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SUMMARY OF RESEARCH ADDRESSING THE POTENTIAL UTILITY OF THEMATIC MAPPER DATA FOR RENEWABLE RESOURCE APPLICATIONS

J. R. Irons

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National Aeronautics and
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Goddard Space Flight Center
Greenbelt, Maryland 20771

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Earth Resources Branch – Code 923

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ABSTRACT

Landsat-D, scheduled for launch in July 1982, will carry a Multispectral Scanner Subsystem (MSS) similar to that flown on earlier missions, as well as a new multispectral scanner called the Thematic Mapper (TM). The TM will offer improvements over the MSS with respect to spectral, spatial, and radiometric characteristics. In preparation for the delivery of actual TM data, extensive research has been conducted using simulated TM data. A review of this research led to the following conclusions: TM's improved radiometric resolution will be a valuable sensor attribute; the availability of spectral bands from each portion of the reflective spectrum (visible, near-infrared, middle-infrared) will be very useful; and TM's finer spatial resolution will enable the identification of smaller spatial features, but research will be needed to develop improved classifiers which take full advantage of finer spatial resolution data. In general, the reviewed research indicates that the collective effect of the TM's improvements will be an increase in the content and utility of information extracted from TM data when compared to information derived from MSS data.

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LIST OF ACRONYMS

AgRISTARS	– Agricultural and Resource Inventory Surveys Through Aerospace Remote Sensing
CORSPERS	– Committee on Remote Sensing Progress for Earth Resources Survey
ERIM	– Environmental Research Institute of Michigan
FSS	– Field Spectrometer System
GSFC	– Goddard Space Flight Center
IFOV	– Instantaneous Field of View
LAS	– Landsat-D Assessment System
MSS	– Multispectral Scanner Subsystem
M^2S	– Modular Multispectral Scanner
MTF	– Modulation Transfer Function
NASA	– National Aeronautics and Space Administration
RBV	– Remote Beam Vidicon
SPOT	– Systems Probatoire d'Observation de la Terre
TM	– Thematic Mapper

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SUMMARY OF RESEARCH ADDRESSING THE POTENTIAL UTILITY OF THEMATIC MAPPER DATA FOR RENEWABLE RESOURCE APPLICATIONS

INTRODUCTION

Landsat-D, the fourth in a series of satellites dedicated to Earth resource observations, is scheduled for launch in the third quarter of 1982. In addition to a Multispectral Scanner Subsystem (MSS) similar to the instruments aboard the first three Landsat satellites, Landsat-D will carry a new sensor, the Thematic Mapper (TM). The TM is also a multispectral scanner, but this new instrument will offer improvements over the MSS with respect to spectral, spatial, and radiometric characteristics. The characteristics of the two instruments are summarized in Table 1.

A major objective of the Landsat-D program, conducted by the National Aeronautics and Space Administration (NASA), is to assess the capability of the TM and associated support systems to provide improved information for Earth resources management. In preparation for the delivery of actual TM data, extensive research has been conducted using simulated TM data. The objectives of such research have been to familiarize investigators with TM-like data, develop analysis techniques which can take full advantage of the sensor's improvements, and evaluate the potential utility of TM data for specific applications. Results of investigations conducted since 1975 are summarized in this document to provide guidance to the initial users of TM data in such matters as analysis techniques and potential applications.

BACKGROUND

The development of the Landsat-D program in general, and the TM in particular, began formally in 1970 when an in-house working group at NASA's Goddard Space Flight Center (GSFC) initiated planning for Earth observation satellite systems to follow the first series of Landsat satellites (GSFC, 1971). The final configuration of the program and instrument evolved from a subsequent progression of study efforts and advisory groups representing all facets of the remote sensing

Table 1. Landsat-D Earth-Observing Instrumentation (Salomonson et. al., 1980).

Band Designation	Thematic Mapper (TM)		Multispectral Scanner Subsystem (MSS)	
	Micrometers	Radiometric Sensitivity (NE$\Delta\rho$)	Micrometers	Radiometric Sensitivity (NE$\Delta\rho$)
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	10.40 – 12.50	0.5 Kelvin (NEΔT)		
Spectral Band 7	2.08 – 2.35	2.4%		
Ground IFOV		30 meters (Bands 1-6) 120 meters (Band 7)	82 meters (Bands 1-4)	
Data Rate		85 megabits/sec	15 megabits/sec	
Quantization Levels		256	64	

community. The studies and groups recommended configurations on the basis of user information and performance needs, the technical feasibility of system hardware commensurate with user needs, economic costs and benefits, recognition of Space Shuttle capabilities, and experience in the acquisition and analysis of data from sensors aboard Landsat 1, 2, and 3, Skylab, and aircraft. Salomonson et. al. (1980) provide an overview of the Landsat-D program which emerged from the development efforts.

The Landsat-D satellite will be launched from the Western Test Range in California during early July of 1982. The spacecraft will be launched into a sun-synchronous, near-polar orbit with a 98.22 degree inclination to the equatorial plane and a nominal altitude of 705 kilometers. On each descending (north-to-south) daylight pass, the satellite will cross the equator at approximately 9:45 a.m. solar time, and the orbit cycle will repeat in a manner which enables the remote sensing instruments to view a particular ground swath once every 16 days. The spacecraft's instrument payload will consist of a four channel MSS and the seven channel TM.

The TM is a nadir-pointing, electro-optical scanning radiometer. It will sense energy within seven distinct spectral bands of the visible, reflective infrared, and thermal infrared portions of the spectrum. Table 2 summarizes the principal application for which each band is intended. The sensor will view the Earth's surface through a scan angle of 15.4 degrees (± 7.7 degrees from nadir) which will result in the imaging of a 185 kilometer wide swath across the satellite's flight path given the nominal 705 kilometer altitude. The altitude, the design of the instrument's optics, and the size of the photosensitive detectors will produce a 30 meter ground resolution (a 30 meter-by-30 meter instantaneous-field-of-view) for the visible and reflective infrared spectral bands and a 120 meter resolution for the thermal infrared band (TM6). The electric signal from each detector will be sampled once per instantaneous-field-of-view (IFOV) and will be quantized to 256 digital levels. The radiometric sensitivity of the entire system in terms of noise equivalent change in reflectance or temperature will range from 0.5 to 2.4 percent depending on the spectral band (Ta-

Table 2. Rationale and Applications for TM Spectral Bands (Blanchard and Weinstein, 1980; Salomonson et. al., 1980).

Band Designation	Wavelength (micrometers)	Rationale	Principal Applications
TM1	0.45 – 0.52	Sensitivity to chlorophyll and carotinoid concentrations	Coastal water mapping, Soil/vegetation differentiation, Deciduous/coniferous tree differentiation
TM2	0.52 – 0.60	Slight sensitivity to chlorophyll plus green reflectance by vegetation	Detection of healthy vegetation
TM3	0.63 – 0.69	Sensitivity to chlorophyll concentration due to chlorophyll absorption	Plant species differentiation
TM4	0.76 – 0.90	Sensitivity to vegetational density due to high vegetational reflectance	Biomass surveys, Water body delineations
TM5	1.55 – 1.75	Sensitivity to leaf water content due to water absorption	Vegetation moisture content determination
TM6	10.4 – 12.5	Sensitivity to surface temperature	Thermal mapping
TM7	2.08 – 2.35	Sensitivity to leaf water content and hydroxyl ions in minerals	Hydrothermal mapping, Geologic mapping

ble 1). Table 3 lists significant TM characteristics and Table 4 presents instrument performance requirements. Engel (1980) describes the TM configuration and performance specifications in greater detail.

TM DATA SIMULATION

The data used to simulate TM data were derived from a variety of sources. For investigations which did not require digital image data, non-imaging spectrometers and radiometers have been employed in the laboratory and the field. In some cases, spectrometers such as the Field Spectrometer System (Bauer, et. al., 1979) sensed energy within narrow spectral bands and data from adjacent bands were integrated over the appropriate intervals to measure the energy within the TM bands. Other instruments, such as the hand-held radiometer described by Tucker, et. al. (1981), were filtered specifically for sensing within TM bands.

Aircraft multispectral scanner data have frequently been used to simulate TM digital image data. NASA operates three aircraft-borne multispectral scanners designed for sensing within the TM spectral bands. An eight-channel scanner called the NS001-MS (Richard, et. al., 1978) has been flown aboard a C130 aircraft at altitudes of 3,000 to 6,000 meters since 1978. In addition to the seven TM bands, the NS001-MS records data for a 1.00-to-1.30 micrometer (μm) wavelength band, and two temperature-controlled blackbodies and an integrating sphere provide in-flight calibrated reference sources which are sampled once per scan line. NASA's National Space Technology Laboratory/Earth Resources Laboratory has flown a modified Texas Instrument's RS-18 multispectral scanner aboard a Gates Learjet aircraft at altitudes near 12,000 meters since 1980. NASA's Ames Research Center operated a modified Daedalus DS-1260 multispectral scanner aboard an ER-2 aircraft at 18,000 meters during 1982. All of these sensors acquire data for all seven TM bands and quantize the data to 256 digital levels (eight bits) as will the TM. The NS001-MS is the only one of the three scanners which acquires in-flight calibration data for the reflective spectral bands. Over the years, investigators have also used data from a variety of other airborne multispectral scanners, with diverse spectral characteristics, for TM data simulation.

