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SPECTRAL SURVEY OF IRRIGATED REGION CROPS AND SOILS

United States Department of Agriculture
Weslaco, Texas

30 September 1969

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SPECTRAL SURVEY OF

IRRIGATED REGION CROPS AND SOILS

ANNUAL REPORT WESLACO, TEXAS

UNITED STATES

DEPARTMENT OF AGRICULTURE

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CONTENTS

PERSONNEL

ARS-SWC personnel assigned to the remote sensing investigations research program at Weslaco include:

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Victor I. Myers [2]	Research Investigations Leader
Ross W. Leamer	Research Soil Scientist
Harold W. Gausman	Research Plant Physiologist
William A. Allen	Research Physicist
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ARS-SWC summer and part-time employees assigned to the remote sensing program include:

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Participation in the Work Study and Neighborhood Youth Corps program by the Weslaco Laboratory has been successful and beneficial--both to the Remote Sensing Program and the college and high school participants. Work Study participants assigned to remote sensing duties during this reporting period included: Homer Garza, Linda Reed, Randy Schwab, Rosa Solis, Beatrice de Leon, and Sandra Garcia. NYC participants included: Guadalupe Cardona, Jose Aleman, Teresa Garcia, Margarita Reyes, Edward Argueta, and Hector Rocha.

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[1] Also, Director of Rio Grande Soil & Water Research Center, Weslaco.

[2] Resigned 1/1/69 to become Director of the Remote Sensing Institute at South Dakota State University, Brookings.

[3] Resigned 4/23/69 to join Vic Myers in South Dakota.

ACKNOWLEDGMENTS/COOPERATORS

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13. Mr. G. A. Thorley, Assistant Chief, Forestry Remote Sensing Laboratory, Berkeley, California, for the loan of certain prints and other assistance.

14. Mr. J. D. Tallant, Biometrician in Charge, Biometrical Services, SU, New Orleans, Louisiana for helpful discussions.

SUMMARY

Chapter I--APPLICATIONS

Use of Apollo 9 SO-65 Experiment Color Recombinations for Soil Survey and Agricultural Feature Studies.

Color recombination imagery of the Southeast Texas Gulf Coast areas, provided by Long Island University under contract with NASA, Houston, was studied for agricultural features of interest, namely soil associations, bare fields, cropped fields, and water bodies. The agreement was good between soil associations evident on the color recombined SO-65 imagery and generalized county soil surveys. More soil associations were generally identified in the maps than could be discerned on the space imagery and transitions between associations were more subtle than indicated on soil survey maps. It is concluded that space imagery would be a tremendously useful tool in soil survey.

Where there were actively growing plants in cultivated fields or dense natural vegetation, the very high reflectance of plants in the photographic infrared compared with the green and red spectral bands caused the infrared signature to dominate the recombinations in which it was used. Provision for differing the exposure indices for vegetated versus barren targets in future manned spacecraft photography is recommended.

The Influence of Ammonia Induced Cellular Discoloration Within Cotton Leaves (Gossypium hirsutum L.) on Light Reflectance, Transmittance and Absorptance.

Cellular discoloration within leaves has important practical implications. The effect on decreasing reflectance (rounding of the plateau) within the wavelength range from 700 to 1350 nm (nanometers), should be useful for detecting non-visual symptoms of plant leaf stress by remote sensing applications. A wavelength band of 700 to 900 nm may be best, since this contains the sharp drop in reflectance from the plateau shoulder caused by chlorophyll absorptance.

Reflectance of Single Leaves and Field Plots of Cycocel-treated Cotton (Gossypium hirsutum L.) in Relation to Leaf Structure.

The results of this experiment relate laboratory measurements of reflectance and transmittance on cotton leaves from field plots to response of Kodak Ektachrome infrared aero film imagery of the same plots. The effects of chlorophyll content and leaf intercellular space variations induced by a plant growth regulating chemical, Cycocel, on remote sensing imagery are demonstrated.

Detection of Insect Activity on Citrus Foliage With Aerial Infrared Color Photography.

The detection of brown soft scale infestations of citrus trees with Kodak Ektachrome infrared aero film, type 8443, has been demonstrated. Texas citrus mite and citrus rust mite were not detectable. Their presence may be detected remotely by multispectral systems which have not yet been employed, or by more careful use of the visible part of the spectrum where reflectance measurements indicate their damage has its strongest influence on the spectral signature.

Early detection of insect damage is beneficial to growers in two ways: (1) spot spraying instead of general spraying reduces direct production costs, and (2) condition of the trees and quality of the fruit can both be maintained. Remote sensing survey methods are attractive to research and regulatory agencies because ground crew surveys are expensive and consequently restrict surveys to sample rather than population surveys.

Detection of Foot Rot Disease of Grapefruit Trees With Infrared Color Film.

The light reflectance, transmittance, and absorptance of leaves from the foot-rot-affected trees and the nonaffected trees were measured at the 450 (blue), 550 (green), and 650 (red) nm wavelengths. Reflectance was 3.3, 31.4, and 23.9 percent higher; transmittance was 0.0, 16.5, and 8.3 percent higher; and, absorptance was 3.3, 47.9, and 32.2 percent lower for the foot-rot-affected than for the nonaffected leaves, respectively, at 450, 550, and 650 nm.

On photographs taken with Kodak Ektachrome infrared aero film and a Zeiss D light-orange filter (approximate 100 percent absorption edge at 500 nm), the foot-rot-affected trees appeared as white images compared with red images for unaffected trees. To the eye the affected trees were yellowish-white whereas the healthy trees were green.

The results demonstrate that the incidence of advanced cases of grapefruit tree foot rot could be readily detected by aerial survey.

CHAPTER II. INTERACTION OF LIGHT WITH PLANTS

In order to interpret remote sensing data acquired from aircraft and spacecraft, understanding is required of the reflectance produced by features on the surface of the earth. The specific problem in agriculture is interpretation of reflectance produced by vegetation usually superimposed upon a soil background.

Interaction of Isotropic Light with a Compact Plant Leaf.

Leaves constitute the bulk of the plant mass which interacts with light. Leaves of certain species such as corn are devoid of air spaces and are termed compact leaves. In this contribution the reflectance and transmittance of a typical compact plant leaf are derived from fundamental considerations. A transparent plate with rough plane-parallel surfaces is the theoretical model used. The analysis yields the effective optical constants of the corn leaf over the 500 to 2500 nm wavelength interval over which experimental reflectance and transmittance data are available. The effective index of refraction in the visible is consistent with the refractive index of epicuticular wax and the effective absorption spectrum is evidently a superposition of the absorption coefficients of chlorophyll and pure liquid water. The model of a compact leaf used also permits one to calculate the water content of the leaf from the reflectance and transmittance measurements.

Plant Canopy Irradiance Specified by the Duntley Equations.

The Duntley equations for propagation of specular light through a diffusing medium have been generalized and interpreted to account for the effect of sun angle on crop canopy irradiance. The Duntley optical coefficients associated with the specular component of light were assumed to vary as the secant of the zenith angle to the sun. Generalization of the Duntley relations was required in order to predict values of irradiance within the canopy and to account for the effect of background reflectance from the soil. Five independent measurements of canopy irradiance suffice to determine the Duntley parameters. Twenty-four measurements of irradiance within the canopy were utilized, however, in a least-squares program to obtain the best fit of the Duntley equations to the corn canopy. The equations fit the experimental results within 3.2% for a period from noon to sundown. If the laboratory measurements of optical constants for a single corn leaf are used as constraints, the Duntley equations fit the data to within 3.7%.

These results show that it is possible to predict remote sensor response to reflectance from vegetation over the 500 to 2500 nm wavelength interval.

Characterization of Incident and Reflected Short Wavelength Radiation.

ISCO spectroradiometers which are responsive in the 450 to 1550 nanometer wavelength interval were mounted 7 meters above row crops; incident solar radiation and reflectance from the integrated crop and soil background were measured. For isolated measurements of the crop or the soil the sensors were mounted 50 cm. above the surface being measured. In the 400 to 700 nm interval soil has a higher reflectance than vegetation; in the 700 to 1600 nm wavelength interval vegetation is more reflective than soil.

CHAPTER III. RELATION OF LIGHT REFLECTANCE TO COTTON LEAF MATURITY

Relation of Light Reflectance to Cotton Leaf Maturity (*Gossypium hirsutum* L).

Plant leaves yield most of the signal measured by remote sensors in aircraft or spacecraft viewing cropped fields. In this contribution the experimentally measured change in diffuse light reflectance and transmittance of cotton leaves as they mature and the theoretical and histological bases for the change are presented.

Cotton and most other crop plant leaves are very compact when they first unfold. As the leaves expand intercellular air spaces develop rapidly and the leaves thicken. In this study, between 3.5 and 8.0 days after macroscopically visible leaves were tagged, they expanded approximately fivefold, numbers of intercellular spaces approximately doubled, and thicknesses increased 14%. Total reflectance increased and total transmittance decreased over the wavelength interval 500 to 2500 nm up to an after-tagging-age of 12 days. After 12 days, reflectance decreased and transmittance increased.

A leaf with intercellular air spaces can be regarded as a pile of N compact layers separated by air spaces. The void area index (VAI) of a leaf with intercellular spaces (a noncompact leaf) is given by N-1 where N is not necessarily an integer. An equivalent water thickness (EWT) is the thickness of the leaf required to yield the reflectance and transmittance of a water layer of thickness D.

A young nonexpanded cotton leaf has a value of D/N about 180 microns which is essentially the leaf thickness. As intercellular air spaces develop during leaf expansion D/N decreases to a value of about 130 microns. Finally the leaf cells increase in size with essentially no increase in intercellular air spaces, this phase is characterized by a D/N of about 140 microns. During the leaf expansion period reflectance increased about 5% for laboratory-reared plants and about 15% for field-grown plants in the wavelength interval 750 to 1350 nm. Maximum reflectance corresponds to a minimum value of D/N.

This understanding of the interaction of near infrared radiation with plant leaves contributes much to understanding the response of remote sensors aimed at crops and provides a basis for anticipating differences among crops. The results also furnish additional evidence that the reflectance and transmittance characteristics of leaves are dominated by their structure and pigment contents in the 500 to 1350 nm wavelength interval and by their water content in the 1350 to 2500 nm wavelength interval.

CHAPTER IV. PHOTOGRAPHY AND OTHER IMAGERY INTERPRETATION

Aerial Film and its Interpretation.

The film types being used and the procedures being developed to extract quantitative digital data from film records by measuring optical density of the film to light transmittal by various filters are described. The contribution amounts to a primer on the films and filters used.

Shadow and other Background Effects on Optical Density of Film Transparencies.

The influence of crop shadows and sunlit furrows on processed Kodak Ektachrome infrared aero film can be detected by using red and blue bandpass filters in a microdensitometer. Responses due to shadows and sunlit soil can be separated from that of the crop plants alone.

Current Methods of Film Analysis.

In the past, optical density of film transparencies has been used directly in trying to identify soil, crops, and ground cover conditions. In this contribution differences between the optical densities measured with different bandpass filters which divide the visible spectrum roughly into thirds and represent the complements of each of the three dye layers in Kodak Ektachrome film, types 8442 and 8443, are investigated for identification and correlation with ground truth. Differences in 'f' stop setting, shutter speed, cloud conditions, film speed, filters, and other factors affect the optical density differences among bandpass filters much less than the optical densities themselves.

The method has been extended by fitting the optical density differences to regression equations over the range of film density to white light encountered. When film density to white light is taken into account, and the regression of film optical density differences are expressed accordingly, variation in a given target's signature among film rolls taken on different days, different times of the day, and differing in manufacture and processing are minimized. Computer programs have been written for the procedures used in Part I of this report. Results of use of these procedures are illustrated in Chapters I and V of this report.

Bendix Mapper Imagery.

The Bendix mapper was leased for a six week period in the summer of 1968 to provide imagery in the 700 to 2500 and 3500 to 5500 nm (0.7 to 2.5 and 3.5 to 5.5 microns, respectively) wavelength intervals on a continuing basis.

Imagery obtained with the mapper in the 0.7 to 2.5 micron region was similar to black and white IR film (response to 0.9 micron) imagery since both respond to the high reflectance of crop surfaces which begins at about 0.7 micron and extends to 1.4 microns.

Imagery obtained with the scanner in the 3.5 to 5.5 micron region was similar in appearance to black and white Plus-X film imagery in that plant surfaces which are not very reflective in the visible are also cool. However, low reflective surfaces which were hot had opposite response. Our conclusion is that at agricultural feature temperatures (around 310°K) the signal to noise ratio is unfavorable for use of the 3.5 to 5.5 micron wavelength interval; the 8 to 14 micron interval is favored for thermal scanning.

Care, Exposure, and Processing of Kodak Ektachrome Film and Paper.

The experience and recommendations of the photographic laboratory staff at Weslaco for storing, exposing, and processing Ektachrome film and paper are summarized.

CHAPTER V. SPECTRUM MATCHING AND PATTERN RECOGNITION

Discrimination of Vegetation by Multispectral Reflectance Measurements.

The leaves of corn, squash, and sorghum grown in the greenhouse and of sorghum, wheat, mature corn, cotton, sugar beets, potatoes, young corn, tomatoes, cabbage, and onions collected from the field have been analyzed for discrimination signatures based upon diffuse reflectance and transmittance measured in the laboratory over the spectral range 500 to 2500 nm. The discrimination criterion used was the infinite reflectance R_{∞}, defined as the maximum reflectance achieved by leaves stacked sufficiently deep. The largest differences in R_{∞} among species occur in the atmospheric windows 1500 to 1750 nm and 2000 to 2400 nm. Thus discrimination procedures using measurements of reflectance from space in these wavelength intervals show considerable promise.

The physical quantity indirectly sensed by a measurement of R_{∞} is the extent to which the water in a leaf has been subdivided by the cellular structure of the leaf. Over the wavelength interval 1400 to 2500 nm, the absorption spectra for typical leaves are not statistically different from that of pure liquid water. A practical reflectance maximum is reached when leaves are stacked two deep, corresponding to a leaf area index of 2, at the useful wavelengths.

Crop Species and Soil Condition Discrimination from Apollo 9 Imagery.

Ground truth from flight line 15A of the Imperial Valley was used to test the ability of Kodak Ektachrome infrared film type SO 180 to discriminate crop species or soil condition categories on SO-65 experiment 70 mm space photography on which the 303 fields occupy 12 square millimeters on the image. The signatures of 50 fields were selected for study. A procedure utilizing film optical density differences was employed. Salt flats and sugar beet fields were reliably identified. Alfalfa, barley, and bare fields could not be properly identified but 200X photomicrographs of the imagery reveal inhomogeneity in signatures of some fields. The overall percentage correct identification was 54%.

It was concluded that the signaturesof crop species at the photographic scale worked with are insufficiently different at the photographic wavelengths to have good discrimination capability using optical density differences. Absolute reflectance data are also presented for the wavelengths 550, 650, and 800 nanometers corresponding to the wavelengths of peak response of the three Ektachrome infrared aero film dye layers.

Cotton, Sorghum, and Bare Soil Discrimination on Ektachrome Infrared Imagery of the Lower Rio Grande Valley.

A computer program was developed to recognize fields of cotton, sorghum, and bare soil from their film optical density differences. Standard signatures are developed for each crop or soil condition of interest and a sum of squares of differences from the crop standards is obtained for each unknown. The unknown is identified as the crop or soil condition from which its signature differs minimally.

Of the four optical densities routinely obtained corresponding to red, green, and blue bandpass filters and no filter in the light beam of the microdensitometer, it is shown that only two of the optical density differences (red - none) and (green - none) suffice to unambiguously identify cotton, sorghum, and bare soil. The technique can be readily expanded to include more crop species and soil condition categories.

Bendix 9-channel Scanner Data Studies.

Overflights with the Bendix 9-channel scanner were made on April 13, May 8 and 9, June 6, and July 9, 1969, of lines on which over 440 fields have been ground truthed for each overflight. No analyses have been made since data are yet to be received. Ground truth, auxiliary measurements, and analyses planned are described. The data should yield much of scientific value as well as aid in defining an operational multi-channel scanner data handling capability, since NASA, Bendix, and USDA will cooperate in a signature data processing study using these data.

CHAPTER VI. EQUIPMENT CALIBRATION AND DEVELOPMENT

Procurement of a field spectrometer.

One of the aims of research in remote sensing at Weslaco is determination of the wavelength bands of energy reflected and emitted from crops and soils that are characteristic and useful for earth resources survey purposes. No instrument is available in Agriculture for the detailed studies that need to be made from an aerial lift which can remain over a target site over a period of time when soil moisture and growth changes are occurring or for diurnal studies when light intensity and sun angle are changing.

An instrument is being built for making measurements in the wavelength interval 0.35 to 14 microns. Four sensors will be used to measure the spectral energy in various bands. Each band will be scanned by rotating a circular variable filter (CVF) in the beam striking the sensor. Continuous recording of the output of the sensors will give a scan of the spectrum from the target area. The target areas will alternate between the ground surface and upward looking diffusion plate.

Random errors associated with measurement of the Kubelka-Munk parameters of a leaf.

The near-infrared reflectance and transmittance of plant leaves stacked in a spectrophotometer have been described by the Kubelka-Munk (K-M) theory for propagation of light through a diffusing medium. Either single leaves or a stack of leaves may be used. Use of stacked leaves enables one to detect instrument errors but requires a supplementary error analysis of the variance due to experimental uncertainties. Once instrument biases have been isolated and removed, the question of measuring single or stacked leaves becomes a matter of preference.

Equations for calculating the variances and standard errors of the optical constants absorption coefficient and scattering coefficient, as well as the Stokes coefficient a and b are presented.

CHAPTER VII. FOREIGN COOPERATION PROGRAM

Dr. Leamer of the USDA, ARS, SWC staff at Weslaco, Texas has been designated the agriculture representative of the USDA to NASA's International Participation Program. In this capacity he accompanied representatives of oceanography, hydrology, geology, and forestry to Brazil in January 1969 on the mission planning tour when sites were picked and objectives chosen for NASA's Mission 96 flown in July 1969. He also accompanied NASA's operation crew to Mexico for Mission 96 in April 1969. He was at the sites during flights over Toluca and Ixthahuaca and visited the Chapingo and Papaloapan test sites. He participated in the review session with NASA and Mexican representatives at MSC Houston of the photography and thermal imagery taken during the Mexican mission. Continuing cooperative efforts are anticipated.

USE OF APOLLO 9 SO-65 EXPERIMENT COLOR RECOMBINATIONS FOR SOIL SURVEY AND AGRICULTURAL FEATURE STUDIES

by

C. L. Wiegand, R. W. Leamer, and A. H. Gerbermann

Introduction:

Soil surveys by ground crews are expensive and time-consuming to make; the survey of a single county frequently takes 5 years or longer. The surveys are usually aided by low altitude black and white photography. One objective of this work was the assessment of the usefulness of space photography for delineating soil associations. A longer report has been furnished NASA[1]; in this report we present only enough data to illustrate the imagery and its application.

Methods and Procedures:

The SO-65 Experiment, "Multispectral Terrain Photography", was one of the scientific experiments conducted during the Apollo 9 mission. For this experiment 4 Hasselblad cameras were mounted in a common frame and triggered simultaneously. The film magazine of one camera contained black and white infrared film. The magazine of two cameras contained black and white Panatomic X film but filters were used so that in one case the film was exposed to the green wavelengths and in the other the red. Ektachrome infrared film was used in the fourth camera. The magazine designations, filters, bandpass of the filters and wavelengths of peak sensitivity of the film are as follows (Apollo 9 Preliminary Plotting and Indexing Report, 1969):

Magazine designation	Film type and filter	Wavelength of peak or plateau film sensitivity		Nominal filter bandpass
A	SO 180, Ektachrome infrared; Photar 15	Green, Red, Infrared,	550 nm 650 nm 800 nm a/	510 - 890 nm
B	3400, Panatomic X/ Photar 58 B	Green,	525 nm	470 - 610 nm
C	Black-and-white IR; Photar 89 B	Infrared,	800 nm	680 - 890 nm
D	3400, Panatomic X; Photar 25 A	Red,	645 nm	590 - 715 nm

a/ There is a small peak at 750 nm and a broad plateau beyond it.

1 Crop Species and Soil Condition Discrimination on Ektachrome Infrared Apollo 9 Imagery and Interpretation of Agricultural Features on SO-65 Experiment Color Recombinations.

The astronauts took pictures of preselected sites and targets of opportunity between March 8 and 12, 1969. Among them were targets of interest to Agriculture.

Immediately following the science screening in April, a request was made through NASA for two duplicate 70 mm transparencies of each of the four SO-65 images of frame AS-9-26A-3726 which is designated "Texas, Matagorda, Eagle Lake, and Freeport."

Simultaneously the Long Island University Science Engineering Group was requested to enhance, through color reconstitution (Yost and Wenderoth, 1968; Yost and Wenderoth, 1969) the vegetated fields, bare fields, permanent vegetation (trees, brush) and water bodies (ponds, lakes, and streams) depicted in the imagery. Positives processed to a gamma of 2.0 with a minimum density value equivalent to the base plus fog level of the film must be available to produce color recombinations (Yost and Wenderoth, 1969). Therefore, the Long Island University group had to make new internegatives and positives to obtain suitable scene brightness range and contrast.

General soil maps of the following Texas counties were obtained from the Soil Conservation Service, USDA, and the Agricultural Information Office, Texas A&M University: Wharton, Colorado, Matagorda, Jackson.

Results and Discussion:

Direct positive transparency to positive contact prints are presented of the Ektachrome infrared and multiband imagery of the SO-65 Experiment in Figure 1. In Figure 1 the Ektachrome infrared film image (upper left) is very sharp. The black and white transparencies seem to have become fogged during duplication. Exposures are good, however, except for the green band (upper right).

The color recombinations are presented in Figure 2. In Figure 2 the corners and edges of the space imagery are deleted from the color enhancements. Since 70 mm renditions of both are presented, the scales involved necessarily differ. This must be considered in comparing the resolvable features in the two formats.

The overlays for Figure 2 identify the highways, cities, streams, counties, soil associations, and water bodies, respectively. Interstate Highway 10 is visible over more of its length than is U.S. 59. Interstate highways, particularly if under construction, are discernible on space photographs.

One of the surprising things about the stream locations of the Colorado and Brazos Rivers is that they are not always where they appear to be. They have meandered and created flood plains which have since been subjected to agriculture. One sees a pattern he would associate with a river but the river isn't there. The stream of the Colorado River in the vicinity of Wharton is particularly deceiving.

The San Bernard River was very difficult to see even on enlargements.

Descriptions of the soil associations enumerated in the overlay of Figure 2 are given in Table I. The agreement between generalized county soil surveys and the appearance of the associations on the space imagery is good. The change from one soil association to another is more subtle in the space imagery usually than in the generalized soil maps. Variation in the color of the surface soil seems to be a big factor in obtaining signature differences in the recombinations.

There are very interesting differences in the tones of the water bodies in the color enhancements. The letters a, b, c, d, e, and f identify some of the more interesting ones.

Summary:

Color recombination imagery of the Southeast Texas Gulf Coast areas provided by Long Island University under contract with NASA, Houston, was studied for agricultural features of interest, namely soil associations, bare fields, cropped fields, and water bodies. The agreement between soil associations evident on the color recombined SO-65 imagery and generalized county soil surveys was good. More soil associations were generally identified in the maps than could be discerned on the space imagery and transitions between associations were more subtle than indicated on soil survey maps. It is concluded that space imagery would be a tremendously useful tool in soil survey.

Where there were actively growing plants in cultivated fields or dense natural vegetation, the very high reflectance of plants in the infrared compared with the green and red spectral bands caused the infrared response to dominate the recombinations in which it was used. Provision for differing the exposure indices for vegetated versus barren targets in future manned spacecraft photography is recommended.

Table 1.--Soil associations, characteristics, natural color, and color on recombination imagery of southeast Texas.

No. on Fig. 2	Soil association	Characteristic and occurrence	Natural color	Color on recombination a/
1	Lake Charles	Swelling, clayey, upland	Black to dark gray	Bluish brown
2	Edna-Barnard	Poorly drained, loamy, upland	Light gray to grayish brown	Bluish tones
3	Miller-Norwood	Clayey and silty, floodplain	Reddish brown	Off-white
4	Katy-Edna	Fine sandy loam, upland, acid	Gray and grayish brown	Tan or beige
5	Katy-Kenny	Sandy loam to loamy sand, acid, upland	Gray to grayish brown	Tan or beige

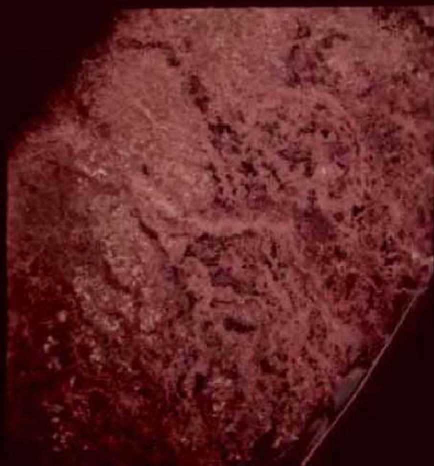
a/ On the recombination with the soils indicated on its overlay.

Literature Cited:

Mapping Sciences Laboratory, NASA, MSC, Houston. Apollo 9 Preliminary Plotting and Indexing Report. April 1, 1969.

Yost, E. and Sondra Wenderoth. Additive Color Aerial Photography. In: Manual of Color Aerial Photography, J. Smith, Editor, American Society of Photogrammetry. 1968.

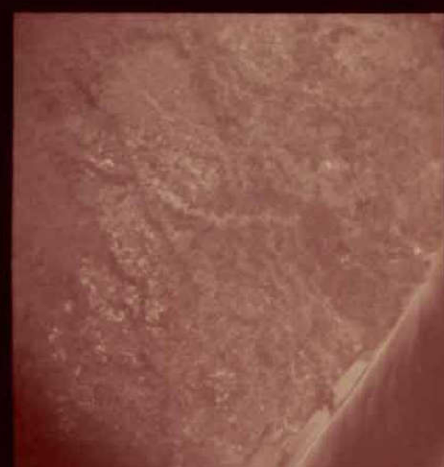
Yost, E. and Sondra Wenderoth. Hints for Experimenters NASA SO-65. Long Island University Science Engineering Research Group Technical Note 05, 10 pp. March 1969.



AS9 - 26A - 3726 A

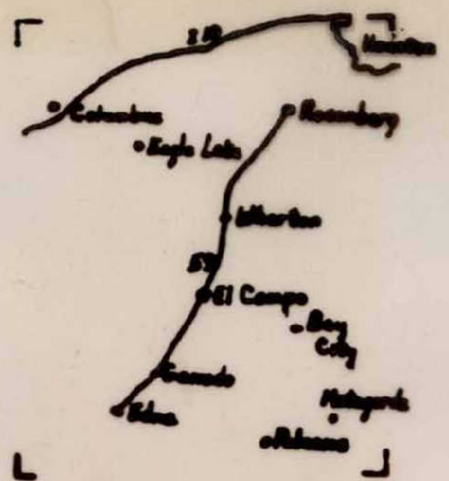
AS9 - 26B - 3726 B

AS9 - 26C - 3726 C



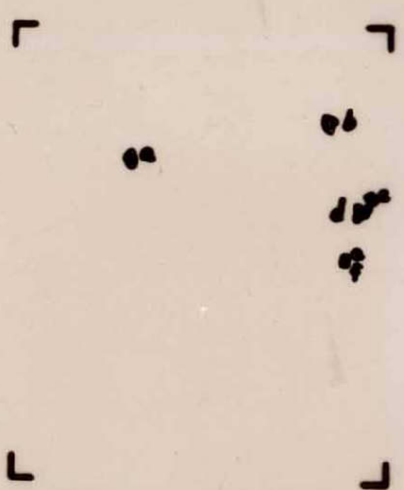
AS9 - 26D - 3726 D

Fig. 1. Apollo 9 frame 3726 Ektachrome infrared (top left), Panatomic X green band (top right), black and white infrared (lower left), and Panatomic X red band (lower right) images of the Freeport, Matagorda, Eagle Lake area of southeast Texas.



CITIES AND ROADS

STREAMS



LAKES AND RESERVOIRS

COUNTIES AND SOILS

3726 Red Band - Green
CX-17-1 IR Band - Red

3726 Green Band - Blue
Red Band - Green
CX-17-2 IR Band - Red

3726 Red Band - Red
CX-17-3 IR Band - Green

3726 Green Band - Green
Red Band - Red
CX-17-4 IR Band - Blue

Fig. 2. Four color reconstituted images of the southeast Texas area. For the color reconstituted images, the information ahead of the hyphen under each image gives the wavelength bands of Fig. 1 black and white imagery used; the color after the hyphen is the color of filter used in reconstituting the band.

THE INFLUENCE OF AMMONIA INDUCED CELLULAR DISCOLORATION WITHIN COTTON LEAVES (Gossypium hirsutum L.) ON LIGHT REFLECTANCE, TRANSMITTANCE, AND ABSORPTANCE

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ABSTRACT

Cotton plants were grown hydroponically in a controlled environment. Five leaves of the same chronological age, third node down from plant apexes, were randomly harvested from 10 uniform plants. Each leaf was divided into lateral halves (sections) at the midrib. The right sections were left untreated (controls), and the left sections were treated with approximately 10,000 ppm anhydrous ammonia. Spectrophotometric reflectance and transmittance measurements were made at 50-mμ increments within the wavelength interval 500 - 2500 mμ.

Ammonia-treated compared with untreated leaf sections had a progressive reduction in reflectance and transmittance and a progressive increase in absorptance within the near-infrared light interval from 1000 - 750 mμ. Reflectance decreased 4.1, 20.0, and 29.8%; transmittance decreased 9.9, 26.5, and 39.5%; and absorptance increased 14.1, 46.5, and 69.2% at 1000, 850, and 750 mμ, respectively. At the green wavelength, 550 mμ, reflectance and transmittance were decreased approximately 4 and 10% and absorptance was increased 20%, respectively.

Microscopic examination of ammonia-treated, transverse leaf sections revealed that a brownish discoloration occurred mainly within palisade and spongy parenchyma cells. Cell walls were intact. Some chloroplasts were ruptured and discolored but many appeared to be unaffected by ammonia treatment. The cell cytoplasm was usually discolored and often appeared to be coagulated. Theoretically, the brownish pigmentation was caused by saponification of chlorophyll and oxidation and polymerization of phenol oxidases. Internal discoloration caused leaves to become more opaque, and absorptance of near-infrared and visible light was increased.

Results with ammonia-treated leaves are compared with other studies where reduced reflectance occurred, particularly over the wavelength interval 750 - 900 mμ. It is possible that this wavelength band may become useful in remote sensing for identifying certain non-visual symptoms of plant leaf stresses.

INTRODUCTION

Spectrophotometric light reflectance, transmittance, and absorptance of individual plant leaves has been intensively studied in the wavelength interval 400 - 2500 mμ. From 400 - 750 mμ plant leaf reflectance is relatively low, with a peak of approximately 10% at 550 mμ in the green region. The reflectance of a leaf increases to about 50% in the near-infrared region and is relatively constant over the wavelength interval 750 - 1350 mμ, a spectral interval for plant materials commonly called the plateau region. A transmittance spectrum has the same shape and approximately the same magnitude as a reflectance spectrum. Absorptance is high in the visible region because of leaf pigments and in the infrared beyond 1350 mμ because of water, but absorptance is at the most 1 or 2% in the 750 - 1350 mμ plateau region (Gausman, Allen, and Cardenas, 1969).

Colwell (1956), while working primarily with cereal rusts, suggested the use of infrared film for recording any disease which interfered with the internal reflection of light within leaves. Keegan (1956), with Colwell's assistance in collecting leaf specimens, did extensive research on effects of stem rust (Puccinia graminis tritici) and leaf rust (Puccinia triticina or Puccinia rubigo-vera tritic) of wheat on light reflectance. Keegan's data showed that severe compared with low rust infestation caused a rounding of the shoulder of the plateau or a decrease in reflectance from 1000 - 750 mμ. This same response in reflectance was noted by Gausman and Cardenas (1968) after hair removal on upper leaf surfaces of the velvet plant (Gynura aurantiaca). It was noted by Allen and Richardson (unpublished data) that the hair removal of leaf hairs had little effect on the refractive index of the velvet plant's upper leaf surfaces, but leaf absorptance was greatly increased within wavelength interval 750 - 1000 mμ. It was theorized that oxidation of polyphenols caused a brownish discoloration of the exudate from "stumps" after hair removal, thus increasing leaf opaqueness with a subsequent increase in absorptance and decrease in reflectance (Gausman and Cardenas, 1969).

The research summarized herein considers the influence of cellular discoloration within leaves on near-infrared light reflectance.

MATERIALS AND METHODS

Cotton leaves (*Gossypium hirsutum* L., Texas Planting Seed Association 110) were obtained from plants grown hydroponically in acid-washed, 20-30 mesh testing sand in 23-cm-diameter glazed, 7.6 liter capacity crocks. The sand was rewashed with .001 N nitric acid to remove chloride and leached several times with chloride-free water (silver nitrate test).

The basic nutrient solution used was after Hoagland and Arnon (1938). Iron was added as iron-ethylenediaminetetraacetic acid (Nieman and Poulsen, 1967). The nutrient solution had a pH of 7.

All plants received one-fourth-strength nutrient solution in their first week of growth. Thereafter, full strength nutrient solution was used. Copious applications of nutrient solutions were made by surface irrigation to maintain uniform matric water suction in the substratum.

Cotton plants were grown with controlled environment using a 12-hour light-dark cycle. Light illuminance approximated 800 ft-c (8.6×10^{-1} lumen cm^{-2}), 50 cm above the substratum surface. Ranges of other parameters were as follows: day temperature, 28.6° - 30.5°C, night temperature, 24.0° - 25.5°C; day relative humidity, 39 - 40%, night relative humidity, 40 - 45%.

Five leaves of the same chronological age from the third node down from plant apexes were randomly harvested from 10 uniform plants. Each leaf was divided into two sections by removing the midrib. The right leaf sections were left untreated (controls) and the left leaf sections were treated with anhydrous ammonia.

Five leaf sections were placed on a screen in each of two, air-tight desiccators, each having a 9,040 cc capacity. A water-saturated sponge with a volume of 110.5 cm^3 had been placed on the bottom of each desiccator to prevent leaves from drying out. The wire screen with 0.5 cm^2 holes was placed above each sponge to separate the leaves from the water-saturated sponges. Both desiccators had the same light and temperature (20°C) conditions. The desiccator used for treatment was injected with 89 cc of anhydrous ammonia to give a concentration of approximately 10,000 ppm after correcting for the sponge volume. The leaf sections were removed from both desiccators after 3 hours and immediately wrapped in Saran [1] to avoid water loss.

Thickness measurements were made on each leaf section before and after treatment at two locations with a linear displacement transducer and digital voltmeter (Heilman _et al._, 1968).

Reflectance and transmittance measurements were made on upper surfaces of leaf sections with a Beckman Model DK-2A spectrophotometer at 50-mμ increments within the wavelength interval 500 - 2500 mμ. Data have been corrected for a decrease in reflectance of the MgO reference caused by deterioration during aging (Sanders and Middleton, 1953). Analyses of variance were conducted on spectral data (Steel and Torrie, 1960).

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1 Trade names and company names are included for the benefit of the reader and do not imply an endorsement or preferential treatment of the product listed by the U. S. Department of Agriculture.

Pieces of leaf tissue were taken near the center of leaves approximately 2 cm on either side of the midrib. They were fixed in formalin-acetic acid-alcohol (Jensen, 1962). Tissues were dehydrated with tertiary butyl alcohol and embedded with paraffin (melting point about 52°C). Transverse sections were obtained with a rotary microtome.

Photomicrographs were made with a Zeiss Standard Universal Photomicroscope at a magnification of 100 X. The 4 X enlargement of a photomicrograph in Fig. 4 represents transections having a thickness of 14 μ.

RESULTS AND DISCUSSION

Figure 1 shows the influence of ammonia and control treatments on total light reflectance of leaf sections over wavelength interval 500 - 2500 mμ. Discoloration of leaf sections became noticeable soon after placing them in the ammonia atmosphere. As shown later, the discoloration occurred mainly in chloroplast-containing palisade and spongy parenchyma cells. The difference between treated and control spectral means was statistically significant, $p = .01$. Ammonia treatment of leaf sections reduced reflectance about 4.5% at the green peak of 550 mμ compared with untreated leaf sections. Between 1000 - 750 mμ, a rounding of the plateau or decrease in reflectance of 4.1, 20.0, and 29.8% occurred at 1000, 850, and 750 mμ, respectively. Ammonia treatment had no statistically significant effect on leaf thickness. Over the wavelength interval 1000 - 2500 mμ, ammonia-treated leaf sections had about 2% higher reflectance than the controls with crossing-over (lower reflectance) occurring at 1150 mμ. It was suspected that the increase in reflectance was caused by water loss because the ammonia was anhydrous. There was no significant difference, however, in leaf water moisture. An average of 77.8 and 77.4% water was present (oven dry weight basis at 68°C) for untreated and treated leaf sections, respectively. Further study on the influence of ammonia on light reflectance needs to be made over the wavelength interval 1150 - 2500 mμ.

Figure 2 illustrates the effects of ammonia and control treatments on light transmittance of leaf sections over wavelength interval 500 - 2500 mμ. Ammonia compared with the control treatment reduced transmittance about 17.0% at the 550 mμ green peak. Rounding of the plateau, decrease in transmittance, occurred in the interval 1350 - 750 mμ. This effect was essentially linear (progressive decrease) from 1000 - 750 mμ. Approximate values were 9.9, 26.5, and 39.5% for 1000, 850, and 750 mμ, respectively.

Figure 3 indicates absorptance of light over wavelength interval 500 to 2500 mμ, calculated as absorptance = 100 - (% reflectance + % transmittance). It is apparent that the reduced reflectance and transmittance revealed in Fig. 1 and 2, at the 500 mμ green peak and over the wavelength interval 750 - 1350 mμ, were caused by the increased absorptance shown in Fig. 3. Absorptance progressively increased for treated leaves from 1000 - 750 mμ. Values were 14.1, 46.5, and 69.2% for 1000, 850, and 750 mμ, respectively.

Figure 4 is a representative, unstained transection of an ammonia-treated leaf section showing internal discoloration. It is evident that a brownish discoloration occurred within chloroplast-containing palisade and spongy parenchyma cells. Very little discoloration occurred in upper or lower epidermal cells. Microscopic examinations revealed that cell walls of discolored cells were intact. Some chloroplasts were deformed or ruptured and discolored, but many appeared to be unaffected by ammonia treatment. The cell cytoplasm was usually discolored and often appeared to be coagulated. Anhydrous ammonia probably reacted with water in the leaf sections to form ammonium hydroxide (NH_4OH) which coagulated the cytoplasmic proteins. A leaf is normally highly transparent to light over the wavelength interval 750 - 1350 mμ. It is theorized that the brownish discoloration increased leaf opaqueness and thereby increased absorptance and reduced reflectance and transmittance over wavelength intervals 750 - 1350 mμ (near infrared) and 500 - 750 mμ.

Since anhydrous ammonia would probably react with water in leaf sections to form NH_4OH, the discoloration may have been caused by the reaction of NH_4OH with chlorophyll. It is well documented (i.e. Goodwin, 1966) that treatment of chlorophyll in vitro with a hot alkali (saponification), usually sodium or potassium hydroxide, yields porphyrins containing four pyrrole nuclei. These are red compounds. If saponification of chlorophyll is conducted in vitro in methyl alcohol, a brown color is produced. All porphyrins have four absorption bands between 500 - 700 mμ (Robinson, 1963).

Figure 5 describes a second chemical reaction which produces brown pigmentation (Bonner and Galston, 1952), which probably occurred concurrently with chlorophyll saponification. The severe treatment with anhydrous ammonia ruptured some chloroplasts and undoubtedly affected the permeability of the chloroplastic membranes, thus releasing polyphenoloxidase into the cellular cytoplasm. Then oxidation and polymerization of polyphenoloxidase to a brown pigmentation would occur.

This discoloration was also noted when pubescent (hairy) leaves of Gynura aurantiaca (velvet plant) were shaven with an electric razor (Gausman and Cardenas, 1968). The exudates developed a brownish color on the "stumps", which remained after hair removal by shaving. The above examples and other conditions which also caused decreased reflectances are illustrated in Fig. 6 for the wavelength interval 750 - 900 mμ. This spectral range may have practical possibilities as a wavelength band for detecting non-visual symptoms of plant leaf stresses by remote sensing. As shown in Fig. 6, reflectance in this range was reduced by severe rust infection on Westar wheat leaves (Keegan, 1956), benzene vapor on cotton leaves, natural freezing of Coccolobis uvifera (sea grape) leaves (Cardenas and Gausman, unpublished data), ammonia treatment of cotton leaves (this paper), and hair removal by shaving velvet plant leaves (Gausman and Cardenas, 1968). At 800 mμ, decreases in reflectances compared with experimental controls were 26.2, 10.8, 4.8, 3.6, and 2.0% for ammonia, wheat rust, benzene, hair removal, and natural freezing studies, respectively. Hair removal, ammonia and benzene treatment, and freezing caused discoloration which increased leaf opaqueness, decreased reflectance and increased absorptance. Relative to rust damage, Bawden (1933), Clark (1946), and Colwell (1956), theorized that fungus hyphae penetrate the intercellular spaces and release by-products that absorb infrared radiation. The fungal hyphae, however, which penetrate plant cells and form haustoria are hyalin (translucent). If cell damage occurs by hyphae penetration, it would seem feasible that some oxidation and polymerization of polyphenoloxidase would occur with a resulting brown color as postulated for results of the ammonia treatment of leaf sections.

CONCLUSION

Cellular discoloration within leaves has important practical implications. The effect on decreasing reflectance (rounding of the plateau) within the wavelength range from 1350 - 750 or 700 mμ, should be useful for detecting non-visual symptoms of plant leaf stress by remote sensing applications. A wavelength band of 700 - 900 mμ may be best, since this contains the sharp drop in reflectance from the plateau shoulder caused by chlorophyll absorptance.

ACKNOWLEDGMENTS

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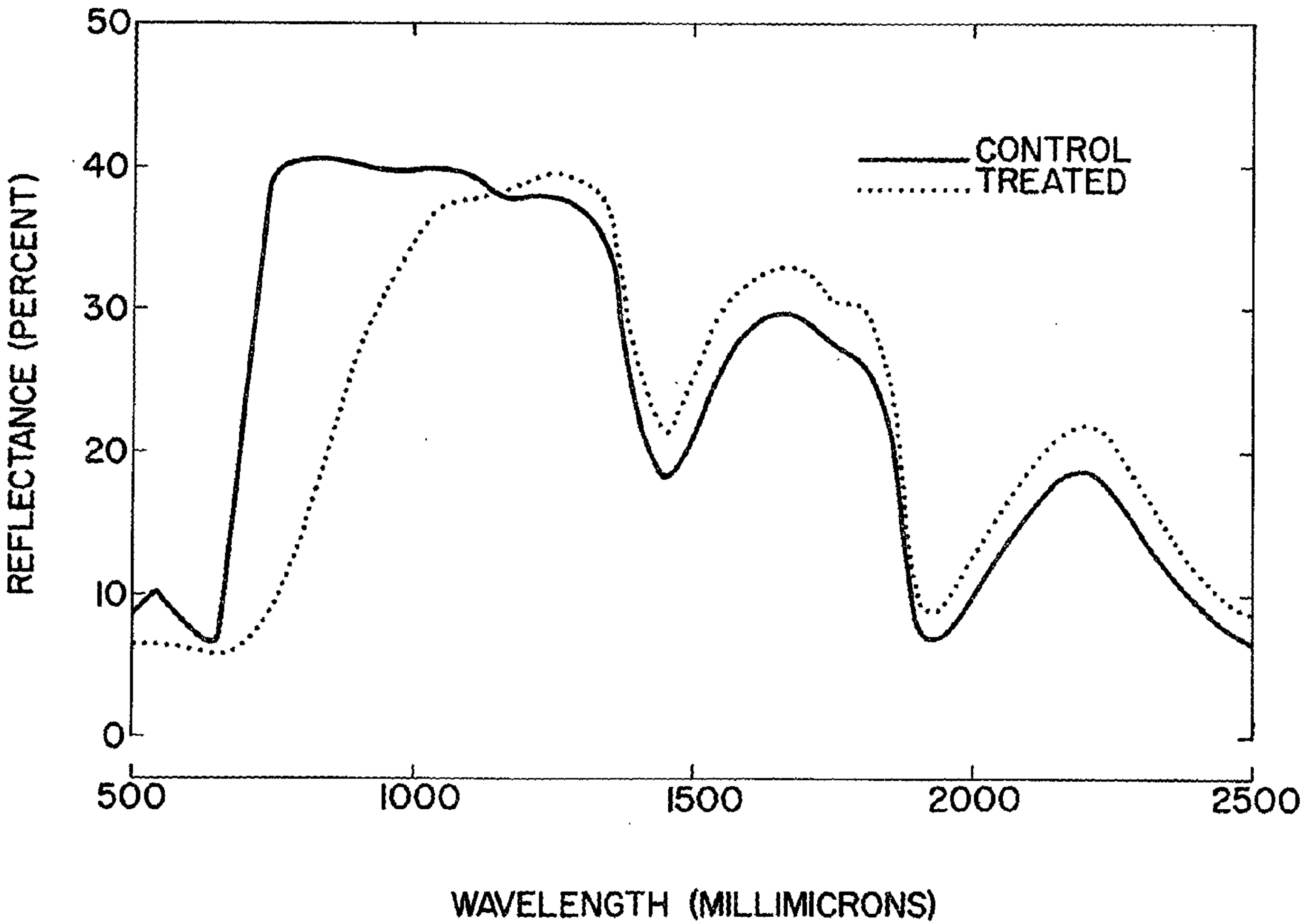

Fig. 1. Total light reflectance of upper surfaces of cotton leaf sections, control (untreated) and ammonia-treated. Each spectrum is an average of five leaf sections.

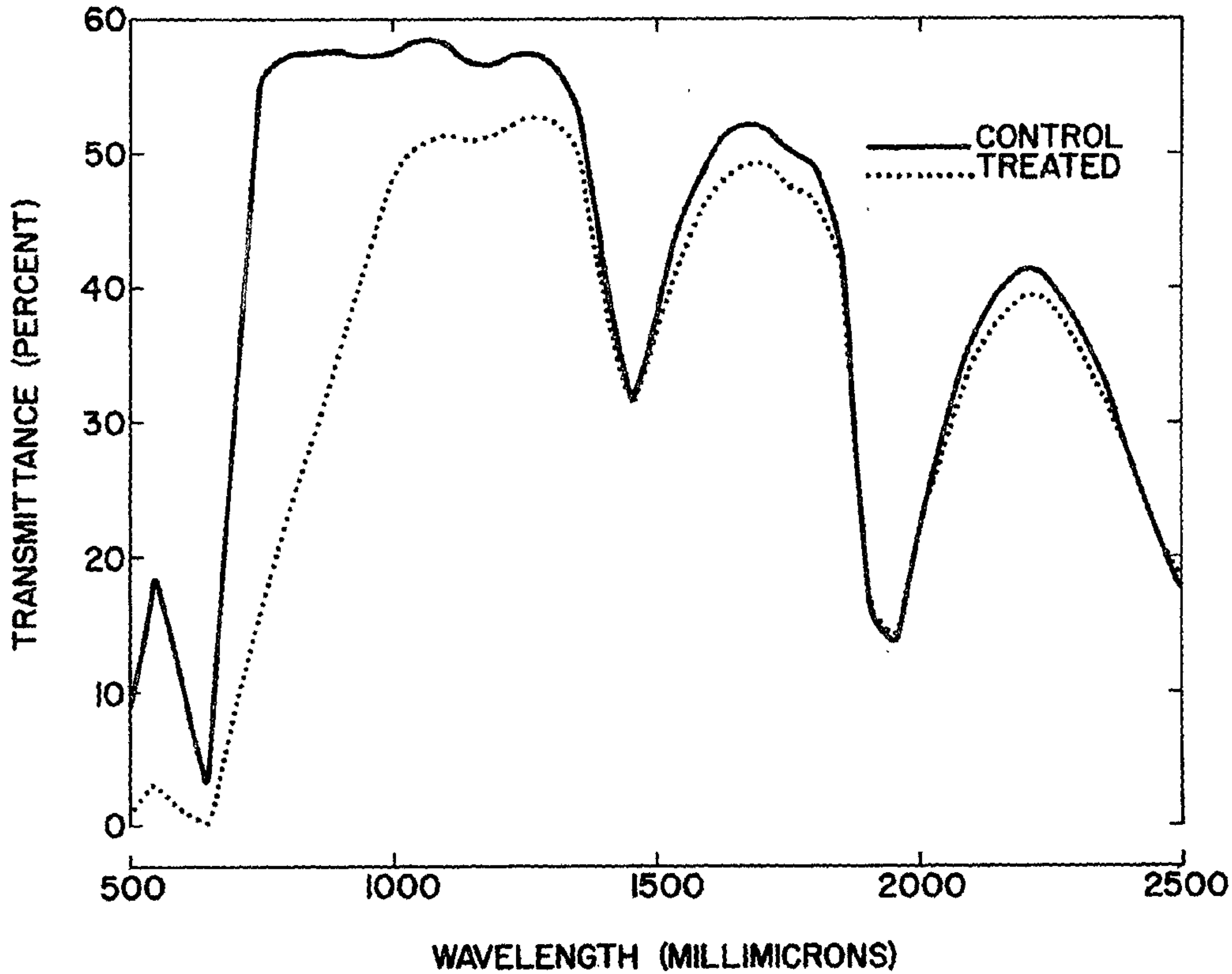

Fig. 2. Total light transmittance of cotton leaf sections, control (untreated) and ammonia-treated. Each spectrum is an average of five leaf sections.

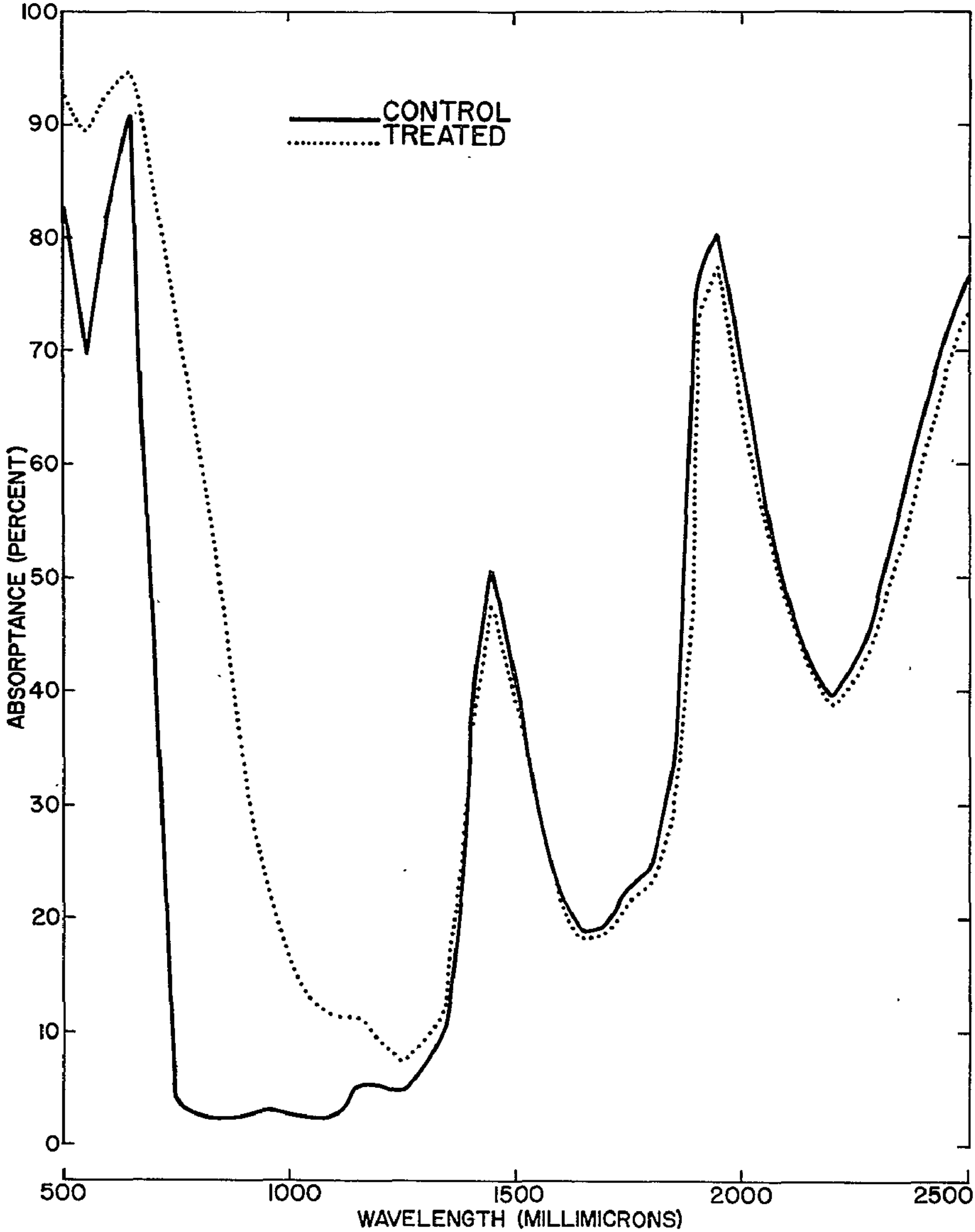

Fig. 3. Total light absorptance of cotton leaf sections, control (untreated) and ammonia treated. Each spectrum is an average of five leaf sections.

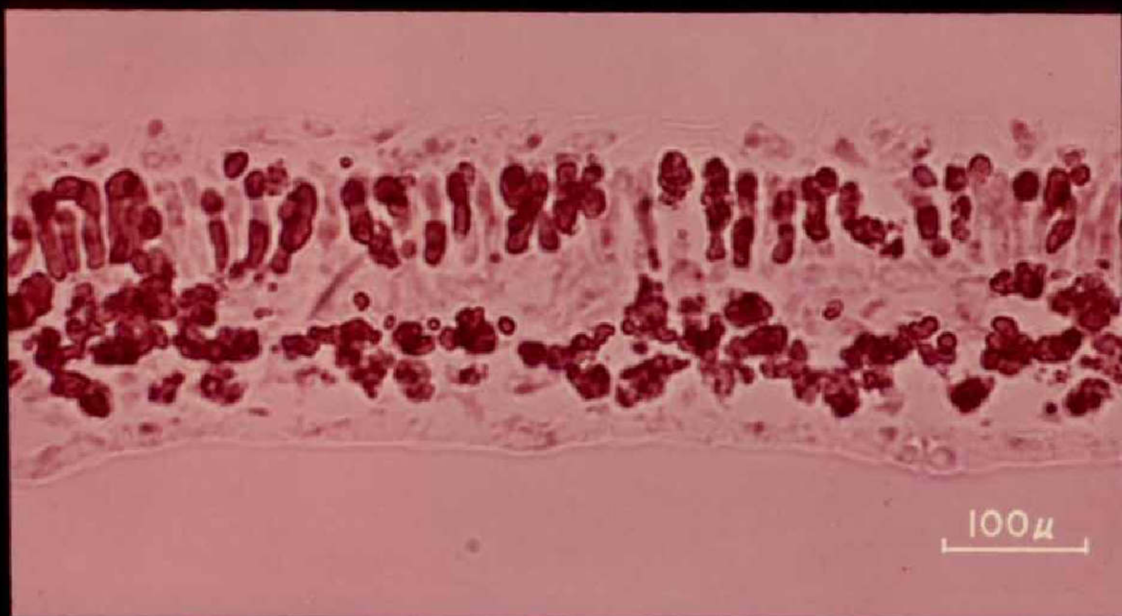

Fig. 4. Photomicrograph representing unstained, transverse sections of ammonia-treated cotton leaves. 400 X

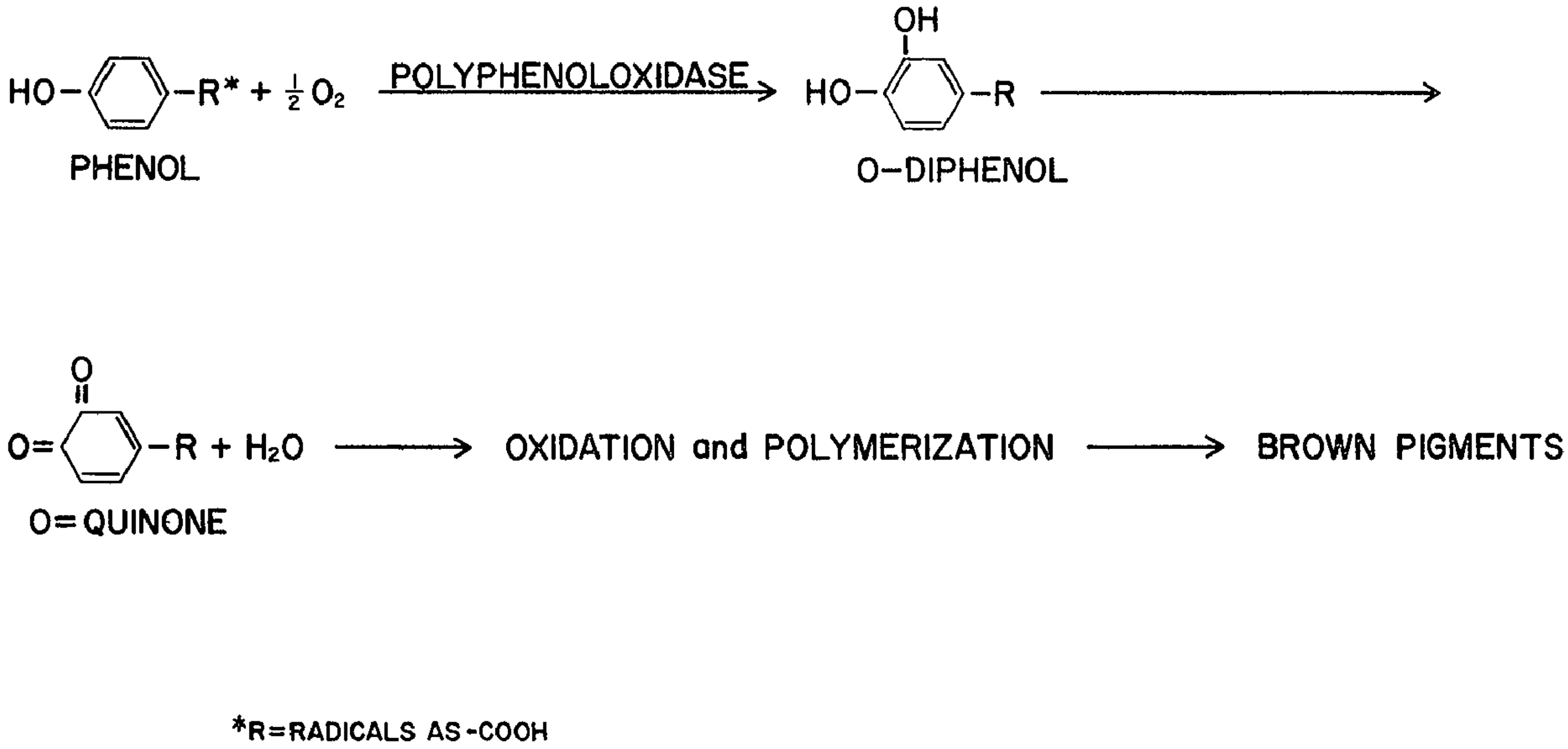

Fig. 5. Diagram showing the oxidation and polymerization of polyphenoloxidase to brown pigments.

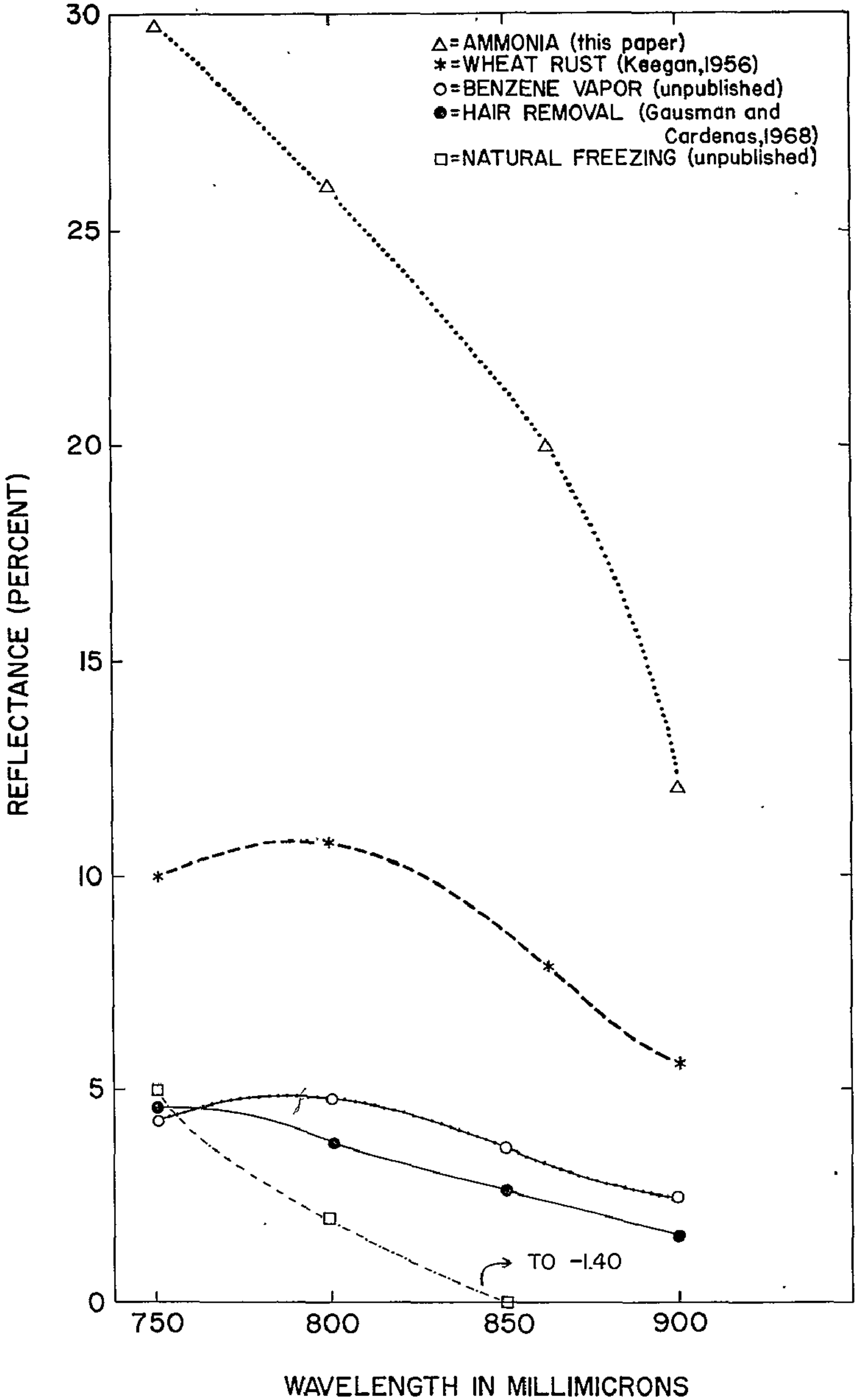

Fig. 6. Influence of (1) treatment of cotton leaves with ammonia and (2) benzene gases, (3) rust infection of Westar wheat leaves, (4) hair removal from the velvet plant by shaving, and (5) natural freezing of sea grape leaves on reducing light reflectance from their upper surfaces over the wavelength interval 750-900 mμ. Values plotted in the figure are decreases in reflectances compared with corresponding experimental controls.

