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Application of the Tasseled Cap Concept to Simulated Thematic Mapper Data

Measurements of agricultural crops and soils in the six reflective bands of the Thematic Mapper primarily occupy three dimensions— two which are equivalent to the MSS data plane, and a third which represents the contribution of the TM mid-infrared bands.

INTRODUCTION AND BACKGROUND

CONSIDERABLE STUDY of the spectral characteristics, correlations, and physical information carried in the Landsat Multispectral Scanner (MSS) bands has been undertaken over the life of the Landsat program. Numerous ratios, sums, differences, and linear combinations of the four MSS bands have been proposed. One set of linear combinations, called the Tasseled Cap Transformation (Kauth and Thomas, 1976), has gained particular at-

features produced are directly correlated to physical characteristics of agricultural fields, and are thus readily interpretable.

With the successful launch of Landsat-4, which carries the Thematic Mapper (TM) as well as the Multispectral Scanner, new spectral bands are available for analysis. Table 1 describes the nominal band widths of the TM. Of particular interest are bands 1, 5, and 7, which measure reflected radiation in spectral regions unsampled by the MSS, and band 6, a thermal imaging band.

ABSTRACT: *Thematic Mapper signal counts in the six reflective bands (i.e., excluding the thermal band) are simulated using field and laboratory spectrometer measurements of a variety of crops, crop conditions, and soil types. The Dave atmospheric model and prelaunch sensor characteristics comprise the other components of the simulation. The simulated data are found to occupy essentially three dimensions, two of which are equivalent to the MSS Tasseled Cap Greenness and Brightness features, and a third which is substantially influenced by the mid-infrared bands of the TM. This new dimension is primarily related to soil characteristics, including soil moisture. The nature and characteristics of each dimension are discussed, as are some of the expected information gains (over MSS data) resulting from the additional dimensionality of the data.*

tention. This transformation is based on the observation that, in agricultural regions, the correlations between the visible bands and between the near-infrared bands of the MSS cause vegetation and soil related information to fall primarily into a single plane. The Tasseled Cap Transformation rotates the data such that a "head-on" view of that plane is obtained, thus capturing the vast majority of MSS data variation in two dimensions. In addition, the

The utility of the Tasseled Cap Transformation in processing and analyzing MSS data, and the added complexity introduced to data from the TM as a result of the greater number and wider spectral dispersion of bands measured by that sensor, make a Tasseled-Cap-like transformation for TM data desirable.

Early simulation studies of the reflective Thematic Mapper bands (excluding band 6, the thermal

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TABLE 1. NOMINAL BAND WIDTHS OF THE THEMATIC MAPPER (50 PERCENT RESPONSE)

Band	Wavelength (μm) Low	High
1	0.45	0.52
2	0.52	0.60
3	0.63	0.69
4	0.76	0.90
5	1.55	1.75
6	10.4	12.5
7	2.08	2.35

band) have found correlations between sets of TM bands similar to those seen in the MSS bands, suggesting that, as with MSS data, the effective dimensionality of TM data may be less than the total number of bands. Holmes (unpublished data, 1979) simulated top-of-atmosphere radiances using geologic as well as agricultural spectra, and predicted at least three significant dimensions. Based on the dispersion of the geologic data, Holmes also postulated the existence of a plane of soils, instead of the line of soils seen in MSS data. Badhwar and Henderson (1981), using exclusively agricultural spectra to simulate ground-level radiances (i.e., no atmospheric effects) predicted only two important information-bearing dimensions. They further characterized the two information-bearing dimensions as resembling Greenness and Brightness in the MSS Tasseled Cap Transformation, although the signs and magnitudes of their coefficients were not entirely consistent with those of the MSS Tasseled Cap Transformation.

The work reported here was undertaken to more fully investigate the applicability of the Tasseled Cap Transformation approach to TM data. It extends the previous work of Holmes and Badhwar and Henderson by (1) using a more extensive data set of crop and soil spectra, (2) including simulation of actual signal counts using pre-launch absolute calibration and detector response data, (3) using a more sophisticated and precise atmospheric model, (4) verifying the simulation with actual TM data, and (5) going beyond principal components analysis to a more thorough evaluation of the dispersion of data in the six-dimensional space defined by the reflective TM bands.

MATERIALS AND METHODS

SIMULATION OF TM SIGNAL COUNTS

The base data for the simulation are spectra collected by the Laboratory for Applications of Remote Sensing (LARS) at Purdue University as part of a vegetation remote sensing research program at the NASA Johnson Space Center (Biehl et al., 1982). These include measurements of field plots of crops at the Purdue Agronomy Farm and laboratory measurements of soil samples (Stoner and Baum-

gardner, 1980). The field spectra include bare soil plots and partially- or fully-vegetated plots of corn, soybeans, and winter wheat collected in 1978, 1979, and 1980. Spectral measurements were taken at intervals throughout the growing seasons of these crops, and various types of agronomic information (e.g., percent cover; proportions of green, yellow, and brown leaves; stage of development) were recorded concurrently. Data were included from experiments in which planting dates, nitrogen fertilization levels, plant populations, and other such factors were varied through a range typical of those found in the U.S. Corn Belt.