Table 3. Significant TM Parameters (Engel, 1980).

Orbit	**Sun Synchronous**
	705.3 km Altitude
	98.9 min Period
	98.2 Inclination
	16 Day Repeat Cycle
Scan	**185 km Swath**
	7.0 Hz Rate
	85% Efficiency
	± 7.7 degrees from nadir
Optics	**40.6 cm Aperture**
	f/6 at Prime Focus
	42.5 μrad IFOV, Bands 1-4
	f/3 at Relay Focus
	43.8 μrad IFOV, Bands 5,7
	170 μrad IFOV, Band 6
Signal	**52 kHz, 3 db, Bands 1-5,7**
	13 kHz, 3 db, Band 6
	1 Sample/IFOV
	8 Bits/Sample
	84.9 Mbps Multiplexed Output

Table 4. TM Mission Requirements (Blanchard and Weinstein, 1980).

Square-Wave Response	
Bands 1 to 5,7	0.35 at 30 m
Band 6	0.35 at 120 m
Band-to-Band Registration	< 6 m
Scan Profile Repeatability	< 6 m
Along-track Overlap/Underlap	< 6 m
Swath Width	185 km
Radiometric Resolution	
Bands 1 to 5,7	0.5 to 2.4% noise-equivalent reflectance (NEρ)
Band 6	0.5 noise-equivalent temperature difference (NETD)
Absolute Radiometric Accuracy	10%
Band-to-Band Radiometric Precision	2%
Channel-to-Channel Radiometric Precision	$< \frac{\text{rms noise}}{4}$
Spectral Coverage	0.45 to 12.5 m
Signal-Quantization Levels	256
Data Rate	84.9 Mbps
Weight	< 243 kg
Power	< 300 W
Envelope	0.6 by 1.1 by 2.0 m

Aircraft multispectral scanner data have required extensi processing to approximate the spectral, spatial, and radiometric characteristics of TM data and to compensate for radiometric and geometric distortions inherent in aircraft scanner data. Commonly applied processing steps include: averaging data from narrow spectral bands to simulate TM spectral bands; adjusting data for the radiometric effects of the wide scan angles employed by aircraft scanners; spatially degrading data to the TM resolutions by various methods including the use of filters whose Modulation Transfer Functions (MTFs) match the MTFs of the TM; geometrically adjusting the data to remove distortions caused by wide scan angles and to register the data to cartographic reference systems; transforming calibrated data to simulate TM radiometric response; and adding noise to approximate the radiometric sensitivity of each TM spectral band. Examples of rigorous applications of these processing steps are provided by Morgenstern, et. al. (1976, 1977), by Landgrebe, et. al. (1977), and by Irons and Labovitz (1982).

METHODS OF EVALUATING INFORMATION EXTRACTED FROM SIMULATED TM DATA

A frequently used approach to the evaluation of potential TM utility was to classify simulated TM digital image data into land cover categories. The evaluations were then based on classification accuracies or the accuracies of area mensurations for the various categories. Classification accuracies were usually expressed as the ratio of correctly classified pixels to the total number of pixels in an image. Often, only pure pixels (i.e., pixels which did not fall on the boundary between two categories) were considered. In some cases, matrices were produced which displayed omission and commission errors by category.

Several indices of mensuration accuracy can be found in the literature. For instance, the root-mean-square (rms) error of category proportion estimates is a useful indice described by Swain (1977):

$$\text{rms} = \left[\frac{\sum_{i=1}^{N} (P_i - r_i)^2}{N} \right]^{1/2}$$

where

N = Number of categories in the image;

P_i = Proportion of pixels classified as category i in the image;

τ_i = True proportion of the study area covered by category i.

Frequently, the classification and mensuration accuracies obtained by the analysis of simulated TM data were compared to results derived from the analyses of spatially or radiometrically degraded data in order to evaluate the effect of spatial or radiometric resolution on information extracted from digital image data.

LITERATURE REVIEW

Several of the Landsat-D design studies and advisory groups reviewed research literature pertaining to the determination of optimum sensor characteristics for various applications, particularly the remote sensing of vegetation (NASA, 1973; Harnage and Landgrebe, 1975; Application Survey Group, 1976; CORSPERS, 1976). This body of literature will not be revisited here. This paper cites literature published after 1975 which specifically addresses the anticipated performance or potential utility of the TM by way of the analysis of simulated TM data. Thus, the research summarized herein was conducted after the configuration of the TM was tentatively established and the characteristics of TM data could be anticipated.

Many of the papers cited herein compare results obtained with simulated TM data to results obtained with actual or simulated MSS data. The major differences expected between the MSS and the TM are: (1) the number, location, and width of the spectral bands; (2) the spatial resolution; (3) the radiometric sensitivity; and (4) the number of quantization levels. Some investigations considered the individual effect of a single TM characteristic while other studies have addressed the collective impact of all the TM improvements. Considered together, the investigations provide useful insight to the probable advantages and limitations of TM data for agricultural, forestry, and land cover mapping applications.

Agriculture

Due to the impetus of the interagency program for Agriculture and Resource Inventory Surveys Through Aerospace Remote Sensing (AgRISTARS), a significant portion of the research conducted with simulated TM data has been directed towards agricultural applications. A major AgRISTARS objective is to investigate and evaluate the application of TM data to the acquisition of accurate mensuration statistics for major trade crops (wheat, corn, soybeans, rice, barley, sorghum) on a worldwide basis throughout the growing season. The crop mensuration task served as a major justification for the implementation of improved spatial, spectral, and radiometric resolutions into the TM design.

To assess the impact of the improved resolutions on the imaging of an agricultural scene, spectrometer data were used in conjunction with aerial photography to synthesize simulated TM digital image data (Badhwar, et. al., 1981). The spatial configuration of an agricultural area in Kingsbury County, South Dakota, was described by drawing field boundaries on an overlay of an aerial photograph. The field boundaries were digitized, and the crop within each field was identified during on-site inspections. The digitized representation of the scene was converted to a grid cell format where each cell was equivalent in area to a TM pixel. For each grid cell, a TM response value for each of the six visible or reflective infrared bands was estimated on the basis of Field Spectrometer System (FSS) data acquired over the appropriate crop species.

To estimate the multivariate statistical distributions of TM data, FSS data were acquired at several locations for each crop. The FSS data were expressed as percent reflectance within narrow spectral bands and were converted to radiance values using estimates of incident solar radiation obtained from Thekaehara, et. al., (1974). The radiance values were then integrated over the TM spectral bands and transformed to TM digital response values using preflight specifications of sensor response for each TM band. At each grid cell in the image, the response value for each TM band was generated using a uniform random number generator and the estimated response value distribution for the crop indicated to exist at the cell by the ground reference data. This procedure resulted in a digital image simulating TM data acquired in July over an agricultural area given a solar zenith angle of zero degrees and an absence of atmospheric effects. Efforts are continuing to incorporate effects of atmosphere, temporal changes, and different solar zenith angles into the simulation.

Pitts and Badhwar (1980) examined the advantages of TM's finer spatial resolution by deriving length, width, and area distributions for agricultural fields in the U.S. Great Plains and Corn Belt. Field size distributions were determined for several crops (corn, wheat, soybeans, grass) and used in conjunction with a theoretical model to estimate the proportion of pure pixels (i.e., pixels which do not overlap field boundaries and thus represent a single cover type per pixel) within an agricultural scene as a function of spatial resolution (Figure 1). On the basis of the authors' estimate, approximately 40 percent of the 80 meter Landsat MSS pixels from an agricultural scene within the Great Plains or Corn Belt can be expected to be pure. The 30 meter resolution of TM will increase the expected proportion of pure pixels to 75 percent. Since mixed pixels (i.e., pixels which overlap field boundaries and thus integrate energy reflected from more than one cover type per pixel) confound data classification and area mensuration, increases in classification and mensuration accuracies were anticipated from the use of TM data.

