THE LANDSAT-5 SYSTEM: DESCRIPTION AND PRELIMINARY ASSESSEMENT

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INTRODUCTION

Five satellites have served the Landsat program as earth-focused observatories, providing a continuous source of earth resources data since July 1972. Throughout these twelve years, spacecraft, instrument and data processing technologies have evolved; and the resulting new developments have been incorporated into the Landsat Program. Major advances were introduced in all three areas with Landsat-4. The spacecraft is of the modular component design developed to be compatible with the U.S. Space Transportation System. It carries the advanced imaging Thematic Mapper (TM) instrument, and ground-based control and data processing is performed via systems designed for and dedicated to Landsat objectives. In addressing the present Landsat Program, we will refer to it as the Landsat-4/5 System. We will describe the major attributes of the Landsat-4/5 System which incorporates many design features driven by experience with the now-retired Landsats-1 through 3, and we will examine system improvements introduced in the Landsat-5 era resulting from lessons learned in Landsat-4 operations.

LANDSAT HISTORY

Landsats-1, 2 and 3 were launched in 1972, 1975 and 1978, respectively. All of these spacecraft functioned successfully well beyond their design lifetimes of one year. Landsat-1 operations terminated in 1978 and Landsat-2 and 3 operations terminated in 1983. Over 1,200,000 Multispectral Scanner (MSS) scenes and 270,000 Return Beam Videcon (RBV) scenes were acquired by the United States and over 90 percent archived for analyses and application. Approximately 2.5 times the number of scenes acquired by the United States were acquired by the several ground receiving and processing stations operated by other countries. This sizable collection of data from the Landsat 1-3 series thus made a very significant impact in providing inventories and improved understanding of the characteristics of the land cover of the earth and associated resources. Evidences of the use of Landsat data products appear in numerous scientific and technical journal articles, magazines, handbooks and textbooks.

The second generation of Landsat operations began on July 16, 1982 with the successful launch of Landsat-4 from Vandenburg Air Force Base in California. Landsat-4 continued the type of observational capability provided by the MSS on Landsats -1 through 3 and provided an improved observational capability in the form of TM.

Since launch, the majority of systems in the flight segment (command and control, data processing, etc.) have performed very well. The systems on the spacecraft including the MSS and supporting ground systems were turned over to the National Oceanic and Atmospheric Administration (NOAA) in January 1983. The Landsat-4 and the pertinent ground processing for the MSS have generally met product requirements requested by the user community up to the present time.

In the case of the new second generation TM, over 6000 scenes were acquired for U.S. processing from Landsat-4 through 1983. 5000 of these scenes were acquired by the Transportable Ground Station (TGS) facility at Goddard Space Flight Center (GSFC), and another 1000 scenes over the United States were acquired for NASA by the Canadian ground station at Prince Albert, Saskatchewan. Another 2000 (approximately) TM scenes from Landsat-4 outside the U.S. have been acquired by Canada and 1200 scenes by the European Space Agency (ESA) station in Fucino, Italy. Of the six thousand scenes acquired over the United States or nearby areas, nearly 300 of the best scenes were fully processed into film and Computer Compatible Tape (CCT) format and archived. Landsat-5 was launched on March 1, 1984. The first MSS scene to be processed and made available to the public was acquired over Long Island, New York on March 4, 1984. The first TM (bands 1-4) scenes processed and made publicly available were acquired on March 6, 1984 over the Corpus Christi, Texas area and the area including Tulsa, Oklahoma and regions to the north. Successful acquisitions of data outside the United States were achieved over Europe and South America. TM scenes of all seven bands have also been acquired. Analyses of these scenes indicate that the data are very good. Landsat-5 obtained an orbit aligned with the World Reference System (WRS) in April 1984.

THE LANDSAT-4/5 SYSTEM OVERVIEW

The Landsat-4/5 System is depicted in Figure 1. The Space Segment consists of two Landsats (4 and 5) which communicate with ground control and data capture facilities through the Ground Spaceflight Tracking and Data Network (GSTDN), the Tracking and Data Relay Satellite System (TDRSS) and with foreign operated ground stations located throughout the world. Spacecraft control and instrument operation commands, including those for image data acquisition and transmission, are initiated at the Ground Segment's control center located at GSFC in Greenbelt, Maryland and transmitted to the spacecraft via GSTDN or the TDRSS ground station at White Sands, New Mexico and the on-orbit Tracking and Data Relay Satellite (TDRS)-East during periods when TDRSS service

