized reflectance values of the facet material, with a polarized source of radiation.

Whereas this multifaceted model has been of great use for large targets

of regular structure (mostly man-made), it is not attractive for modeling the reflectances of rough-textured rock surfaces for several reasons. First, for the specular component it considers only geometrical optics, which is valid only for $\lambda >> d$, where d is particle diameter. Secondly, if it were used to consider every mineral grain as a facet, too much input would be required as to the alignment of each individual facet. On the other hand, it would not make sense to model the reflectance of a boulder, using variously oriented microscopic surfaces of the rock as facet-elements, because the physical shape of a rock does not contain the information diagnostic of either chemical composition or texture that are being sought. Finally, it is an extremely long running and therefore costly program.

In contrast to the faceted model approach, there are other models which do not require such detailed account of the individual crystal facets. One class of these are based on the Kubelka-Munk equations. In 1968, Vincent and Hunt [23] promulgated a theory for qualitatively describing the reflectance of a mineral or rock powder. They assumed that the total reflectance is composed of two components, one specular and one volume. In that theory, the specular component represents radiation which is reflected at one or more particle surfaces, but is never transmitted through any particle. It has a Fresnel-type dependence on the complex index of refraction. Their volume component represents radiation which is transmitted through one or more particles, and has a Kubelka-Munk type dependence on the complex refractive index. They used this theory to show that it is possible to produce dramatic changes in the spectral reflectance features of a powder or rock

merely by changing the particle diameter. They verified these qualitative arguments with experimental data on quartz and calcite powders. They did not, however, explicitly show how these two components could be calculated.

Another theory or model was developed by Aronson, Emslie, Roach, Strong, and Thuna [25] in 1971, which will be referred to as the AERST model. According to them, the total reflectance can be calculated from the Kubelka-Munk equation

$$R_v = 1 + \frac{K}{S} - \sqrt{\frac{K^2}{S^2} + 2\frac{K}{S}} \qquad (13)$$

where the volume reflectance R_v, which is dependent on the scattering and absorption coefficients S and K, is assumed equal to the total reflectance of mineral and rock powders. For larger diameter particles ($\geq$ 12μm), they calculate the "total" reflectance for the i^{th} mineral in a given rock by assuming the particles of that mineral are parallel-sided plates of thickness d. This reflectance is a sum of a first-surface reflection term, (a hemispherically averaged Fresnel reflectivity of the outer plate) and a multiple-surface reflection term, which is standard treatment for thin film reflectance (down to the limit of geometrical optics). This is used to calculate the rock first-surface reflection scattering coefficient $S_{reflection}$, which is equal to $\frac{1}{2}r_i R_k$, where R_i and r_i are the reflectance and average number of interfaces encountered for the i^{th} mineral. Similarly, the

transmission calculated from the transmittance of the thin film is used to calculate a refractive scattering coefficient $S_{refraction}$, and the total scattering coefficient of the rock is taken to be

$$S = G\,[S_{reflection} + S_{refraction}] \tag{14}$$

where G is a "contact factor" that represents the fraction of the powder surface that is not "optically bonded" between particles. In order to calculate G, they assume spherical particles and estimate (based on Newton's rings) that wherever particles are closer than $\tilde{\sim} \frac{\lambda}{10}$ to one another, it is as if no scattering interface between air and particle existed. The absorption coefficient K for the rock is obtained by calculating an absorptance A_i for parallel plates of the i^{th} mineral and summing over all minerals. The S and K thus derived are substituted into equation 13 to obtain the reflectance of the powdered rock or mineral sample.

For small particle diameter samples, they calculate (via spherical wave analysis, using spherical particles) an "average index of refraction" for the medium in a "clump of powder" (including both air and particles), substitute this plus the index of refraction of the particles into Rayleigh scattering equations, and calculate the total scattering coefficient, S. The absorption coefficient for the i^{th} mineral, K_i, is taken to be proportional to $\frac{k_i}{\lambda}$, where k_i is the imaginary part of the complex refractive index for the i^{th} mineral. The total K for the rock is, once again, the weighted sum of the mineral absorption coefficients. The S and K are then

substituted into equation 13, and the reflectance of the powder is calculated.

