# SPECTRAL REFLECTANCE FROM PLANT CANOPIES AND OPTIMUM SPECTRAL CHANNELS IN THE NEAR INFRARED

by

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## INTRODUCTION

This paper deals with the theoretical and experimental aspects of the interaction of light with a typical plant canopy. Both theoretical and experimental results will be used to establish optimum electromagnetic wavelength channels for remote sensing in agriculture. The spectral range considered includes half of the visible and much of the near-infrared regions.

Reflectance from a green plant under natural conditions is an intergrated response from the plant reproductive structures, soil background, leaves, branches, dew, pesticide residue, dust, and innumerable other attributes. Most of the reflectance from vegetation, however, originates from the leaves. If the optical properties of the leaves are understood, the reflectance from plant canopies can be better interpreted. This paper is concerned with optical constants of leaves and the application of these constants to field conditions.

In practice, reflectance of a canopy is measured directly from an aircraft or spacecraft. Reflectance data can then be utilized to draw inferences regarding the nature, vigor, acreage, and maturity of the crop. This approach is empirical and is based upon the existence of extensive ground truth. Less ground truth would be required if the interaction mechanism between plant and light were better understood. That is the reason we address ourselves to the basic theory behind the physical measurements.

Remote sensing imagery in agriculture can be acquired on the ground, from aircraft, or at satellite altitudes. An example will be given for each case.



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Figure 1 is an example of ground-acquired imagery. This is a near-infrared photograph of an agricultural scene that includes sugarcane, citrus trees, and palms. Reflectance from vegetation is about the same amplitude as that from the clouds. The appearance of vegetation in the near-infrared is similar to that of clouds or snow. The infrared reflectance for clouds, snow, and leaves is caused by the presence of water and the manner in which it is subdivided. The elementary scattering centers for clouds, snow, and leaves are water droplets, ice crystals, and plant cellular structure, respectively. The role of water in plant reflectance is obscured in the visible region of the spectrum by plant pigment absorption. In the near-infrared region, however, chlorophyll is highly transparent, and the effect of liquid water becomes dominant (1).

Figure 2 is an example of imagery obtained from an aircraft. This is a photograph of a grapefruit orchard. Note the white-appearing tree in the center. More will be said about this photograph by Dr. Gausman in a later paper.

Figure 3 was acquired from a satellite. This imagery was obtained August 1969 from an elevation of about 200 miles by means of a near-infrared scanner in Nimbus III. The Gulf coast is clearly visible. Vegetation and clouds are both expected to appear white in such imagery. The atmospheric disturbance north of the Yucatan Peninsula is Hurricane Camille. This was the most damaging hurricane, with respect to property, ever to hit the United States. The value of Nimbus III imagery, for purposes of agriculture, is seriously compromised by its 10-mile resolution. The Earth Resources Technology Satellite (ERTS), scheduled for 1972, has considerably improved ground resolution.

## LEAF AND PLANT CANOPY MODELS

The reflectance of a dielectric object can be predicted, at least in principle, if its geometry and the optical constants of its constituents are known. The direct procedure to calculate reflectance of a given object involves tracing a representative bundle of light rays through the object, allowing for absorptance, and applying the Fresnel relations at all interfaces. The sum of all backscattered intensities, relative to incident intensity, is termed reflectance. In practice, however, the actual geometry of all but the most elementary objects is too complicated for exact mathematical analysis. Figure 4, for example, is a transection of a typical cotton leaf. The chloroplasts and spongy parenchyma cells have been accentuated by staining. The leaf contains a large number of different-sized intercellular air spaces in the mesophyll. Despite the complicated internal structure of such a leaf, its optical properties can be described accurately by means of a simple model--that is, a flat plate with rough surfaces.

A total of three different mathematical models (1, 2, 3) have proved applicable to individual leaves and plant canopies. Figures 5a and 5c are models of a plant canopy with light absorbing and light scattering leaves. The leaves are uniformly distributed and oriented, with dimensions much smaller than the height of the canopy. The models are assumed to have infinite lateral extension in order to eliminate canopy edge effects. The appropriate dimension is taken as the cumulative leaf area index n (LAI). The cumulative LAI at a given point is the total one-sided leaf area, per unit ground area, measured downward from the canopy top. The quantity N is the total LAI of the canopy and is measured at the soil. The plane $n = 0$ is the illuminated canopy surface. Monochromatic light in the downward direction (Fig. 5a) is denoted I, while that in the upward direction is denoted J. The incident light $I_o$ on the canopy is considered unity. The quantity R is the reflectance and T is the transmittance defined as the relative light intensity on the background.

