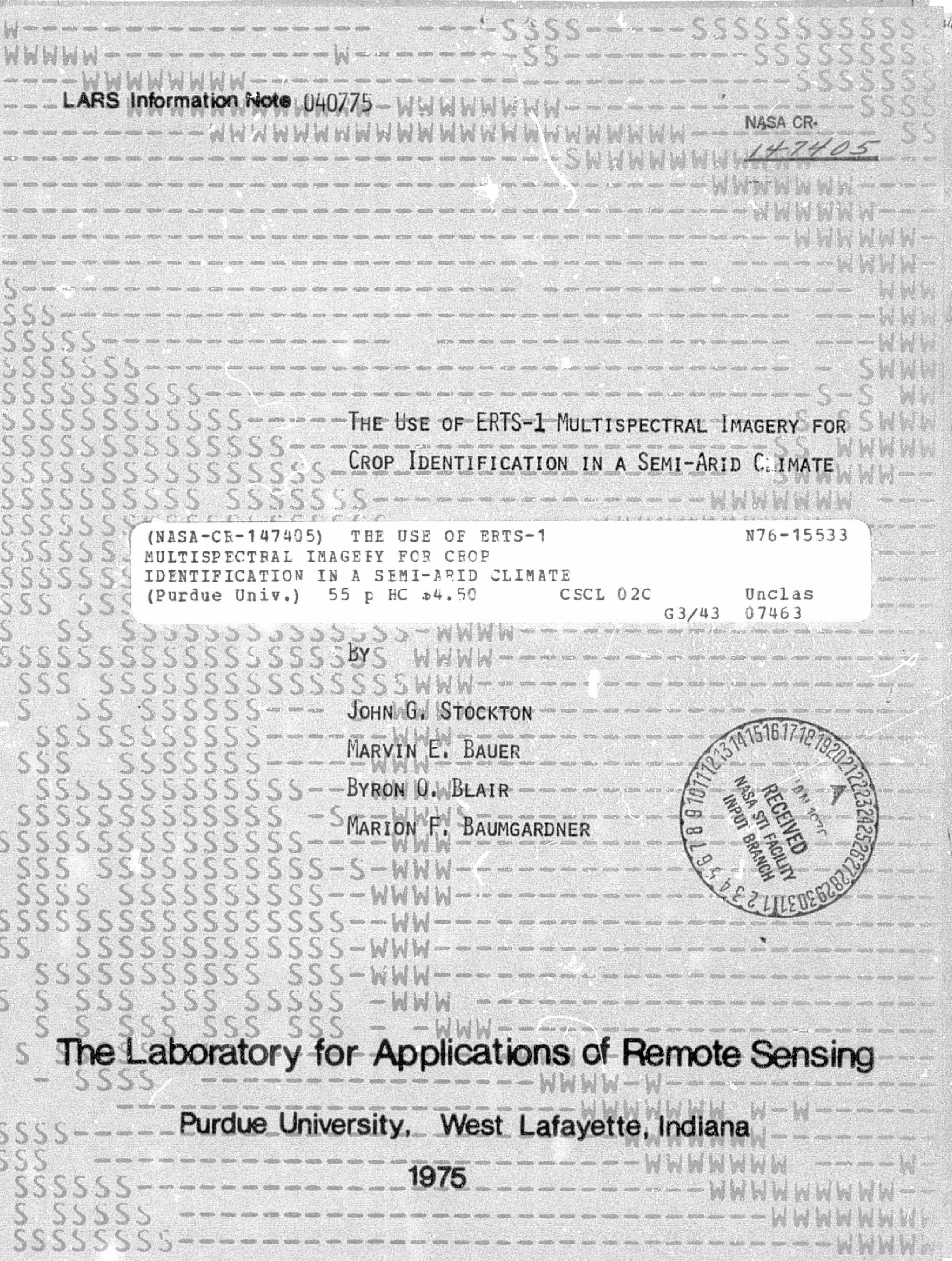

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ABSTRACT

Crop identification using multispectral satellite imagery and multivariate pattern recognition is a relatively new technique enabling rapid evaluation of large areas. The accuracy of this process is examined in this study in a semi-arid climate. Multispectral reflectance data was collected by the Earth Resources Technology Satellite (ERTS-1) over the semi-arid regions of western Kansas and Texas during the 1973 growing season.

Multivariate pattern recognition was used to identify wheat accurately in Greeley County, Kansas. A classification accuracy of 97% was found for wheat and the wheat estimate in hectares was within 5% of the USDA's Statistical Reporting Service estimate for 1973.

The multispectral response of cotton and sorghum in Texas was not unique enough to distinguish between them nor to separate them from other cultivated crops, either singly or multitemporally. The test site of Lubbock County, Texas was deemed too heterogeneous in agriculture practices for correct identification of cotton and sorghum using ERTS-1 imagery.

ERTS-1 imagery may be a useful tool in improving crop surveys. Current data acquisition systems and analysis techniques worked quite well for a homogeneous agricultural area like Greeley County, Kansas. Areas which are quite heterogeneous in agricultural practices, crops and soils are problem areas for which acceptable crop identification may not be obtainable using ERTS-1 imagery. Area estimation of crops in heterogeneous regions does not seem feasible using present satellite imagery.

CHAPTER I

INTRODUCTION

Crop surveys have been considered very important in the past few decades. Their importance will probably remain quite relevant as our total population increases. Current, accurate crop surveys could help stabilize supply-demand relationships for farm products. Distribution of produce from agricultural crops would be more timely if the concentration of crop production was known. The producer, the processor and the consumer of crop products would all benefit from accurate crop surveys over the long run (Eisgruber, 1972). The chaos created by food shortages would be lessened.

Various federal agencies, state agencies and private organizations have strived to obtain crop surveys which would help in forcasting the crop production of a given area. Most surveys to date have been based on information volunteered by farmers and ranchers and on a very small, random sample of the crop land which is observed in the field and measured by field personnel. The accuracy of such crop surveys in the past has shown that crop surveying methods could be improved (Gunnelson, et al., 1972). However, to increase reliability using the crop survey techniques of the past, the number of field observations should be increased; a very costly undertaking. In this thesis a method of sampling much larger areas of crop land at reduced costs will be examined; specifically identification of agricultural crops with multispectral satellite imagery using multivariate pattern recognition techniques.

Remote multispectral sensing (Lars, Vol. 3.) may be defined as the sending, from a remote location, of electromagnetic radiation - either reflected or emitted - in many discrete, usually relatively narrow spectral bands between wavelengths of 0.3 μm and 15 μm and also in radar bands from about 0.86 to 3.0 centimeters.

The new view of the Earth from the Earth Resources Technology Satellite (ERTS-1) at 940 kilometers altitude may provide timely and accurate information which could lead to more useful crop surveys. Since its launch in July 1972, ERTS-1 (NASA has renamed ERTS-1; now LANDSAT-1) has been scanning the entire Earth every 18 days. The satellite views a swath 190 kilometers wide as it orbits the earth. The spacecraft carries a multispectral scanner to obtain image data in various spectral ranges (green, red and infrared). More than 5000 images covering about 180 million square kilometers are collected each week. Techniques to analyze ERTS-1 imagery by computer have been developed at the Laboratory for Applications of Remote Sensing (LARS), Purdue University and these techniques will be discussed further into the text. It was felt that the wide-area, sequential coverage of the ERTS-1 imagery, combined with the capabilities of computer processing, offered a new opportunity to identify crops and improve crop surveys over large areas.

Two areas were selected in the southern Great Plains as trial sites; the sites being Greeley County, Kansas and Lubbock County, Texas. Both sites are considered semi-arid. The major crop of Greeley County is winter wheat and the main crops of Lubbock County are cotton and grain sorghum. If these crops could be correctly identified and mapped using ERTS-1 imagery, which samples <u>all</u> fields in a given area, then this information should demonstrate the usefulness of ERTS-1 imagery. A more complete sampling of an area should result in more accurate crop estimates than are currently available from conventional surveys.

In summary, the overall objective was to determine if crops could be correctly identified using ERTS-1 imagery. A complete, reasonably correct identification of crops for an area should provide additional useful information which should make possible more accurate estimation of crop production.

CHAPTER II

REVIEW OF LITERATURE

Crop surveys have been made by man since the raising of domestic crops was first started in the Middle East. Various methods of identifying and quantifying domestic crop production have been used in years past. Today, much of the world's crop production is surveyed each growing season and many political and economic considerations are affected by the reports of probable crop production. Consequently, the more accurate the survey, the more accurate are the decisions which are based on crop production information.

At present, a great amount of money is spent on crop surveys. Most surveys are of the "statistically random sample" type in which a small percentage of the cropland is checked by a field observer. Inferences are drawn from these observations about overall crop production.

Multispectral Reflectance from Crops and Soils

In general, when electromagnetic radiation strikes a crop canopy or a soil surface, the following phenomena will occur: (1) a portion of the radiant energy may be directionally reflected (Kumar, 1972) but it is most likely that it will be scattered reflectance; (2) a portion of the radiant energy may be absorbed and later emitted at a different energy level; and (3) a portion of the radiant energy may be transmitted. In short, the total amount of radiant energy striking a crop canopy or a soil surface is equal to the amount reflected plus the amount absorbed plus the amount transmitted. Kumar (1972) has written an excellent review on reflectance from plants and soils and the following paragraphs are adapted from his discussion of reviewed literature.

Interaction of Light with a Plant Canopy

The analysis of reflectance from a plant canopy is extremely difficult because many variables are involved. The most important of these variables are:

1. Absorption by oxygen, carbon dioxide and water vapor reduce incoming solar radiation in certain wavelength bands which decreases the accuracy of measurement.
2. Illumination from the sun varies in intensity with numerous conditions.
3. Radiance from field plants is affected by plant geometry, backround soil reflectance, etc.
4. The intensity of the sun has a maximum at about 0.5 μm, falling off rapidly at shorter and longer wavelengths.