The suitability of the first four TM spectral bands (TM1-TM4) for the sensing of vegetative parameters was addressed by Tucker (1978). The placement of the TM bands was compared to the placement of spectral bands on several proposed or operating spaceborne sensors: the Landsat MSS, the Return Beam Vidicon (RBV) of Landsat 1 and 2, the three band sensor of the French Systems Probatoire d'Observation de la Terre (SPOT), and a three band system proposed by Colvocoresses (1977). Narrow band (0.005 μm) spectrometer data within the 0.350-to-1.000 μm wavelength interval were acquired over field plots of blue grama grass on two occasions; September. 1971 and June, 1972. The total wet, total dry, dry green, and dry brown biomass, the leaf water content, and the total chlorophyll content of each plot were determined by destructive laboratory

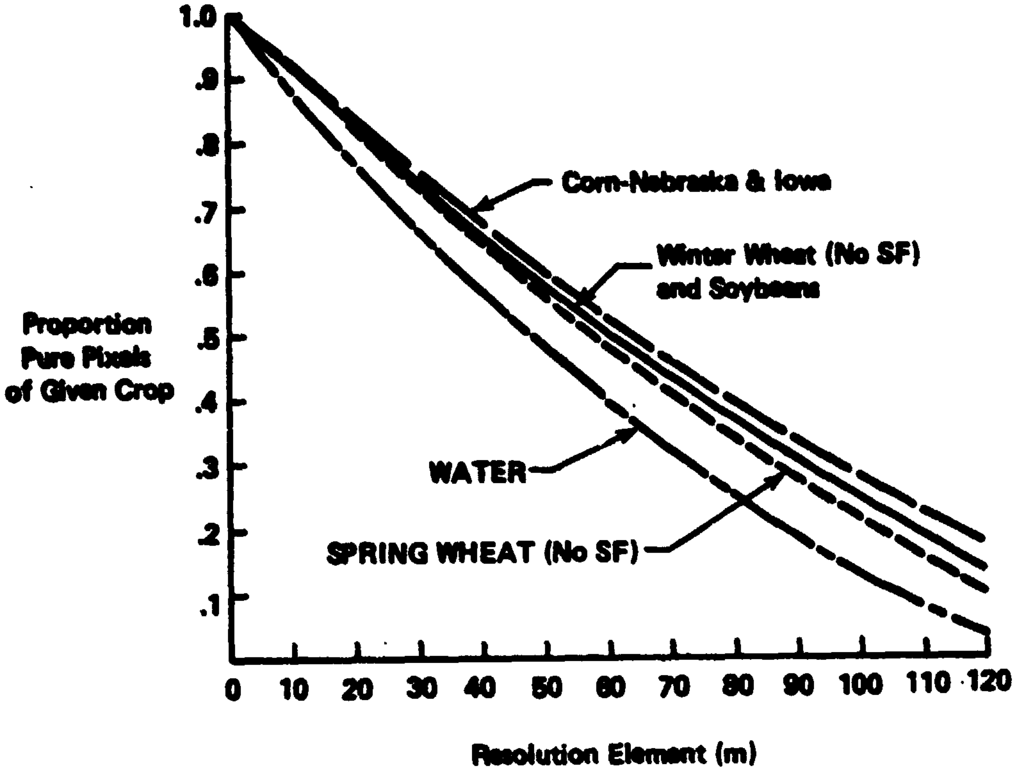

Figure 1. Proportion of a Crop in Pure Pixels as a Function of Sensor Resolution for the U.S. Great Plains (Pitts and Badhwar, 1980).

methods after each occasion. The spectrometer data were integrated over the appropriate intervals to simulate the spectral bands of the sensors under consideration. The integrated data were transformed from reflectance values to radiance values by multiplication with a solar irradiance function, and the data were further modified by passing the radiance values through a model atmosphere to the appropriate sensor altitudes. The utility of the spectral bands were then compared by predicting each vegetative parameter as a function of the data for each band using regression analyses. On the basis of these analyses (Table 5), Tucker concluded that the first four TM bands are well suited for the sensing of vegetation.

The September spectrometer data for the blue grama grass plots were also applied to an evaluation of the number of quantization levels required to monitor vegetative parameters (Tucker,

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Table 5. Coefficient of Determination (r^2) Values Resulting from the Regression Between Integrated Radiance and the Canopy Variables (Tucker, 1978).
(a) June Data
(b) September Data

(a)

Sensor	Bandwidth (μm)	Total Wet Biomass	Total Dry Biomass	Leaf Water Content	Dry Green Biomass	Dry Brown Biomass	Total Chlorophyll Content
RBV 1	0.475-0.575	0.73	0.66	0.76	0.67	0.24	0.77
RBV 2	0.580-0.680	0.88	0.81	0.91	0.82	0.32	0.91
RBV 3	0.690-0.800	0.65	0.63	0.65	0.63	0.51	0.65
MSS 4	0.500-0.600	0.78	0.71	0.81	0.73	0.27	0.81
MSS 5	0.600-0.700	0.88	0.80	0.91	0.82	0.32	0.91
MSS 6	0.700-0.800	0.63	0.62	0.63	0.61	0.54	0.65
MSS 7*	0.800-1.100	0.72	0.71	0.73	0.71	0.61	0.73
TM 1	0.450-0.520	0.69	0.61	0.72	0.63	0.19	0.74
TM 2	0.520-0.600	0.79	0.72	0.82	0.74	0.28	0.83
TM 3	0.630-0.690	0.88	0.80	0.91	0.82	0.32	0.91
TM 4	0.760-0.900	0.78	0.76	0.78	0.76	0.63	0.78
SPOT 1	0.50-0.59	0.76	0.69	0.79	0.71	0.26	0.81
SPOT 2	0.61-0.69	0.88	0.81	0.91	0.82	0.32	0.91
SPOT 3	0.79-0.90	0.77	0.75	0.77	0.75	0.63	0.78
Colvo 1	0.470-0.570	0.71	0.65	0.75	0.66	0.23	0.76
Colvo 2	0.570-0.700	0.88	0.80	0.91	0.82	0.32	0.91
Colvo 3*	0.760-1.050	0.74	0.73	0.74	0.72	0.62	0.75

* Data were incomplete for the 1.00-1.1 μm interval. The simulations for MSS7 and Colvo 3 used 1.00 um as their upper wavelength limits.

(b)

Sensor	Bandwidth (μm)	Total Wet Biomass	Total Dry Biomass	Leaf Water Content	Dry Green Biomass	Dry Brown Biomass	Total Chlorophyll Content
RBV 1	0.475-0.575	0.31	0.28	0.41	0.21	0.10	0.25
RBV 2	0.580-0.680	0.40	0.38	0.64	0.24	0.07	0.33
RBV 3	0.690-0.800	0.48	0.51	0.41	0.43	0.29	0.39
MSS 4	0.500-0.600	0.25	0.22	0.37	0.16	0.07	0.20
MSS 5	0.600-0.700	0.39	0.38	0.65	0.23	0.06	0.33
MSS 6	0.700-0.800	0.53	0.55	0.48	0.47	0.30	0.44
MSS 7*	0.800-1.100	—	—	—	—	—	—
TM 1	0.450-0.520	0.56	0.54	0.69	0.41	0.19	0.45
TM 2	0.520-0.600	0.22	0.20	0.33	0.14	0.06	0.18
TM 3	0.630-0.690	0.43	0.25	0.70	0.41	0.07	0.36
TM 4*	0.760-0.900	—	—	—	—	—	—
SPOT 1	0.50-0.59	0.25	0.17	0.35	0.22	0.08	0.20
SPOT 2	0.61-0.69	0.42	0.24	0.68	0.41	0.07	0.35
SPOT 3*	0.79-0.90	—	—	—	—	—	—
Colvo 1	0.470-0.570	0.33	0.23	0.46	0.30	0.11	0.26
Colvo 2	0.570-0.700	0.37	0.22	0.62	0.35	0.12	0.32
Colvo 3*	0.760-1.050	—	—	—	—	—	—

*The September data covered only the 0.350 - 0.850 μm region. Some sensors, therefore, could not be simulated.

1980). The reflectance data were integrated over the spectral bandwidths of TM3 and TM4, converted to radiance values, and passed through the model atmosphere to the 705 kilometer TM altitude. The radiance values were then quantized to 16, 32, 64, 128, 256, and 512 levels using the specified saturation radiance values for TM3 and TM4 to define the quantization functions. For each number of the levels, the quantized data for each TM band and for two band ratios (TM4/TM3 and the normalized difference, TM4-TM3/TM4+TM3) were individually regressed against leaf water content from the grass plots. On the basis of regression results (Table 6), Tucker concluded that either 128 or 256 quantization levels should be used for the orbital monitoring of leaf water content.

Table 6. Coefficients of Determination (r^2) Values Resulting from the Regression Between the Spectral Variables for Five Solar Zenith Angles and Leaf Water Content for the September 1971 Data (Tucker, 1980).

