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REMOTE MULTISPECTRAL SENSING IN AGRICULTURE

Semi-Annual Progress Report - May 1, 1966

R. A. Holmes and R. M. Hoffer

DEPARTMENTS OF
ELECTRICAL ENGINEERING,
BOTANY AND PLANT PATHOLOGY
Respectively

PURDUE UNIVERSITY
LAFAYETTE, INDIANA

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I. INTRODUCTION

This report outlines progress made on research under the grant NGR-15-005-028, awarded to Purdue University on January 4, 1966, with funding retroactive to November 1, 1965. From November 1, 1965 to February 1, 1966, work was carried on primarily by one man in the Department of Botany and Plant Pathology. Since February 1, 1966 the research has been a joint effort through the Departments of Botany and Plant Pathology and Electrical Engineering.

II. OBJECTIVES

Objectives of this first stage of the research program have been as follows.

- o Perform feasibility studies on multispectral crop discrimination techniques using existing 1964 scanner imagery and 1964 spectrophotometric reflectance curves.
- o Establish a data processing group to study the data reduction and interpretation problem from the user's point of view, and design a prototype user's data reduction station.
- o Interpret spectrophotometric leaf reflectance measurements in terms of histology, moisture content, and pigmentation.
- o Analyze 1964 data in a qualitative manner, and institute theoretical modelling as the first step in a trend to quantitative analysis when calibrated imagery becomes available.
- o Design and develop a field instrumentation system for gathering standardized ground truth spectra from a cherry picker truck.
- o Become knowledgeable in synthetic aperture radar surveillance and radar scatter data interpretation through close liason with the radar instrumentation team.
- o Program a series of flights by the University of Michigan to obtain remote multispectral data over the Purdue University test site, and develop a system of gathering ground truth data in support of these flights.

III. EXPERIMENTAL PROGRESS

Classification of Multispectral Response Patterns

A. Pattern Classification of Densitometer Data - 1964 Scanner Imagery.

A preliminary effort to determine the degree to which selected major crops of the corn belt region can be differentiated on the basis of "Multispectral Response Patterns" at various times during the growing season has been carried out using the data obtained by the University of Michigan over Purdue test sites during the 1964 growing season. Selected portions of this scanner imagery had been densitometered and recorded on punch cards by U-M.

These digital data have been used to date in the following program, the preliminary results of which appear encouraging.

1. Preliminary classification of wheat, oat, and bare soil fields from imagery obtained at 1535 hours on 3 June 1964 was studied. Five densitometer readings per field were recorded by U-M from 6 fields of wheat, 5 fields of oats, and 10 fields of bare soil for imagery in each of 6 different wavelength bands. These densitometer readings resulted in measurements of "relative response" for the various crop types examined. Each crop type or bare soil was considered as a "class" and each wavelength band was considered as a "feature" for classification. The 6 features were assumed statistically independent and uniformly distributed. The range of each feature was determined by taking the maximum and the minimum of all the individual densitometer readings in that class. Table I and Figure 1 show the feature distribution thus obtained.

		Relative Response		
Feature	Wavelength Band	Wheat	Oats	Bare Soil
1	$.32\mu$ - $.38\mu$	48 - 61	48 - 67	54 - 75
2	$.4\mu$ - $.7\mu$	29 - 59	23 - 59	27 - 81
3	$.7\mu$ - $.9\mu$	72 - 82	64 - 77	27 - 84
4	2.0μ - 2.6μ	32 - 65	45 - 55	45 - 78
5	4.5μ - 5.5μ	34 - 62	14 - 52	62 - 74
6	8μ - 14μ	46 - 73	17 - 51	46 - 81

Table I

The statistical decision method was used. The decision procedure was a simple likelihood ratio test. That is, the 6 dimensional measurement vector X is classified into class k,

if $P(X/W_k) > P(X/W_i)$ for all $i \neq k$

then $d(X) = d_k$ where $P(X/W_k)$ is the conditional probability of X given class k is the class.

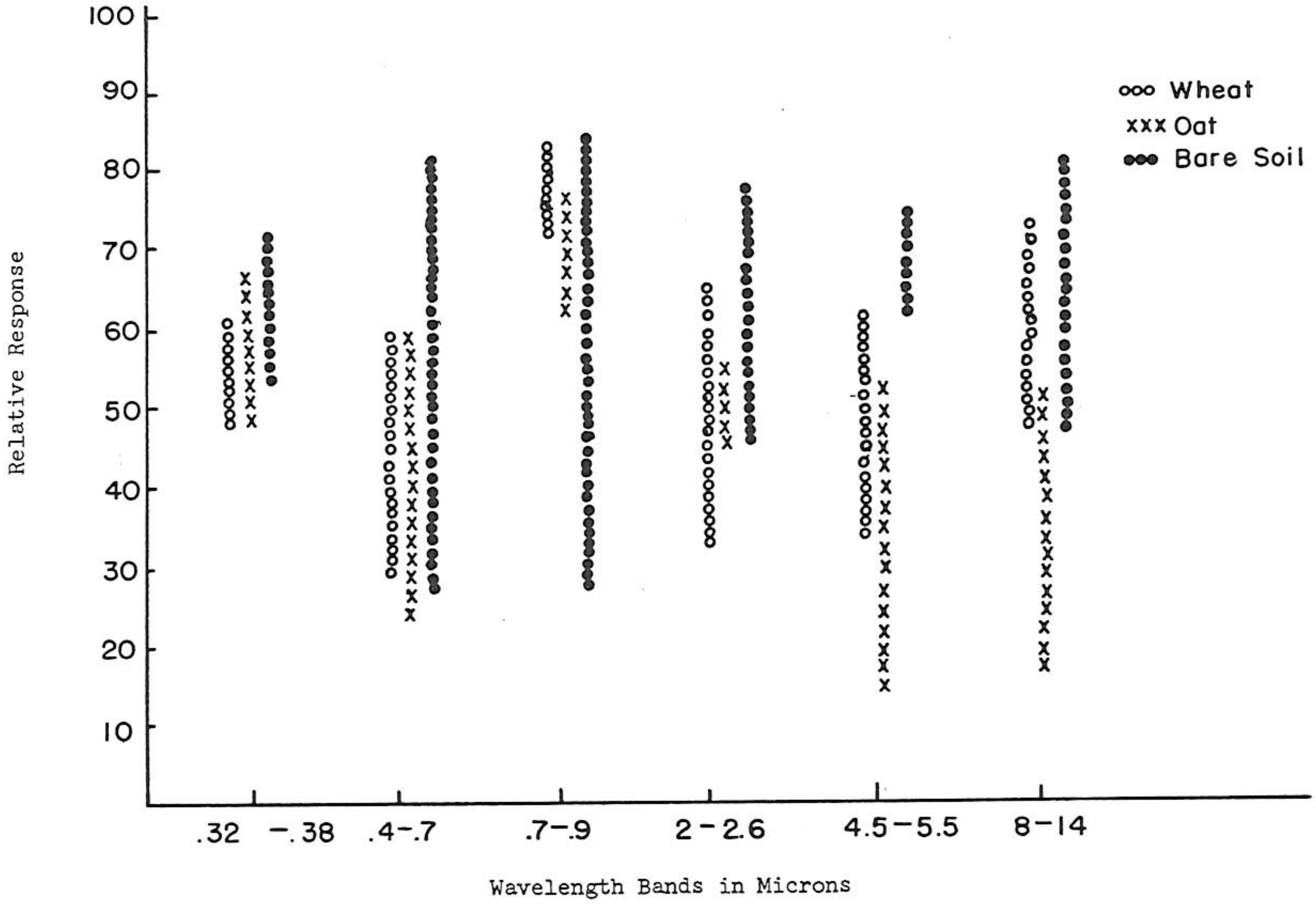


Figure 1. Distribution of Relative Response of wheat, oat and bare soil fields at 1535 hours on 3 June 1964.

For testing the procedure, 500 samples were generated in each class. The results of this classification are shown in Table II.

	No. of Samples Classified As:		
	Wheat Fields	Oat Fields	Bare Soil
500 Samples Generated From Wheat Fields	500	0	0
500 Samples Generated From Oats Fields	6	494	0
500 Samples Generated From Bare Soil Areas	0	0	500

Table II

2. Preliminary classification of soybean, corn, alfalfa, wheat stubble, and oat stubble fields from imagery obtained at 1315 hours on 29 July 1964 was carried out as in (1). Seven features were available from densitometer readings from 7 soybean fields, 4 corn fields, 2 alfalfa fields, 5 wheat stubble fields, (some of which were rather weedy) and 5 oat stubble fields, (some of which had much bare soil). Table III and Figure 2 show the feature distributions obtained as in (1).

		Relative Response				
Feature	Wavelength Band	Soybean	Corn	Alfalfa	Wheat Stubble	Oat Stubble
1	.4 - .7	25 - 42	30 - 52	25 - 41	36 - 62	32 - 68
2	.7 - .9	74 - 92	87 - 91	84 - 90	78 - 90	75 - 92
3	1.5 - 5.5	63 - 91	61 - 82	57 - 61	63 - 84	37 - 82
4	2 - 2.6	65 - 86	61 - 82	59 - 79	76 - 85	70 - 92
5	3 - 4.1	60 - 89	60 - 83	55 - 73	65 - 84	64 - 92
6	4.5 - 5.5	44 - 84	44 - 81	62 - 78	54 - 91	55 - 89
7	8 - 14	6 - 45	13 - 31	9 - 15	28 - 36	57 - 91

Table III

The results of the classification of 500 samples generated in each class are shown in Table IV.

	No. of Samples Classified As				
500 Samples From:	Soybean	Corn	Alfalfa	Wheat Stubble	Oat Stubble
Soybean	478	19	0	3	0
Corn	0	492	0	8	0
Alfalfa	0	0	500	0	0
Wheat Stubble	0	0	0	500	0
Oat Stubble	0	0	0	0	500

Table IV

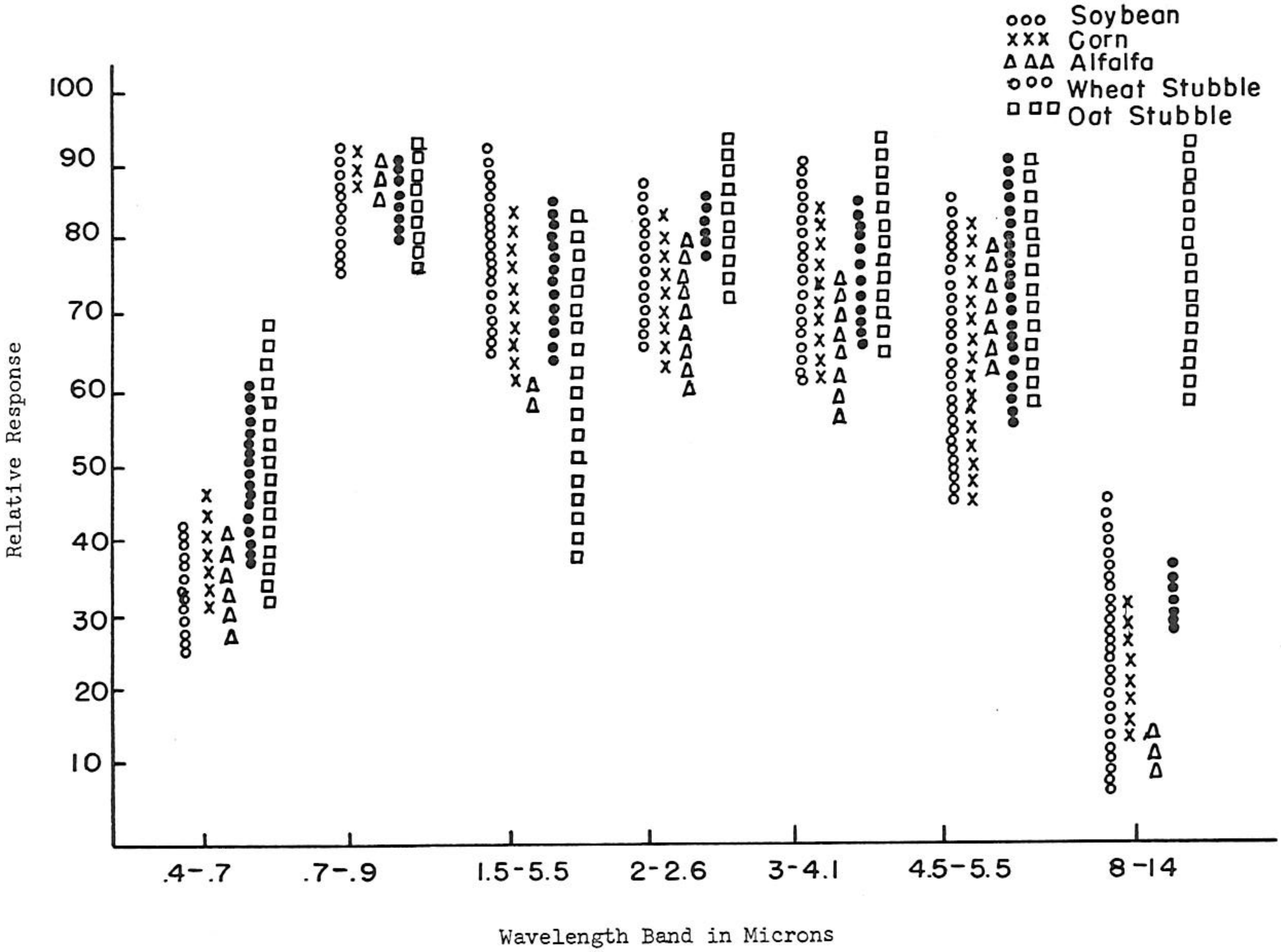


Figure 2. Distribution of Relative Response of soybean, corn, alfalfa, wheat stubble and oat stubble fields at 1315 hours on 29 July 1964.

B. Pattern Classification of 1964 Spectrophotometric Curves

1. Preliminary classification of soybean, corn, alfalfa, fruit (plum, peach, and cherry) and grass (timothy, bromegrass, and orchard grass) leaves using the spectrophometric reflectance data taken in 1964 in the visible and infrared portion of the spectrum from 0.35 microns to 2.6 microns was investigated. Five features (reflectance measurements at a given wavelength) were chosen for the purpose of classification. The features were again assumed statistically independent and uniformly distributed over the range determined by the maximum reflectance and the minimum reflectance of any measurement of samples in that class. Table V shows the feature distribution thus obtained:

		% Reflectance				
Feature	Wavelength	Alfalfa	Corn	Fruit	Grass	Soybean
1	.55µ	10 - 24	10 - 17	9 - 11	8 - 20	14 - 18
2	1.05µ	75 - 78	64 - 68	64 - 76	73 - 80	68 - 69
3	1.15µ	66 - 73	61 - 62	60 - 70	67 - 73	62 - 65
4	1.65µ	38 - 43	34 - 38	38 - 50	45 - 47	42 - 44
5	2.2 µ	18 - 20	14 - 18	18 - 30	22 - 28	22 - 24

Table V

Because of the lack of large numbers of leaves measured, 500 samples were generated in each class for the purpose of testing classification techniques. Several methods of classifications were used and the results were very encouraging.

a. Classification using hyperplane techniques.

One of the techniques investigated is the Class Mean Method.

The decision procedure is as follows:

The 5-dimensional sample vector X is classified into class k if the distance of the sample vector X to the class k mean vector M_k is minimum, that is

$d\ (X) = d_k$ if

$$(X - M_k)' \ (X - M_k) < (X - M_i)' \ (X - M_i)$$

for all $i \neq k$

where X and M_i, $i = 1, 2, \ldots 5$

are column matrices and X' is the transpose of the matrix X.

The results is shown in Table VI. 98% correct classification was obtained.