The laboratory-measured soil spectra were collected under controlled conditions at 0.1 bar moisture tension, and represent samples of soils from across the U.S. as well as a few from Brazil and other countries. Spectra of 294 soil series are included in this data set. A range of descriptive information accompanies the spectral measurements, including particle size distribution, organic matter content, minerology, and parent material.

Both field and laboratory spectra were collected using an Exotech Model 20C spectroradiometer. Reflectance factors were computed by comparison to a barium sulfate standard. In total, 1642 spectra of vegetated plots and 636 spectra of soils were used.

Data from the Dave atmospheric model (Dave, 1978) were employed, along with pre-launch composite detector response functions obtained from the NASA Goddard Space Flight Center (Markham and Barker, 1982; Barker, 1983), to compute top-of-atmosphere radiances for the six reflective TM bands. Dave's Model 3, a clear atmosphere, was used with nadir view and a 45-degree solar zenith angle. Spectra were assumed to derive from infinitely large fields (i.e., background reflectance was equal to target reflectance), thus avoiding the confounding influence of radiation reflected from neighboring fields entering into the field of view by means of atmospheric scattering.

Pre-launch absolute calibration data, also obtained from the NASA Goddard Space Flight Center (Barker, unpublished data, 1982), were used to convert top-of-atmosphere radiances to sensor signal counts. Table 2 shows the gains and offsets used. It

TABLE 2. GAINS AND OFFSETS APPLIED TO TOP-OF-ATMOSPHERE TM RADIANCES (FROM PROTOFLIGHT TEST #5, MEAN VALUES, LANDSAT-D INVESTIGATIONS WORKSHOP, NASA/GSFC, 13-14 MAY 1982, PP. 2-51,2-53.)

Band	Gain	Offset
1	15.777	0.82
2	8.038	0.81
3	10.571	−0.04
4	10.866	0.69
5	79.568	2.64
7	149.197	3.16

should be emphasized that t the pre-launch tests of the TM board lamp calibration is use actual TM data. Thus, some di simulated and real calibratior

The resulting simulated si togrammed and compared to TM data collected on 22 Augu and Tennessee (see Figure were generally similar except wider range of vegetative c through senescent) and prese in the simulation resulted in that of the real data, which wa vegetation. All bands of the displaced lower in signal cc data. A combination of sun a ations in atmospheric condit versus internal calibration are for the observed offset. Overa pears to support the viability

ANALYSIS METHODS

Principal components anal to evaluate data dimensional essentially planar distribution principal components can also plane into which the data ar both simulated and real MSS d cipal components will define i the Tasseled Cap plane, and vide features essentially equi Cap features Greenness and F Crist, 1984).

However, while principal can provide insight into the with more than two dimensior

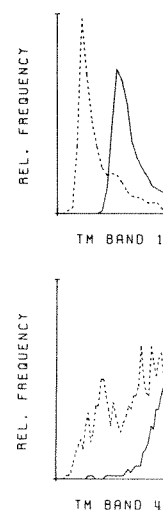FIG. 1. Comparison of simulat Simulated data distributions are

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7	3.16

should be emphasized that these figures apply to
the pre-launch tests of the TM detectors, while on-
board lamp calibration is used in the collection of
actual TM data. Thus, some differences between the
simulated and real calibrations may exist.

The resulting simulated signal counts were his-
togrammed and compared to histograms of actual
TM data collected on 22 August 1982 over Arkansas
and Tennessee (see Figure 1). Histogram shapes
were generally similar except in band 4, where the
wider range of vegetative conditions (emergent
through senescent) and presence of more soils data
in the simulation resulted in a different shape than
that of the real data, which was dominated by green
vegetation. All bands of the simulated data were
displaced lower in signal counts from the actual
data. A combination of sun angle differences, vari-
ations in atmospheric conditions, and pre-launch
versus internal calibration are probably responsible
for the observed offset. Overall, the comparison ap-
pears to support the viability of the simulation.

ANALYSIS METHODS

Principal components analysis is frequently used
to evaluate data dimensionality. In the case of an
essentially planar distribution of data, the first two
principal components can also be used to define the
plane into which the data are dispersed. Thus, in
both simulated and real MSS data, the first two prin-
cipal components will define a plane very similar to
the Tasseled Cap plane, and can be rotated to pro-
vide features essentially equivalent to the Tasseled
Cap features Greenness and Brightness (Ince, 1981;
Crist, 1984).

However, while principal components analysis
can provide insight into the dimensionality of data
with more than two dimensions, it may fail to define

the actual planes into which the data are dispersed.
This phenomenon is illustrated in Figure 2. In this
case, data are distributed into two perpendicular
planes. Assuming that the data are equally dis-
persed throughout the planes, the principal com-
ponents will be defined as shown: one component
parallel to the line of intersection of the two planes,
a second forming a right triangle, of which it is the
hypotenuse, with the edges of the two planes, and
a third dividing that right triangle into two equal
right triangles (reflections of each other). Variations
in the dimensions of and data density in the two
planes will change these results to a degree, but as
long as the basic relationship of two (or more) planes
exists, principal components will not necessarily
provide definition of those planes.

