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NASA

Technical Memorandum 86149

# A PROSPECTUS FOR THEMATIC MAPPER RESEARCH IN THE EARTH SCIENCES

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July 1984

National Aeronautics and Space Administration

**Goddard Space Flight Center**
Greenbelt, Maryland 20771

NASA

Technical Memorandum 86149

# A PROSPECTUS FOR THEMATIC MAPPER RESEARCH IN THE EARTH SCIENCES

July 1984

National Aeronautics and
Space Administration

**Goddard Space Flight Center**
Greenbelt, Maryland 20771

## PREFACE

The Landsat Thematic Mapper (TM) is an advanced remote sensing system designed to measure the intensity of Earth radiation in selected portions of the electromagnetic spectrum. The purpose of this document is to identify prospective research themes in various aspects of the Earth sciences that can be addressed in new and innovative ways through the analysis of multispectral TM imagery. This prospectus specifically describes the measurement capabilities of the TM, the various types of Earth information that can be obtained through the analysis of TM imagery, and potential applications of such information to contemporary research issues in various Earth science disciplines.

The sections of this document dealing with the measurement capabilities of the TM and the orbital performance of the TM sensor system were prepared by the Landsat Project Science Office at NASA's Goddard Space Flight Center. The information presented in this portion of the document is based in part upon the results of the Landsat Image Data Quality Analysis (LIDQA) program that was initiated by NASA in 1982. The purpose of the LIDQA program is to determine the radiometric and geometric characteristics of TM image data in both raw and processed form, and to compare the observed characteristics of orbital TM imagery with technical specifications for image quality that were established prior to the launch of the TM. The investigators participating in this program are as follows:

James Anderson, NASA—National Space Technology Laboratories

Paul Anuta, Purdue University

G. Begui, Centre Nationale d'Etudes Spatiale (France)

Lee Bender, U. S. Geological Survey

Ralph Bernstein, IBM Palo Alto Scientific Center

Eric Beyer, General Electric Space Division

Robert Colwell, University of California at Berkeley

Jeffrey Dozier, University of California at Santa Barbara

Michael Duggin, State University of New York at Syracuse

Jack Engel, Hughes Santa Barbara Research Center

Jon Erickson, NASA—Johnson Space Center

John Everett, Earth Satellite Corporation

Gary Ford, University of California at Davis

Luigi Fusco, European Space Agency Earthnet Program Office

Charlotte Gurney, Systems and Applied Science Corporation

Charles Hill, NASA—National Space Technology Laboratories

Warren Hovis, NOAA—National Environmental Satellite Service

Michael Jackson, National Environmental Research Council (England)

Hugh Kieffer, U. S. Geological Survey

Vic Klemas, University of Delaware

Harold Lang, NASA—Jet Propulsion Laboratory

Don Lauer, U. S. Geological Survey

Robert MacDonald, NASA—Johnson Space Center

William Malila, Environmental Research Institute of Michigan

Nelson Parada, Instituto de Pesquisas Espaciais (Brazil)

John Price, U. S. Department of Agriculture

S. I. Rasool, Ecole Normale Superieure (France)

John Schott, Rochester Institute of Technology

Philip Slater, University of Arizona

W. Murray Strome, Canada Center for Remote Sensing (Canada)

June Thormodsgard, U. S. Geological Survey

Roy Welch, University of Georgia

Robert Wrigley, NASA—Ames Research Center

George Wubelic, Battelle Pacific Northwest Laboratories

Albert Zobrist, NASA—Jet Propulsion Laboratory

LIDQA investigators are currently analyzing data acquired by the TM sensor systems on both the Landsat 4 and 5 spacecraft. This document summarizes the collective results of these ongoing studies as of June, 1984. The sections of this document dealing with prospective scientific applications of TM imagery summarize the findings and recommendations of the TM Science Working Group (TMSWG). The TMSWG was organized by NASA during 1983 to define innovative applications of the TM's measurement capabilities for basic research in the Earth sciences. The TMSWG was composed of the following individuals:

Mark Settle, Co-Chairman, NASA Headquarters

Vince Salomonson, Co-Chairman, NASA—Goddard Space Flight Center

Jim Irons, Executive Secretary, NASA—Goddard Space Flight Center

James Anderson, NASA—National Space Technology Laboratories

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Don Deering, NASA—Goddard Space Flight Center
Diane Evans, NASA—Jet Propulsion Laboratory
Harold Lang, NASA—Jet Propulsion Laboratory
Ken Langren, NASA—National Space Technology Laboratories
M. C. Trichel, NASA—Johnson Space Center
Robert Wrigley, NASA—Ames Research Center

TMSWG participants organized a series of workshops during the spring and summer of 1983 to identify research issues in different disciplinary fields that could be profitably addressed through the analysis and interpretation of TM imagery. The individuals who participated in these workshops are listed below.

Michael Abrams, NASA—Jet Propulsion Laboratory
Gautam Badhwar, NASA—Johnson Space Center
Bryan Bailey, U. S. Geological Survey
Robert Bizzell, NASA—Johnson Space Center
Paul Bock, University of Connecticut
William Bull, University of Arizona
William Cibula, NASA—National Space Technology Laboratories
Carolyn Clark, Lockheed Engineering and Management Services Company
James Conel, NASA—Jet Propulsion Laboratory
B. Dey, Howard University
Jack Estes, University of California at Santa Barbara
Gary Ford, University of California at Davis
James Foster, NASA—Goddard Space Flight Center
Tom George, Camp Dresser & McKee, Incorporated
Jean Gervin, NASA—Goddard Space Flight Center
Alan Gillespie, NASA—Jet Propulsion Laboratory
Edward Guinness, Washington University
Robert Gurney, NASA—Goddard Space Flight Center
Robert Haas, U. S. Geological Survey
Keith Henderson, NASA—Johnson Space Center
John Hill, Louisiana State University
Thomas Jackson, U. S. Department of Agriculture
Chris Justice, NASA—Goddard Space Flight Center
Edward Kanemasu, Kansas State University
Richard Kauth, Environmental Research Institute of Michigan
Siamak Khorram, North Carolina State University
Vic Klemas, University of Delaware
Anthony Lewis, Oregon State University
James Lewis, South Dakota State University
Stuart Marsh, Sun Exploration Company
John McKeon, Gulf Science & Technology Company
Elizabeth Middleton, NASA—Goddard Space Flight Center
Bradley Musick, NASA—National Space Technology Laboratories
Eugene Peck, Hydex Corporation
Gary Petersen, Pennsylvania State University
Russell Pettit, Texas Tech University
David Pitts, NASA—Johnson Space Center
Mel Podwysocki, U. S. Geological Survey
Charles Poulton, Poulton Associates
Robert Ragan, University of Maryland
Doug Rickman, NASA—National Space Technology Laboratories
Ray Sadowski, Amax Exploration, Incorporated
Gary Shelton, Environmental Protection Agency
Ray Sugiura, Woodward-Clyde Consultants
Don Thomas, Dames & Moore
David Thompson, NASA—Johnson Space Center
Paul Tueller, University of Nevada at Reno
Joseph Ulliman, University of Idaho
Steve Wharton, NASA—Goddard Space Flight Center
Darrel Williams, NASA—Goddard Space Flight Center
Chuck Wood, NASA—Johnson Space Center

The contribution of all of the individuals listed above to the preparation of this document is greatly appreciated. Special thanks go to Jim Irons (Goddard Space Flight Center) and Kristine Butera (NASA Headquarters) for their assistance in the final preparation of the report.

Mark Settle
Landsat Program Scientist

Vincent Salomonson
Landsat Project Scientist

# SECTION I
# INTRODUCTION

The surface of the Earth is a fragile and complex interface between the solid interior and gaseous exterior of our planet. It displays a far wider range of cover materials and conditions than any other planetary surface found within our solar system. Furthermore, it is in a continual state of modification and is affected by a far wider range of processes than any other planetary surface known to exist today.

The Earth's surface provides a natural home for mankind, and it is the source of both the renewable and non-renewable resources needed to support our modern human society. At the most fundamental level, the study of the Earth's surface is motivated by our desire as a species to learn more about the processes that constructed the home we live in today, and the processes that may alter or modify the habitability of our home in the future. A phenomenological understanding of the history of our planet and the processes that govern its future evolution is essential for our long term survival.

Much of the current research in the Earth sciences is concerned with forecasting future conditions on our planet. These contemporary research efforts have revealed that the Earth's oceans, atmosphere, and land surface are coupled in many different ways. Subtle changes in such observable parameters as sea surface temperature, atmospheric chemistry, and vegetation distribution can be empirically correlated, suggesting that they may be interrelated in a phenomenological sense. In many instances, however, our understanding of the underlying physical phenomena that produce correlated changes in surface characteristics is quite rudimentary. In many other instances such understanding is lacking altogether. It is generally quite difficult to forecast spatial and temporal changes in terrestrial surface conditions on the basis of our current understanding of terrestrial surface processes.

Space technology provides a unique capability to "step back" from the Earth's surface in both a physical and intellectual sense. Remote sensing systems mounted on Earth-orbiting spacecraft can be used to observe surface conditions on our planet at a uniform scale and format on a globally repetitive basis. This capability provides a means of studying and characterizing the full range of surface conditions found on the Earth in a way that has not been possible in the past. Furthermore, this capability can be used to monitor temporal variations in surface conditions or to compare the characteristics of different regions as a means of obtaining improved insight into the physical processes that modify the Earth's surface.

As the name implies, the Landsat series of spacecraft have been specifically designed to conduct orbital observations of the Earth's land surface. The Landsat program began in earnest in July, 1972, with the launch of Landsat 1. The principal Earth observation sensor on this spacecraft was the Multispectral Scanner (MSS). The MSS was specifically designed to measure the intensity of Earth radiation in the visible and infrared portions of the electromagnetic spectrum at a spatial resolution that was appropriate for detailed observations of land conditions. Landsats 2 and 3 carried the same sensor complement as Landsat 1, and they were launched in 1975 and 1978, respectively. A second generation sensor system capable of conducting multispectral Earth surveys was recently developed and initially launched on Landsat 4 in July, 1982. This sensor is known as the Thematic Mapper (TM). It is superior to the MSS in terms of its spectral range and resolution, its spatial resolution, and its radiometric sensitivity and accuracy. The technical specifications of the TM are presented in detail in Section II of this document.

Landsat research activities conducted during the past decade have passed through several phases. During the mid-1970's, the main objective of these activities was to determine the various types of information that could potentially be extracted from multispectral Earth imagery acquired at a synoptic

scale. A wide variety of projects were conducted in which spatial and temporal variations in the spectral characteristics of the Earth's surface were related to ground-based measurements of surface properties. These research efforts lead to the development of new techniques for the reduction and analysis of multispectral Earth imagery. They also established a rigorous scientific basis for deriving specific types of surficial information from such imagery.

Landsat research activities conducted during the latter 1970's were primarily designed to identify practical applications of Landsat data. The main objective of these activities was to evaluate the utility of Landsat imagery for resource management and monitoring. A variety of large scale research projects were conducted by NASA in collaboration with other government agencies and private companies. The results of these research efforts indicated that Earth information derived from Landsat imagery could contribute significantly to improved methods of crop forecasting, mineral exploration, spring runoff forecasting, flood damage assessment, etc.

The collective results of the first ten years of Landsat research have provided extensive insight into the utility of multispectral surveys for specific types of Earth observations. These results have also indicated that orbital observations of the Earth's spectral characteristics can be applied to the study of changing surface conditions. This historical experience has enabled Earth scientists to develop considerable intuition concerning the fundamental capabilities and limitations of orbital multispectral surveys for studies of the Earth. This experience, in combination with the advanced measurement capabilities of the TM, creates a unique opportunity to apply orbital multispectral surveys to the study of terrestrial surface conditions and processes.

The purpose of this prospectus is to identify topical problems in different aspects of the Earth sciences that could be addressed in new and innovative ways through the analysis of TM imagery. These prospective research themes are defined here in a general sense in relation to the technical measurement capabilities of the TM and the various types of Earth information that can potentially be derived from multispectral TM imagery.

This document is organized into two parts. Section II provides an overview of the total system that has been developed to acquire and reduce TM data. The technical capabilities of this system are presented here in some detail. In addition, the orbital performance of the TM sensor is described, based upon the analysis of Landsat 4 and 5 TM data that have been collected to date. Section III of this document outlines prospective research themes that could potentially be addressed through the analysis and interpretation of TM imagery. This discussion is not intended to be a comprehensive listing of all of the research topics that are amenable to TM image analysis, nor does it reflect a prioritization of research topics in the Earth sciences on the part of NASA. The intent of this discussion is simply to illustrate generic types of scientific issues that could be addressed in new and innovative ways through the analysis of multispectral TM imagery. Section III has been subdivided into a discussion of prospective research themes in the fields of vegetation and soils science, geology, and hydrology. This organization was adopted to reflect the major classes of natural cover materials encountered on the Earth's surface. The subdivision of this discussion into these categories is *not* intended to preclude the application of TM data to the study of topical problems in related disciplinary fields.

In summary, it is anticipated that the information provided in this prospectus will assist Earth scientists in identifying potential scientific applications of TM data and in devising experimental methodologies that make substantive use of TM imagery for basic research in the Earth sciences.

# SECTION II
# CAPABILITIES AND PERFORMANCE OF THE TM SYSTEM

## INTRODUCTION

The first Landsat satellite, originally called the Earth Resources Technology Satellite (ERTS), was launched on July 23, 1972 by the National Aeronautics and Space Administration (NASA). Landsat 1 was designed to acquire Earth imagery in digital format for a minimum period of one year. Data from the satellite's Multispectral Scanner (MSS) proved so useful that the satellite remained in operation until the MSS failed in January 1978. Four additional satellites dedicated to Earth observations have been launched by NASA subsequent to the launch of Landsat 1: Landsat 2 on January 22, 1975; Landsat 3 on March 4, 1978; Landsat 4 on July 16, 1982; and Landsat 5 on March 1, 1984.

The Landsat satellites greatly enhanced our ability to study the Earth by providing multispectral Earth imagery at a synoptic scale on a globally repetitive basis. The first three satellites, which were quite similar in form and operation, all carried the MSS as their primary sensor payload. These satellites were all launched as experimental missions, but image analysis techniques developed to the point where MSS data are now used in an operational manner for mineral and oil exploration, crop monitoring and yield prediction, forest and range management, map making and many other applications. Ground stations which directly receive and process MSS data have been installed in eleven nations to permit worldwide access to the data.

The value of MSS data was developed and demonstrated by extensive research, but this research also revealed limitations in data utility. The potential for such limitations was recognized before the launch of Landsat 1. Planning for a second generation Earth resource observation system to follow the initial Landsat series was initiated by NASA in 1970. The configuration of a system which could enhance Earth observation capabilities evolved from a subsequent progression of study efforts and advisory groups representing the many facets of the remote sensing community. The satellite portion of the enhanced system was launched in July of 1982 and is now called Landsat 4. The launch of a nearly identical satellite, Landsat 5, followed in March, 1984. The Landsat 4 and 5 sensor payload consists of an MSS similar to the instruments carried onboard the initial three Landsat satellites and a new sensor, the Thematic Mapper (TM).

Landsat 4 and 5 offer several technological refinements over the previous systems. The platform portion of the satellites provides superior attitude control when compared to the first three Landsat satellites. These initial systems also relied upon tape recorders to store sensor data for subsequent transmission to a ground receiving station. These tape recorders were often the first system component to fail. Landsat 4 and 5 do not carry tape recorders, but instead transmit data directly to ground receiving stations as the data are acquired.

The TM and the MSS are multispectral scanners which both function in a similar manner. The proven technology of the MSS, however, has been refined to create improved sensor characteristics for the TM. These improvements include a finer spatial resolution, additional spectral bands located in new regions of the spectrum, and a greater number of data quantization levels to take advantage of an enhanced radiometric sensitivity. These sensor attributes are intended to increase both the quantity and quality of Earth information that can potentially be derived from Landsat imagery.

Knowledge of satellite and sensor characteristics is essential to the effective utilization of TM data. This section provides a detailed description of the Landsat 4 and 5 satellites, their instrument payloads, their orbits, and the reception, processing, and dissemination of TM data on the ground. Information on orbital sensor performance and TM data quality is also presented.

## LANDSAT 4 AND 5 SPACECRAFT CHARACTERISTICS

Landsat 4 and 5 are the first satellites in the Landsat series to conform to NASA's standard design for a Multimission Modular Spacecraft (MMS). Each satellite consists of two connected frames (Figure II-1). One frame, the universal MMS structure, supports modules for satellite propulsion, attitude control, power, and data communications. The other frame, the mission-specific Instrument Module Structure, carries the instrument and sensor payload. For Landsat 4 and 5, a single-wing array of solar panels and a large antenna mast are attached to this supporting structure. The antenna is used for data communications with the Tracking and Data Relay Satellite System (TDRSS) and the mast minimizes interference by the solar panel array. The solar array consists of four 1.5-m by 2.3-m panels which can collectively generate up to 2200 watts of power.

The MMS offers improved attitude control capabilities over the previous Landsat satellites. The MMS permits three-axis control of attitude. The pointing accuracy is specified to be within 0.01 degree (one sigma) and the stability is specified to be within $10^{-6}$ degree/second (one sigma). The first three Landsat satellites only provide one-axis control of attitude resulting in a 0.7 degree pointing accuracy and a stability value of 0.01 degree/second (Salomonson et al., 1980). The improved attitude control facilitates the cartographic and multitemporal registration of image data.

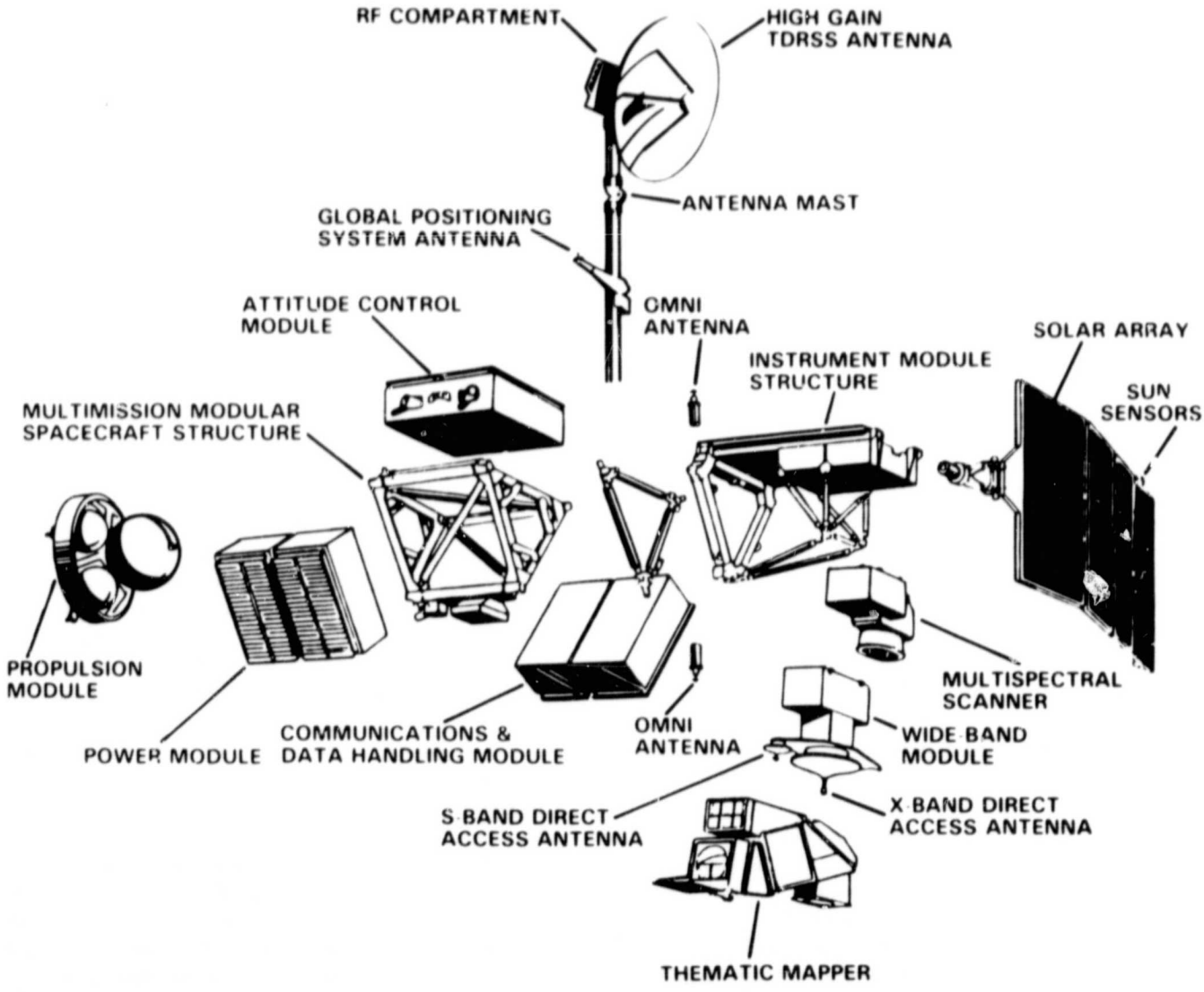


*Figure II-1 Exploded view of the Landsat 4 and 5 Multimission Modular Spacecraft.*

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## SENSOR PAYLOAD CHARACTERISTICS

The Landsat 4 and 5 sensor payload consists of the Multispectral Scanner (MSS) and the Thematic Mapper (TM). Both sensors are object-space line scanners which use moving mirror assemblies to scan across the spacecraft ground track and the orbital motion of the spacecraft to scan the perpendicular (i.e., along-track) direction. Both sensors generate multispectral image data in a digital format.

The MSS sensors on Landsat 4 and 5 are nearly identical to the MSS sensors on previous Landsat satellites. The MSS mirror reflects Earth radiation through a Ritchey-Chretein telescope onto a single focal plane. At the focal plane, optical filters separate the incident electromagnetic energy into the familiar four MSS spectral bands (Table II-1). Fiber optic bundles transmit the separated energy from the focal plane to detectors which convert the energy to electronic signals (Figure II-2). A shutter wheel in front of the fiber optics bundle is involved in the radiometric calibration of MSS data. Six detectors are used for each spectral band; photomultiplier tubes are used for spectral bands MSS1 through MSS3 and silicon photodiodes are employed for band MSS4. The detectors' signals are quantized to six bits (64 digital counts) before the image data are transmitted to the ground. With six detectors per band, the MSS generates six scan lines of data per scan mirror sweep. Data are actively acquired as the scan mirror moves the sensor's field of view from west to east. No data are acquired during the return scan (i.e., east-to-west).

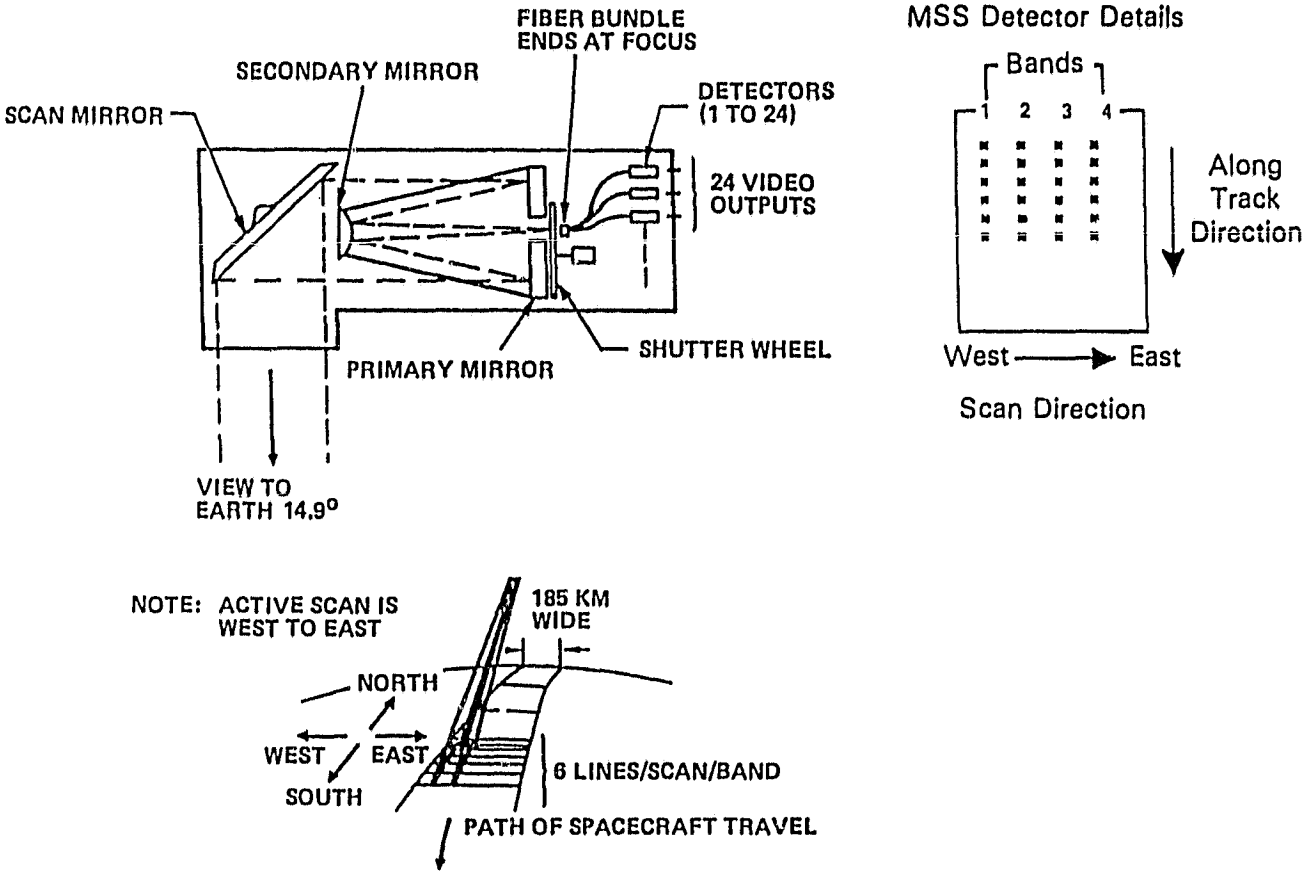


*Figure II-2 Schematic view of the Landsat 4 and 5 Multispectral Scanner. The cutaway diagram in the upper left corner shows how Earth radiation enters the sensor and is focused onto the optical fibers situated in the focal plane. The arrangement of the optical fiber endings is displayed schematically in the upper right corner of the diagram. Note that six scan lines of image data are generated simultaneously every time the scan mirror sweeps from west to east.*

**Table II-I**
**Multispectral Scanner Spectral Bands (Salomonson et al., 1980)**

| Band Dosignation | Specified Band Width (μm) | Specified Radiometric Sensitivity (NEΔρ)* |
|---|---|---|
| MSS1 | 0.5—0.6 | 0.57% |
| MSS2 | 0.6—0.7 | 0.57% |
| MSS3 | 0.7—0.8 | 0.65% |
| MSS4 | 0.8—1.1 | 0.70% |

* NEΔρ: noise equivalent change in surface reflectance.

The across-track swath (185 km) and the instantaneous-field-of-view (80 m) of the new MSS sensors are nearly equal to the swath width and IFOV of the earlier MSS's. Since the earlier Landsat satellites all flew at a higher altitude (920 km) than Landsat 4 and 5 (705 km), the optics and the active scan angle of the new MSS sensors were adjusted to compensate for the difference in altitude. The earlier sensors collected data over a total scan angle of 11.56° whereas the new MSS sensors employ a scan angle of 14.92°.

Several major differences exist between the basic design of the MSS and the design of the TM. First, the TM acquires data during both the forward (west-to-east) and reverse (east-to-west) sweeps of its scan mirror. This bidirectional approach was adopted to reduce the rate of oscillation of the scan mirror and increase the dwell time of individual detectors upon the Earth's surface. The TM actively scans the surface through an angle of 15.4° (plus-or-minus 7.7° measured from nadir). It completes approximately seven complete scan cycles per second (note that each complete cycle consists of a forward and reverse scan).

As another example of design differences, the TM does not rely on fiber optics, as does the MSS, to direct incoming electromagnetic energy onto photosensitive detectors. Fiber optics are incapable of transmitting 100 percent of the incident energy from the focal plane to the sensor's detectors. Instead of using fiber optics, the TM focuses incident radiation through its own Ritchey-Chretein telescope directly onto detectors within a prime focal plane assembly, and, through a set of relay mirrors, to the detectors of a cooled focal plane assembly (Figure II-3). The prime focal plane assembly contains four sets of 16 monolithic silicon detectors for four spectral bands in the visible and near infrared portions of the spectrum. The 16 detectors for each band are mounted in a common module with a spectral filter and preamplifier electronics. The cooled focal plane assembly contains two arrays of 16 indium antimonide (InSb) photodiodes for two middle infrared spectral bands and four mercury cadmium telluride (HgCdTe) detectors for a thermal band along with spectral filters and electronics. The cooled focal plane assembly is mounted in a dewar on the second stage of a passive radiative cooler. The InSb and HgCdTe detectors are mounted on this cooled focal plane to increase their radiometric sensitivity. The use of multiple detectors for each spectral band results in the generation of 16 scan lines of data for the six reflective bands and four lines of data for the thermal band during each sweep of the scan mirror. At any one instant, surface radiance is sensed by a total of 100 TM detectors.

Due to the spatial separation of the individual detector arrays situated within the TM focal planes, an area on the Earth's surface is not simultaneously scanned in all seven TM spectral bands. Figure II-3 illustrates the projection of the detector IFOV's onto-the Earth surface. Accurate band-to-band registration requires precise knowledge of the ground projection of the detectors in the two TM focal planes as a function of time.This information is derived from data concerning spacecraft position and attitude, the relative position of the individual detector arrays with respect to the sensor's optical axis, and the motion of the scan mirror during successive scan cycles. A scan angle monitor on the mirror generates signals indicating the scan mirror's angular position as a function of time. These signals are called mirror scan correction data and they are transmitted to the ground for geometric processing of TM image data.

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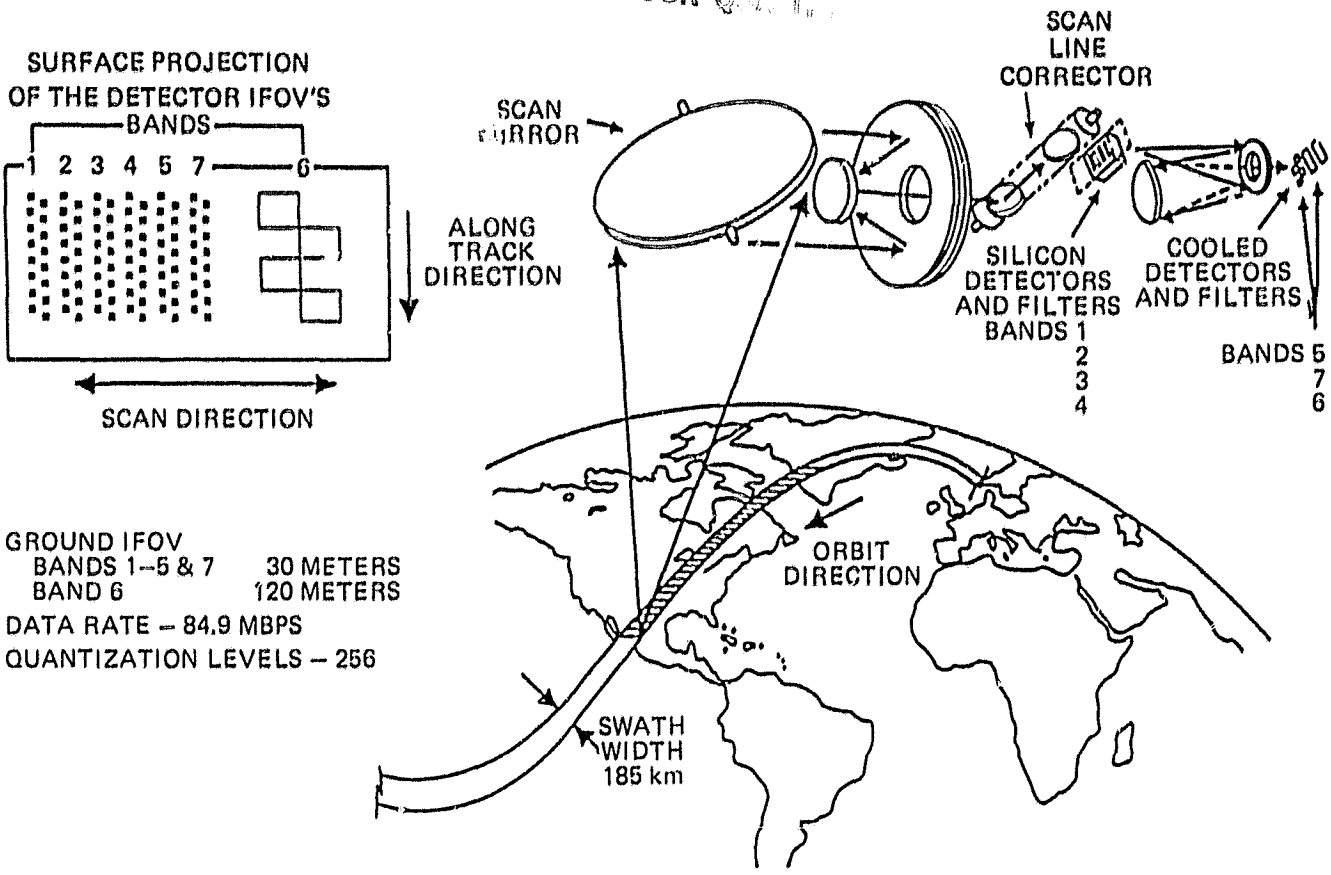


*Figure II-3 Schematic view of optical path of Earth radiation within the Thematic Mapper. Note that the detectors for the TM spectral bands are mounted in two spatially separated focal planes. The diagram in the upper left hand corner displays the instantaneous ground projection of the one hundred detectors within the TM sensor.*

Signals from the scan angle monitor also initiate the motions of the scan angle corrector located in front of the primary focal plane (Figure II-3). During each scan mirror sweep, the scan line corrector rotates the TM line-of-sight backward along the Landsat ground track to compensate for the forward motion of the satellite. The compensation prevents the overlap and underlap of scan lines and produces straight scan lines which are perpendicular to the ground track (Figure II-4). Also located on the TM is a three-axis angular displacement sensor assembly. The assembly contains three angular displacement sensors oriented along orthogonal axes. These sensors provide data to the ground data processing system to compensate for any high-frequency displacements of the TM optical axis caused by the vibrations of the TM and MSS scan mirrors.

