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A Joint Program for Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing

November 1982

FINAL REPORT

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DEVELOPMENT, IMPLEMENTATION AND EVALUATION OF SATELLITE-AIDED AGRICULTURAL MONITORING SYSTEMS

R. CICONE, E. CRIST, M. METZLER, T. PARRIS

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16. Abstract

This document is a final progress report for FY82 ERIM research activities in support of AgRISTARS Inventory Technology Development Project in the use of aerospace remote sensing for agricultural inventory.

Three task areas are described:

1) Corn and Soybean Crop Spectral/Temporal Signature Characterization
2) Efficient Area Estimation Technology Development
3) Advanced Satellite and Sensor System Definition

Studies include an assessment of alternative green measures from MSS variables, the evaluation of alternative methods for identifying labeling or classification targets in an automatic procedural context, a comparison of MSS, AVHRR and CZCS, as well as a critical assessment of Thematic Mapper dimensionality and spectral structure.

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Final Report

DEVELOPMENT, IMPLEMENTATION AND EVALUATION OF SATELLITE-AIDED AGRICULTURAL MONITORING SYSTEMS

by

R. Cicone, E. Crist, M. Metzler, T. Parris

This report describes results of research performed in support of the Inventory Technology Development Project of the AgRISTARS Program.

Environmental Research Institute of Michigan
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November 1982

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PREFACE

The Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing program, AgRISTARS, is a program of research, development, evaluation and application of aerospace remote sensing for agricultural resources. This program is a cooperative effort of the National Aeronautics and Space Administration (NASA), the U.S. Departments of Agriculture, Commerce, and the Interior and the U.S. Agency for International Development. AgRISTARS consists of eight individual projects.

The research reported herein is sponsored by the Inventory Technology Development (ITD) Project under the auspices of the Earth Resources Applications Division of NASA at the Johnson Space Center. Dr. Jon Erickson is the NASA Manager of the ITD Project and Mr. Lewis Wade is the Technical Coordinator of the reported effort.

Research herein reported in the use of remote sensing for inventory and assessment of agricultural commodities is performed under NASA Contract NAS9-16538 by the Environmental Research Institute of Michigan's Infrared and Optics Division headed by Jack L. Walker, Vice-President of ERIM, under the technical direction of Robert Horvath, Program Manager and Richard Cicone, Technical Director.

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1
INTRODUCTION

This final report describes progress made by the Environmental Research Institute of Michigan (ERIM) in support of the Inventory Technology Development (ITD) Project of AgRISTARS during the period 1 November 1981 to 31 October 1982. Since progress in the first six month period was reported in [1], emphasis in this report is placed on the progress during the second six month period. Reports and publications related to this contract are provided in the Appendix.

The major objective of ITD is to investigate methods for "using space remote sensing technology to provide objective, timely and reliable forecasts of foreign crop production without requiring ground observations" [2]. ERIM's primary focus is on research of technical problems requiring attention in order for ITD to achieve its principle objective.

1.1 TASKS AND OBJECTIVES

The research effort is organized into three tasks:

(1) Corn and Soybean Crop Spectral/Temporal Signature Characterization

(2) Efficient Area Estimation Techniques Development

(3) Advanced Satellite and Sensor System Definition

The first two tasks emphasize use of Landsat Multispectral Scanner, while Task 3 explores other alternatives such as Thematic Mapper and NOAA Advanced Very High Resolution Radiometer (AVHRR).

Task 1 aims at providing the underlying understanding of the spectral and temporal behavior of key crops that would enable crop assessment and identification without the use of ground observations. The objectives of this task include:

- Determine the seasonal and regional variability in the spectral development patterns of corn, soybeans and confusion crops (e.g., sorghum).
- Determine the environmental and cultural factors responsible for that variability.
- Evaluate alternative Landsat features in light of their sensitivity to or robustness against these factors.

In the long term this task would provide basic research in support of methods that would adapt automatic information extraction techniques to local or regional conditions without direct ground observation.

Task 2 explores the potential of automatic information extraction by exploiting that understanding gained in crop signature characterization in an area estimation methodology. Two key objectives in this research are to:

- Develop expert-based methods for automatic extraction of crop area information from Landsat, without the use of ground-based training data, that adapt to local conditions within a targeted region (e.g., U.S. Corn Belt).
- Explore the factors influencing such automatic area information extraction techniques such as target feature determination.

In the long term this task would emphasize methods for automatic extraction of crop area that can adapt to entirely new regions (e.g., foreign countries).

Task 3 is designed to examine the potential of remote sensing alternatives to the Landsat Multispectral Scanner for crop assessment and inventory. The primary objective of this task is to:

- Research crop related information extraction techniques for engineered alternative sensor configurations other than Landsat MSS alone, including the Thematic Mapper, Meteorological Satellites (NOAA-6 and NOAA-7 AVHRR and NIMBUS 7 C7CS) and Radar Systems (SEASAT-SAR).

In the long term this task would point at developing an objective technique for future sensor system definition.

1.2 SUMMARY OF PROGRESS

Substantial progress has been made toward achieving the objectives of the three tasks previously identified.

Efforts in Task 1, Crop Signature Characterization, have included 1) a statistical analysis of corn and soybean field measurement data to evaluate cultural and environmental factors influencing spectral profile patterns, 2) a critical analysis of alternative green measures derived from MSS spectral bands, 3) an assessment of alternative derived features (Tasseled Cap transformation and cylindrical transformation) and the effect of alternative preprocessing techniques like XSTAR haze correction and mean level adjustment. Table 1.1 identifies key accomplishments. Section 2 provides a technical discussion of the highlights of the research.

In Task 2, Efficient Area Estimation Techniques Development, achievements included 1) the development and evaluation of an expert-based automatic corn and soybean area estimation procedure and 2) the evaluation of alternative methods for definition of labeling targets including quasi-field based techniques and dot based techniques (systematic random sample, relocated dots and mixture decomposed dots). Table 1.2 identifies key accomplishments, while Section 3 discusses the technical effort.

TABLE 1.1. TASK 1: CHARACTERIZATION OF CROP SIGNATURES

Accomplishments

- Analyses Based on Field Measurement Data

  + Environmental and cultural factors affecting corn and soybean spectral development patterns were analyzed

    ++ Typical corn and soybean spectral development patterns were formulated, corn exhibiting a Greenness plateau not seen in soybean or small grains

    ++ Key factors analyzed included nitrogen fertilization, planting date, population, variety, row spacing and soil moisture

    ++ The effect of each factor on the typical profile was statistically evaluated

  + The relationship of corn and soybean profile features to crop development stages was established

    ++ Unexpectedly, corn achieved peak Greenness prior to peak LAI, a result explainable by the canopy structure

    ++ Soybean vegetative and reproductive stages were not correlated to profile features, probably due to the indeterminate nature of the plant; unlike corn, canopy closure was found to be the overriding factor

  + Detailed analysis of derived profile features was undertaken

    ++ Profile features are not dependent on date of acquisition

    ++ 100% discrimination of corn and soybeans was achieved using a peak greenness and a plateau feature

  + Analysis of alternative measures of green vegetation was undertaken

    ++ Greenness, Normalized Differences (VI), Transformed Vegetation Index (TVI) and 7/5 ratio were compared

    ++ Greenness provides most linear measure of green development

TABLE 1.1. TASK 1: CHARACTERIZATION OF CROP SIGNATURES (Continued)

Accomplishments

++ VI, TVI provide good indication of a field reaching the green arm, normalize variation along the green arm

++ 7/5 ratio compresses soil variation proving to be useful as an indicator of vegetation, however is sensitive to variation on or near the green arm

- Analysis Based on Landsat Data

  + Digitized ground truth for 16 1980-81 sites in the Argentina Indicator Region and incorporated that data into the RTE (now ADABAS) data base at JSC

  + Compared Tasseled Cap Space (a Cartesian Coordinate System) and Cate Color Space (a Cylindrical Coordinate System)

    ++ The two transformations were compared regarding their response to multitemporal vegetation patterns

    ++ Tasseled Cap captures the majority of temporal variation in two features

    ++ Cate Color Space is sensitive to 'Yellow' and 'None-Such' variability

  + Evaluated Yellow and Nonesuch information content

    ++ Yellow extremely sensitive to haze

    ++ Nonesuch and Yellow sensitive to sensor noise and viewing geometries

    ++ 8-10 count variation (under clear atmosphere conditions) in each feature could not be reliably exploited for crop discrimination though some vegetation/non-vegetation separation found in Nonesuch

TABLE 1.1. TASK 1: CHARACTERIZATION OF CROP SIGNATURES (Continued)

Accomplishments

+ Compared XSTAR, Cate Color and Multiple Acquisition Mean Level Adjustment normalization approaches

  ++ Cate Color provides data normalization only in the presence of a full dispersion of the data and under external effects that are multiplicative in nature

  ++ MAMLA provides a low cost normalization without inherent distortion due to partial data dispersions

  ++ Yellow diagnostic feature (Gamma) used by XSTAR was found strongly responsive to the presence of haze

TABLE 1.2. TASK 2: EFFICIENT AREA ESTIMATION TECHNIQUES DEVELOPMENT

Accomplishments

- Developed Automatic Corn and Soybean Classification Technique Based on 'Classic' Crop Features that are Adapted to Segment Specific Factors (e.g., acquisition history)

  + Technology, employing expert-based hierarchial decision logic, was configured into C/S-1B on LARS 4341 and EODL AS/3000

  + Conducted developmental, shakedown and independent testing

    ++ Accurate estimates (within 2% of actual) of corn, soybean and total summer crop were achieved

    ++ Estimates demonstrated extremely low variation (3 to 5% std. dev.), comparable to analyst based systems

    ++ High processibility achieved (greater than 60%)

    ++ Principle error sources include mixed targets and confusion between 'corn' and 'other' classes

- Conducted an Experiment to Compare Several Different Methods for Defining Labeling Targets

  + Since mixture pixels were found to be targets prone to labeling error, the methods selected addressed this problem

  + A new method based on mixture decomposition technology was developed for the experiment

    ++ Only pure pixels are labeled

    ++ Mixed pixels are assigned mixed labels by spectrally decomposing the pixels into pure component classes and labeling neighboring representatives of these classes

  + In addition to mixture decomposition, methods tested were

    ++ Automatic definition of quasi-fields (mixed pixels are treated as field edges or small fields)

    ++ Detection and deletion of mixed pixels

TABLE 1.2. TASK 2: EFFICIENT AREA ESTIMATION TECHNIQUES DEVELOPMENT (Continued)

Accomplishments

++ Alternate target selection (a detected mixed pixel target is replaced with a neighboring pure pixel)

++ Systematic pixel sampling (wherein mixed pixels are treated as pure pixels)

+ Each of the five techniques was evaluated in five Corn Belt sample segments

++ Detection and deletion demonstrated the greatest bias

++ Each of the methods treating the mixed pixel resulted in higher percent correct classification (PCC)

++ However, the systematic sample demonstrated the lowest bias result, although PCC was lower

++ Off diagonal terms in the performance matrix accounted for this unexpected result

In Task 3, Satellite and Sensor System Definition, three analyses were conducted, each addressing a different sensor system configuration. First was an analysis of the joint use of SEASAT-SAR and Landsat MSS for agricultural inventory. This study examined the potential of a cellular-automata-inspired approach for the extraction of information from radar data which resulted in a breakthrough in technology for the reduction of speckle in radar data, while identifying two features, tone and texture, that were found to relate uniquely to crop cover. The second activity was a comparative analysis of Landsat MSS, Nimbus CZCS and NOAA AVHRR sensors for land use analysis. Each sensor was found to respond comparably to incident radiation from vegetation, suggesting the potential for their joint use to take advantage of their unique spectral, spatial and temporal resolution attributes. Finally, an analysis of Thematic Mapper spectral dimensionality was conducted using both simulation methods and actual TM data from the first TM scene of Detroit, Michigan and vicinity. The analysis uncovered a spectral structure of higher dimensionality than observed by MSS alone, while indicating the preservation of all MSS derived features in a subspace of the TM space. The key accomplishments are presented in Table 1.3. Section 4 presents a summary and technical discussion of the achievements.

The Appendix lists reports and articles (published or to be published) that relate to the efforts of this reporting period.

TABLE 1.3. TASK 3: SATELLITE AND SENSOR SYSTEM DEFINITION

Accomplishments

- Explored the combined use of visible/near-IR range sensor (MSS) and a microwave sensor (SEASAT-SAR) for digital crop inventory

  + A cellular automata approach which preserved field edges was used to remove coherent speckle from the SAR

  + Crop related radar features called tone and texture were found to relate to crop canopy structural features

  + Use of canopy structural features combined with MSS could permit discrimination six weeks prior to what is possible with Landsat alone

- Compared Landsat Multispectral Scanner, NOAA Advanced Very High Resolution Radiometer, and NIMBUS Coastal Zone Color Scanner to Establish Common Features for Multi-satellite Agricultural Information Extraction

  + Established a comparable data base by modeling the sensors' spectral response to experimentally controlled field spectrometer measurements of wheat and soils data

  + Highly correlated features corresponding to vegetative biomass and target albedo are available for land use analysis in MSS, AVHRR and CZCS spaceborne sensors

  + Developed a method to intercalibrate these greenness and brightness features among sensors

  + Determined AVHRR minimizes variations of soils in greenness and therefore may be able to provide earlier detection of crop emergence

  + The use of aggregate features (e.g., density, mean) derived from spectral regions called the 'Soil Arm' and 'Green Arm' were defined for joint or separate use of the sensors for crop or rangeland condition assessment

  + A non-linear transform applied to the two principles direction of variation was found to decouple soil related and vegetation related responses

TABLE 1.3. TASK 3: SATELLITE AND SENSOR SYSTEM DEFINITION (Continued)

Accomplishments

- Conducted Detailed Analyses of the Thematic Mapper Feature Space
  - + Both simulated and actual TM data were used in analyses
  - + TM Bands 2, 3, 4 provide equivalent data space to MSS bands with greater dynamic range, S/N and spatial resolution
  - + Crop and soil data viewed through a uniform atmosphere in six TM bands (excluding thermal) occupy a four-dimensional data space, including Greenness and Brightness-like features
  - + Crops and soils viewed separately occupy primarily a three-dimensional space
  - + In at least one 3-D view of the data space, the planes of crops and soils are not orthogonal
  - + A Yellowness-like haze diagnostic may exist in TM data
  - + Even ignoring thermal band, TM provides at least one more dimension of variation than MSS for vegetative applications

2
CORN AND SOYBEAN CROP SIGNATURE CHARACTERIZATION

2.1 BACKGROUND

A goal of the Inventory Technology Development Project is the development of techniques to be used in conducting crop inventories throughout the world under the constraint that ground observed data is not required. This constraint introduces a complexity to the task of technology development that can be surmounted only through an in-depth understanding of crop phenology and the physics of plant and light interaction as affected by cultural and environmental factors and sensor viewing parameters. With that understanding, extracting features from remotely sensed data that correlate to crop type or condition becomes feasible.

The work described in this section aims at providing the underlying understanding of the spectral and temporal behavior of corn and soybeans that would enable crop assessment and identification without the use of ground observations (Section 2.2). In addition, features derived from MSS for crop assessment and identification are comparatively analyzed. Commonly employed alternative green measures are compared and contrasted in Section 2.3. In Section 2.4 the Tassled Cap and Cate Color Spaces are contrasted and scrutinized in light of preprocessing required to diminish scene variability caused by external effects like varying sun angle and atmospheric haze.

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2.2 CULTURAL AND ENVIRONMENTAL FACTORS INFLUENCING CROP PROFILE DEVELOPMENT

Using field reflectance data collected by LARS as a base, work was completed in the first half of FY82 on analyses whose purposes were to: 1) describe average profiles for corn and soybeans in the Tasseled Cap feature space, 2) determine the effects of particular field conditions and cropping practices on those profiles, 3) determine the association of profile features with stages of plant development, 4) assess the separability of the crop profiles and 5) assess the potential impacts of field conditions and cropping practices on the profile separability. Data preparation, development of analysis techniques, and the initial analyses in 2) were completed in FY81 under a separate contract [3]. Reference [4] summarizes the entire analysis, while references [3] and [5] provide greater details on particular aspects of the work.

Characteristic and distinguishable shapes were found for both corn and soybean profiles. Of particular interest was the plateau feature seen in corn Greenness profiles [3]. Also significant was the fact that those characteristic profiles, though altered substantially, were still detectable under all the experimental treatments evaluated [5].

Evaluation of nitrogen fertilization, planting date and row width effects on soybeans revealed that each of the treatments caused statistically significant changes in at least some of the features of the crop profiles [3,4]. Since the range of levels of each treatment was intended to be representative of the variation typically found in a given region, it can be assumed that significant variations in crop profiles will be encountered in a region. Accurate identification of crop type or condition using remotely-sensed data will have to take such variation into account.

The peak of the Greenness profile of corn was found to be strongly correlated with a particular stage of development (Hanway stage 2.5 to 3.0) [4,5]. This stage occurs prior to expected maximum leaf area index or canopy closure. Probably because of the indeterminate growth habit of many soybean varieties, along with the influence of lodging on Greenness, no association of soybean profile feature and stages of vegetative or reproductive development could be made [4].

The separability of the two crops was maximized by using the peak Greenness profile value and the time period required for the Greenness profile to decline from its peak value to one-half of that value [4]. The separability afforded by the time interval is the result of the corn Greenness profile plateau mentioned earlier. Complete separability was achieved using these two features in this data set. However, both of the features are affected by at least some of the field conditions included as experimental treatments. Thus under certain sets of conditions, separation of the two crops will likely be degraded [4].

2.3 ALTERNATIVE GREEN MEASURES

Since the launch of the first Landsat, many different combinations of the MSS spectral bands have been used for monitoring green vegetation, particularly in agricultural regions. Lautenschlager and Perry [6] have described and evaluated most of these indices and described their interrelationships. This study was undertaken to gain a greater understanding of the behavior of and relationships among some of the most widely used of these "green measures" particularly as they relate to temporal-spectral development patterns. Included in the analysis were Tasseled Cap Greenness [7] (or its reflectance equivalent), the ratio of MSS bands 7 and 5 [8], the Vegetation Index [9] or Normalized Difference and the Transformed

Vegetation Index [9]. Table 2.1 gives the equations used to derive these features.

TABLE 2.1. GREEN MEASURE EQUATIONS

Green Reflectance = -.4580*MSS4 - .6245*MSS5 + .1271*MSS6 + .6198*MSS7

7/5 Ratio = MSS7/MSS5

Vegetation Index = (MSS7-MSS5)/(MSS7+MSS5)

Transformed Vegetation Index = $\sqrt{VI+0.5}$

All of these features primarily measure the contrast between the infrared and red (chlorophyll absorption) bands. Another feature, the ratio of MSS Bands 4 and 5 [10], utilizes the contrast between the green reflectance peak and the chlorophyll absorption dip. This measure was looked at briefly. Several other green measures have been used but were not included in this analysis. These include Perpendicular Vegetation Index [11], the Ir-red difference [12] and Cate's Color Coordinates [13] (which are discussed in Section 2.4).

The data used in the analysis consisted of Landsat-MSS inband reflectance factors collected by LARS over 21 corn plots in two years (1979, 1980) [14]. Figure 2.1 shows the dispersion of the data in MSS bands 5 and 7. It should be noted that for the ratio features, the angular location of the data with regard to the origin is of key importance. Because these data are reflectance factors and not signal counts, there is likely some difference in relative location with respect to the origin. The basic relationships, however, and the interpretation of the features which will be presented, will not be significantly affected by such differences.

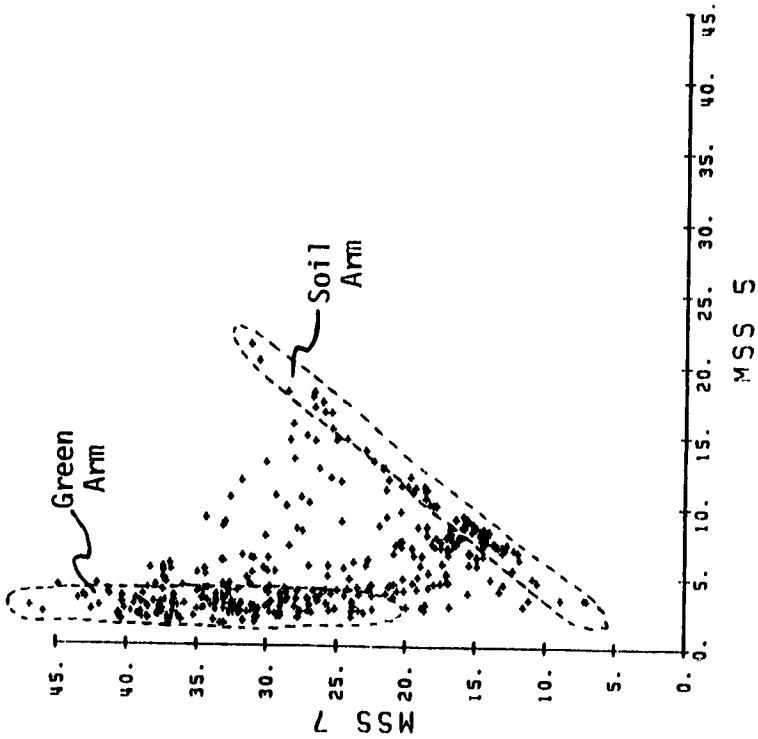

FIGURE 2.2. MSS DATA RELATIONSHIPS

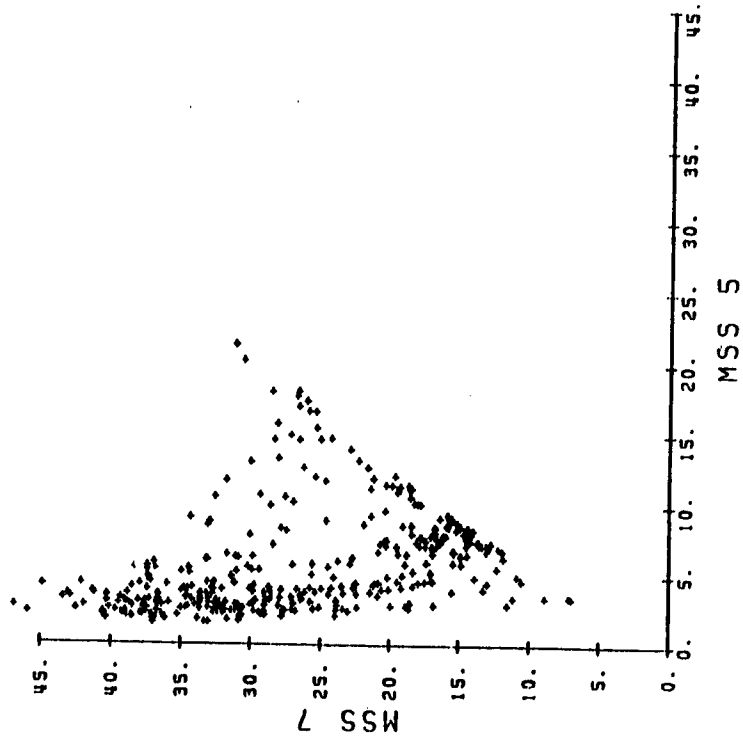

FIGURE 2.1. CORN REFLECTANCE DATA
1979-1980 LARS Plots

General Data Space Description. Experience with Landsat data over agricultural regions has led to the understanding of some basic and stable relationships in the data. Capturing these relationships and maximizing their usefulness are the goals of the Tasseled Cap Transformation. However, for our purposes we will explain them in terms of more widely understood MSS Bands 5 and 7. Figure 2.2 shows some aspects of the Landsat MSS data space. Soils are typically grouped in a narrow band as shown. At the other edge of the distribution is the region known as the green arm, occupied by green vegetation. A typical field of a particular crop will begin on the soil arm and, as the vegetation develops and the vegetation/soil ratio in the field of view increases, move toward the green arm. Once it reaches the green arm, the crop may move along it (toward higher reflectance values) for a time, as the density of the vegetation increases. Then as senescence begins, with brown and yellow vegetation replacing the green vegetation and increasing amounts of soil showing through the canopy, the crop moves back off the green arm toward the soil arm. This pattern of development actually takes place in a two-dimensional plane in the four-dimensional space of the MSS bands. This plane is viewed from a skewed perspective in MSS Bands 5 and 7.

