Agricultural Applications of Remote Multispectral Sensing

R. M. Hoffer, C. J. Johannsen and M. F. Baumgardner[1,2]

Introduction

What would be the rewards to humanity if man could measure and characterize, from remote distances, the ground cover within counties, states, or even nations? Through the use of aircraft or even spacecraft equipped with remote sensing devices, one wonders if the day is approaching when man may realize the capability of measuring crop acreages and estimating potential yields, of mapping climax vegetation on a regional basis, or of using these new developments in aerospace technology for effectively combating floods, insects, weeds, and diseases. Can this new technology be used effectively in the plans to provide food for the world's exploding populations? Although no system with this capability is yet operable, the limited amount of research information we now have leads one to believe that remote sensing will play a very important role in agricultural development and technology in the future.

Remote Multispectral Sensing

Remote Multispectral Sensing may be defined as "the sensing, from a remote location, of electromagnetic radiation — either reflected or emitted—in many discrete, usually relatively narrow spectral bands between 0.3μ and 15μ wavelength, and also in the radar bands from 0.86 to 3.0 cm." These narrow bands of radiation may be sensed and recorded using a variety of devices, such as photographic films and selected filters, or electromechanical scanners with various detector elements which are then coupled to electronic tape recorders.

To develop the concept of how this system works, consider the relatively simple case of a photograph. The photograph is capable of recording relative amounts of reflected energy because of variations in the number of silver halide crystals in the photographic emulsion which are activated upon exposure to light. If one photographs a pair of objects, one of which has a high reflectivity and the other a low reflectivity, the former will appear as a relatively light toned (or high response) area on the resulting photographic print, whereas the latter will produce a relatively dark tone or low response on the print. In such a case it is a simple matter to differentiate one object from the other. In many cases, however, two objects will have a similar response on a photograph and cannot be differentiated. It is sometimes possible in such situations to use different film-filter combinations which will allow objects to be differentiated through the use of two photographs, whereas they could not be differentiated on a single photo of a given wavelength band. This is, of course, dependent upon the two objects having

1. Journal Paper No. 2966, Purdue University Agricultural Experiment Station; Contribution by Department of Botany and Plant Pathology and Department of Agronomy.

2. Research Associate and Instructor in Department of Botany and Plant Pathology and Assistant Professor in Department of Agronomy, respectively, at Purdue University, Lafayette, Indiana.

a different reflectance in different portions of the electromagnetic spectrum. If the characteristics of two objects of interest are such that they reflect or emit radiation in an identical manner in all portions of the spectrum, such objects cannot be differentiated no matter how many film-filter combinations are examined.

To illustrate these comments, suppose one uses photographs obtained in two different portions of the spectrum. Using only two levels of classification of reflectance (either high response or low response), one could positively differentiate up to four different objects, as follows:

	Photo #1	Photo #2
	Reflectance or Tonal Response	
Object A	High	High
" B	High	Low
" C	Low	Low
" D	Low	High

Objects A and B cannot be differentiated on the basis of a difference in response when using only Photo #1. However, when using Photo #2 (the emulsion of which has been sensitized in a different portion of the spectrum), objects A and B can be differentiated, but objects B and C cannot be differentiated. Thus, it can be easily seen that only through the use of both photos that all four objects can be differentiated. As more levels of response are used and as more different wavelength bands of photos or other spectrally responsive media are used, the number of objects which could be differentiated increases enormously. The use of 16 levels of response in each of 18 wavelength bands allows a possibility of 16^{18} unique combinations of spectral response.

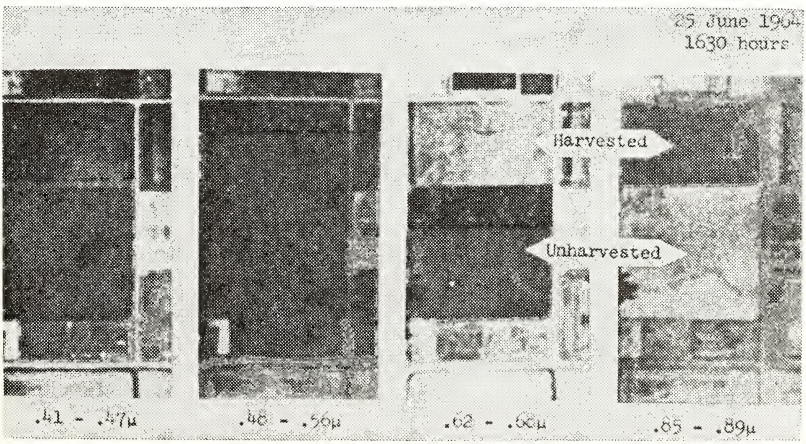

Figure 1. The variations in spectral response of harvested and unharvested alfalfa as shown in four different wavelength bands.