REFLECTANCE OF SINGLE LEAVES AND FIELD PLOTS OF CYCOCEL-TREATED COTTON (Gossypium hirsutum L.) IN RELATION TO LEAF STRUCTURE

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SUMMARY

Leaves from cotton plants sprayed with 100 gm/ha Cycocel in a field experiment were about 40% thicker and 20% larger in surface dimension than non-Cycocel-sprayed leaves. Cycocel-treated leaves had an approximate threefold increase in numbers of intercellular spaces within their mesophylls. Spectrophotometric measurements of spectra of individual leaves over the wavelength interval 500 - 2500 mμ revealed a 5% increase in reflectance over the wavelength interval 500 - 1350 mμ and a 6% decrease in transmittance over the entire 500 - 2500 mμ interval for treated compared with untreated leaves. Increased reflectance and decreased transmittance over the wavelength interval 750 - 1350 mμ were mainly associated with increased numbers of air spaces in leaf mesophylls. Decreased transmittance of Cycocel-treated leaves over wavelength intervals 500 - 750 and 1350 - 2500 mμ was due to increased absorptance caused by increased chlorophyll and water contents, respectively. The Cycocel treatment increased absorptance 13% at the chlorophyll absorption band, 550 mμ; only 2 - 3% over the wavelength interval 750 - 1350 mμ; and 10 and 11% at the water absorption bands approximating 1450 and 1950 mμ, respectively. Near-infrared light reflectance from single leaves,

measured with a spectrophotometer, was inversely related and visible light reflectance was directly related to the reflectivity of field plots of cotton recorded on Kodak Ektachrome infrared aero film, type 8443, with a Kodak Wratten No. 15(G), light-orange filter, during an overflight.

INTRODUCTION

Tolbert (1960a and 1960b) first reported the plant growth regulating properties of CCC or Cycocel [1] ((2-chloroethyl) trimethyl-ammonium chloride). Its chemical formula is: $(CH_3)_3N^+\text{-}CH_2\text{-}CH_2Cl \cdot Cl^-$.

Cycocel was tested on cotton (Thomas, 1964) with the objective of dwarfing plants to facilitate defoliant application and mechanical harvesting.

Cycocel induced wider, thicker, and greener leaves; and shorter internodes on several plant species (Humphries and Wheeler, 1963; Appleby _et al._, 1966; Goodin _et al._, 1966; Larter, 1967; and Adedipe _et al._, 1968). It increased cell wall thickness and number of vascular bundles in the wheat stem (Mayr and Presoly, 1963).

It was surmised that the use of Cycocel would cause changes in internal leaf structure. Preliminary investigations (unpublished data, Gausman, Allen, and Cardenas) indicated that Cycocel-treated compared with untreated cotton leaves were wider with more intercellular spaces within their mesophylls. The primary purposes of this paper are to relate Cycocel-induced increases in numbers of air spaces in cotton leaf mesophylls to (1) spectrophotometric measurements made on individual leaves, and (2) to tonal responses on an infrared photograph taken from an overflight of the experimental plots.

[1] Trade names and company names are included for the benefit of the reader and do not imply an endorsement or preferential treatment of the product listed by the U. S. Department of Agriculture.

MATERIALS AND METHODS

Cotton leaves, variety Stoneville A, were sampled from one block of a replicated field experiment with Cycocel conducted by Heilman, Gonzalez, and Salinas on the research farm of the U. S. Department of Agriculture at Weslaco, Texas. Treatments considered in this paper are: Cycocel at 100 gm/ha (.545 lb./A.) applied as a spray in enough water to produce runoff at the square stage of plant development, 76 days after planting; and a control (untreated) where plants were sprayed with only the amount of water used for applying the Cycocel treatment.

Fifteen leaves were harvested for each treatment, 92 days after planting (16 days after treatment), from the fourth node down from apexes of cotton plants. The leaves were wrapped immediately in Saran to minimize water loss. The leaves were essentially the same chronological age, since treated and untreated plants had equal numbers of nodes. In the laboratory, five leaves were randomly selected from each group of 15 leaves for spectrophotometric measurements. The time between excising of leaves and measurement of their reflectance and transmittance was approximately 4 hours. Spectra presented herein represent mean values for each set of five leaves.

The thickness of each leaf was measured at three locations with a linear displacement transducer and digital voltmeter (Heilman et al., 1968). Leaf area was determined by the method of Johnson (1967).

Spectral diffuse reflectance on upper (adaxial) surfaces of single leaves and transmittance were measured over the wavelength interval 500 to 2500 mμ with a Beckman Model DK-2A spectrophotometer and its reflectance attachment. Data have been corrected for the reflectance of the MgO standard (Sanders and Middleton, 1953) to obtain absolute radiometric values.

For histological studies, leaf tissue was fixed in FAA (formalin-acetic acid-alcohol); dehydrated with a tertiary butyl alcohol series; infiltrated and embedded with paraffin (melting point about 52°C); and stained with safranin-fast green (Jensen, 1962). Photomicrographs of transverse sections, 12 μ thick, were made with a Zeiss Standard Universal Photomicroscope.

An overflight of the experimental plots was made at an altitude of 3000 ft. at 11:56 a.m., daylight saving time, June 21, 1968, one day after leaf samples were taken, 17 days after treatments were applied. Photographs were taken with a 50 mm lens, Hasselblad camera, using 70 mm Kodak Ektachrome infrared aero film, type 8443; and a Kodak Wratten No. 15(G), light-orange filter. Color densities of the treated and untreated plots on the positive transparency were compared with a densichron densitometer using a blue band pass filter. A black and white infrared negative, film exposed with a Kodak 89(B) filter to exclude visible light under conditions comparable to those for the Ektachrome infrared aero film, was also scanned with the densitometer. This was done to help determine if Cycocel-treated or untreated cotton plants were reflecting the most near-infrared light.

Kodak Ektachrome infrared aero film, type 8443, has three image layers sensitized to green, red, and infrared radiation (Fritz, 1967). A light-orange filter, Kodak Wratten No. 12 or 15 or equivalent, is used over the camera lens to absorb approximately 100% of the blue radiation to which all three layers are sensitive. Upon processing, process E-3, yellow, magenta (purplish-red), and cyan (greenish-blue) positive images appear in the green-, red-, and infrared-sensitive layers, respectively. The relative exposure produced in each film layer determines the many possible colors or tonal responses. Healthy plant leaves reflect "brightly" in infrared which produces a light-toned cyan image allowing the red formed in the other layers to predominate.

Statistical techniques were applied to the data (Steel and Torrie, 1960).

RESULTS AND DISCUSSION

Cycocel-treated cotton plants had shortened internodes on growth produced after treatment, and thicker, larger leaves. Average heights of untreated and Cycocel-treated plants, 4 days after leaf sampling, were significantly different, $p = .01$, and were 106 and 83 cm, respectively. Percentages of ground cover, however, in treated and untreated plots were essentially alike.

In discussing spectrophotometric results, the spectral responses within the wavelength interval 750 - 1350 mμ will be stressed, because they are affected largely by internal leaf structure (Gausman et al., 1969). Absorptance by pigments dominates the 500- to 750-mμ interval, and the region above 1350 mμ is influenced greatly by the amount of water in the leaf - strongest water absorption bands occur at approximately 1450 and 1950 mμ.

Figure 1 shows that treatment of cotton leaves with 100 gm/ha of Cycocel, compared with results from untreated leaves, increased their reflectance approximately 5% (statistically significant, p = .01) over the wavelength interval 750 - 1350 mμ. As shown later, increased reflectance was associated with more intercellular spaces in the mesophylls of Cycocel-treated leaves, which increased light scattering. Increased light scattering for Cycocel-treated leaves is also apparent over the wavelength interval 1600 - 1900 mμ, but beyond 1900 mμ, light absorptance by water offset the effects of increased scattering and, therefore, the two spectra coincide. In this respect, Cycocel treatment significantly increased, p = .01, the percentage of water in leaves based on oven drying at 68°C. Average values were 67.1 and 59.1% for the Cycocel-treated and untreated leaves, respectively.

The 100-gm/ha Cycocel treatment significantly decreased, p = .01, transmittance over the entire wavelength interval 500 - 2500 mμ, Fig. 2. The decrease in transmittance over the 500-to 750-mμ interval was probably caused by increased absorptance as a result of increased plastid pigment content. Although chlorophyll determinations were not made in this study, Cycocel-treated leaves were darker green, and it is well documented in the literature that Cycocel increases the chlorophyll content of leaves; e.g., (Appleby et al., 1966). The decrease in transmittance over the range 750 - 1350 mμ was caused by changes in the internal structure of leaves which enhanced light scattering; thereby increasing reflectance and decreasing transmittance. Beyond 1350 mμ, the decrease in transmittance may be attributed to additive effects of water absorptance and scattering.

Absorptance of light was calculated as: % absorptance = 100 - (% reflectance + % transmittance). The Cycocel treatment increased absorptance 13% at the chlorophyll absorption band of 550 mμ, only about 2 - 3% over the wavelength interval 750 - 1350 mμ, and 10 and 11% at water absorption bands approximating 1450 and 1950 mμ, respectively.

Figure 3 shows photomicrographs of transverse sections of cotton leaves from untreated (upper photomicrograph) and Cycocel-treated plants (lower photomicrograph). Untreated leaves had a more compact cellular arrangement in the leaf mesophylls, with fewer and smaller intercellular spaces. This type of structure was associated with lower reflectance and higher transmittance over the wavelength interval 750 - 1350 mμ, Fig. 1 and 2. Treatment with Cycocel induced statistically significant, p = .01, expansion and thickening of the leaf which gave an approximate threefold increase in number of intercellular spaces in the leaf mesophylls. This type of structure gave higher reflectance and lower transmittance over the wavelength interval 750 - 1350 mμ, Fig. 1 and 2. Average areas per leaf were 96 and 77 cm^2 and average thicknesses were .25 and .18 mm for Cycocel-treated and untreated leaves, respectively. Results support the theory of Willstätter and Stoll (1913). Reflectance of Cycocel-treated leaves was increased because of an increase in numbers of intercellular spaces.

Figure 4 is a photograph (40 X enlargement of a positive print from a positive transparency) taken over the experimental plots with Kodak Ektachrome infrared aero film. Plot A with highest reflectivity (lighter tone) and plot B with lowest reflectivity (darker tone) represent untreated and Cycocel-treated cotton, respectively. A significant difference, p = .01, existed between average densitometer readings, using a blue filter and the positive transparency, corresponding to 8.5 and 4.4% transmission for the untreated and treated plots, respectively.

Spectrophotometric and histological results on individual leaves relative to near-infrared light reflectance, Fig. 1, 2, and 3, are inversely related with the reflectivity (tonal responses) from the untreated and Cycocel-treated plots, Fig. 4. Individual leaves from the Cycocel-treated plot B (darker tone on photograph), compared with individual leaves from untreated plot A (lighter tone on photograph), had higher reflectance and lower transmittance over the wavelength interval 750 - 1350 mμ, primarily because of the approximate threefold increase in the numbers of intercellular spaces in their mesophylls. Thus, low reflectivity (dark tone) for plot B is associated with high infrared reflectance from individual leaves from its cotton plants, and high reflectivity (light tone) for plot A is associated with low infrared reflectance of individual leaves from its cotton plants. This inverse relation has been noted in other studies. Thomas _et al_. (1967) found that reflectance from single leaves increased as soil salinity increased, but aerial photographs of field cotton on nonsaline and saline soils showed greater reflectivity from cotton not affected by salt (Ektachrome infrared aero film was used).

Two possible reasons for the inverse relation between spectrophotometric near-infrared reflectance measurements on individual leaves and the reflectivity recorded on photographic film from overflights are: (1) successive layers of stacked leaves, simulating a plant canopy, enhances near-infrared light reflectance (Myers and Allen, 1968); (2) leaves near apexes of cotton plants have more compact mesophylls than some older, subtended leaves (Gausman et al., 1969). Reflectance of light for wavelength interval 750 - 1350 mμ was positively correlated with leaf maturation, leaves sampled down the stem in succession, until leaves on the eighth node down from plant apexes were sampled, when leaf thicknesses and numbers of intercellular spaces in leaf mesophylls ceased increasing.

Stacking of leaves increases reflectance and decreases transmittance (Myers et al., 1966). The interaction of light with stacked leaves has been explained with the Kubelka-Munk theory (Allen and Richardson, 1968). Calculated reflectances of infinite thicknesses of stacked leaves from untreated and Cycocel-treated plots were determined to be 75 and 73%, respectively, at 850 mμ. The difference in reflectance between Cycocel-treated and untreated leaves was reversed in sign when reflectances were calculated for an infinite stack of leaves. Reflectance from stacked leaves increases directly with the number of leaves, but approaches a maximum value R_∞ asymptotically. It has been demonstrated in a paper now in press that R_∞ is inversely related to the mean distance between refraction within the leaf. Thick or thin leaves with the same internal structure produce the same value of R_∞. Reflectance from a single leaf, however, is a function of its thickness. The reversal indicated in this paper is interesting but is not surprising.

In addition, the slight difference in the calculated reflectances is not adequate to explain the large difference in reflectivity between plots A and B, Fig. 4. Instead, the Kodak Ektachrome infrared aero film, infrared sensitivity range is about 700 - 900 mμ, was affected by radiation from the visible region. A correlation exists between the darker green leaves of Cycocel-treated plants in plot B, with increased absorptance of visible light, 500 - 700 mμ, and the darker tone of plot B in the photograph. Apparently the darker tone of Cycocel-treated plot B was caused by the chlorophyll-induced reduction in the amount of visible light impinging on the magenta and yellow dye-forming film layers on the color-infrared film (Fritz, 1967); resulting in the formation of a high density of the yellow and magenta dyes, which produced a dark, red color that showed through a light-toned cyan image. For untreated plot A, the yellow and magenta layers were exposed to more visible light and they became less dense or brighter, thereby giving a red color of a lighter tone. Therefore, visible light reflectance of individual leaves measured spectrophotometrically was directly related to tonal responses (reflectivity) of field plots of cotton, Fig. 1, 2, and 3.

Densitometer tracings on a negative from a black and white infrared film exposed with visible light excluded, indicated that the near-infrared reflectance of vegetation was slightly greater for the untreated plot A with the lighter tone than the Cycocel-treated plot B with the darker tone. This is a reverse relation compared with the increased reflectance shown for individual leaves from Cycocel-treated plants, Fig. 1. It was suspected that there were background differences in reflectance between treated and untreated plots. Although the leaf area indices were not determined, densitometer tracings indicated that plots A and B had essentially the same background soil reflectance. It is possible, however, that the type of plant canopy influenced reflectance, since Cycocel-treated plants had shorter internodes than untreated plants. More research is needed to explain this phenomenon.

CONCLUSIONS

Near-infrared light reflectance, 750 - 1350 mμ, measured in the laboratory, with a spectrophotometer, was higher for individual leaves from the fourth node down from plant apexes of Cycocel-treated cotton plants compared with leaves of the same chronological age from untreated plants, because Cycocel treatment increased intercellular air spaces in leaf mesophylls. Cycocel treatment also increased the chlorophyll content of leaves (darker green color); thereby increasing absorption of light in the 500- to 750-mμ wavelength interval.

Near-infrared light reflectance from single leaves was inversely related and visible light reflectance was directly related to the reflectivity of field plots of cotton recorded on Kodak Ektachrome infrared aero film. Many factors such as type of plant canopy (geometry), background soil reflectance, and differences in maturity of leaves on a plant mask the contribution of a single plant leaf to the reflectance of light from a plant canopy.

The tonal response on Kodak Ektachrome infrared aero film was darker red for Cycocel-treated plots than for untreated plots. This was caused mainly by increased chlorophyll contents (darker green color) in leaves of Cycocel-treated plants, which reduced the reflectance of visible light, causing denser yellow and magenta positive images in the film layers sensitive to green and red radiation.

Experiments can be designed to chemically induce changes in internal leaf structure (compactness) or in crop geometry. Such experiments are useful to study the relation of spectrophotometrically measured reflectance and transmittance on single leaves with the reflectivity from a plant canopy recorded on photographic film.

ACKNOWLEDGEMENTS

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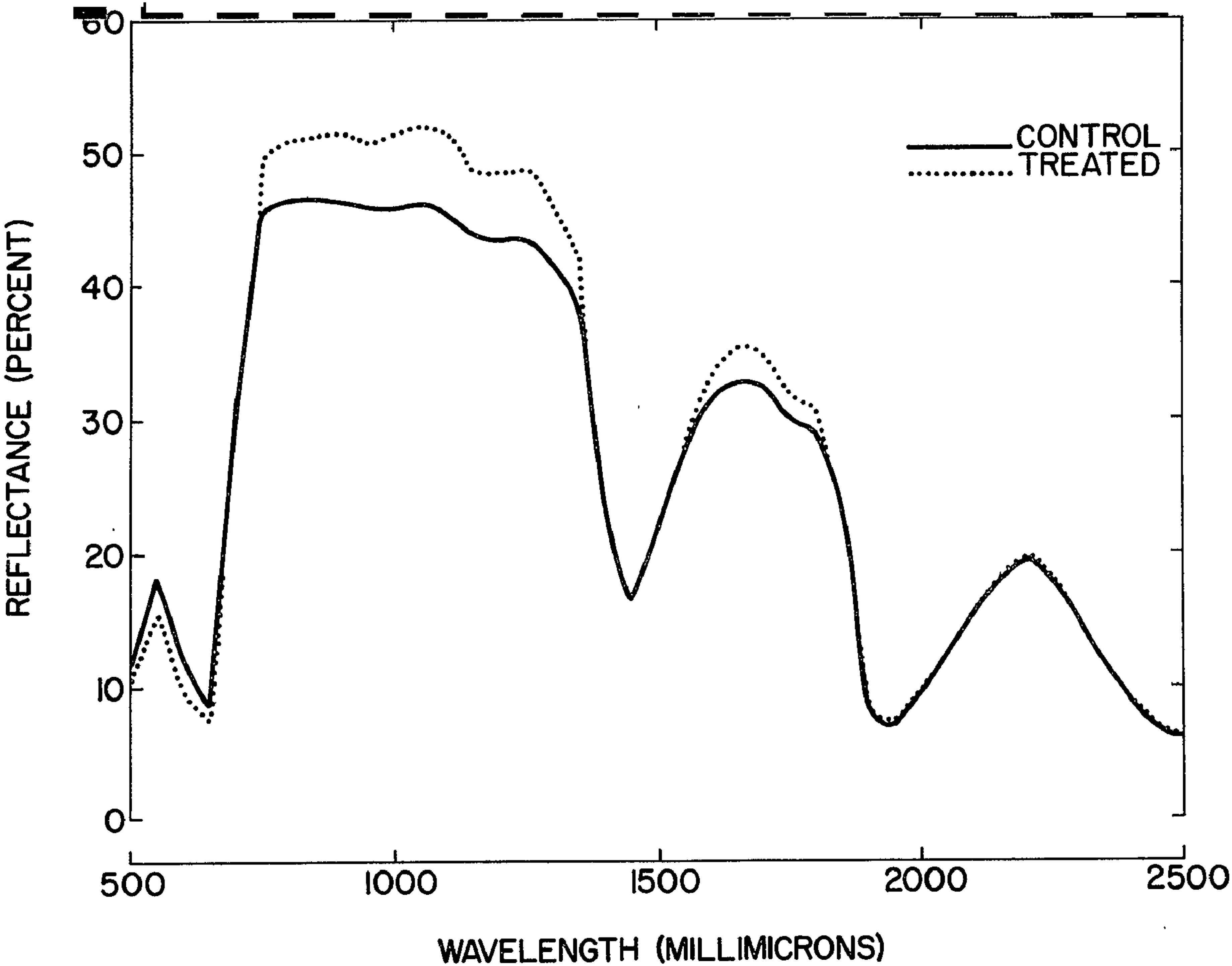

Fig. 1. Light reflectance from upper surfaces of cotton leaves from Cycocel-treated and untreated (control) plants; each spectrum is an average of values for five leaves.

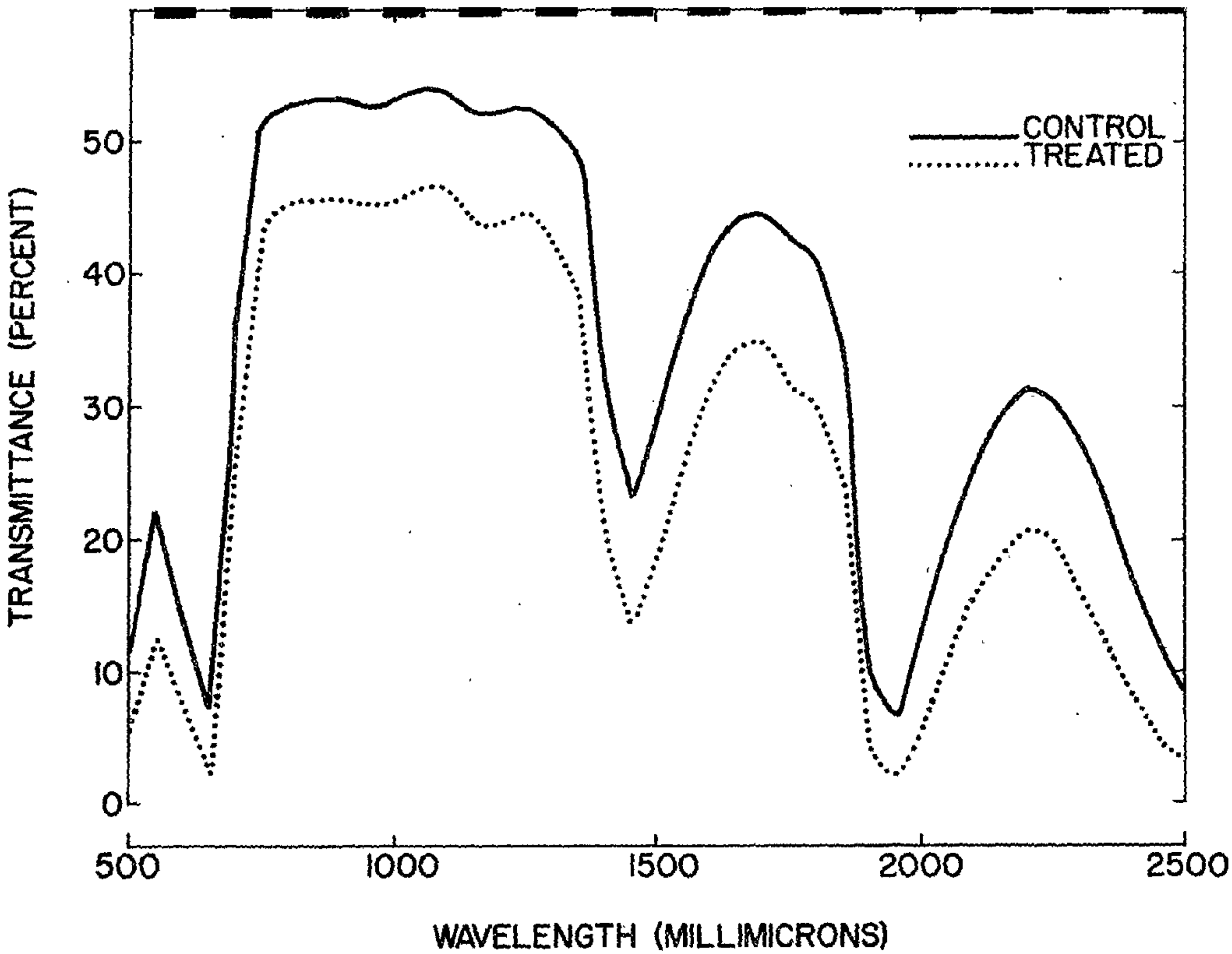

Fig. 2. Light transmittance of cotton leaves from Cycocel-treated and untreated (control) plants; each spectrum is an average of values for five leaves.

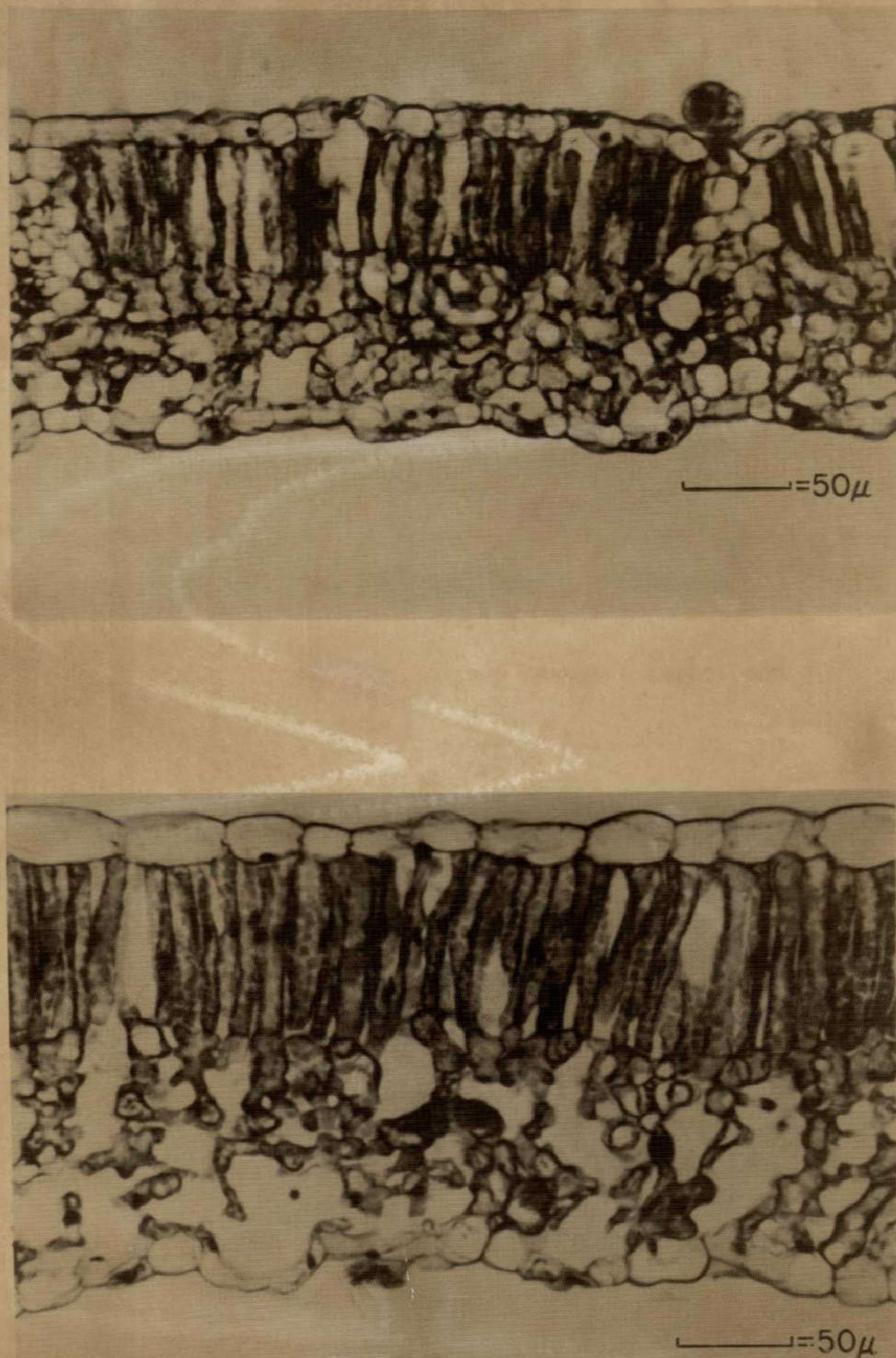

Fig. 3. Internal structure of cotton leaves from untreated (upper photomicrograph) and Cycocel-treated plants (lower photomicrograph). Magnification is identical in the two photomicrographs.

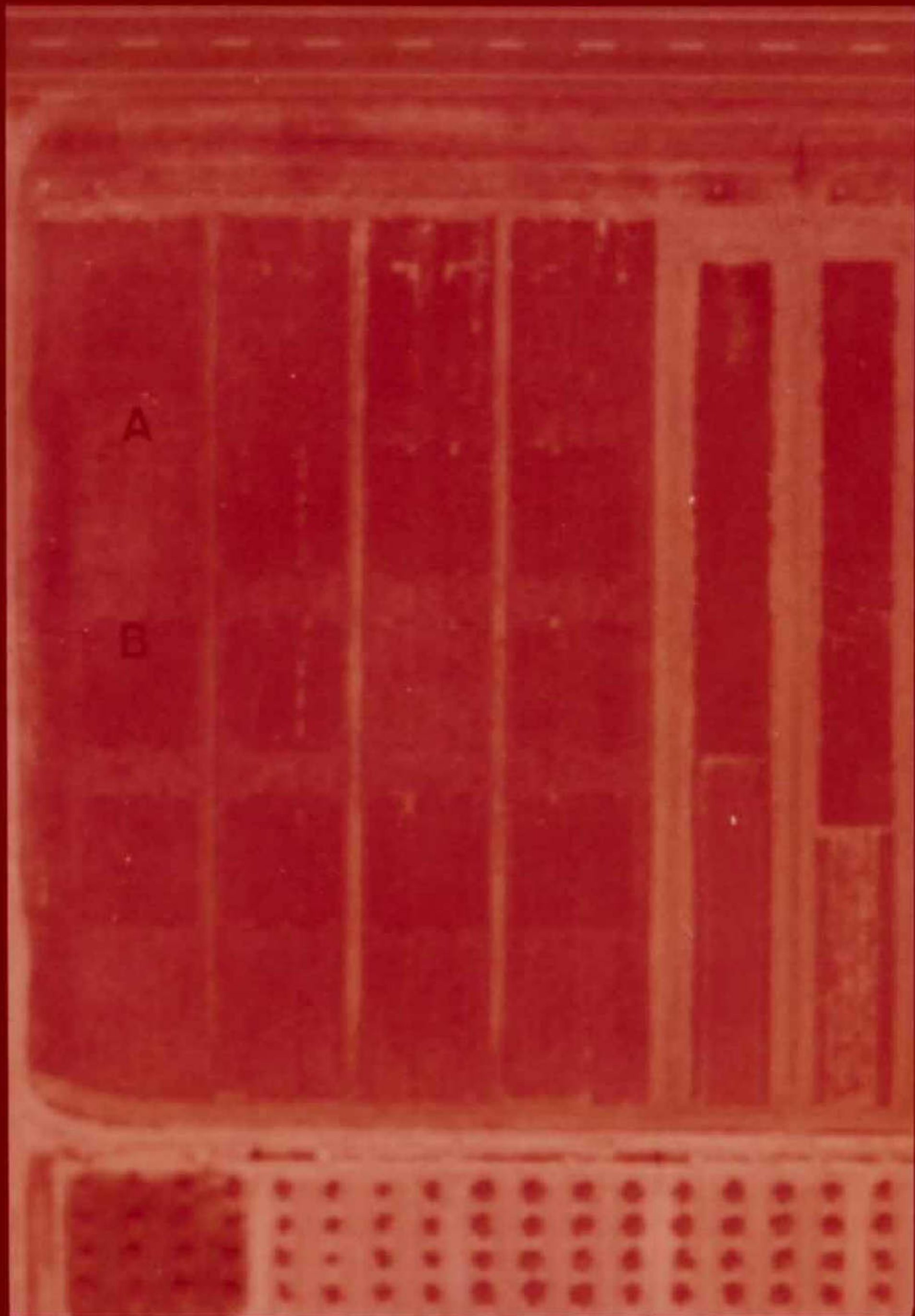

Fig. 4. Photograph (40 X enlargement) of the experimental plots from an overflight using Ektachrome infrared aero film, showing the untreated (A) and Cycocel-treated (B) plots from which leaves were sampled.

DETECTION OF INSECT ACTIVITY ON CITRUS FOLIAGE WITH AERIAL INFRARED COLOR PHOTOGRAPHY

Craig L. Wiegand and William G. Hart

INTRODUCTION

Since the summer of 1965, the Entomology Research Division and the Soil and Water Conservation Research Division of the U. S. Department of Agriculture at Weslaco, Texas, have worked cooperatively on detecting insect infestations in citrus. In this report, applications are brought up to date.

Brown soft scale (Coccus hesperidum L.)

The brown soft scale organism excretes large quantities of a sugary solution known as "honeydew" soon after establishment on the citrus leaf. The black sooty mold fungus, Capnodium citri, Berk. and Desm., develops rapidly when the honeydew is abundant and forms a dense black coating of interwoven filaments. If the coating is heavy and remains on the tree, it interferes with the physiology of the plant and impairs growth and production. Figure 1, taken from Hart and Myers (1968), shows the effect on reflectance of no, light, medium, and heavy deposits of sooty mold on light reflectance in the visible and near infrared. Notice that the decrease in reflectance is very pronounced in the 700 to 900 nanometer wavelength interval. There is also considerable decrease in the visible but the percent reflectance is very low in the visible to begin with.

Figure 2 shows a grove taken with type 8442 Ektachrome film (top) and Ektachrome infrared type 8443 (bottom). The bright red trees on the infrared film image are healthy, nonaffected trees, whereas the darkened ones are brown soft scale infested. The effects are barely apparent in the visible (type 8442 film) but are very pronounced on the near infrared radiation sensitive film (type 8443).

Since 1962, the Entomology Research Division has been making time-consuming monthly ground surveys of 20 citrus groves between Roma and Brownsville, a distance of 110 miles, to determine the status of the brown soft scale. Monthly labor costs are $359 and vehicle expenses are $64 for a total of $423 per month. The estimated monthly cost of flying the groves is estimated at $150 plus $87 for film, processing, and labor. The difference in cost annually would be $2,232 in favor of the photographic survey for these 20 groves alone. Since there are 4,000 groves in the Lower Rio Grande Valley, it would be impossible to ground survey them all, but very feasible to photograph them all and ground check only for indicated infestations.

A commercial service to the growers has definite possibilities. It could function much as ground entomological surveys now function, i.e., for a nominal fee the commercial service would aerial survey the trees, ground check suspicious areas in the groves, and make recommendations for spot or general spraying of the orchard.

Texas citrus mite, Eutetranychus banksi (McGregh)

Texas citrus mites inflict damage to the leaf when they insert their mouth-parts to feed. The damage done results in a silvering or bronzing of the leaf which increases the reflectance in both the visible and photographic infrared. Figure 3 (after Hart and Wiegand, 1969) shows that the reflectance at 1000 millimicrons is increased about 7 percent by moderate infestation. Figure 3 suggests that the part of the spectrum to use is the visible, however, not the infrared since proportionately the effect is much greater in the visible than in the infrared.

There is difficulty in separating mite damage from new growth and a number of other complicating variables; in winter, mesophyll collapse which occurs during conditions of low humidity and high windspeed (passage of cold fronts) causes a similar plant response.

Citrus rust mite, Phyllocoptruta oleivora (Ashmead)

Injury from this pest results primarily in a russeting of the fruit, although some browning of the leaves also occurs. Damage by this insect has not been detectable from the elevations usually flown, 200-3000 feet.

DISCUSSION

The traditional way to survey for insect infestations is with ground crews. Such surveys are time-consuming and costly. The success reported herein for detecting brown soft scale encourages investigating remote sensing procedures for detection of other insects or manifestations of their presence.

As refinements are made in sensing simultaneously in two or more wavelength bands, detection of smaller and smaller differences from the normal condition should become possible. Discoloration, defoliation, geometric distortion, and unusual deposits on leaf surfaces should be detectable. The techniques would apply to aphids, lepidopterous larvae, weevils, root and stem borers, and ants. Early detection would enable us to delimit infestations and start control procedures while the pests are confined to limited areas. The reduction in insecticide application costs would be considerable.

SUMMARY

The detection of brown soft scale infestations of citrus trees with Ektachrome infrared film type 8443 has been demonstrated. Texas citrus mite and citrus rust mite were not detectable. Their presence may be detected remotely by multispectral systems which have not yet been employed, or by more careful use of the visible part of the spectrum where reflectance measurements indicate their damage has its strongest influence on the spectral signature.

Early detection of insect damage is beneficial to growers in two ways: (1) spot spraying instead of general spraying reduces direct production costs, and (2) condition of the trees and quality of the fruit can both be maintained. Remote sensing survey methods are attractive to research and regulatory agencies because ground crew surveys are expensive and consequently restrict surveys to sample rather than population surveys.

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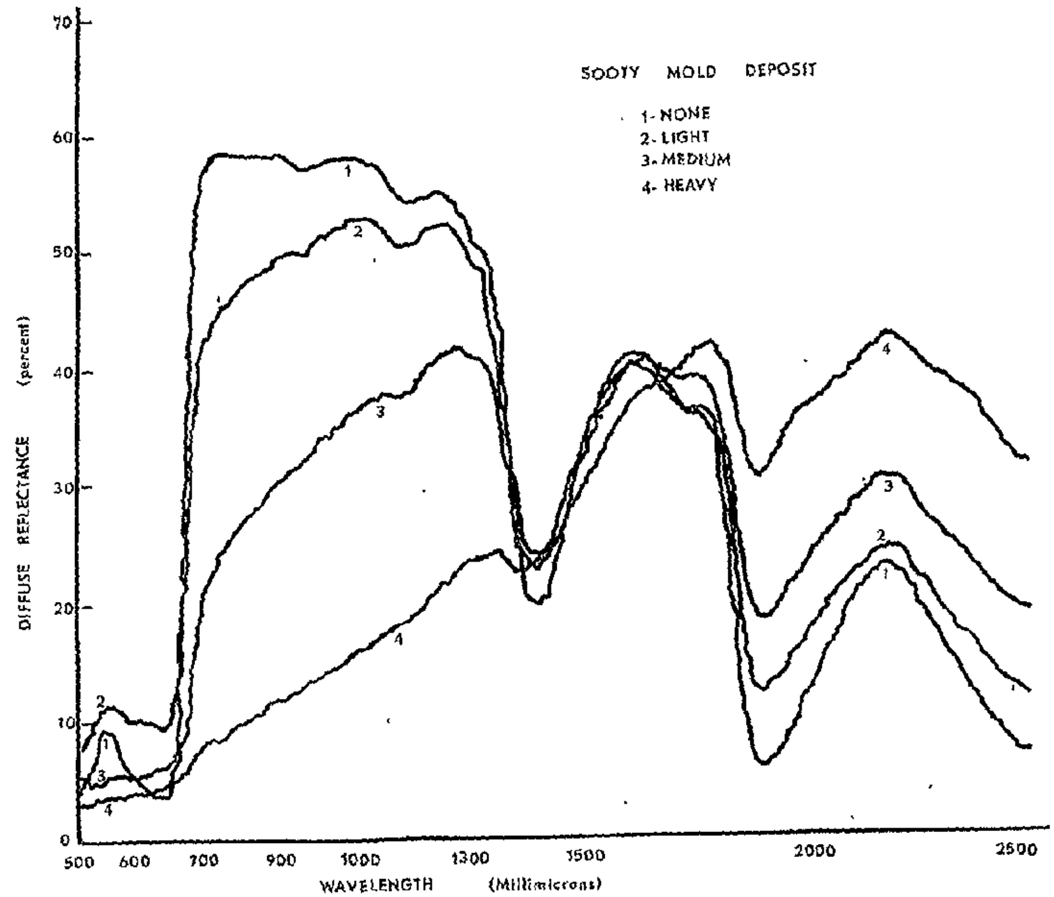
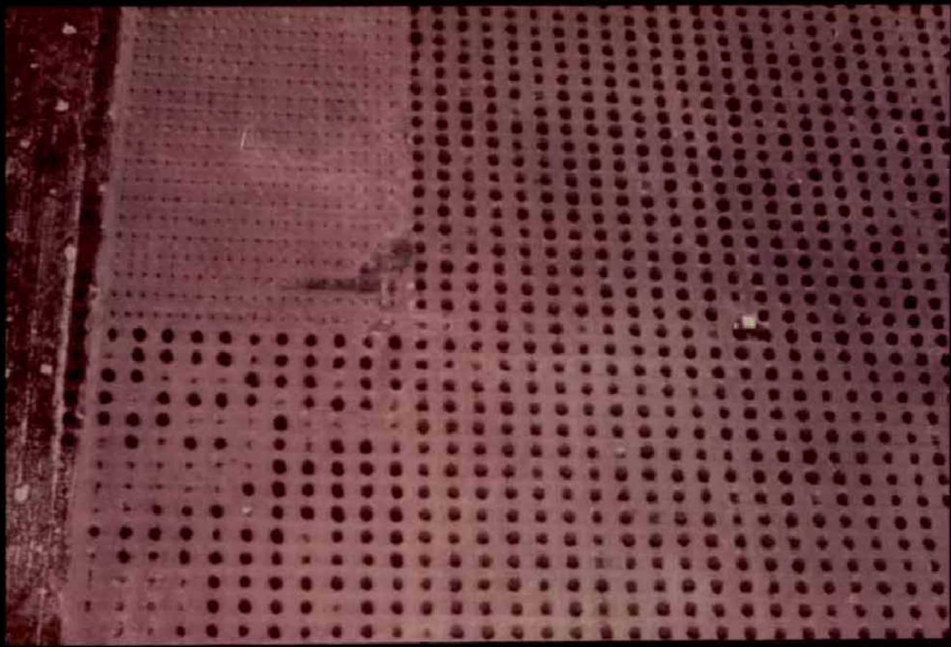


Fig. 1. The effect of sooty mold on citrus leaves on percent reflectance in the 500 to 2500 millimicron wavelength interval. Note that the affect is very pronounced in the photographic infrared, 700 to 900 millimicrons. (Figures after Hart and Myers, 1968).



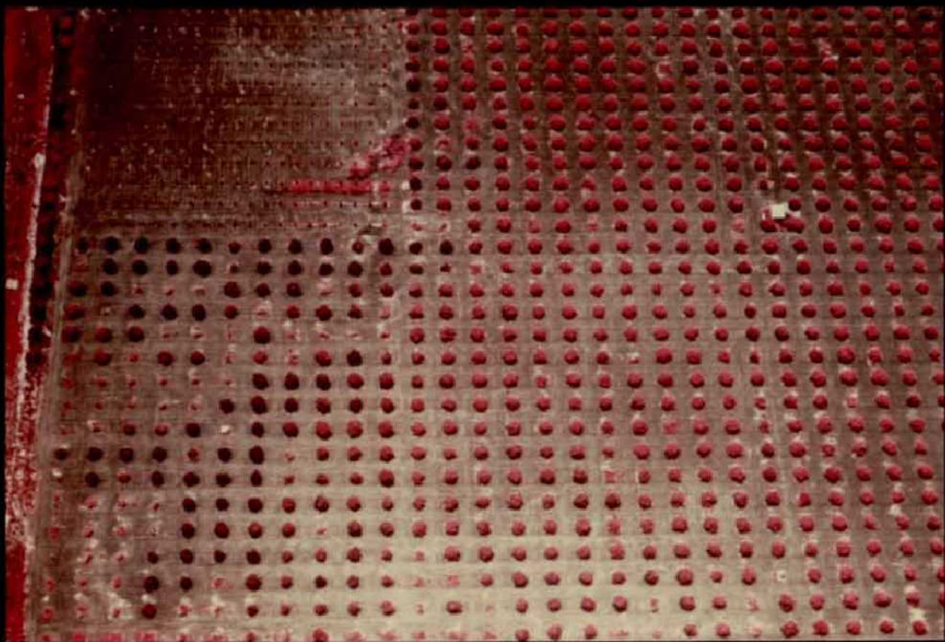


Fig. 2. A citrus orchard, some trees of which are infested with brown soft scale organism, as imaged with type 8442 Ektachrome (upper) and type 8443 Ektachrome infrared film (lower). The detectability on type 8443 Ektachrome results from growth on "honeydew" excreted by the brown soft scale of a black sooty mold. The coating of mold mycelia interferes with the reflectance of light in the photographic infrared (700 to 900 millimicrons). The presence of the mold enables the ready detection of the associated insect pest. Early detection permits the growers to spray only infested trees.

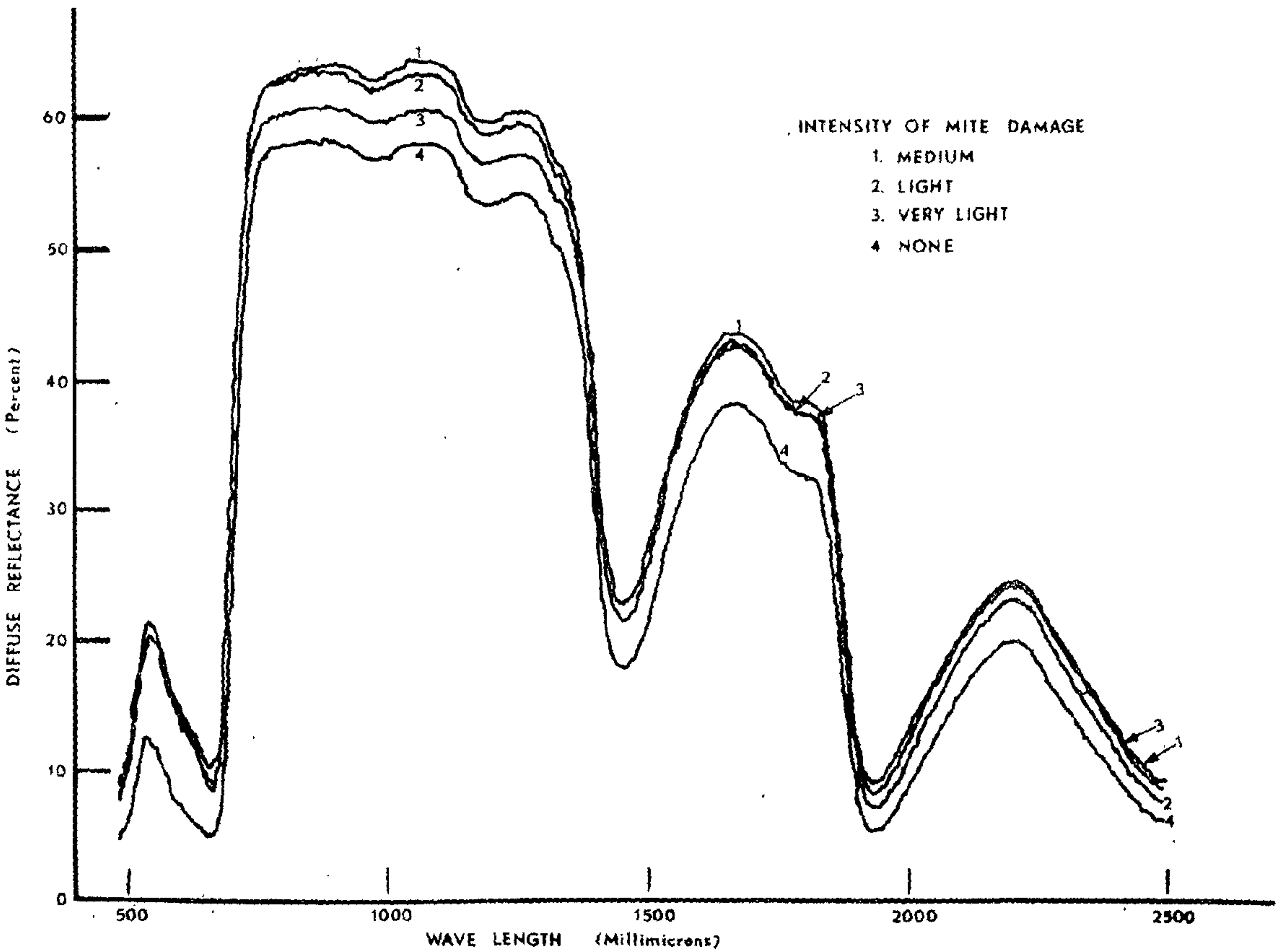


Fig. 3. Effect of varying amounts of mite damage on reflectance (percent) of citrus leaves.

DETECTION OF FOOT ROT DISEASE OF GRAPEFRUIT TREES WITH INFRARED COLOR FILM

H. W. Gausman, W. A. Allen, and R. Cardenas

SUMMARY

Leaves of grapefruit trees affected with foot rot were yellowish-white compared with green-appearing leaves from unaffected plants. Spectrophotometric measurements of individual leaves revealed that foot rot affected light reflectance, transmittance, and absorptance in the visible range, 400 to 750 nm. The reflectance, transmittance, and absorptance of leaves from the foot-rot-affected trees and the nonaffected trees were measured at the 450 (blue), 550 (green), and 650 (red) nm wavelengths. Reflectance was 3.3, 31.4, and 23.9% higher; transmittance was 0.0, 16.5, and 8.3% higher; and, absorptance was 3.3, 47.9, and 32.2% lower for the foot-rot-affected than for the nonaffected leaves, respectively, at 450, 550, and 650 nm. On photographs taken with Kodak Ektachrome infrared aero film and a Zeiss D light-orange filter (approximate 100% absorption edge at 500 nm), the foot-rot-affected trees appeared as white images compared with red images for unaffected trees [1].

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[1] Trade names and company names are included for the benefit of the reader and do not imply an endorsement or preferential treatment of the product listed by the U. S. Department of Agriculture.

INTRODUCTION

Citrus foot rot is a fungal disease caused by *Phytophthora citrophthora* (Sm. & Sm.) Leonian and *Phytophthora parasitica* Dast. (Brandes *et al.*, 1959). These fungi produce a gummy exudate at or near the graft union on citrus trees; wood rots underneath, leaves lose color, and decline sets in.

This paper relates foot-rot-induced changes in grapefruit leaves with: (1) spectrophotometric measurements on individual leaves and (2) Kodak Ektachrome infrared aero film sensing of reflectance from overflights of a grapefruit orchard.

MATERIALS AND METHODS

An overflight of a grapefruit citrus orchard, *Citrus paradise* Macf., Nucellar - CES-3 selection of Red Blush on *Citrus aurantium* Linn. Sour Orange rootstock, near Monte Alto, Texas, was made at an altitude of 2,000 ft., with clear to moderate haze, at 11:29 a.m., central standard time, December 5, 1968, in an easterly direction. Photographs were taken with a Zeiss, 6-in. focal length camera, using 9-in. Kodak Ektachrome infrared aero film, type 8443, and a Zeiss D light-orange filter, approximate 100% absorption edge at 500 nm.

Kodak Ektachrome infrared aero film, type 8443, has three image layers sensitized to green, red, and infrared radiation (Fritz, 1967). A light-orange filter, Zeiss D, Kodak Wratten No. 12 or 15 or equivalent, is used over the camera lens to absorb approximately 100% of the blue radiation to which all three layers are sensitive. Upon processing, process E-3, yellow, magenta (purplish-red), and cyan (greenish-blue) positive images appear in the green-, red-, and infrared-sensitive layers, respectively. The relative exposure produced in each film layer determines the many possible colors or tonal responses. Healthy plant leaves reflect "brightly" in infrared which produces a light-toned cyan image allowing the red formed in the other layers to predominate.

Fifteen leaves of approximately the same size and age were sampled from a foot-rot-affected tree and an unaffected tree (normal appearance by visual observation) five days after the overflight. The leaves on the foot-rot-affected tree were yellowish-white, blooming was profuse, leaf defoliation was beginning, and the foot rot canker did not encircle the trunk. Spectra were determined on five leaves randomly selected from each group of 15 leaves.

Spectral diffuse reflectance on upper (adaxial) surfaces of single leaves and transmittance were measured over the wavelength interval 500 to 2500 nm with a Beckman Model DK-2A spectrophotometer and its reflectance attachment. Data have been corrected for decay of the MgO reference (Sanders and Middleton, 1953) to obtain absolute radiometric values.

Statistical techniques were applied to the data (Steel and Torrie, 1960).

RESULTS AND DISCUSSION

The spectral responses within the wavelength interval 750 to 1350 nm are affected largely by internal leaf structure (Gausman _et al_., 1969). Absorptance by pigments dominates the 500 to 750 nm interval, and the region above 1350 nm is influenced greatly by the amount of water in the leaf - strongest water absorption bands occur at approximately 1450 and 1950 nm.

Figure 1 is a Kodak Ektaprint, 17 X enlargement, from Kodak Ektachrome infrared aero film exposed on an overflight of a grapefruit orchard. Various degrees of white-appearing trees were detected among the expected red-appearing trees. An outstanding example of a very white-appearing tree is shown in the lower center of the photograph. Later investigation revealed that this tree and others like it had foot rot. Its leaves were yellowish-white as compared with green leaves of unaffected trees as judged by the normal appearance of their foliage, Fig. 2. Trees investigated were large, and their trunks were not encircled with foot rot cankers. A distinguishing feature of foot rot is that one side of a tree may be sound while the other side is dying (Brandes *et al.*, 1959).

Leaves of approximately the same age and size were sampled from the affected tree and from the unaffected tree above and next to the affected tree in the same row, Fig. 1. Spectrophotometric measurements on individual leaves over the wavelength interval 500 to 2500 nm indicated that main differences in response, statistically significant, $p = .01$, were in the visible region. Accordingly, reflectance and transmittance spectra were obtained over the wavelength interval 400 to 750 nm. Data, average of values for five leaves for each spectrum, are presented in Table 1. Foot-rot-affected trees, compared with unaffected trees, had higher values of 3.3, 31.4, and 23.9% for reflectance; 0.0 and higher values of 16.5 and 8.3% for transmittance; and lower values of 3.3, 47.9, and 32.2% for absorptance, at 450 (blue), 550 (green), and 650 (red) nm wavelengths, respectively. Spectrum colors can be combined to give non-spectrum colors. A proper mixture of blue and red produces magenta, and a proper combination of red, blue, and green gives white light (Strandberg, 1968). Reflectance of radiation from aerial photographs of foot-rot-affected trees produced white images, compared with red images for unaffected trees, on processed Kodak Ektachrome infrared aero film used with a Zeiss D, light-orange filter having an approximate 100% absorption edge at 500 nm. Exposure of the yellow, magenta, and cyan dye layers on the film to green, red, and infrared radiations, respectively, gave the proper combination of blue, green, and red colors to produce white light or a white-appearing image on the processed film.

CONCLUSION

Foot rot disease of citrus can be detected with aerial photography using Kodak Ektachrome infrared aero film and a light orange filter. Affected foliage of citrus trees give white images on the developed film in contrast to red images for foliage of healthy trees.

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Table I. The spectra over wavelength interval 400 to 750 nm of foot-rot-affected, yellowish-white grapefruit leaves, compared with unaffected, green leaves. Each spectrum is the mean for five leaves.

Leaves	Wavelength, nm 400	450	500	550	600	650	700	750
	Reflectance (Percent)							
Affected	4.56	8.14	18.56	44.68	41.16	28.64	56.06	60.88
Unaffected	4.44	4.88	5.56	13.30	7.42	4.72	27.38	60.92
Difference	.12	3.26	13.00	31.38	33.74	23.92	28.68	-.04
	Transmittance (Percent)							
Affected	0	0	2.98	16.70	15.06	8.26	24.34	28.24
Unaffected	0	0	0	.18	0	0	4.94	25.62
Difference	0	0	2.98	16.52	15.06	8.26	19.40	2.62
	Absorptance (Percent) a/							
Affected	95.44	91.86	78.46	38.62	43.78	63.10	19.60	10.88
Unaffected	95.56	95.12	94.44	86.52	92.58	95.28	67.68	13.46
Difference	-.12	-3.26	-15.98	-47.90	-48.80	-32.18	-48.08	-2.58

a/ Absorptance = 100 - (% transmittance + % reflectance).

Fig. 1. Kodak Ektaprint, 17 X enlargement, from an overflight of a grapefruit orchard showing images of white-appearing, foot-rot-affected trees, center, and red-appearing, unaffected trees.

Fig. 2. Ektachrome color (film type B) photographic comparison of yellowish-white grapefruit leaf on left from foot-rot-affected tree with green leaf on right from unaffected tree.

Interaction of Isotropic Light With A Compact Plant Leaf

William A. Allen, Harold W. Gausman,
Arthur J. Richardson, and James R. Thomas

ABSTRACT

A transparent plate with rough plane-parallel surfaces is used as a theoretical model to explain the interaction of diffuse light with a compact plant leaf. Effective optical constants of a corn leaf have been determined from leaf reflectance and transmittance measured over the spectral range 0.5 - 2.5 μ with a recording spectrophotometer. The effective index of refraction at 0.5 μ for the corn leaf is not inconsistent with the refractive index of epicuticular wax. The effective absorption spectra of the corn leaf appears to be a superposition of the absorption coefficients of chlorophyll and pure liquid water. Residual spectral data from other leaf constituents are at the resolution limit of the spectrophotometer. The plate model of a leaf is also used to determine moisture content of the corn leaf from reflectance and transmittance measurements.

INTRODUCTION

Allen and Richardson[1] have described the near-infrared reflectance and transmittance of plant leaves stacked in a spectrophotometer by means of the Kubelka-Munk (K-M) theory[2] for propagation of light through a diffusing medium. Basic entities in application of the K-M theory to leaves are the reflectance and transmittance of a single leaf. The purpose of this paper is to derive the reflectance and transmittance of a single typical compact plant leaf from fundamental considerations.

Willstätter and Stoll[3], as reported by Gates[4], explained reflectance and transmittance of a plant leaf on the basis of critical reflection of light at the cell wall-air interface of spongy mesophyll tissue. According to Myers and Allen[5], the K-M scattering coefficient for a typical leaf can be explained by Fresnel reflections at normal incidence from thirty-five air interfaces along the mean optical path through the leaf. Gausman, Cardenas, and Allen[6] noted that if oblique reflections are considered, fewer interfaces account for the results. These previous concepts emerge naturally, without additional assumptions, from the leaf model investigated in this paper.

The requirement of isotropy is equivalent to the assumption that the plate surfaces are rough with respect to the wavelength of light; that is, the surfaces are assumed to be lambertian[7]. Walsh, as reported by Duntley[8], and Stern[9] calculated the reflectivity of isotropic light of all polarizations for an interface between two dielectrics. Theory exists[10,11] for evaluating reflectance and transmittance of a plate provided that the reflectivity of each surface and the transmissivity of the plate medium are known. Conversely, if reflectance and transmittance for diffuse light are known, the optical constants of the plate can be determined.

REFLECTANCE AND TRANSMITTANCE OF A PLATE IN ISOTROPIC LIGHT

Figure 1 illustrates unit isotropic radiant flux I_o emanating from medium 1, interacting with the interface between media 1 and 2, passing through medium 2 of thickness D, interacting with the interface between media 2 and 3, and emerging eventually into both media 1 and 3. Light emergence into medium 1 is designated reflectance R and light emergence into medium 3 is termed transmittance T. Media 1 and 3 will be regarded as air and medium 2 will be specified by the relative index of refraction n between air and medium 2 and by the absorption coefficient k of medium 2. Transmissivity at an interface between media i and j will be designated T_{ij}; the corresponding reflectivity is given by $R_{ij} = 1-T_{ij}$. The irradiances associated with multiple reflections within the plate are referenced in Fig. 1 by regions 2, 6, 8, 12 ..., and 3, 5, 9, 11 ... . These regions are assumed to be infinitesimally close to the surface. Analytical values associated with the various regions in Fig. 1 are listed in Table 1.

Reflectance R is determined by contributions from regions 1, 7, 13, ... ; transmittance is determined by contributions from regions 4, 10, ... Reflectance R and transmittance T, respectively, consist of the sums of the infinite series

$$R = R_{12} + T_{12}\, T_{21}\, \tau^2\, R_{23}\, (1+\tau^2\, R_{23}\, R_{21} + \cdots) \quad , \tag{1}$$

$$T = T_{12}\, \tau\, T_{23}\, (1+\tau^2\, R_{23}\, R_{21} + \cdots) \quad . \tag{2}$$

The subscripts in Eqs. (1-2) refer to media 1, 2, and 3; the quantity τ is the transmissivity of the plate. We sum Eqs. (1-2) to obtain the relations

$$R = R_{12} + \frac{T_{12}\tau^2 R_{23} T_{21}}{1-\tau^2 R_{23} R_{21}} \quad , \tag{3}$$

$$T = \frac{T_{12}\tau T_{23}}{1-\tau^2 R_{23} R_{21}} \quad . \tag{4}$$

Equations (3-4) describe a plane-parallel rough transparent plate in isotropic light. Diffuse light is trapped by the second medium for those rays that exceed the critical angle, thus $T_{12} \neq T_{23}$. The transmissivities $T_{21} = T_{23}$ can be calculated either by the relation $T_{21} = n^{-2} T_{12}$ [9] or measured by procedures suggested by Duntley[8]. If the calculated value of T_{21} is used, Eqs. (3-4) can be written in the forms

$$R = (1-T_{12}) + \frac{\tau^2 T_{12}^{\,2}(n^2-T_{12})}{n^4-\tau^2\ (n^2-T_{12})^2} \quad , \tag{5}$$

$$T = \frac{\tau n^2 T_{12}^{\,2}}{n^4-\tau^2(n^2-T_{12})^2} \quad . \tag{6}$$

The absorptance of the plate can be expressed by the relation

$$1-R-T = \frac{T_{12}(1-\tau)n^2}{n^2-\tau\ (n^2-T_{12})} \quad . \tag{7}$$

INDEX OF REFRACTION OF A PLATE

Equations (5-6) can be used to evaluate the index of refraction n of a plate if R and T are known. Eliminate τ from Eqs. (5-6) to obtain the relation

$$F(n) \equiv [T^2-(R-R_{12})^2]\ (n^2-T_{12})-T_{12}^{\,2}(R-R_{12}) = 0 \ . \tag{8}$$

The transmissivity $T_{12} = 1-R_{12}$ for diffuse light at an interface between two dielectrics of relative index of refraction n can be written[9] in the forms

$$T_1 = \frac{4}{3}\frac{2n+1}{(n+1)^2} \quad , \tag{9}$$

$$T_2 = \frac{4n^3(n^2+2n-1)}{(n^2+1)^2(n^2-1)} - \frac{2n^2(n+1)}{(n^2-1)^2}\log n + \frac{2n^2(n^2-1)^2}{(n^2+1)^3}\log\frac{n(n+1)}{n-1} \quad . \tag{10}$$

The subscript 1 in Eqs. (9-10) designates the case in which the electric vector is perpendicular to the plane of incidence, and the subscript 2 pertains to the case in which the electric vector lies in the plane of incidence. Light transmissivity of intermediate polarization can be written in the form

$$T_{12} = \mu T_1 + (1-\mu)T_2 \quad , \qquad (11)$$

where $1 > \mu > 0$. We set $\mu = 1/2$ for the case of random polarization.