The TM also contains an internal radiometric calibration source located behind the primary mirror and in front of the primary focal plane. The calibration source consists of three small tungsten filament lamps, a blackbody for the thermal band, and a flex pivot mounted resonant shutter. The shutter passes through the field of view of the TM detectors each time the scan mirror changes directions. The shutter introduces light from the lamps directly into the field of view of the detectors of the reflective bands (TM1 to TM5 and TM7). The radiant energy from the thermal calibration standard is reflected into the field of view of the thermal band detectors from a mirror mounted on the oscillating shutter. The detectors in all seven bands also view a dark isothermal portion of the shutter which is used to restore the direct current voltage value of each detector to a preset threshold value prior to the next active sweep of the scan mirror. This restoration of voltage is referred to as the "dc restore cycle" that precedes each period of active data collection (Engel, 1980).

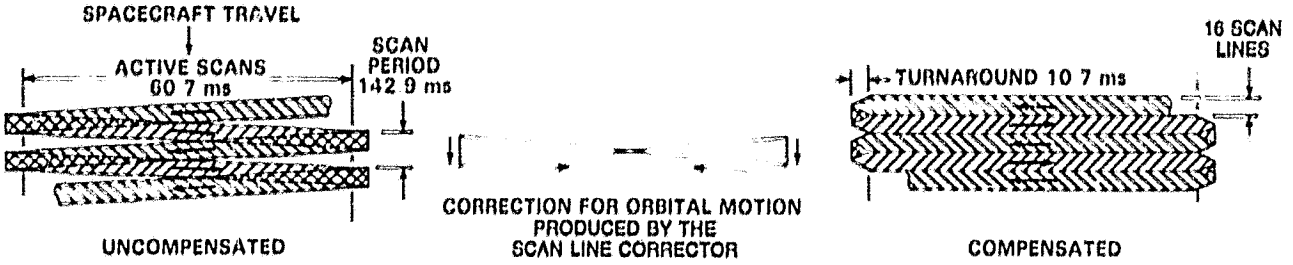


*Figure II-4 Schematic diagram showing how the motion of the scan line corrector within the TM compensates for the overlap and underlap of adjacent scan line sweeps that result from the orbital motion of the Landsat spacecraft. The scan line corrector ensures that individual TM scan lines are oriented perpendicular to the spacecraft's ground track.*

The three tungsten lamps operate at approximately the same intensity, but different neutral density filters in front of each lamp cause a difference in the intensity of light from each lamp for calibration. All possible combinations of two lamp states (on and off) for three lamps provide eight different light levels for detector calibration. These eight levels include a dark level consisting of all three lamps in the "off" state. The light level remains constant for approximately 20 scan cycles (i.e., 20 successive forward and reverse sweeps of the scan mirror). After each 20 cycle interval, the state of one lamp is changed (i.e., turned on or off) to alter the light level. Since 16 detectors are used for each band, a total of 5120 scan lines of image data are generated during the time interval required to view all eight light levels (i.e., corresponding to eight calibration levels times 40 scan mirror sweeps per level times 16 lines of data per mirror per sweep). For the thermal band, the temperature of the blackbody and the temperature of the shutter's dc restore surface are used for a two-level calibration of the four thermal detectors.

Figure II-5 provides an overview of the Thematic Mapper design. The TM is horizontally mounted in the satellite with the sun shade pointing toward Earth. The scan mirror is located directly above the sun shade aperture along with the mirror's drive mechanism, control electronics, and scan angle monitor. The primary mirror is secured approximately in the center of the telescope and is preceded by the secondary mirror and optical baffles. The scan line corrector, the internal calibrator, and the primary focal plane are directly behind the primary mirror. The angular displacement sensors are located within a small assembly mounted to the exterior of the TM telescope (the assembly is hidden in Figure II-5). The back end of the instrument contains the relay optics and the cooled focal plane within the radiative cooler. The electronics package sits in a wedge-shaped box above the telescope and contains the multiplexer, power supplies, signal amplifiers, and electronic filters.

The complex design of the TM affords advanced sensor attributes in comparison to the MSS. For instance, the TM acquires data in seven spectral bands. Four of these bands are located in portions of the spectrum not sensed by the MSS. The location and width of the seven bands were carefully chosen for sensitivity to certain natural phenomena and to minimize the attenuation of surface energy by atmospheric water. Table II-2 lists the spectral bands along with the rationale for selecting each band.

Another advanced feature of the TM is its spatial resolution. The TM instantaneous-field-of-view (IFOV) is 30 m-by-30 m for the six reflective spectral bands (bands TM1 to TM5 and TM7) and 120 m-by-120 m for the thermal band (band TM6). The MSS provides a resolution of approximately 80 m-by-80 m in all bands. Table II-3 lists the optical characteristics of the TM which govern its surface spatial resolution.

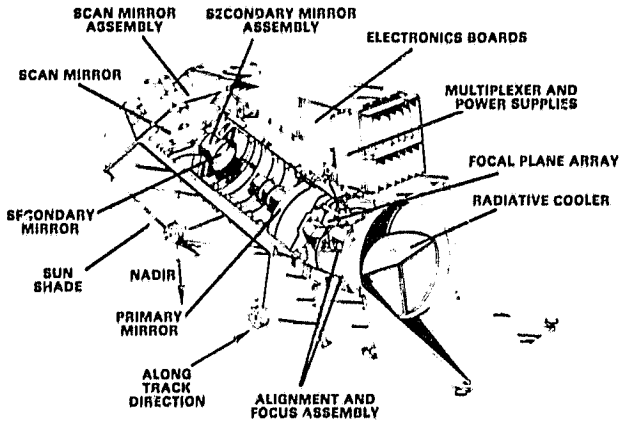


*Figure II-5 Cut-a-Way view of the Thematic Mapper.*



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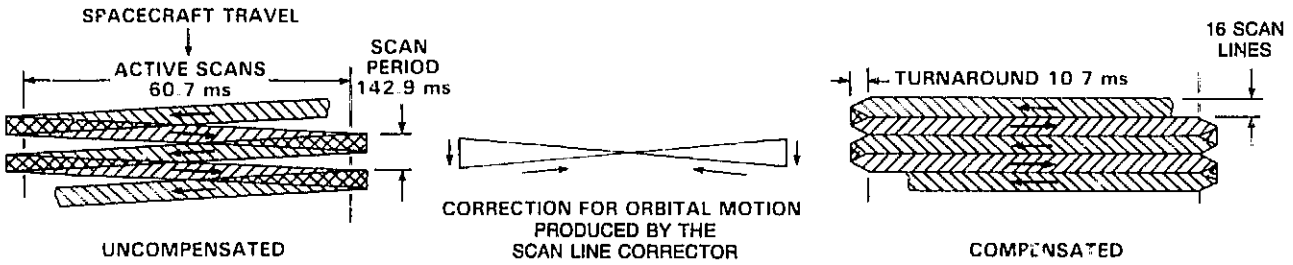


*Figure II-4 Schematic diagram showing how the motion of the scan line corrector within the TM compensates for the overlap and underlap of adjacent scan line sweeps that result from the orbital motion of the Landsat spacecraft. The scan line corrector ensures that individual TM scan lines are oriented perpendicular to the spacecraft's ground track.*

The three tungsten lamps operate at approximately the same intensity, but different neutral density filters in front of each lamp cause a difference in the intensity of light from each lamp for calibration. All possible combinations of two lamp states (on and off) for three lamps provide eight different light levels for detector calibration. These eight levels include a dark level consisting of all three lamps in the "off" state. The light level remains constant for approximately 20 scan cycles (i.e., 20 successive forward and reverse sweeps of the scan mirror). After each 20 cycle interval, the state of one lamp is changed (i.e., turned on or off) to alter the light level. Since 16 detectors are used for each band, a total of 5120 scan lines of image data are generated during the time interval required to view all eight light levels (i.e., corresponding to eight calibration levels times 40 scan mirror sweeps per level times 16 lines of data per mirror per sweep). For the thermal band, the temperature of the blackbody and the temperature of the shutter's dc restore surface are used for a two-level calibration of the four thermal detectors.

Figure II-5 provides an overview of the Thematic Mapper design. The TM is horizontally mounted in the satellite with the sun shade pointing toward Earth. The scan mirror is located directly above the sun shade aperture along with the mirror's drive mechanism, control electronics, and scan angle monitor. The primary mirror is secured approximately in the center of the telescope and is preceded by the secondary mirror and optical baffles. The scan line corrector, the internal calibrator, and the primary focal plane are directly behind the primary mirror. The angular displacement sensors are located within a small assembly mounted to the exterior of the TM telescope (the assembly is hidden in Figure II-5). The back end of the instrument contains the relay optics and the cooled focal plane within the radiative cooler. The electronics package sits in a wedge-shaped box above the telescope and contains the multiplexer, power supplies, signal amplifiers, and electronic filters.

The complex design of the TM affords advanced sensor attributes in comparison to the MSS. For instance, the TM acquires data in seven spectral bands. Four of these bands are located in portions of the spectrum not sensed by the MSS. The location and width of the seven bands were carefully chosen for sensitivity to certain natural phenomena and to minimize the attenuation of surface energy by atmospheric water. Table II-2 lists the spectral bands along with the rationale for selecting each band.

Another advanced feature of the TM is its spatial resolution. The TM instantaneous-field-of-view (IFOV) is 30 m-by-30 m for the six reflective spectral bands (bands TM1 to TM5 and TM7) and 120 m-by-120 m for the thermal band (band TM6). The MSS provides a resolution of approximately 80 m-by-80 m in all bands. Table II-3 lists the optical characteristics of the TM which govern its surface spatial resolution.

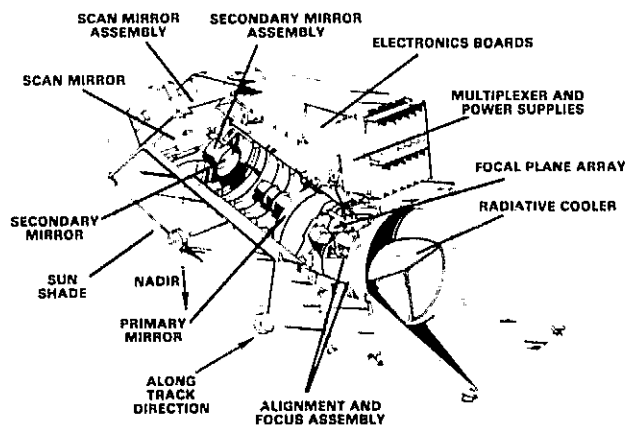


*Figure II-5 Cut-a-Way view of the Thematic Mapper.*



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**Table II-2**
**Thematic Mapper Spectral Bands (Salomonson et al., 1980)**

| Band Designation | Specified Band Width ($\mu$m) | Specified Radiometric Sensitivity (NE$\Delta\rho$)* | Selection Rationale |
|---|---|---|---|
| TM1 | 0.45—0.52 | 0.8% | Sensitive to chlorophyll and cartonoid concentrations for soil/vegetation differentiation, deciduous/ coniferous differentiation. Coastal water mapping. |
| TM2 | 0.52—0.60 | 0.5% | Sensitive to green reflectance by healthy vegetation. |
| TM3 | 0.63—0.69 | 0.5% | Sensitive to chlorophyll absorption for plant species differentiation. |
| TM4 | 0.76—0.90 | 0.5% | Sensitive to near infrared reflectance of healthy vegetation for biomass surveys. |
| TM5 | 1.55—1.75 | 1.0% | Sensitive to vegetation moisture and snow/cloud reflectance differences. |
| TM6 | 10.4—12.5 | 0.5 K NETD** | Thermal mapping. |
| TM7 | 2.08—2.35 | 2.4% | Sensitive to vegetation moisture and to hydroxyl ions in minerals for geological mapping. |

*NE$\Delta\rho$: noise equivalent change in surface reflectance
**NETD: noise equivalent temperature difference

**Table II-3**
**Thematic Mapper Optical Characteristics**
**(Engel, 1980)**

40.6 cm. Aperture
f/6 at Prime Focus
42:5 $\mu$rad Angular IFOV, Bands TM1 through TM4
f/3 at Relay Focus
43:8 $\mu$rad Angular IFOV, Bands TM5 and TM7
170 $\mu$rad Angular IFOV, Band TM6

The TM also offers improved radiometric sensitivity over the MSS, even though the spectral bandwidth and the IFOV of the TM detectors is significantly less than that of the MSS. Sensitivity specifications in terms of noise equivalent change in surface reflectance (NE$\Delta\rho$) are presented for the MSS and TM in Tables II-1 and II-2, respectively. In conjunction with the improved sensitivity, TM data are quantized to eight bits (256 digital counts) while MSS data are quantized to six bits (64 digital counts). This effectively corresponds to a four-fold increase in the gray scale being used to measure the intensity of Earth radiation in each discrete spectral band.

In summary, the TM's improved sensor capabilities relative to the MSS are a result of the advanced design of the TM. Design factors which significantly affect the TM's measurement capabilities include: the detectors' angular IFOV which is a function of detector size and telescope focal length; the optics of the scan mirror and telescope which minimize diffraction and blur and thus enhance radiometric sensitivity and spatial resolution; the use of the bidirectional active scan approach which increases detector dwell time and thus enhances radiometric sensitivity; the internal calibrator which permits eight level, in-flight radiometric calibration; the relay optics and cooled focal plane which enable sensing of energy within middle infrared and thermal infrared spectral bands; and the scan angle monitor and the scan line corrector which facilitate the precise geographic registration of the fine resolution image data. The rationale for creating this advanced design is to generate data which can be better exploited for a wide variety of Earth observations. For future reference, the TM aboard Landsat 4 is called the protoflight (TM/PF) model while the TM aboard Landsat 5 is referred to as the flight (TM/F) model. The designs of the two TM's are identical. Their operating characteristics differ in some minor respects as noted below.

## LANDSAT ORBIT AND COVERAGE

Landsat 4 and 5 travel in repetitive, circular, sun-synchronous, near-polar orbits at a nominal altitude of 705 km. The orbits have an inclination angle of 98.2 degrees with respect to the Earth's equator. The satellites cross the equator at approximately 9:45 a.m. local solar time during the descending (north-to-south) portion of each orbit. The TM can acquire thermal data during the satellites' ascending (south-to-north) portion of an orbit during which the satellites cross the equator at 9:45 p.m. local solar time. Each orbit takes almost 99 minutes, and each spacecraft completes just over 14.5 orbits a day. Due to Earth rotation, the distance between ground tracks for two consecutive orbits is 2752 km at the equator. Figure II-6 illustrates the orbital characteristics of Landsat 4 and Landsat 5.

The orbital configuration described above creates a 16 day repeat cycle for each satellite. In other words, a specific satellite will travel along a particular ground track once every 16 days. The orbits of the two satellites are eight days out of phase. In other words, Landsat 4 and Landsat 5 alternate orbits over a particular ground track every eight days. For either one of these satellites, the time interval between adjacent tracks is seven days (Figure II-7). This arrangement contrasts with the 18-day orbital cycles of the first three Landsat satellites which resulted in a one day interval between orbits over adjacent tracks.

The altitude, optics, and 15.4° scan angle of the TM enable the instrument to view a 185 km swath across the ground track of each satellite. At the equator, adjacent swaths overlap at their east and west margins by 7.6 percent. The overlap increases as the ground tracks move away from the equator toward either pole. At 40 degrees north or south latitude, for example, the overlap is 18.5 percent.

The Landsat 4 and 5 pass over the same ground track after completing 233 orbits of the Earth. This orbital repeat cycle is incompatible with the 251 orbit Worldwide Reference System (WRS) used to index MSS data from the previous Landsat satellites. A new system of path and row indices has been designed for both MSS and TM data from Landsat 4 and 5. A path index number is assigned to the ground track of each orbit. The new system consists of 233 orbital paths numbered east-to-west with the center point of path 001 crossing the equator at 64.95 degrees west longitude. The data for each scene consist of the data acquired during a 25.87-second increment of the orbital motion of the satellite. This increment corresponds to approximately 5700 scan lines of image data. Both the MSS data and the TM data for each scene cover a surface area approximately 170 km along- track by 185 km across-track. A row index is assigned to each scene center. Row one of each path starts at 80°51′ north latitude and the numbering increases southward through the equator (row 60) to 81°51′ south latitude (row 122). The satellites then travel northward for the ascending (nighttime) portion of each orbit, and row numbers increase from south-to-north through the equator (row 184) to 81°51′ north latitude (row 246). Thus, row indices 123 through 246 refer to scenes of nighttime TM thermal data which are not acquired on a routine basis. Maps delineating paths and rows can be obtained from the National Oceanic and Atmospheric Administration (NOAA) by writing to the following address: NOAA Landsat Customer Services, Mundt Federal Building, Sioux Falls, South Dakota 57198.

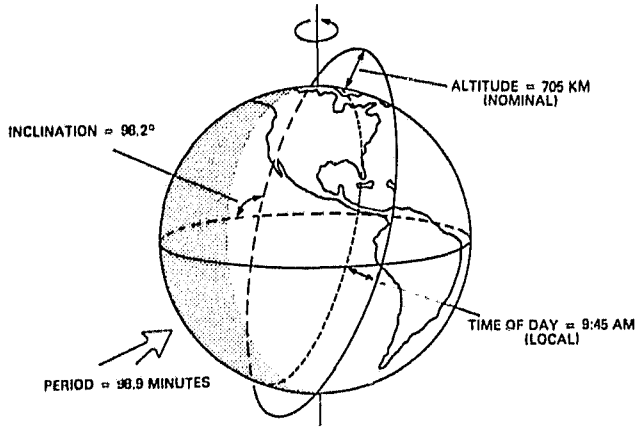


*Figure II-6 The sun-synchronous orbits of Landsat 4 and 5.*

## TM DATA ACQUISITION

As the TM scan mirror sweeps back-and-forth seven times per second, incoming Earth energy is focused onto a total of 100 photosensitive detectors. The detectors translate the incoming energy into low-level electrical signals which are amplified, quantized to eight-bit digital words, and then multiplexed into an 84.9 megabits-per-second (Mbps) data stream. The digital image data are then transmitted to the ground along with additional data concerning TM sensor operation and spacecraft conditions.

The first three Landsat satellites relied upon onboard tape recorders to store data until the satellite passed within range of a ground receiving station.



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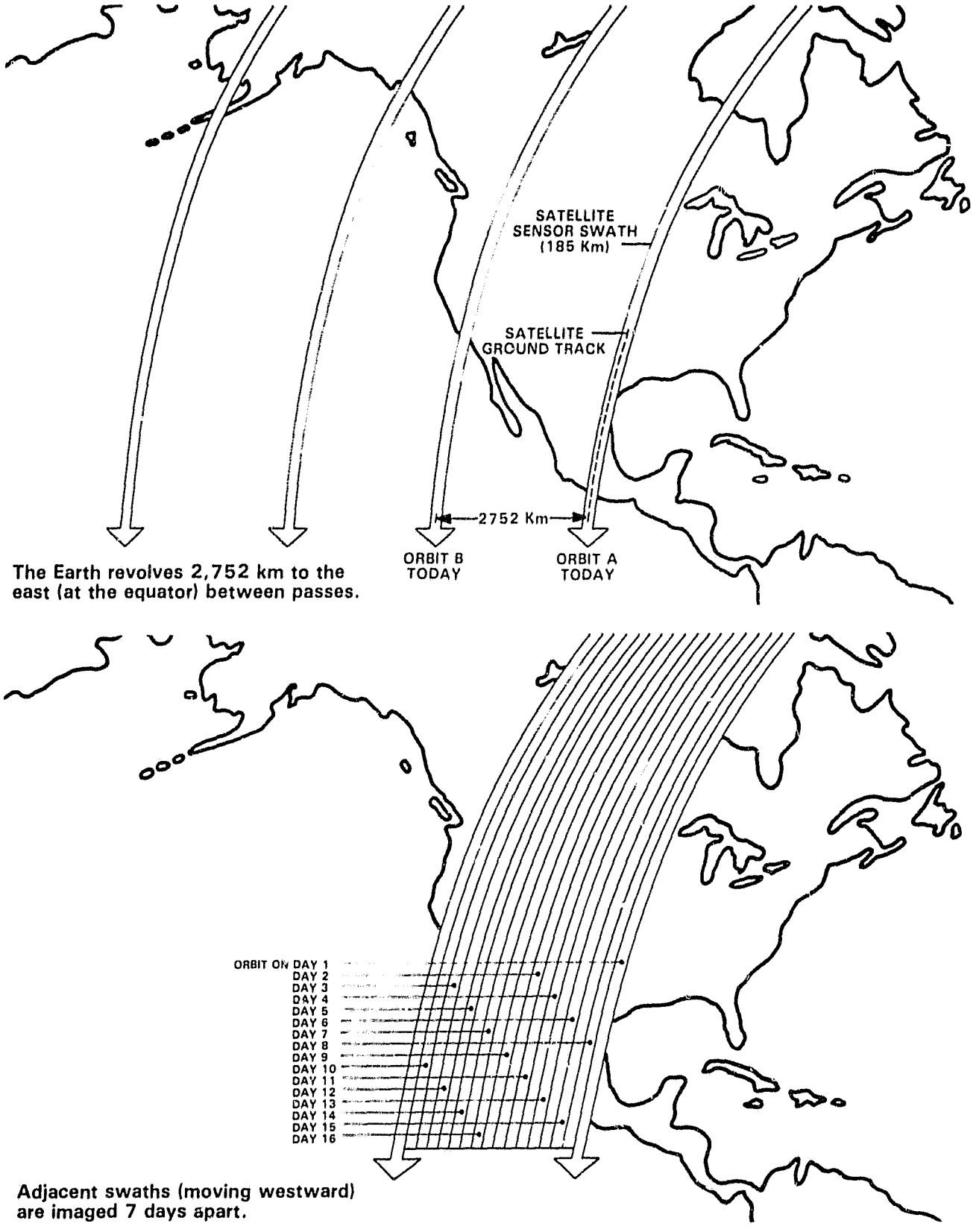


*Figure II-7 The Landsat 4 and 5 orbital repeat cycles.*

These recorders were often the first component to fail. Landsat 4 and 5 use a new communications sytem, called the Tracking and Data Relay Satellite System (TDRSS), which eliminates the need for on-board recorders. TDRSS will eventually consist of two satellites (plus an in-orbit spare satellite) in geosynchronous orbits and a centralized ground receiving station located at White Sands, New Mexico. The first TDRSS satellite (TDRS-East) was launched on April 4, 1983 aboard NASA's space shuttle Challenger (mission STS-6). After overcoming problems caused by a malfunction of its booster rocket, the satellite reached its permanent station on October 17, 1983. TDRS-East is currently in geosynchronous orbit over the equator at 41° west longitude at an altitude of 35,890 km. The second TDRSS satellite is scheduled for launch in February, 1985. When launched, the second TDRSS satellite (TDRS-West) will be located 35,890 km over the equator at 171° west longitude.

The performance of TDRS-East is still being tested, but the satellite is currently (as of July 1, 1984) relaying Landsat 5 TM and MSS data to White Sands on a regular basis. The relay is limited to the data from two or three Landsat 5 ground tracks per day during the current system checkout period. The daily volume of TM data transmitted by the system will increase when TDRS-East is considered fully operational.

With only one TDRSS satellite in orbit, the data relay is also limited to TM and MSS data acquired between approximately 160° west longitude and 60° east longitude (Figure II-8). This excludes data acquired over Australia, India, and Asia from TDRS-East relay. When the second TDRSS satellite, TDRS-West, is placed in orbit in its final position, only data acquired over India and the Indian Ocean (between 67° east and 82° east longitude and between 50° north and 50° south latitude) will be excluded from TDRSS relay (Figure II-8). It is currently anticipated that the complete TDRSS system will become fully operational during the summer of 1985.

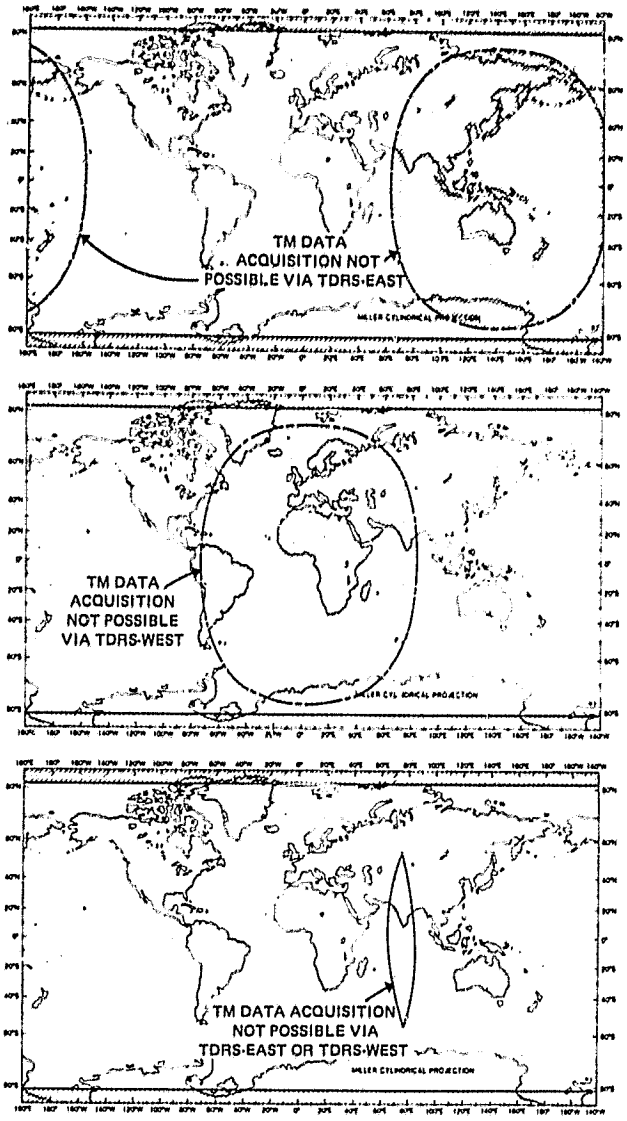


*Figure II-8 Regions where TM data cannot be relayed via one or both of the TDRSS spacecraft.*

To handle the high data rates from Landsat 4 and 5, the TDRSS employs a Ku-band (approximately 15 Gigahertz) frequency for data communications. This frequency is transmitted from the Landsat TDRSS antennas (Fig. II-1) and then relayed through the TDRSS satellites to the ground receiving station at White Sands, New Mexico. The data received by the White Sands facility are demodulated, separated, and recorded on wide-band digital data tapes. These compacted raw data are read from the tapes and then transmitted, by way of a domestic communications satellite (DOMSAT), to a data processing facility at NASA's Goddard Space Flight Center (GSFC) in Greenbelt, Maryland. This scheme enables the reception of data at the GSFC facility within eight hours of data generation by the sensor. After geometric and radiometric corrections are performed at GSFC (described below), the processed TM data, on film and on computer compatible tapes, are sent by air shipment to the Earth Resources Observation System (EROS) Data Center in Sioux Falls, South Dakota, for distribution to the public. The EROS Data Center is operated for NOAA by the United States Geological Survey. Figure II-9 traces the critical pathway for TM data products.

The TDRS data link is augmented by a capability to transmit TM data directly on an X-band (8.025 to 8.4 Gigahertz) frequency. Landsat 4 and 5 both carry



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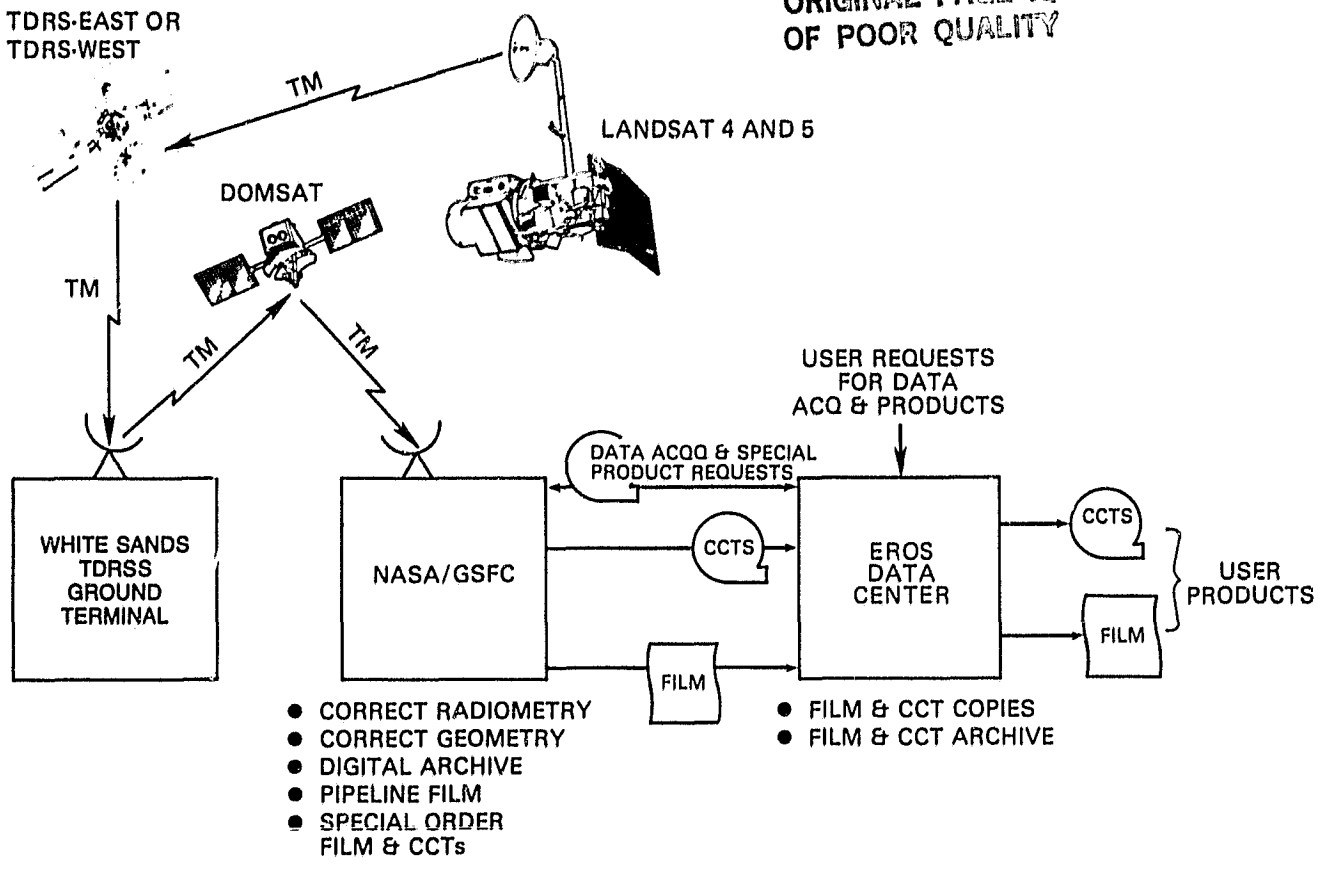


*Figure II-9 End-to-end flow of TM image data from the Landsat 4 and 5 spacecraft to ground-based users.*

X-band transmitters for this purpose. The Landsat 4 X-band transmitter failed on February 15, 1983 after transmitting over 6000 TM scenes. Most of the Landsat 4 TM data were received by the Transportable Ground Station (TGS) located at GSFC. Landsat 5 TM data are currently being received by the TGS and by six additional stations at the following locations: Cuiaba, Brazil; Prince Albert, Canada; Hyderabad, India; Fucino, Italy; Tokyo, Japan; and Kiruna, Sweden. Receiving stations are planned for several more locations around the world including Australia and China.

Along with the TM image data of the surface scene, Landsat 4 and 5 transmit ancillary spacecraft and sensor data required for the radiometric and geometric correction of the image data. These additional data include: radiometric calibration data consisting of the quantized responses of the photosensitive detectors to energy from the internal calibration lamps described above; mirror scan correction data, from the scan angle monitor, describing the angular position of the scan mirror as a function of time; and payload correction data describing the attitude and the ephemeris of the sensor. Payload correction data consist of data from the angular displacement sensor, data from the satellite's attitude control system, Earth-centered ephemeris, and housekeeping information such as timing codes and TM internal temperatures. The ephemeris is computed by on-board computers which receive information on the satellite's position from ground stations of the NASA communications network (NASCOM). Landsat 4 and 5 are also capable of receiving information from the Global Positioning Systems (GPS) satellites, but this system is not used at the present time because the GPS satellite constellation has not yet been fully deployed. Multiplexers aboard Landsat 4 and 5 place all of the payload correction data described above into a standard format. These ancillary data are then integrated with the TM image data (i.e., detector outputs). The integrated data stream is commonly referred to as wideband data. Wideband data are transmitted to the ground via the X-band or Ku-band antennas on the Landsat satellites. Payload correction data are also transmitted separately at a rate of 32 kilobits per second by S-band (2206 to 2300 Megahertz) telemetry to NASCOM ground stations. NASCOM then forwards the payload correction data to GSFC.

## TM DATA PROCESSING

All of the ground stations receiving TM data have or plan to have associated data processing facilities. The operators of these stations have been organized into the Landsat Ground Station Operators Working Group (LGSOWG). The LGSOWG has agreed to some digital image data format standards, but the data processing procedures and available TM data products will likely vary between facilities. *The discussion presented here describes procedures performed at the Landsat data processing facility located at NASA's Goddard Space Flight Center (GSFC) in Greenbelt, Maryland. This facility, called the Landsat Ground Segment, processes all the TM data relayed to the ground through TDRSS.* The facility also processes data received by the Transportable Ground Station (TGS) located at GSFC and by the Prince Albert, Canada, station on the X-band frequency.

The GSFC facilities consist of the Mission Management Facility (MMF), the Control and Simulation Facility (CSF), and the Image Generation Facility (IGF). The MMF receives and processes user requests for data covering specific ground locations and is responsible for data archiving. Data requests are then sent to the CSF which commands, controls, and monitors the Landsat satellites and also schedules TDRSS, DOMSAT, and NASCOM support. Processing of MSS and TM image data is performed by separate systems in the IGF (see Figure II-10).