500 Samples From	No. of Samples Classified As Alfalfa	Corn	Fruit	Grass	Soybean
Alfalfa	499	0	0	1	0
Corn	0	500	0	0	0
Fruit	3	11	456	30	0
Grass	1	0	7	492	0
Soybean	0	0	0	0	500

Table VI

b. Classification using the statistical decision approach:

The decision procedure used is the same as in Section A (1). The results of classifying the 500 samples generated in each class using the features described by Table V are shown in Table VII.

500 Samples From	No. of Samples Classified As Alfalfa	Corn	Fruit	Grass	Soybean
Alfalfa	500	0	0	0	0
Corn	0	500	0	0	0
Fruit	2	0	495	3	0
Grass	0	0	0	500	0
Soybean	0	0	0	0	500

Table VII

C. Analysis of Signatures

Sections A and B show that differentiation of different crops by multispectral response is quite feasible even though there is a large variation of features within a specie as shown in Figure 1 and Figure 2. Because of the large variation, we must have multispectral response measurements over a large number of fields covering all possible variation parameters such as crop variety, degree of maturity and soil type in order to determine the feature distributions with any confidence. Currently, methods for estimating the statistics of multispectral response measurements, and methods for determining the best features (i.e. the best spectral bands) for classification are being investigated.

The Data Processing Group

As indicated above, the success of the pattern recognition research depends upon the availability of large quantities of accurate data. Very early in the work it became apparent that a separate data group was necessary. Such a group has been established at Purdue (a) to assure the availability of quantities of data to researchers, and (b) to develop suitable equipment so that the data processing capability grows at a rate commensurate with the rest of the remote sensing program.

A. The Digital Approach

The data processing group has studied various approaches to the data problem. As a result of this study a digital approach has been selected for the following reasons:

- Flexibility: It is easy to merge different types of data in digital form: e.g., multispectral scanner imagery and ancillary information. It is also possible to make changes in computational procedures and approaches which are dictated by research results or the varied needs of different researchers without making extensive hardware changes.
- Fidelity: Data in digital form can be processed repeatedly and stored over an extended period of years without deterioration or loss of information.
- Speed: Rapid acess and manipulation is possible with high speed digital systems.
- Evolutionary Convenience and Economy: A digital system can be of modular design. This provides for easy expansion, revision, and modernization.

The plan is, therefore, to convert raw data immediately to digital form.

B. The Proposed System

After studying the data handling requirements to be met, a digital data system of sufficient capability and flexibility for the agricultural remote sensing problem has been conceived. A survey of data systems now existing in the field led to the conclusion that a data system with the required specifications does not now exist and that some aspects of it are near the state of the art.

The proposed system may be divided in two parts. Figure 3 shows the portion of the system required to convert analog and photographic data to digital form. This system provides a comparatively low-cost, high-speed, off line digital conversion capability. At present, the cost of the system shown in the solid lines will be shared with other projects in the School of Electrical Engineering. However, as the demand for more data conversion rises, a proportional increase

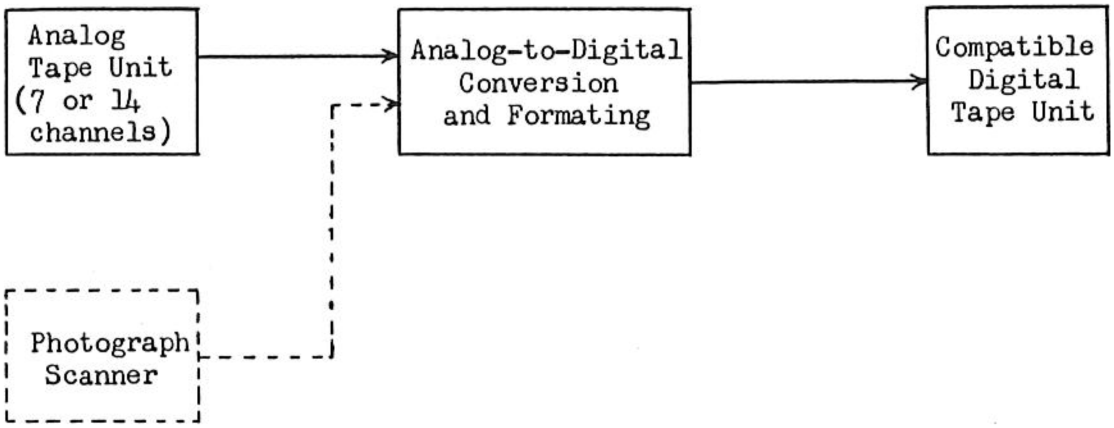


Figure 3. Analog to Digital Conversion

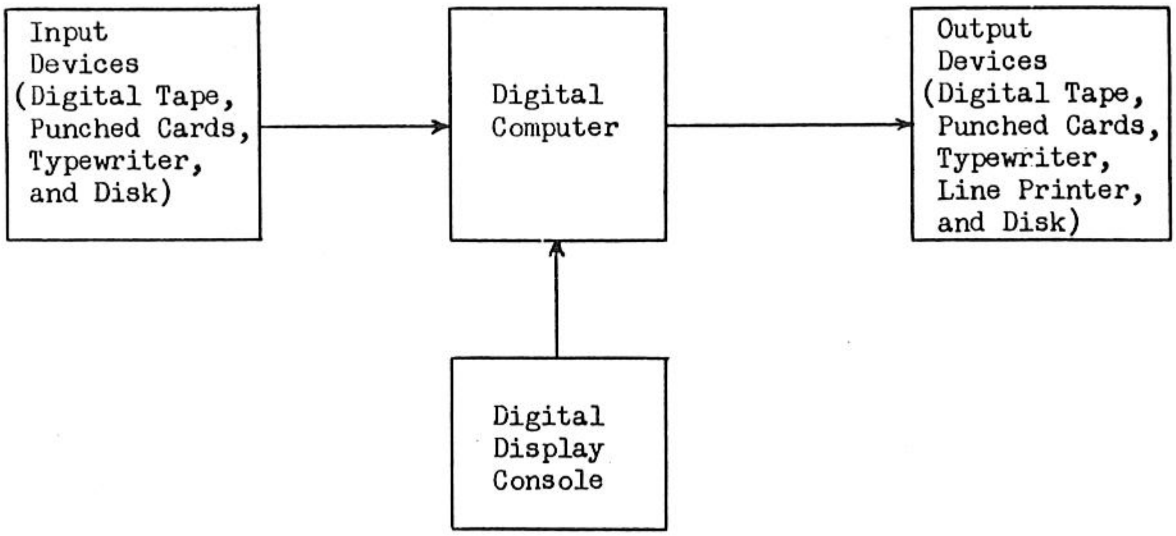


Figure 4. Computation/Data Editing System

in funding for this system will be required of this project. The photographic to digital converter is outside the bounds of available funds, but the Computational facility at the Marshall Space Flight Center in Huntsville, Alabama, has indicated that they may be able to convert some photographs to digital data for the project.

Figure 4 shows the proposed data system required (a) to select required subsets of data from the bulk of the original data, and (b) to do general scientific computation. This system provides a digital visual display of imagery with light pen capability such that geometrically complex areas of data can be easily selected without requiring a highly trained operator. It would also have considerable general purpose digital computational and data handling capability for the pattern recognition and statistical studies.

In operation, an image could be read into the system from magnetic tape and fed to the digital display. The researcher could then examine the image, identify the area of interest, and indicate this area to the computer with a light pen. The data so indicated could then be automatically stored on a digital tape for further processing.

From the standpoint of computer time economy, an important feature of the system is that during the time the operator is examining an image on the display, the computer, itself, is not in any way involved. It could during this time be carrying out some entirely unrelated computation and need only be interrupted briefly for the transfer of data to or from the display on command from the operator.

A request-for-quotation to industry has resulted in proposals to provide this system. Indications at this time are that the system could be in partial operation in about 90 days after an order is placed with final delivery of hardware for a prototype system by the end of the calendar year. Experience gained from the use of this prototype system will lead to specifications for an operational system of lower cost and suitable for use at the various locations where remote sensing research is being carried out.

Leaf Reflectance, Histology, and Pigmentation Studies

Previous work has indicated marked changes in reflectance of leaves due to differences in leaf vigor. It has been hypothesized that leaf histology is a primary controlling factor in these changes in leaf reflectance, particularly in the infrared portion of the spectrum from .7 - 1.3 μ wavelength. In order to determine the amount of variation and to help identify the major sources of such variation in the multispectral response patterns of various crop types and soil conditions, studies using spectrophotometer curves which will be correlated with photographs of leaf cross-sections and a limited amount of pigment analysis have been undertaken. Reflectance readings were obtained on a Beckman DK2-A Spectroreflectometer between 500 and 2600 mμ and all data was recorded both graphically and on punch cards for computer analysis. To date, the following studies have been undertaken and in some cases, completed:

1. Methodology studies to determine the best techniques for sample preparation, storage, and sampling.

2. Gross effects of leaf structure as determined by comparisons between normal and crushed or collapsed corn and soybean leaves.

3. Leaves of similar histology but marked differences in pigmentation have been compared.

4. Corn and soybean plants have been grown in the greenhouse and used to study (a) the changes in leaf reflectance with age of the leaves, (b) variations in reflectance within a leaf and (c) variations in reflectance within and between individual corn plants.

Much additional work remains to be done to establish statistically reliable results for some of these tests, but the following trends have appeared in the data thus far:

1. Leaf layering has a marked influence upon leaf reflectance.

2. Both corn and soybean leaves which were crushed showed marked decreases in reflectance in all peak reflectance areas between .5 - 2.6 μ. This has significance in future work with various pathological situations.

3. Anthrocyanin and chlorophyll pigment areas of leaves showed a consistently higher reflectance than areas of anthrocyanin pigment only, even in the infrared between .7 and 1.3 μ, where chlorophyll pigment is supposedly transparent. In leaves containing areas of no pigments and areas containing chlorophyll only, the areas containing no pigments had a higher reflectance at 1.65 and 2.2 μ in the infrared.

4. Leaf age and leaf reflectance appear to be highly correlated, but the relationship does not indicate a linear trend of decreasing reflectance with increasing age. Youngest corn leaves (1 week old) have the highest reflectance, then the reflectance drops to the lowest level for the next oldest leaves

(1 1/2 weeks) sampled, while the oldest leaves (2 1/2 weeks) are intermediate in reflectance. Microtome cross sections of these leaves have not yet been analyzed, but should offer valuable information to explain these observed changes in reflectance.

5. Using the same corn plants as above, a study was made of the variations within a single leaf. Readings were taken at 2" intervals, starting at the base and moving towards the tip. In all samples taken the same trend occured. The base or youngest portion of the leaf reflected highly, a large drop in reflectance occured two inches from the base, and then the reflectance increased steadily and surpassed the reflectance of the base by approximately 8% at the tip. This trend correlated very well with the trend from the age of leaf study. In both, the youngest portion reflects most highly with a decrease to about one week old and then an increase with age.

6. Soybean leaves showed only a very slight variation in reflectance throughout the blade area. Readings taken over the midvein, however, showed a decrease in reflectance at 2200, 1650, and 1200mμ.

Additional work is in progress to determine the effects of leaf histology, pigmentation, and moisture content upon leaf reflectance. From this will come a better understanding of the amount of variation and causes for such variation in multispectral response patterns. Correlations will be made using reflectance patterns obtained from individual leaves, reflectance patterns obtained over an entire crop area from 50-foot, and 2,000-foot altitudes. This will allow assessment of the usefulness of the methods now being used at ground level to obtain information on crop and soil reflectance for prediction of multispectral response signatures obtained by remote multispectral sensing techniques during the 1966 growing season.

Qualitative Analysis of 1964 Data and Theoretical Modelling

Completion of qualitative analysis of 1964 imagery has indicated the following:

1. Variation in multispectral response patterns within a given species is quite marked at certain times during the growing season, particularly early in the growing season before a maximum ground cover has been established and late in the growing season when crops are maturing.

2. Vegetation and soil variables of primary importance (other than crop species) are:

  a. Crop variety.
  b. Relative size and maturity of a crop at the time of flight missions.
  c. Soil type, moisture content, and relative amounts of soil and vegetation observed.
  d. Geometric configuration of the crop.

A more complete discussion of these vegetation and soil variables, as well as some of the theoretical modelling work that has been done, is given in a paper presented at the 4th Symposium on Remote Sensing of Environment, a copy of which is included as Appendix A of this report.

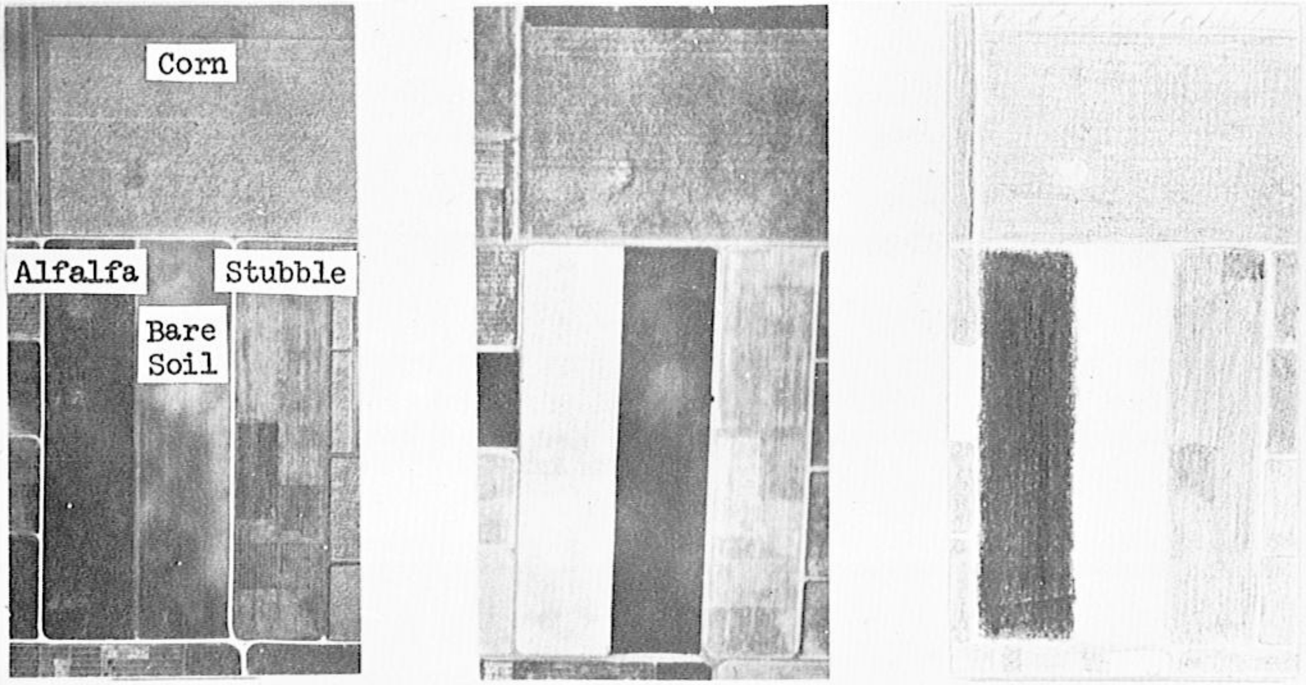
3. There are definite indications of a capability to differentiate:
  a. Bare soil from vegetated areas, as seen in Figures 5 and 6 and as further indicated by the graph in Figure 7.
  b. Wheat from oats during the period when wheat is maturing, as seen in Figure 6 and 8 and as indicated by the graph in Figure 9.
  c. Corn from soybeans when using imagery outside of the photographic region during the middle portion of the growing season, as indicated by the graph seen in Figure 10.
  d. Alfalfa or other green vegetation from corn or stubble and from bare soil during the latter part of the growing season, as seen in Figure 5.
  e. Soil types which have marked differences in reflectance, assuming both to be relatively dry, as seen in Figure 11.

These results from a qualitative analysis of imagery are substantiated by the pattern recognition work reported upon in Section I of this report.