Light passing through a layer of leaves is scattered and absorbed in direct proportion to a differential distance traversed, and in direct proportion to the amplitude of the light at that point. Absorbed radiation disappears from the models. Scattered radiation is merely changed in direction. Since the models are one-dimensional, the scattering must be either forward or backward. Light backscattered from I in Fig. 5a adjoins J and vice versa. The preceding discussion can be formulated into differential equations associated with the names Kubelka and Munk (K-M) (4).

Equations due to Duntley (5) have been generalized to provide values of irradiance within the plant canopy under specular light incident at various sun angles. The Duntley theory, illustrated by Fig. 5c, is based upon five optical parameters. An absorption coefficient, a back-scattering coefficient, and a forward-scattering coefficient are necessary to describe the interaction of specular light with a plant canopy. The unprimed quantities in Fig. 5c pertain to diffuse light generated by scattering. An absorption coefficient and a back-scattering coefficient apply to the diffuse light. There are two radiant fluxes, specular and diffuse, in the positive direction while the diffuse radiant flux in the negative direction is designated s. The specular flux incident on the canopy is designated $I_o'$. If $I_o'$ is unity per unit horizontal area, the reflected light R' is designated reflectance and the transmitted light T' is designated transmittance.

Experiments have indicated that an actual plant canopy is characterized by diurnal effects. Attenuation within a plant canopy depends upon the sun angle. An argument of plausibility suggests that specular-light attenuation is a function of the slant range through the canopy; that is, the optical parameters for specular light are assumed to vary as the secant of the sun angle.

Figure 5b is a model of a compact plant leaf. The model, as mentioned before, is a flat plate with rough surfaces. Radiant flux $I_o$ emanates from medium 1 and interacts with the interface between media 1 and 2 where it separates into two components. One component is reflected. The second component passes through medium 2 and interacts with the interface between media 2 and 3. The indicated multiple reflections produce an infinite number of rays that emerge eventually into both media and 3. Total light emergence into medium 1 is designated reflectance r and total light emergence into medium 3 is termed transmittance t. Media 1 and 3 will be regarded as air. Medium 2 will be specified by its optical constants. The flat plate model of Fig. 5b can be generalized to simulate a non-compact leaf. In this case the leaf is assumed to consist of a stack of compact layers each separated by a layer of air.

## RESULTS

The K-M theory explains the reflectance and transmittance of stacked leaves in a spectrophotometer. Agreement between the observed and computed values is within the experimental uncertainties of the spectrophotometer used.

Figure 6 illustrates the Duntley equations fitted to near-infrared experimental transmission data obtained at Ithaca, New York within a 250 cm-high corn canopy (6). The three lines correspond to elevations 150, 100, and 50 cm within the corn canopy. Measurements were started in the morning and were continued until sundown. The standard deviation between the experimental and theoretical points is 3.2%--a value probably well within experimental error.

The generalized plate description of a typical, noncompact leaf has been applied to 200 mature, field-grown cotton leaves (7). Over the spectral range 1.4 - 2.5 μm, the absorption spectra of leaves are not statistically different from that of pure liquid water. Leaf reflectance differences among the plant leaves over the 0.5 - 1.4 μm range are caused principally by Fresnel reflections at external and internal leaf surfaces and by plant pigment absorption.

Figure 7 is the mean dispersion curve for 200 field-grown cotton leaves. The shaded area is bounded by 95% confidence bands. The dispersion curves of all other crop leaves are roughly similar.

Figure 8 is the absorptance spectra of a typical cotton leaf. The absorption curve can be regarded as a superposition of two independent absorption components: the first region, 0.50 - 0.75 μm, is dominated by the plant pigments such as chlorophyll, and the second region, 1.4 - 2.5 μm, is determined by the properties of liquid water. The intervening region, 0.80 - 1.40 μm, is characterized by relative transparency of both plant pigments and water. The chlorophyll spectra and water spectra are relatively independent.