The coarse-grained part of the AERST model seems to agree reasonably well with experimental data for quartz and corundum in some spectral regions. Furthermore, it is amenable to relatively quick and simple computer calculation. However, despite these advantages, there are several reasons why the AERST model was not chosen to describe the effect of surface roughness on the spectral emittance of rocks. First, it is discontinuous across the coarse-to-fine particle boundary. Secondly, the fine particle theory is not in very good agreement with both quartz and corundum experimental data. Thirdly, the spectral reflectances (or emittances) calculated in the reststrahlen regions (high index of refraction) show very little (if any) variation with decreasing particle size, possibly because the averaged first-surface Fresnel reflectivity, which is independent of particle size, is made overly dominant in this theory. Fourthly, the assumptions made about the particle shapes are inconsistent from one part of the theory to the next, i.e. parallel plates are assumed in one place and spheres in another. Fifthly, the determination of indices of refraction for all the minerals in a rock, as well as the volume fractions of each mineral, requires nearly a complete analysis of the rock before it can be modeled. And finally, if each mineral is to be considered separately, the effect of birefringence must be determined, because many of the rock-forming minerals are highly birefringent in the thermal IR region. Nonetheless, parts of the AERST model may be applicable to the model selected for this problem.

In yet another model, initiated by Conel [26], single particle scattering characteristics (spherical particles) are computed by Mie theory, which simply matches Maxwell's equations to the boundary conditions of a di lectric sphere. The radiative transfer theory is used to calculate the reflectances of a semi-infinite "cloud" of these particles. He assumes the simplest anisotropic scattering phase function (with $\cos\theta$ dependence, where θ is the scattering angle) and approximates the only integral in the radiative transfer equation as a two-point Gaussian sum (a type of two-stream approximation). Besides the spherical particle and simplest anisotropic phase function assumptions, Conel's model assumes that the cloud is uniform (monominerallic), and no provisions are made either for particles to be in physical contact with one another or for them to be birefringent. Input for this model are the complex refractive index (as a function of wavelength) and particle diameter, which he assumes uniform throughout the cloud.

Conel's model agrees qualitatively quite well with experimental data of quartz powders. However, it has not been applied to other minerals or to rocks, and the theoretical spectra of emittance or reflectance versus λ are exaggerated too much in regions of relatively small refractive indices to be in good quantitative agreement. The drawbacks of this model are that no provisions are made to allow the cloud to have more than one mineral constituent, birefringence is unaccounted for, and the computer program running time is longer than that of the AERST model. To obtain the emittance spectrum of a quartz cloud of 30μm diameter particles, for instance, a running time of about 1 minute on an IBM 360 computer is required. However, the primary advantage of this model over the AERST model is that the same model can be

used for all particle sizes, because Conel's model does not use geometrical optics approximations for large particle sizes.

3.2 SELECTED MODEL FOR ROCK AND MINERAL SURFACES

The model selected for describing the effect of surface roughness on the spectral emittance or reflectance of a geological target is based on Conel's model, described above. However, it will be extended to include an accounting for birefringence effects for monomineralic rocks and a method for applying the Mie theory to rocks composed of several minerals. Finally, an attempt will be made to incorporate into this model a provision for "optical contact" that is encountered in a powder (as opposed to a cloud), where particles touch each other. In this regard, the contact factor from the AERST model may be applicable to the Mie scattering model of Conel.