A study of possible modelling methods preparatory to data interpretation has led to a decision to concentrate on gross geometrical effects such as crop-soil coverage percentages, leaf shape and orientation, and view-sun angle combinations. This will be backed up by the detailed leaf study program on morphology and pigmentation effects on leaf reflectance and absorption. The entire modelling program will receive increased emphasis as field spectra become available in late summer and autumn in the form of statistically analyzed data.

Field Instrumentation

A specific format for ground truth measurements in the 1966 growing season has been established. The major goal is the recording and interpretation of

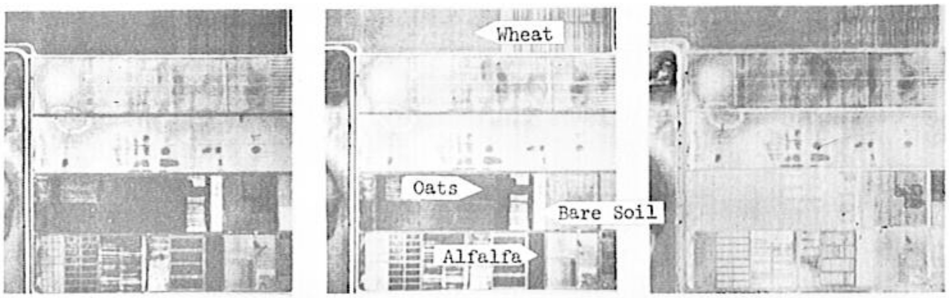


.4 - .7μ

.7 - .9μ

4.5 - 5.5μ (Artist's Concept)

Figure 5. Multispectral response comparison of corn, alfalfa, stubble, and bare soil, as of 1000 hours on 30 September 1964. Note the marked change in relative response of alfalfa and bare soil among the wavelength bands represented. The "artist's concept" is a representation in pictorial form of relative response, deduced from filtered radiometer measurements of the various fields.



.38 - .44μ

.62 - .68μ

.71 - .79μ

Figure 6. Multispectral response comparison of wheat, oats, alfalfa, and bare soil as of 1630 hours on 25 June 1964. The differences in relative response of bare soil in this figure as compared to Figure 5 are largely due to a difference in soil type.

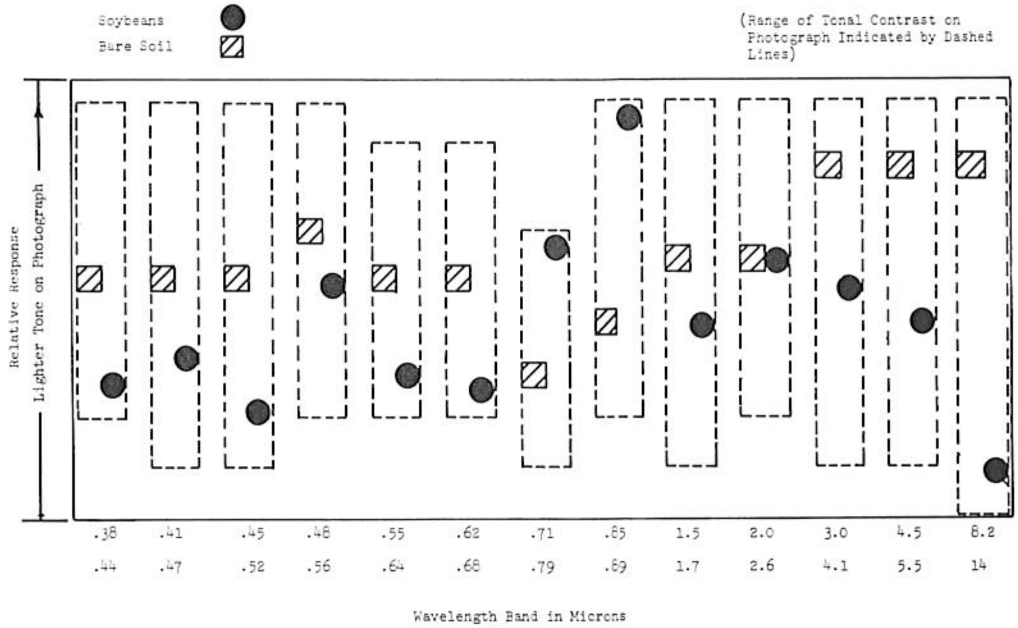
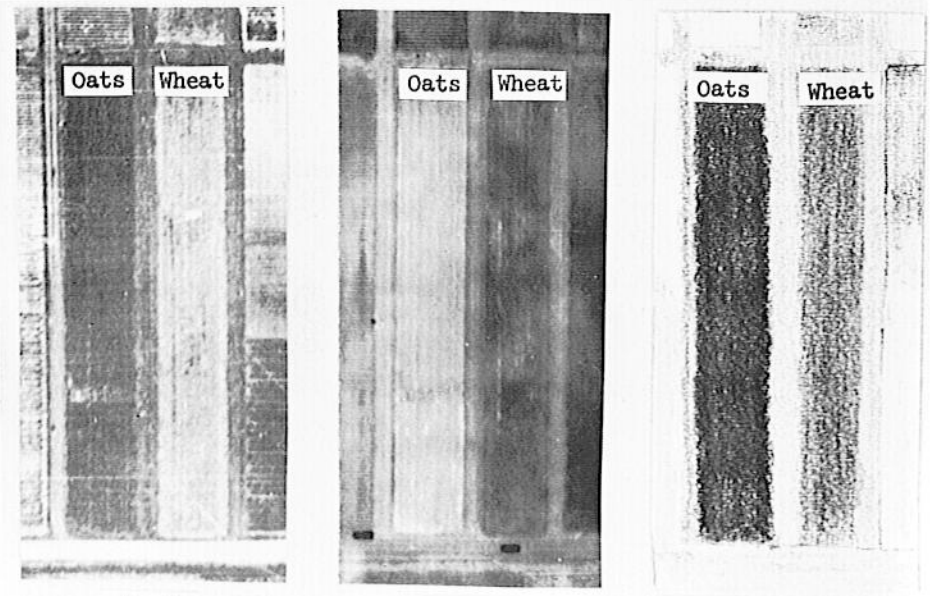


Figure 7. Graph of a multispectral response comparison between bare soil and soybeans, deduced from imagery obtained at 1530 hours on 29 July 1964. Notice comparable response in only a few of the many wavelength bands.



.4-.7μ

.7-.9μ

2.0 - 2.6μ
(Artist's Concept)

Figure 8. Multispectral response comparison of oats and wheat as of 1430 hours on 25 June 1964. The reversals in relative response between wavelength bands seen here are largely due to differences in maturity.

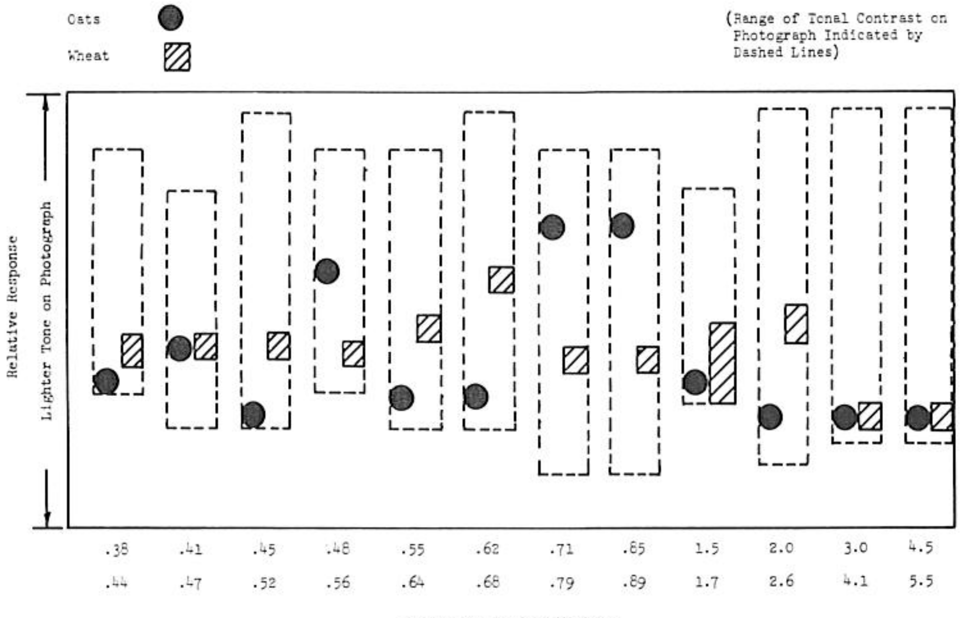


Figure 9. Graph of a multispectral response comparison between oats and wheat as of 1630 hours on 25 June 1964, using 12 wavelength bands of imagery. Compare corresponding wavelength bands shown in Figure 6 and 8 with this graph.

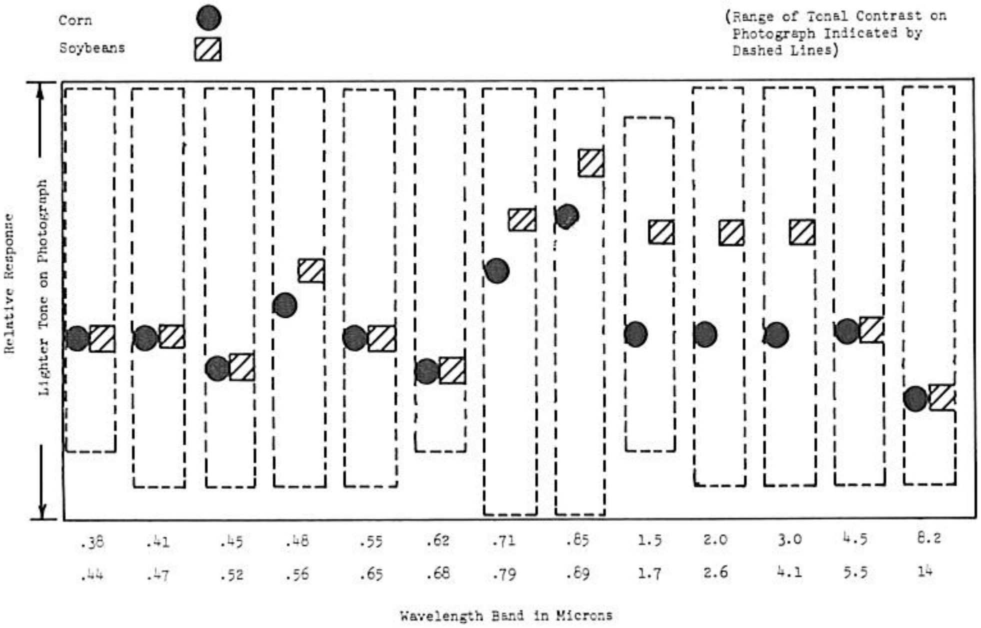


Figure 10. Graph of a multispectral response comparison between corn and soybeans as of 1315 hours on 29 July 1964. Imagery obtained throughout the photographic portion of the spectrum (.38 - .89 μ) or thermal infrared region (3 - 14 u) showed few differences in relative response as indicated on this graph.

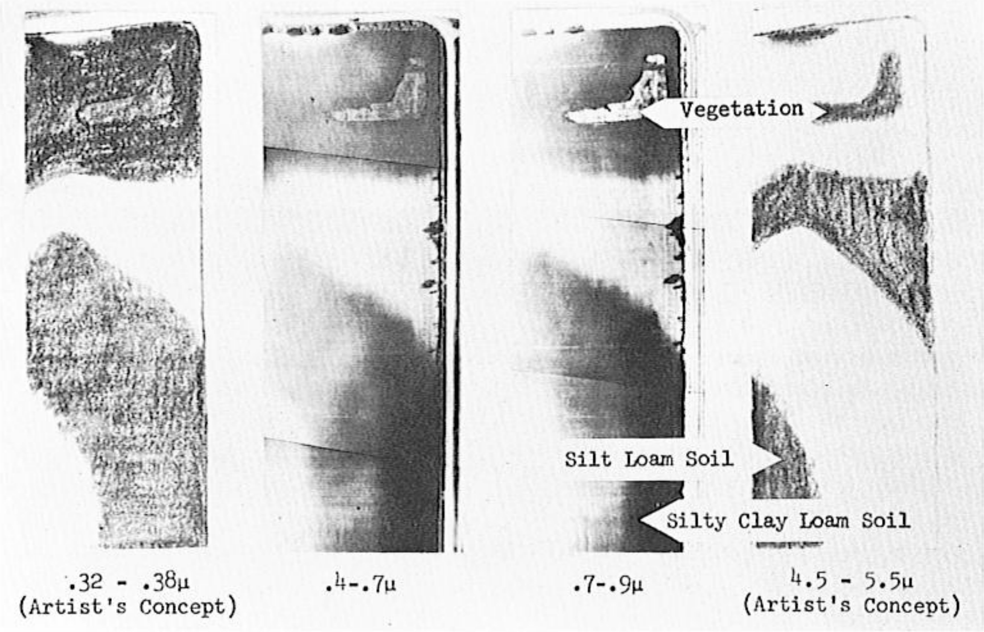


Figure 11. Multispectral response comparison of two soil types, both bare and relatively dry, taken on 3 June 1964. Note the reversal in response of both soil types in the thermal infrared region (4.5 - 5.5 u) as compared to the other three wavelength bands in the reflective portion of the spectrum. The vegetation can be differentiated because of its similarity in response to the silty clay loam soil in the U.V. and visible wavelengths, changing over to similarity in response to the silt loam soil in the reflective and thermal infrared wavelengths.

spectra from a cherry-picker truck in the spectral range of 0.35 to 14 microns over fields of view now established as (1) a 10° conical field, (2) a $4^{\circ} \times 4^{\circ}$ square field, (3) a $2^{\circ} \times 2^{\circ}$ square field, and (4) a $10^{\circ} \times 2^{\circ}$ rectangular field. Data will be recorded at angles of 0°, 15°, 30°, and 45° with respect to zenith, away from the sun and toward the sun in the incidence plane, and at right angles to the incidence plane. Solar and sky irradiance of the field of view will be measured with a filtered Eppley pyrheliometer. All data will be recorded on a 7-channel AM-FM tape recorder with a running commentary voice track.

The entire field instrumentation system is currently in the final engineering design stage. Procurement orders for all major units will be completed by May 20, 1966. All electronic instrumentation has been ordered, the only remaining items being the field truck and the power system. Figure 12 shows the overall field system configuration. Three Block interferometer spectrometers covering ranges of 0.25 - 2.5 μ, 1 - 5.5 μ, and 2.5 - 16 μ obtain spectral measurements while a Barnes PRT-5 radiometer obtains apparent temperature in the 8 - 14 μ band. These four optical units are mounted in the cherry-picker together with a simple 16mm framing camera for pictorial record. One experimenter will work in the cherry-picker bucket. Data monitoring will be done by a second experimenter at the interface board and Tektronix storage oscilloscope in the field truck. Finally, a third experimenter will measure solar and sky irradiance at the outset of the experiment, and thereafter set up reference marks at the site to be spectrally viewed. As an integral part of this program, micrometeorological instrumentation, currently on hand, will be installed for the duration of the growing season at selected crop sites.

A major portion of the effort on engineering aspects of ground truth has concentrated on the design and component choice of the field system.

Radar Study

One experimenter has devoted his time on the project to a study of synthetic aperture radar capabilities and a literature study on radar scattering from crops and soils. A synopsis of information gathered to date is contained in Appendix B.