The appropriate root of Eq. (8) can be evaluated by means of the Newton-Raphson[12] method in which the relation

$$F'(n) = 2n[T^2-(R-R_{12})^2] - [T^2+T_{12}^2+2n(R-R_{12})-(R-R_{12})^2]dT_{12}/dn \qquad (12)$$

must be used. The quantity $dT_{12}/dn = \mu dT_1/dn + (1-\mu)dT_2/dn$ can be calculated exactly, but with some difficulty, from Eqs. (9-11). Over the restricted range $1.2 < n < 1.5$, however, the quantity dT_{12}/dn can be calculated with requisite accuracy from the approximation cubics $T_i = A_i+B_in+C_in^2+D_in^3$ where the polynomial coefficients of T_i are listed in Table II.

TRANSMISSIVITY OF A PLATE IN ISOTROPIC LIGHT

The transmissivity τ of a plate in isotropic light can be obtained from Eq. (5) in the form

$$\tau^2 = \frac{n^4(R-R_{12})}{T_{12}^2(n^2-T_{12})+(n^2-T_{12})^2(R-R_{12})} \qquad (13)$$

The transmissivity τ of the plate can be related to the absorption coefficient k of the plate medium. The transmissivity of the plate is the irradiance at the lower surface in Fig. 1 relative to the irradiance at the upper surface. Let k be the absorption coefficient of the plate medium. The length of a typical slant ray through the plate of Fig. 1 can be designated D sec θ, where θ is measured from the plate normal. The transmissivity of the plate along this slant ray is given by exp(-kD sec θ). Flux emerging from unit area of a rough or lambertian surface varies as cos θ. The total flux emanating from unit area of the upper plate surface that reaches the lower surface is obtained by straightforward integration of all flux over the hemisphere $0<\theta<\pi/2$. The transmissivity τ for isotropic light passing through a rough plate of thickness D is given by the relation

$$G(k) \equiv \tau - (1-z)e^{-z}-z^2 \int_z^\infty x^{-1}e^{-x}dx = 0 \quad , \qquad (14)$$

where $z = kD$.

The exponential integral in Eq. (14) is a tabulated function.[13] The root of Eq. (14) can be evaluated readily by means of the Newton-Raphson method where the relation

$$G'(k) = 2D[e^{-z} - z \int_z^{\infty} x^{-1} e^{-x} dx] \quad (15)$$

must be used.

EXPERIMENTAL VERIFICATION

The elementary theory advanced in this paper applies to a compact leaf, an immature leaf, or a leaf in which the intercellular space has been infiltrated with water. A corn leaf, for example, is a compact leaf; that is, the leaf structure is characterized by relative absence of intercellular space. Figure 2 is the effective dispersion curve of a typical corn leaf, determined from reflectance and transmittance measurements. The effective dispersion curve of this leaf is not inconsistent with values of the epicuticular wax[14] found on the surfaces of many leaves. The additional data point at 0.5 μ is the average published[15] index of refraction, n = 1.4687 at 40° C, for carnauba wax, a substance obtained from the leaf surface of the carnauba palm, Capernicia cerifera.

The solid line in Fig. 3 is the effective absorption spectrum of the corn leaf, calculated by use of the plate model presented in this paper. The data points in Fig. 3 are the published absorption coefficients of pure liquid water.[16] The equivalent water thickness D of the corn leaf was determined by fitting the plate model to the Curcio[16] data over the spectral range 1.4 - 2.5 μ. The equivalent water thickness was determined to be 146 μ while the measured leaf thickness was 188 μ. Justification of the above procedure for moisture determination is based upon the premise that absorption of the corn leaf in the spectral range 1.4 - 2.5 μ is caused principally by pure liquid water. The dashed lines in Fig. 3 are the measured effective absorption curves resolved into components corresponding to pure liquid water and chlorophyll. Residuals between the leaf absorption curve and data for pure liquid water over the range 1.4 - 2.5 μ may be regarded as differential absorption spectra of leaf substances other than water and/or uncertainties of the fundamental constants for pure liquid water.

The plate-model theory of a leaf advanced in this paper contains two substantial improvements upon the K-M formulation. First, the K-M scattering coefficient s has been interpreted in terms of Fresnel reflections from the leaf or cell surfaces. Polarization phenomena have been included in the plate theory in a natural manner. Second, the absorption coefficient of a leaf determined by the plate model is in closer agreement with that of pure liquid water than calculations made from the K-M formulation.

Table III indicates the agreement between absorption coefficients k calculated from Eq. (14) and those values k_o observed for pure liquid water[16] for the 23 spectral values μ = 1.40, 1.45,..., 2.50 μ. Table III also illustrates the agreement between the K-M absorption coefficient k and those for pure liquid water for the same spectral values. In both the plate and K-M comparisons, an optimum constant water thickness D over the range 1.4 - 2.5 μ was assumed in order to obtain the best fit on a semilog plot such as Fig. 3. The Gauss criterion for goodness of fit[17]

$$\Omega \equiv \frac{1}{n-m} \sum [\log (k_o/k)]^2 = \text{a minimum} \qquad (16)$$

was used. The values n = 23 and m = 1 were assumed in Eq. (16). Preliminary calculations listed in Table III suggest that the plate-model values for Ω are substantially better than corresponding K-M values over the same spectral region. The genera listed in Table III correspond, respectively, to a compact leaf, an immature leaf, and a leaf infiltrated with water.

The theory advanced in this paper can be extended easily to a non-compact leaf. Such a leaf can be regarded as a pile of N compact cell layers separated by N-1 air spaces, where N need not be an integer. With this interpretation, the results of reference 1 apply. A consequence of the modified theory is that a measure can be obtained for the intercellular air space of a leaf.

CONCLUSIONS

The reflectance and transmittance spectra of a typical compact plant leaf can be synthesized with considerable accuracy by interaction of isotropic light with a transparent plate. The plate model of a leaf has been justified by successful predictions. The effective index of refraction of a corn leaf is not inconsistent with the published value of epicuticular wax. The effective absorption coefficient of a corn leaf is largely a superposition of two partial coefficients associated, respectively, with chlorophyll and pure liquid water. Differential spectra due to other leaf substances have not been established.

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TABLE I. Irradiance for regions shown in Fig. I.

Region	Irradiance
1	R_{12}
2	T_{12}
3	$T_{12}\ \tau$
4	$T_{12}\ \tau\ T_{23}$
5	$T_{12}\ \tau\ R_{23}$
6	$T_{12}\ \tau^2\ R_{23}$
7	$T_{12}\ \tau^2\ R_{23}\ T_{21}$
8	$T_{12}\ \tau^2\ R_{23}\ R_{21}$
9	$T_{12}\ \tau^3\ R_{23}\ R_{21}$
10	$T_{12}\ \tau^3\ R_{23}\ R_{21}\ T_{23}$
11	$T_{12}\ \tau^3\ R_{23}\ R_{21}\ R_{23}$
12	$T_{12}\ \tau^4\ R_{23}^2\ R_{21}$
13	$T_{12}\ \tau^4\ R_{23}^2\ R_{21}\ T_{21}$
..	...

TABLE II. Coefficients of approximation cubics $T_i = A_i+B_in+C_in^2+D_in^3$ for transmissivity of polarized diffuse light across a dielectric interface.[a] The coefficients T_i are used in calculation of dT_{12}/dn of Eq. (12).

Coefficients	i = 1	i = 2
A_i	+1.435 228	+1.516 853
B_i	-0.549 374	-1.117 852
C_i	+0.127 332	+0.779 349
D_i	-0.013 136	-0.186 815

[a] Valid for the range $1.2 < n < 1.5$.

TABLE III. Values of Ω in Gauss criterion [a] for the best fit between the absorption coefficients of the corn leaf and those of pure liquid water over the spectral range 1.4 - 2.5 μ. The equivalent water thickness D is held constant over the range.

Genera	K-M theory	Plate theory
Corn [b]	0.0161	0.0035
Cotton [c]	0.0159	0.0027
Citrus [d]	0.0227	0.0077

[a] Equation (16).

[b] Compact leaf.

[c] Immature leaf.

[d] Infiltrated with water.

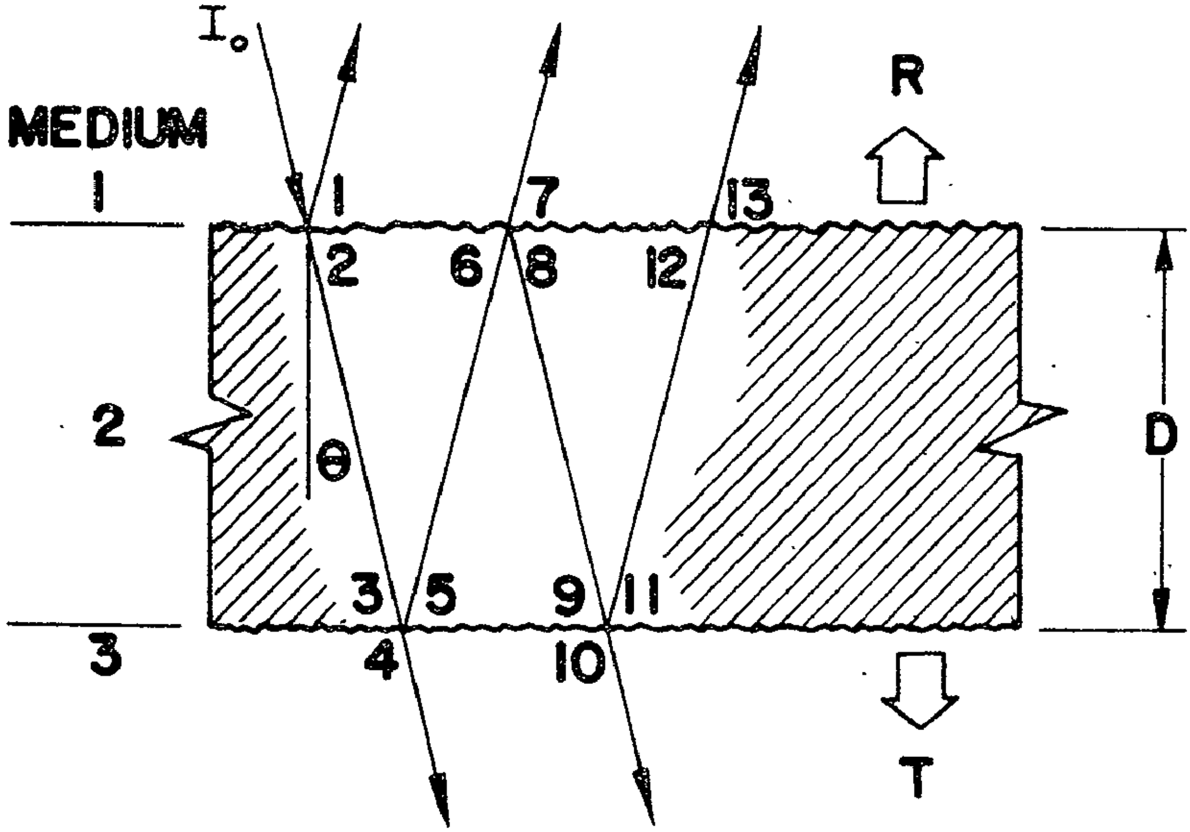

Fig. 1. Multiple reflections produced by a transparent plate with rough surfaces.

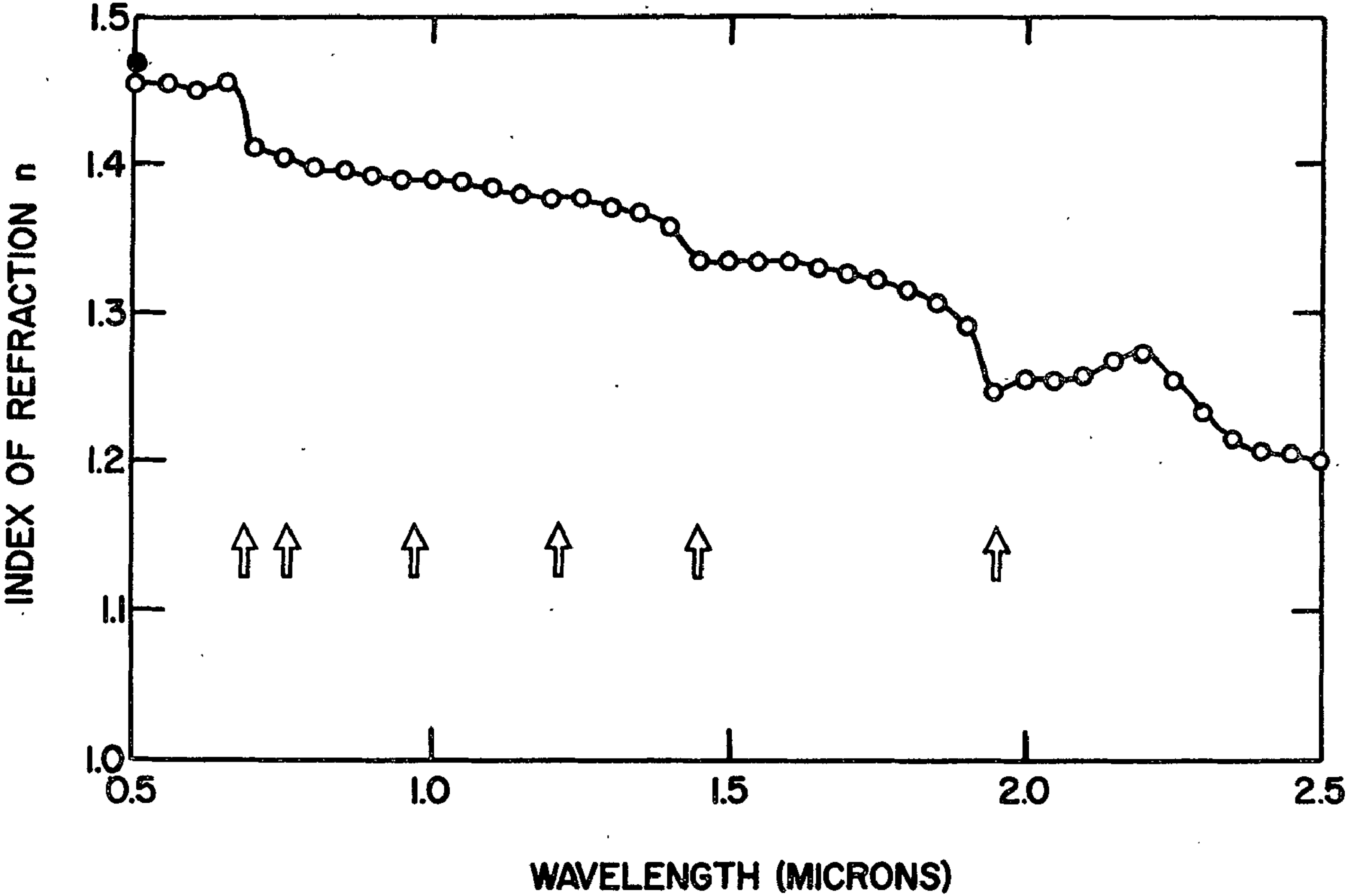

Fig. 2. Effective refractive index of a typical corn leaf. Arrows mark absorption bands due to chlorophyll and liquid water. The additional ● point at 0.5 μ is the published index of refraction for Carnauba wax.

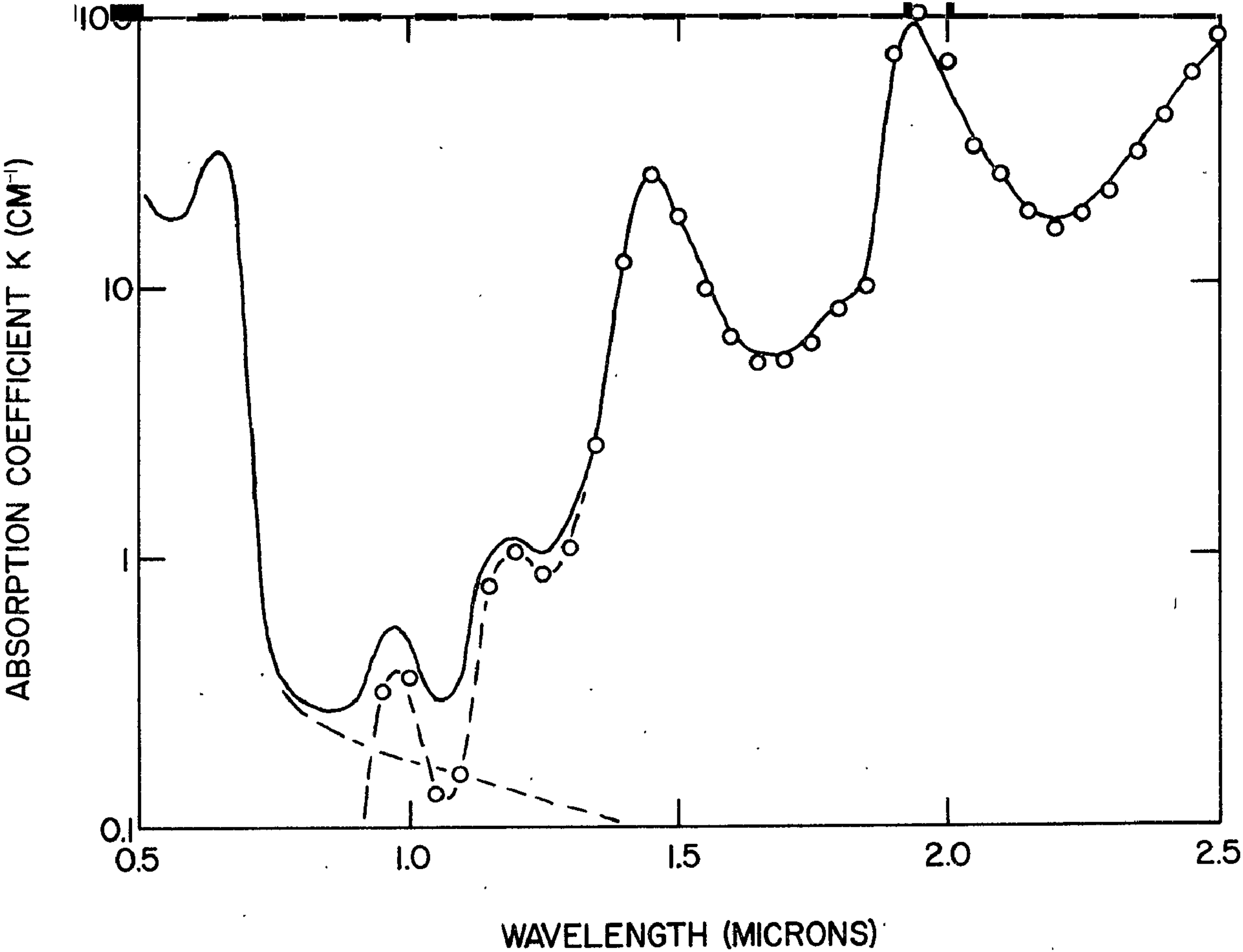

Fig. 3. The solid line indicates the equivalent absorption coefficient of a typical corn leaf with 146 μ equivalent water thickness (EWT). The dashed lines are components due to chlorophyll and pure liquid water. The data points are the Curcio values for pure liquid water.

Plant Canopy Irradiance Specified by the Duntley Equations

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ABSTRACT

The Duntley equations for propagation of specular light through a diffusing medium have been generalized and interpreted to account for the diurnal nature of radiation measured in an Ithaca, New York corn canopy. The Duntley optical coefficients associated with the specular component of light were assumed to vary as the secant of the zenith angle to the sun. Generalization of the Duntley relations was required in order to predict values of irradiance within the canopy and to account for the effect of background reflectance from the soil. Five independent measurements of canopy irradiance suffice to determine the Duntley parameters. Twenty-four measurements of irradiance within the canopy were utilized, however, in a least-squares program to obtain the best fit of the Duntley equations to the corn canopy. The equations fit the experimental results within 3.2% for a period from noon to sundown. If the laboratory measurements of optical constants for a single corn leaf are used as constraints, the Duntley equations fit the data to within 3.7%.

INTRODUCTION

In order to interpret remote sensing data acquired from aircraft and spacecraft, understanding is required of the reflectance produced by features on the surface of the earth. The specific problem in agriculture is interpretation of reflectance produced by vegetation. Reflectance from vegetation is a result of light interaction within the plant canopy.

Interaction of light with a typical plant canopy has been described elsewhere[1,2] by means of a two-parameter representation involving an absorption coefficient and a scattering coefficient. An equivalent treatment[3] involves effective optical constants of the leaf materials. A typical two-parameter representation, such as the Kubelka-Munk (K-M) theory[4], is adequate for many agricultural purposes. The K-M theory, however, is exact only for perfectly isotropic light and an ideal diffusing medium. These conditions are often approximated sufficiently well in agricultural applications of the theory. The K-M relations apply accurately to the case of typical leaves[1] stacked in a DK-2A spectrophotometer[5] in spite of the fact that the DK-2A irradiates the specimen with a directed beam instead of with diffuse light. Although a typical leaf such as corn has strong specular reflection[6], the internal structure of a corn leaf is such that the transmitted light is very diffuse.

The K-M theory has a fair likelihood of representing the irradiance within a plant canopy illuminated by skylight or by light emanating from an overcast or cloudy sky because the light, in these cases, is largely diffuse. The relative irradiance of specular, cloud reflected, and sky light is well known[7].

The K-M theory was never intended for use in situations where the incident light is specular. In the case of an actual plant canopy the specular component of the incident light cannot, in general, be ignored. The inadequacy of the K-M representation to account for the directional component of radiation has been noted by Allen and Brown[2] in the case of a corn canopy. The K-M theory does not account for the observed variation of plant canopy albedo with sun angle[8]. The K-M theory is indeed applicable to a plant canopy after the incident specular light has been reduced to diffuse light. In nature, however, a total leaf-area index (LAI)[9] in excess of five is required to eliminate essentially all sun flecks on the background soil. Most mature plants do not greatly exceed a LAI of five even when mature. The mature corn canopy discussed by Allen and Brown[2], for example, was 250 cm in height with a LAI of 4.33.

When a plant canopy is illuminated by direct sunlight, the K-M two-parameter theory must be generalized to additional parameters in order to account for phenomena produced by sun angle, leaf orientation, or other attributes of the actual physical situation. Theoretical machinery was developed by Duntley in 1942 [10] that generalizes the K-M relations to five or more adjustable parameters. The Duntley equations can be fitted exactly to five independent values of irradiance measured within the plant canopy. Regardless of the physics involved, the use of more than two parameters will improve agreement between theory and experiment. Use of five parameters permits leaf orientation, sun angle, and one other independent plant attribute to be considered.

The purpose of this paper is to demonstrate that the Duntley equations, a generalization of the K-M theory, can be interpreted to include the effects of sun angle on a plant canopy. The reason for restricting the generalization to only one additional canopy property is that accurate data on plant canopy attributes are unavailable.

The Duntley theory, like the K-M representation, is one-dimensional. Restriction to one dimension, however, does not imply that irradiance within a plant canopy cannot be diurnal. The one-dimensional interpretation simply means that conditions at the same depth are identical throughout the canopy. In other words, the irradiance profile is assumed to be invariant over the entire canopy. Edge problems, introduced by rows in cultivated fields, must be treated by special methods.

THEORY

The Duntley equations will be derived at this point for three reasons. First, the calculations are simple and will be included for completeness. Second, the Duntley equations must be generalized to provide values of irradiance within the plant canopy since published forms of the equations apply only to irradiance measured at the boundaries of a diffusing medium. Third, the Duntley relations will be generalized to include the effect of a background.

Figure 1 represents a plant canopy with light-absorbing and light-scattering leaves uniformly distributed and having dimensions much smaller than the height of the canopy. The canopy is assumed to have infinite lateral extension in order to eliminate edge effects. The cumulative LAI is identified as the appropriate dimension n measured downward from the top of the canopy. The quantity N in Fig. 1 will be considered the total LAI of the canopy.

The Duntley theory is based upon the differential equations

$$dI_n'/dn = -(\mu'+B'+F')I_n' \quad , \qquad (1)$$

$$dt/dn = F'I_n' - \mu t - Bt + Bs \quad , \qquad (2)$$

$$-ds/dn = B'I_n' - \mu s - Bs + Bt \quad . \qquad (3)$$

The primed quantities in Eqs. (1)-(3) pertain to incident specular light. The parameters μ', B', and F' are, respectively, an absorption coefficient, a back-scattering coefficient, and a forward-scattering coefficient. The unprimed quantities in Eqs. (1)-(3) pertain to diffuse light generated by scattering. The parameters μ and B are, respectively, the absorption coefficient and back-scattering coefficient for diffuse light. The plane n = 0 in Fig. 1 is the specularly illuminated surface of the canopy and the plane n = N is the surface of the soil. The radiant fluxes, specular and diffuse, in the positive direction are denoted I_n' and t, respectively, while the diffuse radiant flux in the negative direction is designated s. The incident specular flux on the canopy is designated I_o'. If, as in the following, I_o' is considered unity, the reflected flux R' is designated reflectance and the transmitted flux T' is designated transmittance.

The solution of Eq. (1) is

$$I_n' = I_o' \, e^{-q'n} \quad , \tag{4}$$

where $q' = \mu'+B'+F'$. Eliminate I_n' from Eqs. (2) and (3) by means of Eq. (4). Solve Eq. (2) for s, substitute the result into Eq. (3), and rearrange to obtain

$$d^2t/dn^2 - \alpha^2 t = -\left[(\mu+\mu')F' + (B+F')(B'+F)\right]e^{-q'n} \quad , \tag{5}$$

where

$$\alpha^2 = \mu(\mu+2B) \quad . \tag{6}$$

By an analogous method obtain

$$d^2s/dn^2 - \alpha^2 s = -\left[(\mu-\mu')B' + (B-B')(B'+F')\right]e^{-q'n} \quad . \tag{7}$$

Solve Eqs. (5) and (7) and make the substitutions

$$P' = \left[(\mu-\mu')B'+(B-B')(B'+F')\right]\left[(\mu'+B'+F')^2-\mu(\mu+2B)\right]^{-1} \quad , \tag{8}$$

$$Q' = \left[(\mu+\mu')F'+(B+F')(B'+F')\right]\left[(\mu'+B'+F')^2-\mu(\mu+2B)\right]^{-1} \quad . \tag{9}$$

Assume solutions of the form

$$t = A(1-\beta)e^{\alpha n}+B(1+\beta)e^{-\alpha n}+(1-Q')e^{-q'n} \quad , \tag{10}$$

$$s = A(1+\beta)e^{\alpha n}+B(1-\beta)e^{-\alpha n}-P'e^{-q'n} \quad , \tag{11}$$

where $\beta^2 = \mu/(\mu+2B)$. The quantity β has been introduced in Eqs. (10)-(11) for future convenience. Equation (10) includes the unscattered component of the incident specular light in addition to the diffuse component. The arbitrary constants A and B of Eqs. (10)-(11) can be evaluated from the boundary conditions $t = 1$ when $n = 0$ and $s = 0$ when $n = N$. Solve the resultant linear equations to obtain

$$A = [(1+\beta)T_c' P' - (1-\beta)Q' e^{-\alpha N}] [(1+\beta)^2 e^{\alpha N} - (1-\beta)^2 e^{-\alpha N}]^{-1} \quad , \qquad (12)$$

$$B = [(1+\beta)Q' e^{\alpha N} - (1-\beta)T_c' P'] [(1+\beta)^2 e^{\alpha N} - (1-\beta)^2 e^{-\alpha N}]^{-1} \quad . \qquad (13)$$

Make the substitutions $\alpha = \log b$, $\beta = (a-1)/(a+1)$, substitute Eqs. (12)-(13) into Eqs. (10)-(11), and simplify to obtain

$$t = Q' \frac{ab^{N-n} - a^{-1}b^{-N+n}}{ab^N - a^{-1}b^{-N}} + P'T_c' \frac{b^n - b^{-n}}{ab^N - a^{-1}b^{-N}} - (Q'-1)e^{-q'n} \quad , \qquad (14)$$

$$s = Q' \frac{b^{N-n} - b^{-N+n}}{ab^N - a^{-1}b^{-N}} + P'T_c' \frac{ab^n - a^{-1}b^{-n}}{ab^N - a^{-1}b^{-N}} - P'e^{-q'n} \quad . \qquad (15)$$

Equations (14)-(15) apply to the special case of a diffusing medium with no background. Correction relations that result from background reflectance R_g can be inferred from Ref. (1) in the forms

$$t_o = R_g M (b^n - b^{-n})(a - a^{-1})^{-1} \quad , \qquad (16)$$

$$s_o = R_g M (ab^n - a^{-1}b^{-n}) (a - a^{-1})^{-1} \quad . \qquad (17)$$

where

$$M = T_N(1-R_gR_N)^{-1}t(N) \quad , \tag{18}$$

$$T_N = (a-a^{-1})(ab^N-a^{-1}b^{-N})^{-1} \quad , \tag{19}$$

$$R_N = (b^N-b^{-N})(ab^N-a^{-1}b^{-N})^{-1} \quad . \tag{20}$$

The notation t(N) in Eq. (18) is interpreted as Eq. (14) evaluated at the point n = N.

For the special case of negligible absorption, applicable to leaves in the 1 μ region[1], the preceding relations can be simplified considerably. Substitute $\mu = \mu' = 0$ in Eqs. (8)-(9) to obtain

$$P' = (B-B')/(B'+F') \quad , \tag{21}$$

$$Q' = (B+F')/(B'+F') \quad . \tag{22}$$

Substitute Eqs. (21)-(22) and the results of Ref. (1) into Eqs. (14)-(15) to obtain

$$t = \frac{B+F'}{B'+F'}\,\frac{1+B(N-n)}{1+BN} + \frac{B-B'}{B'+F'}\left[T_c'\,\frac{Bn}{1+BN} - e^{-q'n}\right] \quad , \tag{23}$$

$$s = \frac{B+F'}{B'+F'}\,\frac{B(N-n)}{1+BN} + \frac{B-B'}{B'+F'}\left[T_c'\,\frac{1+Bn}{1+BN} - e^{-q'n}\right] \quad , \tag{24}$$

where $q' = B'+F'$ and $T_c' = \exp(-q'N)$. The correction terms that result from background reflectance R_g can be inferred from Ref. (1) in the forms.

$$t_o = R_g\, Bn[1+BNT_g]^{-1} t(N) \quad , \tag{25}$$

$$s_o = R_g(1+Bn)\, [1+BNT_g]^{-1} t(N) \quad , \tag{26}$$

where $t(N)$ is Eq. (23) evaluated at $n = N$ and $T_g \equiv 1-R_g$.

The net radiation, including the background reflectance, can be written

$$t-s=(1+BN)^{-1}(B'+F')^{-1}\ \{(B+F')-(B-B')\exp[-(B'+F')N]\}\ -R_g(1+BNT_g)^{-1}t(N). \tag{27}$$

The net radiation in the region of zero absorptance is independent of n; that is, the net radiation does not vary with location in the canopy.

The Duntley equations, as generalized above, specify the irradiance within a plant canopy superimposed upon a soil background of reflectance R_g. Implicit in the development is the assumption that specular light incident on the soil background is reflected as diffuse light.

Experiments have indicated that an actual plant canopy is characterized by diurnal effects. Allen and Brown[2] have shown that attenuation within a plant canopy depends upon the sun angle. The variation of vegetation albedo with sun angle has been reported by Monteith and Szeicz[11] for kale, potatoes, and grass; by Graham and King[12] for maize; by Chang[13] for cane; and by Chia[14] for sugar cane, pangola grass, and pigeon pea trees.

An argument of plausibility suggests that specular light attenuation through a plant canopy can be characterized by the relation

$$I' = I_o' e^{-q_o' n \sec \zeta} \quad , \qquad (28)$$

where ζ is the zenith angle of the sun. Equation (28) can be interpreted in the following two alternative ways: In the first interpretation use is made of the fact that slant rays interact with more leaves than comparable vertical rays. If q_o' is a constant that applies to the case of a hypothetical zenith sun, then $n \sec \zeta$ is considered to be an effective value of cumulative LAI for a slant ray passing obliquely through the canopy. The effective total LAI of a canopy with respect to a slant ray can likewise be specified by the expression $N \sec \zeta$ where N is the conventional value of total LAI. The second interpretation of Eq. (28) is based upon the conventional definition of LAI illustrated in Fig. I. In this case, the diurnal effect can be incorporated in the coefficient q' defined by the relation $q' \equiv q_o' \sec \zeta$. The latter interpretation is adopted in this paper.

EXPERIMENT

Figure 2 illustrates the Duntley equations fitted by the method of least squares discussed in the Appendix to near-infrared experimental transmission data obtained by the Cornell group on Sept. 13, 1963 in a corn canopy located at Ithaca, New York[2]. The standard deviation between the experimental and theoretical points is 3.2%--a value well within experimental error. Experimental data, indicated in Fig. 2, existed for the three LAI values 1.48, 2.77, and 3.78. The value $R_g = 0.25$ was assumed. Five independent measurements of irradiance associated with the canopy are necessary to determine the five adjustable parameters. The data, however, were consistent with the assumption $\mu = \mu' = 0$. When zero absorption was imposed as a constraint, the reduced Duntley equations consisting of three parameters can be fitted to the three given LAI values. The Duntley parameters μ', B', and F' were specified by the relations

$$\begin{aligned} \mu' &= \mu_o' \sec \zeta \quad , \\ B' &= B_o' \sec \zeta \quad , \\ F' &= F_o' \sec \zeta \quad , \end{aligned} \tag{29}$$

where ζ is the zenith angle of the sun. Ephemeris data and the geographical coordinates Lat. N 42° 26', Long. 76° 23'W. were used to calculate ζ for cooresponding times. The fitted Duntley parameters used in the curves of Fig. 2 are listed as Case 1 in Table 1.

Case 2 of Table I illustrates the fit obtained if μ and B are set equal to the average values $\mu = 0.035 \pm 0.007$, $B = 0.736 \pm 0.048$ measured in the laboratory at 1 μ wavelength on 10 mature corn leaves grown at Weslaco, Texas during 1968. The resultant standard deviation, 3.7%, is not significantly different from the best fit illustrated in Case I. Case 2, however, is likely to be closer to physical reality than Case I in spite of the slightly larger standard deviation. The Duntley equations applied to a plant canopy are not inconsistent with laboratory values of optical parameters measured on single leaves.

Figure 3 illustrates the enhanced reflectance at low sun angles predicted by the Duntley equations for the Ithaca corn canopy where the values for Case 2 in Table I have been used. Slant rays encounter more scattering centers than vertical rays. More slant rays than vertical rays emerge as reflectance and fewer slant rays than vertical rays are transmitted to the soil. Figure 3 also includes for comparison an average value $R_\infty = 0.734 \pm 0.012$ [15] measured at 1 μ in the laboratory on 10 mature corn leaves grown at Weslaco, Texas during 1968.

CONCLUSIONS

The Duntley equations, interpreted appropriately, can account for reflectance from, and attenuation of near-infrared irradiance within, a corn canopy. The observed diurnal effect in a corn canopy is explained by the variation of q' with sun angle. The observed increase in vegetation reflectance at low sun angles is predicted by the Duntley equations. For the case of negligible absorptance, the Duntley equations reduce to a three-parameter representation that describes the transmissivity of the corn canopy with surprising accuracy. A good experimental design to determine the Duntley parameters should be based upon reflectivity as well as upon transmissivity measurements. The Duntley parameters are not inconsistent with laboratory values of optical parameters measured on single leaves.

ACKNOWLEDGMENTS

The authors are pleased to acknowledge the stimulating discussions with Harold W. Gausman and Craig L. Wiegand. Thanks are also extended the Cornell group for use of their published corn canopy data.

APPENDIX

The function to be minimized is given by

$$S = \sum_{i=1}^{n} w_{ti}(T_{oi} - T_{ci})^2 + \sum_{k=1}^{m} w_{rk}(R_{ok}-R_{ck})^2 \quad , \tag{30}$$

where T_{oi} and T_{ci}, respectively, are observed and computed values of downward flux. The terms R_{ok} and R_{ck}, respectively, are observed and computed values of upward flux. The quantities w_{ti} and w_{rk} are relative weights. Introduce the parameters μ_o', B_o', and F_o' by means of Eq. (29). Make the substitutions

$$(\mu \;\; B \;\; \mu_o' \;\; B_o' \;\; F_o') \equiv (\alpha_1 \;\; \alpha_2 \;\cdots\; \alpha_5) \quad , \tag{31}$$

Minimize S in Eq. (30) with respect to α_j and set the result equal to zero to obtain the five relations

$$\partial S/\partial\alpha_j = -\sum_{i=1}^{n} 2\, w_{ti}\,(T_{oi}-T_{ci})\partial T_{ci}/\partial\alpha_j$$

$$-\sum_{k=1}^{m} 2\, w_{rk}(R_{ok}-R_{ck})\partial R_{ck}/\partial\alpha_j = 0 \quad . \tag{32}$$

Expand T_{ci} and R_{ck} at each data point around the respective values C_i and D_k to obtain the relations

$$T_{ci} = C_i + \sum_{k=1}^{5} (\partial T_{ci}/\partial\alpha_k)d\alpha_k \quad ,$$

$$R_{ck} = D_k + \sum_{\ell=1}^{5} (\partial R_{ck}/\partial\alpha_\ell)d\alpha_\ell) \quad . \tag{33}$$

Substitute Eqs. (33) into Eqs. (32) to obtain the five equations

$$\sum_{i=1}^{n} [w_{ti}(T_{oi}-C_i) - \sum_{k=1}^{5} w_{ti}(\partial T_{ci}/\partial \alpha_k)d\alpha_k] \, \partial T_{ci}/\partial \alpha_j \,.$$

$$+ \sum_{k=1}^{m} [w_{rk}(R_{ok}-D_k) - \sum_{\ell=1}^{5} w_{rk}(\partial R_{ck}/\partial \alpha_\ell)d\alpha_\ell] \partial R_{ck}/\partial \alpha_j = 0. \qquad (34)$$

Collect terms in Eqs. (34) to obtain the five normal equations

$$\sum_{i=1}^{n} \sum_{k=1}^{5} w_{ti}(\partial T_{ci}/\partial \alpha_j)(\partial T_{ci}/\partial \alpha_k)d\alpha_k$$

$$+ \sum_{k=1}^{m} \sum_{l=1}^{5} w_{rk}(\partial R_{ck}/\partial \alpha_k)(\partial R_{ck}/\partial \alpha_\ell)d\alpha_\ell = \sum_{i=1}^{n} w_{ti}(T_{oi}-C_i)\partial T_{ci}/\partial \alpha_j$$

$$+ \sum_{k=1}^{m} w_{rk}(R_{ok}-D_k)\partial R_{ck}/\partial \alpha_j \quad . \qquad (35)$$

Equations (35) are five equations in the five unknowns $d\alpha_j$. Solve Eqs. (35) to obtain $d\alpha_j$. Correct initial values α_j to obtain the improved values $\alpha_j + d\alpha_j$. Iterate until convergence is achieved. The necessary differential coefficients can be approximated easily from the defining relations

$$\frac{\partial T_c}{\partial \alpha_j} \cong \frac{T_c(\alpha_j+\Delta\alpha_j)-T_c(\alpha_j)}{\Delta\alpha_j} \quad ,$$

$$\frac{\partial R_c}{\partial \alpha_j} \cong \frac{R_c(\alpha_j+\Delta\alpha_j)-R_c(\alpha_j)}{\Delta\alpha_j} \quad , \tag{36}$$

where $\Delta\alpha_j$ is taken sufficiently small.

TABLE I. Duntley parameters that specify irradiance in corn canopy.[a]

Parameters	Case I	Case 2
μ	0.000	0.035[b]
B	1.369	0.736[b]
μ_o'	0.000	0.125
B_o'	0.978	0.297
F_o'	0.609	0.281
Standard deviation	3.2%	3.7%

[a] Ithaca, New York, September 13, 1963.

[b] Laboratory values for single leaves at 1 μ.

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9. The leaf-area index is defined as the cumulative one-sided leaf area per unit ground area measured from the canopy top to a plane a given distance above the ground. The total LAI is the value determined at the plane of the soil. See D. J. Watson, Ann. Bot. Lond., N. S. 11, 41 (1947).
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15. The infinite reflectance R_∞ is the reflectance attained by leaves stacked to an infinite depth. In practice, a maximum value of reflectance is achieved at all wavelengths when the number of leaves exceed 8.

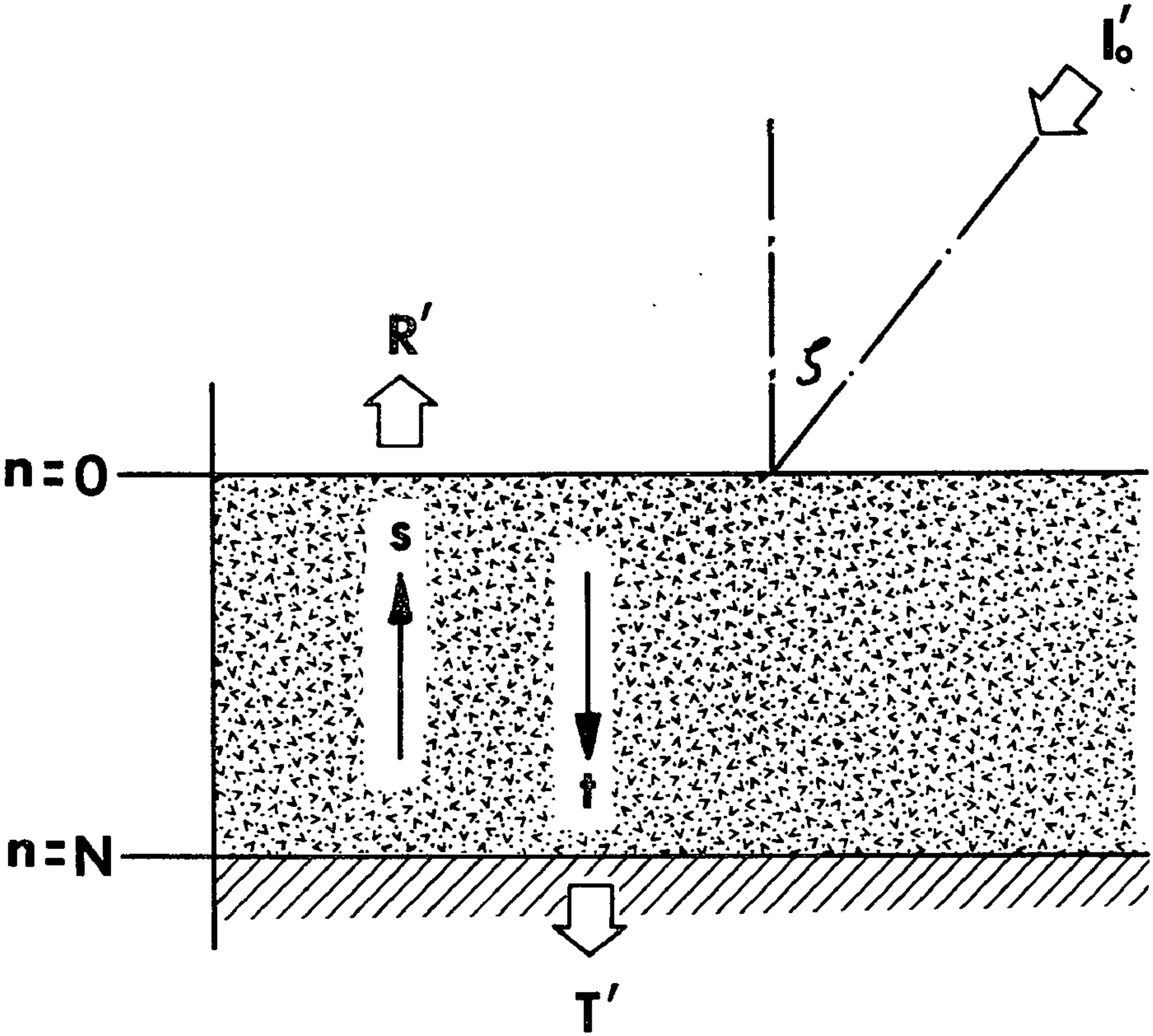

Figure 1. Model of a plant canopy.

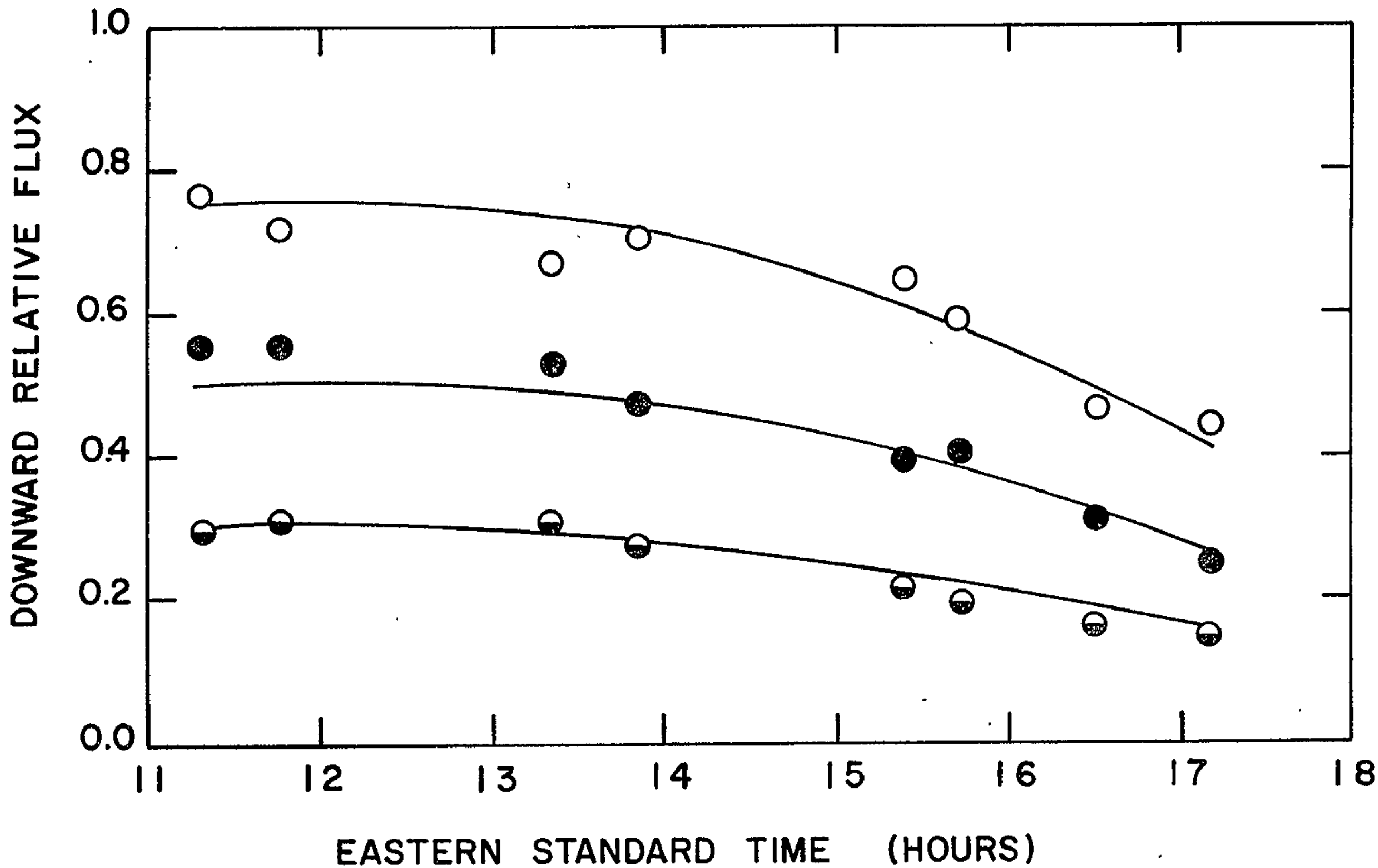

Figure 2. Percent transmission of near-infrared radiation within the 250-cm. high Ellis Hollow (Ithaca, New York) corn corp of September 13, 1963. The top curve ○ is for 150 cm. height, the middle curve ● is for 100 cm., and the bottom curve ⊖ is for 50 cm. The curves are theoretical predictions based upon the Duntley equations; the data points are experimental values. The standard deviation between experiment and theory is 3.2%.

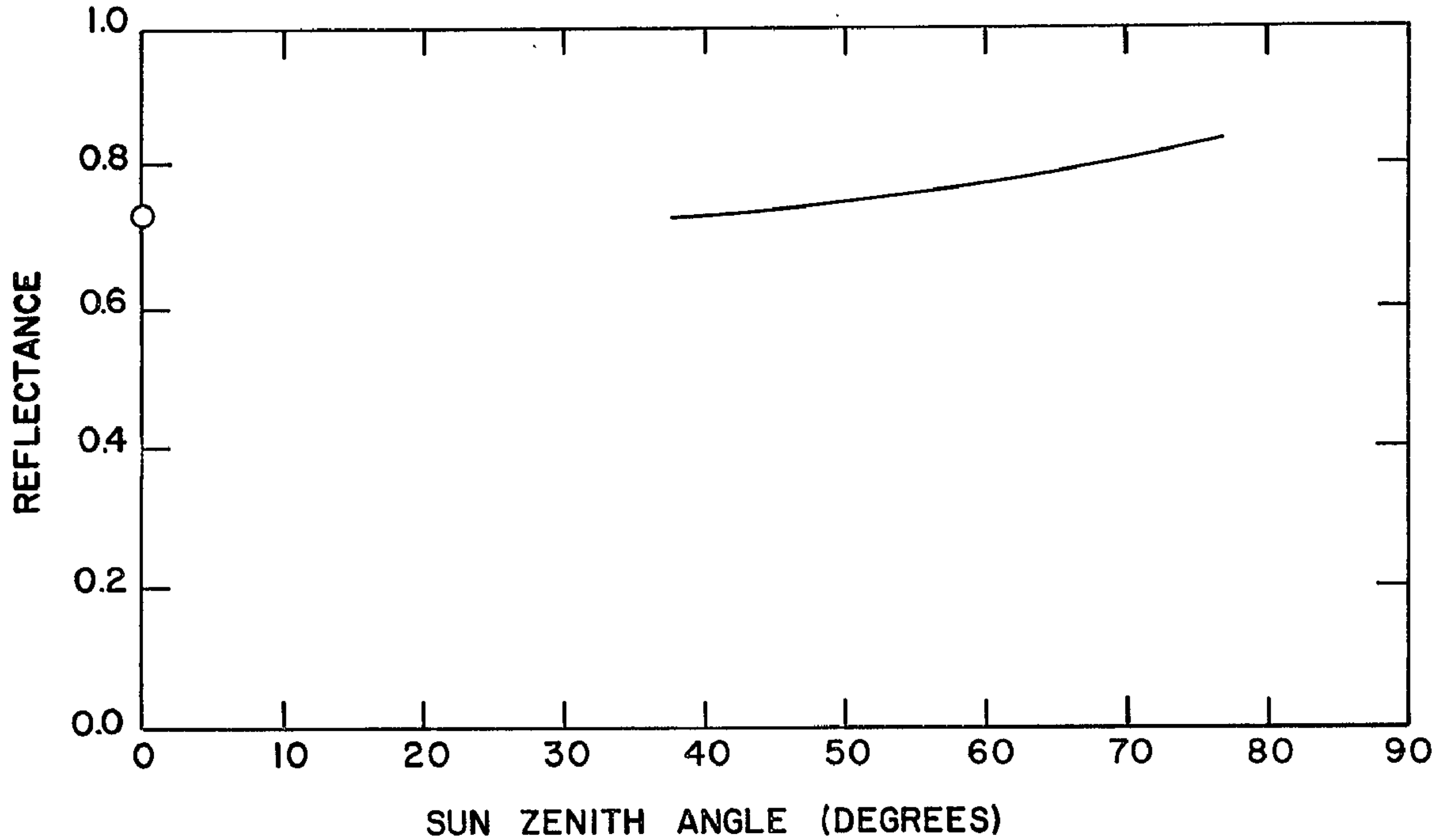

Figure 3. Enhanced reflectance at low sun angles predicted by the Duntley equations. The data point ○ is a laboratory measurement on corn leaves.

Characterization of incident and reflected short wavelength radiation

by

W. J. Rippert

Introduction:

Photographic film registers target reflectance. Various optical mechanical scanners are also able to measure and make provisions for recording the red and near infrared wavelengths of incident and reflected electromagnetic radiation. Such equipment is extremely expensive, at the state-of-the-art technologically, and unavailable at Weslaco.

As an interim measure the needed data for investigating this part of the electromagnetic spectrum are being obtained using ISCO spectroradiometers.

Objective:

To characterize incoming solar and outgoing reflected shortwave length radiation.

Methods and procedures:

These data are meant as support data to be used in interpreting imagery and multi-channel sensor output from a NASA aircraft. An ISCO spectroradiometer was used in making field measurements at various dates from July 6, 1967 through December 14, 1968.

Reflectance data were obtained with the ISCO spectroradiometer mounted on a Truco aerial lift and elevated to a height of 700 cm. above the crop canopy for an integrated measurement of reflectance from canopy and furrow. For isolated measurements of crop or furrow a height of 50 cm was used. A probe angle of -90° from horizontal was used for all measurements.

The ISCO spectroradiometer has a wavelength range of 0.45 to 1.55 microns with bandwidth of 0.015 and 0.03 microns, respectively, in the visible and infrared. Sensitivity is from 0.3 to 1000 $\mu w\ cm^{-2}\ m\mu^{-1}$ in eight ranges, with accuracy of 7 to 10 percent. Two sensing heads, each having a 180° field of view, are provided with the instrument. One is a diffusing screen mounted directly on the instrument case for measurement of incoming radiation, and the other is a six foot fiber optics probe which is used for measurement of scanned reflectance data.

The fiber optics probe has been modified to decrease the field of view from 180° to 20° so that specific areas can be isolated for reflectance measurements. A recorder-scanner used in conjunction with the spectroradiometers record spectral intensity versus wavelength in a continuous spectral distribution curve. A modification has been made to the recorder-scanner so that a single predetermined wavelength may be monitored for detailed studies.

Results and Discussion:

Table I is a listing of various instrument sites used to obtain incoming radiation and reflectance measurements on January 24, 1968 through December 14, 1968.

Figure I compares reflectance from grain sorghum, cotton, pepper and citrus. The units of reflectance are presented in microwatts cm^{-2} $m\mu^{-1}$.

Figure 2 presents the reflectance from cotton plants and the soil in the furrow. Soil shows a higher reflectance in the visible portion of the spectrum and cotton a higher reflectance in the near-infrared portion of the spectrum.

Figure 3 compares the outgoing, or reflected radiation, with the total incoming radiation for a cotton canopy over the wavelength interval 0.4 to 1.6 μ. The spectral albedo is also shown. The peak in albedo at 1.4 μ, a water absorption band, is due to instrument error in measuring reflectance and total incoming radiation.

Figures 4 and 5 present incoming radiation taken with an Eppley pyranometer and spectroradiometer at three wavelengths 0.55, 0.80, and 1.25 μ, on January 24, 1968, and July 6, 1967, respectively. On January 24, 1968, the ambient temperature was 15° to 18°C and relative humidity was 40 to 42 percent. On July 6, 1967, the ambient temperature was 32 to 35°C and relative humidity was 30 to 40 percent. The wind speed on July 6 was 20 to 30 mph with a high concentration of dust particles in the air, whereas January 24 was a calm day.

In January 1968, spectroradiometer readings corresponded to Eppley readings with time. However, on July 1968 spectroradiometer readings at 0.80 μ and especially at 1.25 μ had a sharp increase in magnitude at 1200 hours; this result is believed due to instrument error and not a real phenomenon.

Figure 6 shows a comparison of incoming radiation when monitored at two wavelengths 0.55 and 0.80 μ on June 1968. Readings were taken when scattered clouds occurred to measure the effect of cloud cover on incoming radiation at various wavelengths in the visible and near-infrared. A period of no cloud cover for eight minutes was monitored to show the effect of the clouds edge on incoming radiation measurements. A very small change was noted at 0.80 μ, however at 0.55 μ there was a substantial increase at the cloud edge.

Table I.--Dates and sites at which spectroradiometer measurements were made, and comments.

CROP	DATE	HOUR (CDT)[1]	LINE	SITE	COMMENTS
Sorghum	6/13/68	1342-1426	R.F.	Block E	Ground cover - 95% Height - 137 cm Maturity - milk Cloud condition - 25% Haze condition - None
Sorghum	6/29/68	1002-1026	11	28	Ground cover - 80% Height - 100 cm
Soil	6/29/68	1031-1049	11	28	Maturity - Hard Cloud condition - 25-50% Haze condition - None Plane over site
Cotton	7/ 9/68	1227-1630	12	46a	Ground cover - 80% Height - 80 cm Maturity - Boll Cloud condition - Clear Haze condition - None Plane over site
Cotton	7/15/68	1453-1544	12	29	Ground cover - 95% Height - 83 cm Maturity - Boll Cloud condition - Cloudy Haze condition - Hazey
Citrus	7/18/68	1357-1504	12	89	Ground cover - Height - 600 cm Maturity - Green Cloud condition - Partly cloudy Plane over site
Sorghum	7/20/68	1146-1155	13	85	Ground cover - 75% Height - 125 cm Maturity - Milk Cloud condition - Cloudy Haze condition - None
Pepper	7/20/68	1304-1307	13	85a	Ground cover - 70% Height - 65 cm Maturity - Harvest stage Cloud condition - Cloudy Haze condition - None

(Cont'd.)

[1] CDT - Central Daylight Time.

Table I.--Continued

Soil	7/23/68	1417-1424	13	71	Cloud condition - Some clouds Haze conditions - None
Cotton	7/25/68	1443-1614	13	87a	Ground cover - 96% Height - 141 cm Maturity - Boll Cloud condition - Cloudy Plane over site
Cotton	7/27/68	1009-1037	11	77	Ground cover - 100% Height - 130 cm Maturity - Some open boll Cloud condition - Some clouds Haze condition - Hazey Plane over site
Pepper	12/14/68	1003-1034	12	73	Ground cover - 75% Height - 66 cm Maturity - Harvest stage Cloud condition - Clear Haze condition - None NASA plane over site

Summary:

Comparison of reflectance of cotton and soil in a furrow in Fig. 3 shows a higher reflectance for soils in the 0.4 to 0.7 μ region and a higher reflectance for cotton in the 0.7 to 1.6 μ region. The percent plant cover will therefore influence the overall reflectance of a crop canopy when measured from an elevation where crop and soils are integrated. A higher percentage of soil showing will increase the reflectance in the visible region and the higher percentage of crops will increase the reflectance in the near-infrared region.

The albedo (ratio of outgoing to incoming radiation) of a cotton canopy was found to be similar in shape to the reflectance curve of four stacked leaves using a laboratory spectrophotometer.

The spectra of incoming radiation measured in January and July differed substantially. Incoming radiation in the near infrared increases when the aerosol content of the atmosphere increases.

Comparison of incoming radiation when monitored at two wavelengths under scattered cloud conditions showed that radiation increased at the edge of a cloud and slowly decreased as the cloud moved away from the line of sight between the spectroradiometer and the sun. This increase was small at 0.80 μ, however at 0.55 μ there was a large increase at the cloud edge.

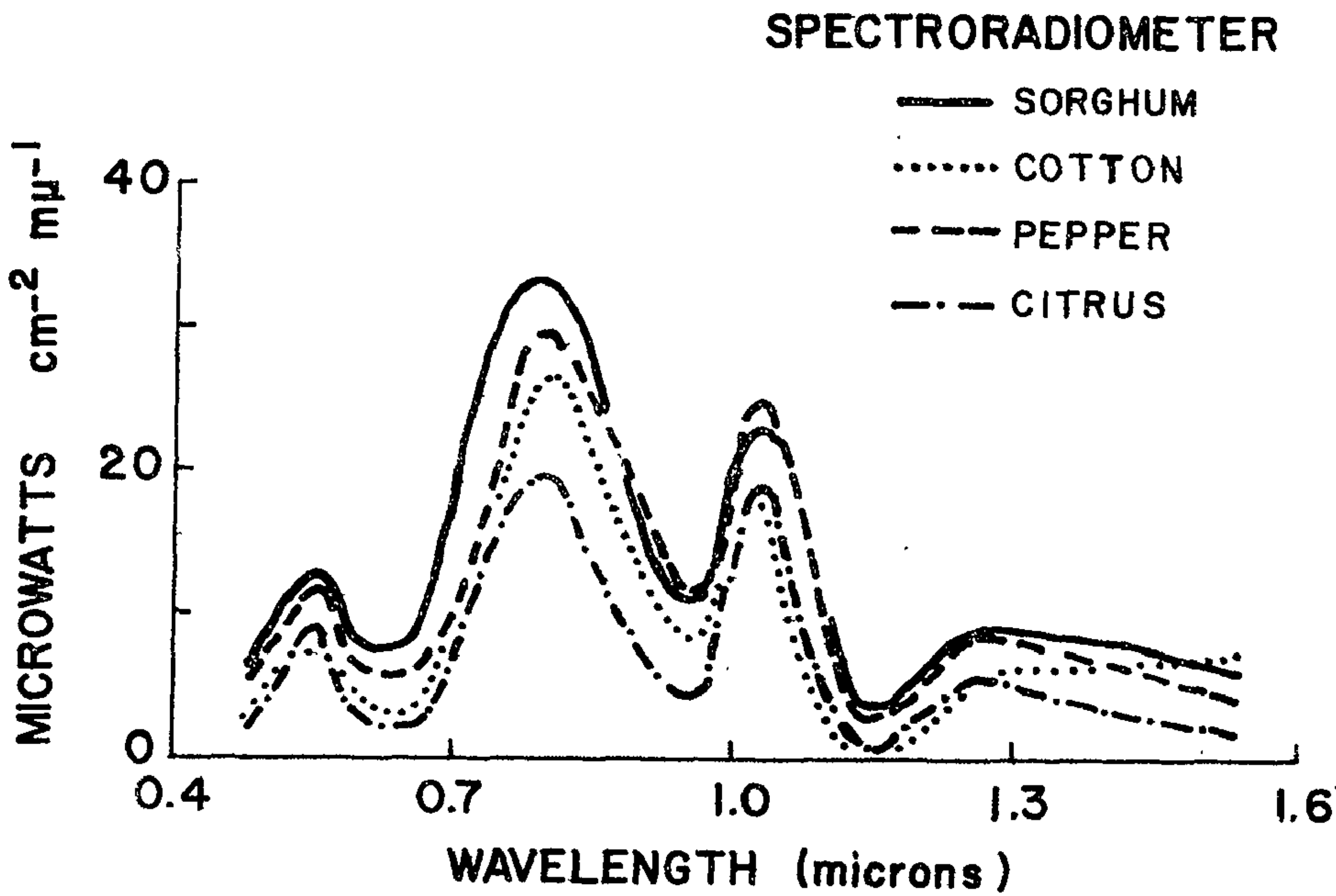

Figure 1.--Reflectance from various agricultural crops as measured with an ISCO spectroradiometer.