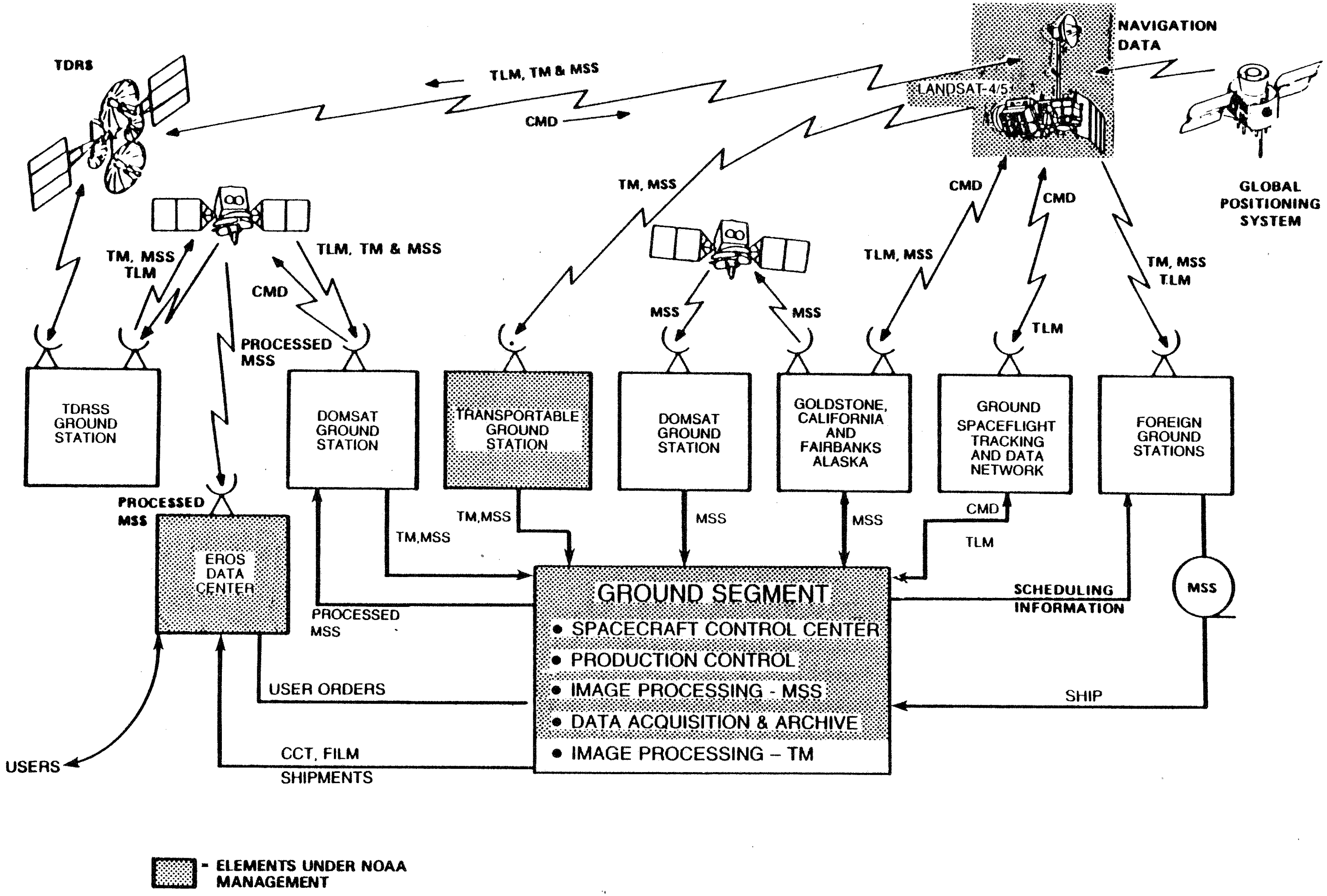


FIGURE 1. LANDSAT-4/5 SYSTEM OVERVIEW

is available to Landsat. Throughout the TDRSS development schedule (which includes launch of two more satellites to complete the TDRSS space complement) GSTDN will continue to provide alternate command and telemetry communications services.

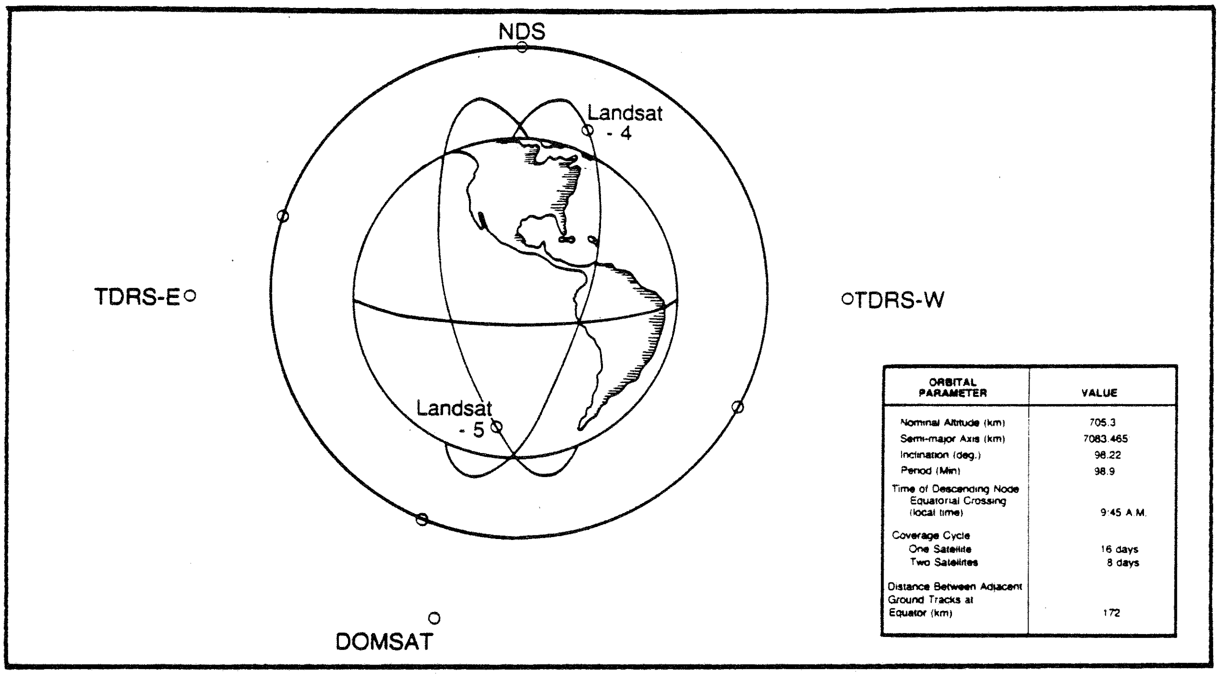
Image data acquired for U.S. processing is transmitted to the Ground Segment's image processing system at GSFC via the TDRSS using a DOMSAT link from White Sands (or alternately, for MSS, via ground stations in California and Alaska). These data can also be downlinked directly to the TGS at GSFC or to ground stations located in selected countries where data are recorded and shipped to the U.S.

The Landsat Ground Segment encompasses those systems which control and schedule the spacecraft and instruments and which process the image data. User orders for image acquisition and image products are provided to the Ground Segment by the NOAA-Operated Data Distribution Center (DDC) at the EROS Data Center (EDC) in Sioux Falls, South Dakota, and by the NASA Landsat Science Office for research and development purposes. Raw image data received and recorded at the Ground Segment are processed by one of two systems depending on the source imaging instrument, the TM or the MSS. MSS imagery is processed to archive format (images are radiometrically corrected and have geometric correction information appended) and is transmitted to the MSS Archive at the NOAA DDC via DOMSAT. User film and digital products are generated and shipped from Sioux Falls in response to user request. TM imagery is processed to archive format, recorded on High Density Tape (HDT), and archived at the Ground Segment. TM imagery for user products is also processed to photographic film master and CCT media. These film masters and CCTs are shipped to EDC for archiving and reproduction. The differences between these two (MSS and TM) processing systems are described later in this paper.

ELEMENTS OF THE LANDSAT SPACE CONSTELLATION

The orbital positioning of Landsats 4 and 5, and of supporting satellite systems, is illustrated in Figure 2. The two sun-synchronous Landsats at their nominal altitude of 705.3km are phased so that the ground coverage repeatability cycle of 16 days for one satellite is reduced to 8 days when both Landsats are employed.

Approximately midway between the Landsat orbits and geosynchronous orbit altitudes are the Navigational Development Satellites (NDS) which provide data to the Global Positioning System (GPS) experiment on Landsat-4/5 for determination of spacecraft position. The objective of the GPS experiment, which will include up to 18 NDSs in its ultimate configuration, is to determine location of Landsats to more precise accuracies than can be achieved through ground-predicted ephemeris computation. Expected accuracies with a five NDS configuration range from 10 to 150 meters, depending on the number of NDSs in view. Positioning



ORBITAL PARAMETER	VALUE
Nominal Altitude (km)	705.3
Semi-major Axis (km)	7083.465
Inclination (deg.)	98.22
Period (Min)	98.9
Time of Descending Node Equatorial Crossing (local time)	9:45 A.M.
Coverage Cycle	
One Satellite	16 days
Two Satellites	8 days
Distance Between Adjacent Ground Tracks at Equator (km)	172

FIGURE 2. THE SPACE ELEMENTS IN POSITION

accuracy of the 18 satellite GPS configuration is expected to be within 10 meters at all times.

TDRS-East (presently on-orbit) and TDRS-West (scheduled for launch in 1985) are shown in their geosynchronous orbits, located 41 and 171 degrees, respectively, West longitude and within one degree of the equator. In this configuration, at least one TDRS will be within view of each Landsat for the great majority of earth coverage. Also shown in geosynchronous orbit is the DOMSAT which does not communicate with the Landsat spacecraft but relays Landsat data between remotely located Landsat ground processing facilities.

