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Interpretation of Remote Multispectral Imagery of Agricultural Crops

Roger M. Hoffer, Research Associate
Department of Botany and Plant Pathology

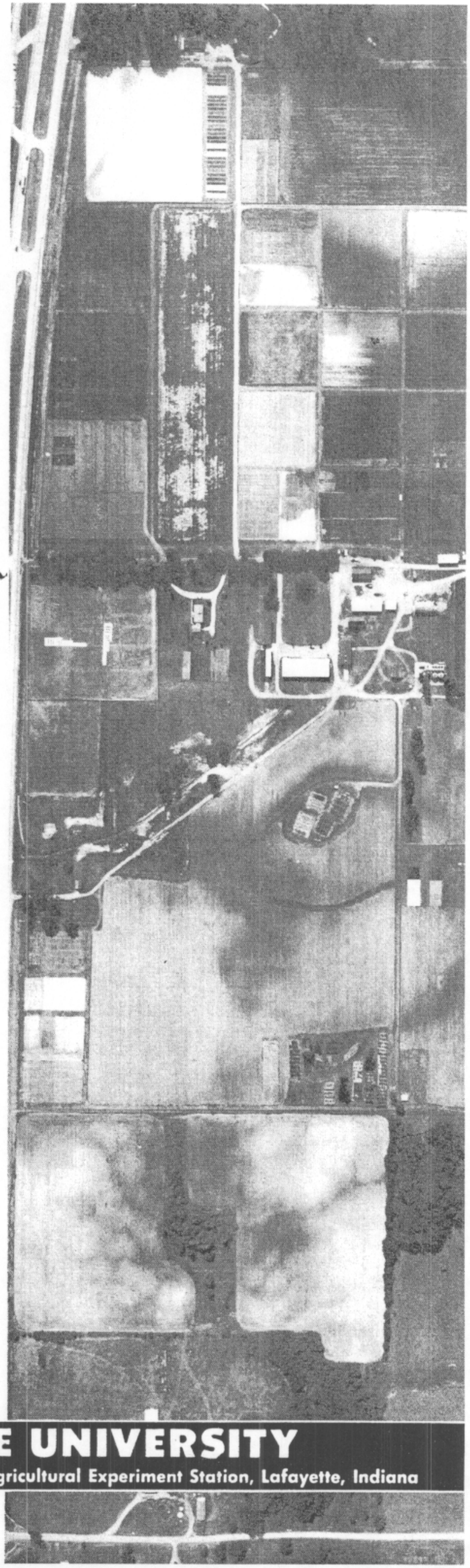
(This report covers work performed from June 1964 through December 1965)

INTRODUCTION

This report covers work done under U. S. Department of Agriculture Economic Research Service RMA contract 2-17-04-1-56. The research was carried out in conjunction with a National Aeronautics and Space Administration grant to the Institute of Science and Technology, University of Michigan. Under this cooperative arrangement, NASA supported the generation and partial analysis of aerial photographs and scanner imagery, and the gathering of "ground truth" data, while ERS supported the evaluation of the "ground truth" data and some analysis of the imagery.

The purpose of this research was "to contribute (a) to the development of specifications for obtaining feasible and optimum imagery to identify and enable area measurements of vegetal species and other ground conditions which determine land use, and (b) toward development of keys that would facilitate rapid and accurate identification and area measurement of land uses by image analysts." Because of year-to-year variation in weather and growing conditions, the results of this study should only be viewed as preliminary. More permanent conclusions will be reached through continued study and testing of the hypotheses developed.

Need for more comprehensive and accurate agricultural and land resources survey data is growing rapidly. Present methods of collecting these data have been devised over more than a century and are reasonably accurate except where sudden changes occur, such as drought, disease, or insect infestation.



PURDUE UNIVERSITY
Agricultural Experiment Station, Lafayette, Indiana

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Acknowledgments

This research was conducted under a contract from the Economic Research Service of the U. S. Department of Agriculture. Dr. Norman E. Landgren served as the ERS Contracting Officer's Designed Representative, and Percy R. Luney coordinated this research program between ERS and Purdue University in its later stages.

The Institute of Science and Technology, University of Michigan, obtained and provided the remote multispectral imagery, in accordance with a grant from the National Aeronautics and Space Administration. The mobile spectrophotometry laboratory used to obtain the leaf reflectance measurements, owned by the Office of Naval Research, was loaned to Purdue University by Charles Olson, Institute of Science and Technology, University of Michigan.

Dr. Raymond Bula, Department of Agronomy, Purdue University, developed the micrometeorological instrumentation and obtained the ground truth data during the summer of 1964. Members of the departments of Agronomy and Botany and Plant Pathology provided detailed ground truth information required for much of the imagery interpretation. Photographer Jack E. Halsema prepared the illustrations for this report. Dr. J. Ralph Shay, former head of the Department of Botany and Plant Pathology, Purdue University, initiated this project and aided in many phases of this work.

To these individuals and agencies, the author expresses his deepest appreciation.

However, survey methods currently used in the U. S. probably would be of limited value in many underdeveloped countries where communications and illiteracy are problems. Accurate and timely agricultural surveys in such countries will be essential if food production is to be successfully stimulated. Even in the U. S., an agricultural survey to determine acres planted to various crops, yield, disease or insect losses, or degree of maturity on a particular date is costly and difficult.

Therefore, a more rapid method of gathering certain types of agricultural data would be tremendously useful to those who deal with production and distribution of food and fiber both in this country and throughout the world.

One potential method of obtaining such information rapidly is through the use of optical-mechanical scanners in high flying aircraft or even spacecraft. Data from these electronic sensors may be processed with a high degree of automation. Among the types of agricultural information which might be obtained by this method are: crop acreage and land use inventories, determinations of weed infestations and control effects, location and measurement of crop disease and insect infestations, characterization of crop and soil moisture conditions, certain phases of soil-type mapping, and assistance in determining watershed and rangeland management practices. Remote multispectral sensing holds much potential for agriculture. The following study was undertaken to explore this potential.

FUNDAMENTALS AND TERMINOLOGY

Figure 1 portrays a portion of the electromagnetic spectrum, showing the types of radiation that occur at different wavelengths or frequencies. Most of the data discussed in this report were obtained in the wavelengths from 0.32μ (microns) in the ultraviolet portion to 14μ in the thermal infrared portion of the spectrum.

In discussing the various wavelength bands, the following terminology will be used: ultraviolet radiation—0.32-0.38μ wavelength; visible—0.38-0.72μ; photographic infrared—0.72-1.3μ; reflected infrared—0.72 to about 3.5μ; thermal infrared—3.5-14μ wavelength. It should be noted, however, that the ultraviolet portion extends below 0.32μ, that the thermal infrared extends above 14μ, and that the divisions between visible and reflective infrared, and between reflected and thermal infrared wavelengths will vary somewhat, depending on the material being sensed and the characteristics of the detector and energy source involved.

The visible portion of the spectrum is just a small segment of the entire range of electromagnetic waves that might be useful for remote sensing. Photographic techniques of recording reflected visible energy on a light-sensitive emulsion are presently the methods most widely used for aerial mapping of agricultural lands. These aerial photographs, particularly colored ones, are readily interpreted because they represent the same scene as observed by the human eye. But by extending the sensitivity of photographic emulsions into the near-infrared portion of the spectrum and by filtering out the visible wavelengths, we can produce a photograph which is similar to the one obtained in the visible portion, but which must be interpreted differently because the image is induced by reflected infrared energy to which the eye is not sensitive.

Optical systems have also evolved which allow sensing of radiant energy reflected from or emitted by the earth's surface (including any vegetation) in portions of the electromagnetic spectrum outside the normal photographic region. By using various detectors and filters, optical-mechanical scanners allow sensing of radiation from about 0.3μ wavelength in the ultraviolet, up to about 14μ wavelength in the thermal infrared. The quantity of emitted thermal energy depends on both the emissivity and the temperature of the object, in accordance with the Stefan-Boltzmann Law, $E = \sigma\epsilon T^4$, where E = energy emitted by the object, σ = Stefan-Boltzmann constant, ϵ = emissivity of the object, and T = absolute temperature of the object.

Imagery in the $0.3\text{-}14\mu$ portion of the spectrum must be obtained in several discrete spectral bands in order to allow proper interpretation of the data, to obtain good quality imagery (high signal to noise ratio), and to overcome certain instrument limitations. The bands are selected at wavelengths that allow data collection in the "atmospheric windows" or portions of the electromagnetic spectrum in which the atmosphere is transparent. For example, beyond approximately 14μ wavelength, most thermal radiation is absorbed by water vapor and carbon dioxide in the atmosphere, but between 8 and 14μ, very little radiation is absorbed. Atmospheric windows between the strong water vapor and carbon dioxide absorption bands exist at the following wavelengths (approximate): 0.3-1:35μ; 1.5-1.8μ; 2.0-2.5μ; 2.9-4.2μ; 4.4-5.1μ; 7.5-14μ. These are the bands in the optical portion of the spectrum in which remote sensing data can be obtained.

Images of topographic features, surface roughness characteristics, and perhaps vegetation and soil moisture differences for the landscape below are possible using side-looking radar of from 0.86 to 3.0 centimeters wavelength. Photographic prints of the radar return have shown dark tones for relatively smooth cultivated fields, but light tones for fields or corn and soybeans. Again, although it may be a photo-

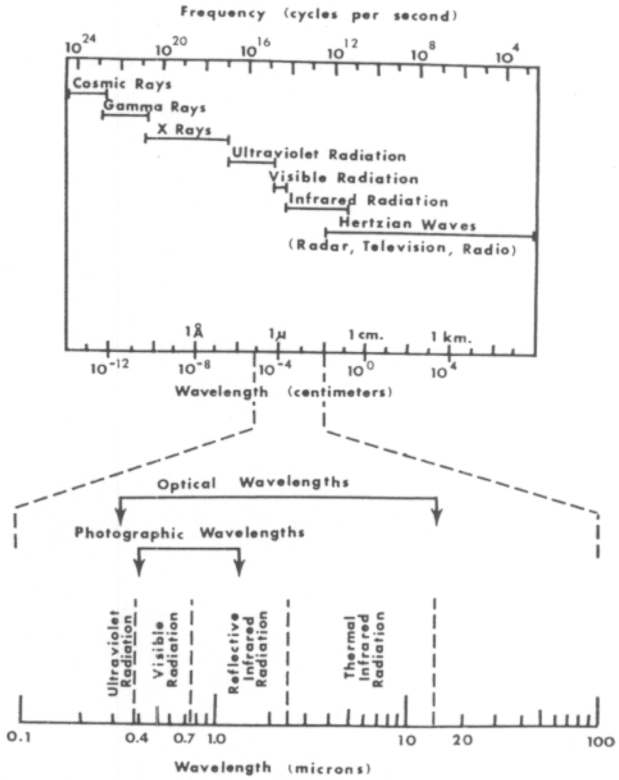


Figure 1. The electromagnetic spectrum. The lower portion emphasizes the regions of primary interest to this study.

graphic type of image, the tonal variations must be interpreted according to the characteristics of the materials being sensed and the type of sensor system used or, in the case of radar, the surface roughness relative to the wavelength of the radar system.

"Remote multispectral sensing," as used here, is the detection and recording, from a distant or remote location, of reflected or emitted electromagnetic radiation in many discrete, relatively narrow spectral bands between 0.3μ and 14μ wavelength and also in radar bands from 0.86 to 3.0 cm. The element used to sense and record such bands of electromagnetic radiation may be photographic emulsions, electromechanical scanners with various types of filters and detector elements, radar or similar devices.

Absorptivity and emissivity in the visible and infrared regions of the electromagnetic spectrum vary with wavelength for different objects. In the visible portion of the spectrum ($0.38\text{-}0.72\mu$), differences in quality and quantity of light reflected by various objects are apparent to the eye and may be recorded photographically as differences in color (using color film) or variations in tone or "response" (using black and white film).

"Response" refers to the relative energy levels received and recorded by a sensor, and may or may not be represented by an image. This term is more meaningful than "image tone," "reflectance," "apparent temperature," etc., because in multispectral imagery, brightness or darkness can be induced by either reflected properties, thermal properties, or both. Thus, high response (light tone on the image) corresponds to high reflectivity, and low response (dark tone on the image) corresponds to low reflectivity throughout the reflective portion of the electromagnetic spectrum (0.3 to 3.5μ wavelength). When dealing with thermal imagery, objects with a higher emitted energy (usually due to higher temperature) will be lighter in tone and will therefore have a higher "response" than the cooler, dark-toned objects or areas.

Because of large differences in response or tone frequently observed on aerial photographs, one should be able to differentiate between classes of objects or vegetation based on these consistent differences in response. However, many objects have approximately the same response in a particular portion of the spectrum and cannot be differentiated. But by using a different wavelength band of imagery or simultaneous photographs taken in different portions of the electromagnetic spectrum, the problem might be overcome. For example, two classifications of tonal response (high or low) could be employed to differentiate between four different objects as follows:

	Tonal Response	
	.4-.7μ	.7-.9μ
Object A	High	Low
Object B	High	High
Object C	Low	Low
Object D	Low	High

Objects A and B cannot be differentiated on the basis of panchromatic imagery (.4-.7μ), but can be differentiated using the infrared photo (.7-.9μ). The same exists concerning objects C and D. Considering only the .7-.9μ imagery, object A could not be differentiated from C, or B from D. Only by using *both* spectral bands can all four objects be differentiated.

Thus, as more film-filter combinations or scanner channels are used to yield additional discrete wavelength bands of imagery, and as more quantitative tonal response ratings are used (i.e., 10 or 100 categories of response rather than just high or low), the number of potential objects that may be differentiated increases enormously. For example, if we obtain 12 spectral bands of imagery and define only 10 response categories for each band, there are 10^{12}, or one trillion unique multispectral response combinations possible.

Figure 2 illustrates the value of sensing a number of objects simultaneously and in several spectral bands. Each spectral band of imagery (.4-.7μ, .7-.9μ, 1.5-1.8μ, and 2.0-2.6μ) exhibits a different combination of tonal patterns among the fields imaged. The pattern of single field may be analyzed throughout the various bands used by "rating" the tone of the field, as compared to calibration panels or other objects on the image and by combining the ratings for all wavelength bands onto a single graph (see Figure 3). The response rating may be made by densitometer or gray scale comparisons.

The total pattern of tonal response from the many wavelength bands (Figure 3) is called the "Multispectral Response Pattern" of a particular crop or target area on a given date or condition of maturity. By obtaining and analyzing many multispectral response patterns for a specific crop, a characteristic pattern may be established which can be quantitatively expressed and which has statistical reliability. Such a pattern is called a "Multispectral Response Signature."

By collecting sufficient remote multispectral sensing data, obtained at various times of the year and under a variety of conditions, a data bank of "Multispectral Response Signatures" can be developed for many crops, crop conditions, geographic regions and seasons.

DATA OBTAINED AND EVALUATION OF GROUND-BASED DATA

Remote Multispectral Imagery Obtained

Under NASA Grant 715, multispectral imagery was obtained of Purdue University agricultural farms near Lafayette, Indiana, during the 1964 growing season. The sensing was done at five different times (approximately every 30-days from 1 June to 1 October), and at 4-hour intervals throughout a 24-hour period during each of the five missions. The data were obtained by the Infrared and Optical Sensor Laboratory, Institute of Science and Technology, University of Michigan, in 18 individual wavelength bands, plus color and camouflage detection film (see Table 1).

During the 1965 growing season, a limited amount of aerial photography and imagery was obtained by a plane from Wright-Patterson Air Force Base. Flights were made on 13 May, 1 July, 26 July, 1 September, and 25 October, with primary emphasis upon obtaining radar, 8-14μ thermal infrared imagery, and color photographs. Some Plus X, aerographic infrared, and color aero infrared photography was also obtained.

Ground-based Data

In 1964, various types of data were gathered from the ground at the time of each remote sensing flight to support the analysis of the multispectral imagery. The four categories of such information are: (1) ground truth, which consists of verbal and photographic descriptions of crop types and conditions at

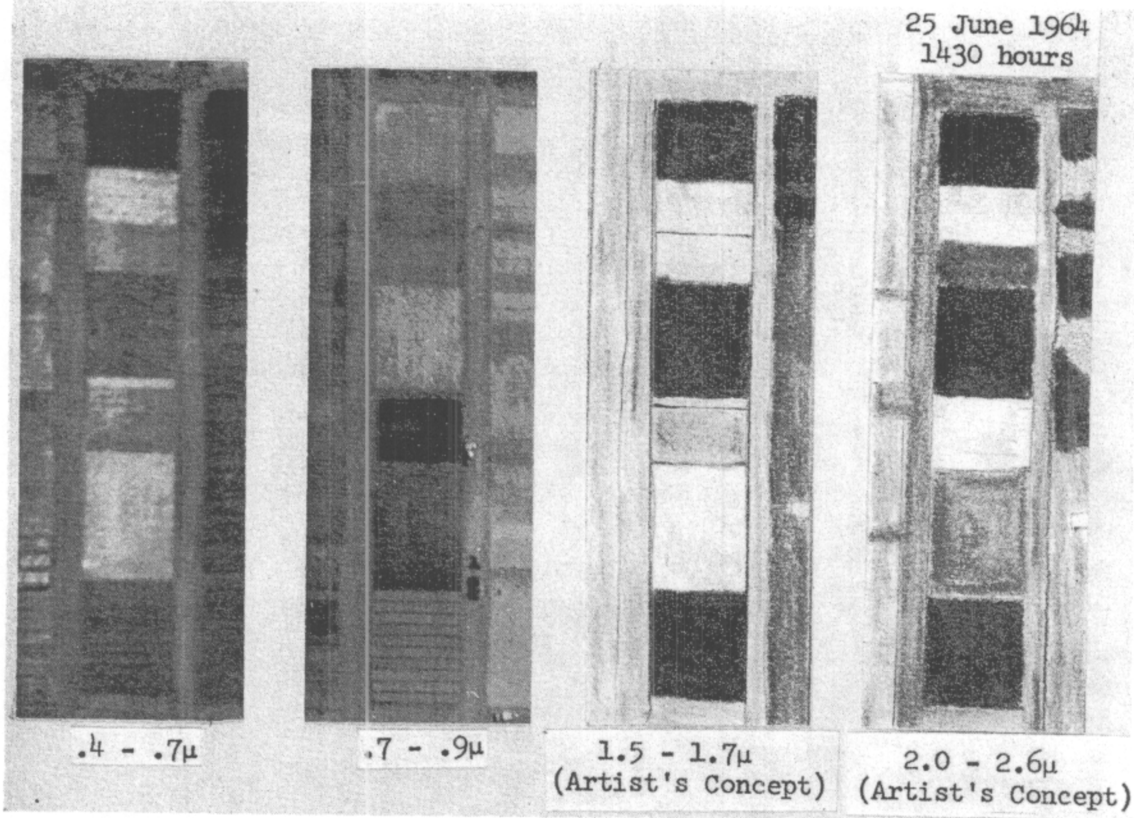


Figure 2. Multispectral comparison of several agricultural fields. This imagery was obtained from a remote location using four wavelength bands. The 1.5-1.7μ and 2.0-2.6μ images are artist's concepts of relative tones (response) deduced from filtered radiometer measurements of the fields. Note the differences in response for each field in the different wavelength bands. Using these four bands, a unique multispectral response pattern is obtained for each of the fields imaged, except the top and bottom fields which are both oats.

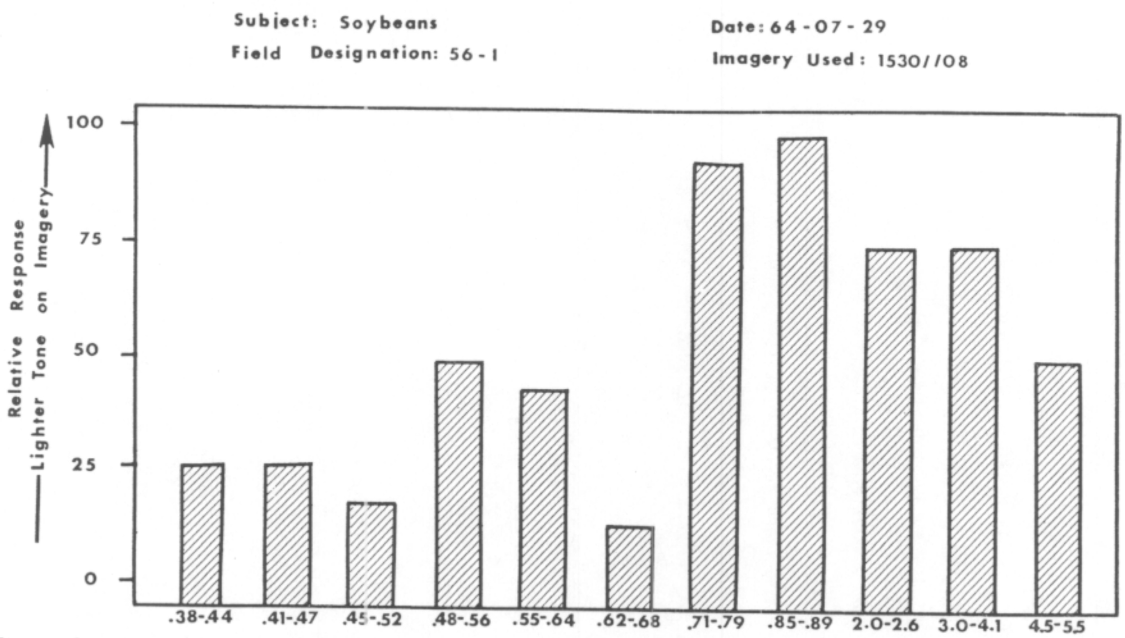


Figure 3. Example of a "Multispectral Response Pattern." Relative response rating is determined by comparing response or tone between the target (the field of soybeans) and the background (other objects on the image). By following this rating procedure for each wavelength band, a series of multispectral response patterns can be obtained for all fields observed on a particular set of multispectral imagery.

the time of each mission; (2) weather and micrometeorological data; (3) spectrophotometer reflectance data on various crops; and (4) PRT-4 data on energy emitted from various fields.

Descriptive and Photographic "Ground Truth"

Descriptions of crop types and conditions, made at the time of each flight, were supplemented by oblique and vertical color photos taken from a portable truck-mounted platform (cherry-picker) with an extendable 50-foot boom (see Figure 4a).