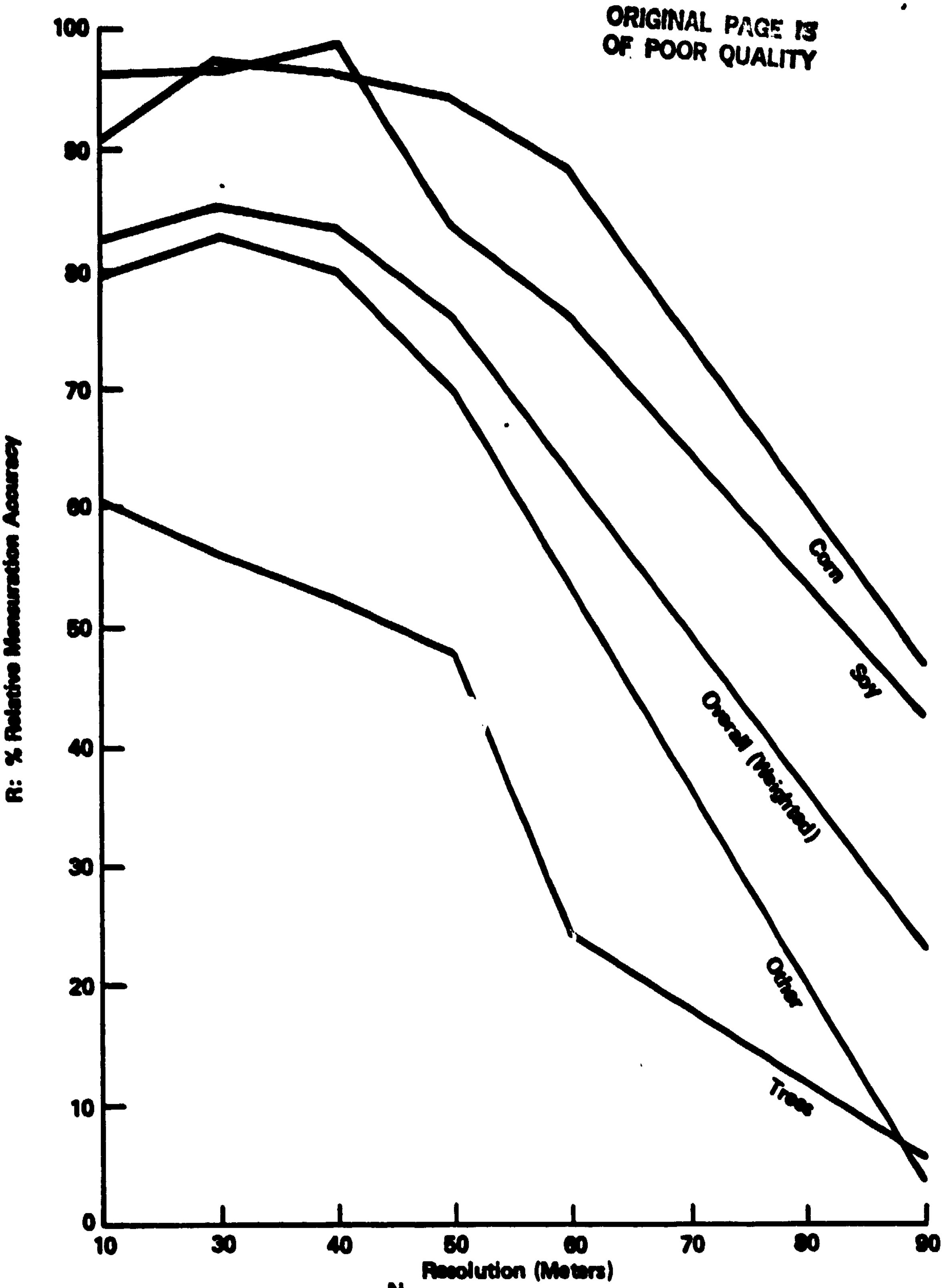
Spectral variable	Solar zenith angle (degrees)	Number of quantizing levels						Radiances at 706 km	Input reflectances
		16	32	64	128	256	512		
TM 3	54.2	0.63	0.77	0.97	0.99	1.00	1.00	1.00	1.00
TM 3	40.27	0.58	0.91	0.98	0.99	1.00	1.00	1.00	1.00
TM 3	34.62	0.83	0.91	0.98	0.99	1.00	1.00	1.00	1.00
TM 3	27.68	0.76	0.92	0.99	0.99	1.00	1.00	1.00	1.00
TM 3	17.65	0.67	0.94	0.98	0.99	1.00	1.00	1.00	1.00
TM 4	54.2	0.76	0.81	0.97	0.99	1.00	1.00	1.00	1.00
TM 4	40.27	0.70	0.91	0.98	0.99	1.00	1.00	1.00	1.00
TM 4	34.62	0.76	0.94	0.98	0.99	1.00	1.00	1.00	1.00
TM 4	27.68	0.86	0.93	0.98	0.99	1.00	1.00	1.00	1.00
TM 4	17.65	0.66	0.92	0.99	1.00	1.00	1.00	1.00	1.00
ND	54.2	0.80	0.90	0.98	0.99	1.00	1.00	1.00	1.00
ND	40.27	0.74	0.96	0.98	1.00	1.00	1.00	1.00	1.00
ND	34.62	0.91	0.93	0.99	1.00	1.00	1.00	1.00	1.00
ND	27.68	0.91	0.95	0.99	1.00	1.00	1.00	1.00	1.00
ND	17.65	0.68	0.98	0.99	1.00	1.00	1.00	1.00	1.00
Ratio	54.2	0.81	0.89	0.96	0.98	0.98	0.98	0.98	0.98
Ratio	40.27	0.73	0.94	0.96	0.98	0.98	0.98	0.98	0.98
Ratio	34.62	0.90	0.95	0.97	0.98	0.98	0.98	0.98	0.98
Ratio	27.68	0.93	0.91	0.98	0.98	0.98	0.98	0.98	0.98
Ratio	17.65	0.70	0.97	0.98	0.98	0.98	0.98	0.98	0.98

The TM middle infrared bands (TM5 and TM7) not used by Tucker (1978 and 1980) were included with bands TM3 and TM4 in a comparison of band ratios by Ungar and Bradley (1981). Data were acquired by the previously mentioned Field Spectrometer System over winter wheat fields in Finney County, Kansas during the 1974/75 growing season. These narrow-band data were also integrated over MSS and TM bandwidths, and atmospheric effects were simulated. The investigators then tracked the development of the wheat using the following band ratios: MSS7/MSS5, TM4/TM3, TM4/TM5, and TM4/TM7. The MSS7/MSS5 and TM4/TM3 ratios contrasted high wheat canopy reflectance in the near-infrared due to leaf structure with low visible-red reflectance caused by chlorophyll absorption. Since leaf structure and chlorophyll content vary as a plant grows, the MSS7/MSS5 ratio has often been used as an index of vegetational development. Ungar and Bradley found the TM4/TM3 was highly correlated (0.99) with the MSS7/MSS5 ratio. Thus, the TM4/TM3 ratio was useful as a development index, but the authors concluded that the TM4/TM3 ratio offered no clear advantage over the MSS7/MSS5 ratio. The TM4/TM5 and TM4/TM7 ratios also proved useful for tracking wheat development because energy within the middle-infrared bands (TM5 and TM7) was absorbed by leaf water content and water content also varies as a plant develops. Again, the authors concluded that the ratios of data from TM bands demonstrated no improvements as development indices when compared to data ratios for the MSS bands. The fact that Ungar and Bradley (1981) addressed only the spectral resolutions of the TM and MSS and did not considered the effects of TM's improved spatial and radiometric resolutions on development indices bears emphasis here.

The information content of reflectance data from all six of the TM reflective spectral bands was considered by Staenz, et. al. (1980). Field reflectance data were gathered with a narrow-band spectrometer for nine crops and bare sand-loam soil. The spectra were collected for a range of instrument view angles (zero to 30 degrees from nadir), solar elevations, solar and viewing azimuths, and crop development stages. The data were integrated over the appropriate bandwidths to estimate reflectance within the TM bands, and then correlations between data for each possible pair of TM bands were determined. The data for the three visible bands were highly correlated (TM1, TM2, TM3) for all crop and soil spectra, while the near-infrared data (TM4) were not well correlated with any other reflectance data. Data for the two middle-infrared bands (TM5 and TM7) were correlated to each other, but did not relate well to data from any of the other bands. Correlations amongst the visible band data were attributed to leaf pigment absorption, while the relation between TM5 and TM7 data was attributed to water absorption. The authors suggested that one band from each portion of the spectrum under consideration (i.e., visible, near-infrared, and middle-infrared) could be chosen as a first step in feature selection during the analyses of actual TM data.

A group of related studies conducted by Morgenstern, et. al. (1976, 1977), General Electric (1977), and Swain (1980) investigated the potential impact of several TM characteristics on agricultural applications. All of these studies utilized aircraft multispectral scanner data collected for the 1971 Corn Blight Watch Experiment (MacDonald et. al., 1972). The data were acquired by the Environmental Research Institute of Michigan's (ERIM) 12-channel M-7 scanner over two Indiana locations on three occasions during the 1971 growing season. The predominant ground cover types in the areas were corn, soybeans, and forest.

Morgenstern, et. al. (1976, 1977) rigorously processed the data to simulate the spectral, spatial, and radiometric characteristics of TM data and assessed the impact of varying several TM parameters on crop discrimination. Results were evaluated in terms of both probability of misclassifying pure pixels and area mensuration errors. Each of three parameters (spatial resolution, radiometric sensitivity, and spectral band placement) were varied while the other two parameters were held constant to TM specifications. The researchers found pure pixel classification accuracies to be independent of spatial resolution, but observed a decrease of area mensuration accuracy as spatial resolution was degraded (Figure 2). In particular, increasing the spatial resolution of the thermal channel (TM6) from 30 meters to the 120 meter TM specification while holding the resolution



$$R = \left(1 - \sum_{i=1}^{N} \left|P_i - \tau_i\right|\right) \cdot 100\%$$

P_i = Proportion of Pixels Classified as Category i

τ_i = True Proportion of Category i

Figure 2. Mensuration Accuracy Versus Resolution (Morgenstern et. al., 1976).

of the other bands at 30 meters significantly decreased mensuration accuracy. These results were attributed to an increase in mixed pixels as spatial resolution was coarsened. For the other analyses, the resolution of the thermal data was left at 30 meters.