LANDSAT EARTH COVERAGE

The Landsat-4/5 orbit parameters differ most significantly from those for Landsats-1 through 3 in altitude. These orbital differences result in changes in ground coverage patterns. Orbital parameters for Landsats -4 and 5 were selected to achieve a repeat cycle (the period required to cover the entire earth surface one time) of 16 days as opposed to 18 days for Landsat-1/2/3. The geographical location of individual (repeatable) ground tracks are also different for the two types of orbits. World Reference framing system of Path and Row identifiers had to be redefined for Landsat-4/5. One further ground coverage pattern difference relates to time between coverage of adjacent paths. With earlier Landsats the adjacent path to the West would be covered the next day. The Landsat-4/5 orbit is such that, given any path, the satellite will cover the adjacent path to the west seven days later. These swathing pattern and scene framing characteristics are illustrated in Figures 3 and 4.

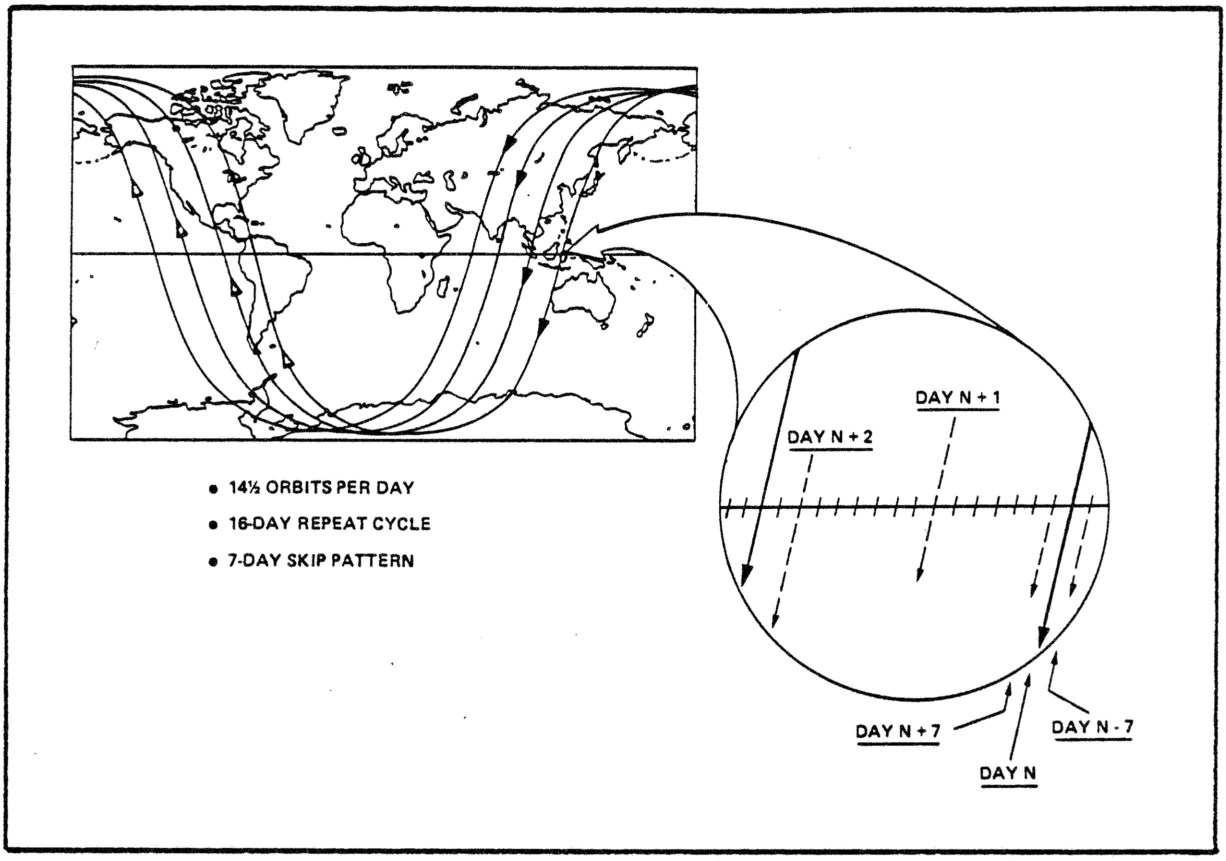


FIGURE 3. LANDSAT-4/5 SWATHING PATTERN

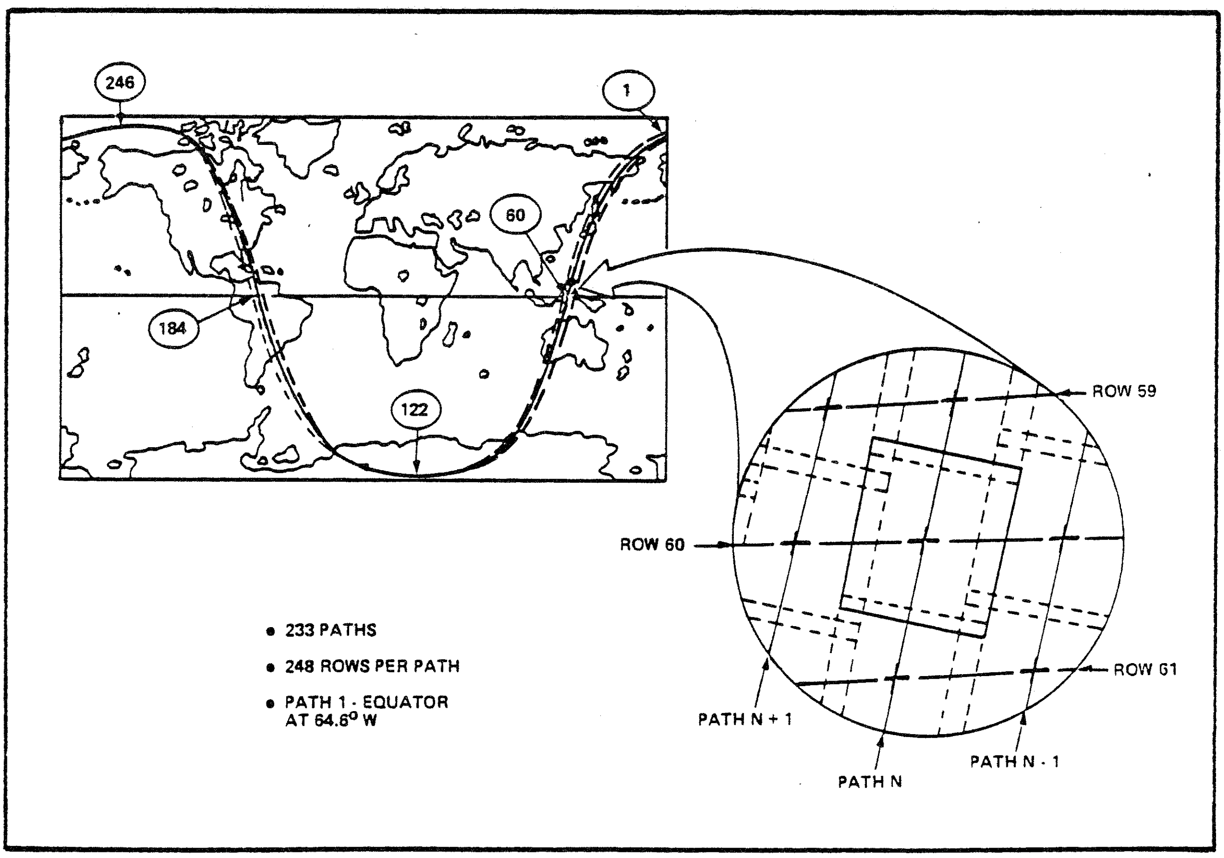


FIGURE 4 WORLD REFERENCE SYSTEM OF FRAMING LANDSAT SCENES

The Landsat-4/5 system was designed to employ TDRSS as the communications link from spacecraft to Ground Segment image processing systems, so no provision was made for on-board image data recording. Earth coverage capability in terms of areas over which imagery can be acquired for processing is thus defined as: 1) areas over which the Landsat is in view of either TDRS-East or West, and 2) areas over which Landsat is in view of a ground receiving station. These coverage areas are outlined in Figure 5.