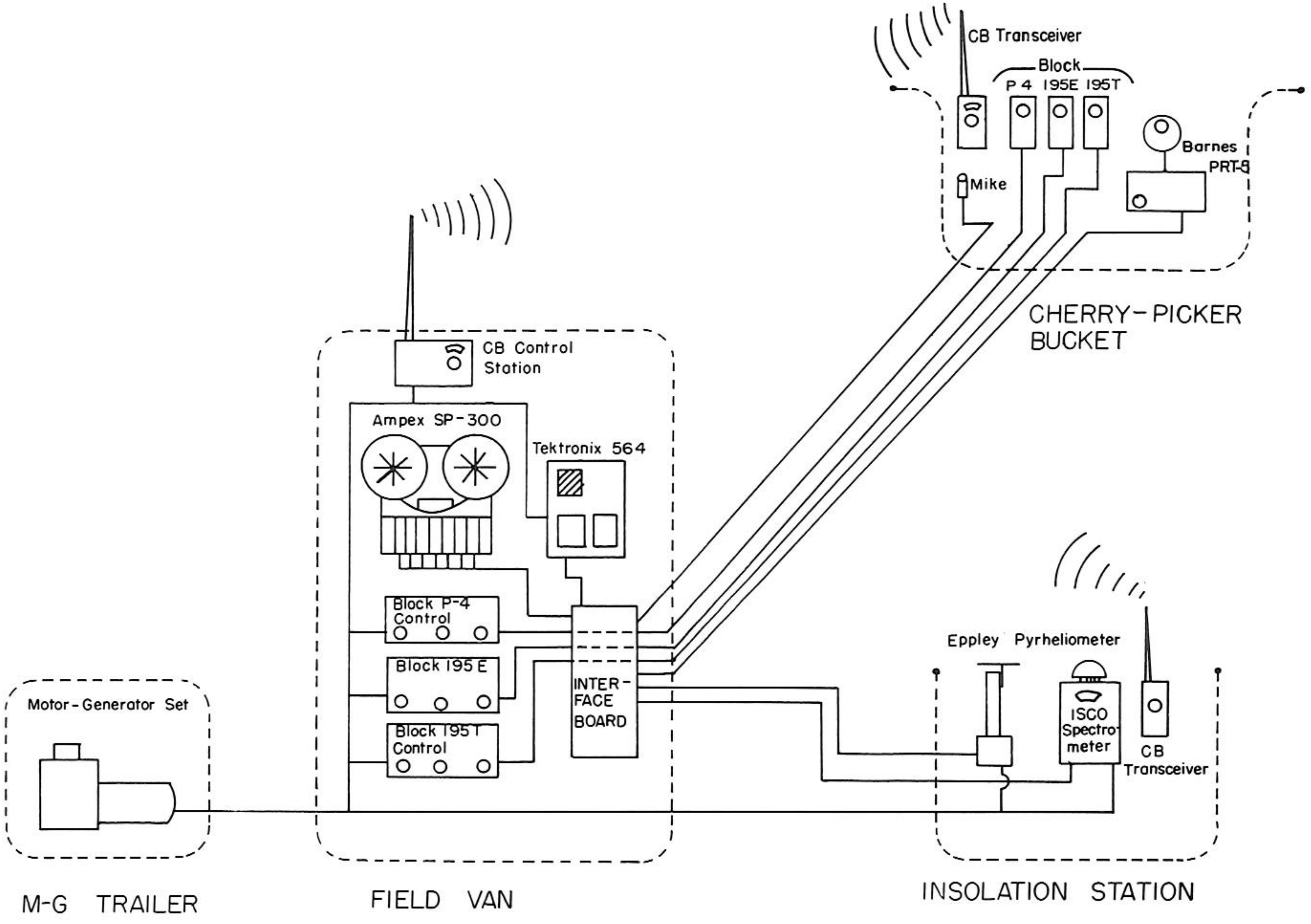


Figure 12. Field Instrumentation

1966 FLIGHT AND GROUND TRUTH PROGRAM

Through joint meetings with University of Michigan personnel, the following flight program by U-M over the Purdue University test site has been agreed upon for 1966:

Flight Number	Flight Time (CDT)	Flight Duration (in hours)	Target Area*	Aircraft Altitude (in feet)	Scanner Data (in Minutes)	Electronic Tapes (Per Flight) (No. of 1/2" Tapes/ No. of 1" Tapes)
0 (Check-out)	1330	1.5	E	3,500	4	
			B	3,500	8	
			A	3,500	4	
			D	3,500	3	
			C	3,500	2	2/2
1	1200	2	A	10,000	4	
			B	10,000	4	
			A	3,500	8	
			B	3,500	16	
			A-2	2,000	1	3/3
2	0800	2	C	3,500	2	
			A	3,500	4	
			B-1	3,500	2	
			A-2	2,000	1	
			A-2	500	4	2/2
3	1200	2	C	3,500	2	
			A	3,500	4	
			B-1	3,500	2	
			A-2	2,000	1	
			A-2	500	4	2/2
4	2200	1.5	A	3,500	4	
			B-1	3,500	2	
			D	2,000	2	
			A-2	2,000	1	
			A-2	500	4	2/0

Flight Number	Flight Time (CDT)	Flight Duration (in hours)	Target Area*	Aircraft Altitude (in feet)	Scanner Data (in Minutes)	Electronic Tapes (Per Flight) (No. of 1/2" Tapes/ No. of 1" Tapes)
5	1400	1.5	C	3,500	2	
			A	3,500	4	
			B-1	3,500	2	
			D	2,000	2	1/1

*The target areas designated are as follows:

A. Purdue University Experimental Agronomy Farm, (470 acres in size) and adjacent area in a flight line 4 miles to the north.

B. Farming area primarily south of Wabash River, of approximately 20 square miles in size.

C. Purdue University Experimental Sand Farm (40 acres in size) near Culver, Indiana, 60 miles north of Lafayette.

D. Purdue University Livestock Farm.

E. High Bridge Area.

This flight schedule will be repeated at selected times during the growing seasons according to the following schedule:

Date	Flight Number
5 May	0 (check-out flight)
28 June	1
29 June	2,3,4
30 June	5
26 July	1
27 July	2, 3, 4
28 July	5
23 August	1
24 August	2, 3, 4
25 August	5

Data gathered during these flight missions will consist of 18 wavelength bands of scanner data, recorded on magnetic tapes; a 16-lens camera using infrared film; 9-inch panchromatic film; 70mm color film; and 70mm infrared ektachrome film.

The Agronomy Farm contains experimental plots of many crop types as well as large, bulk planted fields of oats, wheat, soybeans, and corn, on which detailed ground truth data (variety, date of planting, crop density, yield, soil type, soil moisture, etc.) will be obtained, and on which spectral reflectance curves will be obtained with the DK-2 spectrophotometer and Block interferometers. The section of "Field Instrumentation" has described the nucleus of instrumentation to be used for much of the detailed ground truth measurements.

The Sand Farm comprises the second detailed test site, and consists of bulk planted fields of corn, soybeans, alfalfa, sorghum, sudan grass, as well as one area which will be maintained as bare soil. These fields have been planted to our specifications for purposes of this remote sensing program. Detailed ground truth data such as specified above will also be obtained on these fields.

Ground truth data consisting primarily of crop type and general condition of maturity will be obtained for the other target areas, to be used to test pattern recognition techniques and obtain statistical data on the reliability of such methods.

IV. MEETINGS, WRITINGS, TRAVEL

A. Travel for the purpose of coordinating research efforts in agricultural remote sensing:

1. Ann Arbor, Michigan - January 26, 27, 28, 29, 1966--attended by Roger Hoffer and Roger Holmes.

2. Ann Arbor, Michigan - March 7, 1966--attended by Roger Holmes.

3. Ann Arbor, Michigan - March 22, 23, 1966--attended by David Landgrebe and Terry Phillips.

4. Weslaco, Texas - March 27, 28, 29, 1966--attended by Roger Hoffer.

B. Travel for the purpose of attending symposia, presenting papers, speaking before groups:

1. Washington, D.C. - November 23, 24, 1965--Roger Hoffer, to speak at a USDA Natural Resource Division (ERS) luncheon on "Potential Applications of Remote Multispectral Sensing in Agriculture".

2. Washington, D.C. - February 14, 15, 16, 1966--Roger Hoffer, to speak at at USDA, ERS Joint Division "Natural Resoirce Economics and Farm Production" luncheon on "Remote Multispectral Sensing in Agriculture--Problems and Potentials".

3. Ann Arbor, Michigan - April 11, 12, 13, 14, 1966--Roger Holmes, Roger Hoffer, David Landgrebe, attended the Fourth Symposium on Remote Sensing of the

Environment. Roger Hoffer, Roger Holmes, and Ralph Shay presented a paper on "Vegetative, Soil, and Photographic Factors Affecting Tone in Agricultural Remote Multispectral Sensing".

In addition, Roger Hoffer spoke at a staff seminar, Department of Agronomy, Purdue University, Lafayette, Indiana, on "Remote Multispectral Sensing in Agriculture", March 21, 1966.

C. Travel for the purpose of instrumentation and data processing systems design.

1. Norwalk, Connecticut - March 28, 1966--Roger Holmes discussed instrumentation with Perkin-Elmer, Barnes Engineering, Inc., and Pyrotel Corporation.

2. Houston, Texas and Huntsville, Alabama - March 30, 31, April 1, 2, 1966--David Landgrebe and Terry Phillips to discuss data handling capabilities with respect to aircraft scanner tapes, and also to establish the existence or non-existence of digital display equipment.

V. FINANCES

A brief summary of financial expenditures through April 30, 1966.

Department of Botany and Plant Pathology:	
Salaries Spent	$ 7,650.89
Supplies and Expenses Spent	$ 1,907.59
Encumbered	$ 532.73
	$10,091.21
Department of Electrical Engineering:	
Salaries Spent	$ 6,859.40
Supplies and Expenses Spent	$ 1,945.63
Encumbered	$ 7,993.21
	$16,798.24
Overall Total	$26,889.45

One item has been procured at a cost of over $1,000. In accordance with the grant documentation it is noted as: Tape Recorder, Ampex Model SP-300, 7 Channel, 1/2" AM-FM ($8,450).

APPENDIX A

VEGETATIVE, SOIL, AND PHOTOGRAPHIC FACTORS AFFECTING TONE IN AGRICULTURAL REMOTE MULTISPECTRAL SENSING

by Roger M. Hoffer, Roger A. Holmes, J. Ralph Shay

Aerial photo interpretation is normally based upon principles of size, shape, pattern, shadow, tone, texture, and association (1, 2). In remote multispectral sensing of agricultural crops from high altitudes, many of these principles of photo interpretation no longer apply.

Figure 1 is a photograph of the Salton Sea area in California, taken from Gemini V at an altitude of about 110 nautical miles. (This particular photo has been enlarged somewhat over the original photograph). This photograph demonstrates that one obtains no indication of the crop type or condition due to the size, shape, or pattern of agricultural fields. As seen here, shadow and texture become less important with increased altitude and decreased resolution, although texture is still an extremely important factor in radar returns. Association is useful only in a gross geographic sense. Tone, which varies with wavelength in multispectral imagery, depending upon the spectral reflectance of the object viewed, is, therefore, the primary factor for image interpretation in the remote multispectral sensing research in agriculture. Tone has been defined as "each distinguishable shade variation from black to white" (3). In the past, tone has been a term frequently used in connection with photo interpretation, and represents the relative intensity of photons impinging upon a silver halide plate, in the visible or near-visible portions of the spectrum, as reflected from the objects viewed by the camera. In remote multispectral sensing, one is not confined to the photographic portion of the electromagnetic spectrum, but can use various types of detectors to sense reflected or emitted energy in the 0.3 to 14 μ portion of the spectrum, as well as 0.86 to 3.0 cm wavelengths using radar, and other portions of the spectrum with various types of sensors. Since certain of these sensors do not involve reflected energy nor do they necessarily produce data in the form of photographic images, reference to "tone" is sometimes misleading. Therefore, the term "response" is used hereafter to refer to the relative energy received by the sensor, and which may or may not be represented by an image. Response is, therefore, a meaningful term whether referring to reflected energy in the 0.3 to about 3 μ wavelength portion of the spectrum or

Figure 1. Enlargement of Salton Sea and Emperial Valley Area of California. This photo was obtained at an altitude of approximately 110 nautical miles from Gemini I. Most large fields are 160 acres in size.

emitted energy in the 3 to 14 μ region, or some other portion of the spectrum. Thus, an area that reflects strongly in the visible portion of the spectrum has a high response, or an area that is emitting a large amount of energy in the 8 to 14 μ region of the spectrum relative to other objects being sensed would also have a high response, and an object which has a relatively low reflection or emission would have a low response. In Figure 1, the white area just below the Salton Sea and cultivated region would be considered to have a high response.

One phase of the research program at Purdue University involves the identification of crop species and conditions of health and maturity for several economically important crop types in the corn belt region, using multispectral sensors in up to 19 spectral bands. Comparisons of the response of the various crop types and conditions using several spectral bands may allow a characteristic multispectral response signature to be determined for each crop type or crop condition studied.

There have been a number of examples presented in the past demonstrating the usefulness of multispectral or multiband imagery in differentiating various crop species and conditions (4, 5, 6). In some instances, these examples have involved crop types or conditions which are quite different, such as mature, golden-brown wheat compared to green oats. Such a difference in the condition of maturity between two species represents an important factor when attempting to differentiate and/or identify a particular crop type, providing that such a difference is characteristic of that crop species at that particular time during the growing season. Figure 2 demonstrates this point. This shows imagery obtained on September 30, 1964 in the 0.4 to 0.7 μ wavelength bands and also shows an artist's concept in pictorial form of the relative response of these same areas as measured with a filtered radiometer, operating in the 4.5 to 5.5 μ wavelength band. By this period in the growing season, the corn is dry, light brown, and rather similar in response to the wheat stubble. Alfalfa, however, is still green and transpiring and, therefore, has a lower response than corn in the visible portion of the spectrum, due to a darker color, a higher response in the photographic infrared (due to the high reflectance of most healthy green vegetation in this portion of the spectrum), and a lower response than the corn or bare soil in the 4.5 to 5.5 μ region (due to the cooling effect of evapotranspiration in the alfalfa). In the 4.5 to 5.5 μ wavelength region, the bare soil is emitting more energy and, therefore, has a higher response than any of the crop areas imaged. This is, of course, as one might suspect. (Densitometer measurements of the relative response within a given wavelength of the imagery

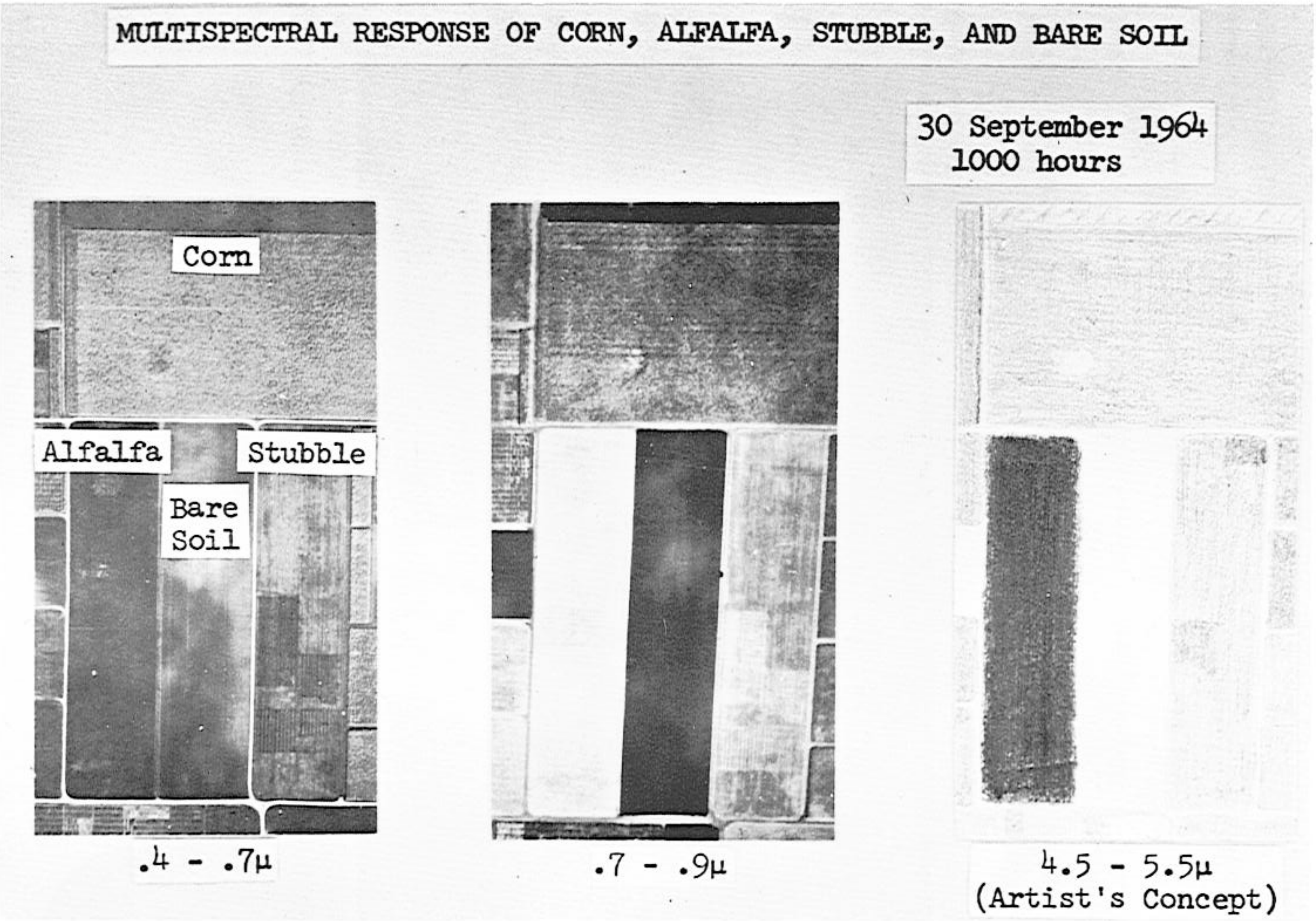


Figure 2. Multispectral Response of Four Cover Types. Note differences in relative response between alfalfa and bare soil, but lack of marked differences between mature corn and stubble, as a function of wavelength band.

shown in this and the following figures are presented in the Appendix.)