Figures 1 and 2 illustrate the manner in which the tonal response can sometimes be entirely different from one wavelength band to the next in a natural, agricultural situation.

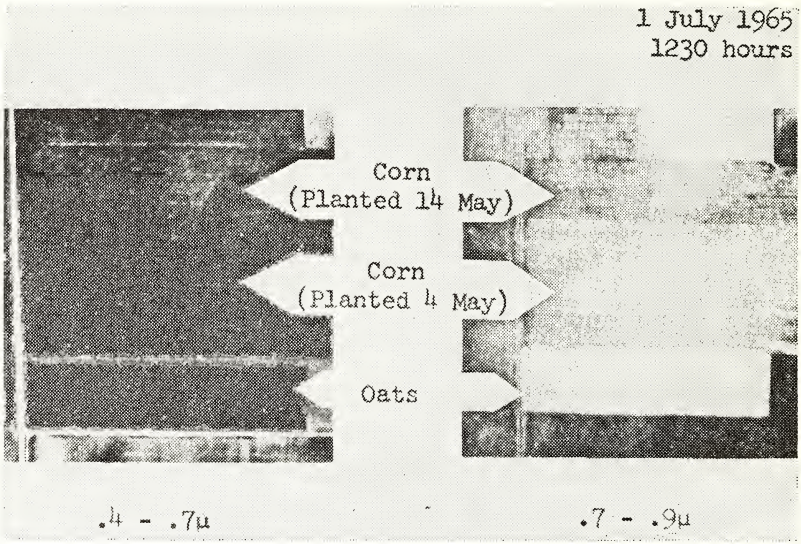

Figure 2. The spectral response of oats compared to two dates of planting for corn using a panchromatic and an infrared photograph.

Figure 1 shows a field of alfalfa, photographed simultaneously with four wavelength bands of imagery. The upper half of the alfalfa field had been harvested. In the .41-.47μ wavelength band (in the blue portion of the visible spectrum), one can distinguish the harvested from the unharvested portions of the field, but in the .48-.56μ wavelength band (green portion of the spectrum), one sees no difference between the two areas. In the .62-.68μ portion of the visible spectrum (red wavelengths), one sees a distinct difference, the harvested area having a higher response than the unharvested area. In the infrared (.85-.89μ) wavelength band shown, the relative response is just the reverse of that in the .62-.68μ band. In this portion of the spectrum, healthy green vegetation is highly reflective of incident light, thereby causing the unharvested portion of the field to have a much higher response than the harvested area.

Figure 2 shows a panchromatic and an infrared photo of three fields; one oat field, one corn field planted on May 4 and a corn field planted on May 14. In the panchromatic photo (.4-.7μ or visible wavelength band), these fields look identical. However, on the aerographic infrared photo (.7-.9μ wavelength), the fields are each distinctly different. This is due to the relative amounts of vegetative cover and exposed soil being viewed—the more healthy, green vegetation present, the higher is the relative response.

The difference in reflectance of healthy green vegetation between the visible and infrared portion of the spectrum is illustrated in Figure 3.

