NASA/DCLC 1983

DC-Y3-04440
NSTL/ERL-212

83-11

AgRISTARS

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

Domestic Crops and Land Cover

NOVEMBER 1983

Technical Report

A CORRELATION ANALYSIS OF PERCENT CANOPY CLOSURE VS. TMS SPECTRAL RESPONSE FOR SELECTED FOREST SITES IN THE SAN JUAN NATIONAL FOREST, COLORADO

M. Kristine Butera

National Aeronautics and Space Administration
National Space Technology Laboratories
Earth Resources Laboratory
NSTL, MS 39529

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
DC-Y3-04440, NSTL/ERL-212		

4. TITLE AND SUBTITLE
A Correlation Analysis of Percent Canopy Closure vs. TMS Spectral Response for Selected Forest Sites in the San Juan National Forest, Colorado

5. REPORT DATE
November 1983

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
M. Kristine Butera

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
National Aeronautics and Space Administration
National Space Technology Laboratories
Earth Resources Laboratory

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.

12. SPONSORING AGENCY NAME AND ADDRESS
National Aeronautics and Space Administration

13. TYPE OF REPORT & PERIOD COVERED
Technical Report

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT
This investigation tested the correlation of canopy closure with the signal response of individual thematic mapper simulator (TMS) bands for selected forest sites in the San Juan National Forest, Colorado. Ground truth consisted of a photointerpreted determination of percent canopy closure of 0 to 100 percent for 32 sites. The sites selected were situated on plateaus at an elevation of approximately 3 km with slope ≤ 10 percent. The predominant tree species were ponderosa pine and aspen. The mean TMS response per band per site was calculated from data acquired by aircraft during mid-September, 1981. A correlation analysis of TMS response vs. canopy closure resulted in the following correlation coefficients for bands 1 through 7, respectively: -0.757, -0.663, -0.666, -0.088, -0.797, -0.597, -0.763. Two model regressions were applied to the TMS data set to create a map of predicted percent forest canopy closure for the study area. Results indicated percent predictive accuracies of 71, 74, and 57 for percent canopy closure classes of 0-25, 25-75, and 75-100, respectively.

17. KEY WORDS
Thematic Mapper Simulator
Forest Canopy Closure

18. DISTRIBUTION STATEMENT

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified		*

NSTL FORM 13 (JAN 1975) *For sale by National Technical Information Service, Springfield, VA 22151

A CORRELATION ANALYSIS OF PERCENT CANOPY CLOSURE VS. TMS SPECTRAL RESPONSE FOR SELECTED FOREST SITES IN THE SAN JUAN NATIONAL FOREST, COLORADO

November 1983

by M. Kristine Butera

National Aeronautics and Space Administration
National Space Technology Laboratories
Earth Resources Laboratory

NASA/NSTL/ERL Report No. 212

AgRISTARS TECHNICAL REPORT
DC-Y3-04440

TABLE OF CONTENTS

		Page
I.	INTRODUCTION	1
II.	STUDY AREA	3
III.	ACQUISITION OF REMOTELY SENSED DATA	3
IV.	GROUND TRUTH DATA ANALYSIS	4
V.	TMS DATA PROCESSING	6
VI.	CORRELATION AND REGRESSION ANALYSIS	7
VII.	RESULTS	9
	A. PREPROCESSING	9
	B. GROUND TRUTH	11
	C. CORRELATION AND REGRESSION ANALYSIS	14
VIII.	DISCUSSION	17
IX.	CONCLUSIONS	23
	ACKNOWLEDGEMENTS	24
	REFERENCES	24

LIST OF FIGURES

FIGURE #	TITLE	PAGE
1	Data Processing Strategy for Mission 221 TMS Data. Selected Names of ELAS Modules are Indicated in Four-Letter Acronyms. . . .	8
2	Generalized Spectral Response Curves for Vegetation and Soil.	20
3	Graph of Relative Reflectance vs. TMS Channels for Mission 221 Data. Graphs Demonstrate Discrimination Capability of TMS 5 for Canopy Closure.	21

LIST OF TABLES

TABLE #	TITLE	PAGE
1	Statistical Analyses of Mission 221 TMS Data. Means, Standard Deviations, and Coefficients of Variation for the Data Set when (A) Uncorrected, (B) Corrected for Sun Angle Effect, (C) Corrected for Sun Angle and Noise.	10
2	Pair-Wise Correlation Matrix for Channels 1-7 of Entire Mission 221 TMS Data Set	12
3	Summary of Ground Truth Data for San Juan National Forest, Colorado, Study Site. Percent Canopy Closure was Derived from Interpretation of September 1981 and September 1980 Color IR Photography and Field Observations. Species Identification is also Indicated	13
4	Results of Linear Regression Analysis of Percent Canopy Closure as a Function of TMS Reflectance from Mission 221 Data	15
5	Summary of Percent Accuracy of Prediction of Canopy Closure using TMS 5 Model.	16
6	Summary of Percent Accuracy of Prediction of Canopy Closure using TMS Multiband (3, 4, 5, 6) Model	18

I. INTRODUCTION

This work was undertaken to test the capability of the Landsat Thematic Mapper (TM) sensor and to develop analytical methods for using these satellite data in anticipation of their availability on a regular basis. This investigation uses Thematic Mapper Simulator (TMS) data acquired by aircraft to evaluate a technique for predicting percent forest canopy closure. It is assumed that the results of this investigation will be directly applicable to TM data analysis.

Previous work in the analysis of TMS data relating to forest canopy is limited. Using portable radiometers with wavelength intervals equivalent to those of the TM, some investigators have concluded that TM band 4 or the ratio of band 4/band 3 is optimum for biomass surveys (Tucker, 1978; Blanchard and Weinstein, 1980; Salomonson, 1980). Biomass may be considered an indicator of canopy closure. However, these studies dealt with grass, not forest, as a target.