## WAVELENGTH RECOMMENDATIONS

Inspection of Figs. 7 and 8 suggests that the bulk of existing information from leaf spectral reflectance must reside with the absorptance curve rather than with the dispersion curve. Figure 8 is plotted on semi-log paper because the absorption coefficient varies by orders of magnitude. The dispersion curve of Fig. 7, on the other hand, changes by only a few percent over the given spectral region.

The preceding physical considerations suggest that the three most useful spectral channels in the range 0.5 - 2.5 μm would be those associated with chlorophyll, water, and a third region where both chlorophyll and water are transparent. Specifically, the three channels centered around the wavelengths 0.68, 0.85, and 1.65 μm appear to be optimum. The first channel is in the visible region and the other two channels correspond to peaks of atmospheric windows I and IV.

The preceding discussion led to tentative consideration of three optimum wavelength channels where selection was based upon physical insight. Consider now the statistical analysis of laboratory measurements on single leaves. The leaves used in this analysis were collected in connection with an experiment to be reported elsewhere. Four crops--corn, cotton, peppers, and sorghum--were sampled at four separate stages of growth during the 1970 growing season in the Lower Rio Grande Valley of Texas. Reflectance and transmittance measurements were taken on single leaves, and were reduced to optical constants at each of 41 wavelengths over the spectral region 0.50, 0.55, •••, 2.50 μm. Reflectance corresponding to an infinitely thick stack of such leaves was used in a correlation analysis. Figure 9 is an abstracted plot of the correlation reflectance matrix for all 41 spectrophotometric channels. The 100% correlation coefficients appear along the diagonal. All plotted coefficients were positive quantities. A few slightly negative correlation coefficients did appear in the extended calculations, but these values were treated as zero in Fig. 9. A low or poor correlation is considered to be in the range 0 - 25 and a high correlation is assumed to lie in the range 75 - 100. The region 20 - 75 will be regarded as intermediate correlations.

Figure 9 displays a high correlation for neighboring channels in chlorophyll region 0.5 - 0.7 μm and a high correlation for neighboring channels in the water region 1.4 - 2.5 μm. Correlation is also high for neighboring channels within the transparency region 0.7 - 1.4 μm. The water absorption channels, 1.45 μm and 1.95 μm, are correlated weakly with all other channels. Inferences drawn from this correlation analysis support the previous finding that channels 0.68, 0.85, and 1.65 μm, are optimum for vegetation since these channels are poorly correlated with each other.

## REFERENCES


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Figure 1.- Infrared photograph of agricultural scene at the Texas A&M University Research and Extension Center, Weslaco, Texas. Reflected light from both clouds and vegetation is scattered by dielectric interfaces where air is one of the media. Photograph taken at 11:30 A.M., 10 November 1969 with Kodak Infrared Aerographic Film 2424 and a Kodak Wratten Filter No. 89B. A 120 mm Hasselblad was used at f/8 and 1/250 sec. The spectral channel is about 0.69 - 0.90 μm.