Accordingly, principal components analysis
(based on the covariance matrix) was used only to
provide a starting point for analysis of TM data dis-
persion. These components were then rotated, two
or three at a time, in a linear fashion which pre-
served the orthogonality of the six components. By
the process of applying various rotations, the data
relationships in the TM data space were discovered
and defined.

Once the TM data space was understood in spec-
tral terms, the descriptive information collected,
along with the spectral data by LARS, was used to
associate the variations of TM data in the defined
feature space with the physical characteristics of the
crop canopy or soil.

FIGURE GENERATION

The data in Figures 4 through 8 and 11 represent
samples taken from the entire simulated data set.
The particular samples plotted in each figure were
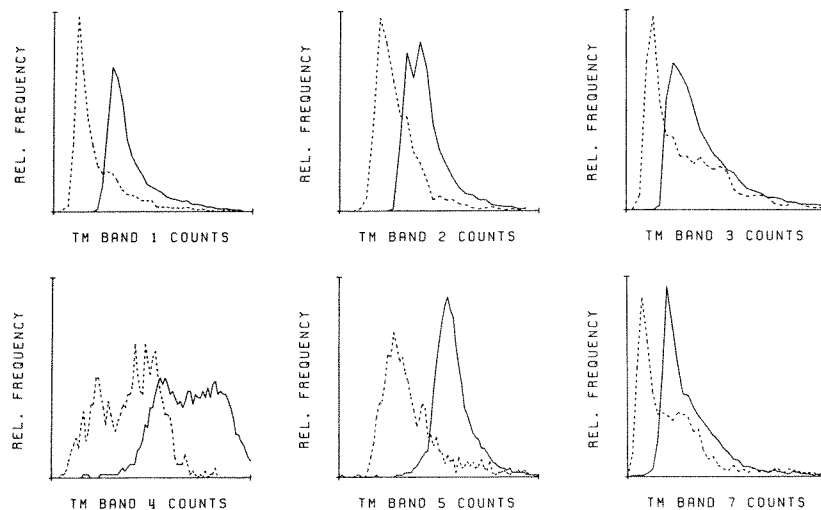selected using a technique designed to highlight the

FIG. 1. Comparison of simulated and actual TM data (actual data from AgRISTARS segment 9653, 22 August 1982).
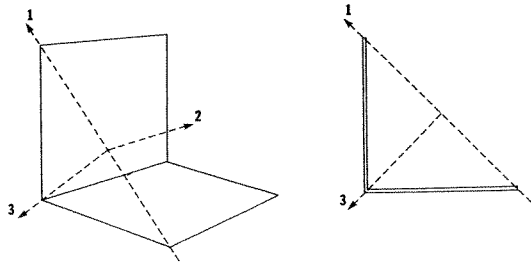Simulated data distributions are shown using dashed lines.

FIG. 2. Principal components of data dispersed in two planes.

distribution of the data while smoothing out differences in density over the range of the data distribution. This sampling was necessitated by the limitations of pen plotting devices, which have difficulty plotting extremely dense data.

The technique involves definition of spectral bins in the two dimensions defined by the features plotted in each figure. Each data point is considered in turn, and assigned to the appropriate bin. The first data point which falls in a particular bin is plotted, while subsequent data points which fall in the same bin are ignored. All figures in this paper were made using three-count bins.

RESULTS AND DISCUSSION

The simulated TM signal counts are dispersed primarily into a three-dimensional space, and, more precisely, define two perpendicular planes and a "transition zone" between the two. This relationship is illustrated in Figure 3. Data from fully vegetated plots define a "plane of vegetation," while bare soils data fall in a "plane of soils." Between the two (roughly filling out a right triangle) are data from partially vegetated plots where both vegetation and soil are visible. Thus, in the course of a growing season, one would expect a field to begin somewhere on the plane of soils, progress through the transition zone, arrive at the plane of vegetation near the end of the crop's vegetative development (i.e., when full canopy closure is achieved), and then move back toward the plane of soils (either
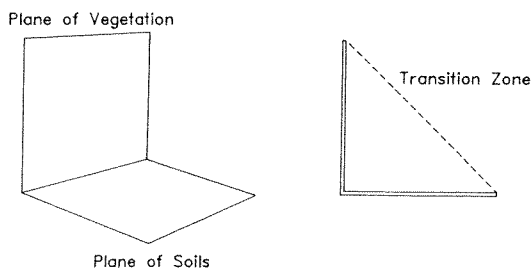
down the plane of vegetation or, perhaps, back through the transition zone).

It should be kept in mind that the angle between the two planes is scale or calibration dependent. With different absolute calibration factors applied to some of the TM bands, that angle might not be 90 degrees. However, the separation of the data into two planes would still occur, and, as will be discussed later, their independence in terms of the scene characteristics affecting variation in the planes would also be preserved, although in a somewhat more complex fashion.

