Landsat-4 Thematic Mapper Scene Characteristics of a Suburban and Rural Area

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ABSTRACT: The primary focus of this study is to evaluate specific spectral discrimination properties of the Landsat Thematic Mapper (TM) and to assess selected methods to improve land cover mapping performance. The major land cover classes evaluated are water, forest, agriculture, excavated sites, major transportation routes, commercial and industrial sites, and residential neighborhoods. Four-band (29 July 1982) and seven-band (2 November 1982) TM data were digitally analyzed for a 200 km^2 area including Beltsville and Laurel, MD, which are northeast of Washington, DC.

Results indicated several important conclusions. Wavebands representing the four spectral regions on TM (visible, near-infrared, middle-infrared, and thermal-infrared) significantly represented the available spectral information for discriminating land cover. Redundancy within spectral regions provided for the deletion of two bands (TM 2: 0.52–0.60 μm and TM 6: 2.08–2.35 μm) without significant ($\alpha = 0.05$) loss of mapping accuracy. Clustered Landsat TM data permitted identification of water bodies to a size approximately three times smaller than that identified with Landsat Multispectral Scanner (MSS) data (11 July 1981). The TM's added dynamic range, finer spatial detail, and redefined and added spectral regions contributed to additional canonical variates of information over MSS.

The utility of specific image processing procedures, to enhance the capability of Landsat TM to map land use and land cover, was evaluated. The largest increase in classification accuracy (approximately 10 percent) was from reducing the within-class variance using a median filter or a smoothing procedure. The next largest improvement (8 percent) was from incorporating a second date in a bitemporal classification. The second date provided additional phenological information in addition to different bidirectional reflectances. Training site subcategorization and multivariate transformations resulted in approximately a 4 percent increase. A three factor analysis-of-variance (ANOVA) of median filtering, subclass categorization and bitemporal classification indicated a significant ($\alpha = 0.05$) increase for each factor without significant interactions. A combination of data filtering, subclass categorization, and bitemporal classification yielded an increase in classification accuracy by 16 percent from the untransformed TM data (79.2 percent to 95.2 percent).

INTRODUCTION

LANDSAT-4 WAS LAUNCHED on 16 July 1982 and Landsat-5 on 1 March 1984, each with two imaging sensors, the Thematic Mapper (TM) and the Multispectral Scanner (MSS). The TM is the latest generation of an Earth resource scanner system. The capabilities of TM for assessing various Earth resource issues are wide ranging. Applications range from determining the extent and changes of land cover to estimating agricultural yields. The TM has improvements over MSS with respect to spatial resolution, spectral regions, and radiometry. Previous work by Williams *et al.* (1984), Irons *et al.* (1985) and Toll (1985a) evaluated the relative merits of MSS and TM for land cover discrimination. Their studies indicated that TM's added spectral bands significantly improved classification accuracy. Dynamic range or signal improvements on TM produced a smaller increase. Results from the finer spatial resolution on TM were mixed and are a function of class type and field size.

OBJECTIVES AND SCOPE

The primary objective of this research effort is to study the application-related capabilities of using TM data for assessing surface cover. The reported research includes an evaluation of the spectral and spatial characteristics of the TM for discriminating suburban and rural land cover. MSS data also are evaluated for a reference. The TM spectral bands are evaluated extensively for numerous band combinations in a classification assessment. Canonical analysis was applied to examine the underlying structure of the TM spectral bands and to determine

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if additional canonical variates of information are contained in TM versus MSS. For assessment of the TM spatial properties,clearly identifiable targets (i.e., water bodies) from medium scale color infrared photography were referenced for comparisons to processed TM and MSS data for determining the minimum size spatial features that may be resolved.

A second aspect of the research effort examines computationally efficient processing procedures for improving TM data classification accuracy. Previous research (Toll, 1985a and Irons *et al.*, 1985) documented the increase in within-class variation with finer resolution TM data. Classification results indicated increases in within-class variation typically confounded per-pixel, maximum likelihood classifiers. Two low-pass data filters were evaluated to determine the effects on reducing spectral class overlap. An additional approach using a clustering procedure to subcategorize spectrally heterogeneous classes into normal frequency distributions was evaluated. After classification, the subclasses were combined back to the original classification scheme for verification. A canonical multivariate transformation was evaluated to reduce the within-class variation while maintaining between-class variation. Summer and fall image data were combined in a bitemporal classification to study the relative increase in accuracy with the other approaches when combining two-date phenological and viewing-illumination geometry information in a single classification. The paper is concluded with combining data filtering, subcategorization, and bitemporal classification in a three factor analysis-of-variance (ANOVA). The three factor ANOVA permits the evaluation of interactions while evaluating the significance levels of the factors. Since the various analyses necessitated different approaches, the methodology is incorporated in specific sections.

STUDY SITE DESCRIPTION

A site including Beltsville and Laurel, MD, north of Washington, DC (Figure 1) was selected for analysis. This area is an example of the developing urban fringe in the United States. In such areas planners and administrators are faced with decisions concerning development policy. Typically they have little information upon which to base their decisions. In the Beltsville–Laurel study area, there are a wide range of land use and land cover types. Here, major land cover classes are water, forest, agriculture, excavated sites, major transportation routes, commercial and industrial sites, and residential neighborhoods. The area has some intensive urban fringe development including multifamily and single family residential tracts and low density single family housing. There are numerous commercial support services such as shopping centers and industrial complexes. There is no heavy industry. The area has several rock quarries and small ponds in addition to the Rocky Gorge Reservoir. However, much of the area remains undeveloped forest, primarily hardwood trees with some softwoods intermixed. The study site encompassed a 500 × 500 pixel, 28.5^2 m resolution, TM image, yielding a 14 sq km size area.

DATA DESCRIPTION

A four-band 29 July 1982, Landsat TM P-data set (radiometrically and geometrically corrected) was obtained; the two middle infrared and one thermal-infrared band detectors were not yet activated. Seven-band, cloud-free TM and MSS P-data were obtained later on 2 November 1982. Plate 1 illustrates a 29 July 1982 TM image enhancement of the study area. The thermal band on TM was determined to be systematically offset and was shifted to register with the other six bands. Landsat-2 MSS P-data, collected on 11 July 1981, were also included in the data base because the coincident 29 July 1982 MSS data were not recorded. A comparison of MSS and TM instrumentation is given in Table 1. To assist all evaluations, color-infrared (CIR) photography of 1:40,000 scale flown on 13 July 1982 was used.