Myers et. al. (1966) have shown that near infrared spectrophotometer studies of single leaves can be very misleading for predicting reflectance from crops. Near infrared light transmitted through the top of the crop canopy changes in light quality because of multiple internal reflections occurring within the canopy. Some radiation is scattered between leaves of a plant canopy by multiple reflection so that the reflectance (albedo) for the canopy as a whole is less than for single leaves and seldom exceeds 25%. The amount of scattering increases with the irregularity of the leaf surface and with solar elevation, because sunlight penetrates further into the canopy as the sun approaches the zenith. Davis (1957) has shown that the reflectance of grass varies with the altitude of the sun. His values varied from 22% at noon to about 43% at sunrise and 48% at sunset.

Existing theory of diffuse light propagation is not limited to one or two parameters. Silberstein (1937), for example, increased the number of parameters to three; an absorption coefficient and coefficients for both forward and backward scattering. In 1967, Duncan et. al. developed an elaborate theory for the penetration of direct and diffuse sunlight through a foliage composed of many layers of leaves with known orientation area, reflectance and transmittance characteristics. The controlled variables of the model are: leaf area, leaf angle, vertical position of layer of leaves, light reflected from leaves, light transmitted through leaves and the physiological relationship between illumination and photosynthesis. The variables of the environment are: elevation of sun above the horizon, solar intensity and skylight brightness. Examples of computer simulations of hypothetical and real problems have been presented. Another elaborate model of a plant canopy was proposed by DeWit (1965).

Anderson and Denmead (1969) have described the method for easy calculation of the flux densities of direct and diffuse radiation on inclined foliage in model plant stands. The stands are composed of randomly oriented, constantly inclined, flat foliage surfaces. The calculations require knowledge of the flux densities of direct and diffuse radiation of a horizontal surface above the stand, foliage inclination, foliage area index and solar attitude. For direct radiation, the effects of changes in foliage inclination angle on the average radiation received by the foliage are shown to depend strongly on solar altitude, and time of the day. Relatively large differences can exist between stands of different foliage inclination. There are only small differences between surfaces of different inclination in the receipt of diffuse radiation, particularly at the top of the stand.

Allen et. al. (1970) have generalized and interpreted Duntley equations (1942) to account for the diurnal nature of near-infrared radiation measured in a corn canopy. The Duntley optical coefficients associated with the specular component of light were assumed to vary as the secant of the sun's zenith angle. Generalization of the Duntley relations was required in order to predict values of irradiance within the canopy and to account for the effect of background reflectance from the soil. Five independent measurements of canopy irradiance suffice to determine the Duntley parameters. Twenty-four measurements of transmittance within the canopy were used, however, to obtain a least squares calculation for the best fit of the Duntley equations to irradiance within the corn canopy. The Duntley equations fit the experimental results within a standard deviation of 3.2% for a period from noon to sundown. The best fit to near - infrared transmittance measurements occurs when zero absorptance is assumed for the canopy. The Duntley equations reduce to a three-parameter representation for the special case of no absorptance. Other models of a leaf - Melamed Theory, and plate theory for a compact and a non-compact leaf have not been applied to a plant canopy thus far.

Spectral Properties of Soil

The pattern of spectral reflectance for soils is considerably different from that for plants (Myers and Allen, 1968). In the near infrared region, very substantial contrasts occur in reflectance between different crop species and soil types. Spectral reflectance contrasts for soils, which show up as tone contrasts on photographs, are substantial throughout the spectral range of reflected solar energy (about 0.25 μm to 3 μm).

Krinov (1947) made the most extensive previous measurements of the reflectance of natural surfaces of soils, sands, and vegetation and showed that the reflectance of soils and sands increased monotonically with increasing wavelength throughout the visible and near infrared (to 0.9 μm). Bauer and Dutton (1962) observed the albedo values of agricultural areas, wooded hills, frozen lakes, and all of these areas covered by snow at semiregular intervals. The instrumentation installation consisted of two Eppley pyrheliometers and a Kipp and Zonen hemispherical solarimeter, mounted on a light aircraft, for measuring solar and hemispherical sky radiation, and reflected radiation. Values between 10% and 20% were observed over agricultural land areas in snow free seasons. With snow, the albedo values were as high as 80% over a frozen lake and as low as 50% over wooded hills. Gates (1964) has reported the spectral reflectance of some soil types.

Several investigators have noted the so-called color effect on soil temperatures. The elevated daytime temperatures of dark-colored soils is attributed to their greater absorption and thus less reflectance of solar radiant energy.

Several authors (Shockley et al. (1962), Kortum et al. (1963), Bowers and Hanks (1965), Orlov (1966)) have concluded that increasing particle diameter of soils results in a decrease of reflectivity. The conclusion is correct only for the laboratory case of dispersed soils. Zwerman and Andrews (1940), working with enameled surfaces, stated that spectral intensity of reflected radiation varies inversely with particle diameter. Orlov explained that the artificial breakdown of aggregates usually leads to an increase of the reflection coefficients caused by the character of the mutual position of aggregates. Fine particles fill the volume more completely and give a more even surface. Coarse aggregates, having an irregular shape, as a rule, form a very complex surface with a large number of interaggregate spaces (pores, cracks, etc.). Steiner and Gutermann (1966) described soil investigations by Beloncgova and Tolchel'nikov (1959) and reported that a decrease of grain size results in an increase of reflectance, caused by greater scattering and lower extinction of light passing through the particles. Also, the area covered by microshadows occurring between particles under oblique illumination becomes smaller with decrease in grain size. They also demonstrated that the reflectance of soil minerals depends on their dispersion in the soil. Structureless soils reflect 15% to 20% more light than soils with well defined structure. Reflectance varies with particle diameter but the shape of the spectral curve remains the same. Measurements by Coulson (1966) of the reflecting and polarizing properties of various soils, sands, and vegetation in the visible and near infrared spectral regions showed that dark surfaces polarize the reflected radiation strongly while highly reflecting surfaces have relatively weak polarizing properties. He found that reflectance of mineral surfaces increases with increasing angle of incidence and with increasing wavelengths to about 2.2 μm. Atmospheric scattering affects principally the reflectance from short wavelengths and dark surfaces. Other factors such as location, acidity and past history of the soil cause difference in the multispectral responses received for any given species of vegetation grown on the soil.

Shockley et al. (1962) reported the influence of soil moisture and bulk density parameters on reflected energy in wavelength range 1.4 μm to 5.0 μm. They demonstrate the value of a soil moisture signature in identifying soils. Obukhov and Orlov (1964) stress that wetting and pulverization of the soil surface bring the reflectivity of soils closer to each other. Because of this, the most contrasting photographs can be obtained at a low moisture content. A low contrast can also be expected with sun at a high angle above the horizon. Myers and Allen (1968) reported that wetting the soil in undisturbed and disturbed conditions substantially reduced the reflectance.

Bowers and Hanks (1965) show that surface moisture content, organic matter, and particle size strongly influence reflectance. Reflectance was found to decrease as moisture increased. The staff of LARS at Purdue University obtained the spectral measurements of 250 soil samples. Ten different soil textures, four drainage profiles and three major soil horizons were represented in these samples. The mean spectral curves for the clay soils at two different moisture levels and sandy soils at three different moisture levels are shown on page 84 of

LARS Vol. IV (1970). These curves show a very large decrease in reflectance in the visible and near infrared range with increase in moisture. Johannsen (1969) studied in greenhouse and field environments the soil moisture - plant moisture relationships and the effect of these relationships on reflected and emitted energy from the soil and plant surfaces.

Crop Recognition Using Automatic Data Processing of Multispectral Reflectance Imagery

Most multispectral reflectance imagery is obtained by an optical system measuring energy from discrete wavelength bands. The range of the energy measured is usually from about 0.4 micrometers (μm) to about 2.6 micrometers (μm). This is the visible and near infrared portion of the electromagnetic spectrum in which the reflected energy is most dominant. Both photographic and optical - scanning systems are used. In general, the photographic systems are better adapted to photointerpretation analysis and the optical - scanning systems producing digital output are better adapted to quantitative analysis by automatic data processing systems using computers. The system at LARS is of the latter type.

In 1968, and again in 1970, the LARS staff reported that crops such as wheat, corn, soybeans and hay could be accurately identified, using computer-aided processing of multispectral reflectance imagery taken from an aircraft. Anuta and MacDonald (1971) reported on crop identification using digitized multiband satellite photography. Their results were only somewhat encouraging as they found that crops exhibiting a low amount of ground cover were indistinguishable from bare soils.

Swain (1972) discusses pattern recognition applied to digital imagery as a basis for remote sensing analysis. Hoffer (1973) discusses the use of automatic data processing (by computer) to analyze multispectral scanner data for land-use considerations. He concludes that automatic data processing is not only feasible but may become necessary when analysis involves large spatial areas and temporal observations at the same time. Hall et al. (1974) have reported on problems encountered in attempting to use ERTS-1 imagery for crop identification studies. They found that location of field boundaries, field size and cloud cover caused the major problems. They concluded that, despite the problems encountered, analysis of ERTS-1 imagery by computer should be relatively cost effective. Landgrebe and the LARS staff (1973) did an early evaluation of machine processing techniques of ERTS-1 data and discussed many different land-use situations in which ERTS-1 imagery might be useful.

Bauer and Cipra (1973) reported that corn and soybeans had been identified satisfactorily in northern Illinois using ERTS-1 multiband imagery. Computer processing of the multispectral imagery was used as the means of analysis. They obtained a overall accuracy for crop identification of 83%. They also found that using multitemporal imagery obtained during the growing season improved the identification of "other"; "other" being features other than corn or soybeans. The area estimates of corn, soybeans and "other" obtained from the ERTS-1 classification agreed closely with the USDA estimate.

