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

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ABSTRACT

Current research at Purdue University has as its purpose the identification of crop species and conditions of health and maturity for several economically important crop types in the corn-belt region, using multispectral imagery ranging from 0.3- to 14-μ wavelength and radar imagery. This study has revealed a large number of vegetative variables which often cause marked tonal variations in portions of the electromagnetic spectrum. Those 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. Spectrophotometric curves on individual leaves do not always indicate accurately the relative reflectance observed on multispectral imagery. Crop or leaf geometry has a marked influence on reflectance of vegetative canopies, particularly in relation to certain photographic instrumentation variables. It is the purpose of this paper to present certain photographic factors and biophysical reasons that cause remote view spectral tonal variations, together with experimental evidence in support of these reasons.

With accurate knowledge of the instrument limitations and biophysical causes of tonal variations over the electromagnetic spectrum, more precise analysis of multispectral response signatures will be possible, assuring detailed remote sensing a role in agricultural information collection and utilization.

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 14μ portion of the spectrum, as well as 0.86 to 3.0 cm wavelengths using radar, and other portions of the spectrum with various

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 V. Most large fields are 160 acres in size.

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 3μ wavelength portion of the spectrum, or emitted energy in the 3 to 14μ 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 14μ 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 involved 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 0.7μ and 0.7 to 0.9μ 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 5.5μ 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 5.5μ region (due to the cooling effect of evapotranspiration in the alfalfa). In the 4.5 to 5.5μ 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 on the imagery shown in this and the following figures are presented in Appendix A.)

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 0.7μ 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 thie 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 0.7μ 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.

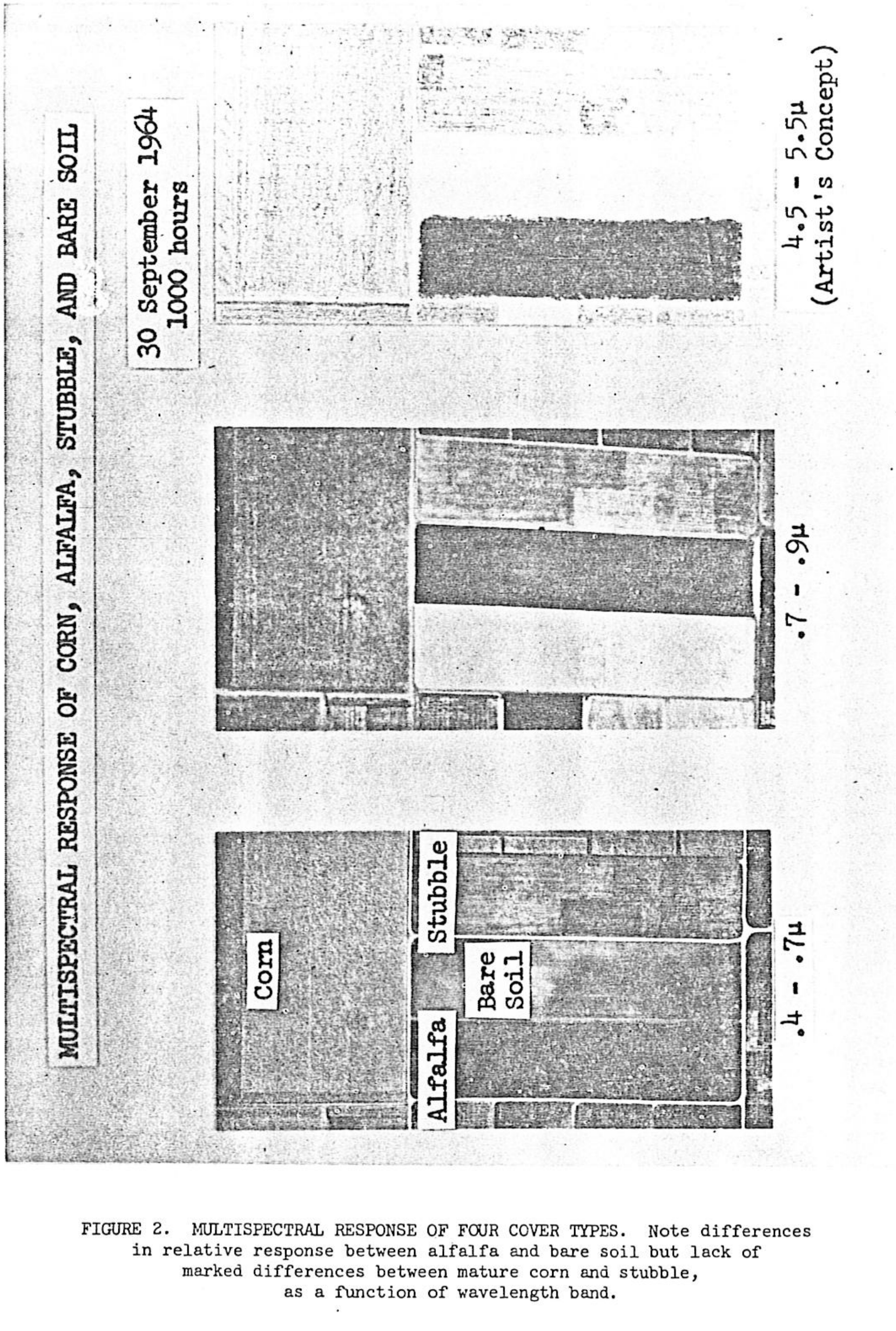


FIGURE 2. MULTISPECTRAL RESPONSE OF FOUR COVER TYPES. Note differences in relative response between alfalfa and bare soil but lack of marked differences between mature corn and stubble, as a function of wavelength band.