ANALYSES AND RESULTS

WAVEBAND COMBINATION

Land cover discrimination performance using Landsat TM data was studied for the 2 November 1982 seven-band data set. Each single band and all possible combinations of two and three bands were analyzed. Evaluation of land cover discriminations between bands was based on estimates of overall classification accuracy for seven land cover classes: water, forest, agriculture, extractive (exposed soil), transportation, commercial/industrial, and residential. Seventy-five pixels were selected in a stratified systematic procedure in order to reduce spatial dependence of pixel data for each class. To reduce possible problems associated with mixed-class pixels, those pixels near class boundaries were not selected. The image data were output on a CRT screen, and a cursor was manipulated in order to implement an aligned-systematic sampling technique (Cochran, 1977). Pixels were selected in a triangular network in which pixels lie at vertices of equilateral triangles. The total number of pixels was estimated by class, and this number was divided by 75 to obtain an estimate of the grid spacing between sample pixels. This procedure yielded 525 pixels for evaluation, a number determined sufficient for comparisons (Hord and Brooner, 1976; Hay, 1979). Since the objective was to evaluate comparisons, and since pixels were systematically selected to reduce statistical independence and were sampled throughout the study site, training and test pixels were combined. A conventional per-pixel Gaussian maximum likelihood classifier was used in the analysis. The overall classification accuracy was derived by dividing the

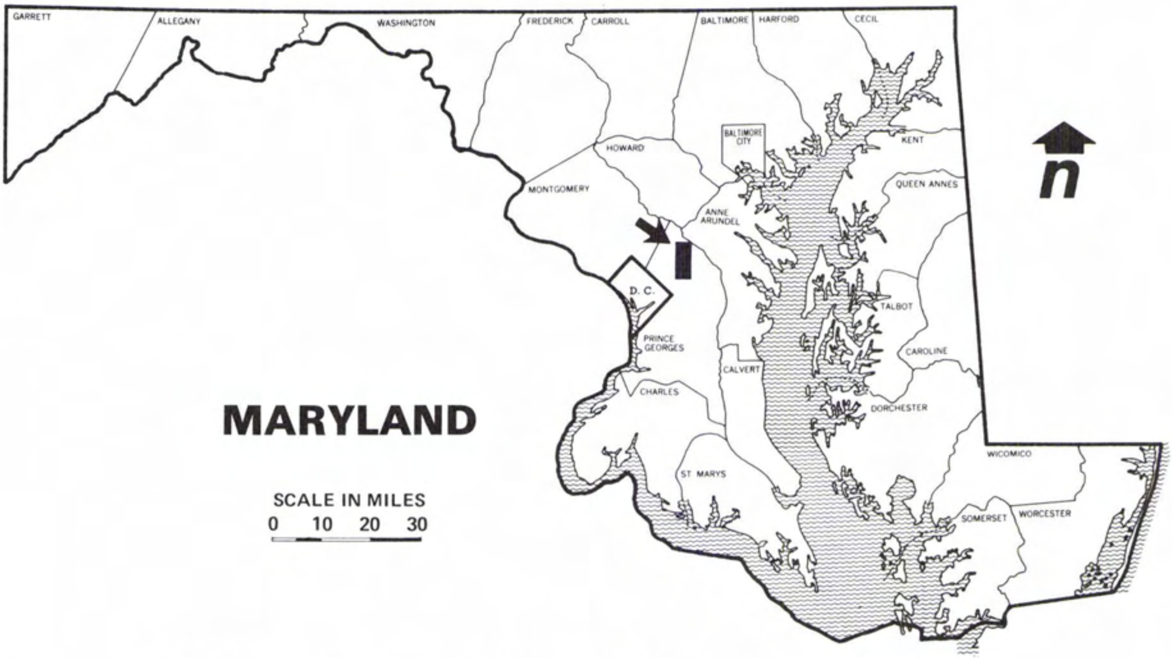


FIG. 1. Study site Is northeast of Washington, DC, including Beltsville and Laurel, MD.

total correct designations for the seven classes by the total pixels evaluated (i.e., $n = 525$).

Single Band Analysis. Table 2 groups overall classification accuracy estimates in 5-percent intervals for selected waveband combinations. An indication of the confidence level (Hord and Brooner, 1976) is included for the middle of each interval ($n = 525$ and $t = 1.96$). Results in Table 2 for the single band study indicate that middle-infrared bands provide the best spectral information to discriminate among classes. The middle-infrared bands, TM bands 5 and 6, are sensitive to surface moisture and canopy variations. The visible bands, TM bands 2 and 3, provided the next best spectral discrimination. For the visible bands, however, the forest class was frequently confused with both water and residental classes, and the commercial and industrial class was confused with residential and transportation classes. The use of the near-infrared band, TM band 4, yielded low classification accuracies for agriculture, commercial and industrial, and residential classes. However, the near-infrared band contributed to a different or unique discrimination in comparison to the other TM bands as evidenced in its low intraband correlations (Table 3). Classification results of the blue band, TM band 1, indicated a lower classification accuracy. This was likely associated with reduced spectral contrasts as a result of increased atmospheric scattering at the shorter wavelengths. The coarse spatial resolution of 120 m and reduced radiometric sensitivity of the thermal band, TM band 7, most likely contributed to its low classification accuracy. These rankings were similar to results from a preliminary study using aircraft data to simulate 30 m TM for a test site in Denver, CO (Toll, 1984a).

Multiband Analyses. Results from analyses of two-band combinations, indicated a representation from two of the three spectral regions—visible, near infrared, and middle infrared—yielded the best classifications (Table 2). For example, with the exception of the combination band 5 and band 6, each of the top 11 combinations had one band from two of the three spectral regions. Inclusion of TM band 4 was associated with the highest ranking as a result of its low intraband correlations (Table 3). Typically, the lowest grouping occurred when incorporating two bands within the visible region or combining a band with the thermal band. The low signal-to-noise ratio and coarse spatial resolution of the thermal band (band 7) typically resulted in the lower classification performance. Previous work in a semi-arid urban fringe area using 30 m TM simulator data indicated the thermal band was as useful as the other TM spectral bands for spectral class discriminations (Toll, 1984a). Hence, the 120 m spatial resolution and reduced dynamic range of band 7 may be the primary factor for the low ranking. An additional factor may be the acquisition time of day (9:30 a.m. local time) which is suboptimal for thermal imaging.