Dottavio (1981) examined the effect of forest canopy closure and other environmental variables on incoming solar radiation using a three-band field radiometer with wavelength intervals corresponding to TM bands 3, 4, and 5. She concluded that percent canopy closure was the most significant variable affecting incoming solar radiation, with r values of 0.84, 0.81 and 0.73 for bands 3, 4, and 5, respectively. She noted that linear models based on the above results performed less well in the midranges of canopy closure. These conclusions were limited, however, to field measurements obtained only for canopy closures ranging between 60 and 97 percent and at 0 percent. The results of this study were based on field radiometric measurements of incoming solar radiation below the canopy and therefore do not represent the same kind of reflectance measurements which would be made by an aircraft or satellite-borne sensor as it samples reflected energy above the canopy.

A more recent study by Dottavio and Williams (1982) had the advantage of utilizing aircraft-acquired TMS data, although the investigation did not examine forest canopy closure. Rather, the study analyzed TMS data and Landsat Multispectral Scanner (MSS) data to evaluate the "future" versus the present capability to map specific forest cover types. Their results indicated that TMS data produced a greater number of cover types than did MSS data. For almost all of the TMS data-derived classes, a subset of bands 2, 4, and 5 resulted in greater classification accuracy than did the full complement of TMS bands. Anderson (1982) also analyzed aircraft-acquired TMS data for forest inventory, but did not address canopy closure. In a comparison of classification accuracy for mixed forest, pine forest, and river bottom forest, he concluded that the choice of channels had a significant effect and that the same channels were not the most desirable for all three forest types. His analyses produced classification accuracies greater than 90 percent.

Percent forest canopy closure is an indicator of forest biomass, in general, although the quantitative relationships between percent canopy closure and forest biomass parameters are not well established. A determination of canopy closure, in addition to its significance to biomass, is also relevant to wildlife habitat assessment, watershed runoff estimation, erosion control, and other forest management activities. The objective of this investigation was to analyze the correlation between percent canopy closure and individual TMS band response for TMS data acquired over the San Juan National Forest, Colorado, in September, 1981. Regression models were then developed from the correlation results to create predictive maps of percent canopy closure. The following text describes the methods used and results obtained.

II. STUDY AREA

The study area for this investigation is an area of 26,375 ha in the San Juan National Forest in southwest Colorado. Elevation ranges from 2.4 to 4.0 km, although particular sites of interest were located on plateaus at an elevation of about 3 km. Areas of bare rock commonly occur within the study area. Annual precipitation varies with elevation and ranges from 30.5 to 127 cm per year. Predominant forest tree species include ponderosa pine (*Pinus ponderosa*, Dougl.), aspen (*Populus tremuloides*, Michx.), Engelmann spruce (*Picea engelmannii*, Parry), subalpine fir (*Abies lasiocarpa*, Hook), Douglas fir (*Pseudotsuga menziesii*, Franco), gambel oak (*Quercus gambellii*, Matt.), and juniper (*Juniperus scopulorum*, Sarg.). The study area is a part of the U.S. Forest Service's southern San Juan Mountains Planning Unit, the subject of a previous investigation to evaluate U.S. Forest Service lands using Landsat MSS data (Krebs et al., 1976).

III. ACQUISITION OF REMOTELY-SENSED DATA

The TMS maintained and flown on an aircraft by the NASA/National Space Technology Laboratories (NSTL) has a field of view $\pm 50^{\circ}$ of nadir and an aperture of 2.5 milliradians, which results in a spatial resolution of 30 m x 30 m for a pixel at nadir if the data are collected from an altitude above the ground of 12,000 m. Spectral resolution for TMS and TM bands in micrometers is as follows:

	1	2	3	4	5	6	7
TMS	0.46-0.52	0.53-0.61	0.63-0.69	0.77-0.90	1.52-1.69	10.4-12.3	2.04-2.24
TM	0.45-0.52	0.53-0.61	0.62-0.69	0.78-0.91	1.57-1.78	10.4-11.7	2.08-2.35

The TMS data were collected by the NASA/NSTL aircraft on September 18, 1981 at 11:30 a.m. local standard time, from an altitude of 12 km above mean terrain elevation. Aircraft mission 221 was flown along a north-south line approximately 27 km in length. Color infrared photography was simultaneously acquired using a Zeiss RMK16/23 gyrostabilized camera. The photography collected by a U-2 aircraft, referred to later in the text, was acquired in September, 1980, for an area overlapping this study area.

IV. GROUND TRUTH DATA ANALYSIS

The TMS data at the full scan of $\pm 50^{\circ}$ of nadir covered approximately 26,375 ha. of ground surface. Because of spatial and spectral distortion caused by variations in illumination and pixel geometry at the shallow look angles, only data $\pm 30^{\circ}$ from nadir were considered in this analysis. The look angle of $\pm 30^{\circ}$ from nadir, as opposed to a narrower swath, was required for coverage of the ground truth sites with TMS data.

Study plots approximately 10.12 ha (25 acres) in size were selected for vegetation type and canopy closure of overstory, as determined by air photointerpretation. Only plots characterized by a spatially uniform distribution of cover were selected. The intent of the approach was to ascertain if a significant relationship existed between percent forest canopy closure, irrespective of the several indigenous species, and spectral response for this environment. Future analyses will be directed at stratifying the species, where a greater number of plots representing the various species will be desired.