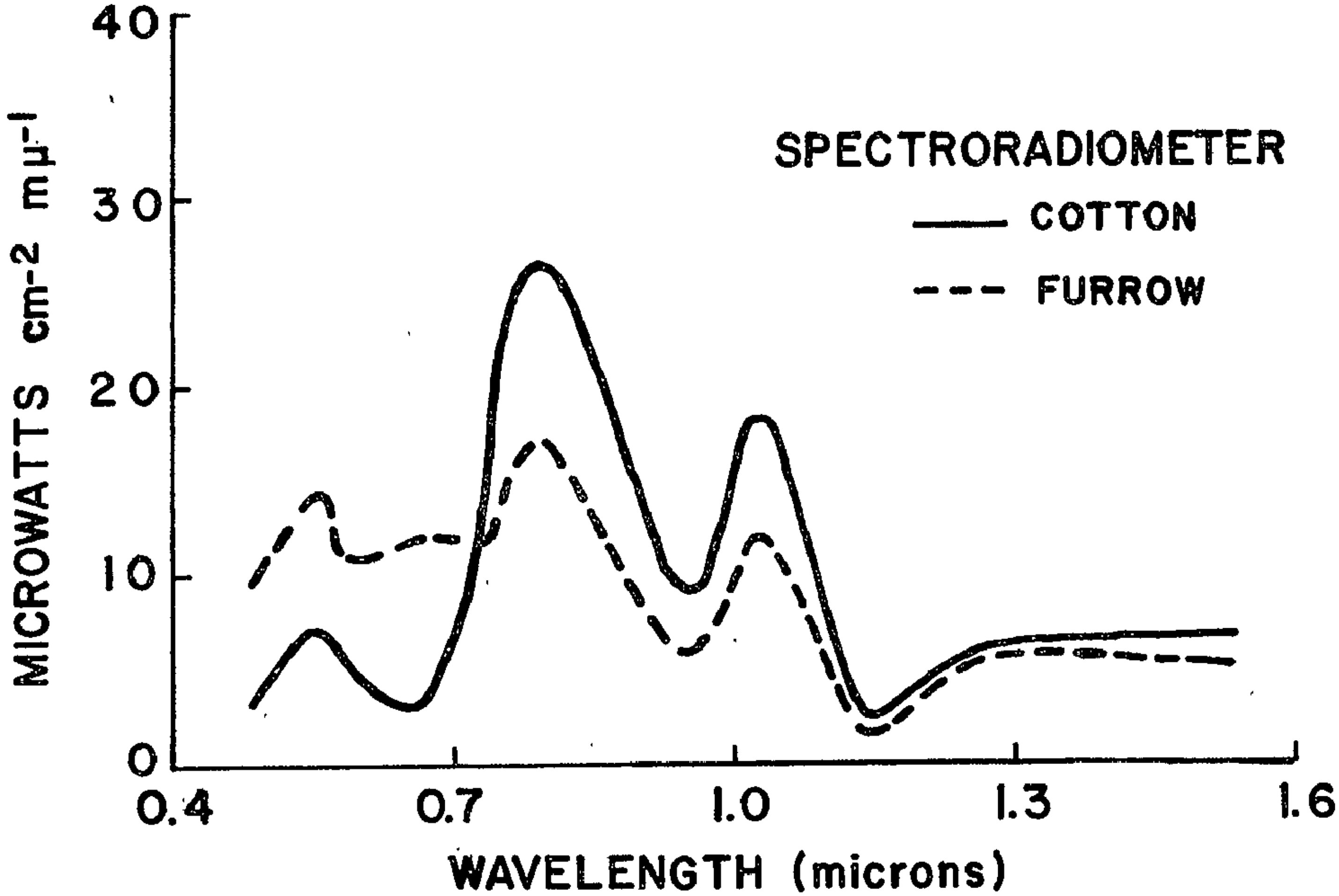

Figure 2.--Reflectance from cotton plant compared with the soil in the furrow as measured with an ISCO spectroradiometer.

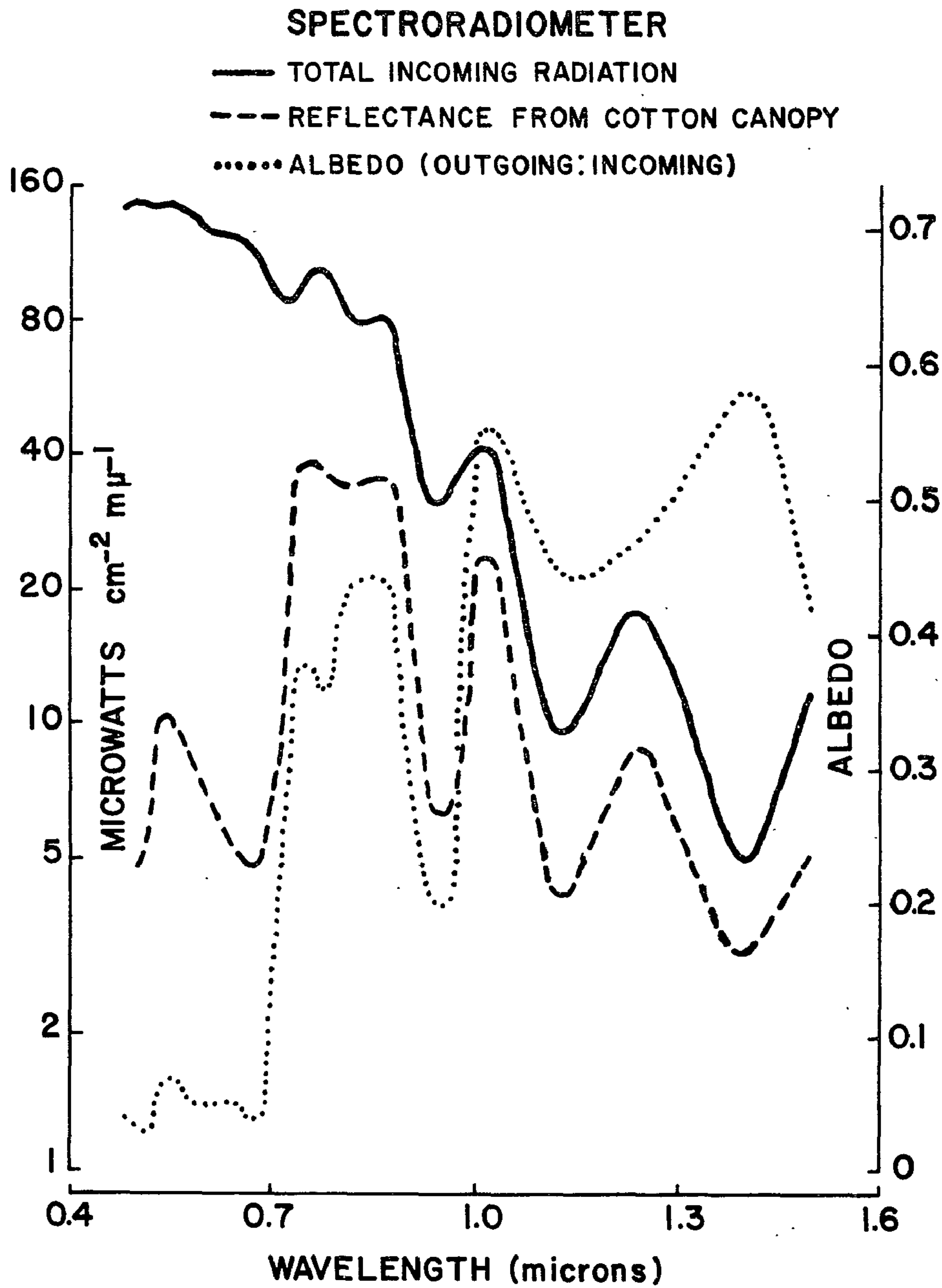

Figure 3.--The incident and outgoing radiation and albedo (ratio, outgoing: incoming) for a cotton canopy.

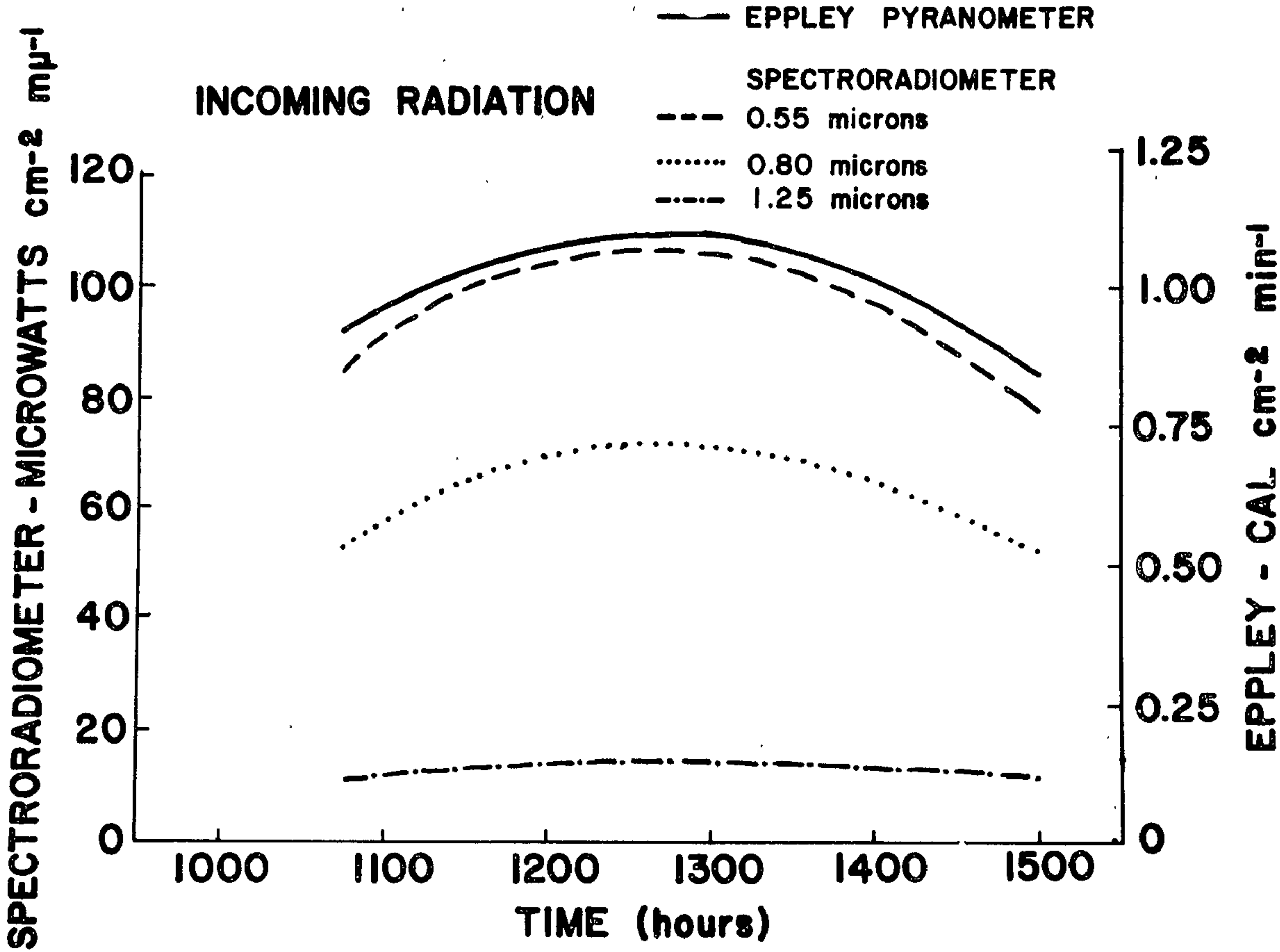

Figure 4.--Comparison of direct plus diffuse sky incoming radiation measured with an Eppley pyranometer and with a spectroradiometer at various wavelengths and time on January 24, 1968.

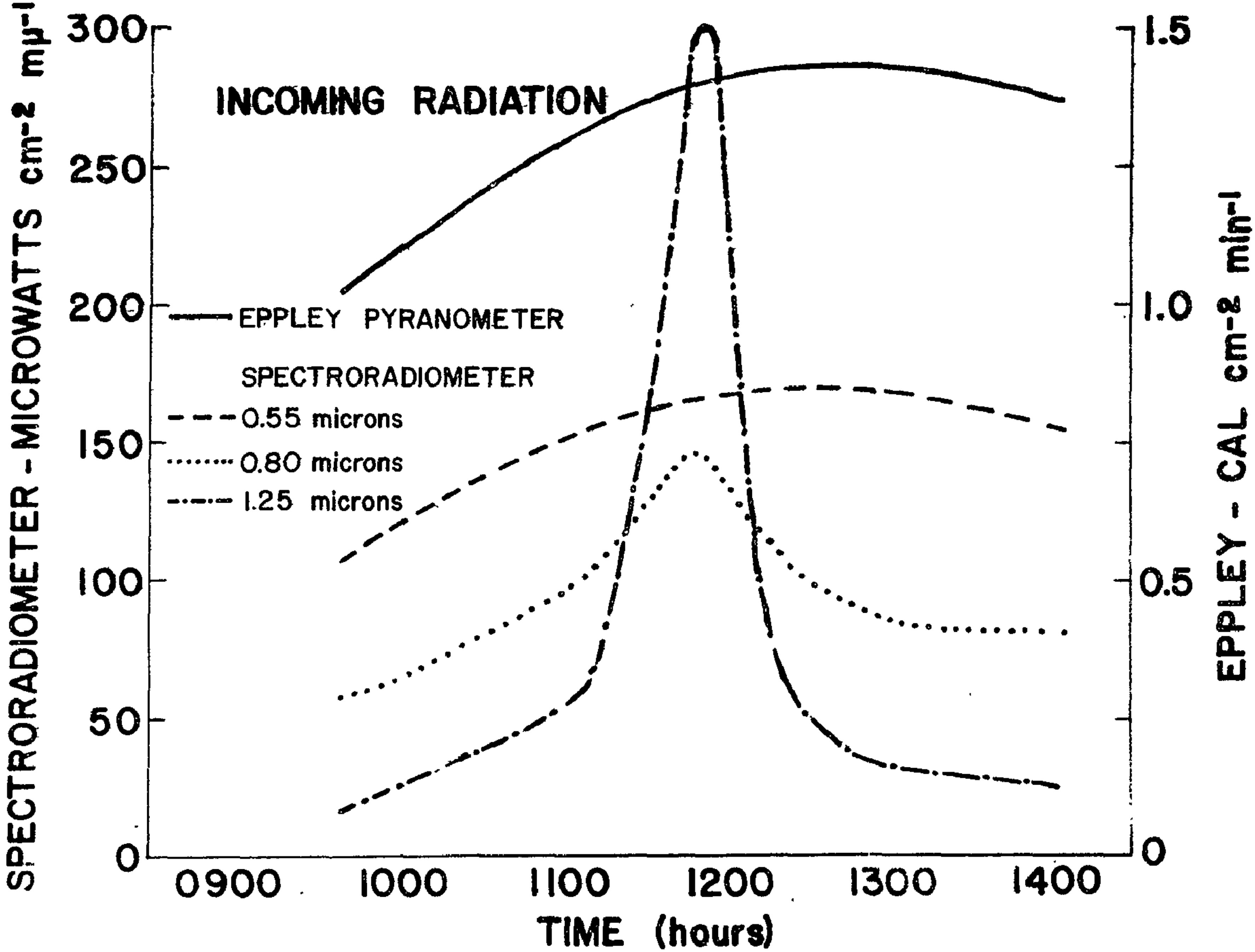

Figure 5.--Comparison of incoming radiation with an Eppley pyranometer and spectroradiometer at various wavelengths and time on July 6, 1967.

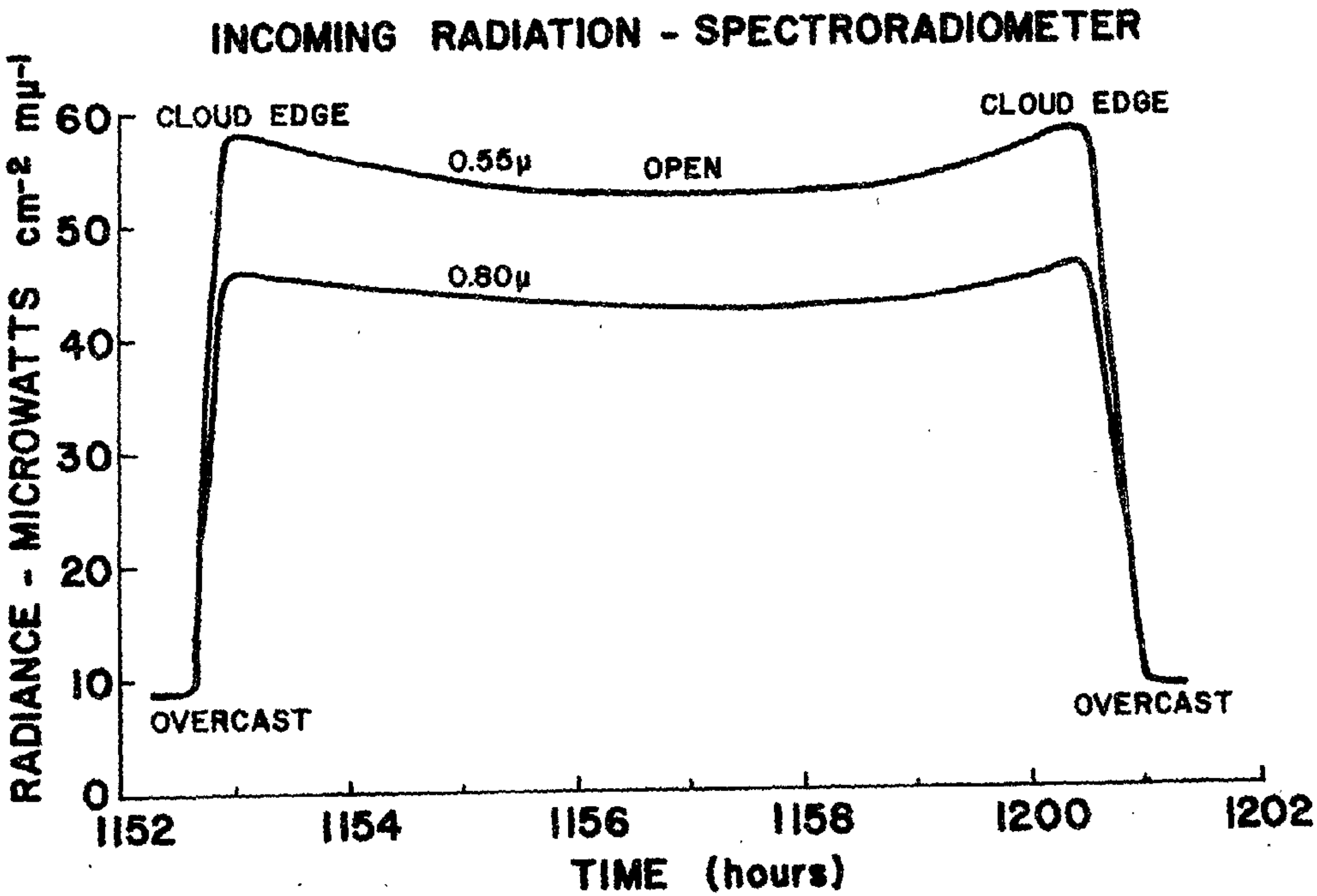

Figure 6.--Comparison of incoming radiation when monitored at two wavelengths on June 14, 1968.

RELATION OF LIGHT REFLECTANCE TO COTTON LEAF MATURITY (*Gossypium hirsutum* L.)

H. W. Gausman, W. A. Allen, R. Cardenas,
and A. J. Richardson

ABSTRACT

Cotton plants were grown hydroponically with controlled environment. Third, true leaves were tagged on the day they became macroscopically visible. Five leaf harvests representing maturity dates were made at successive 2 or 3 day intervals, beginning 3 days after tagging when leaves were at least 2 cm diameter, or large enough to cover the port of the instrument used for spectrophotometric measurements. In general, total reflectance increased and total transmittance decreased over wavelength interval 0.50 to 2.50 μ, as leaves matured, up to an average after-tagging-age of 12.0 days. After 12.0 days, reflectance decreased and transmittance increased.

The largest increase in reflectance, about 5%, and decrease in transmittance, about 8%, occurred between average values for after-tagging-ages of 3.5 and 8.0 days over the wavelength interval 0.75 to 1.35 μ. Differences for field-grown cotton were larger with about a 15% increase in reflectance between after-tagging-ages of 2 and 5 days. Between after-tagging-ages of 3.5 and 8.0 days, leaves from the growth-chamber-grown plants expanded approximately fivefold, numbers of intercellular spaces approximately doubled, and thicknesses increased 14%. In general, results support the theory of Willstätter and Stoll for incident light *in toto*: near-infrared light reflectance of older leaves up to an after-tagging-age of 12.0 days increased because numbers of intercellular spaces increased in the leaf mesophylls. Percent water content of leaves increased with leaf maturity.

The theory of diffuse reflectance and transmittance of a compact leaf of equivalent water thickness (EWT) specified by D is generalized in this paper to include also the non-compact case. A non-compact leaf, characterized by intercellular air spaces, can be regarded as a pile of N compact layers separated by infinitesimal air spaces. The void area index (VAI) of a non-compact leaf is given by N-1 where N is not necessarily an integer. The theory is illustrated by data obtained from the maturing cotton leaves. Predictions from the generalized theory include a measure of the water, air, and plant pigments in a leaf. An effective dispersion curve associated with the leaf surfaces is also obtained. A derived parameter D/N largely determines the reflectance and transmittance of a typical leaf over the spectral range 1.40 - 2.50 μ. A cotton leaf is highly compact when it first unfolds. At this point D/N ∿ 180 μ. This value is essentially the leaf thickness. Intercellular air spaces develop rapidly during the next few days, and D/N decreases in value to about 130 μ. Subsequently, the leaf cells increase in size with no substantial further increase in the number of intercellular air spaces. This final growth phase is characterized by a slight increase in D/N to a maximum value of about 140 μ. Maximum reflectance of the leaf corresponds to a minimum value of D/N. The parameter D/N is highly correlated with the amount of intercellular air spaces in a leaf.

INTRODUCTION

Leaf area is increased by cell division alone or by an increase in both cell numbers and sizes (Humphries and Wheeler, 1963), depending on the plant species and leaf position on the stem (phyllotaxis). Hammond (1941) found larger cells in the larger, early leaves of growing cotton plants (*Gossypium hirsutum* L.) which progressively decreased in size in later and smaller leaves up the stem. There are three types of growth in leaves: (a) cell division continues at the tip and periphery after basal growth ceases; (b) cell division stops almost uniformly in all areas of the leaf and is followed by cell expansion; (c) cell division ceases at the distal end but continues basipetally, the tip being the first to mature (Avery, 1933; Scott et al., 1948; Sunderland, 1960; Strogonov, 1962; Brouwer, 1963; Nieman, 1965).

Many factors such as water and salinity stresses affect leaf growth. With limited water supply prior to and during the leaf expansion period, expansion is suppressed, intervascular intervals are reduced, and leaves are thinner, since leaf expansion precedes leaf thickening (Turrell and Turrell, 1934). In cotton (Strogonov, 1962), sulphate salinity limits cell enlargement much more than cell division, while chloride salinity inhibits cell division but stimulates cell extension. Chloride salinity retards the formation of leaf initials and their differentiation. Anatomical changes caused by salinity and by insufficient water supply were deemed to be much the same. High salinity, which suppresses leaf expansion, causes fewer epidermal cells and stomata per unit area on cotton leaves (Gausman and Cardenas, 1968).

Intercellular spaces, sponge effect, may not develop markedly in the middle and lower mesophyll until a leaf is one-fourth to one-third final size (Avery, 1933). In tobacco leaves (Nicotiana tabacum L.), epidermal cells continue enlarging after cells of the middle and lower mesophyll have stopped growing (Avery, 1933). Resulting stresses pull mesophyll cells apart giving rise to spongy tissues with larger intercellular spaces. Palisade cells (upper mesophyll) may also be pulled apart by enlarging epidermal cells. The palisade parenchyma cells may appear to be compact in transverse sections of leaves, but paradermal sections reveal that a large part of the surface area of each palisade cell is exposed to intercellular air (Slatyer, 1967). The internal surface area of a leaf is usually greater than the external area (Turrell, 1936), and the palisade region usually has a larger internal exposed surface than the spongy parenchyma (Esau, 1965).

Allen and Richardson (1968) have used the Kubelka-Munk (K-M) theory (Kubelka and Munk, 1931) to describe the near-infrared reflectance and transmittance of plant leaves stacked in a spectrophotometer. Basic entities in application of the K-M theory to leaves are the reflectance and transmittance of a single leaf.

Willstätter and Stoll (1913) as reported by Gates (1965) explained reflectance and transmittance of a plant leaf on the basis of critical reflection of visible light at the cell wall - air interface of spongy mesophyll tissue. A more recent paper (Sinclair, 1968) advances the hypothesis that leaf reflectance derives from the diffuse characteristics of plant cell walls. According to Myers and Allen (1968), the K-M scattering coefficient for a typical leaf can be explained by Frésnel reflections at normal incidence from 35 air interfaces along the mean optical path through the leaf. Gausman, Allen, and Cardenas (1969) note that if oblique reflections are considered, fewer interfaces account for the results.

The diffuse reflectance and transmittance of a typical compact plant leaf has been explained (Allen et al., 1969) by means of a flat plate leaf model specified by two optical constants--an effective index of refraction n and an effective coefficient of absorption k. The optical properties of a compact leaf result from Fresnel reflections from the two surfaces together with absorption by leaf pigments and liquid water. The effective index of refraction of a typical compact leaf such as corn is not inconsistent with a known value for epicuticular wax. The effective absorption coefficient of a typical compact leaf can be regarded as a superposition of separate absorption coefficients due to water and plant pigment components. The actual absorption of a typical compact leaf can be simulated closely over the spectral range 1.40 - 2.50 μ by absorption of an equivalent water thickness. Many leaves of agricultural importance, however, are not compact. The flat plate model is generalized in this paper to include the effect of intercellular air spaces in the leaf.

MATERIALS AND METHODS

Cotton plants (Gossypium hirsutum L., variety Texas Planting Seed Association 110) were grown hydroponically in acid-washed, 20-30 mesh sand in 9-inch, diameter glazed crocks, 7.6-liter capacity. The sand was rewashed with .001 N nitric acid to remove chloride and then leached several times with chloride-free water (silver nitrate test; Gausman, 1962). Plants were thinned to one per crock 2 or 3 days after emergence.

The basic nutrient solution used was Hoagland and Arnon's (1938), with iron added as iron-ethylenediaminetetraacetic acid (Nieman and Poulsen, 1967). All plants received one-fourth-strength nutrient solution during their first week of growth. Thereafter, copious surface applications of full-strength nutrient solution were made to maintain uniform matric water suction in the substratum.

Plants were grown with controlled environment. Ranges of parameters were: day temperature, 26.5 - 28.0°C; night temperature, 25.6 - 26.0°C; day relative humidity, 34 - 38%; night relative humidity, 39 - 42%. A 12-hour, light-dark cycle was used. Light illuminance approximated 800 ft. C (8.60×10^{-1} lumen cm^{-2}).

A randomized complete block experimental design was used with four replications of five dates of leaf sampling. Test leaves (third true leaf) were tagged with the date that they became macroscopically visible, beginning 19 days after seedling emergence. Ages of leaves for dates of harvest varied between replications. Although it was intended to harvest leaves within each replication at five harvest times of 3, 6, 7, 10, and 13 day intervals, leaves in some replications were not large enough for the port of the spectrophotometer at an after-tagging-age of 3 days. Therefore, average after-tagging-ages (averages of four replications) at harvest times one through five were 3.5, 5.8, 8.0, 10.8, and 12.0 days, respectively. Leaves harvested for the first date were approximately 5 cm diameter---large enough for reflectance measurements but too small for transmittance measurements. Leaves were wrapped immediately in Saran [1] to minimize water loss. Leaf thickness and reflectance and transmittance measurements and tissue fixation processing were completed within 15 minutes after leaves were harvested. Leaf thicknesses were measured on photomicrographs for intercellular space studies and with a linear displacement transducer and digital voltmeter (Heilman et al., 1968). Leaf areas were determined by Johnson's method (1967). In a complementary study, leaves were tagged on field-grown cotton plants with approximately 20 true leaves, when they became macroscopically visible. Spectrophotometric measurements were made on leaves with average after-tagging-ages of 2, 5, 7, 9, and 12 days.

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[1] Trade names and company names are included for the benefit of the reader and do not imply an endorsement or preferential treatment of the product listed by the U. S. Department of Agriculture.

Spectral diffuse reflectance and transmittance were measured on upper (adaxial) surfaces of single leaves over the wavelength interval 0.50 to 2.50 μ with a Beckman Model DK-2A spectrophotometer and its reflectance attachment. Data have been corrected for the reflectance of the MgO standard (Sanders and Middleton, 1953) to obtain absolute radiometric values.

Tissue pieces, taken near the center of leaves approximately one-half inch on either side of the midrib, were fixed in formalin-acetic acid-alcohol (FAA), dehydrated with a tertiary butyl alcohol series, embedded in paraffin (melting point about 52°C), stained with safranin-fast green (Jensen, 1962), and transversally microtomed at 12 μ thicknesses. Photomicrographs, 100 X, were obtained with a Zeiss Standard Universal Photomicroscope.

Areas of intercellular spaces were measured with a planimeter and their numbers were counted within the mesophylls (palisade and spongy parenchyma) of 400 X magnified, transverse leaf areas of left-hand, one-third segments of 8 x 11.8 cm positive prints from photomicrographs. Twenty prints, five randomly selected microscopic fields for each date within each replication, were used for each maturity date. A template with 12 vertical lines 1 cm apart was also placed over the entire area of each print to simulate rays of light passing through a leaf. The number of air spaces intercepted by each line was recorded.

Analysis of variance techniques and Duncan's multiple range test (Steel and Torrie, 1960) were used on data from 0.05 μ increment, spectrophotometric measurements over the wavelength interval 0.50 to 2.50 μ.

The Void Area Index Concept

The diffuse reflectance and transmittance of a compact leaf such as corn, a leaf impregnated with water, and an immature leaf such as cotton immediately after it unfolds can be predicted from a plate theory (Allen et al., 1969). Maturation of a cotton leaf is characterized by development of intercellular air spaces that increase the reflectance and reduce the transmittance of the leaf (Willstätter and Stoll, 1913). Generalization of the plate theory to include the effect of intercellular air spaces leads to the concept of void area index (VAI) of a leaf. To the extent that a leaf can be regarded as a pile of N compact layers separated by infinitesimal air spaces, the VAI is given by N-1. The VAI is roughly the average number of air cavities penetrated by a ray passing through the leaf. The VAI need not be an integer. The VAI of a compact leaf is zero.

A leaf with an EWT specified by D can be subdivided conceptually into N compact layers of individual thickness D/N which are subsequently piled back to the original thickness D. The thickness of the air plates that separate these compact layers is a matter of indifference but will be taken as infinitesimal in order to facilitate calculations. The theoretical machinery necessary to implement the above procedure has been published (Allen and Richardson, 1968).

Theory: A leaf of EWT specified by D will be regarded as a pile of N compact layers of individual thickness D/N. Transmittance t and reflectance r of a single leaf can be expressed at a given wavelength by the relations

$$\frac{t}{a-a^{-1}} = \frac{r}{b-b^{-1}} = \frac{1}{ab-a^{-1}b^{-1}} \quad , \tag{1}$$

where a and b are parameters to be determined by experiment. If the single leaf described by Eq. (1) is considered to be a pile of N layers, Eq. (1) becomes

$$\frac{t}{a_o-a_o^{-1}} = \frac{r}{b_o^{N}-b_o^{-N}} = \frac{1}{a_o b_o^{N}-a_o^{-1}b_o^{-N}} \quad , \tag{2}$$

where a_o and b_o are new parameters to be determined. Equations (2) were derived by Stokes (1862) on the assumption of an integral number of piled transparent plates. Ingle (1942) has shown, however, that N need not be confined to integral values. The transformation between a, b and a_o, b_o of Eqs. (1) and (2) can be written from inspection by the relations

$$a = a_o \quad , \tag{3}$$

$$b = b_o N \quad .$$

The transmittance t_o and reflectance r_o of a single compact layer can be obtained by setting N = 1 in Eqs. (2). Thus

$$\frac{t_o}{a_o - a_o^{-1}} = \frac{r_o}{b_o - b_o^{-1}} = \frac{1}{a_o b_o - a_o^{-1} b_o^{-1}} \quad \ldots \tag{4}$$

Eliminate a_o and b_o from Eqs. (4) by means of Eqs. (3) to obtain the relations

$$\frac{t_o}{a - a^{-1}} = \frac{r_o}{b^{1/N} - b^{-1/N}} = \frac{1}{a b^{1/N} - a^{-1} b^{-1/N}} \quad . \tag{5}$$

Generalization of the plate theory to a leaf with intercellular spaces is now complete provided that the quantity N can be determined. Unfortunately, the effective index of refraction n and the quantity N are confounded; that is, unless the effective index of refraction n is assumed, the number N cannot be determined and vice versa.

The scattering coefficients of a single leaf and an individual compact layer can be specified by the respective relations

$$s = \frac{2a}{a^2 - 1} \log b \quad , \tag{6}$$

$$s_o = \frac{2a_o}{a_o^{2} - 1} \log b_o \quad .$$

Substitute Eqs. (3) into Eqs. (6) and combine to obtain the relation

$$s/s_o = N \quad . \tag{7}$$

The value N is obtained in practice by the quotient $\overline{s}/\overline{s}_o$ where $\overline{s}$ of a given leaf is the average value of s measured over the spectral range 0.75 - 1.05 μ and $\overline{s}_o = 0.61823$ is the average value of five infiltrated citrus leaves measured over the same spectral range. The VAI calculated by the value N-1 obtained from Eq. (7) is arbitrary. The procedure is justified only by consistency of the results obtained.

RESULTS AND DISCUSSION

Figure 1 depicts effects of cotton leaf maturation on spectrophotometrically measured total reflectance of light for the wavelength interval 0.50 to 2.50 μ. This spectral range can be subdivided as: (1) visible region of 0.50 to 0.75 μ, dominated by pigment absorption; (2) near-infrared wavelength interval of 0.75 to 1.35 μ, a region of high reflectance and low absorptance; and (3) 1.35 to 2.50 μ, a region of high absorption by water--the strongest water absorption bands occurring at approximately 1.45 and 1.95 μ. The high reflectance over the spectral range 0.75 to 1.35 μ is produced by the internal cellular structure of cotton leaves (Gausman, Allen, and Cardenas, 1969). Figure 1 shows that leaf maturation had little effect on reflectance in the visible spectral region 0.50 to 0.75 μ, but maturity increased reflectance beyond 0.75 μ. Statistically, all possible mean comparisons were significant, p = .05, between spectral means for ages-after-tagging of 3.5 vs. 5.8, and 3.5 and 5.8 vs. 8.0, 10.8, 12.0 days; spectral means for 8.0, 10.8, and 12.0 days were alike. The mean square ratio of wavelength X ages-after-tagging to error was very small, indicating that all spectra responded essentially alike to spectrophotometric measurements made at 0.05 μ increments over the 0.50 to 2.50 μ spectral interval. Average after-tagging-dates of 3.5, 5.8, 8.0, and 10.8 days progressively increased reflectance for wavelength interval 0.75 to 1.35 μ. At 1.0 μ, for example, reflectance increased from approximately 38 to 45% for after-tagging-ages of 3.5 and 10.8 days, respectively. A reversal (decrease) occurred in reflectance for the 12.0 days, after-tagging-age; a decrease of about 2% occurred compared with 10.8 days after tagging. Reflectance of light for wavelength interval 0.75 to 1.35 μ, therefore, is positively correlated with leaf maturation until an age is reached when leaf thickness and numbers of intercellular spaces cease increasing and leaf thickness may actually decrease. Since leaves of different chronological ages, but from the same stem node, were used in this study, the reversal with the oldest leaves may be primarily caused by larger cells with increased water contents. Intensive studies are presently in progress to further relate leaf age and position (phyllotaxis) with histological and spectrophotometrical results.

Figure 2 shows a larger influence of cotton leaf maturation on percent total reflectance than does Fig. 1. Data are from spectrophotometric measurements on leaves of field-grown-cotton (only reflectance will be shown); techniques were similar to those for the growth-chamber-grown cotton leaves. At 1.0 μ, reflectance increased from 23 to 38% for 2 and 5 days-after-tagging, respectively. A reversal was apparent again since 9 compared with 12 days-after-tagging had about 3% less reflectance. Leaf maturation of field compared with growth chamber cotton leaves may have had a greater effect on light reflectance because: (1) the first immature leaves from field-grown cotton plants were slightly smaller with a more compact cellular structure, (2) rates of maturation may have differed, (3) tagging was conducted with older plants, twentieth true leaves compared with third true leaves, and (4) intensity of light in the field environment was greater than in the growth chamber. A low light intensity causes the development of shade-type leaves; characterized by thinness, expanded lamina, poor palisade cell development, and larger intercellular spaces in the mesophyll.

The effects of leaf maturation of growth-chamber-grown cotton on percent total transmittance is portrayed in Fig. 3. Transmittance generally decreased as leaves increased in chronological age. All comparisons of spectral means for average ages of leaves after tagging were statistically significant, p = .01, excepting 10.8 vs. 12.0 days. Transmittance was decreased over the entire wavelength interval 0.5 to 2.5 μ; with the minimal decrease in the visible spectral range, 0.50 to 0.75 μ. The decrease in reflectance from after-tagging-ages of 3.5 to 10.8 days was approximately 8% for wavelengths of 1.0, 1.7, and 2.2 μ. The 12-days-sample, compared with 10.8 days, reversed (increased) transmittance about 2%. Transmittance decreased as leaf water contents, oven dry weight basis at 68°C, increased. Percentages of moisture were 43.0, 63.9, 72.2, 76.4, and 79.4 for 3.5, 5.8, 8.0, 10.8, and 12.0 average days after tagging, respectively. Very immature cells in young leaves, 3.5 days after tagging, are primarily protoplasmic with little vacuolate water storage. During cell growth (extension), cell water-filled vacuoles develop which may later coalesce to a central sap cavity, and the protoplasm covers only the cell wall in a thin layer. Hydrated leaves, compared with dehydrated leaves, have greater absorptance of light by water over wavelength interval 0.75 to 2.50 μ. The lesser decrease in transmittance of about 6% at 0.55 μ in the visible spectral range, 0.50 to 0.75 μ, occurred after the average after-tagging-age of 3.5 days for all other sampling ages. Transmittance was higher for the

3.5 days sampling age because absorptance [100 - (% reflectance + % transmittance)] was less. Microscopic examinations of transverse sections of young leaves, 0.5 cm or less in width, indicated that they may have either weakly developed palisade cells or none. Since these palisade cells house most of the chlorophyll-containing chloroplasts in leaves, absorptance of blue and red light was less; correspondingly, reflectance was less, Fig. 1 and 2, and transmittance was greater at the green spectral peak of 0.55 μ, Fig. 3.

The influence of leaf maturation on reflectance and transmittance is associated with compactness of internal cellular structure. Differences in cellular compactness of cotton leaves, sampled from fourth or fifth nodes down from plant apexes, affected reflectance of near-infrared light, 0.75 to 1.35 μ (Gausman, Allen, and Cardenas, 1969). An example of the influence of leaf maturity on cellular compactness of cotton leaves is presented in Fig. 4. A cotton leaf is bifacial and normally consists of: cutinized, bricklike upper epidermal cells; a mesophyll with a single row of long palisade cells and a spongy parenchyma of four or five layers of cells; and a rather irregular lower epidermis (Hayward, 1951). Immature leaves, represented by the upper photomicrograph for the first date of leaf sampling, after-tagging-age of 3.5 days, had compact mesophylls with smaller cells, and were associated with comparatively high transmittance and low reflectance. Conversely, older leaves, represented by the lower photomicrograph for the fourth date of harvest, after-tagging-age of 10.8 days, had larger cells and a much more loosely arranged cellular structure in their mesophylls (lacunose condition), and were associated with comparatively lower transmittance and higher reflectance. Reflectance of older leaves was increased because of an increase in intercellular spaces or air voids. Scattering of light within leaves occurs most frequently at cell wall (hydrated cellulose) - air cavity interfaces which have refractive indices of 1.4 and 1.0, respectively (Weber and Olson, 1967).

Table I shows effects of leaf maturation on average sizes and numbers of intercellular spaces in leaf mesophylls (palisade and spongy layers), evaluated from positive prints of photomicrographs of transverse leaf sections. Theoretically, one air space may exist within a leaf, because of linkage of spaces between cells (maze or labyrinth effect); but in this paper, air space is considered to be "compartmentalized" between mesophyll cells. Numbers of intercellular spaces, Table I, within either the print area measured or per μ^2 of leaf area, progressively increased from 3.5 to 8.0 days-after-tagging. This effect was associated with increased reflectance and decreased transmittance, Fig. 1 and 2. Statistically significant comparisons, $p = .05$, were 9.4 vs. 4.0 counts within print areas and 3.4×10^{-14} vs. 2.0×10^{-14} spaces per μ^2 of leaf cross-sectional area for 8.0 and 3.5 average days after tagging, respectively. Numbers of spaces in transverse sections of leaf mesophylls decreased after the after-tagging-age of 8.0 days. Significant comparisons, Duncan's Multiple Range Test, $p = .05$, were between means for 12.0 vs. 8.0; and 10.8 and 12.0 vs. 8.0 days-after-tagging for numbers of spaces within print areas and per μ^2 of leaf cross-sectional area, respectively. The decline in numbers of spaces was related to the decrease (reversal compared with 3.5, 5.8, 8.0, and 10.8 days) of reflectance, Fig. 1, and increase (reversal compared with 3.5, 5.8, 8.0, and 10.8 days) of transmittance, Fig. 3, for the after-tagging-age of 12.0 days.

Table 1. Effects of cotton leaf maturation on characteristics of their intercellular spaces in transverse leaf sections. Data are averages of counts and planimetry measurements from five photomicrographic prints within each after-tagging-age for four replications.

	Photograph b/		Leaf c/		
Average age after tagging	Area size evaluated on print	No. of spaces within print area	No. of spaces per μ^2 of leaf area	Average space area	Intercellular space
Days	μ^2			μ^2	%
3.5	12.3×10^{8}	4.0	2.0×10^{-14}	1.7×10^{2}	10.2
5.8	14.7×10^{8}	6.2 a/	2.6×10^{-14}	3.0×10^{2}	28.3*
8.0	17.0×10^{8}	9.4*	3.4×10^{-14}*	3.2×10^{2}	28.6*
10.8	15.2×10^{8}	5.8 a/	2.4×10^{-14}	5.6×10^{2}	31.9*
12.0	17.4×10^{8}	6.0 a/	2.2×10^{-14}	9.5×10^{2}*	28.8*

* Significant, p = .05, compared with value for 3.5 days.

a/ Significant, p = .10, compared with value for 3.5 days.

b/ Space counts and planimetry measurements were made on left, 3-cm-sections of 8 x 11.8 cm positive prints, 400 X magnification, from photomicrographs of transverse leaf sections; areas varied because of different leaf thicknesses.

c/ Data were reduced to a leaf basis with 400 X magnification factor of 1.6×10^{5}.

Percentages of intercellular space (total area of spaces by planimetry/planimetry determined cross-sectional leaf area examined) increased from 10.2 to 28.8, Table I, and average space sizes from 1.7 to 9.5 $\mu^2 \times 10^2$ for after-tagging-ages of 10.8 and 12.0 days, respectively. Significant comparisons, $p = .05$, were between mean values for 12.0 vs. 3.5 days for space size, and all other ages vs. 3.5 days for percent intercellular space. Intercellular space means for after-tagging-ages of 5.8, 8.0, 10.8, and 12.0 were alike according to Duncan's multiple range test.

The above data reflects the occurrence of very rapid leaf expansion during maturation. Average areas per leaf were 10.8 and 88.9 cm^2 and average leaf thicknesses were 151 and 198 μ for after-tagging-ages of 3.5 and 12.0 days, respectively. Figure 5 graphically represents the relation between leaf area and thickness. A linear relation is evident, R = .57**, but deviation from linearity is present between 3.5 vs. 5.8 and 10.8 vs. 12.0 after-tagging-ages. Growth of leaves was essentially by lateral expansion until after an average after-tagging-age of 3.5 days when increases in their thicknesses began. This agrees with conclusions of Turrell and Turrell (1934) that leaf expansion precedes leaf thickening. Even for individual cells, cell walls are enlarged many times in the longitudinal direction (intussusception) before apposition or increase in thickness occurs (Lundegardh, 1966). Growth in leaf thicknesses stopped between 10.8 and 12.0 days after tagging, Fig. 5, while longitudinal expansion still continued. This phenomenon needs further investigation. It implies that leaf cells are stretched after their growth in thickness has stopped, with a subsequent decrease in leaf thickness. Preliminary research indicates that this does occur on leaves older in chronological age than the 12.0 day, after-tagging-age used in this study.

Predictions from the plate model as generalized include one parameter, the EWT, that expresses the amount of water in a leaf and a second parameter, the VAI, that specifies the amount of air in a leaf. Figure 6 is a plot of the EWT; that is, the water content of a cotton leaf measured as the leaf matures. The open circles were obtained by the method of Reference 1 where the absorbtant material of the leaf over the spectral range 1.40 - 2.50 μ is approximated by a constant thickness of pure liquid water. The solid circles of Fig. 6 were obtained by a direct experimental method. A cotton leaf of known area was dried 48 hours at 68°C and then weighed. The area density of water for the leaf was determined using the leaf area and making a comparison of the dried leaf weight with the weight of the normal leaf. Experimental difficulties of the latter method are greatest when the leaf is immature. The curve of Fig. 6 has been drawn to favor the values of EWT obtained spectrophotometrically because the indicated standard deviations are generally smaller for these values. Each data point of Fig. 6 consists of four replications.

The second important leaf parameter that emerges from the plate model is the VAI. Figure 7 is a plot of the VAI; that is, the intercellular air spaces; of a cotton leaf measured as the leaf matures. Each open circle data point of Fig. 7 consists of four replications that resulted in the indicated standard deviations. A correlation analysis between the VAI of Fig. 7 and the last column of Table I yielded the value r = 0.9229.

Figure 8 is the effective dispersion curve for the 20 cotton leaves used in this maturity investigation. The variation indicated is one standard deviation. Variation of the effective dispersion curve with maturity is not significant. Figure 9 is the effective absorption curve for the 20 leaves used in this maturity study. Variation between leaf values and pure liquid water is not significant over the spectral range 1.40 - 2.50 μ.

The derived parameter D/N largely determines the reflectance of a leaf over the spectral range 1.40 - 2.50 μ. Figure 10 is a plot of D/N for the 20 cotton leaves. A cotton leaf is compact when it first unfolds and D/N ∿ 180 μ at T = 0 is assumed to be the leaf thickness. Intercellular air spaces develop within the next few days and D/N decreases in magnitude until it reaches a minimum value of about 130 μ. Reflectance passes through a maximum at this time. After about a week the leaf cells increase in size with no appreciable further increase in number of intercellular air spaces. This final growth phase is characterized by the gradual increase of D/N. The value D/N = 143 μ plotted at the assumed leaf age T = 20 days is an average value for 50 mature cotton leaves sampled during the summer of 1968.

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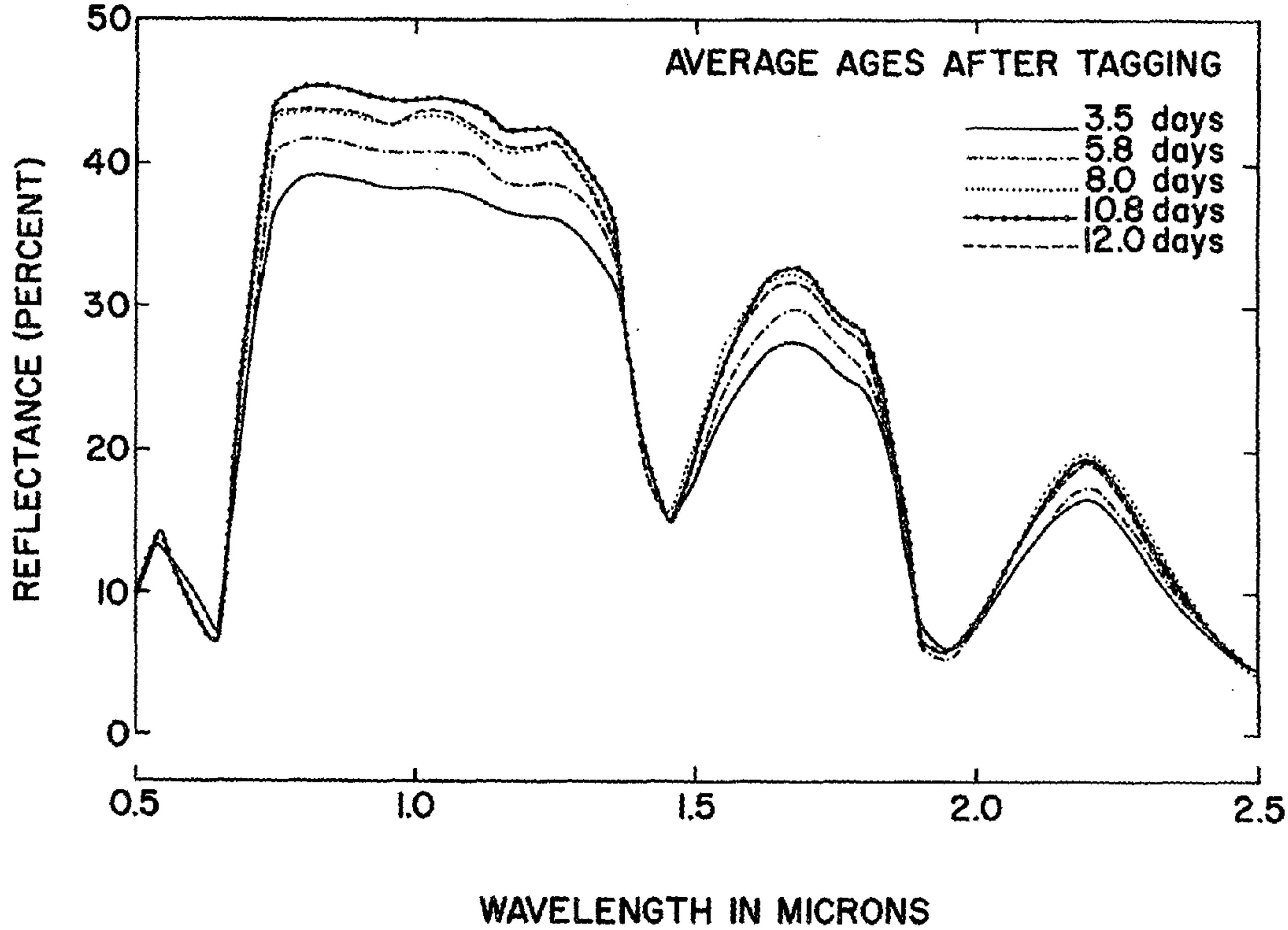

Fig. 1. Percent light reflectance from upper surfaces of third, true leaves of different chronological ages from growth-chamber grown cotton plants. Each spectrum is the mean for four leaves.

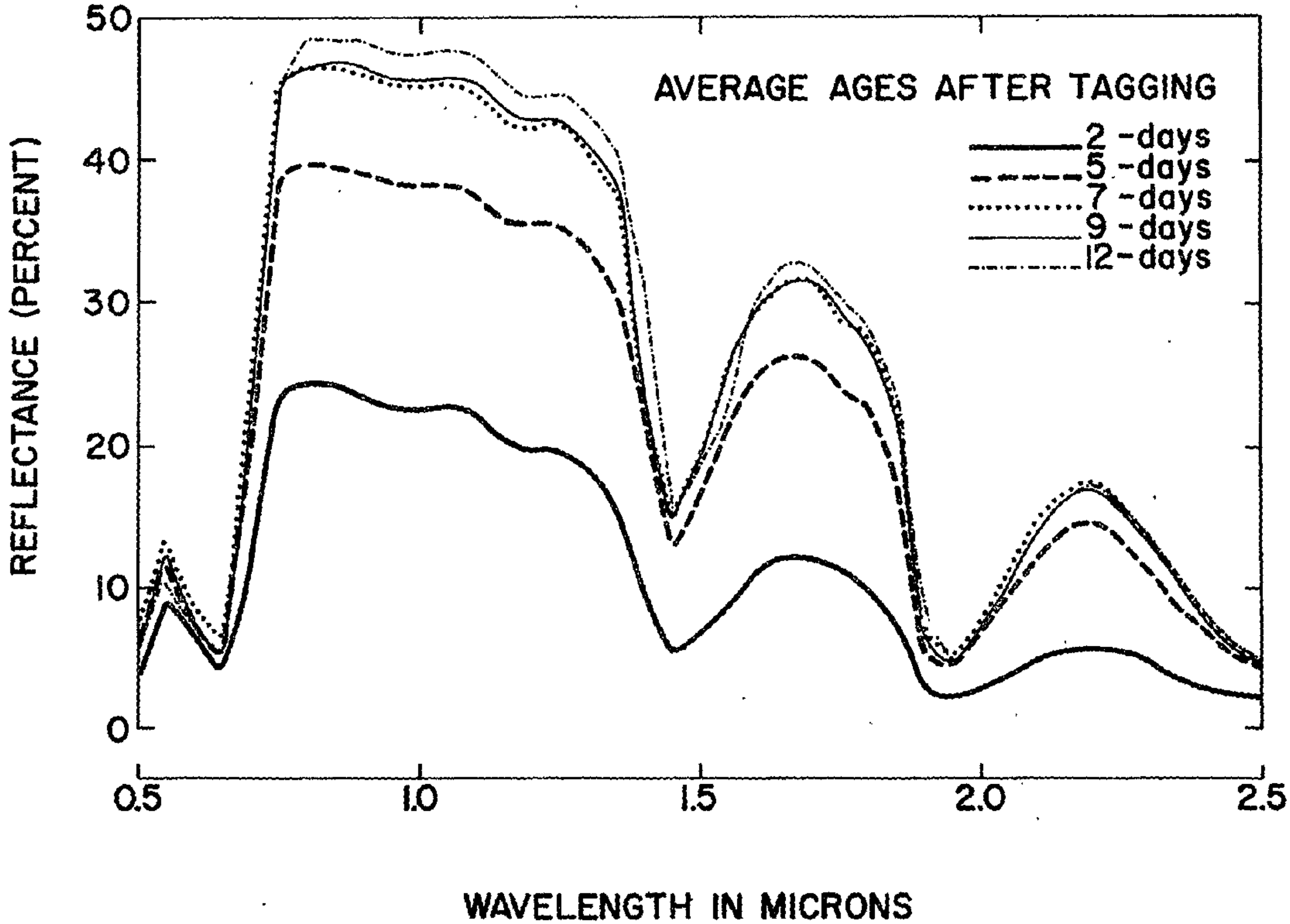

Fig. 2. Percent light reflectance from upper surfaces of approximately the twentieth true leaves of different chronological ages from field-grown cotton plants. Each spectrum is the mean for four leaves.

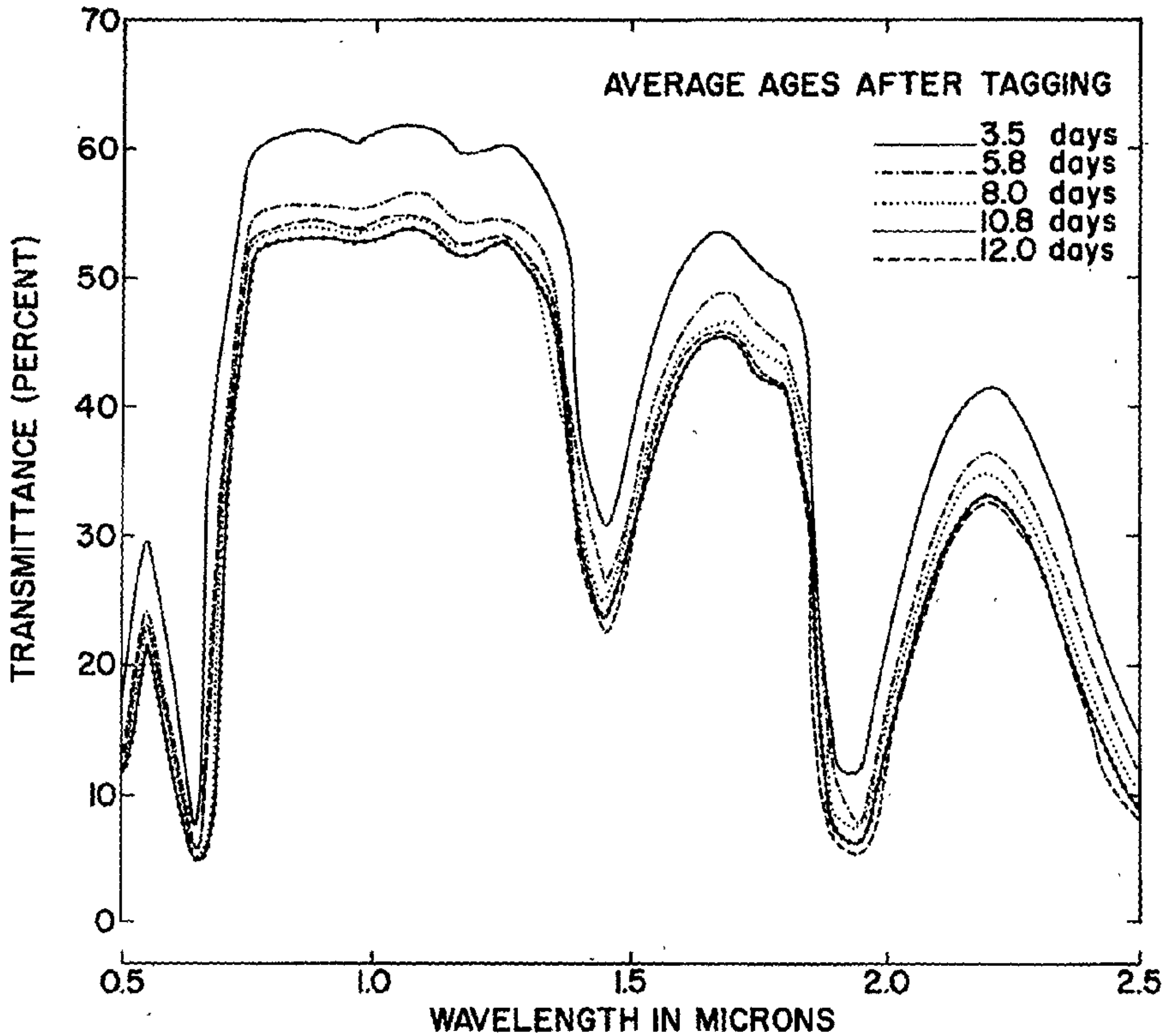

Fig. 3. Percent light transmittance of third true leaves of different chronological ages from growth-chamber-grown cotton plants. Each spectrum is the mean for four leaves.

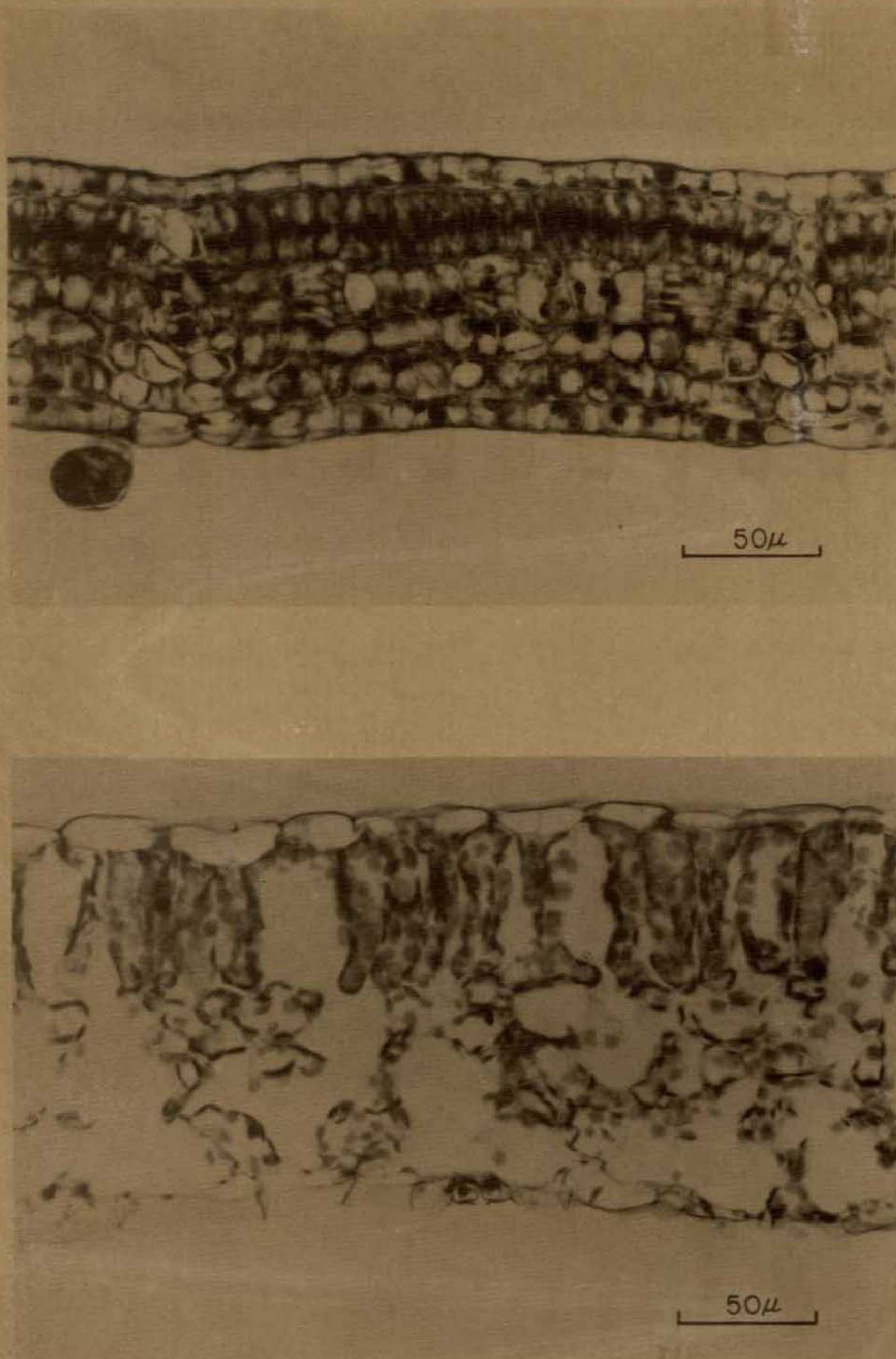

Fig. 4. Transverse sections of leaves showing the relation between leaf maturity and numbers of intercellular spaces. Upper and lower photomicrographs represent leaves with average after-tagging-ages of 3.5 and 10.8 days, respectively.