Williams et al. (1973) found that wheat could be identified by photointerpretation methods for a test site in Finney County, Kansas.

Using two classes, wheat and non-wheat, and only the 0.60-0.70 μm waveband of ERTS-1 satellite imagery, they obtained an observed accuracy of wheat identification of 89%.

Three separate investigations in California by Draeger (1973), Johnson and Coleman (1973), and Thomson (1973) have reported that crop identification is feasible if large fields are available for use in training and for testing accuracies. All of the three studies reported identification accuracies of around 80% using photointerpretive methods of ERTS-1 imagery. Horton and Heilman (1973) found that in South Dakota corn and soybeans could be identified accurately, about 90%, by machine processing all four wavebands of ERTS-1 imagery.

CHAPTER III

METHODS AND OBSERVATIONS

Site Descriptions

Greeley County, Kansas

Greeley County is one of the western Kansas counties on the Colorado border and is centrally located between Nebraska and Oklahoma. Its area is about 200,000 hetares. It occupies part of the nearly level to gently rolling high plains region between the Arkansas River to the south and the Smokey Hill River on the north.

Agriculture is the only industry of Greeley County. Wheat and cattle are the main sources of income. Most of the county is cultivated and most of the farming is dry-land. There is a small amount of irrigation from deep-well sources. Most of the areas remaining in native grassland are found on slopes adjacent to natural drainage ways.

The soils of the county are quite uniform in color and surface texture. They are quite dark when moist and light-gray when dry. About 95% of the soils have a silt loam surface texture. The topography is gently undulating and the soils are quite susceptible to wind erosion.

One striking cultural feature of the county is field patterns. Much of the land in wheat production is sectioned into long, narrow fields with the long sides of fields lying in an east-west direction. The prevailing winds in western Kansas are of a north-south direction.

By locating the fields perpendicular to the dominant wind direction, the wheat and wheat stubble acts as a natural barrier or windbreak. In this manner, much of the wind erosion can be retarded.

Hard red winter wheat is grown in Greeley County. It is planted in the fall, germinates, and tillers before winter, goes through hardening and vernalization in the winter, and has its major growth, flowering and maturity in the spring. Wheat harvest in the county usually starts about the third week of June. Hard red winter wheat is grown in the county because the annual rainfall is only about 40 cm per year. Fallowing on about one-half of the wheat land is practiced. When land is "fallow" it is allowed to lay idle for one year while it accumulates moisture in the soil and has the weeds controlled. The following year, the "fallow" land is planted in wheat and the land which was in wheat the previous year is "fallow".

Lubbock County, Texas

Lubbock County lies in the Southern High Plains in west-central Texas. It is slightly south of the Texas Panhandle and is near the New Mexico border. The county encompasses an area of approximately 230,000 hectares. Yellow House Draw bisects the county on a diagonal from the north-west to the south-east corners. Most of the topography in areas adjacent to the draw is quite rolling. The remainder of the county is nearly level to gently rolling with the most pronounced topographic features being playas; playas are small depressional areas in the landscape which catch and hold the runoff water for a short period of time. After a rain the playas resemble small lakes. A lake, in Spanish, is playa or beach.

The main agricultural products of the county are cotton, grain sorghum and cattle. Almost all of the cotton and grain sorghum is irrigated with water from deep wells. Small amounts of dryland wheat are grown. A few soybeans are also grown. Much of the land near the draws and drainageways is in native grasses which are used to pasture cattle.

The climate in the Lubbock area is also semi-arid. The water loss due to evaporation and transpiration make it necessary to irrigate most summer crops. The soils are quite heterogeneous and exhibit some limitations to production. Salt accumulation, low natural fertility and periodic wetness (in playas) are some of the soil deficiencies.

The main agricultural crops in Lubbock County are "short-day" plants, flowering after the days in summer start to get shorter. Grain sorghum is planted about the middle of June. Cotton is planted near the end of June following grain sorghum planting. Almost all of these crops are planted on ridges. Irrigation water can then flow down the furrows between the ridges to irrigate the crops. Both crops are harvested in late fall.

One observation that can be made in an area which uses furrow irrigation practices is that fields may be irregular in shape and size. The land must be leveled and provided with a slight, unidirectional, constant slope to insure that the irrigation water will reach all of a field uniformly. Fields are leveled in a manner which allows the least amount of soil to be moved. Therefore, original topography is taken into consideration and the resulting fields may have irregular shapes and different sizes.

Acquisition of Multispectral Data

The multispectral data for this study was collected by ERTS-1 which was launched into a polar orbit in July of 1972. The orbit is at an angle of 14° with the longitude of the earth. This 14° angle provides a sun-synchronous orbit which places the satellite over its target at approximately 9:30 A.M. local time.

The multispectral scanner on ERTS-1 measures reflected energy in four wavelength bands. The bands are as follows (ERTS-1 Data Users Handbook, 1972):

0.50 - 0.60 micrometers (μm)	green
0.60 - 0.70 micrometers (μm)	red
0.70 - 0.80 micrometers (μm)	infrared
0.80 - 1.10 micrometers (μm)	infrared

The multispectral scanner on ERTS-1 is an optical-mechanical scanner with a field of view of approximately 185 kilometers. The images or scenes obtained cover about 185 by 185 kilometers or a little over 3,400,000 hectares.

The multispectral data for this study was obtained on computer compatable digital tapes from the Goddard Space Flight Center at Greenbelt, Maryland. The data was received at LARS as part of the multispectral data for NASA Contract NAS5-21785. Only one scene was analyzed for the test site in Kansas. Four scenes covering the growing periods of cotton and grain sorghum were obtained for the Texas test site.

Table 1 lists the ERTS-1 images used. All of the multispectral data was obtained during the summer and fall of 1973 by the ERTS-1

Table 1. ERTS-1 images used for crop identification.

Location	Date	ERTS-1 Scene ID
Greeley County, Kansas	June 19, 1973	1331 - 16571
Lubbock County, Texas	June 18, 1973	1330 - 16531
Lubbock County, Texas	July 24, 1973	1366 - 16521
Lubbock County, Texas	August 11, 1973	1384 - 16524
Lubbock County, Texas	October 22, 1973	1456 - 16523

satellite. Date was collected on June 19, 1973 for Greeley County, Kansas and on June 18, July 24, August 11 and October 22, 1973 for Lubbock County, Texas. Each image contains about 7.7 million data points. This means that the response represented by one data point in each waveband is the integrated response from 0.44 hectares. Only the portion of each image covering the respective test areas was analyzed.

Ground Control Information

Ground control information is that data used to train a photo-interpreter or a computer how to recognize certain characteristics (spatial or spectral) of a scene as having a specific feature. For example, if an analyst wishes to identify corn fields in a heterogeneous agricultural scene photographed from an airplane, a knowledge that some specific fields located in the scene contained corn can greatly aid in identifying correctly the remainder of the corn fields. For these purposes, some ground control information was essential for this study.

Ground control data for Greeley County, Kansas was from three sources. One was simply the Statistical Reporting Service (USDA/SRS) estimate of the total amount of wheat grown in Greeley County in 1973. A second source was in situ observations of some selected fields by the Cooperative Extension agent in Greeley County. About 25 fields around

Tribune, Kansas were observed by the Cooperative Extension Agent. He reported whether fields had been in wheat, fallow, or in permanent pasture for the 1973 crop year. Both this data and the SRS estimate of wheat were used to verify the accuracy of the identification of wheat in Greeley County.

The third source of ground control data and the only ground control used for training was aerial color infrared photography. This photography was obtained by an aircraft flying at an altitude of 9500 meters on a south to north flightline over Kansas State Highway 27, which passes through Tribune, Kansas and is near the middle of the county. The photography was taken on May 14, 1973 when the wheat was a lush green, the permanent pasture was starting to become green and the fallow land was bare.

Interpretation of a scene photographed with color infrared film requires a knowledge of some basic characteristics of the film. The film is sensitive to a near infrared waveband (0.72 - 0.92 micrometers) and requires a filter on the optics which screens out the blue wavelength radiation. Normal color film depicts a blue river with a blue color and a green tree as a green color. Color infrared film displays blue targets with a black color, a green, non-living target as a blue color, a red target as a green color, and a lush green vegetative cover as a red color. The red color on color infrared film corresponds to the 0.72 - 0.92 micrometer waveband. Compared with other types of cover, green plants reflect more highly the near infrared energy, thus the usefulness of color infrared photography when working with green vegetation is apparent.

Ground control data for Lubbock County, Texas was obtained in situ by farmers in the area and by M. F. Baumgardner and J. A. Henderson for LARS. Most of the data was on crop type and crop conditions. Some low altitude aerial photography was taken by Henderson.

Four farmers collected data which was used in this study. Figure 1 indicates the locations of farmer ground control information sites with arrows. Each farmer observed all of the fields on both sides of a paved road near his home. The length of the segment he surveyed for each ERTS-1 pass was ten to twelve kilometers. Each farmer reported land use (crop), planting pattern, growing conditions, percent ground cover, stage of crop residue, soil conditions, crop conditions and row direction for each field in his segment. The voluntary and diligent effort of these four farmers was greatly appreciated. Other ground observers did not collect complete information and their observations could not be used.

During the first week of July in 1973, Baumgardner and Henderson took low altitude aerial photography of thirty-six (36) road intersections in Lubbock County (See Figure 1). These road intersections were located on three lines running north to south through the county; each line was along a north-south county road and each line covered about one-third of the county. The urban area near the city of Lubbock was avoided. Each intersection was marked on a county road map so that the intersections could be located when on the ground.