PLANE OF VEGETATION

Table 3 provides the coefficients used to transform the simulated TM signal counts into this feature space. The coefficients of the first two components are, for the TM bands which sample the same spectral regions as the MSS bands (TM bands 2, 3, and 4), comparable to those which define MSS Greenness and Brightness. These two components, which define the plane of vegetation in the TM data, are displayed in Figure 4. Again, a strong resemblance to the MSS Greenness-Brightness plane is apparent. Although Badhwar and Henderson (1981) reached a similar conclusion, their coefficients differed in sign and/or magnitude for at least some of the TM bands as compared to the MSS bands, because they used only the eigenvectors produced by principal components analysis. With rotations applied, we find that a Greenness-Brightness plane does exist in TM data, with coefficients which are entirely consistent with MSS Tasseled Cap coefficients. Greenness describes the contrast between the near-infrared and the visible bands, with the mid-infrared bands essentially cancelling one another. Brightness is a partial sum of all bands. In another paper (Crist and Cicone, 1984) we show that this TM Greenness is virtually identical to MSS Greenness, while the Brightness features are slightly different. For the most part, however, the plane of vegetation in TM data is equivalent to the MSS data plane.

TRANSITION ZONE

Rotating the data 90 degrees about the y- or Greenness axis (right hand rule), we obtain a view of the edges of both planes, and a data distribution as illustrated in Figure 5. In this figure, Greenness is still on the y-axis, but the x-axis now defines a Third Component, with the Brightness axis perpendicular to the page. Figure 6 shows a sample of the data from Figure 5, in the same projection. Only fully vegetated plots (full or nearly full canopy closure) and bare soils are shown here, with the result that the definition of the two planes is readily apparent. In contrast, Figure 5 highlights the transition zone occupied by partially-vegetated plots.

The location of the brown (senescent) vegetation samples in Figure 6 suggests that the spectral path followed by the plots in the time period from max-

TABLE 3. T

Feature	Ban
Brightness	0.3
Greenness	−0.5
Third	0.1

imum vegetative develoj maturity is primarily, o plane of vegetation rath transition zone. Stratific; 5 by percent cover with l leaves leads to the same zone is populated larg "greening up," whereas etation remain, for the vegetation until they ha level of closure, and a ' these samples begin to starting point in the plai values are so low that the place almost entirely wi

PLANE OF SOILS

In Figure 7, the plane by means of a −90-deg Brightness axis in Figur rule). Now Greenness is and Brightness and the the x- and y-axes, resp tion, with only soils da ure 8.

While detailed unde: teristics expressed in v soils is the object of cur of evidence suggest tha least one important fa Component value of ba

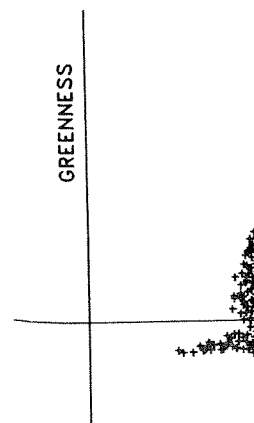FIG. 3. Dispersion of six-band Thematic Mapper data.

FIG. 4. The plane of ' Brightness.

TABLE 3.   TM FEATURE SPACE TRANSFORMATION COEFFICIENTS—FIRST THREE FEATURES

Feature	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Brightness	0.33183	0.33121	0.55177	0.42514	0.48087	0.25252
Greenness	−0.24717	−0.16263	−0.40639	0.85468	0.05493	−0.11749
Third	0.13929	0.22490	0.40359	0.25178	−0.70133	−0.45732

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plane of vegetation rather than back through the
transition zone. Stratification of the data in Figure
5 by percent cover with 100 percent green or brown
leaves leads to the same conclusion: the transition
zone is populated largely by samples that are
"greening up," whereas samples of senescent veg-
etation remain, for the most part, in the plane of
vegetation until they have reached a relatively low
level of closure, and a very low Greenness. Once
these samples begin to migrate back toward their
starting point in the plane of soils, their Greenness
values are so low that the movement appears to take
place almost entirely within the plane of soils.

PLANE OF SOILS

In Figure 7, the plane of soils is viewed head-on,
by means of a −90-degree rotation about the *x*- or
Brightness axis in Figure 4 (again by the right hand
rule). Now Greenness is perpendicular to the page,
and Brightness and the Third Component are on
the *x*- and *y*-axes, respectively. The same projec-
tion, with only soils data plotted, is shown in Fig-
ure 8.

While detailed understanding of the soil charac-
teristics expressed in variation within the plane of
soils is the object of current research, several pieces
of evidence suggest that soil moisture content is at
least one important factor determining the Third
Component value of bare soil targets.

First, because analysis of reflectance spectra has
shown middle-infrared reflectance to be most sen-
sitive to soil moisture (Stoner and Baumgardner,
1980), one could logically assume that the Third
Component of the TM Tasseled Cap, which contrasts
middle-infrared reflectance with visible and near-
infrared reflectance, would show a degree of mois-
ture sensitivity.

Second, the dispersion of the bare soil and sand
plots in Figure 8 can be used to support this hy-
pothesis. Because these data represent, in both
cases, multiple observations over time from a fixed
set of plots, one must conclude that the spectral
variation observed is the expression not of variations
in intrinsic soil *properties* (e.g., particle size distri-
bution or minerology) but rather of variations in soil
condition. One might reasonably expect that soil
moisture content would vary over a period of several
months. Thus, while other candidates may also be
considered (surface crusting, for example), moisture
content is, perhaps, the most likely.

