INVESTIGATIONS OF SPECTRUM MATCHING SENSING IN AGRICULTURE

Final Report
May 1964 Through March 1967

Volume I

GPO PRICE $ ______

CFSTI PRICE(S) $ ______

Hard copy (HC) $3.00

Microfiche (MF) .65

ff 653 July 65

Fabian C. Polcyn

November 1967

Prepared under NASA Grant NsG 715/23-05-071 by
Infrared and Optical Sensor Laboratory
WILLOW RUN LABORATORIES
INSTITUTE OF SCIENCE AND TECHNOLOGY
THE UNIVERSITY OF MICHIGAN
Ann Arbor, Michigan

FACILITY FORM 602

N68-13477 (ACCESSION NUMBER)

(THRU)

36 (PAGES)

1 (CODE)

CR-91522 (NASA CR OR TMX OR AD NUMBER)

14 (CATEGORY)

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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FOREWORD

This report is one of several in a program to determine the feasibility of developing an imaging sensor which uses the spectral characteristics of a scene point to identify materials of interest or to enhance the contrast of selected objects. Multispectral imagery and video data are being generated over scenes of interest from an airborne platform. Multiband images are analyzed and interpreted using conventional photo-interpretation techniques, and the spectral characteristics of targets and background objects are analyzed to determine how to electronically process the spectral information from a scene in real time for improved remote sensing. The general goal of this program is to develop methods of improving and extending current aerial-survey capabilties; improvements are sought in the kinds and quantity of data obtainable and in the quality and economy of imagery interpretation.

This multispectral program was initiated and is being guided by Marvin R. Holter, Head of the Infrared and Optical Sensor Laboratory of Willow Run Laboratories, a unit of The University of Michigan's Institute of Science and Technology. Previous reports issued by the Infrared and Optical Sensor Laboratory under this and related programs are given in the list of related reports which immediately follows.

Because the results of the multispectral processing leading to contrast enhancement and automatic recognition have been declared Confidential by the cognizant authorities, they are being published in a separate volume, classified CONFIDENTIAL. The contractor's number for this report is 6590-9-F(I); the classified volume is numbered 6590-9-F(II).

This report was prepared by the Willow Run Laboratories under Amendment No. 3 of NASA Grant No. NsG 715/23-05-071, "The Investigation of a Method for Remote Detection and Analysis of Life on a Planet." The Principal Investigator for the research is D. S. Lowe, Head of the Sensory Systems Group of the Infrared and Optical Sensor Laboratory. Contributions to this report were made by

F. Polcyn, Project Leader
P. Hasell, Sensory Instrumentation and Data Acquisition
R. Nalepka, Calibration of Data
F. Thomson, Electronic Signal-Processing Schemes
W. Malila, Collection of Statistics and Analysis of Data
R. Horvath, Altitude Studies

The following personnel also contributed to work on the project during this period: J. Penquite, M. Spencer, G. Hurchalla, C. Buxton, N. Spansail, J. Drake, L. Larsen, P. Lowry, J. Lennington, L. Mumford, J. Ladd, R. Jenks, and H. Spring.

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ABSTRACT

To further an investigation of methods to perform automatic recognition of objects remotely sensed on the basis of their spectral properties, new multispectral instrumentation and data processing techniques were developed. Data with seasonal, diurnal, and altitude variations were taken of selected agricultural areas. Scanner signals were calibrated; angle and altitude effects were studied. It was found that calibrated, simultaneous, multispectral sensing does provide a basis for automatic recognition, and that a broadband multichannel (ultraviolet to infrared) instrument would be desirable to collect additional data.

The mathematics of data processing techniques are detailed in Volume II, which also gives experimental results; further development of these techniques is needed for implementing adaptive real-time decision making.

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1
INTRODUCTION

The purpose of this project was to produce and analyze simultaneous multispectral imagery of vegetation and soil. The imagery, taken in selected portions of the ultraviolet, visible, and infrared spectral regions, was to be compared in order to determine the spectral differences evidenced by a number of materials under varying conditions. These differences were to be used as the basis for the design of sensory systems for the observation of other planets or of agricultural phenomena on the earth from space.

To this end, this program was to develop a new technique for collecting data which would reduce interpretation time. Despite the many recent improvements in sensor components such as films, detectors, and lenses, the development of remote sensors for various applications has been slow, especially for rapid surveys and automatic recognition of objects. For wide-area surveys, image interpreters are supplied with volumes of data but have to employ time-consuming methods based on details of shape and context. Where real-time decisions are necessary over vast areas, a new technique was required to assess particular quantities or conditions.

Such a technique would be enhanced if it were able to utilize more of the electromagnetic radiation reflected or emitted by the object under study. Yet the information would have to be collected in a manner that would not constrain the type of manipulation desirable for implementing decision functions. If it were used in space, it would sometimes have to reduce the requirements for data storage and telemetry time to get useful information to a ground station.

As indicated above, the spectral properties of objects had to be used as a necessary input to an automatic recognition system; therefore, spectral signatures of actual vegetation in natural environments were needed for analyses. With these as basic data, we could begin to determine the effects of altitude, solar illumination angles, sensor view angles, vegetation characteristics, planting and harvesting practices, etc., on the uniqueness of the spectral signatures.

The test areas were located at Lafayette, Indiana, where personnel from Purdue University monitored agricultural information and environmental data. Significant support was furnished by Project MICHIGAN* and personnel of the U. S. Department of Agriculture aided in collecting "ground truth" in the test areas. The National Academy of Science National Research Council Committee on Aerial Survey Methods in Agriculture furnished guidance and advice, and some of its individual members performed services for the project.

This final report summarizes the accomplishments of the project in both taking and analyzing data, and lists conclusions and recommendations for future work.

2
ACCOMPLISHMENTS PRIOR TO SEPTEMBER 1966

Very little of the instrumentation needed was available at the start of the program. Early in 1963 Willow Run Laboratories (WRL) had begun a year-long program under Project MICHIGAN (sponsored by the U. S. Army Electronics Command) to collect data in four separate spectral bands in the ultraviolet and infrared regions. Every two weeks, a prescribed flight path was flown at two-hour intervals throughout a 24-hour period. Optical-mechanical scanners were used since camera and films are not available for the spectral regions sensed. The data demonstrated differences in the nonvisible spectra of natural objects; these spectra could be used as part of the signature [1].

Our initial work under the NASA grant was performed in 1964. For details of this work, see references 2 and 3. Other reports were made at the Third Symposium on Remote Sensing of Environment [4-6] and at the 1965 meeting of the American Society of Photogrammetry [7]. Briefly stated: a set of multispectral data was obtained on five separate missions distributed during the crop maturation cycle at the Department of Agriculture Experiment Station, Purdue University, Lafayette, Indiana. Imagery was obtained with four aerial cameras, an experimental University of Michigan 9-lens camera, and optical-mechanical scanner used with the permission of Project MICHIGAN (U. S. Army Electronics Command). Some of the data were tape recorded; the conversion from direct-record film display to magnetic-tape recording for the scanner took place during the summer of 1964. The tape-recorded signals provided the flexibility needed to analyze data and set the stage for future use in testing automatic recognition techniques. The analysis of results of these flights reinforced the desire for a truly common aperture system, a multichannel sensor operating in the UV, visible, and infrared wavelengths with capability for providing electronic signals which could be calibrated, i.e., the set of voltage outputs of the system could be converted into a spectral radiance or an apparent reflectance when ground standards were deployed. Such calibrated data are needed for implementing reliable automatic

*Project MICHIGAN is conducted at Willow Run Laboratories for the U. S. Army Electronics Command under Contract DA-28-043 AMC-00013(E). Multispectral equipment and data processing facilities developed by Project MICHIGAN were made available for work under this NASA grant, but Project MICHIGAN did not participate in any of the operations.

recognition techniques. Besides the expected spectral differences between vegetation species, tonal differences in selected bands for certain crops were observed to depend on the sun and view-angle geometry, state of maturity, (which in turn will be affected by soil and moisture), herbicide treatments, irrigation drainage, row direction, and wind damage such as lodging of wheat. The spectral radiance or reflectance signature contains this information and is sometimes better observed when an unaffected area and an affected area are found together. The detection and identification of the species type on the basis of a single resolution element would be a first level decision function. The determination that the species is diseased or weed infested, or lacks moisture would be a second level decision and may require auxiliary information to complete the identification. Since so many factors can affect the interpretation of the spectral signature, the new instrument has to eliminate as many instrument unknowns as possible, hence the need for calibration.