The day after the aerial photography was collected each of the intersections was visited. The land use and other features like those noted by the four farmers were recorded for each [illegible] the four corner

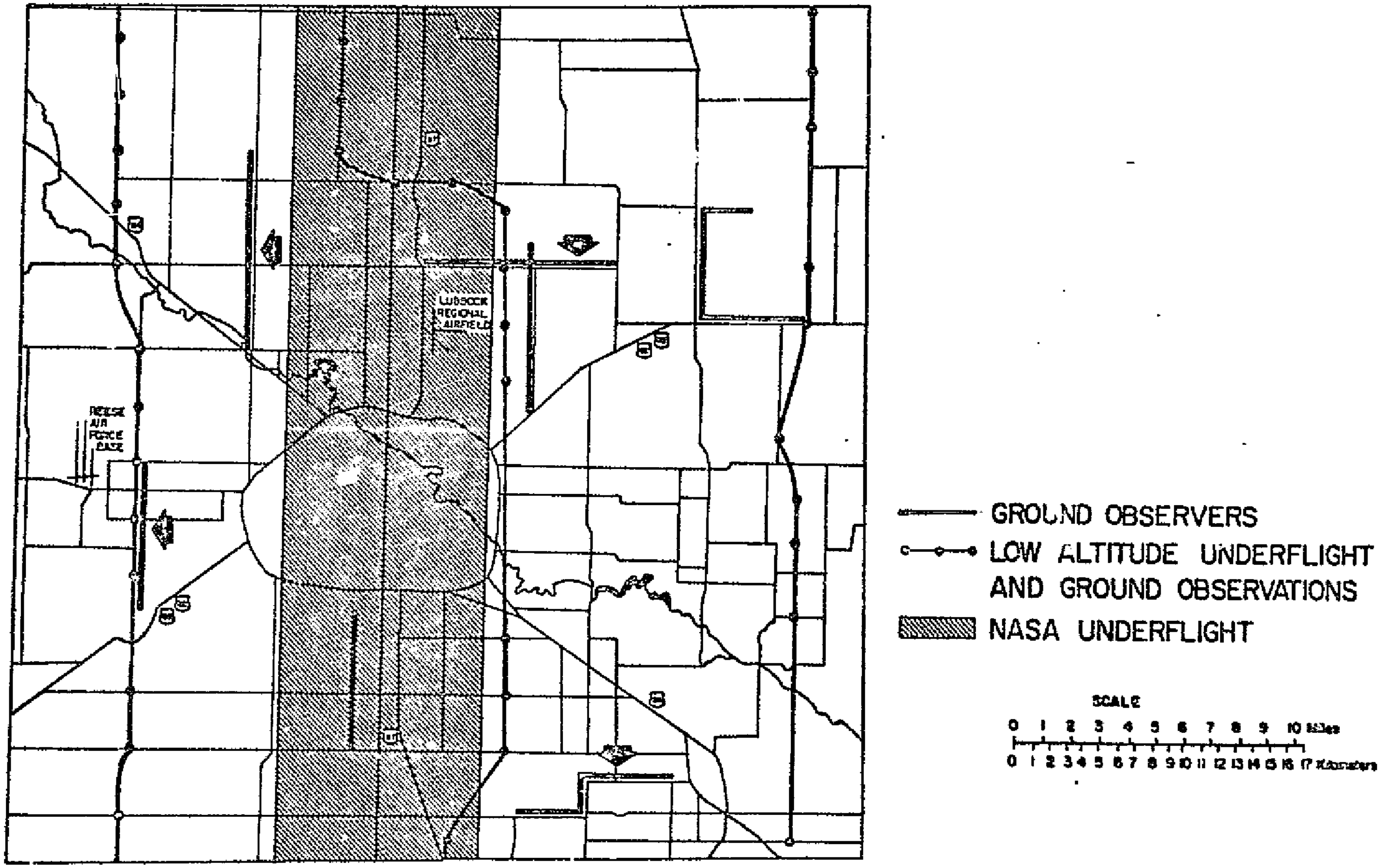

Figure 1. Location of ground information used in the analysis of Lubbock County, Texas.

fields at each intersection. This gave an additional 144 fields of ground control to be used in training or to test classification accuracies. This gave a total of about 300 fields with ground control information in the Lubbock test area, though many of the fields were too small for effective use.

For a more complete description of the method of obtaining ground control for this experiment the reader should refer to the final report for NASA Contract NAS5-21785 by Baumgardner (1974).

Analysis of Multispectral Satellite Imagery

The LARSYS software system was used to analyze the multispectral satellite imagery. LARSYS is a package of computer programs which has been designed to analyze and display remotely sensed multispectral data. The use of these programs is discussed by Phillips (1974) and Hoffer (1973). The computer used was an IBM 360-67.

Eight separate processing algorithms were used in this study: (1) GEMCOR, (2) IMAGEDISPLAY, (3) CLUSTER, (4) STATISTICS, (5) SEPARABILITY, (6) CLASSIFYPOINTS, (7) PRINTRESULTS, and (8) PHOTO. The first five algorithms were used to analyze data from both test sites. The last three were used only for the Greeley County test site. The results of the Lubbock County analysis were such that analysis beyond SEPARABILITY was not necessary.

The first step in the analysis process was to correct the multispectral data for geometric distortion. Due to the multispectral scanner geometry and the heading of ERTS-1, considerable spatial distortion occurred. The algorithm GEMCOR, reported by Anuta (1973), was used to correct the distortion and adjust the scale of the multispectral data. By locating the approximate corner coordinates of the counties in all of the scenes and supplying them to GEMCOR, the area within the designated coordinates was corrected for geometric distortion and scale. Approximate corner coordinates were located using 70 millimeter transparencies of the 0.60 - 0.70 μm waveband of the multispectral imagery, provided with the digital imagery. The corrected sets of digital imagery were used for all further analysis.

Next, the corrected digital imagery was displayed, one scene at a time. The Digital Image Display System displays the image on a black-and-white television screen. An interactive capability to edit, annotate or modify the image is provided through a light pen and a program function keyboard. An additional photographic copying capability is also available.

The computer program which allows the interaction of the Digital Image Display System and the data set is IMAGEDISPLAY. The data in each individual waveband is partitioned into 16 levels and these levels are displayed on the screen as gray levels, low values being dark and high values being bright. The program also provides many other functions such as outlining fields with the light pen and obtaining the coordinates in the multispectral data, magnifying the image on the screen, and many other features.

The corrected scenes were displayed and the ground control sites were located in the multispectral image, usually using the 0.60 - 0.70 μm and 0.80 - 1.10 μm wavebands. A rather large area around a ground control site was outlined since exact location of a ground control site on the display system is most difficult at times, especially when dealing with agricultural crops. For example, in Greeley County an area of about 8 km by 32 km was outlined and coordinates were obtained. Also, in Greeley County, the exact corner coordinates of the county were located in the multispectral imagery and those coordinates recorded. In Lubbock County, a similar procedure was used in outlining the areas around the ground control sites.

After the portion of multispectral data taken over the ground control sites was located, the CLUSTER algorithm was used to produce a map (computer printout) of the area. CLUSTER is an unsupervised classifier, a pattern recognition tool that groups data vectors into an arbitrary number of spectrally distinct classes. To enhance the field boundaries which were somewhat indistinct and undistinguishable on the display system, the data was clustered into eight spectral classes. Each data point within the ground control site was assigned to one of the eight spectral classes by CLUSTER and was displayed on the computer printout as one of eight different symbols.

Unique features such as odd-shaped fields, lakes and road intersections were used to match the CLUSTER map with the ground control data. Then definite fields with known crop type could be located spatially in the CLUSTER map and field coordinates were obtained for each field selected. County road maps, ground control field maps and low altitude airphotos were all useful for precise location of fields in Lubbock County. In Greeley County, the field size and shape could be seen in the color infrared aerial photography.

The land use or crop type in Greeley County was also determined from the color infrared photography. On May 14, 1973 the wheat fields in the color infrared photography were bright red, pasture fields were light pink, and fallow land was black or greenish-brown.

Temporal overlay capability, the aligning of data sets of the same area differing only in time, was employed for the Lubbock County test site. This alignment, or spatial registration of multitemporal data, matched the coordinates of a given point on the ground for all four scenes of data used. This made locating ground control fields in Lubbock County necessary only once and eliminated some possible sampling error.

The STATISTICS processor was used to obtain mean vectors and covariance matrices for the different classes of crops or land-use selected from each test site. A class mean vector was calculated by averaging the response from all of the data points within all of the fields used for training for a specific class (crop or land-use). All four wavebands were considered. The relationship between the waveband responses for a specific class was shown in the covariance matrix.

Five classes of land-use were selected for training in Greeley County. They were wheat, pasture and three types of fallow land. Three classes of fallow land were selected because of differences in cultivation. Some fields were recently cultivated, others were not cultivated when the multispectral imagery was obtained, and some were weedy.

In Lubbock County, Texas a number of classes were defined but cotton and sorghum were the two classes of interest. The main objective at this test site was to identify cotton and sorghum and differentiate the two crops. For comparison purposes classes of permanent pasture, temporary pasture, water, and urban communities were chosen. A separate set of mean vectors and covariance matrices was calculated for each of the ERTS-1 images.

The mean vectors and covariance matrices for each scene were used as input for the SEPARABILITY processor, an algorithm which measures the statistical distance or separability of the class vectors. The processor considers a specified set of wavebands of data (in this study, all four wavebands of the ERTS-1 imagery were specified) and computes a transformed divergence value (Swain, 1973) for all possible combinations of classes. It has been experimentally observed that a minimum value of transformed divergence of 1600 is required if classes are to be considered separable. Values lower than 1600 tend to indicate that the two classes being considered are similar and the probability of discriminating between them accurately is quite low. Values higher than 1600 indicate the classes are separable. The maximum value possible is 2000.

The SEPARABILITY processor is a good method to check to see if the training classes that have been selected will produce acceptable classification results. Classes which are deemed inseparable by SEPARABILITY are not likely to produce accurate classification when used in the CLASSIFYPOINTS algorithm.