Greenness (Green Reflectance). The Tasseled Cap Transformation, which produces Greenness as one of four linear combinations of the MSS bands, is intended to re-orient the data such that the plane of variation described above is viewed "head-on", i.e., virtually all the data variability is captured in two dimensions. Three important differences between Greenness and the other green measures in this analysis are thus evident: it uses all four bands, it is a linear feature in MSS spectral space, and it measures all the variation that exists in one direction of the data plane. Figure 2.3a shows the data in Figure 2.1, transformed to reflectance equivalents of Tasseled Cap

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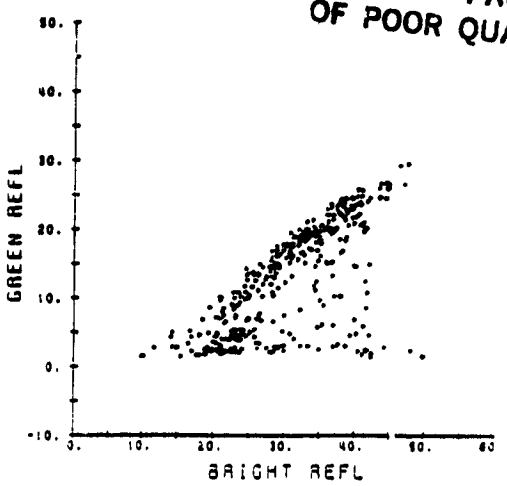
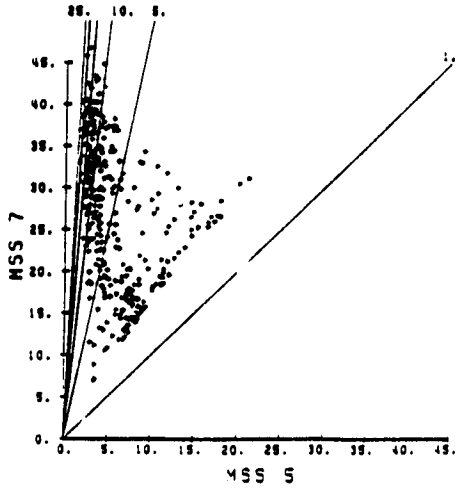
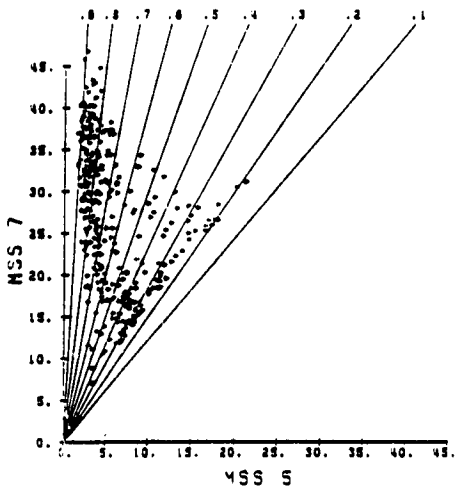


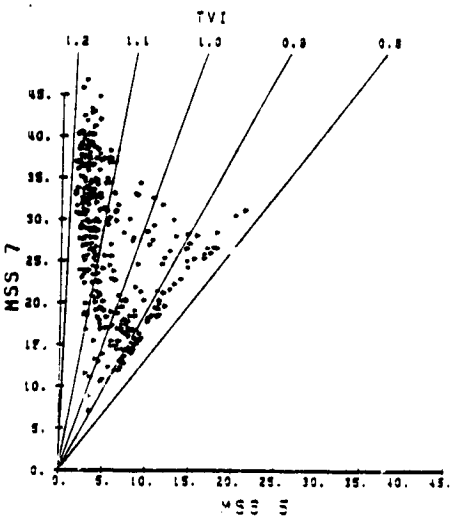
(a) Tasseled Cap Transformation



(b) 7/5 Ratio



(c) Vegetation Index or
Normalized Difference



(d) TVI

FIGURE 2.3. CHARACTERISTICS OF GREEN MEASURES

Greenness and Brightness [4]. Figure 2.4a depicts the same Green Reflectance data plotted against a time variable.

Because it is a linear feature, Greenness does not compress or expand any particular portion of the data relative to original signal values. However, because Greenness is defined to be orthogonal to the direction of principle soil variation, it is insensitive to variations in soil brightness. Greenness does not directly track movement toward or away from the green arm; full description of a field's spectral development, as described earlier, would require both Greenness and Brightness. For the same reason, movement along the Green Arm (the path of development once full canopy cover is achieved) will cause changes in Greenness.

7/5 Ratio. The 7/5 ratio uses only two bands, and as a ratio, is a nonlinear feature (Figure 2.3b). In addition, development toward the green arm is reflected in a nonlinear fashion. Spectral changes of a magnitude which cause a small change in the ratio value near the soil arm will cause sizeable changes in the ratio if they occur near the green arm. This characteristic tends to compress data near the soil arm, and to greatly expand data near the green arm. Figure 2.4b illustrates these effects. Between the soil arm and the green arm, the 7/5 ratio provides a measure of movement toward or away from the green arm. It is largely insensitive to movement along the green arm, since the green arm falls on a line approximately radial from the origin.

Vegetation Index. The Vegetation Index (VI) also uses only two bands. Although it possesses some of the nonlinearities inherent to ratios, the difference in effects of equal changes in reflectance at the soil arm as compared to the green arm is much less (Figures 2.3c and 2.4c). As a result, little compression of data near the soil arm is apparent. However, since the green arm is, as previously stated,

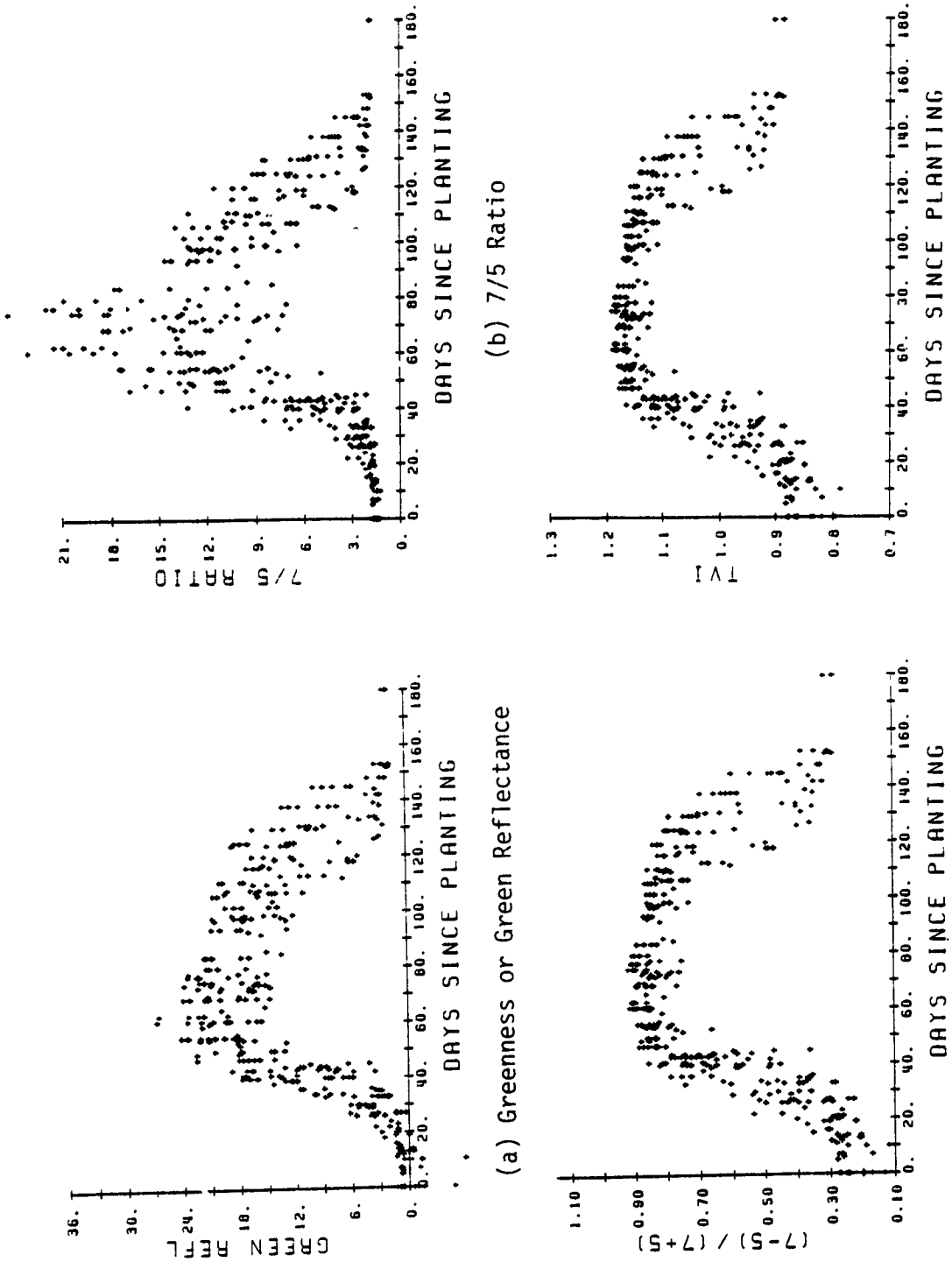


FIGURE 2.4. CHARACTERISTICS OF GREEN MEASURES OVER TIME

essentially radial from the origin, the VI tends to compress data values at or near the green arm. Again like the 7/5 ratio, the VI tracks spectral movement toward or away from the green arm, and is insensitive to movement along the green arm.

Transformed Vegetation Index. The Transformed Vegetation Index (TVI) is essentially the same as the VI in terms of both computation and characteristics (Figures 2.3d and 2.4d). It provides a greater degree of compression of data near the green arm, but is otherwise little different.

Comparison of Green Measures. Clearly the choice of which green measure to use is dependent on the purpose for which it is intended. The linearity of Greenness probably renders it more desirable than the ratios for general purpose applications, but may be disadvantageous in particular applications. For example, if the greatest need is to separate soil data from vegetation data, then the 7/5 ratio may be preferred.

Although all three ratios measure movement toward and away from the green arm, the extreme sensitivity of the 7/5 ratio in that spectral region reduces its utility in determining when the green arm has been reached, and may introduce a substantial amount of superfluous variation in data on the green arm. For detecting when targets are on the green arm, the VI or TVI are probably more useful. Variation along the green arm, which may be related to crop differences or vigor differences within a crop, may or may not be useful information. Where such information is not of value, the ratios would be indicated, while Greenness or a feature which more directly measures location along the green arm (e.g., [15]), should be used if this variation is important.

Since the ratios tend to normalize sun angle differences [16], they may be preferred if other normalization options are unavailable or unattractive. On the other hand, the ratios will probably be more sensitive to haze effects than is Greenness [16].

No one green measure embodies all of the desired attributes. This fact is probably responsible, at least in part, for the proliferation of green measures and spectral transformations that has taken place. However, each has features that make it more or less useful in particular situations. The key is to determine which measure is best for the situation at hand.

2.4 MSS PREPROCESSING AND FEATURE SPACE ANALYSIS

In the previous section, a number of popular measures of green vegetation were compared using field spectrometer data. In this section we analyze two sets of features which include green vegetation indicators as well as other spectral measures, and examine the influence of several preprocessing schemes. The features examined are those derived by the Tasseled Cap Transformation [7] and the Cate Invariant Color Transform [13]. The preprocessing schemes examined are sun angle correction, sensor calibration standardization, XSTAR haze correction, the Cate Color adjustment and multiple acquisition mean level adjustment.

2.4.1 DESCRIPTION OF TRANSFORMS AND PREPROCESSING TECHNIQUES

The Tasseled Cap Transform converts the four Landsat MSS spectral bands into features called Brightness (B), Greenness (G), Yellow (Y) and Nonesuch (N). The transform is given by

$$\bar{t} = A\bar{\ell} + b$$

where

$\bar{t}$ is the resultant vector
$\bar{\ell}$ is the Landsat vector*
b is an offset vector
and
A is an orthogonal matrix identifying the B, G, Y, N transform

This transform is generally employed after $\bar{\ell}$ has been sun angle corrected and sensor calibrated. Brightness has been interpreted to relate to albedo, Greenness to vegetation properties, and Yellowness to atmospheric conditions, while Nonesuch has been ascribed no physical meaning.

The Cate Invariant Color Transform is a non-linear transform based on a modified cylindrical coordinate system. The features, termed Hue (H), Value (V) and Chroma (C), relate to color characteristics of imagery produced by a film generator using MSS Bands 4, 5 and 7. These features are given by

$$V = \frac{1}{\sqrt{3}} c_3$$

$$C = (c_1^2 + c_2^2)^{1/2}$$

*For convenience, column vector notation is assumed for.

$$H = \text{Arctan}\left(\frac{c_2}{c_1}\right)$$

where

$$\bar{c} = (c_1, c_2, c_3)$$
$$= B\bar{\ell}_n \text{ (referred to as the Cate vector)}$$

$$\bar{\ell}_n = D\ell$$

where

$\bar{\ell}$ is the Landsat vector
$\bar{\ell}_n$ is the normalized Landsat vector
B is an orthogonal projection of MSS bands 4, 5, 7 with one axis equal to MSS4 = MSS5 = MSS7 and a second chosen as by Cate (Band 6 is ignored)
D is a diagonal matrix, each diagonal term equal to the inverse of the channel mean

The preprocessing techniques examined included:

(1) Sensor calibration, wherein data were normalized to Landsat 2 LACIE calibration using an affine transformation dependent on the sensor calibration [17].

$$\bar{\ell}_2 = A_i\bar{\ell}_i + b_i$$

where

A_i, b_i define the affine transformation for sensor i

(2) Simple cosine correction which assumes a Lambertian surface response, i.e.,

$$\bar{\ell}_{sL} = \frac{\cos\theta_o}{\cos\theta} * \bar{\ell}$$

where

θ is the sun zenith angle at sensor viewing
θ_o is a reference sun angle, e.g., 39°
$\bar{\ell}$ is the Landsat vector

(3) XSTAR haze correction algorithm, which normalizes data to a standard haze condition based on a simple atmospheric model driven by a diagnostic derived from the Yellow feature:

$$\ell_i' = e^{-\alpha_i \gamma}(\ell_i - x_i^*) + x_i^*$$

where

α_i is a channel correction factor independent of haze

γ is a derived scalar parameter related to the amount of haze in the atmosphere

x_i^* is a haze reference point in spectral space

ℓ_i is the Landsat value for channel i

(4) Cate color normalization based on mean level adjustment

$$\bar{\ell}_{CN} = D\,\bar{\ell}$$

where

D is a diagonal matrix, each diagonal term equal to ℓ_i/μ_i where μ_i is the channel mean

(5) Multiple acquisition mean level adjustment (developed under this subtask)

$$\bar{\ell}_{MAMLA} = D\,\bar{\ell}$$

where

D is a diagonal matrix each term equal to μ'_{ij}

where $'_{ij}$ is the acquisition specific mean derived from the joint density distribution of a set of acquisitions after sun angle and sensor calibration, i.e.,

$$\mu'_{ij} = f^{-1}(\mu_i)$$

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where

μ_i is the joint acquisition scene mean of channel i corrected for sun angle and sensor calibration

f^{-1} is the inverse sun angle, sensor calibration function

Each preprocessing scheme was analyzed in comparison to uncorrected data.

2.4.2 COMPARISON OF THE TRANSFORMS

Given an understanding of the physical interpretation of the Tasseled Cap coordinates, an analysis was conducted to determine the sensitivity of the Invariant Cate Color Transform (H,V,C) to small changes in the Tasseled Cap Transform (ΔB, ΔG, ΔY, ΔN) in order to establish key physical factors influencing H, V and C.

We find that H, V and C are related to ΔB, ΔG, ΔY, ΔN (expressed as Δt_i) as follows:

$$\frac{\partial V}{\partial t_i} = \frac{1}{\sqrt{3}} \alpha_{i3}$$

$$\frac{\partial C}{\partial t_i} = \frac{\alpha_{i1}c_1 + \alpha_{i2}c_2}{(c_1^2 + c_2^2)^{1/2}}$$

$$\frac{\partial H}{\partial t_i} = \frac{\alpha_{i2}c_2 - \alpha_{i1}c_1}{c_1^2 + c_2^2}$$

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where

$\bar{c}$ is the Cate vector and

α_{ij} the linear coefficient that relates $\bar{t}$ and $\bar{c}$

Hence, Value is linearly related to changes in $\bar{t}$, Chroma and Hue are non-linearly related. In order to determine the non-linear relationship between C, H and $\bar{t}$, a Monte Carlo approximation of the sensitivity was carried out.

From

$$\bar{t} = A\bar{\ell} \text{ and } c = BD\,\bar{\ell}$$

we find

$$\bar{t} = AD^{-1}B^{-1}\bar{c}$$

and

$$\bar{c} = BDA^{T}\bar{t}$$

Since H, V and C are functions of the Cate vector $\bar{c}$, we can compute incremental changes in H, V, C due to incremental changes in B, G, Y and N.

Figure 2.5a illustrates the envelope of data representing segment 185/78232, a typical agricultural scene during a crop maturation period. Figure 2.5b is the Tasseled Cap Transform of that scene. Note that Yellow and Nonesuch project in this simulation to a point indicating no relevant information. Four points chosen in the plane as illustrated in Figure 2.5b were perturbed in value by 2 Tasseled Cap counts. Table 2.2 illustrates the effect of this on V, C and H. We find, as expected due to the linear relationship, that Value is

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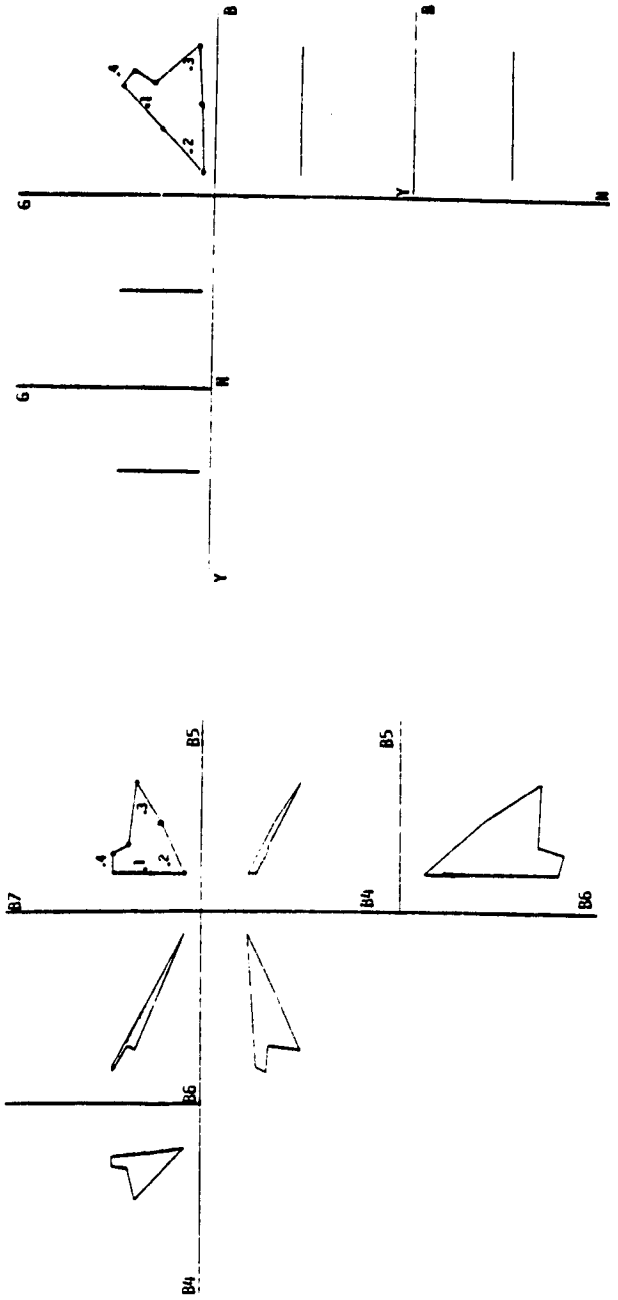

(a) Landsat MSS Representation of Segment 185/78232

(b) Tasseled Cap Representation of Segment 185/78232

FIGURE 2.5. REPRESENTATION OF ACTUAL DATA RANGE FOR TYPICAL AGRICULTURAL SCENES AS VIEWED BY LANDSAT MSS

TABLE 2.2. ILLUSTRATION OF SENSITIVITY OF V, C AND H TO CHANGES IN B, G, Y AND N

		Typical Range of Feature	ΔB = 2 (-40 to +150 (110 counts))	ΔG = 2 (0 to +80 (80 counts))	ΔY = 2 (-5 to -20 (15 counts))	ΔN = 2 (-5 to +5 (10 counts))
1	ΔV	-7 to +7	.17	-.06	-.07	.16
	ΔC	-7 to +7	-.06	.33	.03	.32
	ΔH	-180 to +180	1.29	-.65	-7.07	2.34
2	ΔV		.17	-.06	-.07	.16
	ΔC		.03	-.28	.13	-.34
	ΔH		4.29	-8.69	-17.09	1.59
3	ΔV		.17	-.06	-.07	.16
	ΔC		.08	-.31	.20	-.23
	ΔH		.55	2.21	-5.52	4.61
4	ΔV		.17	-.06	-.07	.16
	ΔC		-.05	.32	.01	.34
	ΔH		.78	-.78	-3.92	.85

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altered as a constant independent of location. Brightness is the dominant influence and hence Value would be expected to be related to albedo. Though Nonesuch also affects Value, typical variation found in Nonesuch is much less, or as in the case of our simulation, nonexistent. Hue is influenced by spectral location. Targets with significant vegetative cover (set 4 in Table 2.2) whose Yellowness may vary would display significantly different Hue. If one can assume that Yellowness is diagnostic of haze, then one would conclude that Hue is not a stable indicator of vegetation in the presence of haze. Chroma appears sensitive to Greenness and Nonesuch fluctuations everywhere in the plane, with little sensitivity to Brightness or Yellow. Hence, Chroma may be a more stable measure of vegetation, though the influence of nonesuch, whose physical interpretation has not been conjectured, is not understood. It is yet to be determined whether the non-linear nature of the Invariant Cate Color Transform provides insight into vegetation targets that cannot be attained through analysis of the more linear Tasseled Cap Features. It is clear, however, that events that affect Yellowness and Nonesuch would have significant impact on these non-linear features.

2.4.3 EFFECTS OF PREPROCESSING

Five methods of preprocessing raw Landsat data were compared to establish their relative effects. The methods are presented in Section 2.4.1 and include 1) sensor calibration, 2) sun angle corrections, 3) spatially varying XSTAR correction, 4) Cate color normalization and 5) multiple acquisition mean level adjustment. Though the 'correctness' of each preprocessing scheme is not conjectured here, the effect of each on the dispersion of original raw data have provided some insight into their relative merit.

Twelve acquisitions of Landsat AgRISTARS scene 127/78 were processed under each scheme. This segment was selected since several agricultural situations were represented (all soil, all vegetation, mixed soil and vegetation) and in addition most dates were very clear. Date 197 showed indications of the presence of spatially varying haze.

Figure 2.6 captures the essence of what was learned (which is the subject of a more detailed forthcoming report). Figure 2.6a is a composite multitemporal scatterplot of Band 7 vs Band 5 for all acquisitions. Data along the diagonal are primarily bare soil, whereas data along Band 7 for which Band 5 values are low would represent varying stages of vegetative development. Figure 2.6b illustrates the joint effect of sun angle and satellite corrections (both Landsat 2 and 3 data sets are represented). Since sun angles ranging between 25^{0} and 55^{0} are represented, one can note that lower signal values (affected by lower solar irradiance at depressed sun angles) are increased radially to represent a normalization to a higher sun angle. The inverse is true for higher sun angles (51^{0} was the normalization angle). Multiple acquisition mean level adjustment resulted in a comparable effect and is not displayed here.

Figure 2.6c illustrates spatially varying XSTAR haze correction. Data along the 'green arm', i.e., that portion of the data structure wherein green vegetation are found are compressed laterally, and some curvature is introduced. The compression is due to the normalization of atmospheric conditions to a fixed condition. Most notable is the compression on day 197, the haziest acquisition, which is identifiable in Figure 2.6a as the data dispersed to the right of the green arm. A favorable interpretation of the curvature may be that the non-linear path of crop spectral development corresponding to vegetation maturation is more trackable. However, this is only speculation.