Because of time and funding limitations during this period, the new instrument took the form of modifications to existing optical-mechanical scanners. With the cooperation of Project MICHIGAN, it was decided in 1965 to construct a 12-channel spectrometer for the visible region to replace one of the detectors. Figure 1 shows a block diagram of a multispectral scanner. Since the entrance aperture of the spectrometer was also the field stop of the scanner, a multispectral sensor truly simultaneous in both time and position was created.

The details of this new unit, the conversion of one of two tape recorders to 14 channels, the introduction of calibrated lamps at the end of each scan line, and the analysis of imagery for angle effects have been reported in the semiannual report for the period ending September 1966 [8]. For the data collection efforts in 1966, an 18-channel sensor was used; twelve of the channels of data were obtained with the spectrometer described above. In June, July, and September, data collection missions were flown again over agricultural areas near Lafayette, Indiana. Large fields containing major midwestern crops were selected, and imagery was obtained at various sun angles and various altitudes. All 18 channels were tape recorded, and steps were taken to prepare the data for sampling and digitizing. The digitized voltages are to be used in statistical analysis of spectral signatures. This analysis and the testing of processing techniques to produce the automatic recognition of selected objects will be completed by WRL under a U. S. Department of Agriculture contract as a part of NASA's Earth Resources Program. A description of decision philosophy which can be employed when the outputs of a multispectral sensor are used has been reported by Lowe and Braithwaite [9].

Simple recognition schemes have already been demonstrated for just two or five of the channels recorded on tape. Examples of recognition maps have been published in reference 8. A coincident scheme was employed so that only those objects with the same spectral coordinates would be chosen for display. A technique used with success for 2-channel recognition has been called the light-pen method. Figure 2 is a schematic of the experimental setup. The video sig-

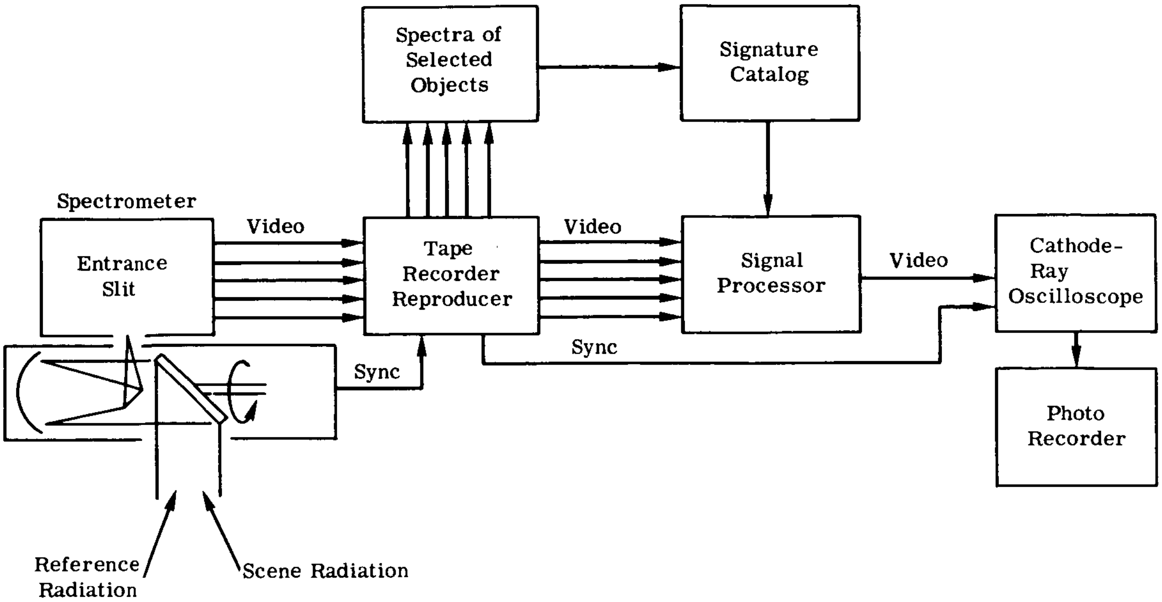

FIGURE 1. SCHEMATIC OF MULTISPECTRAL SCANNER AND DATA PROCESSOR

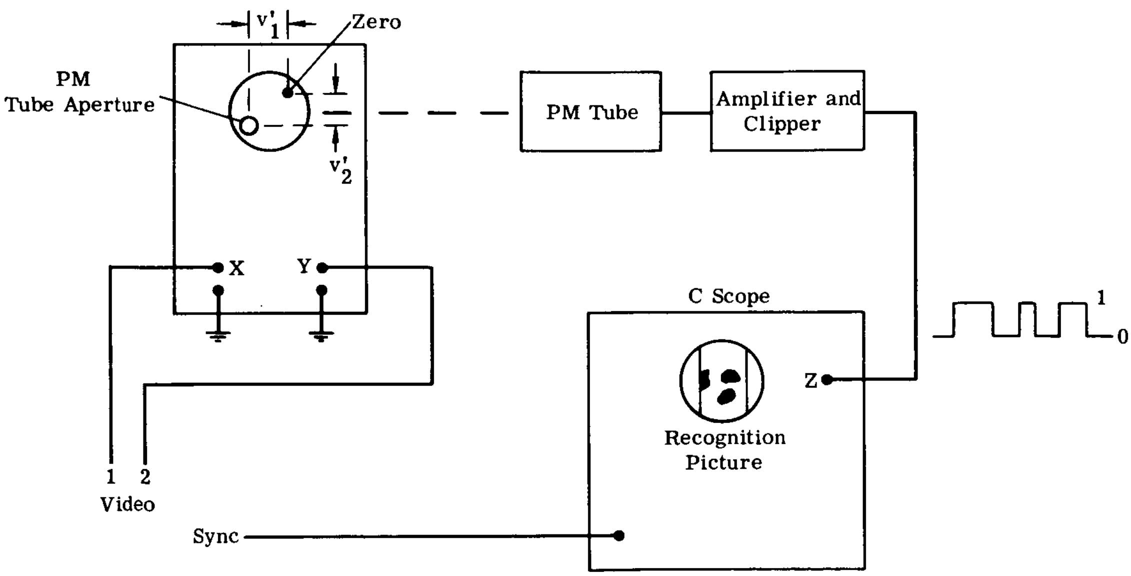

FIGURE 2. EXPERIMENTAL ARRANGEMENT FOR LIGHT-PEN PROCESSING TECHNIQUES. v = voltage.

nal from one spectral channel is used to deflect the cathode-ray oscilloscope (CRO) beam along the x axis; the signal from a second spectral channel is used to deflect the beam along the y axis. A mask is placed in front of the CRO, and a photomultiplier (PM) tube is positioned to detect light passing through a small opening in the mask. The position of the opening in the mask is selected on the basis of the relative intensities of the signals in the two channels used. The relative intensities of the signals in the two channels are color coordinates of the object to be identified.

The detection of the light by the photomultiplier tube only occurs for the times that the (x, y) coordinates of the voltages match the position of the opening, and automatically gives recognition of the object on the basis of spectral characteristics. This technique is an example of a real-time decision process which does not require digitizing of the video signal, and in an operational mode could operate directly on the signals from the sensor; thus tape recording is not required. For the initial exploration work, signals are tape recorded to provide a "real-time" scanner run as the input to the automatic recognition circuitry under development.

The technique does require one to know where to "place the mask"; that is, we must know what the spectral coordinates are in terms of voltages from the sensor. This requirement is satisfied for those applications where we can sample an object to get its signature and then operate to find all other objects like it. Other processing methods are under investigation for implementing more sophisticated decision functions. The particular application of the multispectral technique will dictate the level of decision functions needed. This direction of effort is a part of the work to be investigated by WRL under follow-on Department of Agriculture contracts to NASA Grant NsG 715/23-05-071 as part of the Earth Resources Program sponsored by NASA.

3
PROGRESS SINCE SEPTEMBER 1966

The three data-collection missions over agricultural areas near Lafayette, Indiana, provided a data bank for use in the analysis of spectral signatures. Coverage in June, July, and September provided a sample of different states of crop maturity throughout a season, and enough flight lines were planned to give information on the effects of angle of view, sun angle, and altitude.