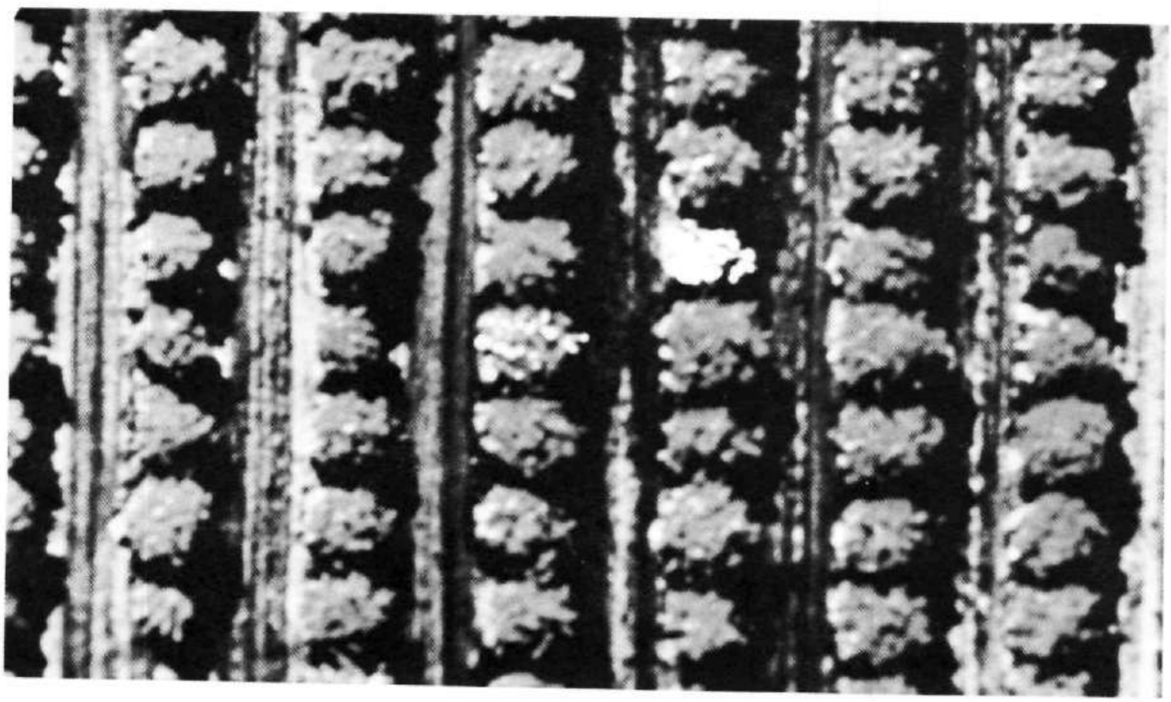

Figure 2.- Photograph of grapefruit orchard taken at 3,000 ft elevation.

Figure 3.- Infrared scanner image from Nimbus III. The atmospheric disturbance north of the Yucatan Peninsula is Hurricane Camille.

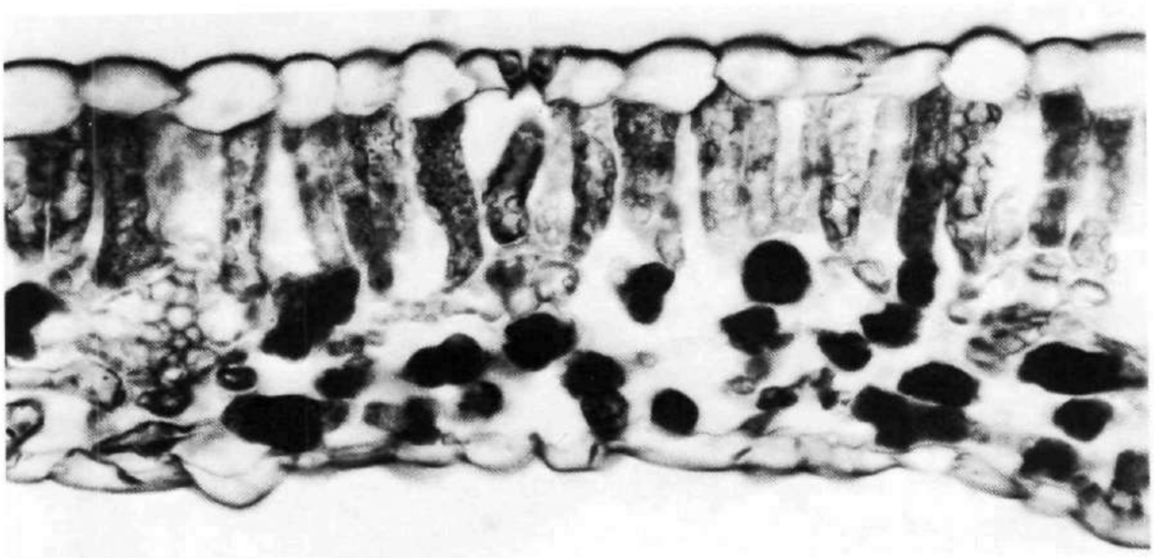

Figure 4.- Photomicrograph of typical dorsiventral cotton leaf transection.