Marked differences were often noted in the multispectral response pattern of fields, even among fields containing the same crop species. In such situations detailed ground truth data were important. By comparing many sets of multispectral response patterns for fields where ground truth had been obtained, the causes of tonal variation could be isolated and the biological factors most responsible for the variations determined.

Among the ground truth data examined were: differences in maturity between two fields of wheat or corn on a given date, differences in amount of tasseling between two corn fields on a given date, differences between awned and awnless wheat, differences in height and density of the same and different crop species, etc.

Color photos taken from the cherry-picker on the day of an aerial flight proved extremely useful. Such photos show in detail the crop maturity and health, weed infestation, amount and condition of soil showing, uniformity of a crop in a particular field, etc. Vertical photos were particularly helpful in determining percent of ground cover. Examples of such vertical and oblique photos are shown in Figures 4b, c, d, e, and f. The color photos from which these black and white prints were obtained contained much information concerning the subtle color differences found among many crop species. However, these black and white photos do give an indication of the type of photographic data obtainable from cherry-picker. (Examples of color photos showing this type of ground truth data can be seen in "Remote Multispectral Sensing in Agriculture" 1967. Laboratory for Agricultural Remote Sensing, Vol. II [Annual Report]. Research Bulletin 832, Purdue University Agricultural Experiment Station, Lafayette, Indiana.)

If this type of photographic information is desired for large fields or over a broad area, low-flying aircraft would probably be more useful to obtain good quality oblique and/or vertical photos. It must be remembered that these photographs are used as back-up to assist in remote multispectral imagery analysis and are not primary data.

Descriptive information recorded in 1964 included crops species and crop height in each field at the time of flight. Analysis of the multispectral imagery revealed that more detailed information was needed, particularly on such items as crop variety, date of planting, row width, and soil type. Much of this information was obtained from Purdue agronomists

Table 1. Wavelength bands of remote multisprectral data obtained in 1964

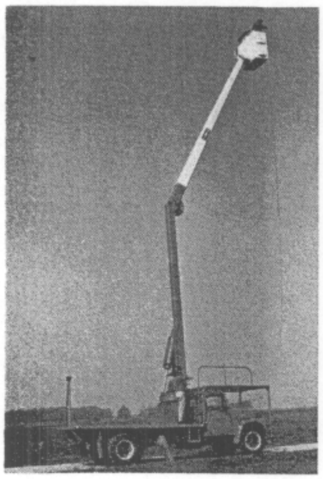
Wavelength bands	Detector	Instrument
microns		
0.32-0.38	Filtered photomultiplier	Optical-mechanical scanner
0.38-0.44	Filtered Kodak I-N spectroscopic film	U-M 9-lens camera
0.41-0.47	Filtered Kodak I-N spectroscopic film	U-M 9-lens camera
0.45-0.52	Filtered Kodak I-N spectroscopic film	U-M 9-lens camera
0.48-0.56	Filtered Kodak I-N spectroscopic film	U-M 9-lens camera
0.55-0.64	Filtered Kodak I-N spectroscopic film	U-M 9-lens camera
0.62-0.68	Filtered Kodak I-N spectroscopic film	U-M 9-lens camera
0.71-0.79	Filtered Kodak I-N spectroscopic film	U-M 9-lens camera
0.85-0.89	Filtered Kodak I-N spectroscopic film	U-M 9-lens camera
0.38-0.89	Unfiltered Kodak I-N spectroscopic film	U-M 9-lens camera
0.4-0.7	Kodak Super XX Aerographic film and Wratten K2-Star filter	K-17 camera (9" format)
0.7-0.9	Kodak Infrared Aerographic film and Wratten 89-B filter	K-17 camera (9" format)
1.5-1.7	Filtered Indium Antimide (In Sb)	Optical-mechanical scanner
2.0-2.6	Filtered Indium Antimide (In Sb)	Optical-mechanical scanner
3.0-4.1	Filtered Indium Antimide (In Sb)	Optical-mechanical scanner
4.5-5.5	Filtered Indium Antimide (In Sb)	Optical-mechanical scanner
1.5-5.5	Unfiltered Indium Antimide (In Sb)	Optical-mechanical scanner
8.2-14.0	Filtered Mercury-doped Germanium (Hg: Ge)	Optical-mechanical scanner
Color (0.4-0.7)	Anscochrome D 200 Color film and color correction filter	P-2 camera (70 mm format)
Infrared color (0.5-0.9)	Kodak Ektachrome Infrared Aero film (or camouflage detection film) and Wratten 12 filter and special infrared color filter	P-2 camera (70 mm format)

after the growing season, but other data could not be obtained.

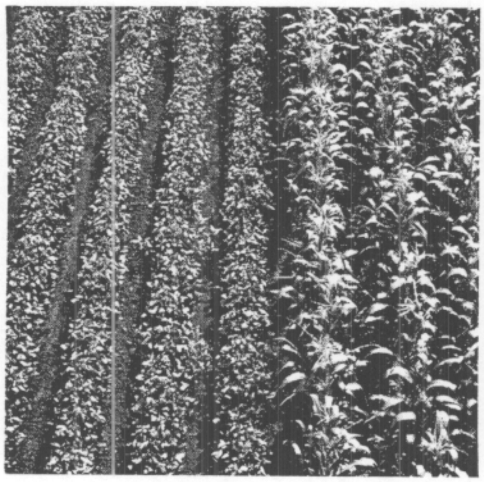
This experience led to development of *Seasonal Information Data Sheets and Periodic Information Data Sheets,* used in 1965 (see Appendix A). These sheets were designed for use on the Purdue Agronomy farm and must be revised for general use. The seasonal data sheet contains information on a particular field throughout the growing season. The periodic data sheet contains information on a given field only for a particular flight mission. Both data sheets have proven extremely useful, but some data were very difficult to obtain.

From the seasonal sheet, items of primary information value involve species, variety, soil type, planting date, planting technique, distance between the rows, row direction, and yield. Of these items, variety, planting date and yield had to be obtained from the person in charge of that particular field—a time consuming job. In a few cases, information on treatment performed on the field such as cultivation, fertilization and spraying, and the dates of such treatments would have been valuable. However, unless extremely detailed records had been kept by the persons in charge, such information was generally not available. Dates of tasseling, harvesting, silking, etc. were also difficult to ascertain. Future records will show only whether these conditions of maturity have been reached at the time of the flight.

Most important on the periodic information data sheets were average crop height and estimated percentage of ground cover. Information on secondary crops, weed, insect, or disease infestations, or other nonuniformities in the field were sometimes useful, particularly in conjunction with aerial or color photos. Cloud and wind conditions were impossible

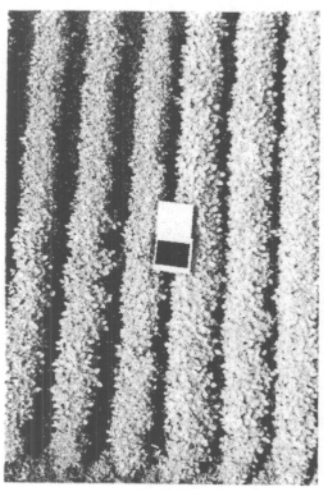


4a.



4c.

4e.



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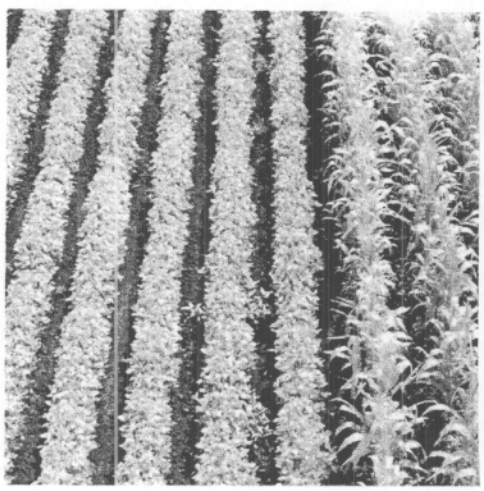
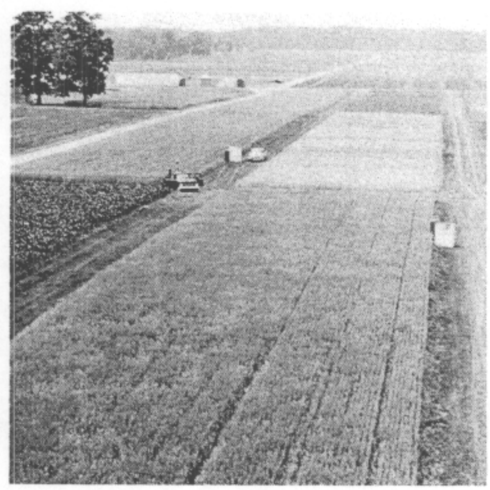


4d.



4f.

Figure 4. "Cherry picker" truck and examples of photographic ground truth obtained from the 50-foot height. (4a) shows the two-man bucket of the cherry picker fully extended. The vertical view of soybeans in (4b) allows estimates of percent of ground cover. (4c) and (4d) are panchromatic and infrared photos of soybeans and corn showing the advantages of infrared film in distinguishing vegetation and dark soil for ground cover estimates. (4e) and (4f) indicate variations in tonal response found on plots of several crop species and also show the utility of such oblique photos from a portable aerial platform for obtaining an indication of crop conditions.

to assess for each field at the time the airplane was overhead, and in the future only general conditions at the time of flight will be recorded. For remote sensing research involving fields of bare or mostly bare soil, data on soil moisture and temperature should be obtained from at least five locations for each area of uniform soil type within the field. A verbal description of the surface condition and cultivation practices performed in the field should also be included.

Weather and Micrometeorological Data

Weather data were obtained for a few days preceding each flight. Temperature, wind velocity, wind direction, solar radiation, and date and amount of last rainfall appear to be the most useful information.

During the 1964 growing season, two 24-point potentiometric recorders were used in conjunction with signal modules and sensors to record various micrometeorological parameters in and over certain crops. Data obtained included (1) solar and total radiation, both incoming and outgoing; (2) temperature above and at two heights within the vegetative canopy, as well as soil temperature at 4-inch depth; (3) relative soil moisture at 4-inch depth; (4) relative humidity above and within the vegetative canopy and (5) wind velocity above the vegetative canopy.

Data collection dates and recorder locations are shown in Table 2. The recorders obtain instantaneous readings of the various parameters at 6-minute intervals. These readings were averaged over hour-long intervals and recorded in tabular form (Appendix B). Then the data were analyzed and compared to determine trends among and between crop types.

Two types of comparisons were made with the micrometeorological (micromet) data: (1) comparisons of data between the two recorder locations for the same time period, and (2) comparisons between the micromet data and relative response on the imagery for the two locations. For example, Step 1 might involve use of micromet data to determine that, as expected, soil temperature was higher in the dry soil than the wet soil at the time of the August flight. Step 2 would involve examining the imagery (thermal infrared in this case) and ascertaining that the dry soil area does indeed have a higher response than the wet soil area. In only a few cases could both steps be completed, primarily because: (1) much of the micromet data was obtained at times other than during flights; (2) plots used in obtaining the data often did not both appear on the same photo and, therefore, could not be qualitatively compared; and (3) plots involved were sometimes too small to be comparatively studied on the imagery.

A major problem in evaluating the micromet data was that 2 to 5 days was too short a time to establish comparative trends of radiation, temperature, etc. during periods of partial cloudiness or changing weather conditions. During clear, sunny weather, such an interval was adequate to establish trends, but these clear conditions did not normally prevail. Another problem experienced was that of missing data due to generator failure or module malfunctions.

Table 2. Locations and dates of micrometeorological records, 1964

Crop description	Recorder	Dates
Sprayed alfalfa	A	July 28, 29, 30, 31
Diseased corn (hilled)	B	July 27, 28, 29, 30, 31
Normal alfalfa	A	August 4, 5, 6, 7
Normal corn (hilled)	B	August 4, 5, 6, 7
Normal birdsfoot trefoil	A	August 10, 11, 12
Sprayed birdsfoot trefoil	A	August 12, 13, 14, 15
Normal corn (drilled)	B	August 10, 11, 12, 13, 14
Immature soybeans	A	August 17, 18, 19, 20
Grass (by weather station)	B	August 20, 21, 24, 25, 26, 27
Bare soil (normal)	A	August 24, 25, 27, 28
Bare soil (wet)	A	August 31, September 1, 2
Bare soil (dry)	B	August 31, September 1, 2
Maturing soybeans	A	September 3, 4, 5, 8, 9
Mature corn	A	September 28, 29, 30, October 1, 2, 3, 4, 5, 6, 7, 8
Immature sudangrass	B	September 28, 29, 30, October 1
Sudangrass stubble	B	October 1, 2, 5, 6, 7, 8

Comparisons between two sets of micromet data indicated several calibration problems with the instrumentation. For instance, wind velocity was consistently 2 to 5 miles per hour greater over wet soil than over dry soil during a period of nearly 3 days, even though the two recorders were less than 100 feet apart in the same large field of bare soil. Comparison between the imagery and the micromet data also revealed anamolous situations. For example, on all sets of 27 August 1964 photos and imagery examined, the wet soil area had a lower response (less reflectance) than the adjacent dry soil area. However, the micromet data indicated, incorrectly, that outgoing solar radiation was consistently much higher (greater reflectance) from wet soil than from dry soil. Possible explanations for the error might be (1) module malfunction, (2) calibration differences, or (3) an error in one of the numerous steps required to reduce the micromet data.

Comparisons between micromet data recorded in specified locations and multispectral imagery of these same plots can be summarized as follows:

27 August 1964, imagery of wet (irrigated) and dry bare soil. (1) Soil temperature measurements corresponded well with thermal infrared imagery, in that temperatures were usually higher and the response on the imagery was higher for dry soil than

wet soil. (2) Outgoing solar radiation showed a negative correlation with all imagery between .4 and 2.6μ wavelength. The outgoing solar radiation was higher from the wet soil, but on all of the imagery the wet soil had a lower response than the dry soil. This is believed due to a malfunction in the micromet equipment.

30 SEPTEMBER 1964 IMAGERY OF MATURE CORN AND IMMATURE SUDAN GRASS. (1) In some cases, no difference in response between dry, brown corn and moist, green Sudan grass could be detected on the imagery, even though the temperature in and above the corn was at least 5° F higher than in and above the transpiring Sudan grass. In other cases, air temperatures in and above corn and Sudan grass showed a positive correlation with the thermal infrared imagery, the corn having a slightly higher response than the Sudan grass, as one might expect (assuming equal emissivity of these two crops). (2) Outgoing solar radiation showed a positive correlation with imagery in the .38-.44, .41-.47, .45-.52, .55-.64, and .62-.68μ wavelength bands. The outgoing solar radiation was consistently higher in corn than Sudan grass, and in these wavelength bands the corn had a higher response or higher reflectance. Because the corn was mature and the Sudan grass was green and immature, the latter had a higher response than corn in the .48-.56, .71-.79, .85-.89, and .38-.89μ wavelengths. The 2.0-2.6μ wavelength bands showed little difference in response.

In summarizing the micrometeorological data, it appears that the parameters of major importance are: (1) incoming and outgoing solar radiation obtained in the visible and reflective infrared portions of the spectrum; (2) soil temperature and moisture; (3) air temperature in and above the vegetation canopy; and (4) wind speed (and direction, which was not obtained but would have been desirable).

One major problem encountered was placement of the temperature sensors above and within the crop canopy to obtain a representative set of temperature data that could be correlated with data sensed remotely from above. Height of the vegetative canopy of various species, row width variations, and differences in plant morphology all probably influence the micromet results. Therefore, it is important (1) that many such micromet measurements be obtained in each field, (2) that the instruments be properly located in large fields so the data represent the true situation found in each field (no "edge effects") and (3) that each field be readily discernable on the remote multispectral imagery.

PRT-4 Data on Emitted Radiation

A Barnes Portable Radiation Thermometer, sensitive to emitted radiation in the 8-14μ wavelength band, was field tested during the September 1964 flights. It was used to determine "apparent temperature" or emitted radiation in various fields from a 50-foot altitude. The PRT-4 has a 3° field of view which, from a distance of 50 feet, allowed sensing of energy emitted from a circle of approximately 2.6 feet in diameter. The small area being sensed, along with variations in crop density and maturity, often caused variation of a few degrees in the reading obtained from a scan across a field. However, use of the PRT-4 did allow for relative estimates of energy being emitted by fields of various crops or by bare soil. The measurements obtained were not temperature alone, but a combination of temperature and emissivity of the objects sensed, as can be seen from the formula $E = \sigma\epsilon T^4$, where E is the radiant flux per unit area emitted from a surface (or of the energy being sensed by the PRT-4 in this case), σ is the Stefan-Boltzmann constant, ϵ is the emissivity of the object, and T is temperature in degrees Kelvin. It is erroneous to assume that ϵ is a constant and that E will vary only as a function of T^4. Most natural objects are thought to have a rather high emissivity, but it is difficult to measure emissivity accurately, and relatively few such measurements have been made on plants and soils.

Comparisons were then made between "apparent temperature" data, obtained with the PRT-4, and relative response of the same objects on the thermal infrared imagery. Since the 8.2-14μ imagery obtained during the September flights was generally poor, imagery in the 4.5-5.5μ wavelength band was used. A comparison between the 4.5-5.5μ and the 8.2-14μ imagery showed the relative response ranking among various fields to be the same in both wavelength bands.

Initial comparisons between radiometer readings and imagery revealed that a 2°F or larger difference in "apparent temperature" between fields will produce a difference in response on the imagery. With this background information, the following evaluation procedure was adopted:

(1) Fields sampled with the PRT-4 were ranked according to apparent temperature. (2) A ranking was predicted for the thermal infrared imagery. (3) The imagery was then examined to locate the fields sampled, and to evaluate and rank the relative response for these fields. The results are given in Table 3. The response designation "A" indicates a white tone on the imagery, whereas an "E" indicates a black tone. These tonal response designation were determined through the use of an Ansco Gray-scale and Density Evaluator. In most cases, the response ranking had been predicted reasonably well, simply on the basis of the PRT-4 readings.

Possible explanations for discrepencies are: (1) many areas sampled with the PRT-4 were small and therefore difficult to accurately identify on the imagery; (2) the imagery was not obtained at the same time the PRT-4 readings were taken; (3) gain settings on the scanner were incorrect for the particular range of emitted energy involved.

From this preliminary test the PRT-4 appears to be a valuable tool for studying the fluxes and ranges of emitted energy from various crop and soil situations. Further study is needed to determine (1) the value of thermal infrared imagery in differentiating various crop and soil conditions, (2) the best time of day and season to differentiate crops or soil conditions using thermal infrared remote sensors, and (3) how to predict range and amplitude of signal received by remote sensor systems.

Spectrophotometer Data

A Beckman DK-2 Spectrophotometer, mounted in a house-trailer, was used from 15 September to 15 October 1964, to obtain diffuse reflectance curves from 0.3 to 2.6μ wavelength for plant leaves of several crops and for various degrees of crop maturity. Double leaf layers were used for this work and reflectance values are, therefore, higher in the infrared portion of the spectrum than would be true for single leaf layers.

Reflectance curves were obtained on 172 plant specimens. These included (1) curves for leaves of various species, (2) a few curves on other plant parts, such as tassels, leaf veins, bark of trees, etc., and (3) curves for various parts of the same leaf, for comparable locations on different leaves, from various parts of the same plant, and from different plants in the same field. Data were obtained on corn (65 samples), soybeans (46 samples), sorghum (13), alfalfa (11), and only a few or a single curve for orchard grass, red and white clover, timothy, birdsfoot trefoil, bromegrass, tall fescue, reed canary grass, and several species of fruit trees. Copies of all curves were sent to the Target Signature Analysis Center, Institute of Science and Technology, University of Michigan, for inclusion in their data bank of spectrophotometric curves.

Table 3. Comparison of PRT-4 data and relative response ratings from thermal infrared imagery

	PRT-4 data		Thermal infrared imagery data (4.5-5.5μ wavelength)	
Description of area sampled	Apparent temperature in degrees F	Predicted response ranking	Relative response designation	Actual response ranking
DAYTIME, 1 OCTOBER 1964				
	0900 hours		**1010 hours**	
Bare soil, freshly tilled	78	1	A	1
Grass lawn	76	2	C+	2
Soybeans, from dry and mature to yellow leaves	74—76	2	C	2
Corn, mature	72—74	3	D+	3
Alfalfa, green	72—73	3	D	3
Maple tree foliage	67—70	4	E	4
	0935 hours		**1010 hours**	
Building roof, green asphalt, (sunlit)	95	1	A	1
Building roof, dull metal color, aluminum (sunlit)	78	2	A—	1
Bare soil	78	2	B+	2
Grass lawn	76—77	3	C	3
Gravel road	75—76	3	C	3
Building roof, green, aluminum, (shaded)	68	4	E	4
	1020 hours		**1010 hours**	
Bare soil, freshly tilled	86—88	1	A	1
Stubble field	84—85	2	B+	2
Corn, mature	70—80	3	C—	3
Sudan grass, green	79—81	3	C—	3
NIGHTTIME, 29 SEPTEMBER 1964				
	2240 hours		**2350 hours**	
Gravel road	63	1	A	1
Stubble field	60—62	2	A—	1
Corn, mature	60—62	2	B	2
Sudan grass, green	58—62	3	C+	3
	2320 hours		**2350 hours**	
Corn, mature	59	1	A	1
Soybeans, green to yellow leaves	57—58	2	C	2
Bare soil, freshly tilled	58	2	D	3
Grass road	54	3	E	4
	2350 hours		**2350 hours**	
Gravel road	63—64	1	A	1
Maple tree foliage	62—63	1	A	1
Building roof, green aluminum	57—58	2	E	2
Grass lawn	56—58	2	E	2

In evaluating the reflectance data, the following questions were posed: (1) Do characteristic differences in reflectance exist between the various species considered, and if so, at which wavelengths? (2) How much variation in this spectral reflectance exists among individual leaf samples within a field?

This problem of variation in spectral reflectance within a field may be divided into three parts, namely: (a) How much variation exists among different portions of a single leaf? (b) How much variation exists among leaves growing in different portions of a single plant? (c) How much variation exists among different plants in the same field?