Finally, evidence exists in the laboratory-mea-
sured soils data which points to moisture content as
an important factor in determining Third Compo-
nent values. Most of the soil series in this portion
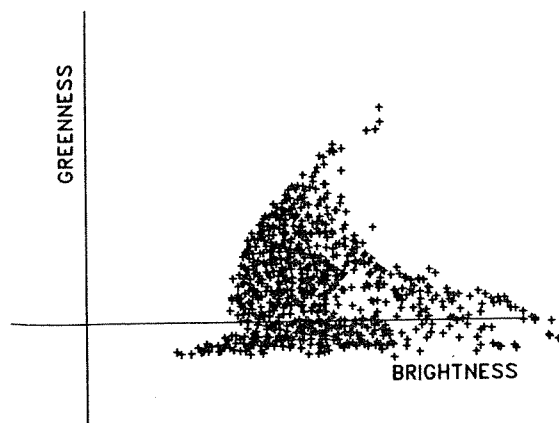of the data set are represented by two samples. The

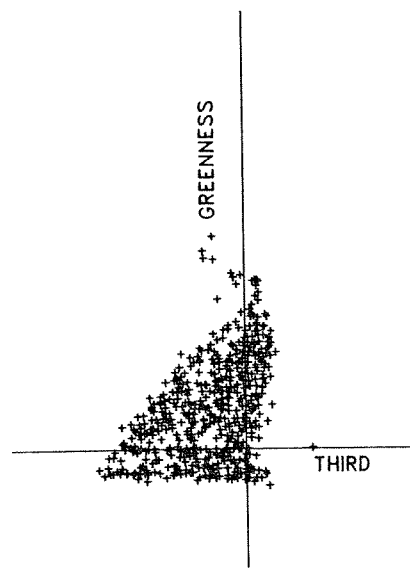FIG. 4.   The plane of vegetation. TM Greenness and
Brightness.

FIG. 5.   Side view of the planes in TM Feature Space.
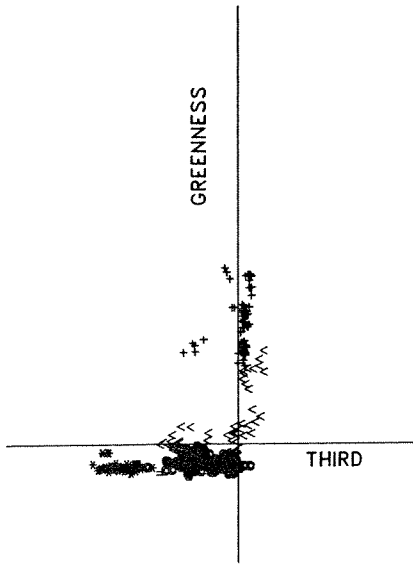Greenness versus Third Component.

FIG. 6.   Greenness versus Third Component-Samples. KEY: '+' = 100 percent green, 100 percent cover; '<' = 90 to 100 percent brown, 75 to 100 percent cover; '@' = lab-measured soils; '*' = field soil samples; '=' = sand samples.
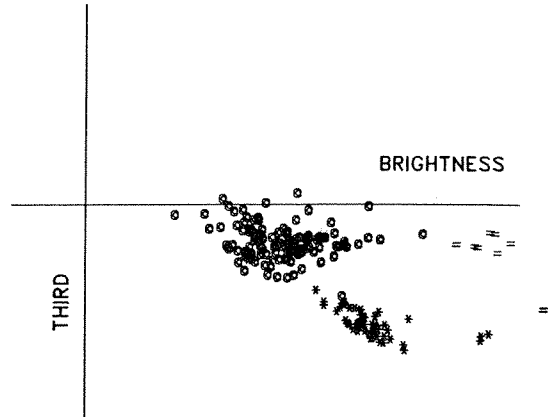
FIG. 8.   The plane of soils. Only soils data plotted. KEY: '@' = lab-measured soils; '*' = field soil samples; '=' = sand samples.

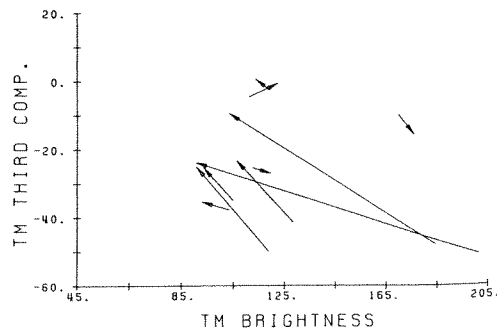FIG. 7.   The plane of soils. Third Component versus Brightness.

FIG. 9.   Direction and magnitude of change in plane of soils associated with change in soil moisture content. Each vector represents the two samples of a single soil series.

mechanism by which these samples were selected (Stoner and Baumgardner, 1980) allows for the possibility that some soil properties will vary between the two samples. By identifying those pairs of samples which have substantial differences in a particular characteristic and small differences in other characteristics, the impact of each soil property on spectral response can be considered essentially independently.