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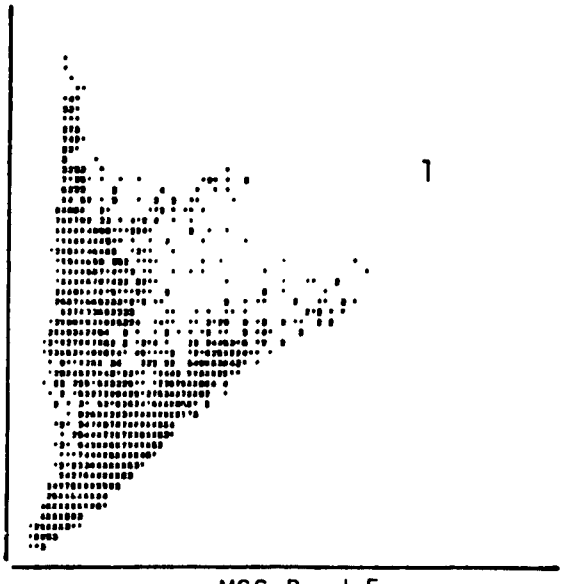
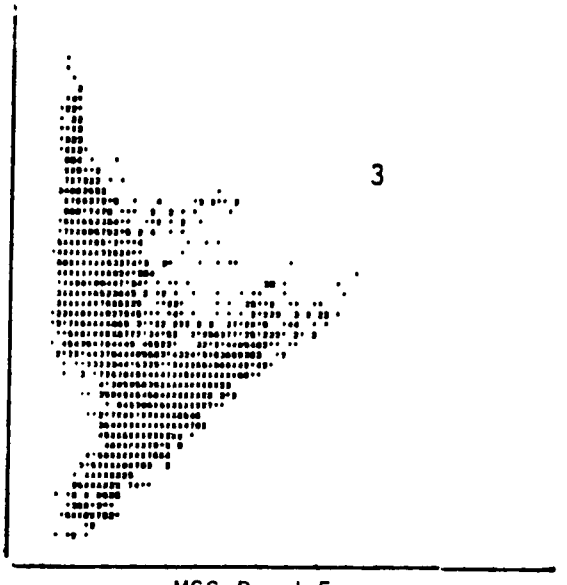


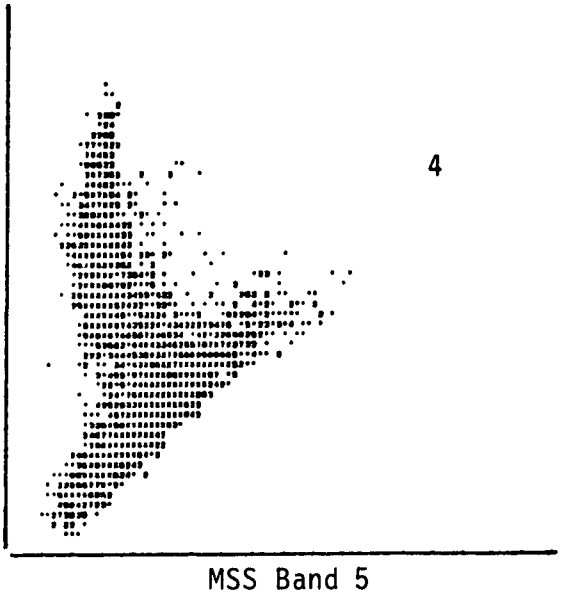
MSS Band 5

(a) Raw Landsat Signal Counts



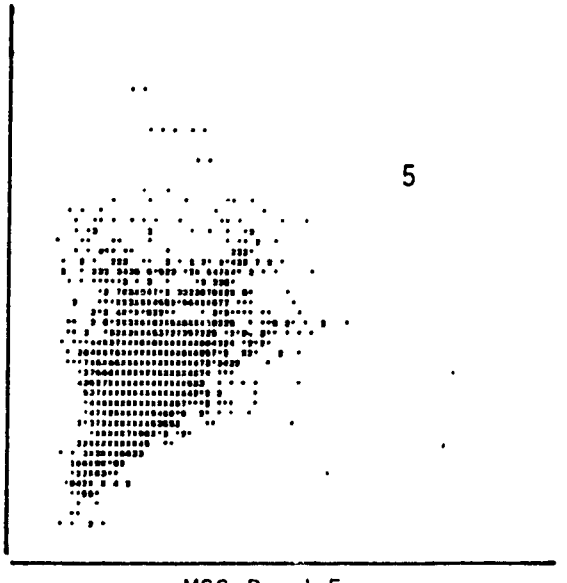
MSS Band 5

(b) Cosine Sun Angle and Satellite Corrections Applied



MSS Band 5

(c) Spatially Varying XSTAR Applied



MSS Band 5

(d) Mean Level Adjustment Applied (Cate Color Adjustment)

FIGURE .6. LANDSAT MSS DATA PREPROCESSING EFFECTS. Segment 127, 1978 - 12 acquisitions plotted (same scale used in all plots).

The Cate Color Normalization, a mean level adjustment approach, is illustated in Figure 2.6d. It is clear that the data is greatly perturbed. The fact that scene content greatly influences the degree of normalization renders this approach a less stable preprocessing.

3
EFFICIENT AREA ESTIMATION TECHNIQUES DEVELOPMENT

As mentioned earlier, a goal of the ITD project is the development of technology to be used in conducting crop inventories throughout the world. For these inventory technologies to be useful, they must be accurate and efficient with respect to time and resources, and must not require ground observed data. Satisfying the goals for efficiency and accuracy has often been a source of conflict, with the most accurate procedures making extensive use of expert analysts, and efficient procedures lacking the flexibility afforded by those human analysts.

Over the years, an understanding of the relationship between agro-physical phenomena pertinent to this problem and their manifestation in Landsat signal space has been developed by ERIM, the University of California at Berkeley Space Sciences Lab, and others. Through this understanding, crop spectral developmental profiles have been utilized in crop identification procedures [18-21]. The work reported in this section describes, first, the development of a corn and soybean area estimation procedure called C/S-1B, which uses this agrophysical understanding to adapt itself to local conditions, and second, an analysis of several techniques designed to provide optimal labeling targets.

3.1 EXPERT-BASED AUTOMATIC CORN AND SOYBEAN AREA ESTIMATION

This section briefly describes work which was completed during the first half of the contract year and reported in detail in the semi-annual report and elsewhere [1]. It is summarized here to provide context for the other work reported in this section.

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In an attempt to obtain the efficiency delivered by an automated procedure and simultaneously gain the flexibility and accuracy associated with an analyst-based procedure, an expert-based, multi-stage corn and soybean labeling procedure was developed. This technique is expert based in that the objective steps which would be followed by an expert analyst in the identification of corn and soybeans were automated, and it is multi-stage in that targets which were progressively more difficult to identify were deferred to later stages which then had a greater knowledge base from which a decision could be drawn.

In this labeling procedure, a target is first examined for "classic" developmental characteristics. Those targets which are "classic" (or easy) are used to form scene specific reference profiles, from which a measure of normal summer crop growing season length is derived. This measure of growing season length is used to eliminate targets which are definitely not summer crops (corn or soybean). The remaining non-labeled targets are classified using the reference profiles developed in the first stage. In this manner, all targets are labeled automatically, with all but the initial, easy, targets using extensive, scene specific information to derive their labels.

This labeling logic was embedded in a quasi-field (BLOB) based area estimation procedure and tested over 22 Landsat segments of 1980 Iowa data. The results are presented in Figures 3.1 and 3.2. Examination of these results reveals a very high accuracy (within 4% relative) and a variance of lesser magnitude than that normally associated with analyst-based procedures. This low variance is an indication of the success the procedure had in performing its self-adaptation to segment specific conditions. Figure 3.2 illustrates that according to test results this procedure achieves a 90% accuracy better than 90% of the time. For example, corn representing 40.76% of thescenes will range in error from about an

overestimate of just over 3 to an underestimate of less than 1 at the 90% confidence level.

3.2 TARGET DEFINITION ANALYSIS

The selection of labeling targets is a critical step in area estimation procedures. Multitemporal Landsat MSS data classification requires dealing with data of two types: that which is spectrally pure (represents a single target class on the ground), and that which is spectrally mixed. Previous work has demonstrated that the classification of those targets designated "pure" is significantly more accurate than the classification of "mixed" targets, i.e., >90% correct classification vs. >75% for "mixed" targets.

Because of this difficulty in classifying mixed targets, numerous techniques have been developed in an attempt to eliminate the necessity of directly classifying them.

Four of these techniques plus a fifth technique which was developed to directly classify the mixed pixels were evaluated. The techniques are as follows:

(1) Systematic Sample: This method, employed by Procedure 1 [22], generally selects labeling targets through the use of a fixed grid, e.g., every fifth line and every fifth pixel. All of the selected pixels are labeled, making scene proportion estimation a simple matter of determining the relative count of each scene class.

(2) Ignore Mixed Pixels: This technique employs some method of stratifying the scene into "pure" and "mixed" pixel strata, then labels only the "pure" targets. The assumption is made that the "pure" targets are representative of the scene as a whole. Procedure M utilized this method of target selection [20].

(3) Spectral/Spatial Clustering: In this method, pixels which are spectrally similar and spatially adjacent are grouped to form field-like entities. The interiors of these fields are then assumed

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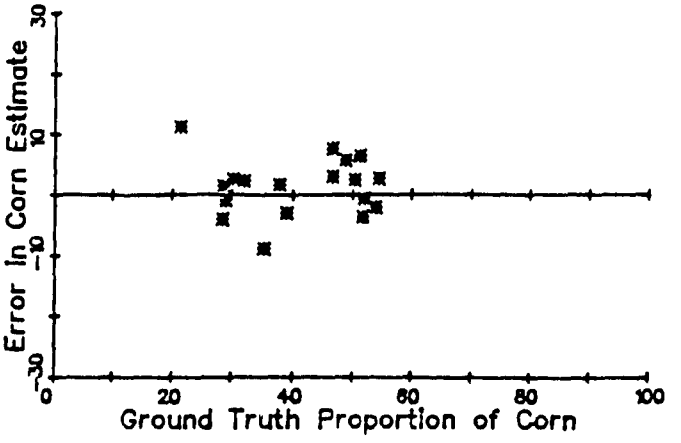
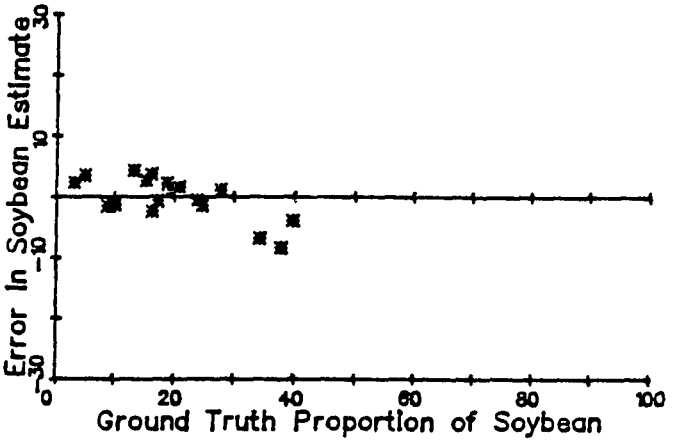
$\bar{e}$	1.51
S_e	4.74
R.M.E.	3.70
M.A.E.	3.87
$\bar{p}$	40.76
n	18



$\bar{e}$	-0.23
S_e	3.52
R.M.E.	-1.17
M.A.E.	2.74
$\bar{p}$	19.52
n	18



$\bar{e}$	0.86
S_e	4.51
R.M.E.	1.47
M.A.E.	3.37
$\bar{p}$	58.42
n	22

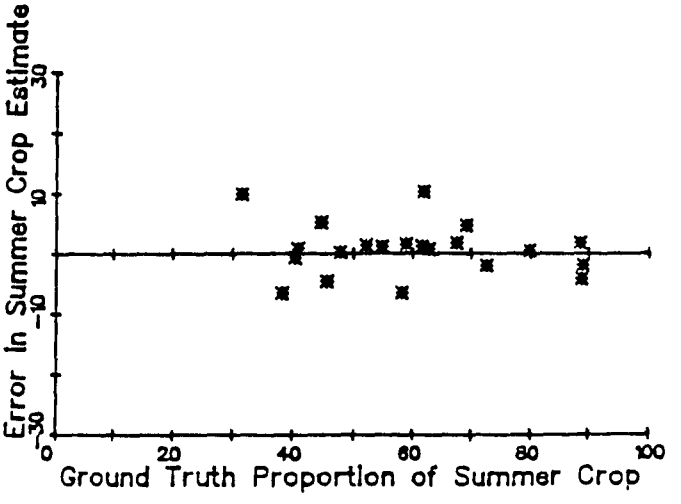


FIGURE 3.1. C/S-1B RESULTS

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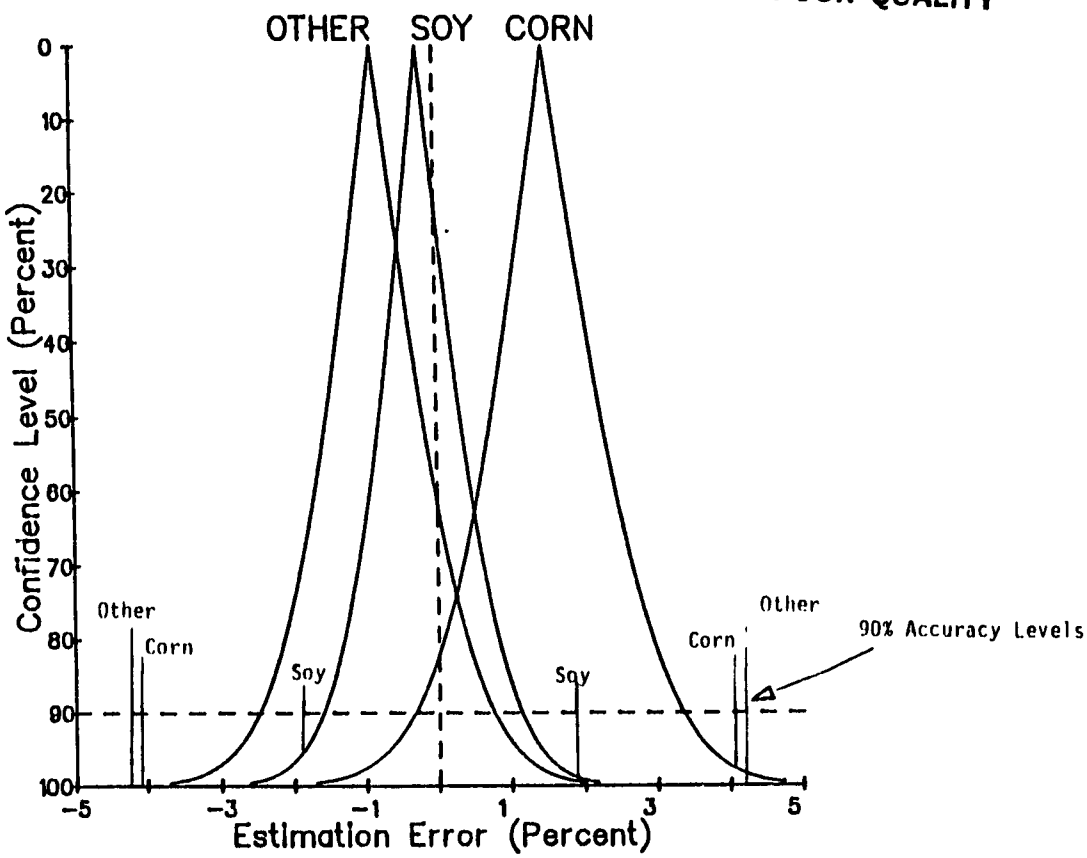

FIGURE 3.2. SIGNIFICANCE OF C/S-1B RESULTS

to be pure, with the mixed pixels assigned to field boundaries, non-fields, or fields without interiors. The BLOB algorithm in the C/S-1 family of procedures and the spatial/color field finder in the MC procedure family fall within this class of target selection mechanisms [23,24].

(4) Alternate Pixel Selection: As in Technique 2, a scene is stratified into "pure" and "mixed" pixels. A systematic sample of pixels is taken as in Technique 1. If a sampled pixel is in the "mixed" stratum, a neighborhood about that pixel is searched to find a "pure" pixel. That "pure" pixel then replaces the original pixel as the labeling target [25].

(5) Mixture Decomposition: Instead of indirectly classifying the mixture pixels as in Techniques 2, 3 and 4, this method attempts to directly estimate the spectral components of the mixed signature. This technique is similar to the fourth method listed in that a systematic sample of pixels is taken, with those pixels stratified into "pure" and "mixed" strata. The treatment of the mixed pixels is the significant difference between this technique and the fourth. Based on understanding of the physical processes involved in causing signatures of neighboring pixels to be mixed, pure pixels within a neighborhood of the mixed pixel are searched to find some set of pure pixel signatures which in some convex combination best represent the signature of the mixed pixel. For the sake of efficiency, it is assumed that at most two pixels contribute to the mixture, i.e., all possible pairwise combinations of pure pixels within the neighborhood are examined. Figures 3.3 and 3.4 describe this mixture decomposition process graphically and analytically.

Procedure C/S-1C was developed to provide a testbed for evaluating these five target selection techniques. Stratification of the scene into "mixed" and "pure" pixel classes was performed by the BLOB algorithm, which also defined the field-like targets used in the third technique listed above. Automatic labeling of the various

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* mixed target pixel $\bar{t}$

• pure pixel with 1σ random noise ball

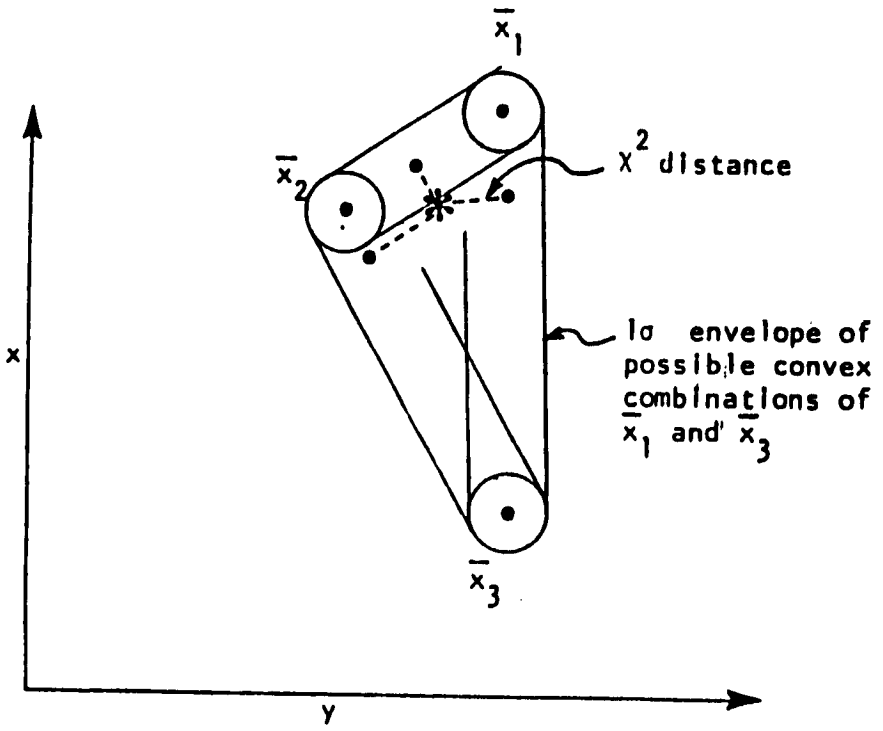

FIGURE 3.3. ILLUSTRATION OF PAIRWISE MIXTURE DECOMPOSITION (IN THIS EXAMPLE THE TARGET PIXEL $\bar{t}$ IS MOST LIKELY, A 50-50 COMBINATION OF $\bar{x}_1$ AND $\bar{x}_2$)

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Let $\bar{t}$ be the mixed target pixel, and $\{\bar{x}_i\}$ a set of n pure pixels in a neighborhood of $\bar{t}$, then under the assumption that $\bar{t}$ is a pairwise mixture from this set, i.e.,

$$\bar{t} = \lambda_{ij}\,\bar{x}_i + (1 - \lambda_{ij})\bar{x}_j \quad \text{for } i \neq j$$

we wish to choose the $\bar{x}_i$ and $\bar{x}_j$ that minimize the χ^2 distance between t and the convex combination of $\bar{x}_i$ and $\bar{x}_j$ as follows:

for each i, j ($i \neq j$) we compute λ_{ij} for $\lambda \in [0,1]$ which minimizes:

$$d(\bar{t}, \lambda\bar{x}_i - (1 - \lambda)\bar{x}_j))$$

where $d(\bar{u}, \bar{v}) = \bar{u}\,R\bar{v}^t$ R the covariance matrix of $\bar{v}$

letting

$$\hat{t}_{ij} = d(\bar{t}, \lambda_{ij}\bar{x}_i - (1 - \lambda_{ij})\bar{x}_j)$$

we choose the i,j pair that minimizes

$$d(\bar{t}, \hat{t}_{ij})$$

letting $L(\bar{x}_i)$ and $L(\bar{x}_j)$ be the labels of the selected pure pixels, then the expression

$$L(\bar{t}) = \lambda_{ij}L(\bar{x}_i) + (1 - \lambda_{ij})L(\bar{x}_j)$$

defines the label of $\bar{t}$.

FIGURE 3.4. ANALYTIC DESCRIPTION OF PAIRWISE DECOMPOSITION OF MIXED PIXEL $\bar{t}$

targets was accomplished with the original labeling procedure of C/S-1B. It should be noted that this analysis was performed prior to minor modifications to the C/S-1B labeling procedure. The modified C/S-1B produced the results reported in the preceding section.

As Procedure C/S-1B provided the basic structure for Procedure C/S-1C itself (data normalization, feature extraction, BLOB, target labeling), the resultant data set from the C/S-1B shakedown testing provided the data base for the evaluation of target definition techniques. This data base consisted of five 5 x 6-mile LACIE segments (ten segment-years) of U.S. Corn Belt data from crop years 1978 and 1979.

In summarizing the results of this evaluation (Figure 3.5), three major conclusions stand out.

(1) All of the techniques which attempted to provide better (more pure) labeling targets produced targets which had a significantly better Percent Correct Classification (PCC) than could be achieved for targets selected by systematic sampling alone.

(2) Selecting only pure targets in the hope that they accurately represent the entire scene leads to significant bias in scene proportion estimation. This bias results from the relationship between quasi-field size and crop class, i.e., non-corn tends to be found in smaller quasi-fields than does corn, and therefore is more likely to be missed when mixed pixels are ignored. This field size distribution bias is less evident in the Great Plains, where BLOB was developed.

(3) Utilizing a systematic sample and forcing the labeling procedure to label all targets resulted in the best crop proportion estimate, even though the PCC for the systematically sampled targets was significantly lower than the PCC for the targets selected by other means. The poorer estimation performance of the procedures which had better PCC's comes from the interaction of the off-diagonal terms of the classification performance matrices with the quasi-field size

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Procedure		Machine Labels: Corn	Machine Labels: Soybean	Machine Labels: Other	Ground Truth Labels: Corn	Ground Truth Labels: Soybean	Ground Truth Labels: Other
Systematic	$\bar{e}$	3.17**	-1.87	-1.31	0.24	0.04	-0.28
Sample	S_e	3.77	4.80	7.20	0.78	0.66	0.65
Ignore	$\bar{e}$	5.77**	-5.01**	-0.76	7.75**	-4.85**	-2.90
Mixed	S_e	1.88	4.49	5.59	4.91	2.75	5.05
Decompose	$\bar{e}$	4.88**	-3.27*	-1.62	1.53**	-0.15	-1.39**
Mixed	S_e	2.70	4.70	6.70	1.37	1.26	0.99
Relocate	$\bar{e}$	---	---	---	1.57**	-1.15**	-0.42
Mixed	S_e	---	---	---	0.80	0.39	0.91
BLOB	$\bar{e}$	3.57	-4.84**	1.26	---	---	---
	S_e	5.46	3.61	8.17	---	---	---

*Indicates bias is significant at 10% level
**Indicates bias is significant at 5% level

FIGURE 3.5. ESTIMATION PERFORMANCE OF PROCEDURE

distribution bias mentioned above. When mixed targets are labeled as in the systematic sample of pixels, the labeling errors tend to offset each other, reducing the overall bias.