The amount of spectrophotometer data gathered in 1964 was limited, so statistically reliable results are not possible. However, study of the data revealed the following trends: (1) There is relatively little variation within a single leaf, exclusive of vein areas. Maximum differences in reflectance were 5%, observed at 1.25μ, 1.65μ and 2.2μ wavelengths (Figure 5). The differences may be related, in part, to moisture content. The tip of the leaf normally had the highest reflectances at these wavelengths. (2) Little variation was noted between green leaves of a single plant, the maximum being 5% in the infrared portion of the spectrum (.7-2.6μ), and 7% in the visible portion (.4-.7μ). When dry leaves were compared with green leaves from the same corn plant, a marked difference in reflectance was found throughout the spectrum (Figure 6). Comparisons between leaves of similar appearance but from different plants within a given field produced results similar to Figure 5 for corn, soybeans, sorghum, and alfalfa.

Differences in reflectance between crop species were difficult to determine because all the curves of green leaves had about the same shape—similar to Figure 5, and differences among the species were small. Several curves were obtained for corn, soybeans, sorghum, alfalfa and orchardgrass. Comparisons among these curves indicated that, generally, corn was higher reflecting than soybeans in the visible, soybeans were higher in the infrared. There was some overlap, however, between these species throughout the spectrum in the bands of maximum-minimum reflectance. Curves for corn and sorghum were similar in shape, but corn had a lower reflectance than sorghum between 1.25-1.40μ, 1.6-1.7μ, and 2.1-2.28μ.

Alfalfa and orchardgrass curves can be differentiated from corn, soybeans or sorghum. Comparing corn to alfalfa, it was found that (1) from 0.75-1.1μ, alfalfa definitely had higher reflectance than corn, (2) from 1.1-1.3μ alfalfa usually had higher reflectance, and (3) from .35-.75μ and from 1.3-2.6μ, corn and alfalfa had similar reflectances. Comparing curves for corn and orchardgrass indicated that corn reflected more from .62-.68μ, but orchardgrass reflected more from .80-1.10μ, from 1.18-1.26μ, and from 1.67-1.90μ.

This type of comparative analysis was performed for each pair of crop species. On the basis of these comparisons, using limited numbers of spectral reflectance curves of green vegetation, the following species could be differentiated: (1) corn from sorghum, alfalfa, or orchardgrass; (2) soybeans from sorghum, alfalfa, or orchardgrass; (3) sorghum from corn, soybeans, alfalfa, or orchardgrass; (4) alfalfa from corn, soybeans, sorghum, or orchardgrass; and (5) orchardgrass from corn, soybeans, sorghum, or alfalfa.

Thus, among the species examined, only corn and soybeans could not be definitely differentiated. However, differentiation on the basis of spectral reflectance should be possible when maturity differences become pronounced. It has been found that corn and soybeans can be differentiated on .4-.7μ photos taken late in the summer.

The analysis of this group of spectrophotometer curves indicated that following wavelength bands are useful for differentiation of crop species: 0.41-0.45μ, 0.45-.50μ, .62-.68μ, .80-.90μ, 1.00-1.09μ, 1.20-1.25μ, 1.40-1.49μ, 1.60-1.80μ, 1.90-2.00μ, and 2.10-2.30μ.

Pattern recognition techniques for species identification, using digitized 1964 spectrophotometer data, are being investigated. Preliminary results are encouraging, but larger samples must be obtained before statistical reliability can be achieved.

ANALYSIS OF REMOTE MULTISPECTRAL IMAGERY

Objectives

The objectives involving analysis of the multispectral imagery are summarized as follows: (1) To determine if dependable differences in multispectral response patterns exist among various crop species at given periods in the growing season. (2) To determine the primary causes of variations between the multispectral response patterns of a given species. (3) To evaluate the effectiveness of remote multispectral sensing for agricultural crop surveys. (4) To evaluate the potential value to agriculture of the sensors and wavelength bands of imagery used in this program for possible incorporation into a remote multispectral sensing system.

Methods

All imagery obtained, either by cameras or optical-mechanical scanners, was reduced to a photographic film format and qualitatively analyzed using a gray-scale step wedge. This step wedge is a series of gray color chips, ranging from black to white in numbered

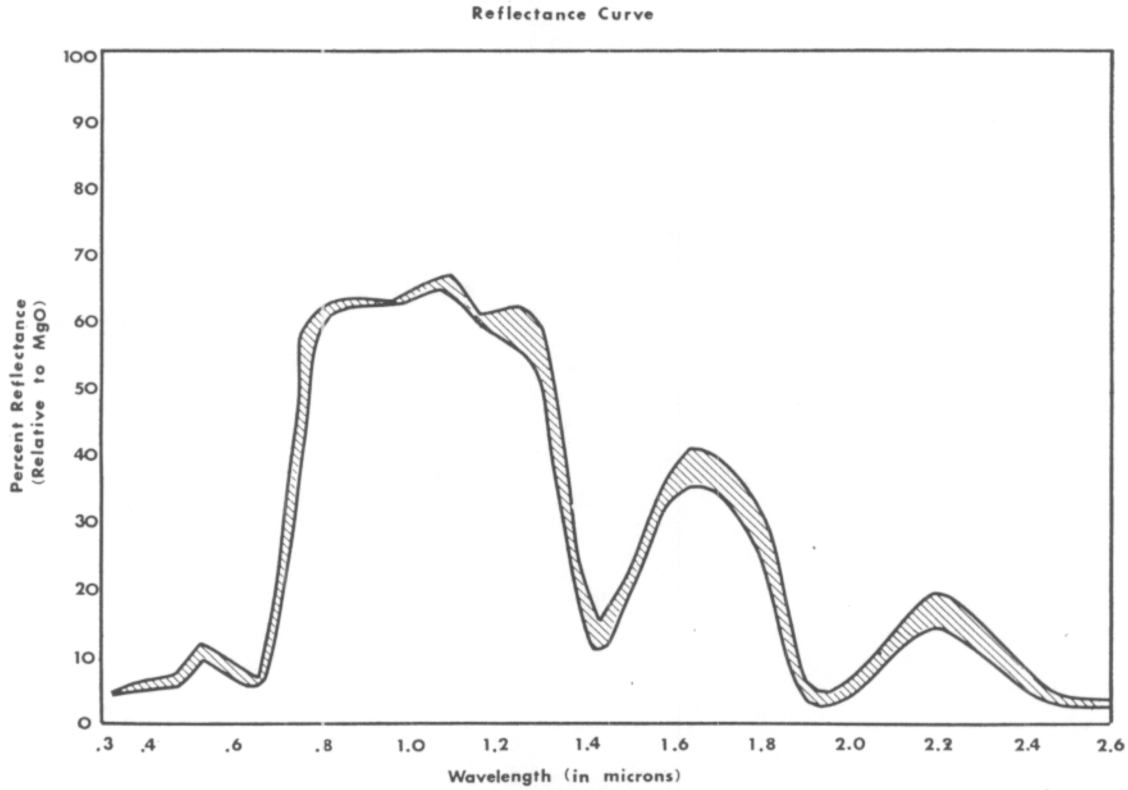


Figure 5. Maximum variation in spectral reflectance within a single green corn leaf. Low reflectance at 1.42μ and 1.96μ is due to water absorption at these wavelengths. Little pigment or water absorption between .7-1.3μ wavelength results in very high reflection and transmission values in this portion of the spectrum.

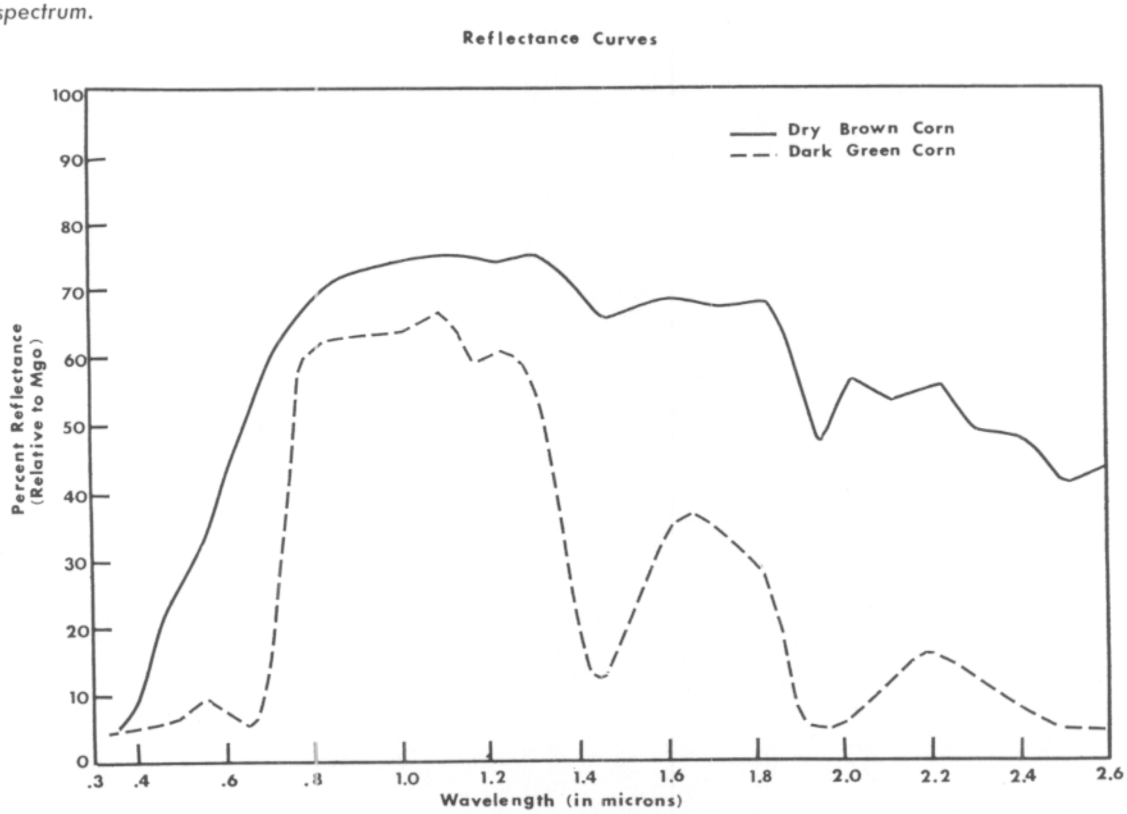


Figure 6. Difference in spectral reflectance of a green and a dry brown corn leaf. These marked differences are due to changes in color, moisture content and leaf histology. Double thickness of leaves were used in obtaining these spectra which accounts for the unusually high reflectance in the infrared wavelengths.

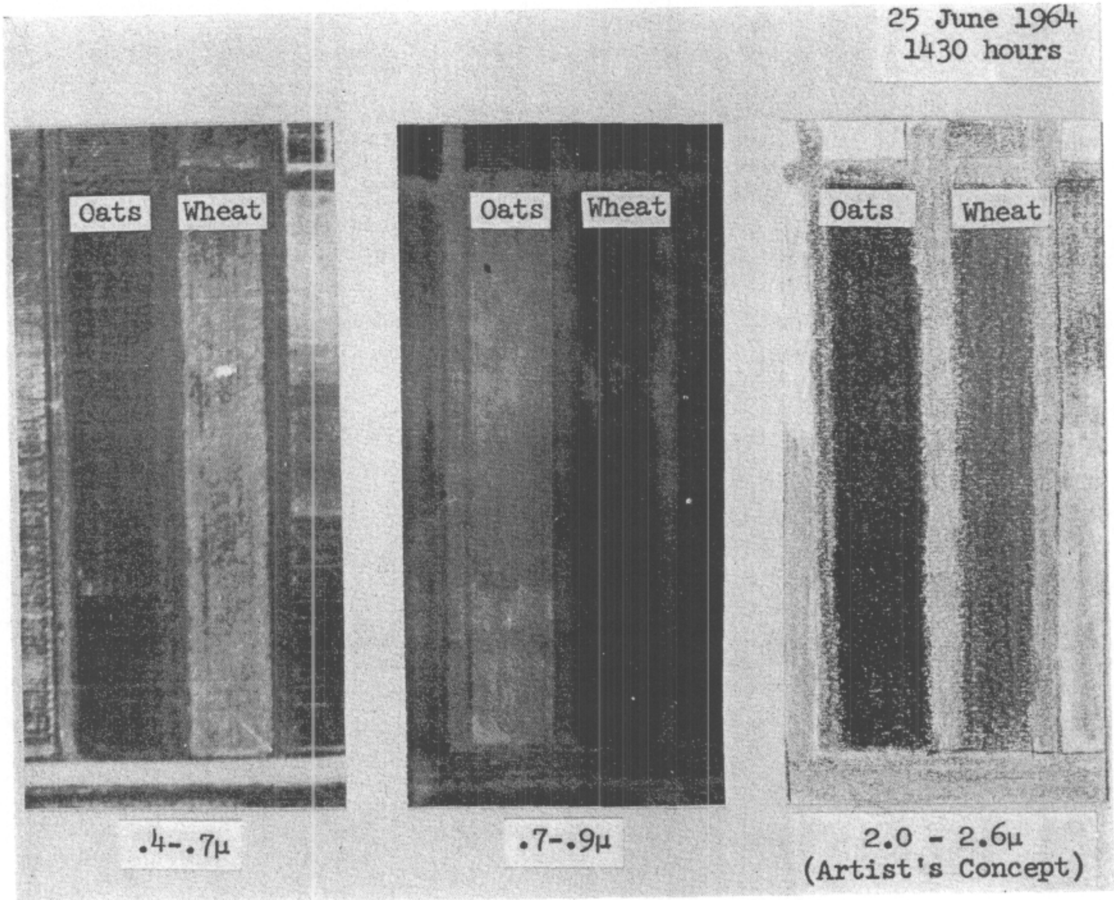


Figure 8. Multispectral comparison of wheat and oats in three wavelength bands. This imagery shows the differences in reflectance between wheat and oats that were graphically portrayed in Figure 7.

strongly than moist, green vegetation (such as the oats) in the 2.0-2.6μ wavelength band.

Figure 9 shows three 9-lens images obtained on 25 June 1964, which include several cover types in the eastern portion of the Purdue Agronomy Farm. As in Figure 7, the oats and wheat in the .38-.44μ band cannot be differentiated. But in the .62-.68μ band, wheat is higher in response than oats, while in the .71-.79μ band, the reverse is true. Alfalfa and oats in this imagery can be differentiated only in the .71-.79μ wavelength band, where alfalfa has a slightly higher response. The bare soil (a silt loam) stands out in both of the visible wavelength bands because of its relatively high response, but it blends in with the oats and other areas of green vegetation in the photographic infrared (.71-.79μ) region.

Figure 10 shows the variations in relative response among bare soil and several crop covers as of 29 July 1964, using six wavelength band images from the 9-lens camera. Notable features of this figure are:

1. Differences in response in the field of bare soil, particularly in the .48-.56μ image. The soil type in the lower left is Chalmers silty clay loam, whereas in the center of the image the soil type is Romney silty clay loam.

2. Drainage tile lines, especially noticeable in the .48-.56μ wavelength under the Romney silty clay loam soil but not under the Chalmers silty clay loam.

3. Intermediate response of wheat stubble compared to bare soil in the four visible wavelength bands, but a distinct difference in the infrared wavelength bands.

4. Slightly higher response of soybeans compared to corn in the .48-.56μ and infrared wavelength images, but the reverse situation in the .38-.44μ image.

Figure 10 also illustrates the problem of variation in exposure between wavelength bands, in this case, particularly between the two photographic infrared wavelengths (.71-.79μ and .85-.89μ). Slight differences in exposure also cause marked differences in relative response between two sets of objects, as seen when comparing the corn and wheat stubble in the slightly underexposed .71-.79μ image, then comparing these same two areas, as well as others, in the .85-.89μ image.

Figure 11 shows a representative multispectral response comparison for one field of soybeans and one steps. By matching the tone of an area of interest on a photographic print with the step wedge, one can rate the tonal response of that area. Because of variations inherent in the photographic process—exposure time, development time and chemical strength, and the film itself—comparisons by the step wedge method were made only between fields appearing on the same photograph.

The general procedure was to select and evaluate 5 to 20 fields on a photo, always checking to be sure that the designated response value was correct in relation to the other fields. The tonal evaluations were then recorded for all wavelength bands of imagery available. From these data, a multispectral response pattern was plotted for each field, and then all fields were compared for similarities and differences among and within various crop species.

Multispectral Response Comparisons Among Species and Cover Types

Analysis of many pieces of multispectral imagery in many wavelength bands indicates that a capability exists to differentiate and perhaps identify various crop species or crop cover types by remote sensing. The key is to obtain multispectral data at the proper period of crop development and at intervals throughout the growing season. For example, the flight on 25 June 1964 proved useful to differentiate oats and wheat but not corn and soybeans. The 27 August 1964 flight proved useful for the latter crops, but wheat and oats had already been harvested. It would appear that no single flight during the growing season will suffice for crop identification of all crop types.

Figure 7 compares several fields of wheat and oats on a single set of imagery, obtained on 25 June 1964. From this graph, it is evident that many wavelength bands recorded no response differences between the fields, while others recorded distinct differences.

Figure 8 offers pictorial evidence, in three wavelength bands, of response differences between wheat and oats, similar to those in Figure 7. The .4-.7μ and .7-.9μ wavelength bands in Figure 8 correspond closely to the .62-.68μ and .71-.79μ bands, respectively, in Figure 7. The artist's concept is a sketch showing relative tonal differences observed on the 2.0-2.6μ scanner imagery which could not be shown.

The marked differences in response in these wavelength bands is because the wheat is mature and golden-brown, whereas the oats are green. Therefore, the wheat reflects more than the oats in the .4-.7μ (visible) portion of the spectrum, but does not reflect as strongly in the .7-.9μ (photographic infrared) portion. On the basis of spectrophotometer curves using other types of plant materials, dry vegetation (such as the wheat) would be expected to reflect more

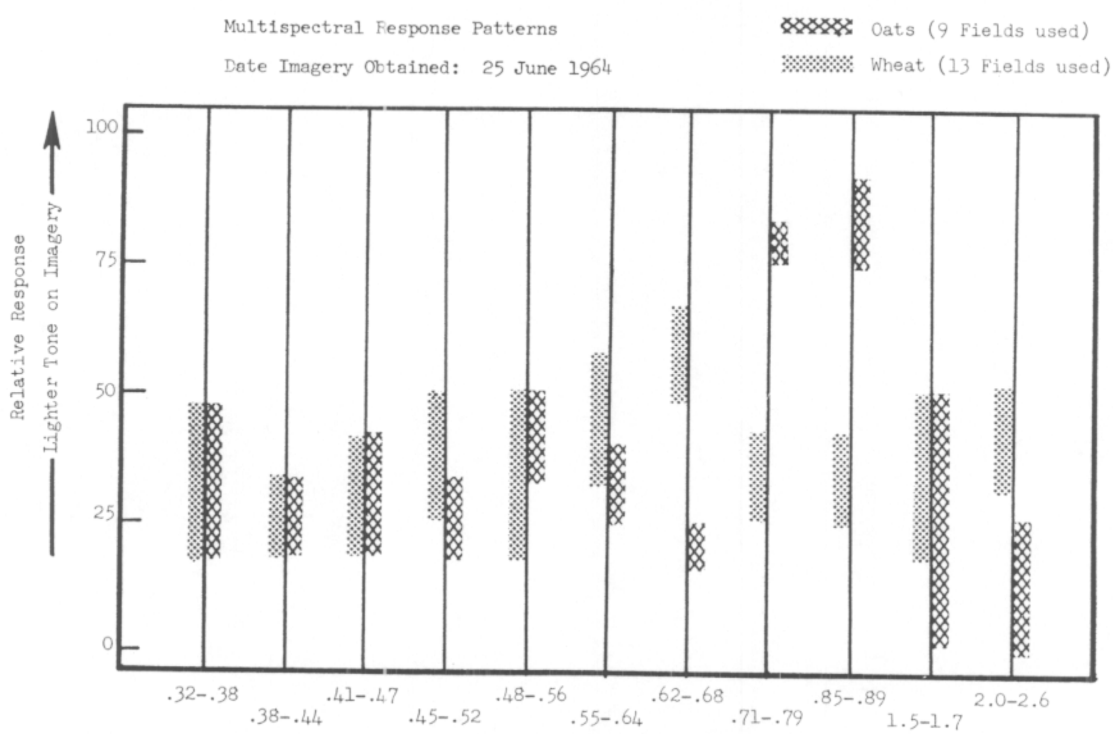


Figure 7. Comparison of multispectral response patterns of oats and wheat. Many wavelength bands did not allow differentiation. Only the .62-.68, .71-.79, .85-.89 and 2.0-2.6μ bands showed distinct differences in reflectance of oats and wheat at this stage of maturity.

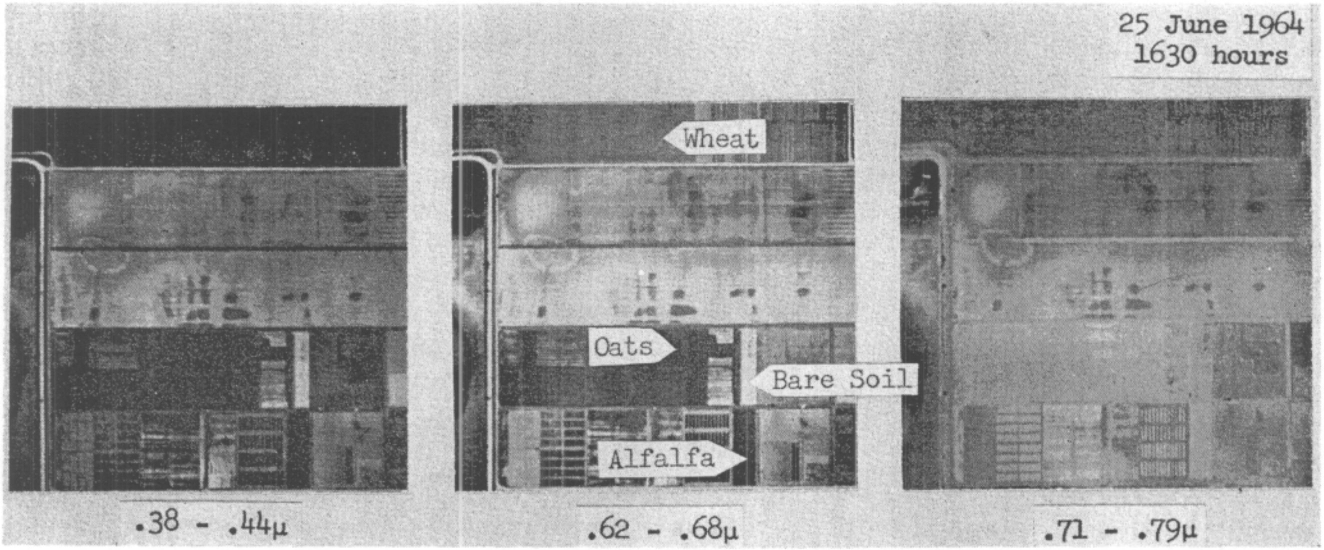


Figure 9. Multispectral response of several crop species and bare soil, 25 June 1964. Bare soil has a distinctly higher response in the .38-.44μ wavelength band, but not in the .71-.79μ band. The wheat can be differentiated from oats and alfalfa on both the .62-.68μ and .71-.79μ imagery. Alfalfa has a slightly higher response than the oats in the .71-.79μ band, but no difference shows up in either of the shorter wavelength images.