Morgenstern, et. al. (1976, 1977) did report a decrease in expected pure pixel classification accuracies when the radiometric sensitivity of the data was degraded from TM specifications by the addition of random noise (Figure 3). The impact of sensitivity degradation was most severe for data acquired early in the growing season when the major classes, corn and soybeans, were spectrally similar.

With the radiometric sensitivity held constant, Morgenstern, et. al. (1976, 1977) regarded the TM spectral bands as effective as the six optimum original M-7 scanner spectral bands for class discrimination. This conclusion was based on average pairwise probabilities of misclassification for all pairs of dissimilar classes. TM3 (0.63-0.69 μm) was considered the most important band for discriminating between blight levels of corn.

The results obtained by Morgenstern, et. al. (1976, 1977) were used in the support of the General Electric Company (1977) Sigma Squared study. The objective of the Sigma Squared study was to evaluate the performance of remote sensing systems for global agricultural crop production forecasting. The study compared an MSS-based system to a theoretical system based on TM data. The measure of performance was the coefficient of variation of forecast error as a function of time. The evaluation assumed the use of a methodology developed by the Large Area Crop Inventory Experiment (LACIE) for global wheat production forecasting (MacDonald, 1976).

The Sigma Squared study identified three sources of error in the LACIE methodology: crop classification, yield estimation, and sampling. A theoretical model simulated the impact of TM data on wheat and corn classification within several countries, and the theoretical simulations were compared to the empirical results obtained by Morgenstern et. al. (1976, 1977) for validation.

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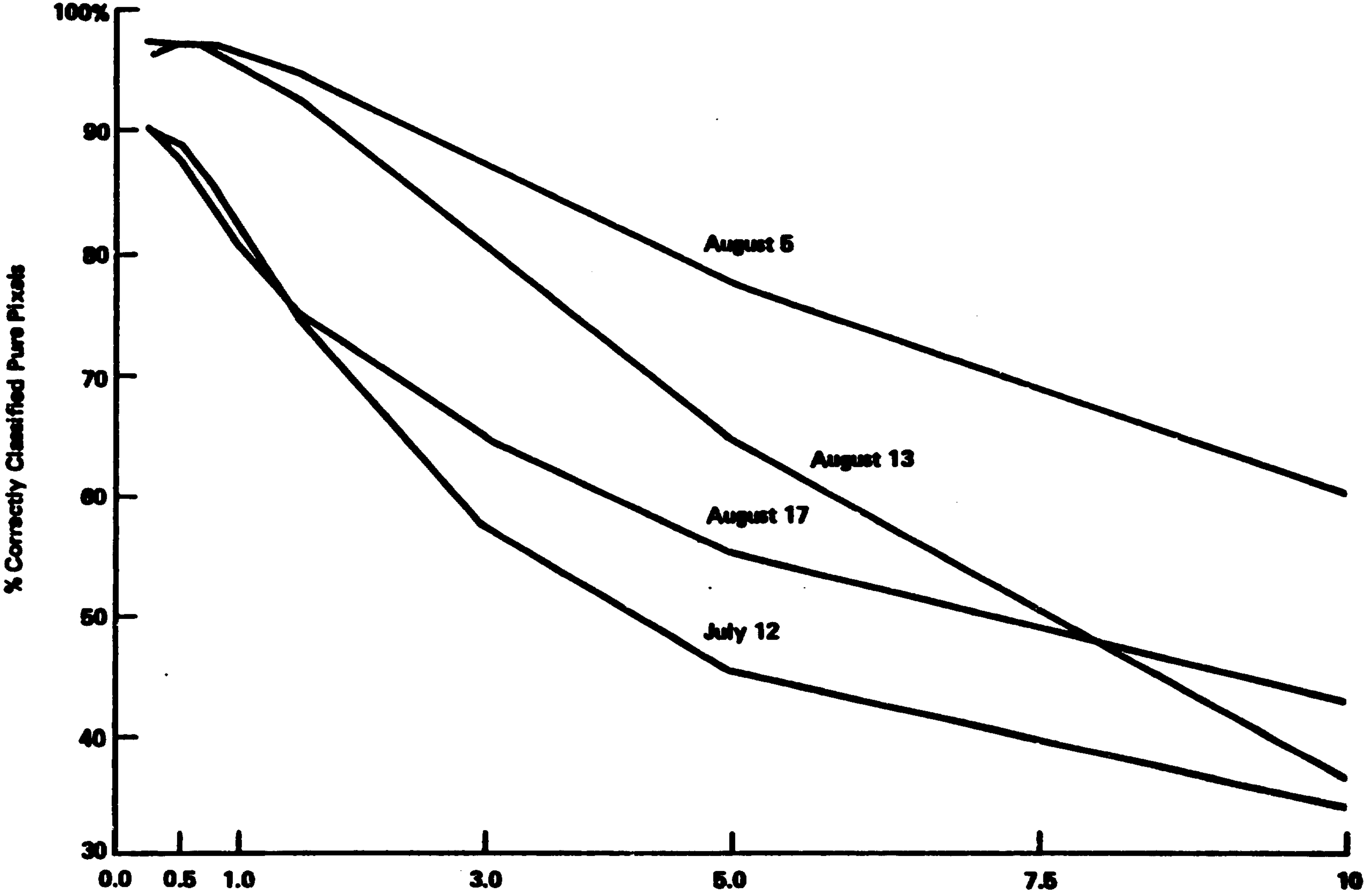

Percent NE$\Delta\rho$ (For Bands 1—4. In Band 5 [1.55-1.75μm] NE$\Delta\rho$ Is Twice the Value Shown; For Band 6, the NEΔT Value is as Shown on the Axis)

Figure 3. Classification Accuracy Versus Radiometric Sensitivity (Morgenstern et. al., 1976).

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Classification errors were then aggregated with independent errors in yield estimation and sampling to predict the coefficients of variation for the total crop production forecast errors. TM data generally reduced the coefficients of variation of forecast error when compared to predicted results from a forecasting system based on MSS data. The predicted results for wheat production forecasts in the United States are shown in Table 7.

Table 7. Predicted Production Forecast Errors for U.S. Wheat (General Electric, 1977).

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
SAMPLING ERROR CV_s		2.04	2.03	2.02	2.02	2.02	2.02				2.30	2.10	2.05
YIELD ERROR CV_y			8.4	7.12	5.84	4.56	3.28	2.0					
CLASSIF. ERROR CV_c	MSS	1.71	1.70	1.70	1.70	1.70	1.70				1.93	1.76	1.72
	TM	.86	.85	.85	.85	.85	.85				.97	.88	.86
TOTAL ERROR, CV_p	MSS	8.81	8.81	7.59	6.41	5.27	4.21	3.31			8.92	8.84	8.82
TOTAL ERROR, CV_p	TM	8.69	8.69	7.45	6.24	5.06	3.94	2.97			8.76	8.70	8.69

TABLE ENTRIES ARE COEFFICIENT OF VARIATION EXPRESSED IN PERCENTAGE. DATA PREPARED 15 NOVEMBER 1976.

The simulated TM data from the Corn Blight Watch Experiment were used by Swain (1980) to investigate the effects of pixel misregistration. The non-cooled detectors of the visible and near-infrared spectral bands (TM1-TM4) and the cooled detectors of the middle- and thermal-infrared bands (TM5-TM7) are located on physically separate focal planes in the TM. The separation creates a potential for band-to-band spatial misregistration, and Swain investigated the impact of misregistration on the classification of the simulated TM data. The data corresponding to TM bands 3, 4, 6, and 7 at a 30 meter spatial resolution were classified into three categories: corn, soybeans, or "other." Classification was repeated for data sets with varying levels of misregistration (no misregistration to three pixel along-track misregistration) between the non-cooled detector bands (TM3 and TM4) and the cooled detector bands (TM6 and TM7). The classification accuracy with respect to pure pixels within test fields was then determined. Accuracy generally decreased with increasing misregistration (Figure 4). For example, the classification accuracy for soybeans decreased 11 percent for a data set with 0.3 pixel misregistration when compared to a registered data set.