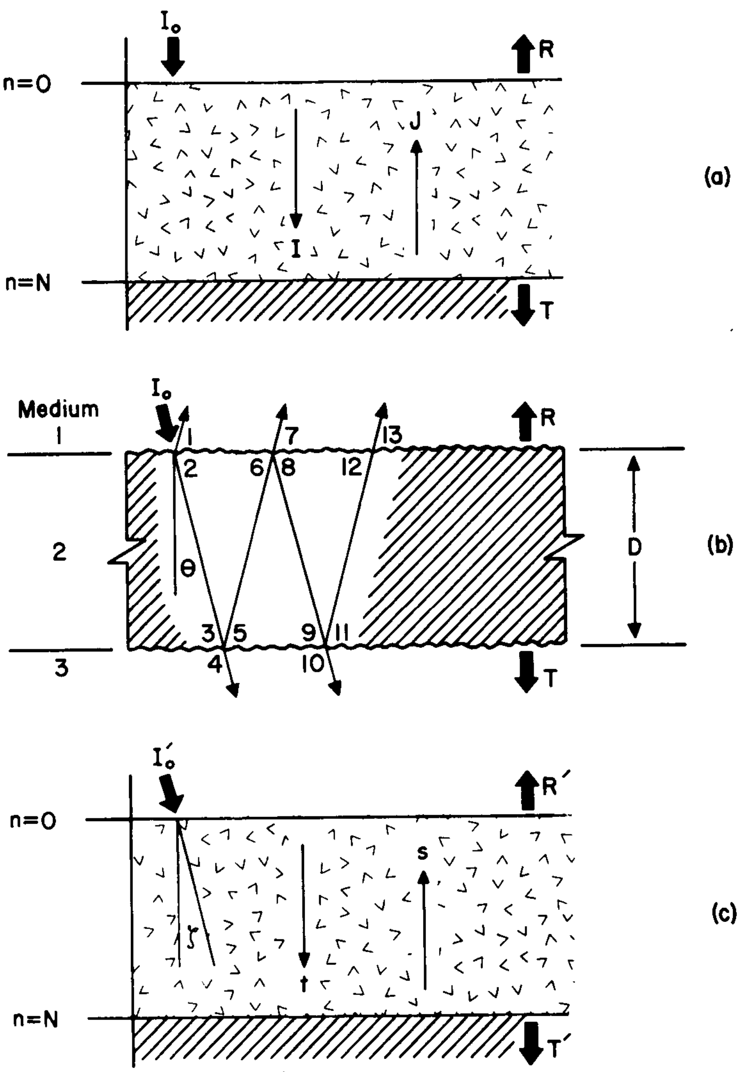


Figure 5.- Models of light interaction with leaves. The planes n = 0 and n = N are the canopy surfaces and soil backgrounds. a) Diffuse light $I_0$ impinging upon a plant canopy. Reflectance and transmittance are designated R and T. Diffuse light fluxes generated by scattering are designated I and J. b) Multiple reflections within a transparent plate with rough surfaces (a simulated compact plant leaf). Incident ray $I_0$ impinges at angle $\theta$. Reflectance and transmittance are designated R and T. c) Specular light $I_0'$ at sun angle $\zeta$ impinging upon a plant canopy. Reflectance and transmittance are designated R' and T'. Diffuse light fluxes generated by scattering are designated s and t.