THE LANDSAT-4/5 SPACECRAFT

The Landsat-4/5 spacecraft is illustrated in Figure 6 in its orbital configuration with antenna and solar panel deployed and earth pointing apertures facing down. It consists of two major sections, the Multimission Modular Spacecraft (MMS) and Landsat-specific Instrument Module. The MMS contains the standard service subsystems for the satellite including attitude control, power, command and data handling, propulsion and on-board computing. The Instrument Module contains the MSS and TM instruments plus the solar array, high gain antenna and communications systems.

The four panel solar array extends out from one side of the spacecraft and is approximately 6 meters long by 2.3 meters high. The Landsats-1 through 3 spacecraft had two solar arrays. However, for Landsat-4/5 the array is on one side only so that it does not obstruct the field of view of the TM cooler. The antenna mast high gain is 4 meters high, with a two axis azimuth over an elevation gimbal drive system mounted at the top. The two access gimbal system permits the antenna to view slightly more than hemispherical coverage allowing communication with either of the two TDRSs. Since there are positions in orbit where the antenna has to look directly over the outer edge of the solar array, the mast has to be sufficiently long to see over that edge. A mast of this length, however, has to fold to fit into the Delta launch vehicle shroud. One of the design challenges in building the satellite was to make a folding mast rigid enough so that it would not vibrate in orbit.

Characteristics of major MMS systems are summarized in Table 1. Table 2 summarizes the Instrument Module component characteristics.

THE IMAGING INSTRUMENTS

The MSS and TM are both scanning imagers, responding in regions of the visible and near infrared (IR) spectrum. Key characteristics are summarized in Figures 7 and 8. The Landsat-4/5 MSS is the same instrument design flown on earlier Landsats. Necessary modifications to the instrument (e.g., those dictated by the lower Landsat-4/5 orbit) were made following a policy of introducing as few resulting differences in MSS image products as possible, thus insuring data continuity.

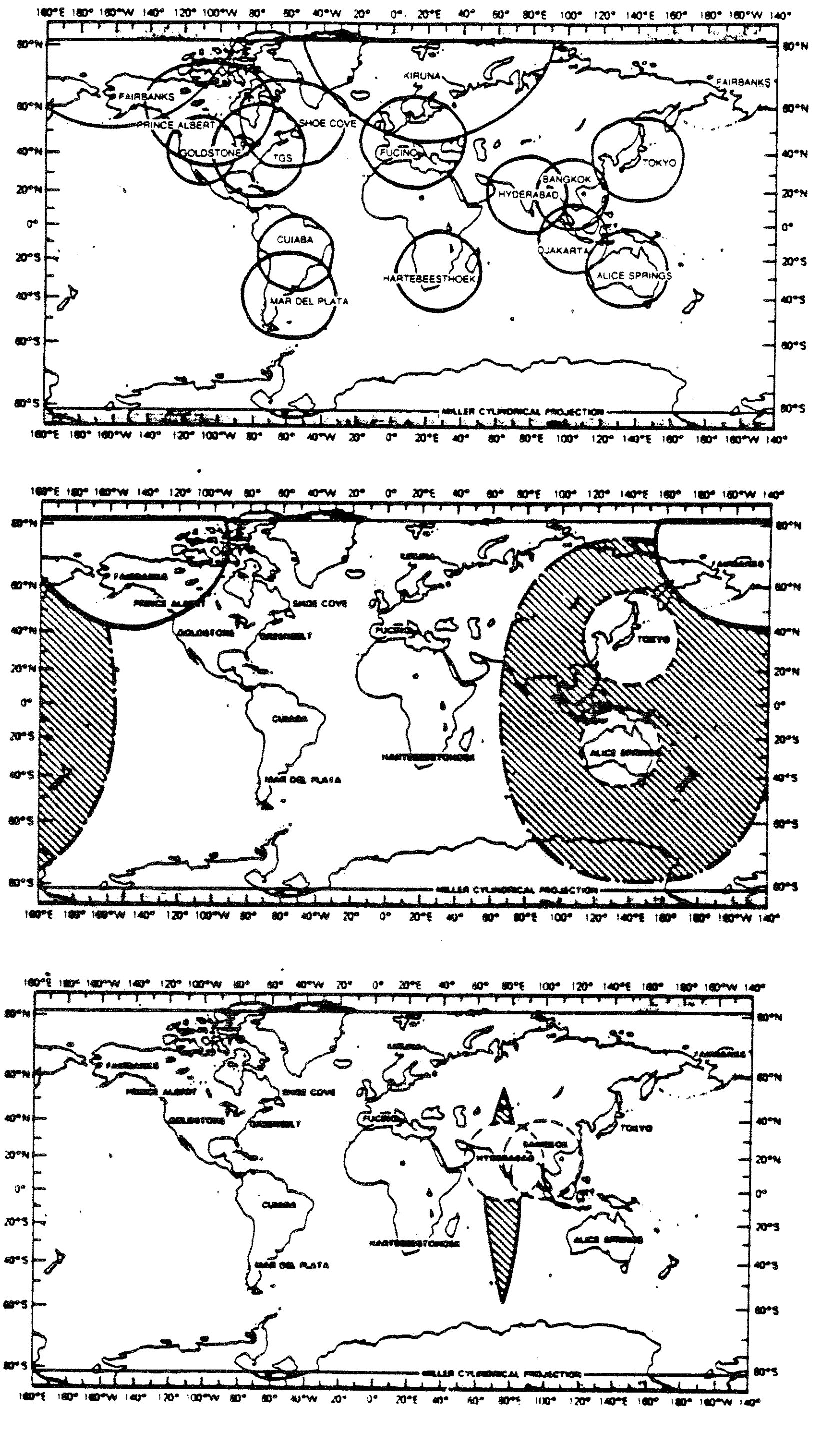


FIGURE 5. LANDSAT EARTH COVERAGE CAPABILITY

a. Active Ground Stations for Direct Data Receipt

b. Area where U.S. Acquisition Coverage is Possible (area not shaded) with TDRS-East and Two Supporting Ground Station Tape Recorders

c. Area where U.S. Acquisition Coverage is Possible with TDRS-East, TDRS-West and Supporting Tape Recorders