Examining individually each of the target definition techniques which attempt to label pure targets and account for mixed pixels as well, we see:

(1) Spatial/Spectral Clustering: BLOB did produce targets which could be labeled with a high PCC as mentioned above. However, in the U.S. Corn Belt there exists a relationship between crop class and quasi-field size. This relationship will inevitably lead to a bias in favor of those crops in the larger quasi-fields.

(2) Alternate Pixel Selection: As labeling targets, the alternate pure pixels were much better than the mixed pixels they replaced. As unbiased estimators of those mixed pixels, however, the pure alternate pixels fared less well, again as a result of the relationship between quasi-field size and crop class.

(3) Mixture Decomposition: This technique also replaced mixed targets with pure ones, and therefore produced better labeling targets. Additionally, each pair of pure pixels and their coefficients did a good job of representing the mixed pixel that was being decomposed. Once again, though, the interaction of this technique with the quasi-fields used to stratify pure and mixed pixels resulted in a degradation of estimation performance from that achieved by systematic sampling alone.

4
SATELLITE AND SENSOR SYSTEM DEFINITION

The Landsat 1-3 multispectral scanner's key spectral, spatial and temporal attributes include two visible and two near IR bands resolved at a nominal 57 x 79 meter optical footprint with an orbit repeat cycle of 18 days. This task explores the potential of other spaceborne sensor spectral, spatial and temporal configurations for agricultural inventory assessment. Section 4.1 briefly summarizes work performed and reported in [1,26] exploring the potential of the microwave region of the energy spectrum for discrimination of corn and soybeans. The potential of augmentation of MSS with sensors having coarser spatial and finer temporal resolution, as represented by the NOAA 6/7 Advanced Very High Resolution Radiometer (AVHRR) and NIMBUS 7 Coastal Zone Color Scanner (CZCS), is presented in Section 4.2. Finally our initial exploration into the spectral and spatial attributes of the Thematic Mapper are described in Section 4.3.

4.1 AUGMENTATION OF LANDSAT MSS DATA WITH SEASAT SAR IMAGERY FOR AGRICULTURAL INVENTORY

The goal of this task was to investigate the technical potential of augmenting Landsat MSS by Synthetic Aperture Radar (SAR), specifically SEASAT SAR, for agricultural inventories. Landsat MSS is a passive sensor which is primarily responsive to surface composition. SEASAT SAR is an active sensor in the microwave region which also responds to surface composition, but is primarily responsive to the structure or geometry of the target. Additionally, different factors of the surface composition drive the response of the two sensors, e.g., chlorophyll absorption with MSS and moisture content with SAR. The joint spectral attributes of these sensors affords an intriguing view of the agricultural scene. This work was

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reported in detail in the semi-annual report [1] and in a technical report [26]. It is briefly summarized here.

SEASAT SAR data collected over Jasper County, Indiana was optically processed, digitized of 6.25m x 8m resolution, resampled to 25m resolution to correct for slant range effects and to reduce speckle via multiple look processing, and registered to Landsat Segment 844 consisting of seven MSS acquisitions. Digital SEASAT radar data was then preprocessed using a non-linear isotropic filter which separated speckle noise without loss of spatial resolution or spectral information as may occur with conventional smoothing algorithms. The process resulted in the creation of two image features dubbed "tone" and "texture". The texture image was in fact the extracted speckle noise and was found to contain information pertinent to crop canopy idenification.

Results of this investigation revealed that the finer spatial resolution of SEASAT provides a better definition of field boundaries. In addition the tone and texture images combined with Landsat data were used to produce an accurate estimate of corn and soybean acreage six weeks prior to when an accurate estimate could be generated using Landsat alone.

4.2 DEVELOPMENT OF COMMON FEATURES FOR MULTI-SATELLITE AGRICULTURAL INFORMATION EXTRACTION

The Landsat Multispectral Scanner has been shown to be a valuable tool for monitoring earth resources through remote sensing. The particular spectral, spatial and temporal characteristics of the instrument have been successfully exploted for crop identification assessment [27] and crop condition assessment [2]. Temporal coverage is of critical importance for crop inventory applications [28]. The application of the technology in areas of frequent cloud cover (e.g., Rio Grande do Sul, Brazil) may require more frequent acquisitions to

assure adequate temporal coverage. The Coastal Zone Color Scanner (CZCS) on NIMBUS 7 and the Advanced Very High Resolution Radiometer (AVHRR) on NOAA 6 and 7 have repeat cycles of six days and one-half day, respectively, compared with 18 days for Landsat 3. Both CZCS and AVHRR systems have sensors in the visible and near infrared regions, the regions utilized in MSS land use investigations. It is the objective of the study described in this section to compare the response of these sensors to soil and vegetation targets in order to develop common features for use in crop inventory and assessment applications. The analysis is currently limited to examining relative spectral attributes of the sensors, though spectral features are proposed that consider the coarse resolution characteristics of AVHRR and CZCS.

4.2.1 THE SENSORS

The four channel AVHRR on board NOAA 6 and five channel AVHRR on NOAA 7 each have two channels in the visible and near IR region. Channel 1 and 2 bandwidths are from 0.55-0.68 μm (50% points) and 0.71-0.98 μm, respectively (see Figure 4.1a). The two satellites are in near polar sun-synchronous orbits at 850 km altitude, with NOAA 6 orbiting south across the equator at 07:30, and NOAA 7 orbiting north across the equator at 14:30. The sensor IFOV is 1.4 milliradians, which translates to 1.1 km ground resolution at nadir. The field of view is $\pm 56^{\circ}$, yielding a swath width of 2700 km. With the satellites each completing 14.1 orbits/day, the wide swath gives an effective repeat coverage every 1/2 day [29]. NOAA 6 is no longer operating.

The NIMBUS 7 CZCS is a six channel radiometer with an IFOV of 0.825 km at nadir. The bandwidths of the five visible and near-IR channels are 0.43-0.45 μm, 0.51-0.53 μm, 0.54-0.56 μm, 0.66-0.68 μm and 0.70-0.80 μm (see Figure 4.1b). Each of the first four channels has a separate gain which is normally determined by the sun elevation

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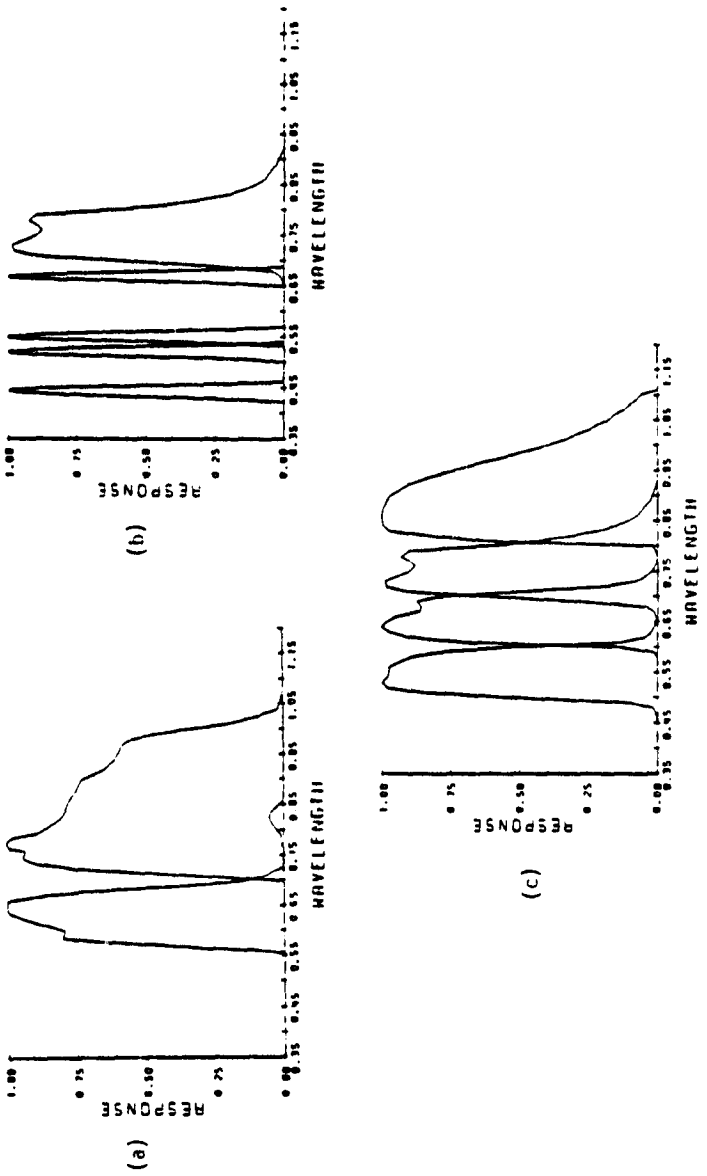

FIGURE 4.1. SENSOR SPECTRAL RESPONSE FUNCTIONS. NOAA AVHRR utilizes a visible band located in the green-red portion of the spectrum and at near IR band (a). Nimbus CZCS utilizes 5 narrower bands in the visible/IR region. The fifth band is identical to Landsat MSS Band 6 (b). Landsat MSS utilizes two visible and two near IR bands (c).

angle. However, these gains may be set by command to accommodate special conditions. The gain of channel 5 is fixed to give the same response over land targets as channel 6 of Landsat MSS. As the first four channels are designed for sensing water conditions, they may saturate over most land targets. NIMBUS 7 follows a sun-synchronous, near polar orbit at 955 km, has a swath width of 1566 km, and provides repeat coverage of a given target every six days. Overflight occurs approximately at local noon [30].

Landsat's MSS is a four channel sensor with bandwidths of 0.50-0.60 μm, 0.60-0.70 μm, 0.70-0.80 μm and 0.80-1.10 μm (see Figure 4.1c). These channels (labeled 4 through 7, respectively) have an IFOV of 80 m and a swath width of 185 km. Landsat's sun-synchronous, near polar orbit at 955 km gives repeat coverage every 18 days, occurring at approximately 9:30 local time [31].

Key sensor characteristics are summarily presented in Table 4.1.

4.2.2. EXPERIMENT DESIGN

Previous work has demonstrated the correlation between the difference of AVHRR channels 2 and 1 and the difference of MSS channels 7 and 5 [32]. Other studies have shown that most of the variation of MSS data for typical vegetation scenes lies within a plane called the Greenness-Brightness plane [16]. To investigate whether a comparable phenomenon occurs with the CZCS or AVHRR scanners and to compute green measures, a simulated data set was constructed and used. Spectral reflectance measurements in the visible and near-IR region for various targets of interest were available through the Laboratory for Applications of Remote Sensing LARSPEC data base. Employing the nominal spectral response functions for each sensor along with the Turner radiation transfer model [33], inherent inband radiances were computed by:

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TABLE 4.1. CHARACTERISTICS OF AVHRR, CZCS, MSS, and TM SENSORS

	AVHRR		CZCS	MSS		
	NOAA 6	NOAA 7	NIMBUS 7	Landsat 1-3	Landsat 4	TM
# Bands (Reflective)	4 (2)	4 (2)	6 (5)	4 (4)	4 (4)	7 (6)
Orbit Altitude	850 km	850 km	955 km	920 km	705 km	705 km
Equator Crossing	7:30	14:30	12:00	9:30	9:30	9:30
Nadir Ground Resolution	1100 m	1100 m	825 m	79 m	83 m	30 m
Swath Width	2700 km	2700 km	1566 km	185 km	185 km	185 km
Field of View	$\pm 56^0$	$+56^0$	$\pm 39^0$	$\pm 5.5^0$	$\pm 7^0$	$\pm 7^0$
Repeat Coverage*	1/2 day	1/2 day	6 days	18 days	16 days	16 days

*AVHRR repeat coverage may be at wide view angle differences

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$$L_{i,j,k} = \frac{1}{\pi} \int_{\lambda_1}^{\lambda_2} E(\lambda)\rho_i(\lambda)R_{jk}(\lambda)d\lambda$$

where

$L_{i,j,k}$ is the inherent radiance for target i and channel j of sensor k

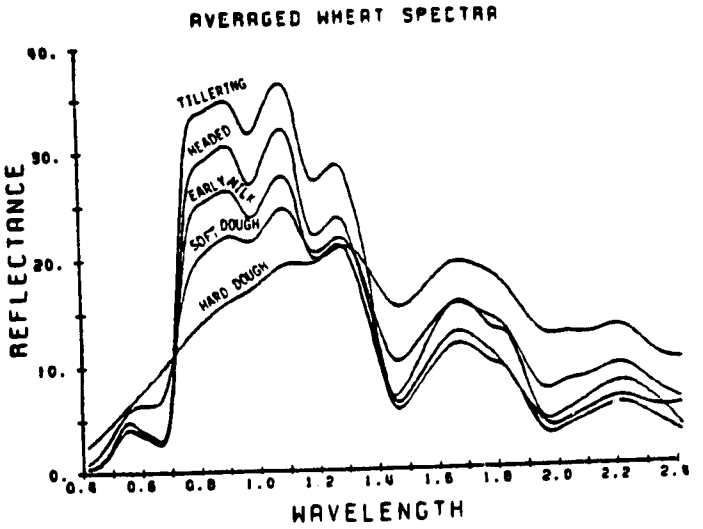
$E(\lambda)$ is the global spectral solar irradiance

$\rho(\lambda)$ is the global spectral reflectance the target

$R(\lambda)$ is the channel spectral response function

Transmittance of the atmosphere, path radiance and sensor dynamic range and absolute signal calibration were not simulated. However, global incident solar irradiance was modified according to solar time of sensor overpass for an August time of year. Variations in a canopy's reflectance due to bidirectional effects at different solar zenith angles were not available for this simulation. CZCS Band 1 (.43-.45 μm) was not simulated due to the unavailability of reflectance data.

For purposes of simulation, the scene was considered to consist of soils from throughout the continental U.S., and wheat at all stages of development and at various stages of nitrogen fertilization or disease. Figure 4.2 illustrates typical wheat and soil reflectances used in this study. This simulation does not represent a 'real' scene, however it enables the simultaneous examination of a variety of factors influencing the detection of radiation by remote sensors. Over 500 soil reflectance samples (LARS soil experiment 78100701) [34] and close to 400 measurements of 30 wheat plots (experiment 79100806) [35], under experimental control for disease and nitrogen fertilization effects are included in this analysis.



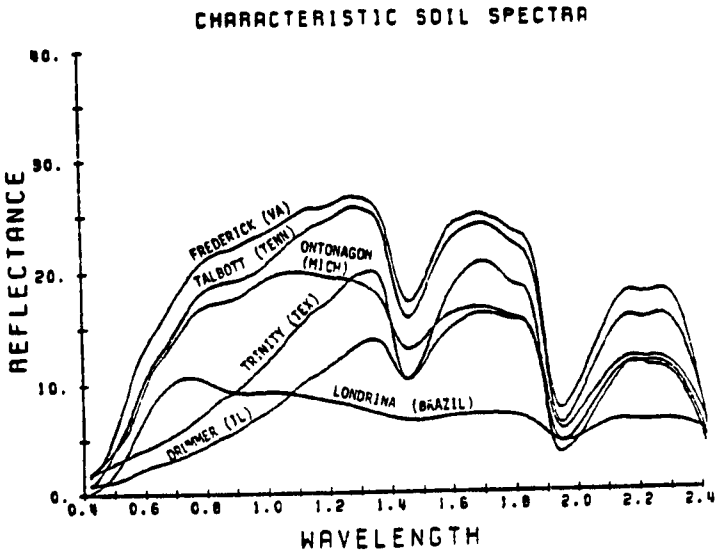


FIGURE 4.2. SIMULATION DATA BASE

4.2.3 ANALYSIS

The primary method of analysis carried out was based on the Tasseled Cap Transformation as a frame of reference for comparison of sensor response. The Tasseled Cap [7] is an invariant linear transformation of the four MSS band values which has been shown to capture the vast majority of the spectral variation of typical agricultural scenes in two dimensions. In addition, the derived features are easily interpretable in terms of physical phenomena. The first Tasseled Cap variable, called Brightness, corresponds to spectral variations in the MSS spectral domain that relate to soil Brightness or target albedo. The second variable, called Greenness, is aligned in the spectral direction of principle variation associated with the amount of green biomass present in the scene. Greenness is a measure of contrast between the infrared and visible channels. These two variables typically represent more than 95% of the total variability in an agricultural scene. The third variable, called Yellow, has been found to correspond to external effects like haze and sun angle as well as scene features like soil or rock color and water. Yellow is a contrast between the visible bands. The fourth variable, Nonesuch, is a measure of contrast between infrared bands and has been observed to contain little significant information.

In this analysis, Tasseled Cap-like features were computed for each sensor in a manner comparable to that employed in determining the Tasseled Cap for actual Landsat MSS. A principal component analysis of the soil data was carried out and the first principal component was chosen to be the direction of soil brightness. A greenness feature was derived by selecting a vigorous sample of green vegetation and determining a perpendicular from that target to the direction of soil brightness. For MSS and CZCS, yellow was established by determining an orthogonal component to Greenness and Brightness that emphasized contrast in the visible bands. Greenness and Brightness were of

primary concern in the analysis. Figure 4.3 illustrates the approach for AVHRR. The data scattered along channel 2 shall be referred to as the 'Green Arm' and that scattered in the direction of soils as the 'Soil Arm'.

Figures 4.4a, 4.4b and 4.4c demonstrate the resulting Greenness/Brightness transformation of each sensor. The remarkably comparable visual appearance is borne out in statistical analysis. For MSS, as expected, 98.5% of the scene variation was found to reside in the principal plane. This transformation was of course simply a rotation of the two AVHRR bands. Ninety-five percent of the variation of CZCS response in channels 2 to 5 was represented in the Greenness/Brightness plane, with a yellow feature explaining the remainder. More significantly, both Greenness and Brightness measures were strongly related when compared between sensors. A linear relationship was sufficient to achieve an R^2 greater than .99 in all cases. Figure 4.5 illustrates the strong relationship between MSS Greenness and AVHRR Greenness. These findings indicate that the sensor on the whole can be expected to respond to incident radiation from vegetated scenes in a comparable fashion. This suggests, at least conceptually, the applicability of technology developed for MSS spectral analysis to AVHRR and CZCS, with appropriate recalibration. Note, however, in comparing the three sensors that the variation in soils in the green feature increases with decrease in spectral resolution, indicating NOAA/AVHRR to be least sensitive to soil effects in this direction. The fact that AVHRR is least sensitive to soil variation in the greenness direction in fact implies greater sensitivity to detection of emergence of vegetation.

A number of green measures are routinely employed in land use analysis. Four are compared here for AVHRR: greenness, EVI (Environmental Vegetative Index), the greenness ratio and normalized difference. EVI is calculated as the difference of the two AVHRR bands (in this case normalized in scale). The greenness ratio is the

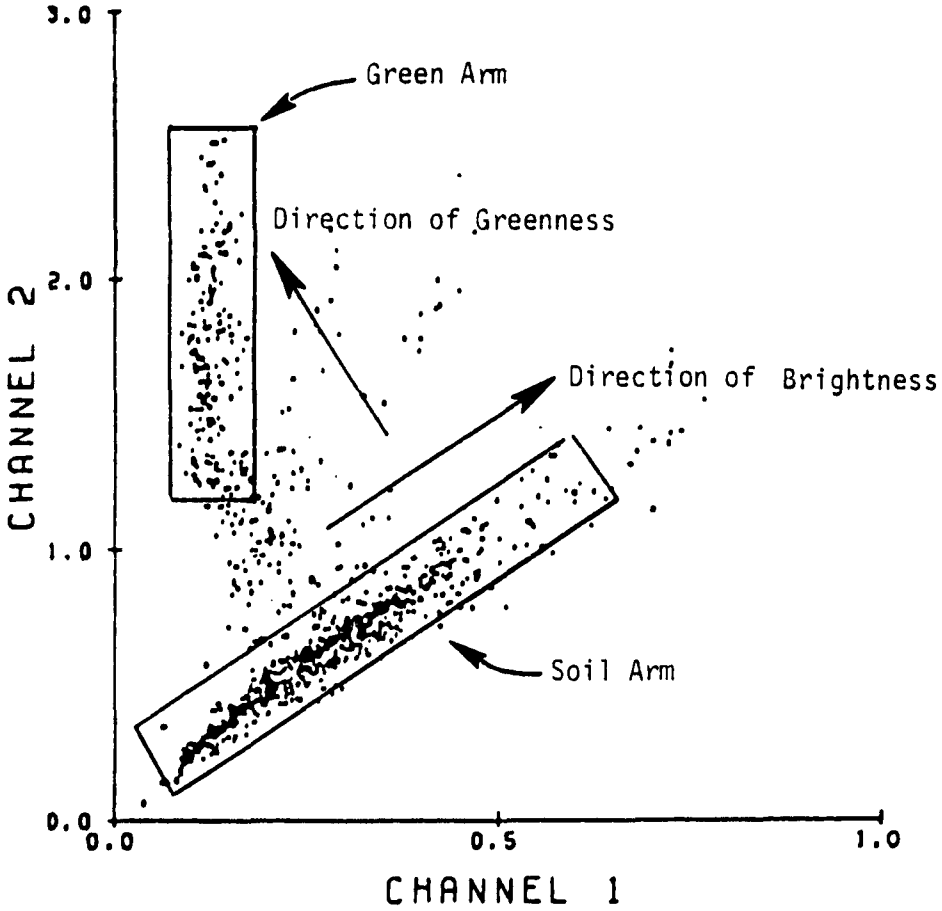


FIGURE 4.3. AVHRR CHANNEL 2 VS. CHANNEL 1. The Green Arm and Soil Arm portions of AVHRR response are delineated. Tasseled Cap Greenness and Brightness are identified. Note that Greenness is not orthogonal to the direction of principle variation in the Green Arm.

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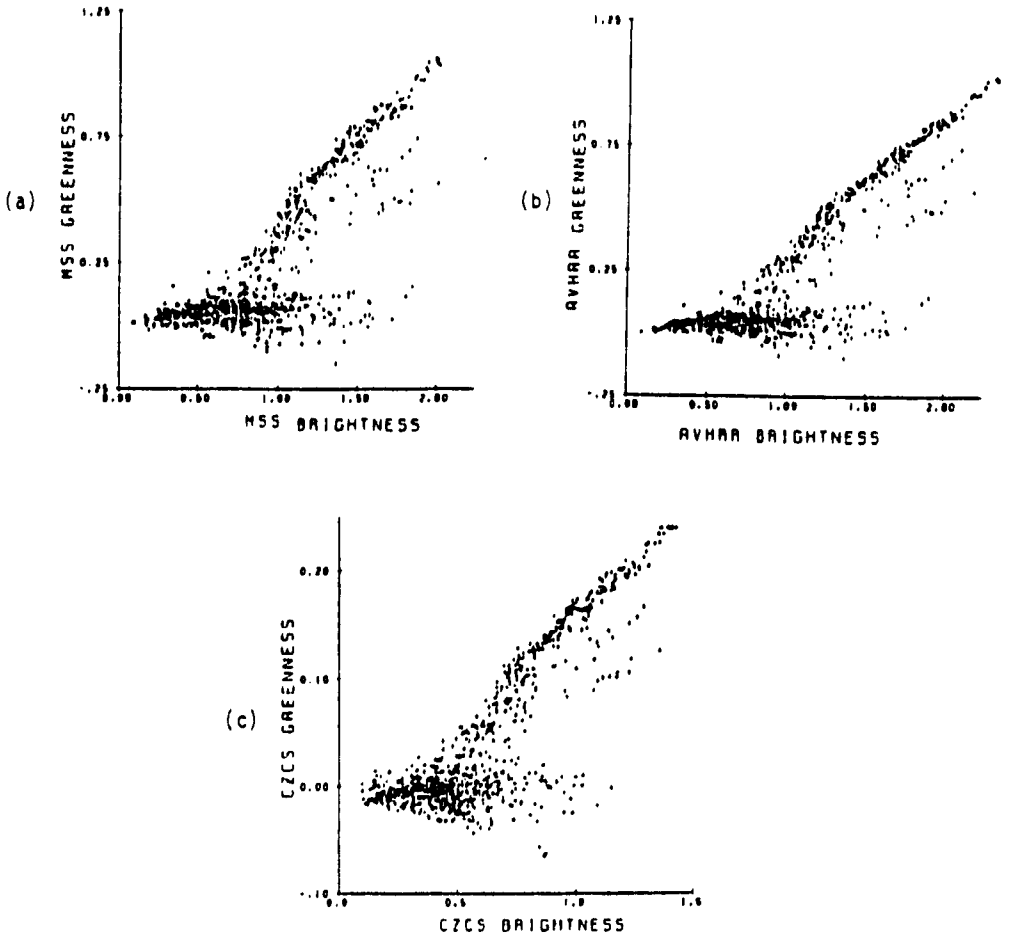

FIGURE 4.4. GREENNESS VS. BRIGHTNESS OF MSS (a), AVHRR (b), and CZCS (c) shows the comparability of the data structures among sensors. Note that the variation in the Greenness direction of the Soil Arm increases with increased spectral resolution.