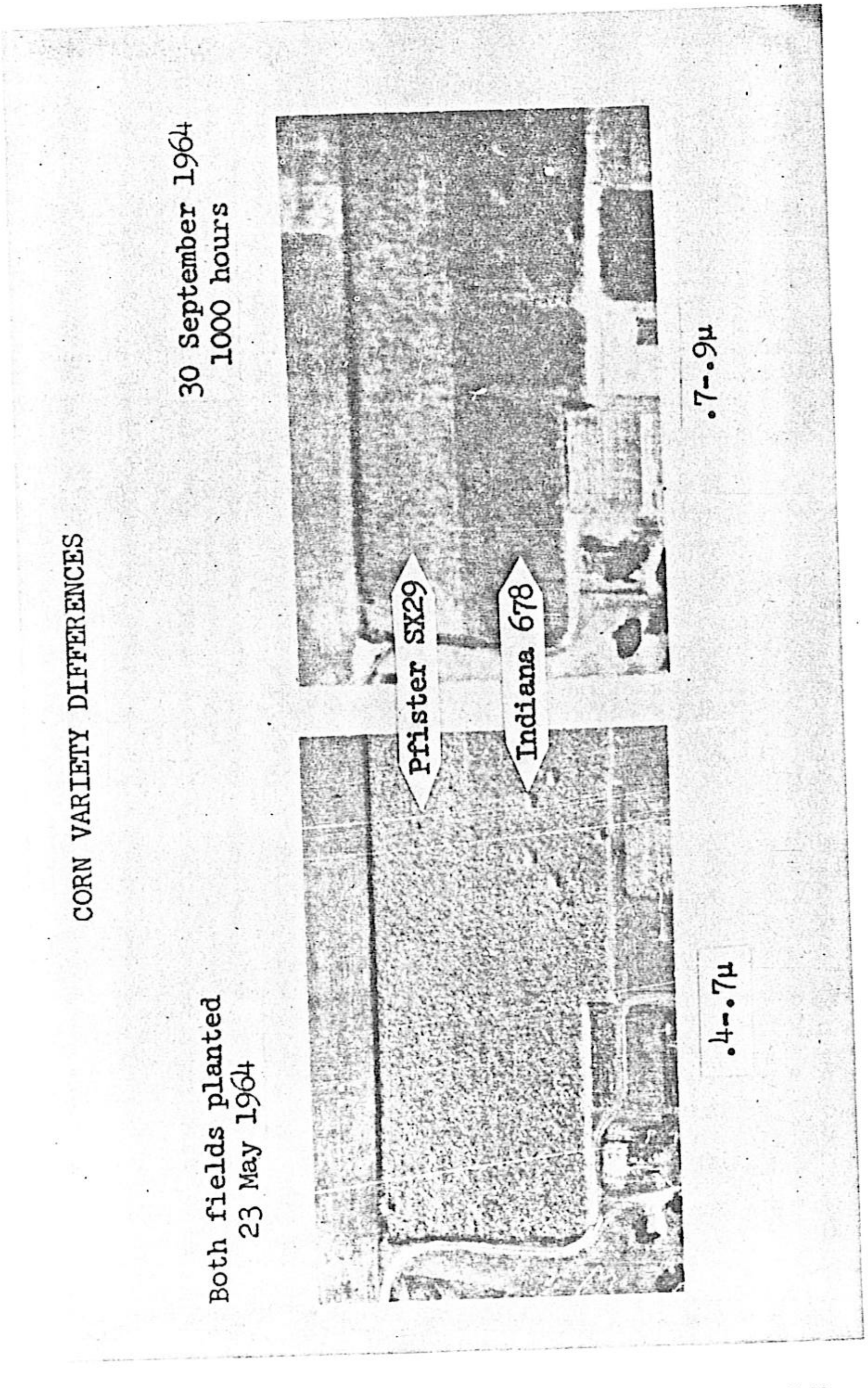


FIGURE 3. CORN VARIETY DIFFERENCES. Relative rates of maturing differ, thereby causing marked variations in response within a given crop species.