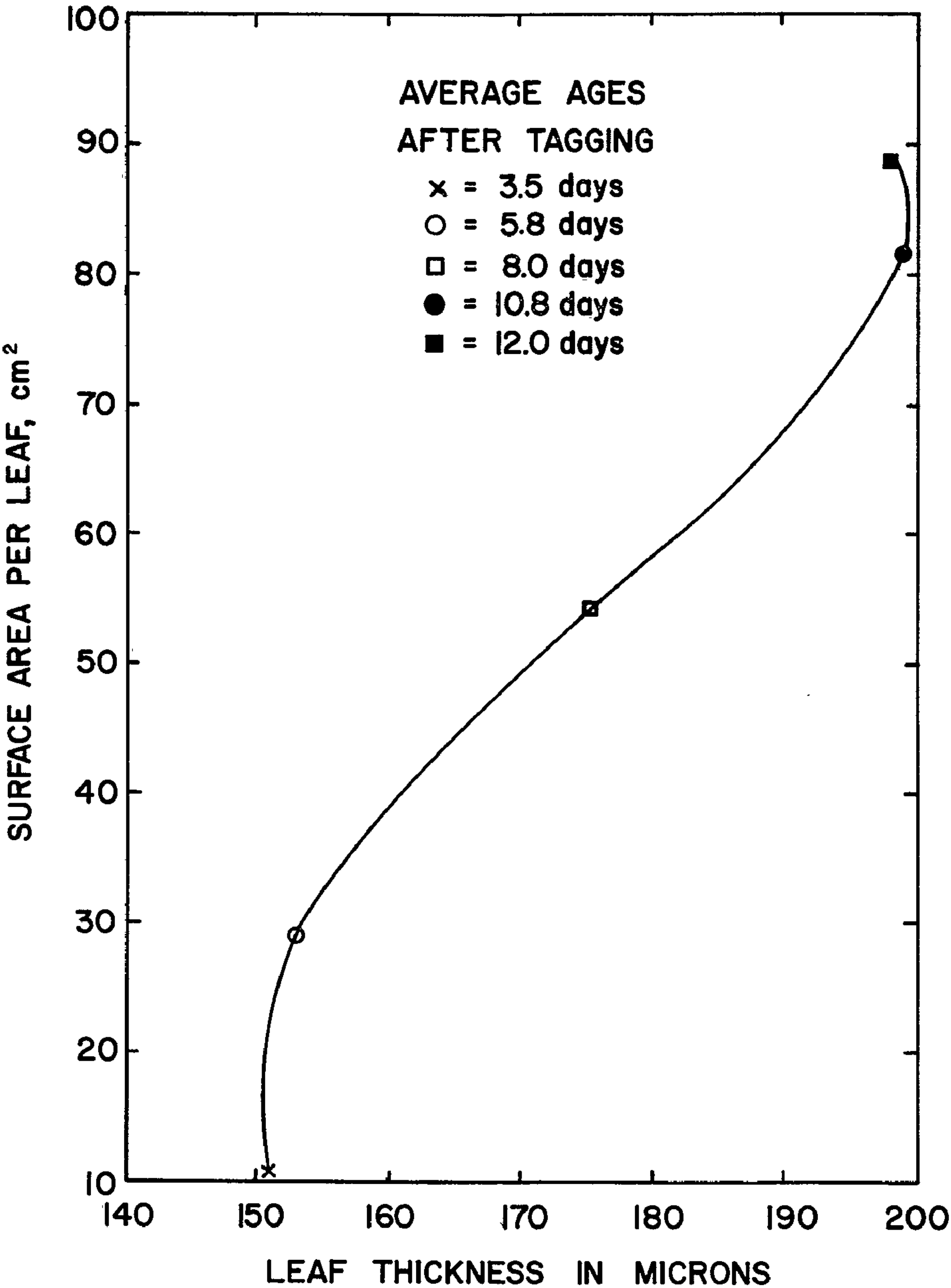

Fig. 5. Relation between the growth of cotton leaves in surface area (horizontal direction) and thickness. Each after tagging age is an average of four replications.

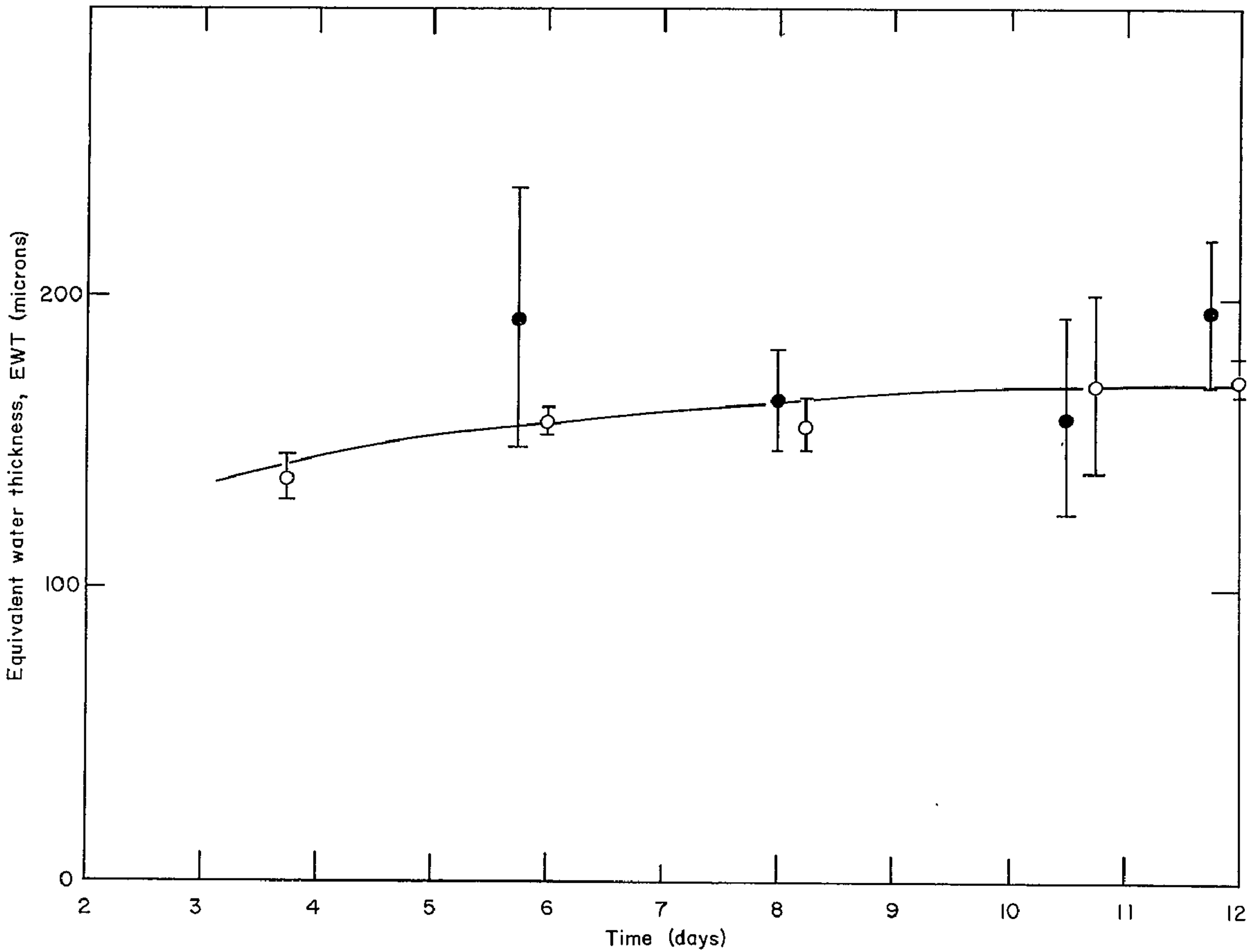

Fig. 6. Equivalent water thickness (EWT) of a maturing cotton leaf. Open circles represent spectrophotometric values and solid circles are experimental data.

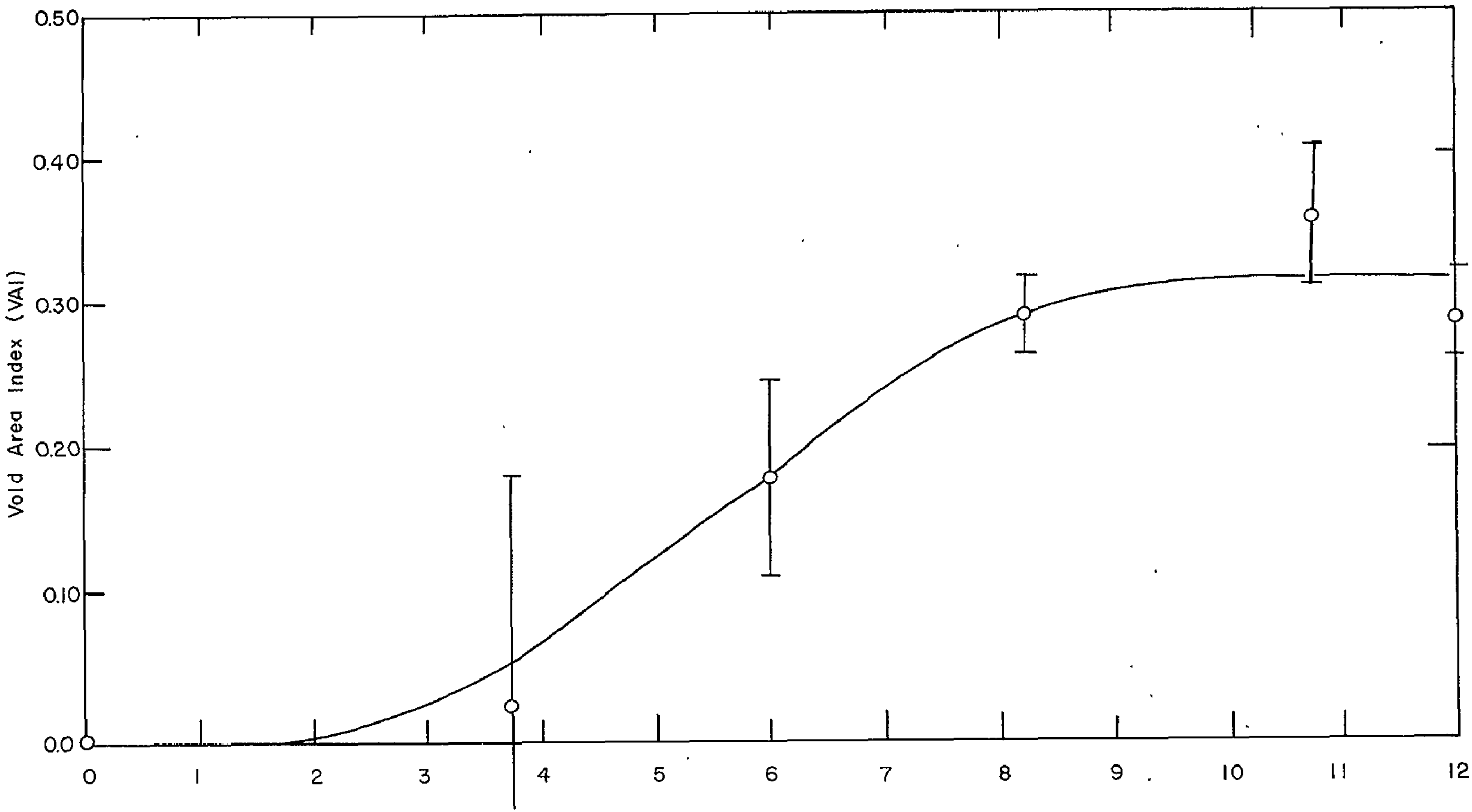

Fig. 7. Void area index (VAI) of a maturing cotton leaf.

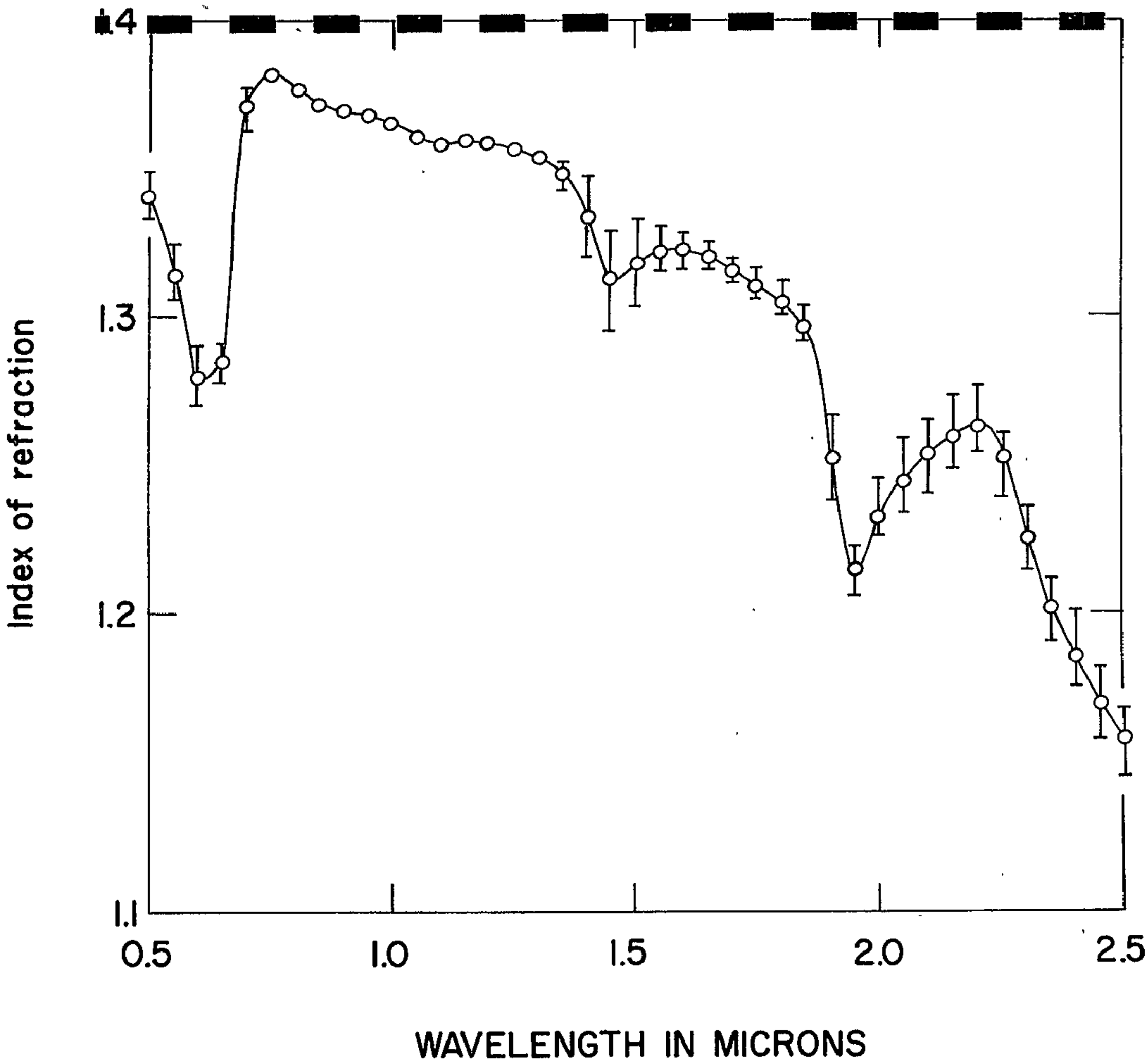

Fig. 8. Effective dispersion curve of a maturing cotton leaf.

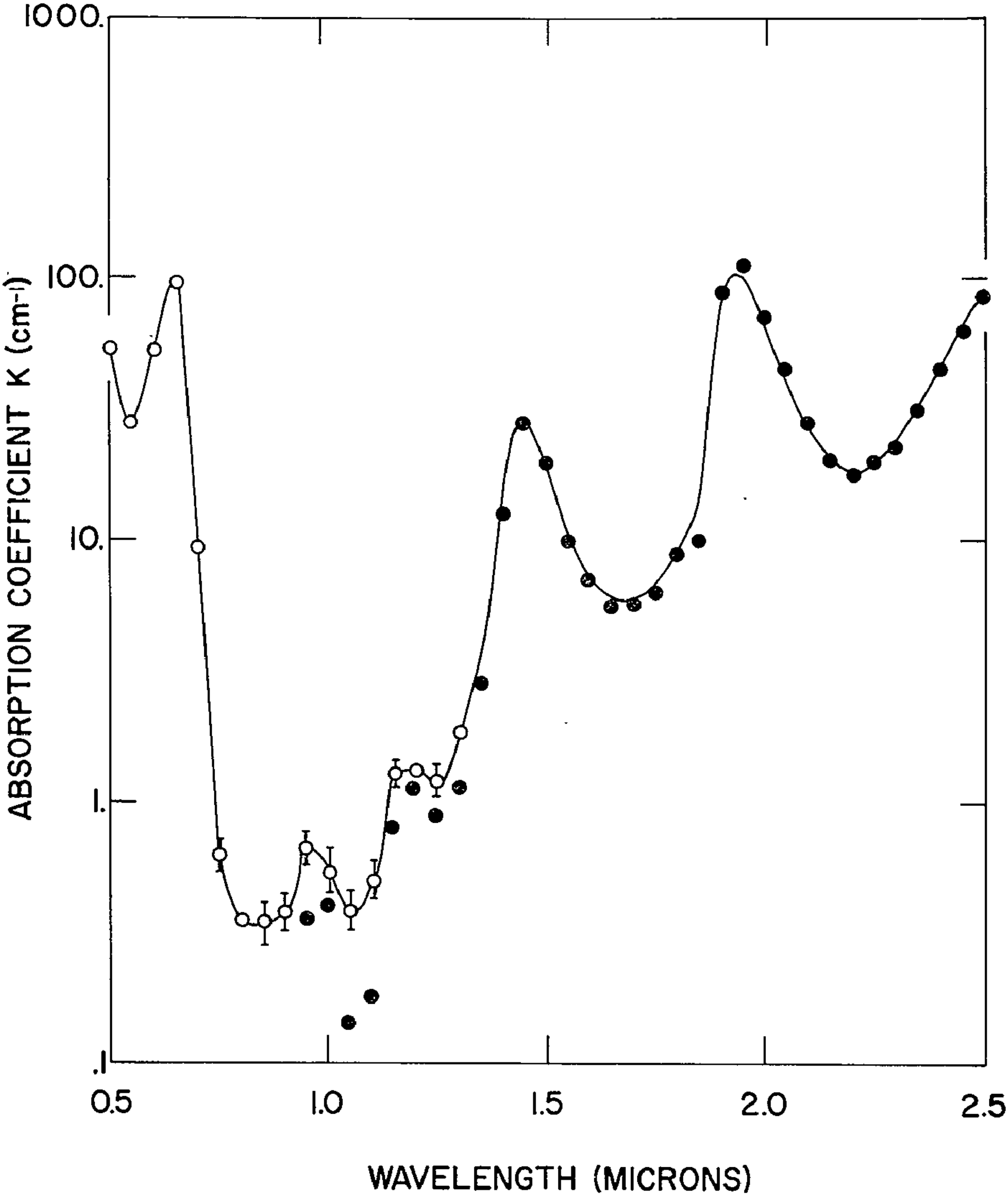

Fig. 9. Effective absorption curve of a maturing cotton leaf. Solid points are values for pure liquid water (Curcio and Petty, 1951).

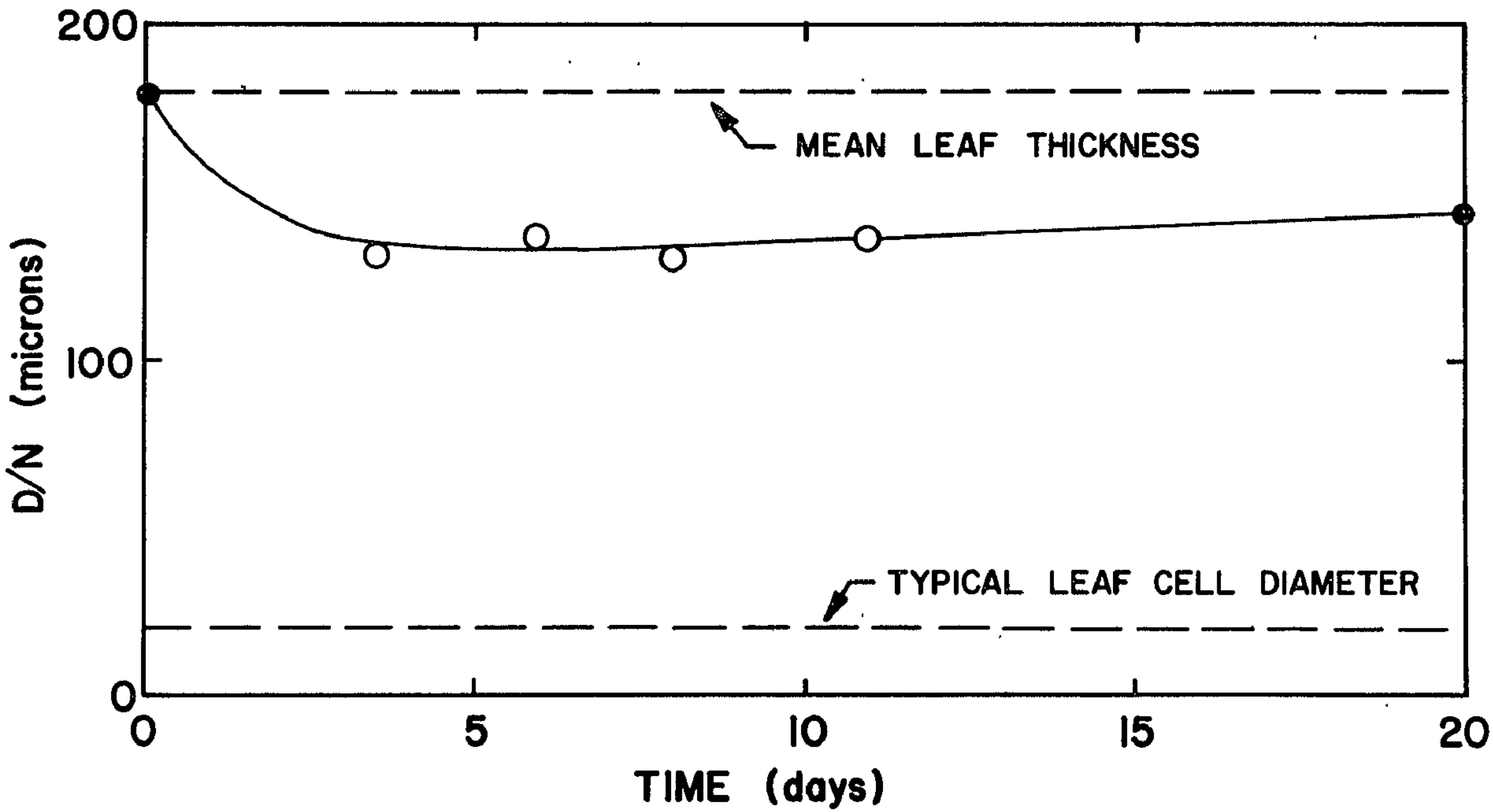

Fig. 10. Mean free path between refraction of a light ray within a cotton leaf.

Aerial film and its interpretation

By A. H. Gerbermann

Introduction:

One of the best ways of recording crop and soil data over a large area is through the use of aerial photography. Literally billions of bits of data are recorded on a single 9-inch frame of film, but no technology has developed for routinely extracting and quanitizing the recorded data. So there is need for procedures to analyze data stored on film. In addition, since many types of film are available it is worthwhile to determine which film types are most useful.

Objective:

To gain knowledge of how to put data recorded on film into a state where it can be compared with other data and to obtain an idea of which film type to use in recording a certain type of data.

Methods and Procedures:

Aerial Ektachrome infrared, Ektachrome, and black and white films were flown at various altitudes during midday; the film was developed, then density readings were made using a Joyce Loebl Microdensitometer with red, green, and blue filters, as well as no filter. Later these values were correlated with ground truth data.

Ektachrome infrared film, type 8443

Ektachrome infrared film (color IR) has the unique capability of recording the high near-infrared reflectance characteristics of plants. It was developed during Work War II as a camouflage detection film because it differentiated between real foliage and objects camouflaged to look like foliage in the visible wavelengths where all other film was sensitive. The film recorded the high infrared reflection of the leaves as red in color and the green painted surfaces as green.

Since World War II it has been improved in sensitivity and color balance to where it records small differences in infrared reflection fairly accurately.

The film is exposed with either a Wratten 12 or Wratten 15G filter, which cuts out the blue light.

On cameras with a 6-inch focal length and that use 9-inch film (width) it is necessary to use an antivignetting filter to disperse the light evenly over the area of the film being exposed (Fig. 1). This filter prevents an overexposed area in the center of the frame because of uneven distribution of light. On cameras with 12-inch focal length and longer, this filter isn't needed because the lens normally disperses the light evenly over the film.

This film records the reflected light in the spectrum from .5 μ to .9 μ. Its response spectrum is comprised of green, red, and the near IR wavelengths. The reflected green light is recorded as yellow, the reflected red light as magenta, and the reflected infrared light is recorded as cyan. Each of these is recorded in a separate layer of the emulsion on the film (Fig. 2). When one views a transparency, he sees combinations of the yellow, magenta, and cyan color densities.

Ektachrome, type 8442

This film (ordinary color Ektachrome) records scenes as they actually appear to the eye with regard to color conditions of plants, soils, etc. Some films, such as Kodachrome II, make plants look much prettier on photographs than they actually appear in nature. Such is not the case with Ektachrome.

This film is usually exposed in the air with a haze filter since haze tends to give this film a dusty-white cast, or make it look blurry. Haze does not affect Ektachrome IR because the longer IR wavelengths penetrate the haze whereas the shorter visible rays are scattered by the dust particles in the haze.

Tri-X Aerocon Black and White

This is a fast aerial film with an extended red sensitivity. This film is very useful in multispectral photography (where filters are used to let only certain wavelengths of light into the camera).

Black and White (Infrared) aerographic, type 5424

This film records the visible as well as the near infrared. This film can be exposed with either a Wratten 12, 25A, or 89B filter. This means we can record the reflected green, red, and infrared light using Wratten 12; or using a 25A record only red and infrared; or with an 89B record only the infrared light (Fig. 3).

Analysis of color film

In order to analyze data taken on photographic film in a computer, it must be converted to digital form. One way of digitizing information on photographic film is to measure its optical density.

Dyes formed in color IR are cyan, yellow, and magenta. All other colors in color photographs are combinations of these three. It seems logical when making optical density measurements on color film to measure the density of the film to the light of each of these three colors plus white light (a combination of all colors).

The optical density of film can best be measured with a microdensitometer that has facilities to control the color of light passing through the film. A variable aperture to change the size of the area being measured is also useful.

Optical density is defined as the opaqueness of a film to light (any color or white). Different colored light is obtained by the use of colored filters put into the light paths on the microdensitometer. The filter is opaque to all light except that which it transmits, i.e., the filters are band pass filters (Fig. 4).

It is important that these color filters be as pure a color as possible, because different tones of the same color on the transparencies have different amounts of other colors in them and thus will also transmit a small amount of these other colors, e.g., a light tone of red will contain some blue, whereas a dark tone of red will contain much less. Also the closer to a true color the color on the transparency is, the lower the density of the transparency measured with a band pass filter of that color, provided a pure color filter is used. It must also be kept in mind when measuring the optical density of a transparency to a certain color light, that the densities of all colors to that light are measured, i.e., if red light is being used and a certain shade of blue has a small amount of red in it, the optical density of that shade of blue to red light will be lower than if the blue were a pure blue. The pure blue would be opaque to red light and have a high density.

Different color lights can be used in film analysis to separate different parameters, such as different crops, crop vigor, diseased crops from non-diseased crops, etc. This is done in the following manner. If in a transparency there are various shades of red and blue representing soil and various crops and all colors have almost the same density to white light; a red filter can be put into the microdensitometer and the colors will be separated far enough so that differences can easily be determined. This is true because all red colors will have a lower density to red light than to white light, and all other colors read higher than they do to white light so it can be said they are separated (Fig. 5).

In some cases a filter of a color not in the photograph will yield a more stable reading than filters that have colors in the photograph. This happens in cases where shaded areas are involved (like in crops) or in cases where there are clear spots as in crops with exposed soil. In the first case all colors in the film are opaque to the filter and so only the amounts of light stopping material on the film is measured. In the second case the filter lowers the density value of one of the major colors in the film to a point where it is almost comparable to the clear spots and thus a smooth uniform density curve is obtained.

As the film is being scanned the data are put on punch tape; later it can be put into a computer and average density values obtained for each site. These values can be used in any manner desired by the investigator to relate them to ground truth data.

Black and white film is exposed using a desired filter (usually red or green). After it is developed, its density to white light is measured.

When interpreting data from black and white transparencies the investigator must know whether the density measurements were made on positive or negative transparencies. In order for black and white film data to be comparable to color data, it must be in the positive state. Data in the negative state is opposite in tone to that in the positive state.

Discussion:

The analyses referred to above have been based on use of Ektachrome infrared type 8443 film. Experience to date shows that the closer the wavelengths of the filter, the closer the correlation between optical densities from the two filters. Thus if optical densities of the same areas on the film are measured with blue, green, and red filters the correlation between the optical densities with the blue and green filters or with the red and green filters is higher than between the optical densities of the blue and red filters. Consequently the information content for identifying crops and soils is greater from separated than adjacent wavelengths because of greater probability of independent information. Plants versus soils have contrasting exposure values on the different emulsion layers, due to differing reflectance; otherwise no separation would be possible.

The optical densities with a green filter and no filter (white light) of the same measurement sites on type 8443 film are usually closely correlated.

Summary:

The film types being used and the procedures being developed to extract quantitative digital data from film records by measuring optical density of the film to light transmittal by various filters are described. The contribution amounts to a primer on the films and filters used.

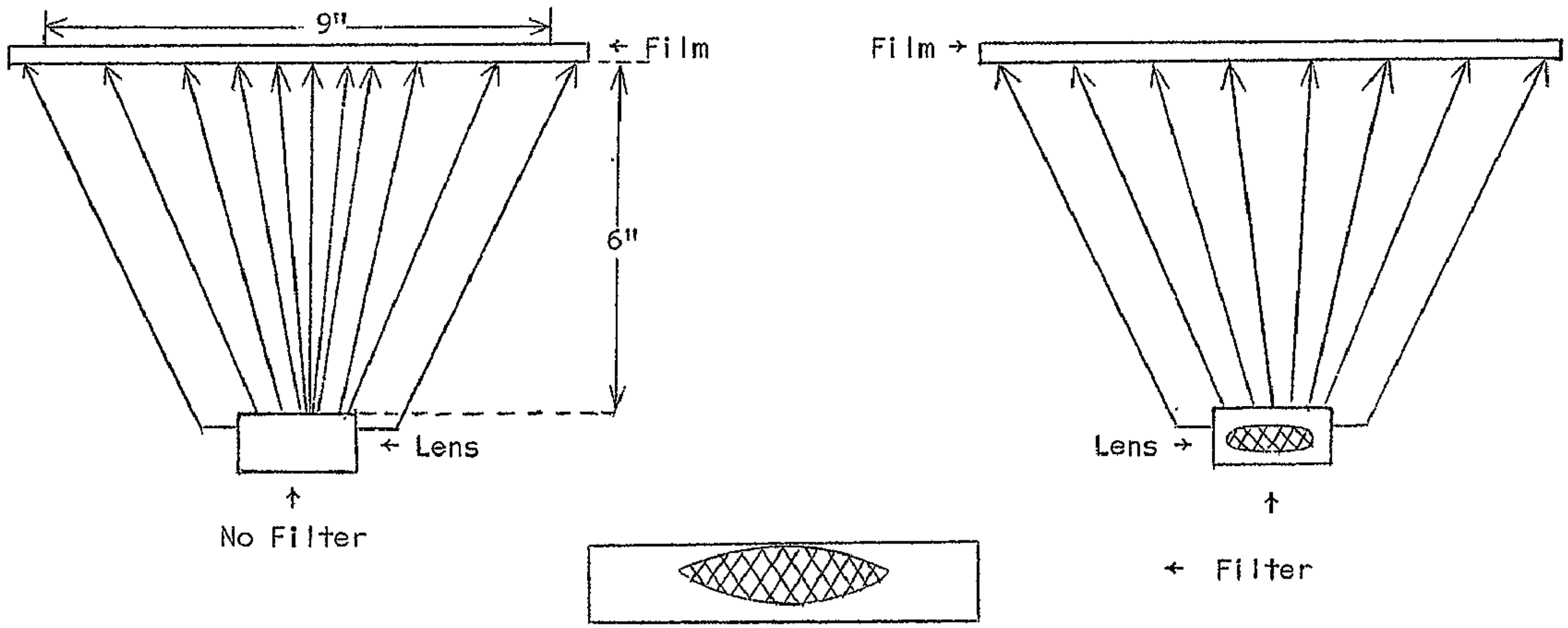

Figure I.--Antivignetting filter distributes light evenly over the area of the film.

Wavelength Sensitivity	Image Color
Infrared	Cyan
Green	Yellow
Red	Magenta

B A S E

Figure 2.--Different color light record in different layers in the emulsion.

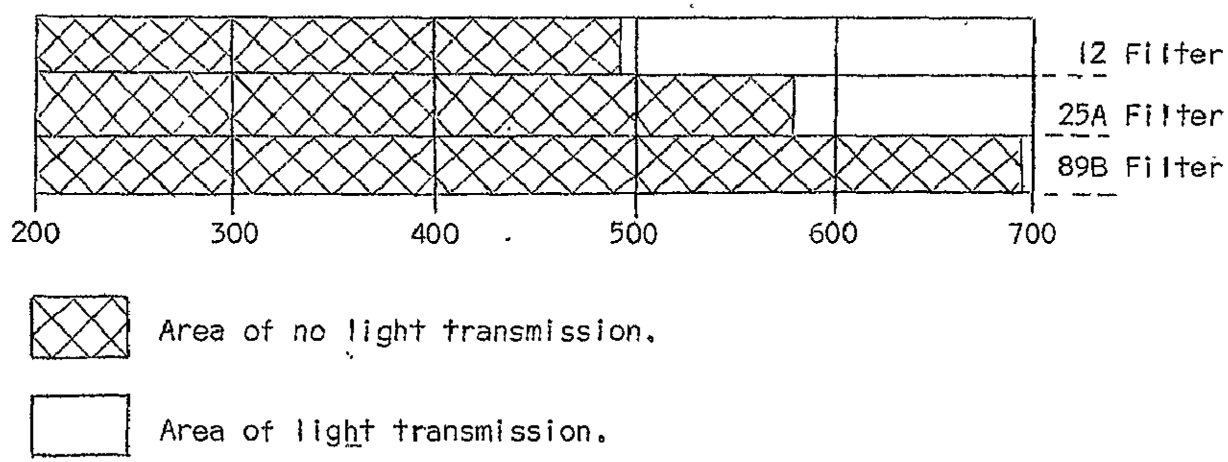

Figure 3.--Black and white infrared film can be exposed with any of the above filters. Each filter cuts off the wavelengths marked

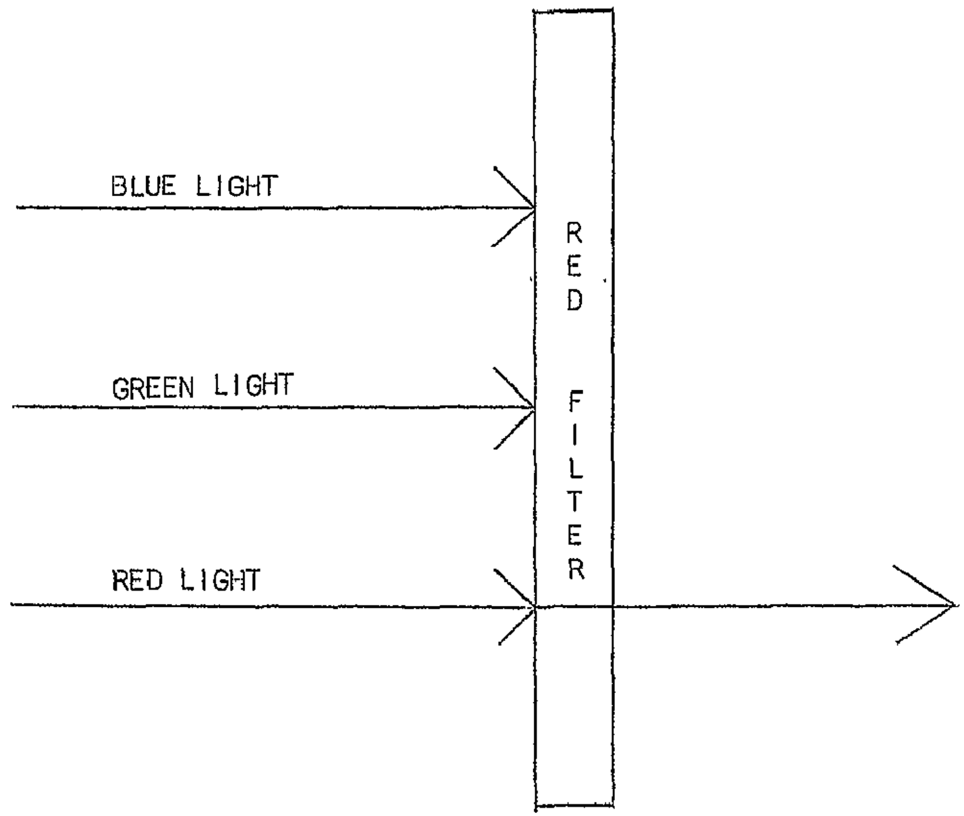

Figure 4.--Absorption filters absorb all light except the wavelengths in the spectrum they are designed to transmit.

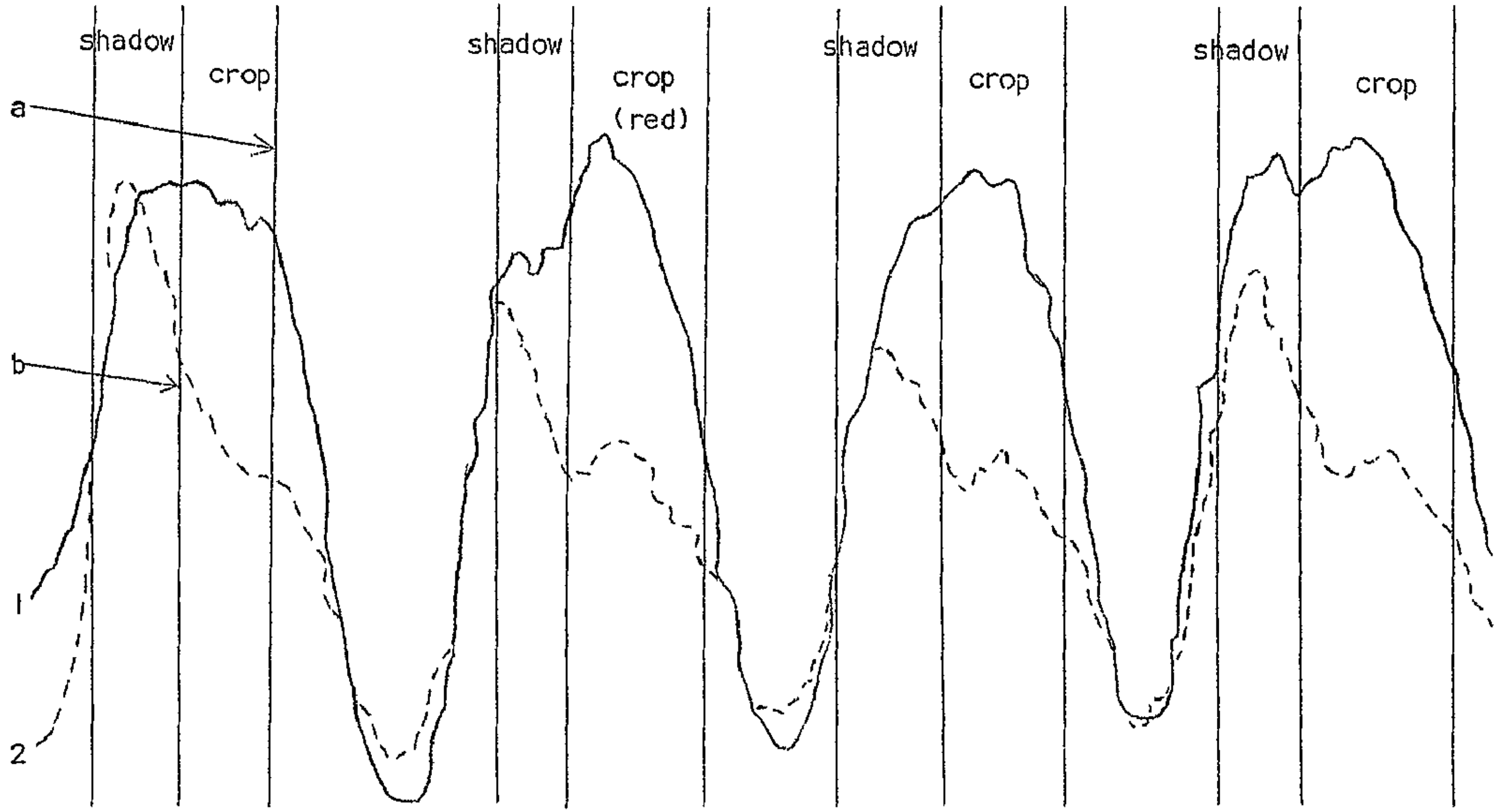

Figure 5.--The upper curve (1) was made with a blue filter, the lower curve (2) with a red filter. Crop (a) red color and shadow (b) is black, and as can be seen the density differs more between parameter with red filter than with no filter.

SHADOW AND OTHER BACKGROUND EFFECTS ON OPTICAL DENSITY OF FILM TRANSPARENCIES

A. H. Gerbermann, H. W. Gausman, and C. L. Wiegand

INTRODUCTION

Aerial photography has been used in agricultural surveys; however, the resulting exposed films have been analyzed and interpreted largely by visual comparisons of photographs, or by using unrefined measurements made on photographs for calculating comparative differences. Considering the enormous amount of information that can be recorded on aerial photographs, it is mandatory that a system of automatic analysis be used. Such a system would require that all like points within a target area yield the same measurement so that different targets could be identified. This study was conducted to evaluate the influence of crop shadows, furrow- and between-row-backgrounds on the density of exposed Ektachrome infrared aero film within a field or target area.

MATERIALS AND METHODS

A field of cotton plants (*Gossypium hirsutum* L.) in the boll stage of maturity was photographed from an altitude of 3,000 ft. with a Hycon KA-74 camera (6-inch focal length, 4 3/4- x 4 3/4-inch format) using Ektachrome infrared aero film, type 8443, with Wratten 12 and EF 2200 filters at 1202 hours, C.D.T., July 24, 1968.[1] The Wratten 12 filter had an approximate 96% absorption edge at 510 mμ (Eastman Kodak Co., 1965). The EF 2200 rose-colored filter was used for color balance.

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[1] Trade names and company names are included for the benefit of the reader and do not imply an endorsement or preferential treatment of the product listed by the U. S. Department of Agriculture.

Ground truth measurements, made on the date of the overflight, showed that the average height of cotton plants was 141 cm and that the plants covered 90% of the ground area. The cotton plants were in two rows (100 cm apart) in a north-to-south direction centered on approximately 200-cm-wide beds, with deep furrows on their sides, Fig. 1. Non-aerial Ektachrome photographs were taken of the cotton crop, and they were used to study the presence and amount of shadows.

Nine locations were chosen on one frame of the processed film (positive) showing the field of cotton, Fig. 1. At each location, four density readings and tracings (200 X magnification) were made across four beds or eight cotton rows with a Joyce, Loebl recording microdensitometer using white, red, green, and blue band pass filters. Readings (180 per 2 mm film distance) were recorded on punch tape for computer analysis.

Processed film was viewed with a Zeiss Standard Universal Photomicroscope to study its film grain composition. Photomicrographs were taken with Kodachrome-X at a 200 X magnification.

RESULTS AND DISCUSSION

Average densitometer readings made with a white band pass filter indicated wide differences in film densities between locations on the film, Fig. 2. Locations 1, 2, and 3; 4, 5, and 6; and 7, 8, and 9, had high, intermediate, and low film densities, respectively. Microscopic examination of the film and comparisons of photomicrographs revealed that locations with the lowest density (7, 8, and 9) had essentially no crop shadows, compared with locations 1, 2, and 3 which had the highest shadow effect. Locations 4, 5, and 6 had intermediate shadow casting. Figure 3, a typical photomicrograph, shows that there is a dark area in part of the furrow caused by plant shadows and a white, sunlit area in the remaining part of the furrow. Red, blue, and green band pass filters were used on the densitometer to evaluate this influence of shadow and sunlit areas, respectively, Fig. 4. The results with a green filter, not included in this paper, were comparable to those with a blue filter. The dashed line represents results with the red filter. The four peaks are caused by shadows in the furrows and very little valley is evident. In contrast, the solid line, representing the blue filter, shows shorter peaks as a result of furrow shadows and a deep valley caused by sunlit portions of furrows. The valley effect does not appear with a red compared with a blue band pass filter because the red-colored area on the film is as transparent to red light as is the transparent furrow area. The peaks for the red filter, compared with the blue filter, are taller because nonred color densities are greater.

When the tracings from blue and red band pass filters were superimposed as in Fig. 4, the area representing the cotton crop fell within the boundaries of the tallest peak for the red filter and the valley for the blue filter. This area fell between the influence of crop shadows and sunlit portions of furrows. All density measurements made within this area, for any given filter, were essentially alike for all locations on the film, Fig. 1.

CONCLUSION

The influence of crop shadows and sunlit furrows on processed Ektachrome infrared aero film can be detected by using red and blue band pass filters on a densitometer. This facilitates identifications and comparisons of targets in aerial photography.

ACKNOWLEDGMENTS

Special thanks are due Clarita Coulson for laboratory assistance.

REFERENCE

Eastman Kodak Company. 1965. Kodak Wratten filters for scientific and technical use. Scientific and Technical Data Book B-3, Rochester, N. Y. P. 28.

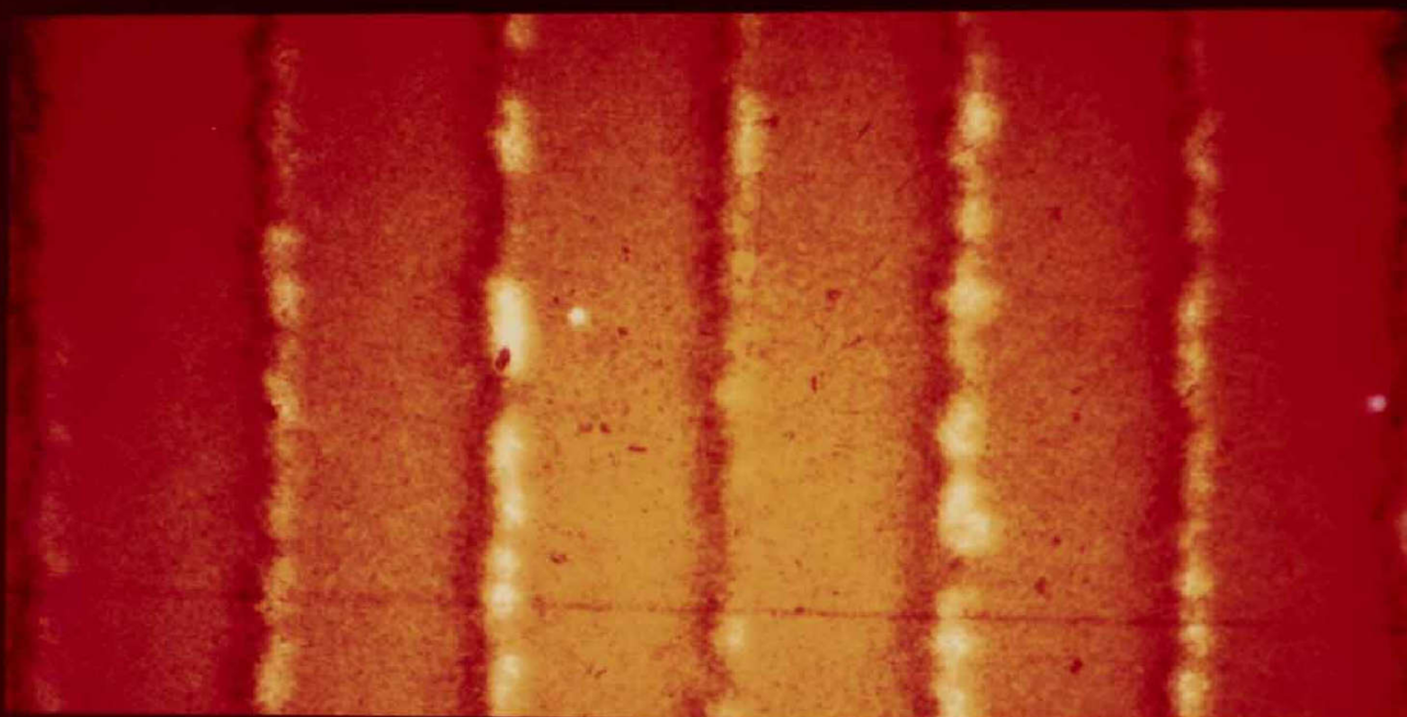


Fig. 3. A photomicrograph (200 X magnification) of an approximately 10 meter width of the field shown in Figure 1. The cotton was planted in two rows 100 cm. apart centered on approximately 200 cm.-wide beds. Rows were planted in the north-south direction; the photograph was taken at 1202 C.D.T. hours July 24, 1968. The narrow bright yellow strips are soil showing between the double rows of plants; the dark red beside the bright yellow is caused by shadows which have a higher optical density than the cotton canopy. Lighter tones in the center of the image are due to greater light concentration in the center of the microscope field of view.

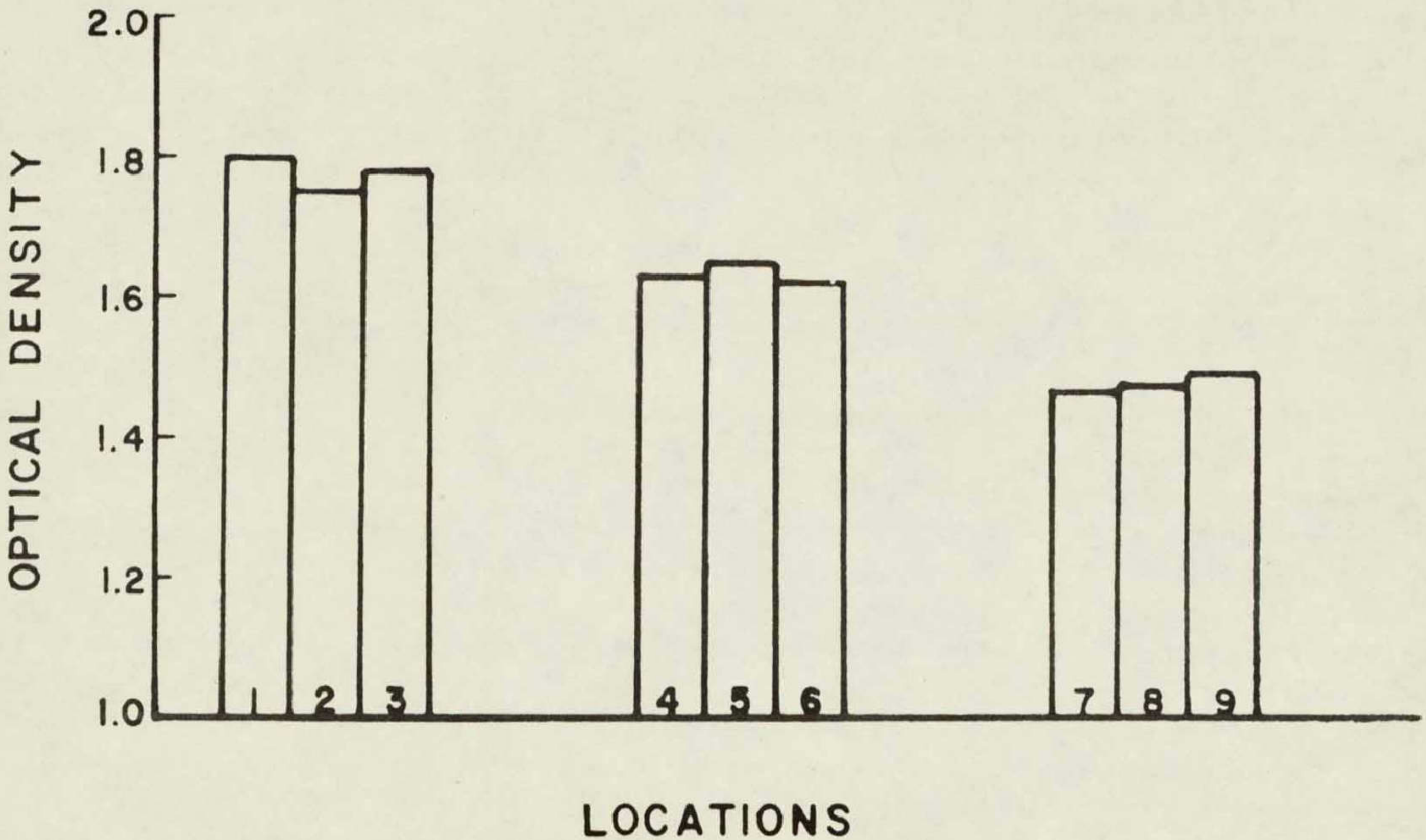


Fig. 2. Average optical densities of the film at nine locations in the field studied. The optical density measurements were made with white light.

Fig. 1. The cotton field utilized in this study was photographed from an altitude of 3,000 feet with Kodak Ektachrome infrared aero film. Average plant height was 141 cm. and ground cover was 90%. Sampling sites numbered 1 through 9 were studied in detail to determine the influence of crop shadows, furrow and between-row-backgrounds in the optical density of the positive transparency.

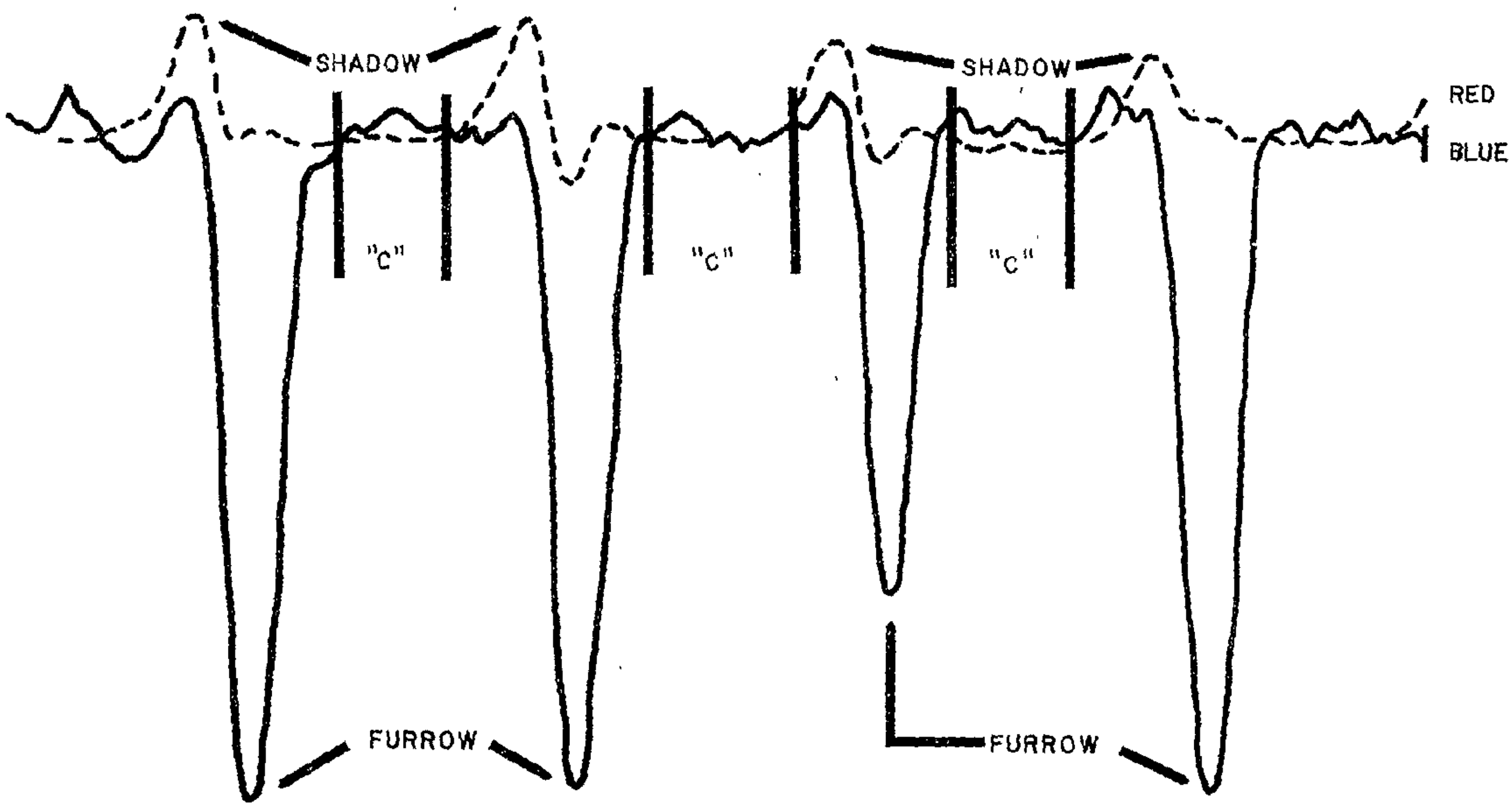


Fig. 4. Microdensitometer tracings (200 X magnification) of the transparency corresponding to Fig. 1 obtained with red and blue filters in the light beam. One hundred eighty discreet measurements were made for 2 mm distance on the transparency. The area designated "C" represents the pure signal from the cotton plants; furrow and shadow areas are also designated. The wider widths of furrow and shadow in this figure than is evident in the photomicrograph of Fig. 3 are due to the integration of optical density for everything within the field of view of the microdensitometer light beam. Inclusion of soil background and shadow information in signatures of crops that incompletely cover the ground complicate their discrimination.

CURRENT METHODS OF FILM ANALYSIS

Tom Sapp, Craig Wiegand, Alvin H. Gerbermann,

and Steve Stratton

OBJECTIVE

To present recent improvements in film quantitization and analysis techniques.

INTRODUCTION

Density of film transparencies has been used in procedures to identify soil, crops, or other earth subjects. Since density alone can be changed drastically by a number of variables ('f' stop, shutter speed, cloud conditions, film speed, filters, etc.), measurements other than optical density *per se* must be used to quantitize film for crop and soil condition discrimination.

METHODS AND PROCEDURES

I. Use of density differences to identify subjects.

After exposure and development color film contains a certain amount of pigment in each of the three emulsion layers. The amount depends on the wavelengths of light reflected from the subject being photographed and the responsiveness of the emulsions to those wavelengths. Although the density of the film is changed drastically by varying shutter speed or 'f' stop, the ratios between colors on a target will remain nearly constant--within certain limits, of course.

The film itself can be imagined as a light filter which allows only specific colors to pass through it. When a finite region of film is measured for density with no filter, only the presence or absence of light stopping pigment is ascertained. By measuring this same area with band pass filtered light, the density to only that particular color is measured.

The density for no filter (N) is the density of the film to white light. Density values obtained for blue (B), green (G), and red (R) filters give the density of the film to the wavelength intervals these filters pass. Although blue, green, and red colors exist in the transparencies only as combinations of the cyan, magenta, and yellow formed on development of the film, the difference between no and blue filter readings (ΔNB) can be said to measure the amount of blue in the film. This is also true for the red and green light readings.

In this study the optical step count of the transparencies to unfiltered light is used as a base, and the readings with colored filters are subtracted algebraically from the no filter reading. The optical step counts used here are the encoder outputs on the microdensitometer paper tape recording system. They consist of a base line count corresponding to the standard optical density of the first step of the calibrated step wedge in use plus added counts which depend on the particular step on the wedge which balances the light transmission by the film being analyzed in the second light beam. In short, the process is to null balance the light transmission through the film being analyzed by the step wedge. The distance the uniformly graduated step wedge travels to balance the transmission by the film determines the count registered by the encoder. The encoder count is related to the optical density by the relation,

$$OD = \text{(Encoder reading - base reading)} \times \text{wedge factor} + \text{step wedge density}$$

For quick identification purposes the optical density differences among filters can be expressed in a graph of count readings (which could also be converted directly to densities) vs. filters (Fig. 1). The differences dealt with here are symbolized as follows:

ΔNB = No (N) - Blue (B)

ΔNG = No (N) - Green (G)

ΔNR = No (N) - Red (R)

The ΔNB, ΔNG, ΔNR counts can be visualized as the slope of a line from No to each filter with the abscissa interval equal to one. The <u>greater</u> the optical count difference between each filter and No filter the <u>more</u> of this specific color is present and vice versa.

In Fig. 1 the double dotted line represents readings taken from more than 80 bare fields. The other patterns are random fields which were run in the same manner as the bare fields. The ground cover for the random fields was identified from the ground truth data.

Site or Run No.	Ground cover	ΔNB	ΔNG	ΔNR
		- Optical	count difference	-
71	Bare field	6	-18.5	8
4	Bare field	6	-22	8
5A	Green crop	-8	- 8	5
5B	Repeat of 5A	-7	- 8	6
6	Lawn	-3	-16	11
7	Purple cabbage	6	-21	1
8A	Weeds	0	-12	0
8B	Repeat of 8A	-1	-13	-1
Average of 80 bare fields		6.5	-17.7	12.6

The surface conditions of the 80 bare fields (furrowed, flat, large or small clods, crustiness, etc.) were carefully noted and were observed to have a pronounced effect on the actual density of the film, but little or no effect on the relative differences between filters (ΔNB, ΔNR, ΔNG). The inverted 'w' pattern was found to be characteristic of all of the bare fields (on Ektachrome film). The standard deviations for each ΔNX over 80 fields were:

S.D. of ΔNB = ± 1.88 optical counts or ± 0.025 in optical density

S.D. of ΔNG = ± 2.80 optical counts or ± 0.037 in optical density

S.D. of ΔNR = ± 2.26 optical counts or ± 0.031 in optical density

These very small standard deviations showed remarkable precision; the optical count readings themselves ranged from 4 to 155 (density of .346 to 2.42) for different bare fields. It must be kept in mind that the standard graph of the bare fields (dotted line) may be shifted up or down the Y axis on the graph to be compared with each of the other graphs since the relative positions of the filter readings to each other is all that is taken into account.

The standard bare field pattern (dotted line) can be matched with only two other patterns (4 and 71). Both of these fields are bare, and although their readings differ by more than 30 optical counts from each other (.414 in density) the patterns are almost identical. This cumbersome visual method of matching can be done much more quickly and accurately by computer.

DISCUSSION

It must be emphasized that the same area on the film must be covered with each of the four filters. A change in the area or path of measurement from one filter to the other could drastically change the density reading and thus give erroneous differences among filters.

The standard deviation in the 80 bare fields can be attributed to the differences in soil color. As the quality of filters used in the microdensitometer improves, it may be possible to tell soil colors and equate these with soil types. This method of study is easily adaptable to computerized analysis in that once a pattern is established for a certain soil or crop, the computer could be instructed to print out the most probable cover or soil type.