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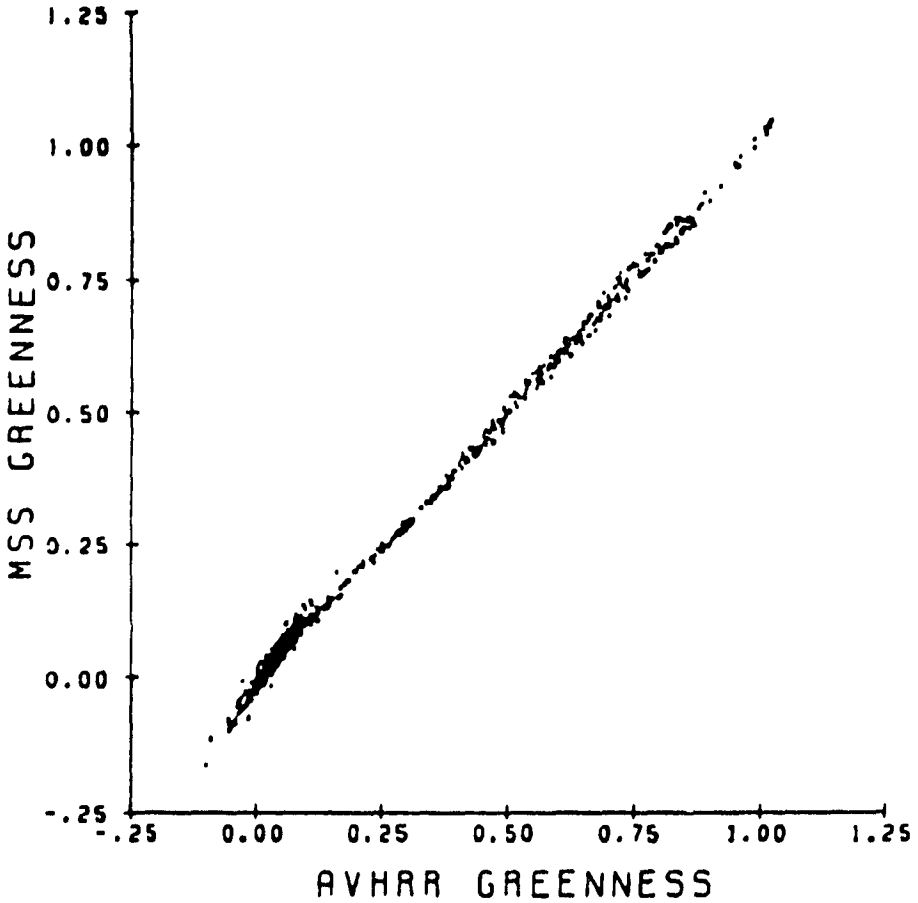

FIGURE 4.5. MSS GREENNESS VS. AVHRR GREENNESS. The essentially linear response between MSS and AVHRR response to vegetation resulted in an $R^2 > .99$ at the .05 level. Response to soil variation in Greenness differed slightly in slope and intercept.

quotient of the second and first bands (again normalized). Figures 4.6a, 4.6b and 4.6c illustrate each feature as compared to Tasseled Cap Greenness. EVI is most similar to Greenness, as they are both differences. EVI, however, is sensitive to soil brightness. Hence sparsely vegetated canopies would be indistinguishable from bright soils. The greenness ratio is sensitive to small changes in Brightness for vegetative targets spectrally on the green arm with equal greenness. Normalized difference is insensitive to changes along the green arm and in fact saturates relative to the Greenness measure.

4.2.4 DISCUSSION

The comparability of AVHRR, MSS and CZCS, illustrated by this analysis through simulation of a vegetated scene, points to promise for the joint or interchangeable application of these sensors while using common features for monitoring land conditions. The application of AVHRR and CZCS sensors for land use analysis is certainly desirable on the basis of both repetitive coverage and data volume. However, certain key limitations in this simulation must be kept in mind. Certain parameters of observation have not, as of this writing, been modeled, particularly bidirectional reflectance, atmospheric conditions and absolute sensor calibration and dynamic range. Any one of these may introduce non-linearities in the perceived linear relationship among sensor spectral features, especially the automatic gain control employed in CZCS. Saturation over land targets has been detected as a problem for CZCS, whose primary application is hydrological exploration.

A most significant difference is the effect of disparate resolution sizes of the sensors. CZCS and AVHRR with 825 m and 1100 m resolution respectively do not favorably compare to MSS at 79 m resolution. Certainly the application of CZCS and AVHRR for crop

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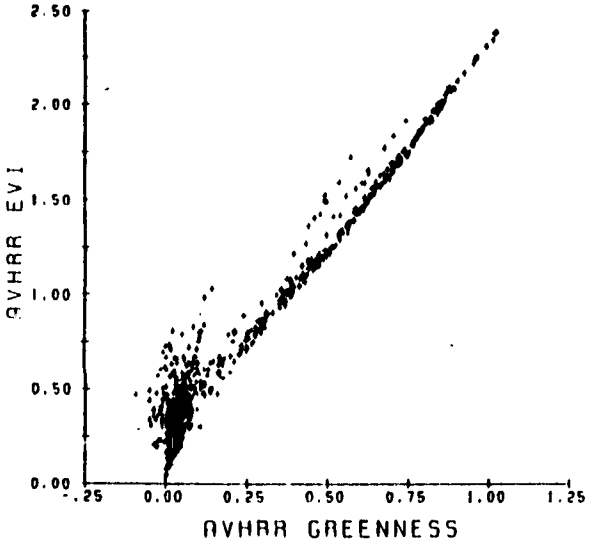
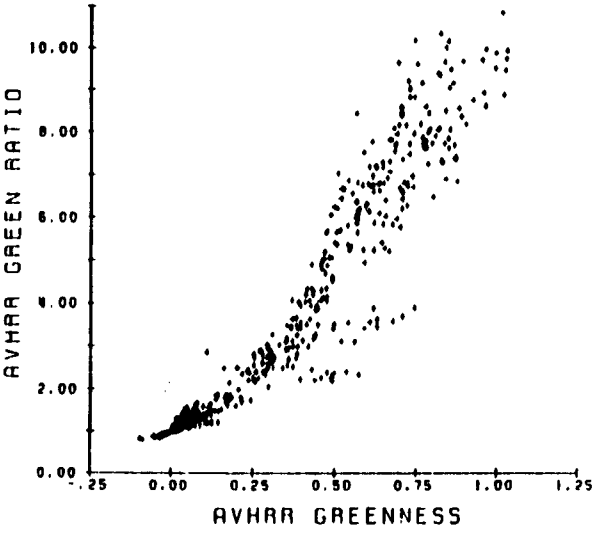
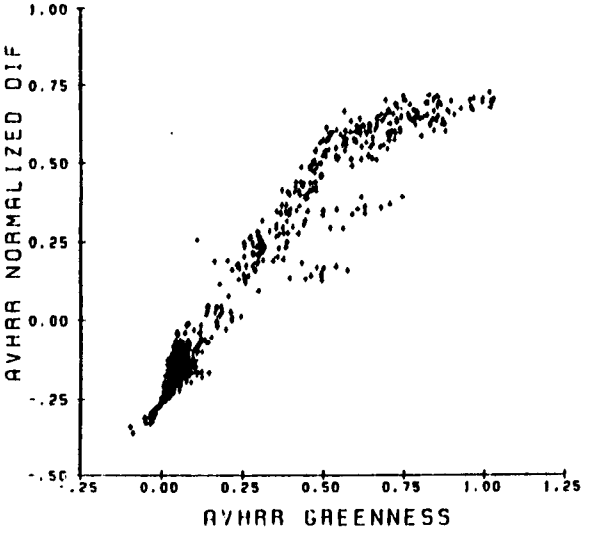


(a) AVHRR EVI vs. Greenness



(b) AVHRR Green Ratio vs. Greenness



(c) AVHRR Normalized Difference vs. Greenness

FIGURE 4.6. COMPARISON OF AVHRR GREEN MEASURES

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identification would be ill-advised. However, the potential of these sensors for assessment of overall crop condition on a large area basis may exceed that of Landsat due to favorable temporal and data volume attributes. The simulation analysis suggests a method that would enable the use of common features between sensors for condition assessment.

Examining Figures 4.4a through 4.4c, note that the density of measurements along the soil arm and green arm would be a comparable feature among sensors. Figure 4.7 illustrates a method of decoupling Greenness and Brightness so that the axes represented relate primarily to the presence or absence of green vegetation or soil. These features referred to as soil (s) and vegetation (v) are derived as follows:

$$v = ||(b,g)||\sin\theta_F = ||p||\sin\theta_F$$

$$s = ||p||\cos\theta_F$$

where

$$\theta_F = 90 * \frac{\theta_I}{\Delta\theta}$$

$$\theta_I = \text{Arc cos } \frac{\bar{p}\cdot\bar{j}}{||\bar{p}||}$$

$$\Delta\theta = \text{Arcos } (\bar{u}\cdot\bar{v})$$

for

$\bar{p}$ the greenness/brightness vector
$\bar{u}$ a unit vector in the direction of the soil arm
$\bar{v}$ a unit vector in the direction of the green arm

It is suggested that the stratification of this feature space into zones, as illustrated in Figure 4.7, and computation of multitemporal features of scene density and magnitude by zone would apply to large area assessment of crop condition and determination of cultural events like crop emergence or harvest.

4.2.5 CONCLUSIONS

AVHRR, MSS and CZCS, three operating civilian remote sensing systems with spectral responses in the visible and infrared regions of the energy spectrum, are found to respond comparably to incident radiation from typical agricultural targets simulated using field reflectance measurements. A methodology based on the Tasseled Cap transform can be used to intercalibrate common features. The principal variation in the signals of the three sensors is found to reside in two dimensions that are highly correlated between sensors. These dimensions, called Greenness and Brightness, are related to green vegetative biomass and target albedo. It is conjectured that there is potential for the joint or interchangeable application of these sensors, using common features, for crop condition assessment or the detection of agronomic cultural events. The multitemporal stratification of the data from each sensor according to two features that partially decouple spectral response to soil related and green vegetation related phenomena is proposed. Future work to establish practical intercalibration coefficients and develop methods for joint use of the sensors so as to exploit advantages of each is recommended.

4.3 THEMATIC MAPPER DIMENSIONALITY ANALYSIS

Experience with the four bands of Landsat MSS, particularly in agricultural regions, has shown that the data do not fill the entire four-dimensional space defined by the four bands. The high

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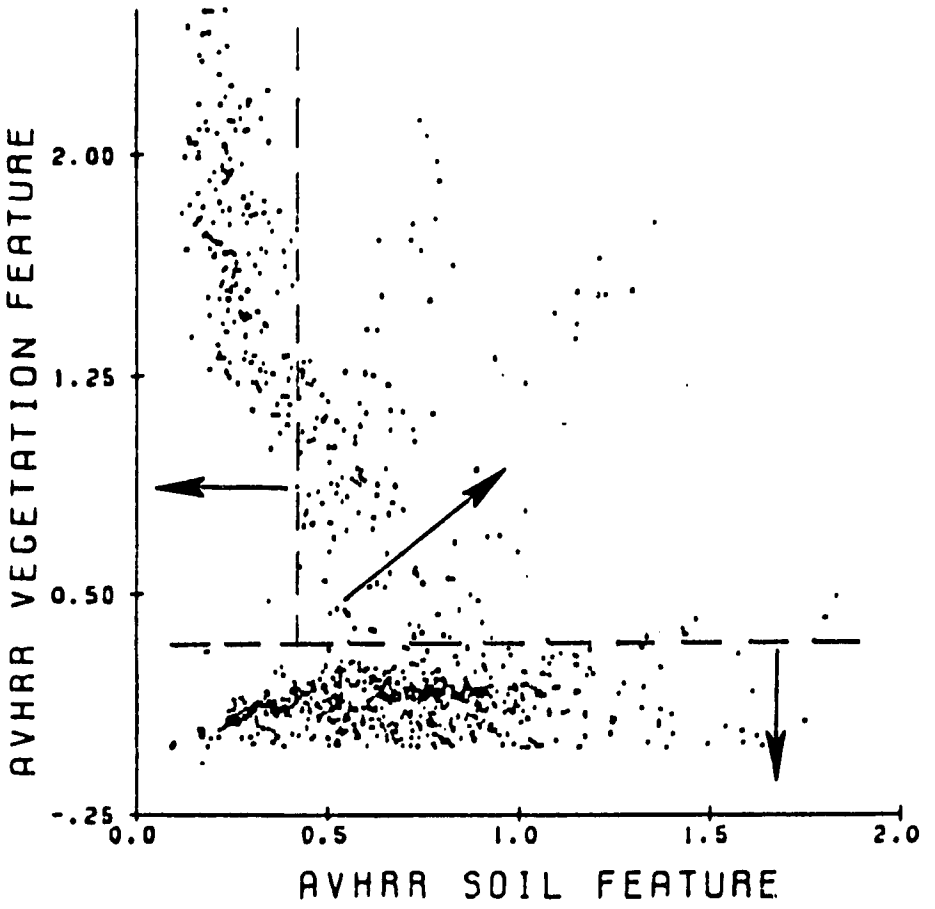

FIGURE 4.7. AVHRR VEGETATION FEATURE VS. AVHRR SOIL FEATURE. Green Arm and Soil Arm responses are statistically decoupled to provide two directions that are essentially 'informationally' orthogonal. Strata are superimposed to identify bare soils, vegetation with high percent cover, and emerging, senescing or mixed ground covers.

correlations between Bands 4 and 5 (the visible bands) and Bands 6 and 7 (the near-infrared bands) cause the vast majority of data from agricultural regions to occupy a two-dimensional plane. The Tasseled Cap transformation [7] developed at ERIM rotates the raw MSS bands to obtain a "head-on" view of that data plane, and extracts features which can be readily interpreted in terms of the physical characteristics of the target. This transformation has proven to be extremely useful both in terms of dimensionality reduction and interpretation of observed events.

Early simulation studies, using limited data sets, have suggested that similar correlations exist among the bands of the Thematic Mapper [36,37]. Thus the potential for reducing dimensionality and enhancing interpretability may exist for the Thematic Mapper as well. The need for a Tasseled-Cap-like transformation is probably even greater for the TM than for the MSS, since the TM has more bands covering a broader region of the spectrum.

The work reported herein was undertaken for the purpose of understanding, or beginning to understand, the dimensionality of TM data, and the effects on those data of variations in target characteristics.

4.3.1 SENSOR CHARACTERISTICS

Figure 4.8 illustrates the pre-launch composite detector response functions for the six bands of the TM (excluding the thermal band in the 10.4-12.5 μm region) [38]. Three of the six bands fall in spectral regions unsampled by the MSS: 0.45-0.52 μm (TM Band 1), 1.55-1.75 μm (TM Band 5) and 2.08-2.35 μm (TM Band 7). As seen in Figure 4.9, the other three TM bands are roughly equivalent to the MSS bands. This equivalency will be discussed in a later section.

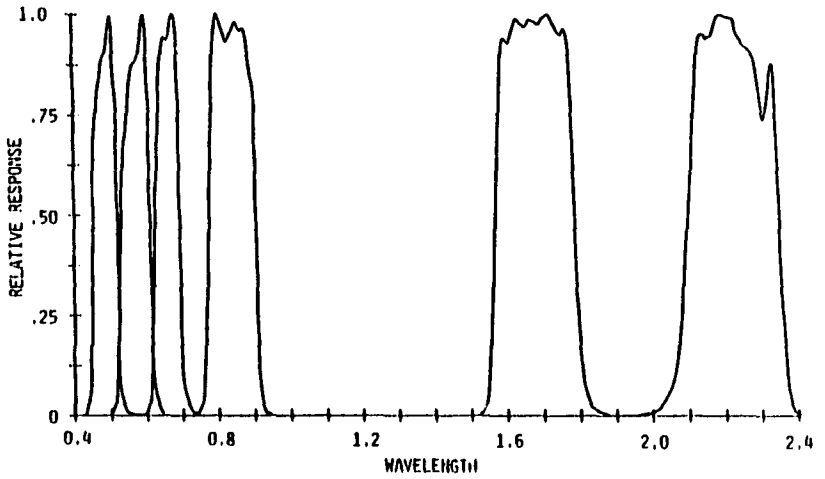

FIGURE 4.8. THEMATIC MAPPER PRE-LAUNCH COMPOSITE DETECTOR RESPONSE FUNCTIONS

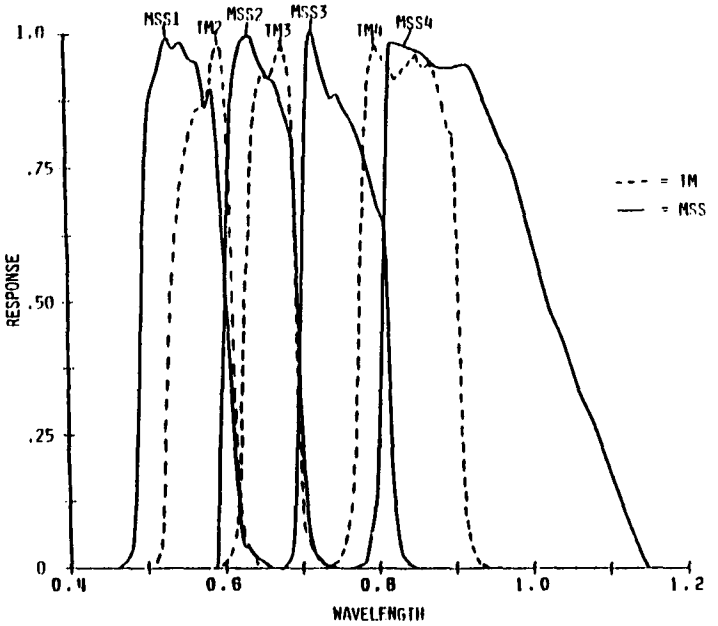

FIGURE 4.9. COMPARISON OF MSS AND TM RESPONSE FUNCTIONS

In addition to the new spectral coverage, the Thematic Mapper provides improvements over the MSS in terms of signal-to-noise ratio, dynamic range and spatial resolution. However, only the increased spectral coverage, and to a lesser extent the enhanced dynamic range, were evaluated in this analysis.

4.3.2 SIMULATION

Although Landsat-4 is now fully operational, it will be some time before a quantity of data exists which 1) includes crops at all stages of development and 2) has accompanying ground information registered to the spectral data. In the interim, simulation provides the best means of analyzing the characteristics of TM data. In addition, simulation allows confounding factors such as variations in atmospheric conditions, influences from surrounding pixels and surrounding fields, and differences in resolution to be removed from evaluation of sensor characteristics or comparison of different sensors. Finally, the level of control and measurement of plot characteristics found in simulation cannot be duplicated on any large scale with real data.

In this analysis, spectroradiometer data collected by and at Purdue/LARS for NASA [14] were used to simulate TM data. Inband reflectance factors were determined using the composite detector response functions illustrated in Figure 4.8. Data produced by the Dave atmospheric model [39] were used to convert the reflectance factors to top-of-atmosphere radiances, simulating a very clear and perfectly uniform atmosphere. Finally, pre-launch calibration data [40] were used to convert the radiances to sensor signal counts. A similar process was used to derive simulated Landsat-4 MSS signal counts for the same field spectra, allowing direct comparison of sensor spectral characteristics.

The final data set was comprised of reflectance factors, radiances and signal counts for corn, soybeans and winter wheat spanning the 1978-1980 growing seasons, and for soil samples collected throughout the U.S. A total of 1640 vegetated spectra and 636 soil spectra were included. Along with the spectral data, a variety of target descriptors were recorded by LARS personnel. These included, for some of the spectra, plant moisture content, percent cover, percent green, brown and yellow leaves, nutritional status, etc., for vegetation data and series, particle size distribution, parent material, minerology, organic matter content, etc., for soils data.

4.3.3 COMPARISON OF MSS AND TM BANDS

Band-by-band correlations were computed between the TM signal counts and the MSS signal counts, with results described in Table 4.2. Very strong correlations were apparent between MSS Bands 4, 5 and 7 and TM Bands 2, 3 and 4, respectively. These correlations are also clearly evident in Figure 4.10. Also evident in this figure is the increased dynamic range of the TM. The TM counts cover a much wider range than do the MSS counts simulated from exactly the same spectra.