The IGF system for TM data is called the Thematic Mapper Image Processing System (TIPS). TIPS commenced operations in July, 1983. Before then, TM data were processed for research purposes by an improvised computer system popularly known as the "Scrounge System."

The Scrounge System was assembled from available pieces of computer hardware prior to the launch of Landsat 4. The system consisted of the Applications Development Data System (ADDS), the Landsat Assessment System (LAS), and elements of the Mission Management Facility (MMF). ADDS is primarily a test system designed to evaluate the use of array processors for the efficient processing of digital image

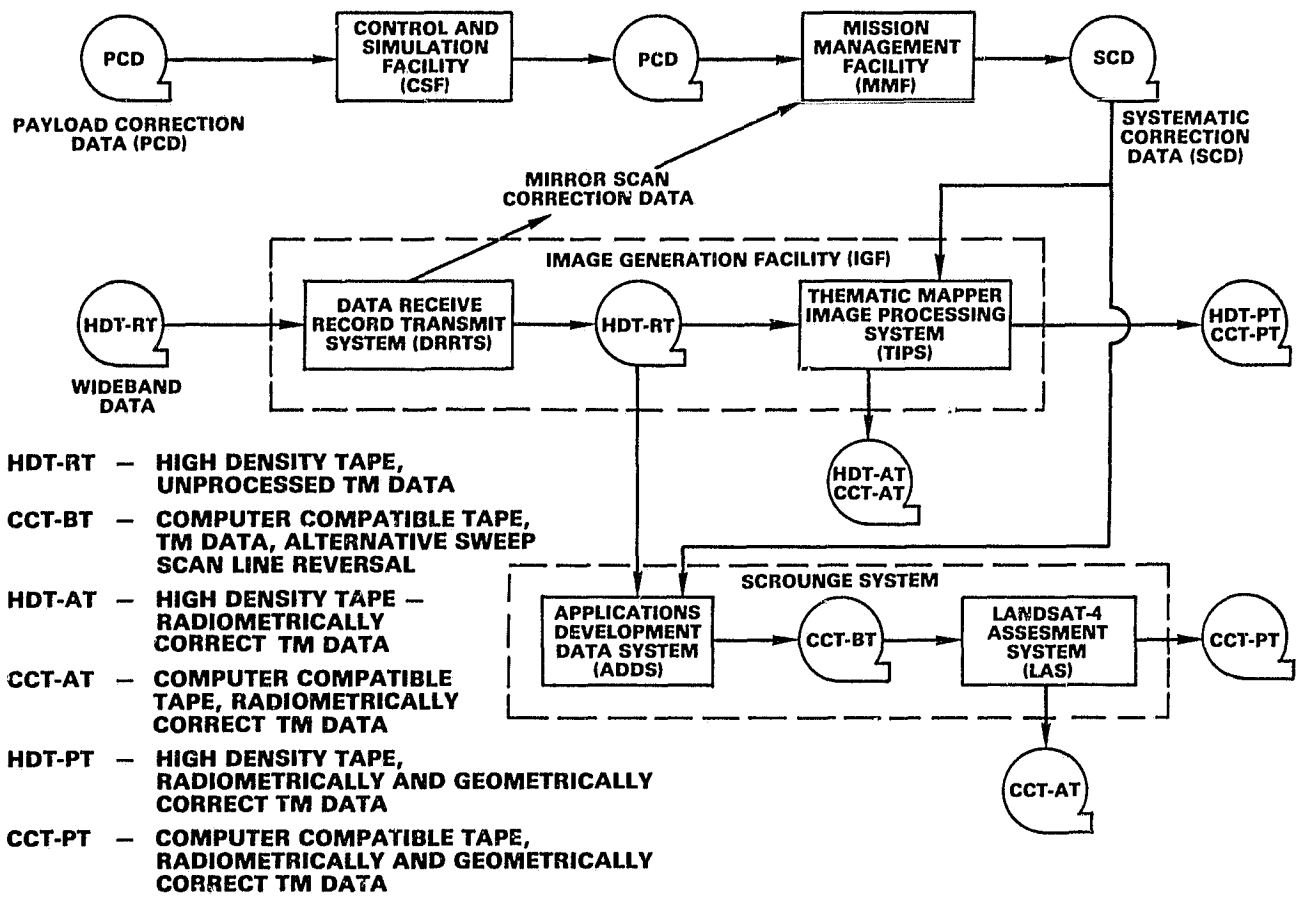


*Figure II-10 Thematic Mapper data flow through the ground segment facilities. Note that the use of the Scrounge System for routine processing of TM image data was discontinued in July, 1983.*



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data. The central processing unit of ADDS is a minicomputer which serves as a host for two array processors. The original intent of the LAS was to expedite the scientific utilization of TM data by providing investigators with an advanced image analysis facility. The system supports interactive image analysis stations which include cathode ray tubes for the video display of image data. The LAS central processing unit is a minicomputer supported by an array processor (Fischel, 1983). Another two computers within the MMF are used to process payload correction data for both the Scrounge System and TIPS. ADDS and LAS were pressed into service for TM data processing until TIPS began operations.

TIPS consists of two identical systems operating in parallel. The central processing unit of each system is a minicomputer interfaced to an advanced, high-speed array processor. The advanced array processors enable TIPS to process an entire TM scene in under 15 minutes (Fischel, 1983).

The main functions of both TIPS and the Scrounge System are the radiometric and geometric correction of TM image data. The Scrounge System correction algorithms emulated the procedures implemented by TIPS, and experience gained during Scrounge System processing was incorporated into the final development of the TIPS. The Scrounge System, however, operated at a much slower throughput rate than the specified rate for TIPS. The Scrounge System processed data at an approximate rate of one TM scene per day. TIPS currently processes data at a rate of 12 scenes per day to fully processed film products, and two scenes per day of completely processed data on computer compatible tapes (CCT's). This rate will increase to 50 completely processed scenes per day on CCT's.

Data processing begins with the reception of a scene of TM wideband data at the Data Receive Record Transmit System (DRRTS) within the Image Generation Facility and the reception of the associated, but separated, payload correction data (PCD) by the Control and Simulation Facility (Figure II-10). DRRTS sends the mirror scan correction data to the Mission Management Facility (MMF) for geometric processing (described below) and passes the rest of the wideband data to TIPS.

To facilitate the discussion of TM data processing, the radiometric correction procedures will be explained first followed by a discussion of geometric correction procedures. The actual sequence of data processing steps employed by TIPS will then be presented.

## Radiometric Correction Procedures

The two primary objectives of radiometric correction are to remove detector-to-detector striping and to permit conversion of TM digital counts to absolute radiometric units. The conversion of digital counts to absolute radiometric units enables investigators to measure spatial and temporal variations in scene radiance in a consistent, quantitative fashion. Recall that the TM employs 16 detectors for each reflective spectral band (bands TM1 to TM5 and TM7) and four detectors for the thermal band (TM6). The amplified and quantized signals from an individual detector are referred to as a data channel. Each datum from a channel consists of an integer value between zero and 255, inclusive, and is called a digital number (DN). For each channel, a response function mathematically relates digital numbers to absolute spectral radiance (expressed in units of power per unit area per unit solid angle per unit wavelength) incident on the TM entrance aperture.

The response function for a data channel may vary in orbit due to variations in the performance of individual detectors and other system components. The internal calibration lamps and thermal references (discussed above) are used to characterize the in-orbit response functions of all TM data channels. The continued cycling of the lamp states through eight calibration light levels permits the monitoring of channel response functions at regular intervals. Without radiometric corrections, variations between the response functions for the 16 channels within a reflective spectral band (or four channels within the thermal band) would be manifested as horizontal striping in pictorial imagery. The correction procedure for TM data minimizes striping by normalizing the digital numbers to a common response function for each spectral band. The corrected digital numbers can then easily be converted to absolute radiometric units by inverting the appropriate common response function for a particular band.

Several assumptions are implicit in the radiometric correction procedure. First, the TM detectors and data system were designed to generate a linear response to incident spectral radiance. Assumptions of linear response appear valid on the basis of prelaunch calibration of channel response functions and post-launch analyses of channel response to the internal calibration lamps. Linearity simplifies the mathematical expression of channel response functions. A function can be defined by the slope and intercept of the line relating ditigal number to spectral radiance. The

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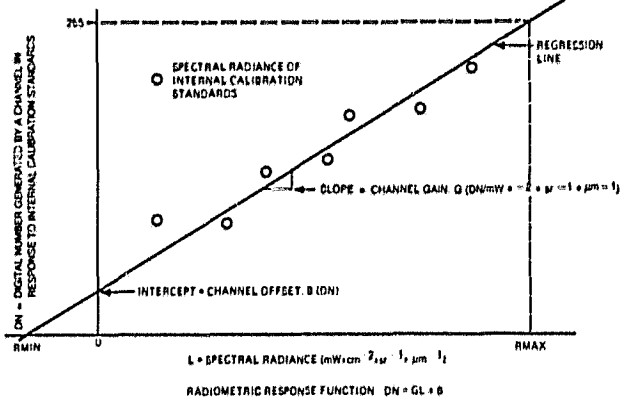


*Figure II-11 Radiometric response function of an individual TM channel.*

slope and intercept of a linear response function are called gain and offset, respectively (Figure II-11). Equivalently, a linear response function can be defined by the spectral radiance corresponding to a digital number response of zero (RMIN) and by the minimum radiance required to generate the maximum digital response of 255 (RMAX; i.e., the saturation radiance). The range from RMIN to RMAX is the dynamic range of a channel.

A second assumption involves the stability of the internal calibration lamps. The spectral radiance incident on each TM detector at each of the eight calibration levels (or two thermal reference levels) was measured during pre-launch calibration. The calibration light levels incident on each detector are assumed to have remained constant during launch and in orbit. Changes in observed channel responses to calibration light levels are attributed to changes in the performance of TM detectors and/or data system components, not to changes in calibration lamp output. This assumption is difficult to test once the sensor has been placed in orbit.

The actual radiometric correction procedure for TM data consists of several steps. These steps are summarized here and described in greater detail below. In the first step, output values for malfunctioning detectors are replaced by the output values of adjacent detectors in the same band. This correction has only been needed for two channels from the Landsat 4 TM/PF sensor. In the second step, channel responses to the on-board calibration standards are used to characterize the in-orbit response functions of the individual channels. These in-orbit response functions are up-dated at intervals of 360 scan cycles (i.e., every 11520 scan lines). In the third step, a histogram equalization procedure is used to refine the channel response functions. The purpose of histogram equalization is to prevent residual radiometric striping caused by imprecision in the in-orbit calibration of the channel response functions. Once the in-orbit response functions of individual channels have been calibrated and refined, the raw digital numbers can be normalized to a common response function for each spectral band. In the fourth and final processing step, the normalization is accomplished by defining and applying radiometric look-up tables (RLUT's) which map raw digital numbers to corrected digital numbers. For a specific spectral band, the full range of corrected digital numbers represents the same dynamic range of spectral radiance regardless of the individual channel that generated the raw data. This common dynamic range remains constant from scene-to-scene. The common dynamic range for each band was specified on the basis of a pre-launch calibration of the individual channels within each band. The collective result of this multiple-step radiometric correction procedure is the production of TM imagery which exhibits minimal radiometric striping. In addition, this procedure generates radiometrically calibrated TM image data which can be used to measure differences in scene radiance in a quantitative fashion both within and between individual TM scenes.

In the radiometric processing of TM/PF data from Landsat 4, data from two channels are replaced; the third detector of band TM5 has no radiometric response and the fourth detector of band TM2 has a poor spatial resolution. The digital numbers from each malfunctioning detector are replaced by the raw digital numbers from an adjacent detector in the band. The replacement data are then treated in the same manner as the original data from the functioning detectors during subsequent processing. All of the detectors in the Landsat 5 TM/F are operating and data replacement is unnecessary.

The next step determines the in-orbit linear response function for each data channel. The digital responses of individual channels to the internal lamps are fit to the eight calibrated (and presumably unchanging) levels of incident spectral radiance from the internal calibration lamps by simple linear regression (i.e., a least-squares fit) for the six reflective spectral bands (Figure II-11). The two internal thermal references are monitored by on-board heat sensors. The response function of each of the four thermal channels is determined by a linear regression between the observed digital responses of a thermal channel and the measured temperatures of the two internal thermal standards. The slopes and intercepts of these regression lines described above correspond to the

gains and offsets, respectively, of the measured channel response functions.

The possibility of imprecision in the estimation of individual channel response functions was recognized during the design of the radiometric correction procedure. A histogram equalization process was included at this stage in the correction procedure to refine the estimates of channel response functions. The purpose of histogram equalization is to minimize residual line-to-line striping in final TM image products which could occur given imprecise estimates of channel gain and offset. This procedure has been routinely used in the past for relative radiometric corrections of MSS data.

The equalization procedure begins with the production of a digital number frequency histogram for each channel. The histogram is constructed by sampling every fourth digital number generated by a channel during an interval of 360 scan cycles. This sampling protocol is based upon the assumption that each channel within a band views the same distribution of Earth radiation during a 360 scan cycle interval. The mean and standard deviation of the digital numbers sampled for each histogram are subsequently computed. The mean and standard deviation for each histogram are then converted to absolute units of spectral radiance using the original estimates of channel gain and offset and the inverse of the radiometric response function (see Figure II-11).

At this point in the process, if all estimates of gains and biases were precise and all distributions of observed radiance were equal, then the histograms for all channels within a particular band would have equal means and equal standard deviations in terms of absolute spectral radiance units (e.g., in terms of milliwatts per square centimeter per steradian per micrometer). These equalities rarely occur due to imprecision in gain and offset estimates or inequality between observed radiance distributions. To generate equal histograms in terms of absolute spectral radiance units, the original estimates of channel gain and offset are refined in the following manner:[1]

$$(1) \quad G'_{c,b} = G_{c,b} \frac{S_{c,b}}{S_b}$$

$$(2) \quad B'_{c,b} = B_{c,b} + G_{c,b} \left( M_{c,b} - \frac{S_b M_b}{S_{c,b}} \right)$$

where

| | |
|---|---|
| $G_{c,b}$ and $B_{c,b}$ | are the original estimates of gain and offset, respectively, for channel c and spectral band b. These estimates are derived from in-orbit observations of the TM internal calibration standards. $G_{c,b}$ is in the following units: $DN/mW \cdot cm^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$. $B_{c,b}$ is in units of DN. |
| $M_{c,b}$ | is the mean associated with the histogram for channel c, band b, in units of absolute spectral radiance: $mW \cdot cm^{-2} \cdot sr^{-1} \cdot \mu m$. |
| $M_b$ | is the average of the 16 histogram means ($M_{c,b}$'s) for all channels in a spectral band (four means for the thermal band) in units of absolute spectral radiance: $mW \cdot cm^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$. |
| $S_{c,b}$ | is the standard deviation associated with the histogram of channel c, spectral band b, in units of absolute spectral radiance: $mW \cdot cm^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$. |
| $S_b$ | is the average of the 16 histogram standard deviations ($S_{c,b}$'s) for all channels in a spectral band (four standard deviations for the thermal band) in units of absolute spectral radiance: $mW \cdot cm^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$. |
| $G'_{c,b}$ and $B'_{c,b}$ | are the refined estimates of $G_{c,b}$ and $B_{c,b}$, respectively, and are in the same units as $G_{c,b}$ and $B_{c,b}$, respectively. |

[1]Note: Data from the TM thermal band are calibrated and corrected in terms of absolute temperature. When considering the correction of thermal data in the discussion above, units of absolute spectral radiance ($mW \cdot cm^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$) should be considered units of absolute temperature (degrees Kelvin).

If the refined estimates of individual channel gain and bias were used to convert the histogram means and standard deviations from digital numbers to absolute radiometric units, then the histograms for all channels within a spectral band would have equal means and equal standard deviations in terms of absolute spectral radiance. The effect of this equalization process on the absolute radiometric accuracy of corrected TM data is unclear (Barker, 1984), but very little channel-to-channel striping is apparent in corrected TM imagery (Salomonson, 1984).

The preceding correction steps account for variability in the orbital performance of individual TM channels and they serve to minimize image striping. The last procedural step transforms raw digital numbers (DN's) to corrected DN's using the refined estimates of channel gains and biases. The intention of the transformation is as follows: for a given channel, the corrected DN's can be related to absolute units of spectral radiance by a linear response function which remains constant from channel-to-channel and between scenes. In other words, the full range of corrected DN's for a specific band represents a constant dynamic range of spectral radiance no matter which channel generated the raw data or when the raw data were acquired. This transformation facilitates the quantitative comparisons of surface radiance both within scenes and between scenes.

A constant dynamic range (i.e., radiometric response function) was specified for each spectral band on the basis of prelaunch calibration of the individual channel response functions. The smallest dynamic range observed for a single channel in each band was chosen as the standard to which all within-band data would be normalized. This choice prevents data compression. In other words, this choice allows a one-to-one mapping between corrected DN's and raw DN's except at saturation (i.e., except at a corrected value of 255). The standard dynamic ranges (i.e., RMIN and RMAX values) selected for the spectral bands are shown in Table II-4. The values selected for Scrounge System data processing (Table II-4a) were based on the prelaunch calibration of the Landsat 4 TM/PF sensor. The dynamic range values chosen for TIPS were slightly altered on the basis of the prelaunch calibration of the Landsat 5 TM/PF sensor (Table II-4b). TIPS uses the values given in Table II-4b for the radiometric correction of both TM/PF and TM/F data. As shown in Table II-4, the standard dynamic range values define the common linear radiometric response functions to which the data from all channels within a band are normalized.

The common gains and offsets for a spectral bands (see Table II-4) are used in conjunction with the refined estimates of individual channel gains and offsets (see Figure II-11 and equation 1 and 2) to define the transformation of raw DN's to corrected DN's. The transformation is based on the following equation:

$$(3)\quad D_{cor,b} = \frac{G_b}{G'_{c,b}}\, D_{raw,c,b} + B_b - \frac{G_b}{G'_{c,b}}\, B'_{c,b}$$

where,

$D_{raw,c,b}$ is a raw digital number generated by channel c of spectral band b;

$G'_{c,b}$ is the refined estimate of the gain of the radiometric response function for channel c, band b (see Figure II-11 and equation 1);

**Table II-4**
**Dynamic Ranges of Radiometrically Corrected Thematic Mapper Data**

**Table II-4a**
**Dynamic Ranges of Thematic Mapper Data Processed by the Scrounge System Prior to August, 1983 (Barker, 1984).**

| | Spectral Bands | | | | | | |
|---|---|---|---|---|---|---|---|
| | TM1 | TM2 | TM3 | TM4 | TM5 | TM7 | TM6* (thermal) |
| RMIN ($mW \cdot cm^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$) | -0.15 | -0.28 | -0.12 | -0.15 | -0.04 | -0.02 | 260°K |
| RMAX ($mW \cdot cm^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$) | 15.84 | 30.82 | 23.46 | 22.43 | 3.24 | 1.70 | 320°K |

**Table II-4b**
**Dynamic Ranges of Thematic Mapper Data Processed by TIPS After January 15, 1984 (Barker, 1984).**

| | Spectral Bands | | | | | | |
|---|---|---|---|---|---|---|---|
| | TM1 | TM2 | TM3 | TM4 | TM5 | TM7 | TM6* (thermal) |
| RMIN ($mW \cdot cm^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$) | -0.15 | -0.28 | -0.12 | -0.15 | -0.04 | -0.02 | 200°K |
| RMAX ($mW \cdot cm^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$) | 15.21 | 29.68 | 20.43 | 20.62 | 2.72 | 1.44 | 304°K |

RMIN is the spectral radiance corresponding to a detector response of zero digital counts
RMAX is the minimum radiance required to saturate detector response (i.e., produce a response of 255 digital counts)

Common Radiometric Response Function for All Corrected Data in a Spectral Band

$$D_{cor,b} = G_b L_b + B_b$$

where

$D_{cor,b}$ is a corrected digital number from spectral band b;

$L_b$ is spectral radiance ($mW \cdot cm^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$) within band b;

$G_b$ is the common gain for band b in the following units:
$DN/mW \cdot cm^{-2} \cdot sr^{-1} \cdot \mu^{-1}$
$G_b = 255/(RMAX-RMIN)$

$B_b$ is the common offset for band b in units of DN;
$B_b = -(255 * RMIN)/(RMAX-RMIN)$

*The thermal band, TM6, is calibrated with respect to black body temperature. When considering the corrections of TM thermal data above, units of spectral radiance ($mWcm^{-2}sr^{-1}\mu m^{-1}$) should be considered units of absolute temperature (degrees Kelvin).

$B'_{c,b}$ is the refined estimate of the offset of the radiometric response function for channel c, band b (see Figure II-11 and equation 2);

$G_b$ and $B_b$ are the gain and offset, respectively, of the common radiometric response function for band b (Table II-4);

$D_{cor,b}$ is a corrected digital number for band b.

To expedite computer processing, equation 3 is used to derive radiometric look up tables (RLUT's) which map raw digital counts to the corrected values. One RLUT is generated for each of the 100 TM channels, and the RLUT's are used to actually conduct the correction. Corrected DN values ($D_{cor,b}$) appear in all processed TM digital image data products (i.e., on the computer compatible magnetic tapes containing the A-data and P-data described below).

A corrected digital number can be converted to absolute units of spectral radiance by inverting the common radiometric response function (Table II-4) for the appropriate spectral band. The inverted function can be expressed as follows:

$$(4) \quad L_b = \frac{(RMAX-RMIN)}{255} D_{cor,b} + RMIN$$

where

$D_{cor,b}$ is a corrected digital number for spectral band b; and

$L_b$, RMIN, and RMAX are defined in Table II-4.

The total within-band radiance corresponding to a particular digital number, $D_{cor,b}$, can be estimated by multiplying the appropriate value of spectral radiance, $L_b$, by the bandwidth of the spectral band under consideration. A more precise estimate of within-band radiance requires more precise knowledge of spectral response curves for the TM bands. Markham and Barker (1984) provide measurements of TM bandwidths and spectral response curves.

## Geometric Correction Procedures

The purpose of geometric correction is to create a nearly conformal representation of the Earth surface consisting of TM multispectral digital image data. This conformal representation is generated by first computing correction data and then applying the correction data to the resampling of TM image data. The correction data locate the position of each radiometrically corrected TM image data sample (i.e., each digital number) onto an output coordinate system which corresponds to a cartographic projection. A resampling procedure assigns a digital number to each row/column coordinate (i.e., pixel) of the output system on the basis of interpolation between neighboring input data samples. The resampled TM data are evenly spaced with respect to cartographic location which enables the generation of nearly conformal pictorial imagery of the Earth's surface.

At any one instant, the 100 TM detectors all view different areas on the Earth surface. The instantaneous-field-of-view (IFOV) of an individual detector varies in size and location with satellite altitude, satellite ephemeris (i.e., location with respect to the center of the Earth), satellite and sensor attitude, and scan mirror motion. Registering these unevenly-spaced detector IFOV's to an evenly-spaced, cartographically-based coordinate system accomplishes three main objectives. First, the resampled data are registered band-to-band. This means that an object depicted in the corrected data from a particular band can be located at the same coordinates within the corrected data from any other spectral band from the same TM scene. Second, corrected TM data are temporally registered. An object depicted within a particular TM scene can be located at the same coordinate in any other TM scene acquired over the same geographic area on a different date (i.e., a previous or subsequent overpass). Third, the corrected TM data are geodetically registered. The cartographic location (e.g., latitude and longitude coordinates) of an object can be accurately determined from the object's row/column coordinates in the corrected image data. These band-to-band, temporal, and geodetic registrations generally render corrected TM data more useful than raw TM data for investigators. Specifications for registration accuracy are given in Table II-5.

**Table II-5**
**Geometric Registration Accuracy Specifications for Thematic Mapper Data (Beyer, 1984)**

| Type of Registration | Accuracy Required for 90% of the Data Samples |
|---|---|
| Band-to-Band for Spectral Bands on the Same Focal Plane* | 0.2 pixels |
| Band-to-Band for Spectral Bands on Different Focal Planes* | 0.3 pixels |
| Temporal | 0.3 pixels |
| Geodetic | 0.5 pixels |

* The detectors for spectral bands TM1 to TM4 are located on the primary focal plane. The detectors for spectral bands TM5, TM7, and TM6 (thermal band) are located on the cooled focal plane (see Figure II-3).

The output coordinate system for corrected TM data is an evenly-spaced grid where each grid cell, called a pixel, represents a 28.5 m-by-28.5 m area on the Earth's surface. Each pixel is identified by its row/column coordinate and each pixel is assigned seven digital numbers for the seven TM spectral bands. Most corrected TM scenes are registered to a coordinate system corresponding to the Space Oblique Mercator (SOM) cartographic projection. Investigators may make special requests for use of the Universal Transverse Mercator (UTM) or the Polar Stereographic projections.

The geometric correction data define the inter-pixel location of each raw TM image data sample on the output coordinate system. The geometric correction data consist primarily of three types of data matrices. Two types of matrices, the Benchmark Matrices and the High Frequency Matrices, trace the projected TM optical axis across the Earth surface as a function of time. These matrices are derived from the payload correction data (PCD) and the mirror scan correction

data (MSCD) described earlier. The Benchmark Matrices trace the TM optical axis as a function of satellite ephemeris and scan mirror position assuming nominal operating conditions (i.e., perfect sensor and satellite attitude and linear scan mirror motions and scan line corrector motions). The High Frequency Matrices account for frequent attitude deviations and non-linearities in scan mirror motions and scan line corrector motions as measured by PCD and MSCD. A third matrix type, the Focal Plane Geometry Matrices, geometrically relates the individual detector IFOV's to the TM optical axis. This relationship remains constant with time. The Focal Plane Geometry Matrices were derived from prelaunch measurements of TM optics and detector locations on the focal planes and remain constant from scene-to-scene. The three types of matrices are multiplied to form a master set of matrices which locate the projected IFOV of each TM detector on a cartographic projection as a function of time. This final set of matrices is collectively called systematic correction data (SCD) (Beyer, 1984).

By use of the payload correction data, the derivation of the systematic correction data (SCD) takes into account the following factors: satellite ephemeris; sensor and satellite attitude; high frequency structural disturbances, commonly called jitter, caused by operation of the instruments aboard the satellite; nonlinearities in the scan mirror profile and the operation of the scan line corrector; the TM optics and the location of the detectors on the focal planes; and the desired cartographic representation of the three-dimensional surface viewed by the sensor. Errors, however, may remain in the spatial transformation defined by the SCD due to limits in the accuracy of the payload correction data (PCD) used in the computation of the SCD. To minimize these errors, TIPS is capable of using ground control points to adjust the SCD. The adjusted data are called geodetic control data (GCD).

The adjustment of the SCD requires the building of a control point library for each scene area (i.e., path/row location) viewed by the TM. Each "point" in a library actually consists of a 32 pixel-by-32 scan line data set extracted from a base line TM scene. The base line scene has been radiometrically corrected and geometrically corrected using SCD.

The extracted data segments are called "chips", and each chip is located on a standard map (e.g., USGS topographic sheet). The latitude, longitude and elevation relative to the standard geoid (i.e., the idealized surface of the Earth which coincides everywhere with mean sea level) is determined for an easily identified point within each chip from the map. The number of chips extracted from a particular scene depends on the number of stable geographic features (e.g., road intersections) which can be easily identified on TM imagery and on the map. Control point libraries are not yet available for all TM scenes. If a library is unavailable for a particular scene, SCD are used for the TM data resampling.

Given a control point library with its cartographic information, SCD are used to define the expected locations of the ground control points in an uncorrected TM scene. A 128 pixel-by-256 scan line search neighborhood is then extracted for each control point from the uncorrected TM data. Each neighborhood is centered on the expected control point location and the neighborhood is sufficiently large to contain the associated 32 pixel- by-32 scan line control point chip even for large errors in SCD. Each neighborhood is also radiometrically corrected using RLUT's and geometrically corrected using SCD. The precise location of the control point within a neighborhood is then determined by correlation between the base line chip and the search neighborhood in the spatial frequency domain. The correlation process involves gradient enhancement of edge features to reduce temporal differences between the base line data and the neighborhood data (Beyer, 1984). The difference between the precise location of the control point in the neighborhood, as determined by correlation, and the expected location is considered mislocation error. The mislocation errors for all available ground control points are used to adjust the SCD to create geodetic control data (GCD). The use of SCD to define TM data resampling produces acceptable band-to-band registration accuracy, but GCD are generally required for accurate temporal and geodetic registration.

The GCD (or if unavailable, the SCD) define the inter-pixel location of each uncorrected TM data sample on the output coordinate system. For resampling, the GCD (or SCD) project the TM data samples onto the standard geoid and topographic effects are not considered (Beyer, 1984). Resampling then assigns digital numbers to the discrete, evenly-spaced pixels of the output system to create the digital format for the final, fully-processed TM data products. Two resampling procedures are available. Investigators may specially request the use of nearest-neighbor resampling. This procedure simply assigns the digital number value of the closest TM image data sample to the output pixel.

Cubic convolution is the standard procedure used to resample TM data. This procedure assigns the weighted average of nearby TM samples to each output pixel. A cubic spline function defines the weighing

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factors which decrease with increasing distance from the output pixel. Cubic convolution is implemented in a two step process (Figure II-12). The data samples along each uncorrected scan line are first resampled to assign digital counts to temporary pixels located at the intersection of the output columns and the input scan lines. The temporary pixels are then resampled to assign digital counts to the equally-spaced output pixels.

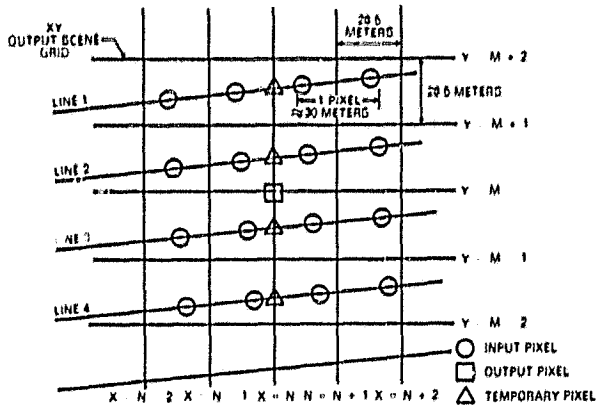


*Figure II-12 Resampling of Thematic Mapper image data for geometric correction (Beyer, 1984).*

The resampling procedures also compensate for spatial gaps which occur between the last scan line generated during a scan mirror sweep and the first scan line of the subsequent sweep. The gaps are a function of scene latitude and fluctuations in spacecraft altitude and attitude. To fill in the gaps with data, pixels are generated for locations on synthetic scan lines which extend into the spatial gap and run parallel to the scan lines of the upper mirror sweep (Figure II-13). The extension pixels are then resampled to derive digital numbers for output pixels falling in the gaps of the input image data. This resampling procedure is rather complex and is described in more detail by Beyer (1984).

Geometric correction of the TM thermal data requires special consideration. Recall that only four detectors are used to acquire thermal data, and one image sample of raw thermal data represents an area equivalent to four image samples from any of the reflective bands. To facilitate multispectral analyses of TM data, the coarse resolution thermal data is also resampled to form a registered grid of 28.5m-by-28.5m pixels. Thus, all bands of geometrically correct TM data contain the same number of pixels per unit area.

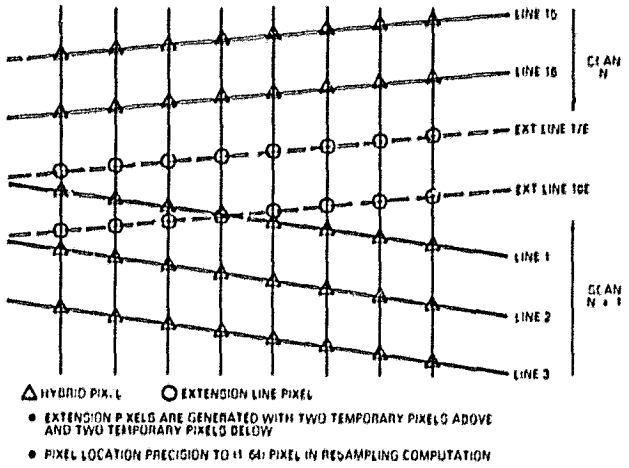


*Figure II-13 Scan line extension for geometric correction.*

## Sequence of TM Data Processing Steps

The sequence of TM data processing steps is illustrated in Figure II-14, and the flow of TM data through the GSFC data processing facilities is shown in Figure II-10. To initiate the sequence, TIPS accepts two or three input data sets. One set is the TM wideband data containing the image data of the surface scene and the internal calibration data. The Data Receive Record Transmit System (DRRTS) provides these data to TIPS on a high density tape (HDT). Another data set is the systematic correction data (SCD) derived by the Mission Management Facility (MMF) and provided to TIPS on a CCT.

TIPS may also accept a set of ground control points. A ground control point library is currently being built for TIPS at the rate of one scene per day. If points are available, the systematic correction (SCD) are adjusted to generate geodetic correction data (GCD) for geometric corrections. Otherwise, TIPS uses the SCD for corrections. Ground control points were not available during Scrounge System operations and the Scrounge System employed the SCD exclusively.

TIPS begins processing by extracting the internal calibration data and by building histograms of digital detector output values for radiometric corrections. Also early in the processing, TIPS locates control point search neighborhoods corresponding to the expected locations of available ground control points.