However, to reduce spectral variability caused by surface elevational differences, the sites used in the analysis were chosen from relatively flat, mesa formations as indicated by topographic contour information presented on USGS topographic maps. A flat area was defined as no greater than 10 percent slope from a USGS topographic map with a scale of 1:24,000. The geographic area covered by the TMS data $\pm 30^{\circ}$ of nadir was reviewed for as many such "flat" homogeneous plots as could be determined by using mission 221 photography and topographic information. The plots were also selected to represent a full range of canopy closure (0 to 100 percent). Of 36 plots originally selected, only those plots which lay within TMS coverage of the study area $\pm 30^{\circ}$ from nadir were used. These numbered 32. The potential number of plots with the required characteristics located within the TMS coverage was a limiting factor in the analysis.

Enlarged prints were made from the original 3.54cm (1:70,000 scale) mission 221 photography. Only frames 003, 004, and 005 were used and these were printed at a final scale of approximately 1:20,000. A Bruning areagraph chart no. 4849 dot grid reduced four times was used to determine percent canopy closure with a measurement precision of about 97 percent, according to the manufacturer of the chart. The percentage of dots that overlaid tree canopies in each plot was considered to be the percent canopy closure.

Photography acquired at a scale of 1:80,000 during a U-2 mission in September 1980, a year earlier, was prepared in a similar manner. Of the 32 plots, 13 were covered by the U-2 photography. A dot count was performed on these to determine percent canopy closure for comparison with results derived from the mission 221 photography acquired during the TMS overflight.

As a check on the photointerpretation, a field mission was conducted to collect data on each plot regarding the overstory and understory vegetation, i.e., percent canopy closure and species. Observations were also made on the soil surface material and general terrain. The ground truth mission was conducted April 14-18, 1982.

V. TMS DATA PROCESSING

TMS data were collected by the scanner in an analog format and subsequently converted to eight-bit digital format. The TMS digital data were then processed through various algorithms using ELAS, a comprehensive computer software system developed by the Earth Resources Laboratory (Graham et al., 1980). All computer processing was performed at ERL on a 32-bit minicomputer configured with adequate memory, associated peripherals, and image display devices. All data processing programs cited in this report are parts of the ELAS system.

Each channel of TMS data was reviewed in black and white on an image display device to evaluate data quality. As geometric distortion in the data $\pm 30^{o}$ from nadir was minimal, no geometric corrections were applied. Channels 1 and 7 exhibited some bad scan lines in the data, most probably caused by detector noise or interference due to air traffic communication. Data from all channels exhibited a gradient of values across the scan caused by shadows induced by a sun angle which was oblique to the north-south flight line at the time of data acquisition.

Several computer programs were employed to normalize the scan angle variations within the TMS data in each channel. These included: (a) an across-scan data analysis (CRSX) which computes the means and standard deviations of data values across the scan, and (b) a determination of correction coefficients and application of the same to the TMS data (RAMP/DRMP). The "noise" observed in channels 1 and 7 was corrected by a series of directives in a general algorithm for statistical processing of principal components (GASP). With this program, the TMS data were transformed into principal components. The component which constituted the noise was identified and removed, and the channel of the original data exhibiting the noise was corrected and restored using an inverse principal component transformation. Execution of CRSX on the TMS data before and after the RAMP/DRMP and GASP corrections provided a means of visualizing the change in average pixel value per column effected by the corrections. Image analysis of the corrected data verified the improvement in image quality.

In the next step, the 32 plots of photointerpreted percent canopy closure were located in the TMS data. This was accomplished by referring to the photo maps and interactively outlining the boundaries of each plot on a black and white image of channel 2 of the TMS data using a cursor on an image display device. The coordinates of the resulting polygons were stored in a polygon file.

Two steps extracted the reflectance data for the areas on the ground defined by the polygons. First, an eighth channel was created by duplicating one of the existing channels of data, superimposing the polygon coordinates on these data, and changing the data values within each polygon to a single value (PGUD). For example, all data values within polygon #1 were changed to 1, polygon #2 to 2, etc. The data values for all cells outside the polygon boundaries were changed to a single value (e.g., 255) not already represented by one of the 32 polygons. The second step involved the analysis of data from channels 1 through 7 within the geographical areas defined by the polygons. This was accomplished by executing MUCS, a program that computed basic statistics for each polygon on each of the seven channels as sorted by the polygon designations in channel 8. The output data included the means, standard deviations, coefficients of variation, and covariance matrices for reflectance data in the seven channels for all the polygons. Figure 1 summarizes the data processing strategy and ELAS modules employed to analyze the TMS data.

VI. CORRELATION AND REGRESSION ANALYSIS

For each polygon, a data table was created containing the reflectance statistics per channel and the percent canopy closure