4.3.4 THREE-BAND TM DATA SPACE

Using the four bands of the MSS and the equivalent three bands (2, 3 and 4) of the TM, principal components were defined and rotated to produce Greenness and Brightness features. The results are shown in Figure 4.11. Figure 4.12 shows the strong correlations ($R^2 \geq .99$) between the MSS and TM Features. These results suggest that the three bands of the TM provide all or nearly all the information available in the four MSS bands. The greater narrowness of the TM Bands, the greater dynamic range (clearly seen in Figures 4.11 and 4.12), and improved signal-to-noise ratio may result in the three TM bands

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TABLE 4.2. MSS AND TM BAND CORRELATIONS
(Simulated Signal Counts)

MSS						
1	.93	.99	.94	-.01	.79	.78
2	.91	.96	.99	-.22	.74	.78
3	-.01	.21	-.03	.97	.15	-.09
4	-.15	.02	-.21	.99	.05	-.20
TM	1	2	3	4	5	7

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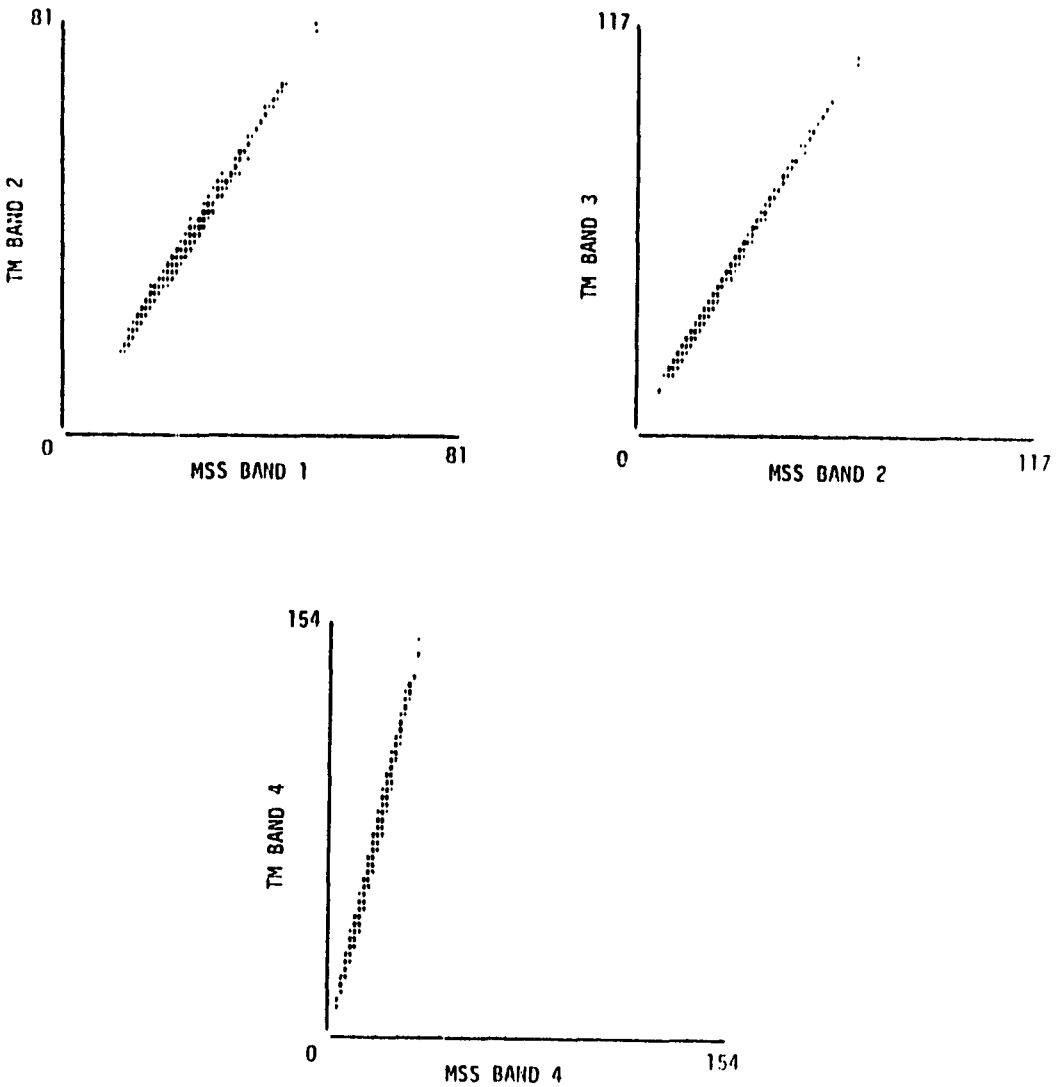

FIGURE 4.10. CORRELATIONS OF MSS AND TM BANDS
(Simulated Counts)

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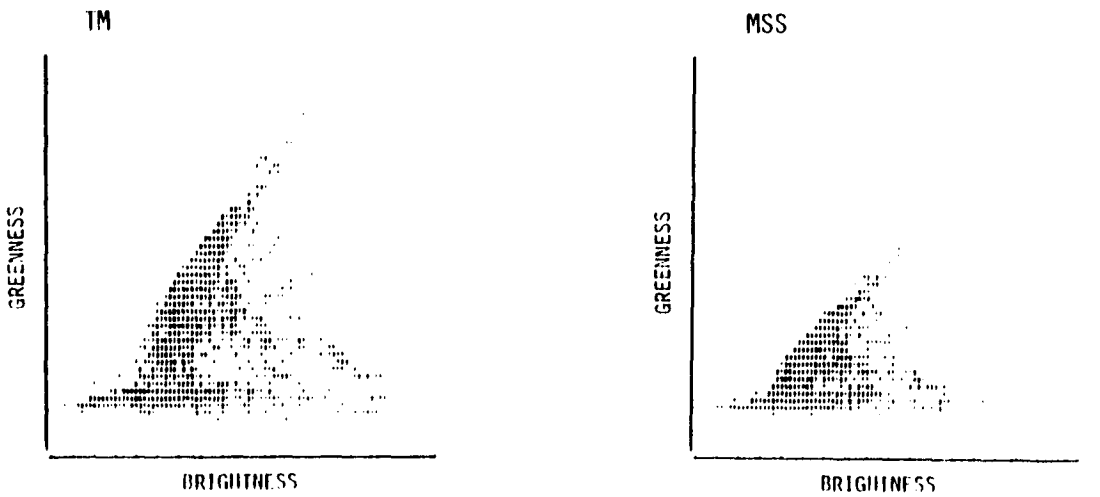

FIGURE 4.11. MSS AND 3-BAND TM TASSELED CAP SPACE

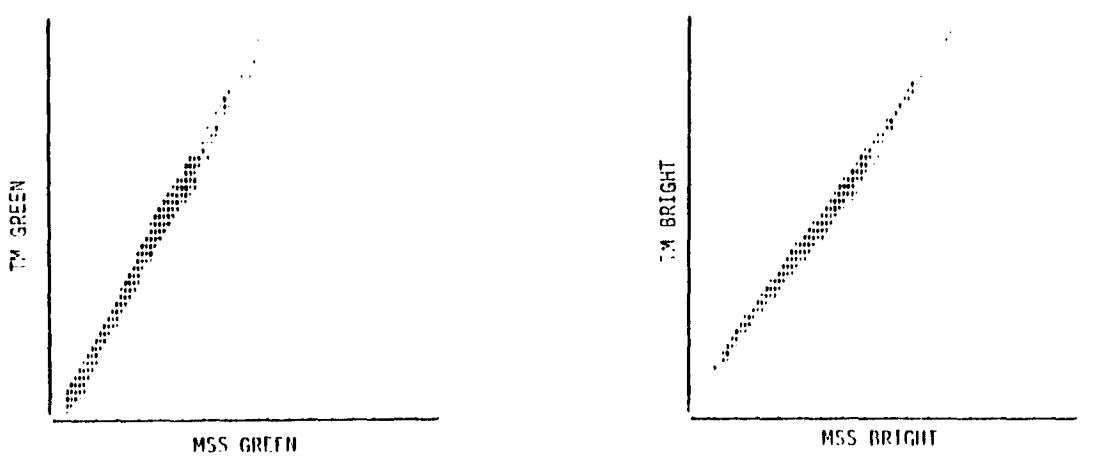

FIGURE 4.12. COMPARISON OF MSS AND 3-BAND TM TASSELED CAP FEATURES

actually providing more information in some circumstances. In addition, there may be situations in which important information exists in the 0.9-1.1 μm spectral region sampled by MSS Band 7 but unsampled by the TM. Nevertheless, in most agricultural situations, it appears that TM Bands 2, 3 and 4 provide at least the information available in the MSS, and as such could be used with little adjustment in data analysis approaches designed for MSS data.

4.3.5 SIX-BAND TM ANALYSIS

The most important spectral feature of the TM is not its ability to duplicate the MSS, but the new information potentially carried in the additional bands in the blue and mid-IR regions. Accordingly, a six-band analysis (excluding the thermal band) was carried out using the same field spectra converted to simulated signal counts. Principal component analysis served as a starting point for the analysis. Once the components were identified, rotations of the data, three dimensions at a time, were used to find and align the planes into which the data were actually dispersed. Figure 4.13 illustrates the differences between the principal components and the planes of data dispersion. With linear rotations of three components, all the orthogonalities of the system are preserved, so that the final result is still six perpendicular directions.

Figure 4.14 provides a stylized description of the primary relationships discovered in the six-band TM data. Most of the samples of pure vegetation (high percent cover) fall in one plane, while most of the soil samples fall in a second plane perpendicular to the first in between are samples of partial vegetative cover. A typical field would start somewhere in the plane of soils, move through the transition zone, reach the plane of vegetation, perhaps move up that plane (away from the plane of soils), then move down the plane of vegetation toward the plane of soils. The coefficients required to

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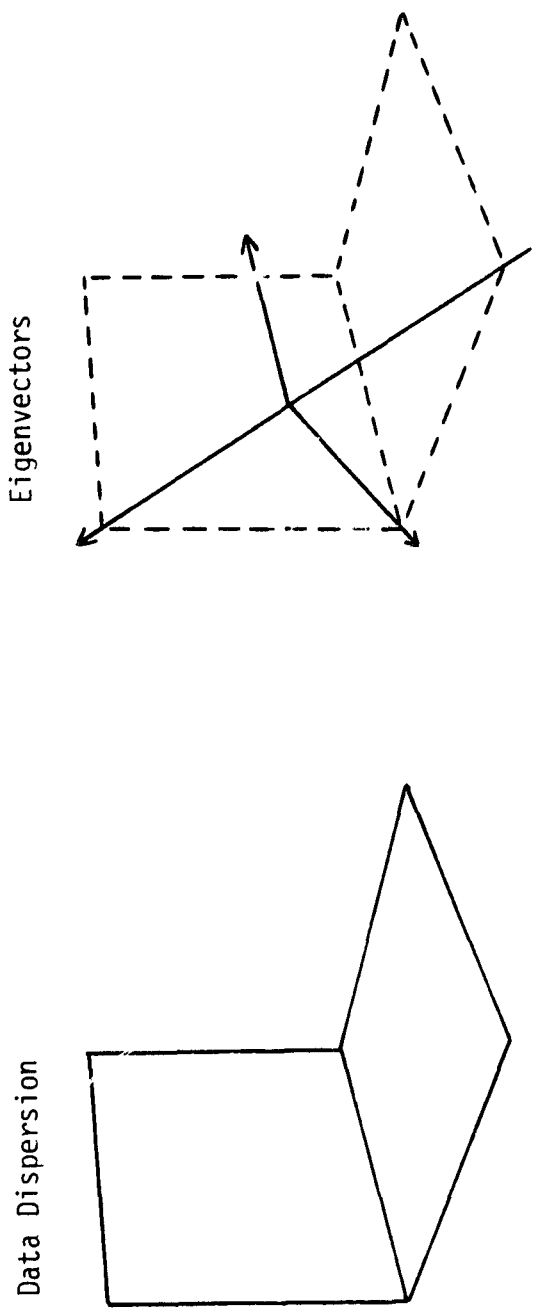

FIGURE 4.13. RESULTS OF PRINCIPAL COMPONENTS ANALYSIS WHEN DATA ARE DISPERSED IN PLANES

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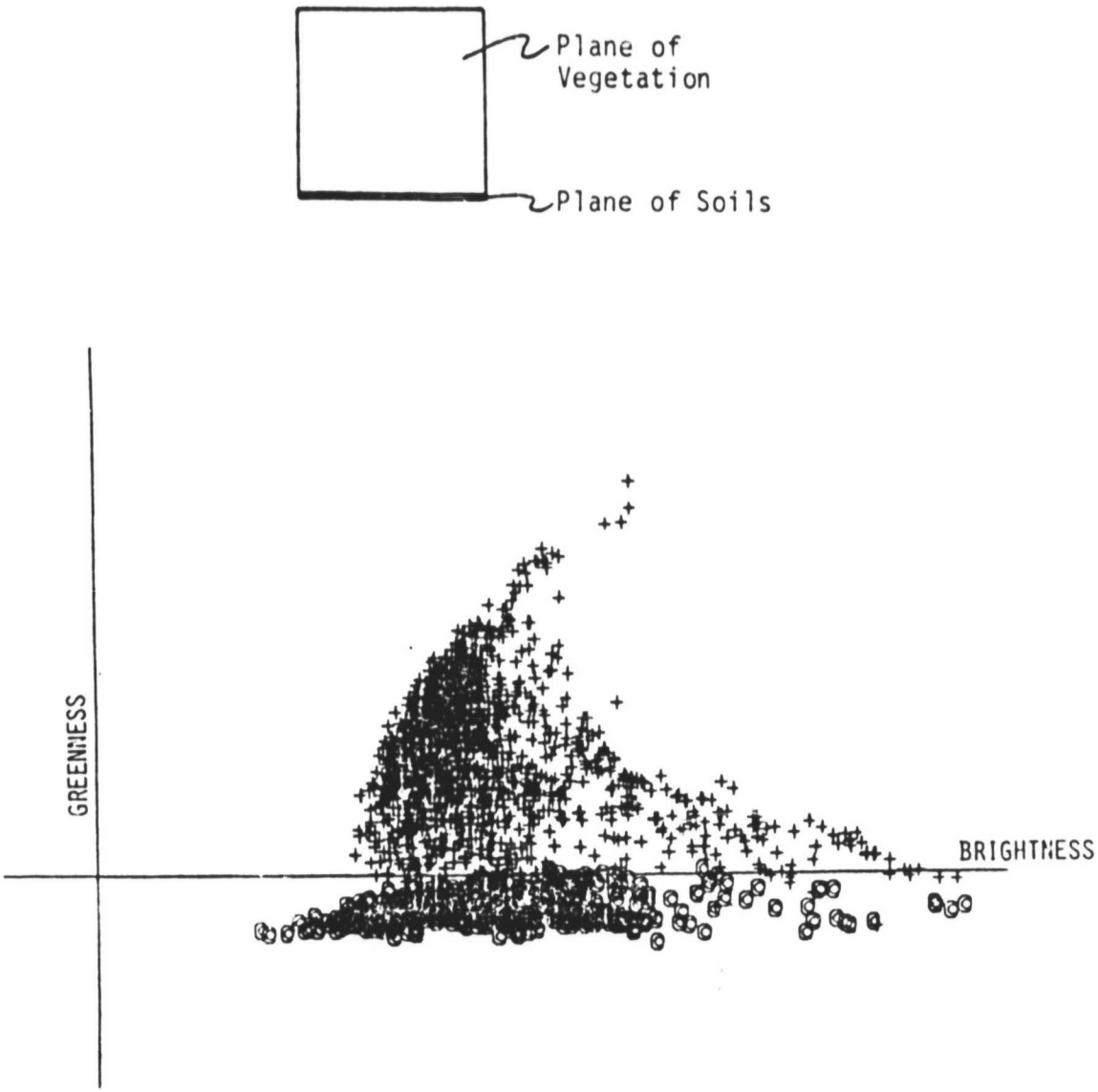

FIGURE 4.14. SIX-BAND THEMATIC MAPPER FEATURE SPACE - GREENNESS AND BRIGHTNESS

transform the simulated TM band counts to this new feature space are provided in Table 4.3.

Figure 4.14 shows a head-on view of the plane of vegetation. The familiar shape of the Tasseled Cap in MSS data is readily apparent. Figure 4.15 which identifies particular sample groups in the plane, lends further support to the Tasseled Cap identification. Both a "soil line" and a "green arm" are present. Like the MSS Tasseled Cap features, TM Greenness is a contrast between the near-IR and the visible bands, while TM Brightness is an albedo-like measure. Comparison to the Tasseled Cap features derived for the simulated Landsat-4 MSS data proves that the six-band TM Greenness is indeed the same Greenness as seen in MSS and the three-band TM (Figure 4.16). Some differences are seen, however, in the Brightness feature derived for the six TM bands compared to that derived from the four MSS bands. This is most likely a reflection of the new information available in the blue and mid-IR bands of the TM. The lack of any difference in Greenness measures can be attributed to the fact that the coefficients for the six-band TM Greenness are such that TM Bands 5 and 7, the mid-IR bands, essentially cancel each other out. While the blue band does play a role in the TM Greenness equation, it could be expected to be low for all vegetation, and to behave, to a much-reduced degree, like TM Band 3. Thus the new contribution of the blue band to TM Greenness is insignificant.

Figure 4.17 stratifies the pure green and pure brown vegetation samples by percent cover. The result is a quasi-development pattern which provides another way of understanding the data relationships. The progression from low to full cover for completely green vegetation (Figure 4.17) can be thought of as the vegetative development phase of a crop from planting to full vegetative development. As expected, the samples migrate from the soil line (starting point at planting) to the green arm during this phase. The progression from full to low cover for almost completely brown vegetation (Figure 4.17) can be thought of

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TABLE 4.3. TRANSFORMATION OF RAW TM DATA (SIX-BAND)

.33183	.33121	.55177	.42514	.48087	.25252	BR
-.24717	-.16263	-.40639	.85468	.05493	-.11749	GR
.13929	.22490	.40359	.25718	-.70133	-.45732	3rd
-.83104	.07447	.42144	-.07579	.23819	-.25247	4th
-.32530	.05361	.11485	.11140	-.46571	.80549	5th
.11381	-.89714	.42038	.06686	-.01629	.02706	6th

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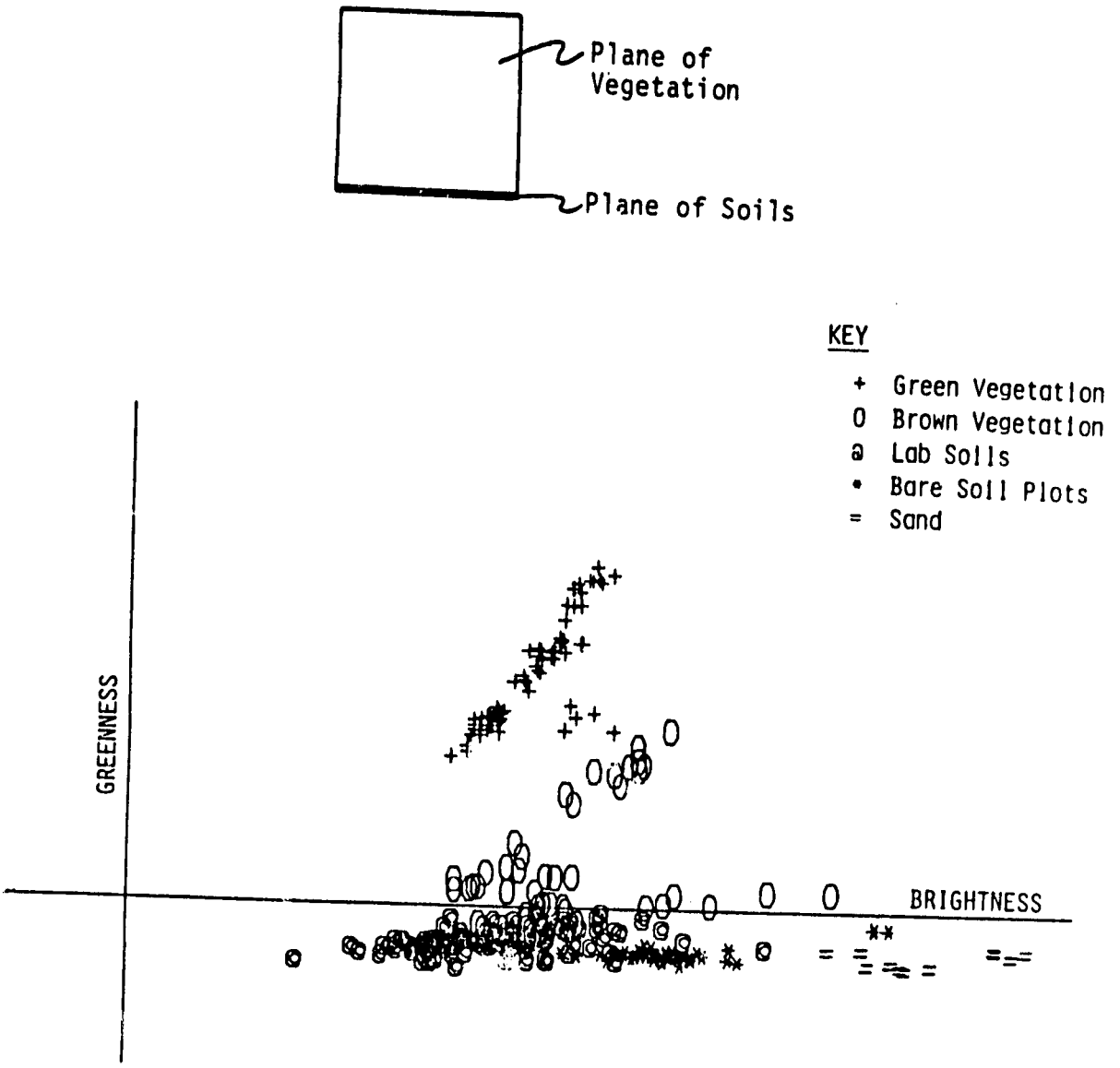

FIGURE 4.15. SIX-BAND THEMATIC MAPPER FEATURE SPACE - GREENNESS AND BRIGHTNESS (Samples)

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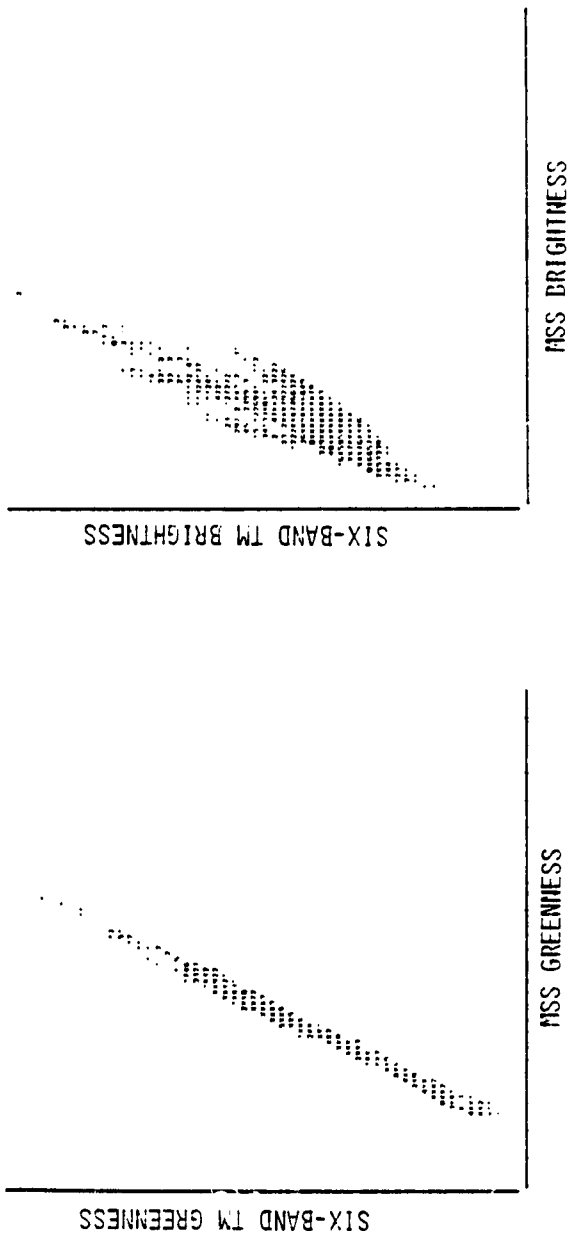

FIGURE 4.16. COMPARISON OF MSS AND SIX-BAND TM - GREENNESS AND BRIGHTNESS

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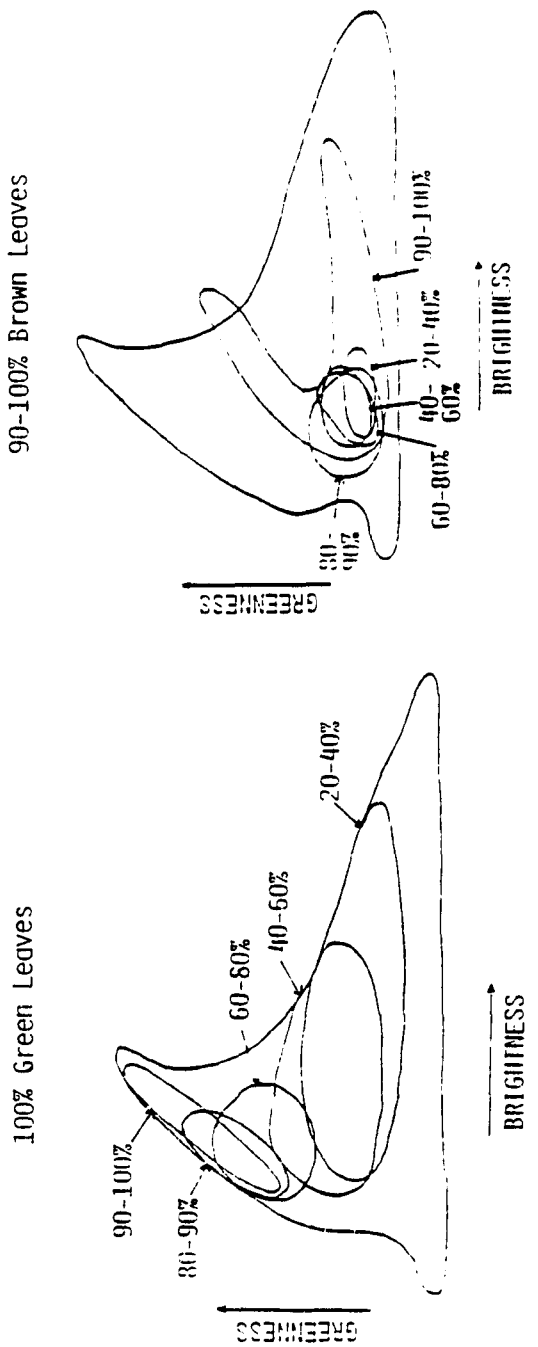

FIGURE 4.17. EFFECTS OF CHANGES IN PERCENT COVER ON 6-BAND TM - GREENNESS AND BRIGHTNESS

as the senescence phase of crop development, and shows a migration back toward the soil line.

Figures 4.18 and 4.19 illustrate a "head-on" view of the plane of soils defined by Brightness and the third component (as yet unnamed). In Figure 4.18, lab (moist) soils, sand samples, and some dry field soils data are separately identified. One can clearly see the separation between those three groups. The third component is largely a contrast between the mid-IR bands, particularly Band 5, and the visible and near-IR bands (particularly Band 3 for soils). Since Band 5 is expected to show sensitivity to moisture, one might expect some moisture effect in this third component. Indeed, some of the sand samples, and most of the dry field samples, do show higher signal levels in the third component than do the moist lab-measured soils. Analyses are currently underway to determine the important physical processes driving variation in this third component.

Figures 4.20 and 4.21 show a side view of the two planes, highlighting the transition zone between them. While there is some deviation of vegetation samples from the plane of vegetation, and some occurrence of brown vegetation samples on or near the plane of soils, the relationships are, for the most part, clearly defined.