With this data bank on tape, the research emphasis was placed in three areas:

(1) The computation of statistics on the multispectral data

(2) The analysis of multispectral data statistics with respect to

   (a) Angle effects
   (b) Altitude effects

(3) The analysis, simulation, and implementation of discrimination methods and processors

3.1. COMPUTATION OF STATISTICS

The radiation that can be sensed remotely from crops, other natural objects, and man-made objects depends on many variables such as time and month of observation, altitude, angles of illumination and observation, weather, and properties of the objects themselves. These variables and their effects on the sensed radiation can in many instances be adequately described only in statistical terms. Therefore, the recognition process, i.e., discriminating between the radiation sensed from various objects, often becomes a multiple-classification problem in statistical decision theory.

In restricted situations on particular data tapes about which some a priori knowledge exists relatively simple techniques can be used to detect the presence of a crop at a time at which it contrasts considerably with its background. Techniques have yet to be developed that can process a "green" data tape, i.e., a tape to which we apply prior statistical knowledge and try to discriminate reliably between the objects on it in real time. For such a task, we must have a good, widely inclusive statistical sample of data from the real world in addition to real-time processing techniques.

Willow Run Laboratories has developed techniques for extracting the statistical properties of the radiation data obtained from various objects by its multispectral sensors. As reported in reference 7, serialization equipment has been assembled to permit a sampling of the 12-channel spectrometer data. The sample values are digitized, and means, variances and covariances* are computed. For each channel and each scan line, the mean and standard deviation are found for radiation from selected vegetation areas, for the calibration signals at the end of each scan line, and for the zero level. These statistics are also derived for each scan angle and for various altitudes between 700 and 10,000 ft. From an analysis of these statistical properties and key variables, statistical signatures for use in recognition processors can be developed.

3.2. CALIBRATION

In the analysis of data taken for this program, one important question which had continually to be assessed was how accurately the airborne instrument measured the spectral reflectance

*Although means and variances do not depend on simultaneity, covariances can only be computed where data are true simultaneous multispectral samples of the radiation collected. This means, for the 1966 data, that either the 12-channel visible spectrometer data or the 4-channel infrared data are usable.

of an object on the ground. In order for the signature data to be comparable and universally applicable, the scanner taking video data had to be calibrated. This was necessary for optimal results in the research into discrimination processing methods and techniques.

Two types of calibrations were made for the 12-channel spectrometer: reflectance calibrations and radiance calibrations. Basically the scanner system is calibrated internally by using quartz-iodine lamps whose emissions are constant with time. During each rotation of the scanner mirror, two lamps operated at different light-output levels are observed, only one of which is used as a reference in any given spectral channel. The lamps are mounted inside the scanner housing and are intended to serve primarily as a check on the constancy of the system's responsivity and to provide a means for comparing spectral shapes. Their use as radiance standards are justified through laboratory tests and calculations. The irradiance of the lamp is known at a specified distance, and by use of a surface whose reflectance properties are known or have been measured, a value of radiance per volt is obtained for the scanner output. When reflectance measurements are to be made, external reflectance standards are required. Large panels whose reflectance properties are known have been placed on the ground along the flight path during various missions. Sunlight reflected from the reference panels is compared with sunlight reflected from the crop or field of interest in terms of the voltage ratio as sensed at the output of the scanner. The voltage ratio is a measure of the relative reflectance of the unknown field. The ratio is made in each channel so that a spectral reflectance signature is measured.

The analytical efforts to date have concentrated on (1) understanding which factors are important in using the signals from the calibration references to standardize the other data (e.g., spectral characteristics of scanner, illumination, references, and targets), (2) developing the procedures for making such calibrations, and (3) performing calculations to verify the developed procedures and to determine the accuracies attainable. The data available for 1966 were not complete enough to provide a thorough check of the calibration procedures, so special test flights were conducted during March 1967 at Willow Run Airport, Michigan. A series of 40 × 40 ft canvas panels representing a 5-step grey scale and a set of red, green, and blue color panels were deployed. These panels were the same ones used for reference during the 1966 collection missions. A ground-based spectrophotometer was used to measure the spectral reflectance of the panels at the same time that the airborne instruments took data. Both sets of data were obtained as nearly as possible under the same environmental conditions. Comparisons of the results are shown in figures 3, 4, and 5. A laboratory measurement of reflectance made by Data Corporation, which supplied the panels, is also shown. (It is not to be inferred that the laboratory curve represents the "true reflectance." The instrumentation used in the laboratory normally measures a quantity called directional reflectance, following the definition outlined by Nicodemus [10]. That is, the sample is uniformly and hemispherically illuminated and viewed

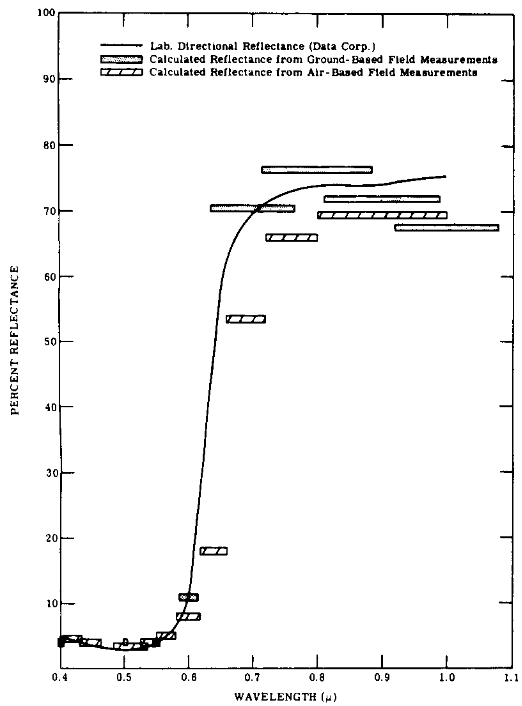

FIGURE 3. RED PANEL REFLECTANCE

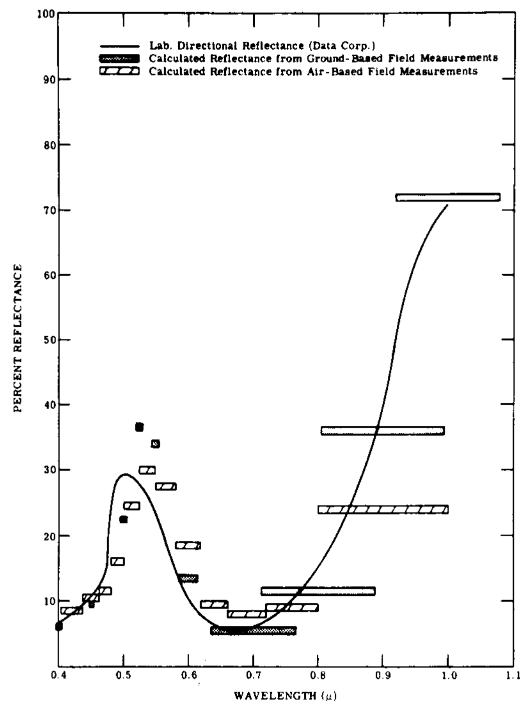

FIGURE 4. GREEN PANEL REFLECTANCE

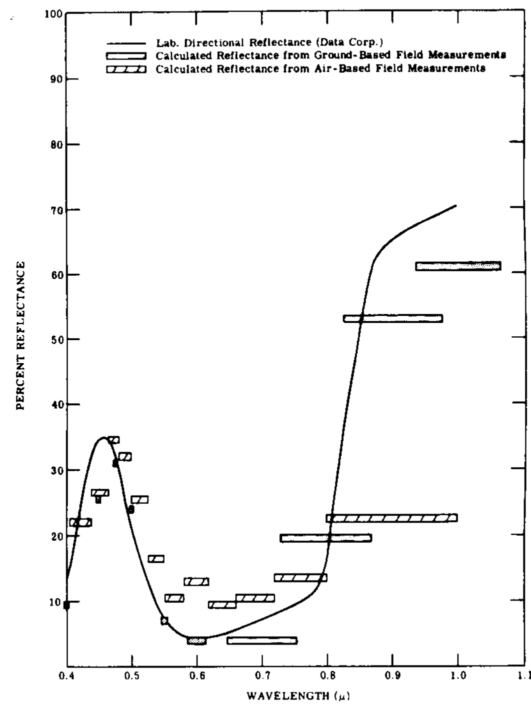

FIGURE 5. BLUE PANEL REFLECTANCE

from a single direction, whereas on the ground or from an airborne platform an object is viewed from a single direction but the object is illuminated nonuniformly. At some wavelengths, particularly in the red end of the spectrum, most of the illumination is directly from the sun, so that a bidirectional reflectance is measured. Towards the blue end of the spectrum, the blue-sky light provides a more nearly hemispherical distribution of illumination and an approximation to the directional reflectance is obtained.