Next, TIPS derives the channel gains and offsets and generates the radiometric look-up tables (RLUT's) for

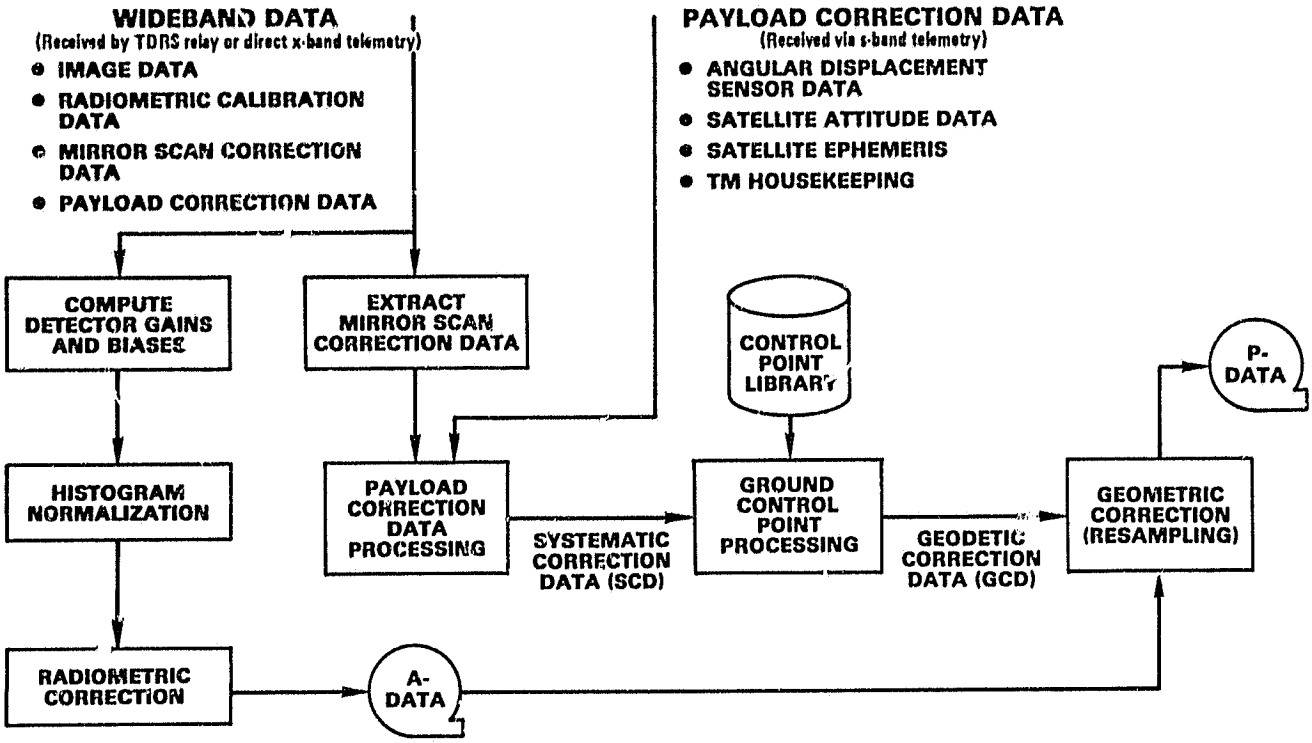


*Figure II-14 Overview of Thematic Mapper data processing flow at the GSFC facility (Lyon et al., 1983). Note that payload correction data (PCD) are received as a part of the wideband data and are also received separately via S-band telemetry.*

radiometric correction. If ground control points are available, TIPS correlates the control point neighborhoods to the known locations of the ground control points and adjusts the SCD to create GCD.

Before applying the radiometric corrections, TIPS commutates the pixel order of the image data, aligns the data, and converts the data from a band-interleaved-by-pixel to a band-interleaved-by-line (BIL) format. The commutation is made necessary by the generation of image data during both the forward and reverse sweeps of the TM scanning mirror. Since 16 scan lines of data are generated during each sweep of the scanning mirror, the directional order of pixels along a line is reversed every 16 lines. The commutation alters the order of data acquired during each reverse (east-to-west) mirror sweep to a west-to-east orientation. Once the data are oriented in the same direction, TIPS aligns the beginning of each scan line to form a contiguous image of the surface.

The commutated and aligned image data are next radiometrically corrected using the RLUT's, and the corrected data are stored on a high density magnetic tape (28 tracks, 33.3 kilobits per inch on each track). These data are considered partially processed having undergone radiometric correction but not geometric correction. TIPS also appends header, ancillary, annotation, and trailer (HAAT) files to the tape. The HAAT files contain geometric correction parameters, and ancillary data such as scene path and row indices, date of data acquisition, and orbit number. The HAAT files plus the partially processed image data are referred to as archive data or A-data. In summary, the data archive for each TM scene consists of HAAT files and commutated, aligned, radiometrically corrected, digital image data stored in a band- interleaved-by-line (BIL) format on a 28-track high density tape (HDT-AT).

TIPS creates a fully processed TM scene by resampling the image A-data for geometric correction on the basis of the SCD or GCD. The resampled image data are reformatted to a band sequential (BSQ) format and written to a high density tape along with HAAT files. The HAAT files and fully processed image data are called P-data and a high density tape containing these data is called an HDT-PT.

Final TIPS products consist of radiometrically corrected archival data (A-data) and fully processed data (P-data) on computer compatible tapes (CCT's). Radiometrically and geometrically corrected data in

P-data format are also available on 241-mm film products. The processed TM data are written directly from the HDT-AT's or HDT-PT's onto CCT's (CCT-AT's and CCT-PT's). A laser film recorder is used to generate film products from the HDT-PT's. The CCT-AT's and CCT-PT's are shipped to the NOAA Landsat data archive at the EROS Data Center in Sioux Falls, South Dakota. These tapes are stored and duplicated for users. The TIPS film products are also shipped to the NOAA archive where they serve as masters for user film products.

The Scrounge System employed a very similar sequence of steps to correct TM data before July, 1983 (Lyon et al., 1983). The only major difference is that image data on HDT-AT's generated by the Scrounge System are in a band sequential, rather than a band-interleaved-by-line, format.

## TM DATA PRODUCTS

Standard TM data products generated by the TIPS facility consist of digital image data recorded on magnetic CCT's and pictorial image data recorded on film. The following discussion describes the format of the digital and film products generated by the TIPS facility at GSFC. Readers of this document should realize that the format of data products produced by other TM data processing facilities may be slightly different. The products described below are available to the general public and can be purchased from the NOAA Landsat data archive at the EROS Data Center in Sioux Falls, South Dakota.

## TM Digital Image Data Products

The standard TM CCT product contains multispectral image data in digital format for approximately one-quarter of a full 170 km along-track- by-185 km across-track TM scene. A full scene of radiometrically and geometrically corrected TM data (P-data) consists of 5965 scan lines with over 6000 pixels per line. A standard scene quadrant contains approximately one-

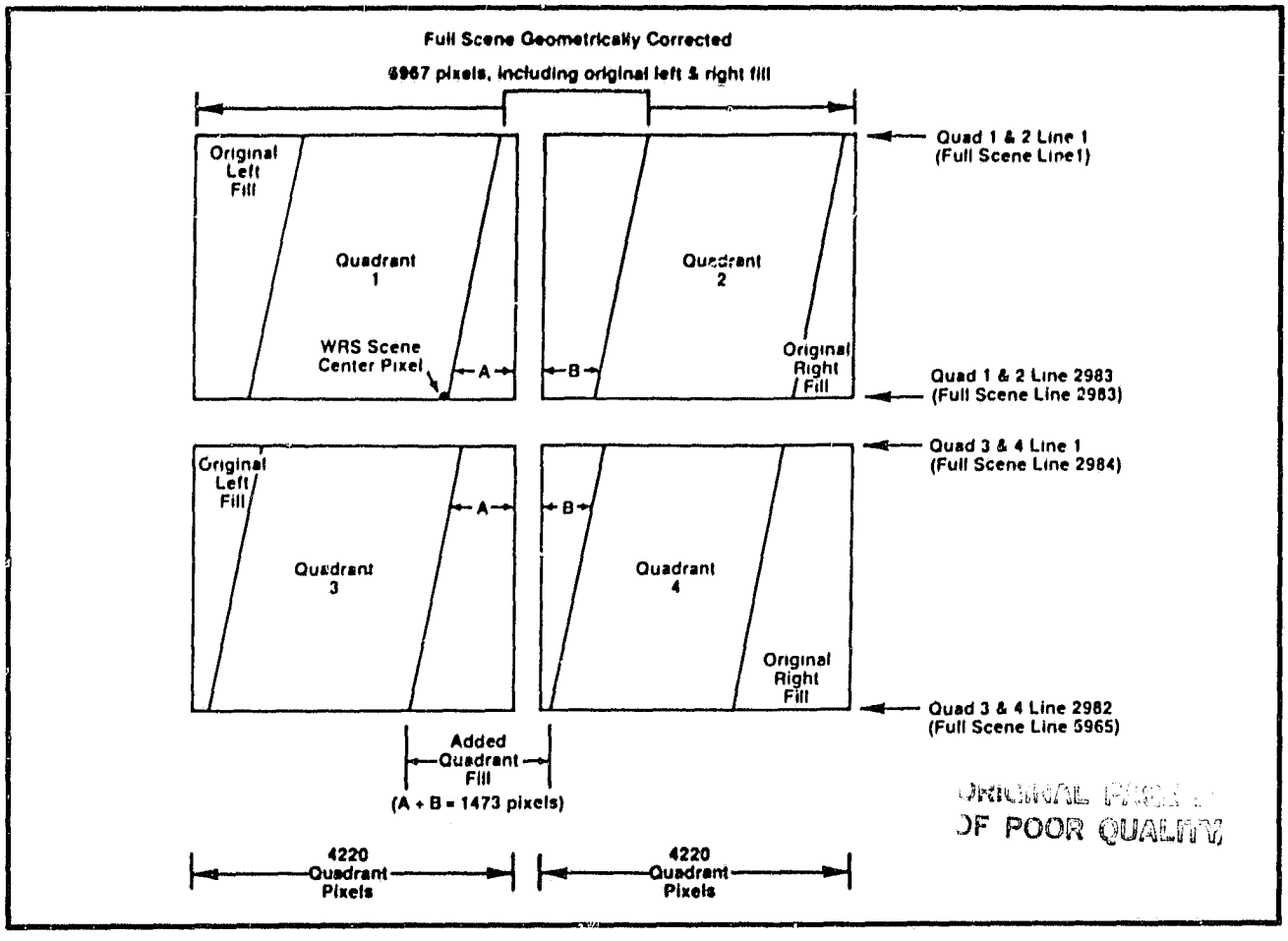


*Figure II-15 Pixel and scan line dimensions of TM scene quadrants for P-data store on CCT's.*

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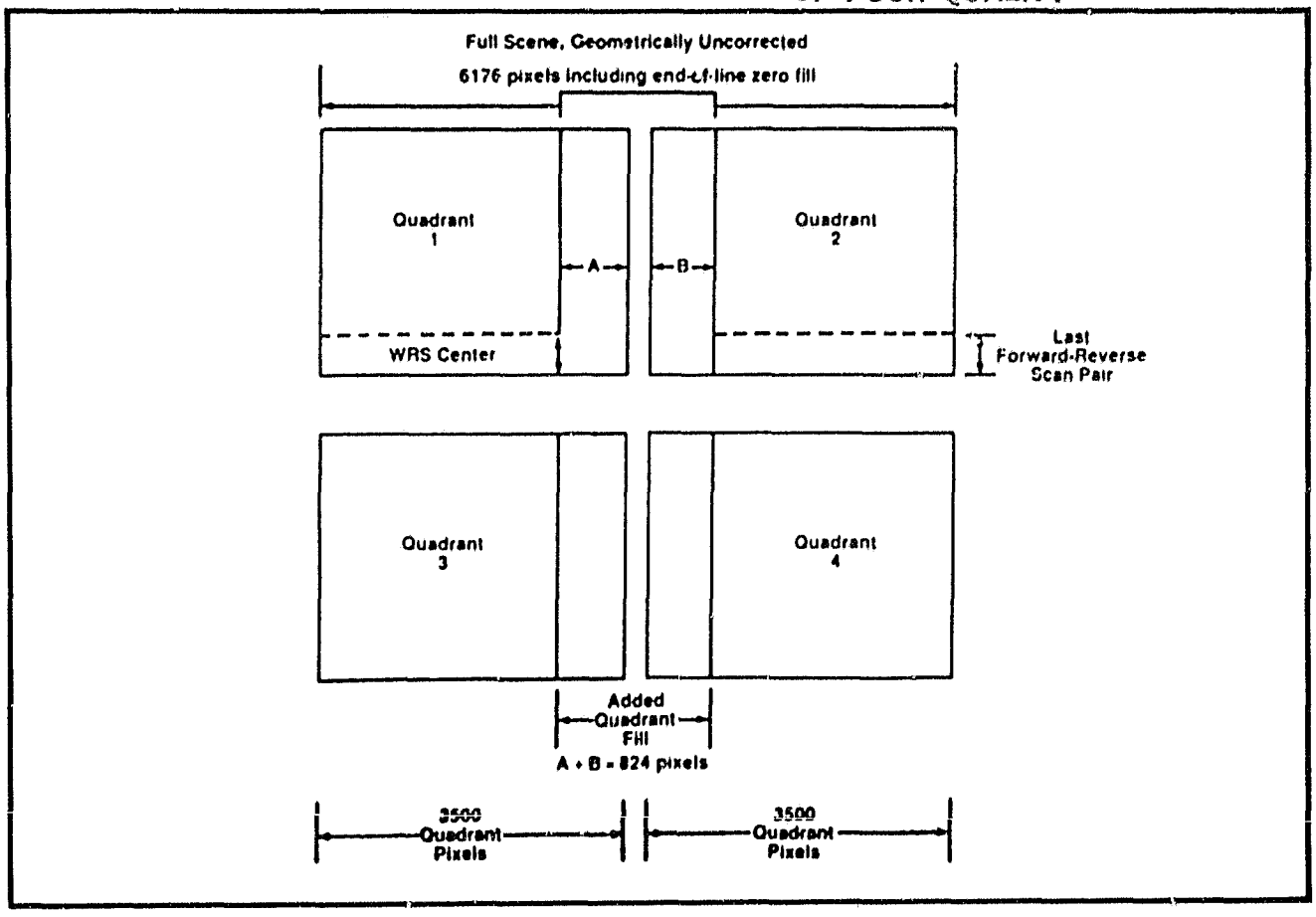


*Figure II-16 Pixel and scan line dimensions of TM scene quadrants for A-data stored on CCT's.*

quarter of the pixels within a full scene. The number convention employed in identifying TM scene quadrants is presented in Figure II-15 along with the pixel and scan line dimensions of scene quadrants.

TM P-data is resampled onto a square pixel grid aligned with respect to true north before being recorded on magnetic tape. As described earlier, the orbit of the Landsat 4 and 5 spacecraft are inclined 98.2° with respect to the Earth's equator. Consequently, there are blank areas at the edges of full TM scenes and scene quadrants when they are projected onto the square pixel grid described above (see Figure II-15). Pixels with digital counts of zero for all spectral bands are assigned to these blank areas to provide numerical values for all pixel locations within the square grid projection. These zero value pixels are commonly referred to as "fill pixels". Fill pixels are also employed in dividing TM A-data into scene quadrants for storage on digital CCT's (Figure II-16).

An investigator is offered the following options when ordering a scene quadrant of digital image data:

1) Extent of data processing: Tapes of partially processed image data (CCT- AT's) or fully processed image data (CCT-PT's) may be ordered.

2) Cartographic projection: Investigators may order P-data registered to the Universal Transverse Mercator (UTM) or Polar Stereographic projections instead of the standard Space Oblique Mercator (SOM) projection.

3) Data resampling: Investigators may request that a nearest-neighbor resampling be performed instead of a cubic-convolution resampling for geometric correction.

4) Digital image format: The digital image data may be obtained in either a band sequential (BSQ) format or a band-interleaved-by-line (BIL) format.

5) Data density: The data may be packed onto a CCT at 1600 bits-per-inch (bpi) or 6250 bpi. All of the TM data for one quadrant are contained on one 6250 bpi CCT. Three 1600 bpi CCT's are required per quadrant.

## TM Film Products

All TM film products available from the NOAA archive are derived from the film masters generated by TIPS. Seven film masters, one per spectral band, are generated for each fully processed TM scene. Each master contains the black-and-white image of an entire scene at a scale of 1:1,000,000 along with annotation, tic marks showing cartographic coordinates, and gray scales.

The film masters are produced by a laser film recorder having an instantaneous spot size of a 0.0285 mm square. The film masters are used to generate images for investigators at the following three scales: 1:750,000 (18.5 cm film); 1:375,000 (37.1 cm film); and 1:187,500 (74.2 cm film). All standard film products represent an entire TM scene. Black-and-white film products may be obtained for each of the seven spectral bands. Investigators may also obtain color composites derived from three spectral bands. The investigator must specify which bands are to be depicted as red, green, and blue. Black-and-white images are available as positive transparencies, negative transparencies, and positive paper prints. Color composite images are available as positive transparencies, positive paper prints, and 35 mm, positive slides.

## TM Data Availability

Between the launch of Landsat 4 (July 16, 1982) and the failure of its X-band transmitter (February 15, 1983), over 6000 TM scenes were received by the Prince Albert, Canada, ground station and the Transportable Ground Station (TGS) in Greenbelt, Maryland. Scenes received by the Prince Albert station cover western Canada, the western United States, and a few areas in northern Mexico. Scenes received by the TGS cover eastern Canada, eastern United States, and the Bahamas. More than 1000 of these scenes are nighttime scenes consisting of thermal (TM6) data. Masuoka (1984) provides maps showing the number of Landsat 4 TM scenes acquired for each path-row location in North America. The utility of many of these images is limited by cloud cover and poor solar illumination conditions.

After the launch of TDRS-East, Landsat 4 TM data were occasionally relayed through TDRS-East for engineering test purposes. Sixty TM scenes were relayed on August 12 and 13, 1983, and approximately 40 scenes were relayed on November 16 and 18, 1983. The scenes covered areas in the United States, Africa, and Argentina. Although the Landsat 4 TM/PF is still functional, the sensor has not been extensively operated since the launch of Landsat 5 (March 1, 1984). TM/PF data acquisition was suspended because of power problems aboard the Landsat 4 spacecraft. The problems are discussed below.

The Landsat 5 TM/F is currently acquiring data on a regular basis. Over 120 scenes per day are sent to TIPS at GSFC for processing. These data are either relayed by TDRS-East or directly received on the X-band frequency by the TGS or the Prince Albert station. Landsat 4 and 5 TM data received by the Prince Albert station are shipped to GSFC for processing as a result of an agreement between the United States and Canada. Processed data are sent from GSFC to the EROS Data Center for distribution. Canada also maintains an independent archive of TM data received by the Prince Albert station.

Only a small portion of the TM scenes sent to the GSFC facility are eventually processed by TIPS. The utility of many scenes is limited by cloud cover or low solar elevation during acquisition. These scenes are generally not processed unless specifically requested by an investigator. Of the over 6000 available Landsat 4 TM scenes, only 1900 scenes are currently scheduled for TIPS processing.

An investigator may request the processing of any available TM scene through NOAA Landsat Customer Services. This organization may be contacted at the following address and telephone number:

NOAA Landsat Customer Services
Mundt Federal Building
Sioux Falls, South Dakota 57198
Telephone: (605) 594-6151

This service organization offers assistance in the location of available TM scenes. An investigator can request a computer listing of all available TM scenes for a particular location by specifying geographic coordinates (e.g., latitude/longitude) or path/row coordinates. The list provides the following information: scene identification number, acquisition date, geographic coordinates, extent of cloud cover, and data product availability. Listings of available TM scenes may also be obtained on microfiche film cards. An investigator can initiate processing of a particular TM scene by ordering specific data products from the NOAA archive.

The most readily accessible TM scenes are those for which fully processed digital data and film masters have already been archived by NOAA. As of June 20, 1984, TIPS had provided both fully processed data and a film master for 286 TM scenes to the EROS Data Center. Eighty-seven of these scenes were acquired by the Landsat 5 TM/F and the remaining 199 scenes

were acquired by the Landsat 4 TM/PF. In addition, the Scrounge System generated 287 scenes of fully processed TM/PF data on CCT's prior to the initiation of TIPS operations in August, 1983.

Inquiries regarding the availability of TM data received by foreign ground stations should also be directed to NOAA Landsat Customer Services with the following exceptions. The Canada Centre for Remote Sensing (CCRS) has an archive of digital data for over 3000 TM scenes. The data were received by the Prince Albert station and were acquired primarily over Canada. Inquiries should be directed to:

Mr. I. Press
Landsat Production Coordinator
Canada Centre for Remote Sensing
2464 Sheffield Road
Ottawa, Ontario
K1A OY7, Canada

The European Space Agency's Earthnet Program Office has approximately 1200 scenes of TM data available. These data were received by the Kiruna, Sweden, and Fucino, Italy, stations and were acquired over Europe. Inquiries should be directed to:

Earthnet User Services
Earthnet Program Office
Galileo Galilei
00044 Frascati, Italy

## TM SENSOR PERFORMANCE AND DATA QUALITY

NASA is conducting an extensive characterization of the orbital performance of the TM/PF and TM/F sensors and the quality of the data they are producing. The characterization program, called the Landsat Image Data Quality Analysis (LIDQA) program, involves investigators selected from the full breadth of the terrestrial remote sensing community. Results have shown that the Landsat 4 TM/PF performed beyond expectations and produced data that met or exceeded most prelaunch specifications. Preliminary results indicate that the Landsat 5 TM/F is also performing well and generating high quality data.

Problems with the Landsat 4 spacecraft have curtailed operation of the Landsat 4 TM/PF. The first problem was the failure of the X-band transmitter. As described earlier, the X-band transmitter was originally designed for direct readout of TM data to ground receiving stations within view of the spacecraft's X-band antenna transmission pattern. Following the failure of this system in February, 1983, the only means of acquiring TM imagery was by the Ku-band transmitter which was designed to relay TM data to the ground through TDRSS. The first TDRSS satellite (TDRS-East) was launched April, 1983 and it was not available for use prior to August, 1983. By this time, a second Landsat 4 technical problem had emerged which placed additional restrictions on TM data acquisition. This problem involves the loss of electrical power from two of the spacecraft's four solar panels. This problem has been attributed to the mechanical disruption of power cables onboard the spacecraft. Thermal stress within a cable potting compound has apparently caused disconnections in two of the electrical power cables connected to the satellite's solar array. The remaining power is currently being used only to maintain the orbit and intermittently operate the MSS. If another panel should fail, the satellite will be lowered to a 500 km orbit to create the possibility of repair and retrieval using the Shuttle. Landsat 5 was modified before launch to prevent reoccurrence of the problems experienced by Landsat 4.

An adequate amount of Landsat 4 TM/PF data were received prior to the failure of the X-band transmitter to examine the orbital performance of the TM/PF sensor. The radiometric performance of the sensor is a characteristic of prime interest. Investigations have demonstrated that the relative radiometric responses of the individual data channels are intercalibrated to a high degree of accuracy. The radiometric correction procedure described earlier effectively accounts for radiometric response variations between channels, and only minor striping remains in radiometrically corrected data. The striping is usually on the order of the least significant bit (one or two digital counts) out of eight bits (256 digital counts) (Salomonson, 1984). This residual striping is not visually evident in pictorial TM imagery unless extreme contrast enhancement is applied to data acquired over uniform areas. The absolute radiometric accuracy of TM data is still under study, but on the basis of early results, the absolute accuracy is believed to be within specifications (i.e., 10% of the full dynamic range within each spectral band) (Barker, 1984).

Much of the residual striping may be attributable to within-scene variation in channel radiometric response. As described earlier, the channel radiometric response functions are monitored at intervals of 360 scan cycles (i.e., every 11,520 scan lines). Therefore, the procedure does not correct for variation in radiometric response during acquisition of the approximately 5700 scan lines of data which constitute a scene. Several sources of within-scene radiometric variation have been identified (Barker, 1984).

One important source of within-scene radiometric response variability is the analog-to-digital (A/D) converters in the TM/PF. The A/D converters do not distribute the analog voltage from the detectors into 256 equal increments. In other words, the increment of radiance represented by a particular digital count does not necessarily equal the radiance increment represented by another count. This problem is referred to as "bin radiance dependence" The inequalities range from radiance increments of nearly zero to twice the specified radiance increment and cause errors up to one count when relating absolute radiance to digital counts (Barker, 1984). Fortunately, the TM/PF digital response functions (digital counts versus spectral radiance) remained fairly linear over the entire 256 count range of the A/D converters. A least-squares fit of known spectral radiance from an integrating sphere to the prelaunch digital response of the TM/PF had a root-mean-square error of approximately 0.5 counts (Barker, 1984). The inequal bin sizes caused local deviations from a perfectly linear response, but did not destroy the linearity over the entire response range.

The effects of the A/D converter performance are apparent in partially processed data (A-data) by inspecting the frequency histograms of data from each detector. A particular digital value will occur much more or much less frequently than neighboring values. This effect is masked in P-data by the resampling procedure used to geometrically correct the data.

An additional radiometric problem was encountered with TM/PF thermal (TM6) data. The gains of the thermal band detectors are observed to decrease with time (Lansing and Barker, 1984). The decrease is attributable to condensation of water vapor on the window of the dewar containing the cold focal plane. Internal heaters were temporarily turned on and the sensor was outgassed to vaporize the condensed water and restore the thermal detector gains. The radiometric correction procedure compensates for the loss of detector gain with respect to relative and absolute calibration. The loss, however, reduced the thermal sensitivity of the detectors.

The geometric fidelity of fully processed TM/PF data has proved to be excellent. Early problems registering data from the primary focal plane (spectral bands TM1, TM2, TM3, and TM4) to data from the cold focal plane (TM5, TM6, and TM7) have been overcome. The early problems were attributable to a slight shift in the relative position of the two focal planes due to the stress of launch. The problems were corrected by adjusting the Focal Plane Geometry Matrices, described earlier, to account for the shift in the geometric correction procedure. Data are now registered to within 0.1 pixel between any two bands (Salomonson, 1984), well above specifications (Table II-5). The temporal and geodetic registrations of TM data are also within specifications. An analysis of several corrected TM scenes by Brooks et al. (1984) demonstrated that the data consistently met specifications for temporal registration (0.3 pixels) and usually met geodetic registration accuracy specifications (0.5 pixels). Colvacoresses (1984) has demonstrated the ability to generate TM pictorial imagery which meets national map accuracy standards at 1:100,000 scale. In comparison, MSS imagery cannot generally meet accuracy standards at scales greater than 1:200,000 (Salomonson, 1984).

Before the launch of Landsat 4, much concern was directed towards the potential effects of high frequency structural disturbances, commonly called jitter, on the geometric quality of TM imagery. These disturbances are caused by the mechanical operations of spacecraft and sensor components such as antenna motors and scanning mirrors. These disturbances are sensed by the angular displacement sensors described earlier, which measure deviations in the TM sensor attitude occurring between frequencies of two to 125 Hertz. Data from the angular displacement sensor are incorporated into the payload correction data (PCD) for geometric corrections. The concern regarding the effects of jitter have been alleviated by post-launch data analyses. The high band-to-band, temporal, and radiometric registration accuracies observed for corrected TM data (Brooks et al., 1984; Salomonson, 1984) indicate that geometric processing effectively minimizes the effect of jitter on data quality.

Markham and Barker (1984) have completed an extensive evaluation of the spectral resolutions of both the TM/PF and TM/F. Their analyses were based on prelaunch measurements by Santa Barbara Research Center of the spectral transmission and response of individual components (i.e., optics, spectral filters, and detectors). They have determined spectral response curves, band edges (50% of peak response), and the spectral matching between the detectors for each band. Their studies showed that both sensors met all spectral response specifications for the reflective bands with the following exceptions: (1) spectral bands TM2, TM3, and TM7 did not meet spectral flatness specifications in both sensors; and (2) the upper edge for TM5 was greater than the specified edge for both sensors. Table II-6 lists the specified and measured band edges. In addition, the spectral response curves for the reflective bands were observed to be quite similar between the two models.

**Table II-6**
**Calculated TM Spectral Band Edges for the TM/PF and TM/F (Markham and Barker, 1984).**

| Spectral Band | | Specification | TM/PF | TM/F |
|---|---|---|---|---|
| TM1 | Lower Edge (nm) | 450 + 10 | 452 | 452 |
| | Upper Edge (nm) | 520 + 10 | 518 | 518 |
| TM2 | Lower Edge (nm) | 520 + 10 | 529 | 528 |
| | Upper Edge (nm) | 600 + 10 | 610 | 610 |
| TM3 | Lower Edge (nm) | 620 + 10 | 624 | 626 |
| | Upper Edge (nm) | 690 + 10 | 693 | 693 |
| TM4 | Lower Edge (nm) | 760 + 20 | 776 | 776 |
| | Upper Edge (nm) | 900 + 10 | 905 | 904 |
| TM5 | Lower Edge (nm) | 1550 + 20 | 1568 | 1567 |
| | Upper Edge (nm) | 1750 + 20 | 1784* | 1784* |
| TM7 | Lower Edge (nm) | 2080 + 30 | 2097 | 2097 |
| | Upper Edge (nm) | 2350 + 30 | 2347 | 2349 |
| TM6 (Thermal) | Lower Edge ($\mu$m) | 10.4 + 0.01 | 10.42 | 10.45 |
| | Upper Edge ($\mu$m) | 12.5 + 0.1 | 11.6* | 12.43 |

* Out of Specification

The spectral responses of the thermal band are not similar between the TM/PF and the TM/F. The upper band edge of the Landsat 4 TM/PF was much less than the specification (Table II-6). The reduced band width did not cause concern because the thermal sensitivity of the band remained greater than specifications (Markham and Barker, 1984). The TM/F thermal band edges were within specifications.

Evaluations of postlaunch Landsat 5 TM/F data have just begun. Early results indicate that TM/F data are comparable to TM/PF data with respect to radiometric and geometric fidelity. Evidence of problems with the TM/F A/D converters and with the thermal detector gains has again been encountered. These problems do not appear any more severe with TM/F data than with TM/PF data. Investigators can reasonably anticipate a reliable flow of high quality TM data from Landsat 5.

Researchers have also begun to study the information content of TM data. Several investigators have noted the capability to use TM data, particularly the middle infrared bands (TM5 and TM7), to identify land cover categories which could not be accurately discriminated using MSS data (Degloria, 1984; Pitts et al., 1984). Other classification studies have shown that the prevalent per-pixel, maximum likelihood decision rules do not fully exploit the high TM spatial resolution and they suggest the use of alternate approaches to classification (Williams et al., 1984). The dimensionality of TM data in spectral data space has also been explored by eigenvector analyses. Results indicate that TM reflective band data typically contain four independent dimensions of useful terrestrial information as compared to two dimensions in MSS data (Anuta et al., 1984; Bernstein et al., 1984; Crist and Cicone, 1984). The utility of TM data will become even more apparent as investigators extend TM data applications to a broad range of scientific research.

## USEFUL DOCUMENTS FOR TM DATA USERS

This document presents a broad overview of information an investigator might need to effectively use TM data. Several references are recommended for

more detail and in-depth coverage of the relevant topics. The "Landsat 4 Data Users Handbook" describes the spacecraft, TM and MSS sensors, orbits and coverage, data communications, TM and MSS data products, and procedures for ordering data products. Forthcoming appendices to the handbook will describe TM data processing and CCT formats in detail. The handbook can be purchased from the following address:

Distribution Branch
Text Product Section
U.S. Geological Survey
604 South Pickett Street
Alexandria, VA 22304

Details on data processing and tape formats can also be found in the series of NASA reference documents listed in Table II-7. A document describing the for-

**Table II-7**
**List of Landsat Reference Documents**

| Accession Number | Document |
|---|---|
| N83-21469 | "Applications Notice for Participation in the Landsat-D Image Quality Analysis Program" |
| N83-21472 | "Landsat-D to Ground Station Interface Description" |
| N83-21479 | "Landsat-D World Reference System Users Guide" |
| N83-21482 | "Landsat-D Investigations Workshop" |
| N83-21473 and N83-21474 | "Landsat-D Mission Operations Review" |
| N83-21466 | "LGSOWG CCT Format CCB Document: The Standard CCT Family of Tape Formats" |
| N83-15750 | "Spectral Characterization of the Landsat-D Multispectral Scanner Subsystems" |
| N83-21467 | "Landsat-4 MSS Radiometric Characterization Report" |
| N83-21481 | "Partially Processed Multispectral Scanner High Density Tape (HDT-AM)" |
| N83-21468 | "Landsat Multispectral Scanner Computer Compatible Tape Format" |
| N83-21470 | "Landsat-D Assessment System Library Computer Compatible Tape" |
| N83-21480 | "Thematic Mapper High Resolution 241mm Film" |
| N83-21471 | "Landsat-D Project ADDS/LAS Scrounge Interface Control Document" |
| N83-21477 | "Landsat-D Data Format Control Book, Volume VI, Appendix A, Partially Processed Thematic Mapper High Density Tape (HDT-AT)" |
| N83-21478 | "Landsat-D Data Format Control Book, Volume VI, Appendix D, Thematic Mapper Computer Compatible Tape (CCT-AT, CCT-PT), Format Specification: |
| N83-21475 | "Landsat-D Accelerated Payload Correction Subsystem, Output Computer Compatible Tape Format" |

mat of TM CCT-AT's and CCT-PT's is particularly useful and is listed under accession number N83-21478 (Table II-7).

These documents can be obtained from the following address:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161

Results of the NASA LIDQA program are summarized in a two volume document, "Landsat-4 Science Investigations Summary" (NASA Conference Publication 2326). This document contains valuable information on data processing and quality. Selected articles from LIDQA investigations are also present in a special issue of *IEEE Transactions on Geoscience and Remote Sensing* (Volume GE-22, Number 3) published in May, 1984. These articles include useful reports on the information content of TM data.

Up-to-date information on the status of the Landsat satellites, sensors, and data can be obtained from the "Landsat Data Users Notes" published quarterly by NOAA. Subscriptions to this publication may be obtained at no charge by contacting NOAA Landsat Customer Services at the address or phone number provided earlier.

## REFERENCES


Anuta, P.E., L.A. Bartolucci, M.E. Dean, J.A. Valdes, and C.R. Valenzuela. 1984. Landsat-4 MSS and Thematic Mapper data quality and information content analysis. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. GE-22, No. 3: pp. 222-236.

Barker, J.L. 1984. Relative radiometric calibration of Landsat TM reflective bands. *Landsat-4 Science Investigations Summary*, Vol. I, NASA Conference Publication 2326: pp. 140-180.

Barker, J.L., R.B. Abrams, D.L. Ball, and K.C. Leung. 1984. Radiometric calibration and processing procedure for reflective bands on Landsat-4 Protoflight Thematic Mapper. *Landsat-4 Science Investigations Summary*, Vol. I, NASA Conference Publications 2326: pp. 90-91.

Bernstein, R., J.B. Lotspiech, H.J. Meyers, H.G. Kolsky, and R.D. Lees. 1984. Analysis and processing of Landsat-4 sensor data using advanced image processing techniques and technologies. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. GE-22, No. 3: pp. 192-221.

Beyer, E.P. 1984. An overview of the Thematic Mapper geometric correction system. *Landsat-4 Science Investigations Summary*, Vol. I, NASA Conference Publication 2326: pp. 92-100.