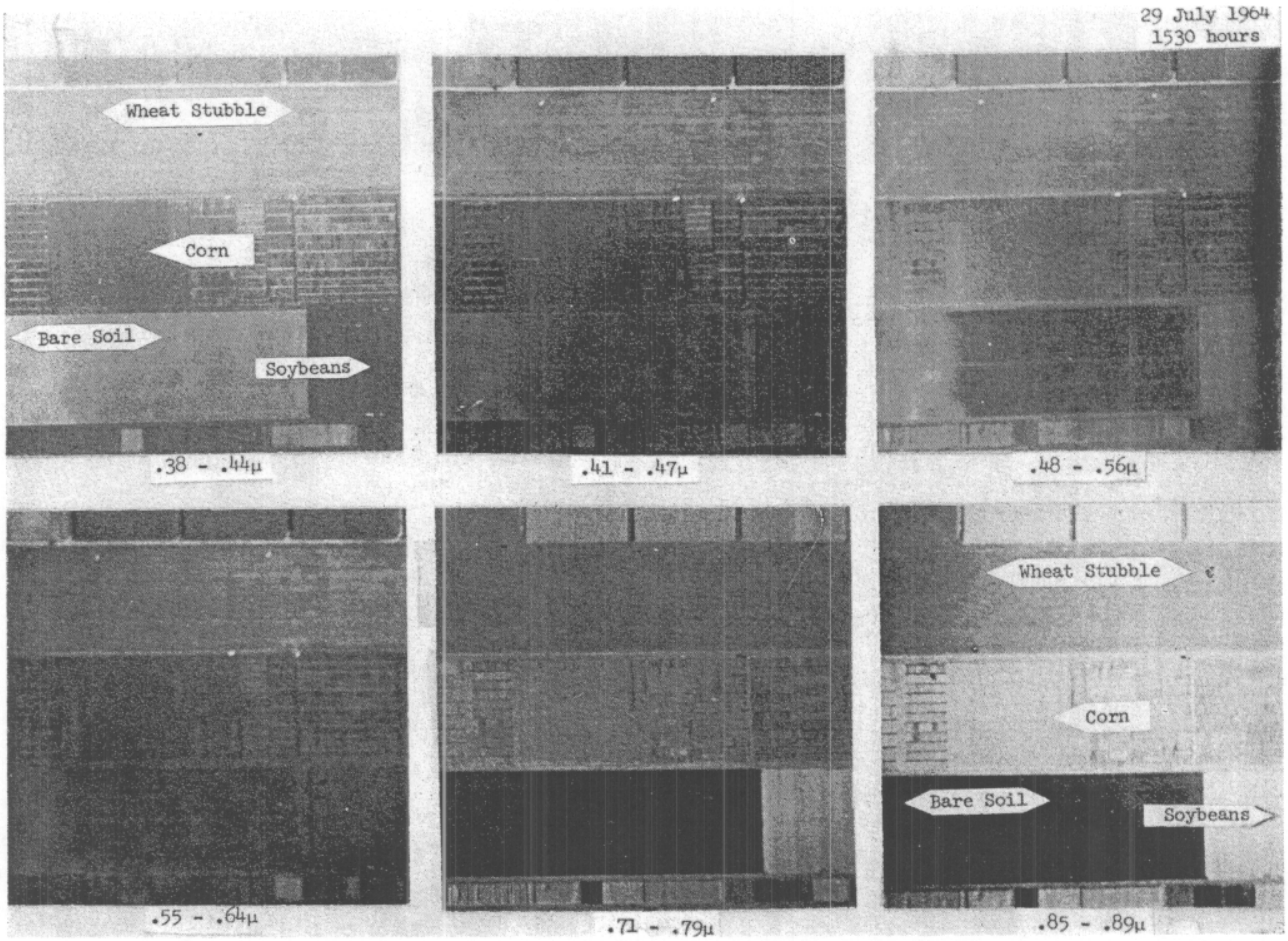


Figure 10. Multispectral response of bare soil, stubble, corn, and soybeans, 29 July 1964. Differences in response between corn and soybeans are slight. Wheat stubble can best be differentiated in the .38-.44μ and .85-.89μ wavelength bands. The .48-.56μ image best defines the two soil types, while the bare soil area is best distinguished from vegetative cover in the infrared wavelengths. The contrasts between bare soil versus vegetation in this figure, as compared to Figure 9, are due to differences in reflectance of the silty clay loam and silt loam soils.

area of bare soil, using 13 wavelength bands of imagery. The primary feature of this graph is the reversal of differences in response between bare soil and soybeans in different regions of the spectrum. In the .71-.79μ and .85-.89μ wavelength bands, for instance, the soil had a distinctly lower response than the soybeans; whereas in the visible wavelengths, the soil had a higher response. The same situation was observed in Figure 10. Note also in Figure 11 the lack of difference in the 1.5-1.7μ and 2.0-2.6μ wavelength bands, but the distinct differences in the thermal infrared wavelengths.

Figure 12 is a comparison between several fields of corn and soybeans. As was observed in Figure 10,

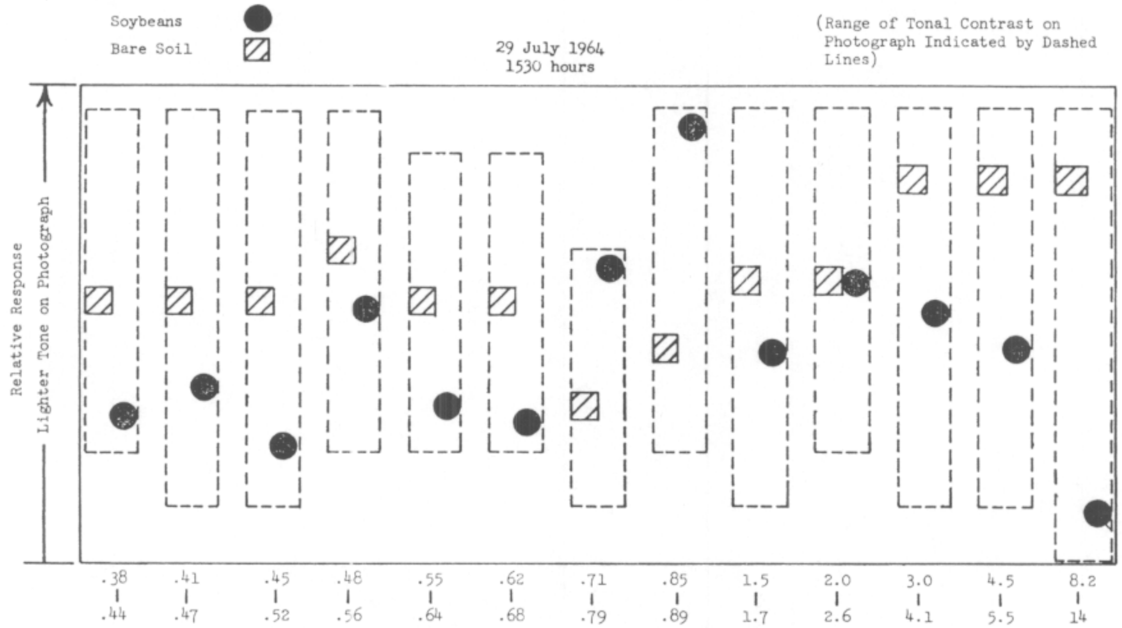


Figure 11. Comparison of multispectral response patterns of bare soil and soybeans, 29 July 1964. A comparable response was found in only one of the thirteen wavelength bands represented (2.0-2.6μ).

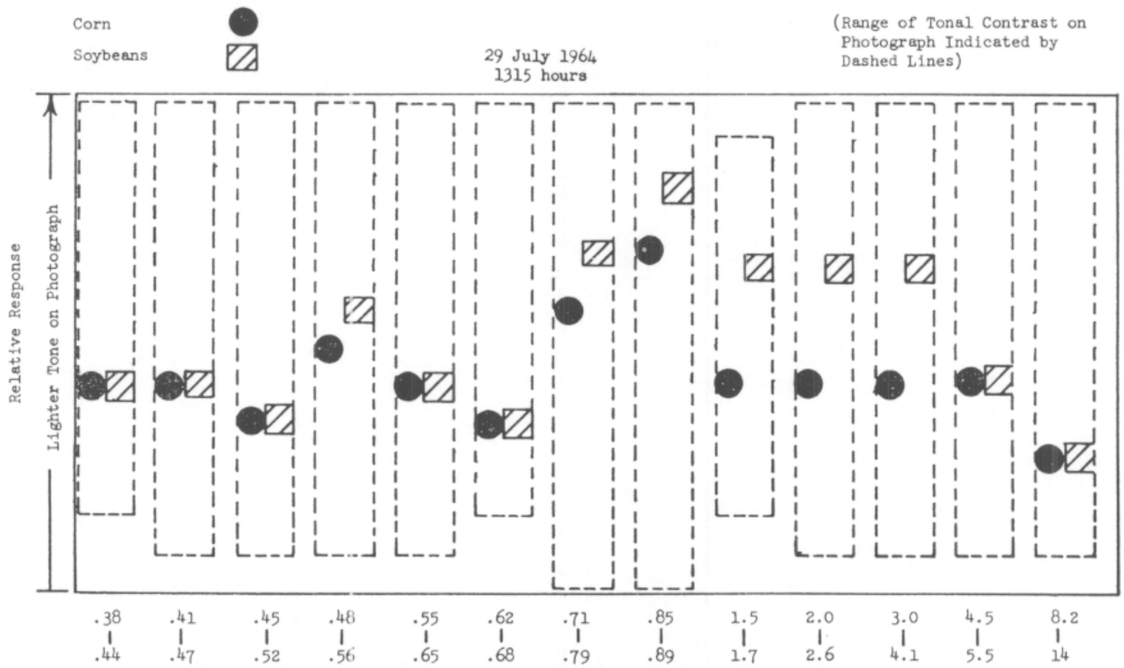


Figure 12. Comparison of multispectral response patterns of corn and soybeans, 29 July 1964. Wavelength bands throughout the photographic and thermal infrared portions of the spectrum show little, if any, differentiation between the corn and soybeans at this time of the year. The value of obtaining reflectance data in wavelengths beyond the range of sensitivity of photographic emulsions is seen by the response differences in the 1.5-1.7μ, 2.0-2.6μ, and 3.0-4.1μ bands.

differences in response between corn and soybeans were small throughout the photographic portion of the spectrum. In Figure 12, however, distinct differences between these crop covers are recorded in the 1.5-1.7μ, 2.0-2.6μ, and 3.0-4.1μ wavelength bands, but no differences are seen in the 4.5-5.5μ or 8.2-14μ wavelength bands. This again points to the value of obtaining multispectral imagery in bands outside the photographic portion of the spectrum.

Figure 13 dramatically illustrates the differences in response that may be recorded (1) for a given cover type in different wavelength bands of imagery and (2) for different cover types within a given wavelength band. The alfalfa—having a dense, green vegetative canopy at this time—yields a high response in the reflective infrared (.7-.9μ), but a low response in both the visible (.4-.7μ) and thermal infrared (4.5-5.5μ). The corn—being dry, brown and mature at this time—has a response similar to stubble in all three images. As expected, the bare soil has a very high response in the thermal infrared, rather low response in the photographic infrared, and a varied response in the visible region (the lighter soil being silt loam and the darker being silty clay loam).

An example of unclassified K-band radar imagery, obtained in September 1965, is shown in Figure 14. Responses of a limited number of individual fields on this imagery have been compared with ground truth data, and the following crop cover-tonal relationships determined: (1) High response—corn or soybean fields (differentiation between these species not possible on this imagery); (2) Medium response—stubble fields, pasture and alfalfa fields; and (3) Low response—bare soil and water.

As expected, forested areas produced a much coarser texture on the radar imagery than did cultivated cropland. However, somewhat surprising was the fact that corn and soybeans differed little in response, even though there are great physical differences between them at this time of year.

The 1964 multispectral imagery obtained at about the same time of year as this radar image showed that dry, mature corn and stubble fields were quite similar, but that stubble and alfalfa fields were very different (Figure 13). The radar imagery, however, showed distinct differences between corn and stubble, but no differences between stubble and alfalfa. This is another example where using more than one wavelength of imagery will allow differentiation between cover types. Further analysis of radar imagery with regard to different wavelength bands or cross-polarizations of a single band may prove radar useful to a multispectral sensing system.

Variation in Multispectral Response Patterns Within a Given Species

Variations in response were found with single spectral bands for certain species, particularly in the early

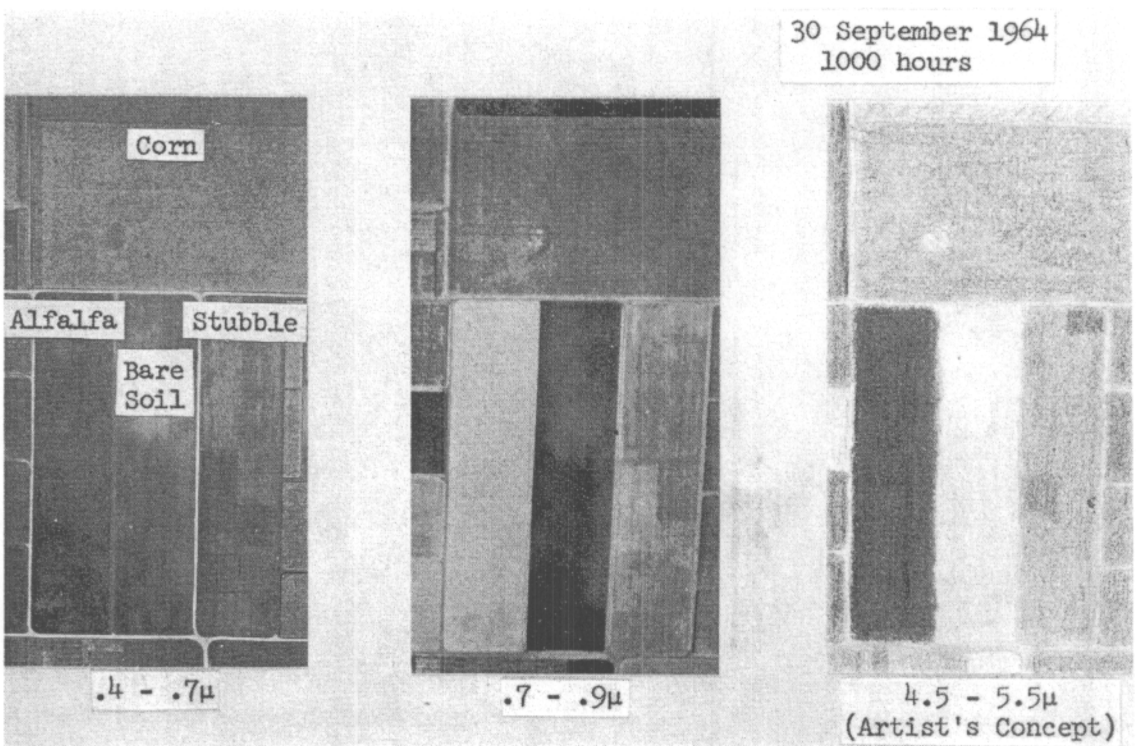


Figure 13. Multispectral response of corn, alfalfa, stubble and bare soil, 30 September 1964. Note the differences between alfalfa and bare soil, but lack of marked differences between mature corn and stubble.

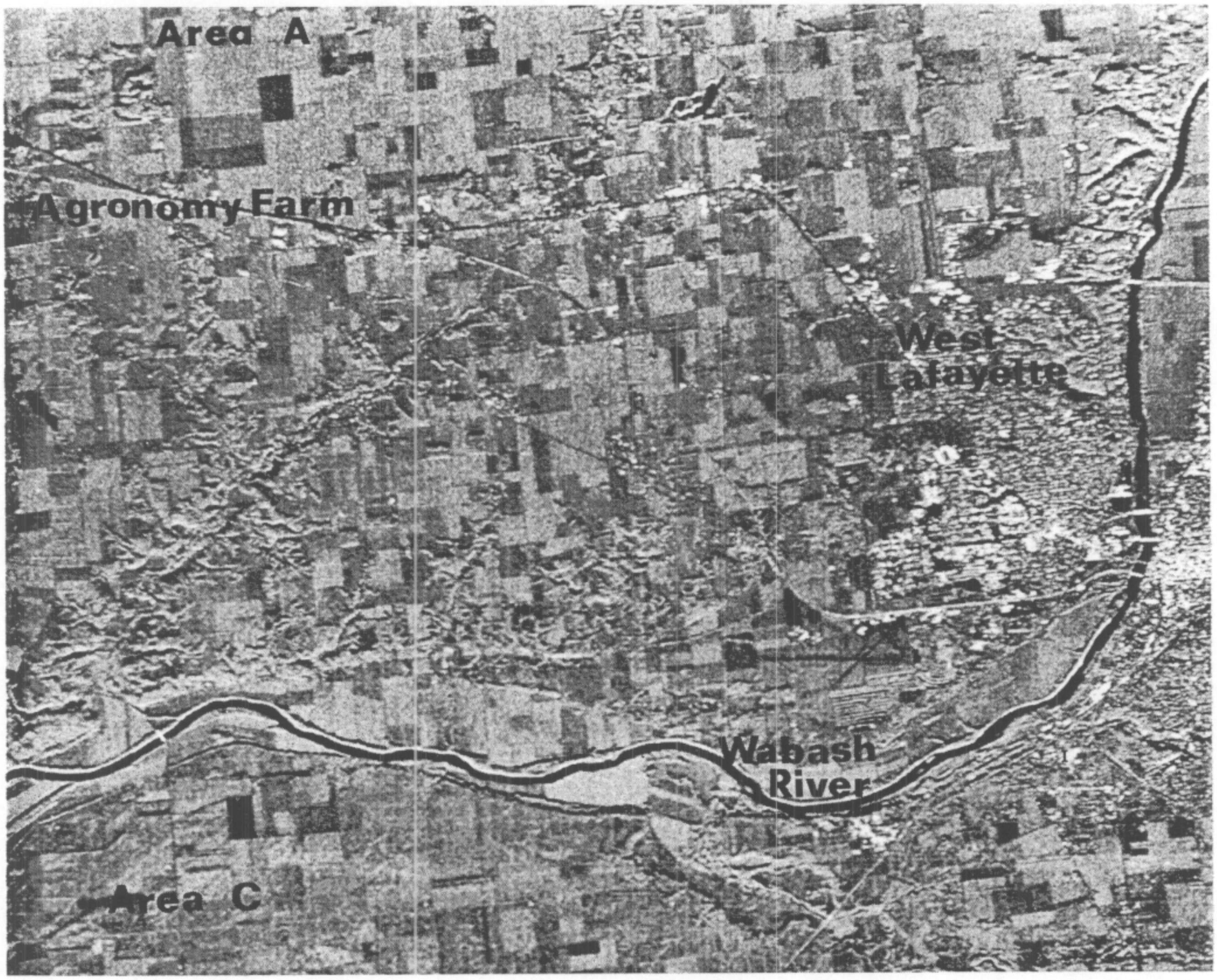


Figure 14. Unclassified K-band radar imagery, vicinity of Lafayette, Indiana, 14 September 1965. The high response areas are fields of corn or soybeans; medium response areas are alfalfa, pasture or stubble; very low response areas are water or bare soil.

and late periods of crop development. And in several instances, such variations were surprisingly large. Major causes of these within-species variations were density of crop canopy and crop maturity. Variations in mid-season were due largely to weed infestations, diseases, and cultural practices.

Crop Cover and Soil Type

A major variable in response patterns was the proportion of soil covered by the crop canopy—that is, the relationship between crop cover and bare soil as observed from above. In the early growing season, crop cover is influenced by date of planting, row spacing, and growth vigor.

The effect of date of planting on relative response in two wavelength bands is illustrated in Figure 15. Here a series of corn plots, with plants ranging from 1½ to 4 feet high, is compared using panchromatic ($.4$-$.7\mu$) and infrared ($.7$-$.9\mu$) film. On the panchromatic photo, the taller the corn, the darker the tone. This is because a greater percent of the light-colored, highly-reflective soil is masked by the corn canopy, which has low reflectance in the visible wavelengths. On the infrared photo, variations in ground cover are not so evident, because the green corn leaves and light-colored soil are both highly reflective in this wavelength band. Such situations of highly reflective soils blending with the normal high reflectance of green healthy vegetation in the photographic infrared wavelengths are not frequently encountered. Normally, agricultural soils will have a lower response than the vegetation in the $.7$-$.9\mu$ wavelengths, as is shown in Figures 16 and 17. A situation commonly encountered on light colored soils shows the vegetation to be lower in response than the bare soil in the visible wavelengths and the photographic infrared wavelengths also show a difference in response—the soil being lower in response than the vegetation.

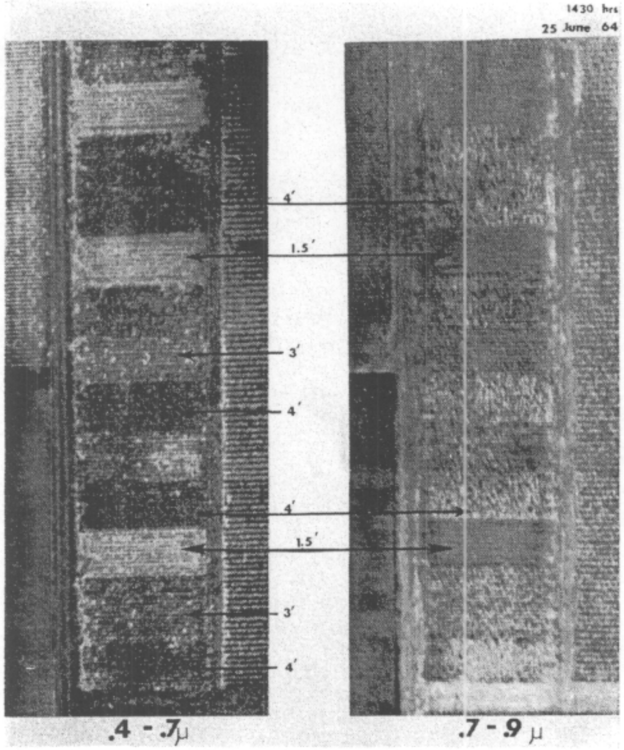


Figure 15. Variations in response due to differences in crop canopy on a light-colored soil. On this soil type, the panchromatic photo (.4-.7μ) records marked differences in response, depending on the percent of crop canopy, which correlates with the height of the corn. Soil and vegetation reflect more nearly the same in the infrared, and therefore, differences in canopy coverage cause less variation in response.