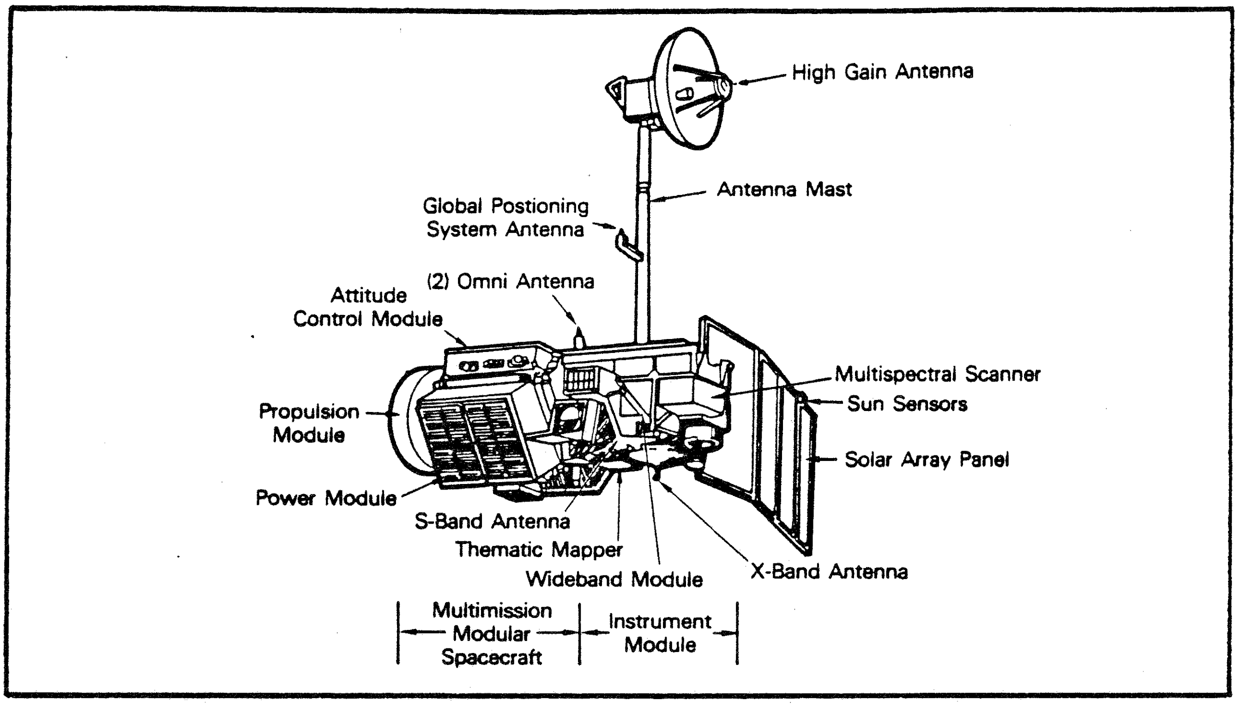


FIGURE 6. THE LANDSAT-4/5 SPACECRAFT

The TM instrument is introduced with Landsat-4 and incorporates many advances. Its detector array includes 16 detectors each for six visible and near IR bands (as opposed to six detectors for each of the four MSS bands) plus four detectors in the thermal range. (See Figure 9 for spectral band comparisons.) It scans actively in both forward and reverse directions and has considerably higher resolution (smaller IFOV) than the MSS. Data content for a given TM raw data image (approximately 185 x 170 km) in terms of pixels alone has increased from 7.6 million, 83 meter, six-bit pixels per image for MSS to 36.0 million 30 meter eight-bit TM pixels. The impact on image processing system design of this increase in data volume and resolution is dramatic. Processing challenges and solutions are discussed in later sections of this paper.

The TM on Landsat-5 differs from the Landsat-4 TM only in certain detector response calibration values, and these differences are minor.

LANDSAT-5 SPACE SEGMENT ENHANCEMENTS

Several enhancements were made to the Landsat-5 Space Segment based on operational experience with Landsat-4. These modifications and the conditions which prompted them are briefly summarized as follows:

- The Landsat-4 high gain antenna boom did not deploy from its stowed position due to a blockage condition which appeared to be elastic such as tape or pliable adhesive. The boom was successfully deployed by continuously driving it against the blockage boundary. For Landsat-5, a release spring for initiating boom deployment was installed. An antenna

TABLE 1
MAJOR MSS SYSTEM CHARACTERISTICS

PROPULSION MODULE
- Orbit Adjust: 5 LB Thrusters (4)
- Attitude Control: 0.2 LB Thrusters (12)
- Capacity: Up to 510 LB Hydrazine

POWER MODULE
- Voltage: 22 to 35 VDC (Unregulated)
- Batteries: Three 50 Amp-Hr

COMMUNICATIONS & DATA HANDLING SYSTEM
- Telemetry: 1,8,32 KBPS
- Onboard Computer: 64 K Words Memory
- Narrow Band Tape Recorders (2)

ATTITUDE CONTROL SYSTEM
- Pointing Accuracy: 0.01 Deg, 1 sigma
- Pointing Stability: 10^{-6} Deg/Sec (Average Rate)
- Includes Star Trackers/Gyros Magnetics/Momentum Wheels

EARTH SENSOR ASSEMBLY
- Post Separation Attitude Control
- Back-Up Attitude Control

SIGNAL CONDITIONING AND CONTROL UNIT
- Heater Control
- Temperature Monitors
- Pyro Arming/Staffing/Firing

TABLE 2
INSTRUMENT MODULE COMPONENT CHARACTERISTICS

INSTRUMENT MODULE STRUCTURE
- Multimission Modular Spacecraft Interface
- Smaller Component Housing

MULTISPECTRAL SCANNER
- Similar to Previous Landsats
- Four Bands
- 83 Meter Instantaneous Field of View (IFOV)
- Dimensions: 88.6cm x 59.4cm x 38.2cm
- Weight: 54.9Kg
- Power: 82 watts

THEMATIC MAPPER
- New Instrument
- Seven Bands
- 30 Meter Resolution
- Dimensions: 201cm x 66cm X 109 cm
- Weight: 244.4 Kgm
- Power: 330 watts

SOLAR ARRAY
- Drive Rate Selectable at 1, 2 and 3 Time Orbital Rate
- Dimensions: 6.0m x 2.3m
- Offset 22 Degrees
- Power: 2200 Watts

ANTENNA MAST
- Provide Unobstructed Antenna View to TDRSS
- Two Sections
- Two Powered Hinges