Chlorophyll and other leaf pigments absorb incoming light in the blue and red portions of the visible spectrum, but do not absorb in the green; hence the increased reflectance of a green leaf at .55μ which is the green portion of the visible spectrum. However, Figure 3 shows a maximum reflectance anywhere in the visible wavelengths (.4-.7μ) of only 14%, whereas, in the infrared wavelength (starting at about .7μ) the reflec-

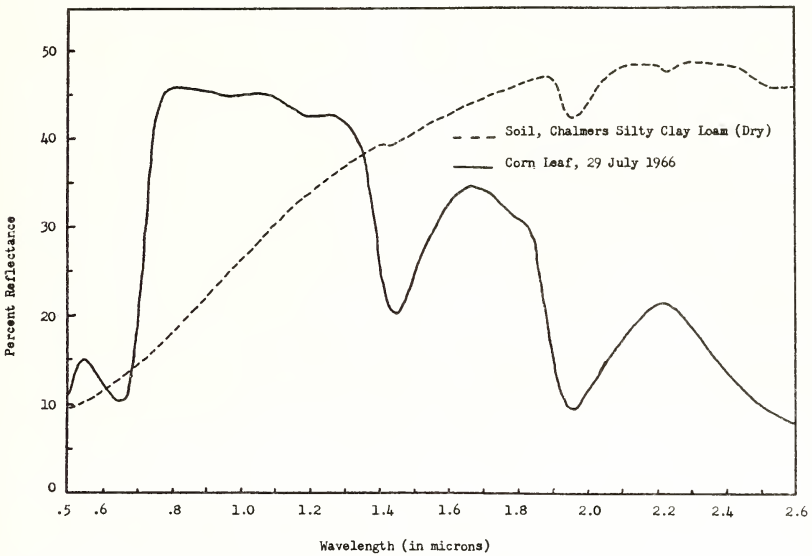

Figure 3. Spectral reflectance of a green corn leaf compared to Chalmers silty clay loam soil, as obtained on a Beckman DK-2 spectrophotometer.

tance climbs more than 45% in the region from 0.8μ to 1.25μ. The marked decrease in reflectance at 1.44μ and 1.94μ is due to strong water absorption at these wavelengths.

The capability now exists to sense reflected or emitted electromagnetic energy in many discrete wavelength bands, using multispectral optical-mechanical scanners. This equipment can be used in aircraft and possibly satellites, and will allow the energy reflected or emitted from a relatively small area of the earth's surface to be recorded on an electromagnetic tape. Two of the primary advantages of this type of sensor system over photographic sensors is that the data can be analyzed 1) very rapidly and 2) in large quanties through the use of computers. One other major advantage is the capability to sense reflected and emitted energy in wavelengths far outside the spectral regions in which any photographic emulsion is sensitive.

Through the use of such remote sensor systems, providing they have been properly calibrated, one can integrate the energy in a given wavelength band which is received from a relatively small portion of the earth's surface. (The size of the area covered is dependent upon the optical characteristics of the system being used, as well as the altitude from which one is obtaining such data.) By sensing the reflected

or emitted energy from a given area in each of many discrete wavelength bands, one can obtain a "multispectral response pattern," similar

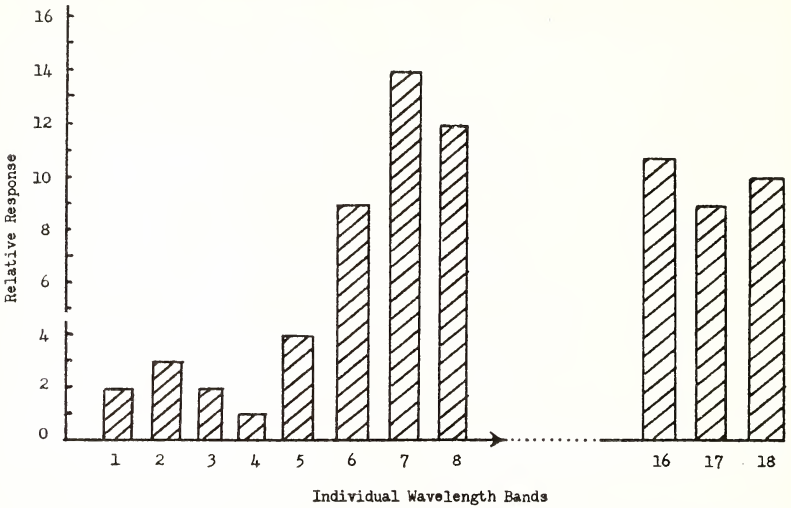

Figure 4. An illustration of a multispectral response signature which can be obtained through the use of eighteen wavelength bands of imagery. The current computer system allows a single wavelength band to have up to 16 levels of response. Data from a combination of 18 wavelength bands can therefore yield up to 16^{18} unique multispectral response signatures.