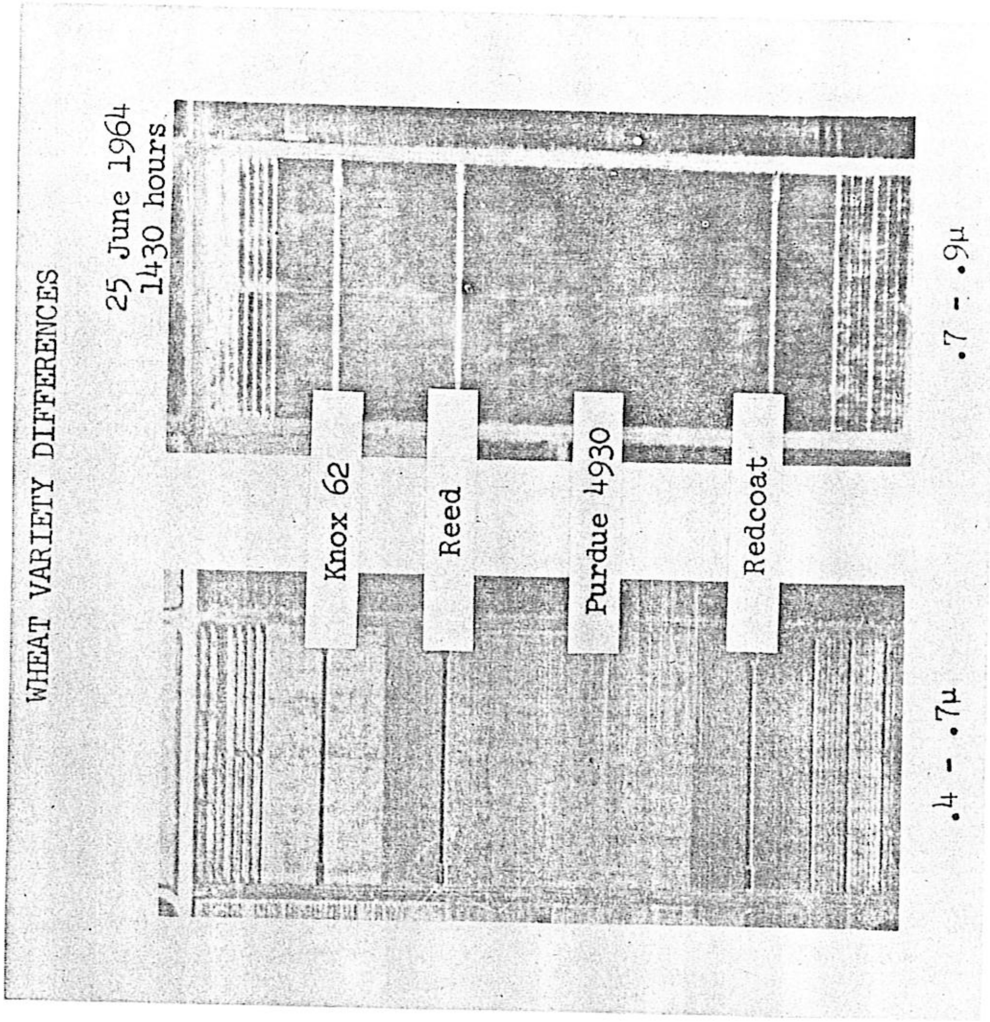


FIGURE 4. WHEAT VARIETY DIFFERENCES. Note lack of response differences in 0.7-0.9μ wavelength band, but distinct differences in visible portion of spectrum, as compared to Figure 3. The differences observed between these two figures are due to differences in stage of maturity of the variety and species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

Not only do inherent differences in the rate of maturing of a particular 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) influence 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 0.7μ 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 0.9μ 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 0.9μ 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 0.9μ 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.

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 area of dark silty clay loam having a very low response, and 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, using multispectral camera data, there have also been found 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