Brooks, J., A. Jai, T. Keller, E. Kimmer, and S. Su. 1984. Thematic Mapper geometric correction performance evaluation. *Proceedings, Tenth International Symposium, Machine Processing of Remotely Sensed Data*, West Lafayette, Indiana: pp. 22-28.

Colvocoresses, A.P. 1984. Mapping of Washington, DC, and vicinity with the Landsat-4 Thematic Mapper. *Technical Papers of the Fiftieth Annual Meeting of the American Society of Photogrammetry*, Washington, D.C.: pp. 757-764.

Crist, E.P., and R.C. Cicone. 1984. A physically-based transformation of Thematic Mapper data—the TM tasseled cap. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. GE-22, No. 3: pp. 256-262.

Degloria, S.D. 1984. Spectral variability of Landsat-4 Thematic Mapper and Multispectral Scanner data for selected crop and forest cover types. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. GE-22, No. 3: pp. 303-311.

Engel, J.L. 1980. Thematic Mapper—An interim report on anticipated performance. *Proceedings of the AIAA Sensor Systems for the 80's Conference*, Colorado Spring, CO: pp. 25-37.

Fischel, D. 1983. Some current uses of array processors for preprocessing of remote sensing data. *Seventeenth International Symposium on Remote Sensing of Environment*, Ann Arbor, MI.

Lansing, J.C., and J.L. Barker. 1984. Thermal band characterization of Landsat-4 Thematic Mapper. *Landsat-4 Science Investigations Summary*, Vol. I, NASA Conference Publication 2326: pp. 186-187.

Lyon, J.C., D. Fischel, and E. Beyer. 1983. Production and analyses of output data products for Landsat-4 in the engineering check-out phase. *Space Applications at the Crossroads: Twenty-First Goddard Memorial Symposium*, eds. McElroy, J.H., and E.L. Heacock, Univelt, Inc., San Diego, California.

Markham, B.L., and J.L. Barker. 1984. Spectral characterization of the Landsat Thematic Mapper sensors. *International Journal of Remote Sensing* (in press).

Masuoka, P.M. 1984. Availability of Landsat-4 Thematic Mapper data. *Technical Papers of the Fiftieth Annual Meeting of the American Society of Photogrammetry*, Washington, D.C.: pp. 464-471.

Pitts, D.E., G.D. Badhwar, D.R. Thompson, K.E. Henderson, S.S. Shen, C.T. Sorenson, and J.G. Carnes. 1984. Evaluation of corn/soybean separability using Thematic Mapper and Thematic Mapper Simulator data. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. GE-22, No. 3: pp. 312-317.

Salomonson, V.V. 1984. Landsat 4 and 5 status and results for Thematic Mapper data analyses. *Proceedings, Tenth International Symposium, Machine Processing of Remotely Sensed Data*, West Lafayette, Indiana: pp. 13-18.

Salomonson, V.V., P.L. Smith, Jr., A.B. Park, W.C. Webb, and T.L. Lynch. 1980. An overview of progress in the design and implementation of Landsat-D systems. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. GE-18, No. 2: pp. 137-146.

Williams, D.L., J.R. Irons, B.L. Markham, R.F. Nelson, D.L. Toll, R.S. Latty, and M.L. Stauffer. 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*, Vol. GE-22, No. 3: pp. 294-302.

## INDEX OF ACRONYMS

| | |
|---|---|
| ADDS | Applications Development Data System |
| ADS | Angular Displacement Sensor |
| BIL | Band Interleaved by Line |
| BSQ | Band Sequential |
| CCRS | Canada Centre for Remote Sensing |
| CCT | Computer Compatible Tape |
| CCT-AT | Computer Compatible Tape containing Thematic Mapper Archive data |
| CCT-PT | Computer Compatible Tape containing fully processed Thematic Mapper data |
| CSF | Control and Simulation Facility |
| DOMSAT | Domestic Communications Satellite |
| DRRTS | Data Receive Record Transmit System |
| EROS | Earth Resources Observation System |
| ERTS | Earth Resources Technology Satellite |
| GCD | Geodetic Control Data |
| GPS | Global Positioning System |
| GSFC | Goddard Space Flight Center |
| HAAT | Header, Ancillary, Annotation, Trailer |
| HDT | High Density Tape |
| HDT-AT | High Density Tape containing Thematic Mapper Archive data |
| HDT-PT | High Density Tape containing fully processed Thematic Mapper data |
| IFOV | Instantaneous Field of View |
| IGF | Image Generation Facility |
| LAS | Landsat Assessment System |
| LIDQA | Landsat Image Data Quality Analysis |
| MMF | Mission Management Facility |
| MMS | Multimission Modular Spacecraft |
| MSCD | Mirror Scan Correction Data |
| MSS | Multispectral Scanner |
| NASA | National Aeronautics and Space Administration |
| NASCOM | NASA Communications Network |
| NE$\Delta\varrho$ | Noise Equivalent Change in Reflectance |
| NETD | Noise Equivalent Temperature Difference |
| NOAA | National Oceanic and Atmospheric Administration |
| PCD | Payload Correction Data |
| RLUT | Radiometric Look-Up Table |
| RMAX | Minimum Spectral Radiance Value Corresponding to a Maximum Digital Number of 255 |
| RMIN | Spectral Radiance Value Corresponding to a Digital Number of Zero |
| SCD | Systematic Correction Data |
| SOM | Space Oblique Mercator |
| STS | Space Transportation System |
| TDRS-East | Tracking and Data Relay Satellite-East |
| TDRS-West | Tracking and Data Relay Satellite-West |
| TDRSS | Tracking and Data Relay Satellite System |
| TGS | Transportable Ground Station |
| TIPS | Thematic Mapper Image Processing System |
| TM | Thematic Mapper |
| TM/F | Thematic Mapper Flight Model (Landsat-5) |
| TM/PF | Thematic Mapper Protoflight Model (Landsat-4) |
| UTM | Universal Transverse Mercator |
| WRS | Worldwide Reference System |

# SECTION III

# PROSPECTIVE THEMATIC MAPPER RESEARCH APPLICATIONS IN THE EARTH SCIENCES

## VEGETATION AND SOILS SCIENCE

### Introduction

Vegetation and soils are principal components of the Earth's biosphere, a cosmic description of the living organisms found on our planet. Vegetation and soils are continually changing in form and distribution over a wide range of time scales. Yet they play a pervasive role in the dynamics of the biosphere. Through photosynthesis, green vegetation manufactures food and fiber, and it releases the oxygen essential to man and all other living organisms. In counterbalance, the process of respiration causes the release of organically-derived energy critical to biological growth, and it liberates carbon dioxide to the atmosphere. Soils provide a reservoir of energy and essential elements, and the physical substrate to support these metabolic processes.

In addition to these primary molecular processes, vegetation and soils play an integral role in biogeochemical cycling, global and local energy balance, and the hydrologic cycle. The type, condition, and distribution of the vegetation/soil complex determines the habitat and distribution of the Earth's animal population, as well. Vegetation and soils are also among the most sensitive environmental parameters responding to the activities of man and changing climatic conditions.

As changes on the Earth's surface increase with increasing human population and advancing technology, the opportunity to investigate the natural functioning of terrestrial ecosystems may become increasingly limited. It is important to understand the natural relationship between plants and soils in different environmental settings to better understand the response of ecosystems to the activities of man. In developing this understanding, knowledge of the distribution and condition of vegetation and soils in time and space is critical. Because of its unique discrimination capabilities and synoptic view, the Thematic Mapper (TM) may provide a new means to improve our understanding of the role of vegetation and soils in the biosphere.

### Background

Remote sensing systems placed on Earth-orbiting spacecraft are uniquely able to conduct surveys of terrestrial surface conditions at uniform scales and formats on a globally repetitive basis. Our current understanding of the utility of such surveys is based largely upon the analysis of Landsat Multispectral Scanner (MSS) data collected by the first generation of Landsat spacecraft. Analysis of MSS imagery has shown that multispectral surveys of reflected solar radiation can be used to identify the type, condition, and stage of growth of various forms of surface vegetation. MSS surveys can also be used to discriminate various types of soils on the basis of their compositional and textural properties. These earlier studies have shown that the accuracy of the information derived from MSS imagery can vary significantly depending upon local relief, solar illumination conditions, and seasonal variations in the form and nature of the vegetation-soil complex. Certain types of information such as the growth stage or phenologic development of individual plant species can best be determined through the analysis of multitemporal MSS imagery.

The measurement capabilities of the TM are significantly more diverse and sophisticated than those of the MSS. The TM holds great promise for obtaining more accurate assessments of many of the biospheric parameters described above. In addition, the TM potentially provides a capability to obtain wholly new types of information concerning the nature and condition of surface vegetation and soils.

Our current understanding of the utility of TM data for studies of the vegetation-soil complex is based upon the analysis of data collected in the past by airborne sensors that simulate the general measurement capabilities of the Landsat TM. In addition, a number of investigators have employed TM imagery obtained by Landsat 4 to compare the utility of MSS and TM data for specific types of Earth observations. On the basis of these earlier studies, the following observations can be made concerning the use of TM data for vegetation and soil investigations:

a) Far more classes of vegetation can be discriminated than ever before during certain times of the year. This is true both for natural and cultivated vegetation and has been attributed particularly to the new shortwave infrared bands (TM 5 and 7) and the improved spatial resolution of the TM. It appears that several common southern pine species can be spectrally differentiated, for example, as can sugar beets and alfalfa (see Figure III-1). The enhanced spectral and, in particular, spatial resolution of TM data allows the discrimination of various forms of riparian vegetation and small agricultural fields. The identification of these latter features is achieved by invoking an understanding of their geometric shape and geographic context in the analysis of a TM image.
b) Patterns correlated with soil type are clearly discernible in many images, even in areas containing dense vegetation.
c) The thermal detection capability of the TM is useful in the discrimination of some vegetation types as, for example, tree identification in forests and crop differentiation, such as soybeans and sorghum, which can not be achieved by the use of the visible and short wave infrared bands alone.
d) The spatial resolution of the TM provides far more information on the variability of the landscape, particularly in areas disturbed by man and those that have been subjected to dramatic and sudden climatic changes.
e) Geometric fidelity of the TM data is excellent, implying that high quality image rectification and multitemporal registration can be readily achieved.
f) The radiometric quality of the TM data exhibits superior stability and sensitivity suggesting an unparalleled capability to derive measurements of absolute Earth radiance on a repetitive basis.

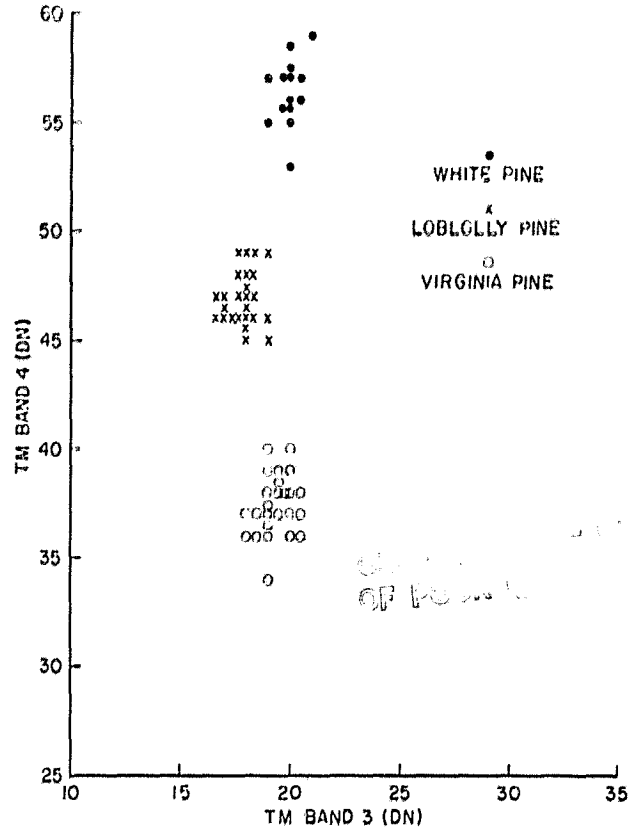


*Figure III-1*

*This graph illustrates the relative spectral response of different evergreen tree species observed in a Landsat 4 TM image of northern Virginia acquired in the fall of 1982. These species have a relatively similar spectral response in the red portion of the visible spectrum (TM band 3), but markedly different spectral characteristics in the near infrared (TM band 4). The level of species discrimination achieved in this scene is due in part to the improved spatial resolution of the TM. (Illustration courtesy of Nancy Milton, U. S. Geological Survey).*

The contribution that TM data might make to the enhancement of surface observations, the refinement of existing models, and the development of altogether new ones is yet to be tested. Certainly, improvements in the identification and measurement of both natural and cultivated vegetation and associated soils could have a significant impact on the study of animal habitats, the condition of arid lands, soil moisture and water holding capacity, and surface heating and cooling. The same direct measurements of the surface may serve, by inference, to support the development of more definitive models of land processes that will ultimately increase our understanding of ecological interactions at both regional and global scales.

## Prospective Research Themes

The purpose of the following discussion is to stimulate creative thinking about various topical problems in the field of biospheric research that could potentially be addressed in new and innovative ways through the analysis of orbital TM imagery. This discussion is not intended to be a comprehensive compendium of all of the research topics that could potentially be conducted, nor is it intended to represent a prioritization of research topics to be explored by NASA in the future. Rather, the goal of the following discussion is to illustrate generic types of scientific investigations that are potentially amenable to TM image analysis.

The following discussion has been divided into three sections that are broadly concerned with studies of terrestrial ecology, the response of ecosystems to environmental change, and fundamental biospheric processes. A series of topical problems is presented in each section. One should note that these problems are not mutually exclusive nor are they categorized by traditional scientific discipline. Rather, they serve to illustrate generic processes that have a multidisciplinary relevance.

Prospective investigators should carefully consider the identification of specific problems and the development of experimental methodologies in relation to the spatial and temporal measurement capabilities of the TM which are described in Section II. If current surface conditions in one geographical location can be used to simulate the predicted conditions in another geographical location for some past or future time, such as in the study of soil erosion, for example, then the constraints on the study due to temporal requirements for TM data could potentially be alleviated. Other kinds of data may also be enlisted to satisfy the need for information that is temporally and/or spatially specific and significant to the conduct of an investigation. Other remotely sensed data, such as that which exists from the past twelve years of Landsat MSS data collection, are available. Also, other records and sources of data and maps should be considered.

## *Terrestrial Ecology*

The term "ecology" is derived from the Greek word "oikos" meaning house. In the most literal sense, the study of terrestrial ecology involves the characterization and understanding of the system that houses mankind and all the other forms of life on our planet. The availability of TM data on a near global basis provides an opportunity to observe ecological relationships between regional flora, fauna, and soils in a wide range of environmental settings. In fact, the TM provides an opportunity to conduct comparative studies of ecological conditions and relationships in selected regions at a level of detail that has not been possible in the past. The observational capabilities of the TM can also be exploited to study the relationships within and between individual ecosystems, leading to an improved understanding of the global ecology of the Earth. A variety of topical research issues in this field are presented below.

***Plant Phenology, Community Maturation, and Ecological Succesion.*** Plant succession is basically a community process in which the structure and function of individual plant species changes over time. All types of vegetation undergo an inherently natural kind of change, ranging from the rapid phenological development of annual crops, to the decadal growth of trees, to the still slower processes of community maturation, to the process of succession, which may take thousands of years. These changes are complex functions, many associated with changes in localized and/or regional climate which affect vegetation and the soil substrate. TM imagery may be instrumental in testing models of plant succession which require knowledge of the distribution of individual plant species and their associations in different environments. An analysis of TM imagery of multiple geographic sites representing various ecological seres of a successional paradigm may enable us to learn more about ecological succession without having to depend on long term observations of a specific area. Such an approach might be applied to the study of forest succession, for example.

A forest is a complex biological community in a continual state of flux. The forest community is composed of numerous components, among which are trees, shrubs and herbaceous vegetation, as well as insects and higher order animals and the micro-flora and -fauna of the underlying soils. These components interact over time, and their relative health and abundance change in ways that are often predictable in accordance with the laws of natural selection. The successional processes that govern the evolution of the different components of this community are poorly understood at the present time. TM data may provide valuable information in characterizing both autogenic succession (the natural replacement of one biotic community by another in the absence of catastrophic disturbances) and allogenic succession (replacement resulting from an external force such as man, floods, etc.) within the forest ecosystem.

In the study of wetlands ecology, TM imagery may allow us to improve our understanding of community

maturation and ecological succession by better understanding the coupling of the biological and physical environment. TM data are expected to enhance the identification of vegetation indigenous to wetlands and improve the measurement of their condition, distribution, and areal extent (see Figure III-2). Associations of given species and changes in their composition are meaningful environmental indicators. Improved observations should increase the inferential information available to better understand

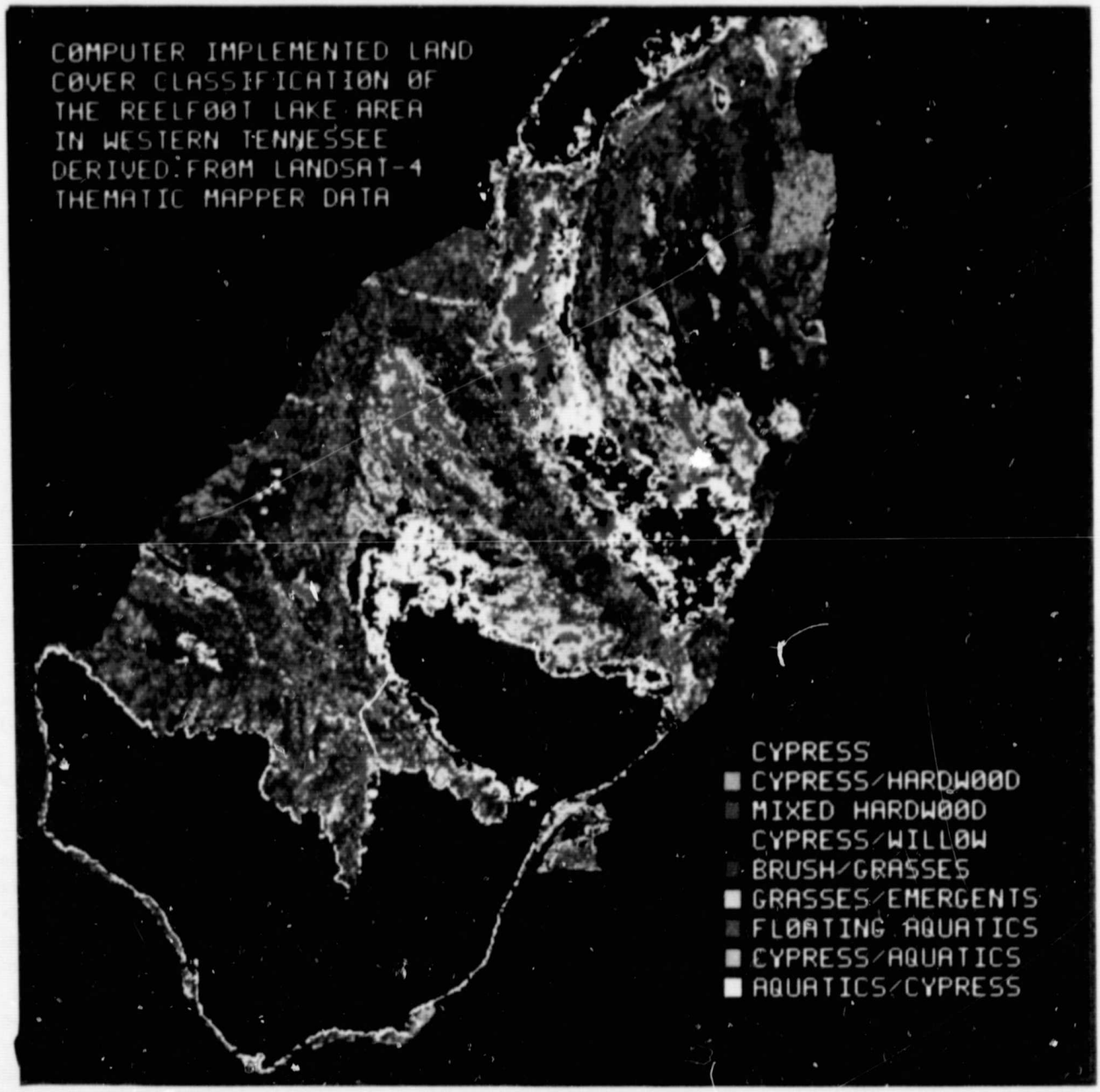


*Figure III-2*
*This is a land cover classification map of Reelfoot Lake, Tennessee based upon the statistical analysis of a Landsat 4 TM image acquired in August, 1982. The classification of different forms of natural vegetation occurring in this wetland environment is based upon variations in spectral response observed in TM bands 2, 3, 4, 5, and 7. Note the large degree of spectral separability that has been achieved among the tree, grass, and aquatic species present in this area. The portion of the lake outlined in this classification map is roughly 6 x 13 kilometers in size. (Illustration courtesy of Dale Quattrochi, NASA—National Space Technology Laboratories).*



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basic questions about water inundation patterns, soil chemistry, and plant growth and productivity, and the interdependence of these phenomena. For example, a current puzzle to many wetlands scientists is the cause for growth of two distinct forms—the short and tall forms—of *Spartina alterniflora*, a dominant salt marsh grass species, in what are thought to be non-limiting nutrient environments. Unraveling this puzzle may help to understand the factors influencing plant productivity and its role in the estuarine trophic chain.

The natural succession of plant communities is normally characterized by an increase in species diversity, the structural complexity of individual species, and total community biomass. In wetland environments, the local accumulation of organic matter that naturally accompanies community succession can produce significant changes in the local hydrologic regime. The accumulation of organic matter can serve to trap suspended sediments leading to a concomitant decrease in water depth. As the local water level decreases, the frequency and depth of water inundation decreases so that less organic matter is removed during subsequent runoff cycles. TM imagery can be used to monitor spatial and temporal variations in species distribution and water depth within the wetlands environment. Observations of this nature could directly contribute to studies of the factors governing community succession within coast estuaries.

***Soil Genesis.*** Soils are an integral component of vegetation communities. Soils form a structured matrix of minerals and organic matter which anchors and physically supports vegetation while serving as a reservoir of plant nutrients and moisture. Soil formation results from the interaction of climatic conditions, living matter, and geologic materials, as conditioned by regional variations in topographic relief and the activities of man. TM data can be used to map regional vegetation patterns which are a consequence of and factor in soil development. As discussed in subsequent sections, TM data can also be used to characterize and map geologic parent materials and geomorphologic features which play a significant role in soil formation. The TM provides the spatial resolution and synoptic view required to relate spatial variations in these soil forming factors to the variability of natural soils as depicted in soil maps.

Conventional soil maps divide the natural soil continuum into discrete units with sharp boundaries. In reality, individual soil units are rarely separated by sharp boundaries. Soil characteristics commonly vary both within and between units. Soil scientists are beginning to use mathematical descriptions of spatial variability to better characterize the continuum of soil units commonly encountered in nature. The use of TM data to remotely measure soil parameters would greatly facilitate the gathering of sufficient contiguous data to support the development of such mathematical techniques. Image texture, which is the characterization of image spectral data within the spatial context of the image, may be useful for defining soil boundaries over broader scales. The discrimination of soil types from TM imagery, particularly for areas where soil maps are lacking, when combined with other kinds of environmental data such as geologic, topographic, and climatic data, may advance our understanding of soil genesis.

TM data may be of particular value for studies of remote areas or areas otherwise lacking detailed soil information. Detailed soil maps are already available for much of the United States, but detailed maps are not available for many other regions around the world. Furthermore, there is a lack of standardization among the maps which are available. TM data offers the potential for discriminating different soil types either by direct observation of bare soil or by inference from observations of vegetation, geomorphology, and geologic materials. Information on the different soil types may then be applied to studies of bioproductivity, climatology, and hydrology.

***Ecological Competition.*** Certain biological and physical pressures induce members of a plant community to exhibit complementary growth patterns. Such a response is characteristic of ecological competition, but the true cause and effect relationship is not well understood. This applies to the biological interaction among members of a plant community and between communities, as well. Plants have been found to emit chemical substances as a defensive mechanism for survival. The soil environment can act as a carrier of such substances. The high spatial, as well as spectral, resolution capabilities of the TM may provide valuable insight into the study of phytosociology and allow interferences to be made about the underlying biochemical/physical processes.

As an example, knowledge of the distribution and condition of individual tree species within a forest canopy can contribute significantly to an understanding of the ecological competition that occurs among the forest flora. The spatial variability of individual species is an important factor in understanding how forest members relate to one another in both natural and managed situations. TM data may also be used to detect variations in the density and thermal characteristics of forest canopies. Information of this nature could potentially be used

to study the response of individual species and plant communities to various types of stress (e.g. air pollution and insect infestation).

TM data analysis may contribute to a different level of understanding about the forest system by addressing the relationship between forest *community* morphology and environmental influence. The distribution of forest plant communities is determined by genetic, as well as environmental influences. If such patterns result in a characteristic surface texture as expressed in multispectral TM imagery, it may be possible to infer the physiological and morphological factors that govern the development and proliferation of specific plant communities.

A classic phenomenon in the study of ecological competition is the case of species invasion, for which the underlying causes are not well understood. Semi-arid regions are particularly susceptible to species invasion. By virtue of such physical characteristics as low and erratic precipitation, rough topography, poor drainage, or cold temperatures, semi-arid regions are typically unsuited to cultivation and are characterized by a relatively low density of indigenous plant species. The improved spatial resolution and radiometric sensitivity of the TM could prove to be particularly useful in monitoring subtle variations in the density and distribution of vegetation in extended semi-arid regions (see Figure III-3). Temporal trends and spatial gradients in surface vegetation can be used to detect local areas of incipient desertification in such regions. In principle, the TM's spectral capabilities could be used to monitor the growth and distribution of key species such as juniper [Juniperas accidentalis] which reduce the susceptibility of surface soils to wind erosion. The invasion of specific species in such environments may also produce diagnostic variations in surface thermal conditions which could potentially be sensed by the TM.

***Animal Habitats.*** Plant communities control the types and numbers of animals present in a region, not only by controlling the food supply, but also by providing shelter from weather and predation. The animal population, in turn, influences the local distribution of vegetation through selective herbivory and the transportation of seeds. The balance between food supply and animal populations in different environments is a major research topic in the study of animal habitats. Habitats can be identified on the basis of the type, diversity, and amount of vegetation present, and tend to be concentrated along interfaces between vegetative communities. Pattern recognition algorithms that can map the geometric shapes and boundaries of plant communities could prove to be extremely useful in delineating the shape and extent of animal habitats.

*Figure III-3*

*Airborne multispectral scanner image of Lisbon Valley, Utah in which spectral variations in the red portion of the visible spectrum (corresponding to TM band 3) have been used to infer relative variations in vegetation density. The area displayed in the image is approximately 5 x 9 kilometers in size. The scale at the bottom of the figure denotes the areal density of surface variation in percent. Vegetation density is highly correlated with surface geology in this semi-arid environment. For example, many of the areas containing 20% vegetative cover or less are correlated with the surface expression of a regional sandstone unit which is outlined in white in the figure. (Illustration courtesy of James Conel, Jet Propulsion Laboratory).*

Certain wildlife species make extensive use of the forest periphery for feeding and protection. For example, elk require four basic vegetative habitat categories to survive in rangeland environments: hiding cover, winter thermal cover, summer thermal cover, as well as forage. Maintaining forage-to-thermal cover ratios and hiding-to-forage cover ratios within



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specific distances is critical to elk survival. The use of TM imagery to define the edges of forest plant communities could make an important contribution to studies of wildlife movement and distribution. The improved spectral and spatial resolution, including the thermal detection capability of the TM, may contribute to an improved understanding of rangeland habitats and the quality and quantity of life that can be supported in specific environments.

***Detection of Extraordinary Plant Species.*** The evolutionary development of plant species has depended on climatic and edaphic factors, dispersion mechanisms for plant germplasm, and competitive pressures among living organisms which rely on plants for nutrition. Globally synoptic views of the Earth's natural plant communities, using the improved resolution capabilities of the TM, may significantly enhance the current understanding of species phylogeny. Many treacherous and remote areas of the world remain essentially unexplored at the present time. By virtue of their isolation, these regions may contain new and as yet unknown plant species. The use of TM data in a predictive or inferential mode may provide a unique capability to identify areas with anomalous spectral and textural characteristics which may contain extraordinary species. The discovery of such species could lead to major advances in the sciences of genetics and ecology. Such a prediction mode might involve the incorporation of TM data in descriptive models of environments where genetic anomalies are likely to occur.

***Integrated Functioning of Complex Ecosystems.*** The concept of holism represents the view that an integrated ecosystem can behave in certain ways that are independent of and greater than the additive behavior of its component parts. For example, in a river-floodplain system, the river, the floodplain, and the vegetation and soils represent hierarchical components of progressively lower order. The characteristics of the river floodplain system are distinct from those of any of its components. In a similar manner, the processes of a coastal estuary that result from the interaction of wetlands and the nearshore marine environment become more than the processes associated with low-lying vegetative growth and tidal flooding. The higher-order holistic processes of an estuary may be viewed in terms of the exchange of nutrients between the land and ocean within an area of active sedimentation.

In the holistic study of a system, it may not be necessary to study the functional parts in fine detail to gain insight into their mutual interdependence. Holistic studies are concerned with the dynamic relationship between ecosystem components for the purpose of obtaining improved understanding of the functioning of the overall system. Holistic studies can be conducted on many scales. Synoptic TM imagery acquired on a repetitive basis can potentially support such studies from the local to the regional scale.

## *Ecosystem Response to Dynamic Change*

The response of ecosystems to changing environmental conditions can be exceedingly complex. Certain components of the integrated system may be altered in diagnostic ways by specific environmental changes. Identification of the system components that manifest the greatest short term change in response to changing environmental conditions is especially important.These components provide a basis for identifying ecosystems that may be experiencing major changes in form and function.

Long term studies of ecosystems that are subjected to changing environmental conditions can provide considerable insight into the physical processes that connect different system components. In particular, many of the more subtle processes occurring within a system may become more apparent or obvious when the system as a whole is striving to reach a new state of internal equilibrium. Ecosystems responding to changing environmental conditions can serve as natural laboratories for studies of the relationships between system components. Such studies are particularly important in attempting to anticipate the impact of man's activities upon the condition and evolution of individual ecosystems. This section discusses several topical problems related to the study of ecosystem response to dynamic change.

***Botanical Stress.*** Plants are subjected to many kinds of stress including droughts, floods, nutrient deprivation, insect infestation, thermal stress, soil toxicity, disease, and animal predation. The response of certain plants and communities to various types of stress has been studied in some detail, particularly for agricultural species of economic interest. However, current understanding of how stress conditions are manifested and ameliorated in plants is far from complete, even for many major crop species. Our knowledge of the type and magnitude of stresses experienced by natural vegetation is even more rudimentary at the present time. In fact, our limited ability to detect and delineate stress in natural vegetation is based upon our ignorance of what constitutes normal conditions for individual species in different environmental settings. TM observations

can be used to obtain selected types of information concerning the density, distribution, and condition of plant species which could potentially be employed in studies of plant stress (see Figure III-4).

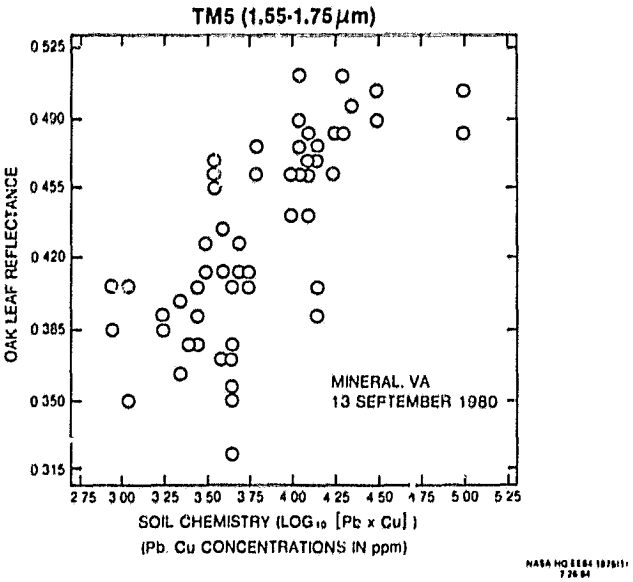


*Figure III-4*

*This graph displays variations in oak leaf reflectance and soil geochemistry observed within a forested test site in northern Virginia during September, 1980. Leaf reflectance measurements were obtained with a portable field spectrometer over a spectral interval corresponding to TM band 5. Soil samples were obtained at the base of individual trees that were selected for detailed observation. The general trend of the plotted data suggests that oak leaf reflectance increases with increasing concentration of lead and copper in the local soils during this stage of the growing season. This trend may result from early leaf senescence in areas characterized by toxic soil conditions. (Illustration courtesy of Mark Labovitz and Robin Bell, NASA—Goddard Space Flight Center).*

The characterization of vegetation stress could potentially benefit from the use of agricultural fields as controlled test sites. For example, these fields could be used to improve our understanding of the effects of air and mineral pollution on plants, and the natural variability of healthy vegetation at the most elementary level. An individual crop field is ordinarily subjected to the same management practices throughout, which can be either beneficial or deleterious to growth. The field usually contains a single crop, planted nearly simultaneously with uniform spacing, with similar applications of fertilizer and other treatments. In addition, contiguous agricultural fields are normally subjected to the same weather conditions. Nonetheless, substantial variations in plant biomass, stage of development, and yield occur within agricultural fields. While remote sensing does not offer the possibility of directly assessing yield, it provides the most practical approach available to assessing variability in biomass and stage of development as they relate to healthy and stressed conditions within fields. Since these factors can be quantified, it permits the use of each field as a "natural" laboratory to understand environmental effects on crop growth. In principle, such experiments would enable plant ecologists to determine the range of variability in plant morphology and biomass produced under healthy conditions in a controlled environment. Information of this nature could, in turn, be used to establish criteria for identifying abnormal conditions in the morphology or biomass of selected species that commonly occur in nature. The ability to recognize abnormal conditions in natural vegetation canopies, and to relate the occurrence of such conditions to local environmental conditions could provide considerable insight into the causes, manifestation, and long term effects of stress in natural environments (see, for example, Figure III-5).