to that shown in Figure 4. Such a pattern is a coarse approximation of the reflectance curve shown in Figure 3. This "pattern" represents a combination of signals received from a given target (an object, land area, etc.) on a given date. It is hoped that by studying many such patterns for each crop and soil condition of interest, one may establish a characteristic, consistent, and predictable pattern, capable of quantitative expression and of known statistical reliability. Such a pattern would be called a "multispectral response signature." A multispectral response signature can thus be defined as "a particular set of reflectance and emittance properties of a target (an object or area of interest) which enables such a target to be distinguished and identified from a remote location, with an acceptable degree of statistical reliability."

Figure 5 illustrates the type of comparison that one might make between two target areas, using multispectral imagery. This graph shows the relative response observed in a field of soybeans and in a field of bare soil, on July 29, 1964. In some wavelength bands, the response of the soybeans is much like that of the bare soil, whereas in some bands (notably the .71-.79μ and .85-.89μ wavelength bands), the soybeans have a much higher response because the green vegetation is much more reflective than the soil in these wavelengths. However, in the thermal infrared wavelengths (3.0-4.1μ, 4.5-5.5μ, and 8.2-14μ) the soil is emitting much more energy than the crop canopy, which is being effectively cooled by evapotranspiration. For these reasons, the bare soil has a higher response on the graph than do the soybeans.

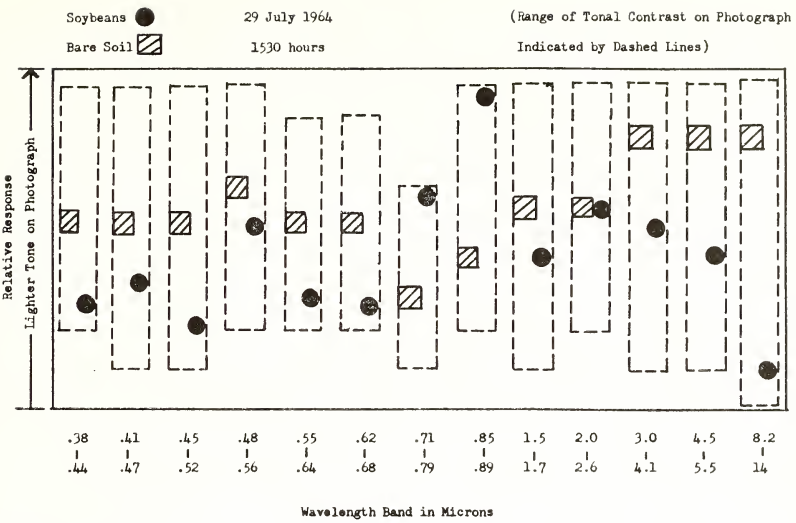

Figure 5. A multispectral response comparison between soybeans and bare soil, in relation to the total tonal contrast of individual wavelength bands of imagery.

By studying large quantities of remote multispectral sensing data, obtained at different times of the year and under a variety of crop and soil conditions, it is hoped that a reliable data bank of multispectral response signatures will be developed for many different crop and soil conditions. Such a data bank will probably have several subsets of signatures for each crop and soil condition according to geographical locations. In time, it is believed that an unknown target area or condition could be correctly identified with a reasonable degree of statistical reliability, using automatic pattern recognition techniques.

Pattern Recognition

The key to developing such a capability for identification of unknown situations using remote multispectral sensing techniques lies in a rapid method of handling and processing large amounts of quantitative data. Methods currently being studied involve the processing of scanner data obtained on electronic analog tapes, calibrating this data and reducing it to digital multispectral response patterns for each target of interest. One then applies pattern recognition techniques to the unknown multispectral response patterns for each target area and automatically classifies the unknown pattern. There are many pattern recognition techniques and many ways which these can be applied to the data obtained.