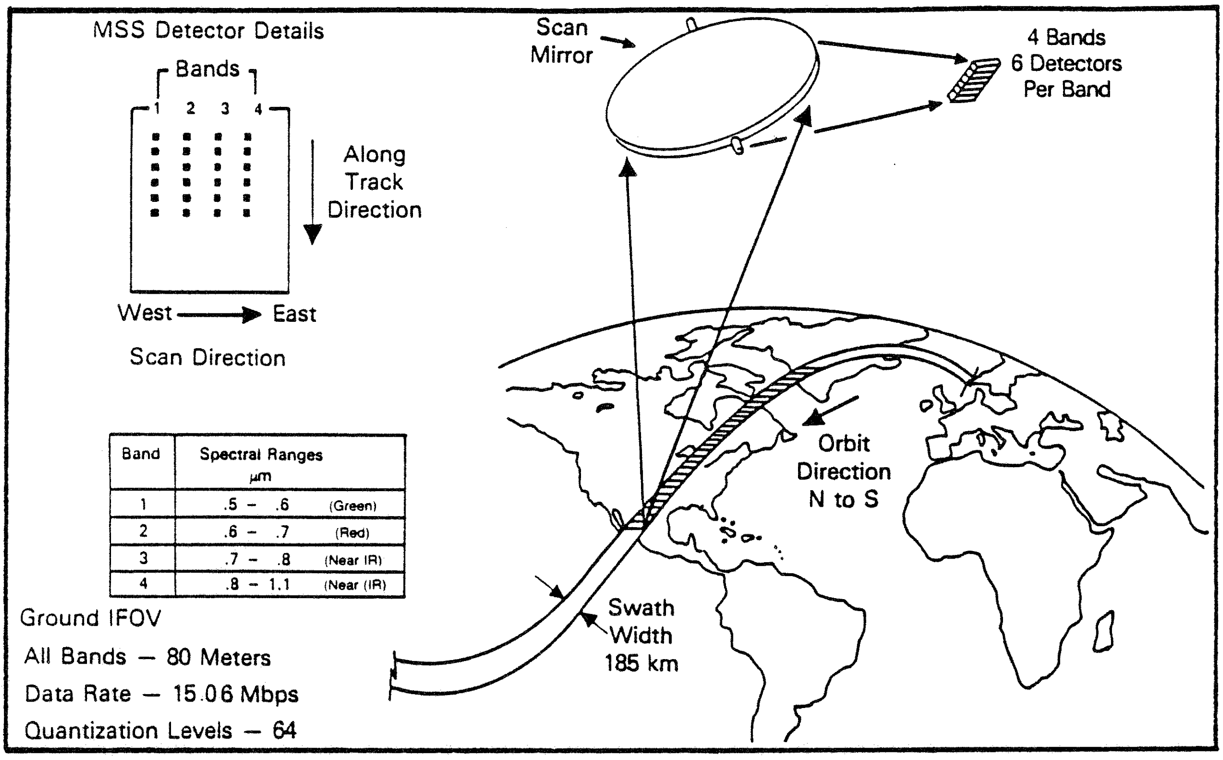
RF COMPARTMENT
- Ku-Band Electronics
- Two-Axis Gimbal

HIGH GAIN ANTENNA
- Primary Link to TDRSS
- Ku-Band - Instrument Data
- S-Band - Telemetry/Command

WIDEBAND MODULE & ANTENNAS
- Direct Downlink
- X-Band - TM/MSS Data
- S-Band - MSS Data

GPS ANTENNA
- Greater Than Hemispherical Coverage
- L-Band Receive-Only

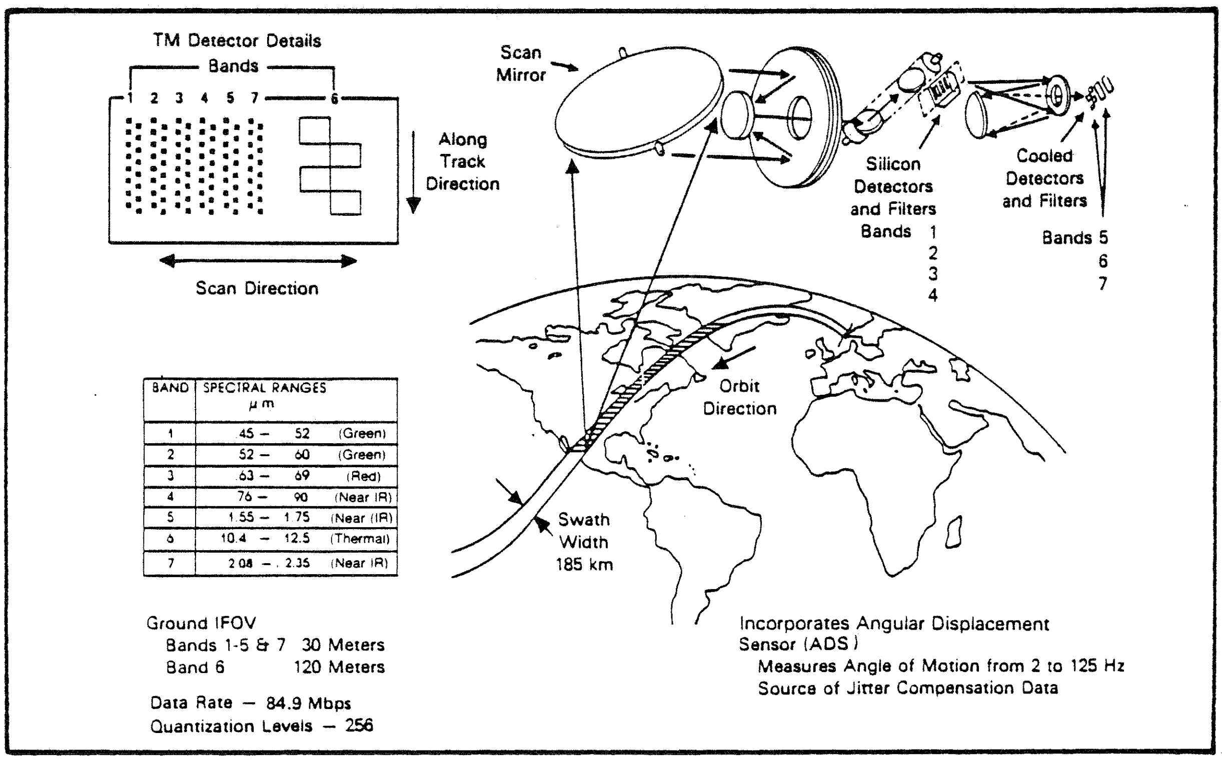
OMNI ANTENNAS
- S-Band
- Telemetry & Command
- Spherical Coverage



Band	Spectral Ranges µm	
1	.5 – .6	(Green)
2	.6 – .7	(Red)
3	.7 – .8	(Near IR)
4	.8 – 1.1	(Near (IR)

Ground IFOV
All Bands — 80 Meters
Data Rate — 15.06 Mbps
Quantization Levels — 64

FIGURE 7. MULTISPECTRAL SCANNER (MSS) SENSOR



BAND	SPECTRAL RANGES µm	
1	.45 – 52	(Green)
2	52 – 60	(Green)
3	.63 – 69	(Red)
4	76 – 90	(Near IR)
5	1.55 – 1.75	(Near (IR)
6	10.4 – 12.5	(Thermal)
7	2.08 – . 2.35	(Near IR)

Ground IFOV
Bands 1-5 & 7 30 Meters
Band 6 120 Meters

Data Rate — 84.9 Mbps
Quantization Levels — 256

Incorporates Angular Displacement Sensor (ADS)
Measures Angle of Motion from 2 to 125 Hz
Source of Jitter Compensation Data