Examples such as Figure 2 help to demonstrate a capability for differentiating various crop species under certain conditions of growth and maturity. However, in attempting to specify characteristic multispectral response signatures for a given species, one finds several variables which can markedly affect the response in one or more wavelength bands. Studies to date have indicated that the vegetation and soil variables of primary importance are (1) crop species and variety, (2) relative size and maturity at the time of flight missions, (3) soil type, moisture content, and relative amounts of soil and vegetation observed, and (4) geometric configuration of the crop. Crop or leaf geometry has a marked influence on reflectance of vegetative canopies, particularly in relation to sun angle and view angle.

The particular variety of a crop species can affect response, particularly due to variations in maturity of the different varieties. Some varieties of wheat and corn, for example, mature at a faster rate than other varieties. This becomes particularly critical late in the growing season for the species concerned. Figure 3 shows a field of corn which contains two different varieties, both of which were planted on the same date. In the visible portion of the spectrum (approximately 0.4 to 0.7 μ wavelength), there is little difference in response between the two varieties involved, as of the date this was obtained. However, in the photographic infrared portion of the spectrum, the variety Pfister SX29 has a much higher response than does the variety Indiana 678, due to the fact that the Pfister SX29 did not mature as fast as the Indiana 678, and therefore, has more healthy, green leaves which reflect a greater amount of energy in this portion of the spectrum than the browner, drier, mature leaves of the Indiana 678.

Figure 4 shows variations in response of four winter wheat varieties, all of which were again planted on the same date. In this case, however, all four varieties are quite mature as of the date this imagery was obtained, and, therefore, the response in the 0.7 to 0.9μ wavelength region is low and approximately the same for all of these varieties. However, in the 0.4 to 0.7 μ wavelength band, color variations due to differences in variety become evident and produce distinct differences in response, particularly in the case of the Knox 62 variety.

Not only do inherent differences in the rate of maturing of a particular

CORN VARIETY DIFFERENCES

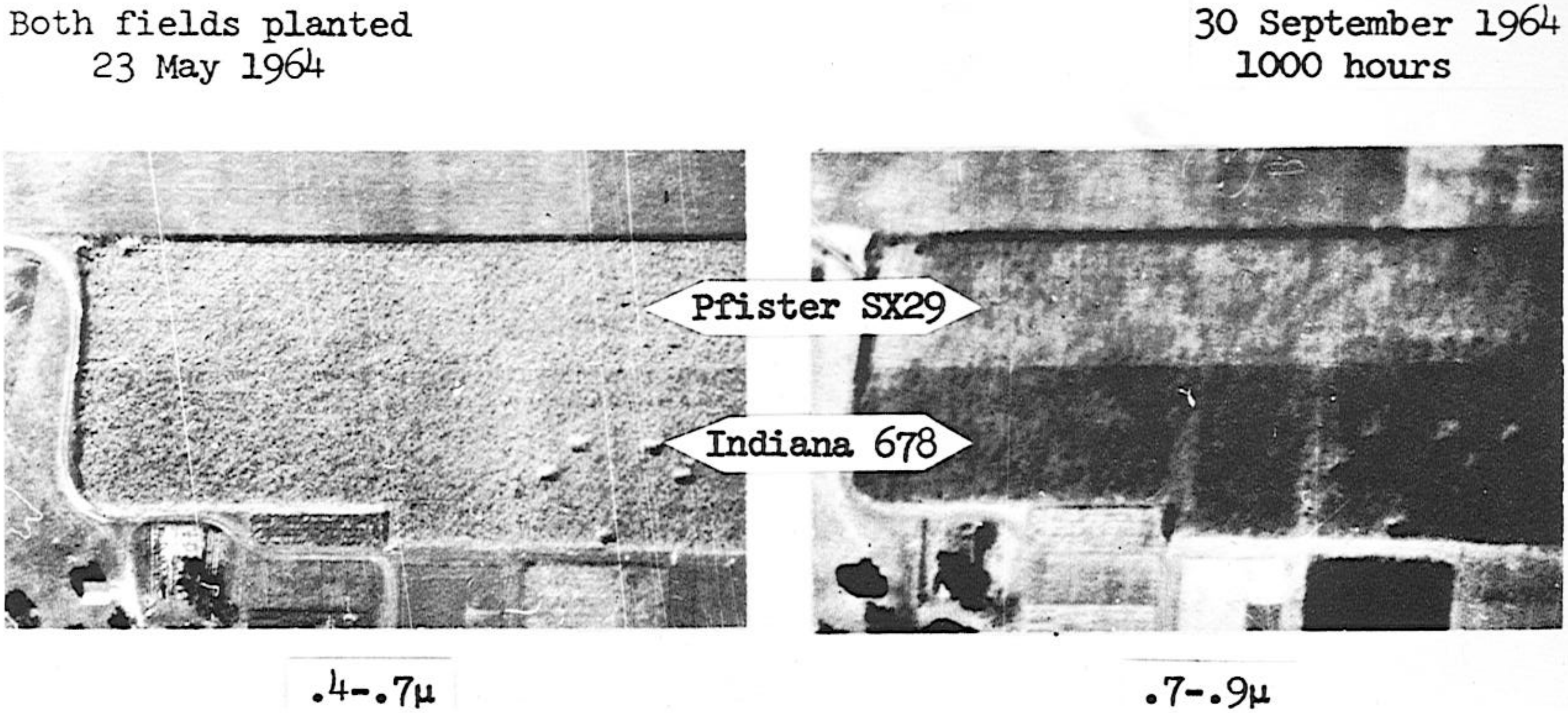


Figure 3. Corn Variety Differences. Relative rates of maturing differ, thereby causing marked variations in response within a given crop species.

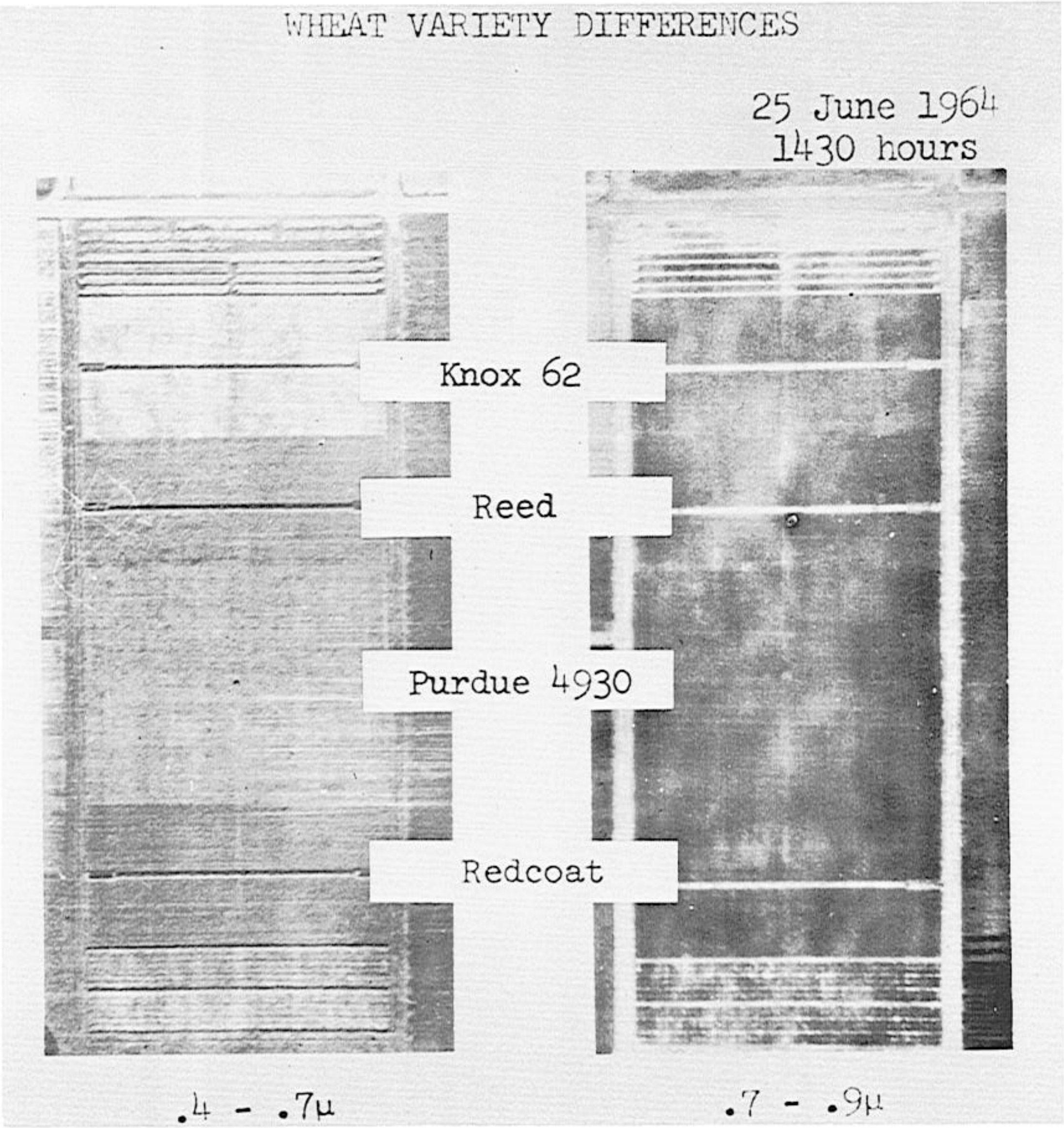


Figure 4. Wheat Variety Differences. Note lack of response differences in 0.7 - 0.9 μ wavelength band, but distinct differences in visible portion of spectrum, as compared to Figure 3. The differences observed between these two figures are due to differences in stage of maturity of the variety and species concerned at the time imagery was obtained, and the effect of these maturity differences upon the variety.

variety cause marked variations in response, but the date of planting of the same variety can cause differences in response. The date of planting is particularly important late in the growing season when differences in maturity become more evident, and early in the growing season when variations in the crop height (which are related to date of planting) influences the relative amounts of soil and vegetation sensed remotely. Figure 5 illustrates the effect of date of planting upon two fields of corn late in the growing season. Note that these two fields contain the same variety of corn, but that there was a difference in planting date of only eight days. One finds in this case that color differences due to the difference in maturity are so slight that there is little difference in response in the visible portion of the spectrum. However, in the photographic infrared portion of the spectrum, this slight difference in maturity due to an eight day difference in the date of planting over 4 1/2 months earlier causes a distinct variation in response.

As pointed out above, a difference in date of planting will affect response early in the growing season primarily because of a difference in the relative amount of soil being sensed. Figure 6 shows this effect, in an area of relatively low reflecting soil. In the 0.4 to 0.7 μ region, no difference in response is observed between either field of corn or the field of oats. All three fields have a uniform low response. However, in the 0.7 to 0.9 μ region, the most recently planted corn field (May 14) does not have as dense a crop canopy and a greater proportion of the soil is sensed, as compared to the field planted on May 4. The thick green canopy of oats allows relatively little soil to be sensed, and therefore, has a higher response than either corn field as of this date. Such a difference in response would probably not be found a short time later in the growing season after the corn canopy has become denser, but soon the oats would start to mature and then will have a much lower response than the corn in this 0.7 to 0.9 μ wavelength band.

Variations in soil type, however, can cause marked reversals in the situation presented in Figure 6. On a light colored, highly reflective soil, it has been found that in the 0.7 to 0.9 μ wavelength band the highly reflective vegetation will blend with the soil and result in a relatively uniform response despite variations in crop density (6). But in these situations, the light colored, highly reflective soil will not blend with the relatively low response of the vegetation in the visible portion of the spectrum, and therefore, the thinner the crop canopy being sensed, the higher will be the response. This is just the opposite effect with respect to wavelength band as seen in Figure 6.

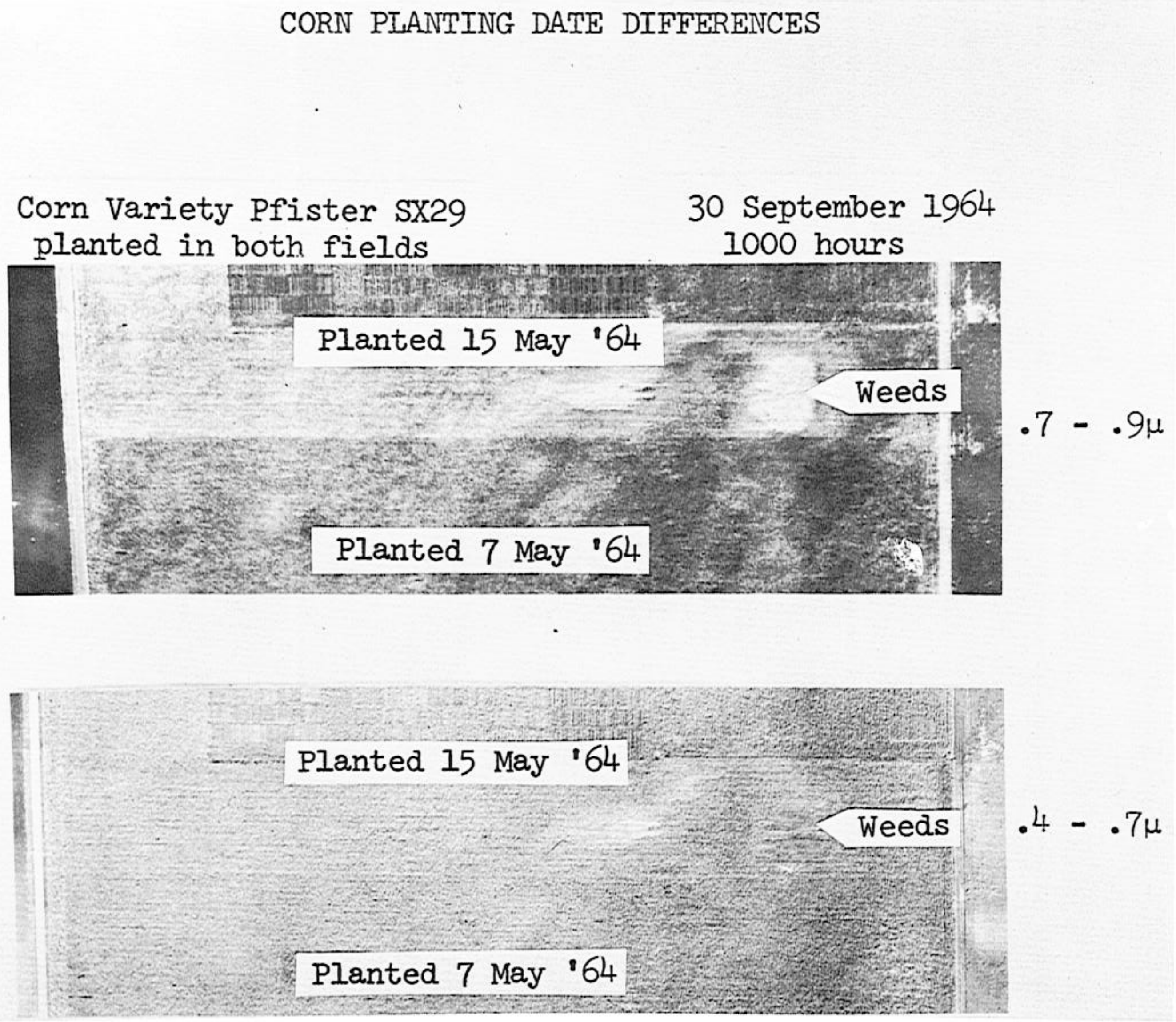


Figure 5. Corn Planting Date Differences. Maturity differences late in growing season cause distinct variations in response. This is the same result as seen in Figure 3, but in this case a different agricultural factor was involved (e.g. date of planting versus corn variety).