The three-band combination analyses exhibited

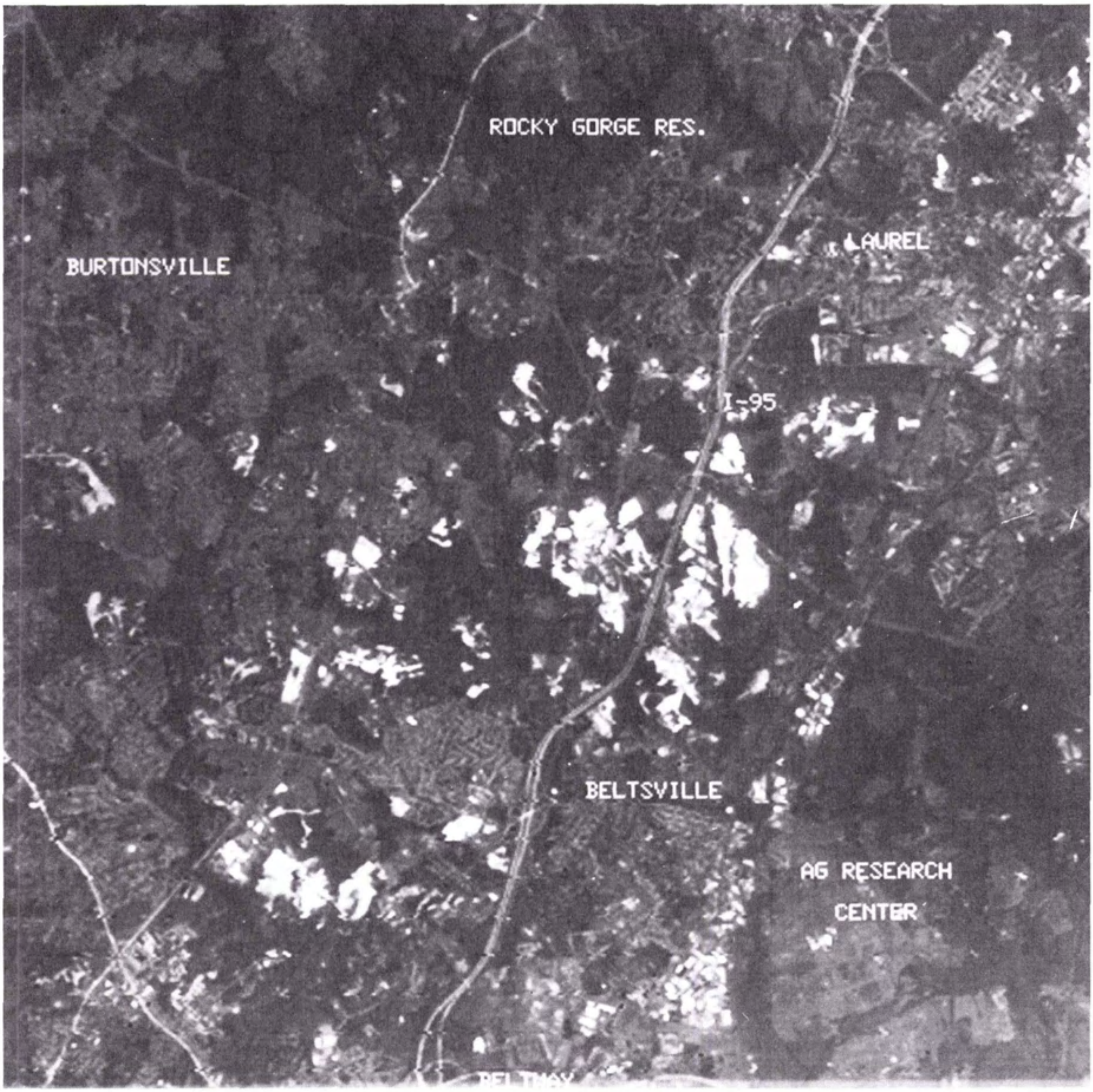


PLATE 1. Landsat-4 TM contrast enhancement of study site, 29 July 1982.

many of the same patterns observed for the two-band combinations. Typically, the best spectral discriminations were observed when spectral bands from each of the visible, near-infrared, and middle-infrared regions were included. These findings agree with a previous study using Thematic Mapper simulator data of suburban cover in Denver, CO, (Toll, 1984a) and in two forest discrimination studies using TM simulator data by Hoffer *et al.* (1975) and Dottavio and Williams (1982). Again, the thermal band generally contributed to the lowest classification accuracy.

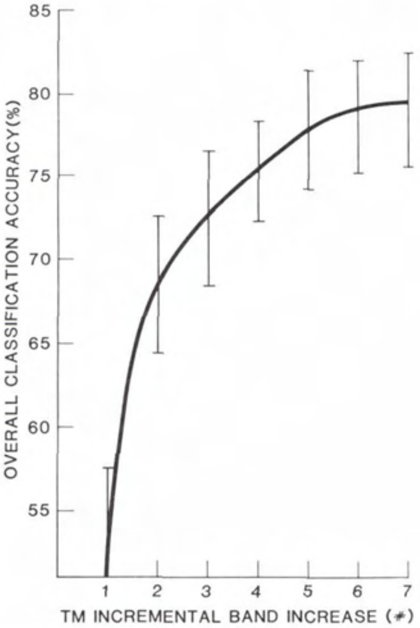
Incremental Band Increase. Figure 2 shows increases in overall accuracy as additional bands are added to the analysis. The increase in classification accuracy is most significant with the inclusion of TM band 4 and TM band 2 in a two-band classification. As the number of bands increases the rise in slope decreases. After five of the seven TM bands were included, subsequent additions of bands produced negligible increases in accuracy. Exclusion of a specific multispectral band in a multiband classification is optimized when the band to be excluded is highly correlated with other spectral bands. Two such candidates for exclusion are bands 2 (0.52–0.60 μm) and 6 (2.08–2.35 μm). Band 2 is highly correlated