The CLASSIFYPOINTS processor uses the mean vectors and covariance matrices for training classes calculated by STATISTICS to perform a maximum likelihood Gaussian classification, data point by data point, for a specified set of data. The classifier (pattern recognition algorithm) compares the response at each data point specified with the statistics of the training classes and makes a maximum likelihood estimate as to which class it belongs. In Greeley County, the data set specified was the area in the data which was within the county boundries. No classification was performed for Lubbock County because the results of SEPARABILITY indicated that the resulting classification would be highly inaccurate.

The PRINTRESULTS processor has two main functions: (1) to display the point-by-point classification of the specified data as an alphanumeric map-like printout on a line printer, in which the user selects the symbols to be used for each of the different classes, such as C for cotton or W for wheat; and (2) to produce a quantitative evaluation of a classification in tabular form. A table listing how many data points fell into each specific class is one product. Also, coordinates of fields of known land-use or crop type (not fields used in training) can be input into the program as test fields. PRINTRESULTS will compare the classified points within the test fields with their known class and will compute a table of classification accuracies. This is the most widely used method, for crop studies, to evaluate the accuracy of the CLASSIFYPOINTS procedure.

Another method of displaying the results of the CLASSIFYPOINTS procedure is the photographic capability of the Digital Image Display System. A program called PHOTO causes the different classes of the classification to be displayed at selected intensities on the image display screen. A black and white photograph may be taken at this time from the photographic image display screen. Color photography is also possible with PHOTO. The color for each class is selected from a color chart and is specified in the program. Then, by using a combination of filters and ordinary color film, color-coded classifications can be produced.

CHAPTER IV

RESULTS AND DISCUSSION

Greeley County, Kansas

The mean and standard deviation of the relative spectral responses for wheat and other land-use types in Greeley County on June 19, 1973 are listed in Table 2. All relative response values are rounded to the nearest whole number.

Table 2. Response of wheat and other land-use types in Greeley County ($\bar{X}$ and s).

Land-Use Type	Wavelength Band (µm) 0.50-0.60		0.60-0.70		0.70-0.80		0.80-1.10	
	$\bar{X}$	s	$\bar{X}$	s	$\bar{X}$	s	$\bar{X}$	s
Wheat	37	3	40	5	51	3	28	2
Pasture	39	2	38	2	53	3	28	2
Fallow 1	43	2	50	2	50	2	24	1
Fallow 2	61	4	73	6	73	4	35	2
Fallow 3	53	3	63	4	63	3	31	1

The means are plotted in Figure 2. The relative reflectance of fallow land is higher than wheat or pasture in the visible wavebands. The response in the 0.50-0.60 µm waveband is higher for pasture than for wheat. The same is true for the 0.70-0.80 µm infrared waveband; however, the reverse is true in the other two wavebands: the response for wheat is higher than pasture. It would not be correct to compare the means from waveband to waveband because the wavebands are all

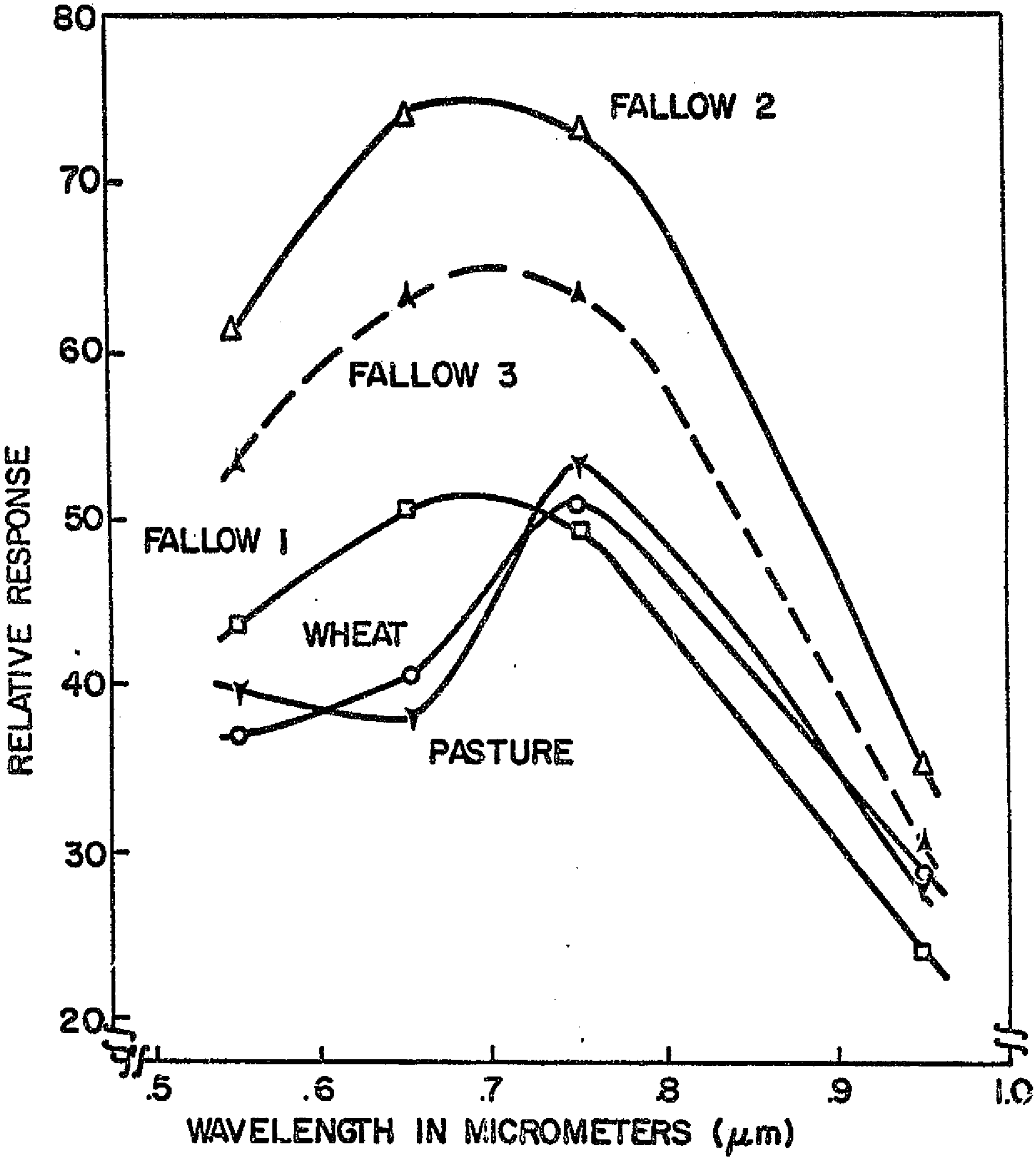

Figure 2. Multispectral response of wheat and other land-use classes in Greeley County.

calibrated individually. The response inversions for wheat and pasture and their large differences in response with the fallow classes suggested that the five classes were separable classes.

The standard deviations listed in Table 2 were considered relatively small. This suggests that the classes selected have a small response variance in each waveband and the probability density functions for the classes would be less likely to overlap. Fallow 1 was believed to be freshly cultivated land, Fallow 2 was considered uncultivated, and Fallow 3 was thought to be uncultivated, weedy fields.

The SEPARABILITY processor affirmed the conclusion that the wheat could probably be classified (identified) correctly. Table 3 lists the results obtained from SEPARABILITY indicating that the multispectral response of wheat was different enough so that there should be little confusion with the other classes considered. The average transformed divergence for all class pairs was 1921 (2000 is the maximum obtainable value). The minimum divergence between wheat and any of the other classes was 1739. On this basis, the wheat should be identified correctly as wheat by the CLASSIFYPOINTS processor.

Table 3. SEPARABILITY results listing divergence of the five classes identified in Greeley County, Kansas using all four ERTS-1 wavebands.

Class Combination Compared	Transformed Divergence
Wheat vs. Pasture	1739
Wheat vs. Fallow 1	1999
Wheat vs. Fallow 2	1996
Wheat vs. Fallow 3	1995
Pasture vs. Fallow 1	2000
Pasture vs. Fallow 2	2000
Pasture vs. Fallow 3	2000
Fallow 1 vs. Fallow 2	2000
Fallow 1 vs. Fallow 3	1995
Fallow 2 vs. Fallow 3	1487

When the entire county was classified, the classification was tested for correct identification of wheat and the other classes by introducing test fields of known land-use type. The test fields were chosen from the underflight color infrared photography and from a limited number of fields visited by the local county agent. All test fields for fallow land were combined for purposes of testing the classification accuracy (i.e., no attempt was made ...). The percent correct classification was computed by taking the total number of data points classified correctly within the test field coordinates for each class and dividing that number by the total number of data points for that class. Table 4 lists the classification accuracies.

Table 4. Classification accuracy for wheat, pasture and fallow in Greeley County.

Class Name	No. of samples per class	% Correct Classification	No. of samples classified with Wheat	Pasture	Fallow
Wheat	400	97.0	388	4	8
Pasture	318	96.1	9	305	4
Fallow	431	97.9	7	2	422

These classification accuracies for tested fields were considered excellent. A further test was made of the classification. Multiplying the number of data points in the county classified as wheat by 0.44 yields the number of hectares of wheat identified in Greeley County. Table 5 compares the results of a Statistical Reporting Service (SRS) estimate of wheat in Greeley County for 1973 with the number of hectares of wheat identified by the analysis of the imagery. The SRS estimate was obtained from the county extension agent.

Table 5. 1973 area estimates of wheat, fallow and row-crop, and pasture in Greeley County.