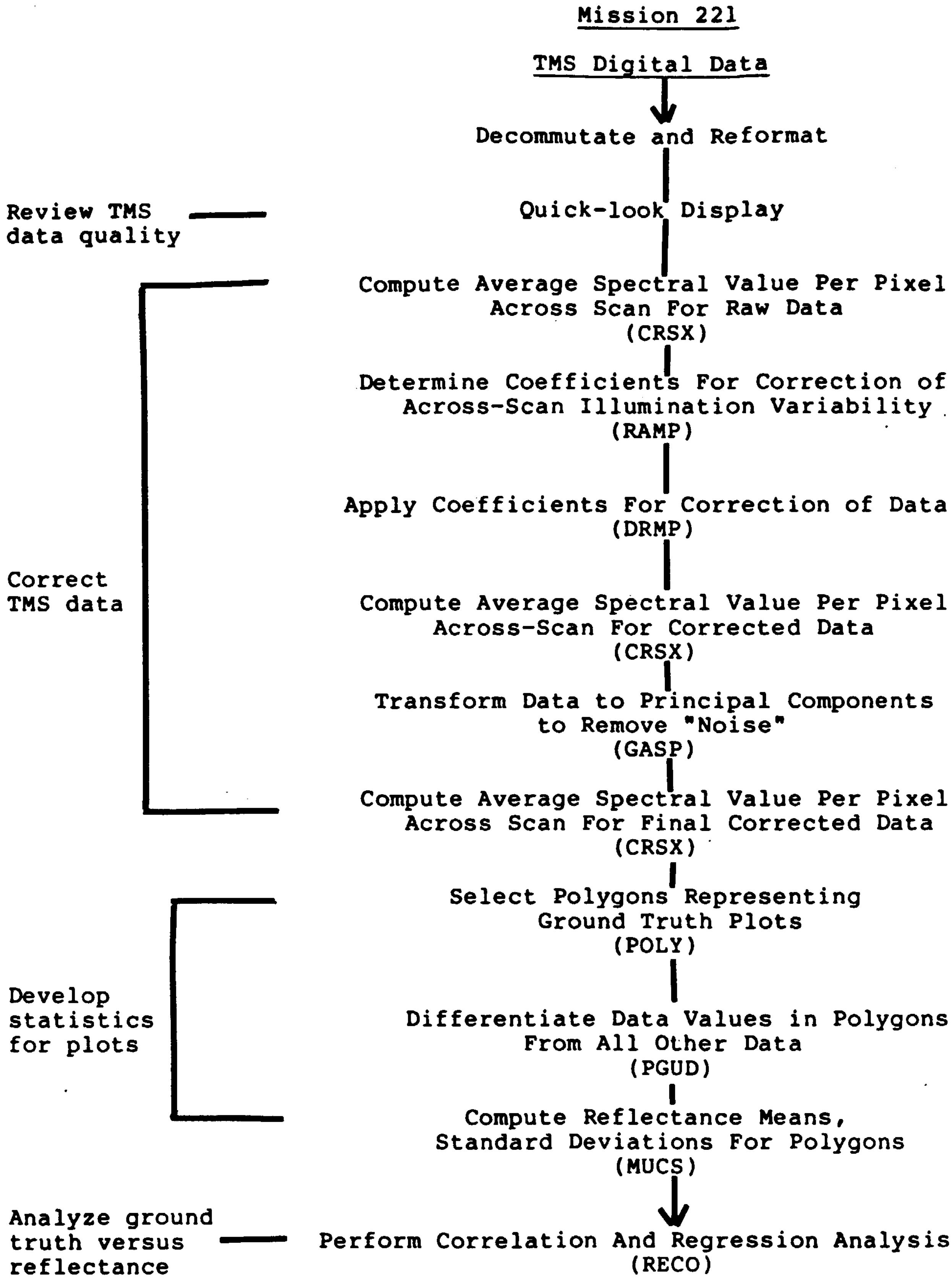


FIGURE 1. DATA PROCESSING STRATEGY FOR MISSION 221 TMS DATA. SELECTED NAMES OF ELAS MODULES ARE INDICATED IN FOUR-LETTER ACRONYMS.

as determined by the photointerpretation of the TMS overflight photography. Since the canopy variable was expressed as a binomial proportion, the percent canopy closure data were transformed to better approximate the variance expected in a normal distribution by using the following formula:

$$P_t = \text{Arcsin}\sqrt{P_a} \qquad \text{Eq. 1}$$

where P_t = transformed percent canopy closure

P_a = actual percent canopy closure

The arcsin transformation of the variable supported the testing of the significance of the regression models. A linear correlation and regression analysis was performed on P_t as a function of TMS reflectance for each channel using the ELAS program RECO.

VII. RESULTS

A. Preprocessing

As stated earlier, the analysis of the TMS data was restricted to $\pm 30^{\circ}$ of nadir. Each scan line, then, contained 418 elements. The dimension of an element at nadir for all 7 channels was approximately 30 m x 30 m. (The resolution of channel 6 of the TMS varies from that of channel 6 of the Thematic Mapper, which is actually 120 m.)

The data were corrected for scan angle variations in all channels and noise in channels 1 and 7, as described earlier. Table 1 presents the means, standard deviations, and coefficients of variation of the data set. In comparing the uncorrected with the corrected data, the mean reflectance decreased slightly in the latter by the following percentage for each channel: one - 0.9%, two - 0.8%, three - 0.9%, four - 0.4%, five - 1.6%, six - 0.7%, and seven - 2.2%.

TABLE 1. STATISTICAL ANALYSES OF MISSION 221 TMS DATA. MEANS, STANDARD DEVIATIONS, AND COEFFICIENTS OF VARIATION FOR THE DATA SET WHEN (A) UNCORRECTED, (B) CORRECTED FOR SUN ANGLE EFFECT, (C) CORRECTED FOR SUN ANGLE AND NOISE.

A. Statistical Analysis of Mission 221 TMS Data (Uncorrected)

	CH1	CH2	CH3	CH4	CH5	CH6	CH7
MEAN	56.34	66.20	59.88	121.74	33.34	89.00	25.37
STD. DEV	8.85	13.83	18.76	27.52	11.71	26.30	10.71
COEF. OF VAR.	0.16	0.21	0.31	0.23	0.35	0.30	0.42

B. Statistical Analysis of Mission 221 TMS Data Corrected for Sun Angle

MEAN	55.84	65.66	59.32	121.15	32.79	88.39	24.83
STD. DEV	7.18	10.63	15.37	25.58	10.41	22.02	9.81
COEF. OF VAR.	0.13	0.16	0.26	0.21	0.32	0.25	0.40

C. Statistical Analysis of Mission 221 TMS Data Corrected for Sun Angle and Noise in Channels 1 and 7

MEAN	55.81	65.66	59.32	121.15	32.79	88.39	24.81
STD. DEV	7.18	10.63	15.37	25.58	10.41	22.02	9.63
COEF. OF VAR.	0.13	0.16	0.26	0.21	0.32	0.25	0.39

A more significant change occurred with the correction of the data for the sun angle effect, rather than for the miscellaneous noise in channels 1 and 7. This change was observed by comparing the across-scan variation in the mean reflectance per pixel column per channel of the uncorrected data with that of the corrected data.