To illustrate the fundamentals of pattern recognition, let us take an example in which we wish to decide whether the multispectral response pattern of an unknown field should be classified as a field of oats, wheat, or alfalfa. One must first have information on the multispectral response patterns of a number of fields known to be corn, wheat, and alfalfa. Figure 6 illustrates a hypothetical portrayal of the response

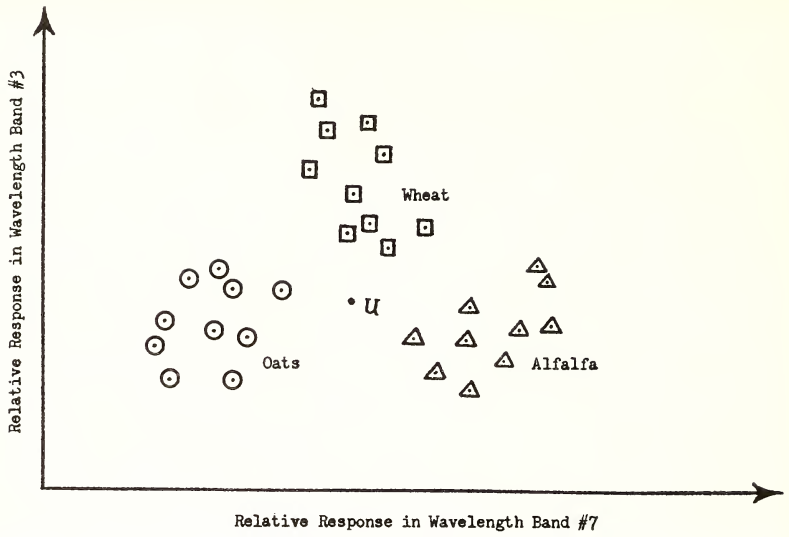

Figure 6. Hypothetical example of relative response of oats, wheat, and alfalfa in each of two wavelength bands of imagery. An unknown field which must be correctly categorized by the pattern recognition device is represented by the letter "U".

in only two wavelength bands for ten fields each of oats, wheat, and alfalfa. In this representation, one sees that in one wavelength band of imagery (response along the ordinate), the oats and alfalfa have approximately the same response and could not be separated on the basis of that one wavelength band of imagery only. The second wavelength band of imagery does allow these two crop types to be separated because of a marked difference in response. An unknown field which needs to be classified is represented by the dot and the letter U.

It is seen that the unknown field does not obviously fall into any of these known categories. The pattern recognition technique involves a decision as to which category the unknown data best fits. One such method would be the "minimum distance to the means criterion" in which the mean of each known class would be computed and decision boundaries would then be drawn to separate the classes of known objects. The unknown object would then be classified into whichever category the point fell. The "minimum distance to the nearest member of a class" would be another technique. It must be remembered that the decision would not be based on a comparison of data in only two wavelength bands as shown here, but rather on a combination of data from eighteen wavelength bands.

"Statistical pattern recognition" is another technique which can be used. In this case, for each field of interest, a set of likelihood ratios can be computed which express the relative probability that a point in question belongs to one category of interest rather than any others. Figure 7 illustrates the application of such a technique to some actual remote sensing data, using just six wavelength bands of imagery.

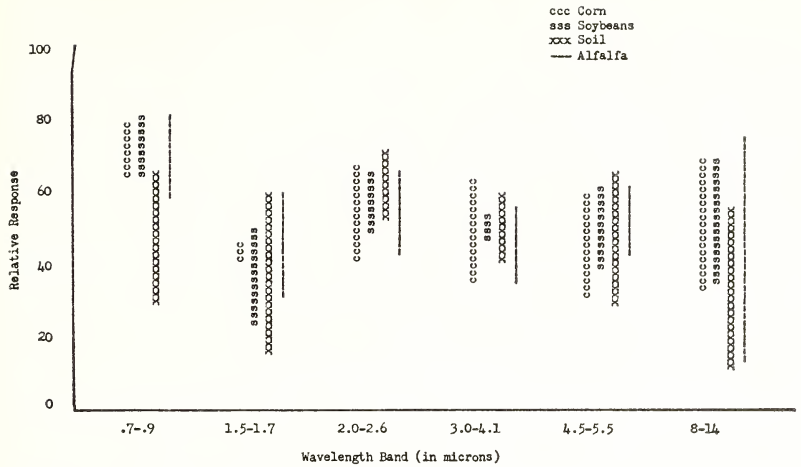

Figure 7. The distribution of the relative response within individual wavelength bands for corn, soybeans, alfalfa and bare soil. (Taken from flight data obtained at 1055 hours on 27 August 1964.)