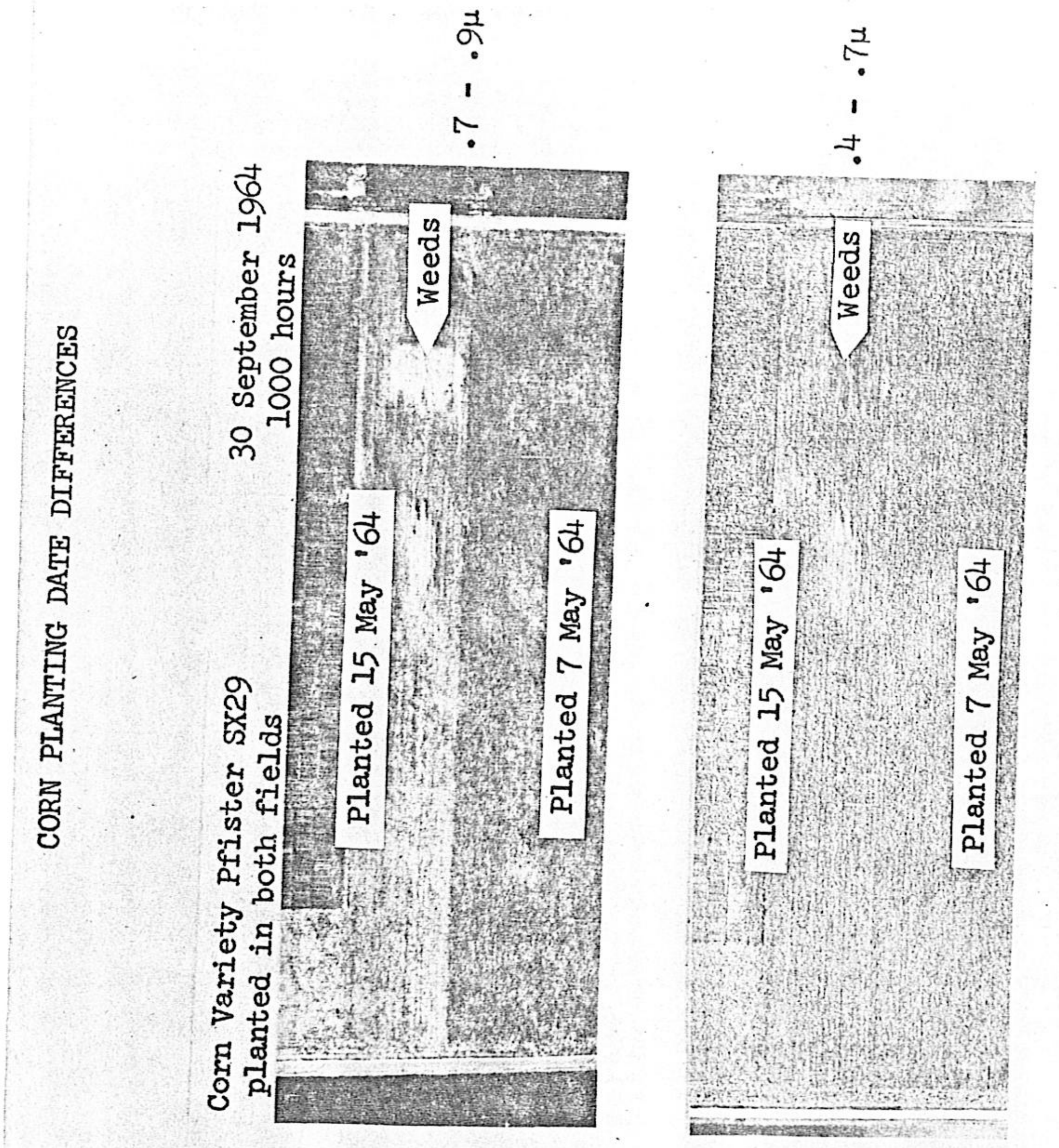


FIGURE 5. CORN PLANTING DATE DIFFERENCES. Maturity differences late in growing season cause distinct variations in response. This is the same result as seen in Figure 3, but in this case a different agricultural factor was involved (e.g. date of planting versus corn variety).

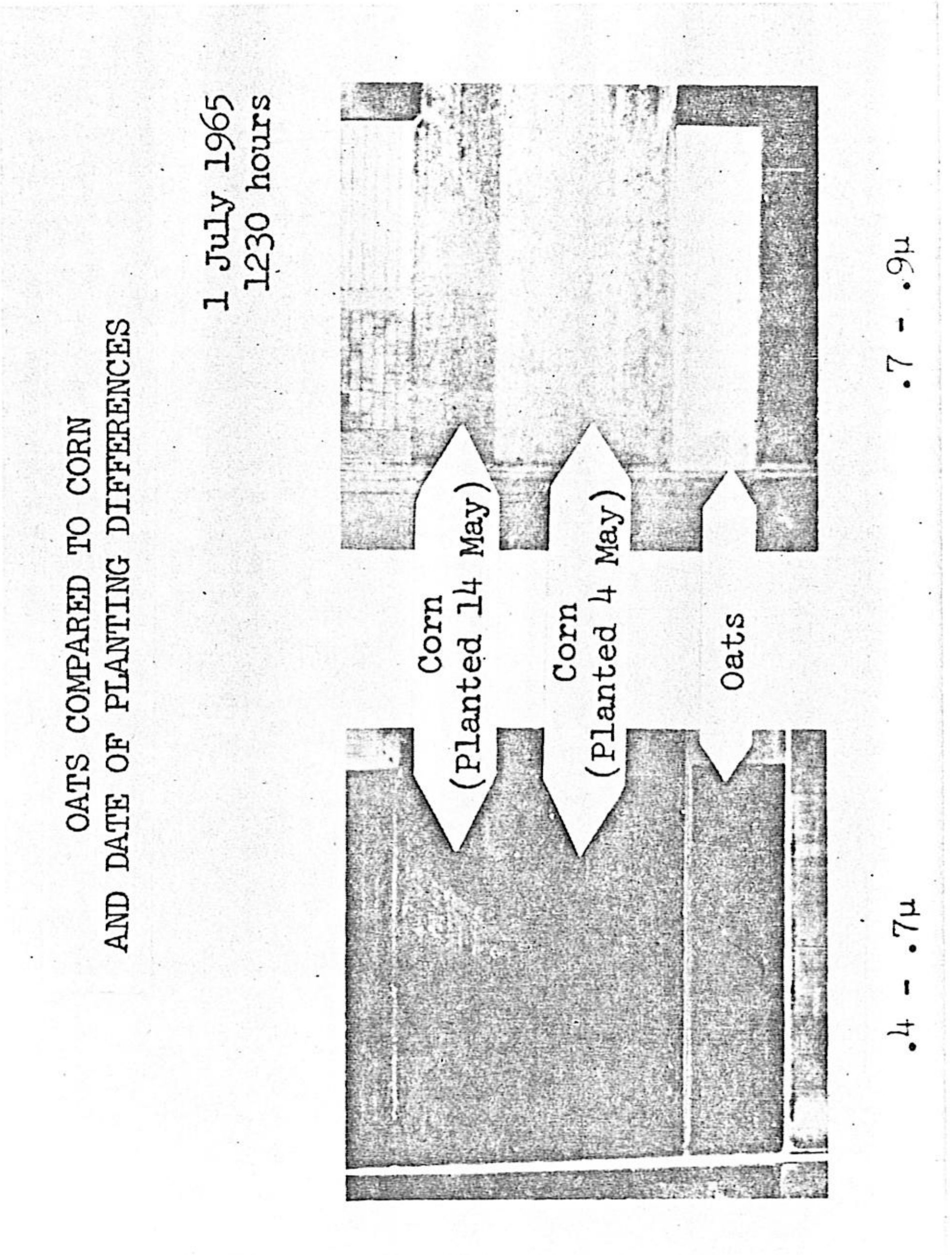


FIGURE 6. OATS COMPARED TO CORN AND DATE OF PLANTING DIFFERENCES EARLY IN THE GROWING SEASON. Variations in crop density and, therefore, in the relative proportions of soil sensed cause response differences in the photographic infrared in situations of dark, relatively low reflecting soil.