II. Regression of optical count differences on white light density.

In Part I the differencing technique was used to identify targets in a "normal" density range. It has been found, however, that "normal" density ranges are not always the case. And, although the contribution to film density among dyes is similar for a given target for a range of white light optical density, the range in density can be such that the optical density differences tend to overlap when several types of cover are considered at once.

In a second exploratory study, use was made of the fact that although the emulsion layers do not react to light in a linear fashion they do react in a predictable manner. See Fig. 2.

The differencing technique of Part I was kept intact, but a system was developed which would consider the difference between white light and band-pass filter optical density of a target as a function of film density to white light. The study was made with the following objectives in mind:

1. To expand the differencing technique to encompass over- and under-exposed film.

2. Reduction of redundant calculations by using the differences of each of the three filter readings from the white light reading, since the remaining three combinations of differences can be derived directly from the first three.

3. Use of the white light density to predict the difference between white light and filtered readings on a specific target.

4. To apply the final technique to automated analysis.

Figure 3 will be used to illustrate improvements in the technique described in Part I. In the figure, ΔF, on the ordinate, is the difference in readings between the observation without a filter and that of red, green, and blue filters. Density, the abscissa, is calculated from the reading made without a filter.

Example: (Refer to Fig. 3).

Filter	Counts
Red	R_I counts
Green	G_I counts
Blue	B_I counts
None	N_I counts

A single reading without a filter is first changed to optical density and used to establish a position on the abscissa. The conversion equation is

$$D_I = C\ (N_I - B) + S$$

wherein D_I is the density at this particular observation site on the film transparency, N_I is the number of optical counts, B is a base correction factor of 40 counts, C is the wedge constant or density increments per count (.012054 density unit/count), and S is the density of the step at which the microdensitometer was zeroed.

Each filter reading is then subtracted from the white light reading and entered into a multiple regression analysis to generate the curves ΔR, ΔG, and ΔB in Fig. 3. For a particular observation on a transparency with optical density D_I,

$$N_I - R_I = \Delta R_I$$

$$N_I - G_I = \Delta G_I$$

$$N_I - B_I = \Delta B_I$$

$$N_I - N_I = \Delta N_I = 0$$

The data for each type of cover or soil condition are fed into the regression program. From the best fit regression equations, the following three estimates of ΔR_I, ΔG_I, and ΔB_I are computed:

$$\Delta R_I \simeq \Delta R_c = \beta_o + \beta_1 D_I + \beta_2 D_I^2 + \ldots.\ \beta n D_I^n \qquad (1)$$

$$\Delta G_I \simeq \Delta G_c = \beta_o + \beta_1 D_I + \beta_2 D_I^2 + \ldots.\ \beta n D_I^n \qquad (2)$$

$$\Delta B_I \simeq \Delta B_c = \beta_o + \beta_1 D_I + \beta_2 D_I^2 + \ldots.\ \beta n D_I^n\ . \qquad (3)$$

The degree of the regression equation is varied from 1st to 3rd or higher until the best "fit" is obtained. The process is repeated for each crop as well as different stages within each crop, thus giving a "profile" for each different type of crop or soil condition.

Once the profile for each soil or crop condition of interest is generated, observations of optical counts from unknown subjects can be tested against all standards and an identification can be assigned.

The procedure for identifying an unknown is as follows: three filtered readings and the white light reading from an unknown are used to calculate ΔRu, ΔGu, ΔBu, and Du (density) for a particular observation. Du is first used to determine which of the known profiles are to be tested for fit, since not all profiles overlap in density. (The optical density of water differs considerably from that for soil or crops, e.g.). This greatly reduces the number of calculations. Du is then substituted into equations which have been derived for training samples (equations 1, 2, 3) to compute ΔRc, ΔGc, and ΔBc. Using the stored 95% confidence limits (2 σ) for each profile to be tested, ΔRc, ΔGc, and ΔBc are substituted in the following equations. It is possible that ΔRu, ΔGu, and ΔBu are equal to ΔRc, ΔGc, and ΔBc in which case the unknown would be identified as that particular crop:

$$\frac{|\Delta Rc - \Delta Ru|}{2\ \sigma_R} = \Delta Ru \text{ test}$$

$$\frac{|\Delta Gc - \Delta Gu|}{2\ \sigma_G} = \Delta Gu \text{ test}$$

$$\frac{|\Delta Bc - \Delta Bu|}{2\ \sigma_B} = \Delta Bu \text{ test}$$

A diagram of the program logic from this point on appears in Fig. 4.

If ΔRu test is greater than one, this particular group of equations is bypassed and the next group is tested. When the ΔRu test is less than or equal to one, it is stored and ΔGu test is considered. If ΔGu test is less than or equal to one, ΔBu test is considered. If ΔBu test is also less than or equal to one, ΔRu test, ΔGu test, and ΔBu test are summed and stored. After all standard samples have been tested, the sums of all the valid tests are compared and the unknown is labeled as the standard sample with the smallest sum. If the unknown fails all tests, it is considered unidentified since its standard is not in memory.

DISCUSSION

The procedures of Part II have been too recently developed to have received much application. The profiles for the following crop and soil condition categories have been developed for use with Ektachrome IR (8443) film, E-3 process. (NOTE: All of the following equations were arrived at from data taken from at least six different film rolls taken on six different dates during the summer of 1968.).

Cotton 95 - 100% cover (Fig. 5)

$\Delta R cotton = 30.576 + 39.447D - 0.054D^2$
with 940 observations
± 5.86 counts=95% confidence bands

$\Delta G cotton = -43.605 + 73.072D - 44.205D^2 - 0.185D^3$
with 940 observations
± 5.79 counts=95% confidence bands

$\Delta B cotton = 67.173 - 158.546D + 36.118D^2$
with 880 observations
± 16.95 counts=95% confidence bands

Dry Bare Soil 0-05% cover (Fig. 6)
(Surface textures vary radically)

$\Delta R_{DBS} = 13.329 - 8.19 > D + 15.393D^2$
with 580 observations
± 7.10 counts=95% confidence bands

$\Delta G_{DBS} = -26.196 + 105.432D - 106.672D^2 + 32.147D^3$
with 580 observations
± 3.50 counts=95% confidence bands

$\Delta B_{DBS} = 218.529 - 863.289D + 938.128D^2 - 338.004D^3$
with 580 observations
± 14.62 counts=95% confidence bands

Wet (or freshly plowed) Bare Soil 0-05% cover (Fig. 7)
(Appears dark on film)

$\Delta R_{WBS} = -86.771 + 333.054D - 282.393D^2 + 70.236D^3$
with 140 observations
± 5.80 counts=95% confidence bands

$\Delta G_{WBS} = 61.464 - 127.446D + 91.036D^2 - 20.727D^3$
with 140 observations
± 2.14 counts=95% confidence bands

$\Delta B_{WBS} = -431.492 + 771.227D - 543.467D^2 + 124.516D^3$
with 140 observations
± 15.80 counts=95% confidence bands

Water (without high reflection or glare) (Fig. 8)

$$\Delta R = 38.775 - 145.123D + 86.431D^2 - 11.948D^3$$
with 380 observations
$\pm$ 8.16 counts = 95% confidence limits

$$\Delta G = -7.962 + 29.673D - 29.269D^2 + 8.818D^3$$
with 380 observations
$\pm$ 3.37 counts = 95% confidence limits

$$\Delta B = -19.100 + 78.145D - 111.418D^2 + 40.171D^3$$
with 380 observations
$\pm$ 5.99 counts = 95% confidence limits

These equations and their confidence bands are presented in Fig. 5 and as overlays on Fig. 5.

SUMMARY

In the past, optical density of film transparencies has been used directly in trying to identify soil, crops, and ground cover conditions. In this contribution differences between the optical densities measured with different band pass filters which divide the visible spectrum roughly into thirds and represent the complements of each of the three dye layers in Kodak Ektachrome film, types 8442 and 8443, are investigated for identification and correlation with ground truth. The method has been extended by fitting the optical density differences to regression equations over the range of film density to white light encountered. Differences in 'f' stop setting, shutter speed, cloud conditions, film speed, filters, and other factors affect the optical density differences among band-pass filters much less than the optical densities themselves. When film density to white light is taken into account, and the regression of film optical density differences are expressed accordingly, variation in a given target's signature among film rolls taken on different days, different times of the day, and differing in manufacture and processing are minimized. Computer programs have been written for the procedures used in part I of this report. Results of use of these procedures are illustrated in Chapters I and V of this report.

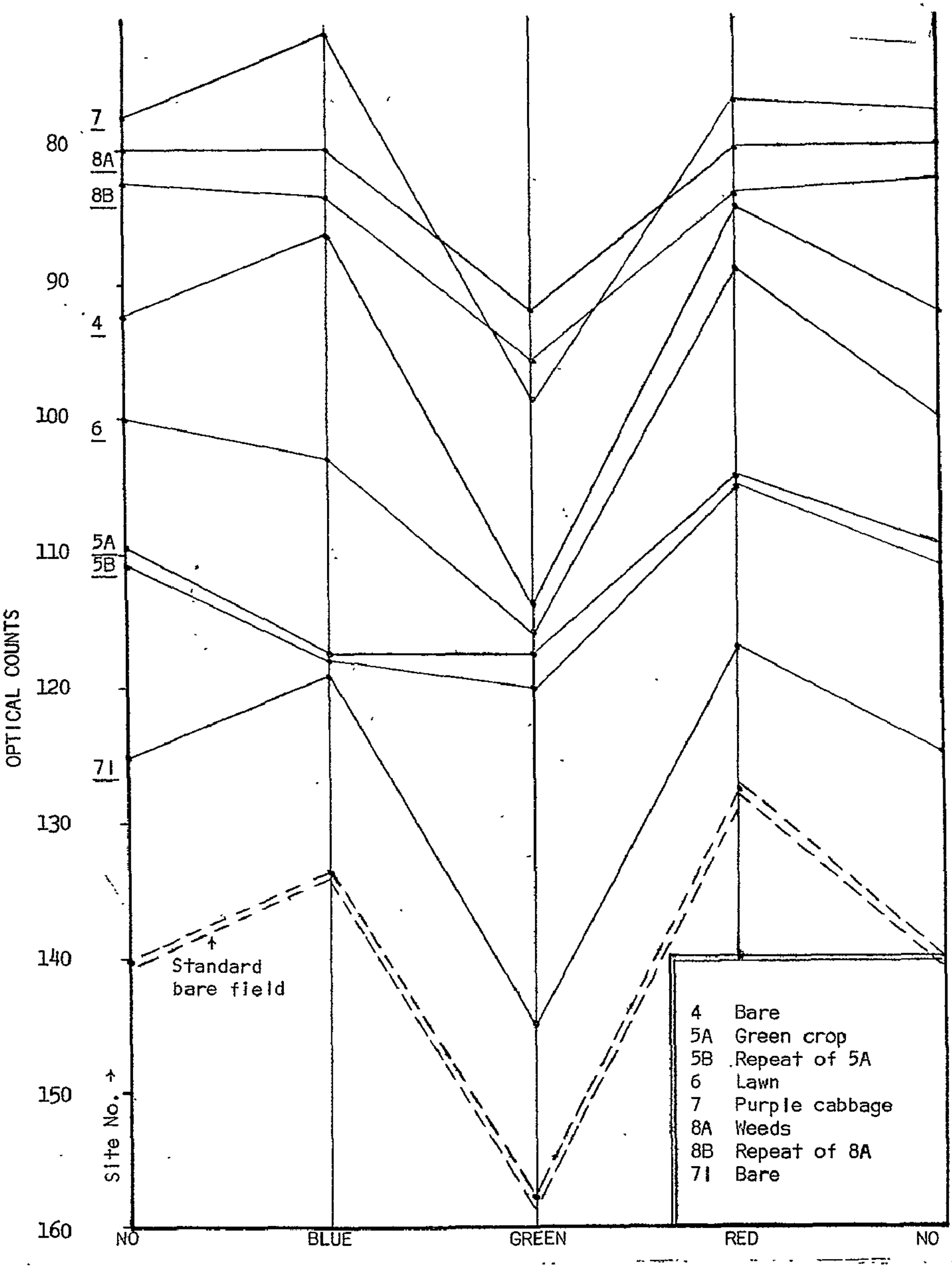


Fig. I. Optical counts for various sites differing in crops and cover conditions for each filter in the light beam. The optical density differences for a given cover condition form a pattern whereas optical densities *per se* are wild.

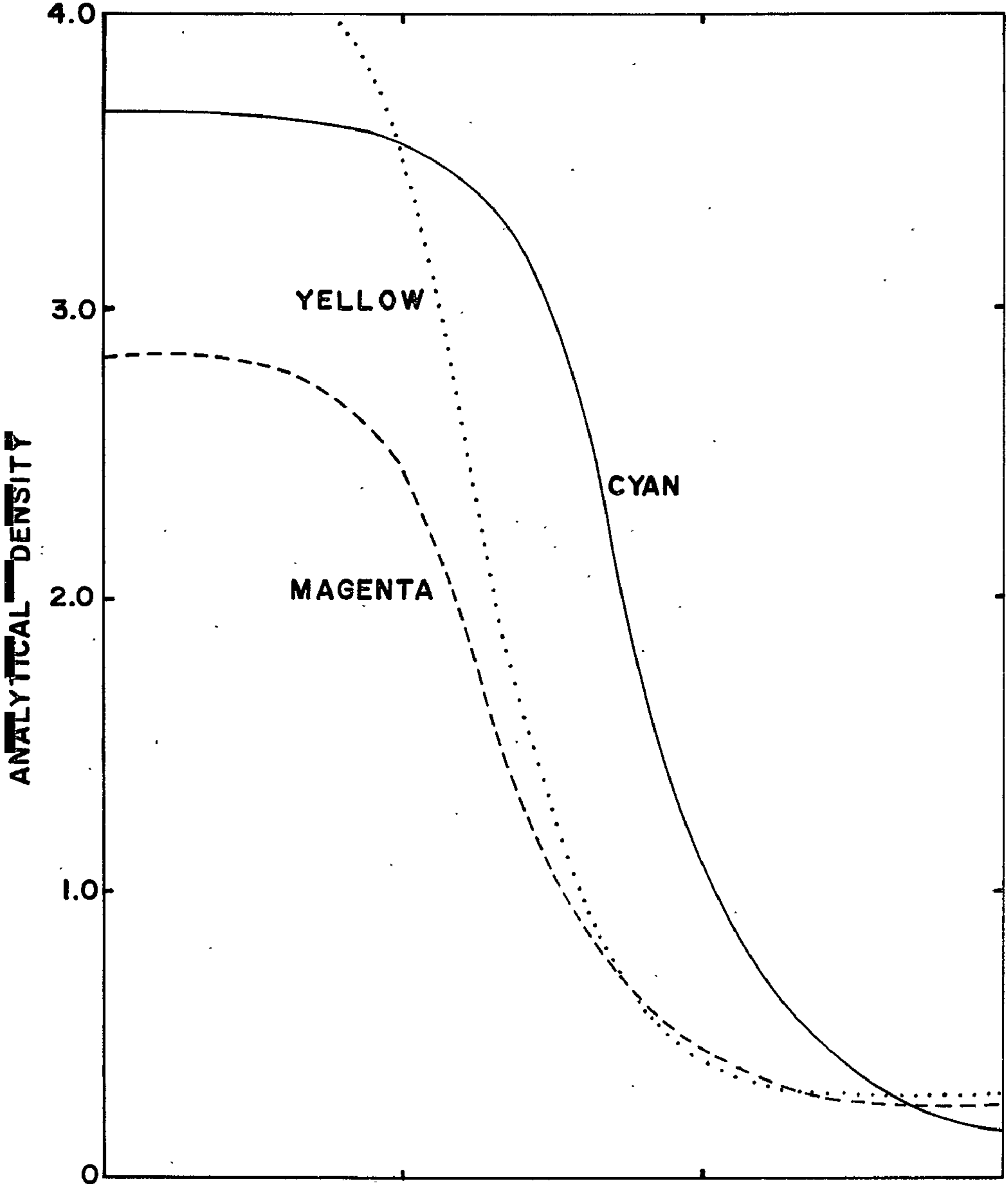


Fig. 2. Sensitometric curves for the three dye layers in Kodak Ektachrome infrared aero film type 8443. The film analysis procedure reported herein takes into account the changing relation among dye layer optical densities with film exposure in discriminating among crop and soil condition subjects in aerial or space photography. (From N. L. Fritz, Eastman Kodak Co., Rochester, N.Y.).

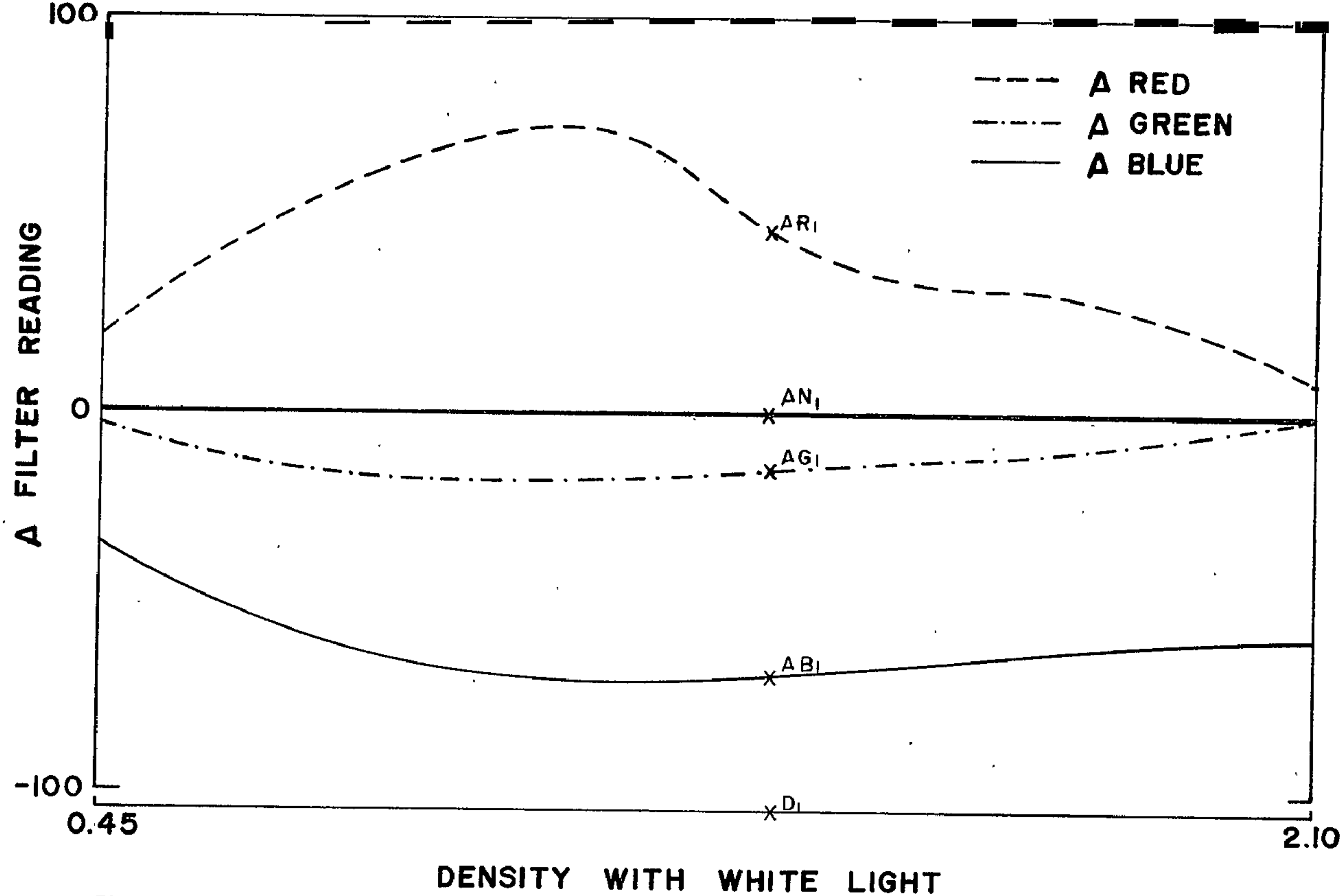


Fig. 3. Illustration of the film analysis procedure given in this report. ΔF on the ordinate designates the optical count difference between the no filter and band-pass filters. Density on the abscissa is the film density to white light (no filter) corresponding to a range in film exposure conditions. The curves ΔR, ΔG, and ΔB illustrate how the (No-Red), (No-Green), and (No-Blue) optical counts vary over a range in film exposure conditions. ΔR_I, ΔN_I, ΔG_I, and ΔB_I are the differences associated with a given exposure condition which yields a transparency with white light density D_I. The ΔR, ΔG, and ΔB curves are mathematically fitted for the film density range encountered due to light conditions, 'f' stop variations, film manufacturer lot, and processing for each crop or soil condition of interest. These profiles are entered in computer memory and all unknowns tested against them and assiged an identity.

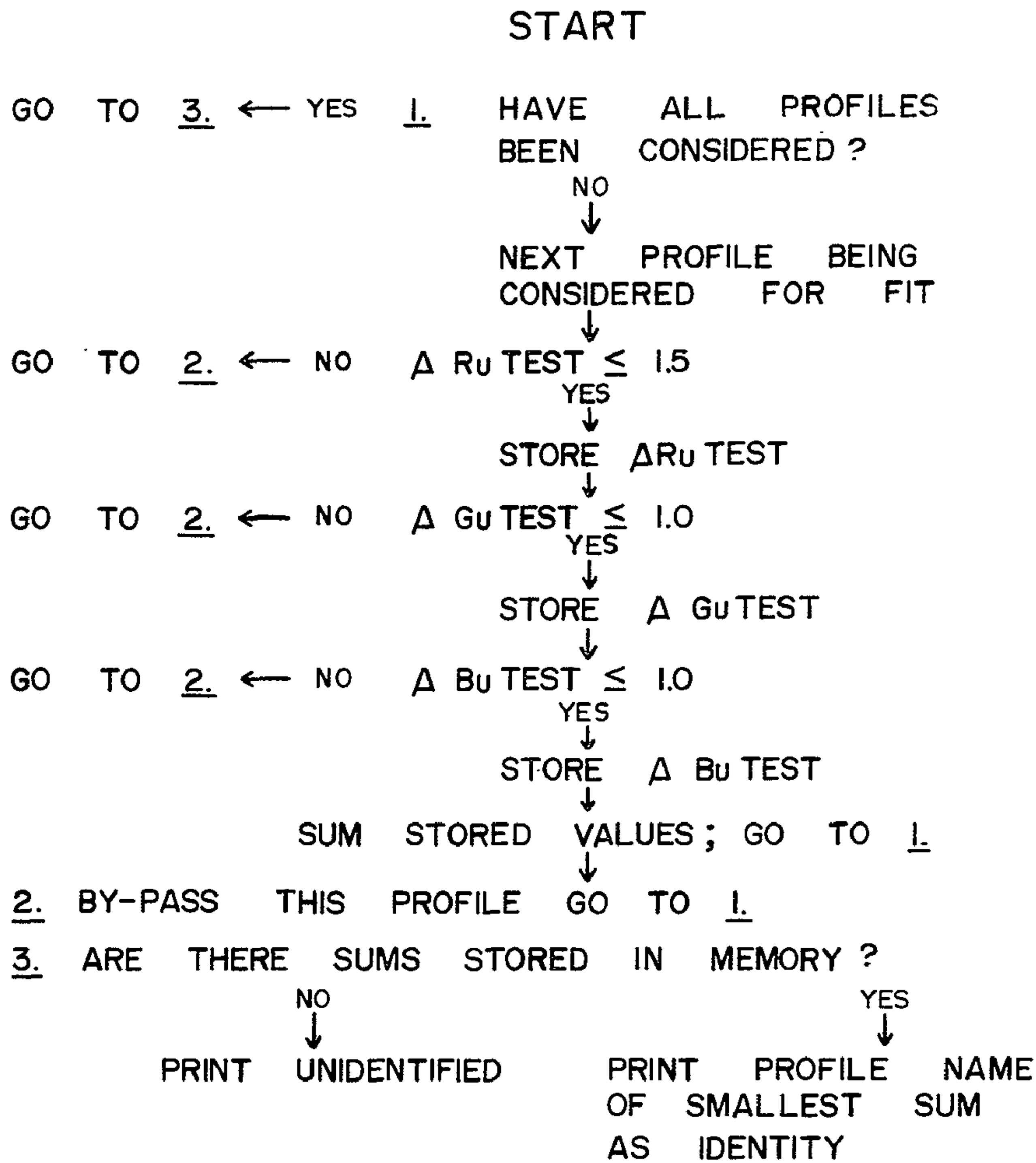


Fig. 4. Flow chart illustrating program logic for computerized identification of crop and soil conditions against training profiles stored in computer memory. After ΔRu test, ΔGu test, and ΔBu test have been computed, their values are compared with 1.0. To be within the 95% confidence bands each test must be less than one and their total must be less than three. 1.5 is used as a threshold value for ΔRu test in order to encompass near misses for a second trial. If the test value exceeds 1.0 on any of the following trials the profile is automatically rejected as a possible identity.

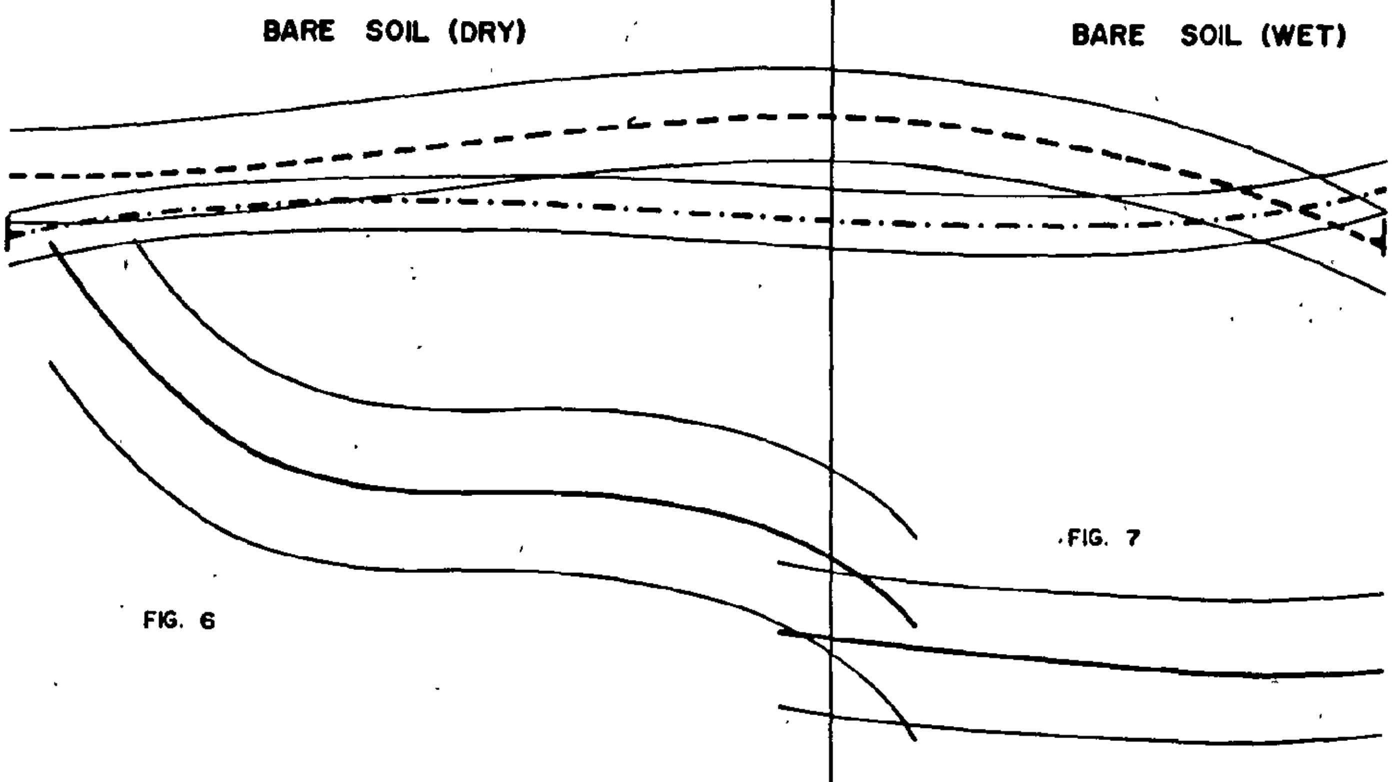
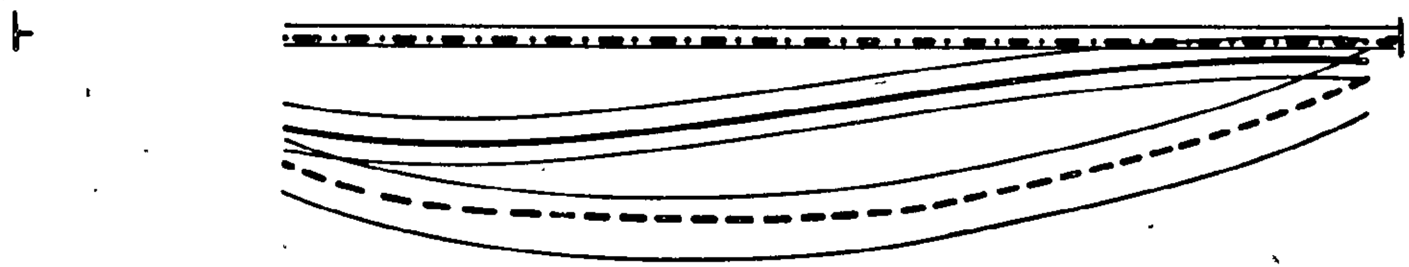


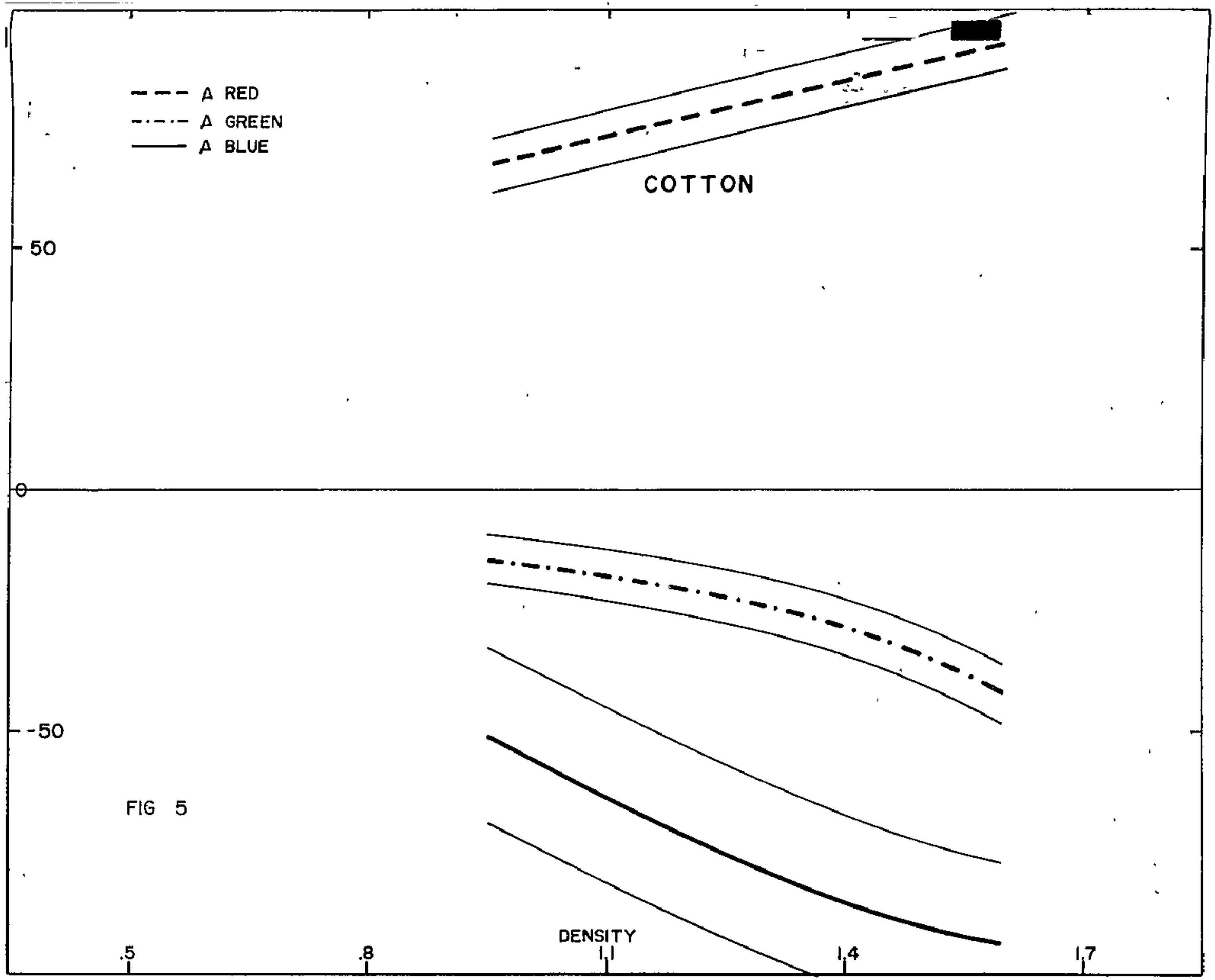
FIG. 6

FIG. 7



WATER

FIG. 8



Figs. 5-8. The optical count difference between No filter in the light beam and red, green, and blue filters in the light beam are depicted (ordinate) versus the optical density of the film to white light (abscissa). Confidence bands of 2 standard deviations are shown around the curves. A procedure has been developed which tests unknown observations against the standard profiles for different crops and soil conditions. The profiles represented by the curves are sufficiently different among crop and soil conditions to enable discrimination and the procedures are being computerized.

Bendix Mapper Imagery

By W. J. Rippert and C. L. Wiegand

Introduction:

Data from the thermal infrared region has been shown in previous studies to reveal differences in plant cover, in need for irrigation of crops when the crop canopies completely cover the soil surface, in soil moisture differences, and to some extent differences in profile characteristics. In a complete multispectral approach the data are needed on a continuing basis. For this reason a Bendix thermal mapper was leased for a six week period in the summer of 1968.

Objective:

To compare Bendix thermal mapper imagery with photographic imagery.

Methods and Procedures:

The Bendix mapper was airplane-mounted and was used at the same time photography was being obtained using the Hycon camera or the Hasselblad cluster. It was also flown in support of one NASA Convair mission.

A description of the ampper follows:

The airplane-mounted Bendix mapper scans the scene in its field of view mechanically, in a line by line fashion. The output is recorded on film, as an analogous image. The device maps irradiance differences corresponding to variations in near infrared radiance of objects in its field of view.

Two wavelength ranges are available. One is 0.7 to 2.5 microns, for reflectance measurements of plants and soils. The second is 3.5 to 5.5 microns, for emittance measurements of plants and soils.

An oscilloscope is used to continually monitor the video signal, permitting exact adjustment of the amplifier controls. This is advantageous for obtaining optimum images of subjects of particular interest.

The scan head contains both the energy pick-up and the film recording unit. The energy pick-up system consists of the rotary scanning mirror and the collecting optics. The rotating mirror sequentially looks at each part of the scene, and focuses the radiation collected by the optics upon an indium antimonide detector, which is sensitive to the wavelength interval 0.7 to 5.5 μ. The detector which must be cooled to liquid nitrogen temperature in order to function, is mounted in a Dewar. The detector and the preamplifier and optical filters are located in this part of the scan head.

The preamplified electric signal is fed through a cable to the console, for processing and operating adjustments. The final output signal is fed through the cable back to the film recording part of the scan head, where the video signal is reconstructed into a photographic image. This part of the scan head contains a flow modulator tube, recording optics, and a film cassette. There, the amplified electrical signal is turned into a modulated beam of visible light and recorded line by line on the film. This builds up an image which is a representation of the near infrared radiation coming from the targets on the ground.

An image is obtained in only one of the wavelength intervals at a time. Two band-pass filters are used for selecting 0.7 to 2.5 and 3.5 to 5.5 micron images. These filters are electrically changed from the mapper controls.

The Hasselblad 500EL is an electrically driven single-lens reflex camera. The negative size is 2 1/4 x 2 1/4 inch format on 70 mm film. Focal length of lens was 50 mm. Black and white plus-X film with a 25-A filter which has an absorption edge at 0.59 microns was used part of the time. The rest of the time black and white infrared film with an 89-B filter which has an absorption edge at 0.69 microns was used.

Results:

Scans and photographs of the Research Farm taken June 20 and July 6, 1968, are presented in Figs. 1 and 2. The various soil conditions and plant covers are identified in Fig. 1 by letters. Descriptions of the sites corresponding to the letters are given in Fig. 2.

On June 20 (Fig. 1) mapper imagery was obtained in the 3.5 to 5.5 μ region and camera imagery was obtained using Plus-X film with a 25-A filter and black and white IR film with an 89-B filter at 1200 hours CDT.

On July 6, 1968, mapper imagery was obtained in the 0.7 to 2.5 μ region and camera imagery was obtained using Plus-X film with a 25-A filter and black and white IR film with an 89-B filter, again at 1200 hours CDT.

Figure 3 shows the wavelength distribution and intensity of the typical solar reflected and emitted object radiation.

The 3.5 to 5.5 μ image shown in Fig. 1 is similar to images that have been obtained before using the University of Michigan thermal scanner and the infrared camera. That is, warm objects such as bare soil are light toned whereas cool surfaces such as water or crop canopies are dark. The energy emissions are very low, however, because thermal infrared emission for objects at temperatures encountered in agriculture are low (Fig. 3). Signal strength would be much greater for hotter objects such as forest fires.

The darker areas in the citrus of Block B are irrigation treatment plots which had been irrigated on June 17, 3 days before these images were taken. This irrigation effect is visible in all the images--in the visible and near infrared because of the lower albedo of the wet than dry soil, and in the thermal due to the dissipation of much of the incident radiation in evaporating water.

The image shown in Fig. 2 for the 0.7 to 2.5 μ wavelength interval is similar to the black and white infrared photograph of the targets. The crop surfaces, which reflect strongly in the 0.7 to 1.4 μ wavelength interval, are lighter in tone than objects such as soil or water which reflect less strongly. The diagonal in block G_2 separates the cotton of this block into the nonirrigated eastern part and the western part which was irrigated on June 10.

In Figs. 1 and 2 the 50 ft square plywood panel south of the buildings is a good control panel for comparing the response of objects in the different wavelength intervals. Half (25 ft x 50 ft) of this panel is painted with 3M optical white and half with optical grey 3M paint. (The fact that the white half appears larger is characteristic of photography; the higher the elevation the larger the white half appears relative to the grey half.).

In the visible and near infrared the white panel is much more reflective than the grey half of the panel. Thus in the Plus-X Pan,[1] black and white infrared, and 0.7 to 2.5 μ mapper images the white surface is light in tone (high response or exposure of the film) and the grey half is dark in tone (low film response). However, in the 3.5 to 5.5 μ mapper images the white half of the panel shows low response (dark tone) whereas the dark half causes high film response (light tone) due to the approximate 20 C temperature difference between the white (cool) and grey (warm) halves.

Discussion:

Several problems were noted in attempting to obtain imagery with the Bendix mapper.

It was impossible to obtain sufficient energy signal to noise earlier in the morning than one or two hours after sun up or later in the day than about sun down. Naturally, objects would have a higher reflectance when the solar radiation is large and a higher emittance later in the day than in early morning because of higher target temperature. Inability to make diurnal emittance measurements around the clock is a serious handicap.

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1 The tone difference apparent in the original photographs are not evident in the Plus-X Pan reproduction.

It was noted that whenever the temperature measurement was narrowed down by hot and cold blocking to amplify the signal from low contrast targets such as water surfaces, an eliptical signal would be recorded with high energy response in the center of the flight path which tapered off to a lower response on the sides. This variation in signal was usually greater than the irradiance difference between targets. Interpretation of the signal was difficult or impossible under these circumstances.

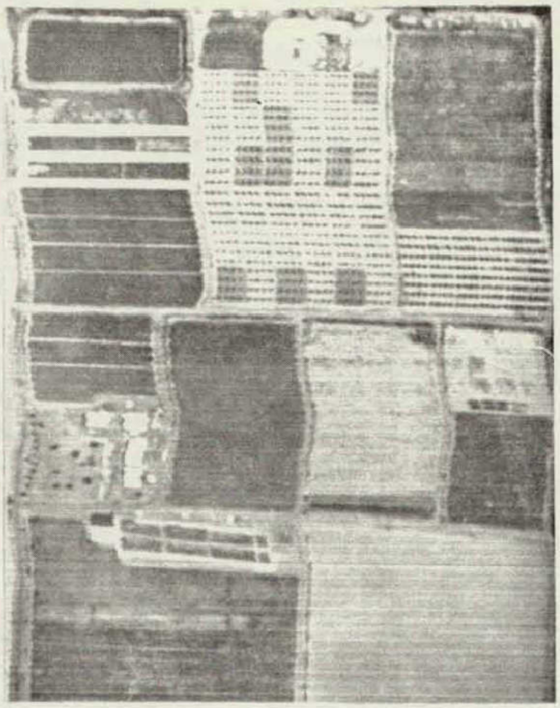
Emissivity in the 3.5 to 5.5 micron region varies more than in the 8 to 14 micron wavelength band. This may have contributed to noncorrespondence between signals from the mapper and temperatures of ground targets measured with portable radiation thermometers filtered to be sensitive in the 8 to 14 micron wavelength interval.

Much difficulty was experienced due to inadequate roll stabilization. The mapper was equipped with ±6° roll stabilization but it was insufficient for optimum use of the mapper in the single engine aircraft used.

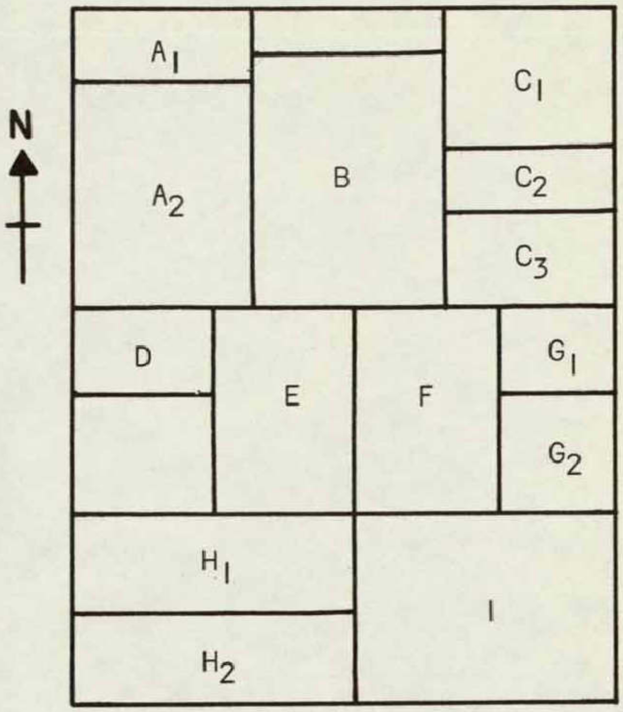
Summary:

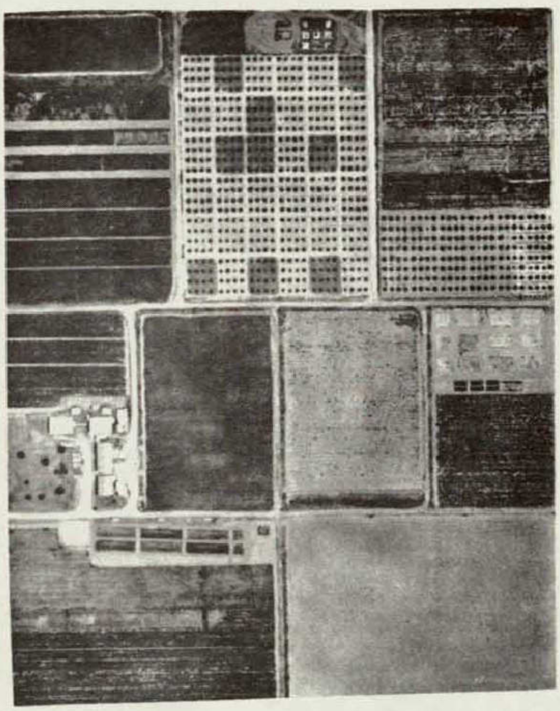
The Bendix mapper was leased for a six week period in the summer of 1968 to provide imagery in the near infrared wavelengths on a continuing basis. The mapper utilizes an indium antimonide detector which is sensitive to the wavelength interval 0.7 to 5.5 microns. In the wavelength region of 3.5 to 5.5 microns the available energy from earth terrain at 310°K is limited and emissivity varies considerably with wavelength. The 8 to 14 micron region would be better for broad-band thermal scanning in that more energy is available from earth terrain and emissivity values are more constant with wavelength.

Imagery obtained with the scanner in the 3.5 to 5.5 micron region was similar in appearance to black and white Plus-X film imagery in that plant surfaces which are not very reflective in the visible are also cool. However, low reflective surfaces which were hot had opposite response. Imagery obtained with the mapper in the 0.7 to 2.5 micron region was similar to black and white IR film (response to 0.9 micron) imagery since both respond to the high reflectance of crop surfaces which begins at about 0.7 micron and extends to 1.4 microns.

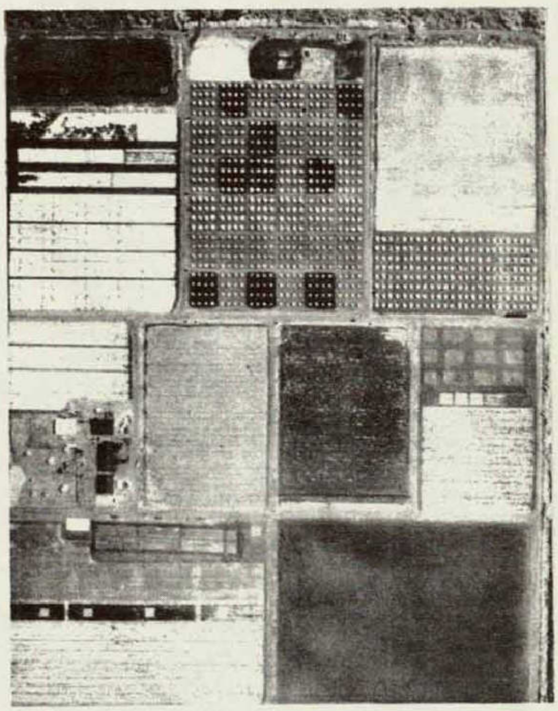


Mapper 3.5-5.5 μ





Black and White Plus-X

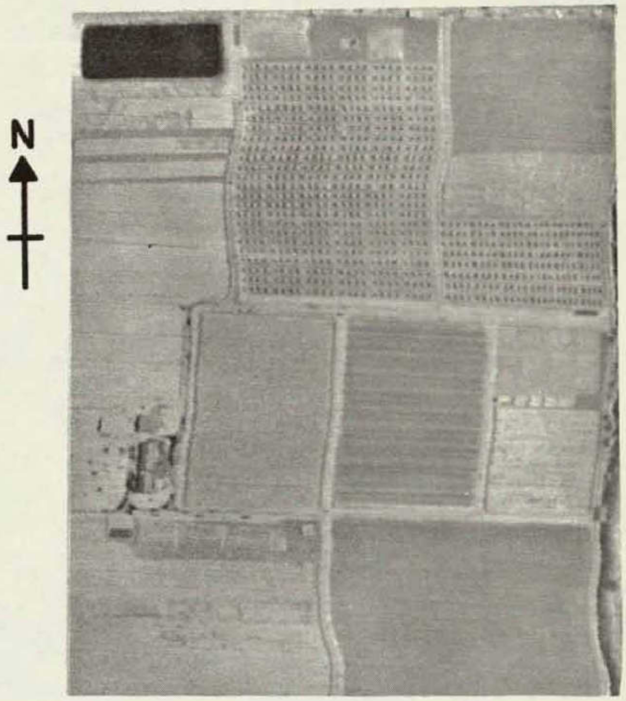


Black and White IR

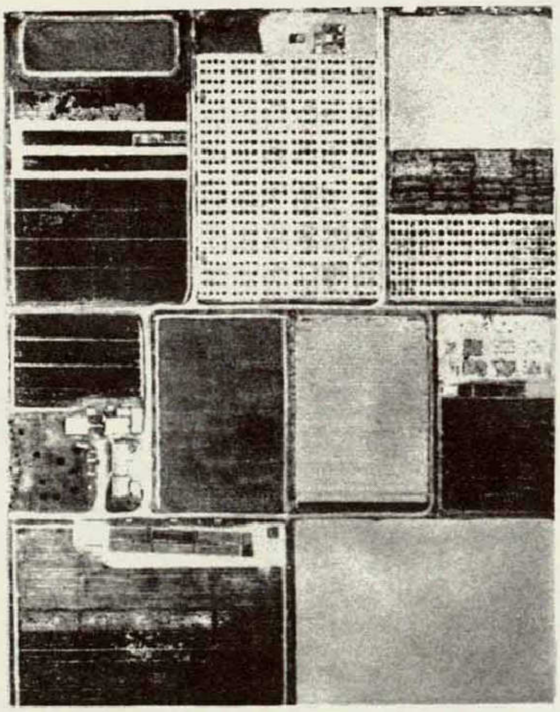
Figure 1. Imagery obtained of Research Farm with the Bendix mapper and Hasselblad cameras on June 20, 1968.

DESCRIPTION

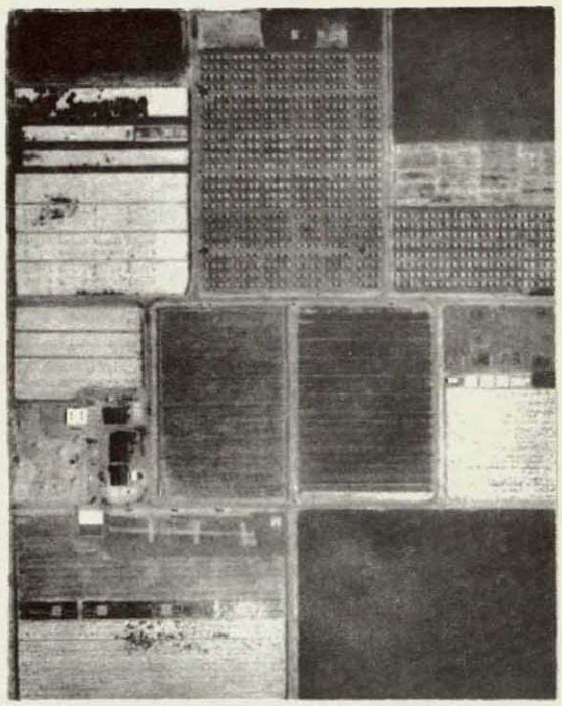
A_1 Water reservoir
A_2 Cotton
B Citrus and bare soil
C_1 Blackeye peas (6/20)
Bare soil (7/6)
C_2 Cantaloupe and weeds
C_3 Citrus and bare soil
D Cotton
E Grain sorghum
F Bare soil
G_1 Chemical fallow (bare soil)
G_2 Cotton (wet and dry)
H_1 Sorghum stubble
H_2 Cotton
I Bare soil



Mapper 0.7-2.5 μ



Black and White Plus-X



Black and White IR

Figure 2. Imagery obtained of Research Farm with the Bendix mapper and Hasselblad cameras on July 6, 1968.

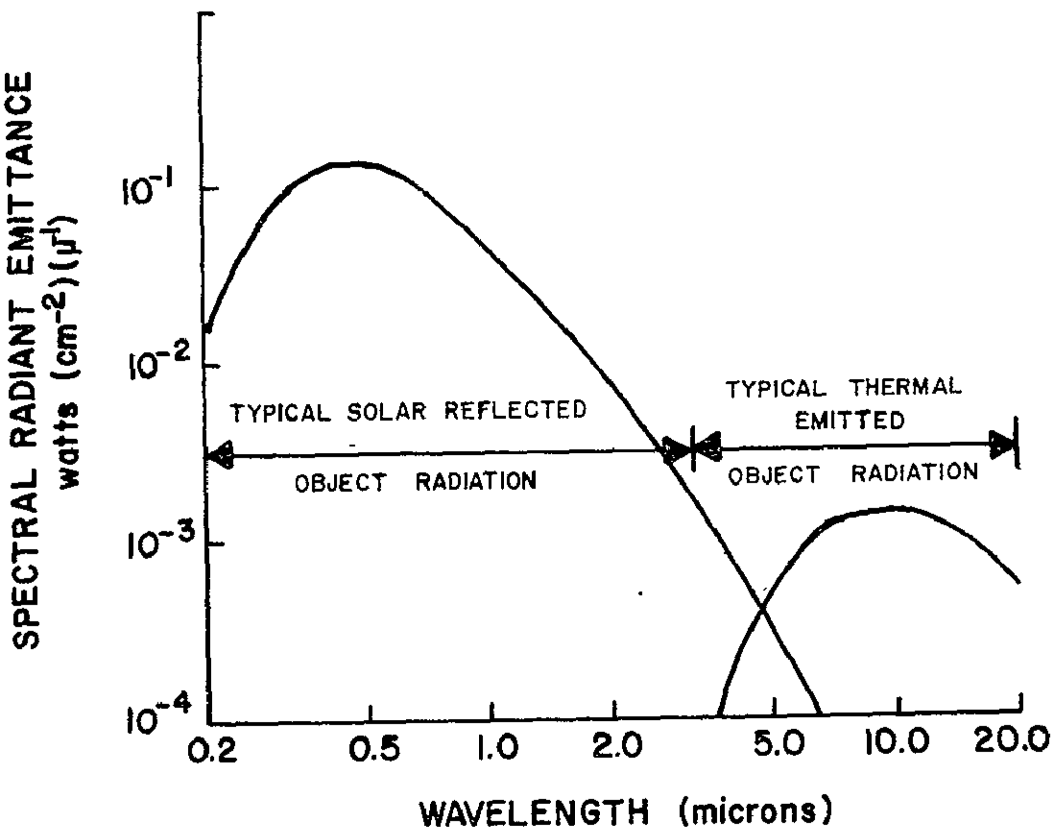


Figure 3.--Comparison of typical solar reflected and emitted object radiation. (Figure adapted from Multispectral Program Staff, Investigation of Spectrum Matching Technique for Remote Sensing in Agriculture, Willow Run Laboratory, Univ. of Mich., Ann Arbor. Final Rpt. Jan 68 - Sept 68. Bul. 167-4-10-F. Dec 68. 48 pp.).

CARE, EXPOSURE, AND PROCESSING OF EKTACHROME FILM AND PAPER

Ron Bowen

This note summarizes the experience and recommendations of the photographic laboratory staff at Weslaco for exposing and processing Ektachrome film and paper.

A. Proper care of film and paper.

1. Proper care of Ektachrome film and Ektachrome paper is a very important part of a quality finished product. The film and paper must be stored at a temperature lower than 40°F, or frozen until time of use. The film and paper should be allowed to come to room temperature for at least three hours before it is used.

2. Ektachrome film and Ektachrome paper must be loaded in cameras and easels, respectively, in total darkness. The very smallest amount of light will fog the film or paper.

B. Proper exposure of film and paper.

1. Proper exposure of film. The two types of Ektachrome film we will consider are Kodak Ektachrome Aerial, type 8442; and Kodak Ektachrome infrared aero, type 8443.

   The 8442 Ektachrome film is high speed (aerial index of 25). We have had good results taking photographs on the ground using camera settings determined with the light meter set for an ASA speed of 350. On a very bright day, f16 at 1/250 sec has given very good results without any filter.

   The 8443 Ektachrome IR film is also high speed aerial film which has an aerial index of 10 and an approximate ASA speed of 100 for ground truth photography. On bright days with a Kodak 15(G) filter, we get good results using f10 at 1/500 sec.

2. Ektachrome paper must be exposed in total darkness. Overexposed Ektachrome paper will turn white, not black. Underexposed paper will turn black. Black borders are normal. To expose your first Ektachrome print use no filter and print with white light. Guess at the time and the f stop. Not knowing what kind of equipment you have, I recommend a short time of about 0.5 sec and an f stop of 8 to start. If the print is black, or dark you need more time or more light. If the print is white, or light you need less time or less light. When exposure (density) is right add a color filter to make a balanced color print. You will find you can make a sharp, color-balanced print in this manner of high quality. One word of caution: never place color filters between the positive transparency and the paper. Always place the filters between the light source and the transparency so you will have no light diffusion, and thus your enlargement and contact print will be "razor sharp". Also, you should always add the color you need to balance the print. For instance, if you need red color, add a red filter; if you need green color, add a green filter.

C. Proper processing of film and paper.

1. Ektachrome aerial film 8442 or Ektachrome IR film 8443 can be processed in the same chemical at the same time. Follow the Kodak E3 process step by step. Make no changes in recommended chemical solutions or in temperature and times of immersion in the chemical solutions and water baths. Since E3 instructions are easy to obtain, they are not given here.

2. Tray processing of Ektachrome paper is quite simple so long as the chemicals are properly mixed. First developer Ektaprint R and the stop bath should be mixed as indicated on the container labels. The color developer, however, should be modified from the directions on the container label by using 358 ounces (2.80 gallons) of water instead of 3-1/2 gallons. The Ektaprint R hardener also should be changed so that only 3-1/2 gallons of water will be used for two chemical mixes. This doubles the strength of the hardener. Mix the CP5 bleach, CP5 formula fixer, and CP5 stabilizer as indicated on container labels. If you follow the above instructions, you should have no problem.

3. To have a color print in just 15 minutes, do the following steps very carefully: Check temperature; 100 F is required. Ektaprint R first developer for 1-1/2 minutes. Ektaprint R first stop bath for 1/2 minute. First wash for 3 minutes. Reversal exposure for 15 seconds. Ektaprint R color developer for 2 minutes. Ektaprint R hardener stop bath for 1 minute. First CP5 bleach for 1 minute. Second CP5 bleach for 1 minute. CP5 formula fixer for 1 minute. Wash for 2 minutes. CP5 stabilizer for 2 minutes. Please notice that we have repeated the CP5 bleach 1-minute step twice. Thus, there must be two CP5 bleach tanks. In order to get a very good gloss on the paper all excess moisture must be squeegeed from the print. Then simply let the print air dry; do not heat, ferrotype, or drum dry it. If you have controlled the time and temperature, you will have an excellent color print. Be careful not to inhale chemical fumes or get the chemicals on you or in your eyes.

The Ektachrome color and Ektachrome IR prints in this report have been produced according to the above procedures.

DISCRIMINATION OF VEGETATION BY MULTISPECTRAL REFLECTANCE MEASUREMENTS

Arthur J. Richardson, William A. Allen, and

James R. Thomas

Abstract

Plant leaves grown in a greenhouse and leaves collected from the field have been analyzed for information content based upon diffuse reflectance and transmittance measured in the laboratory over the spectral range 0.5 - 2.5 μ. The discrimination criterion used was that of infinite reflectance R_∞ defined as the maximum reflectance achieved by leaves stacked sufficiently deep. The criterion R_∞ was chosen because there is a high probability that R_∞ can be measured from remote distances. Greenhouse leaves could not be discriminated with respect to known nutritional deficiencies and marginally with respect to species. Reflectance and transmittance spectra over the wavelength range 1.4 - 2.5 μ, reduced to the Kubelka-Munk format, suggest that the absorption spectra for typical leaves are not statistically different from that of pure liquid water. Greenhouse leaves tend to produce the same value of R_∞, but field leaves exhibit decided variation in R_∞. The differences in R_∞ appear at wavelengths that peak within the atmospheric windows. Discrimination procedures for vegetation based upon appropriate wavelength channels show considerable promise. The physical quantity indirectly sensed by a measurement of R_∞ is the extent to which the water in a leaf has been subdivided by the cellular structure of the leaf.

Introduction

In order to interpret remote sensing data acquired from aircraft and spacecraft, understanding is required of the reflectance produced by features on the surface of the earth. The specific problem in agriculture is interpretation of reflectance produced by vegetation. The complete problem of plant recognition from remote distances must allow for atmospheric absorption and scattering, polarization considerations, soil background complications, and the entire three-dimensional complex of plant, canopy, and field geometry. Reflectance from aggregates of individual leaves probably is the most important factor in the remote sensing of vegetation, but interactions from fruit, stems, seed pods, and other plant parts must also be considered as complicating factors in the total reflectance determination.

The plant recognition problem is restricted in this investigation to a determination of the possible information content in plant leaves piled to a sufficient depth. Reflectance of leaves stacked upon a background of reflectance R_g changes with the number of leaves in the stack but a stable value of reflectance, designated <u>infinite reflectance</u> R_∞, is essentially reached at all wavelengths in the spectral range 0.5 - 2.5 μ when the leaves have been stacked to a depth of eight [Allen and Richardson, 1968]. The value eight applies specifically to reflectance in the range 0.8 - 1.3 μ. At other wavelengths, such as those in the visible region of the spectrum, and those at wavelengths in excess of 1.5 μ, a practical reflectance maximum is reached when leaves are stacked two deep. In the spectral regions around 1.65 μ and 2.20 μ, for example, R_∞ is reached at an earlier stage of crop maturity than in the 1 μ region where a leaf is virtually transparent.

The problem of leaf reflectance is analogous to that encountered in measuring the reflectance of powders superimposed upon a background. If the powder is too shallow, the reflectance is characteristic of the background. As the depth of powder is gradually increased, a depth of powder is reached at which the powder reflectance predominates over background reflectance. The maximum reflectance of the powder is an intrinsic property only of the powder. The reflectance maximum R_∞ is reached both with powders and leaves at a thickness of a few millimeters. The concept of infinite reflectance is very useful because R_∞ can be measured directly in the laboratory and is likely to be characteristic of mature plant canopies.

Substantial information can be inferred from a measurement of plant canopy reflectance even if little else is known about the canopy except that it is thick. A value for R_∞ is available to a sensor, however remote, if the measurement is made in the spectral regions of atmospheric transparency. Subsequently in this paper the terms reflectance and R_∞ will be used interchangeably unless otherwise stated.

Diffuse reflectance and transmittance measurements on single leaves over the spectral range 0.5 - 2.5 μ were utilized to determine whether the corresponding plants could be discriminated by means of R_∞. All measurements were performed in the laboratory. A negative finding would have done violence to the prospect of discriminating vegetation under field conditions. A positive finding signifies that further progress is possible on the discrimination problem applied to agricultural vegetation.

Experimental Procedures

All measurements of leaf reflectance and transmittance were obtained with a Beckman DK-2A Spectrophotometer*. Measurements were taken at increments of 0.05 μ over the spectral range 0.5 to 2.5 μ.

The integrating sphere of the DK-2A was given a thick coating of MgO prior to the growing season. The integrating sphere was not touched again until all leaf measurements were made. Thus, differential effects obtained were real and were not a result of imprecision introduced by recalibration and instrument overhaul.