In Figure 9, vectors are plotted which show the magnitude and direction of change in spectral response within the plane of soils for ten soil series

whose samples vary with respect to moisture content (defined as percent by weight of dry samples). Selection of the ten soil series was based on two sortings. First, all the series were sorted with respect to the relative change in moisture content between samples. Second, the 20 series with the largest relative change in moisture content were sorted based on the largest relative change in other properties expected to influence the middle-infrared versus visible and near-infrared contrast. The data in Figure 9 represent the ten series with the least variation in those other properties. A clear preference can be seen in the alignment of the vectors, a preference which is consistent with the previous discussion of the field plot data—increases in moisture content tend to be associated with lower Brightness values, and Third Component values nearer to zero.

Other soil properties, including the proportions of fine sand, medium sand, and clay, cation exchange capacity, iron oxide content, and organic matter content, were evaluated in the same way,

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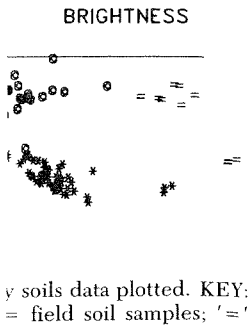
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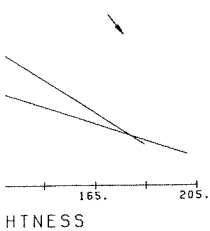
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but none were found to show a preferential align-
ment or magnitude of change comparable to that
seen in Figure 9. Thus, while the influence of other
soil properties cannot be dismisssed, soil moisture
appears to be a major influence on spectral variation
in the plane of soils.

As is clear from both Figures 8 and 9, the spectral
response attributed to moisture content occurs in
both Brightness and the Third Component. Because
soil moisture is known to affect albedo (Stoner and
Baumgardner, 1980), the correlation in spectral re-
sponse is not unexpected. However, while both fea-
tures appear to respond to moisture, new informa-
tion is still being provided by the Third Component.
Looking again at the field data from bare soil and
sand plots in Figure 8, one can see that the Bright-
ness of all the sand plots is higher than that of all
but a few of the soil plots. More importantly, the
Brightness of those sand plots with near-zero Third
Component values is greater than that of the bare
soil plots with very negative Third Component
values. If in fact the response in the Third Com-
ponent is the result of moisture status, then this new
dimension has indeed allowed the discrimination of
condition classes which are undetectable using
Brightness alone. We conjecture that *changes* in
Brightness are associated with *changes* in moisture
status, but that the Third Component provides a
more *absolute* measure of moisture condition. If this
is the case, then the added information is of consid-
erable importance.

Complete understanding of the new information
provided by this new spectral dimension will only
be achieved over time through experience with a
wide range of TM data. Further analysis may show
that other directions in the plane of soils are better
correlated to particular soil properties or conditions.
Clearly, however, an important new source of soil
information is made available through inclusion of
the middle-infrared bands of the Thematic Mapper.

EXPLANATION OF PLANAR DISPERSION

The reason that the TM data primarily fall into two
roughly perpendicular planes can be understood, at
least in part, by examination of typical vegetation
and soil spectra (Figure 10). The high near-infrared
reflectance and low visible reflectance associated
with green vegetation, the contrast between which
is detected by Greenness, is a function of the cel-
lular structure of the plant (Knipling, 1970). Thus,
the lack of soil variation in the Greenness direction
is not surprising. The high near-infrared reflectance
values associated with green vegetation also result
in a positive absolute difference between near- and
mid-infrared reflection for these data. This relation-
ship is seen in all green vegetation samples, and in
many brown vegetation samples, and thus explains
the near-zero Third Component values of most ve-
getated spectra. It should be noted that few spectra
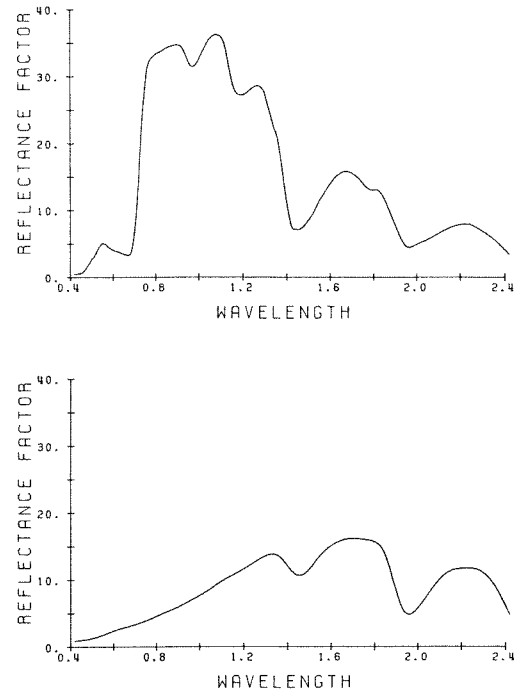of moisture-stressed vegetation were available for

FIG. 10.   Typical green vegetation and soil spectra. (a) Av-
erage of tillered wheat spectra. (b) Laboratory-measured
moist soil sample (series: Drummer).

analysis, and it is possible that such samples would
deviate from the plane of vegetation in the direction
of more negative Third Component values (larger
difference between the mid-IR and other bands).
Nevertheless, it appears that the high near-infrared
reflectance of green vegetation is responsible both
for the definition of the Greenness component and
for the restriction of vegetation variation in the di-
rection of the Third Component.