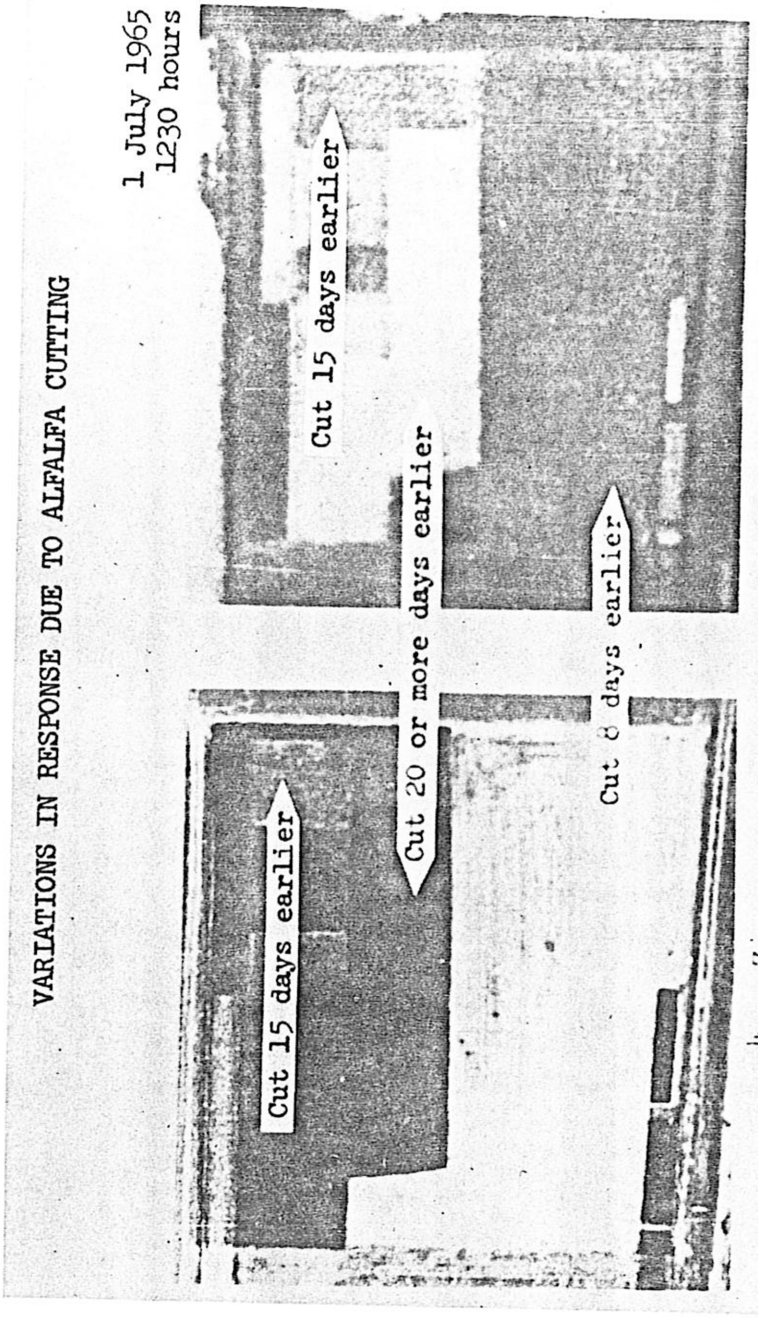


FIGURE 7. VARIATIONS IN RESPONSE DUE TO ALFALFA CUTTING. Relative amounts of green vegetation, stubble, and bare soil due to harvesting of forage crops cause distinct but variable differences in response, thereby creating severe problems in remote identification of cover type.

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 this 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 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, 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.