The DK-2A was modified slightly in order to yield absolute radiometry. The instrument was designed originally by the manufacturer to measure relative reflectance with respect to MgO as a standard. The instrument is a commercial device designed essentially for transmittance measurements of non-scattering media. The electronic circuitry of the instrument was balanced to yield a linear response within specifications when used to measure transmittance. When the instrument is used in the reflectance mode, care must be exercised that: (a) excessive light is not scattered laterally from the sample; (b) the reflectance of the standard is known to prescribed accuracy; and, (c) residual non-linear corrections are applied throughout the entire wavelength region of reflectance response.

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* Beckman Instruments, Inc., Fullerton, California. Trade names are included for information only and do not constitute endorsement by the U. S. Department of Agriculture.

Reduction of lateral scattering from a turbid sample is relatively easy to attain [Norris, 1965]. A thin sample such as a leaf or a small stack of leaves must be placed as close as possible to the entrance port of the spectrophotometer. The sample holder of the DK-2A was modified slightly to meet this requirement.

Acquisition of a suitable reflectance standard for the spectrophotometer was a more difficult problem. The National Bureau of Standards (NBS) does not issue a reference surface for the spectral range 0.5 - 2.5 μ. The procedure evolved is based upon the NBS recommendation [Schleter, 1967] to calibrate a highly-reflecting Vitrolite glass surface against a fresh MgO surface. The fresh MgO surface used was first calibrated to an absolute basis by means of published reflectance values for MgO [Sanders and Middleton, 1953]. The advantage of the Vitrolite as a standard is that it can be cleaned and is not subject to deterioration. In actual operation, the MgO surface was used in the reference port of the instrument. MgO has a greater reflectance than leaves. Vitrolite, over part of the spectral range, has a reflectance less than leaves. Use of the MgO standard instead of the Vitrolite permitted the reflectance response of the instrument to remain within the range of the recorder. The Vitrolite standard was measured on each spectrophotometric run, however, and absolute values of reflectance were calculated from ratios between the MgO, Vitrolite, and the Sanders-Middleton data.

Non-linear deviations in the reflectance and transmittance responses of the DK-2A were revealed by measuring these properties for glass plates piled to successive thicknesses 1, 2, 3, . . . N. Glass plates have been used previously [Benford, 1923] as spectrophotometric standards. The reflectance and transmittance of piled glass plates is a solvable problem in electromagnetic theory. A conventional method of checking the accuracy of an instrument is to take measurements on a material where the results are known exactly from theory. This method was used to calibrate the DK-2A.

The standard adopted was a pile of No. 1, 25 mm square cover glasses supplied commercially by the Corning Glass Works. The cover plates, with a nominal thickness between 0.13 mm and 0.16 mm, were composed of stirred glass. Measured indices of refraction at the wavelengths 0.4861, 0.5893, and 0.6563 μ were determined to be 1.5325, 1.5260, and 1.5231, respectively [Jolley, 1967]. These values are consistent with published values for crown glass [Smith, 1966]. The glass plates were measured in total reflectance and transmittance operational modes over the spectral range 0.5 - 2.5 μ with the DK-2A for piles consisting of 1, 2, 3, ..., N plates.

Residuals $\Delta R = R_o - R_c$ between observed and computed values of reflectance were fitted by a function of the form

$$\begin{aligned} R_o - R_c = a_0 R + a_1 R\lambda + a_2 R\lambda^2 + a_3 R\lambda^3 + \dots \\ + b_1 R^2 + b_2 R^3 + b_3 R^4 + \dots \\ + c_2 \lambda R^2 + c_3 \lambda R^3 + \dots \\ + d_3 \lambda^2 R^2 + \dots \end{aligned} \quad (1)$$

The form of Eq. (1) was selected to ensure that residuals vanish when R = 0. The observed values of reflectance R_o were corrected for the reflectance bias introduced by the MgO standard. The computed values R_c were obtained by application of the Kubelka-Munk theory [Kubelka and Munk, 1931] which happens to be exact for piled transparent plates. An expression similar to Eq. (1) was written to specify residuals $\Delta T = T_o - T_c$ between observed and computed values of transmittance.

It is possible to obtain good agreement between spectrophotometric results over all amplitudes and pertinent wavelengths by calculation of the appropriate coefficients in Eq. (1) and those of the similar equation that involves transmittance. Equation (1) for reflectance and the corresponding transmittance function were fitted by regression over the entire amplitude and spectral range 0.5 - 2.5 μ. The 20 coefficients obtained are stored in a computer where the non-linear corrections are made automatically to the data.

Data

Reflectance and transmittance measurements were obtained from two separate sources of vegetation. The first source consisted of three species of plants: corn, squash, and sorghum. Each of these species was subjected to five different treatments. Specifically, the plants were deprived of nitrogen, sulfur, potassium, and iron. A control plant was grown with no deficiencies. The plants were grown hydroponically in a greenhouse. The greenhouse data consisted of 6 to 12 replications. All plants were mature. Leaves were harvested randomly throughout the plant with prime consideration being given to whether the leaf would present a homogenous appearance over the measurement port of the DK-2A.

The second source of plant leaves came from plant species sampled under field conditions from test areas in the Lower Rio Grande Valley, Texas. The field plants involved 20 to 50 replications of sorghum, wheat, mature corn, cotton, sugar beets, potatoes, young corn, tomatoes, cabbage, and onions. Many of the field leaves were taken on dates that corresponded to NASA aircraft flights over the Weslaco test site. The bulk of the spectral information was obtained during 1968. A lesser number of leaves, collected primarily to fill gaps in the data, were acquired in 1969. All leaves were harvested from the third and fourth nodes down from the apex of the plants. The collection procedure was designed to acquire leaf material that would simulate the target of a remote sensor operating above the canopy under field conditions. Collected leaves were immediately wrapped in Saran* to minimize water loss.

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* Saran. Trade names are included for information only and do not constitute endorsement by the U. S. Department of Agriculture.

Reflectance and transmittance spectra were obtained within a few hours after the leaves were removed from the plants. All leaves were kept as nearly as possible in their natural condition until measured. Diffuse reflectance from the upper surface and transmittance were measured on each leaf. Prior experimental procedure involved stacking leaves to successive depths for both reflectance and transmittance measurements. The stacking procedure was instituted because leaves in a natural canopy stack roughly behind each other as the plant matures. It was determined, however, by statistical analysis that stacking leaves in a spectrophotometer was not necessary--equivalent information is available by replicating reflectance and transmittance measurements on single unstacked leaves. Both single leaf and stacking procedures were used interchangeably in this investigation.

Reflectance and transmittance spectra were recorded automatically on paper tape. Typical examples of the kind of data obtained are reproduced as Figure 1 published elsewhere [Myers and Allen, 1968].

Analysis

All reflectance and transmittance measurements of single plant leaves taken over the last two years have been analyzed and reduced to the Kubelka-Munk format [Kubelka and Munk 1931] in the manner discussed elsewhere [Allen and Richardson, 1968]. Error tracing and statistical procedures were utilized at each wavelength to specify the standard deviation of the determined parameters. Figures 1 and 2 include plots of the respective values k, s, and k/s for 50 mature cotton leaves taken during 1968. There appears to be no statistical difference in the wavelength interval 1.4 - 2.5 μ between the absorption curve of Figure 1 and that for pure liquid water [Penner and Goldstein, 1964]. Figure 3 is a plot that contains the same information as Figures 1 and 2. The lower line in Fig. 3 is the average absolute diffuse reflectance of the 50 single field cotton leaves. The upper line in Fig. 3 is a calculated quantity that represents the average reflectance of the 50 cotton leaves if stacked to an infinite depth. As stated previously [Myers and Allen, 1968], at least two curves are essential to specify the diffuse optical properties of a single leaf. The necessary information can be displayed in several equivalent representations, but the data set reproduced in Fig. 3 is probably the best. The two curves of Fig. 3 are both measurable quantities. Two such curves can never intersect and the two curves can always be reproduced without ambiguity on a single graph. Figures 4a, 4b, and 4c include all the greenhouse data discussed in this paper. The two points plotted at each wavelength represent standard deviations. Figures 5a, 5b, ..., 5i include the additional field data discussed. The value R_∞ of each plant leaf, illustrated by the upper curve in Fig. 4 and 5, was the plant attribute used in discrimination procedures dealing with plant species.

All analyses, including computer print-out graphs, were accomplished on a real-time basis. The reflectance and transmittance curves were recorded on paper tape by means of a SDS-I Spectrophotometer Data Recording System*. The raw data passed through minor editing procedures and was introduced into a computer by means of a remote time-sharing console. The data reproduced in Fig. 1 to 5 are reproductions of actual IBM sheets produced by the computer.

Discrimination Procedures

Effectiveness of two different pattern recognition techniques was investigatec The first criterion is referred to as the "Minimum Distance to the Mean" (MDM) [Fu and Cardillo, 1968]. The second criterion is called the "Statistical Pattern Recognition" method (SPR) [Fu and Cardillo, 1968; Rosenfield, 1962; Kashyap, 1968; Langrebe et al, 1968; Freeze, 1964]. The two pattern recognition techniques were investigated for discrimination reliability and amount of computer usage. Recognition criteria such as MDM schemes are relatively simple in construction and involve minimum computer usage. Statistical criteria such as SPR schemes are more complex in construction and involve greater computer usage. Effectiveness of these two recognition systems was determined by a measure of their percent recognition reliability and computer usage.

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* Datex Corporation,Monrovia, California. Trade names are included for information only and do not constitute endorsement by the U. S. Department of Agriculture.

Analysis of variance tests for R_∞ means were performed for species and treatment effects at 41 wavelengths (0.05 μ intervals) between 0.5 and 2.5 μ. Analysis of variance results were used to select wavelengths for use as optimum pattern recognition features in discrimination schemes.

Results

The data in Table I are based upon all leaf measurements for plant species discussed previously. Table I indicates that optimum discrimination features for the greenhouse data occur near the water absorption bands at 1.9 μ and 2.7 μ. These features, if real, would probably be obscured from aircraft or satellite by water vapor absorption in the atmosphere. Table I also illustrates that optimum features for recognition schemes exist for the field data at wavelengths 1.25 μ, 1.65 μ, and 2.20 μ. These wavelengths lie near the peak of the atmospheric windows and would be accessible to remote sensors above the atmosphere.

Large differences exist in the reflectance response among field species. Discrimination possibilities, therefore, are far more favorable for field reflectance data than for reflectance data obtained from greenhouse leaves.

Table II displays the reliability in terms of percent recognition for a MDM scheme using the greenhouse reflectance data. The relatively low recognition reliability is due in part to inadequate replication.

A second factor affecting the recognition results in Table II is that a characteristic reflectance exists for all typical greenhouse leaves [Gausman, et al. 1969]. Low light intensity in a controlled growth environment causes development of shade-type leaves which yield essentially the same reflectance for leaves of different species.

Selected combinations of field data were tested in an MDM scheme for percent recognition reliability as shown in Tables III and IV. The SPR systems have been shown to have good reliability [Fu and Cardillo, 1968; Kashyap, 1968; Langrebe et al., 1968]. Fifty to 100 observations are necessary for statistical approaches to pattern recognition in practical remote sensing applications. A good statistical representation of the data for fewer than 50 observations was not obtained as shown by the frequency distribution of 20 to 21 observations of onions, potatoes, and wheat in Fig. 6.

A determination was made for the number of formula steps necessary in the classification of an unknown observation by each scheme into one of four groups. The number of formula steps increased linearly for each system as new classification groups are added and therefore are equivalent in this respect. However, the number of formula steps has a non-linear dependence on the number of recognition features for the SPR system and a linear dependence on number of recognition features for the MDM system as illustrated in Fig. 6. For a recognition scheme with 5 features a total of 244 formula steps would be necessary using the SPR scheme. For the MDM scheme a total of 60 formula steps are necessary. This is a ratio of about 4:1 in favor of the MDM scheme. Table V lists the formula steps of SPR and MDM schemes for 1 to 10 recognition features.

Conclusions

Useful spectral signatures in the range 0.5 - 2.5 μ were obtained for species of vegetation grown in the field. Leaves grown in a greenhouse and subjected to different nutritional deficiency treatments could not be discriminated by means of reflectance. Leaves of different plant species grown in a greenhouse were discriminated only marginally.

As discussed elsewhere [Gausman, Allen, Cardenas, 1969] the principal information available in leaf reflectance in the near-infrared is the extent to which the water in the leaf has been subdivided by the cellular structure of the leaf. Leaves grown in a greenhouse tend to have the same size cellular structure and, consequently, produce the same reflectance irrespective of treatments and species. Leaves grown under natural conditions have a greater variation in size of cellular structure and, therefore, yield a wider variation in reflectance.

Discrimination schemes are available to classify common vegetation using reflectance as a spectral signature. Relatively simple approaches to the pattern recognition problem are adequate in agricultural applications. Reliability of MDM (Minimum Distance to the Mean) systems appear to be equivalent to SPR (Statistical Pattern Recognition) systems when sufficient data have been obtained.

MDM schemes involve fewer formula steps than SPR schemes. As recognition features are added to increase recognition reliability, the ratio of SPR to MDM formula steps increases in a non-linear manner in favor of the MDM scheme. This means that MDM schemes involve less computer time than SPR systems by the same ratio.

Leaves of a large number of agricultural plants grown in the field were easily discriminated by reflectance characteristics measured at wavelengths that peak within the atmospheric windows. Reflectance measurements in these regions can be obtained from aircraft and spacecraft because the signal would not be obscured by water vapor absorption.

Acknowledgments

The authors acknowledge the advice and unfailing cooperation received from Harold W. Gausman and Craig L. Wiegand.

Table 1. Statistical significance between means of R_∞ for various greenhouse-grown and field-grown leaves at selected wavelengths. Greenhouse-grown species were corn, squash, and sorghum. Field-grown species were sorghum, wheat, mature corn, cotton, sugar beets, potatoes, young corn, tomatoes, cabbage, and onions.

Greenhouse		Field	
Wavelength (μ)	F-Ratio	Wavelength (μ)	F-Ratio
2.50	10.87**	2.20	137.18**
2.45	7.01*	2.15	132.24**
2.40	6.08*	1.80	181.26**
2.00	7.31*	1.75	181.52**
1.95	15.20**	1.70	186.47**
1.90	5.76*	1.65	193.97**
1.30	1.75	1.60	182.39**
1.25	1.85	1.30	134.72**
1.10	2.46	1.25	102.16**
1.05	0.98	1.20	101.38**

* Significant at the 5% level of probability.

** Significant at the 1% level of probability.

Table II. Percent correct recognition using R_∞ for greenhouse-grown corn (C), squash (Sq), and sorghum (So) using wavelengths 2.50, 2.45, 2.40, 2.00, 1.95, and 1.90 μ.

Vegetation	Total number of observations	Samples classified into C	Sq	So	Percent recognition
Corn	10	6	2	2	60.00
Squash	6	1	5	0	83.00
Sorghum	12	4	0	8	67.00
	Overall percent recognition				67.90

Table III. Percent correct recognition using R_∞ for field-grown potatoes (P), onions (O), and wheat (W) using wavelengths 2.20, 2.15, 1.80, 1.75, 1.70, 1.65, 1.60, 1.30, 1.25, and 1.20 μ.

Vegetation	Total number of observations	Samples classified into W	P	O	Percent recognition
Wheat	21	21	0	0	100.00
Potatoes	20	0	20	0	100.00
Onions	20	0	0	20	100.00
	Overall percent recognition				100.00

Table IV. Percent correct recognition using R_∞ for field-grown wheat (W), cotton (Co), potatoes (P), cabbage (Ca), and onions (O) using wavelengths 2.20, 2.15, 1.80, 1.75, 1.70, 1.65, 1.60, 1.30, 1.25, and 1.20 µ.

Vegetation	Total number of observations	Samples classified into W	Co	P	Ca	O	Percent recognition
Wheat	21	21	0	0	0	0	100.00
Cotton	50	1	45	4	0	0	90.00
Potatoes	20	0	2	14	4	0	70.00
Cabbage	20	0	1	3	13	3	65.00
Onions	20	0	0	0	1	19	95.00
	Overall percent recognition						85.49

Table V. Comparison of total number of formula steps for SPR and MDM schemes based on the classification of an unknown observation into one of four known groups.

Number of Recognition Features	Total Number of Formula Steps		Ratio
	SPR	MDM	SPR : MDM
1	16	12	1.333
2	52	24	2.166
3	100	36	2.777
4	164	48	3.416
5	244	60	4.066
6	340	72	4.722
7	460	84	5.476
8	588	96	6.125
9	712	108	6.592
10	872	120	7.266

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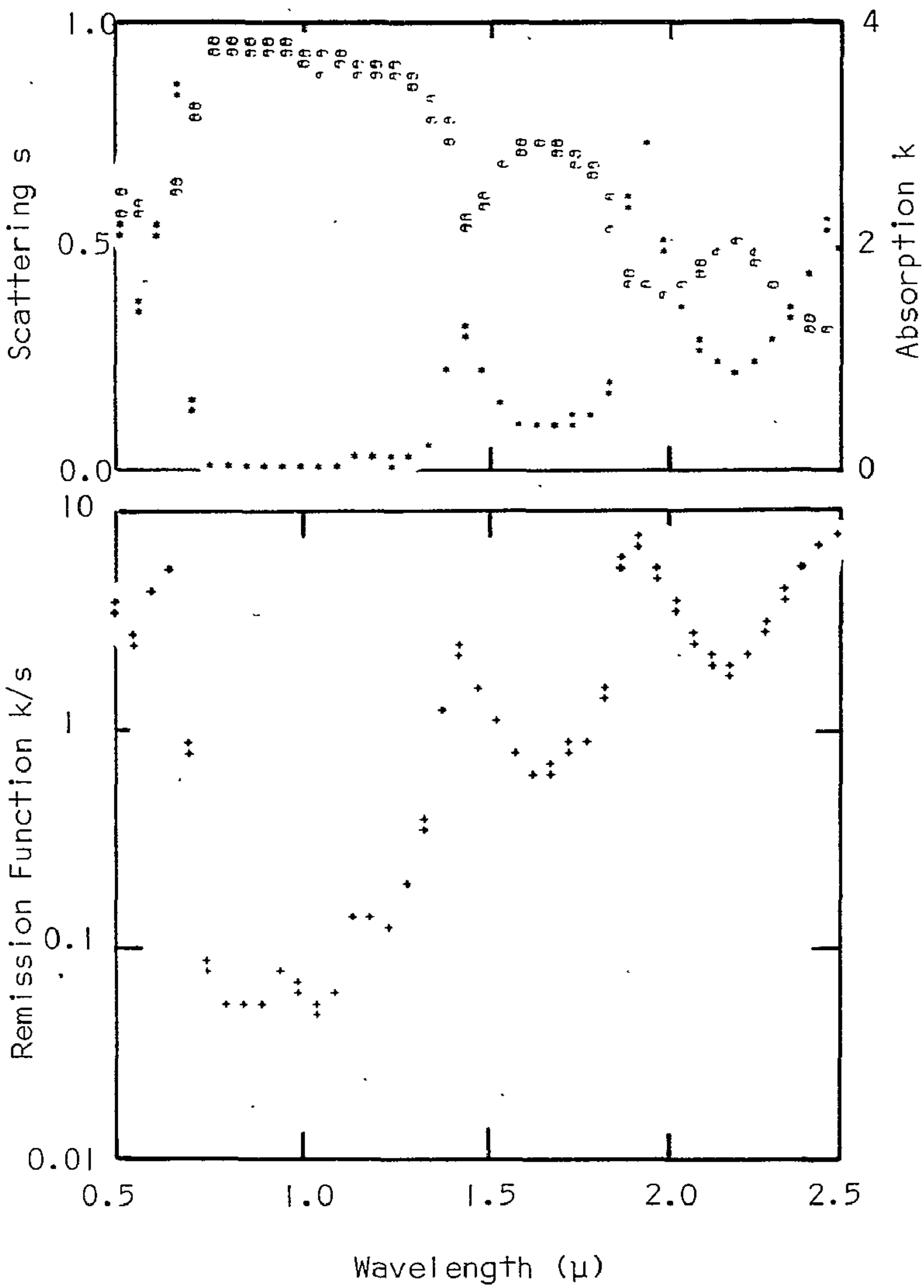

Figure 1. Computer print-out of average scattering θ and absorption * curves for 50 replicated mature field cotton leaves. Data is based upon 200 separate spectrophotometric runs. Confidence bands are plotted in this figure, and in all subsequent figures, based upon ± one standard deviation. These data, and all subsequent data, have been truncated to next lower line of printer.

Figure 2. Average remission function + curve for 50 replicated mature cotton leaves.

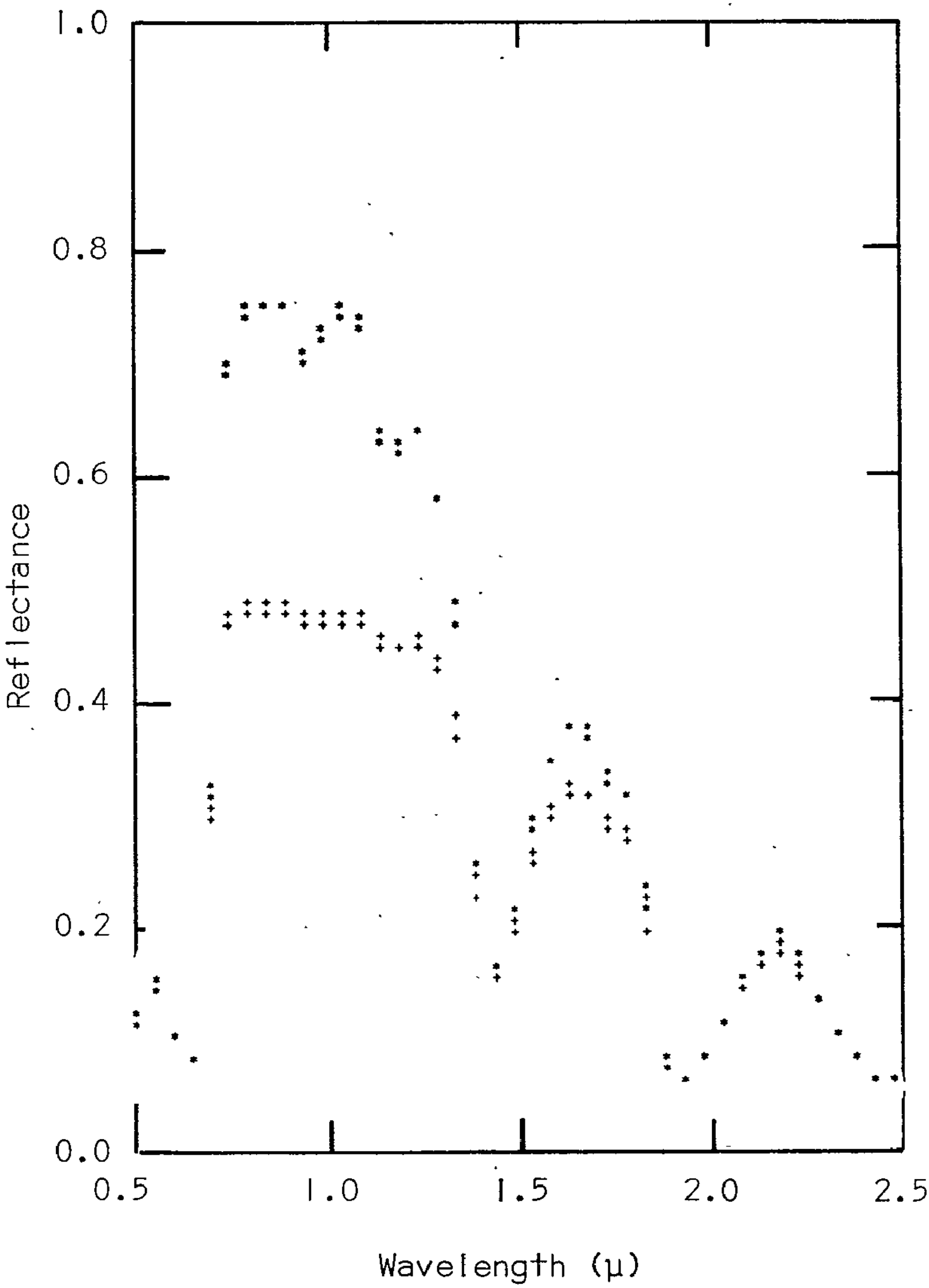

Figure 3. The lower curve + is the average diffuse reflectance of 50 single cotton leaves. The upper curve * is the average calculated infinite reflectance R_∞ for these leaves.

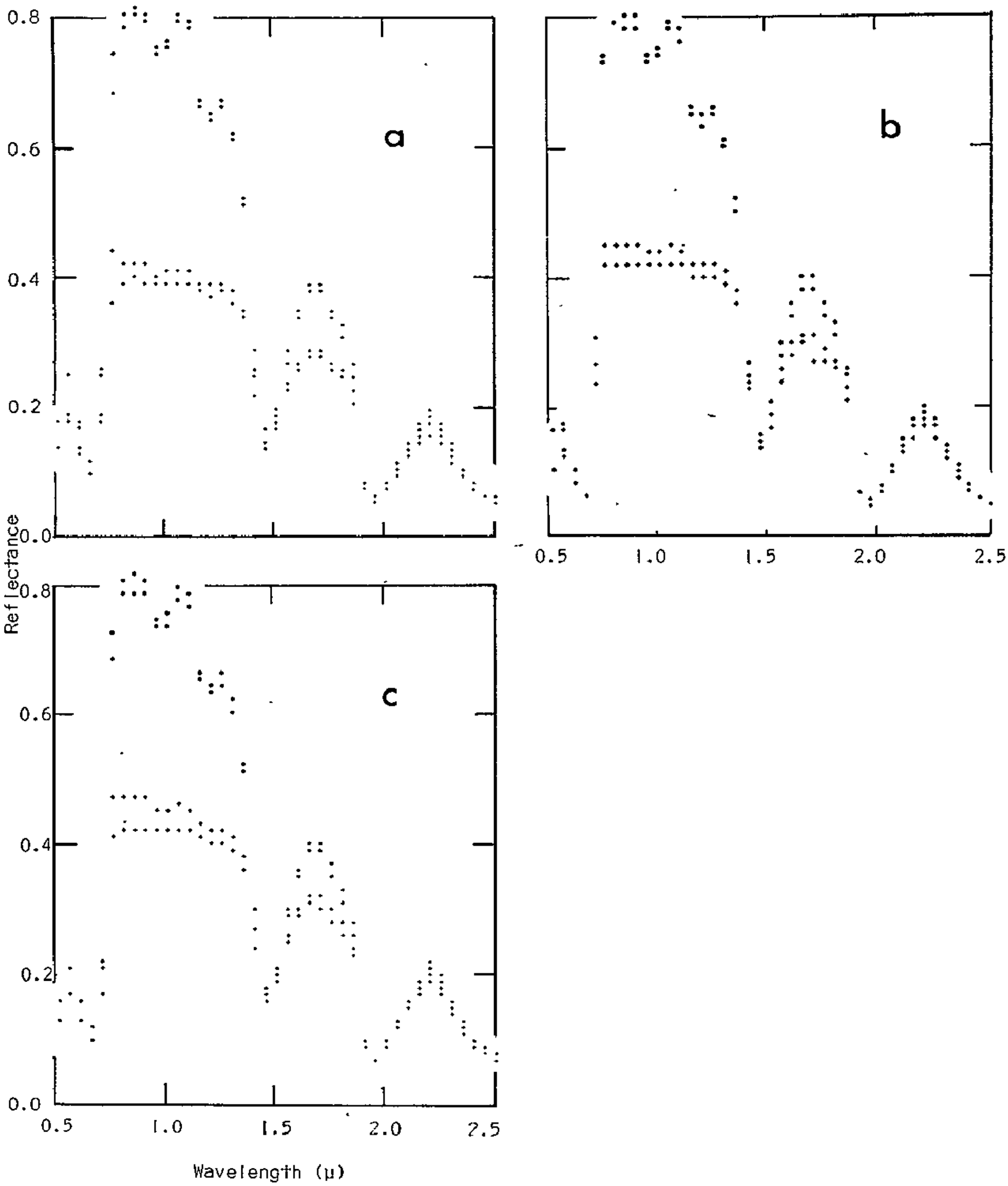

Figure 4. The lower curve + is the average diffuse reflectance of single greenhouse-grown leaves: a) corn; b) squash; and c) sorghum. The upper curve * is the average calculated reflectance R_∞ for these leaves.

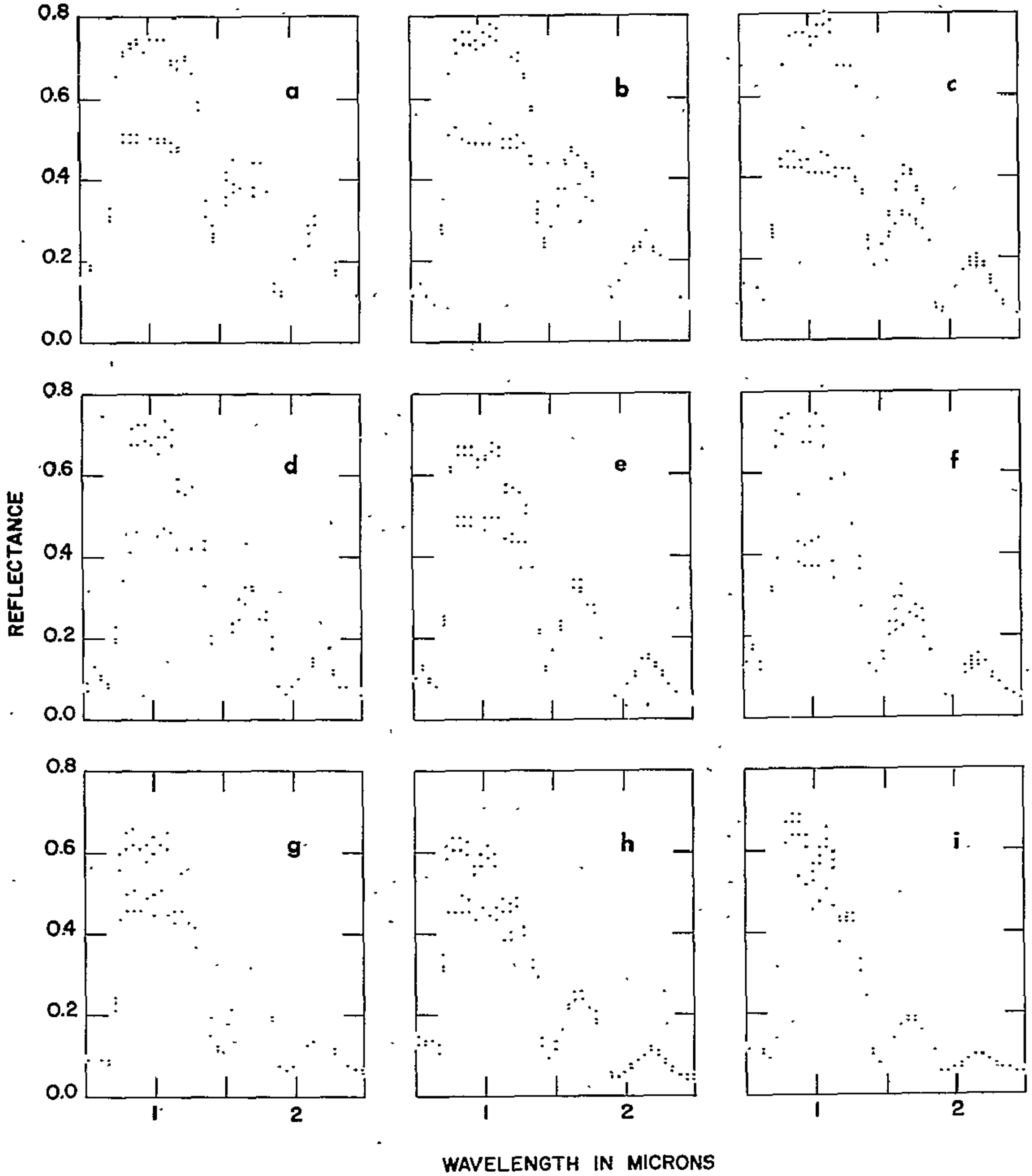

Figure 5. The lower curve + is the average absolute diffuse reflectance of single field-grown leaves: a) sorghum; b) wheat; c) mature corn; d) sugar beets; e) potatoes; f) young corn; g) tomatoes; h) cabbage; and i) onions. The upper curve * is the average calculated infinite reflectance R_∞ for these leaves.

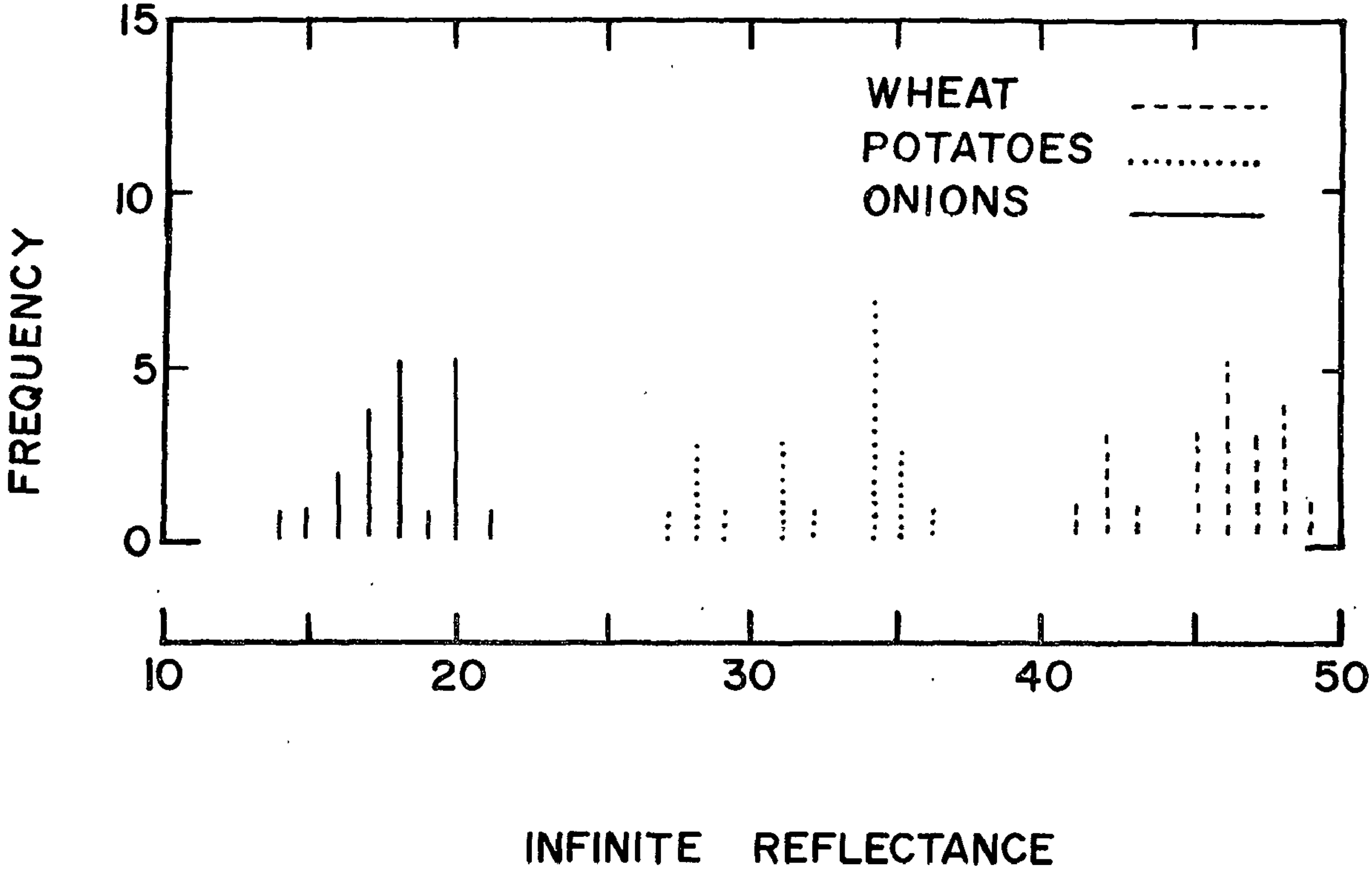

Figure 6. Frequency distribution of three kinds of leaves.

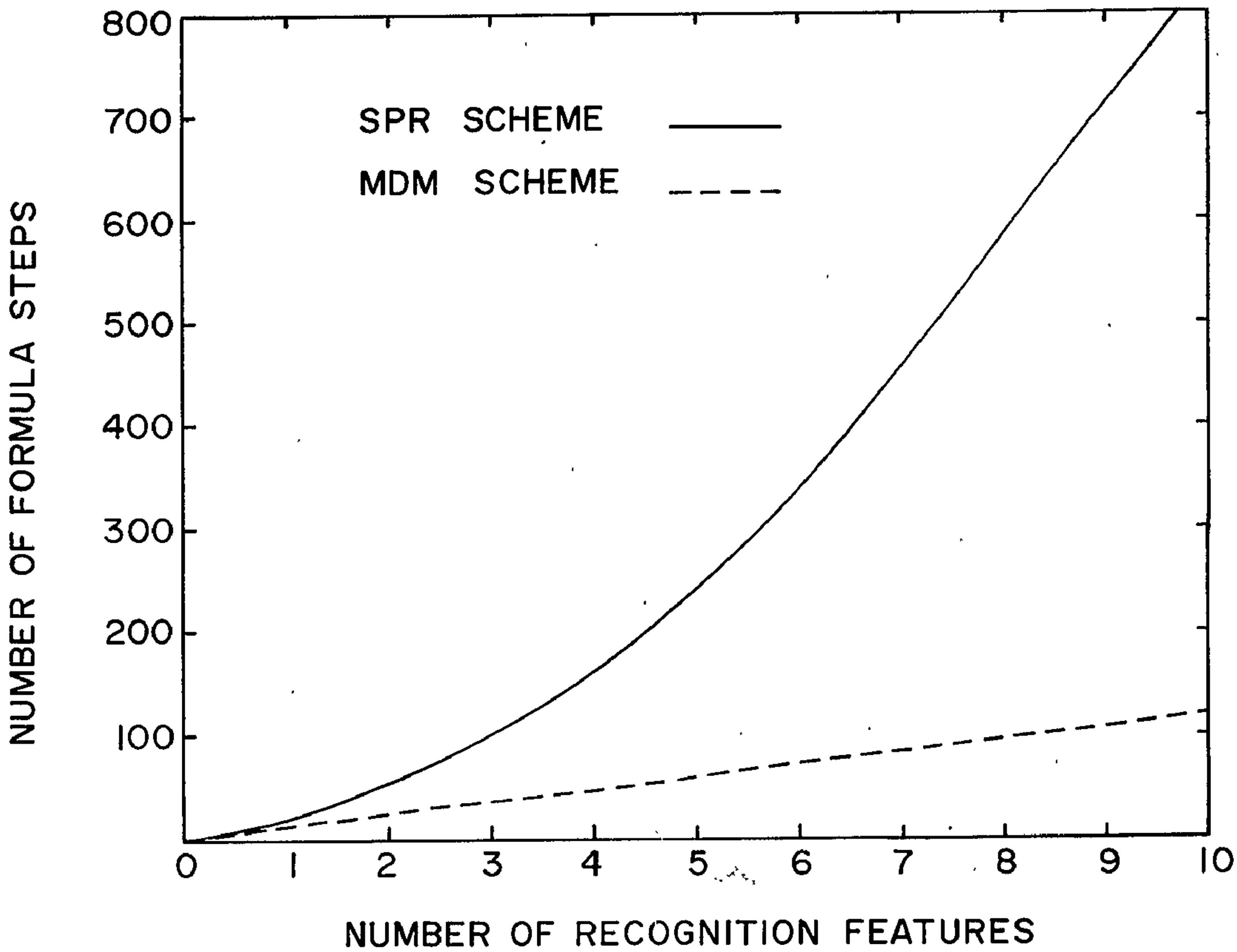

Figure 7. Comparison of computer usage for SPR and MDM schemes. Based on number of formula calculations needed to classify one unknown observation into one of four known groups.

Crop Species and Soil Condition Discrimination from Apollo 9 imagery

C. L. Wiegand, R. W. Leamer, and A. H. Gerbermann

Introduction:

About 95% of the land mass of the United States is occupied by farmland, forests, and rangelands. Therefore, there is very much of agricultural interest included in space imagery of the United States. Space imagery of sufficient resolution should be extremely valuable for surveying and inventorying these resources.

There are more specific studies which can be undertaken from such imagery as well: studying flow production of whole drainage basins; relating sediment yield in run-off waters to the land cover conditions (vegetation density, percent of area occupied by bare fields); mapping soil associations, geographic crop distribution, and areas of low productivity; and, relating size of fields with type of farming and amounts of farm machinery needed for various enterprises--to name a few.

The science screening view of the Apollo 9 imagery indicated that the quality of the space imagery was sufficient to investigate the multispectral quality of individual fields as affected by crop cover and growing conditions.

Objective:

Attempt identification of crop species and soil condition from film optical density differences where ground truth of fields was available.

Methods and Procedures:

Immediately following the science screening session for Apollo 9, duplicate 70-mm transparencies of each of the four wavelength images for frame No. AS-9-26A-3799, Imperial Valley, Salton Sea, Mexicali, were requested from NASA, Houston.

Miss Norma Spansail and Dr. Don Lowe of the University of Michigan were contacted since the University of Michigan plane overflew the Imperial Valley and obtained photographic and optical mechanical scanner data. They also provided a copy of the ground truth (Spansail, et al., 1969) for line 15A, Dogwood Road, as well as a print of the scanner imagery simulating type 3400 film (Panatomic X) with 25A filter. Line 15A was 10.5 miles long and the Michigan scanner which flew at 10,000 feet sensed 1-3/4 miles on each side of Dogwood Road. The ground truth data furnished by Michigan listed 303 fields within this area. On the 70-mm transparency taken from space the 35 square miles along this flight line occupies an area 2-mm wide and 6-mm long.

In order to study the Imperial Valley flight line more intensively, an isodensitracing was prepared of the 1:2,000,000 scale, 2 mm x 6 mm section covering line 15A in the duplicate 70-mm Ektachrome IR transparency. The scene was enlarged 100-fold. A red transmission filter was used in the approximately 12-micron diameter light beam of the microdensitometer to accent the film density difference between cropped areas, which develop red tones on Ektachrome IR film and hence have low optical density to red light, from noncropped areas characterized by blue tones. This produced a facsimile image of the target scene to the same scale as the Michigan imagery (1:30,000). Both the University of Michigan imagery and the isodensitracing with fields located and enumerated are shown in Figure 1.

Over the area of the isodensitracing at the points indicated in Figure 1, 18 microdensitometer scan lines, corresponding to 18 transects of the flight line, were chosen for quantification. These 18 lines were retraced without a filter in the light beam and with blue, green, and red filters, respectively, in the light beam. The optical counts (related to optical density by the relation, (optical count - 30) (.0111) +.39 = optical density) were recorded on punched paper tape simultaneously with their tracing. The paper tape optical counts per scan line were listed by Flexowriter, matched to the corresponding fields, and the average optical count was determined. Taking the ground truth data into account in sorting the fields into crop species and soil condition categories that were sufficiently replicated, 50 useable fields resulted. Among the 50 fields there were 9 sugar beet, 10 alfalfa, 11 bare soil, 9 barley, and 11 salt flat fields represented.

The analysis procedure used was the following: The arithmetic mean of the optical count for each filter was used as the representative or standard signature for that field condition. The data were entered into a computer where the mean optical counts were converted to optical densities. Every possible optical density difference among the various filters was obtained for the standard signature. Optical density differences corresponding to the following filters were taken: red-green, red-blue, red-no filter, green-blue, green-no filter, and blue-no filter. Algebraic signs of the differences are honored.

The deviation from each standard signature for every filter combination optical density difference of each individual field was taken, squared, and accumulated. The computer then identified the individual field in question into the crop or field condition category which it most closely resembled. Each field was identified as belonging to that category from which its signature deviated minimally. Therefore, every field was unambiguously assigned an identification. This minimum distance to the standard signature computer procedure was developed by Dr. Leamer.

Results and discussion

The crop and soil condition categories investigated from the Ektachrome IR transparency of the Imperial Valley were sugar beets (SB), alfalfa (A), bare soil (BS), barley (B), and salt flat (SFT). Table I identifies each field by number and crop species or soil condition category, lists the sums of squares of deviations of each field's optical density from the crop or condition standard, presents the computer identification of each field based on its minimum deviation from the standard (the arithmetic mean optical density for all fields in the category was used as the standard), and states the ground truth for each test field. The ground truth data show that there is considerable variation in plant height of each crop. Crop height does not appear to be very closely related to proper identification. For example,

Table I.--Crop and soil condition categories, sums of squares of deviations of each field's optical density from the crop and soil condition category standard, computer identifications, and ground truth of each field studied to evaluate identification of Imperial Valley fields on Ektachrome IR space photography.

Crop	Field No.	Sums of squares of deviations of each field's optical density from crop standards; SB	A	B or BS	SFT	Computer identification	Plant ht. inches	% grd. cover	Other comments
Sugar beet, SB	59	.04	.02	.01	.27	B or BS	10-12	95	Yellow mottling
	62	.07	.03	.00	.18	B or BS	6-8	80	
	66	.00	.02	.07	.46	SB	12-18	80	Recently irrigated
	291	.00	.02	.06	.45	SB	15-18	70	
	292	.13	.21	.37	1.03	SB	8-15	70	
	268	.00	.02	.08	.50	SB	15-18	90	Yellow mottling
	248	.01	.02	.08	.47	SB	10-12	80	
	262	.03	.02	.02	.29	B or BS	15-18	80-90	Double rows
	245	.04	.11	.22	.78	SB	18-20	95	
Alfalfa, A	50	.01	.06	.14	.62	SB	10-12	80	
	58	.02	.01	.02	.29	A	6-8	95	Some rye
	288	.01	.05	.13	.61	SB	6-8	95	Pastured
	293	.02	.00	.01	.28	A	3	80-90	Pastured
	160	.29	.17	.09	.04	SFT	2-4	80	Weedy
	65	.13	.20	.35	.98	SB	2-6	80	Recently cut & irrigated
	50	.18	.28	.46	1.17	SB	10-12	80	
	42	.48	.34	.19	.00	SFT	10-12	70	
	14	.01	.00	.04	.35	A	10-12	100	
	15	.29	.17	.08	.02	SFT	10-12	100	
Bare soil, BS	5	.01	.04	.12	.57	SB	Bedded EW for cotton		
	7	.04	.10	.15	.63	SB	do		
	8	.04	.10	.15	.63	SB	do		
	21	.01	.03	.06	.43	SB	Bedded NS for cotton		
	41	.41	.27	.15	.00	SFT	do		
	44	.56	.41	.25	.04	SFT	Bedded EW for cotton		
	45	.13	.06	.05	.17	B or BS	Bedded NS for cotton		
	222	.40	.26	.14	.00	SFT	Bedded EW for cotton		
	230	.36	.23	.12	.01	SFT	Bedded NS; scattered wh salt deposits		
	258	.01	.04	.11	.55	SB	Recently plowed		
	269	.03	.08	.18	.71	SB	Bedded NS for cotton		

Table I. (Cont'd.)

Barley, B	12	.08	.16	.29	.91	SB	18-24	95	
	60	.00	.02	.06	.44	SB	12-16	95	
	119	.01	.02	.08	.47	SB	18-24	60	
	227	.57	.41	.25	.01	SFT	5-8	90	
	143	.12	.05	.01	.11	B or BS	6-8	40	
	285	.20	.11	.03	.06	B or BS	15-18	100	
	279	.38	.26	.13	.01	SFT	18-22	100	
	249	.03	.01	.01	.27	A	10-12	95	
	243	.50	.36	.20	.02	SFT	20-28	100	
Salt flat, SFT	98	.28	.17	.08	.03	SFT	No vegetation		
	101	.29	.17	.09	.04	SFT	Sparse natural vegetation		
	106	.25	.14	.07	.04	SFT	do		
	108	.54	.37	.23	.01	SFT			
	124	.59	.43	.27	.02	SFT			
	125	.41	.27	.15	.00	SFT			
	126	.74	.56	.36	.04	SFT			
	127	.84	.64	.44	.06	SFT			
	128	.32	.20	.10	.01	SFT			
	158	.67	.49	.31	.02	SFT			
	159	.36	.23	.12	.01	SFT	Sparse natural vegetation		

of the alfalfa fields properly identified, ground truth plant height was 3 inches for one, 6 to 8 inches for the second, and 10 to 12 for the third.

Percent ground cover of row crops is usually overestimated by a ground observer, in our experience. It is difficult to visualize as similar ground cover percentages as listed in Table I for a crop varying as much in height as the sugar beets do; percent ground cover should increase as plant height increases.

The sums of squares of the deviations of each field's optical densities from the crop standards is notably small. Whereas the optical densities themselves ranged from .323 to 1.256 most of them were in the middle range. Therefore, optical density differences were mostly about 0.2, and sums of squares were necessarily small.

Table 2 is a summary of the identifications, misidentifications, and percentage identifications of the various crop and soil condition categories. The results show that all 11 salt flats were properly identified, that 6 of 9 sugar beet fields were properly identified, that 7 of 10 alfalfa fields were misidentified and that only 3 of 20 bare or barley fields were correctly identified. The overall percentage of correct identifications is 54%.

Bare soil and barley fields were combined into one category because after scanning the optical densities it appeared they were similar.

Table 4 contains the mean optical density, the standard error of the mean optical density, and the coefficient of variation of each crop or soil condition category for each filter. In Table 3 the above information for bare soil and barley is presented both separately and combined.

Table 2--Summary of crop or soil condition, identity of misidentifications, and percent identification.

Crop	No. of fields	No. misiden-tified	Misidentifications identified as follows:	% Correct identification
Sugar beet	9	3	All as bare-or-barley	67
Alfalfa	10	7	Four as sugar beets; three as salt flats	30
Bare or barley	20	17	Nine as sugar beets; seven as salt flats; one as alfalfa	15
Salt flats	11	0		100
Total	50	23	Overall percentage	54

Table 3.--The mean optical density, the standard error of the mean, and the coefficient of variation of optical density of the Ektachrome IR transparency of the Imperial Valley for each of the filters used in the light beam of the microdensitometer.

Crop	No. of fields	Filter	Mean optical density	Standard error of the mean	Coefficient of variation
					%
Sugar beets	9	None	0.8463	0.0165	1.95
		Red	.5540	.0230	4.15
		Green	1.0165	.0162	1.59
		Blue	.8019	.0324	4.04
Alfalfa	10	None	.8917	.0580	6.50
		Red	.6742	.0546	8.10
		Green	1.0549	.0650	6.16
		Blue	.8651	.0697	8.05
Bare soil	11	None	.9238	.0450	4.87
		Red	.7371	.0469	6.36
		Green	1.0772	.0456	4.23
		Blue	.8421	.0466	5.53
Barley	9	None	.8574	.0356	4.15
		Red	.7255	.0397	5.47
		Green	1.0153	.0399	3.93
		Blue	.7834	.0498	6.36
Salt flat	11	None	.5817	.0545	9.37
		Red	.6423	.0782	12.17
		Green	.7058	.0608	8.61
		Blue	.4808	.0485	10.09
Bare soil and barley combined	20	None	.8939	.0297	3.32
		Red	.7319	.0306	4.18
		Green	1.0493	.0308	2.94
		Blue	.8157	.0338	4.14

A survey of the information in Table 3 shows that the salt flats had a much lower optical density for three of the four filters than the other cover conditions. Therefore, even though the coefficient of variation was larger than for any of the other cover conditions, there was no ambiguity in their identification.

Sugar beets have a distinctively low optical density for the red filter in agreement with their bright red appearance on the space imagery. They also have very low variability in optical density with the green filter and no filter in the light beam (1.59% and 1.95%, respectively).

On the other hand the optical densities of the alfalfa, bare soil, and barley fields are nondistinctive for any color filter used in this study. The coefficients of variation are moderate.

Table 4 is a listing of the simple correlation coefficient matrices for optical densities among the various filters. It is evident that there is a high correlation between the no filter and the green filter optical densities and between the green and the blue filter optical densities.

The high correlation between the optical densities with a green filter in the light beam and no filter in it suggests that the green filter readings might be deleted. The analysis was repeated with the green filter readings left out. The crop and soil condition discrimination decisions were identical with those obtained with the green filter optical densities in the procedure. Since deletion of one filter decreases the number of optical density differences by half it also halves the computer time required for comparison of unknowns against the standards.

Table 4.--Simple correlation coefficients of Ektachrome IR film optical densities among the filters used in the light beam for each crop and soil condition category.

Crop	Filter	None	Red	Green	Blue
Sugar beet	None	1.000			
	Red	-.062	1.000		
	Green	.955	-.065	1.000	
	Blue	.897	-.328	.880	1.000
Alfalfa	None	1.000			
	Red	.469	1.000		
	Green	.995	.437	1.000	
	Blue	.964	.267	.962	1.000
Bare soil	None	1.000			
	Red	.104	1.000		
	Green	.941	.064	1.000	
	Blue	.851	-.001	.964	1.000
Barley	None	1.000			
	Red	-.318	1.000		
	Green	.995	-.304	1.000	
	Blue	.966	-.492	.950	1.000
Salt flat	None	1.000			
	Red	.994	1.000		
	Green	.997	.992	1.000	
	Blue	.985	.975	.986	1.000

In judging the usefulness of the approach used in this report it is well to look at Figure 2. The left half, printed directly from the space photograph, shows a 2 mm x 6 mm area from the 70-mm space image enlarged 25 times. An image is also produced which was obtained by enlarging 1.5 times the mosaicked 35-mm photomicrographs (40X enlargement) of the 70 mm transparency. The photomicrographs were obtained using Kodachrome X, 35 mm film and a blue filter in a Zeiss Standard Universal Photomicroscope. In the photomicrographs the film grain is clearly evident.

The area chosen for the study was cut up by the Rose Canal, the Southern Pacific Railroad, and in addition, many of the fields are salt affected. Since the fields are not uniform, it was difficult to truly represent the fields in the ground truth and microdensitometer data obtained.

A severe limitation is also put on the photographic analysis approach by the narrow wavelength interval available for exploitation. Table 5 presents the single leaf reflectance and infinite reflectance (R_∞) data for nine different species at the wavelengths of peak [or plateau] response of Ektachrome IR film. Both the single leaf and infinite reflectance data are unpublished absolute radiometric data furnished by A. J. Richardson and W. A. Allen of the Remote Sensing Investigations Group at Weslaco. Infinite reflectance is a theoretical quantity typifying the maximum reflectance each species would have at an extremely dense leaf canopy (Allen and Richardson, 1968). The signature of a crop from space would range from a negligible response superimposed upon the soil background up to the infinite reflectance maximum depending upon maturity of the crop.

The data of Table 5 show that the reflectance from a horizontal layer of unstacked leaves is very close to the infinite reflectance at both the 550 and 650 nanometer wavelengths. This means that as long as the plants just obscure the soil, the density of the plant canopy makes no difference in the signature of a given species recorded on the green and red layers of the Ektachrome infrared film. In the infrared, however, six to eight leaf layers are required to give the signature corresponding to the infinite reflectance so that differences in plant size, density, and vigor, and hence number of leaf layers, do affect the signature recorded on the emulsion sensitive to the 700 to 900 nanometer wavelength. Thus, on Ektachrome infrared film we are dealing with weak signals in the green and red wavelengths and a strong signal in the infrared. Strong exposure of the cyan producing infrared sensitive layer results in light tones for this layer which allows the red color produced by combination of the yellow and magenta of the other two layers to predominate (Gausman et al., 1970).

It is very likely that the variability in ground cover and height of the plants in the test fields of this study exceeded the differences among species. Geometrical differences in plant height and row direction could have introduced additional nonuniformity within species. Row direction effects could not be discerned in the discrimination results of Table I, however.

Results of Richardson and Thomas (1969) show that the photographic wavelengths are not very useful for species differentiation. Within the wavelength interval 500 to 2500 nanometers, wavelengths between 1.3 and 2.4 microns are most useful. Information in this region, however, bears primarily on plant cell size and secondarily on species (Gausman et al., 1969).

Table 5.--Single leaf and infinite reflectance (R_∞) of nine crop species at the wavelengths of peak [or plateau] response of each of the emulsion layers in Ektachrome Aero Infrared film.

Crop	Single leaf reflectance, %			Infinite reflectance, %		
	Wavelength, nanometers			Wavelength, nanometers		
	550	650	800	550	650	800
Sugar beet	12.2	7.4	42.5	12.3	7.4	67.6
Alfalfa	10.4	9.0	45.2	10.5	9.0	53.5
Corn	15.0	8.4	41.9	15.3	8.4	73.0
Cotton	14.3	7.7	47.6	14.5	7.7	73.2
Potatoes	11.4	7.3	47.2	11.5	7.3	63.9
Tomatoes	11.4	7.4	46.3	11.4	7.4	61.1
Sorghum	18.1	11.4	48.7	18.2	11.4	69.1
Purple cabbage	14.5	13.0	48.3	14.5	13.0	62.5
Onion	13.6	7.9	58.5	13.7	7.9	64.4

Summary

Ground truth from flight line 15A of the Imperial Valley was used to test the ability of Ektachrome infrared film type SO 180 to discriminate crop species or soil condition categories on SO-65 experiment 70 mm space photography. The flight line consisting of 303 fields occupied 12 mm^2 on the image. The optical density of the 9 sugar beet, 10 alfalfa, 11 bare soil, 9 barley, and 11 salt flat fields selected for study was determined on a microdensitometer utilizing no filter, and red, green, and blue filters in the approximately 12 micron diameter light beam. The standard signature for each category was taken as the mean optical density of all fields in the category. The cumulative sum of squares of all optical density difference combinations for each field was compared with the same quantity for each category; each field was assigned an identification corresponding to the standard from which it deviated minimally.

The procedure correctly identified all 11 of the salt flats and 6 of the 9 sugar beet fields. The alfalfa, barley, and bare fields could not be properly identified; 200 X photomicrographs of the imagery reveal inhomogeneity in signatures of some fields. The overall percentage correct identification was 56%.

It is concluded that the signatures of crop species at the photographic scale worked with are insufficiently different at the photographic wavelengths to have good discrimination capability using optical density differences. Absolute reflectance data which substantiate the conclusion are presented for 9 crop species for the wavelengths 550, 650, and 800 nanometers corresponding to the wavelengths of peak response of the 3 Ektachrome infrared film dye layers.

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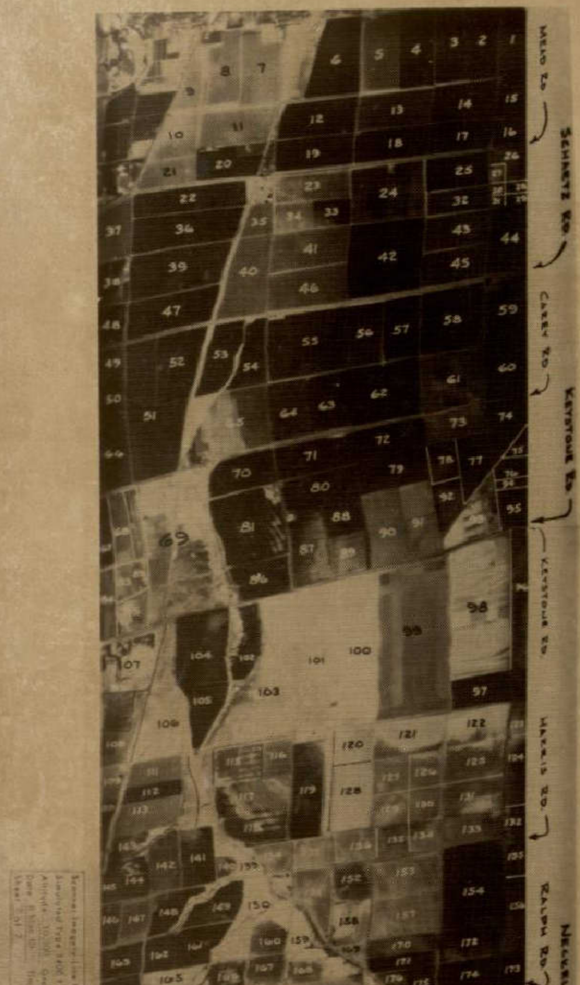
Spansail, Norma et al. Imperial Valley Ground Truth for Apollo 9 Overflight of March 1969. U. of Mich., Inst. Sci. & Tech., Report No. 2264-7-X, May 1969.



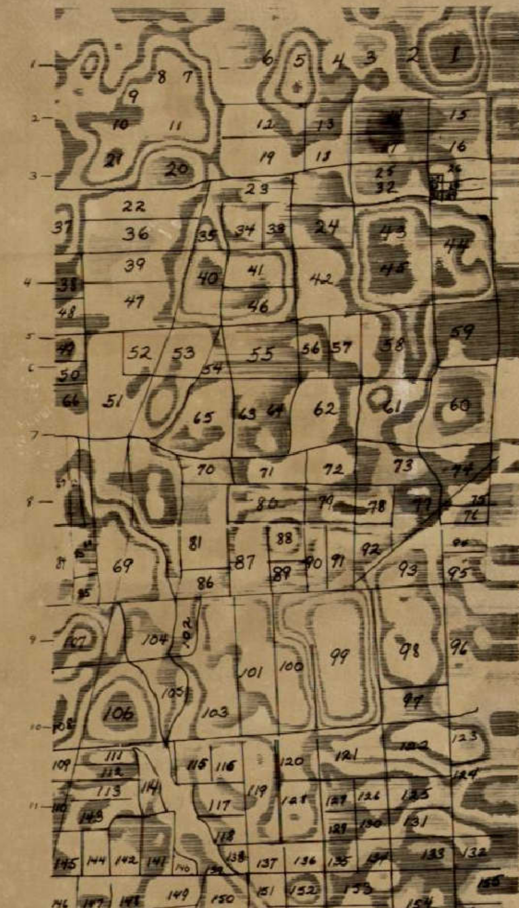


Figure 1.--University of Michigan optical mechanical scanner imagery simulating Panatomic X film with 25A filter obtained of Imperial Valley flight line 15A from 10,000 feet, and a 100-fold enlargement isodensitracing of the same flight line prepared from the space photo of the Imperial Valley. Scale of the space photograph was 1:2,000,000; flight line 15A represents an area 2 mm by 6 mm on the space photograph. Numbers on the images are field designations (see detailed ground truth, Appendix I). Scale of both Michigan imagery and isodensitracing is 1:30,000.