TABLE 1. LANDSAT-4 EARTH-OBSERVING INSTRUMENTATION

Band Designation	Thematic Mapper (TM) Micrometers	Thematic Mapper (TM) Radiometric Sensitivity (NEΔρ)-Specification	Multispectral Scanner Subsystem (MSS) Micrometers	Multispectral Scanner Subsystem (MSS) Radiometric Sensitivity (NEΔρ)-Specification
Spectral Band 1	0.45–0.52	0.8%	0.5–0.6	0.57%
Spectral Band 2	0.52–0.60	0.5%	0.6–0.7	0.57%
Spectral Band 3	0.63–0.69	0.5%	0.7–0.8	0.65%
Spectral Band 4	0.76–0.90	0.5%	0.8–1.1	0.70%
Spectral Band 5	1.55–1.75	1.0%		
Spectral Band 6*	2.08–2.35	2.4%		
Spectral Band 7*	10.40–12.50	0.5 Kelvin (NEΔT)		
Ground IFOV		30 meters (Bands 1–5, 7) 120 meters (Band 6)		82 meters (Bands 1–4)
Date Rate		85 megabits/sec		15 megabits/sec
Quantization Levels		256		64

* Because all output was with the thermal band as the last entry, in this paper the TM 6 and TM 7 designations were switched with the thermal band as TM 7.

with band 1 (0.45–0.52 μm) and band 3 (0.63–0.69 μm), whereas band 6 is highly correlated with band 5 (1.55–1.75 μm) (Table 3). On the other side, band 4 (0.76–0.90 μm) has the lowest TM intraband correlations, and hence when included in a classification, the independent spectral data optimizes mapping performance.



NUMBER OF BANDS	BAND DESIGNATIONS	OVERALL ACCURACY (%)	95% CONFIDENCE INTERVAL, n = 525
1 BAND	5	53.5	49.2 - 57.7
2 BANDS	24	68.6	64.5 - 72.4
3 BANDS	246	72.9	68.9 - 76.5
4 BANDS	3457	75.0	71.1 - 78.5
5 BANDS	13457	78.1	74.3 - 81.4
6 BANDS	123457	78.7	75.0 - 82.0
7 BANDS	1234567	79.2	75.5 - 82.5

FIG. 2. Overall accuracy increase when spectral bands are added to the analysis.

LANDSAT TM VERSUS LANDSAT MSS WATER BODY IDENTIFICATION ANALYSIS

The potential of using Landsat TM and MSS data in identifying 55 water bodies scattered throughout the study area was evaluated. The water bodies were identified by examination of CIR photography (13 July 1982; 1:40,000) and were grouped by water body size (i.e., eight sizes between 11 m and 80 m). The eight groups were based on the diameter of the largest circle from a comparator placed on the CIR aerial photographs that could be totally inscribed within the water body. Assessment of shape was not evaluated. A line-printer map of the water bodies was produced through cluster analysis (i.e., unsupervised analysis) for both the Landsat TM and MSS data sets. Each water body identified from the CIR was compared with the clustered-derived water bodies from TM and MSS. A hit was tallied for the water body if one or more TM (or MSS) pixels were cluster-labeled as water. A false hit was indicated if the TM- (or MSS-) derived results indicated an area as water that was not observed on the CIR.

Results from the evaluation are given in Table 4. In general, water bodies with at least a 20 m water body size were identified by cluster analysis of 30 m TM data. The coarser 80 m resolution of Landsat MSS resulted in identification of water bodies approximately 60 m or greater in size. For both systems, then, water bodies were successfully identified when their sizes were approximately two-thirds or greater than the sensor's ground resolution. These results resemble the four-group water body analysis by Markham (1983) using 2 November 1982 TM and MSS data covering the La Plata, MD, area. In his study 86 percent of the water bodies between

TABLE 2. WAVEBAND CLASSIFICATION ANALYSIS SUMMARY

Overall Classification Accuracy (%) (95% confidence interval)*	1 Band	2 Band Combinations		3 Band Combinations	
70–75 72.5 (68.5–76.1)				TM 2 4 6 (72.9) TM 1 4 5 (72.6) TM 2 4 5 (72.4) TM 3 4 6 (71.2) TM 1 4 6 (71.0)	TM 1 3 4 (70.9) TM 1 2 4 (70.7) TM 2 3 4 (70.3) TM 3 5 6 (70.1)
65–70 67.5 (63.4–71.3)		TM 2 4 (68.6) TM 3 4 (67.2) TM 1 4 (66.8) TM 1 5 (66.0) TM 2 5 (65.9) TM 3 5 (65.5)	TM 5 6 (65.3)	TM 3 4 5 (69.7) TM 4 5 6 (68.6) TM 2 3 5 (67.8) TM 2 4 7 (67.8) TM 1 3 5 (67.6)	TM 2 5 6 (67.6) TM 1 5 6 (66.9) TM 1 4 7 (66.5) TM 1 2 5 (66.3) TM 3 4 7 (65.5) TM 2 5 7 (65.1)
60–65 62.5 (58.2–66.5)		TM 4 6 (64.0) TM 3 6 (60.7)		TM 1 2 7 (63.0) TM 1 2 6 (62.3) TM 1 6 7 (61.7) TM 3 5 7 (61.5) TM 2 3 6 (61.2)	TM 1 5 7 (60.4) TM 1 3 6 (60.2) TM 5 6 7 (60.0)
55–60 57.5 (53.2–61.6)		TM 1 6 (58.7) TM 4 5 (58.5) TM 2 3 (56.9) TM 1 3 (56.6)		TM 4 6 7 (59.0) TM 1 2 3 (58.1) TM 2 6 7 (58.1) TM 4 5 7 (56.7)	
50–55 52.5 (48.2–56.7)	TM 5 (53.5) TM 6 (52.6) TM 3 (50.5)	TM 2 7 (53.1) TM 3 7 (50.7)		TM 2 3 7 (54.3)	
45–50 47.5 (43.3–51.8)	TM 2 (46.7) TM 4 (45.9)	TM 5 7 (49.7) TM 1 2 (49.5) TM 6 7 (49.3) TM 4 7 (49.1)			
40–45 42.5 (38.3–46.7)	TM 1 (42.0)				
35–40 37.5 (33.4–41.7)	TM 7 (39.3)				

* number of samples = 525

30 m and 80 m were detected using TM data, whereas 23 percent were detected with MSS. For those water bodies greater than 80 m, 8 of 8 were successfully detected by analysis of both TM and MSS derived results. The improvement in identification of smaller water bodies by TM, indicates the finer resolvable surface features which can be detected and/or identified by 30 m resolution data versus 80 m resolution data. Of course, the detection of small surface features is directly affected by the spectral contrast. Water bodies were chosen in this analysis because of the significant spectral contrast with adjacent land cover.