FIGURE 8. THEMATIC MAPPER (TM) INSTRUMENT

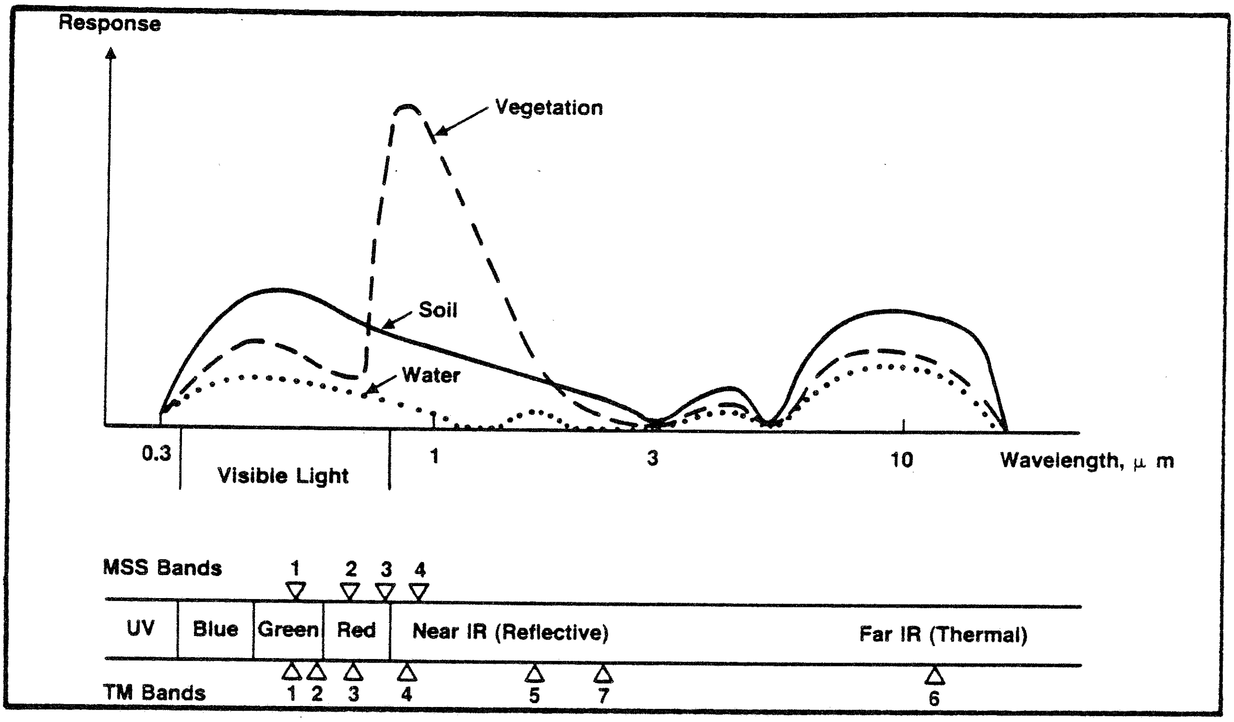


FIGURE 9. SPECTRAL REGION SENSING CAPACITY OF LANDSAT-4/5 MSS AND TIM SENSORS COMPARED TO RESPONSE CURVES FOR VEGETATION, SOIL AND WATER

deployment test was conducted following installation of the thermal blanket, and an inspection for possible obstructions made at the launch site. Boom deployment for Landsat-5 was nominal.

- The Landsat-4 high gain antenna drive generated excessive spacecraft disturbance at 2.8 degrees per second slew rate. Onboard computers for both Landsats-4 and 5 were reprogrammed to operate the antenna at 1.4 degrees per second.

- Star tracker operation was disrupted by bright object interference. This was corrected for Landsats-4 and 5 by closing the star trackers during moon interference periods and eliminating stars with bright neighborhoods from the star catalog.

- One of the two redundant Central Units (CUs) failed as a result of scintillation of a solid state tantalum capacitor. This scintillation caused the CU to execute spurious commands. It also caused the switching transistors to fail, disabling the CU. The resulting Landsat-5 enhancement replaced tantalum capacitors in these two critical areas with ceramic capacitors.

- The Landsat-4 wideband communication module X-band system failed due to cracks which developed in the frequency source power amplifier substrates over a period of 1500 to 3500 hours of operation. For Landsat-4, the failure is not recoverable. For Landsat-5, the frequency source amplifiers in the X-Band and K-Band systems were redesigned to include lower drive level into the second stage amplifier and modified mounting for the transistor substrate to relieve excessive stress.

- The Landsat-4 solar array is in a degrading failure condition as flat conductor cables open due to high stresses induced by the cable to connector solithane potting. Conductors have opened in two of the four cables which independently connect power from the four solar array panels to the spacecraft regulator unit. Landsat-4 is being operated in a manner which slows the degradation by minimizing thermal stress and power demand. For Landsat-5, power cables were redesigned to include conventional round stranded wire in a woven flat cable configuration, crimp termination at connector, stress relief clamps at connectors and added stress relief loops near connector termination.

- Additional enhancements were made to the Landsat-5 Space Segment to improve capability or quality. These include the addition of on-board computer software to support telemetry monitors for quick assessment of spacecraft functions, the addition of floating point capability in the attitude update filter to ensure long-term filter convergence and additional filtering of MSS detector outputs to reduce coherent noise.

LANDSAT-5 SPACE SEGMENT PERFORMANCE

The Landsat-5 launch and activation sequence was executed without problem. All subsystems are performing properly. Performance levels for subsystems of interest can be characterized based on Landsat-4 experience as follows:

- The Precision Attitude Control System has performed well within its design specificaton of .03 degrees, 3 sigma. The system routinely maintains earth pointing attitude control of less than .015 degrees, 3 sigma and attitude knowledge of less than 10 arc seconds. Attitude pointing transients of .05 degrees have been observed to occur due to Solar Array thermal shock which is experienced for a period of one minute at sun rise. Since this occurs only at the North Pole it does not pose any problem to image processing. A second attitude pointing transient of .05 degrees occurs when the High Gain Antenna drive is started up. This low frequency (.3Hz) disturbance settles out after 5 minutes. The High Gain Antenna is currently being managed to ensure that spacecraft pointing is within specification during imaging periods. In addition, the onboard antenna start up control law is being revised to reduce the amplitude and duration of the distrubance.

- A 3-axis Angular Displacement Sensor (ADS) is flown on Landsats 4 and 5 to measure spacecraft motion experienced at the foot of the TM instrument, using outputs of gyros to measure distrubances below 2Hz and the ADS to measure disturbances between 2Hz and 125Hz. The following jitter levels have been observed (note that yaw and pitch axis jitter is negligible):

Operating Modes	Roll Axis Jitter (Peak to Peak)
TM only	2 arc second
TM and High Gain Antenna	3 arc second
TM and MSS	3.5 arc second
TM, MSS, and High Gain Antenna	5.5 arc second

  The above data show that ground systems must correct image data for jitter effects in order to achieve subpixel geometric accuracy.

- An experimental GPS package consisting of a receiver/processor assembly, antenna, preamp and stable oscillator was placed on Landsat-4 as the first spaceborne navigation set to use the GPS. A GPS package is also included on Landsat-5. The objective of the experiment to determine the ultimate accuracy with which the GPS can provide real-time onboard estimates of satellite position. Experiment results to date can be summarized as follows.

  During the GPS evaluation period only 4 of the planned 18 NDS satellites were available. As a result, all Landsat revolutions contained periods of up to 40 minutes when no NDSs were in view.

  The memory system in the GPS is sensitive to radiation induced bit flips. Software to detect and correct bit flips when they occur is currently being developed.

  Reference ephemeris comparisons indicate that errors in Landsat position and velocity from GPS are consistently less than 50 meters and 6 centimeters per second during periods of good NDS visibility. When GPS meaurement gaps occur, these orbit errors grow exponentially; but the peak position errors during a Landsat revolution are generally less than 1500 meters.

  In summary, some additional work is necessary to solve for the onboard memory radiation induced bit flips, to optimize the Kalman filter 50 peak orbit errors will be reduced, and to refine the operational software. It follows that upon completion of this work, GPS will become an attractive alternative for supplying onboard ephemeris to future spacecraft systems.

Direct experience with Landsat-5 provides the following performance measures for critical subsystems:

- X-band error rates of less than or equal to 1×10^{-8} have been achieved in both direct access and via TDRSS.

- Solar Array power output has been measured at 1200 Watts. This exceeds the requirement for full spacecraft operation by 200%.