Figure 4.22, which uses the same spectra as shown in Figure 4.20, illustrates the pattern of vegetative development, using percent cover with all green or all brown leaves as a substitute for stage of development. Here too, the planar relationships in the data are clear. Green vegetative development (Figure 4.22) is expressed in a migration from the plane of soils to the plane of vegetation, while senescence results in migration, largely within the plane of vegetation, back toward the plane of soils.

Finally, Figure 4.23 shows relationships in the higher components. Of particular interest are: 1) the non-perpendicular relationship between the principal axis of vegetation variation and the principal axis of soil variation in Greenness plotted against the

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FIGURE 4.18. SIX-BAND THEMATIC MAPPER FEATURE SPACE - BRIGHTNESS AND THIRD COMPONENT

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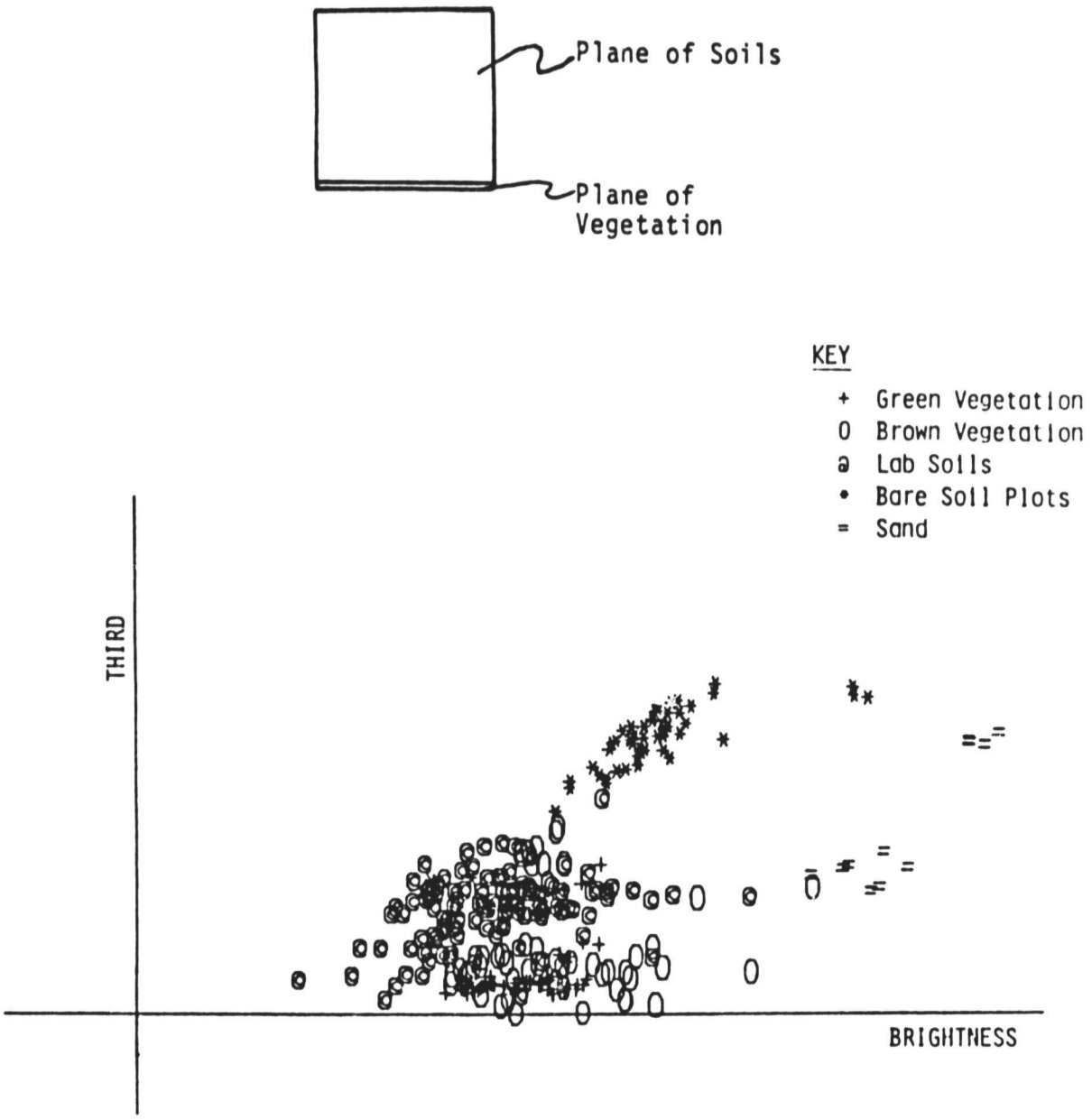

FIGURE 4.19. SIX-BAND THEMATIC MAPPER FEATURE SPACE - BRIGHTNESS AND THIRD COMPONENT (Samples)

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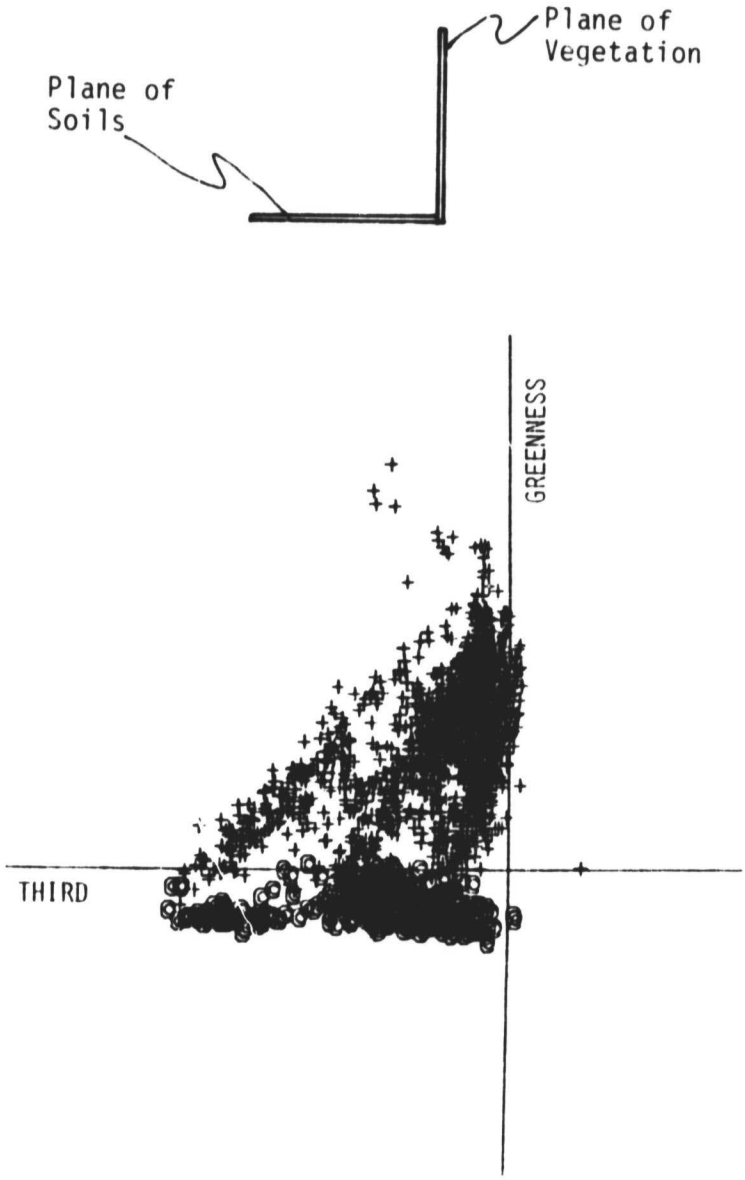

FIGURE 4.20. SIX-BAND THEMATIC MAPPER FEATURE SPACE - GREENNESS AND THIRD COMPONENT

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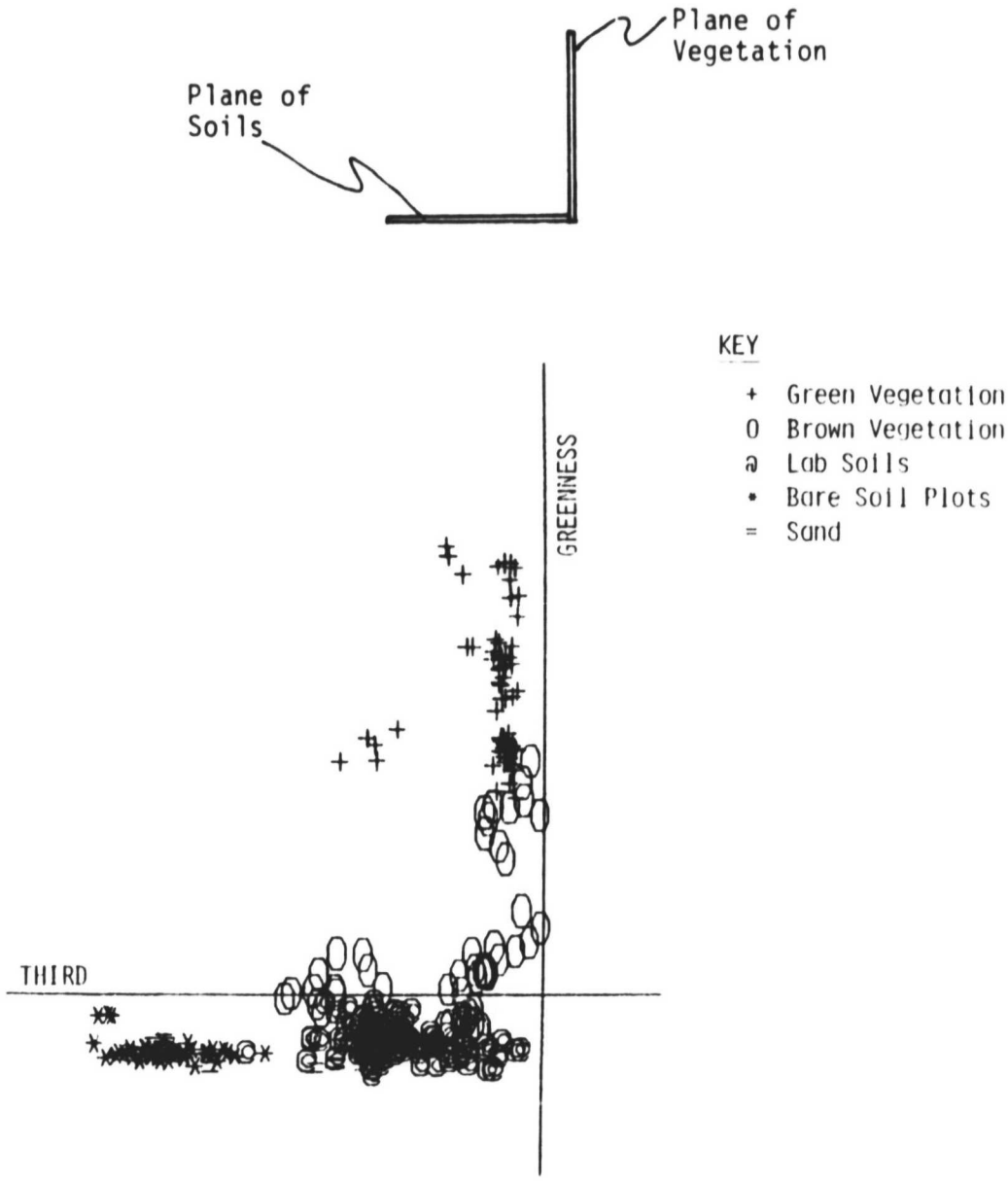

FIGURE 4.21. SIX-BAND THEMATIC MAPPER FEATURE SPACE - GREENNESS AND THIRD COMPONENT (Samples)

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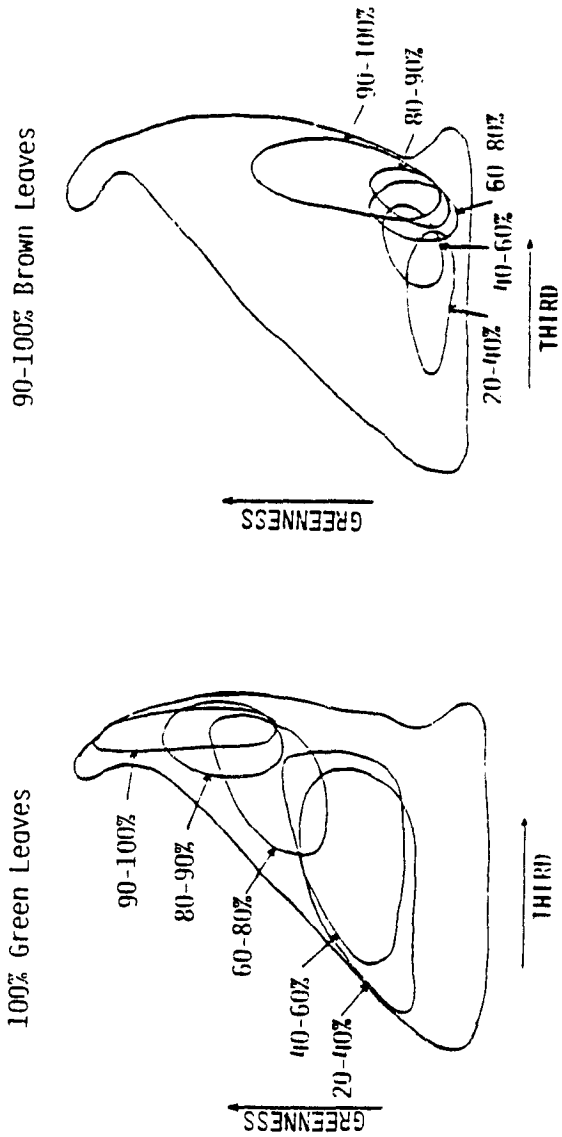

FIGURE 4.22. EFFECTS OF CHANGES IN PERCENT COVER ON SIX-BAND TM - GREENNESS AND THIRD COMPONENT

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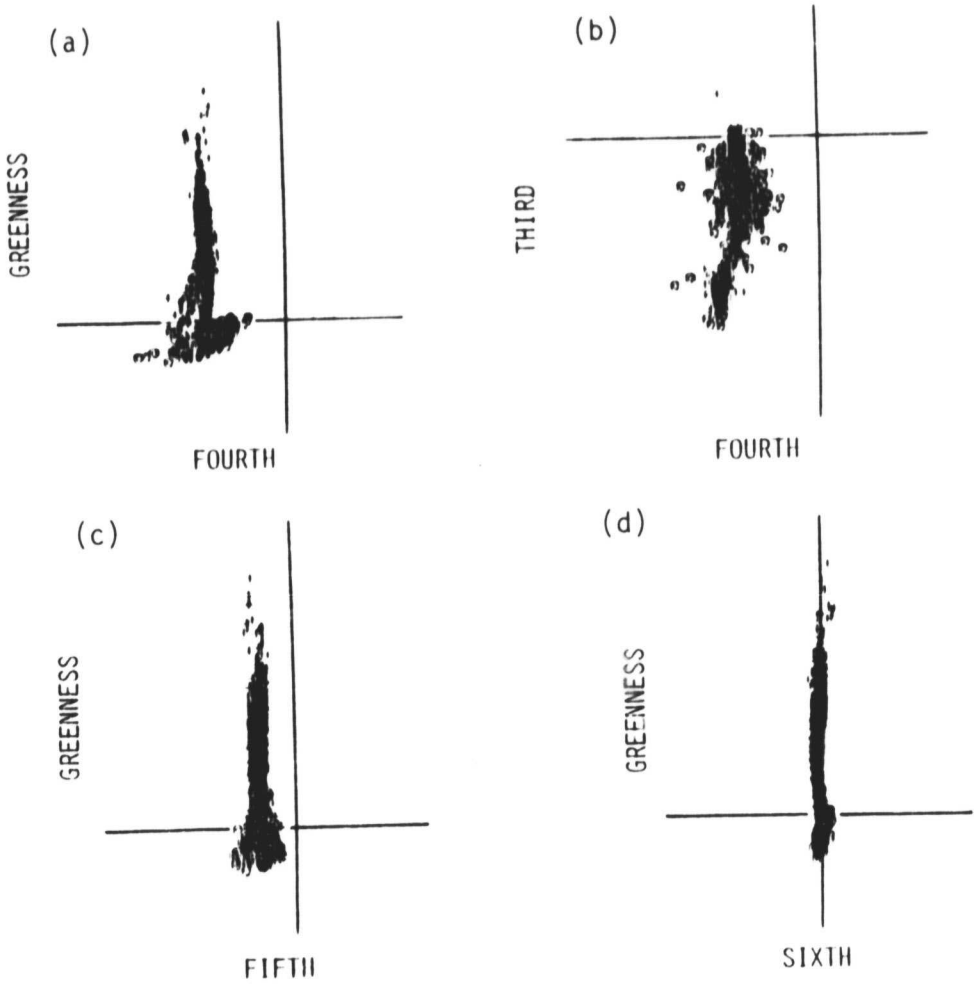

FIGURE 4.23. SIX-BAND THEMATIC MAPPER FEATURE SPACE - HIGHER COMPONENTS

fourth component (Figure 4.23a), 2) the curvilinear nature of the variation in the plot of the third vs. the fourth component (Figure 4.23b) and 3) the lack of significant variation in the sixth component (Figure 4.23d). This last feature is of interest largely because the sixth component is essentially a contrast between TM Bands 2 and 3, the equivalent to "Yellowness" in the MSS Tasseled Cap space. Variations in Yellowness serve as a haze diagnostic in ERIM's XSTAR haze normalization algorithm. Since little variation occurs in this component in agricultural data viewed under uniform haze conditions, it appears that an XSTAR-like algorithm could be used to normalize TM data as well.

4.3.6 INITIAL ANALYSES OF REAL DATA

Three sub-scenes from the first two available TM scenes were analyzed to get an early indication of the reliability of the results obtained through simulation. One segment from the four-band Detroit, Michigan scene (25 July 1982) and two segments from the seven-band Arkansas scene (22 August 1982) were used. All three segments had limitations. Most notable for the Detroit-scene segment was the absence of the mid-IR bands. Furthermore, in both scenes, and all three segments, the vast majority of data were from very green agricultural fields, with few or no samples of bare soil of senescent vegetation.

In spite of these limitations, attempts were made to find the planes of data dispersion through rotation of principal components. Figure 4.24 illustrates the results for the Detroit scene segment. The results for the three- and four-band cases show a clear Tasseled Cap structure, and essentially occuppy only two dimensions. This latter result confirms the strong effect of the mid-IR bands on the third component described earlier. The two Arkansas scene segments, whose data dispersions are illustrated in Figures 4.25 and 4.26 show

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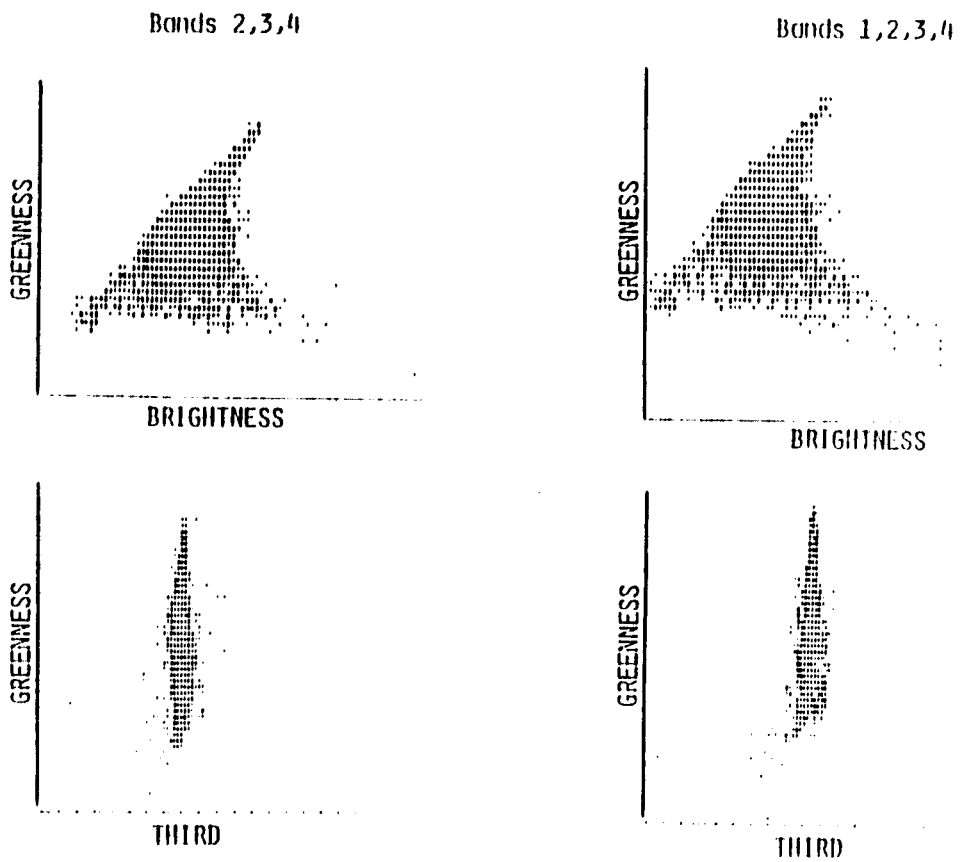

FIGURE 4.24. DATA DISPERSION IN DETROIT SCENE - TECUMSEH

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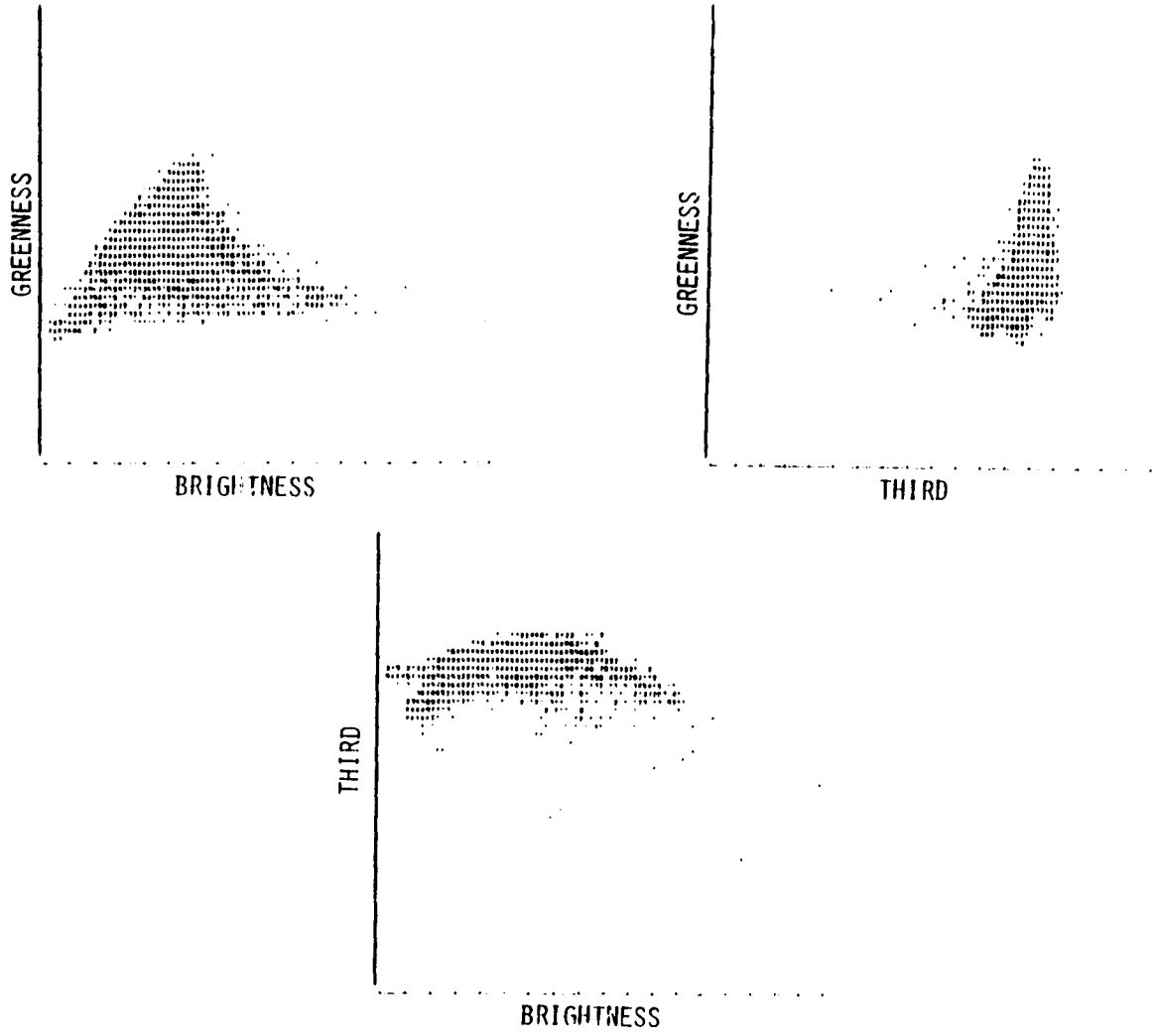