While differences in absolute calibration of some
of the TM bands could, as mentioned earlier, alter
the angular relationship between the planes of soil
and vegetation, the calibration of the sensor has no
effect on the independence of the physical factors
which are responsible for the presence of planes of
data dispersion in the TM Tasseled Cap space, nor
on the physical factors causing variation in those
planes. The loss of statistical independence would,
however, require non-linear techniques to extract
independent soil- or vegetation-related information.

LESSER COMPONENTS

The other components in the TM feature space
are shown in Figure 11. It would appear that some
information of interest may be present in the Fourth
Component, particularly with respect to soils. As
seen in Table 4, TM Band 1, which falls in the blue
wavelength region unsampled by the MSS bands,
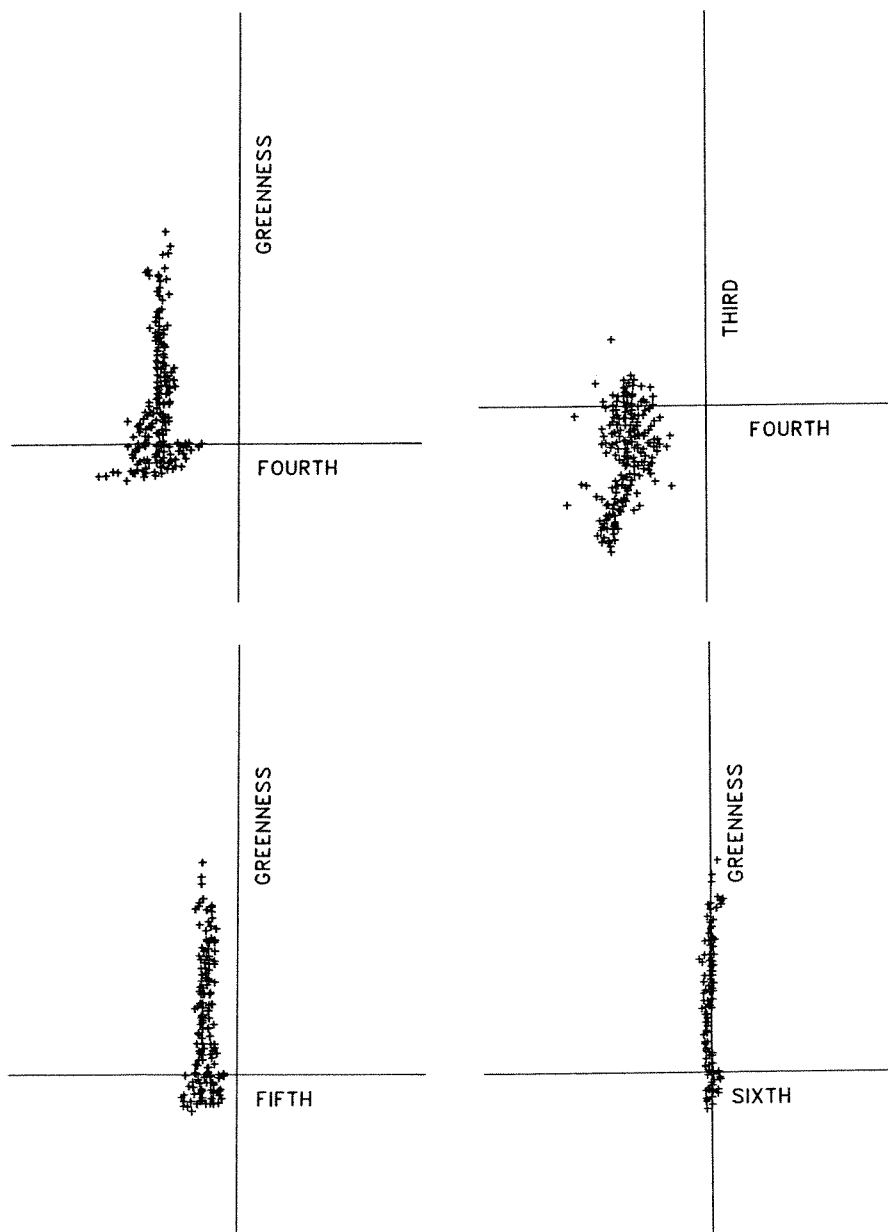plays an important role in this Fourth Component.

FIG. 11.   The lesser components of the TM feature space.

TABLE 4.   TM FEATURE SPACE TRANSFORMATION COEFFICIENTS—LESSER COMPONENTS

Feature	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Fourth	−0.83104	0.07447	0.42144	−0.07579	0.23819	−0.25247
Fifth	−0.32530	0.05361	0.11485	0.11140	−0.46571	0.80549
Sixth	0.11381	−0.89714	0.42038	0.06686	−0.01629	0.02706

However, it is also appar
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SUMMARY

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However, it is also apparent that the axis of principal soil variation in the Greenness and Fourth Component dimensions (Figure 11a) is not parallel to the x-axis (Fourth Component), indicating that any information relevant to soils in the Fourth Component will also show up in Greenness. Rotation of these two components to align the soil variation with the x-axis, which would eliminate most of the variation in soil Greenness values, would also increase the variation of vegetation in the Fourth Component and reduce the dynamic range of the Greenness variable. However, in either case the total data variation relative to the first three components is small.