EFFECT OF SOIL TYPE ON TONAL RESPONSE AND SEASONAL VARIATION IN CROP COVER

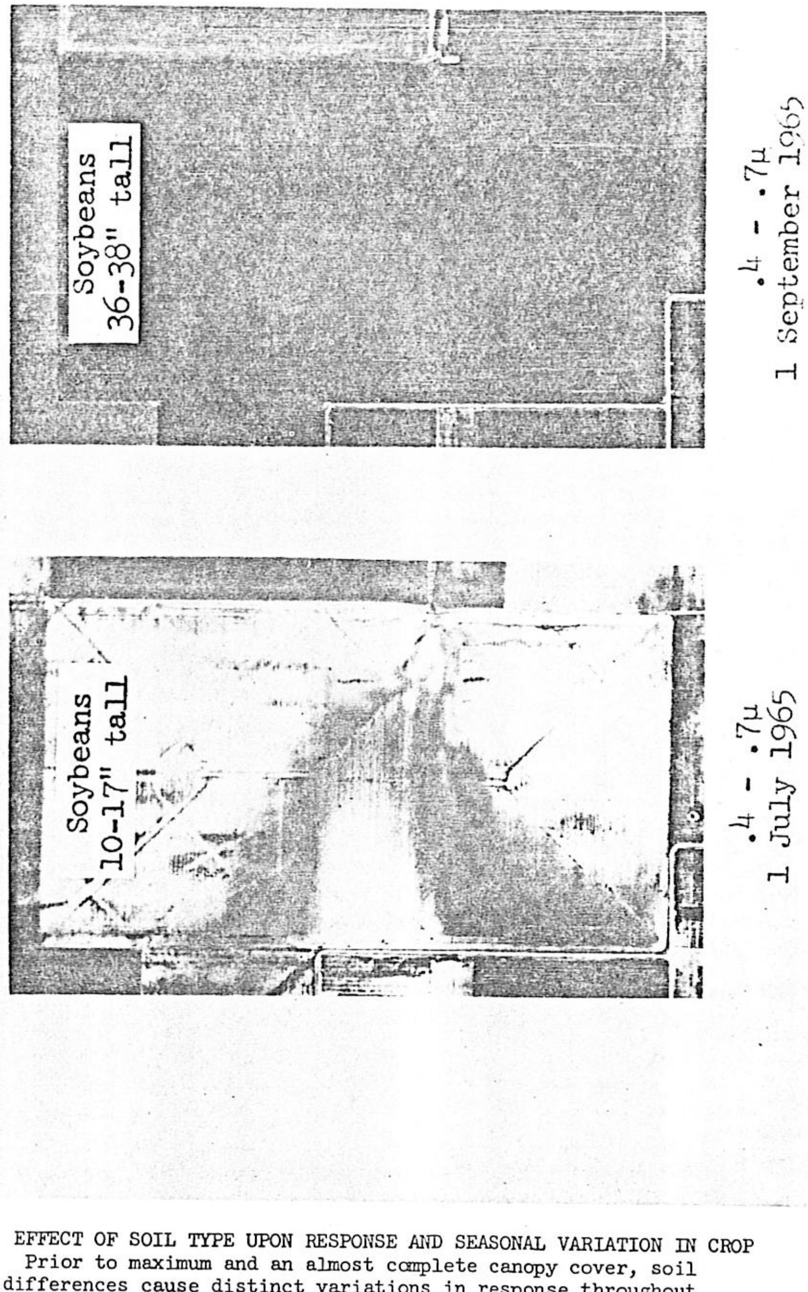


FIGURE 8. EFFECT OF SOIL TYPE UPON RESPONSE AND SEASONAL VARIATION IN CROP COVER. Prior to maximum and an almost complete canopy cover, soil type differences cause distinct variations in response throughout all wavelength bands of imagery from 0.3 to 14μ, but here represented by only the .4-.7μ wavelength band.

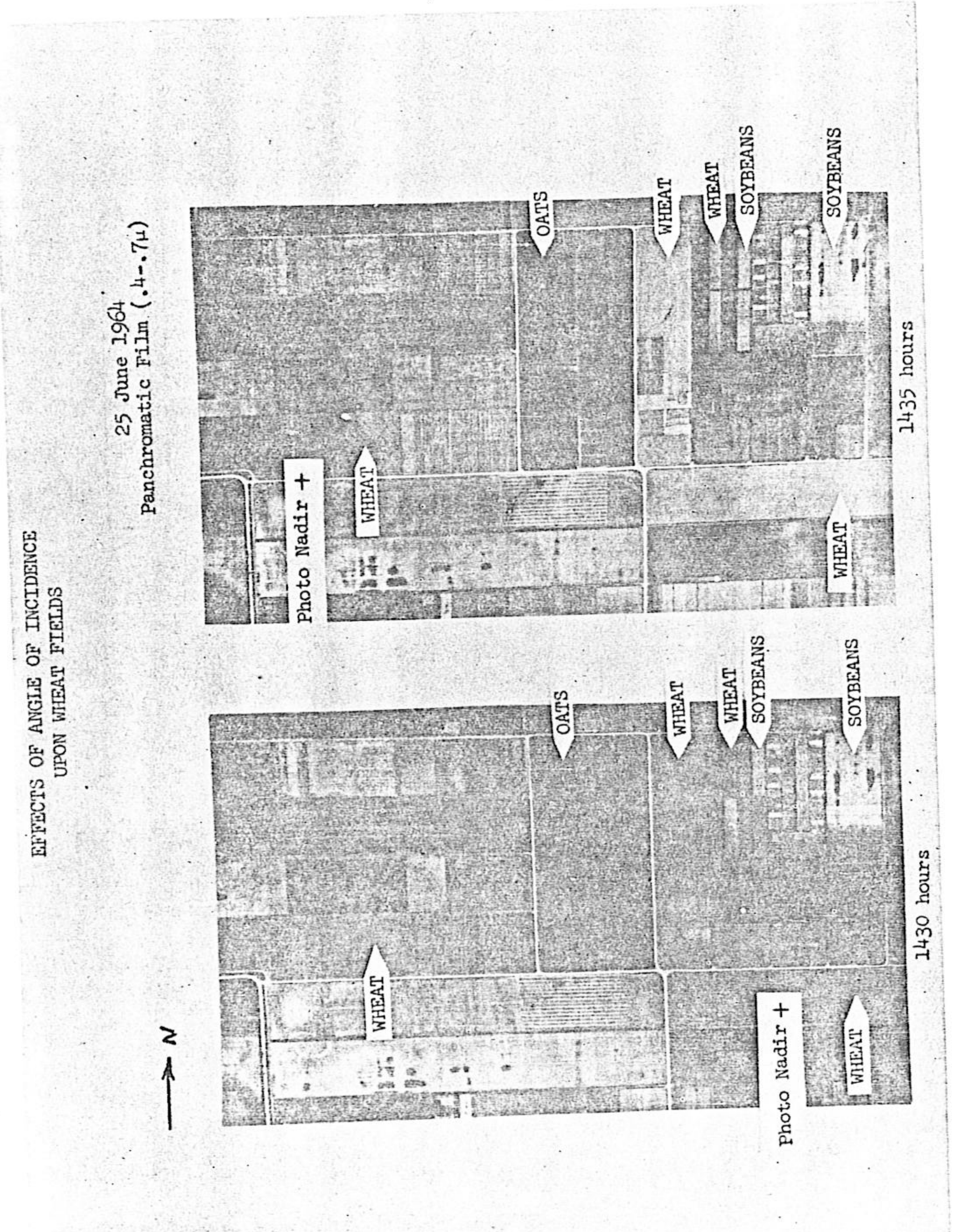


FIGURE 9. EFFECTS OF ANGLE OF INCIDENCE AND BACKSCATTERING UPON RESPONSE OF WHEAT FIELDS. Differences in photo nadir indicate relative airplane positions in obtaining the photos which included this area. Note low response in all wheat fields in photo on left--a condition not obtained in photo on right.