CANONICAL ANALYSIS

A canonical transformation was applied to the TM and MSS data to explore the underlying structure of the spectral bands and to evaluate its effectiveness in land cover classification. Canonical analysis uses multivariate statistics associated with the specific categories to define an orthogonal linear transformation. This linear transformation reduces within-class variation with minimum loss of between-class variation. Merrembeck *et al.* (1976) indicated its utility in reducing random noise. The canonical transformation of Landsat data were based

TABLE 3. TM CORRELATIONS (R^2) FOR STUDY SITE PIXEL AREA (500^2 TM PIXELS)

	Band	1	2	3	4	5	6	7
2 Nov 1982	1	1.0						
	2	.96	1.0					
	3	.83	.89	1.0				
	4	.57	.62	.65	1.0			
	5	.76	.81	.79	.70	1.0		
	6	.84	.87	.84	.60	.95	1.0	
	7	−.05	−.10	−.16	.05	−.09	−.10	1.0
29 July 1982	1	1.0						
	2	.96	1.0					
	3	.96	.98	1.0				
	4	.10	.18	.16	1.0			

on the mean vectors, covariance matrices, and the number of observations for the categories (Lachowski *et al.*, 1978). These data were derived through clustering of image data to 60 spectral clusters. The 60 clusters were used to derive a canonical transformation and were not cluster-labeled in a classification procedure. Classification analyses of the canonically transformed image data were derived using the procedure described earlier.

Fall Data. Table 5 summarizes results from the canonical transformation and classification analysis for the 2 November TM and MSS scenes. Both TM and MSS had similar factor loadings for the first two canonical variates. The first variate consisted of positive loadings that were approximately proportional to the band standard deviations. Further, the first variate of the MSS and TM transformation both ranked the classes from low to high in the same order: water (MSS-56, TM-27), forest (MSS-67, TM-36), residential (MSS-73, TM-40), commercial (MSS-75, TM-43), transportation (MSS-76, TM-45), agriculture (MSS-79, TM-46), and extractive (MSS-95, TM-63). The second canonical variate produced differences between the visible and near-infrared data that were related to green leaf density. Examination of canonical variate two spectral data indicated the water, commercial, and extractive classes as grouped together, with the transportation (i.e, grass-covered median), residential, forest, and agricultural ranked in ascending order. Low classification accuracy and observed random variation in the third and fourth canonical variates of MSS, indicated the data were primarily noise (see exception below for the MSS canonical variate three discrimination of extractive). In contrast, TM canonical variate three provides a contrast between middle-infrared and visible spectral data. The primary spectral class discrimination was between the impervious classes transportation, commercial, and residential from the other classes. TM canonical variate four separated the extractive class from the other classes. The other variation was predominantly noise. Similarly, MSS canonical variate three also discriminated extractive from the other classes with the other variation consisting of random noise and banding. However, the overall accuracy is lower and compares with TM canonical variate six. As indicated by the low classification accuracy, TM canonical variate five has a strong correlation with the thermal band, TM band 7 ($r^2 = 0.79$). TM canonical variates six and seven provided little useful land cover discrimination information.

Summer Data. Results from the canonical transformation and classification analysis are given in

TABLE 4. WATER BODY IDENTIFICATION ANALYSIS

	29 July 1982 TM			11 July 1981 MSS		
Water Body Size	Hit	False Hit	Miss	Hit	False Hit	Miss
11–20 m	2	0	9	0	0	11
21–30 m	8	0	1	0	0	9
31–40 m	8	2	2	1	0	8
41–50 m	4	1	0	1	0	4
51–60 m	5	0	0	2	0	3
61–70 m	5	0	0	4	0	1
71–80 m	3	0	0	3	0	0
>80 m	5	0	0	5	0	0

TABLE 5. CANONICAL ANALYSIS SUMMARY FOR THE 2 NOVEMBER 1982 LANDSAT-4 TM AND MSS SCENES

Transformed Canonical Axes		Canonical Factor Loadings (and Correlations, r^2)—Band Number 1	2	3	4	5	6	7	Percent Variation	Overall Classification Accuracy (%)
2 Nov. 1982 TM	1	.07(.31)	.11(.38)	.09(.32)	.09(.32)	.20(.74)	.17(.58)	−.10(.04)	81.0	57.5
	2	−.11(−.51)	−.16(−.51)	−.14(−.38)	.19(.62)	.09(.34)	−.07(−.22)	.05(.11)	11.2	43.4
	3	−.13(−.46)	−.10(−.43)	−.01(−.18)	−.21(−.69)	.15(.48)	.06(.30)	.04(−.01)	6.5	29.3
	4	−.25(−.62)	.11(−.14)	−.24(.72)	.03(.17)	−.04(−.15)	.00(−.13)	−.07(−.26)	1.5	33.9
	5	−.13(.20)	−.30(−.20)	.16(.42)	−.03(.08)	.03(.11)	−.11(−.11)	−.36(.79)	0.3	34.7
	6	−.20(−.14)	.20(.11)	−.08(−.12)	.05(.08)	−.18(−.19)	−.36(.60)	.27(.45)	0.3	25.5
	7	−.22(−.01)	−.58(.58)	−.05(−.08)	−.06(−.04)	.09(.19)	−.25(−.36)	.20(.31)	0.1	20.7
Bands 1–7									100.0	83.4
2 Nov. 1982 MSS	1	.20(.30)	.26(.39)	.56(.76)	.36(.49)				76.7	52.8
	2	−.36(−.46)	−.54(−.70)	.15(.18)	.41(.49)				20.6	47.0
	3	−.07(.07)	.30(.39)	−.47(−.59)	.53(.69)				2.2	25.5
	4	−.65(−.83)	.37(.46)	.16(.20)	−.14(−.19)				.5	29.7
Bands 1–4									100.0	71.0

Table 6 for the four-band 11 July 1981 MSS and 29 July 1982 TM scenes. The 11 July 1981 MSS scene was chosen as a substitute for the unrecorded 29 July 1982 MSS scene. For both scenes, the canonical loadings and band correlations are similar. As indicated by the difference in canonical factor loadings and correlation between the visible and near-infrared bands, the first canonical variate is associated with information from the visible bands and the second with that information from the near-infrared. Examination of canonical variate three classification results indicates significantly more land cover discrimination potential for TM versus MSS data. Similar to the fall data, the canonical variates following the second variate provided greater classification performance for TM relative to MSS. This improvement is likely to be the effect of added spectral bands, increased dynamic range, and finer spatial resolution (Toll, 1985a; MacDonald, 1985). Canonical variate four for the summer and fall TM scenes exhibits factor loadings apparently related to chlorophyll absorption. The loadings are negative for the blue and red bands but positive for the green bands.