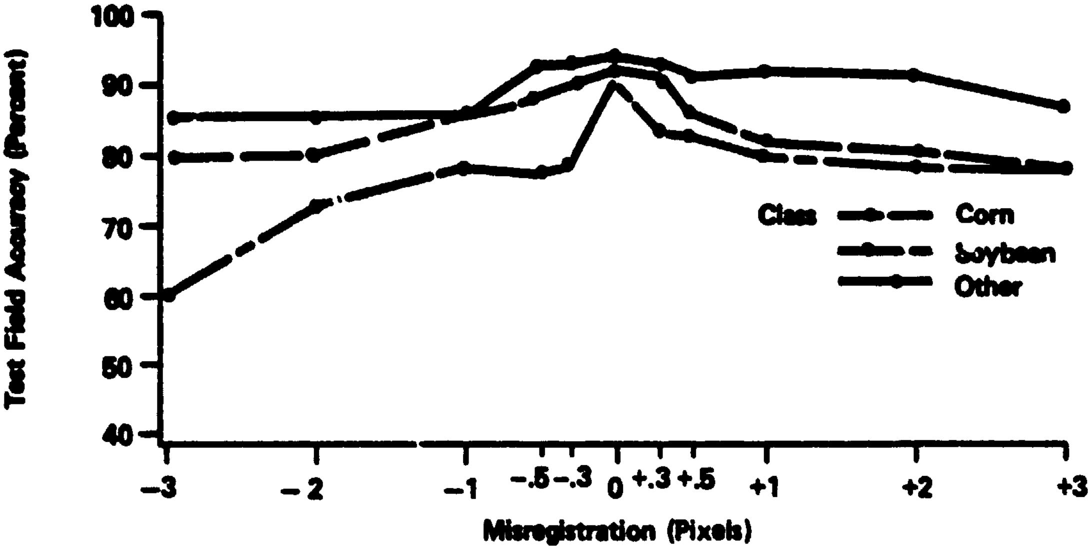

Figure 4. Classification Accuracy Versus Misregistration (Swain, 1980).

Swain (1980) also considered the 120 meter resolution of the TM thermal band. Using spatially registered data from the research discussed above, Swain classified three data sets: one set consisted of 30 meter resolution data for TM bands 3, 4, 6, and 7; the thermal data (TM6) were degraded to a 120 meter resolution for the second set; and the thermal data were excluded from the third data set. Table 8 summarizes the classification accuracies for pure pixels within test fields. In this experiment, the inclusion of coarse resolution thermal data significantly impaired capabilities for discriminating corn.

Aircraft scanner data collected over several other agricultural areas have also been used to simulate TM data. Landgrebe, et. al. (1977) acquired data with a 24-channel multispectral scanner on July 6, 1975 over Finney County, Kansas and on August 15, 1975 over Williams County, North Dakota. Thirty-six distinct data sets were derived from the original two data sets by spatially degrading the data to four resolutions (30, 40, 50, and 60 meters) and by adding eight different levels of random noise to the data at two spatial resolutions (30 and 40 meters). The data were otherwise processed to simulate the TM spectral resolutions, and the spatial resolution of the thermal infrared band (TM6) was left at 120 meters for all of the derived data sets. The data within each set were then classified into crop categories using a supervised training approach and a per pixel maximum-likelihood classification algorithm. As the spatial resolution of the data grew more coarse, the classification accuracy of pure pixels increased slightly while mensuration accuracy decreased significantly. The increase in classification accuracy was attributed to higher signal-to-noise ratios at coarse resolutions, and the reduction in mensuration accuracy was attributed to the increase in boundary pixels. At a constant spatial resolution, the degradation of radiometric sensitivity by noise addition significantly impaired classification performance.

Table 8. Comparison of Classifications With and Without Thermal Band – No Misregistration (Swain, 1980).

	Test-Field Accuracy (Percent)			
Spectral Bands	Corn	Soybeans	Other	Overall
4 bands, 30 m thermal	91.9	97.6	92.4	93.4
4 bands, 120 thermal	56.1	96.3	94.2	72.3
3 bands (no thermal)	87.3	95.6	84.3	88.8
Number of Pixels	4355	1816	1251	7422

Landgrebe et. al. (1977) also considered the effect of using a different classification algorithm called ECHO (Kettig and Landgrebe, 1975). This algorithm employs a homogeneity criterion to merge adjacent pixels into windows and a likelihood ratio to annex windows into fields. Each field is then classified on the basis of the spectral properties of the entire field of pixels. The use of the ECHO classifier diminished the impact of adding noise to the data (Figure 5). Apparently, the use of information from multiple pixels somewhat offset the loss of radiometric sensitivity.

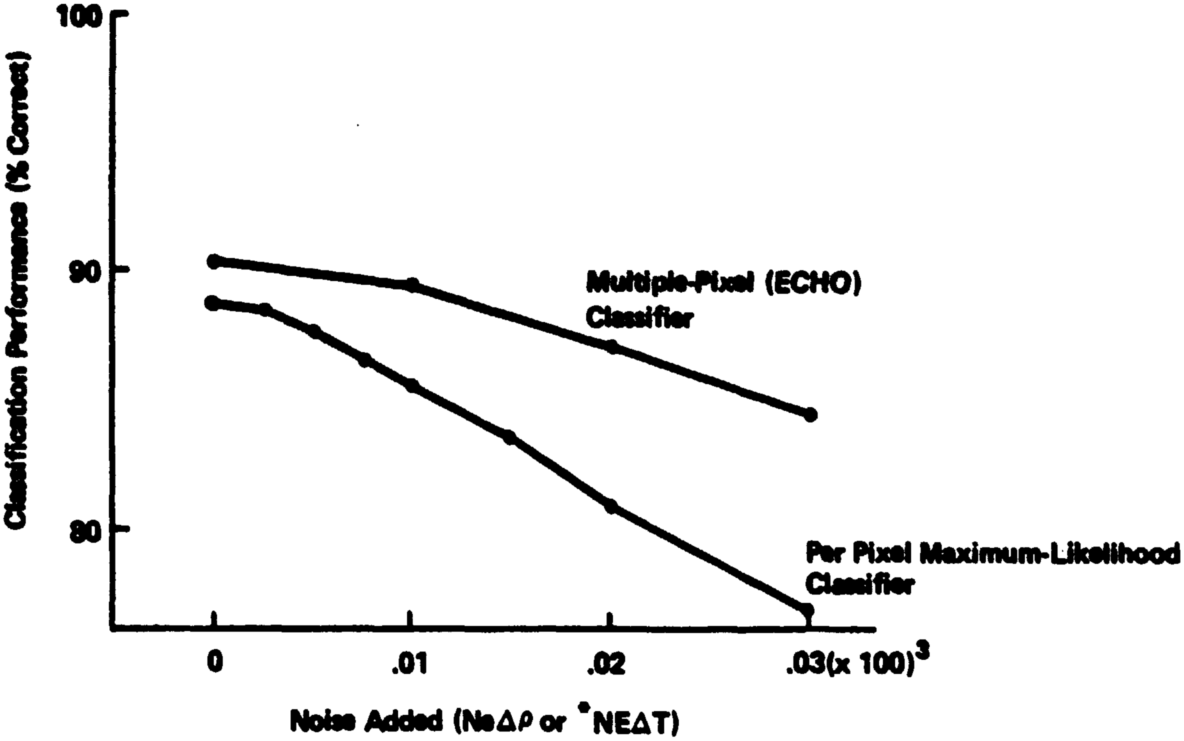

Figure 5. Classification Accuracy Versus Added Noise Using a Multiple-Pixel (ECHO) Classifier or a Per Pixel Maximum-Likelihood Classifier (Landgrebe et. al., 1977).

Sigman and Craig (1981) analyzed NS001-MS aircraft scanner data acquired over Knox and Lewis Counties, Missouri on September 9, 1979. Eight distinct digital images were derived from the raw data by creating all possible combinations of three data parameters given two levels for each parameter: number of spectral bands (four or seven); spatial resolution (30 meters or 60 meters); and quantization (six bits or eight bits). The digital image consisting of seven bands, 30 meter resolution, and eight bits (256 quantization levels) simulated TM data. The four band, 60 meter, six bit image roughly approximated Landsat MSS data. Each digital image was then classified in order to mensurate the acreage planted in corn, soybeans, and forest within eleven 130 hectare sites in the two county area. Three factor analysis of variance was used to compare the accuracy of the acreage estimates from the eight digital images. On the basis of the analysis, the use of the simulated TM data slightly improved area mensuration accuracy for soybeans and forest and significantly increased the corn area accuracy when compared to acreage estimates derived from the simulated MSS data. The improvements were attributed primarily to the interaction between the additional spectral bands and finer spatial resolution of the TM.

Simulated TM data have also been collected for Canadian agricultural scenes. An 11-channel aircraft scanner was flown over a site in Saskatchewan containing quarter-section (64 hectare) and larger fields of wheat, rapeseed, barley, peas, flax, and bare soil during July, 1979 (Ahern et. al., 1980). The data were processed to simulate both TM and MSS data. The effects of varying the number of quantization levels and the spatial resolution on classification accuracy were then studied. For both TM and MSS spectral bands, classification accuracies were decreased when the data were reduced from 256 to 64 quantization levels. The degradation of spatial resolution from 30 meters to 80 meters, however, resulted in an increase in classification accuracies. The improved classifications were attributed to a reduction of within class spectral heterogeneity at coarser resolutions.

Median filters were applied to the 30 meter simulated TM data to reduce within class data variability while maintaining the distinct boundaries depicted in the fine resolution data (Ahern et. al., 1980). Visual inspection of imagery derived from filtered data confirmed the preservation of clear boundaries. The classification of filtered data (3X3 filter) resulted in a 3.4 percent improvement in accuracy when compared to the classification of unfiltered simulated TM data and a 6.9 percent improvement when compared to results obtained with simulated MSS data.