The fifth and sixth components, unrotated from those produced in the original principal components analysis, show little variation and are unlikely to carry much, if any, important information with respect to agricultural crops or soils. It is of interest to note, however, that other uses may be found for these higher components. The XSTAR haze normalization algorithm (Lambeck *et al.*, 1978), which was developed for use with MSS data, utilizes the third component of the Tasseled Cap Transformation as a haze diagnostic. This component, termed Yellowness, is primarily a contrast between MSS Bands 4 and 5, and is sensitive to atmospheric scattering effects. The sixth component in the TM feature space described here is primarily a contrast between the equivalent TM bands (Bands 2 and 3), and thus may be of use in an XSTAR-like algorithm. Certainly, this study indicates that the amount of variability in this component associated with vegetation or soil characteristics is negligible.

SUMMARY AND CONCLUSIONS

Simulated Thematic Mapper data from a variety of soils and crops at a wide range of development stages primarily occupy three dimensions: two analogous to the MSS Tasseled Cap features Greenness and Brightness, and a third related primarily to soil features including moisture status. The behavior of moisture-stressed vegetation in the Third Component could not be assessed in this data set. With a uniform atmosphere, most of the variability of the crop and soil data is confined to these three dimensions, with a lesser amount of soil variation in a fourth dimension.

While most of the new information in the TM bands for this data set seems primarily related to soils, the new dimension will make achievement of full canopy closure easier to detect, and may also enhance the ability to estimate the relative mix of vegetation and soil in any particular picture element. Thus, the potential exists for improvement in our ability to assess the condition of vegetation and draw inferences related to that assessment. Certainly, more understanding is needed as to the gains in information, both direct and indirect, that are offered by the increased data dimensionality. In addition, geologic spectra should be evaluated with

respect to their location in this TM feature space. Finally, of course, actual Thematic Mapper data must be evaluated, once data from a sufficient mix of field conditions, crop types, stages of development, and cover classes are available, in order to establish the similarities and differences in data dispersion as compared to these simulated data. Clearly, however, a Tasseled-Cap-like transformation of Thematic Mapper data shows promise of being as valuable a tool as the Tasseled Cap Transformation has been for MSS, both in terms of data reduction and enhanced interpretability.

REFERENCES

Badhwar, G. D., and K. E. Henderson, 1981. *A comparative study of the Thematic Mapper and Landsat spectral bands from field measurement data*. NASA Report SR-JO-04029, NASA Johnson Space Center, Houston, Texas.

Barker, J. L., 1983. *Spectral characterization of Landsat-D Thematic Mapper subsystems*. NASA Technical Memorandum, NASA Goddard Space Flight Center, Greenbelt, Maryland.

Biehl, L. L., M. E. Bauer, B. F. Robinson, C. S. T. Daughtry, L. F. Silva, and D. E. Pitts, 1982. A crops and soils data base for scene radiation research. *Proceedings of the Symposium on Machine Processing of Remotely Sensed Data*, Purdue University, West Lafayette, Indiana, pp. 169-177.

Crist, E. P., 1984. Effects of field conditions and cropping practices on corn and soybean spectral development patterns. *Remote Sensing of Environment* (In Press).

Crist, E. P., and R. C. Cicone, 1984. Comparison of the dimensionality and features of simulated Landsat-4 MSS and TM data. *Remote Sensing of Environment* (In Press).

Dave, J. V., 1978. Extensive datasets of the diffuse radiation in realistic atmospheric models with aerosols and common absorbing gases. *Solar Energy* 21:361-369.

Ince, F., 1981. The application of the coalescence clustering algorithm to remotely sensed multispectral data. *Pattern Recognition*, 1980 Conference on Pattern Recognition, 14:N1-6.

Kauth, R. J., and G. S. Thomas, 1976. 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*

Band 7

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of Remotely Sensed Data, Purdue University, West Lafayette, Indiana, pp. 4B41-4B51.

Knipling, E. B., 1970. Physical and physiological basis for the reflectance of visible and near-infarared radiation from vegetation. *Remote Sensing of Environment* 1:155-159.

Lambeck, P. F., R. J. Kauth, and G. S. Thomas, 1978. Data screening and preprocessing for Landsat MSS data. *Proceedings of the Twelfth International Symposium on Remote Sensing of Environment*, Environmental Research Institute of Michigan, Manila, Phillipines, pp. 999-1008.

Markham, B. L., and J. L. Barker, 1982. *Spectral characterization of Landsat-D Multispectral Scanner subsystems*. NASA Technical Memorandum 83955, NASA Goddard Space Flight Center, Greenbelt, Maryland.

Stoner, E. R., and M. F. Baumgardner, 1980. *Physiochemical, site, and bidirectional reflectance factor characteristics of uniformly moist soils*. Technical Report 11679, Laboratory for Applications of Remote Sensing, Purdue University, West Lafayette, Indiana.

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