When the underlying soil is dark, differences in crop cover are more apparent in the infrared (.7-.9μ) wavelengths, due to the contrast between the low reflectivity of the dark-colored soil and the high reflectivity of plants. This is demonstrated in Figure 16, where peppermint is shown growing on a black organic (muck) soil.

Contrast in response due to differences in crop canopies is also seen in Figure 17. In the visible (.4-.7μ) wavelength band, the field of oats and two fields of corn show little contrast, regardless of planting dates. In the photographic infrared (.7-.9μ) band, however, the dense canopy of oats gives a high response; the corn planted on 4 May gives a lower response because of less canopy, and therefore, more dark soil being sensed; and the corn planted on 14 May gives a still lower response. Thermal infrared imagery obtained at the same time showed an equally low response in the oats and the corn planted on 4 May. The corn field planted on 14 May had higher relative response, which would correspond to the greater percentage of bare soil being sensed. The small, dark toned area to the right of the oats in Figure 17 is bare soil, which indicates the very low response in the reflective infrared wavelengths for this dark colored soil.

Variations in plant density in fields of headed, 22-30 inch tall oats and wheat were also more readily discerned in one wavelength band of imagery than another, depending upon the soil background. The

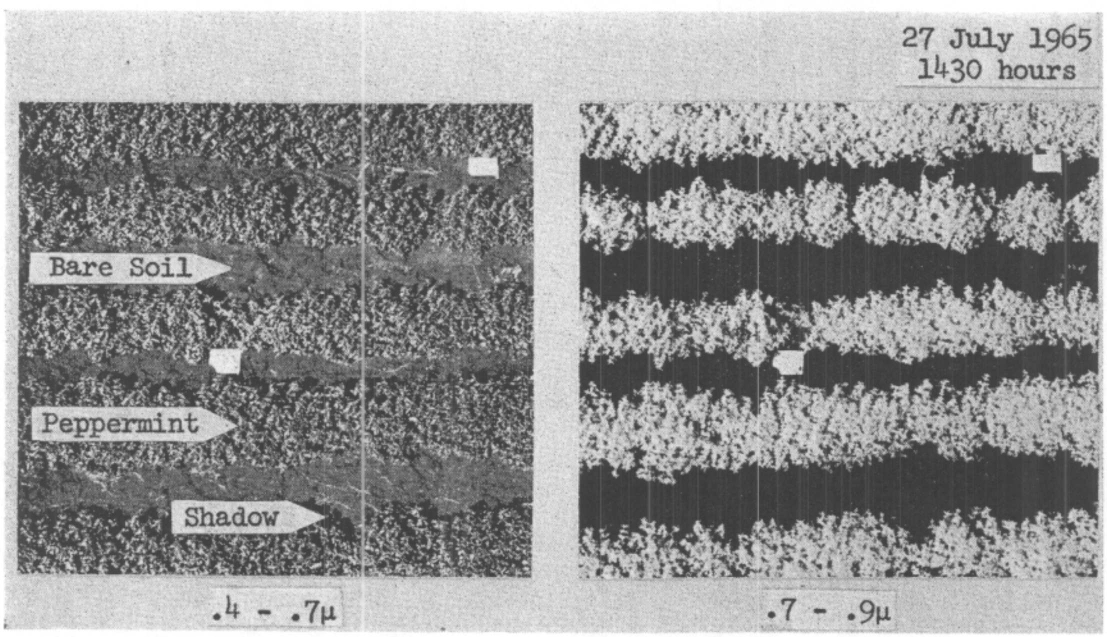


Figure 16. Spectral differentiation between vegetation and dark-colored soil. Vegetation and dark-colored soil have relatively low reflectance in the visible (.4-.7μ) wavelengths. However, in the infrared (.7-.9μ), vegetation reflects much more than the bare soil. On this soil type, variations in percentage of canopy cover would cause marked differences on aircraft imagery in the infrared wavelength, but not in the visible.

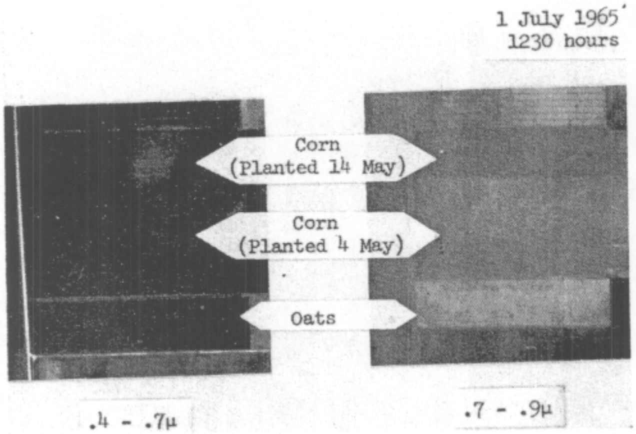


Figure 17. Oats compared to corn and date of planting differences, 1 July 1965. Variations in crop density and, therefore, in proportions of soil sensed cause response differences in the photographic infrared if the soil is dark.

two wavelength bands of imagery that showed the best contrast in response were 0.62-0.68μ and 0.71-0.79μ.

The influence of soil type and plant cover on tonal response is further seen in Figure 18. On 1 July 1965, the soybeans in this field were about 10-17 inches tall, and ground cover was estimated at 10-20%. The Ɔ-shaped area is a dark-colored silty clay loam and on the 1 July photo is much darker in tone than the rest of the field which is light-colored silt loam soil. By 1 September, when the second photo was taken, the soil differences were almost completely obscured by the soybean canopy.

It is apparent from Figures 15-18, that early in the growing season tonal response of a field is due to the combined reflectance from both the crop and the soil. In areas of light colored soils, differences in vegetative canopy cover from field to field will be more apparent on imagery obtained in the visible than in the photographic infrared wavelengths. For areas of dark soils, the reverse is true. For remote sensing purposes, variations in tonal response among fields of the same crop species should be minimized. This can be accomplished, in part, by obtaining imagery for each particular crop when that species has maximum or nearly maximum canopy coverage.

From a limited number of situations studied, it would appear that very early in the growing season radar and thermal infrared imagery may be more useful than visible or infrared photography in differentiating between fields of crops in early developing stages and fields of bare soil. For example, from 13 May aerial color photos, fields with crops less than 6 inches high looked like fields of bare soil, whereas these same crop fields showed lower response on thermal infrared and higher response on radar imagery than did adjacent fields of bare soil. These

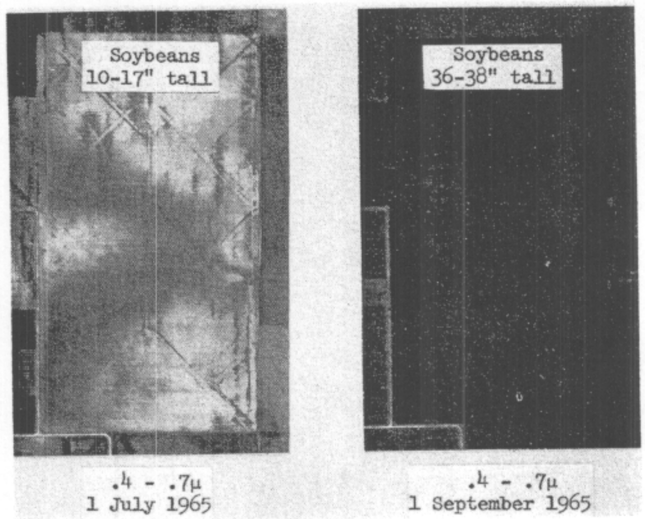


Figure 18. Effect of soil type on response and seasonal variation in crop cover. Prior to maximum and an almost complete canopy cover, soil type differences will cause distinct variations in response throughout all wavelength bands of imagery from 0.3-14μ, but here represented only by the .4-.7μ wavelength band.

differences in response on the side-looking radar imagery may be due to differences in texture between fields of soil and the fields of small, growing plants. The cooling effects of evapo-transpiration in the crop fields as well as differences in cultivation dates, could be responsible for the situation observed on thermal infrared imagery.

Maturity

Stage of maturity causes considerable tonal variation within a crop species. A week's difference in the planting date of corn, for instance, caused some tonal variation at various times throughout the summer, not just early in the growing season. In Figure 19, the panchromatic (upper) photo shows little difference in response between the north and south halves of the corn field, planted about a week apart. But the infrared photo shows a marked difference. The north half, planted later, had a higher response because it was not as mature on 30 September, and had somewhat greener foliage.

Varieties which mature at different rates will also cause differences in tonal response. Figure 20 shows panchromatic and infrared photos of a cornfield containing two hybrids planted on the same date. Again, little tonal difference is observed on the panchromatic photo, but a marked difference is seen in the infrared, because the hybrids differ in maturity dates. Such variation in date of maturity among varieties was common in soybeans and wheat, as well as corn, especially near harvest time.

Figure 21 shows a field containing four varieties

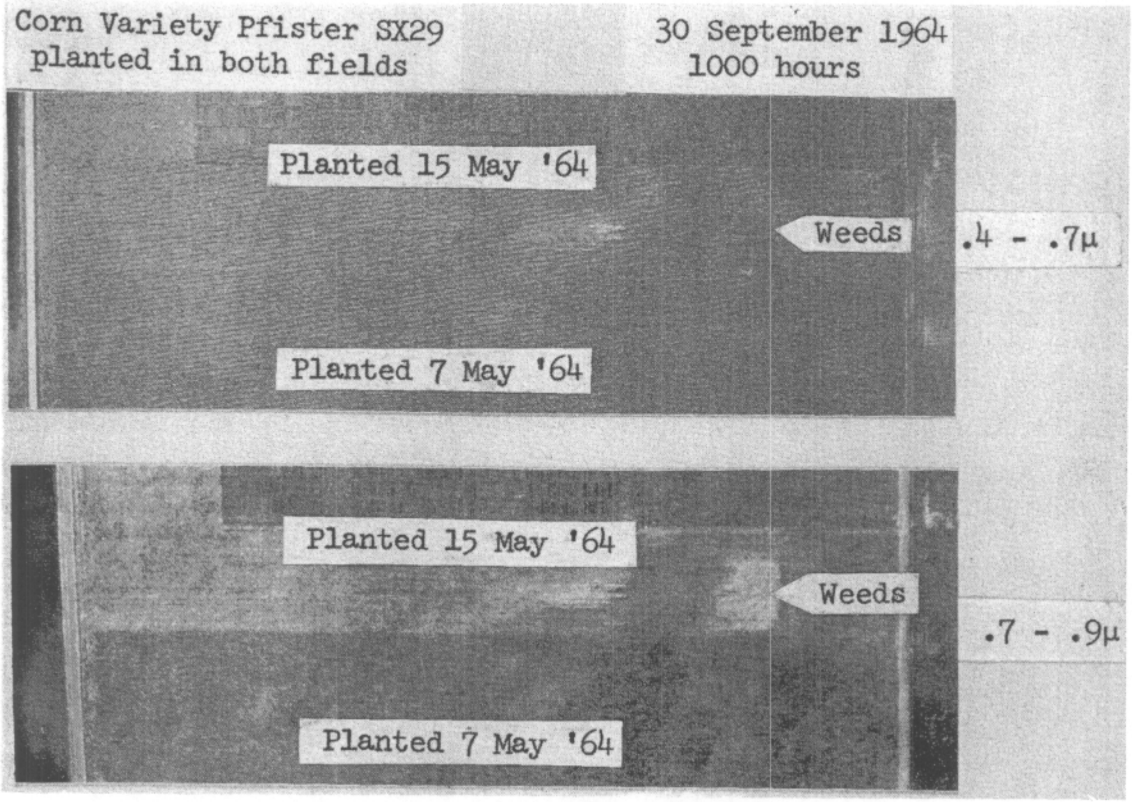


Figure 19. Corn planting date differences. Variations in crop maturity may cause marked differences in response late in the growing season, as seen in the infrared wavelength band. This difference in condition of maturity was caused by a difference in planting date.

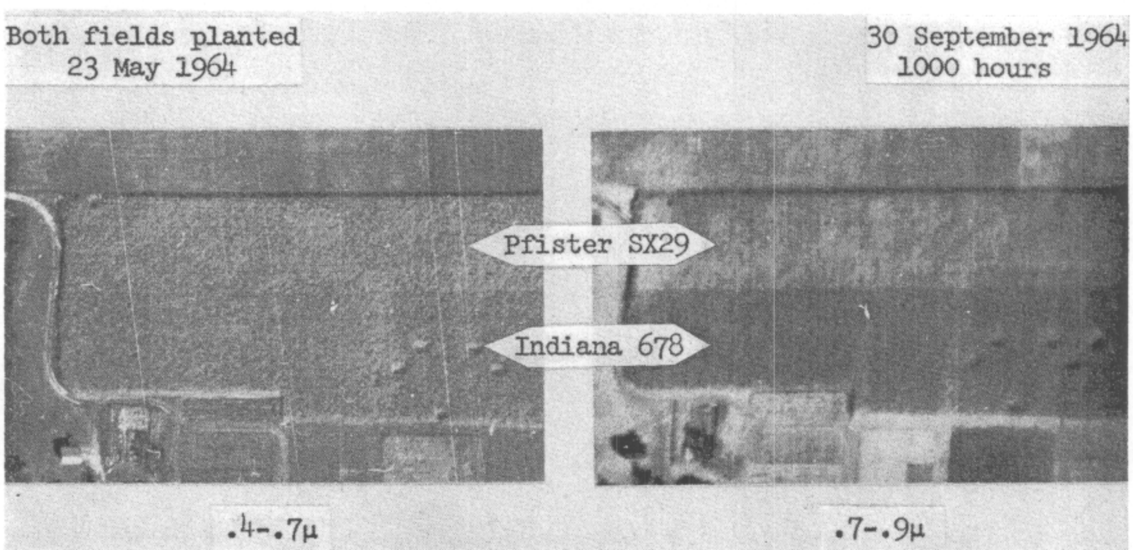


Figure 20. Corn variety differences. Differing rates of maturity among varieties of the same crop species cause variations in response in some wavelength bands.

of wheat with differing maturity dates. When photographed, the wheats were nearing maturity, having golden brown heads and brown leaves, thus causing uniform low response in the infrared. On the panchromatic photo, however, distinct variation is seen, just the opposite to that observed on the panchromatic photo of corn (Figure 20).

Tasseling date of corn may also affect tonal contrasts. Figure 22 shows the same corn field as in Figure 15, but a month later—27 July. On that date, the corn planted on 25 April and 6 May had tasseled, and exhibited a low response on the infrared photo. But the corn planted on 25 May had not yet tasseled and therefore had a relatively high response. Corn planted on 18 May was in the process of tasseling and was intermediate in response. There was almost no difference between these plots on the panchromatic photo.

Detasseled plots showed very little difference in tone from normal tasseled areas late in the growing season on either panchromatic or infrared films.

Disease and Weeds

Colwell (1956), Manzer (1966), and others have found the photographic infrared portion of the spectrum most useful in detecting certain plant diseases. Throughout the summer of 1965, attempts were made to assess various disease situations. Most of this photography was obtained from the "cherry-picker" truck (50-foot height).

Figure 23 shows peppermint on dark muck soil with several patches infected with Verticillum wilt. These diseased areas are barely seen in the panchromatic photo, but are readily seen in the infrared.

In its early stages, Verticillum wilt is difficult to diagnose. One symptom, however, is a reduction in secondary growth, which means greater exposure of soil between rows of infected plants. This characteristic would be useful in detecting diseased areas on vertical aerial photos. In Figure 23, the diseased foliage gives a lower response on the infrared film, but little difference in response on panchromatic film, thus indicating the usefulness of the infrared wavelengths in detecting and mapping this disease condition.

Plots of maize dwarf mosaic disease were photographed in an oblique view from a low-flying aircraft (Figure 24). On infrared film, only a slight difference in response is seen between healthy, uninoculated plots and severely infected plots. No difference is seen on the panchromatic film. It is probable that the differences in the infrared photograph are due, in part, to exposed soil, for the diseased corn is severely stunted and many plants are missing. Vertical photos from a 50-foot height over this corn field showed no obvious decrease in infrared reflectance of individual diseased corn plants. Additional work is needed to determine (1) the usefulness of multispectral imagery in detecting maize dwarf mosaic disease and (2) whether spectral response differences are due only to a decrease in infrared reflectance of the diseased plants, or a combined plant-soil effect.

Another virus disease—bud blight of soybeans—was studied at 2,250 feet and 500 feet altitude (Figure 25). Marked differences in tonal response were noted between diseased and healthy soybeans in the higher altitude aerial infrared photo, the alternating *plots* of diseased beans having a lower response. At 500

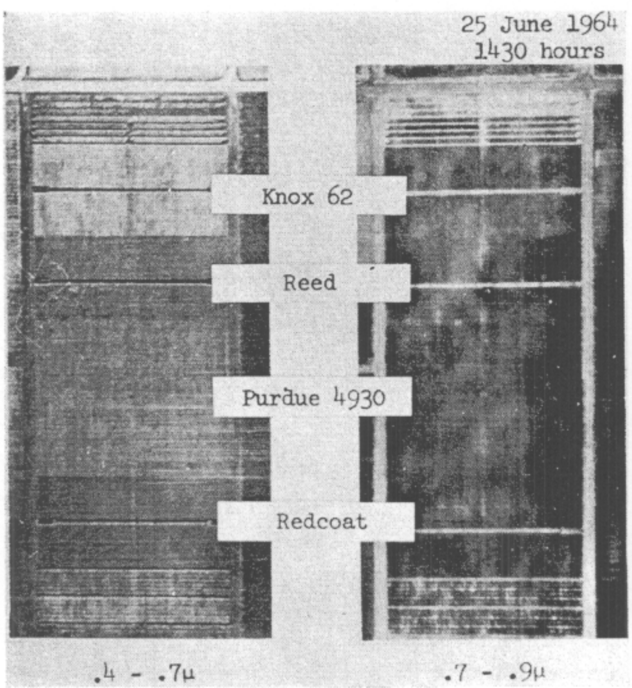


Figure 21. Wheat variety differences. Note the lack of variation in the .7-.9μ wavelength band, but distinct differences in the visible wavelengths, as compared to Figure 20. Relative differences in maturity of these varieties are indicated by the heading dates of these fields in 1964: Knox 62—18 May, Reed—24 May, Purdue 4930—23 May, and Redcoat—24 May.

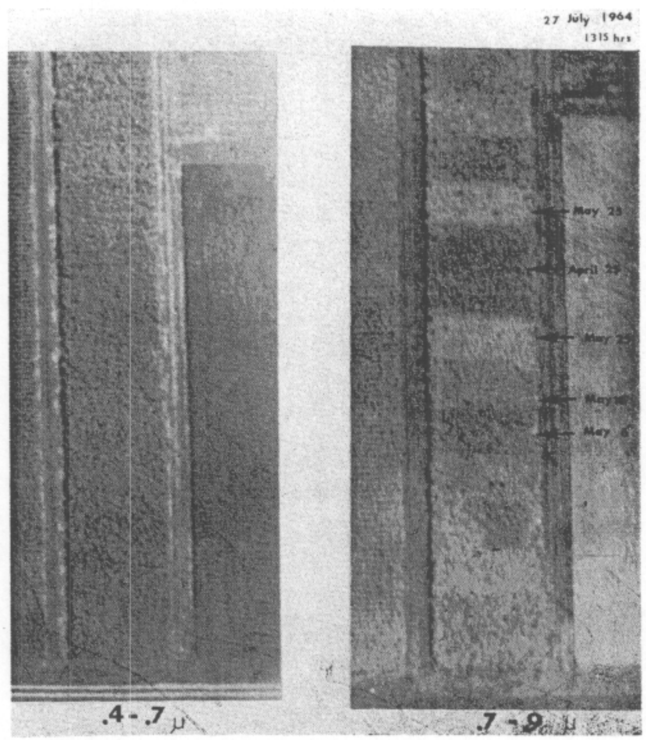


Figure 22. Response differences due to tasseling. Little difference in reflectance is observed in the .4-.7μ wavelength band among the various corn plots. However, in the infrared photo, plots which have tasseled are lower in response than the plots planted on 25 May which have not yet tasseled.