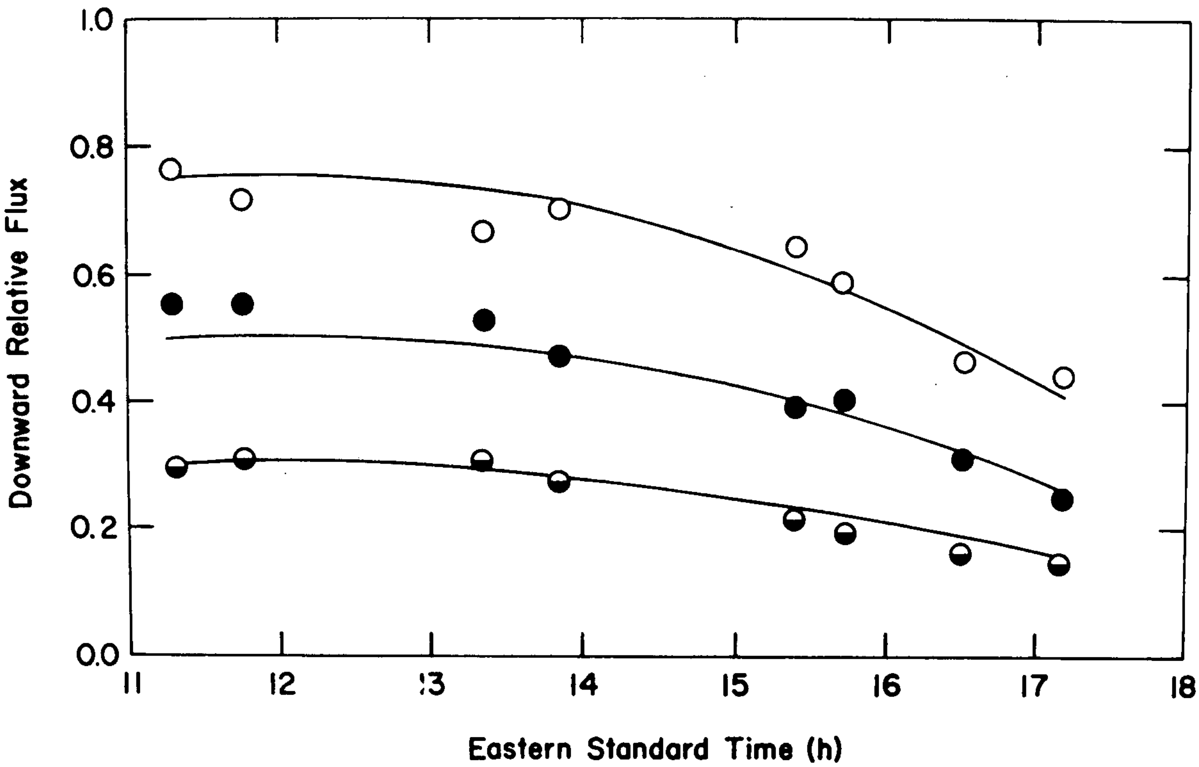


Figure 6.- Percent transmittance of near infrared flux within a 250-cm-high Ithaca, New York corn canopy on 13 September 1963. The curves; representing canopy heights 150, 100, and 50 cm. respectively; are theoretical predictions based upon the generalized Duntley equations. The data points are experimental values.

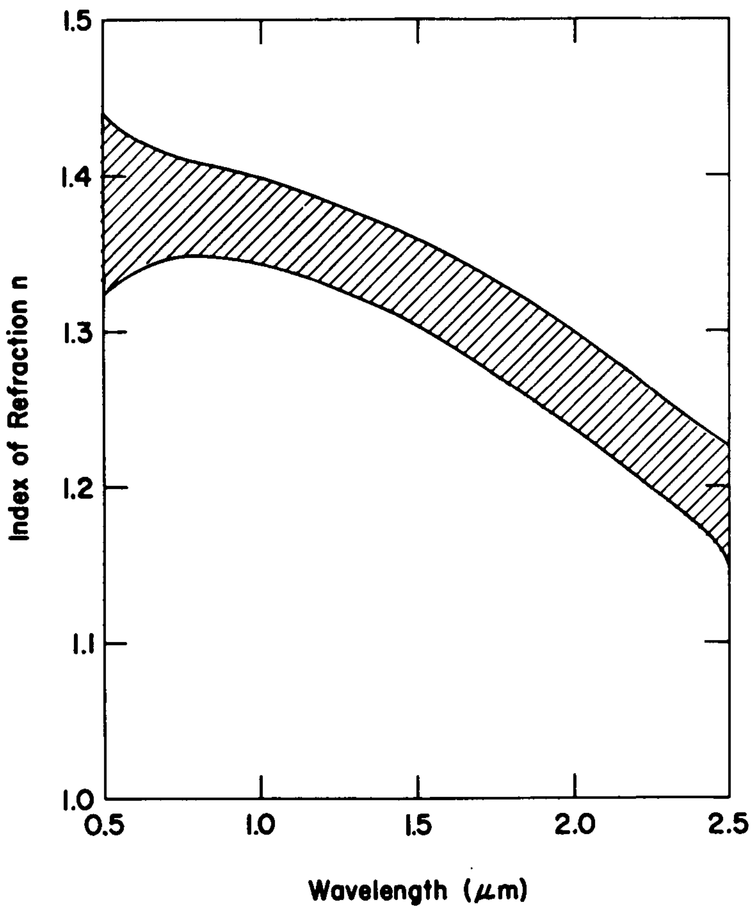


Figure 7.- Mean dispersion curve for 200 field-grown cotton leaves. The shaded area is bounded by 95% confidence bands.