CLASSIFICATION IMPROVEMENT STUDY

Previous studies have documented an increase in classification accuracy when using TM data versus MSS data (e.g., Middleton *et al.*, 1983; Quattrochi, 1983; Brumfield *et al.*, 1983). Studies by Toll (1984a), Toll (1984b), Williams *et al.* (1984), and Markham and Townshend (1981) indicated the 30 m TM data for spectrally heterogeneous classes typically resulted in a decrease in classification accuracy versus 80 m MSS data. Reported improvements in accuracy for TM then were for spectrally homogeneous classes or a result of TM's improved radiometry and/or added spectral bands. For this study, selected procedures were evaluated to test their utility to improve the land cover classification for TM image data. Selected were two TM data filtering procedures, a canonical variate transformation, a training data subcategorization procedure, and a two-date classification procedure. As a baseline, the 2 November 1982 seven-band TM data were processed and classified. The seven-band land use and land cover classes and classification analysis procedure described earlier was used.

Filtering. Both a Gaussian weighted smoothing procedure and a median filtering procedure were evaluated. The Gaussian filter was circularly symmetric. The median filter sorted the pixel values from low to high and selected the median value for replacement. The two filtering procedures were selected to reduce the within-class heterogeneity, typically high in finer spatial resolution data such as TM. In two previous studies (Toll, 1984a; Toll, 1984b) and in a related study by Markham and Townshend (1981), classification results indicated that a coarser spatial resolution contributes to a

TABLE 6. CANONICAL ANALYSIS SUMMARY FOR THE 29 JULY 1982 LANDSAT-4 TM AND 11 JULY 1981 LANDSAT-2 MSS SCENES

Transformed Canonical Axes		Canonical Factor Loadings (and Correlations, r^2)—Band Number				Percent Variation	Overall Classification Accuracy (%)
		1	2	3	4		
29 July 1982 TM	1	.15(.58)	.08(.55)	.28(.82)	−.07(−.12)	73.2	55.4
	2	−.01(.10)	.02(.19)	.05(.24)	.25(.99)	25.5	50.8
	3	−.26(.79)	.03(.03)	−.24(−.50)	.02(.09)	1.2	42.5
	4	−.11(−.15)	.45(.81)	−.19(−.13)	−.01(−.02)	0.1	22.7
Bands 1–4						100.0	78.5
11 July 1981 MSS	1	.20(.66)	.38(.94)	.06(.24)	−.11(−.15)	61.4	51.8
	2	.06(−.08)	−.02(−.15)	−.21(−.81)	−.28(−.90)	37.9	52.0
	3	.60(.61)	−.43(−.32)	.21(.25)	−.15(−.07)	.4	28.9
	4	−.31(−.43)	−.02(−.05)	.42(.47)	−.34(−.41)	.3	26.0
Bands 1–4						100.0	73.9

higher classification accuracy for many urban fringe cover types such as residential. The coarser spatial resolution reduced the effects of within-class heterogeneity (e.g., roofs, driveways, and lawns of residential cover) through averaging and hence decreasing the spectral class overlap. However, there was an increase in class boundaries from the larger pixel size that typically confounded classifications.

A 5 × 5 pixel window cell was applied during the filtering procedures. Ideally, the window operator should be sufficiently large to decrease within-class variance but small enough to reduce contamination from adjacent classes or boundaries. In a study evaluating the utility of smoothing versus median filtering in reducing the variation in radar data, the median filtering procedure was found to maintain the multimodes of class signature distributions while reducing the within-class variation (Toll, 1985b). The smoothing procedures also reduced the within-class variation but tended to transform the frequency distributions to more of a unimodal distribution.

Results from the filtering procedure indicated a significant ($\alpha = 0.05$) increase in overall accuracy of 9.9 percent from median filtering and 11.3 percent from smoothing (see Table 7). Both filtering procedures reduced within-class variance, without causing a significant reduction in the distance between class means due to the inclusion of boundary class pixels. Forest and transportation classes produced the largest accuracy increases. The transportation classes exhibited an increase because the primary areas sampled were from interstate highways with significant amounts of surrounding vegetation. Hence, for the filtered data the impervious highway and vegetated adjacent cover was averaged. The more spectrally homogeneous classes such as water, agriculture, and extractive yielded similar accuracies between filtering and nonfiltering results.

Two-Date Classification. A comparison of a four-

TABLE 7. LANDSAT TM SUPERVISED CLASSIFICATION IMPROVEMENT STUDY

	Overall Classification Accuracy (%)	Confidence Interval (%) (95%)
Untransformed		
2 Nov. 1982 (7 bands)	79.2	75.5–82.5
Data Transformation		
Median Filtering	89.1	86.1–91.5
Smoothing	90.5	87.7–92.7
Canonical Transformation	83.4	80.0–86.3
Training Site Manipulation		
Class Clustering	83.2	79.8–86.2
Multidate Classification		
29 July 1982 and 2 Nov. 1982 (11 bands)	87.2	84.1–89.7
29 July 1982 (4 bands)	77.5	73.9–80.7
2 Nov. 1982 (4 bands)	72.9	68.0–75.4
2 Nov. 1982 (7 bands)	79.2	75.5–82.4

band TM classification (TM bands 1 through 4) of the 29 July 1982 scene with the 2 November 1982 scene indicated a 5.2 percent decrease in accuracy. The difference in classification performance may be attributable to phenological and reflectance changes between dates over the imaged area. On 29 July vegetation is at a near maximum growth, and thus the classes are distinguished by their association with differing vegetation cover. In the 2 November scene, the foliage loss and color change reduced vegetative cover contrast. In addition, the lower solar elevation on 2 November may have further changed the spectral contrast between classes. In an attempt to increase the classification accuracy of a single date, the 2 November seven-band and 29 July four-band scenes were merged forming an 11-band multitemporal composite image. Results from the multidate classification indicated a significant ($\alpha = 0.05$) increase by eight percent (79.2 percent to 87.2 percent) in overall classification accuracy (Table 7). This increase may be attributed to the two different stages of phenology including two different bidirectional reflectances (i.e., viewing and sun angle relationships).