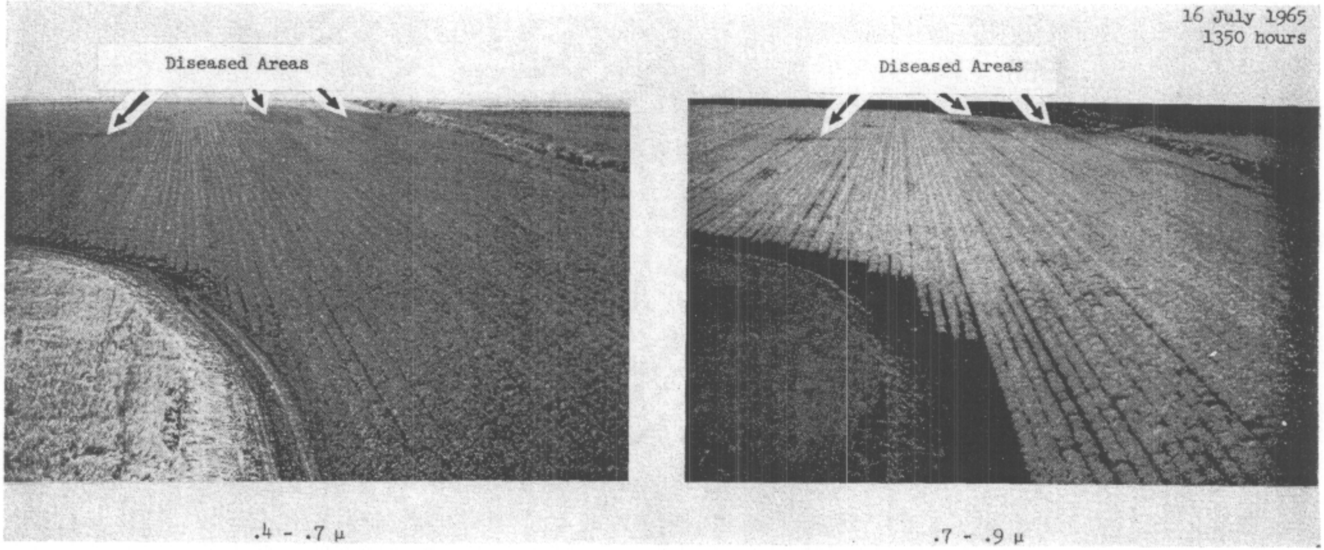


Figure 23. Influence of verticillum wilt in peppermint on spectral response. Because of the oblique angle of these photos, the lower response of the diseased areas in the infrared photo is due to a difference in reflectance of the plants, rather than a greater percentage of soil being sensed.

feet, however, little difference in response between healthy and diseased *rows* of plants is evident in either the visible or infrared wavelengths. The reason for the tonal differences observed between these healthy and diseased soybeans *plots* is that the diseased beans, being severely stunted, allowed more soil to be exposed causing a lower response of the diseased plots, especially in the higher altitude photos. Individual plants and rows of healthy and diseased plants have little or no difference in reflectance—a fact supported by photography from a 50-foot height over similar plots of healthy and diseased soybeans grown in 1965. The diseased plants were severely dwarfed but no obvious decrease in reflectance in the near infrared was noted, as compared to healthy plants.

From these examples, it would appear that capability to detect areas of diseased plants may not simply be a case of a reduction in infrared reflectance. Rather, the lower response of the diseased areas as compared to healthy areas may be caused by a reduction in growth and crop canopy in the diseased areas and thus a greater proportion of a low reflecting soil may be sensed.

Weed infestations in various crops were observed. In some instances infestations are quite apparent on the panchromatic photos but not the infrared. For example, in the .41-.47μ image of Figure 24, the weeds are light streaks in the field to the right of the corn field; they do not appear in the infrared photo. In other cases, however, weeds are prominent on infrared but not on the visible photographs. (See the infestation of small grass and thinly scattered weeds in Figure 19).

Weed areas were detectable on other sets of imagery in *both* visible and photographic infrared wavelengths, because of differences in spectral reflectance between weeds and surrounding crop foliage. Differences in thermal emission also allowed weed detection on several sets of the 8-14μ wavelength imagery.

Cultural Practices

Causes of major variations in spectral energy response from crops and soils are cultural practices such as soil tillage, harvest operations, fertilizer treatments and herbicide treatments. Soil tillage such as disking, which may break up a dry, relatively smooth soil surface to expose moist, darker-colored soil, causes marked differences in response in many spectral regions. In one instance, the pattern used to disk a field could be deduced from imagery generated in the thermal infrared region (8-14μ) *after* the disking operation had taken place. Moisture differences caused the recently-disturbed tilled soil to be cooler than the undisturbed areas. This temperature difference, detected on the thermal infrared imagery, persisted longer than the color differences, detected on the panchromatic and infrared photographs.

Harvesting of alfalfa created distinct differences in response. Figure 26 compares a recently-harvested field with an uncut field where plants are about 17 inches tall. The .41-.47μ wavelength band (blue portion of the visible spectrum) shows slight difference between the harvested and unharvested areas. The .48-.56μ (green) region shows no difference; however, the .62-.68μ (red) band shows the harvested portion as a much higher response than the unharvested. (This latter situation also was found on .4-.7μ panchromatic photos.) In the infrared photo (.85-.89μ

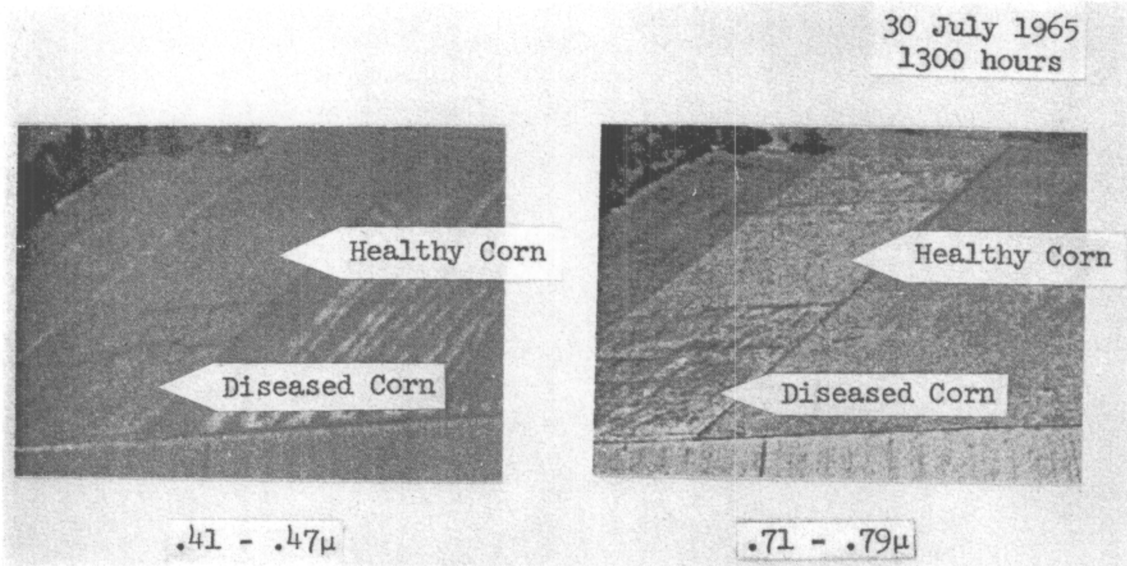


Figure 24. Spectral response differences due to maize dwarf mosaic. Photos taken only 50-feet above this field showed little difference between diseased and healthy corn plants. It is possible that the lower response of the diseased area shown here in the .71-.79µ band is due to a reduced crop canopy.

wavelength), the response difference between harvested and unharvested alfalfa is the reverse of the .62-.68µ band. The dense green cover of the unharvested alfalfa reflects strongly in the infrared wavelengths, causing a relatively high response. These photographs illustrate the discriminating power of multispectral imagery. In agricultural pattern recognition programs, similarities in relative response in some wavelength bands are thought to be as important as the contrasts in response found in the .62-.68µ and .85-.89µ wavelengths.

Amount of regrowth of alfalfa following harvesting also strongly influences response. In Figure 27, amount of regrowth reverses the response between the visible and photographic infrared wavelength bands and also causes differences within each band. It is apparent that multispectral signatures of hay crops will vary considerably during the growing season as cutting and regrowth occur. Since all alfalfa fields would not be cut at the same time, there may be periods during the growing season when positive identification will not be possible.

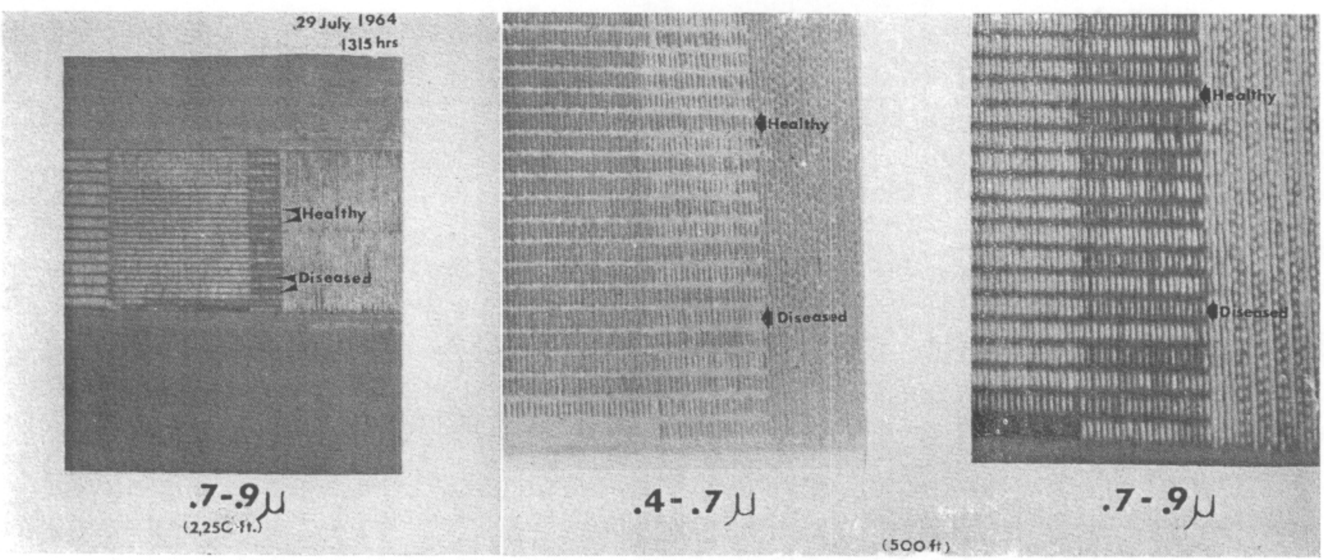


Figure 25. Soybean bud blight plots at two altitudes. The arrows designate healthy and diseased plots of soybeans, each plot (horizontal orientation) consisting of 19-20 rows (vertical orientation) of soybeans. Reduction in response of diseased plots is not a function of decreased reflectance of the plants, but rather a reduction in size of plants. Smaller plants allow a greater percentage of dark soil between the rows to be sensed, thereby causing the overall lower response for the diseased plots.

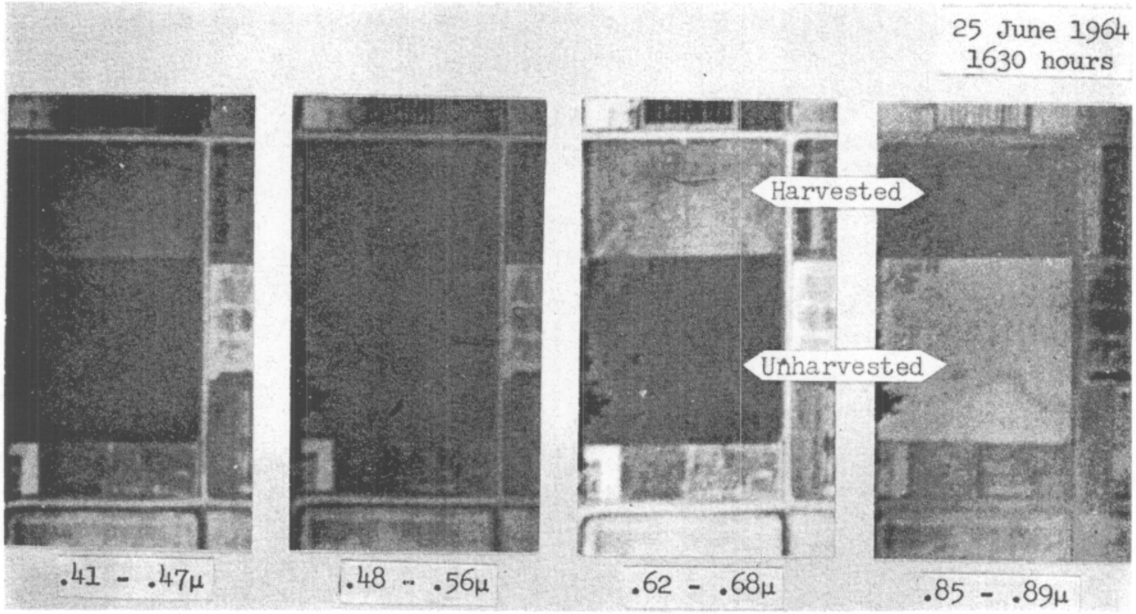


Figure 26. Differences in spectral response between harvested and unharvested alfalfa. In the .41-.47μ wavelength band, only a slight difference is seen; in the .48-.56μ band, no difference; in the .62-.68μ (red) and .85-.89μ (infrared) bands, however, relative response differences are distinct and reversed.

Photos taken on 25 June and 29 July 1964 were studied to determine the effects of nitrogen, phosphorus and potash treatments on corn, soybeans and wheat. Response differences due to lack of fertilizer were found only on the 25 June panchromatic photos, and no differences were seen on the 29 July panchromatic or infrared photos. Response differences were ascribed to the lighter green foliage and reduced vigor, which allowed more light-colored soil to be exposed. Higher response was observed for plots of corn with potash deficiency, but lack of phosphorus caused no tonal contrast, as compared to fertilized plots. In wheat, 0-phosphorus plots had a higher response, but no difference was discerned due to 0-potash. In soybeans, neither potash or phosphorus treatments caused any discernible differences in response.

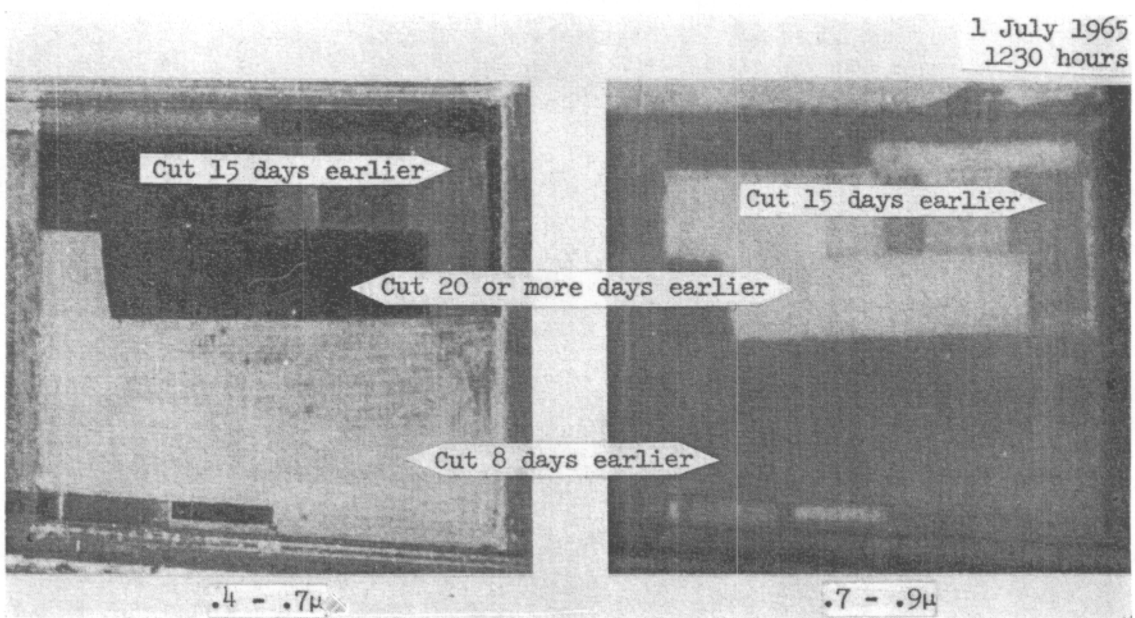


Figure 27. Variations in response due to date of harvesting. Differing amounts of green vegetation, stubble, and bare soil due to harvesting of forage crops cause distinct but variable responses. This creates severe problems in remote identification of cover type.

Moiré Patterns in Row Crops

Moiré patterns sometimes occur on scanner imagery, but only in situations involving row crops. From these patterns, information can be obtained on row direction, row width, and general crop category.

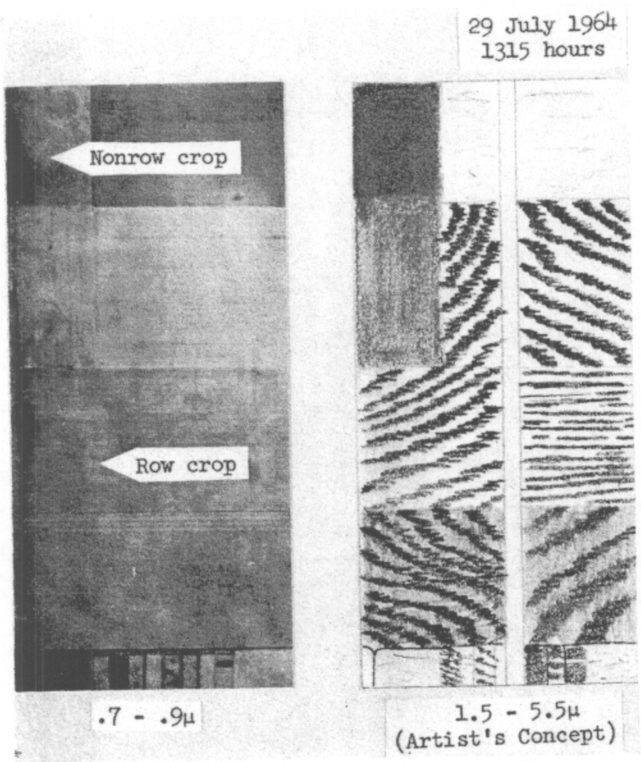


Figure 28. Moiré patterns in row crops. Geometric relationships between the airborne scanner and row crops can cause moiré patterns. Presence of such patterns indicates the presence of a row crop, but absence of moiré patterns does not necessarily mean absence of a row crop.

Lack of moiré patterns, however, does not necessarily mean that the field does *not* contain a row crop. In the left photograph of Figure 28, row crops are rather difficult to differentiate from non-row crops. However, in the artist's concept of scanner imagery on the right, the moiré patterns readily identify the fields occupied by row crops.

Figure 29 shows a low altitude photograph and artist's concept of the scanner imagery indicating effect of row direction upon the moiré pattern. Horizontal rows cause a moiré pattern on the imagery, whereas vertical rows do not allow a moiré pattern to be created. These last two figures indicate that under certain conditions of obtaining scanner imagery (altitude, scanner resolution, direction of flight, field orientation, etc.), moiré patterns may result. The occurrence of these patterns may be of potential use, but they may also cause severe problems in determination of spectral response patterns of individual fields.

Soil Type and Soil Moisture Situations

Differences in soil type may cause marked differences in response within a single wavelength band of imagery (see Figure 18). Figure 30 illustrates the differences in response between two soil types in four different wavelength bands. Silty clay loam soil is much darker than silt loam, and at the time this imagery was obtained, both types were quite dry. The silty clay loam, therefore, had a much lower

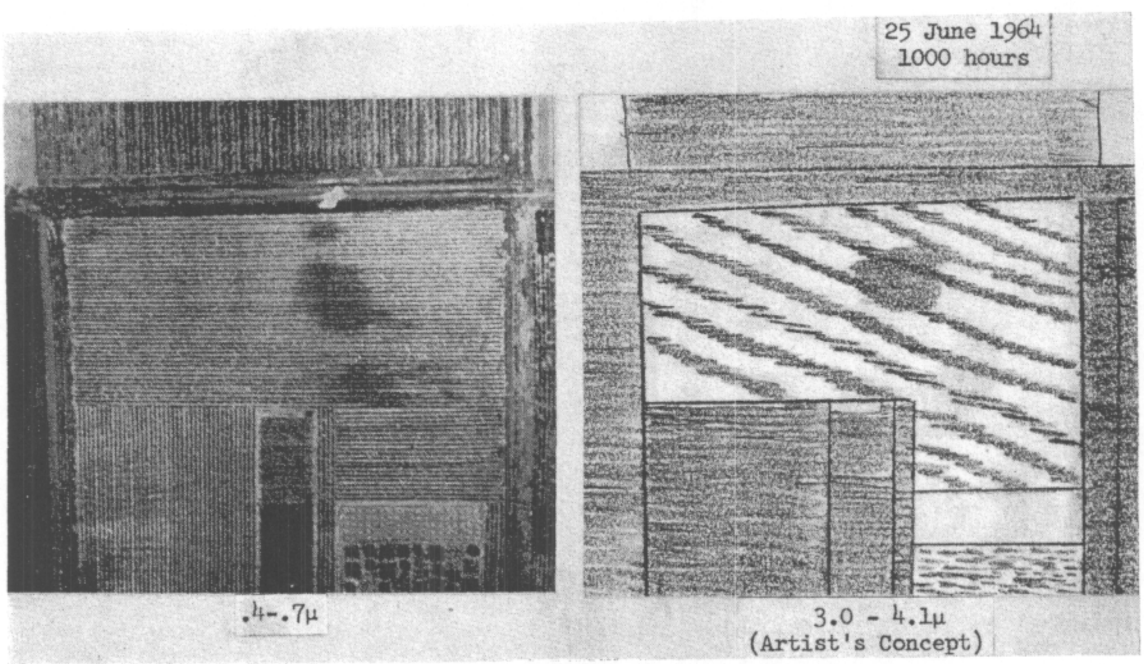


Figure 29. Moiré patterns as affected by row direction. Only when the scan line of the optical-mechanical scanner is nearly parallel to the row direction will a moiré pattern be formed. Rows in a perpendicular orientation cannot cause a moiré pattern.

response than the silt loam in the *reflective* wavelengths (.32-.38μ in the ultraviolet, .4-.7μ in the visible, and .7-.9μ in the photographic infrared). The opposite relative response occurred in the thermal infrared. This was caused by differences in "apparent temperature" between the two soil types. Since both soils were dry, the darker silty clay loam absorbed more solar radiation and was warmer than the silt loam.

The area of vegetation had a low response in the ultraviolet, visible, and thermal infrared wavelengths, but a high response in the photographic infrared. Since this vegetation pattern is unlike that of either soil type, the vegetation can be readily differentiated.

Comparisons were also made between areas of dry, bare soil and irrigated soil. In these cases, the wet soil had a lower response than the dry soil throughout the optical spectrum from .38μ-14μ wavelength. Evaporation cools the wet soil causing low response in the thermal infrared, while the darker color of the wet soil causes a lower response in the visible and reflective infrared.

Such reversal or lack of reversal in response between reflective and thermal infrared portions of the spectrum is potentially useful in distinguishing wet from dry soils where soil types vary. For example, if one had only visible wavelength photography of bare soil, and an area of low response appeared against a background of high response, would this be caused by two different soil types (both dry), or by two levels of soil moisture? A reversal in response between these two areas on thermal infrared imagery would indicate two different soil types; no reversal on the thermal infrared would indicate two levels of soil moisture. Of course, such a situation would have a cross-over point at some degree of intermediate soil moisture. Much work remains to establish a statistically-reliable decision criterion.