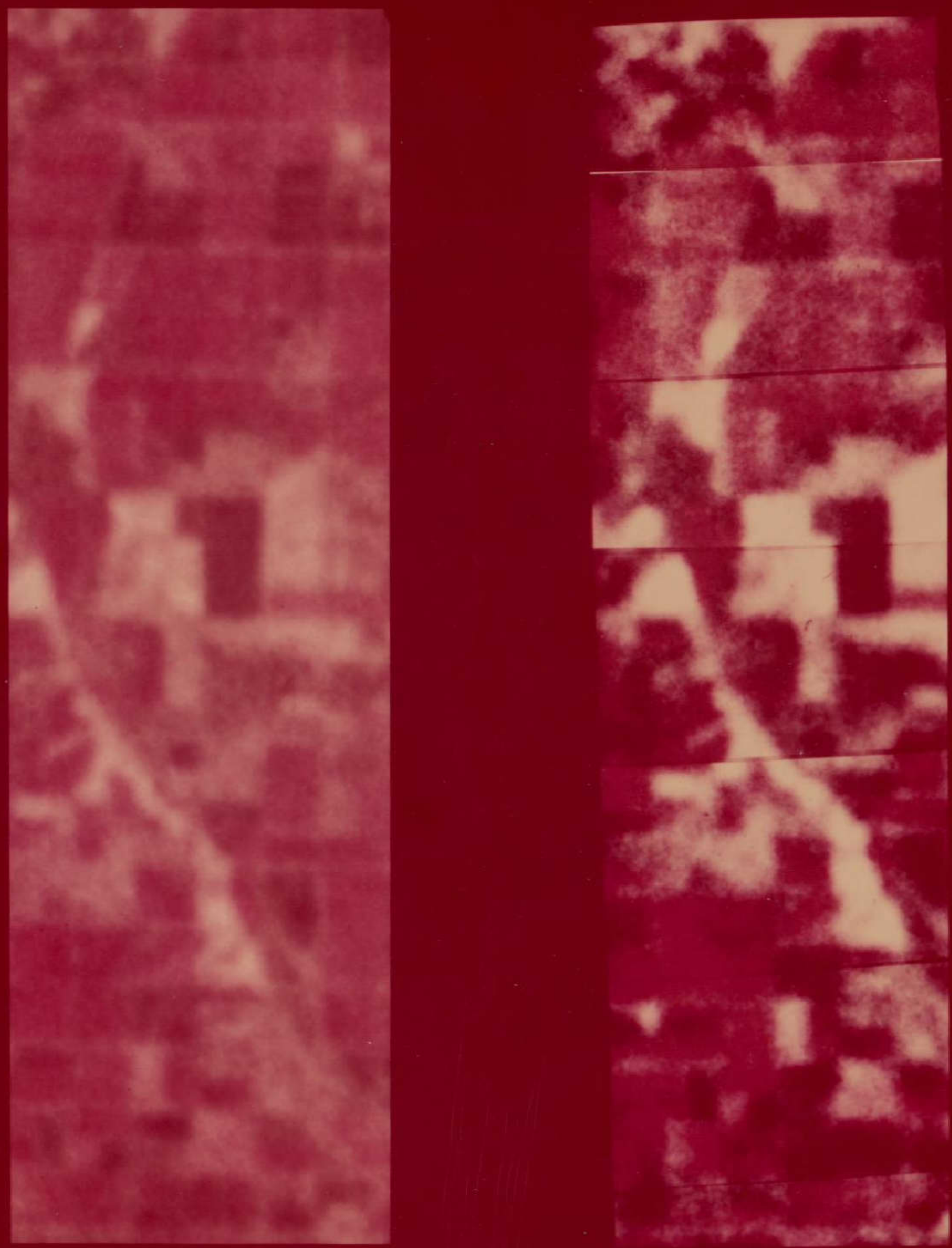


Figure 2.--Flight line 15A of the Imperial Valley from the 70 mm space image enlarged 25 times printed directly from the space photograph (left) and a composite of photomicrography (40X enlargement) obtained using 35 mm Kodachrome X and blue filter enlarged 1.5 times (right). The red tones indicate vegetation, the blue tones noncropped soil, and the white tones are salt-affected soil. Note that the film grain is apparent in the images and that the photomicrographs do not extend as far to the right as the left image does. See Figure 1 for field numbers and Appendix I for ground truth.

COTTON, SORGHUM, AND BARE SOIL DISCRIMINATION ON EKTACHROME INFRARED IMAGERY OF THE LOWER RIO GRANDE VALLEY

Ross W. Leamer, Daniel A. Weber, and Craig L. Wiegand

INTRODUCTION

The primary purpose of this study was to develop a procedure to recognize fields of cotton, sorghum, and bare soil from their film optical densities. Films and supporting ground truth data were carefully studied to provide representative fields for use in arriving at good standards for discrimination tests.

FIELD AND FILM SELECTION

For this experiment, positive transparencies were used from 70 mm, Kodak Ektachrome infrared aero film rolls exposed during July 14 to 27, 1968. This imagery contains a variety of crops and crop and soil conditions. Dominant crops are cotton and mature sorghum. Fields exist in many conditions ranging from bare soil to a very high percentage of weed and/or sorghum stubble or straw cover.

Film rolls catalogued 850, 854, 855, 857, 858, 865, and 867 were used. All were flown between 1000 and 1618 hours, central daylight time, at an altitude of 3000 feet, except 867 which was flown at 1800 feet. Ground truth data were collected on approximately the same dates that the photographic flights were made.

Since the photography was taken with 60% overlap between frames, the same fields (sites) were photographed on more than one frame. Time of exposure is the most significant variable affecting the films and the data obtained from them. Therefore, film rolls used were selected from those judged to have normal exposure; they were neither too dark from underexposure nor too light from overexposure.

Optical densities for 30 to 50 fields on each roll were obtained by scanning the fields with a Joyce, Loebl microdensitometer and converting the average optical count reading for each field to optical density. In addition to taking readings of an unfiltered beam of light passing through the film, red, green, and blue filters were used for each field. Therefore, four film densities were obtained for each field on each film.

Even through normally exposed films were used, very slight differences in exposure make the optical densities of a given crop vary considerably from film to film so that densities through a given filter for one crop on one film might be exactly like the densities through the same filter for another crop on a different film. This is reflected in Table I which lists mean optical densities and standard deviations of the mean for the same fields that were later selected for use in determining the standard crop signatures. Field discrimination, especially between cotton and sorghum, is clearly impossible using optical density because of the similarity of the mean optical densities for different crops at the same wavelength band and the large standard deviations which easily bridge the difference between these means.

Table I. Crop mean optical densities and standard deviation of the mean of the filters used in the light beam of the microdensitometer.

Percent ground cover and crop	Number of fields	Filter	Mean optical density	Standard deviation of the mean
95-100%; cotton	27	None	1.0463	.1034
		Red	.1813	.0592
		Green	1.2919	.1513
		Blue	1.8068	.1947
90%; sorghum	14	None	.9610	.1649
		Red	.3787	.2462
		Green	1.0286	.2733
		Blue	1.7930	.2102
Bare soil	20	None	.5505	.1658
		Red	.3522	.1425
		Green	.5071	.1732
		Blue	.9270	.2980

To eliminate this variation from film to film, optical density differences among the different filters are calculated for each field. These differences for each crop are fairly constant throughout the normal exposure range and differ from crop to crop for the combinations of filters being considered.

What, then, are the characteristic optical density differences for various crops? This study included fields with 95-100% cotton cover, 90% sorghum cover, and bare soil with less than 5% weed cover. Great care must be exercised in selecting samples of these fields. If bare soil, weeds, or root rot are present the density differences obtained will not be characteristic of the crop.

Each field used in computing the crop standards was carefully selected to be uniform throughout with good ground cover and good appearance on the film as judged from ground truth reports and densitometer readings. Bare soil fields were also carefully selected.

CHARACTERISTIC SIGNATURES

Because four film densities are obtained (red, green, blue, and no filter or none) for each crop, there are six possible optical density differences. This experiment utilized only four of the six possible difference of densities: red filter - none, green filter - none, red - blue filter, and blue filter - none. It will be shown that only two of these four differences are needed to correctly discriminate among cotton, sorghum, and bare soil.

Table 2 lists the field types studied and the standard crop signatures obtained by averaging the optical density differences for each field included in the standard. Note the high standard deviations of the readings obtained for red - blue filter, and blue filter - none. These two density differences are not included as characteristic crop signatures. (This is supported by the very high standard deviations of the blue filter mean densities found in Table 1.) The average density difference obtained for red filter - none and green filter - none for each crop are separated by at least two standard deviations and are considered the characteristic crop signatures or crop "standards".

SAMPLE IDENTIFICATION USING CHARACTERISTIC CROP SIGNATURES

It is not difficult to identify a sample using characteristic crop signatures. Once the density of the sample crop is obtained through red, green, and no filters, the differences of these densities can be compared with the standard crop differences to see which of the standard crop signatures is most closely approximated.

To do this quickly a computer program has been designed which, given either the film optical densities or the optical count from the microdensitometer, will compute the density differences: red filter - none and green filter - none for the sample. Then the two differences are algebraically subtracted from the corresponding crop standards. A sum of squares of differences from the crop standards is obtained for each crop. The crop sample which gives the lowest sum of squares most closely approximates the corresponding crop standard.

Table 2. Crop mean optical density differences and the standard deviation of the mean for combinations of the filters used in the light beam of the microdensitometer.

Percent ground cover and crop	Number of fields	Filter combination	Mean optical density difference	Standard deviation of the mean	Considered characteristic signature
95-100%; cotton	27	Red - None	-.8649	.0632	Yes
		Green - None	.2469	.0520	Yes
		Red - Blue	-1.6254	.1670	No
		Blue - None	.7605	.1200	No
90%; sorghum	14	Red - None	-.5823	.0374	Yes
		Green - None	.0676	.0300	Yes
		Red - Blue	-1.4143	.2328	No
		Blue - None	.8320	.0693	No
Bare soil	20	Red - None	-.1983	.0480	Yes
		Green - None	-.0435	.0173	Yes
		Red - Blue	-.5748	.1800	No
		Blue - None	.3754	.1510	No

The computer prints out a line of letters, each letter standing for the crop identification at the given point. Data input can either be point by point from a densitometer scan across a given frame of film, or it can consist of optical densities representing a number of different fields.

RESULTS

Several tests have been made on known samples using the technique previously described to see if the characteristic optical density differences for each crop correctly identified the sample.

First, the fields used in calculating the standard optical density differences for cotton, sorghum, and bare soil were tested and recognized 100% correctly.

Next, densitometer scans were made across two different frames never before scanned on a roll from which fields had been selected for use in determining the standards. Each scan was taken across cotton, sorghum, and bare soil sites, not just one crop. When the readings were converted to densities and their differences compared with the standard crop density differences, excellent recognition resulted. This is illustrated in Fig. 1, which shows the frames scanned and the point by point crop identification obtained from the computer print out superimposed on the Kodak Ektachrome infrared picture of the crops.

Red regions are cotton (C), reddish-brown regions are sorghum (S), and olive green strips are bare soil (B). Notice that some cotton is identified as sorghum in the middle of the cotton fields because of existing cotton root rot. Bare soil readings appear in the sorghum fields because the microdensitometer by chance reads bare soil strips between sorghum plant rows.

Frame Y on film 858, exposed at 3000 feet between 1200 and 1415 hours and not used in determining the standard, was used as <u>another</u> recognition test. This frame has imagery of adjoining cotton, sorghum, and bare soil fields. The microdensitometer scanned a 2/5 inch film segment with these three crops present. All readings (100 per inch on film) were correctly identified when compared with the crop standards presented.

The total sum of squares of the differences between the sample readings and crop standards are by necessity quite small. For instance, in the film 858 test, the largest sum of squares of readings recognized as sorghum, cotton, and bare soil was .029, .007, and .033, respectively. Thirteen readings were sorghum, 11 were cotton, and 16 were bare soil.

SUMMARY

A computer program was developed to recognize fields of cotton, sorghum, and bare soil from their optical density differences. Standard signatures are developed for each crop or soil condition of interest and a sum of squares of differences from the crop standards is obtained for each unknown. The unknown is identified as the crop or soil condition from which its signature differs minimally.

Of the four optical densities routinely obtained corresponding to red, green, and blue bandpass filters and no filter in the light beam of the microdensitometer, it is shown that only two of the optical density differences (red-none) and (green-none) suffice to unambiguously identify cotton, sorghum, and bare soil. The technique can be readily expanded to include more crop species and soil condition categories.

APPENDIX I

Fields selected as standard listed according to flight line and film roll number.

Film No.	Line No.	Field No.	Crop	Notes
850	12	14	Cotton	
850	12	27	Cotton	
850	12	29	Cotton	
850	11	77	Cotton	
850	11	30	Cotton	
850	11	21	Cotton	
854	12	29	Cotton	
855	12	27	Cotton	
855	12	29	Cotton	
855	12	35	Cotton	
857	12	27	Cotton	
857	12	29	Cotton	
857	12	35	Cotton	
857	11	21	Cotton	
858	12	27	Cotton	
858	12	29	Cotton	
858	12	80	Cotton	
858	12	35	Cotton	
858	12	27	Cotton	Different frames
858	12	27	Cotton	
858	12	16	Cotton	Different frames
858	12	16	Cotton	
858	12	16	Cotton	
865	13	80	Cotton	Different frames
865	13	80	Cotton	
867	12	35	Cotton	
867	12	29	Cotton	
850	12	57	Sorghum	
850	11	16	Sorghum	
854	12	57	Sorghum	Different frames
854	12	57	Sorghum	
854	12	57	Sorghum	
854	12	57	Sorghum	
855	12	57	Sorghum	
855	12	56	Sorghum	
857	12	56	Sorghum	
858	12	57	Sorghum	Different frames
858	12	57	Sorghum	
858	12	57	Sorghum	
858	12	56	Sorghum	
867	12	57	Sorghum	

Film No.	Line No.	Field No.	Crop	Notes
850	12	11B	Bare Soil	
854	12	41	Bare Soil	
854	12	70	Bare Soil	
854	12	69	Bare Soil	
854	12	11B	Bare Soil	
854	12	87	Bare Soil	Different frames
854	12	87	Bare Soil	
855	12	52	Bare Soil	
855	12	11B	Bare Soil	Different frames
857	12	11B	Bare Soil	
857	12	41	Bare Soil	
857	11	45	Bare Soil	
858	12	87	Bare Soil	
858	12	70	Bare Soil	
858	12	41	Bare Soil	
858	12	69	Bare Soil	
858	12	71	Bare Soil	
858	12	68	Bare Soil	Scan line across 3 bare soil fields
858	12	Φ	Bare Soil	
867	12	41	Bare Soil	

Figure 1. Computer recognition of crops (C = cotton, B = bare soil, S = sorghum) superimposed on actual crop imagery taken July 27, 1968 from 1000 - 1200 hours at 1800 feet (Film 867). Letters appear just below the microdensitometer scan lines made on two adjacent frames across bare soil strips (green), cotton (red), and sorghum (brown) fields.

BENDIX 9-CHANNEL SCANNER DATA STUDIES

by

Craig Wiegand, Ross Leamer, and Alvin Gerbermann

Objective: To present the status of the studies and indicate future plans.

Introduction:

The U. S. Department of Agriculture remote sensing investigations at Weslaco are making good progress in understanding the interaction of electromagnetic energy with crop plants. The results are based mainly on laboratory studies encompassing the 500 to 2500 nanometer wavelength interval. Quantitative reflectance data from aircraft-borne multispectral scanners are needed to test crop discrimination procedures using wavelengths which the laboratory data indicate are useful. The quantitative scanner data are also needed for explaining sensor response and response variations in terms of ground truth. The long range objectives are identification of yield-limiting crop and soil conditions, and prediction of yields.

Until now the quantitative scanner data have been unavailable. However, this spring and summer NASA Houston provided overflights with the 9-channel Bendix scanner which promise the desired data in the 380 to 1000 nm wavelength interval. The overflights were made on April 13, May 8 and 9, June 6, and July 9. These data provide seasonal coverage from the time signals represent mainly the soil background, due to very young row crop plants, up to full canopy development where signals should be almost wholly due to the crop. The data have not been delivered to Weslaco; hence no results can be provided. Considerable effort will be put into studying the data in the coming year.

Very recently NASA (MSC, Houston) has contracted with Bendix Aerospace Systems Division (Ann Arbor, Michigan) for a signature data processing study. The study will evaluate a number of techniques for processing and analyzing multi-channel data. The set of data obtained during the four flights mentioned above has been selected for use in evaluation of the various techniques. The USDA scientists at Weslaco will work closely with Mr. David Hanson, Study Manager, of Bendix and with Mr. Sidney Whitley and Dr. Dean Norris, Cognizant Scientists of NASA Houston on analysis and on interpreting analysis results. A very necessary input from Weslaco is the ground truth collected during the flights.

It is anticipated that these cooperative efforts will yield much information of scientific value as well as contribute to defining an operational multichannel scanner data handling and analysis capability with which NASA can serve the user agencies. (Bendix is currently building a 24-channel scanner for NASA).

Methods and Procedures:

The channel and performance data on the Bendix 9-channel scanner are as follows:

Channels (Numbers)	Spectral Band (Microns)	Detector
1	0.38 - 0.44	S-20 PM
2	0.44 - 0.50	S-20 PM
3	0.50 - 0.56	S-20 PM
4	0.56 - 0.62	S-20 PM
5	0.62 - 0.68	S-20 PM
6	0.68 - 0.74	S-20 PM
7	0.74 - 0.86	S-1 PM
8	0.86 - 1.0	S-1 PM
9	1.0 - 1.2	Photodiode
Scanning Rate (nominal)		100 revolutions/sec
Instantaneous Field of view (Spatial Resolution)		2.5 milliradians
Lateral Scan Angle		120°
Output Each Channel		Terrain Spectral Reflectance
Spectral Reflectance Accuracy		1.0%
Design V/h (aircraft velocity fps/altitude in ft)		0.25
Analog Tape Recorder		Ampex AR 1600
Tape Running Time (per reel)		30.0 min

NOTE: Channel 9 was not operative for any of the Weslaco site overflights.

The instrument is basically an imaging grating spectrometer using multiple photomultiplier detectors for data output. It is purportedly the first scanner system in operation that has been specifically designed to measure and record directly quantitative measurements of spectral reflectance. This is accomplished by signal referencing and preflight calibration of the scanner against panels of known reflectance.

Six flight lines and a total of 483 fields along them were selected for study prior to the first Bendix overflight. The fields studied are those immediately adjacent to the roadways which serve as the center of each flight line. The fields represent a range in soil types from heavy clay to sandy loam. Table I lists the flight lines by number, gives their geographical location, their length in miles, and the soil types present on each flight line.

Table 1.--Flight line numbers, location, soil types, and length of each flight line over which Bendix 9-channel scanner data were obtained in 1969.

Flight line No.	Location	Soil Types Present	Line length miles
1	Research Farm Highway 88 (Mi 5 W & 12 N)	Sandy clay loam	1
3	FM Rd 1015 (Mi 3 W from Mi 12 N to Floodway)	Clay Clay loam Fine sandy loam Sandy clay loam Silty clay	7
10	Highway 281 from Red Gate to Linn (Linn is 21 miles N of Edinburg)	Clay Clay loam Fine sand Fine sandy loam Loamy fine sand	5
11	"I" Rd (between Pharr and San Juan) from Exp 83 N for 5 mi.	Clay loam Sandy clay loam Fine sandy loam	5
12	FM 1426 (E of San Juan) from Rio Grande to Exp 83	Clay Silty clay loam Silty clay	7.5
13	Highway 281 (Military Highway) from Hidalgo to S of Donna then cross country to Int'l Bridge at Nuevo Progreso.	Clay Silty clay Silty clay loam	17

The crops and soil conditions and the number of fields in each category on each flight date are given in Table 2. Six categories (citrus, corn, cotton, pasture, grain sorghum, and bare soil) make up the bulk of the fields. There are entries for cantaloupe, onions, cabbage, flax, beans, watermelon, tomatoes, forage sorghum, potatoes, peppers, carrots, cucumbers, oats, and alfalfa, however, which should be useful for establishing their reflectance signatures. Maturation and harvest of crops or tillage to create a new condition for the field results in the number of fields in some categories changing among flight dates. Total number of fields in the categories listed in Table 2 also varies with flight date since Table 2 does not include every crop and soil condition encountered.

Ground truth has been obtained on each field on or about the date of the Bendix overflights. A sample ground truth data sheet for one field is included as Table 3.

In addition to the above observations by ground crews, ground level photographs using 70 mm Kodak Ektachrome film type 8442 were obtained of a representative site in each test field as close to the time of the overflight as cloud conditions and manpower permitted. An identification board appears in each photograph. The positive transparencies stored as film strips on reels by flight lines and dates are available should questions about any particular field arise.

Aerial photography from the 2000 foot elevation (AGL) using a locally leased plane and a 9-inch format Zeiss camera and Kodak Ektachrome infrared aero film (type 8443) were obtained on the following dates for each of the listed flight lines:

Date	Flight lines flown
4-13	1, 3, 10, 11, 12, 13
5-9	1, 10, 11, 12, 13
5-13	1, 11, 12
5-20	1, 3, 11, 12, 13
6-6	1, 3, 10, 11, 12, 13
6-10, 11, 12	3, 11, 12, 13
7-9	1, 3, 11, 12, 13
7-29	1, 3, 11, 12, 13

Information in these photographs should be useful for film optical density difference studies and may be of value in supplementing the Bendix photography and scanner data. (The camera on the Bendix plane was non-functional for the July 9 flight, e.g.).

It is recommended that the ground truth data sheets, ground photographs, and aerial photographs all be consulted to determine the 9-channel scanner data to use in the signature data processing study.

Table 2.--Variety of crops and number of fields of each by flight date.

Crop	Flight date 4/13	5/8-9	6/6	7/9
Citrus	44	44	44	44
Corn	36	35	24	17
Cotton	145	151	153	151
Pasture	30	31	32	34
Sorghum	72	90	95	69
Bare soil	67	54	57	85
Cantaloupe	11	11	8	3
Onion debris	1	10	3	2
Onions	22	6	1	0
Cabbage	7	3	0	0
Flax	4	2	2	2
Beans	1	1	1	0
Watermelon	0	1	1	1
Tomatoes	5	5	3	1
Forage Sorghum	3	3	9	9
F. S. debris	0	11	5	12
Potatoes	1	1	0	0
Broccoli	2	0	0	0
Peppers	3	3	3	2
Carrots	5	2	0	0
Turnips	1	0	0	0
Cucumbers	1	1	1	0
Red cabbage	1	2	1	0
Parsley	1	0	0	0
Oats	5	2	0	0
Alfalfa	1	1	1	1
Corn stubble	0	0	0	1
Sorghum stubble	0	0	0	17
Sorghum debris	0	0	0	3
Sorghum regrowth	0	0	0	1
TOTAL	469	470	444	455

Stubble includes standing plant parts after harvest; debris is plant parts visible after tillage.

Table 3.--A sample seasonal ground truth data sheet for one cotton field. Such information as well as aerial and ground level photographs should enable careful sorting of fields to be included in detailed signature data processing study.

FLIGHT DATA SUMMARY SHEET 1969

LINE 12 FIELD NO. 34 SOIL COLOR (DRY) 10YR 6/2 SOIL COLOR (WET) 10YR 4/2

SOIL SERIES HARLINGEN SOIL TEXTURE CLAY

DATE	VEGETATION	% Cover CROP	% Cover WEED	MATURITY	Height (cm)	SURFACE CONDITION	NOTES:*
1-27-69	BARE SOIL	—	—	—	—	SEMI-ROUGH	
4-9-69	COTTON	1	—	PRE-SQUARE	7	SMOOTH	
5-6-69	COTTON	15	—	PRE-SQUARE	21	RAIN CRUSTED	SOME BURNED LEAVES
6-5-69	COTTON	55	—	BLOOM + BOLL	54	RAIN CRUSTED	HOLES IN LEAVES
7-9-69	COTTON	97	—	BOLL	79	—	RED SPOTTED LEAVES SOME BLOOMS ON TOP OF CROP

*ROW WIDTH 100 cm

ORIENTATION E - W UNLESS STATED OTHERWISE IN NOTES

SURFACE MOISTURE Dry

Calibrated Eppley pyranometers and Yellot Sol-A-Meters whose outputs were fed into recording potentiometers were set up at 3 locations on the flight lines on each overflight day to monitor incident direct solar plus diffuse sky radiation. The time the Bendix aircraft was over the particular site where the pyranometers were installed was recorded on the strip chart. The average incident radiation while the plane was in the vicinity of the monitoring sites has been determined and is listed in langleys per minute (1 langley = 1 calorie/cm^2) in Table 4.

The Bendix aircraft passed 2000 feet above the fields in all overflights. Thus the spacial resolution in the analog signals is good.

Analyses planned:

The reflectance data would have many uses including the following:

1. Plot the field reflectance curves for each major crop using the digitized scanner outputs.

2. Use the information from (1) above, to develop a standard reflectance curve for each crop species and bare soil condition.

3. Determine the percent recognition of each species tested against the standard by the minimum distance to the mean technique[1].

4. Try to determine through multiple regression and other techniques which ground truths explain the variability in the Bendix signals.

5. See if the 800 to 1000 nm wavelength signatures are more variable than others. (Reflectance in this wavelength interval is reduced by growth stress conditions so that greater variability here than at other wavelengths would indicate that some of the test fields are affected by disease, drought, or salt).

6. Extend previously developed procedures for laboratory reflectance data to the field data to learn if:
   a) The wavelengths useful from lab data are equally useful for the scanner data for species discrimination.
   b) Leaf area index or percent ground cover can be predicted from the scanner data from:
      1) Where the reflectance curve for the fields of interest fall between those for the optimal stand and bare soil, or
      2) Using the field reflectance of well developed plant canopies as if it were the theoretical quantity, infinite reflectance, to predict percent ground cover, plant height, or yield.

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[1] Fu, K. S., and G. P. Cardillo. 1968. Optimum finite sequential pattern recognition. Laboratory of Agricultural Remote Sensing, Purdue Univ., Infor. Note 070767.

Table 4.--Incident radiation and general conditions by flight date for selected flight lines.

DATE	LINE	HOUR	GENERAL CONDITION	INCIDENT RADIATION, LANGLEYS, PER MINUTE	MEASUREMENT INSTRUMENT
4-13-69	10	1126		1.38	Eppley S.N. 7489
	11	1134-1146	Clear	1.44	Eppley S.N. 7490
	12	1139		1.45	Eppley S.N. 7490
5-9-69	11	1212		1.37	Eppley S.N. 7489
	12, 13	1219	Partly cloudy	1.39	SOL-A-METER I.G. 1151
		1220.30		.91	
		1221.30		1.25	
		1222		1.15	
		1228		1.44	
		1229		1.47	
		1230		1.59	
6-6-69	11	1018-1023	Clear	1.09	Eppley S.N. 7490
	12, 13	1027-1034		1.02	SOL-A-METER I.G.
7-9-69	11	1710	Clear	.89	Eppley 7489
	12	1718		.98	SOL-A-METER I.G.
	13	1729		.95	SOL-A-METER I.G.

7. Compare the Bendix scanner reflectance curves against Instrument Specialties Company Spectroradiometer curves on hand.

8. Compare Kodak Ektachrome IR film optical density differences with red, green, and blue filters in the light beam with the scanner response for the wavelength intervals the film dye layers are sensitive.

9. Use the film optical densities and the similar wavelength interval scanner responses in the minimum distance to the mean discrimination procedure to determine the relative merits of the two procedures for crop identification.

The above studies would be in addition to the factor, regression, and discriminant analyses Bendix will perform using the Weslaco overflight data in the signature data processing study for NASA.

Summary

Overflights with the Bendix 9-channel scanner were made on April 13, May 8 and 9, June 6, and July 9, 1969, of lines on which over 450 fields have been ground truthed for each overflight. No analyses have been made since data are yet to be received. Ground truth, auxiliary measurements, and analyses planned are described. It is anticipated the data will yield much of scientific value as well as aid in defining an operational multi-channel scanner data handling capability, since NASA, Bendix, and USDA will cooperate in evaluating a number of techniques for processing and analyzing multi-channel data.

PROCUREMENT OF FIELD SPECTROMETER

Ross W. Leamer

Many sensors being used in remote sensing research measure portions of the spectrum beyond the visible and photographuc infrared wavelengths. Each sensor is responsive to an identified wavelength band of the electromagnetic spectrum. A collection of properly chosen sensors will measure the intensity of the specified bands throughout the spectrum. Optical filters placed in front of the sensors can further define the specific bands measured by dividing the spectrum into narrower bands thus giving more detail of the spectrum being reflected from or emitted by plants and soils. Continously variable filters moved in front of appropriate sensors will give a signal representing the complete spectrum over the wavelength range covered by the sensors.

Laboratory instruments are available which measure continuous spectral energy by rotating a grating or a prism in a reflected light beam under rigidly controlled conditions of illumination and geometry. Satellite or airborne sensors operate under conditions of varying illumination and geometry. An instrument is needed, therefore, which will measure continuous spectra of agricultural targets under field conditions. Such an instrument would make possible the determination of spectral signatures of various crop and soil conditions.

Specifications for a field spectrometer have been written and the instrument is being built. The spectrum from 0.35 to 14 μ will be scanned by six circular variable filter (CVF) segments in beams focused on four detectors. The six CVF segments will be mounted in four filter wheels as follows:

Filter wheel	CVF segment, μ		Detector
	1	2	
1	0.35 - 0.56	0.50 - 0.90	Si (Silicon)
2	0.80 - 1.40	1.30 - 2.40	PbS (lead sulfide)
3	2.80 - 5.60	Blank	InSb (Indium antimonide)
4	7.00 - 14.00	Blank	HgCdTe (Mercury-cadmium telluride)

This spectrometer will be operated under a variety of environmental conditions ranging from a moderate-sized aircraft to a ground based truck with an aerial lift ("cherry picker"). To accommodate this range of operational conditions, the scanning speed will be adjustable from two spectral scans per second to one scan in 30 seconds. The field of view will be adjustable from 1 to 15°. This adjustment will facilitate scanning the spectra from, for example, a single plant or from a plant canopy. The accuracy of output signals at all scanning speeds and at both fields of view will be at least 1% of the wavelength at each point in the spectral scan. The linear dynamic range of the system will be at least 10^4 power. The signal to noise ratio of the system will be 1000:1 for the wavelengths between 0.35 to 2.30 μ and greater than 100:1 for the longer wavelengths.

This field spectrometer is being built under a contract signed January 2, 1969 with Exotech Incorporated of Rockville, Maryland. In August 1969 (the date this report was written), delivery to the USDA is estimated to be October 1969.

PROCUREMENT OF FIELD SPECTROMETER

Summary

One of the aims of research in remote sensing at Weslaco is to ascertain the wavelength bands of the spectrum most likely to yield information on the energy reflected and emitted from crops and soils for earth resources survey purposes. Many sensors being used in remote sensing measure portions of the spectrum beyond the range of visible and infrared light. No instrument is available in Agriculture for the detailed studies that need to be made from an aerial lift which can remain over a target site or closely bunched targets for diurnal studies when light intensity, sun angle, and other variables are changing.

An instrument is being built for making measurements in the wavelength interval 0.35 to 14 microns. Four sensors will be used to measure the spectral energy in various bands. Each band will be scanned by rotating a circular variable filter (CVF) in the beam striking the sensor. Continuous recording of the output of the sensors will give a scan of the spectrum from the target area. The target areas will alternate between the ground surface and an upward looking diffusion plate.

Random Errors Associated with Measurement of the Kubelka-Munk Parameters of a Leaf

By W. A. Allen

Introduction:

A paper has appeared[1] in which the near-infrared reflectance and transmittance of plant leaves stacked in a spectrophotometer were described by the Kubelka-Munk (K-M) theory for propagation of light through a diffusing medium. A basic entity in application of the K-M theory is the reflectance and transmittance of a single leaf. Prior practice at this location has been to measure the reflectance and transmittance of stacked leaves[2]. The reflectance of n stacked leaves approaches a limiting value R_∞ for each wavelength which is essentially reached when $n > 8$. Similarly, the transmittance of n stacked leaves approaches zero when $n > 8$. Reflectance R and transmittance T of n stacked leaves are given by the relation

$$\frac{R}{b^n - b^{-n}} = \frac{T}{a - a^{-1}} = \frac{1}{ab^n - a^{-1}b^{-n}} , \qquad (1)$$

where a and b are parameters to be determined.

Statistical procedures used in the determination of optical constants for leaves involve regression analysis of reflectance and transmittance data for 1, 2, ... , n stacked leaves at 0.05 μ increments over the spectral range 0.50 - 2.50 μ.

Measurements of stacked leaves may be equivalent to compilation of statistics by replication of measurements. In other words, measurements of leaves piled to a thickness 1, 2, ... , n yield, more or less, the same information obtained from measurements made on the separate single leaves. One advantage of the stacked leaf method, however, is that unsuspected instrumental biases are revealed. Equation (1) should apply equally well to reflectance and transmittance with the same values of a and b. If Eq. (1) does not represent the data within experimental error, then instrumental biases probably exist in the system. The reflectance bias that results from deterioration of the MgO standard, discussed in the previous section, was detected in this manner.

A second advantage of the stacked leaf method is that reflectance and transmittance of multiple leaf layers are measured directly. Multiple layers of leaves occur naturally in a plant canopy, and it is more appropriate to obtain their optical properties by measurement than by calculation. Multiple layers, moreover, tend to diffuse the transmitted light more than a single leaf. Thus, the K-M theory, based upon perfectly diffused light, is likely to be more appropriate for stacked than for single leaves.

Methods and procedures:

Once the instrumental biases have been isolated and removed, the question of measuring single or stacked leaves becomes a matter of indifference. Statistical procedures exist that permit a wide application if the leaves are measured singly. If the leaves are stacked, however, a supplementary error analysis must be made in order to determine the variance in optical constants based upon experimental variance. Assume that residuals between observed and computed reflectance values for 1, 2, ..., N stacked leaves are designated ΔR_1, ΔR_2, ... , ΔR_N. Let the residuals between observed and computed transmittance values for these stacked leaves be specified by ΔT_1, ΔT_2, ... , ΔT_N. Reference 1 has indicated that the Stokes parameters a and b can be calculated uniquely from any pair of reflectance and transmittance curves. Possible pairs of equations fall in the following three catagories:

$$a = a(R_i,\ T_j)\ , \qquad b = b(R_i,\ T_j)\ , \tag{2}$$

$$a = a(R_i,\ R_j)\ , \qquad b = b(R_i,\ R_j)\ , \qquad (i \neq j) \tag{3}$$

$$a = a(T_i,\ T_j)\ , \qquad b = c(T_i,\ T_j)\ , \qquad (i \neq j) \tag{4}$$

Equations (2-4) constitute 2N(2N-1) relations not all independent. The variance of a and b are given by

$$\Delta a^2 = \frac{\sum\ [(\partial a/\partial R_n)^2 \Delta R_n{}^2 + (\partial a/\partial T_n)^2 \Delta T_n{}^2]}{2N(2N-1)}\ , \tag{5}$$

$$\Delta b^2 = \frac{\sum\ [(\partial b/\partial R_n)^2 \Delta R_n{}^2 + (\partial b/\partial T_n)^2 \Delta T_n{}^2]}{2N(2N-1)}\ , \tag{6}$$

where one degree of freedom has been allocated to both Eqs. (5) and (6).

The standard errors Δk and Δs for the K-M parameters k and s can be obtained by means of the relations

$$\Delta k^2 = (\partial k/\partial a)^2 \Delta a^2 + (\partial s/\partial b)^2 \Delta b^2 \quad , \qquad (7)$$

$$\Delta s^2 = (\partial s/\partial a)^2 \Delta a^2 + (\partial s/\partial b)^2 \Delta b^2 \quad , \qquad (8)$$

where

$$\frac{\partial k}{\partial a} = \frac{2}{(a+1)^2} \log b \quad , \qquad (9)$$

$$\frac{\partial k}{\partial b} = \frac{2}{b(a+1)^2} \quad , \qquad (10)$$

$$\frac{\partial s}{\partial a} = - \frac{2(a^2+1)}{(a^2-1)^2} \log b \quad , \qquad (11)$$

$$\frac{\partial s}{\partial b} = \frac{2a}{b(a^2-1)} \quad , \qquad (12)$$

The relationship between the Stokes and the K-M parameters appear as Eqs. (31) and (32) of Reference 1. The remaining differential coefficients needed in evaluation of Eqs. (5) and (6), obtained by differentiation of Eq. (1), can be written in the forms

$$\frac{\partial a}{\partial R} = - \frac{a(ab^n+a^{-1}b^{-n})}{b^n-b^{-n}} \quad , \qquad (13)$$

$$\frac{\partial b}{\partial R} = - \frac{2b}{n(a-a^{-1})} \quad , \qquad (14)$$

$$\frac{\partial a}{\partial T} = - \frac{2a}{b^n-b^{-n}} \quad , \qquad (15)$$

$$\frac{\partial b}{\partial T} = -\frac{b(ab^n + a^{-1}b^{-n})}{n(a - a^{-1})} \tag{16}$$

Discussion:

Data analysis procedures in current use at this location determine the variance of all parameters. Automatic computer plotting procedures display the standard error at each point. For example, Fig. 1 is a computer plot of the K-M scattering coefficient s and absorption coefficient k for a normal corn leaf over the spectral range 0.5 - 2.5 μ. The standard error indicates the relative strength of the data at each plotted point. Standard errors are also plotted for the K-M remission function k/s as shown in Fig. 2.

Summary:

The near-infrared reflectance and transmittance of plant leaves stacked in a spectrophotometer have been described by the Kubelka-Munk (K-M) theory for propagation of light through a diffusing medium. Either single leaves or a stack of leaves may be used. Use of stacked leaves enables one to detect instrument errors but requires a supplementary error analysis of the variance due to experimental uncertainties. Once instrument biases have been isolated and removed, the question of measuring single or stacked leaves becomes a matter of preference.

Equations for calculating the variances and standard errors of the optical constants are presented.

References:

1. William A. Allen and Arthur J. Richardson, "Interaction of light with a plant canopy," J. Opt. Soc. Am. 58, 1023-1028 (1968).
2. V. I. Myers, C. L. Wiegand, M. D. Heilman, and J. R. Thomas. Proceedings of the Fourth Symposium on Remote Sensing of Environment (Infrared Physics Laboratory, the University of Michigan, 1966), p. 801-813. (Entitled, Remote sensing in soil and water conservation research).

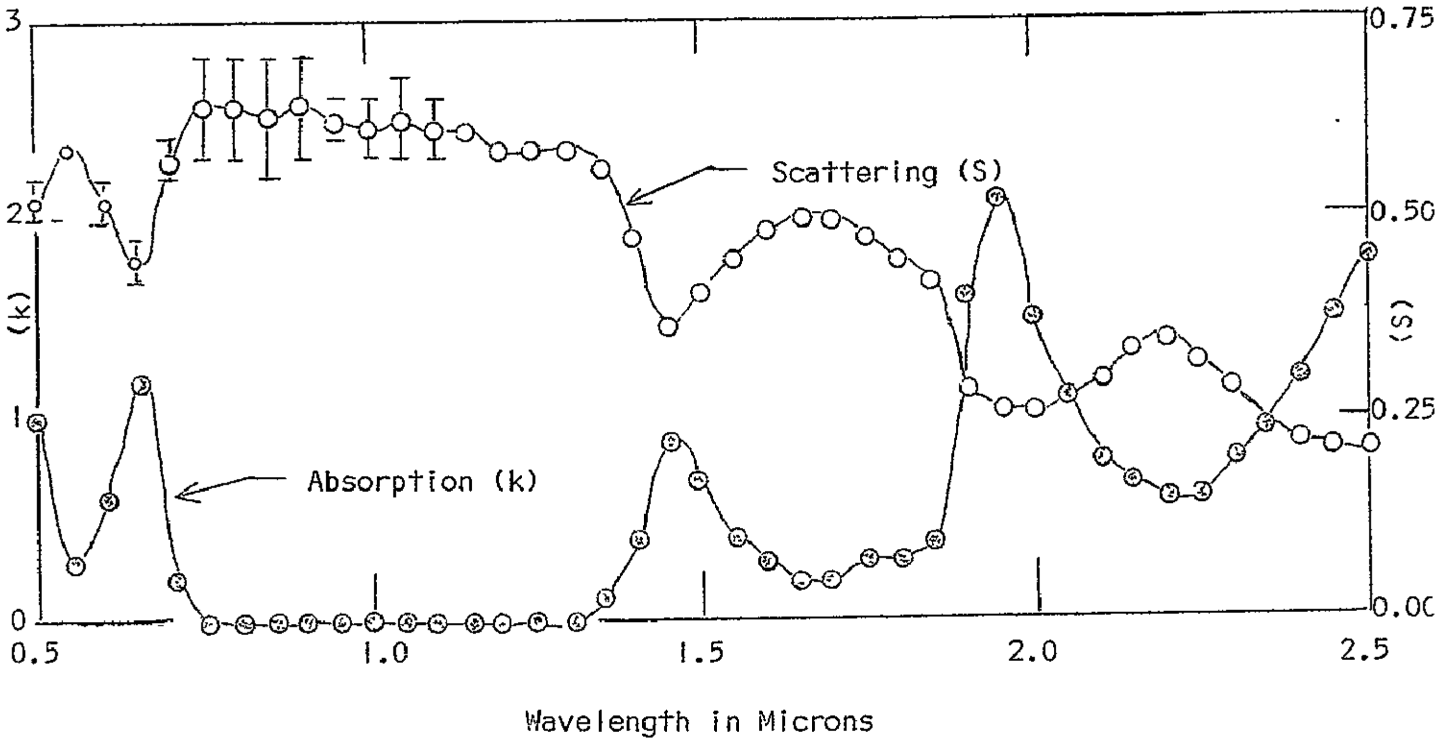

Figure 1.--Absorption (open circles) and scattering (solid circles) coefficients for a normal corn leaf. The bars indicate one standard error.

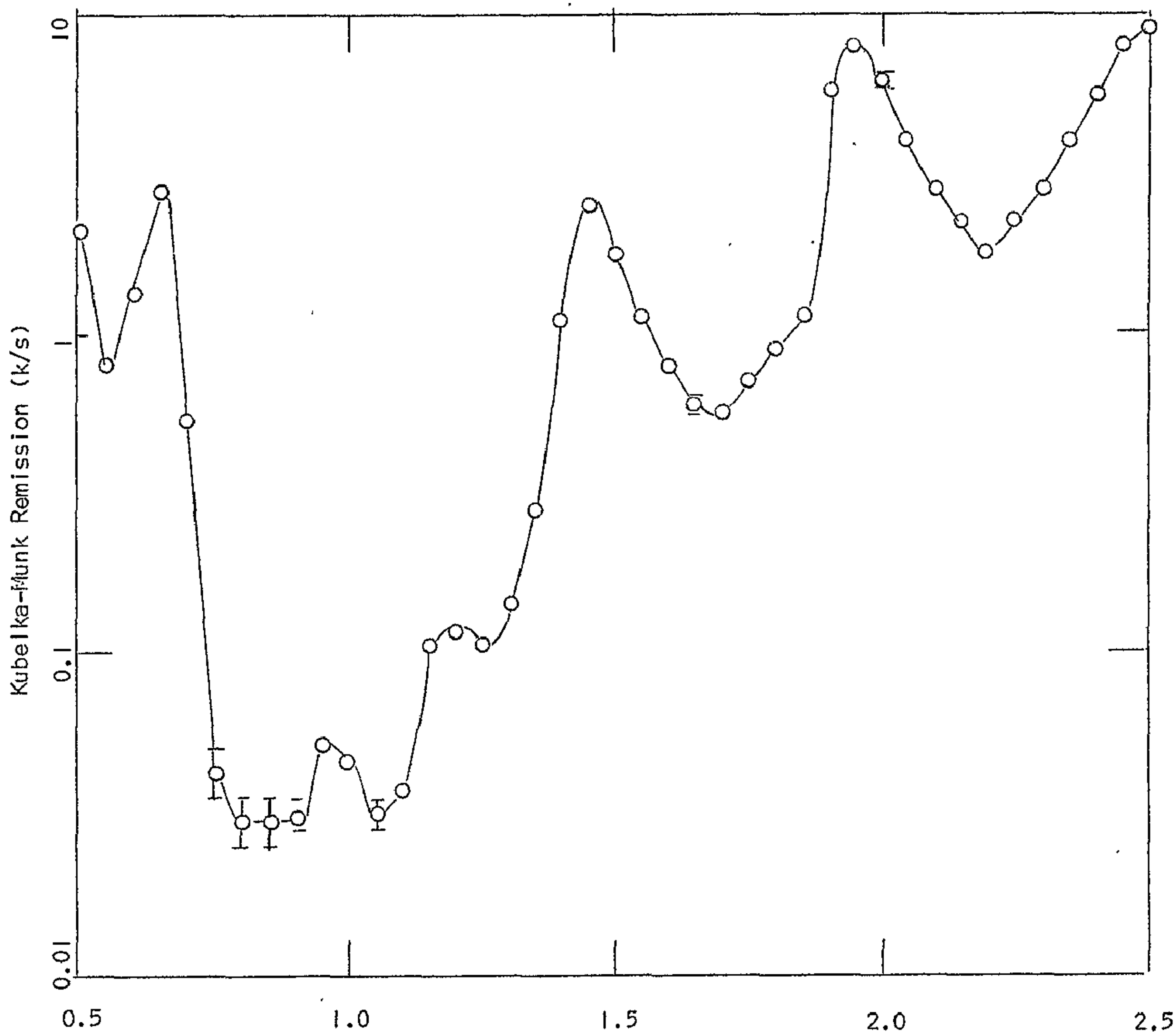

Figure 2.--Kubelka-Munk remission function for a normal corn leaf. The bars indicate one standard error.

FOREIGN COOPERATION PROGRAM

Summary

Dr. Ross W. Leamer of the USDA, ARS, SWC staff at Weslaco, Texas has been designated the agriculture representative of the USDA to NASA's International Participation Program. In this capacity Dr. Leamer has participated in the Mexican and Brazilian cooperative remote sensing programs. He accompanied representatives of oceanography, hydrology, geology, and forestry to Brazil in January 1969 on the mission planning tour where sites were picked and objectives chosen for NASA's Mission 96 flown in July 1969. He also accompanied NASA's operations crew to Mexico for Mission 96 in April 1969. He visited the agricultural sites in Mexico and was in the ground party during the flights over the Toluca and Ixthahuaca sites. He visited also the Chapingo and Papaloapan agricultural areas and toured the test sites. He also participated in the review session with NASA and Mexican representatives at MSC, Houston of the photography taken during the Mexican mission.

Continuing cooperative efforts are anticipated in the international program. Plans are being made for an exchange of data and consultations on instrumentation, interpretation, and analyses among scientists of cooperating countries.

The Lower Rio Grande Soil and Water Conservation Research Center of the USDA located at Weslaco, Texas is cooperating with the Earth Resources Aircraft Program of NASA in the International Participation Program. Dr. Ross W. Leamer of the Weslaco staff is the agricultural representative of USDA on the foreign cooperation phases of the program. Dr. Leamer has participated in this program by making trips to: 1) Brazil to assist in the final planning for 1969 missions and activities and to review test sites and proposed test site instrumentation; 2) Mexico to participate in the data collection during flights over agricultural test sites in Mexico and to assist in the final plans for Mission 91; and 3) Houston to review with NASA and Mexican representatives the photography obtained in Mission 91.

The International Participation Program has the following stated objectives:

"1. To develop techniques and systems for acquiring, interpreting, and utilizing earth resources data from aircraft.

2. To contribute to cooperating countries competence in an advancing technology.

3. To provide additional scientific and technical experience and research data useful in the development of earth resources survey techniques.

4. To familiarize personnel of cooperating countries with the acquisition, processing, reduction, and analysis of airborne sensor data.

5. To identify promising applications of remotely sensed earth resources data.

6. To develop compatible data management systems to facilitate the exchange of data between the U. S. and cooperating countries."

The program is divided into four phases to accomplish these objectives. These phases are:

A. Cooperative study and research program in the U. S. and establishment of program structure in the cooperating countries.

B. Selection and development of test sites; procurement of necessary equipment and instruments; and establishment of data processing and reduction centers by the cooperating countries.

C. NASA aircraft flights over test sites and collection of ground truth information.

D. Operational flights by aircraft of individual countries.

The Weslaco Research Center cooperated under phase A of the program by conducting a three day review of local remote sensing research for 16 scientists and engineers from Mexico and Brazil. Two forestry specialists, one from Mexico and one from Brazil, spent an additional five days at Weslaco and two agricultural specialists spent three weeks observing the data collection and handling operations at Weslaco.

Participation in phase B of the program consisted of sending Mr. Victor Myers to Mexico in December 1968 and Dr. Ross Leamer to Brazil in January 1969 and to Mexico in April 1969. Dr. Leamer's reports for the two trips follow.

REPORT OF REMOTE SENSING TRIP TO BRAZIL

January 18 to 29, 1969

Ross Leamer

The trip reported here was in partial fulfillment of phase B of the international participation program between NASA and CNAE (Comissao Nacional de Atividades Espaciais). The trip was financed through the agencies represented by the participants.

The American participants and the agencies they represented were:

Robert Piland	NASA (MSC, Houston)
Jay Harnage	NASA (MSC, Houston)
James Morrison	NASA (Headquarters, Washington)
Robert McDonald	Purdue University
Ross Leamer	USDA (ARS, Weslaco, Texas)
Robert Aldrich	USDA (Forest Service, Berkeley, California)
Jules Friedman	USDI (Geologic Survey)
Herbert Skibitzke	USDI (Geologic Survey)
Dave Simonett	University of Kansas
James Zaitzeff	U. S. Navy (Oceanographic Office)

The objectives of the trip were:

1. To complete planning for 1969 missions and activities.

2. To review test sites and proposed test site instrumentation.

The route taken to Brazil was from Weslaco early Saturday, January 18, via Houston, Mexico City, Guatemala City, Panama City, and Rio de Janeiro to Sao Paulo late Sunday, January 19.

The NASA, USDA, and Purdue representatives visited on Monday the Instituto Agronomico de Campinas. This Institute of Agronomy, operated by the State of Sao Paulo, is located in the city and county of Campinas. It was established in 1887 by the Emperor D. Pedro II (Peter, the Second). The research is now organized under six divisions: Secao de Agrogeologia, Secao de Fertilidade do Solo, Secao de Conservacao do Solo, Secao de Irrigacao, Secao de Technologia de Fibras, and Secao de Mechanica Agricola, which are working in a total of 36 fields of research. A total of 4,000 people are employed by the Institute. The Institute Library is the largest agricultural library in South America.

The Campinas Institute operates 16 test farms in various ecological regions of the State of Sao Paulo. The farm adjacent to Campinas, the Santa Eliza Farm, includes about 1,750 acres. Weather records have been kept for more than 50 years from a first-class meteorological station. Current research is being conducted in coffee, cotton, sugar cane, corn, rice, vegetables, tropical and temperate fruits, *Eucalyptus* and native vegetation.

The remote sensing project is to be directed by a special commission headed by Arnaldo Guido S. Coelho which will cut across division lines. Mr. Coelho will be able to request help from any of the divisions to get the ground truth and local data collection required during the July NASA flights.

Tuesday the NASA representatives went to meet with another of the Brazilian groups while the USDA representatives continued to work with Mr. Coelho and Mr. Gonzaga (Luis Gonzaga O. Carvalho of Brazilian DPEA, Ministerio Agricultura) on detailed plans for the Campinas area. The following objectives for the July flight were agreed upon.

1. Identify and develop photointerpreters keys to distinguish coffee, citrus, sugar cane, pasture, brush, *Eucalyptus*, and bare soil.
2. Differentiate between red (good) soil and yellow (poor) soil.
3. Identify weed species (broad-leafed and grassy type).
4. Identify sugar cane at various stages of growth.
5. Identify noncitrus orchards.
6. Identify three stages of *Eucalyptus* (recut, young regrowth, and dense regrowth).
7. Classify natural vegetation into four classes (mature dense, mature open, immature dense, immature open).
8. Identify *Pinus* species and Brazilian pine.

Four flight lines were chosen which will cover areas in which all these objectives can be accomplished. These lines all lie along a path starting near Sao Paulo over a forestry experimental planting of pines, then over an area of noncitrus orchards, between Campinas and Sao Paulo, over the Campinas farm and into an area of larger farms just beyond the Santa Eliza Farm, and an area near Americano where there are large plantings of sugar cane. Each flight line is approximately 5 miles long. One pass should give adequate coverage of each.

Although the Institute has agreed to cooperate in the July remote sensing flight by setting up the commission headed by Mr. Coelho, there was no enthusiasm for the project apparent at the time of this visit. Mr. Coelho is a photointerpreter. His interests and abilities are in this field. Some instrumentation is expected to be obtained through CNAE, but none of the people appeared to have had training in the use or maintenance of such equipment. Voltage stabilizers are required on such simple equipment as pH meters, so it seems likely there will be numerous problems with sensitive instruments.

Wednesday evening the USDA representatives joined most of the rest of the U. S. participants in Rio.

Thursday NASA, USDA, and Purdue representatives visited the Institute de Pecquisas e Experimentacao Agropecuarias de Centro Sul (Central South Agricultural and Livestock Experiment and Research Institute), I.P.E.A.C.S. This Institute is located at a road marker indicating it is 47 kilometers from Rio on the road to Sao Paulo; the local name for the Institute is thus Kilometer 47 Farm.

I.P.E.A.C.S. was established on October 11, 1962, within the Ministerio de Agricultura as one of the major organizational units of the D.P.E.A. (Department for Experiment and Research in Agriculture and Livestock, Brazilian Department of Agriculture). Dr. Otto Schrader is the Director. There are three major Divisions: 1) Agriculture, 2) Animal Husbandry, and 3) Animal Pathology. The Division of Agriculture is divided into the following sections:

1. Plant Multiplication and Seed Laboratory
2. Entomology
3. Phytopathology
4. Botany
5. Agriculture and Genetics
6. Horticulture
7. Irrigation and Drainage
8. Soils
9. Climatology

The Institute as a whole has 130 technically trained personnel in a staff of 950. They have only recently become acquainted with the Brazilian Remote Sensing Program but are anxious to learn more about it and to apply remote sensing techniques to their problems.

The economic crops in which they are particularly interested include rice, corn, sugar cane, cocoa beans, beans, vegetable crops and certain fruit crops such as citrus, bananas, guava, cassaba, mangos, and coconuts. They are working to develop successful culture of peanuts, soybeans, and Irish potatoes. The farm on which these crops are grown includes between 9 and 10 thousand acres.

A general discussion (conducted half in Portuguese and half in English) with several members of Agriculture Division Staff developed the following objectives for a remote sensing project.

1. Develop methods of detecting diseases of citrus, bananas, Irish potatoes, and sugar cane.
2. Detect manganese toxicity in cultivated crops.
3. Distinguish fertility status of soils.
4. Detect plant pests.
5. Detect nutrient deficiencies in vegetation.
6. Measure pasture productivity.
7. Study soil patterns.
8. Detect and measure soil moisture stress.
9. Determine ways to identify plant species.

Friday morning Ross Leamer and Robert McDonald met in Rio with a committee from IPEACS composed of Helio de Oliveira Vascohcellos (Chief of Horticulture Section), Octario A. Drummond (Plant Pathologist), Walter Francisco de Costa (Rice Research), and J. A. Barreto de Castro (Soils) to draw up specific objectives and to lay out flight lines for the July NASA flight. The following objectives were chosen:

1. Construct a soil type map from photoanalysis of type and vigor of vegetative cover.
2. Measure pasture vigor under different levels of grazing, drainage, and insect infestation.
3. Identify citrus species and detect diseased areas and note stage of disease.
4. Identify two major varieties of bananas and detect areas of disease.
5. Identify Irish potatoes and detect disease therein and separate water stressed areas.

All these objectives can be met by photo coverage of the IPEACS Farm plus one line extended about 5 miles along the road toward the coast where a range of soil types is located.

Friday afternoon all the Americans and their Brazilian counterparts met for a protocol luncheon with the Brazilian National Research Council and the Executive Group of CNAE.

Saturday and Sunday were spent in Rio.

Monday the group went by Brazilian Air Force plane from Rio to CNAE headquarters at Sao Jose dos Campos. Each discipline (Oceanography, Hydrology, Geology, and Agriculture) held a short session to finalize plans for presentation to the whole group.

Mr. Piland outlined the schedule, past and future, of the steps for the July NASA flight in Brazil. The steps are:

1. Submit a mission request (done in July 1968).
2. Discussion between Brazil and America (this trip in January 1969).
3. Matrix of flight lines, instrumentation, and scheduling (January 27, 1969).
4. Mission planning, preliminary, by NASA (March 1, 1969). Experiment plans by Brazil (March 1, 1969).
5. Final mission plan (May 15, 1969).
6. Fly mission (July, 1969).
7. Data processed and distributed, one copy to Brazil, one to U. S. representative, one to NASA (30 days after mission).
8. Screening by investigators, both Brazilian and U. S. (30 to 45 days after mission).
9. Preliminary evaluation of mission and data (90 days after mission).

Each discipline presented its objectives and outlined the flight lines and instrumentation requested. Objectives for the two agricultural sites were presented as outlined earlier in this report. NASA will coordinate the requests and schedule aircraft time to best meet the needs of the individual test sites.

Several of the group, both Brazilian and American, left Sao Jose dos Campos Monday evening. NASA and USDA representatives left Tuesday morning from Viracopos International Airport near Campinas. We returned via Rio, Caracas, Miami, and Houston.

REPORT OF TRIP TO MEXICO, April 7-12, 1969

Ross W. Leamer

This trip was made to Mexico as part of phase B of the international participation program between NASA and CNEE (Comision Nacional del Espacio Exterior). My participation in phase B was timed to coincide with the beginning of phase C (the flight of the NASA remote sensing plane). Mr. Vic Myers had represented the USDA in phase B (the final planning and selection of flight lines) by his trip to Mexico during December 1968.

I arrived in Mexico City on the evening of April 7. Tuesday, April 8, I attended a premission briefing session along with 20 NASA representatives and 35-40 Mexican officials. The Mexican program includes the Secretaria del Patrimonio Nacional and representatives of the Comision Federal de Electricidad, Secretaria de Recursos Hidraulicos, Secretaria de Agricultura, Secretaria de Marina, and the Secretaria de Defenso. This briefing lasted from 9:00 a.m. until 2:00 p. m. After lunch most of the group inspected the instruments and equipment on the NASA Lockheed NP3A aircraft.

Wednesday morning Dr. Chesnutwood (a geographer with NASA) and I were taken to the National School of Agriculture at Champingo, about 15 miles east of Mexico City. Offices of the National Institute for Agricultural Research and the Mexican Extension Service are located along with the School of Agriculture in this modern and beautiful complex. Each unit has its own program with only a little coordination between the three in spite of their close proximity. The college has an experiment farm east of the campus and the Research Institute has a farm west of the campus. The School of Agriculture was established at San Jacinto in 1854. It was moved to Champingo in 1924. At present there are approximately 1000 undergraduate students and about 200 graduate students. The area around Champingo is an important vegetable, dairy, and poultry producing area for the Mexico City market. Corn, wheat, alfalfa, and tree fruits are important crops.

The flight lines over this area start in the salt lake at the edge of Mexico City and run east across the salt flats where there is no vegetation because of high Cl^- salts with up to 60% of the exchange capacity saturated with sodium. East of the bare flats is a grass covered transition zone which can be leached to about 20% sodium saturation and to acceptable levels of chlorides. The big problem is lack of a way to dispose of the leachate. East of the grassy area, slightly higher up the lake bed slope, are some of the most productive soils in Mexico.

East of the college campus and farm are beach ridges and terraces of the old lake. This area is cultivated and partially irrigated but production is generally low. The flight lines continue east up the badly eroded foothill slopes and into the mountain forest area. The whole transition takes place in about 11 miles.

Plans for collecting ground truth information and locating recording instruments were poorly made at this site. Dr. Chesnutwood and I spent approximately 3 hours outlining to 15 local personnel what we thought should be done before, during, and after the flight scheduled for April 14. We then toured the low elevation flight lines from the mountain forest area to the salt flats.

Thursday morning Dr. Chesnutwood and I were taken to the Toluca/Ixtlahuaca area. These are interconnected valleys of the Rio Lerma Basin in the central part of the State of Mexico. The area is of particular interest to the Mexican Remote Sensing Program because in recent years it has been the source of the major water supply for Mexico City. The capacity of the aquifer has not yet been fully developed so interest in plans for additional development is great. Basic economic development in the state is industrial (Toluca is the Mexican Detroit), but agriculture is also an important economic factor. Approximately 1,200,000 hectares are available for agricultural purposes; about 250,000 hectares are irrigated in some manner.

Like most areas having irrigated areas in mountainous country, the irrigated areas are scattered and separated by rough waste land. The low elevation flight lines covered two relatively large irrigated areas. I was in each of these main areas when the low elevation flights were made. It seemed somewhat incongruous to see the plane containing all the modern, electronically sophisticated instrumentation flying over men plowing with oxen and a straight stick, women washing the family's clothes on a rock in the irrigation canal, and families planting corn by hand, five kernels per hill. Other farmers in the area have tractors and other modern equipment. The main instrumented site in each irrigated area was in a large field where modern equipment had been used. In one area a herd of cattle was grazing along the canal. One, or more, of the cattle found the leads on the thermistors palatable so a couple of temperature data points are missing in the record. The main crop growing at the flight time was alfalfa. Corn was being planted, minor areas of small grains were growing. Preparations for the flight and the ground truth collection were excellent at this site.

Friday morning Mr. Pedro Navarro took me from Mexico City to Aleman in the Popoloapan Basin in the tropical area of Mexico near Veracruz. The Popoloapan Basin includes 17,582 square miles in three physiographic regions and nine principal river basins completely within the torrid zone. Average annual rainfall varies from less than 12 inches in the southwest to 134 inches in the southeast. Measuring stations established too recently to establish long term averages have averaged 164 inches for the last 10 years.

The economic development of the Popoloapan Basin is being coordinated and encouraged by the Comision del Popoloapan. This federal agency appears to be similar in scope and activities to the TVA.

Mr. Navarro and I flew in a twin Beechcraft 18 plane belonging to the Secretaria de Recursos Hidraulicos in Mexico City. We covered the lower agricultural areas from the air, then landed at the Comision's airstrip at Aleman, and then visited a number of the main ground truth stations with local personnel. The area we visited was completely covered by ground vegetation. Any separations made from the remote sensing data will have to be made on differences in the character of the vegetative cover. Sugar cane, bananas, mango, and pasture grasses represent the major crops. In the irrigated areas at the edge of the tropical forest area, corn, rice, alfalfa, and sorghum are major crops.

Poverty and lack of modern conveniences were more apparent in this tropical area than in the higher elevations around Mexico City. This may be due to the differences in climate. In the Popoloapan Basin there is more outdoor living, the houses are more open, with palm thatched roofs where more of the living area and conditions are within sight of the roads. In the cooler, higher elevations each family tends to build a wall around their living and household area. These walls assure more privacy and protection than the open, windowless houses of the tropics.

The flights were to take place over the Popoloapan Basin the week following my visit. Much of the ground instrumentation was to be moved from Toluca to Aleman over the weekend. Local personnel were ready to install the equipment as soon as it was available. Plans for the flight were well made and were well understood by field personnel. At each site a pit had been dug to get a detailed soil profile description. (A cow fell into one of these pits and broke her neck the day I was there. This added an item of unexpected expense to the remote sensing program.)

Mr. Navarro and I returned to Mexico City from Aleman in the Recursos Hidraulicos plane Saturday morning. I returned home via Matamoros Saturday evening.

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