The radiative transfer model to be used for calculation of emittances is the same as that used by Conel. A plane-parallel "cloud" of infinite optical thickness consisting of uniform spherical particles of diameter d is assumed. The assumed anisotropic phase function is

$$p = w_o [1 - w_1' \cos\theta] \tag{15}$$

where w_o and w_1' are the single particle scattering albedo and anisotropy factor, respectively, and θ is the angle between the incident and scattered wave normals. All three quantities are wavelength dependent, but the λ subscript has been suppressed. The quantities w_o and w_1' are calculable from Mie scattering theory as follows:

$$w_o = \frac{Q_{SCA}}{Q_{EXT}} = \frac{\sum_{m=1}^{\infty} (2m+1)\ [|a_m(\alpha,N)|^2 + |b_m(\ ,N)|^2]}{\sum_{m-1}^{\infty} (2m+1)\ R_e[a_m(\alpha,N) + b_m(\alpha,N)]} \qquad (16)$$

$$w'_1 = 3\langle\cos\theta\rangle = \frac{\sum_{m=1}^{\infty} 6\left[\frac{m(m+2)}{m+1} R_e\{a_m(\alpha,N)a^*_{m+1}(\alpha,N)b^*_{m+1}(\alpha,N)\} + \frac{2m+1}{m(m+1)} R_e\{a_m(\alpha,N)b^*_m(\alpha,N)\}\right]}{\sum_{m+1}^{\infty} (2m+1)\ [|a_m(\alpha,N)|^2 + |b_m(\alpha,N)|^2]} \qquad (17)$$

where Q_{SCA} = scattering efficiency factor, Q_{EXT} = extinction efficiency factor, $\alpha = \frac{2\pi d}{\lambda}$, and $a_m(\alpha,N)$ and $b_m(\alpha,N)$ are Mie coefficients, which are functions of α and the complex index of refraction, $N = n - ik$, at that wavelength. After employing a simple two-point Gaussian quadrature method to solve the radiative transfer equation and then matching the proper boundary conditions at the cloud surface, such as done by Conel, one obtains for the spectral emittance

$$E = (1 - R) = \frac{2}{U + 1} \qquad (18)$$

where

where $U = \left[\frac{1 - w_o \frac{w'_1}{3}}{1 - w_o}\right]^{1/2}$.

There are two qualifications to the theory which should be mentioned here. Emission and reflection of the topmost layer of grains in the powder is neglected, so that E calculated from the above equation is a "bulk" emittance.

Secondly, an n-point Gaussian quadrature method is used to replace an integral by a weighted sum of the integrand evaluated at n discrete points; for a two-point approximation, only one point in each hemisphere (forward and backward scattering directions) is selected. Therefore, the calculated emittance represents a rough approximation of the total hemispherical emittance.

Inputs to this model are particle diameter and complex refractive index as a function of wavelength. At this point, two complications arise. Rocks usually consist of mineral grains that are randomly oriented. But silicate and carbonate minerals, which are the most important constituents of igneous and sedimentary rocks, are birefringent in the thermal infrared wavelength region. This means that the complex index of refraction of a mineral crystal is dependent on the angle θ between the direction of propagation and the optical axis (or axes) of the crystal. These two directions define what is called a principal plane. Therefore, some accounting must be made for the birefringence of the randomly oriented mineral grains in the rock surface. The second complication arises because, although some rocks are monomineralic, most rocks consist of several minerals. Therefore, the complex refractive indices of the individual minerals must be combined in some way to produce an effective index of refraction for a multimineralic rock.

There are two possible approaches to these problems. One is to experimentally determine the refractive indices of the individual constituents and theoretically combine them to produce an effective refractive

index. This approach is appealing only for the simplest cases. For instance, the effective index of a monomineralic rock consisting of uniaxial (one optical axis) crystals, such as nearly pure sandstone (quartz) or limestone (calcite), may be described in terms of linear combinations of the ordinary ray (electric vector perpendicular to the principal plane and θ-independent) and extraordinary ray (electric vector parallel to the principal plane and θ-dependent) reflectances theoretically calculated for randomly oriented crystals in the rock surface. For more complex cases, where both birefringence and multiple minerals are present, a different approach is called for. It involves the experimental measurement of effective indices for the total rock surface, which become inputs to the theory described by equations 16-18. The resulting calculated reflectances or emittances, hopefully, will then represent the optimal properties of the complicated rock surface.