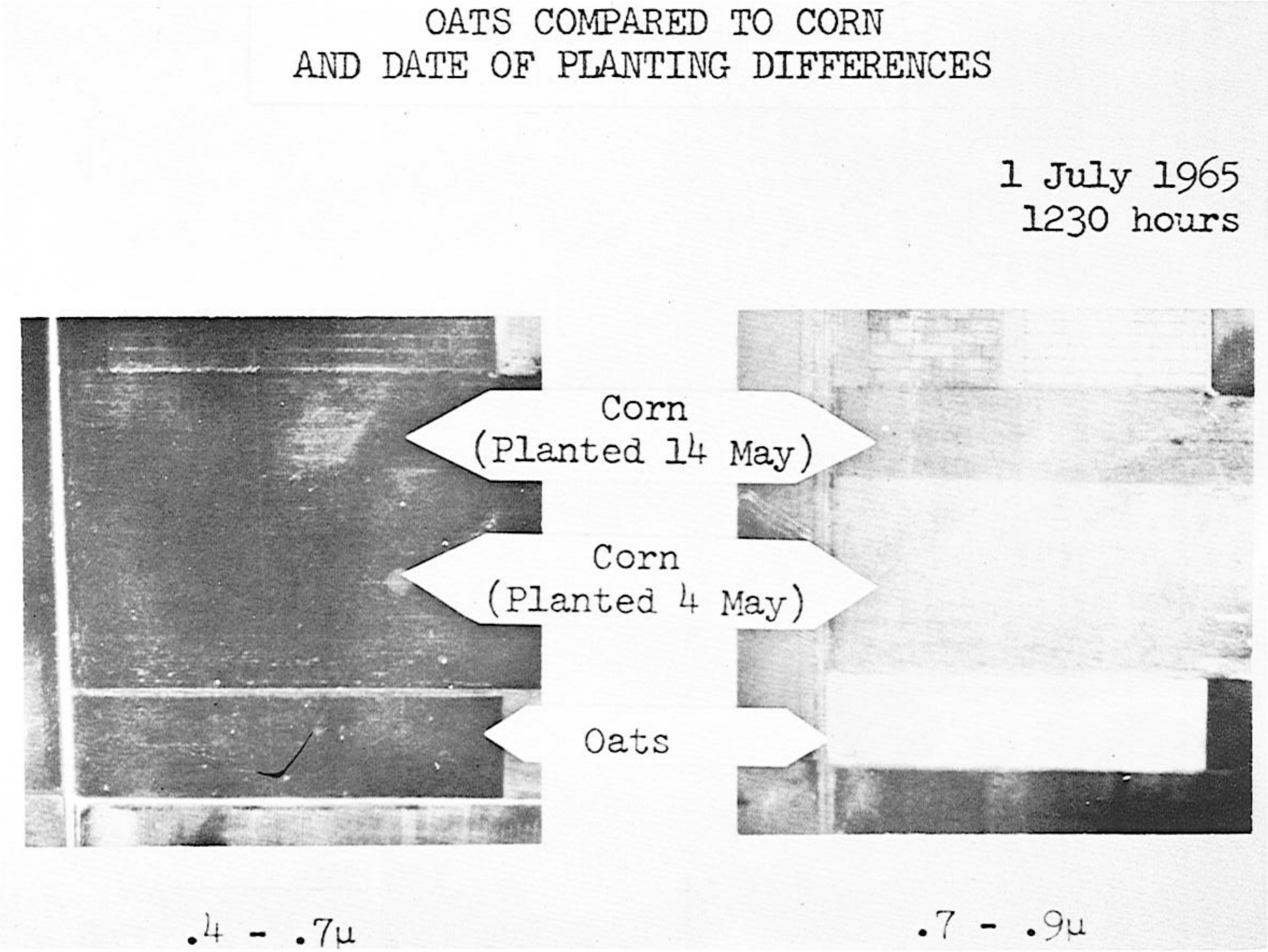


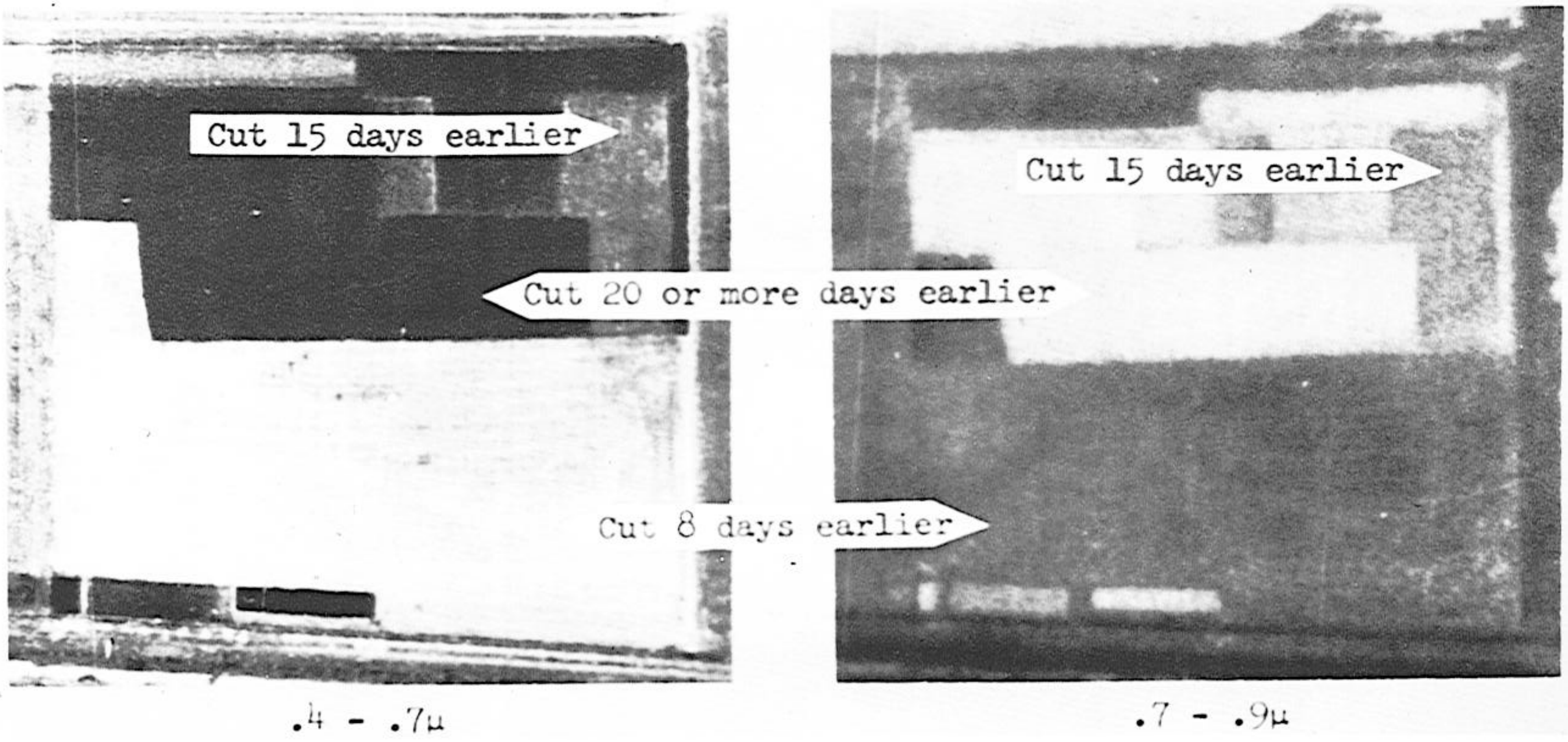
Figure 6. Oats Compared to Corn and Date of Planting Differences Early in the Growing Season. Variations in crop density and therefore in the relative proportions of soil sensed cause response differences in the photographic infrared in situations of dark, relatively low reflecting soil.

The amount and condition of vegetation and soil being sensed remotely may cause major variations and even reversals in response of a given crop species in both the visible and photographic infrared portions of the spectrum. Such variations in response are not only due to species, variety, and date of planting differences as seen above, but in the case of forage crops, differences between harvested and unharvested and how recently the crop has been harvested may cause distinct variations in response, as evidenced by Figure 7. In this situation, the alfalfa that had been cut 20 or more days earlier has grown enough to respond as a dense vegetative canopy. The most recently cut area is largely bare soil and stubble, and therefore has a much higher response in the visible region and a much lower response in the photographic infrared region than the areas that have a good vegetative canopy. The area cut 15 days earlier has not yet had enough regrowth to result in a complete cover, and presents an intermediate response in both wavelength bands.

From some of these comments it becomes apparent that soil type as well as vegetative condition plays an extremely important and variable role when working with multispectral response patterns. If a characteristic, statistically meaningful multispectral response pattern is to be determined for each crop type or species of interest, as many of these vegetation and soil variables must be eliminated or accounted for as possible. In the case of field crops, one important method of eliminating unwanted variations in response is to obtain imagery on a particular crop type only during those portions of the growing season when the crop canopy has reached its maximum. Figure 8 illustrates this point. Using only the visible wavelength region (Plus X film) one sees that on July 1, the soybeans were not yet large enough to allow a complete canopy coverage, even though ground measurements showed them to be 10 to 17 inches tall. Therefore, the difference in soil type in this particular field becomes a major factor in the response, the areas of relatively light colored silt loam showing a rather high response. However, after the canopy cover has reached its maximum, the influence of soil type becomes minimal, and in this case of soybeans, is negligible on September 1, when the complete canopy cover presents a fairly uniform response, despite the marked difference in underlying soil type.

Not only have certain vegetative and soil factors been found to cause marked contrasts in response, but in the reflective portion of the spectrum and

VARIATIONS IN RESPONSE DUE TO ALFALFA CUTTING



1 July 1965
1230 hours

Figure 7. Variations in Response Due to Alfalfa Cutting. Relative amounts of green vegetation, stubble, and bare soil due to harvesting of forage crops cause distinct but variable differences in response, thereby creating severe problems in remote identification of cover type.

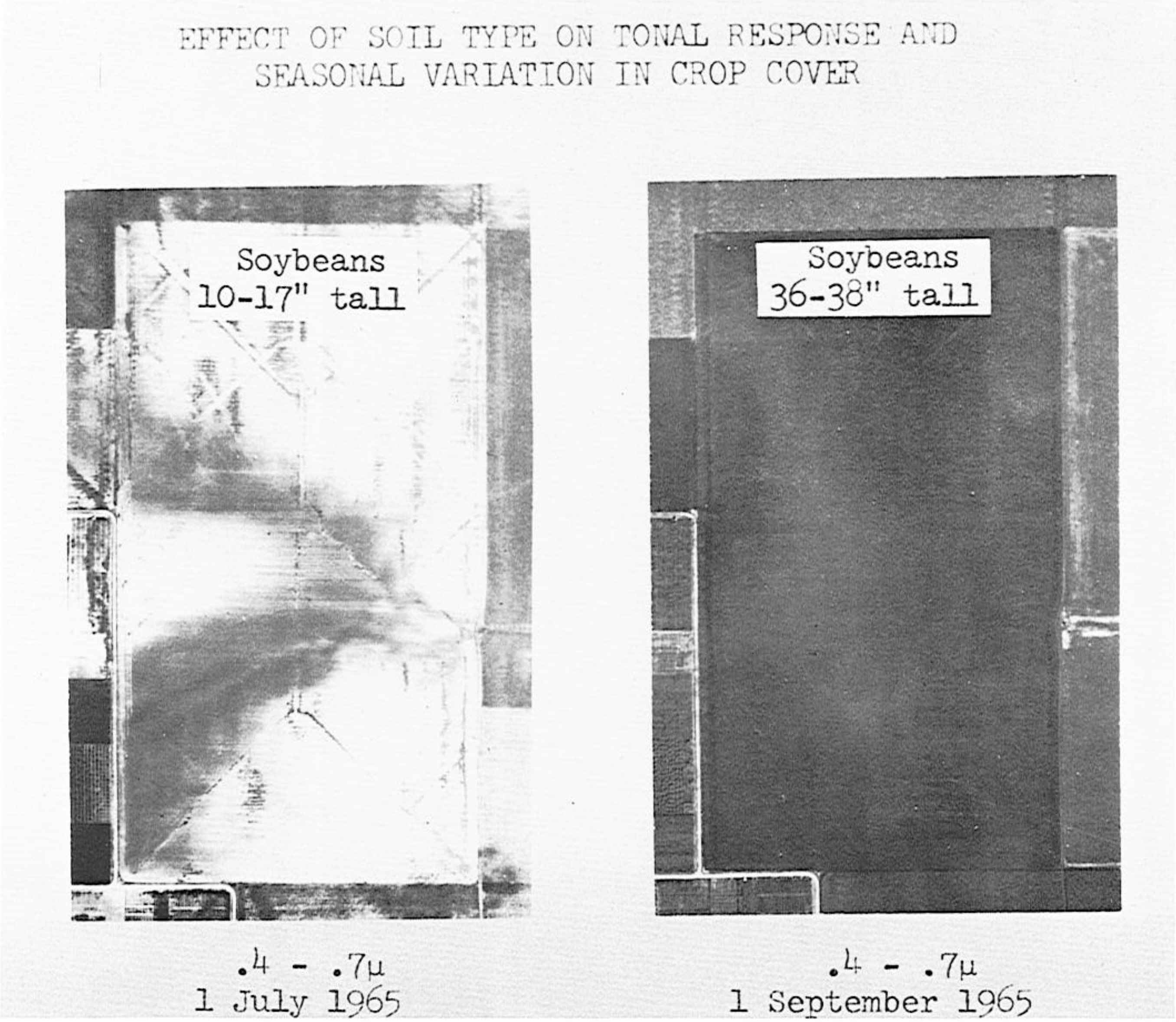


Figure 8. Effect of Soil Type Upon Response and Seasonal Variation in Crop Cover. Prior to maximum and an almost complete canopy cover, soil type differences cause distinct variations in response throughout all wavelength bands of imagery from 0.3 to 14 μ, but here represented by only the .4 - .7 μ wavelength band.

in particular, multispectral response data obtained by camera, has been found to have marked differences in response due to a number of factors involving the instrumentation and crop geometry. Differences in backscattering from a vegetative canopy due to a change in angle of incidence in relation to the area of interest on the ground is one problem area that has received relatively little attention. About a year ago, Steiner and Haefner wrote an excellent paper on the subject of tonal distortion and pointed out the importance of consideration of certain angular factors, noting that very little work had been done in the problem area (7). One factor of primary importance discussed by them was "reflectance characteristics of the terrain". Figure 9 illustrates the problem. In this situation, two Plus X aerial photos were taken from different positions. These photos were obtained by the Institute of Science and Technology, University of Michigan, on one of their 1964 NASA sponsored flight missions to Purdue. The photos were taken on adjacent flight paths no more than 5 minutes apart, and the photo on the left is a portion of photo No. 212 on the roll, the photo on the right is part of photo No. 210, so each was subject to the same development variables. In the case on the left, the response from all wheat fields is relatively low, both immediately below the camera at photo nadir and off to the side toward the sun. Note that the difference in response is distinct between the wheat and soybean fields, the latter actually consisting mostly of bare soil at this particular time in the growing season. In the photo on the right, however, the wheat fields off to the side of the photo away from the sun have a high backscatter, and therefore, a high response, and cannot be differentiated on the basis of response from the soybean fields. However, the wheat field at photo nadir still has a relatively low response. Note also that this change in response due to backscattering occurs only to a minor extent in the field of oats in this particular set of imagery, probably due to the fact that the oats were still green but the wheat was a mature golden brown vegetative canopy as of this date, and the wheat is thus more likely to demonstrate marked changes in response due to backscatter and specular reflectance.