Forestry

Landsat MSS data have been successfully applied to the inventory and monitoring of forest resources, but such applications have been limited by the spatial, spectral, and radiometric resolutions of MSS data. Williams and Stauffer (1979) reviewed research literature which documented requirements for higher resolution data in forest applications. Several additional investigations have specifically addressed the potential ability of the high-resolution TM to provide data containing information of adequate detail for these applications.

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Sadowski and Sarno (1976) examined the influence of spatial resolution on the identification of forest categories at levels of detail appropriate to both large scale surveys and detailed local inventories. Features of the Sam Houston National Forest in eastern Texas were categorized into a four level hierarchy where category detail increased at each successive level. Data acquired by the Modular Multispectral Scanner (M^2S) at an altitude of 610 meters over the Forest on November 20, 1974 were then analyzed. The data were processed to six spatial resolutions (2, 4, 8, 16, 32 and 64 meters), and all 11 channels, supervised training, and a linear decision rule were applied to the classification of the data at each resolution into the categories of each hierarchical level. Signal-to-noise ratios were maintained at a constant level by adding random noise as the resolution was degraded. Classification was also repeated for the 32 meter and 64 meter data using only five data channels which had spectral resolutions approximating TM bands (TM1 to TM4 and TM6, the thermal band). Classification accuracy generally increased as the spatial resolution was degraded to 32 meters (Figure 6). At a constant spatial resolution, the general categories were more accurately identified than the detailed categories of the hierarchy. The use of only five data channels resulted in lower classification accuracies.

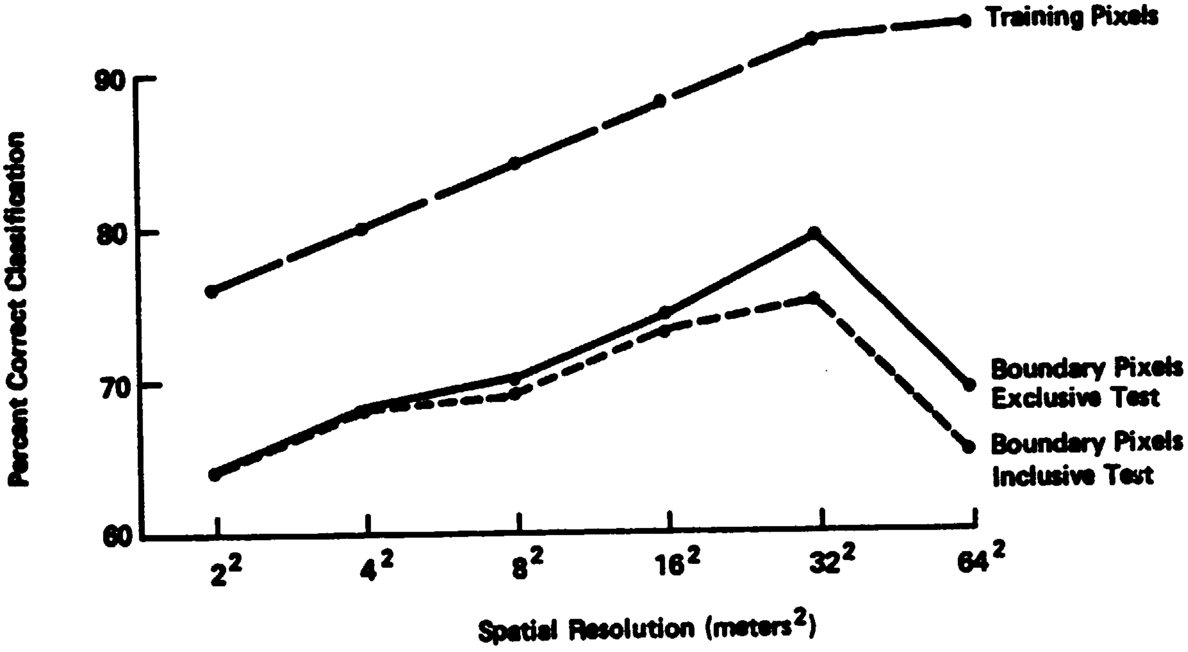

Figure 6. Classification Accuracy Versus Spatial Resolution for Forest Categories of a Detailed Local Survey (Sadowski and Sarno, 1976).

Aircraft scanner data collected over an area just south of Camden, South Carolina were used to select the optimum subset of TM spectral bands for forest cover type identification by Latty and Hoffer (1980). The NS001-MS scanner was flown over the area on April 2, 1979 at 6000 meters and the resulting data were processed to simulate TM data. Data were then extracted from training areas representing the following cover types: soil, pasture, row and cereal crops, pine forest, pine-hardwood mix, old hardwood, second growth hardwood, water tupelo, sycamore, clearcut areas, marsh vegetation, and water. All possible combinations of TM spectral bands were analyzed to determine the most useful number and combination of bands for discriminating between these cover types. For each band combination, the average transformed divergence measure of the statistical distance between all pairs of cover types was computed. On the basis of the divergences, four bands, TM1, TM3, TM4, and TM5, were chosen as the most useful subset of bands.

An evaluation of the effect of simulated spatial resolution was also conducted with the data obtained over the Camden, South Carolina area. Simulated spatial resolutions of 30 meters, 45 meters, and 60-by-75 meters were computed from the original 15 meter data. Latty and Hoffer (1981) found that the overall classification accuracy of pure pixels increased as the spatial resolution grew coarser when using a per pixel maximum-likelihood classifier. This trend was not observed for all cover classes when assessed individually for each cover class. The differences in classification accuracy achieved with each spatial resolution were significant only for pine-hardwood mix, old-age hardwood, clear-cut, second growth hardwood, and pine. The decrease in classification accuracy achieved with the finer spatial resolution was attributed to the increased level of variation in spectral response level across adjacent areas within the cover class. The data were reclassified with the previously discussed ECHO classifier which utilizes the spectral information from multiple pixels for classification (Kettig and Landgrebe, 1975). Higher overall classification accuracies were achieved with the ECHO classifier (94.1% training and 75.0% test) than were achieved with the maximum-likelihood per pixel classifier (89.3% training and 71.0% test) using data at the 30 meter spatial resolution.

The selection of optimum TM bands for forest classification and the identification of categories at different levels of detail were both addressed by Dottavio and Williams (1981). NS001-MS data were acquired over a forest plantation in North Carolina on June 14, 1979. Only five of the data channels (TM1 to TM5) were operating during the overflight, and these data were processed for TM data simulation. The processed data were then classified into seven forest categories (clearcut, hardwood, mixed hardwood and pine, and four developmental stages of pine) using an unsupervised training procedure and maximum-likelihood classifier. An overall classification accuracy of 60 percent was obtained. Three spectral bands, TM2, TM4, and TM5, were then chosen on the basis of a stepwise linear discriminant analysis as the most useful of the available bands for the identification of the seven categories. Classification was repeated using only the data from these three bands and a classification accuracy of 63 percent resulted.

Landsat MSS data collected over the North Carolina forest plantation on July 3, 1979 were also classified into the seven forest categories. The resulting overall classification accuracy was 39 percent. The seven categories were then grouped into four broader categories (clearcut, hardwoods, young pine, and mature pine) and both the MSS data and the full complement of simulated TM data were reclassified. The overall classification accuracy for the broad categories were comparable: 77 percent accuracy resulted from the classification of simulated TM data and 71 percent accuracy was obtained via the analysis of the MSS data.

Land Cover Mapping

A wide variety of potential applications exist beyond agricultural and forestry for TM data. These other applications have not been as intensively investigated, but enough work has been done to indicate the potential versatility of TM data. Several diverse applications have been addressed by the analysis of simulated TM data.

Both Clark and Bryan (1977) and Markham and Townshend (1981) studied the effect of spatial resolution on the ability to identify land cover types using simulated TM digital image data.

Clark and Bryan (1977) considered an urban area in Los Angeles, California while Markham and Townshend (1981) observed urban cover in Annapolis, Maryland and salt marshland in Dorchester County, Maryland. Two factors were identified which affect classification accuracy as a function of spatial resolution. First, independent of sensor noise, the spectral heterogeneity (variability) of data associated with a particular category often increased as resolution became finer. This increase was due to the resolving of category components (e.g., the leaves, branches, shadows, and the understory within a forest) which may have diverse spectral characteristics. The increase in spectral heterogeneity caused overlap between categories in spectral data space and thus impaired per pixel classification into the categories. At coarser resolutions, the reflected energy was integrated over the category components and within-category spectral variability was often reduced. The second factor affecting classification accuracy was the increase in mixed pixels as spatial resolution was degraded. The increase in mixed pixels hindered classification at coarse resolutions because the sensor response at a mixed pixel resulted from the reflectances of more than one cover type.

Clark and Bryant (1977) observed the impact of increasing spectral heterogeneity on the identification of urban categories. Data acquired by a 24-channel airborne multispectral scanner on November 14, 1973 over Los Angeles were spatially degraded to four resolutions (7.5, 15, 30, and 60 meters), and data from spectral bands approximating TM2, TM3, and TM4 were analyzed. Supervised training and a maximum-likelihood classifier were used to classify the data. Classification accuracies for pure pixels decreased as resolution became finer. The difference in accuracies at the 30 meter resolution and at the 60 meter resolution, however, were small, and the investigators considered the 30 meter resolution of TM suitable for the identification of urban categories.