The first of these two approaches will be taken for the sedimentary rocks, sandstone and limestone. Both quartz (SiO_2) and calcite ($CaCO_3$) are uniaxial minerals for which the ordinary and extraordinary ray refractive indices are known, as described in a former report under this contract [3]. With these complex refractive indices, the Conel model, outlined in the above equations, will be used to calculate the spectral emittances of sandstone and limestone for various particle diameters.

For rocks of more complicated composition, the second approach will be attempted. As described in a previous technical report [3], a classical oscillator fitting program can be used to accurately estimate the complex refractive index of a solid material as a function of wavelength, if the

Fresnel reflectivity spectrum of a polished slab of the material is known. If a randomly cut cross-section of the rock is polished and a Fresnel reflectivity spectrum is measured over a spot that is large enough to include several crystals of each mineral constituent, oriented in several directions, the dispersion curves estimated from fitting that reflectivity spectrum should represent an effective complex index of refraction for the rock. The resulting effective complex index can then be fed into Conel's model, which will yield an emittance spectrum for various particle diameter surfaces of the rock. Accuracy of the effective index method will increase with the number of mineral grains included in the spatial resolution element during the Fresnel reflectivity measurement. For a given spot size, therefore, effective indices for fine-grained rocks should be more accurate than for coarse-grained rocks. This method can be simply tested with Fresnel reflectivity curves already in existence. If it works, it will be a useful tool for aerosol scattering problems as well as for improving the infrared ratio technique being developed for geologic mapping.

4

CONCLUSIONS

To improve the link between laboratory spectra and airborne and spaceborne scanner data, a search has been made for two theoretical models, one to predict the reflectance of a plant canopy and the other to describe the effect of textural variations on the spectral emittance or reflectance of

natural rock surfaces. Several models were reviewed, from which it was possible to select the types of model best suited for these applications.

The selected plant canopy model, Suits' model, is an extension of the Allen-Gayle-Richardson model, which employs the six-parameter Duntley reflectance equations. This improved model differs from previous models in three respects. First, it allows for more than one canopy layer, whereas past models have been monolayer. This is an important feature because it offers a means to account for greatly different plant components at various heights above the ground. For instance, corn tassels are different in shape and in color from corn leaves and stalks; in this model, a top layer would primarily consist of corn tassels (just before harvest) and lower layers would be composed of leaves and stalks. Secondly, this model actually relates laboratory spectra of plant components (leaves, stalks, etc.) and approximate plant geometry (planting density and average horizontal and vertical component cross-sections) to the reflectance of the crop field. Heretofore, empirical constants were used to calculate field reflectance. Thirdly, unlike the Lambertian field reflectance assumptions of previous models, this model allows for the calculation of bidirectional reflectance of a field crop. The model has been verified for two corn fields, with worst-case errors of approximately 15%. Other verification is underway for certain grass canopies, but difficulties in leaf area index measurement for grasses must be overcome before verification for grass canopies can be satisfactorily completed. The model suggests that bidirectional reflectance properties (reflectance as a function of observation

angle) should be investigated as "signatures" for crop recognition.

The selected geological model will differ from previous models by accounting for birefringence, multiple mineral constituents, and varying particle diameters all within the same mathematical structure (same equations for all cases). In the case of monomineralic rocks, it will theoretically account for birefringence effects, and for rocks composed of several minerals it will calculate an effective complex refractive index for such a rock. For both cases, the indices will be substituted into equations of a model for particulate media derived from Mie (single particle scattering) and radiative transfer (multiple scattering) theories. The resulting spectral emittances will be used to investigate the effects of textural variations on the infrared ratio method for rock-type discrimination derived earlier. This model should also be useful for calculating spectral emittances of naturally-occurring aerosol particles in the atmosphere.