The data shown as bars in figures 3, 4, and 5 represent the value of "reflectance" obtained from a field measurement made by an instrument with finite resolution bandwidths. The extremities of the bars are the 50% response points. The peak response is not necessarily at the center of the bar since it depends on the spectral characteristics of each channel and the spectral profile of the illumination. For the red panel, the ground and airborne spectral data agree quite well. For the green and blue panels, the agreement is best below 0.75 μ, where the spectral resolution is best.

Detailed calculation of the spectral reflectance derived from the ratio of voltages has shown that the accuracy of the measurement depends on spectral shape of the detector response, of the reflected radiation of the object being measured, and of the spectral distribution of the illumination. A report dealing with the details of implementation of the calibration technique for optical-mechanical scanners is in preparation.

3.3. ANALYSIS OF MULTISPECTRAL DATA STATISTICS

The principal method for computing the statistical moments in twelve channels involve digitization of selected data and digital computations; thus far, unimodal multivariate normality has been assumed.

One of the more important processing schemes being investigated uses the decision test based on the maximum likelihood ratio, which takes into account the means and covariances of both the object to be recognized and its backgrounds. In order to apply this test, more information about the statistics of various objects is required. After determining the means and standard deviation for the selected fields, covariance matrixes are computed. A computer program has been written which combines multispectral data (up to 16 channels) from up to 20 fields or from a number of data runs over the same field to form a single covariance matrix on the assumption that all samples are from a unimodal normal distribution. In addition, a program exists to compute the determinant of the covariance matrix, the inverse of the covariance matrix, a correlation matrix, the triangular decomposition of the covariance matrix, and the maximum-likelihood processor's coefficient matrix for data from as many as 16 channels.

Another important investigation deals with determining the geometry of the multivariate normal distribution of data points in N-space. The spectral signature of an object can be considered as a vector in this N-space. The value for N depends on the number of spectral channels available for determining a reliable signature. For the present, the spectrometer added to the scanner permits calculation in 12-space for the visible region and the four-element infrared detector array provides a capability for calculation in 4-space for the region 1 to 5 μ. The ability to discriminate between objects will depend on the separation of the set of points representing the class of objects to be recognized. The present plan is to compute the ellipsoid of concentration around the set of points in N-space.

A computer program exists to determine the eigenvalues and eigenvectors of the N-dimensional ellipsoid of concentration. The eigenvector gives the directions of the ellipsoid's axes, and the eigenvalues are proportional to the square of the lengths of the semi-axes. It is planned to explore the possibility of using eigenvalues and eigenvectors for reducing the number of processing channels that are required to make a discrimination decision (see Thrall [11]).

By studying the various criteria for measuring the separations between spectral distributions for various types of vegetation, we can select and use the most meaningful criteria. It is also of importance to examine the possibility that the distributions are non-normal, multimodal, or both, and the implication of these, if any of them obtain, in implementing discrimination processes.

Finally, the data and their distributions are being analyzed for effects of altitude, scan angle (and flight direction), time of day, weather, and time of year as well as for the difference between vegetation types.

3.3.1. ANGLE EFFECTS. The means and variances of the signals from individual fields on individual tapes are by themselves not usually sufficient statistics from which processors can determine signatures. The statistics must be combined and factored appropriately to account for the variables mentioned earlier. To illustrate the importance of these variables, consider the scan-angle and scan-direction dependencies that have been noted (at about 0.5 μ) in some of the data which were obtained at low altitude during 1966. As shown in figure 6, corn shows little scan-angle dependence when it is scanned in a plane perpendicular to the sun's direction (and here coincidentally the row's direction as well). When it is scanned in a plane parallel to the sun's direction and toward the sun, significant changes in radiation levels are observed; an intermediate variation is observed for scans at 45° to the sun's direction. A larger backscatter signal is evident when the scan is away from the sun. The data for corn in figure 6 represent the averages of more than 70 scan lines of data for each angle plotted; also, each point of each scan line was adjusted to correct for scan-angle-dependent effects due solely to the instrumentation and aircraft roll. It has been found that the scan-angle dependence in this example, channel 5, is different from those of other channels. For example, it is as much

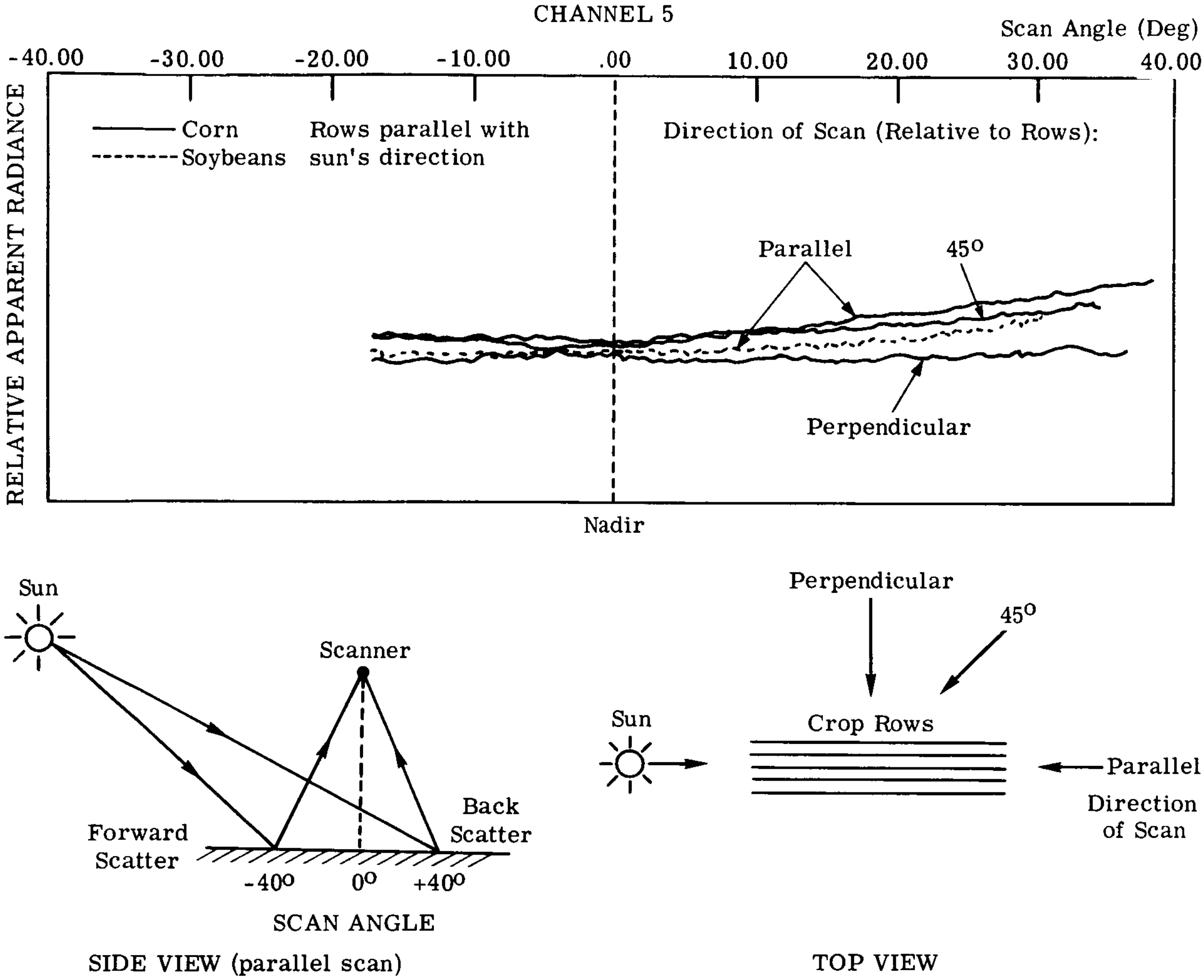

FIGURE 6. EFFECTS OF SCAN ANGLE AND SCAN DIRECTION

as +60% of the nadir (0°) value in channel 8 (0.58 to 0.62 μ) and as little as +5% to +10% in the infrared channels 11 (0.72 to 0.80 μ) and 12 (0.80 to 1.00 μ).