A correlation matrix, based on the corrected TMS data, shows the relationship between all band pairs (Table 2). TMS band 4, the near IR band, correlates less well with all other bands than does any other individual band, indicating that it may be a meaningful discriminator. However, as a discriminator, TMS band 4 apparently bears no significance to canopy closure measurements as discussed in a subsequent section of this paper.

B. <u>Ground Truth</u>

Table 3 displays the results of the percent canopy closure determination from (1) photointerpretation of the TMS overflight mission 221 photography, (2) photointerpretation of U-2 photography, and (3) field observations. Of those plots located on both photographic data sets, the mean difference between the percent canopy closure determinations was 3.1 percent. The field observations (April 1982) of a subset of the plots indicated close agreement with the photointerpreted results. Thus, the sum of these results lends confidence in the accuracy of the photointerpreted determinations of percent forest canopy closure used as the ground truth data. However, the mid range category of canopy closure (25-75 percent), which is the most difficult to determine, was unavoidably under-represented in the ground truth sampling.

Ponderosa pine, aspen, and gambel oak were the dominant tree species in the plots. The extent to which the fall color change might have influenced the spectral properties of the aspen and

TABLE 2. PAIR-WISE CORRELATION MATRIX FOR CHANNELS 1-7 OF ENTIRE MISSION 221 TMS DATA SET.[1]

	1	2	3	4	5	6	7
1	1.00						
2	0.93	1.00					
3	0.95	0.95	1.00				
4	0.45	0.55	0.40	1.00			
5	0.90	0.85	0.88	0.53	1.00		
6	0.68	0.68	0.70	0.38	0.75	1.00	
7	0.97	0.90	0.95	0.39	0.93	0.81	1.00

---

[1] Corrected for sun angle effect and noise in channels 1 and 7.

TABL[illegible]. SUMMARY OF GROUND TRUTH DATA FOR SAN [illegible]N NATIONAL FOREST, COLORADO, STUDY SITE. PERCENT CANOPY CLOSURE WAS DERIVED FROM INTERPRETATION OF SEPT. 1981 AND SEPT. 1980 COLOR IR PHOTOGRAPHY AND FIELD OBSERVATIONS. SPECIES IDENTIFICATION IS ALSO INDICATED.

GROUND TRUTH DATA FOR SAN JUAN NATIONAL FOREST, COLORADO, STUDY SITE

% Canopy Closure Derived From Photographic and Field Ground Truth				Species Identification		
PLOT # (25-ACRE SITE)	MX 221 (Sept. 1981)	U-2 MISSION (Sept. 1980)	FIELD OBSERVATION OF UPPER CANOPY (April 1982)	OVERSTORY	UNDERSTORY	GROUND
1	12.5			*Ponderosa pine/aspen		
2	97.1	97.2	100	Aspen (mature)	(none, no regeneration)	litter
3	5.8			*Ponderosa pine		
4	3.1		8	Englemann spruce/ Ponderosa pine/ aspen	Englemann spruce/ Ponderosa pine/ aspen	grasses/exposed soil
5	5.5	7.4	0	(None)	(None)	meadow/brush
6	4.9	7.5	0	Aspen regeneration (4-6)	(None)	grazed grasses/ exposed soil
7	0.0	0.0		*(None)	(None)	grasses
8	0.0	0.0	0	(None)	(None)	grasses/forbs
9	0.0	0.0	0	(None)	(None)	brush/grasses/ forbs
10	2.8	2.1	5	Ponderosa pine	Aspen	grazed grasses/ exposed soil
11	12.0	12.4	10	Ponderosa pine	gambel oak	grasses/forbs
12	22.1			*Ponderosa pine		
13	30.5			*Ponderosa pine		
14	88.2			*Ponderosa pine		
15	77.1			*Ponderosa pine		
16	75.5			*Aspen		
17	0.0		0	(None)	(None)	grazed grasses
18	0.0		0	(None)	(None)	grazed grasses
19	100.0	100.0	100	Englemann spruce/ sub-alpine fir	(None)	litter
20	97.4			*Englemann spruce/ sub-alpine fir		
21	23.4	12.8		*Aspen		
22	17.7			*Ponderosa pine		
23	45.0			*Ponderosa pine		
24	76.5		60	Ponderosa pine	(None)	gambel oak/ litter
25	55.2			*Ponderosa pine		
26	37.2		25	Ponderosa pine	gambel oak	grasses
27	91.9	79.6		Ponderosa pine		
28	99.5	99.6	100	Aspen	aspen (regeneration)	litter
29	95.1	99.4		*Aspen		
30	79.5			*Aspen		
31	50.8			*Aspen		
32	23.5	24.0	20	Ponderosa pine	gambel oak	grasses/ exposed soil
33	20.1		20	Ponderosa pine	(None)	grasses/ exposed soil
34	39.9		40	Ponderosa pine	(None)	grasses/ exposed soil
35	33.9	46.3		*Ponderosa pine		
36	54.9			*Ponderosa pine		

*Upper canopy species determined by photo-interpretation. No filed observations were made.

oak was considered minimal for the date of TMS data acquisition. Most of the plots did not exhibit an understory of trees, although most were covered by dry grasses or forbs, and one-third included exposed soil.