***Soil Destruction.*** Soil destruction by erosion, laterization, or other processes can be exceedingly rapid compared to soil genesis because the former phenomena are generally attributed to dramatic changes in the physical environment whereas the latter phenomenon occurs over geological time scales. Soil distribution historically has been a major problem for countries undergoing agricultural and commercial development. Tropical forest soils, in particular, are very fragile. Certain agricultural techniques currently in use actually induce erosion and accelerate nutrient depletion. Remote sensing data may be used to map existing soils directly or by inference from the discrimination of vegetation types. TM data may specifically be used to monitor or predict soil erosion by assessing changes in soils and vegetation, hence providing more accurate inputs to soil erosion models.

Most of the commonly used models of soil erosion, such as the Universal Soil Loss Equation and Chepil's wind erosion equation, predict the average annual erosion from single, uniform fields. Although adequate for the recommendation of field-by-field soil management practices, the models cannot be directly extended to large, heterogeneous areas or to individual soil erosion events. These models are often based on empirical observations of erosion that occurs on small plots. They do not account for the



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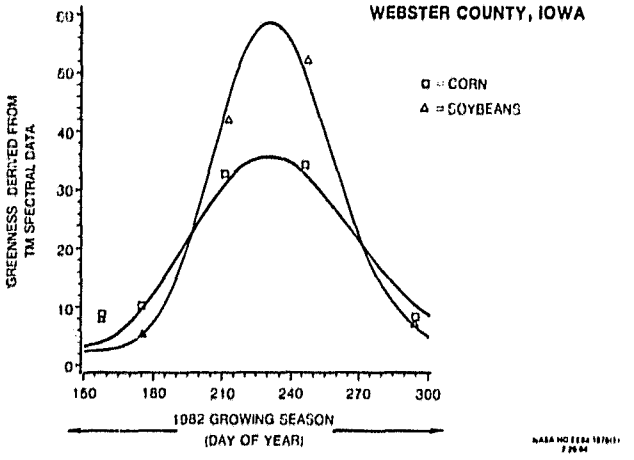


*Figure III-5*

*This graph displays temporal variations in the spectral response of two different crops during the 1982 growing season. The "greenness" parameter displayed in the graph is a statistical transformation of the spectral response of TM bands 1, 2, 3, 4, 5, and 7 which can be correlated with the visual greenness of the Earth's surface. The data points appearing in the graph are derived from airborne and orbital TM surveys conducted over Webster County, Iowa. The continuous curves represent modelled variations in surface "greenness" anticipated for corn and soybean crops. Changes in the "greenness" of agricultural fields as a function of time have been used in the past to discriminate different crop species. In principle, multitemporal variations in canopy reflectance could be used in the future to detect stress conditions in both natural and cultivated vegetation. (Illustration courtesy of Gautam Badhwar, NASA—Johnson Space Center.)*

total variability of soil conditions and tillage practices encountered in different geographic areas, nor do they account for temporal changes in surface cover and climate. Also, such models do not always reflect a theoretical understanding of the physics of the soil erosion process. Consequently, their applicability to different environmental settings is uncertain.

TM data may aid in the development and validation of theoretical models which extend the understanding of soil erosion to larger geographic areas and a wider variety of soil conditions and management practices. Through the use of the shortest TM wavelength band (band 1), it may be possible to estimate the sediment bedload of flowing rivers. Suspended sediments in running water are a primary indicator of soil loss from selected regions.

Soil erosion in semi-arid environments is intimately related to spatial and temporal variations in the local abundance of surface vegetation and soil moisture. Some forms of arid land vegetation serve to stabilize the local soil surface and deter wind erosion. In other instances, arid vegetation serves to disturb the ground surface, locally exposing underlying deposits of sand and gravel to aeolian erosion. The distribution and density of different plant species is critically dependent upon the ability of local soils to retain moisture. Multispectral TM imagery can be used to monitor variations in canopy closure and biomass in arid regions over a variety of time scales. Such observations could be related to ground based observations of soil transport to develop improved models of soil erosion potential in arid regions. These models could subsequently be employed to identify areas of incipient desertification in semi-arid terrain.

***Short Term Environmental Change.*** Immediate environmental change is occurring in many parts of the world due to the activities of man and the effects of storms, fire, and flooding. The destruction of tropical forests and desertification of the Sahel have received popular attention, but equally profound changes are occurring in many other regions, such as the rangelands of Texas and New Mexico. TM data may be able to provide a new capability for measuring the impact and consequences of such events.

The enhanced spatial resolution of the TM may be particularly useful for detecting incipient environmental change. For example, the TM thermal detection capability may provide a unique means of identifying and measuring the effects of desertification over large areas. Semi-arid regions which are prone to desertification are commonly characterized by high spatial and temporal variability in surface cover conditions, probably more than any other ecosystem. Erratic precipitation, animal grazing patterns, the appearance of ephemeral plant species, and the use of defoliants all contribute to this variability. Spatial and temporal variations in vegetation distribution, moisture conditions, and soil distribution produce commensurate variations in the spectral reflectance and thermal emission properties of semi-arid terrain. The ability to measure and monitor this variability with the TM will help in understanding arid ecosystems and their response to environmental change.

In wetland environments, the enhanced spectral discrimination capability of the TM should improve our ability to detect variations in water quality, planktonic biomass, and macrophytic biomass. All of these parameters are sensitive indicators of environmental change. In wetlands, the land and water are coupled through a number of complex biological, geological, and physical processes. For instance, an-

thropogenic activity may cause changes in river flow or in watershed vegetative cover, which can result in a dramatic change in the supply of silt and nutrients to the downstream environment. This alteration of the water regime may have profound impacts on biological activity downstream, both in the wetlands themselves and adjacent estuarine waters. Therefore, an improved understanding of the water regime, specifically the relative rate and distribution of surface water movement through the wetland, may be an area to which TM research may contribute.

By improving our ability to differentiate species and vegetation density in wetlands, TM data may provide insight into overland waterflow rates that can substantially increase our present knowledge of surface water movement. TM data may also enhance the detection and definition of drainages and the land/water interface. The TM thermal band may provide inferential information regarding the mixing of fresh and saltwater within wetlands, depth of small water bodies, eutrophication levels, and potential sources of thermal loading. Contextural information derived from TM observations may provide a totally new capability for understanding the geomorphological development of wetlands, as the degree of water body dispersion and connectivity of the wetlands signifies stages of ecosystem development directed by response to environmental change. All of these capabilities are potentially applicable to studies of dynamic changes in the wetland environment.

Two sources of stress induced by man cause severe detrimental effects to the environment and have received a great deal of public attention. Air pollution and acid rain can severely stress many species of both natural and cultivated vegetation, although the extent and spatial distribution of the damage is essentially unknown. Remote sensing data offers the possibility of detecting, quantifying, and mapping various manifestations of stress within extended vegetation canopies. TM observations, in particular, can be used to detect variations in canopy closure, chlorophyll abundance, leaf moisture, and canopy temperature which may be diagnostically related to particular forms of vegetation stress. In principle, it may be possible to develop spectral indices for different ecosystems that are diagnostic of stress conditions caused by the deposition of airborne pollutants. The occurrence of such stress conditions could, in turn, be related to local variations in slope, slope azimuth, elevation, and annual precipitation to learn more about the processes governing the transportation and deposition of airborne pollutants.

## *Fundamental Biospheric Processes*

The living organisms that inhabit the outer portions of the Earth play an integral role in many planetary scale processes that occur over a wide range of time scales. For example, the Earth's biota are involved in the chemical modification and physical destruction of geological materials exposed at the Earth's surface. They also provide a means of collecting, storing, and transforming solar energy which can have a long term impact upon the global climate. The potential application of TM observations to the study of these fundamental biospheric processes is illustrated in the following discussion of selected biospheric phenomena.

***Biogeochemical Cycling.*** The biogeochemical cycling of carbon, nitrogen, sulfur and phosphorous is critical to all life on Earth. These elements are essential to the metabolism of all forms of living biomass, and they must be available in a wide variety of forms and quantities to support specific terrestrial lifeforms. Vegetation, both above-ground and below-ground phytomass, plays a major role in the biogeochemical cycles of all the elements listed above. Since vegetation can be drastically altered by fire, flood, and storms, the remote sensing of environments subjected to such catastrophic events can provide extremely useful and otherwise difficult to measure information about the storage and release of selected elements. TM data may improve the measurement accuracy of surface conditions, such as vegetation, that are significant input variables for models of elemental fluxes over large geographical areas.

***Energy Transfer at the Earth's Surface.*** The distribution of soils, vegetation, and water at the Earth's surface controls the amount of solar radiation that is absorbed by the Earth. Vegetation density and distribution have a major impact upon the local energy budget of the Earth's surface because of the role of plant transpiration in latent heat transfer. Plant transpiration is a far more effective process of liberating water vapor from the Earth's surface than direct evaporation from a free water surface. Consequently, vegetation can have a major influence upon the net heat flux of extended areas. Changes in the form and distribution of surface vegetation can greatly alter the energy budgets of both localized areas and extended regions. TM observations can be used to monitor spatial and temporal variations in surface vegetation. These types of observations could be used

to place boundary conditions on models of net energy flux at the Earth's surface. In addition, the thermal band on the TM (band 6) can be used to monitor variations in surface thermal emission. What is truly unique about the TM is its ability to monitor variations in surface cover conditions and thermal characteristics at a synoptic scale. The use of TM data to place boundary conditions on models of energy flux over extended areas could potentially lead to major breakthroughs in studies of regional meteorology and atmospheric circulation, particularly in environments that experience large variations in surface cover conditions on a seasonal basis.

## GEOLOGY

### Introduction

Geology is the scientific discipline devoted to the study of the rocks and soils that make up the Earth. These materials are the ultimate sources of the gases that are currently found in the Earth's atmosphere, the water that is found in the Earth's hydrosphere, and the nutrients that support the vegetation found on the Earth's surface. The geological materials that constitute the outer crust of the Earth play an important role in the biogeochemical cycling of key elements and organic compounds that are essential for life on our planet. In addition, geological resources found in the Earth's outer crust are essential for the daily operation and future growth of our modern industrial society. An understanding of the geological history of the Earth and the processes that shape its crust is fundamental to being able to predict the future behavior of our planet, and to forecast the quality of life for future generations of mankind.

Geologic processes occur over a wide range of spatial and temporal scales. A considerable degree of insight into the nature of these processes can be obtained by simply observing the current composition and distribution of geological materials that are situated near the Earth's surface. These types of observations place important boundary conditions on models of crustal growth and evolution. In addition, they enable geologists to unravel the geologic history of specific crustal provinces.

During the past forty years, geologists have developed considerable expertise in deriving geological information from imagery of the Earth's surface. Following World War II, geologists were quick to adopt aerial photographic techniques that had originally been developed for purposes of military reconnaissance. These techniques are now used routinely to detect variations in the color, texture, and weathering characteristics of surficial geological materials. Information of this nature provides important clues about the chemical composition and physical properties of surficial deposits. In vegetated areas, geologists employ aerial photography to detect variations in vegetation density, distribution, or condition that may be correlated with the composition or properties of underlying geological materials. Finally, geologists employ aerial photographs to detect variations in surface relief that may be indicative of folds and faults in the Earth's outer crust.

Prior to the nineteen-seventies, optical imagery of the Earth's surface was collected and analyzed primarily in the form of photographic prints and transparencies (i.e., in analog format). Two important events occurred during the nineteen-seventies that served to expand the range of photointerpretive techniques potentially available to geologists. One of these events was the advent of the Landsat series of spacecraft. Landsat was the first spacecraft designed to acquire multispectral Earth imagery at a synoptic scale on a repetitive, global basis. This imagery was collected in digital form and stored on magnetic tapes. The second major technological advance that occurred during the nineteen-seventies was the proliferation of computer facilities that could be used to reduce and analyze data in digital format. By the end of the seventies, these facilities were available to many, if not most, geologists.

The availability of computerized facilities for digital data analysis and the availability of Landsat imagery in digital format has lead to the development of new techniques for extracting geological information from pictures of the Earth's surface. Following the initial launch of Landsat 1, Landsat data products were analyzed primarily in analog format, employing the conventional methods of photointerpretation that had been developed in the past. During the past ten years, however, there has been a growing realization among geologists that Landsat imagery can be digitally manipulated to enhance the expression of specific surface features on a highly selective basis. This realization has lead to the development of a wide range of digital image analysis techniques which complement and extend conventional methods of photointerpretation. With growing sophistication in digital image analysis, geologists have come to treat Landsat imagery as a geophysical data set, comparable to seismic data or potential field surveys, which must be digitally

manipulated in various fashions to address different types of geological questions.

Our current understanding of the utility of Landsat imagery for geological research and applications is based primarily upon the analysis of imagery acquired by the Multispectral Scanner (MSS) on Landsats 1, 2, and 3. The Thematic Mapper (TM) on Landsats 4 and 5 is a second generation sensor system which is far superior to the MSS. As described elsewhere in this document, the TM possesses approximately twice the spectral resolution, two and one-half times the spatial resolution, and three times the radiometric sensitivity of the MSS. The TM offers geologists a new range of Earth observation capabilities which can potentially be applied to basic studies of crustal processes and to the exploration of remote crustal provinces. The purpose of the following discussion is to briefly summarize the anticipated observational capabilities of the TM in a geological context, and to identify prospective research topics that could potentially be addressed through the analysis of TM data. The overall goal of this discussion is to stimulate creative thinking about how TM imagery could be used in the future to conduct basic studies of geological conditions and processes on the Earth.

## Geological Observation Capabilities of the Thematic Mapper

In attempting to exploit the measurement capabilities of the TM for basic research in geology, two questions immediately come to mind, namely:

1) What types of geological information can potentially be derived from TM measurements?, and

2) What is unique about the TM's Earth observation capabilities?

A variety of experiments have been conducted in the past employing airborne scanner systems which simulate the measurement capabilities of the TM. In addition, geologists have gained some insight into the characteristics of orbital TM data through the analysis of Landsat 4 TM imagery that was collected during the fall and winter of 1982 over portions of the western U. S. These earlier studies have indicated that multispectral TM imagery can potentially be used to obtain information about the following characteristics of the Earth's surface:

***Rock and Soil Lithology.*** Iron-bearing minerals possess diagnostic spectral absorption features within the visible and near infrared portions of the electromagnetic spectrum. These features extend across TM bands 1-4 and they can be used to detect limonite stained rocks and soils in arid environments. Hydroxyl(OH) bearing minerals such as clays and carbonate($CO_3$)-bearing minerals such as calcite are characterized by diagnostic absorption features in the so-called shortwave infrared spectral region. TM band 7 is situated in the shortwave infrared and it is sensitive to the presence of clays and carbonate rocks where they are exposed directly at the Earth's surface. TM bands 2-5 and 7 can be used in combination to detect iron-bearing clay minerals which are commonly considered to be diagnostic indicators of hydrothermal alteration. Under certain circumstances, it is even possible to detect variations in the local concentration of surficial clay minerals (see Figure III-6). TM band 6 is designed to measure the intensity of thermal radiation being emitted by the Earth's surface. Previous airborne experiments have shown that night-time thermal infrared surveys can be used to discriminate certain types of rocks on the basis of their thermal inertia or heat retention properties. Quartz, in particular, has a relatively high thermal inertia. Consequently, quartz-bearing rocks such as sandstone are commonly warmer than their surroundings in night-time thermal infrared imagery and they can be readily discriminated. The various types of compositional information that can potentially be obtained through the analysis of TM imagery are not sufficient to characterize the lithology of many common rocks and soils. However, analysis of airborne TM simulator data has demonstrated that the stoichiometry and abundance of the minerals described above are sufficiently variable in nature to produce marked differences in the spectral reflectance properties of natural terrain. In particular, analysis of TM simulator imagery acquired in semi-arid regions has shown that variations in terrain reflectivity detected in the TM spectral bands can be used to discriminate a wide variety of natural rock and soil units exposed at the Earth's surface. A high degree of lithologic discrimination can commonly be achieved in TM image analysis, even in cases where direct identification of individual lithologic units is difficult or impossible.

***Surface Landforms.*** The 30 meter instantaneous field of view of the TM is ideally suited for large scale studies of surface geomorphology. The TM is a nadir-viewing sensor, and TM imagery can be used to detect the presence of specific landforms and characterize their shape in a planimetric sense. Standard photoclinometric techniques can be applied to TM imagery obtained under different solar illumination conditions to determine the relative relief of selected

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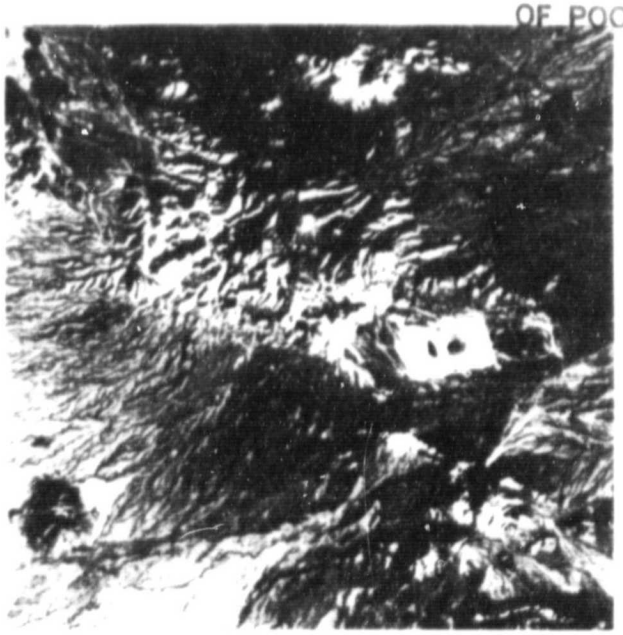
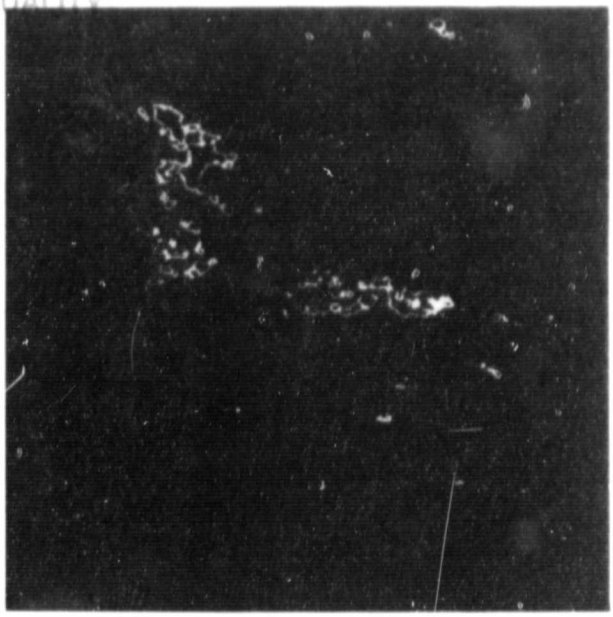


TM BAND 4



TM BAND 5/TM BAND 7

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*Figure III-6*
*The two images shown above have been derived from a Landsat 4 TM image of the Silver Bell, Arizona area that was originally acquired in November, 1982. Each subscene is approximately 15 x 15 kilometers in size. The subscene on the left is a TM band 4 view of the area; the subscene on the right is a ratio image constructed from TM bands 5 and 7. The mountainous area in the center of the subscene has been mined in the past for copper. The bright rhomboidal features seen in the TM band 4 subscene are tailings ponds associated with these earlier mining activities. Variations in the TM 5/TM 7 ratio image are produced by variations in the surface concentration of clay minerals. Progressively larger values of the TM 5/TM 7 ratio are indicative of progressively larger concentrations of surface clays. The brightest areas observed in the ratio image represent the surface expression of the hydrothermal alteration zone that was produced when copper mineralization was originally emplaced in this area. (Illustration courtesy of Pat Chevez, U. S. Geological Survey).*

landforms. Finally, TM imagery can be used to determine the distribution of landforms over broad areas and detect alignments, offsets, and variations in landform shape which may be indicative of local folding or faulting in the crust. Certain types of rocks have a natural tendency to weather in characteristic fashions in different types of weathering environments. The improved spatial resolution of the TM will enable geologists to detect more subtle variations in the weathering habit of rock units that outcrop directly at the Earth's surface. Under certain circumstances, landform morphology can be used to infer the lithology of surficial rock units. It is also possible to infer the strike and attitude of surficial rock units on the basis of landform shape and distribution under certain circumstances. Studies conducted to date with Landsat 4 TM data indicate that TM imagery will support terrain analysis and structural mapping at a scale of 1:24,000.

***Ground Temperature.*** The TM thermal band (band 6) can be used to survey areal variations in ground temperature at a spatial resolution of 120 meters. In principle, this capability could be used to study variations in surface heat flow related to regional volcanism of both an extrusive and/or intrusive nature. Night time thermal surveys have been used in the past to detect variations in rock lithology as discussed above. Night time thermal surveys have also been employed to detect surface faults and fracture patterns. Near surface moisture commonly collects along fractures and joint surfaces. Under these circumstances, near surface fractures are significantly cooler than their local surroundings and

they are readily detectable in thermal infrared imagery.

***Surface Vegetation.*** MSS imagery has been used in the past to detect the occurrence and map the relative abundance of surface vegetation over a variety of temporal and spatial scales. These same types of studies can now be performed at an improved level of spatial resolution with the TM. In addition, the improved spectral resolution of the TM can be used to differentiate a wider variety of vegetative species. Specifically, the TM spectral bands can be used to discriminate both deciduous and coniferous tree stands that are dominated by a single species such as white oak, red maple, loblolly pine, and white pine. Past research has shown that vegetation distribution and density can be correlated with discontinuities in the lithologic characteristics of underlying geological materials under certain circumstances. Past research has also indicated that the TM spectral bands can be used to detect stress conditions in natural vegetation which are related to soil toxicity and water deprivation. Vegetation stress can sometimes be related to anomalous geological conditions such as the concentration of metallic elements in surface soils or the local seepage of underground hydrocarbons.

The potential utility of orbital TM surveys for basic geological research is also governed to a large degree by the spatial extent and temporal frequency of TM observations. Multispectral TM data are unique in three important respects: they are collected over a ground swath of 185 kilometers on a near global basis every 16 days. Each of these considerations has important implications for the types of geological investigations that can potentially be conducted with TM imagery, and the experimental methodology to be employed in addressing specific types of geological problems. These implications are briefly summarized below.

***Synoptic Scale Observations.*** The synoptic scale of TM imagery can provide a basis for interrelating various types of geological information obtained at a local scale by conventional field mapping and sampling techniques. For example, TM imagery can be used to integrate maps of surficial geology, fracture patterns, or soil geochemistry obtained at much more limited spatial scales by relating the occurrence of specific surface materials or geologic structures to spectral patterns and landform patterns observed in a TM image. Furthermore, the synoptic scale of TM imagery may be used to identify geological features of regional significance that are not readily apparent to ground based observers or aerial photointerpreters. For example, TM imagery can be used to recognize major systems of crustal fractures which may have a discontinuous expression at the Earth's surface. TM imagery can also be used to recognize key marker horizons in sedimentary terranes which may outcrop in a discontinuous fashion over a large area. The synoptic scale of TM imagery is inherently useful for integrating and extending point measurements of geological conditions that are spatially discontinuous in nature.

***Near Global Observations.*** In principle, TM data can be collected over more than 90% of the exposed landmass area of the Earth. The availability of multispectral Earth imagery acquired at common scales and formats over most of the world poses some interesting opportunities for basic crustal research. For example, many remote parts of the world remain unmapped at the present time due to their inaccessability. TM imagery could be used to make pioneering observations of geological conditions in many arid, tropical, and arctic regions. Analysis and interpretation of TM imagery acquired over such areas could lead to the production of regional scale geological maps for the first time. The near global availability of TM imagery also presents an opportunity to test geological models or theories that are based upon intensive studies of specific crustal features. For example, our current understanding of continental rifting is based upon detailed studies of a limited number of continental rifts (e.g. the East African Rift, the Rio Grande Rift, and the Red Sea Rift). TM imagery could be used, in principle, to determine similarities and differences between those rift features that have been studied intensively in the past as a means of developing more generic models of rift formation and evolution. In addition, TM imagery could be used to study continental rifts which have received little attention in the past as a means of testing and refining existing models of rift formation. This is not to suggest that crustal processes can be modeled solely on the basis of TM image analysis. However, the TM is a powerful tool for conducting comparative studies of crustal features on a worldwide basis. Studies of this nature can make a significant contribution to current understanding of crustal processes, particularly when they are performed in conjunction with more conventional methods of crustal analysis.

***Repetitive Multitemporal Observations.*** There is a popular misconception that geologists have little interest in multitemporal Earth imagery. It is true that many geologic phenomena occur over time scales that are several orders of magnitude greater than the 16 day repeat cycle of the Landsat 4 and 5 spacecraft.

However, certain geologic processes such as lava flow emplacement, aeolian transport of desert sand, and surface flooding and sedimentation can be studied with multitemporal TM imagery. Multitemporal Earth imagery is also useful for structural mapping because certain geological structures may be more prominently displayed under different solar illumination conditions. Earlier studies have demonstrated that selected structural features may be more readily apparent in Landsat imagery acquired in late autumn (following crop harvesting), early winter (following periods of snowfall at higher elevations), and/or late winter (following the early melting of regional snowpacks at lower elevations). Consequently, photogeologists conducting regional scale studies of crustal structure commonly employ Landsat imagery acquired during different seasons. Finally, multitemporal TM observations will play a major role in future studies of geobotanical phenomena. Changes in the spectral reflectance characteristics of vegetated terrain during the annual growing season are potentially an important source of information about the nature of the vegetation that occurs on the surface. In addition, variations in the duration of the growing season of selected species can potentially provide information about the lithology of underlying geological materials.

## Prospective Research Themes

The purpose of the following discussion is to identify prospective research themes in the geosciences that could be addressed in new and innovative ways through the analysis of TM imagery. These themes involve the use of TM data for the exploration of remote areas, the study of crustal processes, and research in the interdisciplinary field of geobotany. A series of topical problems is presented to illustrate the nature of these themes and provide the reader with examples of research projects that are potentially amenable to TM analysis. The research themes and topical problems discussed below are not intended to be an exhaustive or comprehensive listing of all geoscience investigations that could potentially be conducted with TM imagery. Furthermore, the various procedures for TM data collection and analysis described below are not intended to be definitive blueprints for the conduct of specific investigations. The overall goal of the following discussion is to stimulate creative thinking about different types of geological problems that could be addressed through the analysis of TM data. This discussion is not intended to be restrictive or prescriptive in any way.

### *Earth Exploration*

Current understanding of the surface structure and composition of the Earth's crust is highly variable. Certain crustal provinces such as the Basin and Range province in the southwestern U.S. have been studied extensively in the past. Knowledge of the composition and distribution of the rocks exposed in this province has been accumulated through years of field mapping and sample analysis. This knowledge is summarized in geological maps which display the local distribution of rock types, the strike and attitude of rock formations, and major structural features such as folds and faults.

Many non-geologists consider geological maps to be definitive statements of geological conditions within a specific area. In reality, geological maps are "living documents" which must be changed as new concepts are developed concerning the nature and history of local rock units, the structure and composition of adjacent districts, and the nature of the geologic processes that acted upon the Earth's crust in the past. Geologic maps generally summarize the results of earlier scientific investigations, and, like any good scientific study, they tend to raise many more questions about the nature and history of a particular province than they necessarily answer. To many geologists, a geologic map does not represent an end in itself, but rather it is a point of departure for many other types of geologic investigations. As discussed in the previous section, analysis of multispectral TM imagery can yield information about rock lithology and crustal structure at synoptic scales. This type of information can play an important role in developing regional scale geologic maps. In principle, this type of information can be used to conduct pioneering studies of geological conditions in both well studied and poorly understood crustal provinces. Three general categories of prospective TM mapping projects are briefly outlined below:

**(1)** Current geological understanding of many parts of the world is quite rudimentary or lacking altogether. This is particularly true for crustal provinces located in arid, tropical, and arctic regions which are remote and relatively inaccessible. The global availability of TM imagery provides a unique opportunity to conduct observations of regional geologic conditions and establish reconnaissance geological maps of such areas for the first time. By way of example, TM imagery could potentially be used to identify local areas of rock outcrop in arid terrain, correlate outcrop areas of similar lithology, and develop preliminary maps of bedrock geology.

This type of approach is particularly applicable to arid environments in which outcrop areas are discontinuous and widely separated by deposits of windblown sand. Alternatively, the improved spatial resolution of TM imagery could be used to conduct detailed mapping studies of drainage patterns in tropical terrain. Under certain circumstances, these drainage patterns can be used to detect lithologic boundaries between different types of bedrock formations and to identify major structural discontinuities within the underlying crust.

**(2)** TM image analysis can also refine or extend current geologic understanding of areas that have been studied extensively in the past with conventional field mapping techniques. As discussed earlier, multispectral TM surveys can provide information about iron occurrence, clay mineralogy and abundance, and the carbonate mineralogy of surface rocks on a synoptic scale. These various types of lithologic information are not always readily obtainable with conventional field mapping techniques. Such information could be used to extend existing geologic maps of selected areas. For example, the sensitivity of TM band 7 to variations in carbonate mineralogy could potentially be used to map facies variations in carbonate formations that are commonly exposed in the intermontane basins of the western U.S. Alternatively, the sensitivity of TM bands 2-5 and 7 to clay mineralogy and abundance could potentially be used to map areas of hydrothermal alteration in arid and semi-arid environments. The spectral coverage of the TM is particularly well suited for the discrimination of iron-bearing clay minerals. This capability is directly applicable to studies of ancient weathered soils such as those found in the interior of Australia.

**(3)** Finally, the synoptic scale and spectral coverage of TM imagery could potentially be used to tie together conventional geological maps prepared at more limited spatial scales, and to develop regional scale maps of selected crustal provinces for the first time. The synoptic dimensions of individual TM scenes can easily support mapping studies conducted at scales of 1:250,000. TM image mosaics could potentially be used to develop maps of selected provinces at even larger scales. In principle, it should be possible to develop spectral and spatial indices for correlating rock units of similar lithology that have been independently mapped by different field workers in the past. These indices could potentially be used to interrelate the occurrence of specific rock units appearing on existing geological maps. These indices could also be used to interpolate between existing maps and identify the probable occurrence of similar rock units in adjoining areas which have not been mapped in the past. The use of TM multispectral imagery to interrelate existing geologic maps and interpolate the occurrence of specific rock units could lead to the development of regional scale maps of selected crustal provinces for the first time. Maps of this nature could, in turn, be used to develop alternative models for the history and evolution of such provinces.

The common feature of all of the mapping investigations described above is the use of TM data to conduct exploratory observations of geological conditions in different crustal regions. They specifically make use of the TM's measurement capabilities to establish new and/or improved understanding of crustal composition and structure. As such, they represent the use of the TM system to explore the surface of our planet in a pioneering fashion.

## *Geologic Processes*

The current distribution of crustal rocks and landforms is the ultimate result of a myriad of processes that have shaped the crust in the past. In many other Earth science disciplines, such as oceanography or meteorology, it is possible to conduct repetitive observations of in situ conditions and deduce something about the nature of the processes that are responsible for observed changes in surface conditions. Geology differs from many of these other disciplines because so many geological processes occur over time scales that are much longer than the average human lifetime. In fact, many geological processes occur over periods of time that are longer than recorded human history! Geologists examine the nature, sequence, and configuration of rocks exposed in different parts of the world, and they employ inductive reasoning to develop models of many crustal processes. The TM can contribute to this inductive method of studying the Earth by providing geologists an opportunity to examine the current configuration of crustal materials and landforms almost anywhere in the world. In fact, TM observations provide geologists with a unique opportunity to study a variety of crustal provinces in a comparative fashion that has not been possible in the past.

At the same time, however, events such as the eruption of Mt. St. Helens in 1980 or the San Francisco earthquake of 1906 serve as compelling reminders that certain geologic phenomena do occur over time scales that are directly amenable to human observa-

tion. The TM can obviously play a role in the study of these short term phenomena, particularly when they occur in remote and relatively unpopulated areas.

The purpose of the following discussion is to illustrate some of the types of geological processes that could potentially be studied through the analysis of TM data. The phenomena described below do not represent the only processes that could potentially be studied, nor do they necessarily represent the most important topics for process-related research.

***Erosional Processes.*** The current morphology of the Earth's crust reflects a balance between the effects of constructional phenomena such as tectonism and volcanism, and destructive phenomena such as fluvial and aeolian erosion. The nature of the balance between these competitive phenomena can vary enormously from one crustal province to the next.

Landscape morphology is locally governed by regional environmental conditions and the nature of the rocks that are locally exposed at the Earth's surface. Conventional geological wisdom predicts that certain landform assemblages are always produced when selected types of rocks are exposed to specific types of weathering environments. For example, limestone formations exposed to tropical weathering conditions break down in a characteristic fashion to produce a highly dissected landscape known as karst terrain (see Figure III-7). The extent to which variations in limestone lithology or interbedded formations of different lithology affect the nature and development of karst terrain is poorly understood at the present time. Furthermore, qualitative understanding of the equilibrium landform assemblages that should result from certain combinations of rock lithology and environmental conditions is lacking altogether.

TM observations could potentially be used to extend current understanding of how erosional processes control landscape development in both a quantitative and qualitative sense. In the case of well-known associations between landscape morphology, rock lithology, and weathering conditions, TM observations of landform shape and distribution could be used to establish quantitative models of the landrorm assemblages that should be produced in a specific area. Detailed measurements of landform morphology could potentially be related to the surface exposure ages of specific formations to establish quantitative models of landscape evolution as a function of time. In theory, these types of relationships could potentially be inverted to infer the length of time a particular area has been subjected to a specific set of weathering conditions.

Improved understanding of the landforms that should appear in a particular province would also enable geologists to identify relict landforms with greater accuracy. Relict landforms are ancient features which have been inherited by the regional landscape and they can provide clues about regional weathering conditions that may have existed in the past. The shape and arrangement of relict landforms can, in principle, be used to reconstruct the paleoclimatic history of selected portions of the Earth. Information of this nature can, in turn, place important constraints on climatic models.