FIGURE 4.25. DATA DISPERSION IN ARKANSAS SCENE - CARUTHERSVILLE

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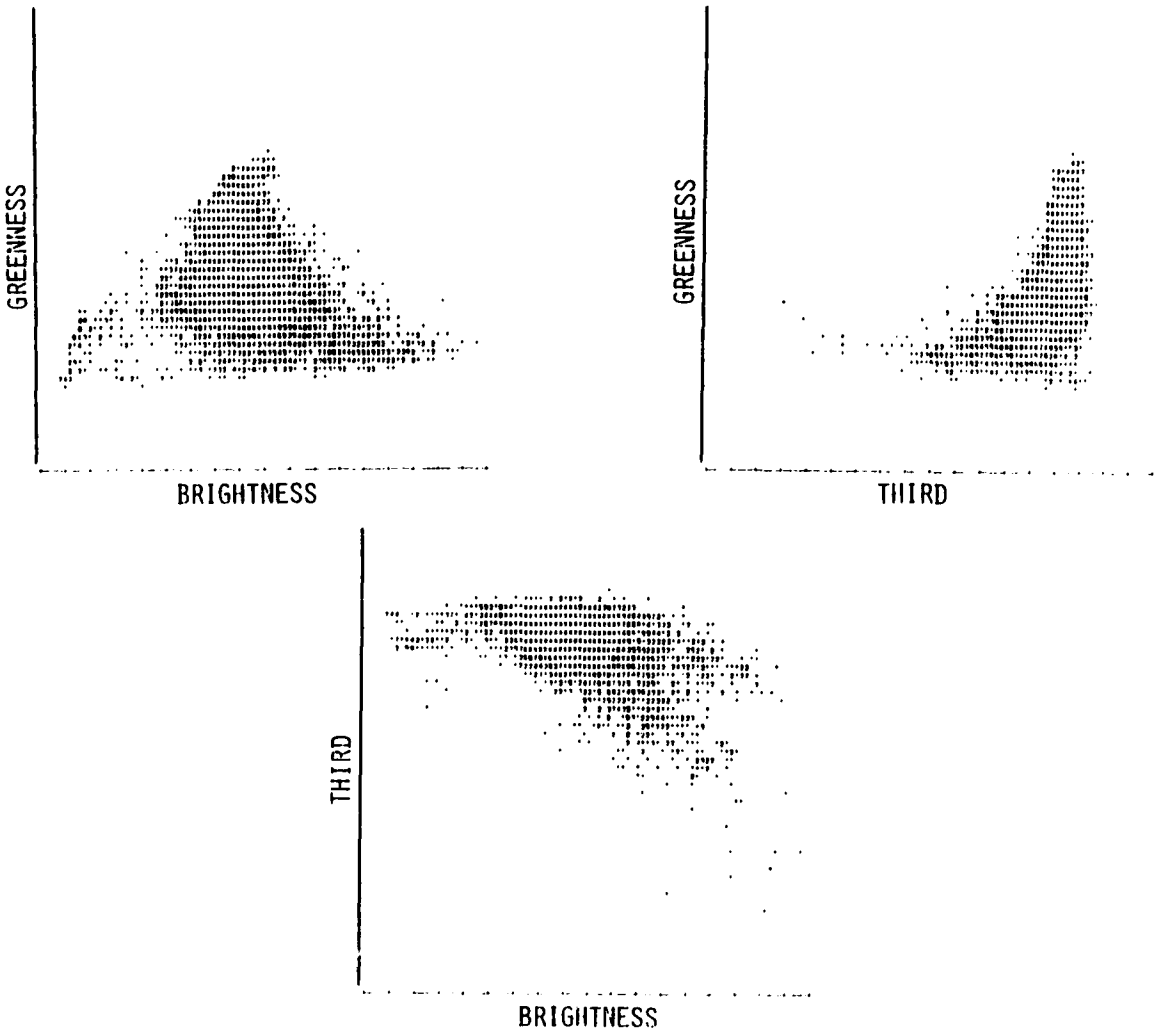

FIGURE 4.26. DATA DISPERSION IN ARKANSAS SCENE - BLYTHEVILLE

three primary dimensions with overall characteristics similar to those seen in the simulated data (Figures 4.14, 4.18 and 4.20). Thus on a gross scale at least, these first looks at real data seem to confirm the results of the simulation.

4.3.7 SUMMARY AND CONCLUSIONS

Based on the analysis presented here, two major conclusions can be reached:

(1) Three bands of the Thematic Mapper (Bands 2, 3 and 4) provide an equivalent data space to the MSS bands. More information may be available in the TM bands as a result of greater dynamic range, improved signal-to-noise ratio, greater spatial resolution, etc., but for the conditions represented in this data set, no information loss from the four MSS bands to the three TM Bands was apparent.

(2) Agricultural data viewed in the six bands of the Thematic Mapper (excluding the thermal) primarily occupy three dimensions, with fully-vegetated data and soils data occupying perpendicular planes. A fourth dimension contains some information, particularly for soils. In this fourth dimension, the principal axis of vegetation variation is not perpendicular to the principal axis of soil variation, and data relationships viewed in the third vs. fourth components are curvilinear.

While the coefficients required to derive the planes of variation in actual TM data are expected to differ somewhat from those defined in this simulation, it is also expected that the general relationships described will be consistent with those seen in the simulated data.

Variations in atmospheric conditions, the influence of neighborhood on the signal received from any given field, and the presence of conditions or cover classes not represented in the simulated data will all affect the relationships observed in real data. Cover types considerably different from those in the simulated

data (e.g., water, geologic materials, urban areas, etc.) may occupy entirely new portions of the data space. Thus, when a data base of TM data which represents a wide range of cover types, conditions and crop development stages is amassed, thorough analysis of the dimensionality and dispersion of real TM data should be undertaken. The results presented here using simulation serve as a starting point, and can be used to understand the results obtained using the real data, with all its complexity and confounding influences.

5
SUMMARY

ERIM's support to the Inventory Technology Development Project of AgRISTARS in FY82 was structured into three tasks:

(1) Corn and Soybean Crop Spectral/Temporal Signature Characterization

(2) Efficient Area Estimation Techniques Development

(3) Advanced Satellite and Sensor System Definition

Substantial progress has been made toward achieving the objectives of these tasks.

In Task 1, typical profiles for corn and soybeans were developed based on field measurement data. Changes in those profiles resulting from changes in particular field conditions or cropping practices were statistically and qualitatively evaluated, as was the utility of the various profile features for discrimination between the two crops. Complete separability in this data set was achieved using the maximum value of the Greenness profile and another feature which indirectly expresses the plateau effect observed in corn Greenness profiles. The association of profile features and crop development stages was also assessed. The corn Greenness profile peak was strongly correlated with a stage which occurs well before expected peak CAI or canopy closure. Because of the indeterminate nature of most soybean varieties, and the frequency of and spectral impact of lodging in the test plots, no strong association could be made between soybean development stages and profile features.

Also in Task 1, two evaluations of alternate features were carried out. Field measurement data were used to compare Greenness, 7/5 ratio, Normalized Difference and Transformed Vegetation Index, particularly as related to temporal-spectral development patterns. Each was found to have characteristics which made it well-suited for

some applications and less appropriate for others - no single measure provides all the characteristics required by the range of possible applications.

A second study compared the Tasseled Cap Transformation and the Cate Invariant Color Transformation, as well as the effects of sun angle correction, XSTAR haze normalization and mean level adjustment. The XSTAR haze diagnostic feature (Gamma) was shown to be strongly responsive to the presence of haze. Scene content was found to have a substantial effect on the results of mean level adjustment, rendering the technique unreliable for general application.

In Task 2, an expert-based automatic corn and soybeans area estimation procedure was developed and evaluated, and found to provide very accurate, low variance crop proportion estimates. Bias of less than 2% and standard deviation of 3-5% were achieved in a 22 segment test. The procedure utilizes a hierarchical decision logic, and adapts to local conditions. The low variance of the estimates is an indication of the procedure's success in carrying out this adaptation.

Alternative methods for defining labeling targets, primarily aimed at dealing with the problem of impure or mixed pixels, were also evaluated. Methods considered included both quasi-field-based and dot-based approaches. The methods which attempted to deal with mixed pixels all produced higher percent correct classification figures than a simple systematic sample. Labeling only pure targets resulted in significant bias in crop proportion estimates, due to a crop-field size correlation. Because labeling errors associated with mixed pixels tended to offset one another, using the systematic sample approach and forcing the labeling procedure to label all targets resulted in the best proportion estimates.

In Task 3, the joint use of SEASAT SAR and Landsat MSS data was considered as a means of obtaining earlier corn/soybean discrimination. In addition to devising new means of extracting important information from the radar data, this study showed that joint use of radar and MSS data yielded an accurate estimate of crop proportions in the test site six weeks earlier than was possible using Landsat alone.

A comparison of several existing sensors - Landsat MSS, NIMBUS CZCS and NOAA AVHRR - was also carried out under Task 3. Using field measurement data, the spectral characteristics of the three sensors were simulated and evaluated. Other sensor featues such as spatial resolution, view geometry and rate of repeat coverage were not directly considered.

Tasseled-Cap-like transformations of the data simulated for the three sensors revealed a strong similarity in response to agricultural scene elements, suggesting potential for joint or interchangeable use of these sensors in certain applications.

Finally, an analysis of Thematic Mapper spectral dimensionality and data structure was carried out using both simulated and actual TM data. TM Bands 2, 3 and 4 were shown to provide most or all of the agricultural scene information contained in the four MSS bands, with greater dynamic range. The six reflective TM bands (excluding the 10.4-12.5 μm thermal band) primarily occupy three dimensions, with some soil-related variation in a fourth dimension. Two of the three primary dimensions are defined by features equivalent to MSS Tasseled Cap Greenness and Brightness. The third dimension is largely associated with soil characteristics; the new mid-IR bands on the TM contribute heavily to this new dimension of information.

REFERENCES

1. Cicone, R., E. Crist, M. Metzler and D. Nuesch. Development, Implementation and Evaluation of Satellilte-Aided Agricultural Monitoring Systems, Semi-Annual Report. NASA Report IT-E2-04311, Environmental Research Institute of Michigan (ERIM), Ann Arbor, MI, June 1982.

2. AgRISTARS Annual Report - Fiscal Year 1981. AP-J2-04225. NASA Johnson Space Center, January 1982, p.9.

3. Crist, E.P. Cultural and Environmental Effects on the Spectral Development Patterns of Corn and Soybeans - Field Data Analysis. NASA Report SR-E2-04224, ERIM, Ann Arbor, MI, January 1982.

4. Crist, E.P. Analysis of the Profile Characteristics of Corn and Soybeans Using Field Reflectance Data. NASA Report IT-E2-04310, ERIM, Ann Arbor, MI, June 1982.

5. Crist, E.P. Association of Spectral Development Patterns with Development Stages of Corn. NASA Report IT-E2-04235, ERIM, Ann Arbor, MI, February 1982.

6. Lautenschlager, L.F. and C.R. Perry, Jr. An Empirical, Graphical, and Analytical Study of the Relationship Between Vegetation Indices. NASA Report EW-J1-04150, NASA Johnson Space Center, Houston, TX, October 1981.

7. Kauth, R.J. and G.S. Thomas. The Tasseled-Cap -- A Graphic Description of the Spectral-Temporal Development of Agricultural Crops as Seen by Landsat. Proceedings of the Symposium on Machine Processing of Remotely Sensed Data, Purdue University, West Lafayette, IN, 1976.

8. Carneggie, D.M., S.O. deGloria and R.N. Colwell. Usefulness of ERTS-1 and Supporting Aircraft Data for Monitoring Plant Development and Range Conditions in California's Annual Grassland. BLM Final Report 53500-CT3-206(N), 1974.

9. Rouse, J.W., R.H. Haas, J.A. Schell and D.W. Deering. Monitoring Vegetation systems in the Great Plains with ERTS. Third ERTS Symposium, NASA SP-351, I:309-317, 1973.

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10. Kanemasu, E.T. Seasonal Canopy Reflectance Patterns of Wheat, Sorghum, and Soybean. Remote Sensing of Environment, 3:43-47, 1974.

11. Richardson, A.J. and C.L. Weigand. Distinguishing Vegetation from Soil Background Information. Photogrammetric Engineering and Remote Sensing, 43:1541-1552, 1977.

12. Tucker, C.J. Red and Photographic Infrared Linear Combinations for Monitoring Vegetation. Remote Sensing of Environment, 8:127-150, 1979.

13. Cate, R.B., D.E. Phinney, M.C. Kinsler, M.L. Sestak, T. Hodges and J.J. Dishler. Interpretation of Landsat Digital Data Using a Cubic Color Model Based on Relative Energies. NASA Report SR-LO-00418, LEMSCO, Houston, TX, February 1980.

14. Biehl, L.L., M.E. Bauer, B.F. Robinson, C.S.T. Daughtry, L.F. Silva and D.E. Pitts. A Crops and Soils Data Base for Scene Radiation Research. Proceedings of the Symposim on Machine Processing of Remotely Sensed DAta, Purdue University, West Lafayette, IN, 1982.

15. Roller, N., K. Johnson, J. Odenweller and C. Hay. Analyst Handbook of the Augmented Corn and Soybean Segment Classification Procedure (C/S-1A). NASA Report FC-E1-00723, ERIM, Ann Arbor, MI, October 1981.

16. Kauth, R.J., P.F. Lambeck, W.R. Richardson, G.S. Thomas and A.P. Pentland. Feature Extraction Applied to Agricultural Crops as Seen by Landsat. Proceedings of the Technical Sessions, Vol. II, the LACIE Symposium, JSC 16015, NASA Johnson Space Center, Houston, TX, 1979.

17. Holmes, Q.A., R. Horvath, R.C. Cicone, R.J. Kauth and W.A. Malila. Development of Landsat-Based Technology for Crop Inventories: Appendices. NASA Report SR-E9-00404$_2$, ERIM, Ann Arbor, MI, December 1979.

18. Hay, C.M., C.A. Kuretz, J.B. Odenweller and E.J. Sheffner. Development of AI Procedures for Dealing with the Effects of Episodal Events on Crop Temporal-Spectral Response and Development of AI Guidelines for Corn and Soybean Labeling. Space Sciences Laboratory Series 20, Issue 24, Space Sciences Laboratory, University of California, Berkeley, CA, 1979.

19. Crist, E.P. and W.A. Malila. Development and Evaluation of an Automatic Labeling Technique for Spring Small Grains. NASA Report SR-E1-04065, ERIM, Ann Arbor, MI, 1981.

20. Cicone, R., E. Crist, R. Kauth, P. Lambeck, W. Malila and W. Richardson. Development of Procedure M for Multicrop Inventory, With Tests of a Spring-Wheat Configuration. NASA Report CR-160140, ERIM, Ann Arbor, MI, 1979.

21. Dailey, C.L., K.M. Abotten and J.D. Nichols. Corn/Soybean Decision Logic: Improvements and New Crops. NASA Report FC-LO-00420, LEMSCO, Houston, TX, 1980.

22. Austin, W.W. Detailed Description of the Wheat Acreage Estimation Procedure Used in the Large Area Crop Inventory Experiment. Technical Memorandum 644-845, LEC-11497, Lockheed Electronics Company, Inc., Houston, TX, February 1978.

23. Johnson, K., M.D. Metzler and J.B. Odenweller. Specifications for and evaluation of an Analyst Based Corn and Soybean Segment Classification Procedure (C/S-1A). NASA Report, ERIM, Ann Arbor, MI, 1982 (to be published).

24. Dennis, T.B. Spatial/Color Sequence Proportion Estimation Techniques. NASA Report SR-LO-04028, LEMSCO, Houston, TX, 1980.

25. Erickson, J.D. AgRISTARS: Information Presented at the Quarterly Project Technical Interchange Meeting, July 9-10, 1981. NASA Report IT-J1-04199, Houston, TX, 1981.

26. Nuesch, D.R. Augmentation of Landsat MSS Data by SEASAT SAR Imagery for Agricultural Inventories. NASA Report IT-E2-04233, ERIM, Ann Arbor, MI, April 1982.

27. The LACIE Symposium. Proceedings of the Plenary Session (JSC-14551) and Independent Peer Evaluation of the Large Area Crop Inventory Experiment (JSC-14550), NASA Johnson Space Center, Houston, TX, October 1978.

28. Hay, C.M. Manual Interpretation of Landsat Data. Proceedings of the Technical Sessions, Vol.I, the LACIE Symposium, JSC 16015, NASA Johnson Space Center, Houston, TX, 1979.

29. Kidwell, K.B. NOAA Polar Orbiter Data, Users Guide. Department of Commerce, National Climatic Center, Satellite Data Services Division, Washington, D.C., 1979.

30. Hovis, W. The Coastal Zone Color Scanner (CZCS) Experiment, Nimbus 7 User's Guide. GDFC and NOAA, August 1978.

31. U.S. Geological Survey, Landsat Data Users Handbook, revised edition. Arlington, VA, 1979.

32. Gray, T.I. and D.G. McCrary. Meteorological Satellite Data - A Tool to Describe the Health of the World's Agriculture. EW-N1-04042, JSC-17112, AgRISTARS Early Warning and Crop Condition Assessment Project, U.S. Department of Commerce, NOAA, Houston, TX, February 1981.

33. Turner, R.E. Radiative Transfer in Real Atmospheres. ERIM Report 190100-24-T, ERIM, Ann Arbor, MI, 1974.

34. Stoner, E.R., M.F. Baumgardner, L.L. Biehl and B.F. Robinson. Atlas of Soil Reflectance Properties. Research Bulletin 962, Agricultural Experiment Station, Purdue University, West Lafayette, IN, May 1980.

35. Bauer, M.E., L.L. Biehl, C.S. Daughtry, B.F. Robinson and E.R. Stoner. Agricultural Scene Understanding and Supporting Field Research. NASA Report SR-P9-00410, LARS, Purdue University, West Lafayette, IN, November 1979.

36. Holmes, Q.A. The Tasseled Cap and Thematic Mapper. Presentation at Quarterly Review, NASA Johnson Space Center, Houston, TX, December 1979.

37. Badhwar, G.D. and K.E. Henderson. A Comparative Study of the Thematic Mapper and Landsat Spectral Bands from Field Measurement Data. NASA Report SR-J0-04029, NASA Johnson Space Center, Houston, TX, 1981.

38. Barker, J.L. Spectral Characterization of Landsat-D Thematic Mapper Subsystems. NASA Goddard Space Flight Center, Greenbelt, MD (to be published).

39. Dave, J.V. Extensive Datasets of the Diffuse Radiation in Realistic Atmospheric Models with Aerosols and Common Absorbing Gases. Solar Energy, 21:361-369.

40. Landsat-D Investigations Workshop. NASA Goddard Space Flight Center, Greenbelt, MD, May 1982.

APPENDIX
REPORTS AND PUBLICATIONS RELATED TO CONTRACT NAS9-16538

Cicone, R., E. Crist, M. Metzler and D. Nuesch. Development, Implementation and Evaluation of Satellite-Aided Agricultural Monitoring Systems, Semi-Annual Report. IT-E2-04311, NAS9-16538, Environmental Research Institute of Michigan (ERIM), Ann Arbor, MI, June 1982.

Cicone, R.C. and M.D. Metzler. Comparison of Landsat MSS, Nimbus CZCS and NOAA 6/7 AVHRR Features for Land Use Analysis. Proceedings of the Symposium on Machine Processing of Remotely Sensed Data, Purdue University, West Lafayette, IN, 1982, to be published in Remote Sensing of Environment.

Cicone, R.C. and M.D. Metzler. Development of Common Features for Multi-Satellite Agricultural Monitoring. Poster paper delivered at AgRISTARS Mini-Symposium, 1-2 December 1982.

Crist, E.P. Cultural and Environmental Effects on the Spectral Development Patterns of Corn and Soybeans - Field Data Analysis. NASA Report SR-E2-04224, ERIM, Ann Arbor, MI, 1982.

Crist, E.P. Association of Spectral Development Patterns with Development Stages of Corn. NASA Report IT-E2-04235, ERIM, Ann Arbor, MI, 1982.

Crist, E.P. Cultural and Environmental Influences on the temporal-Spectral Development Patterns of Corn and Soybeans. Proceedings of the Symposium on Machine Processing of Remotely Sensed Data, Purdue University, West Lafayette, IN, 1982.

Crist, E.P. Effects of Field Conditions and Cropping Practices on Corn and Soybean Spectral Development Patterns, to be published in Remote Sensing of Environment.

Crist, E.P. Analysis of the Profile Characteristics of Corn and Soybeans Using Field Reflectance Data. NASA Report IT-E1-04310, ERIM, Ann Arbor, MI, 1982.

Crist, E.P. The Thematic Mapper Tasseled Cap - A Preliminary Formulation, accepted by Symposium on Machine Processing of Remotely Sensed Data, 21-23 June 1983.

Crist, E.P. and R.C. Cicone. Investigations of Thematic Mapper Data Dimensionality and Features Using Field Spectrometer Data, accepted by 17th International Symposium on Remote Sensing of Envirionment, 9-13 May 1983 and delivered at AgRISTARS Mini-Symposium, 1-2 December 1982.

Crist, E.P. and R.C. Cicone. Application of the Tasseled Cap Concept to Simulated Thematic Mapper Data, submitted to Photogrammetric Engineering and Remote Sensing.

Crist, E.P and R.C. Cicone. Comparisons of the Dimensionality and Features (Simulated Landsat 4 MSS and TM Data, submitted to Remote Sensing of Environment.

Metzler, M.D., J. Odenweller, R.C. Cicone and K.I. Johnson. Experiments with an Expert-Based Crop Area Estimation Technique for Corn and Soybeans, accepted by 17th International Symposium of Remote Sensing, 9-13 May 1983 and presented at AgRISTARS Mini-Symposium, 1-2 December 1982.

Metzler, M.D. and R.C. Cicone. Assessment of Technologies for Classification of Mixed Pixels, accepted by 17th International Symposium of Remote Sensing, 9-13 May 1983.

Metzler, M.D., R.C. Cicone and K. Johnson. The Evaluation of a Semi-Automatic Procedure for Classifying Corn and Soybeans Without Ground Data. Proceedings of the Symposium on Machine Processing of Remotely Sensed Data, Purdue University, West Lafayette, IN, 1982.

Metzler, M.D. and R.C. Cicone. Description and Independent Test Analysis of Automatic Corn and Soybean Labeling Procedure (C/S-1B). NASA Report IT-E2-00741, ERIM, Ann Arbor, MI, 1982 (to be published).

Mykolenko, O. and M.D. Metzler. Operators Manual for the Augmented U.S. Baseline Corn and Soybean Classification Procedure (C/S-1A). NASA Report IT-E1-00721, ERIM, Ann Arbor, MI, 1981.

Nuesch, D.R. Augmentation of Landsat MSS Data by Seasat SAR Imagery for Agricultural Inventories. NASA Report IT-E2-04233, ERIM, Ann Arbor, MI, 1982.

Nuesch, D.R., Q. Holmes and M.D. Metzler. Augmentation of Landsat MSS by Seasat SAR for Agricultural Inventories, presented at AgRISTARS Mini-Symposium, 1-2 December 1982.

Parris, T. and R.C. Cicone. Effects of Preprocessing Landsat MSS Data on Derived Features, accepted by Symposium on Machine Processing of Remotely Sensed Data, 21-23 June 1983.

Roller, N., K. Johnson, J. Odenweller and C. Hay. Analyst Handbook for the Augmented U.S. Baseline Corn and Soybean Segment Classification Procedure (C/S-1A). NASA Report FC-E1-00723, ERIM, Ann Arbor, MI, 1981.