C. Correlation and Regression Analysis

Of the 36 ground truth plots, 32 were used for the extraction of the TMS data. (The other four plots did not lie within the $\pm 30^{o}$ of nadir TMS data set.) The mean spectral response per band per plot was then calculated and analyzed against the transformed ground truth data (P_t). Table 4 shows the results of the linear correlation and regression analysis. (As a point of interest, the correlation analysis was also performed on the non-transformed percent canopy closure data versus the TMS data, resulting in correlation coefficients that were only slightly lower than those obtained with the use of the transformed data.) The correlations were all negative, with the highest coefficients occurring for TMS bands 1, 5, and 7. It is noteworthy that these bands have been included in the TM sensor, but do not exist for Landsat MSS.

The linear regression model for TMS band 5:

$$\arcsin \sqrt{\%\ \text{canopy closure}} = 114.69 - 2.363\ (\text{TMS } 5) \qquad \text{Eq. 2}$$

was applied pixel by pixel to the entire TMS data set, although only predictions of percent canopy closure for areas of topographic slope $\leq$ 10 percent were considered valid based on the ground truth data from which the model was developed. The r^2 value indicates that 65 percent of the variance in transformed percent canopy closure is explained by the regression on TMS 5 response. The regression was found to be significant at the 99.99 percent level. Table 5 summarizes the predictive performance of the band 5 model for the 32 plots categorized in percent canopy closure ranges of 0-25, 25-50, 50-75, and 75-100,

TABLE 4. RESULTS OF LINEAR REGRESSION ANALYSIS OF PERCENT CANOPY CLOSURE AS A FUNCTION OF TMS REFLECTANCE FROM MISSION 221 DATA.[1]

TMS CHANNEL	r	r^2	m	b
1	-0.764	0.584	-3.695	239.591
2	-0.682	0.465	-2.188	175.172
3	-0.661	0.437	-1.509	124.360
4	-0.142	0.020	-0.246	66.933
5	-0.807	0.651	-2.363	114.685
6	-0.574	0.329	-0.887	116.067
7	-0.763	0.582	-2.588	99.842

r = correlation coefficient

m = slope

b = intercept

[1] % Canopy closure data were transformed using arcsin square root function to create a normal distribution.

TABLE 5. SUMMARY OF PERCENT ACCURACY OF PREDICTION OF CANOPY CLOSURE USING TMS 5 MODEL.

% CANOPY CLOSURE CLASS	% ACCURACY OF PREDICTION
0 - 25	67.6
25 - 50	29.2
50 - 75	37.5
75 - 100	48.7
0 - 25	67.6
25 - 75	73.9
75 - 100	48.7
0 - 50	77.5
50 - 100	88.1
0 - 100	100.0

where the percent accuracy of prediction was 67.6, 29.2, 37.5, and 48.7, respectively. Combining the midlevel classes into one range of 25 to 75 percent resulted in a predictive accuracy of 73.9 percent.

A multiple regression model was developed from covariance data and applied pixel by pixel to the TMS data. The model combines TMS bands 3, 4, 5, and 6 in the following relationship:

$$\arcsin \sqrt{\%\ \text{canopy closure}} = 38.359 + 1.533\ (\text{TMS } 3) + 0.427\ (\text{TMS } 4) - 4.614\ (\text{TMS } 5) + 0.15\ (\text{TMS } 6) \qquad \text{Eq. 3}$$

In the development of this model, randomly selected combinations of the independent variables were tested. Eq. 3 represents the multiple regression model with the best Wilk's Lambda statistic, indicative of significance at the 99.99 percent level, for the models tested. Table 6 summarizes the predictive performance of the multiband model for the 32 plots categorized in percent canopy closure ranges of 0 to 25, 25 to 50, 50 to 75, and 75 to 100, where the percent accuracy of prediction was 71.2, 29.2, 35.1, and 57.2, respectively. The midclasses regrouped to a range of 25 to 75 percent canopy closure resulted in an accuracy of 60.7 percent.

VIII. DISCUSSION

An analysis of the correlation results for percent canopy closure vs. TMS spectral response must address the integrated effect of target and background on reflectance. In this investigation, the correlation between canopy closure and spectral response was negative for all bands, indicating that the mean response decreased as canopy closure increased. If one considers the background of dried grasses or exposed soil, it may

TABLE 6. SUMMARY OF PERCENT ACCURACY OF PREDICTION OF CANOPY CLOSURE USING TMS MULTIBAND (3, 4, 5, 6) MODEL.

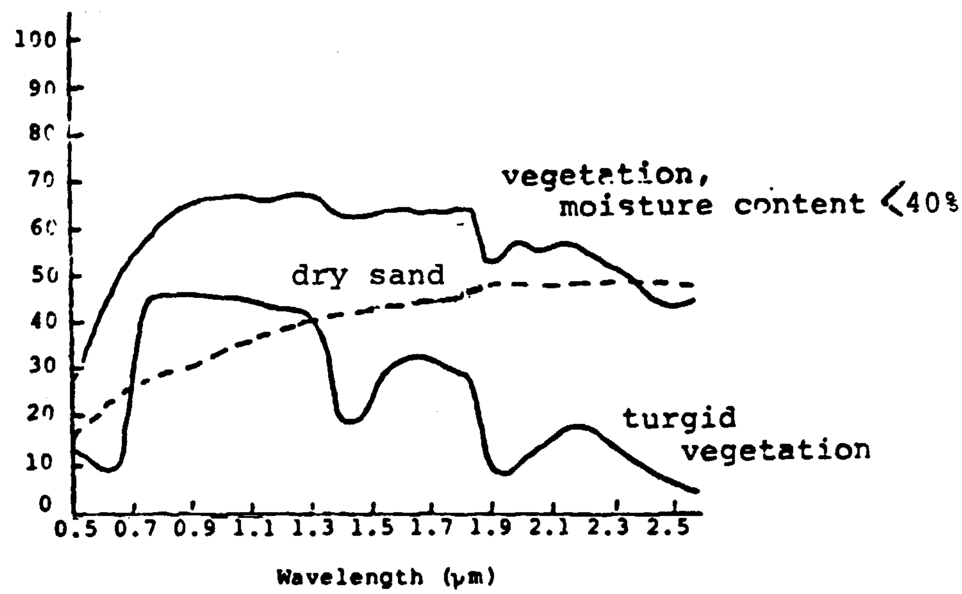
% CANOPY CLOSURE CLASS	% ACCURACY OF PREDICTION
0 - 25	71.2
25 - 50	29.2
50 - 75	35.1
75 - 100	57.2
0 - 25	71.2
25 - 75	60.7
75 - 100	57.2
0 - 50	80.4
50 - 100	82.2