REFERENCES

1. V. Leeman, D. Earing, R. Vincent, and S. Ladd, "The NASA Earth **Resources Spectral Information System: A Data Compilation,"** Willow Run Laboratory Report 3165-24-T, NASA Contract NAS 9-9784, Ann Arbor, Michigan, (1971).

2. V. Leeman, R. Vincent, and S. Ladd, "The NASA Earth Resources Spectral Information System: A Data Compilation, Supplement 1," Willow Run Laboratory Report 31650-77-T, NASA Contract NAS 9-9784, Ann Arbor, Michigan, (1972).

3. R. Vincent, R. Horvath, F. Thomson, and E. Work, "Remote Sensing Data-Analysis Projects Associated with the NASA Earth Resources Spectral Information System," Willow Run Laboratory Report 3165-26-T, NASA Contract NAS 9-9784, Ann Arbor, Michigan, (1971)

4. J. D. Erickson, "Automatic Extraction of Information from Multispectral Scanner Data," International Archives of Photogrammetry; Vol. 17, Ottawa, Canada, January 1973.

5. A. Schuster, Astrophys. J., 21, 1, (1905).

6. P. Kubelka and F. Munk, Z. Tech. Physik, 12, 593, (1931).

7. L. Silberstein, Phil. Mag., 4, 129, (1927).

8. J. W. Ryde, Proc. Roy. Soc., A90, 219, (1931).

9. S. Q. Duntley, "The Optical Properties of Diffusing Materials," J. of the Opt. Soc. of Amer., 32, 61, (1942).

10. C. M. Sakamato and R. H. Shaw, Agron. J., 59, 7, (1967).

11. L. H. Allen, C. S. Yocum, and E. R. Lemon, Agron. J., 46, 253, (1964).

12. T. Takeda and A. Kumura, Proc. Crop Sci. Soc. Japan, 26, 165, (1957).

13. J. L. Davidson and J. R. Philip, in Proc. UNESCO Symposium on Climatology and Microclimatology, Canberra, p. 109, (1956).

14. M. Monsi and T. Saeki, Japan J. Botony, 14, 22, (1953).

15. J. H. Allen, Jr. and K. W. Brown, Agron. J., 57, 575, (1965).

16. W. A. Allen and A. J. Richardson, "Interaction of Light with a Canopy;" J. of the Opt. Soc. of Ameri., 58, 1023, (1968).

17. W. A. Allen, T. V. Gayle, and A. J. Richardson, "Plant-Canopy Irradiance Specified by the Duntley Equations," J. of the Optical Soc. of Amer., 60, 372, (1970).

18. G. H. Suits, "The Calculation of the Directional Reflectance of a Vegetative Canopy," Remote Sensing of Environment, 2, 117-125, 1972.

19. G. H. Suits, G. R. Safir, "Verification of a Reflectance Model for Mature Corn with Applications to Corn Blight Detection," Remote Sensing of Environment, 2, 183-192, 1972.

20. G. H. Suits, "The Cause of Azimuthal Variations in Directional Reflectance of Vegetative Canopies," Remote Sensing of Environment, 2, 175-182, 1972.

21. G. R. Safir, G. H. Suits, M. V. Wiese, "Application of a Directional Reflectance Model to Wheat Canopies under Stress," International Conference on Remote Sensing in Arid Lands, November 9, 1972, Tucson, Arizona.

22. R. J. P. Lyon, "Evaluation of IR Spectrophotometry for Compositional Analysis of Lunar and Planetary Soils: Rough and Powdered Surfaces," Final Report - Part II, NASA Contract NAS4-49 (04), Stanford Research Institute, Menlo Park. Calif., (1964).

23. R. K. Vincent and G. R. Hunt, "Infrared Reflectance from Mat Surfaces," Applied Opt., 7, 53, (1968).

24. _____, "Target and Background Characteristics: Analysis and Applications (U)," Section 8 by J. Beard, G. Leedy, H. Horwitz and D. Earing, Rept. No. AFAL-TR-71-239 (AD-517691L), Air Force Avionics Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio, October 1971 (CONF-NFN).