In the biophysical interpretation of the data in the previous figures the simplest aspect is that of the degree of soil coverage by crop canopy, for this is thought of as the addition of fractions of two well-defined spectral signatures. The aspects of crop maturity and resultant changes in leaf and other plant part spectra are more involved and were discussed mainly in a phenomenological way

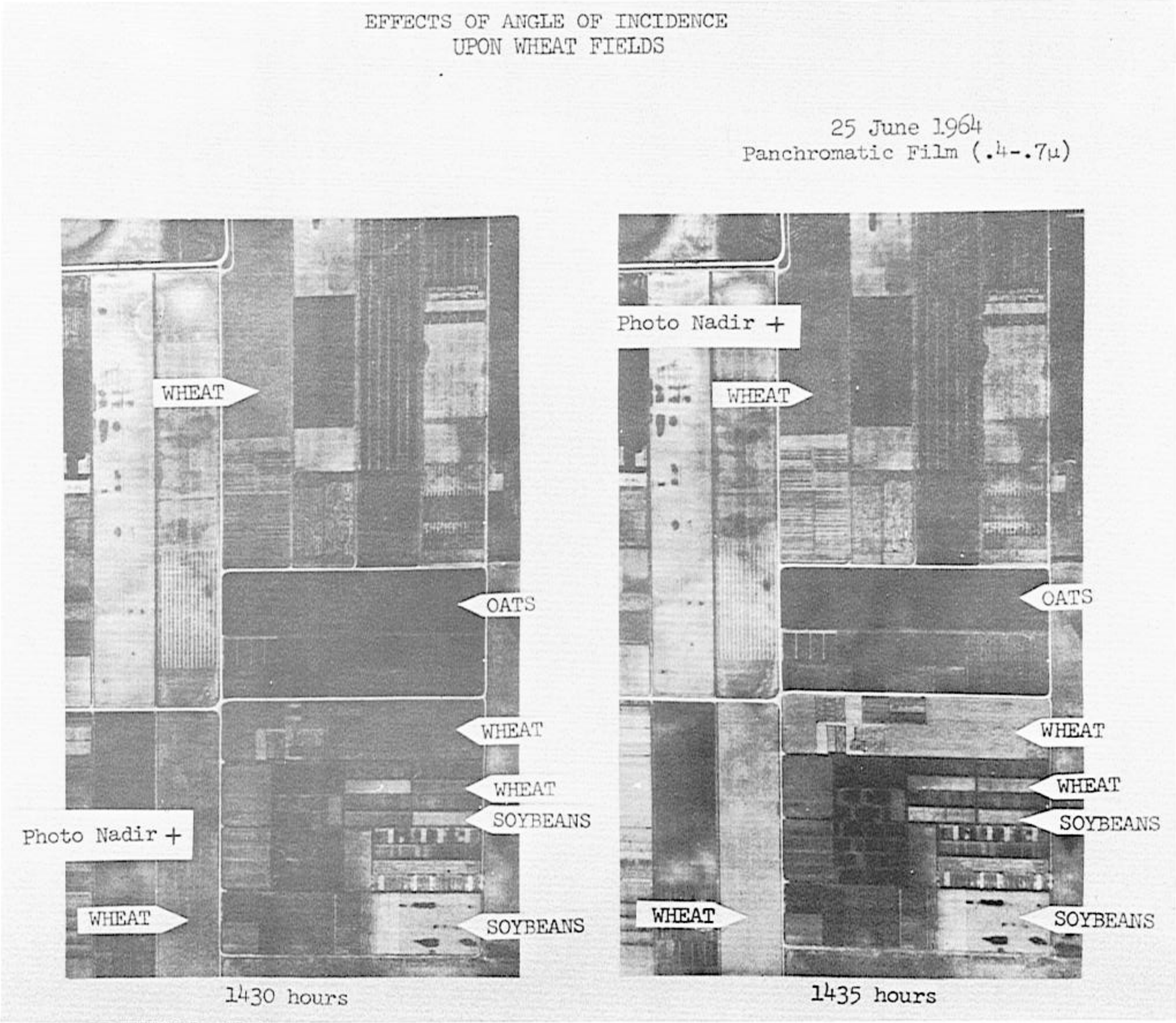


Figure 9. <u>Effects of Angle of Incidence and Backscattering Upon Response of Wheat Fields.</u> Differences in photo nadir indicate relative airplane positions in obtaining the photos which include this area. Note low response in all wheat fields in photo on left--a condition not obtained in photo on right.

based on the well-known near infrared reflectance of green, healthy vegetation. In the remainder of this paper major attention is given to sun altitude - view angle effects on response in a given wavelength band.

Steiner and Haefner (7) have described the tone (response) distortion resulting from varying view angles due to both conventional $\cos^4\theta$ off-axis loss in illumination and the view and sun angle - dependent reflectance of the crop cover or terrain. In the discussion that follows the $\cos^4\theta$ function is ignored, assuming the instrument (camera, spectrometer, scanner) has sufficiently small field of view to do so.

The hypothesis put forth here is that several aspects of the observed variation of gross reflectance with sun and view angle can be explained in terms of crop geometry details. To begin, three models are illustrated that fail to explain increased reflectance at lower view angles. Figure 10 (a) shows the crop canopy considered to be simply a Lambertian surface with the result of constant energy per unit time received at the detector of a fixed field of view instrument regardless of view angle. Illuminance is presumed to come primarily from the sun, and a fixed wavelength band is implicitly considered. Next, in (b) of Figure 10, the crop canopy is assumed to be made up of flat Lambertian surfaces of reflectance r partially covering a "ground" surface assumed black. Again, a constant energy per unit time enters the fixed field of view instrument as a function of view angle with the exception of minor variation due to the "patchiness" of the field of view. The constancy follows from the fact that the relative coverage of the reflectance r surfaces on the projected area normal to the view axis is independent of view angle. Finally, in (c) of Figure 10, a significant specular character is assumed for what had been Lambertian surfaces in (b). The major effect is to put a specular bump in the response curve, as shown. It is clear that none of these models account for the observed rise in reflectance with lower view angle.

Next, consider a somewhat far-fetched but illustrative model of a closely-planted idealized Lambertian cactus crop, shown in (a) of Figure 11. For the present assume that all incident sunlight is either absorbed or reflected - no transmission. Four scenes are shown for four different viewing points, indicating reflectance behavior similar to that noted by Steiner and Haefner. In (b) the field is viewed from the plane of incidence on the illumination side, showing high response which would become even higher as view angle was lowered,

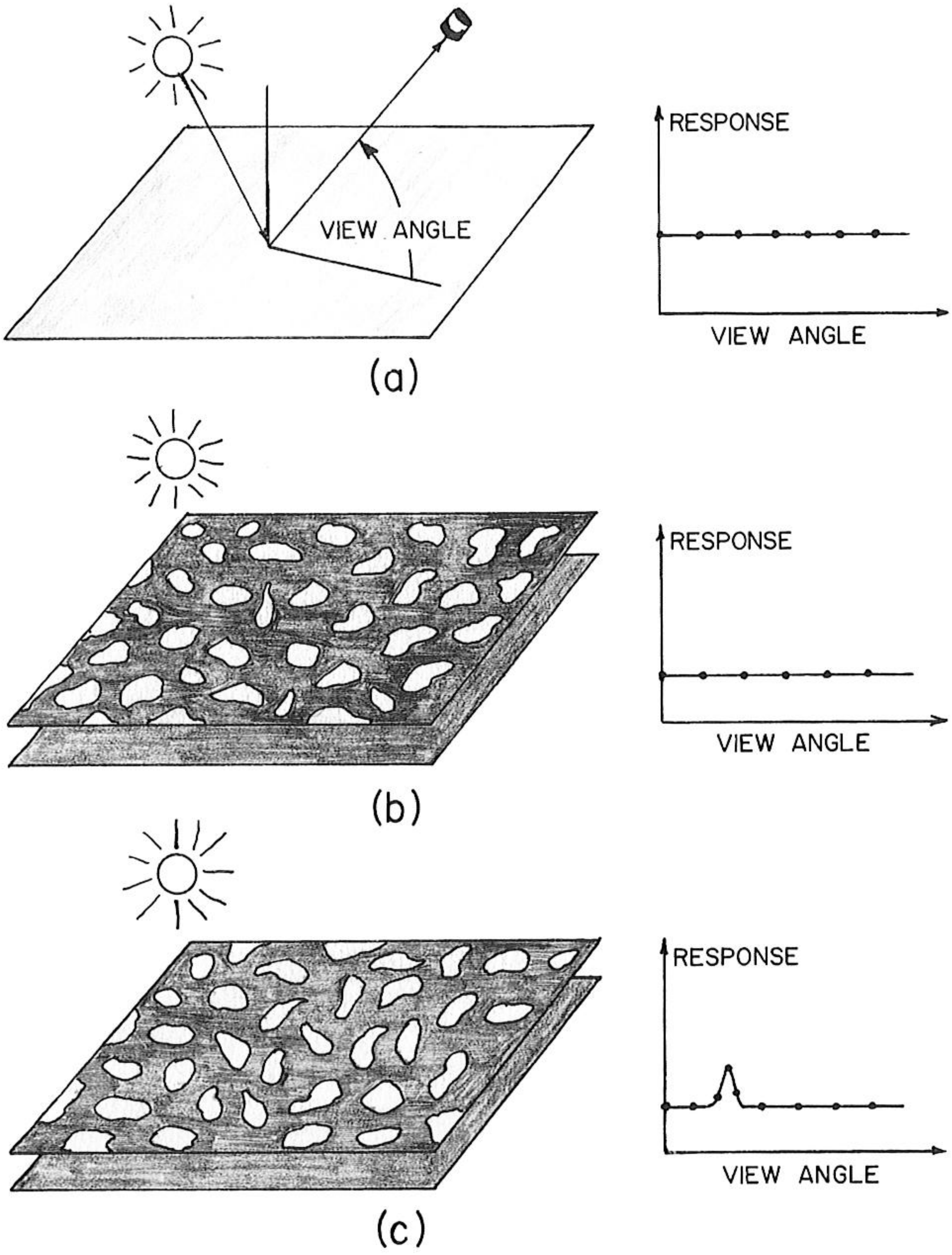

VIEW ANGLE
RESPONSE
VIEW ANGLE
(a)
RESPONSE
VIEW ANGLE
(b)
RESPONSE
VIEW ANGLE
(c)

Figure 10.