In this case, a limited number of agricultural fields were sampled and 500 bits of data was generated for each of the three cover types of interest, using the assumptions of uniform distribution of response within a given wavelength band, and independence between wavelength bands. One sees that in this data, there is no clear-cut difference in response in any individual wavelength band between the corn and alfalfa. If you were to examine multispectral imagery of these crop types, there would be crop areas in every wavelength band of imagery examined where the response of the alfalfa is identical to that of the corn. By comparing combinations of several wavelength bands of imagery, however, one can arrive at a statistical decision as to the likelihood of a given piece of data falling into any one of the categories of interest. This is dependent upon having previously examined data in all categories of interest. The following results were obtained when this statistical pattern recognition test was carried out:

TABLE I.

Results of statistical pattern recognition using multispectral scanner data obtained on 27 August 1964

Sample Types	Classification of Samples			
	Corn	Soybeans	Alfalfa	Bare Soil
Corn	500	0	0	0
Soybeans	71	429	0	0
Alfalfa	37	37	426	0
Bare Soil	0	0	17	483
	(91% correct recognition)			

Due to the lack of calibration of the sensors and the limited amounts of data used to generate the 500 samples of each sample type used in this example, the above results should be considered as somewhat questionable *per se*. They do serve to indicate the potential of pattern recognition techniques, and allow one to see the importance of such techniques in rapidly classifying an unknown piece of data. Such a method for rapidly processing and analyzing data from large land areas will hopefully lead to a capability for mapping crop types, for projecting crop condition surveys, and for many other types of surveys and censuses. Such survey capabilities would have broad spread applications, not only to agriculture, but also to forestry, ecology, geology, hydrology, geography, oceanography, and other disciplines.

Uses and Economics

If these remote multispectral sensing techniques and other techniques still to be adapted can be developed to the capability of identifying and characterizing ground cover, what are some of the potential uses? What can this capability contribute to agriculture?

Potential uses might be divided into two categories. The first would be those applications in highly productive and mechanized agricultural countries. The second would be extensive survey-type operations in many countries whose development of the natural resources, including agricultural lands, is still at a relatively low level.

Let's consider a few specific potential uses in the first category. In the United States approximately $40 million is spent annually in agricultural census and statistical data-gathering services. Remote multispectral sensing techniques certainly would not replace these very effective services, but could rapidly provide valuable supplementary information.

If in fact these techniques can be developed, it is reasonable to assume that remote multispectral sensing devices can be used to monitor the movements of cattle herds on our extensive Western ranges. By early detection of drought areas or diagnosis of overgrazing problems in early stages, it might be possible to increase the carrying capacity of our range lands through improved range management practices. Of the 107 million cattle in the U. S. approximately 35 million are on the range. An improvement of 10% in carrying capacity through the application of remote sensing techniques could mean an increase of 3½ million calves per year, or an economic benefit of $350 million annually at the present price of $100 per weaning calf.

The annual cost of weeds to American agriculture is estimated to be $3.8 billion. Detection by remote sensing of regional areas of heavy infestation could provide more complete information for the planning and execution of weed control programs. These techniques could be used to estimate the rates of spread of new weed infestations. If remote sensing could assist in obtaining a 5% reduction in weed losses, the annual economic benefit to American agriculture would be $190 million. A reduction of 10% in weed losses would provide a saving of $390 million over present losses.

Similar savings or economic benefits could be realized if these techniques could also be applied to reduce losses from insect and disease

infestations and to provide information on watershed conditions, water movement, and potential flood conditions.

On the international scene, in the second category mentioned above, remote sensing techniques might come to play a key role in international agricultural development. The use of these capabilities could provide vast amounts of data on the natural resources of a country—data which are essential for development planning and which are almost impossible to obtain with the use of present techniques.

Since 1950 large sums of capital have been invested by private foundations, international agencies, and national governments for the purpose of developing the natural resources of countries on every continent. A key to the planning of any regional or national development project is an inventory of resources. It is here that remote multispectral sensing may potentially play a leading role—that of rapidly providing more complete and accurate data concerning the land, vegetation, water, mineral, and meteorological resources of a country. The use of RMS techniques might provide a giant step forward in the planning stages for international agricultural development.