Training Class Subcategorization. In the baseline approach a single signature was computed for each class. However, the higher spatial resolution TM data (30 m) were observed to have an increased variance with a multimodal frequency distribution. The increased variability and modality indicates subclass information (or within class cover noise) for a given cover class. Clustering was implemented for the baseline 2 November 1982 TM data in an attempt to statistically represent this added variability and also to have normal or unimodal distributions in the maximum likelihood classifier procedure that assumes multivariate normal density. Each of the seven land cover classes of 75 pixels were independently clustered to obtain subclasses or clusters. Classification results from the clustered class signatures indicated a significant ($\alpha = 0.05$) increase in overall classification accuracy of 4.0 percent (Table 7). A comparable increase was obtained when using many more pixels (i.e., 300 per class) in a related study (Williams *et al.*, 1984).

Canonical Transformation. A canonical transformation was applied to the TM data that provided linear and orthogonal transformations of axes to obtain maximum spectral class separability. The mean vector and covariance matrix were input to a canonical analysis procedure (Lachowski *et al.*, 1978). The mean and covariances were derived through clustering of TM data to 60 spectral clusters. After the TM data were canonically transformed, the data were sampled and analyzed by the procedure previously described. Results from the canonical analysis indicated the overall classification accuracy significantly ($\alpha = 0.05$) increased by 4.2 percent (Table 7). The increase may be attributed to a reduction in random noise as reported by Merembeck *et al.* (1976).

Three Factor ANOVA. To study the combined effects of data filtering, cover class subcategorization, and bitemporal classification, a three-factor analysis of variance (ANOVA) with two levels (i.e., with and without procedure) per factor (median filtering, clustering and bitemporal classification) was implemented. This yielded a design of eight treatments. A discussion of the specific ANOVA procedure followed may be found in Toll (1985a). Neter and Wasserman (1974) provide a good overview of ANOVA theory and procedures. The ANOVA results in Table 8 indicate each of the three factors significantly ($\alpha = 0.05$) improves classification accuracy. The most significant improvement was from data filtering followed by the two-date classification. However, clustering to obtain subclasses was barely significant at the 0.05 significance level. Results from ANOVA indicate interactions are not significant. Hence, the three procedures may be separately evaluated. A combination of filtering, subclass categorization, and bitemporal classification yielded an increase in classification accuracy by 16 percent (79.2 percent to 95.2 percent).

TABLE 8. THREE FACTOR ANOVA SUMMARY. CLASSIFICATION ACCURACY WAS CONVERTED TO DEGREES USING THE ARCSINE TRANSFORMATION

Source	Sums of Squares	Degrees of Freedom	Mean Square	F-Value	Tabular F-Value ($\alpha = 0.05$)
Subclass Categorization (A)	10.8	1	10.8	6.9*	3.84
Median Filtering (B)	72.7	1	72.7	46.6*	3.84
Bitemporal Classification (C)	70.1	1	70.1	44.9*	3.84
AB Interaction	1.9	1	1.9	1.2**	3.84
BC Interaction	0.7	1	0.7	0.4**	3.84
AC Interaction	2.0	1	2.0	1.3**	3.84
ABC Interaction/Error			1.56		

* Significant at 0.05 confidence level

** Interaction terms are not significant at $\alpha = 0.05$, hence $821/n = 1.56$, where $n = 525$, may be used as mean square-error with ∞ degrees of freedom (Landgrebe *et al.*, 1976)

SUMMARY AND CONCLUSIONS

This paper addressed two major points related to the analysis of the Landsat TM. First, evaluation of the utility of TM to discriminate surface cover was studied. In many cases, comparisons to Landsat MSS were conducted. Results indicated several important conclusions. Wavebands representing three spectral regions on TM (visible, near-infrared, and middle-infrared) were found useful for discriminating land cover. Redundancy within spectral regions led to deletion of two bands (TM band 2: 0.52–0.60 μm and TM band 6: 2.08–2.35 μm) without a significant decrease in classification accuracy. Clustered Landsat TM data allowed identification of water bodies to a size approximately three times smaller than that identified with processed Landsat MSS data. The TM's added quantization, finer spatial detail, and redefined and added spectral regions contributed from one to three additional canonical variates of land classification information over MSS with similar results reported by MacDonald *et al.* (1983), Sadowski *et al.* (1983) and Anuta *et al.* (1984).

The second portion of the study evaluated the utility of selected image processing procedures to enhance the capability of Landsat TM to map land cover. The largest increase in classification accuracy (approximately 10 percent) resulted from smoothing the data to reduce the spectral class overlap produced from within-class spectral heterogeneity. This was achieved through both a median filtering and a data smoothing procedure. The next largest improvement (8 percent) was from incorporating a second date in a bitemporal classification. Training site subcategorization and multivariate transformations resulted in approximately a 4 percent increase. A three factor ANOVA of median filtering, subclass categorization and bitemporal classification indicated an overall accuracy increase by 15 percent when including each of the three factors. Interactions were indicated to be nonsignificant.

TM-derived results from this study reinforced results from other studies using TM or TM simulator data under different land cover conditions (Toll, 1984a; Dottavio and Williams, 1983; Price, 1984; Williams *et al.*, 1984). Hence the analyses should indicate possible procedures that users may implement in their TM data processing. Specifically:

- In many digital land cover classifications, representation of a single band from the four major spectral regions will suffice;
- TM data may be used for discriminating smaller targets, such as agricultural fields, city blocks, etc. than previously obtainable with MSS data;
- The spatial information of TM is at a cost of increasing within-class variation, leading to errors in conventional per pixel maximum likelihood classifiers. Hence for many users a procedure to reduce these error variations while maintaining or enhancing the between-class variations, the signal, is recommended. Low pass filtering was found to be the most effective procedure for increasing classification accuracy.