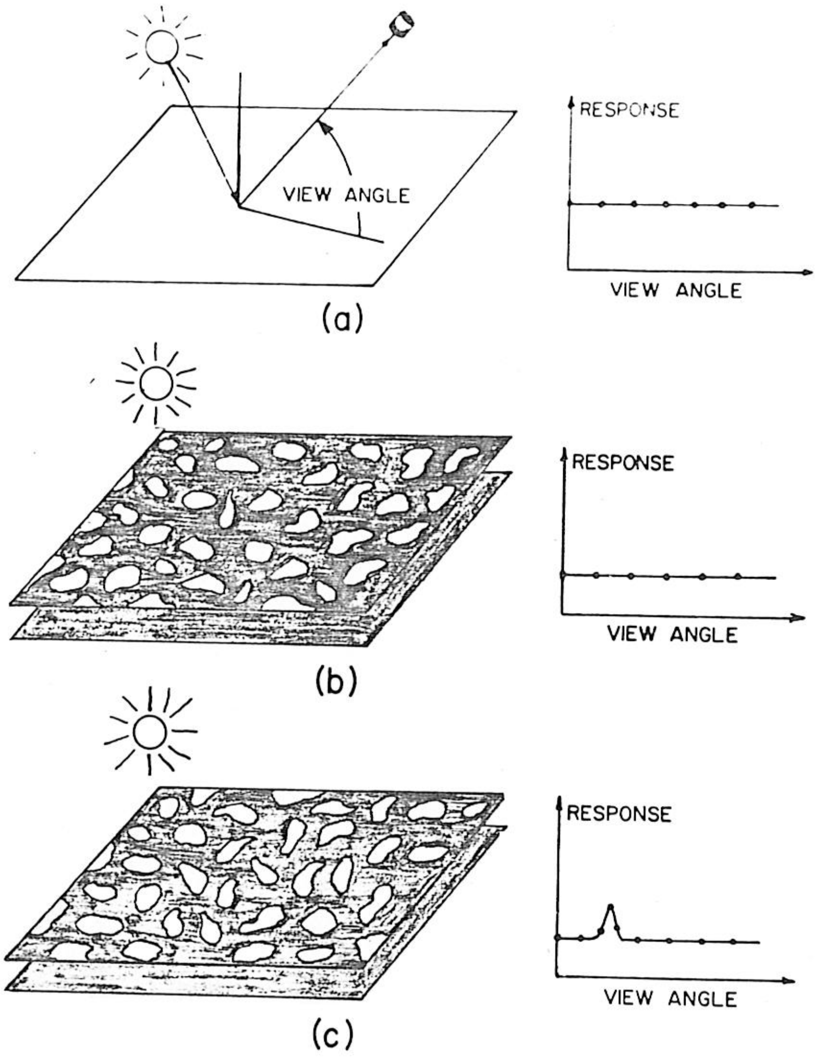

VIEW ANGLE
RESPONSE
VIEW ANGLE
(a)
RESPONSE
VIEW ANGLE
(b)
RESPONSE
VIEW ANGLE
(c)

FIGURE 10.