TM imagery could also be employed to conduct pioneering observations of landform morphology and distribution in areas characterized by complex bedrock geology or transitional weathering conditions. These observations would enable geologists to develop qualitative models of equilibrium landform assemblages for certain rock lithologies and weathering environments for the first time. In fact, research of this nature would provide an interesting test of the theory that a specific assemblage of landforms is necessarily produced when certain types of rocks are exposed to a particular setof weathering conditions. Under certain geological and environmental conditions, landscape evolution may be more probabilistic than deterministic. It's possible that more than one equilibrium assemblage of land forms may be produced in transitional weathering environments of similar geology. If true, this conclusion would have important implications for the geologic and climatic histories of selected areas.

***Tectonism and Crustal Deformation.*** The solid outer shell of the Earth is known as the lithosphere. Crustal rocks constitute the outermost portion of the lithosphere and they are underlain by denser materials that form part of the Earth's mantle. The Earth's lithosphere is segmented into a collection of fragments that are referred to as "plates". These plates can move in both a horizontal and vertical sense with respect to one another. Plate collisional processes are responsible for the construction of mountain chains, the formation of oceanic trenches, and much of the earthquake activity that occurs today.

A wide variety of internal and external forces act upon the Earth's lithosphere plates. These forces include the internal upwelling of molten material within the Earth's lower mantle, the centrifugal acceleration produced by the rotation of the Earth, gravitational accelerations produced by the Earth's core and lower mantle, and tidal forces exerted by the moon and the sun. Variations in the magnitude and direction of these and other forces that occur across individual plates produce stresses within the

Earth's crust which are periodically relieved through episodic crustal motions. The deformation of the Earth's crust in response to these forces is expressed in the form of folds and faults.

In unraveling the history of individual provinces, geologists seek to determine the orientation and magnitude of the stress field that is currently acting upon the crust, and to determine how this stress field has changed over the course of geological time. The orientation, extent, and sense of motion of crustal folds and faults place important boundary conditions upon the geometry and magnitude of stresses that

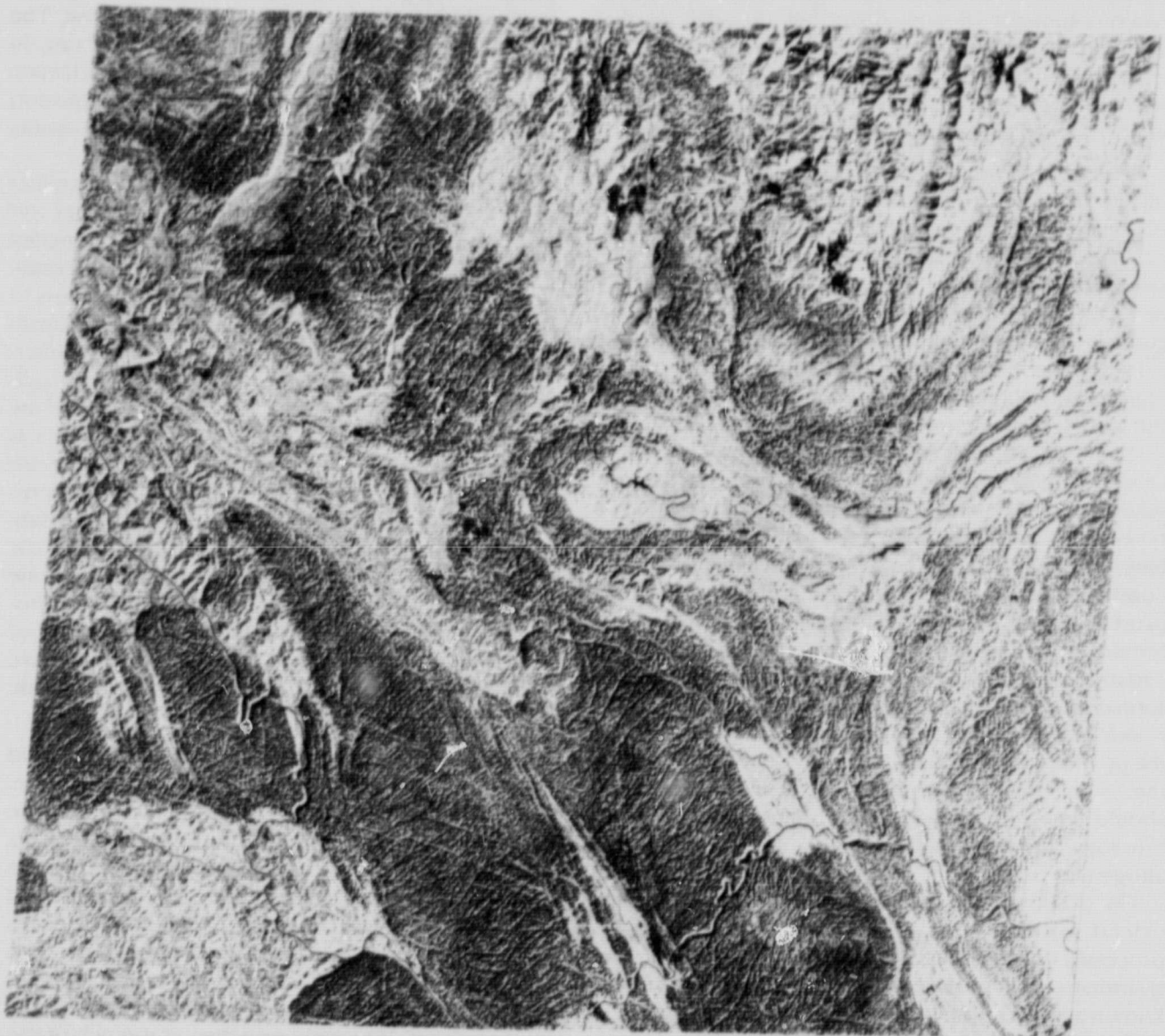

*Figure III-7*

***Multispectral Scanner band 7 image of karst terrain in Guangxi Province, China. This image was originally acquired in November, 1973 by Landsat 1. It is a standard MSS image encompassing an area of 185 x 185 kilometers. The darker, highly dissected limestone formations exposed in this region contrast sharply with surrounding formations in terms of their tone and texture. Steep-sided linear depressions exposed in the karst terrain can be traced continuously over distances of 30—80 kilometers suggesting that the dissection of the regional limestone formations has occurred along pre-existing fracture systems. The improved spatial resolution of the TM could be used in the future to study the morphometric characteristics of karst landforms at a level of spatial detail that has not been possible in the past. Such studies could potentially be conducted in a globally comparative fashion to determine similarities and differences in the morphology of different karst terrains. (Image courtesy of Nick Short, NASA—Goddard Space Flight Center).***

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have deformed the crust in the past. The improved spatial resolution of TM imagery can clearly contribute to the identification of such features, and to the determination of displacement along surface faults (see Figure III-8). Furthermore, the synoptic scale of TM imagery enables a photogeologist to determine the length, alignment, and relative displacement of such features on a regional scale. Observations of this nature are extremely useful in attempting to distinguish regional trends from localized patterns of apparent crustal deformation. They also enable geologists to identify key districts within a broader province where ground based measurements of fault motion and displacement are needed to resolve alternative interpretations of stress field geometry.

Field investigations of fault displacement play a key role in determining the relative ages of different fault and fracture systems. In many instances, individual rock formations are multiply deformed by a series of tectonic events. Detailed observations of the sense of motion and apparent displacement that has occurred along crosscutting fracture systems enable geologists to assign relative ages to specific deformation events. Information of this nature is essential in attempting to determine how the regional stress field has changed over the course of geologic time Synoptic scale TM imagery could prove to be extremely useful in identifying areas of fault and fracture intersection, and targeting such areas for detailed field analysis. The distribution and orientation of surface folds and faults can potentially provide important insight into the structure of the deep crust. Crustal provinces are commonly defined on the basis of the age or lithology of the rocks exposed at the Earth's surface. Crustal provinces can also be defined on the basis of the tectonic fabric or style of deformation of extended regions. As described above, TM imagery can be used to map patterns of crustal deformation over a wide range of spatial scales. Such patterns can, in turn, be used to identify crustal provinces characterized by different styles of structural deformation. Boundaries separating structural provinces may not necessarily correspond to provincial boundaries identified on the basis of rock lithology or stratigraphy. Sharp discontinuities in the tectonic fabric of individual regions may be indicative of major structural discontinuities in the lower crust. In principle, TM imagery could be analyzed in conjunction with more conventional geophysical data (e.g. seismic surveys and potential field measurements) to detect and characterize major structural features in the lower crust.

Crustal stresses are commonly relieved at a local scale along pre-existing zones of weakness. These zones of weakness may be aligned in a highly random fashion with respect to the regional stress field. Seismic data can provide information about the location, depth, sense of motion, and strain energy released during an earthquake event. Information of this nature can be used to estimate the direction and magnitude of regional crustal stresses if the orientation and attitude of the fault zone can be determined. Crustal faults are commonly exposed at the Earth's surface. Under certain circumstances, the orientation and attitude of such features can be determined through the analysis of TM imagery If historical seismic activity can be related to specific zones of weakness identified in TM imagery, it should be possible to develop stress field models for selected portions of the Earth's crust. Combined analysis of TM imagery and historical seismic data could prove to be particularly effective for determining the nature of the current stress field in many remote and poorly explored crustal provinces.

***Volcanism.*** Volcanism is, by its very nature, an episodic process that adds material to the Earth's crust. Like tectonism, it has had a dominating influence upon the recent geologic history of certain crustal provinces. Many areas of recent volcanic activity are located in remote parts of the world. Basic understanding of the nature and frequency of volcanic activity in many of these provinces is lacking altogether. Furthermore, our basic understanding of how volcanoes work and what factors govern the outbreak of volcanic activity is quite rudimentary at the present time.

Knowledge of the composition, age, and volume of lava that has been erupted by an individual volcano in the past places important boundary conditions on models of future eruptive activity. The TM is particularly well suited for mapping the spatial extent of lava flows in light of the 30 meter spatial resolution of TM imagery. The TM spectral bands are also well suited for detecting variations in the iron oxide chemistry and clay mineralogy of weathered flow surfaces. Under certain circumstances, it should be possible to distinguish flows of different chemical composition on the basis of the spectral characteristics of their weathered surfaces. Past research has also suggested that the devitrification of lava flow surfaces and the corresponding development of clay alteration products is directly related to the surface exposure age of individual flows. As discussed earlier, variations in the surface abundance of clay minerals produce variations in natural surface reflectivity which can be measured by the TM (specifically by TM band 7). In principle, it may be possible to exploit this observational capability of the TM to detect variations in the clay abundance, and, hence, the relative ages of weathered flow units (see, for example, Figure

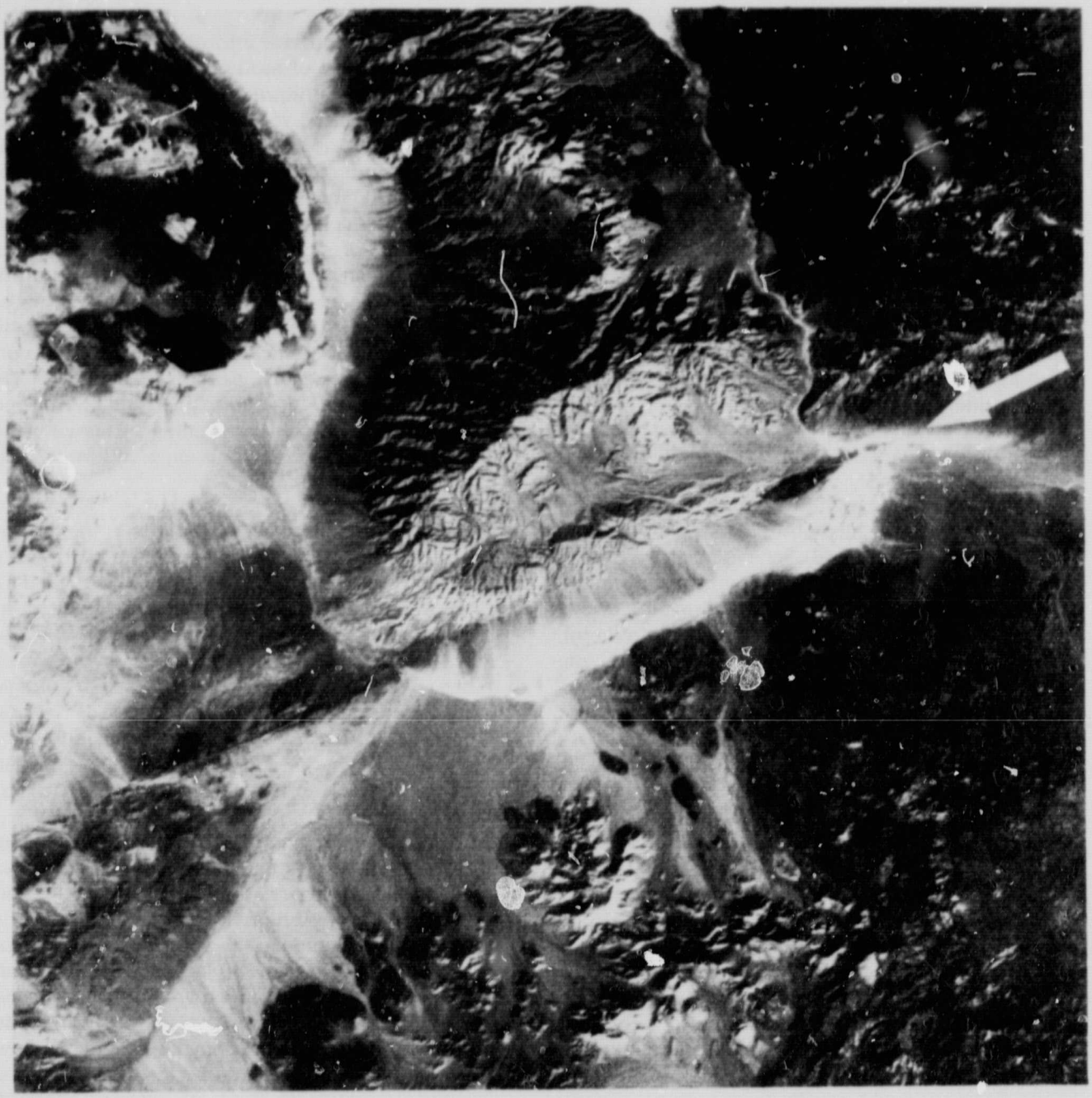

*Figure III-8*

*Sharp discontinuities in the shape and distribution of surface land forms can be used to identify the surface expression of crustal faults, as illustrated in this TM image of southern California. This image was originally acquired in November, 1982 over path 40/row 35 of the Landsat 4 and 5 World Reference System. The arrow denotes the surface expression of a right lateral shear fault that is regionally exposed in this area. The linear feature observed in the image is the eastern most extension of the Garlock Fault which is a major tectonic feature in southern California. The section of the fault displayed in this imageis roughly 35 kilometers long. Note the marked differences in alluvial fan development along various segments of the fault. The improved spatial resolution of the TM should enable geologists to detect much more subtle expressions of neotectonic features in many different parts of the world, particularly in semi-arid environments. (Image courtesy of Locke Stuart, NASA--Goddard Space Flight Center).*

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III-9). Information concerning the composition, age, and extent of individual lava flows derived from synoptic scale TM imagery could contribute to the development of predictive models which would enable geologists to forecast the nature, timing, and volume of future eruptive events in a more quantitative fashion.

On a global scale, volcanism is the most efficient terrestrial process for transferring thermal energy from the Earth's interior to its surface. The thermal band on the TM provides a unique opportunity to observe and monitor variations in the thermal characteristics of natural terrain in areas of incipient or current volcanism. Large scale surveys of surface thermal emission could prove to be particularly useful for forecasting the eruption probability of many stratovolcanoes, particularly those that are situated at higher latitudes and elevations. Stratovolcanoes are steep-sided, conical landforms. These features are characterized by summit craters or calderas which are

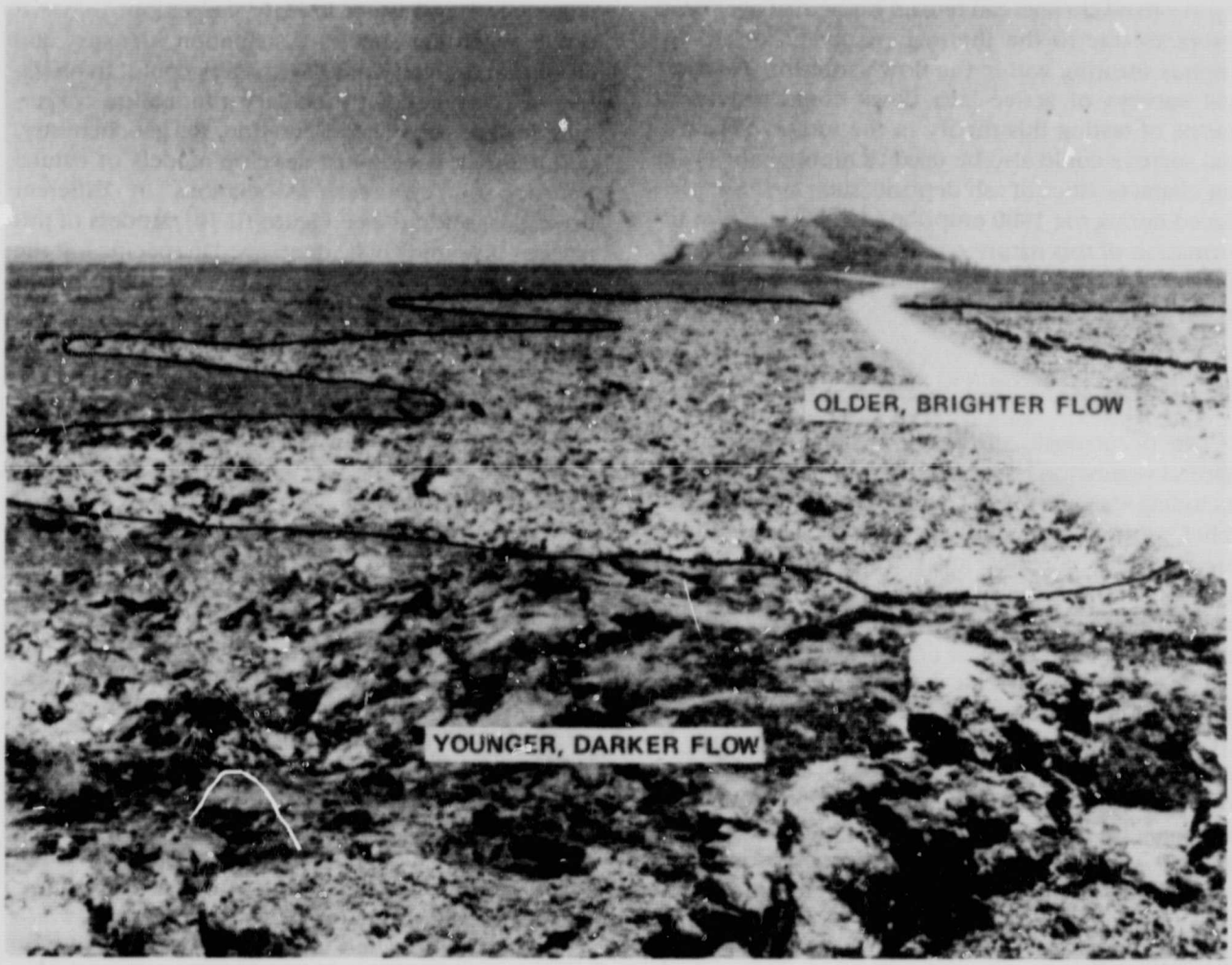


*Figure III-9*

*This is a ground-based photograph of two interfingered lava flows situated in the saddle area between Mauna Kea and Mauna Loa on the island of Hawaii. Although both flows possess similar chemical compositions, they display very different reflectance properties. The surface of the older flow on the right has been chemically altered into an assemblage of amorphous silica gels, iron oxides, and clay minerals. The younger flow on the left is relatively fresh and unaltered. The older, weathered flow has a brownish visual appearance and a higher net reflectance in the visible portion of the spectrum than the younger flow surface. TM measurements will enable geologists to detect variations in the spectral characteristics of lava flow surfaces that can theoretically be correlated with the exposure ages of individual flows. This capability could, in principle, be used to study the eruptive history of many historically active volcanoes. (Photograph courtesy of John Adams, University of Washington.)*

commonly filled with water. The TM provides a unique capability to monitor temporal variations in the thermal characteristics of such summit lakes. Variations in the thermal state of volcanic lakes could be combined with seismic data and crustal deformation surveys to develop refined eruption forecasting models.

Thermal surveys conducted by the TM could also prove useful in studying the physical properties and cooling characteristics of recent volcanic deposits. For example, recent studies have suggested that lava flowing in a fixed channel can remain isothermal over large distances due to the thermal energy produced by viscous shearing within the flow's interior. TM thermal surveys of active lava flows could provide a means of testing this theory in the future. TM thermal surveys could also be used to monitor the cooling characteristics of ash deposits such as those produced during the 1980 eruption of Mt. St. Helens. Information of this nature could be used to refine and quantify models of welded tuff formation that have been developed in the past.

## *Geobotany*

The occurrence, distribution, and condition of natural vegetation is governed by a variety of factors including seasonal thermal variations, local rainfall and relief, nutrient availability, animal predation, and the physical and chemical characteristics of the local geological substrate. Any one of these factors can potentially have a controlling influence on the germination and development of individual plant species.

The extent to which local geological conditions influence plant succession, proliferation, and condition is poorly understood at the present time. Research in this area is currently being pursued by a variety of investigators for very different reasons. From a botanical or ecological perspective, improved understanding of natural associations between bedrock, soils, and vegetation can be used to develop better models of the type of vegetation that is likely to develop in different geological terranes. This knowledge is needed to isolate the effects of local geology and determine the influence of other factors, such as climate and drainage, upon vegetation potential. From a geological perspective, improved understanding of natural associations between bedrock, soils, and vegetation can be used to infer local geological conditions on the basis of observed variations in the characteristics of natural vegetation. Furthermore, improved understanding of natural plant-substrate associations would potentially enable geologists to recognize anomalous variations in substrate geology on the basis of stress conditions in natural vegetation canopies. Of key interest to geologists is the ability to recognize vegetation stress that may be produced by abnormal concentrations of metallic ions in surficial soils or the local seepage of hydrocarbon gases from a subsurface oil reservoir.

The expanded spectral range of the TM can be used to differentiate a far wider range of natural vegetation species than was possible in the past with the Landsat MSS. In addition, selected TM bands can be used to detect variations in the abundance of chlorophyll and water in leafy vegetation. Information concerning species distribution, density, and condition derived from TM imagery could, in principle, be combined with ancillary information concerning surface slope and orientation, soil geochemistry, and bedrock geology to develop models of natural bedrock-soil-vegetation associations in different ecological settings (see Figure III-10). Models of this nature could initially be developed in specific test site areas where a wide variety of ancillary information concerning local substrate characteristics is readily available. They could subsequently be tested in other areas where canopy characteristics inferred from multispectral TM surveys would actually be used to predict the chemical nature and physical properties of the underlying substrate materials. The ability to infer local geological conditions on the basis of observed variations in the spectral properties of natural vegetation could potentially revolutionize geological mapping methods in many temperature and tropical portions of the world.

Improved understanding of natural plant-substrate associations could also lead to the development of new methods for recognizing geologically-induced stress conditions in vegetated terrain. Some forms of geological stress have an obvious impact upon natural vegetation. For example, soils that develop on ultramafic rocks contain large concentrations of metallic ions which most forms of vegetation cannot tolerate. There are significant variations in plant occurrence and distribution in ultramafic terranes which can be directly related to the metal toxicity of local soils. In many other instances, however, small variations in the geological properties of the local substrate produce much more subtle variations in the characteristics of the natural vegetation canopy. Identification of these subtle effects could be effectively studied with the TM, by developing improved understanding of what constitutes "normalcy" in terms of the plant-substrate associations to be expected in different ecological settings. The definition of "normal" associations between vegetation, soils, and bedrock is an essential first step in attempting to

study and classify anomalous variations in canopy characteristics that can potentially be attributed to local geological factors.

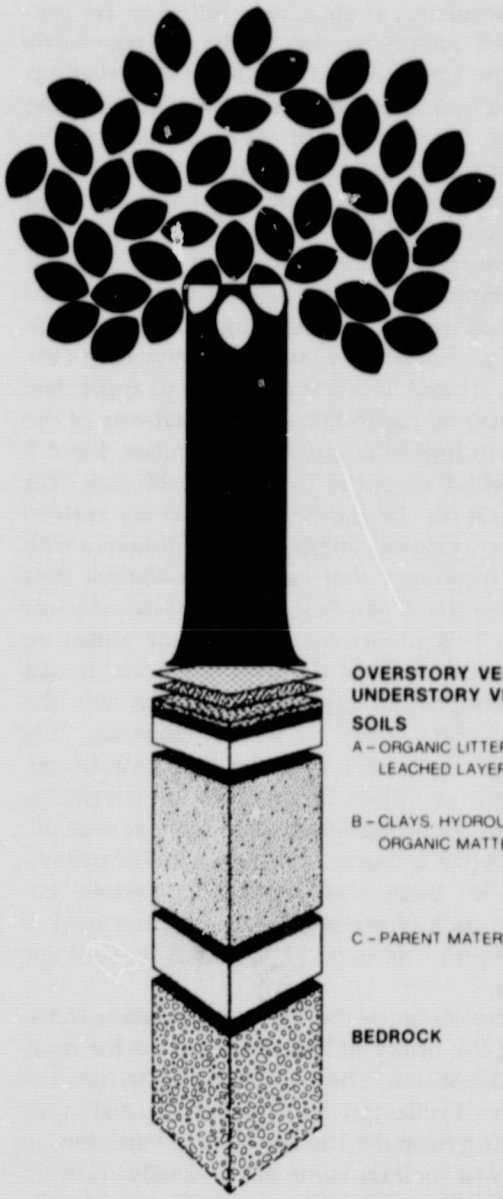


*Figure III-10*

*Natural relationships between vegetation, soils, and bedrock characteristics are exceedingly complex and poorly understood at the present time. The use of TM data to determine areal variations in vegetation density, distribution, and condition in areas of known geology could make a significant contribution to the study of vegetation-soil-bedrock associations.*

# HYDROLOGY

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## Introduction

One of the characteristics of the Earth that distinguishes it from all of the other planets in our solar system is the abundance of water in gaseous, liquid, and solid form near the Earth's surface. Hydrology has been defined as "the science that treats the waters of the Earth, their occurrence, circulation, and distribution, their chemical and physical properties, and their reaction with their environment, including their relation to living things." Hydrologists are fundamentally concerned with the transport and storage of water in its various forms within the Earth's oceans, atmosphere, and continents. The cycling of water through these various reservoirs has been described by L'vovich (1979) as "the most magnificent process that takes place on the Earth. The interaction between water and the other components of nature is so substantial and its consequences so great that it requires the most serious attention."

Many researchers have attempted to characterize the range of interactions that occur within the Earth's hydrosphere. Figures III-11 and III-12 illustrate the various dimensions of the hydrologic cycle as defined by Eagleson (1970) and Horton (1931). It is important to realize that the processes illustrated in these figures occur over a wide range of spatial scales.

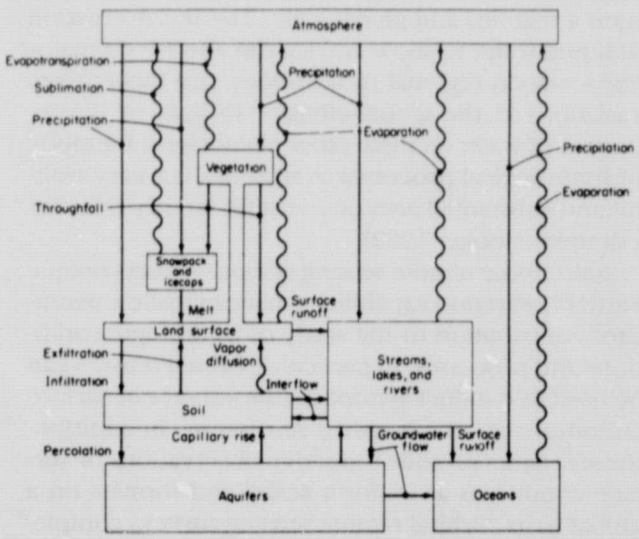


*Figure III-11*

*An engineering view of the hydrologic cycle after Eagleson (1970).*

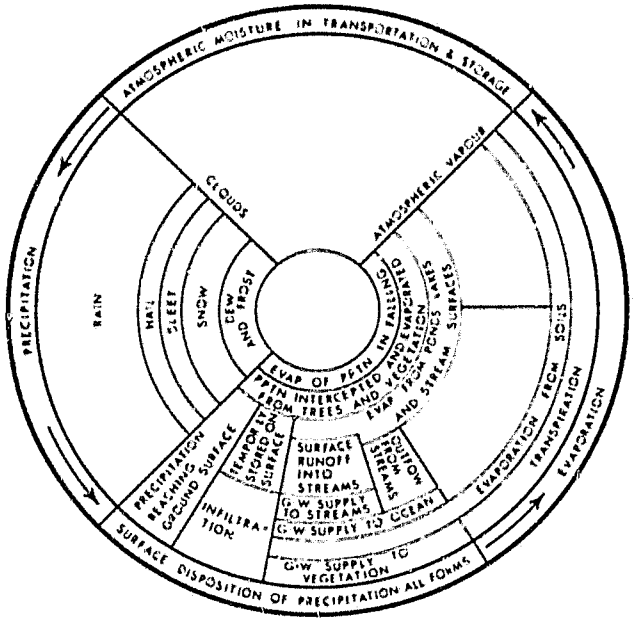


*Figure III-12*

*A qualitative representation of the hydrologic cycle after Horton (1931).*

Changes in the form and distribution of water have important consequences on the weather, climate, and ecology of the Earth's surface. Water is the primary constituent of terrestrial vegetation. Variations in water availability can have a major impact upon the dynamics and distribution of the Earth's biomass on both a regional and global scale. The transformation of liquid water to snow and ice can also have a major impact upon regional meteorology and longer term variations in the global climate. In light of the influence of water on these other phenomena, the study of hydrological processes at all scales is a very fruitful and substantial area of scientific inquiry (see, for example, Dooge, 1982).

Spaceborne remote sensing systems possess unique Earth observation capabilities that can make a significant contribution to the study of hydrologic conditions and processes. In particular, orbital sensors can be used to conduct synoptic scale surveys of surface conditions at a high spatial resolution. In addition, these sensors provide repetitive observations of surface conditions at uniform scales and formats on a global basis. Orbital remote sensing surveys complement more conventional methods of ground-based observation that typically obtain high accuracy measurements of ***in situ*** conditions on a point-by-point basis. Expressed in another way, conventional field techniques can provide information about surficial conditions with relatively high accuracy and high temporal frequency; whereas, orbital remote sensing techniques generally provide less accurate but highly dense observations over large areas. Orbital sensors possess observational capabilities that can contribute to improved understanding of hydrologic processes occurring at all scales, but they are particularly well suited to the study of large scale phenomenon. Uniform and consistent observations of land cover conditions are generally lacking at large spatial scales. These types of observations must be performed if we are to understand the dynamic processes and storage capacities of different portions of the hydrological cycle.

The measurement capabilities of the Landsat Thematic Mapper (TM) can potentially be used to study selected aspects of hydrology in new and innovative ways. However, to make effective use of the TM for such studies, it is first necessary to appreciate the observational capabilities and limitations of the TM in a hydrological context. The Landsat 4 and 5 spacecraft which carry the TM sensor each pass over the same spot on the Earth's surface every sixteen days. TM observations can generally be obtained with a temporal frequency that varies from sixteen days to several months depending upon local cloud cover conditions. This obviously restricts our ability to monitor a wide range of dynamic phenomena that produce changes in surface conditions on the timescale of hours, days, or weeks. However, it is possible to partially overcome this limitation by obtaining random observations of a particular phenomenon occurring simultaneously in several different places (for example, the dispersion of turbidity plumes in lakes and rivers). In certain circumstances, such observations can be combined to develop generic models of selected hydrologic phenomena.

The spectral range of the TM is also a major factor in assessing the utility of TM observations for basic hydrological research. The TM is designed to measure the intensity of reflected sunlight and thermal radiation emanating from the Earth's surface. Variations in the intensity of such radiation are generally controlled by the chemical composition and physical properties of the outermost material exposed directly at the surface. Earth radiation measured by the TM generally emanates from the upper few micrometers of the cover materials exposed at the surface. Such measurements provide little direct information about bulk surface properties. However, the spectral range of the TM does provide hydrologists with new observation capabilities that are directly applicable to studies of snow state, water quality, and the thermal state of water bodies. TM bands 1-3 and 5 & 7 can



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specifically be used to discriminate clouds from snow and ice. TM band 1 is situated in the blue portion of the visible spectrum, and it can be used to measure the intensity of radiation which has been transmitted through liquid water and reflected from suspended materials or submerged surfaces. TM band 1 has also proven useful for characterizing the surface properties of snow and ice. Finally, TM band 6 is situated in the thermal infrared and it can be used to detect variations in the surface temperature of lakes, rivers, coastal zones, and snow covered areas. The use of the TM's spectral capabilities for the study of specific phenomena is discussed in greater detail in a later section.

Finally, the TM has been designed to conduct synoptic scale multispectral surveys at a spatial resolution of 30 meters (note that the spatial resolution of the thermal band TM 6 is 120 meters). The improved spatial resolution of the TM can be used to characterize the hydrogeomorphology of selected areas at a level of detail that has not been possible in the past. In addition, this improved resolution can be used to characterize the distribution of surface cover materials in a more detailed fashion. Information of this nature is directly applicable to studies of water storage and runoff in different hydrologic environments.

In summary, the measurement capabilities of the TM are significantly more sophisticated than those of the MSS sensor carried on earlier Landsat spacecraft. These advanced measurement capabilities can potentially be used to study a far wider range of hydrologic phenomena. They can specifically be used to monitor the surface manifestation of such phenomena on a globally repetitive basis. The temporal, spectral, and spatial measurement capabilities place important constraints on the nature and frequency of hydrologic observations that can actually be performed by the TM. Investigators seeking to employ the TM for basic research in hydrology must be mindful of these limitations in designing specific hydrological experiments.

## Prospective Research Themes

The purpose of the following discussion is to identify a series of topical problems in different aspects of hydrology that could be profitably addressed through the analysis and interpretation of TM data. This discussion is not intended to be all-inclusive, rather it is intended to illustrate generic types of hydrologic problems that are potentially amenable to TM analysis. The reader is encouraged to employ the following discussion as a point of departure in defining specific experiments that make innovative use of the TM's measurement capabilities for basic research in hydrology.