Figure 31 shows a portion of southwest Texas, taken from Gemini IV at an altitude of 102 miles, and includes a long finger-like area of relatively low response (dark area) extending through both cultivated and uncultivated areas. Is it caused by differing soil types or differing soil moisture? Use of thermal infrared imagery would help answer such a question, for a rain storm had passed through the previous day, and the dark-toned area is a result of higher soil moisture (Hope, 1966).

Figure 32 shows sequential photos in which a moist soil pattern could be readily identified by its transitory nature. Four days before this imagery was obtained, there had been a 1.2 inch rainfall. The left photo taken at 8:40 a.m. on 25 June shows large areas of low response. Eight hours later, however,

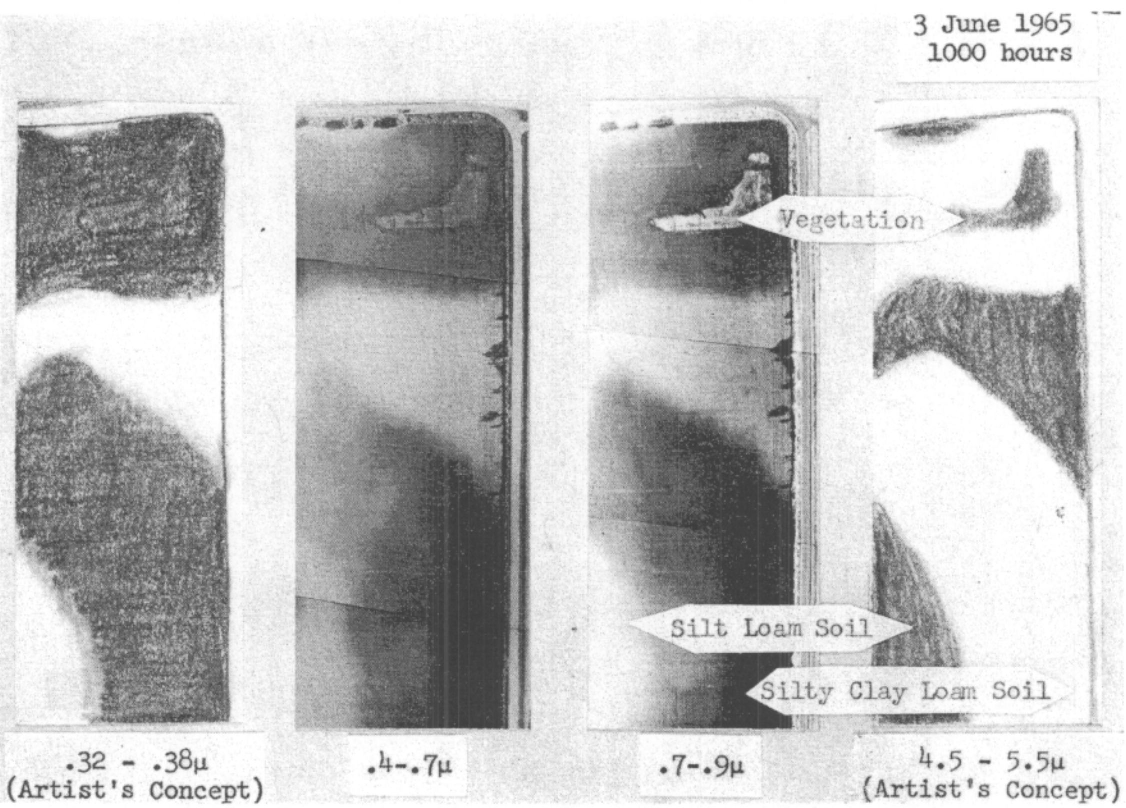


Figure 30. Multispectral differentiation between soil types. In this example, both soil types were dry and, therefore, the darker soil absorbs more solar radiation, becomes warmer and results in a higher response in the 8-14μ thermal imagery. An area of wet soil would not have such a reversal in response between the reflective and thermal wavelengths.

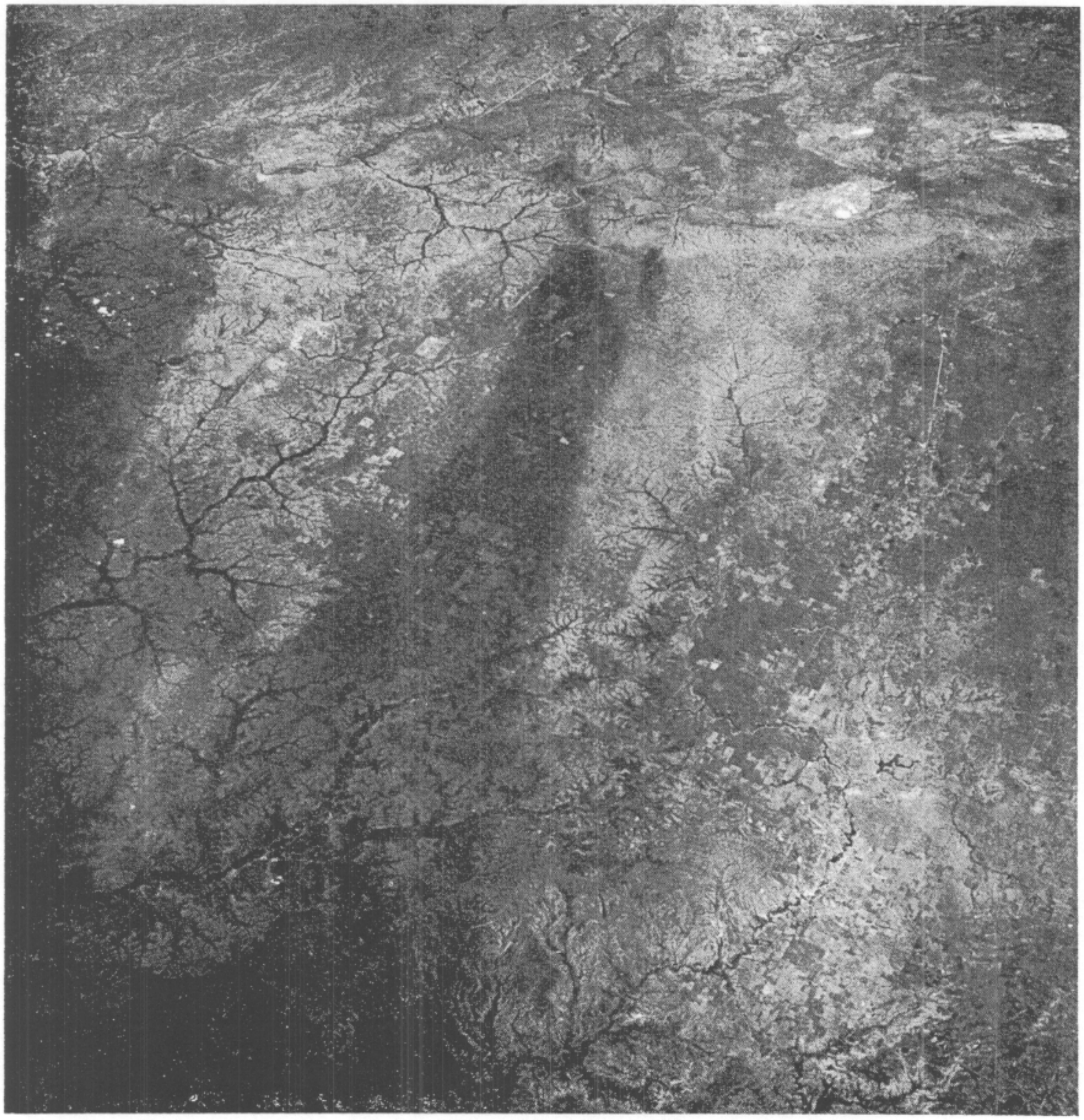


Figure 31. Rain patterns in Texas, as photographed from Gemini IV at an altitude of 102 miles. The dark-toned areas correspond to the path of a rain storm the previous day.

these low response areas were much smaller or had disappeared altogether.

Drainage tile lines also become distinct in wet soil situations. In Figure 33, the silt loam soil immediately above the tiles had drained, causing the surface soil to dry out much sooner than between the tile lines. Tile patterns were also evident on thermal infrared imagery as lines of high response against a low response background.

SUMMARY AND CONCLUSIONS

Results of work done in 1964 and 1965 indicate that remote multispectral sensing is a potentially useful means of differentiating, identifying, surveying, and mapping major cover types, such as vegetation, water, and bare soil. Under certain conditions of crop maturity, a capability exists for using remote multispectral sensing to differentiate and identify crop species, such as wheat and oats, corn and soybeans. Such a capability is realized either (1) by gathering multispectral data at specified times during the growing season or (2) by comparing imagery obtained over the same area at different times during the growing season. Statistical reliability of this capability has yet to be established.

Analysis of multispectral imagery revealed much variation in response within a given species in different wavelength bands and at different times during the growing season. These within-species variations are greatest early in the growing season before the crop canopy has reached its maximum and again, late in the growing season of the particular species

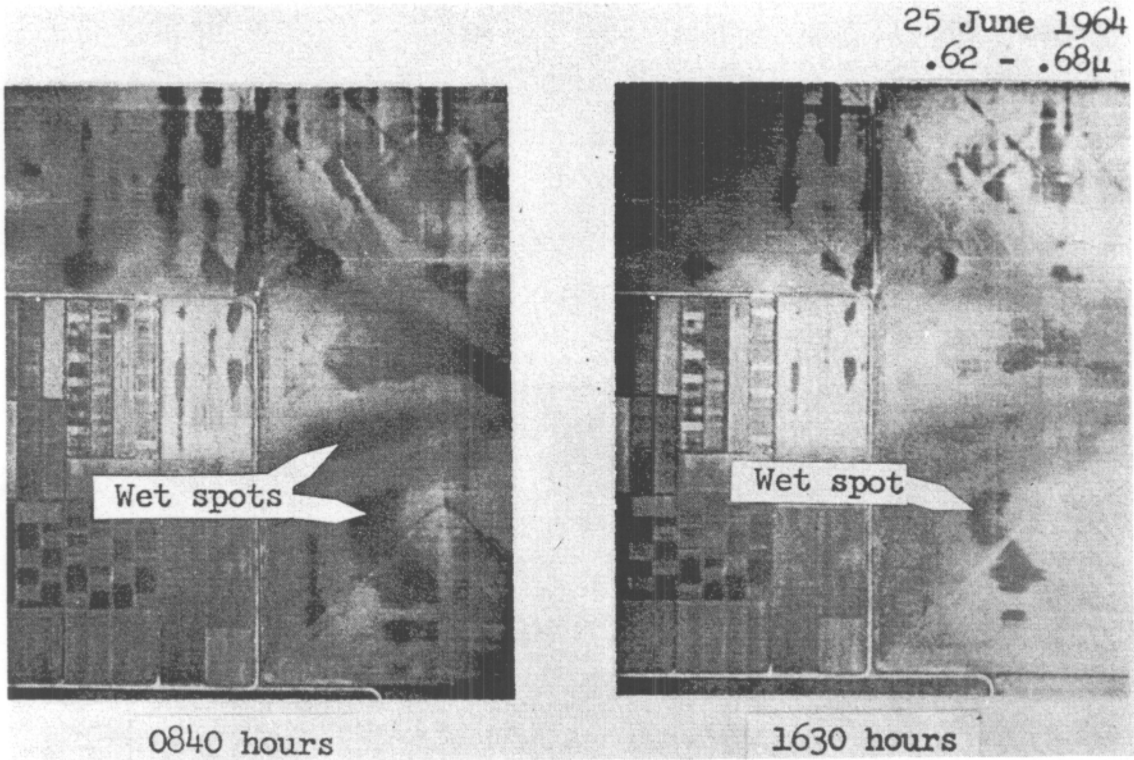


Figure 32. Diurnal variation in soil moisture. Areas of low response changed drastically in size in only 8 hours. Such temporal changes assist in interpreting sequential imagery.

of interest when differences in maturity are most pronounced. Primary causes for variations in response within a species are:

1. Variations in amount of *ground cover,* due to differences in planting date, soil type, soil moisture, uneven germination, and/or disease conditions which cause stunted, small plants. When ground cover is not complete, then soil type and soil moisture conditions *per se* may cause marked differences in response.
2. Variations in *maturity,* due to differences in variety, planting date, soil type and soil moisture.
3. Differences in *cultural practices,* such as fertilizing or harvesting.
4. Changes in reflectance and emission characteristics of the plants caused by *disease* and/or *moisture stress.*
5. Geometric *configuration of the crop,* due to differences in row width, row direction or lodging of plants.
6. *Environmental variables,* such as atmospheric conditions, wind, angle of reflection in relation to angle of solar incidence, and soil moisture conditions as affected by amount of previous rainfall and length of time and weather conditions since the last rainfall.

To eliminate or account for as much variation in remote multispectral data as possible, the following procedures are recommended:

1. Remote multispectral data must be obtained when variations for a given species of interest are minimal, e.g., near the middle of the growing season for corn, to minimize variations in ground cover or maturity.
2. Since optimum periods to obtain remote multispectral data differ for different crops, such data must be collected at intervals throughout the growing season. For example, in north-central Indiana, data on oats should be obtained in mid-June, while data on corn and soybeans should not be obtained until 6 weeks later.

Multispectral response patterns may not be the same on a given date from year to year, even for the same geographic region. This was the case for corn and soybean imagery obtained near the end of August, 1964 and 1965. Possible reasons for year to year variation are: differences in spring planting conditions causing a difference in planting date from one year to the next; or differences in moisture conditions from year to year, after the crops have been planted.

Such annual and seasonal variations in multispectral response patterns indicate a need for the following:

1. To gather accurate ground truth information prior to and at the time of any data collection flights. This would allow further study of the causes of spectral response variations, as well as correlation between weather conditions and the multispectral response patterns obtained.

2. To obtain spectral response data and/or descriptive ground truth information of all crop species collected (a) throughout each growing season and (b) over a period of several years in each geographic region of interest. Such information would allow reasonable predictions of optimum times for species identification using remote multispectral data.

3. To determine the statistical realiability of multispectral response patterns. This will involve many thousands of pieces of data, e.g., reflection and emission from crop and soil types and conditions at many times of the day and season. Thus, quantitative data handling and analysis capability is absolutely necessary, even before the feasibility of an operational remote multispectral sensing system can be established.

Photographic film is difficult to calibrate accurately due to possible variation in film development, spectral sensitivity of film and non-linear film response. Therefore, reliable quantitative spectral response information in many wavelength bands might better be obtained through use of single aperture, multispectral, optical-mechanical scanners and electromagnetic tape recorder systems, rather than film. However, color film and color infrared film are extremely valuable in interpreting multispectral data. Furthermore, there may be times when multispectral imagery will not obtain the desired information, but color aerial photos will. Thus, multispectral imagery and color aerial photos are both useful when used together.

Analysis of the multispectral data revealed that many wavelength bands are important in a remote sensing system. In the optical portion of the electromagnetic spectrum, one or more wavelength bands should be used in each of the following spectral regions: 0.4-0.7μ; 0.7-1.3μ; 1.3-3μ; 3-14μ.

The 0.4-0.7μ (visible) region probably should include at least four wavelength bands, representing the blue, green, yellow and red portions of the spectrum. One or probably two spectral bands should be included in both the 0.7-1.3μ and 1.3-3μ regions. The thermal infrared region should be represented by at least one wavelength band, probably in the 8-14μ region of maximum radiation by most natural objects.

The specific wavelength bands to use in future programs cannot be positively determined until more studies are done on reflective and thermal properties of vegetation and soil and until more is known about the effects of atmospheric attenuation and angular solar illumination on remote multispectral data.

Evaluation of ground truth data indicates that color photographs are valuable in multispectral imagery interpretation. In this research, the most important ground-based descriptive information and data included: (1) crop species and variety; (2) planting technique, row spacing and direction; (3) average crop height and estimated ground cover; (4) conditions of maturity; (5) yield; and (6) soil type and soil moisture conditions.

The micrometeorological data were of limited value, primarily because sufficient measurements were lacking to establish meaningful micrometeorological relationships between the fields of interest. Collection of micromet data also involves handling large quantities of data. So unless an adequate method of processing such data is developed and unless statistically meaningful quantities can be obtained, micromet data will continue to be of limited value. Radiation, temperature and soil moisture appeared to be the most useful of the micromet data obtained.

Emitted radiation, measured with a Barnes PRT-4 in the field at the time of flight missions, is useful ground truth information, particularly in analyzing thermal infrared imagery. A PRT-4 will allow reasonably accurate predictions of the capability to differentiate objects on thermal infrared imagery. A field of view larger than 3° would be desirable when obtaining measurements from an altitude of only 50 feet.

Spectra obtained on individual leaves may help determine which wavelength bands will differentiate various crop species and perhaps which species will be differentiated on remote multispectral imagery. However, the reflectance pattern of a single leaf may differ considerably from a remote multispectral response pattern, which involves not just leaves, but also soil, shadow, other plant organs, etc. Therefore, to

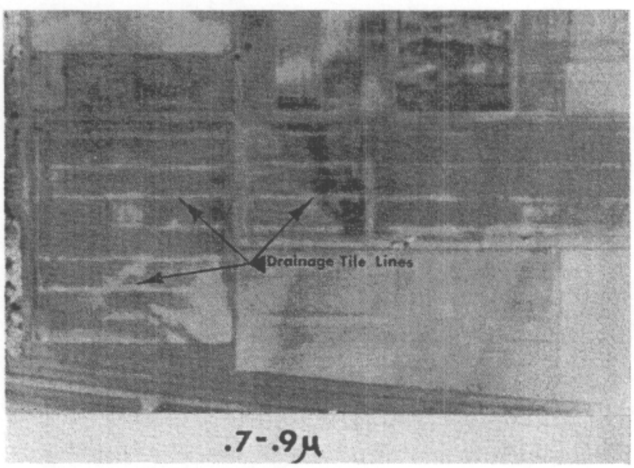


Figure 33. Drainage tile patterns. Shortly after a rainfall, soil above the drainage tile has dried much more than the areas between the tile lines. Thermal infrared wavelengths show similar results, since dry soil above the tile is warmer than the wetter areas being cooled by evaporation. Although the imagery appears similar in the .4-.7μ and the 8-14μ regions of the spectrum, the causes of spectral response differences are for different physical reasons. In the .4-.7μ region, the dry and wet soils have color differences, and therefore reflect differently, whereas in the 8-14μ region, response difference is due to apparent temperature variation.

better predict response of remote multispectral imagery without going to the expense of actually obtaining such imagery, a field spectrometer should be used. It should be capable of obtaining data in a natural environment over an area of several square feet and should operate in the same portions of the spectrum as the remote scanner system. Spectra of individual leaves should be used primarily for microphysical studies involving correlations between reflectance and such parameters as leaf histology or moisture content.

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APPENDICES

Appendix A. Seasonal and Periodic Information Data Sheets, 1965: The two forms shown on page 32 were used to record ground truth information for each field of interest during the 1965 growing season. The seasonal data sheet recorded general information on a particular field for the entire growing season, whereas the periodic data sheet recorded crop conditions at the time of each remote sensing flight.

Appendix B. Micrometeorological Data Sheets and Charts: Two sets of micrometeorological data are shown on pages 33-36. The first set was obtained on 1 October 1964 in a field of nearly mature corn on a clear, sunny day. It is a record of average hourly values of the various types of micromet data, followed by graphs plotted for (1) solar radiation data, both incoming and outgoing; (2) temperature measurements in the soil, at two levels within the crop canopy, and above the crop canopy; and (3) relative soil moisture and wind speed. The wind speed chart has the individual instantaneous 6-minute readings, as well as the hourly averages plotted. This shows the variability of the individual 6-minute readings and indicates the difficulty of obtaining meaningful data which can be related to remote sensing imagery.

The second set was obtained in a corn field earlier in the growing season (August 1964), and indicates the variability of such micromet data on days which are partially cloudy. Individual values of incoming radiation obtained at 6-minute intervals have been plotted, again to indicate variability which occurs in collecting data of this type, and therefore, the difficulty in establishing meaningful averages and trends for such data.

APPENDIX A

1. **Seasonal Information Data Sheet, 1965** ☐☐
2. Serial Number (within this series)________ ☐☐☐☐☐☐
3. Field Designation: ________ ☐☐☐☐☐☐☐
4. Size of Field: ______ ft x ______ ft ________ ☐☐☐☐☐☐
5. General Location:
6. Person (s) in Charge:
7. Location designation by person in charge:
8. Primary Crop Species or Cover: ________ ☐☐
9. Variety (line or cross): ________ ☐☐
10. Experimental Use of Field: ________ ☐☐
11. Soil Type: ________ ☐☐☐☐☐
12. Planting Date: ________ ☐☐☐
13. Seeding Rate: ______ lbs. per acre ________ ☐☐
14. Planting Technique: (1. Uniform Rows) (2. Broadcast) (3. Spaced Plants) (4. Small Plots) (5. Other)________ ☐
15. Average Number of Plants per foot:________ ☐☐
16. Distance Between Rows:______ inches ________ ☐☐
17. Row Direction: (1. N-S) (2. E-W) (3. Other)________ ☐
18. Number of rows in field:________ ☐☐☐
19. Flowering or Silking Date:________ ☐☐☐
20. Date of Heading or Tasseling:________ ☐☐☐
21. Date Mature: ________ ☐☐☐
22. Date Harvested: ________ ☐☐☐
23. Yield:________(per acre basis)________ ☐☐☐
24. Treatments Performed on Field and Dates: (Cultivation, Fertilization, Spraying, etc.)