Markham and Townshend (1981) not only reported classification accuracies, but also quantified changes in spectral heterogeneity and the proportion of pure pixels as spatial resolution was varied. Data for spectral bands approximating TM2, TM3, and TM4 were acquired by the airborne Modular Multispectral Scanner on April 10-11, 1980. The raw data were degraded to 10, 20, 40 and 80 meter pixel sizes. At each resolution and for each spectral band, the variation and coefficient of variation of the data were determined within training areas representing urban and marshland categories. These values provided a quantitative measure of spectral heterogeneity, and the rate of change of heterogeneity with coarsening resolution varied considerably between categories and between spectral bands for particular categories. In most cases, the spectral variability of urban categories declined more rapidly than did the variability of herbaceous categories as resolution was degraded. Also, as expected, the proportion of pure pixels in the data decreased as the resolution was coarsened.

The effects of decreasing spectral heterogeneity while increasing the proportion of mixed pixels offset each other with respect to overall classification accuracy. For the marshland, classification accuracies for the overall aggregate of pure and mixed pixels (the predominant category within a mixed pixel was considered the "correct" category) decreased only slightly as resolution was degraded; from 89 percent at 5 meters to 75 percent at 80 meters. The decrease was due mainly to an inability to recognize narrow features such as roads and streams at coarser resolutions. Accuracies for categories of greater areal extent (e.g., wetland, forest, grassland) remained nearly constant for all resolutions.

The potential utility of TM data for coal surface mine inspections was addressed by Irons, et. al. (1980). Landsat MSS data and NS001-MS data were acquired over Pennsylvania surface mines during 1979. The MSS data were found useful for surface mine inventory, but the spatial and spectral resolution of the data were insufficient for the recognition of ground cover conditions associated with mines such as graded spoil, rough spoil, and revegetated spoil. These categories, however, were identified and accurately mensurated by the analysis of NS001-MS data processed for TM data simulation (Table 9). Information at this level of detail is required to assess reclamation success and compliance with regulations.

Table 9. Area Mensuration Accuracies for Surface Mine Categories (Irons et. al., 1980).

Category		Accuracy* of Area Measurement from TM Simulator Data	Ground Reference (hectares)
Level II	Level III		
Barren		0.95	776.8
	Graded	0.89	413.9
	Ungraded	0.88	362.9
Revegetated		0.93	758.7
	Grass	0.84	380.0
	Trees	0.71	378.7

*Accuracy = 1 – (Measurement-Ground Reference/Ground Reference)

CONCLUSIONS

The TM is designed to increase the detail and accuracy of Earth resource information extracted from the remotely acquired data of a spaceborne system. In comparison to the Landsat MSS, the enhanced information content is expected to result from the number, location, and width of the TM spectral bands, from the sensor's improved radiometric sensitivity and resolution, and from the instrument's finer spatial resolution. Investigations conducted with simulated TM data have addressed the effects of the individual sensor characteristics as well as the collective impact of the overall instrument design on renewable resource applications. These studies provide insight to the potential utility of TM data.

Extensive forethought was applied to the placement of the TM spectral bands (Harnage and Landgrebe, 1975). Data from various combinations of TM bands were found useful for several applications. Radiometer data corresponding to the TM bands were found suitable for estimating vegetative parameters and for monitoring plant development. Digital image data for the TM bands were applied to the accurate discrimination of crop, forest, and various other land cover categories.

The availability of spectral bands from each major portion of the reflective spectrum (visible, near-infrared, and middle-infrared) was shown to be important by several band selection studies. Thus, results of the reviewed investigations indicate that data for the TM spectral bands will prove useful, and the addition of the middle-infrared bands will be beneficial.

Although data from the TM spectral bands have been shown to be valuable, extensive comparisons have not been made with data from the MSS spectral bands for remote sensing in the visible and near-infrared regions. In some studies, comparable results were obtained using data from either TM bands or MSS bands. In most other investigations, the effects of the TM's spectral resolution were not isolated from the effects of other sensor characteristics. Analytical justifications for the placement of the TM visible and near-infrared bands remain strong, but the observational investigations summarized here did not strongly substantiate the advantages of the TM band placements relative to the MSS visible and near infrared bands.

The utility of the TM thermal band (TM6) has not received extensive consideration. Thermal data offer several promising capabilities, but these capabilities were not exploited in the analyses of simulated TM data summarized here. Conclusions regarding the utility of the thermal band should be reserved until further investigations are conducted:

The reviewed investigations conclusively demonstrated the value of improved radiometric sensitivity and resolution. The degradation of sensitivity by noise addition to simulated TM data consistently reduced classification accuracy. Similarly, the reduction of quantization levels below eight bits (256 levels) was shown to impair both classification and the sensing of vegetative parameters. These results strengthen the justification for costs associated with the telemetry of eight bit data.

The TM's 30 meter spatial resolution will enable users to locate and recognize smaller fields than can be identified using MSS data. The improved resolution should be of immediate benefit to those applications requiring photointerpretation of pictorial imagery. The finer resolution, however, presented a dilemma to many researchers in their digital analyses of simulated TM data. The fine resolution often increased within-class spectral heterogeneity causing class overlap in spectral data space and thus reduced pure pixel classification accuracies when per pixel classifiers were used. On the other hand, the finer resolution reduced the number of mixed pixels in a scene thereby improving overall classification and area mensuration accuracies. Spectral heterogeneity and mixed pixel proportions were found to be highly dependent on the specific scene, application, and classes under consideration. The ability to identify small fields will be valuable, particularly in agricultural applications, but additional research on classification algorithms is required before full advantage can be taken of the TM's spatial resolution by way of digital analyses.

The effects of the individual sensor characteristics will not be isolated when actual TM data are acquired. On the basis of the classifications of simulated TM digital image data, the collective effect of the instrument's attributes will be an increase in the information content of TM data when compared to MSS data. Classifications of simulated TM data were invariably an improvement over results obtained by way of the analysis of actual or simulated MSS data when either overall classification or area mensuration accuracies were applied to the evaluation. Also, analysis of simulated TM data enabled the recognition of land cover and forest categories which could not be accurately identified with MSS data.

The TM data corresponding to a unit area will consist of nearly an order of magnitude more bits-of-data than the MSS data for the same unit of area. The increased data quantity will cause an increase in the expense of data telemetry, processing, and analyses. Vindication of these costs will require effective utilization of TM data. Analyses of simulated data have begun to indicate the potential utility and limitations of the actual data. Perhaps more importantly, the reviewed research has highlighted aspects of data analyses which require further research and development before full advantage can be taken of Thematic Mapper data.

RECOMMENDATIONS

The above conclusions point to areas of research which deserve further consideration. For instance, a major hinderance to the use of TM data will be the data quantity per unit area on the ground. Users will not want the expense and difficulty of processing and analyzing a full complement of data when a subset will suffice for a specific task. Since a reduction of quantization levels has been shown to degrade results, a more promising approach to data quantity reduction is the selection of a subset of spectral bands. Several studies indicated that data from three or four TM bands are adequate for the recognition of forest categories. The selection of spectral bands for a variety of other tasks requires further consideration.

TM thermal data also require further study. Research on thermal data applications has been widely conducted, but few investigators have specifically addressed the potential utility of TM thermal data. This utility may be limited by the constant time-of-day of the Landsat-D overpass and by the spatial resolution of the thermal channel, but these limitations do not eliminate all potential applications. Since thermal data applications may be quite distinct from reflective data applications, the potential utility of TM thermal data deserves further evaluation.

The development of methods to classify fine spatial resolution data is important. Fine resolution often reduced pure pixel classification accuracies when familiar per-pixel classifiers were used in past studies. The extraction of features or the use of classifiers which take into account the spatial, textural, and contextural characteristics of the data are techniques which may improve the classification of high resolution data. Development and evaluation of these techniques will enable the effective exploitation of TM's spatial resolution.

Research on TM data utility needs to extend to a wider variety of applications. Past investigations have focused primarily on agriculture and forestry. TM data, however, can potentially provide valuable information for a wide range of Earth resource management issues. Applied research should be conducted to extend TM data utility to such areas as land use and urban planning, land capability assessment, soil mapping, snow mapping, and watershed management.

The development of future sensors can be facilitated by additional research on the effect of each sensor parameter on information content and utility. Sensor design involves tradeoffs between engineering or cost limitations and spectral, spatial, and radiometric resolution deseridata. The launch of Landsat-D will afford an opportunity to observe the effects of upgrading the MSS resolutions to the TM resolutions. Research is needed to both isolate the effects of each sensor parameter improvement and to evaluate the interactions between sensor attributes.

The launch of Landsat-D will be an important event for the remote sensing community. The Thematic Mapper aboard Landsat-D will be the first significant refinement of spaceborne sensors dedicated to Earth resource observations since the launch of the MSS aboard Landsat-1 in 1972. Analyses of simulated TM data have demonstrated that the sensor's attributes will effect not only data utility, but also the manner in which the data are analyzed and applied. Continued research will prepare the user community for effective utilization of the data as soon as it becomes available.

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