### *Hydrogeomorphic Analysis*

Water catchment areas (i.e. watersheds) consist of a network of stream channels that transport running water from higher to lower elevations. Watersheds represent the spatial transfer function between surface precipitation and runoff. They evolve in shape and character as a function of local geological and botanical conditions, regional climatic conditions, and the orientation of the watershed with respect to the sources and sinks of surface precipitation. The improved spatial resolution of the TM provides a unique opportunity to characterize the morphology of catchment areas at a level of detail that has not been possible in the past. TM imagery can specifically be used to determine stream order, density, and sinuosity at mapping scales of 1:25,000 (see Figure III-13). Detailed information of this nature would potentially enable hydrologists to define the size and distribution of sub-basins within broader catchment areas. Stream morphometric characteristics derived from TM imagery could also be analyzed in conjunction with existing maps of soil distribution, vegetation, and regional rainfall to determine the extent to which geological, botanical, and meteorological factors control stream geometry and watershed morphology.

The ability to acquire TM imagery on a near global basis also presents an interesting opportunity to study watershed development in different climatic settings. For example, the occurrence of permafrost terrain and seasonally frozen bodies of water at higher latitudes may have a significant influence upon the organization of regional drainage systems in polar regions. The seasonal release of large quantities of liquid water during periods of spring runoff could also have an important influence upon the size and spatial distribution of stream networks in high latitude regions.

Information concerning the regional geomorphology of stream networks situated in many parts of the world is quite limited at the present time. This is particularly true for many polar, tropical, and arid regions that are remote and relatively inaccessible. The TM provides a unique capability to explore the hydrogeomorphology of such regions at a level of detail that has not been achievable in the past. TM imagery acquired under different illumination conditions can specifically be used to determine the occurrence, length, size, and orientation of stream channels at both local and regional scales. Information concerning stream morphometry derived from TM imagery could be used to study the geomorphic characteristics of different regions in a comparative fashion that has

not always been possible in the past. Comparative studies of the hydrogeomorphology of selected regions could provide a quantitative test of existing theories concerning the influence of climatic conditions upon watershed development. Comparative studies of this nature could also be used to determine

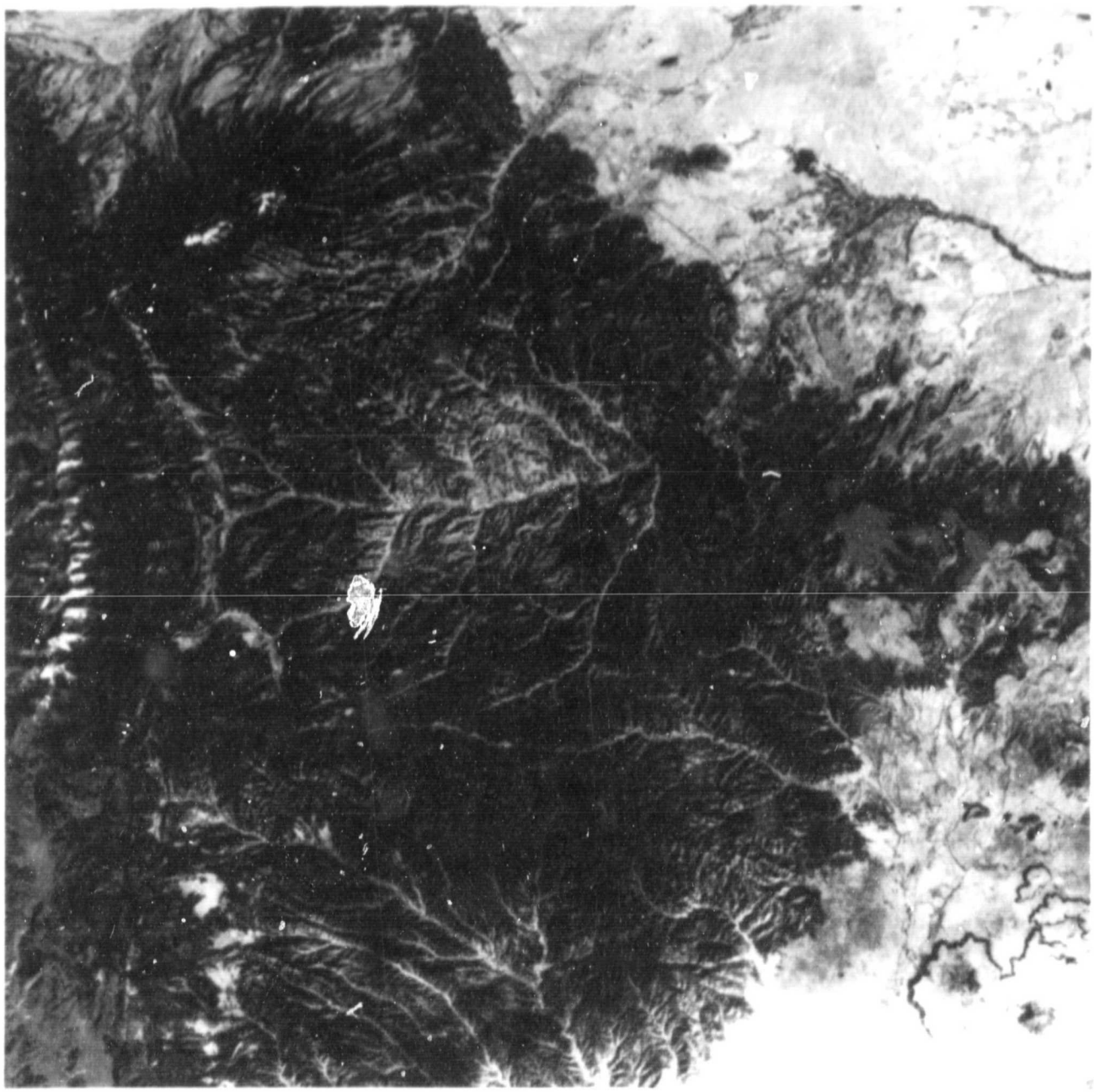

*Figure III-13*

*This is a portion of a Landsat 4 TM image acquired on November 16, 1982 over south-central Colorado near Trinidad, Colorado. The major drainage feature running west-to-east through the center of the image is the Purgatory River. The mountain range situated along the left hand margin of the image is the Sangre de Cristos mountains. Note the sharp difference between the radial drainage pattern associated with the two snow-capped peaks in the upper left corner and the dendritic drainage pattern associated with the Purgatory River. The improved spatial resolution of the TM could potentially be used to study the regional geomorphology of selected watersheds at a level of detail that has not been possible in the past.*



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whether stream network geometry is governed to a significant degree by the size of the catchment area (see, for example, Gregory and Walling, 1973).

## *Snow and Ice Studies*

Water in the form of snow and ice is a major component of the hydrologic cycle. Eleven percent of the Earth's land surface is permanently covered by glaciers, whereas more than fifty percent of the land surface is blanketed on a seasonal basis by snow. Snow and ice are sensitive indicators of climatic variability at all scales ranging from regional areas to the entire globe. In fact, areal variations in snow cover that occur on an annual basis are greater than the areal variability of surface vegetation or any other type of natural cover material. Because snow possesses an extremely high albedo, this variability produces large spatial and temporal variations in the surface radiation budget. Surface deposits of snow and ice modulate regional variations in air temperature, buffer the moisture content of the atmosphere, and they can insulate underlying materials. Some of the critical scientific questions regarding the role of snow and ice in the hydrologic cycle have recently been identified by the Polar Research Board of the National Research Council (1983) and Meier (1982).

In attempting to study the boundary layer meteorology of snow covered areas a variety of questions arise concerning how time-varying weather conditions affect the properties of the snowpack and vice versa. The spectral bands of the TM offer some specific observational capabilities that can be applied to studies of snowpack extent and condition. For example, frozen water is a more effective absorber of solar radiation at wavelengths greater than 1.0 micrometer than liquid water. In addition, large ice particles are more absorptive than smaller particles at these longer wavelengths (Dozier, 1983). As a consequence of these factors the liquid and frozen droplets that make up clouds tend to be much more highly reflective than surface snow and ice at wavelengths beyond 1.0 micrometer. TM band 5 is centered at a wavelength of 1.65 micrometer. It can be used in conjunction with other TM bands situated at shorter visible wavelengths to discriminate surface snow from clouds in a highly accurate fashion (see Figure III-14).

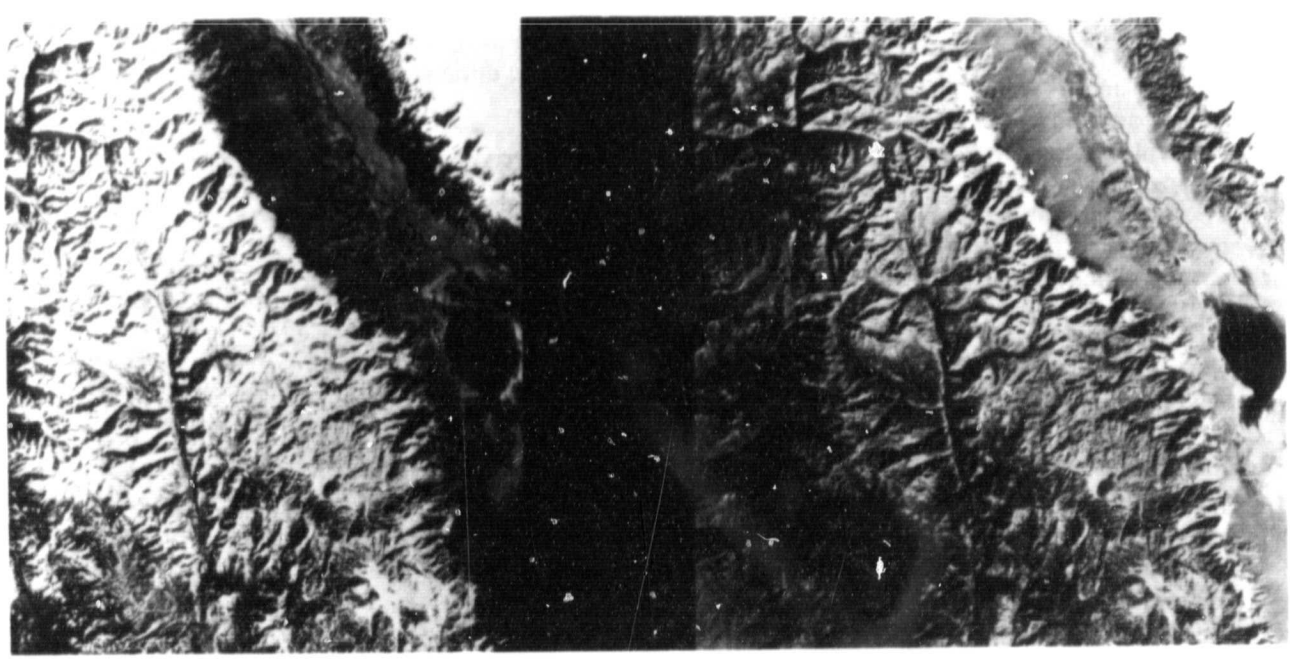

*Figure III-14*

*The two images shown above are segments of a full TM image of Owens Valley in southern California. This imagery was originally acquired during the winter of 1982. The image on the left was constructed from TM bands 2, 3, and 4. Snow and cloud covered areas both appear bright within the spectral region covered by these bands. The image on the right was constructed from TM bands 2, 5, and 7. Snow reflectance is less than that of clouds in TM bands 5 and 7. Consequently, snow covered areas appear dark in this image whereas cloud covered areas remain bright. Note that the area of extensive cloud cover situated in the upper right corner of each image can be clearly discriminated from snow covered areas situated on the left side of both images. (Imagery courtesy of Jack Engel, Hughes—Santa Barbara Research Corporation).*

Several of the other TM spectral bands can be used to characterize snow state or condition. Snow reflectance is a sensitive function of surface grain size in TM bands 4 and 7, whereas snow reflectance properties are sensitive to surface contamination at shorter wavelengths corresponding to TM bands 1, 2, and 3. Finally, TM band 6 can be used to monitor spatial variations in snowpack thermal conditions. In principle, it should be possible to combine information derived from these different spectral bands to form new spectral indices of snow condition. Such indices could be monitored in repetitive TM surveys to study snowpack response to constantly changing meteorological conditions.

The inverse problem is equally intriguing, namely how the snowpack influences or modulates regional weather and climate. TM imagery could potentially be used to monitor annual variations in snow accumulation, the altitude, slope, and aspect of interconnected catchment basins, and the concavity or convexity of the snowpack itself. These various types of observations could be used to test and refine radiation budget models for high latitude watersheds.

## *Glaciology*

Glaciers are unique features of high mountain and arctic environments that are important in a climatological, ecological, and hydrological sense. Smaller glaciers react passively to the climate, whereas large ice sheets interact with or even control it. On intermediate scales, the linkages between glacier occurrence and climatology are not well understood at the present time. A large mountain glacier system may dominate the local climate; whereas, a large tabular iceberg may carry climatic anomalies with it during its drift. At the other extreme, some modeling results suggest that the deterioration of global climate to full glacial conditions may have trailed the development of ice sheets in North America and Scandinavia. Because glaciers may be extremely sensitive indicators of climatic change, variations in the extent of glaciers have been measured sporadically for many centuries. Except for some reconnaissance scale estimates, the total area of the Earth covered by glaciers, and the hydrological impact of glaciers has been largely undefined. TM observations may help in defining the extent and impact of glaciers in selected regions.

Glacier variations may be monitored by satellites if small scale glacial features are larger than the instantaneous field-of-view of the orbital sensor system. The motion of calving glaciers, surging glaciers, and small ice caps has been successfully measured using Landsat MSS imagery in the past (see Figure III-15). However, most glacier variations are so slow that annual changes in glacier position cannot be seen on MSS imagery. Similarly, glacier motion can, in some instances, be measured but the motion must be rapid in order to exceed the inherent positioning error of about 100 meters for the MSS sensor on Landsats 1-3. However, with the higher resolution of the TM and smaller positioning error of Landsats 4 and 5, it may be possible to measure small motions of glaciers for the first time.

Periodic glacier surges are an important problem and in some areas constitute an economic danger. Surging glaciers can be identified and monitored using MSS imagery. It has been suggested that there are three classes of glaciers: those that never surge, those that surge periodically, and those that surge continuously at variable rates of movement depending on the available ice flux and the degree of supercavitation. A variety of theories have been advanced concerning the causes and dynamics of glacial surges. The TM with its seven bands in the visible, near infrared and thermal infrared and with its spatial resolution of 30 m should provide more information regarding surface configuration, ice flow velocities, and ice temperatures than was heretofore possible from a remote sensing platform and thereby, contribute to improved understanding of the dynamics of surging glaciers.

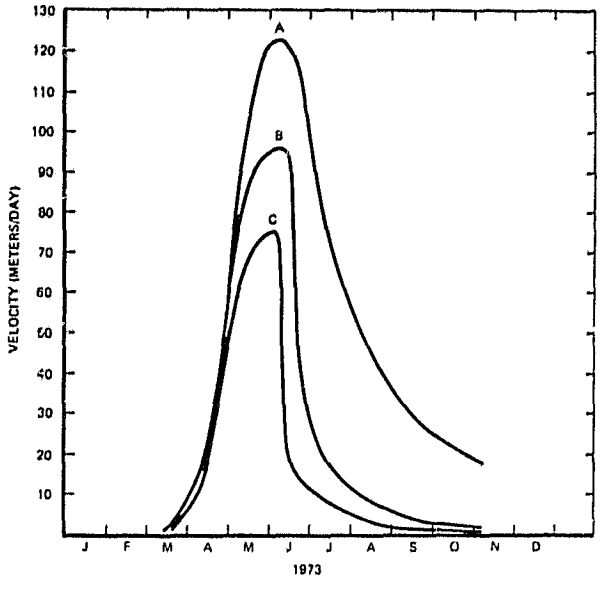


*Figure III-15*

*This graph displays estimates of downslope surface velocity that were inferred from Landsat Multispectral Scanner imagery of the Tweedsmuir Glacier acquired during 1973. The surface velocity of the glacier was estimated along three lateral transects labelled A, B,*



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*and C in this figure (see Miller, 1973 for details). Note the sharp surge in the surface velocity of this glacier that occurred during the spring of 1973. The improved spatial resolution of the TM should enable hydrologists to estimate the surface motions of glaciers with improved precision in the future.*

Snowlines on glaciers have been found to be relatively easy to identify in MSS imagery. It may be possible to monitor changes in the mass of individual glaciers in the future by exploiting the improved spatial resolution of the TM. The mass balance of a glacier is determined by rates of net snow accumulation or ablation, and it is controlled by precipitation, wind, and radiation. TM band 5 would play a critical role in such mass balance studies because of the prevalence of clouds at higher latitudes during both the summer and winter seasons. The synoptic scale of TM imagery and its availability on a near global basis also provides an interesting opportunity to determine the degree of correlation between the mass fluctuations of individual glaciers. Earlier studies of mass fluctuations have generally been limited to individual glaciers within specific regions. TM imagery could, in principle, be used to determine whether the expansion of a selected set of glaciers is compensated in a broader context by the attenuation of glaciers situated in other polar regions. Observations of this nature are essential in attempting to forecast the climatic significance of temporal fluctuations in the mass of individual glaciers or regional glacier fields.

The properties of surface albedo and temperature of a glacier are of primary interest to energy balance studies. As previously mentioned in the discussion on snow, the albedo of frozen water is sensitive to grain size in TM bands 4 and 7, whereas it is sensitive to surface contamination in TM bands 1, 2, and 3. In principle, it should be possible to estimate the extent to which ice albedo is degraded by the deposition of atmosphere aerosols. The thermal channel on the TM (band 6) permits the surface temperature to be measured at a spatial resolution of 120 meters that is superior to all other orbital sensors. Thus, the TM may prove to be useful in developing improved models of energy balance in polar areas on both a regional and global scale.

## *Runoff Estimation and Modeling*

Water plays a critical role in most of the biophysical processes that occur on the Earth's land surface. In many environments, the principal source of water for such processes is surface precipitation. Hydrologists are keenly interested in developing quantitative models that will enable them to predict how surface precipitation is distributed and stored in surface vegetation and soils (see Figure III-16). Such models can be used to assess the viability of selected biophysical processes. They can also be used to study the biogeochemical cycling of water-soluble elements and compounds which can be transported over large distances by running water.

Runoff estimation and modeling is closely linked to studies of catchment morphology and snow condition discussed in earlier sections. TM data could make a significant contribution to modeling the runoff potential of selected regions. TM data can specifically be used to map the occurrence and distribution of different land cover conditions (e.g. bare fields, agricultural fields, grasslands, forested areas, etc.). They provide a means of determining the extent and condition of snow cover in mountainous or high latitude areas. They can also be used to identify small depressions, ponds, and lakes that may serve as temporary storage sites during periods of runoff. All of these various types of information are important considerations in attempting to forecast the response of a particular catchment area to surface precipitation. Knowledge of the extent and nature of cover materials derived from TM observations could presumably be combined with ancillary information regarding surface relief, soil permeability, etc. to develop models that predict the volume, rate, and location of runoff in response to specific types of precipitation events. Expressed in another way, land cover information derived from TM imagery could be used to develop distributed parameter models of the surface boundary conditions that govern water infiltration and storage. Models of this nature could be tested and evaluated with respect to more conventional methods of runoff estimation (see Kirkby, 1973). Quantitative runoff models based upon TM image analysis could, in turn,

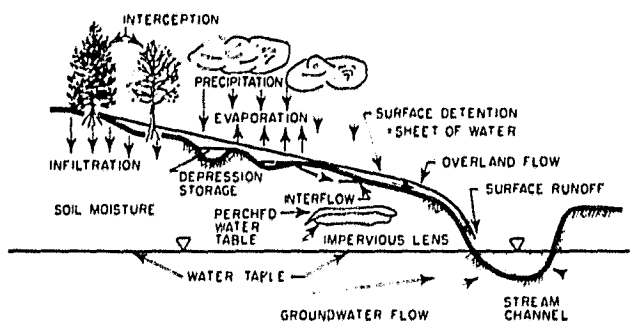


*Figure III-16*

*A simplified representation of the principal factors involved in predicting the runoff of surface precipitation (after Gray, 1970).*

be coupled with models of aerosol deposition, plant respiration, and soil formation to predict the net transport of selected elements and compounds through a particular watershed that occurs in response to different types of precipitation events.

Discussions of the measurement capabilities of the TM have suggested that TM data might lead to significant improvements in modeling the runoff potential of urban areas. The improved spatial resolution of the TM is particularly effective in identifying many small scale impervious features such as roads and buildings that commonly occur in urban landscapes. The TM spatial resolution may also prove effective in characterizing the spatial variability of surface vegetation in urban environments. It may even provide a basis for distinguishing different types of urban neighborhoods (e.g. industrial, residential, business, recreational parks, etc.) which, in turn, have very different runoff characteristics. Improved characterization of urban landcover conditions should not only lead to better quantification of runoff volume from urban watersheds, but it would also improve our ability to forecast water quality variations in neighboring rivers and lakes resulting from non-point sources of pollution.

As discussed in other portions of this document, the measurement capabilities of the TM can be used to monitor temporal variations in the condition and extent of land cover materials. For example, temporal variations in TM bands 3 and 4 can be used to monitor the budding, flushing, and subsequent senescence of leafy vegetation in temperate regions. TM bands 4-7 can be used to monitor water and thermal stresses in vegetation canopies. Day and night time observations of natural thermal emission in TM band 6 can be analyzed in conjunction with meteorological data to monitor variations in the moisture conditions and water holding capacity of surface soils. Finally, TM observations can be used to monitor major changes in cover conditions associated with logging activities, forest fires, crop harvesting, and man's activities. All of these various types of information could potentially be used to re-parameterize existing runoff models in a fundamental fashion, and develop a new generation of models which predict the time-varying runoff potential of selected watersheds as a function of the current condition of the surface materials found within the catchment area. The solubility of selected elements and compounds is particularly sensitive to the conditions of cover materials. Consequently, time-varying models of runoff potential could lead to significant improvements in our ability to forecast the net flux of selected elements and compounds out of individual watersheds during different times of the year.

In areas where soils are exposed directly at the Earth's surface, TM data may be used to discriminate soils on the basis of their textural characteristics which, in turn, may be related to their infiltration characteristics. It may be possible to employ the textural characteristics of soils, as expressed in multispectral TM imagery, to map variations in soil roughness coefficient over extended watersheds. Quantitative descriptions of the spatial variability of soil type, texture, and roughness properties in relation to the regional stream network would presumably contribute to runoff modeling. TM data may also be used to study the nature of runoff phenomena in different portions of an extended watershed (e.g. overland flow, sheet erosion, detentional flow, depressional storage, etc.), and to determine the factors that govern different runoff regimes.

## *Water Quality*

Water quality refers to the nature and concentration of materials suspended or dissolved in water. The suspension or dissolution of the materials results from the processes of the hydrologic cycle, and the nature and concentration of the entrained materials determine the suitability of the water for different applications (e.g. irrigation and human consumption). At least two spaceborne instruments, the Coastal Zone Color Scanner (CZCS) on the Nimbus-7 satellite and the Ocean Color Experiment (OCE) on board the second flight of the Space Shuttle (STS-2), have been used to study the nature and distribution of suspended materials within large bodies of water. The TM, however, offers new capabilities for the remote sensing of water quality. In particular, the TM offers a much finer spatial resolution than either CZCS or the OCE while sensing energy within spectral bands similar to bands of the CZCS and the OCE. TM data can potentially provide new water quality information applicable to a wide range of hydrologic research areas which include the following topics. A review of past efforts using MSS data for water quality studies is provided by Salomonson *et al.*, 1983.

The water quality parameters which seem most amenable to remote measurement are the concentrations of chlorophyll and suspended solids. These parameters can be measured by physically sampling the water, but concentrations can change quickly and acquiring sufficient samples to characterize the distribution of chlorophyll and sediments within a large water body is often impossible. By virtue of its fine spatial resolution, the TM can simultaneously provide a large number of spectral reflectance observations and an instantaneous synoptic view of a water body. Characterization of the spatial variability of

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water quality or turbidity, as derived from the spectral data, could significantly contribute to the understanding of other hydrologic phenomena such as sediment loading, biological production in water, eutrophication, and circulation and mixing.

***Circulation and Mixing.*** Models of water circulation are necessary to forecast the distribution and deposition of suspended materials, and, on a global scale, for studies of meteorology and climatology. Circulatory patterns are expressed by the distributions of suspended sediments, chlorophyll, and surface water temperature. These various parameters can be directly observed with TM data. Static images of circulatory patterns can certainly aid in the development and testing of water circulation models. TM data can also be used to observe the mixing of water from different sources (see Figure III-17). Mixing can dramatically impact water quality. For instance, fresh water flowing into saline bays and estuaries significantly alters the salinity, temperature, quality, and biota of the local aquatic environment. As another example, the use of large volumes of water to cool power plant generators can impact water quality

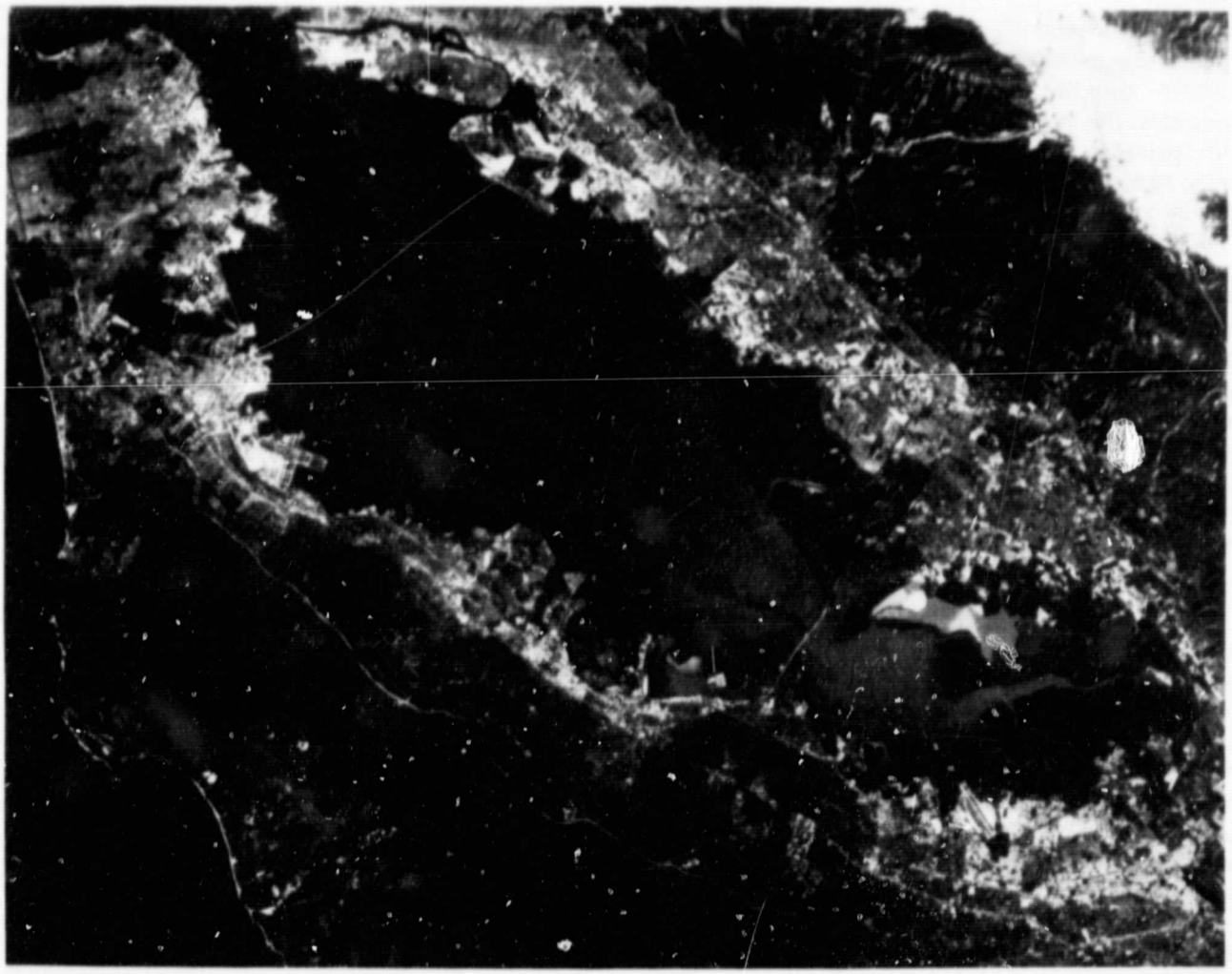

*Figure III-17*

*This is a portion of a TM band 1 image of San Francisco Bay that was originally acquired in December, 1982. The albedo contrast observed in the upper reaches of the bay marks a boundary between two water masses. The brighter waters to the south contain a significant concentration of suspended silt particles, whereas the darker waters to the north contain lower concentrations of suspended particles. TM band 1 is particularly well suited for studies of water quality because of the optical transmission properties of water in the blue portion of the visible spectrum. Fine scale variations that occur along the boundary between the two water masses are caused by local mixing and they are readily observable in TM band 1 imagery.*

when warm water is mixed back into the source of the cooling water. Remote obsservations of sediment, chlorophyll, and temperature distributions could potentially aid in the development of mixing models describing the effects of mixing on water quality.

***Biologic Productivity and Eutrophication.*** In addition to the remote sensing of terrestrial plants, the TM spectral bands are appropriate for remote observations of chlorophyll-containing algae in rivers, lakes, and oceans. Many of the major research issues related to the study of aquatic ecosystems that are potentially amenable to TM analysis are analogous to research issues discussed earlier for land-based ecosystems containing natural and cultivated vegetation. These issues include: biogeochemical cycles of carbon dioxide, nitrogen, phosphorous, and nutrients; the energy budget in aquatic ecosystems; the primary biologic productivity of aquatic ecosystems; and algal growth in response to water quality and ecosystem dynamics.

Algal growth is controlled by a range of water quality factors which include: water chemistry, temperature, nutrient cycles, and the energy budget. Variations in algal growth indicate changes in water quality and observations of changes in algae are thus useful in the study of the hydrological processes which effect water quality. TM data can potentially be used to monitor spatial variations in the nature, density, distribution, and temporal succession of algal species. The temporal succession of algae in fresh water lakes provides a direct indication of lake eutrophication.

***Sediment Loading.*** Ground water runoff is a portion of the hydrological cycle which directly impacts water quality by carrying suspended and dissolved materials into water bodies. TM data can provide information on both the terrestrial features which contribute materials to the runoff and the resultant sediment load in the water. This information can aid in the development and testing of runoff models and is necessary for characterizing non-point sources of water pollution. Characterizing the sources of pollution is the first step in the development of strategies to prevent water quality degradation.

Water circulation plays a major role in cycling nutrients through coastal wetland areas. Nutrients are assimilated within wetlands during the spring and early summer, and they are released in late summer and fall. The cycling of nutrients is closely linked to seasonal variations in water circulation. Studies of nutrient fluxes in wetlands are difficult to conduct due to a lack of sufficient hydrological detail with which to help calculate nutrient budgets. The various capabilities of TM to penetrate shallow water, sense subtle soil moisture differences, discriminate vegetation species and density, and assess water quality variables can all contribute to a better understanding of the hydrologic regime in wetland environments. TM image analysis can specifically contribute to improved delineation of hydrologic features, saltwater intrusions, depth of small water bodies, eutrophication levels, potential sources of thermal loading, and water quality. Studies of seasonal water circulation and the impact of major storms on nutrient fluxes represent important areas for future research.

## *Water Balance Studies*

The concept of water balance over regions of all sizes links together most of the ideas, concepts, or research areas discussed above (see again Figure III-11). To do an effective water balance study the magnitudes of storages in lakes, rivers, streams, soil moisture, atmospheric moisture, ground water, etc., must be evaluated as well as the principal water fluxes such as evapotranspiration, precipitation, and runoff.

TM image analysis could contribute to studies of water balance through the delineation of large scale variations in land cover characteristics, particularly those variations associated with climatic change or the activities of man. For example, studies quantifying the extent of rice planting in Southeast Asia, or the reduction of forests in the Amazon region may lead to better estimates of the water balance over those large areas through better estimation of evapotranspiration and runoff. Studies depicting the spatial patterns of the water budget over relatively large areas ($10^4 - 10^5$ km$^2$) would make a very significant contribution to our understanding of the global hydrologic cycle (see Miller, 1977).

## REFERENCES


Dooge, J. C. I., 1982: On the study of water. *Hydrological Sciences Journal, 28*, 23-48.

Eagleson, P. S., 1970: *Dynamic Hydrology*, McGraw-Hill Publishing Company, New York.

Gray, D. M., 1970: *Handbook on the Principles of Hydrology*, Water Information Center, Inc., Huntington, NY.

Gregory, K. J. and D. E. Walling, 1973: *Drainage Basin Form and Process*, John Wiley and Sons, New York, NY. 456 pp.

Horton, R. E., 1931: The field, scope and status of the sciences of hydrology. *Trans. Amer. Geophys. Union*, 189-202.

Kirkby, M. J. (Editor), 1978: *Hillslope Hydrology*, John Wiley and Sons, New York, NY. 389 pp.

Meier, M., 1982: Snow and ice in a changing world. *Hydrological Sciences Journal, 28*, 1-22.

Miller, D. H., 1977: *Water at the Surface of the Earth*. Academic Press, New York, NY. 557 pp.

Miller, J. M., 1973: Environmental surveys in Alaska based upon ERTS data. Proceedings of the Third Earth Resources Technology Satellite Symposium, Volume II, Summary of Results, NASA Special Publication 356, p. 12-40.

Polar Research Board, 1983: Snow and Ice Research: An Assessment. *National Academy Press, Washington, DC.* [Copies available from Polar Research Board, 2101 Constitution Avenue, NW, Washington, DC. 20418]

Salomonson, V. V., T. Jackson, J. R. Lucass, G. K. Moore, A. Rango, T. Schmugge and D. Schulz, 1983: Water Resources Assessment. Chapter 29 of the *Manual of Remote Sensing* (R. N. Colwell, Editor in Chief; J. E. Estes and G. A. Thorley, Editors of Volume II). American Society of Photogammetry, Falls Church, VA, pp. 1497-1570.