Variations such as those above can mask differences between various crops unless the geometry of illumination and observation is accounted for. To illustrate this effect and also to show the strong similarities between signals from corn and soybeans in July, figure 6 shows a dashed line which represents the signal obtained from a soybean field (that also had east-west rows) on a pass with scans perpendicular to the sun's direction. Similar results were obtained in the other eleven channels. The discrimination between corn and soybeans in July then becomes a function of angles of view for a given sun illumination angle and scan direction.

3.3.2. EFFECTS OF ALTITUDE

3.3.2.1. Objective. As a part of the 1966 program, multispectral data were collected at several altitudes in order to conduct a study of the effects of atmospheric transmission and scattering on the uniqueness of the vegetation's spectral signature. The analysis was preliminary, but it was done to find the general trend of effects and to provide guidelines for defining future experimental studies.

The initial analysis of the data dealt primarily with the 0.4-1-μ region of the visible spectrum. Three questions were raised:

(1) What are the general effects of altitude upon the apparent radiance of the object?

(2) Are the effects spectrally dependent?

(3) What meteorological parameters correlate with these effects?

3.3.2.2. Theoretical Considerations. The effect of sensor altitude upon the appearance of a target which fills the sensor's instantaneous field of view can be ascribed to two simultaneous processes. The matter in the path between the target and the sensor (1) attenuates the radiation emanating (by reflection of sunlight or self-emission) from the target by absorption and scattering, and (2) scatters and emits unwanted radiation into the field of view of the sensor. If $N^t_{\Delta\lambda}$ is the actual radiance of the target in a small spectral band $\Delta\lambda$, then the apparent radiance, $N^t_{\Delta\lambda,h}$, sensed from altitude h is given by

$$N^t_{\Delta\lambda,h} = \tau^{path}_{\Delta\lambda,h} N^t_{\Delta\lambda} + N^{path}_{\Delta\lambda,h} \tag{1}$$

where $\tau^{path}_{\Delta\lambda,h}$ is the path transmission coefficient which indicates the degree to which the actual target radiance is attenuated, and $N^{path}_{\Delta\lambda,h}$ represents the extraneous radiation emitted by or scattered into the beam collected by the remote sensor. $\tau^{path}_{\Delta\lambda,h}$ and $N^{path}_{\Delta\lambda,h}$ are functions of the atmospheric conditions as well as of $\Delta\lambda$ and h. They are, however, independent of the properties of the target.

If equation 1 is differentiated with respect to altitude, then

$$\frac{\partial}{\partial h} N^t_{\Delta\lambda,h} = N^t_{\Delta\lambda} \frac{\partial}{\partial h} \tau^{path}_{\Delta\lambda,h} + \frac{\partial}{\partial h} N^{path}_{\Delta\lambda,h} \tag{2}$$

Now $\frac{\partial \tau^{path}}{\partial h}$ is negative while $\frac{\partial N^{path}}{\partial h}$ is positive. Consequently the direction of change with altitude for the apparent target radiance will depend upon their relative magnitudes and upon the magnitude of the actual target radiance. Qualitatively, it can be seen that, if the actual target radiance is quite small, then the apparent radiance may increase with altitude. Conversely, if the actual target radiance is large, and if, in addition, its attenuation is predominately due to absorption rather than to scattering, then the apparent target radiance might very well decrease with altitude.

3.3.2.3. Data Analyzed. The data chosen for analysis were acquired in July and September 1966 near Lafayette, Indiana. On the morning of July 26, 1966, multispectral imagery was acquired in consecutive flights at altitudes of 2000, 4000, and 6000 ft. On the morning of September 15, 1966, similar imagery was acquired at six different altitudes ranging from 700 to 10,000 ft.

The data analyzed were acquired by the 12-channel spectrometer which senses in twelve contiguous narrow bands over the wavelength range from 0.4 to 1 μ. Table I shows the spectral range of each of the twelve channels. Once during each complete revolution of the scanning mirror, the spectrometer field of view scanned each of two Fiberfax reflective panels illuminated by calibrated lamp sources, thus providing two calibrated signals in each of the twelve channels. The voltage signals from the twelve channels, including the calibration signals, were recorded in parallel on a 14-channel tape recorder.

TABLE I. SPECTRAL BANDWIDTHS OF THE 12-CHANNEL SPECTROMETER (defined for 50% Response Level)

Spectrometer Channel	Spectral Band (μ)
1	0.404-0.437
2	0.437-0.464
3	0.464-0.482
4	0.482-0.502
5	0.502-0.524
6	0.524-0.549
7	0.549-0.580
8	0.580-0.617
9	0.617-0.659
10	0.659-0.719
11	0.719-0.799
12	0.799-1.000

In the laboratory, this recorded data was transformed by electronic sampling techniques into a form suitable for analysis. Electronic gating was used to retrieve samples of the signal from a given ground target simultaneously from each of the twelve channels, for various altitudes. These voltages were then averaged, channel by channel, to produce twelve voltages,

$V^t_{\Delta\lambda,h}$, which are proportional to the average apparent radiance of the target in each channel. Similar sampling of the calibration signals produced twelve reference voltages $V^r_{\Delta\lambda}$, proportional to the known radiances $N^r_{\Delta\lambda}$ of one of the calibrated lamps. The absolute apparent radiance of the target $N^t_{\Delta\lambda,h}$ was then computed as

$$N^t_{\Delta\lambda,h} = \frac{V^t_{\Delta\lambda,h}}{V^r_{\Delta\lambda}} N^r_{\Delta\lambda}$$

By this method, values were obtained of the absolute apparent radiances as a function of spectrometer channel and altitude for wheat stubble and soybeans on July 26, and for corn and soybeans on September 15.

3.3.2.4. Results. Figure 7 is a typical example of the type of data obtained. It presents the apparent radiance of soybeans versus spectrometer channels for three altitudes. This is not a true spectral representation since each channel measures the average radiance in a wide (by spectrometry standards) band, and the straight lines connecting points are only for convenience. There is, however, a recognizable spectral shape as seen by radiance peaks in the green (channel 7) and near infrared (channels 11 and 12), separated by several channels of reduced response which include the chlorophyll absorption region.

Figures 8 and 9 present the data in terms of a normalized radiance (radiance ratio) versus altitude. The normalization is relative to the radiance at 2000 feet; vis.:

$$\frac{N^t_{\Delta\lambda,h}}{N^t_{\Delta\lambda,2000}} = \frac{\tau^{path}_{\Delta\lambda,h} N^t_{\Delta\lambda} + N^{path}_{\Delta\lambda,h}}{\tau^{path}_{\Delta\lambda,2000} N^t_{\Delta\lambda} + N^{path}_{\Delta\lambda,2000}} \tag{3}$$

Such a ratio provides a means of comparing the relative change with altitude in apparent radiance among the several spectral bands.

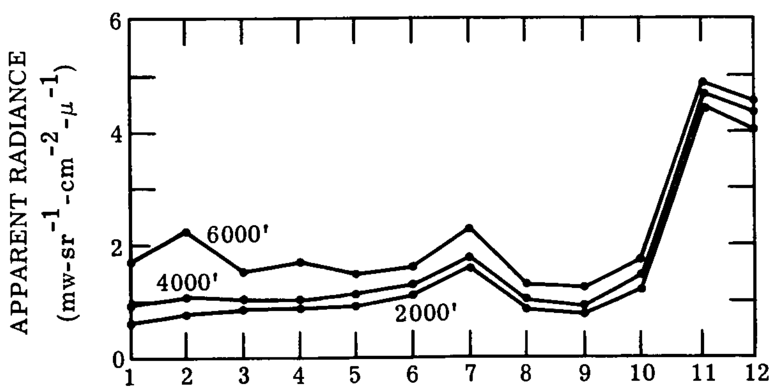

FIGURE 7. APPARENT RADIANCE OF SOYBEANS VS. SPECTROMETER CHANNEL. July 27, 1966, 11:40 A.M.

In general, the ratio, and thus the apparent radiance, is seen to increase or remain constant with altitude in all spectral channels. This indicates that the scattering of radiation into the beam (the term $N^{path}_{\Delta\lambda,h}$ in eq. 3) is greater than or equal to the loss due to the attenuation of the actual target radiance by the path.

The exceptions occur at the longer wavelengths for the soybean data on September 15. These anomalies may not be real, however. Because of the many altitudes flown on September 15, the intensity of solar illumination increased considerably between the 10,000-ft flight (0850 hours) and the 700-ft flight (1024 hours). An attempt was made to account for the illumination change for each altitude by use of ground-based solar illumination measurements made at the time. The correction procedure used was necessarily approximate since the ground illumination measurements were made by a very broadband instrument, and the integrated values had to be divided into contributions from each of the twelve channels.