25. J. R. Aronson, A. G. Emslie, L. H. Roach, P. F. Strong, and P. C. Von Thuna, "Development of a Theory of Spectral Reflectance of Minerals - Part II," A. D. Little Report ADL C-72594, NASA Contract NAS9-10875, Cambridge, Mass., (1971).

26. J. E. Conel, "Infrared Emissivities of Silicates: Experimental Results and a Cloudy Atmosphere Model of Spectral Emission from Condensed Particulate Mediums," J. Of Geophys, Res., 74, 1614, (1969).

APPENDIX I

LIST OF RELATED REPORTS

The following reports describe remote sensing work performed by the Infrared and Optics Laboratory, Environmental Research Institute of Michigan, Ann Arbor (formerly known as Willow Run Laboratories before separation from The University of Michigan).

OPTICAL TRANSFER TECHNIQUES FOR ORBITAL SCANNERS, J. Braithwaite, E. Work, Report No. 31650-21-T, March 1971.

DETECTOR UTILIZATION IN LINE SCANNERS, L. Larsen, Report No. 31650-29-T, August 1971.

A PROTOTYPE HYBRID MULTISPECTRAL PROCESSOR (SPARC/H) WITH HIGH THROUGHPUT CAPABILITY, F. Kriegler, R. Marshall, Report No. 31650-23-T, March 1971.

DATA DISPLAY REQUIREMENTS FOR A MULTISPECTRAL SCANNER PROCESSOR WITH HIGH THROUGHPUT CAPABILITY, R.E. Marshall, F.J. Kriegler, Report No. 31650-28-L, July 1971.

CALIBRATION OF MULTISPECTRAL SCANNERS, J. Braithwaite, Report No. 31650-27-L, September 1970.

STUDIES OF SPECTRAL DISCRIMINATION, W.A. Malila, et al., Report No. 31650-22-T, May 1971.

INVESTIGATIONS OF MULTISPECTRAL SENSING OF CROPS, R. Nalepka, et al., Report No. 31650-30-T, May 1971.

INVESTIGATION OF SHALLOW WATER FEATURES, F. Polcyn, et al., Report No. 31650-31-T, August 1971.

THE NASA EARTH RESOURCES SPECTRAL INFORMATION SYSTEM: A DATA COMPILATION, V. Leeman, et al., Report No. 31650-24-T, May 1971.

NASA/MSC EARTH RESOURCES SPECTRAL INFORMATION SYSTEM PROCEDURES MANUAL, V. Leeman, et al., Report No. 31650-32-T, 1971.

DATA GAPS IN THE NASA EARTH RESOURCES SPECTRAL INFORMATION SYSTEM, R. Vincent, Report No. 31650-25-T, March 1971.

REMOTE SENSING DATA ANALYSIS PROJECTS ASSOCIATED WITH THE NASA EARTH RESOURCES SPECTRAL INFORMATION SYSTEM, R. Vincent, et al., Report No. 31650-26-T, April 1971.

INVESTIGATIONS RELATED TO MULTISPECTRAL IMAGING SYSTEMS FOR REMOTE SENSING, J. Erickson, Report No. 31650-17-P, September 1971.

INVESTIGATIONS RELATED TO MULTISPECTRAL IMAGING SYSTEMS (Final Report), J. Erickson, Report No. 31650-18-F, 1972.

NASA/MSC EARTH RESOURCES SPECTRAL INFORMATION SYSTEM PROCEDURES MANUAL, SUPPLEMENT, V. Leeman, Report No. 31650-72-T, September 1971.

ESTIMATING PROPORTIONS OF OBJECTS FROM MULTISPECTRAL DATA, R. Nalepka, et al., Report No. 31650-73-T, 1972.

INFORMATION EXTRACTION TECHNIQUES, W. Malila, et al., Report No. 31650-74-T, 1972.