Source	Wheat (Ha)	Pasture (Ha)	Fallow and Row-Crop (Ha)
SRS (USDA)	77,000	35,000	88,000
Identification via ERTS-1	78,000	32,000	92,000

The USDA/SRS estimate for wheat is only about 1% smaller than the amount of wheat identified using ERTS-1 imagery. This close agreement of statistics carries through in the pasture class, the difference being about 4%. SRS row-crop estimates were combined with estimates of fallow (12,000 Ha and 76,000 Ha, respectively) and were displayed as one class in Table 5. At the time the ERTS-1 imagery was obtained for Greeley County (June 19, 1973) any row-crops such as corn or sorghum would have low ground cover and would look like the bare fallow fields. Identification of wheat and other land-uses by satellite imagery is similar to the estimate obtained using present SRS techniques for Greeley County, Kansas. It is impossible to determine with available data which of the two estimates is the better estimate of the actual situation.

A visual aid or map is useful for observations of spatial distribution and cultural patterns of wheat in Greeley County. By using the PHOTO processor, a photographic map of the wheat classified in Greeley County was produced and is shown in Figure 3. The long, narrow fields of alternating fallow and wheat are easily observed. This cultural practice is used to control wind erosion. The dominant pasture areas appear along the drainage ways as they should. The area displayed in

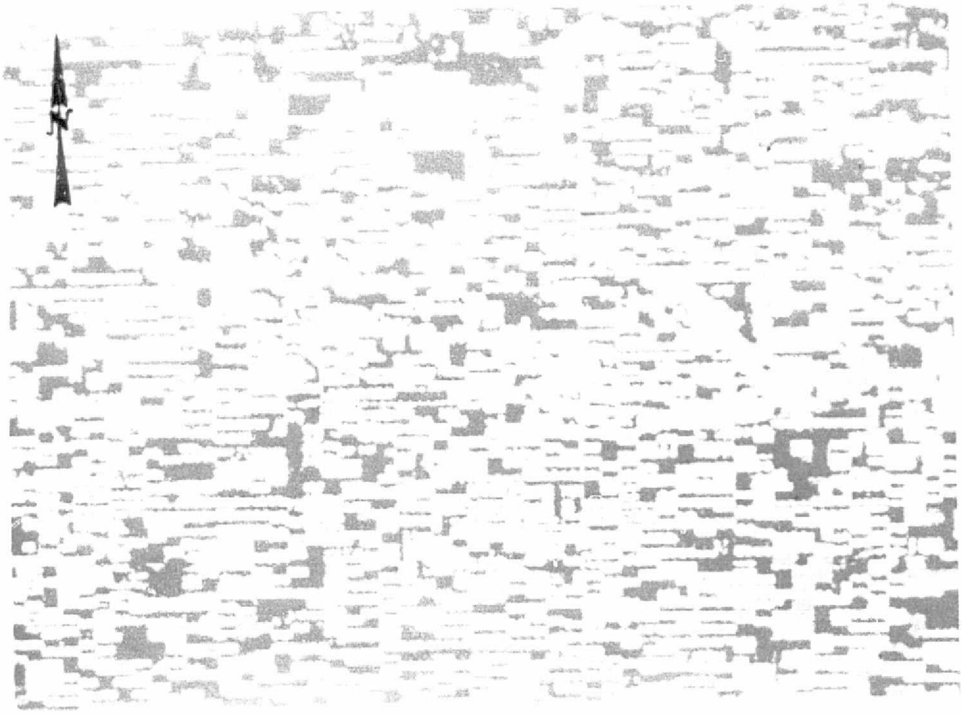

Figure 3. Photographic map of wheat classification for Greeley County; color code is: white = wheat, gray = pasture, and black = fallow land.

the photograph is about 200,000 hectares. The classification appears spatially reasonable as well and illustrates the homogeneity of the agricultural practices in Greeley County. Under similar conditions, wheat, and perhaps other crop types, can be expected to be identified correctly using satellite imagery.

Regression analysis was used to help explain the reflectance characteristics of the various cover types and the relationships among the several variables. A multiple regression model using the four wavelength bands as independent variables was adapted from Draper and Smith (1966). The dependent variable, land-use or surface condition, was coded with a five factor, orthogonal polynomial as follows: fallow 3 = -2, fallow 2 = -1, fallow 1 = 0, wheat = 1, and pasture = 2. The practice of coding qualitative variables with orthogonal polynomials reduces bias in the regression model (Anderson, 1974). The regression model used was:

$Y = b_o + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_4 X_4 + \varepsilon$ where:

Y is the dependent variable for land use;

b_o is the intercept when $X_1 = X_2 = X_3 = X_4 = 0$;

b_1, b_2, b_3, and b_4 are coefficients in the regression model;

X_1 is the response in the 0.50 - 0.60 μm waveband;

X_2 is the response in the 0.60 - 0.70 μm waveband;

X_3 is the response in the 0.70 - 0.80 μm waveband;

X_4 is the response in the 0.80 - 1.10 μm waveband;

and ε is the random error term distributed normally with mean equal to zero and variance equal to σ^2.

A plot of land-use with the response from the 0.60-0.70 µm wavelength band is shown in Figure 4. This simple linear regression for one waveband yielded an $r^2 = 0.757$ which is very good for one waveband. This says that about 76% of variability in spectral response from the land-use classes is explained by the response noted with the 0.60 - 0.70 µm wavelength band.

A prediction equation using multiple regression was formed in a stepwise manner. A step-wise regression procedure used enters the independent variable which explains the most variability into the equation first, then adds the second best independent variable, and continues to add independent variables to the prediction equation until it has no more to add or until the next independent variable makes no significant contribution to the model (when the error sum of squares is not reduced significantly). The prediction equation formed for land-use conditions in Greeley County was formed without the 0.70-0.80 µm waveband as it contributed nothing to the model:

$$Y = 1.26 + 0.18X_1 - 0.23X_2 + 0.08X_4$$

The multiple r^2 for this regression model was $r^2 = 0.85$. Thus the three variable model explains 10% more than the linear model in Figure 4 and should be quite useful in predicting what land-use type occurs if the spectral response is known. By substituting the spectral response for the respective independent variables, the type of surface condition can be computed and can be expected to be accurate about 85% of the time.

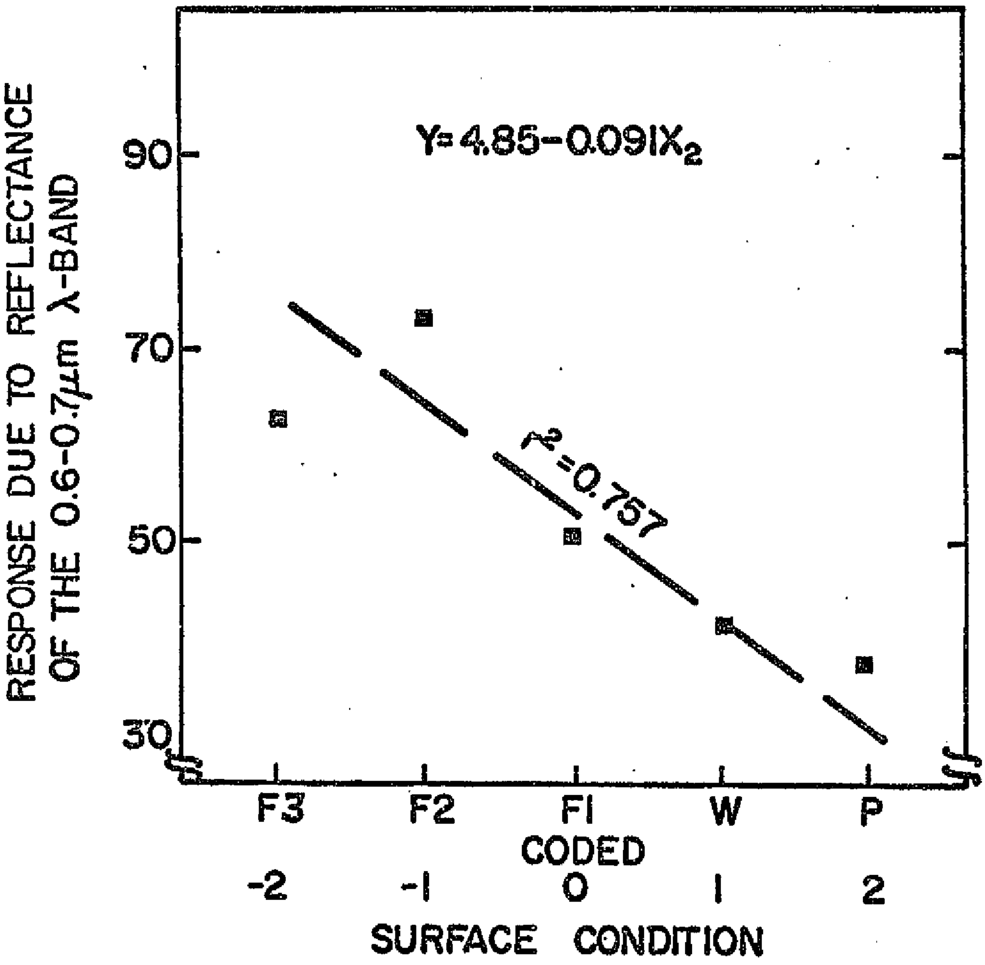

Figure 4. Plot of surface conditions and the spectral response from the 0.60 - 0.70 μm wavelength band.

Lubbock County, Texas

In this test site, cotton and sorghum were the two crops that were investigated. The multispectral response measured by ERTS-1 was obtained from a set of training fields for each of the four ERTS-1 images obtained during the growing season. Table 6 lists the results for cotton and sorghum by image date and by wavelength band. The means ($\bar{X}$) and standard deviations (s) are products of STATISTICS and are rounded to the nearest integer value.

Table 6. Means ($\bar{X}$) and standard deviations (s) for cotton and sorghum by image date and waveband.