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REFERENCES

Anuta, P. E., Bartolucci, L., Dean, M., Lozano, D., Malaret, E., McGillen, C., Valdes, J., and Valenzuela, R., 1984. Landsat-4 MSS and Thematic Mapper Data Quality and Information Content Analysis: *IEEE Transactions on Geoscience and Remote Sensing*, v. GE-22, no. 3 (May), pp. 222-236.

Brumfield, J. O., Witt, R., Blodget, H., and Marcel, R., 1983. Comparative Techniques used to Evaluate Thematic Mapper Data for Land Cover Classification in Logan County, West Virginia: *Proceedings Landsat-4 Science Characterization Early Results*, NASA Conference Publication 2355, pp. 403-414.

Cochran, W. G., 1977. *Sampling Techniques*, 3rd ed, John Wiley and Sons, New York, p. 428.

Dottavio, C. L., and Williams, D. L., 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*, v. 8.

Hay, A. M., 1979. Sampling Designs to Test Land-Use Map Accuracy: *Photogrammetric Engineering and Remote Sensing*, v. 45, no. 4, pp. 529-533.

Hord, R. M., and Brooner, W., 1976. Land-Use Map Accuracy Criteria: *Photogrammetric Engineering and Remote Sensing*, v. 42, pp. 671-678.

Hoffer, R. M., and Staff, 1975. Computer Aided Analysis of SKYLAB Multispectral Scanner Data in Mountainous Terrain for Land Use, Forestry, Water Resource and Geological Application, Final Report: Contract no. NAS9-13390, SKYLAB-EREP Project 398, LARS Information Note 121275, p. 381.

Irons, J., Markham, B., Nelson, R., Toll, D., Williams, D., Latty, R., and Stauffer, M., 1985. The Effects of Spatial Resolution on the Classification of TM Data: *International Journal of Remote Sensing*, (in press).

Lachowski, A. M., Borden, F. Y., and Merembeck, B. F., 1978. CANAL Program Description: in *Satellite and Aircraft Multispectral Scanner Digital Data User Manual*, B. Turner, D. Applegate, and B. Merembeck, eds., Orser Tech. Report 9-78, Pennsylvania State University, University Park, PA.

Landgrebe, D. A., and Staff, 1976. Final Report: NAS9-1039, MA-128TF, Laboratory for Applications of Remote Sensing, Purdue University, W. Lafayette, IN.

MacDonald, R., Hall, F., Pitts, D., Bizzell, R., Yao, S., Sorenson, C., Reyna, E., and Carnes, J., 1983. Preliminary Evaluation of the Thematic Mapper Image Data Quality: *Proceedings Landsat-4 Science Characterization Early Results*, NASA Conference Publication 2355, pp. 403-414.

Markham, B. L., 1983. Preliminary Comparisons of the

Information Content and Utility of TM versus MSS Data: *Proceedings Landsat-4 Science Characterization Early Results*, NASA Conference Publication 2355, Vol. IV, pp. 313-324.

Markham, B. L., and Townshend, J. R. G., 1981. Land Cover Classification Accuracy as a Function of Sensor Spatial Resolution: *Proceedings 15th International Symposium on Remote Sensing of Environment*, Environmental Research Institute of Michigan, Ann Arbor, MI, pp. 1075-1090.

Merembeck, B. F., Borden, F. Y., Podwysocki, M. H., and Applegate, D., 1976. Application of Canonical Analysis to Multispectral Scanner Data: *Proceedings 14th Annual Symposium on the Applications of Computer Methods in the Mineral Industries*, Oct. 4-8, University Park, PA, pp. 867-879.

Middleton, B., Witt, R., Lu, Y., and Sekhon, R., 1983. Relative Accuracy Assessment of Landsat-4 MSS and TM Data for Level I Land Cover Inventory: *Proceedings Landsat-4 Science Characterization Early Results*, NASA Conference Publication 2355, pp. 431-446.

Neter, J., and Wasserman, W., 1974. *Applied Linear Statistical Models*, Irwin, Homewood, IL, p. 842.

Price, J., 1984. Comparison of the Information Content of Data from the Landsat-4 Thematic Mapper and the Multispectral Scanner: *IEEE Transactions on Geoscience and Remote Sensing*, v. GE-22, no. 3, pp. 277-280.

Quattrochi, D., 1983. An Initial Analysis of Landsat-4 Thematic Mapper Data for the Discrimination of Agricultural, Forested Wetlands and Urban Land Cover: *Proceedings Landsat-4 Science Characterization Early Results*, NASA Conference Publication 2355, pp. 131-152.

Sadowski, F., Sturdevant, J., Anderson, W., Seevers, P., Feuquay, J., Balick, L., and Waltz, F., 1985. Early Results of Investigations of Landsat-4 Thematic Mapper and Multispectral Scanner Applications: *Proceedings Landsat-4 Science Characterization Early Results*, NASA Conference Publication 2355, pp. 281-298.

Toll, D., 1984a. An Evaluation of Simulated Thematic Mapper Data and Landsat MSS Data for Discriminating Suburban and Regional Land Use and Land Cover: *Photogrammetric Engineering and Remote Sensing*, v. 50, no. 12, pp. 1713-1724.

Toll, D., 1984b. Landsat-4 Thematic Mapper Scene Characteristics for a Suburban and Regional Test Site: *Proceedings of Landsat-4 Science Characterization Early Results*, NASA Conference Publication 2355, Vol. IV, 387-402.

Toll, D., 1985a. Effect of Landsat Thematic Mappers Sensor Parameters on Land Cover Classification: *Remote Sensing of the Environment*, v. 17, pp. 129-140.

Toll, D., 1985b. Analysis of digital Landsat MSS and Seasat SAR data for use in Discriminating Land Cover at the Urban Fringe at Denver, Colorado: *International Journal of Remote Sensing*, (in press).

Williams, D., Irons, J., Markham, B., Nelson, R., Toll, D., Latty, R., and Stauffer, M., 1984. A Statistical Evaluation of the Advantages of LANDSAT Thematic Mapper Data in Comparison to Multispectral Scanner Data: *IEEE Transactions on Geoscience and Remote Sensing*, v. GE-22, no. 3, pp. 294-302.

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