A very definite spectral trend is evident in figures 8 and 9. The ratio of apparent radiances increases much more with altitude in the blue wavelengths (channels 1 and 2) than in the longer wavelengths. This spectral variation results from the fact that the scattering effect of the atmosphere varies inversely with wavelength. The flatness of some of the longer wavelength curves also indicates that the tendency of scattered radiation to increase the apparent radiance can be offset by the tendency of attenuation to decrease the apparent radiance.

The effect of atmospheric conditions is very evident in a comparison of the July 26 data and the September 15 data. On July 26, the air was quite hazy; on September 15, it was quite clear. As a result, the radiance ratios for the July data increase much more rapidly with altitude, so much so that the radiance ratio of 6000 ft on July 27 exceeds that at 10,000 ft on September 15.

The foregoing data show the combined effect of attenuation and scattering into the beam. The effect of attenuation alone may be studied by looking at the apparent radiance difference between two targets as a function of altitude. This difference is defined as

$$N^{1}_{\Delta\lambda,h} - N^{2}_{\Delta\lambda,h} = \tau^{path}_{\Delta\lambda,h} N^{1}_{\Delta\lambda} + N^{path}_{\Delta\lambda,h} - \tau^{path}_{\Delta\lambda,h} N^{2}_{\Delta\lambda} - N^{path}_{\Delta\lambda,h}$$

or

$$N^{1}_{\Delta\lambda,h} - N^{2}_{\Delta\lambda,h} = \tau^{path}_{\Delta\lambda,h}\left(N^{1}_{\Delta\lambda} - N^{2}_{\Delta\lambda}\right)$$

Since $\tau^{path}_{\Delta\lambda,h}$ cannot increase with altitude, it is evident that the apparent radiance difference cannot. Figure 10 shows the difference in apparent radiance between soybeans and wheat stubble on July 27 versus spectrometer channel for the three altitudes flown. An increase of 0.1 $mw\text{-}sr^{-1}\text{-}cm^{-2}\text{-}\mu^{-1}$ in the apparent radiance difference between 2000 and 6000 ft in channel 1

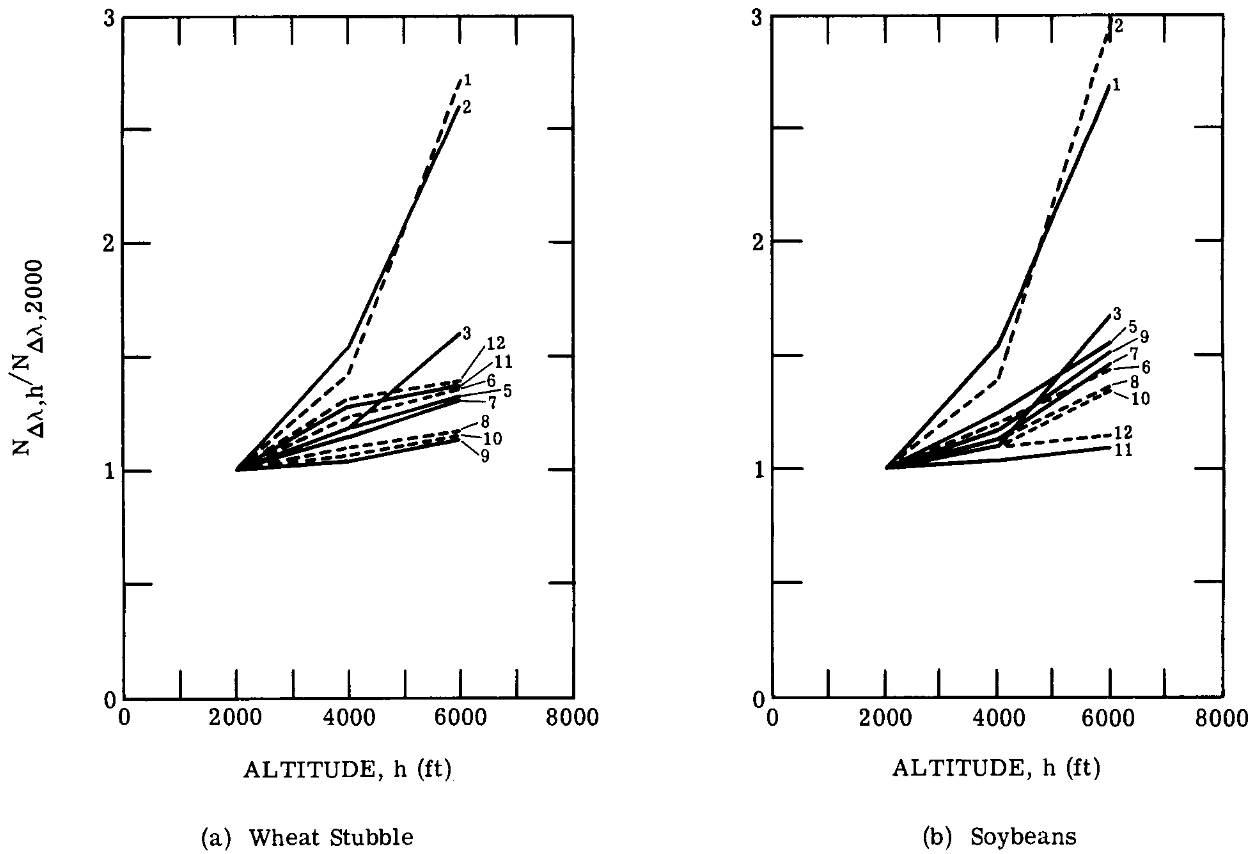

FIGURE 8. RATIO OF APPARENT RADIANCE AT ALTITUDE h TO THAT AT 2000 ft. July 27, 1966, 11:33 A.M. to 12:17 P.M.