	Waveband		Cotton		Sorghum	
Date	µm	#	$\bar{X}$	s	$\bar{X}$	s
JUNE	0.50-0.60	1	38	4	37	3
	0.60-0.70	2	48	6	46	6
	0.70-0.80	3	53	5	51	5
	0.80-1.10	4	27	3	25	3
JULY	0.50-0.60	1	42	5	41	10
	0.60-0.70	2	48	10	43	13
	0.70-0.80	3	68	5	64	9
	0.80-1.10	4	34	3	32	4
AUGUST	0.50-0.60	1	32	3	32	4
	0.60-0.70	2	32	8	33	9
	0.70-0.80	3	59	6	59	6
	0.80-1.10	4	32	4	32	4
OCTOBER	0.50-0.60	1	28	3	28	4
	0.60-0.70	2	33	6	33	7
	0.70-0.80	3	41	5	39	6
	0.80-1.10	4	21	2	21	3

A suspicion developed immediately upon observing the means and standard deviations of Table 6 that perhaps cotton and sorghum could not be differentiated under the conditions that existed in Lubbock County. The modified bar graph shown as Figure 5 illustrates the closeness of the means and the overlap of the data distributions. The means are quite close in most cases and are the same in some wavebands. Furthermore, the overlap suggests that it is improbable that cotton can be separated spectrally from sorghum in this study.

The SEPARABILITY processor was used to quantify the difference in the multispectral response of cotton and sorghum. Values of 300 to 400 were obtained as the measure of separability of cotton and sorghum for individual dates and for combinations of dates by SEPARABILITY. An acceptable value for class separation is on the order of 1600 or greater so the cotton and sorghum were considered quite inseparable, spectrally. Also, the cotton and sorghum were found to be inseparable spectrally from all other cultivated crops in the Lubbock test site. Therefore, no classification was made of Lubbock County as it was unlikely that accurate identification of cotton and sorghum could be achieved.

A more conventional means of determining the closeness of the mean spectral response for cotton and sorghum is Analysis of Variance. The model for the analysis is a split-plot design (Anderson, 1974). The model is:

$$Y_{ijk} = \mu + D_i + \delta_{(i)} + C_j + DC_{ij} + B_k + DB_{ik} + CB_{jk} + DCB_{ijk} + \varepsilon_{(ijk)} \text{ where:}$$

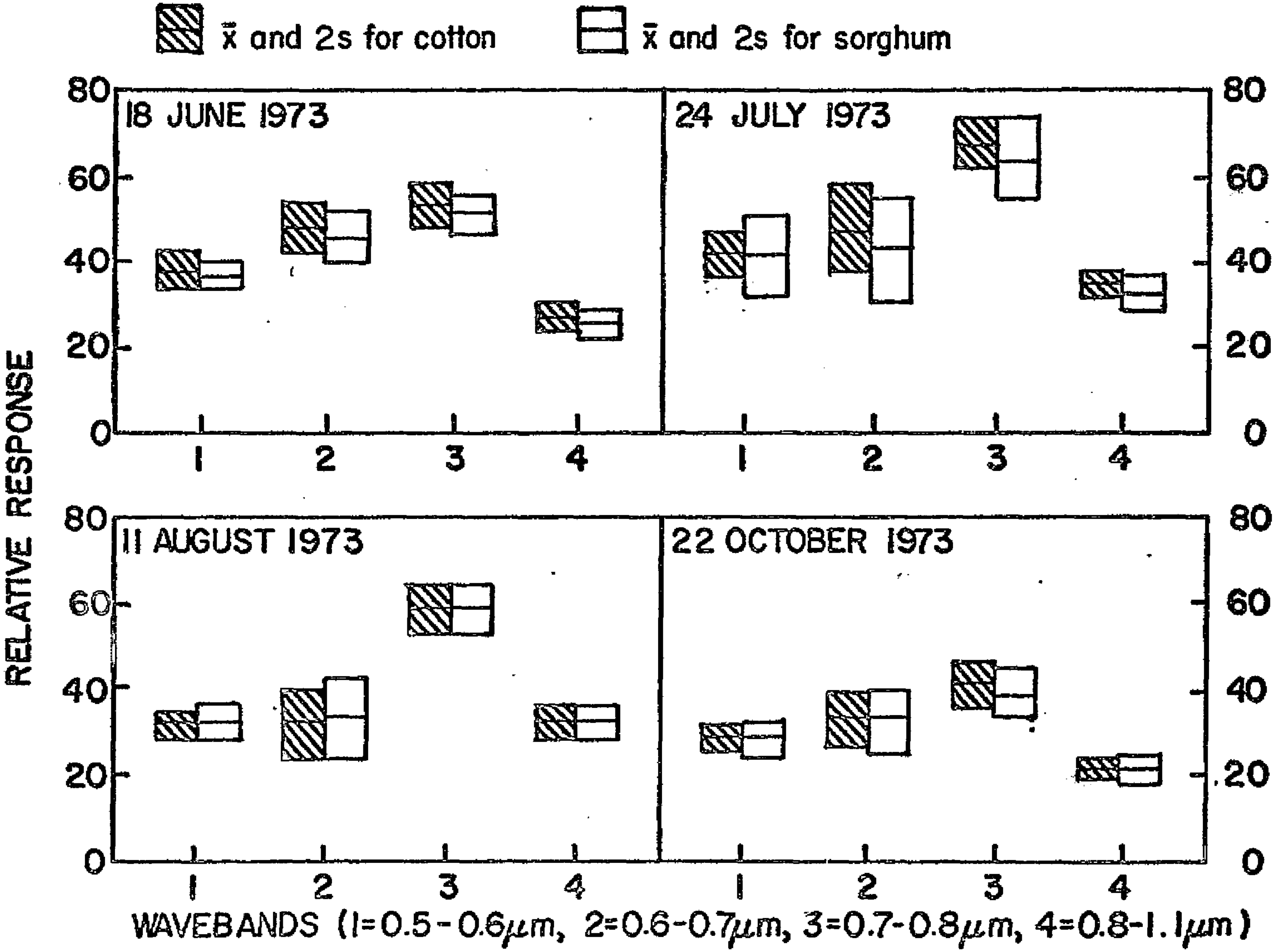

Figure 5. Mean response and standard deviation for cotton and sorghum from their respective ERTS-1 images by waveband.

Y_{ijk}	is the response of the kth wavelength band from the jth crop type within the ith scene of data;
μ	is the overall mean;
D_i	is the variation due to the ith scene of data;
$\delta_{(i)}$	is restriction error due to each scene being a single set and not replicated;
C_j	is the variation due to the jth crop type;
DC_{ij}	is the variation due to the interaction of the ith scene with the jth crop;
B_k	is the variation due to the kth wavelength band;
DB_{ik}	is the variation due to the interaction of the ith scene with the kth wavelength band;
CB_{jk}	is the variation due to the interaction of the jth crop type with the kth wavelength band;
DCB_{ijk}	is the variation due to the interaction of the ith scene with the jth crop type and the kth wavelength band; and
$\varepsilon_{(ijk)}$	is the error.

The means shown in Table 6 are the Y_{ijk}. As there is only one observation per cell, the DCB_{ijk} and the $\varepsilon_{(ijk)}$ terms cannot be separated and will be called error in the results of the analysis of variance in Table 7. The F-test for significant difference gives no significant difference for the variation due to crop type (C_j). This is computed by dividing the mean square of C_j by the mean square for DC_{ij}. This gives a calculated F-value (12.5/4.1) of 3.05 with one and three (1,3) degrees of freedom. The tabular F-value for one and three degrees of freedom and at alpha = 0.05 ($F_{1,3,.05}$) is 10.13. Since the calculated

F-value is smaller than the tabular F-value, the variation in spectral response due to crop type is determined to be not significant at a 95% level of confidence. The mean square for DC_{ij} had to be used as the denominator in the F-test instead of the mean square for error because the ERTS-1 scenes must be considered a random variable.

Table 7. Results of analysis of variance for cotton and sorghum.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	Significance of F-test
D_i	3	1048.8	349.6	no test
$\delta_{(i)}$	0	0.0	0.0	
C_j	1	12.5	12.5	no
DC_{ij}	3	12.3	4.1	no
B_k	3	2974.5	991.5	yes
DB_{ik}	9	456.3	50.7	yes
CB_{jk}	3	2.5	0.8	no
error	9	4.8	0.5	
TOTAL	31	4511.5		

All of the results from the Lubbock County test site indicate that cotton and sorghum cannot be identified or delineated using ERTS-1 multispectral imagery and pattern recognition techniques. This is in definite contrast with the results obtained for the Greeley County test site. The explanation may be that the Lubbock area is heterogeneous agriculturally. The fields are not uniform in either size or shape. There is also a broad variety of crop types. Most of the soils have a predominantly reddish-brown color which may dominate the response characteristics of the crops when the ground cover is low. Also, cotton and sorghum are usually planted about the same time and have the same planting practices. Finally, although cotton and sorghum differ morphologically, they have about the same ground coverage while growing and the results suggest that the morphological differences are not great enough to be distinguished from satellite altitudes. The conclusion must be that cotton and sorghum cannot be identified accurately under conditions like those which existed at the Lubbock County test site using current ERTS-1 imagery.

CHAPTER V

SUMMARY

The overall objective of the study was to identify important crop types in a semi-arid climate, using ERTS-1 multispectral imagery and pattern recognition techniques. Greeley County in western Kansas and Lubbock County in the western high-plains region of Texas were the test sites chosen. Wheat, cotton and sorghum were the major crops.

Excellent results were obtained in Greeley County with wheat being identified correctly 97% of the time. The estimate of wheat for the whole county was within 5% of the USDA/SRS estimate. A multivariate regression equation formed for cover types in the county yielded an $r^2 = 0.85$. For a situation similar to that in Greeley County, ERTS-1 multiband imagery appears to be a good tool for identification and area estimation of wheat provided that the multispectral imagery is obtained in late spring.