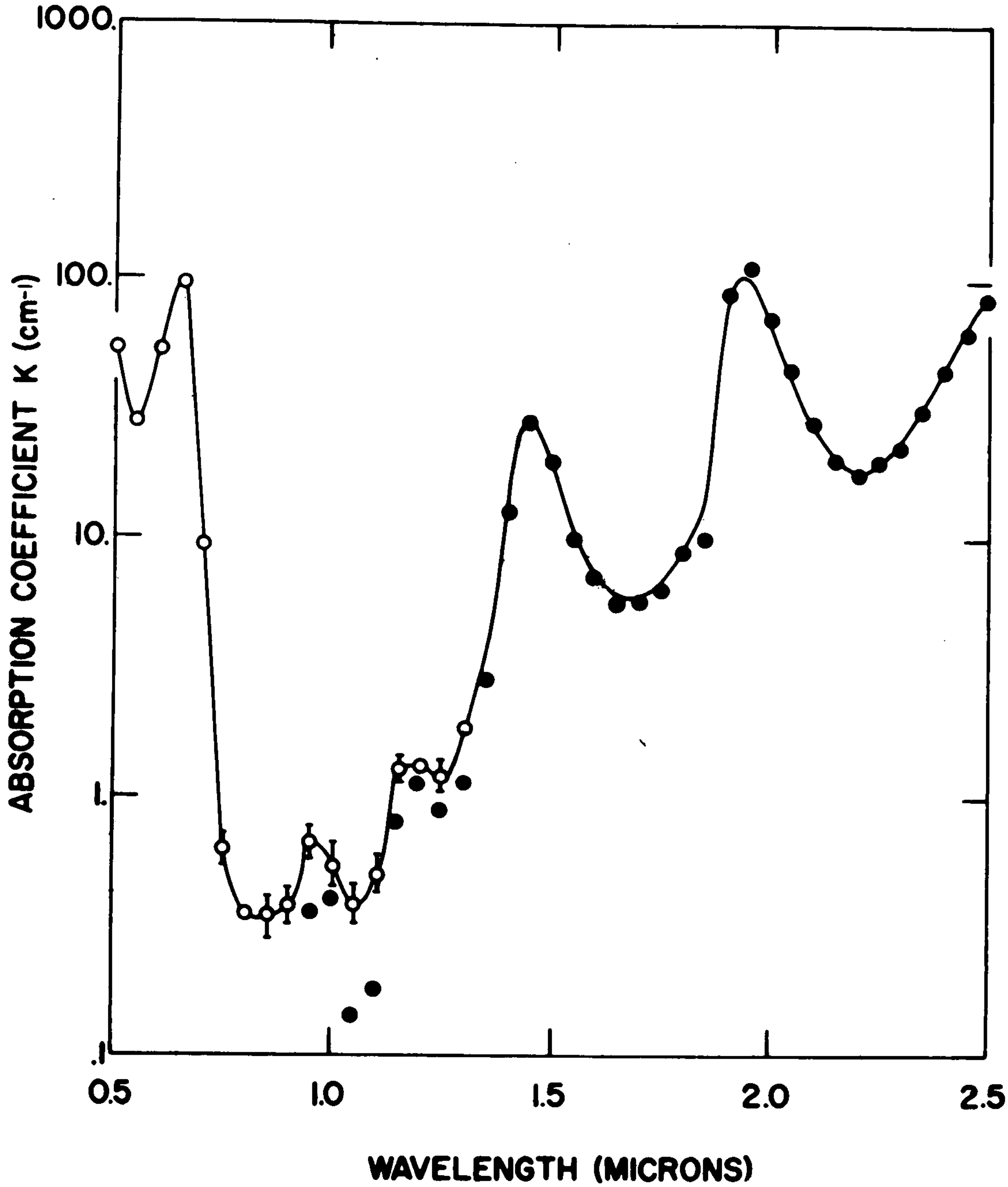


Figure 8.- Absorptance spectra of a typical leaf (solid line and open circles). The absorption curve can be regarded as a superposition of two independent absorption components. The first region is dominated by the plant pigments such as chlorophyll, and the second region is determined by the properties of liquid water. Properties of liquid water are indicated by closed circles.