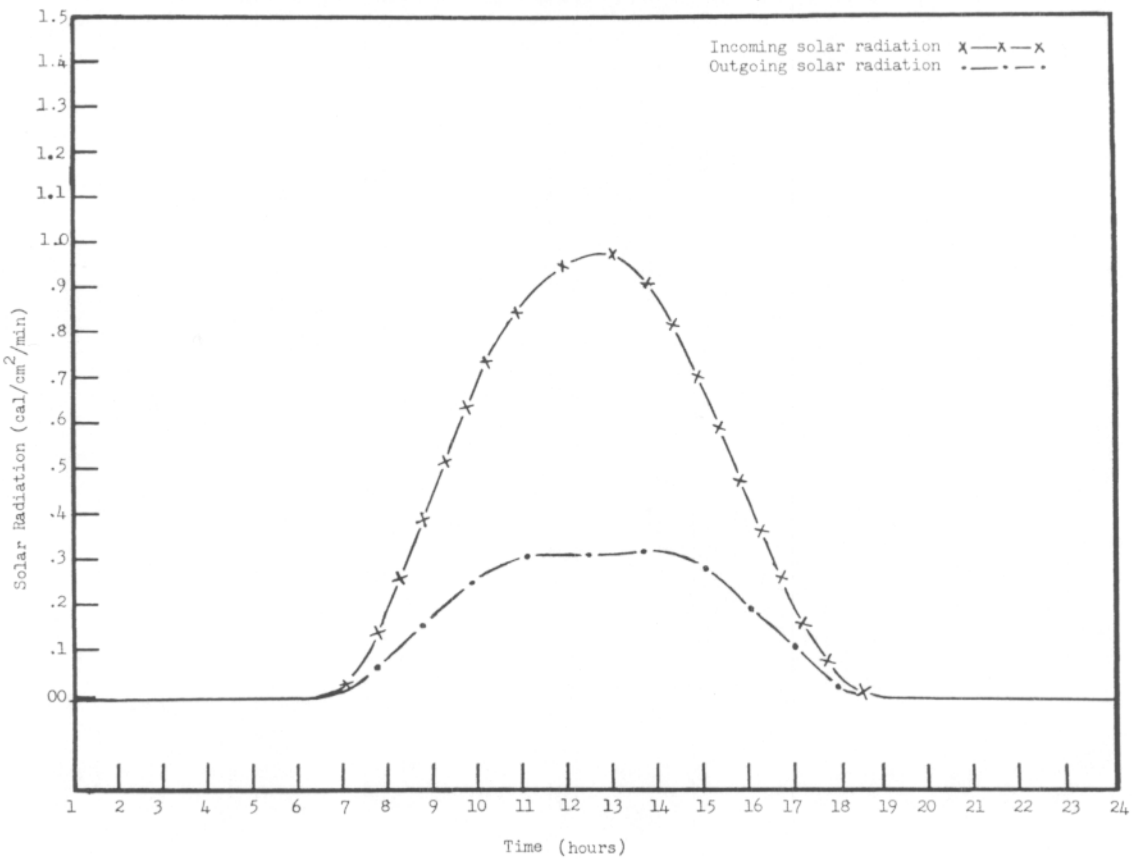
1. **Periodic Information Data Sheet, 1965** ☐☐
2. Serial Number (within this series):________ ☐☐☐☐☐☐
3. Field Designation: ________ ☐☐☐☐☐☐☐
4. Date: ________ ☐☐☐
5. Time: ________ ☐☐☐☐
6. Cloud Conditions: (O. Clear) (1. Partially Cloudy) (2. Overcast)________ ☐
7. Is field of interest influenced by cloud shadows? (O. no) (1. yes)________ ☐
8. Wind Conditions: A. (O. Calm*) (1. Windy); [*If calm is checked, go to #9]________ ☐
   B. (2. Light) (3. Moderate) (4. Strong)________ ☐
   C. (5. Steady) (6. Gusty) ________ ☐
   D. Direction : (O. Variable) (1. N) (2. NE) (3. E) (4. SE) (5. S) (6. SW) (7. W) (8. NW)________ ☐
9. A. Average Crop Height:______ft______ inches = ______inches ________ ☐☐☐
   B. Variation in Height: From ______ to ______ inches________ ☐☐☐☐☐
10. Ground Cover:________% cover (total) ________ ☐☐☐
11. Is there a secondary crop present? (O. no) (1. yes) ________ ☐
    A. What is it?________ ☐☐
12. Are there obviously weeds present? (O. no) (1. yes)________ ☐
    A. Location in field: ________ ☐☐
    B. Extent of weed infestation: (O. Light) (1. Moderate) (2. Heavy)________ ☐☐
13. Is the crop diseased or unhealthy appearing? (O. no) (1. yes)________ ☐
    A. What is the disease?________ ☐☐
    B. What is the effect on the crop? ________ ☐☐
    C. Location in field: ________ ☐☐
14. Are there apparent nonuniformities in the field? (O. no) (1. yes) ________ ☐
    A. What is the cause? ________ ☐
    B. What is the effect? ________ ☐☐
15. What is the crop's state of maturity? ________ ☐☐
16. Does the field appear to be of a suitable condition for study at this time? (O. no) (1. yes) ________ ☐

APPENDIX B

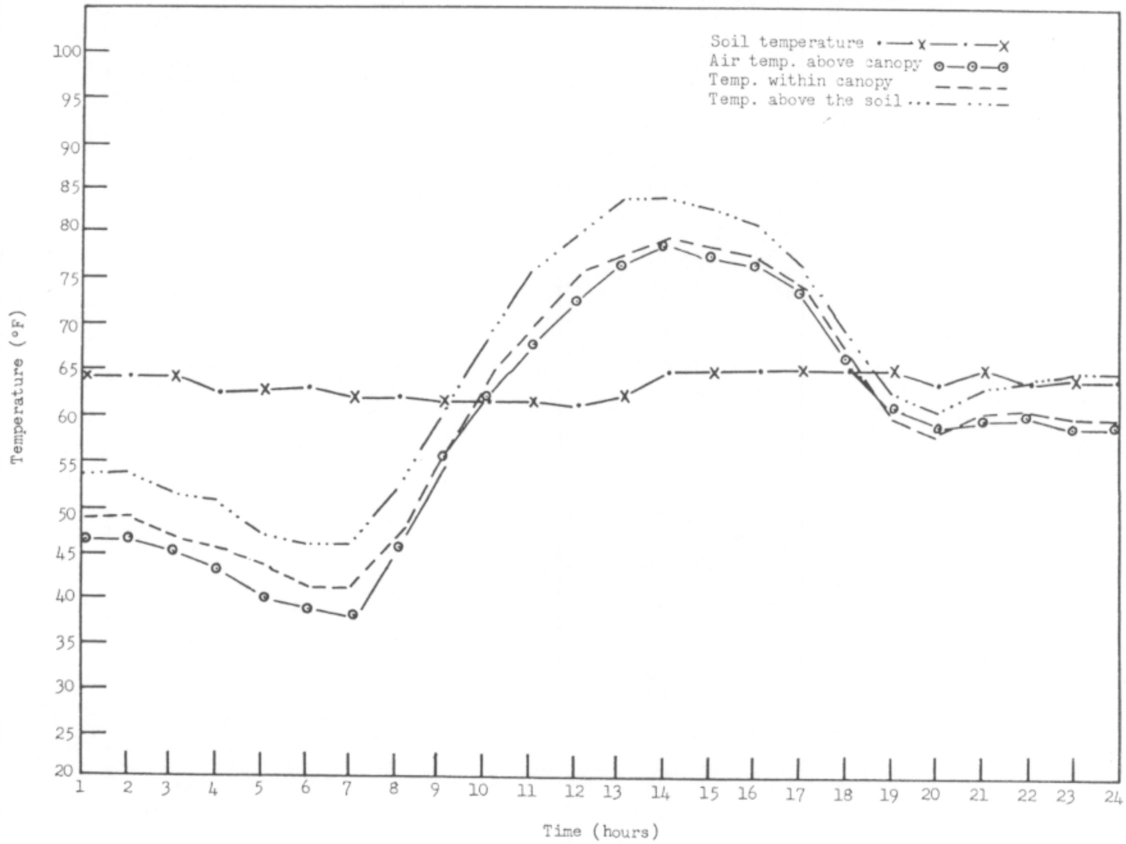
Micrometeorological Data Chart (Hourly averages, data obtained in a field of nearly-mature corn, 1 October 1964).

	Radiation*		Soil		Air Temperature			Relative Humidity		
Time	Incoming ly/min	Outgoing ly/min	Temp °F	Moisture	Above Canopy °F	Within Canopy °F	Above Soil °F	Top %	Bottom %	Wind Speed
0100	0	0	65.5	26.5	47.0	49.0	53.5	65.0	64.0	1.5
0200	0	0	65.5	26.5	47.0	49.0	53.5	66.5	64.0	3.0
0300	0	0	65.5	26.0	46.0	47.0	51.5	67.5	65.0	1.5
0400	0	0	64.0	26.0	44.0	46.0	50.5	68.0	65.5	1.0
0500	0	0	64.0	26.0	40.5	44.0	47.0	68.0	65.0	0
0600	0	0	64.0	26.0	39.5	41.5	46.0	68.0	65.5	0
0700	.025	.017	63.0	25.5	38.5	41.5	46.0	67.0	65.0	.5
0800	.211	.102	63.0	25.5	46.0	47.0	51.5	68.0	66.5	2.0
0900	.475	.203	63.0	25.0	56.5	55.5	60.0	51.4	60.0	2.0
1000	.720	.279	63.0	25.0	63.0	64.0	68.5	38.5	48.5	4.5
1100	.881	.322	63.0	25.5	68.5	69.5	76.0	36.5	40.0	4.5
1200	.966	.322	62.0	26.0	73.0	76.0	80.5	34.0	34.5	6.0
1300	.991	.322	63.0	26.5	77.0	78.0	84.5	32.5	34.5	8.0
1400	.889	.330	65.5	27.5	79.0	80.0	84.5	32.5	34.0	5.5
1500	.678	.288	65.5	28.0	78.0	79.0	83.5	32.0	34.5	8.0
1600	.432	.203	65.5	28.0	77.0	78.0	81.5	32.0	35.5	6.0
1700	.186	.119	65.5	28.5	74.0	74.0	77.0	33.0	39.0	5.5
1800	.034	.017	65.5	28.5	66.5	67.5	69.5	43.0	51.0	1.0
1900	0	0	65.5	28.5	61.0	60.0	63.0	56.0	62.5	1.0
2000	0	0	64.0	28.0	59.0	58.0	61.0	61.5	65.0	1.0
2100	0	0	65.5	28.0	60.0	60.0	63.0	65.0	66.5	6.0
2200	0	0	64.0	28.0	60.0	61.0	64.0	67.5	66.0	4.0
2300	0	0	64.0	28.0	59.0	60.0	64.0	69.5	67.5	5.0
2400	0	0	64.0	28.0	59.0	60.0	64.0	70.5	68.0	7.0

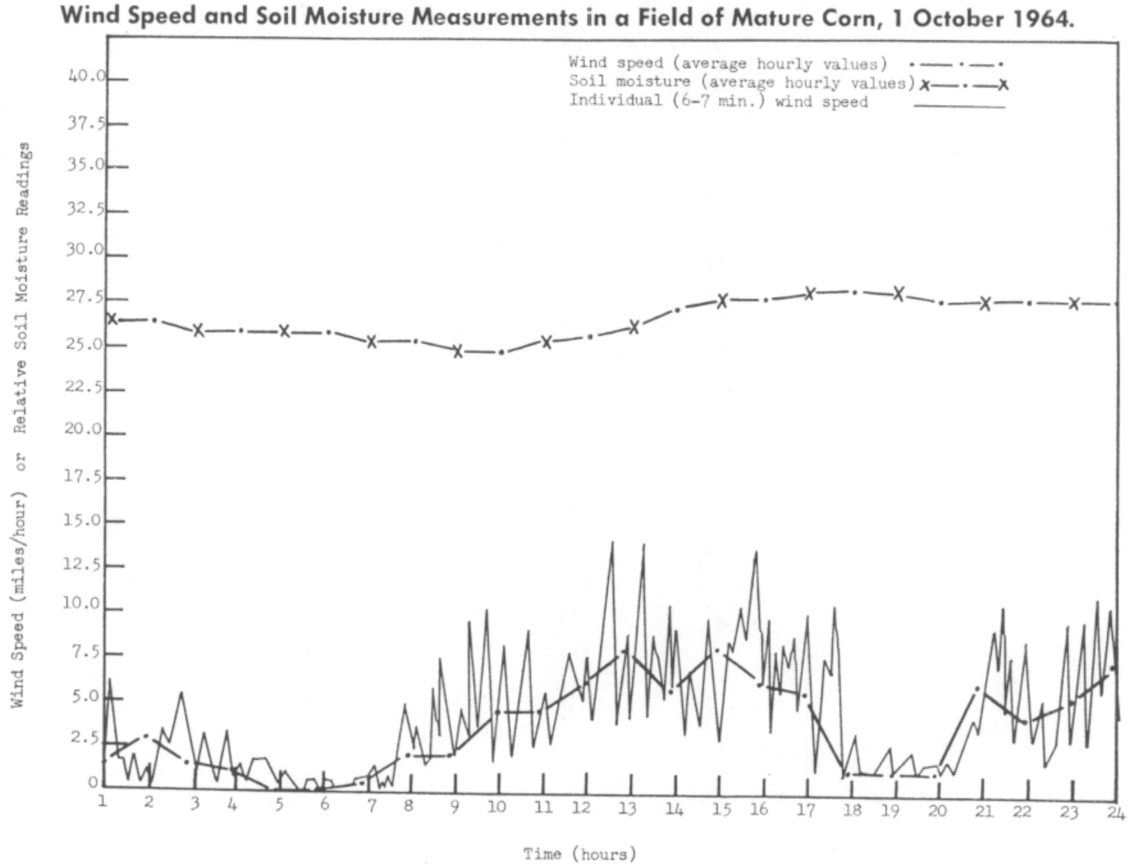
Radiation Measurements in a Field of Mature Corn, 1 October 1964.



Temperature Measurements in a Field of Mature Corn, 1 October 1964.



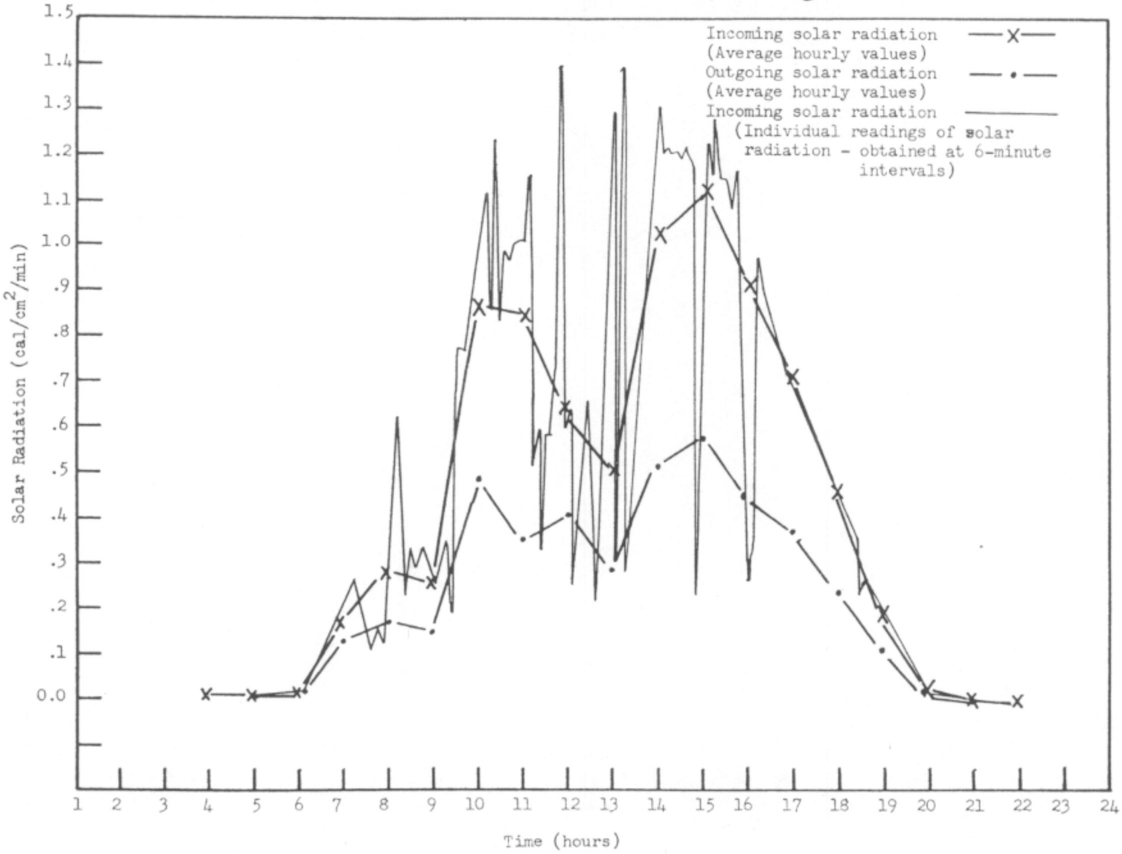
Wind Speed and Soil Moisture Measurements in a Field of Mature Corn, 1 October 1964.



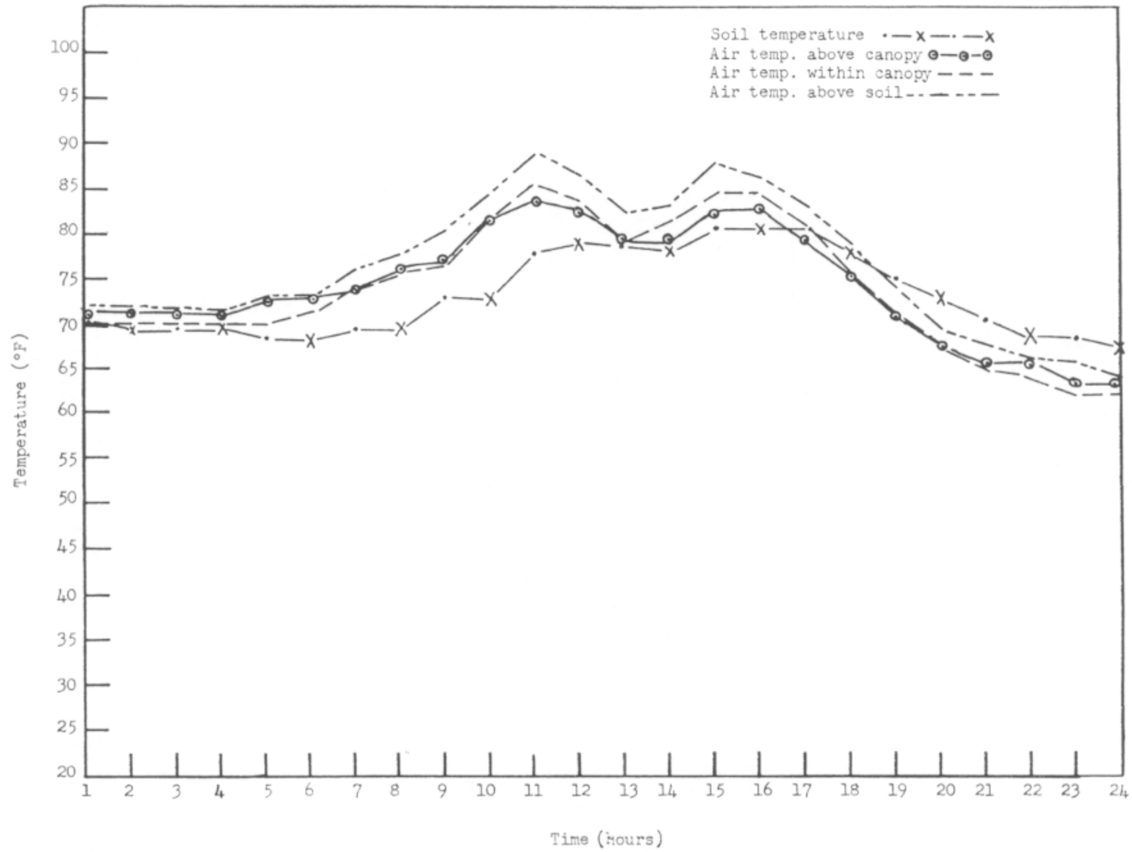
Micrometeorological Data Chart (Hourly averages, data obtained in a field of corn, 11 August 1964).

Time	Radiation: Incoming ly/min	Radiation: Outgoing ly/min	Soil: Temp °F	Soil: Moisture	Air Temperature: Above Canopy °F	Air Temperature: Within Canopy °F	Air Temperature: Above Soil °F	Relative Humidity: Top %	Relative Humidity: Bottom %	Wind Speed
0100	0	0	69.5	5.5	71.5	70.5	71.5	54.5	67.0	8.7
0200	0	0	69.5	5.5	71.5	70.5	71.5	53.5	66.5	7.2
0300	0	0	69.5	5.4	71.5	70.5	71.5	55.0	69.0	10.8
0400	0	0	69.5	5.4	71.5	70.5	71.5	62.5	74.5	9.2
0500	0	0	68.5	5.4	73.0	70.5	73.0	67.0	77.5	11.5
0600	.008	.007	68.5	5.4	73.0	71.5	73.0	73.5	82.5	10.1
0700	.160	.121	69.5	5.4	74.0	74.0	76.0	72.5	83.0	12.1
0800	.269	.156	69.5	5.4	76.0	76.0	78.0	70.0	82.0	13.9
0900	.248	.143	73	6.5	77.0	77.0	80.5	72.0	81.0	16.8
1000	.862	.478	75	6.5	81.5	81.5	81.5	65.5	78.5	17.6
1100	.843	.351	78	6.5	83.5	85.5	89.0	60.5	71.5	19.3
1200	.615	.400	79	6.5	82.5	83.5	86.5	65.0	76.0	18.3
1300	.500	.281	79.0	6.6	79.0	79.0	82.5	70.0	80.5	14.3
1400	1.023	.512	78	6.6	79.0	81.5	83.5	65.0	77.9	12.8
1500	1.119	.567	80.5	6.6	82.5	84.5	87.5	53.5	64.5	24.7
1600	.906	.436	81.5	6.5	82.5	84.5	86.5	48.0	62.0	27.9
1700	.739	.373	80.5	6.5	79.0	81.5	83.5	47.0	60.5	34.0
1800	.458	.243	78.0	6.4	75.0	76.0	79.0	48.5	61.0	34.8
1900	.175	.108	75.0	6.4	70.5	71.5	74.0	49.7	61.5	32.5
2000	.017	.010	73.0	6.4	67.5	67.5	69.5	54.0	63.0	21.0
2100	0	0	70.5	6.3	65.5	65.5	67.5	55.5	63.5	22.0
2200	0	0	68.5	6.3	65.5	64.0	66.5	56.0	64.0	23.0
2300	0	0	68.5	6.3	63.0	62.0	65.5	58.5	65.5	18.5
2400	0	0	67.5	6.3	63.0	62.0	64.0	60.5	67.5	16.1

Radiation Measurements in a Field of Corn, 11 August 1964.



Temperature Measurements in a Field of Corn, 11 August 1964.



Wind Speed and Soil Moisture Measurements in a Field of Corn, 11 August 1964.