The results for the more heterogeneous area of Lubbock County did not confirm the hypothesis that crops can be identified using ERTS-1 multispectral imagery. In this study, cotton and sorghum could not be separated from other cultivated crops using ERTS-1 imagery collected during a complete growing season using image dates taken in June, July, August and October. Neither were they spectrally dissimilar enough to be identified as two separate crops. These results are important because they indicate that present ERTS-1 imagery may not be suitable for identifying crops in areas with characteristics similar to Lubbock County.

The results demonstrate the feasibility of using this space-age technology for obtaining crop production information if the crops are spectrally separable. Areas having uniform soils and cropping patterns, and relatively few crops are most likely to meet these conditions. Some knowledge of the land and its cropping patterns is essential for any crop survey, especially if current ERTS-1 imagery is being used. Multispectral satellite imagery currently available does not appear acceptable for identifying cotton and sorghum in areas with extremely mixed cropping patterns and soils. If, however, a sensor with greater spectral and spatial resolution, wavelength bands in the middle and thermal infrared, and greater signal to noise ratio were available, it might be possible to accurately classify crops under these more difficult situations.

LIST OF REFERENCES

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1. Allen, W. A., T. V. Gayle and A. J. Richardson, 1970. "Plant-Canopy Irradiance Specified by the Duntley Equations." Journal of the Optical Society of America, 60:372-376.

2. Anderson, M. C. and O. T. Denmead, 1969. "Short Wave Radiation on Inclined Surfaces in Model Plant Communities." Agronomy Journal, 61:867-872.

3. Anderson, V. L. and R. A. McLean. Design of Experiments. Marcel Dekker, Inc., New York, 1974.

4. Anuta, P. E., 1973. "Geometric Correction of ERTS-1 Digital Multispectral Scanner Data," LARS Information Note 103073, Laboratory for Applications of Remote Sensing, Purdue University, W. Lafayette, Indiana.

5. Anuta, P. E. and R. B. MacDonald, 1971. "Crop Surveys from Multiband Satellite Photography Using Digital Techniques." Remote Sensing of Environment, 2:53-67.

6. Bauer, K. G. and J. A. Dutton, 1962. "Albedo Variations Measured from an Airplane over Several Types of Surface." Journal of Geophysical Research, 67(6):2367-2376.

7. Bauer, M. E. and J. E. Cipra, 1973. "Identification of Agricultural Crops by Computer Processing of ERTS-1 MSS Data." Symposium on Significant Results Obtained from the ERTS-1 Satellite, National Aeronautics and Space Administration, Washington, D.C. Vol. I, Section A:205-212.

8. Belonogova, I. N. and J. S. Tolchelnikov, 1959. Izv. Akad. Nauk. SSSR, Ser. Geol., 11:98.

9. Bowers, S. A. and R. J. Hanks, 1965. "Reflection of Radiant Energy from Soils." Soil Science, 100:130-138.

10. Coulson, K. L., 1966. "Effects of Reflection Properties of Natural Surfaces in Aerial Reconnaissance." Applied Optics, 5(6):905-917.

11. Davis, P. A. In Exploring the Atmosphere's First Mile. H. H. Lettau and B. Davidson Eds., Pergamon Press, Ltd., London, 1957.

12. DeWit, C. T., 1965. Agr. Res. Report 663. Institute of Biological and Chemical Research on Field Crops and Herbage, Wageningen, Netherlands.

13. Draeger, W. C., 1973. "Agricultural Application of ERTS-1 Data." Symposium on Significant Results Obtained from the ERTS-1 Satellite, National Aeronautics and Space Administration, Washington, D.C. Vol. I, Section A:197-204.

14. Draper, N. R., and H. Smith. Applied Regression Analysis. John Wiley and Sons, Inc., New York, 1966.

15. Duncan, W. G., R. S. Loomis, W. A. Williams, and R. Hanau, 1967. "A Model for Simulating Photosynthesis in Plant Communities." Hilgardia, 38(4):181-205.

16. Duntley, S. Q., 1942. "The Optical Properties of Diffusing Materials." Journal of the Optical Society of America, 32(2):61-69.

17. Eisgruber, L. M., 1972. "Potential Benefits of Remote Sensing: Theoretical Framework and an Empirical Estimate," LARS, Information Note 030872, Laboratory for Applications of Remote Sensing, Purdue University, W. Lafayette, Indiana.

18. Gates, D. M., 1964. "Characteristics of Soil and Vegetated Surfaces to Reflected and Emitted Radiation." Proceedings of the Third Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, 573-600.

19. Gunnelson, G., W. D. Dobson, and S. Pamperin, 1972. "Analysis of the Accuracy of USDA Crop Forecasts." American Journal of Agricultural Economics, 54, No. 4, Part I.

20. Hall, F. G., M. E. Bauer and W. A. Malila, 1974. "First Results from Crop Identification Technology Assessment for Remote Sensing (CITARS)." LARS Information Note 041874, The Laboratory for Applications of Remote Sensing, Purdue University, W. Lafayette, Indiana.

21. Hoffer, R. M., 1973. "ADP of Multispectral Scanner Data for Land Use Mapping." LARS Information Note 080372, Laboratory for Applications of Remote Sensing, Purdue University, W. Lafayette, Indiana.

22. Horton, M. L. and J. L. Heilman, 1973. "Crop Identification Using ERTS-1 Imagery." Symposium on Significant Results Obtained from the ERTS-1 Satellite, National Aeronautics and Space Administration, Washington, D.C. Vol. I, Section A:27-33.

23. Johannsen, C. J., 1969. "The Detection of Available Soil Moisture by Remote Sensing Techniques." Ph.D. Thesis, Purdue University, Lafayette, Indiana.

24. Johnson, C. W. and V. B. Coleman, 1973. "Semi-Automatic Crop Inventory from Sequential ERTS-1 Imagery." Symposium on Significant Results Obtained from the ERTS-1 Satellite, National Aeronautics and Space Administration, Washington, D.C. Vol. I, Section A:19-25.

25. Krinov, E. L., 1947. Akademiia Nauk SSSR Lab. Aeromet.

26. Kortum, G., W. Braun and G. Herzog, 1963. Agnew. Chem. 2:333.

27. Kumar, R., 1972. "Radiation from Plants-Reflection and Emission: A Review." Purdue Research Foundation-Research Project No. 5543, Purdue University, W. Lafayette, Indiana.

28. Laboratory for Applications of Remote Sensing. LARSYS User's Manual. T. L. Phillips (editor), Purdue University, W. Lafayette, Indiana, 1974.

29. Laboratory for Applications of Remote Sensing, 1970. "Remote Multispectral Sensing in Agriculture," Annual Report, Vol. 3, Purdue University, W. Lafayette, Indiana.

30. Laboratory for Applications of Remote Sensing, 1971. "Remote Multispectral Sensing in Agriculture." Annual Report, Vol. 4, Research Bulletin 873, Purdue University, W. Lafayette, Indiana.

31. Landgrebe, D. A. and the LARS Staff, 1973. An Evaluation of Machine Processing Techniques of ERTS-1 Data User Applications. LARS Information Note 121373, The Laboratory for Applications of Remote Sensing, Purdue University, W. Lafayette, Indiana.

32. Monteith, J. L., 1965. Expt. Agr. Rev., 1:241.

33. Myers, V. I. and W. A. Allen, 1968. "Electrooptical Remote Sensing Methods as Nondestructive Testing and Measuring Techniques in Agriculture." Applied Optics, 7:1819-1838.

34. Myers, V. I., C. L. Wiegand, M. D. Heilman and J. R. Thomas, 1966. "Remote Sensing in Soil and Water Conservation Research." Proceedings of the Fourth Symposium on Remote Sensing of Environment, University of Michigan Press, Ann Arbor:801-813.

35. NASA Staff. NASA Earth Resources-Technology Satellite Data User's Handbook. Goddard Space Flight Center, Greenbelt, Maryland, 1972.

36. Obukhov, A. I. and D. S. Orlov, 1964. "Spectral Reflectivity of the Major Soil Groups and Possibility of Using Diffuse Reflection in Soil Investigations." Pochvovedeniye. Translation: Soviet Soil Science, 174-184.

37. Orlov, D. S., 1966. Soil Sci., No. 13, Supplement.

38. Robertson, G. W., Agr. Met. Tech. Bull., 4, 1964.

39. Shockley, W. G., S. J. Knight, and E. B. Lipscomb, 1962. "Identifying Soil Parameters with an Infrared Spectrophotometer." Proceedings of the Second Symposium on the Remote Sensing of Environment, University of Michigan Press, Ann Arbor:267-288.

40. Silberstein, L., 1937. Phil. Mag., 4:1291.

41. Steiner, D. and T. Gutermann, 1966. "Russian Data on Spectral Reflectance of Vegetation, Soil and Rock Types." Final Tech. Report, European Research Office, United States Army, Dept. of Geogr., Univ. of Zurich.

42. Swain, P. H., 1972. "Pattern Recognition: A Basis for Remote Sensing Data Analysis." LARS Information Note 111572, Laboratory for Applications of Remote Sensing, Purdue University, W. Lafayette, Indiana.

43. Thomson, F. J., 1973. "Crop Species Recognition and Mensuration in the Sacramento Valley." Symposium on Significant Results Obtained from the ERTS-1 Satellite, National Aeronautics and Space Administration, Washington, D.C. Vol. I, Section A:181-188.

44. Williams, D. L., S. A. Morain, B. Barker and J. C. Coiner, 1973. "Identification of Winter Wheat from ERTS-1 Imagery." Symposium on Significant Results Obtained from the ERTS-1 Satellite, National Aeronautics and Space Administration, Washington, D.C. Vol. I, Section A:11-18.

45. Zwerman, C. H., and A. I. Andrews, 1940. "Relation of Particle Size and Characteristic of Light Reflected from Porcelain Enamel Surfaces." J. Am. Ceram. Soc., 23:93-102.