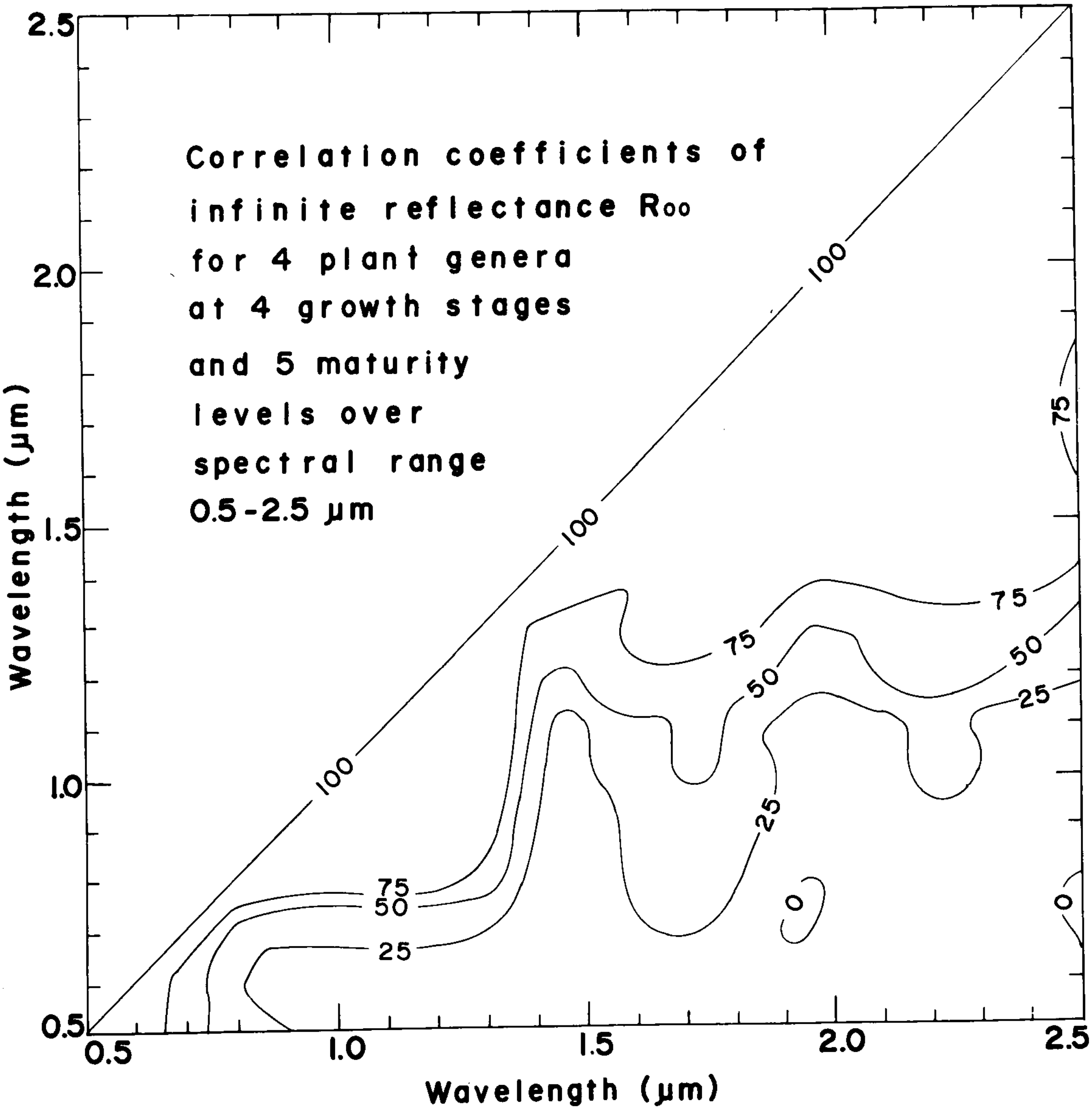


Figure 9.- Correlation coefficients of leaf reflectance.