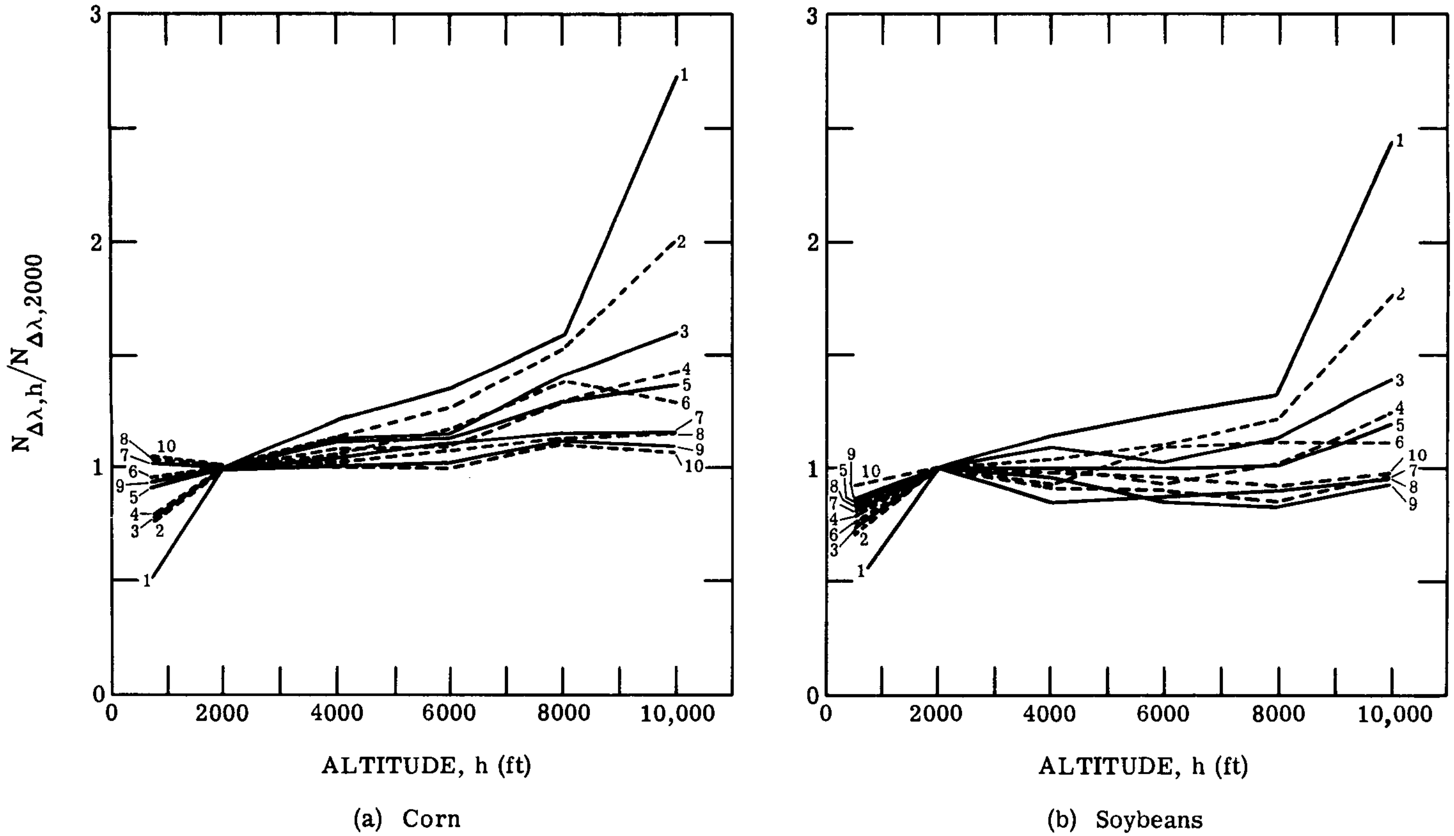

FIGURE 9. RATIO OF APPARENT RADIANCE AT ALTITUDE h TO THAT AT 2000 ft. September 15, 1966, 8:50 A.M. to 12:24 A.M.

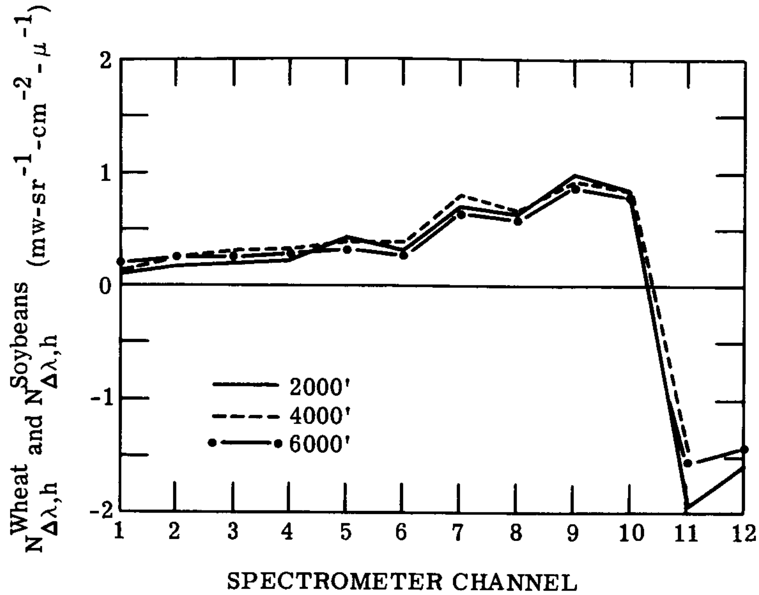

FIGURE 10. APPARENT RADIANCE DIFFERENCE BETWEEN WHEAT STUBBLE AND SOYBEANS. July 27, 1966, 11:33 A.M. to 12:17 P.M. Hazy atmospheric conditions.

of the figure is indicative of the relative uncertainty in the calculated differences, since such an increase is not possible. The magnitude of the uncertainty is even greater for channels 11 and 12 because of excessive noise in the instrumentation.

Figure 10 indicates that any change in $\tau^{path}_{\Delta\lambda,h}$ between the several altitudes was no more than the uncertainty in our measurement. If, for example, the uncertainty is taken to be 0.1 mw-sr^{-1}-cm^{-2}-μ^{-1}, then the change in $\tau^{path}_{\Delta\lambda,h}$ between 2000 and 6000 ft could be no more than $100 \times 0.1/1.0 = 10\%$ in channel 9 and $100 \times 0.1/0.2 = 50\%$ in channel 1.

In section 3.3.2.2 it was stated that, according to theory, the rate of change with altitude of apparent radiance depended upon the magnitude of the actual target radiance in such a way that, the larger the actual target radiance, the less positive the rate of change. This was shown in equation 2 because $\partial\tau^{path}/\partial h$ was negative. Similarly, if the radiance ratio (eq. 3) were differentiated with respect to altitude, the same relationship would hold. Thus, according to theory, if for two targets (1 and 2)

$$N^1_{\Delta\lambda} > N^2_{\Delta\lambda}$$

it must follow that

$$\frac{N^1_{\Delta\lambda,h}}{N^1_{\Delta\lambda,2000}} < \frac{N^2_{\Delta\lambda,h}}{N^2_{\Delta\lambda,2000}}$$

Table II shows the results of such a comparison for the data of 27 July 1966. The first column indicates the sign of the difference between the actual radiances of wheat stubble and soybeans as implied by figure 10. The second column indicates the sign of the differences between the apparent radiance ratios at 6000 ft as presented in figure 8. It will be noted that, for every spectral channel, the two differences are of opposite sign, as predicted. Table III presents the same comparison for the September 15 data on corn and soybeans. The apparent radiance ratio differences were taken from figure 9 for the 10,000-ft data. Again, the differences are of opposite sign in each spectral channel, as predicted by theory.

TABLE II. DIFFERENCE IN ACTUAL TARGET RADIANCES COMPARED WITH DIFFERENCES IN APPARENT RADIANCE RATIOS, WHEAT STUBBLE AND SOYBEANS, JULY 27, 1966

Spectrometer Channel	$N_{\Delta\lambda}^{wheat} - N_{\Delta\lambda}^{soybeans}$	$\frac{N_{\Delta\lambda,10,000}^{wheat}}{N_{\Delta\lambda,2000}^{wheat}} - \frac{N_{\Delta\lambda,10,000}^{soybeans}}{N_{\Delta\lambda,10,000}^{soybeans}}$
1	+	-
2	+	-
3	+	-
4	+	-
5	+	-
6	+	-
7	+	-
8	+	-
9	+	-
10	+	-
11	-	+
12	-	+

On the basis of this exploratory study in the visible region of the spectrum, the following preliminary conclusions can be drawn.

(1) Increase in altitude increases apparent target radiance.

(2) The magnitude of the increase in apparent radiance with altitude is inversely related to wavelength.

(3) The increase in apparent radiance with altitude is directly related to the amount of particulate matter (e.g., haze) in the path.

(4) Attenuation of the spectral radiance differences between objects is small compared to the increase in individual radiances with altitude.

TABLE III. DIFFERENCE IN ACTUAL TARGET RADIANCES COMPARED WITH DIFFERENCE IN APPARENT RADIANCE RATIOS, CORN AND SOYBEANS, SEPTEMBER 15, 1966

Spectrometer Channel	$N^{corn}_{\Delta\lambda} - N^{soybeans}_{\Delta\lambda}$	$\frac{N^{corn}_{\Delta\lambda,10,000}}{N^{corn}_{\Delta\lambda,2000}} - \frac{N^{soybeans}_{\Delta\lambda,10,000}}{N^{soybeans}_{\Delta\lambda,10,000}}$
1	-	+
2	-	+
3	-	+
4	-	+
5	-	+
6	-	+
7	-	+
8	-	+
9	-	+
10	-	+

(5) The increase in apparent radiance with altitude can be lessened, or even reversed, if the actual target radiance is large enough.

Because of the very tentative nature of the above conclusions, it is recommended that further, more intensive investigations be conducted, especially regarding (4) above. The most important technical problem to be overcome in such an investigation is concerned with the necessity of reducing to a minimum the elapsed time between the first and last run over the target, in order to insure fairly constant illumination conditions. This may best be realized by starting with the highest altitude run first, and limiting the target area to a very small size in order to minimize the time taken for each run.

3.4. ANALYSIS, SIMULATION, AND IMPLEMENTATION OF DISCRIMINATION METHODS AND PROCESSORS

A variety of signature-recognition techniques can be applied to agricultural discrimination problems. Willow Run Laboratories is analyzing many of them both theoretically and experimentally through simulation on analog and digital computers. Real-time processors are being investigated in particular. In some cases, simulation of various discrimination techniques on a digital computer is made to test a specific implementation scheme and to investigate how much variation can be tolerated in the auxilary parameters measured and in the spectral data themselves.

The prime recognition techniques under investigation include:

(I) Single-channel tone or contrast detection (all that can be extracted from single-channel data).