be hypothesized that these elements contributed relatively higher reflectance values than did the forest canopy to the overall scene. Plots with a greater percentage of canopy closure, then, also had a lesser percentage of the more highly reflective ground cover contributing to the spectral signature. Indeed, published spectral reflectance curves for vegetation and soil support this idea (Figure 2). In the figure, reflectance curves for low-moisture-content vegetation and dry sand are both higher than for turgid vegetation.

The absolute correlation coefficient was higher for the relationship between TMS 5 and the transformed percent canopy closure than for any other band. Again referring to general reflectance curves for vegetation and soil in Figure 2, one may infer that for the interval 1.52 to 1.69μm corresponding to TMS band 5, it is possible that the distance between curves of turgid vegetation and a background of soil and senescing grasses might be maximized. No data were acquired representing the individual tree canopy and background spectral contributions to substantiate this hypothesis, however.

The low correlation between canopy closure and TMS band 4 was surprising in that this band supposedly relates to biomass, at least in the case of herbaceous material. Figure 3 displays relative signal response curves for three ground truth plots with 0 percent canopy closure and three ground truth plots with nearly 100 percent canopy closure, demonstrating the lack of discrimination in band 4 with respect to the true canopy variable. It is possible that for the particular conditions of the forest target and background soil and grasses in this study, reflective responses may have been relatively equal in TMS band 4. Figure 3 clearly demonstrates the greater separability between curves of 0 and 100 percent canopy closure for TMS bands 1, 5, and 7.

In development of the regression models to predict percent canopy closure, the influence of topographic slope as a variable



TMS Channels (μm)

1	2	3	4	5	6	7
0.46-0.52	0.53-0.61	0.63-0.69	0.77-0.90	1.52-1.69	10.4-12.3	2.04-2.24

Figure 2. GENERALIZED SPECTRAL RESPONSE CURVES FOR VEGETATION AND SOIL. (After Swain and Davis, 1978, Figures 5-10 and 5-13.) These curves provide an understanding of conditions of high spectral contrast that can occur between background and target.