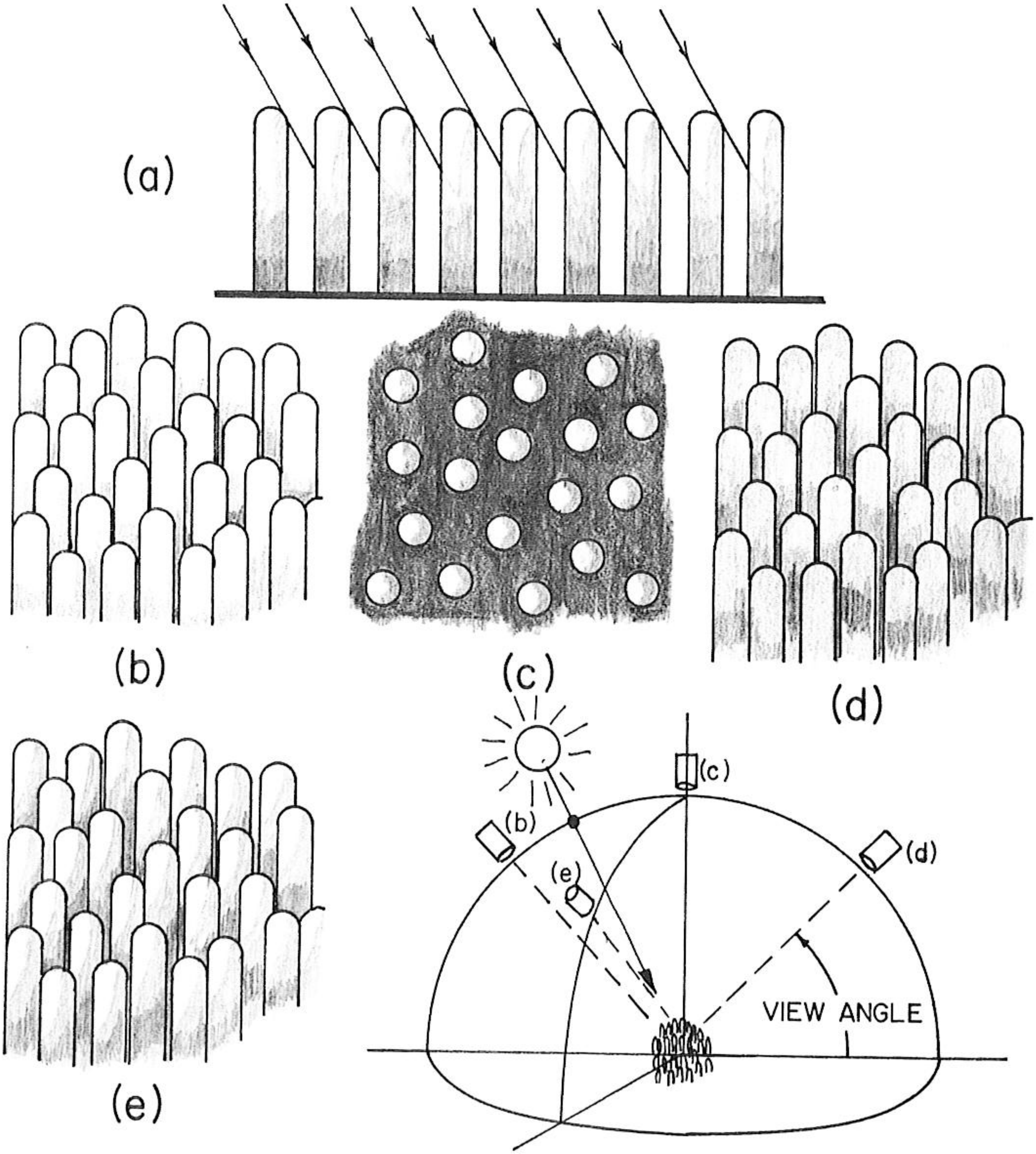
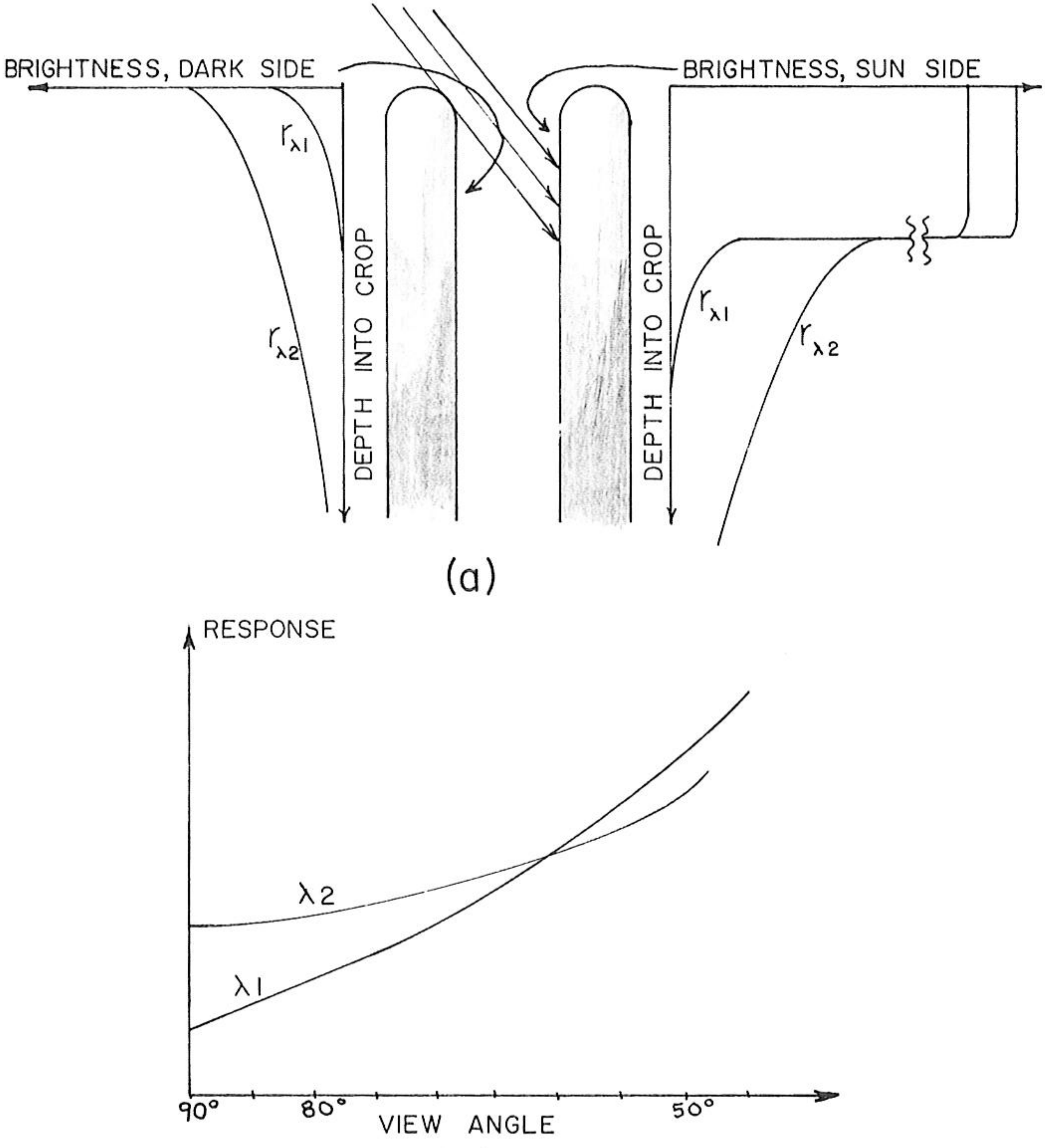


Figure 11.

seeing only the brightest top-lit portions. In (c), a nadir view shows lowest response due to direct viewing of weakly illuminated soil. In (d) the field is viewed from the plane of incidence opposite from the illumination side, showing crop portions moderately illuminated by scattered sunlight and skylight. Again, as view angle is lowered the scene will brighten. Finally, in (e), the field is viewed transverse to the plane of incidence, giving a response intermediate between (b) and (d). All this behavior is in accord with the data reported by Steiner and Haefner.

Simply by altering the model geometry some variation in response with view angle may be predicted. For example, a sparsely-planted crop would be expected to show less abrupt rise in response with lower view angle than a thickly-planted crop. Along a similar line, a short crop would be expected to show less abrupt rise in response with lower view angle than a tall crop with similar plant spacing. With this idealized cactus field it can be argued further that the addition of some specular character to the Lambertian plant surfaces will appear as a view angle effect primarily through enhanced illumination of the deeper portions of the field of view. The active specular element of area on the top of the plant is independent of sun angle - view angle combinations, and so no variation in response would be caused by this source as view angle was varied.

The angular effects were exhibited vividly in Figure 9 using broad band visible region film. In the multispectral technique employing correlations of any one narrow band response to all other narrow band response, it is important to determine possible spectral response variation with view angle for, say, a fixed sun angle. Figure 12 illustrates an expected behavior based again on crop geometry. Just two "plants" are shown in (a) for clarity, and now two different wavelengths in the illuminations, $\lambda 1$ and $\lambda 2$, are considered. The plant surface is assumed to have low reflectance $r_{\lambda 1}$ for $\lambda 1$, high reflectance $r_{\lambda 2}$ for $\lambda 2$. While a precise calculation of the variation of surface brightness with depth is tedious even for this simple model, the general behavior will be as shown in Figure 12 (a). For the highly reflected wavelength the deeper portions of the crop will be more effectively illuminated than for the lower reflected wavelength. This implies that in the $\lambda 1$ band the scene will show less response at 90° view angle but rise more rapidly as view angle is lowered, with the converse true for the $\lambda 2$ band. These trends must be taken into account in


BRIGHTNESS, DARK SIDE
BRIGHTNESS, SUN SIDE
$r_{\lambda 1}$
$r_{\lambda 2}$
DEPTH INTO CROP
DEPTH INTO CROP
$r_{\lambda 1}$
$r_{\lambda 2}$
RESPONSE
$\lambda 2$
$\lambda 1$
90°
80°
50°
VIEW ANGLE

(a)

(b)

Figure 12.

multispectral decision instrumentation, particularly when trying to cover large scanner strip widths. The biophysical ground truth program at Purdue University will gather experimental data in the 1966 growing season on this aspect of multispectral sensing.

APPENDIX

DENSITOMETER MEASUREMENTS OF RELATIVE RESPONSE OF IMAGERY*

Figure 2 - Multispectral Response of Corn, Alfalfa, Stubble, and Bare Soil

	0.4-0.7μ	0.7-0.9μ	4.5-5.5μ
Corn	75	61	68
Alfalfa	69	72	17
Bare Soil, Silt Loam, Light Colored	87	56	
Bare Soil, Silty Clay Loam, Dark Colored	70	51	92 (avg., both types)
Stubble	75	65	Not Measured

Figure 3 - Corn Variety Differences

	0.4-0.7μ	0.7-0.9μ
SX29	89	72
Indiana 678	88	67

Figure 4 - Wheat Variety Differences

	0.4-0.7μ	0.7-0.9μ
Knox 62	58	79
Reed	49	77
Purdue 4930	50	74
Redcoat	46	75

Figure 5 - Corn Planting Date Differences

	0.4-0.7μ	0.7-0.9μ
May 15	88	73
May 7	88	68

*For purposes of compairson of relative response within a given wavelength band only. Differences between film types and film sensitivities do not allow meaningful comparison between wavelength bands for these data.

Figure 6 - Oats Compared to Corn and Date of Planting Differences

	0.4-0.7μ	0.7-0.9μ
Corn, May 14	51	59
Corn, May 4	51	62
Oats	52	65

Figure 7 - Variations in Response Due to Alfalfa Cutting

	0.4-0.7μ	0.7-0.9μ
Cut 8 Days Earlier	72	69
Cut 15 Days Earlier	61	76
Cut 20 Days Earlier	49	83

Figure 8 - Effects of Soil Type on Tonal Response and Seasonal Variation in Crop Cover (0.4-0.7μ)

	1 July	1 September
Silty Clay Loam, Dark Colored	58	48
Silt Loam, Light Colored	75	47

Figure 9 - Effects of Angle of View Upon Wheat Fields (0.4-0.7μ)

	1430 Hours	1435 Hours
Wheat, West Edge (Top) of Photo	48	51
Wheat, SE Corner (Lower Left) of Photo	50	62
Wheat (Larger Field)	48	62
Wheat (Smaller Field)	49	61
Oats, Center of Photo	39	49
Soybeans (Smaller Field)	58	62
Soybeans (Larger Field)	64	63

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APPENDIX B

RADAR IDENTIFICATION OF AGRICULTURAL CROPS

Introduction

A field of wheat exhibits a characteristic backscattering of radar waves different from that exhibited from a field of corn. Similarly, the backscattering of radar waves is different for other types of crops and for different fields of the same crop. It is possible then to use this difference in the backscattering to type or identify the crop in a field illuminated by a radar beam from an aircraft or an orbiting spacecraft. The problem is to determine why these differences exist and thus how the differences may best be used to identify the crop.

The Radar Systems

In order to experimentally approach the problem, it is essential that a thorough knowledge of the equipment to be used is known. The need for this knowledge results from the differences in processing of the return signal, thus, yielding different system outputs for the same return signal. For one example, the display of a signal on a radar scope, the storage of the signal on magnetic tape, or the storage of the signal on photographic film in the form of a radar image, involve different non-linear processes. The differences in the return signals from different crops will be different for each of these non-linear processes. Thus, an important difference between crops observed with one system might be obscured when another system is used.

For the purpose of sensing crops on the ground from an aircraft or an orbiting spacecraft, a radar system with resolution elements less than the size of the fields to be examined is required. A conventional antenna system has a linear resolution capability given by (1) linear resolution = wavelength x range/ antenna aperture. Since the wavelength is determined by the operating capabilities of the electronic system and the antenna aperture is limited by the physical size of the antenna, the linear resolution will be mainly determined by the altitude of the aircraft or spacecraft. For the altitudes required for these craft, the linear resolution is too large to permit the use of a conventional antenna system in resolving fields and typing the crops.

A radar system designed to take advantage of the forward motion of an aircraft to increase the antenna aperture length and thus increase the linear resolution capability, is the synthetic aperture antenna radar system. This system is essentially a data processing antenna system which can be compared in principle, but not in operation, to a large physical linear array of small dipoles. In a linear dipole array, a radar pulse is simultaneously transmitted in phase from each dipole. The transmitted signals interfere with each other forming a sin (x)/x antenna gain pattern whose main lobe has a width given by equation (1). The transmitted wave is then scattered by the target and a portion of the scattered wave determined by the antenna gain pattern is received by the linear array. The resolution of this system is determined essentially by the antenna gain pattern which is dependent upon the interference of the transmitted or received signals.

In the synthetic aperture antenna system, a single dipole is placed successively at the different positions of the antenna array. At each position a radar pulse is transmitted, scattered by the target, received, and stored in the radar system. Great care is taken to store the transmitted and received phase information along with the magnitude of the received signal. When this process has been completed at all of the array positions, the stored signal information is added vectorially. During the addition process, interference occurs as a result of the difference in phase of the signals scattered from each target point. This phase difference is due to the small differences in the distance from the target to each array element position. Thus, an effective antenna gain pattern is created with a main lobe width, and thus, the linear resolution, given by (2) linear resolution = wavelength x range/2 x array length. The linear resolution for the synthetic array antenna is improved by the factor of two over the conventional antenna since in the synthetic array antenna, interference occurs when the signals are added, thus, giving a two-way antenna gain pattern instead of the one-way antenna gain pattern of the conventional antenna where interference occurs immediately after transmission. There is a maximum useable length to the synthetic antenna imposed by the Fresnel zone effect as the antenna becomes longer. This restriction can be removed by focusing the antenna.

The synthetic array antenna radar system can be conveniently focused by further processing of the stored signals since it is already necessary to store and process the signals in order to obtain the synthetic array. For a point target at a given range from the center of the synthetic array, the focusing process is essentially an adjustment of the phase angle of the signal received at each successive array element position such that the target appears to be the same distance from each transmission point. For a point target, this phase adjustment could also be made by flying the aircraft in a circle with the target at the center. Since the target is usually a strip perpendicular to the flight path of the craft, and not a point, the phase adjustment must be different for the signal received from each point along the strip. In this case, focusing consists of a continuous phase adjustment for the signals received along the strip and an antenna array length which varies for the range from which the signal is received. This length varies according to the width of the main lobe of the physical aperture of the individual array element. Thus, (3) array length = wavelength x range/antenna aperture. Substituting this expression into equation (3) gives (4) linear resolution = antenna aperture/2. The best resolution achievable with a synthetic array antenna is given by one-half of the antenna aperture of the physical antenna used to form the array elements.

The above discussion gives the resolution length obtainable for the distance along the flight path for a broadside antenna. The resolution in distance perpendicular to the flight path is dependent upon the pulse duration and the bandwidth in order to receive all of the information contained in the pulse.

The main disadvantages of the synthetic array radar system are the power consumption and the equipment weight. The amount of equipment required results from the data processing (usually analogue) and the equipment necessary to detect and correct for small deviations from the true flight path of the craft. The increase in equipment results in an increase in power consumption.

Target Properties

The parameters involved in determining the power in the received signal are given by the basic radar equation (5) $S = (P \times G^2 \times \lambda^2 \times \sigma)/((4\pi)^3 \times R^4)$, where S = signal power, G = gain of the antenna, λ = wavelength, R = range, and σ = scattering cross-section of the target. All properties of the target are contained in the scattering cross-section, while the other factors concern the radar signal and equipment. This equation is for a point target. If an area target were illuminated, the scattering cross-section may be written in differential form where σ is replaced by $\sigma_o dA$. σ_o is an average scattering cross-section per unit area. The scattering cross-section is a function of the wavelength, the angle of incidence of the transmitted wave, the aspect angle, the incident polarization, the complex dielectric constant, the surface texture or roughness, and the penetration of the signal. The variations of the scattering cross-section with these parameters are the key to crop identification with radar.

The wavelength of the radar system is usually at a fixed frequency. However, information from another source such as infrared radiation or another frequency radar could be used in differentiation between crop types. The angle of incidence and the aspect angle must be considered since these angles change with range from the transmitter. Previous work has shown that the polarization of the incident wave and the polarization of the scattered wave show significant differences with different crops. Combinations of horizontal transmit and horizontal receive and horizontal transmit and vertical receive may be used to distinguish certain characteristics of a target which causes depolarization of the transmitted wave. The complex dielectric constant will be a function of the water and mineral contents of the plants and their structure. The strength of the reflected signal will depend upon the complex dielectric constant. The surface texture has been shown to play a major role in the scattering cross-section. Along with the roughness of the surface is the periodicity of the surface due to planting in rows. The depth of penetration of the signal is dependent upon the many factors above. For the deeper penetration of the signal, the bulk material such as the stems and ground must be considered in addition to the surface properties.

All of the above factors are dependent upon time since the crops must grow and mature. Various weather conditions will cause changes in soil dampness and plant water content as well as geometric changes due to plant wilt and change of direction of leaves to face the sun.

Future Work

Immediate plans include a trip to determine certain details concerning the recording of the radar imagery such as the non-linearity of the processes involved for use in analyzing both past and present data. Trips are also planned for purposes of discussion of work being done by other groups in radar scattering by agricultural crops. Use of the imagery obtained will be complemented by extensive ground surveys to determine ground truth data such as crop condition and soil moisture.

Long range plans include continuation of the above work plus possible modeling of the fields with studies of the radar scattering from these models.