(II) Spectrum matching

(a) 2-channel: Requires signals simultaneously within two preset gates in any pair of channels (conveniently implemented in real time at WRL by the light-pen method).

(b) N-channel: Requires signals in N channels to simultaneously be within N preset gates (real-time implementation capability has been developed).

(c) Distance between incoming spectrum and stored spectrum

(1) Sum of single channel distances, $D = \sum_{i=1}^{N} |d_i|$

(2) Hyperspherical decision boundary, $D = \sqrt{\sum_{i=1}^{N} d_i^2}$

(III) Contrast enhancement (weighted sum of spectral signals)

(a) 2-channel: $C_1 \leqq a_i S_i - a_j S_j \leqq C_2$

(b) N-channel: $C_1 \leqq \sum_{i=1}^{N} a_i S_i \leqq C_2$

(IV) Maximum likelihood (takes into account the means and covariances of both the target and its background.

(V) Specialized adaptive techniques (processor will account for certain general parameters such as time of day, and environmental conditions, but will not necessarily adapt to the incoming data independently of other auxiliary information).

Automatic recognition of objects has already been successful. Examples are shown in volume II of the semiannual report for the period ending September 1966 [8]. Additional examples of the results obtained by the light-pen method are given in volume II of this report, which is classified CONFIDENTIAL. (These results of the multispectral processing leading to contrast enhancement and automatic recognition have been declared Confidential by the cognizant authorities. It should be recalled that this equipment has been used on a loan basis from Project MICHIGAN and, although the sensor itself has recently been declared Unclassified, the imagery and processing results are still subject to security review by the U. S. Army Electronics Command.)

Automatic recognition of fields by the light-pen method was implemented by the following process: First, the video voltage levels corresponding to the field (target) were determined; then these d-c levels were subtracted from the corresponding video signals in each channel and the absolute value of the difference was taken. The absolute values were summed, and a threshold detector was used to determine target presence by the criterion

$$\sum_{k=1}^{2} \left| V_{video}^{k} - V_{target}^{k} \right| \begin{matrix} < \epsilon; \text{ target present} \\ \geqq \epsilon; \text{ target not present} \end{matrix}$$

where V_{video}^{k} = kth channel video signal (a function of time)

V_{target}^{k} = d-c voltage corresponding to target level in the kth channel

ϵ = threshold level

A 2-channel spectrum matching of wheat and pasture (see, e.g., vol. II) is characterized by good probability of detection with low false detection rate. The technique has been recently extended to twelve channels. The 12-channel processor is expected to give better results than the 2-channel processor because the spectrum of an object must match the target spectrum in twelve channels (rather than only two) before the object is recognized.

An analog computer has been used to simulate a 5-channel maximum-likelihood processor. Results of these tests along with recognition maps were compiled (see vol. II, app. I).

A program exists to simulate a maximum-likelihood processor on a digital computer by generating random samples from multivariate normal distributions that correspond to those of the targets and backgrounds selected. This program has been used to partially simulate the work done on the analog computer. More extensive use will be made of it to explore various alternatives to automatic recognition processing. The digital computer has the capability of modeling and simulating all the processors in full 12-channel operation. For example, programs have been written to simulate the 12-channel maximum-likelihood processor and they will be used as soon as sufficient signatures have been extracted from the data on hand; some preliminary runs have been made using the 5-channel data. For the maximum-likelihood process, processor coefficients are now computed digitally from the statistical moments of the targets and the backgrounds.

4
CONCLUSIONS AND RECOMMENDATIONS

(A) Simultaneous multispectral sensing (with common aperture) is feasible, but calibration of the scanner output is required.

Simultaneous (common aperture) multispectral sensing of terrain is feasible from airborne platforms. Multichannel aerial cameras have demonstrated multispectral sensing, but only the optical-mechanical scanners (4 and 12 channels) have provided multispectral capability with all channels having time and space coincidence. The total spectral bandwidth of a multispectral system with a common aperture has been limited so far to the visible (0.4 to 1.0 μ) of mid-infrared (1.5 to 5.5 μ) wavelengths by available research equipment. The instrument must have electrical signal outputs which include internal calibration references such that the multispectral signals are comparable in an absolute sense. This registration of spectral signatures in an absolute sense at the instrument is essential if the subtle differences in signatures are to be used for discrimination of targets. Multichannel camera systems do not lend themselves well to absolute calibration or to the generation of electrical signals required for machine processing.

(B) Dramatic recognition of selected objects with simple processing is possible.

Applying electronically implemented spectrum-matching techniques to the simultaneous video signals from the 12-channel spectrometer (covering 0.4 to 1.0 μ) permits reliable automatic recognition of certain crops. The results reported in volume II were obtained with only two channels selected to optimize the difference between the crop type of interest and its background.

(C) Variations in crop and field conditions must be understood in terms of their influence on the spectral signature.

Although the studies described above have been useful as indicators, continued studies are required to determine more completely the major auxiliary factors that affect crop and background signatures and to account for or compensate for them. These factors can be divided into three groups.

(1) Variations in spatial and spectral distributions of the illumination, caused by

Month
Time of day
Clouds
Absorbers and scatterers in the atmosphere (dust and water vapor)

(2) Variations in spatial and spectral reflection and emission properties of crops and backgrounds, caused by

(a) Crop geometry: row spacing, row direction, height of plants, orientation of plants, percent of ground covered

(b) Conditions of the crop itself: species and variety, maturity, vigor, damage, insect infestation, disease, moisture, wind effects

(c) Factors that affect radiation properties: most of those in (b), soil type, soil temperature

(3) Variations in the way that the sensor obtains data, such as

Scan angle
Flight direction relative to sun and crop geometry
Flight altitude
Instrumental effects themselves

(D) Additional data will be needed to broaden the base for determining statistics of signatures as a function of season, etc.

The data obtained by WRL during 1966 provide a good starting point for the signature extraction efforts needed to apply multispectral remote sensing techniques to agricultural problems. Sufficient data were taken under a reasonable range of conditions to permit the initial investigation of many of the various effects and dependencies given in (C). Nevertheless, new data will be desirable in the future for a number of reasons. (1) Gaps in the existing data base should be filled in. (2) More variables should be accounted for, e.g., different varieties of the major species, and different rates of maturation and degrees of maturity (this will be valuable in determining just how early in the growing season we can discriminate reliably between crops that appear similar, such as corn and soybeans). (3) True simultaneous spectral data are needed over all wavelengths from ultraviolet through visible to long-wavelength infrared.

(E) A truly common-aperture (30 bands) multispectral instrument will be necessary to extend the investigation into the infrared for direct comparison with visible wavelengths.

Simultaneous (common aperture), broadband, multispectral, quantitative sensing of terrain from airborne platforms will be required for reliable discrimination of targets by their spectral signatures. Sensing in the visible and near-visible (0.4 to 1.0 μ) wavelengths has established the feasibility of multispectral discrimination of selected targets under fixed environmental conditions, but the results indicate that broadband (0.4 to 13.5 μ), multiple-channel (6 to 30), quantitative sensing will be required to discriminate targets with subtle spectral signature differences under variable environmental conditions. Such an instrument was designed by WRL under NASA Contract No. NAS 8-21000, but its fabrication and use is currently unsupported. Although the sensor may have as many as thirty data channels, no more than six to twelve channels may be selected for discrimination processing of a given target under particular environmental conditions. However, other targets and environmental conditions may indicate a different optimum choice of selected channels for processing from the 30 channels available.

(F) More research is required to find the optimum configuration for a real-time electronic processor to be a part of the sensor package.

The real-time processor feature is needed to avoid a log jam of data-reduction efforts from operational outputs and to satisfy the need for timely data reporting (such as that required in agricultural applications).

In addition to the need for research on the electronic processor as an integral part of the sensor, there is need for more knowledge of the crop signature statistics and what influences them. The program in the past has benefited greatly by using equipment developed by the U. S. Army and studies supported by the U. S. Air Force of reflectance spectra of various objects. It is becoming necessary for agencies who will use multispectral data to contribute to the development of multispectral sensors and processors configured to their specifications.

In summary, The University of Michigan has demonstrated the feasibility of multispectral sensing with calibrated optical-mechanical scanners, has collected data for analysis, has begun research on the analysis of the data and the implementation of recognition schemes based on multispectral signatures. Future work in these areas will be performed by WRL under USDA sponsorship (Contract No. 12-14-100-8293(20) as part of NASA Earth Resources Program).

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