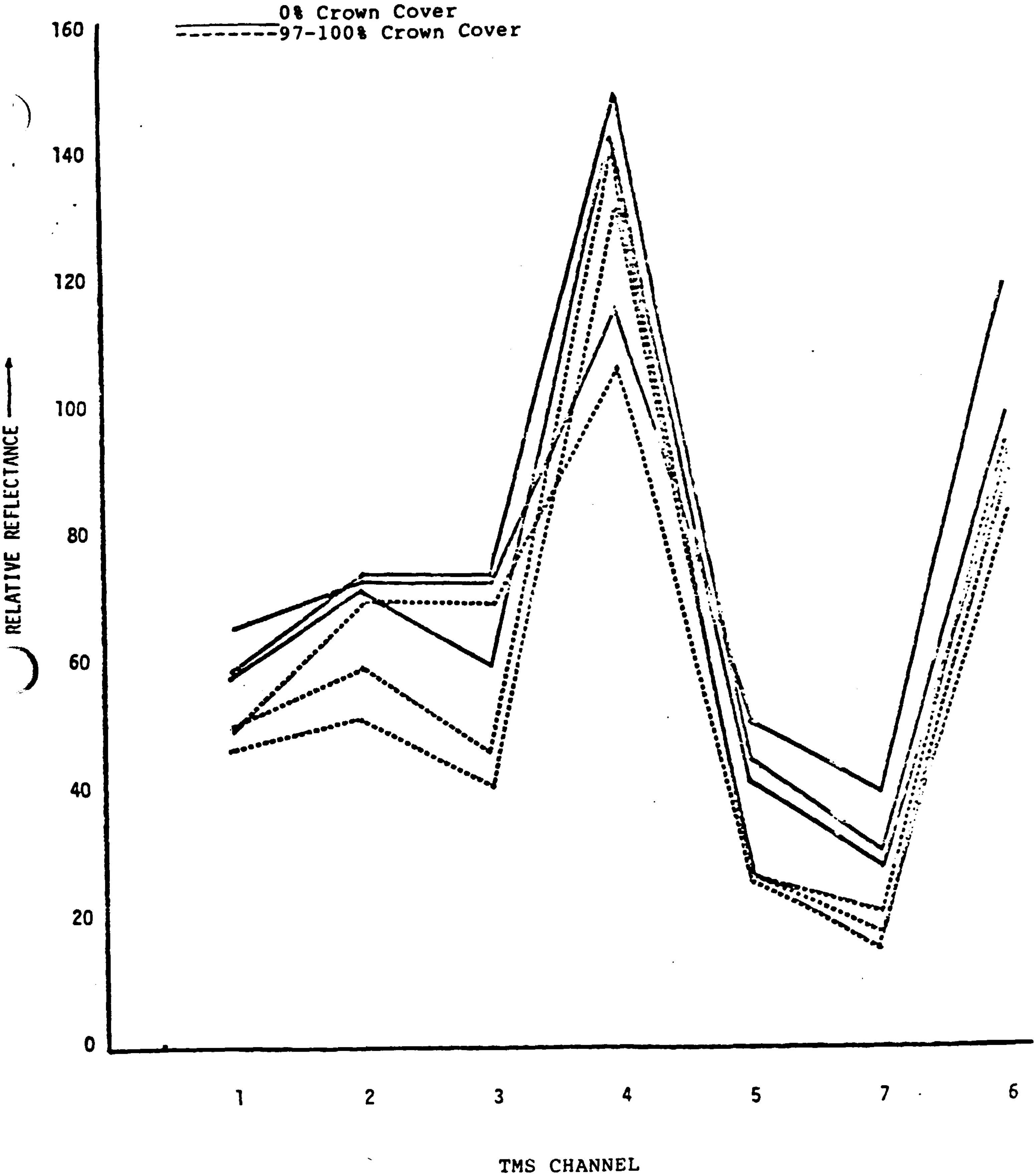


Figure 3. Graph of Relative Reflectance vs. TMS Channels for Mission 221 Data. Graphs demonstrate discrimination capability of TMS 5 for canopy closure. (Colorado Test Site, September 18, 1981)

was intentionally minimized. Vegetation species as a variable was minimized to some extent, but not eliminated, as the area considered for the analysis was dominated by ponderosa pine and aspen with lesser coverage by Douglas fir, Engelmann spruce, and gambel oak. Thus, it can be said that valid application of the models to predict percent canopy closure for this environment is not restricted to a monospecific condition.

A recommendation for the most accurate technique for prediction of percent canopy closure based on the results of this investigation can be derived by examination of the prediction accuracies summarized in Tables 5 and 6. It is apparent that these accuracies are lower for the middle classes of canopy closure, i.e., 25 to 50 and 50 to 75 percent. Dottavio (1981) also noted greater difficulty in estimating canopy closure for the midranges using her incoming solar radiance technique. Regrouping the middle classes into one range class of 25 to 75 percent raises the accuracy, although the utility of such a broad class may be questioned.

Using only the techniques evaluated in this investigation, a combination of the results from the application of the single band and multiband models is recommended. The optimum overlaying of the two data sets would include pixels with estimates from the band 5 model only for the 25 to 75 percent canopy closure class and pixels with estimates from the multiband model for the 0 to 25 and 75 to 100 percent classes. By combining results of the two models predictive accuracies for canopy closure classes of 0 to 25, 25 to 75, and 75 to 100 percent would then be 71.2, 73.9, and 57.2 percent, respectively.

This investigation focused on regression model development as a technique for predicting percent canopy closure from TMS spectral response. A follow-on effort should include an evaluation of other techniques, such as feature extraction, canonical correlation, and brightness/greenness component analysis. For whatever technique is developed to predict percent canopy closure, the performance of that technique should also be evaluated on an independent data set.

IX. CONCLUSIONS

Based on the results of this study, the following conclusions were reached:

- TMS bands 1, 5, and 7, essentially wavelength intervals not covered by the Landsat MSS, proved most significant in relating percent forest canopy closure to spectral response.

- The negative correlations resulting from the analysis of percent canopy closure and TMS spectral response for all bands were probably caused by a spectral contribution from the background (dry soil, senescing grasses) with higher reflectivity than the forest canopy.

- The results of this investigation were specific to one ecosystem for a given date and to a location of minimal slope.

- For a given ecosystem, the best predictive model is developed when conditions of greatest spectral contrast between background and forest vegetation occur.

- The techniques developed and conclusions reached in this TMS study are applicable to the utilization of TM data.

ACKNOWLEDGEMENTS

Special thanks are extended to Ms. Maria Kalcic for her assistance in the statistical analysis in this investigation and to Dr. Armond Joyce and Mr. John Ivey for providing direction and coordination of activities related to this study.

REFERENCES

1. Anderson, J. E. and M. T. Kalcic. 1982. Analysis of Thematic Mapper Simulator Data Acquired During the Winter Season Over Pearl River, MS, Test Site. AgRISTARS Technical Report RR-Y1-04217, NSTL/ERL-202. National Technical Information Service, Springfield, VA.

2. Blanchard, L. E. and O. Weinstein. 1980. Design Challenges of the Thematic Mapper. IEEE Transactions on Geoscience and Remote Sensing, Vol. GE-18, No. 2: pp. 146-160.

3. Dottavio, C.L. 1981. Effect of Forest Canopy Closure on Incoming Solar Radiance. In Proceedings of the 1981 Machine Processing of Remotely Sensed Data Symposium, Purdue University, West Lafayette, Indiana. pp. 375-383.

4. Dottavio, C. Lisette and Darrel L. Williams. 1982. Mapping a Southern Pine Plantation With Satellite and Aircraft Scanner Data: A Comparison of Present and Future Landsat Sensors. Journal of Applied Photographic Engineering. Vol. 8, No. 1. pp. 58-62.

5. Junkin, B.G. et al. 1981. ELAS-Earth Resources Laboratory Applications Software Report 183. NASA/NSTL Earth Resources Laboratory, NSTL Station, MS.

6. Krebs, Paula V. et al. 1976. Multiple Resource Evaluation of Region 2 U.S. Forest Service Lands Utilizing Landsat MSS Data. Type III - Final Report. NA55-20948. National Technical Information Service, Springfield, VA.

7. Salomonson, V.V. et al. 1980. An Overview of Progress in the Design and Implementation of Landsat-D Systems. IEEE Transactions on Geoscience and Remote Sensing, Vol. GE-18, No. 2: pp. 137-146.

8. Swain, Philip H. and Shirley M. Davis, eds. 1978. Remote Sensing: The Quantitative Approach. McGraw-Hill. p. 386.

9. Tucker, C. J. 1978. A Comparison of Satellite Sensor Bands for Vegetation Monitoring. Photogrammetric Engineering and Remote Sensing, Vol. 44, No. 11: pp. 369-138