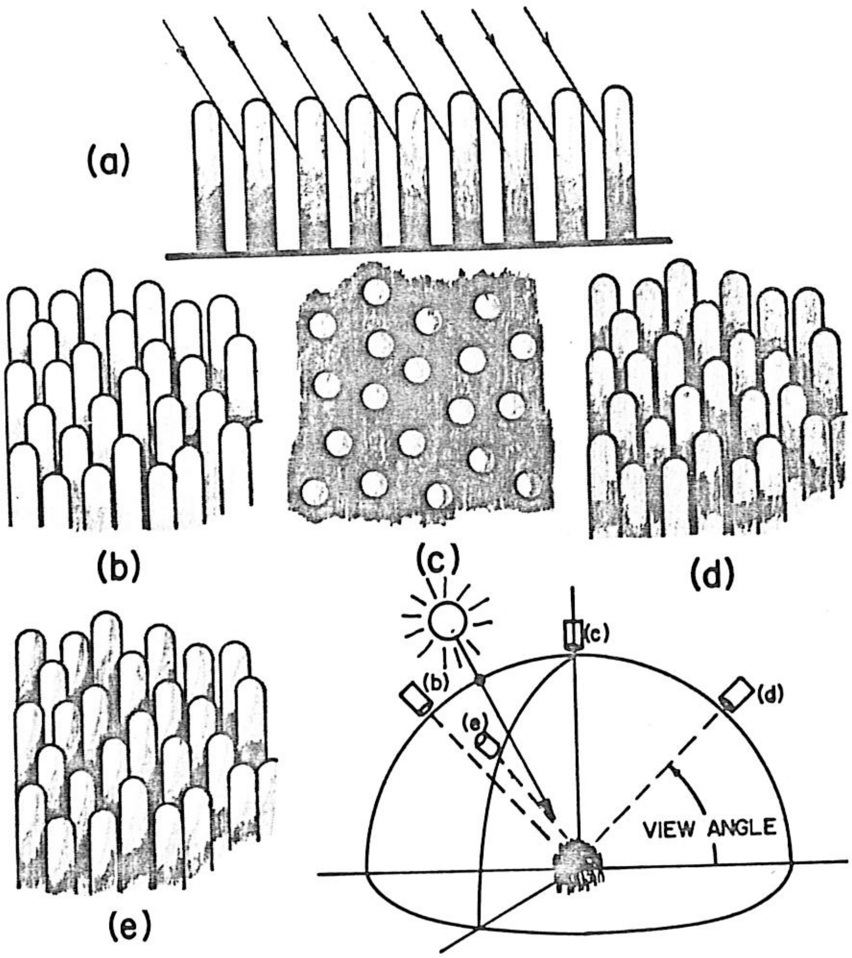
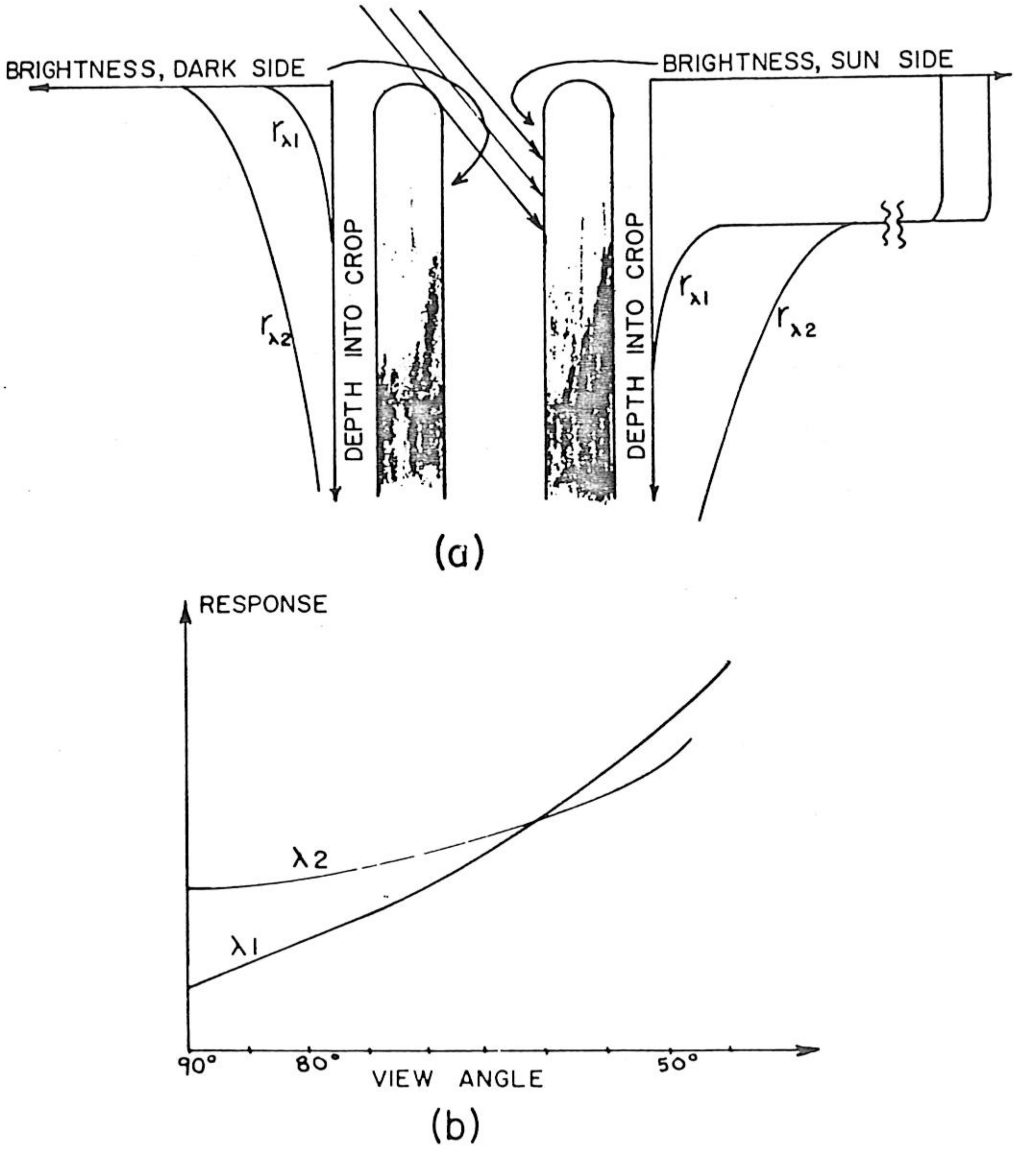


FIGURE 11.

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 illumination, $\lambda 1$ 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 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.


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.

APPENDIX A

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	92 (avg., both types)
Bare Soil, Silty Clay Loam, Dark Colored	70	51	
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

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

*For purposes of comparison 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.

APPENDIX A (cont.)

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 (6.4-0.7μ)

	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

REFERENCES

(1) American Society of Photogrammetry. 1960. Manual of Photographic Interpretation. George Banta Co., Menasha, Wisconsin. pp. 99-105.

(2) Olson, Charles E., Jr. 1960. "Elements of Photographic Interpretation Common to Several Sensors." Photogrammetric Engineering 26: 651-656.

(3) Reference (1), p. 857.

(4) Colwell, Robert N. 1956. "Determining the Prevalence of Certain Cereal Crop Diseases by Means of Aerial Photography." Hilgardia 26(5): 223-286.

(5) Lowe, D. S., Polcyn, F. C., and Shay, J. R. 1965. "Multispectral Data Collection Program", in Proceedings of the Third Symposium on Remote Sensing of Environment: 14, 15, 16 October, 1964. Report No. 4864-9-X, Institute of Science and Technology, University of Michigan, Ann Arbor, Michigan. pp. 667-680.

(6) Hoffer, R. M., and Miller, L. D. 1965. "Potential Applications of Remote Multispectral Sensing in Agriculture". Paper Presented at 30th Semi-Annual Convention of the American Society of Photogrammetry, September 24, 1965, Dayton, Ohio.

(7) Steiner, D. and Haefner, H. 1965. "Tone Distortion for Automated Interpretation." Photogrammetric Engineering 31(2): 269-280.