- MSS and TM performance has been nominal. The MSS coherent noise was reduced by 30% as a result of adding filters.

THE LANDSAT-4/5 GROUND SEGMENT

The Landsat-4/5 Ground Segment refers to the facilities and systems which perform satellite scheduling and control, image processing and production control functions. Ground Segment systems are located in Building 28 at GSFC. The major components of the Ground Segment and their functions are outlined in Figure 10. These systems were designed for and are dedicated to the Landsat-4/5 system. While initial system design was based on experience with earlier Landsats, considerable design modifications, especially in image processing, were introduced during development as more was understood of the TM instrument performance.

DATA PROCESSING FOR THE THEMATIC MAPPER: DESIGN CONSIDERATIONS

Processing of data from the TM, when compared with processing MSS data, poses formidable challenges. The Landsat-4/5 MSS is a fourth generation instrument whose on-orbit performance has been well characterized and is well understood. The ground processing of MSS data is also well understood. The Landsat-4/5 MSS Image Processing System (MIPS) is the final evolution of MSS data processing. The MIPS design and configuration take advantage of advances in hardware and computer technology, and improved software management, development, and implementation techniques. Lessons learned regarding process control and data management, and from years of analysis of MSS instrument and Landsat spacecraft performance, resulted in improvements in data correction techniques and algorithms. The result is an efficient, reliable MSS data processing system that consistently produces high quality products in a high throughput, quick turnaround environment. MSS continues to be the primary source of earth resources data for the majority of users in the land remote sensing disciplines.

The TM instrument, however, because of its complexity and unique design, is designated an R&D instrument. However, the performance requirements for radiometric and geometric correction placed upon the data processing system for TM are identical with those placed on the MSS system. It was clear from the beginning that achieving geometric performance accuracies commensurate with MSS, that is ± .5 pixel geodetic and ± .3 pixel temporal registration accuracy, would be the most formidable challenge because of the smaller TM IFOV (30

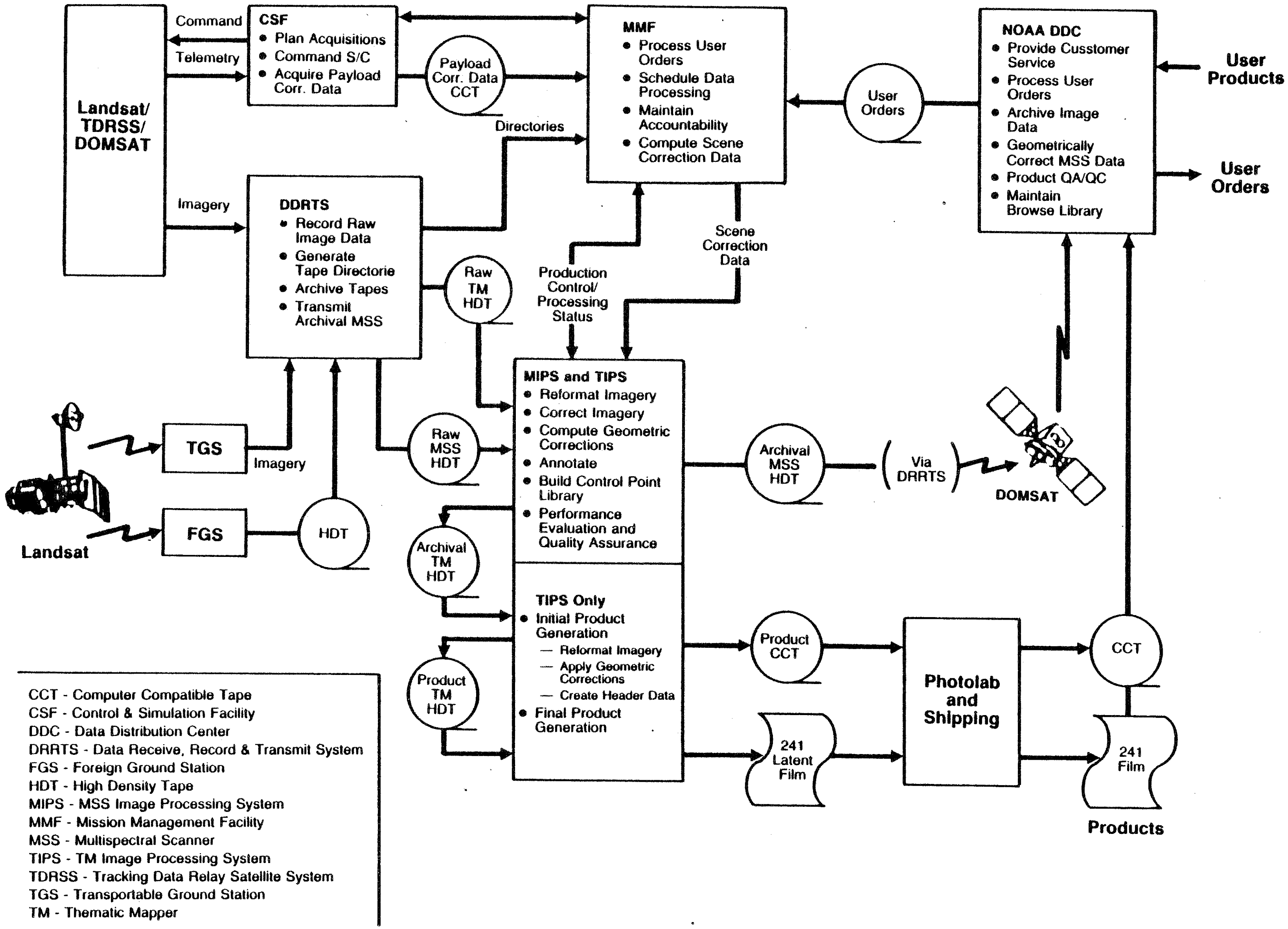


FIGURE 10. MAJOR COMPONENTS OF THE LANDSAT-4/5 GROUND SEGMENT AND THEIR FUNCTIONS

meters square). Sources of geometric errors in the instrument, spacecraft and ground processing system that can be ignored when correcting MSS have to be considered when correcting TM. The design of the TM itself creates a complete new set of error sources not present (or not requiring correction) with MSS. These include:

- Scan mirror nonlinearity
- Scan line corrector nonlinearity
- Scan repeatability
- Scan gap
- Timing and channel delays
- Band to band alignment
- Bi-directional scan alignment.

The problem of geometrically correcting TM data is further compounded by structural disturbances (jitter) in the form of low amplitude motion caused by mechanical resonances produced by the interaction of the TM, MSS and High Gain Antenna. The effect is significant and requires correction on a scan basis. Identification of this effect had a major impact on the program since it required the mounting of a 3-axis Attitude Displacement Sensor (ADS) on the TM instrument, the additional use of the 32 Kbps link to transmit ADS data to the ground and a partial redesign of the telemetry handling and image data processing systems.

The second major performance requirement, that of correcting the radiometry to within $\pm$ 1 quantum level, has not been difficult to meet, even though TM is quantized to 8 bits and MSS to only 6 bits. Methodology for calibrating and correcting TM radiometry is essentially identical to established MSS techniques. TM has all solid state detectors with significantly improved signal-to-noise performance compared to the less stable photomultiplier tubes in three of the MSS bands. Post launch analysis of TM data has, in fact, led the Landsat Project Science Office to characterize the instrument as the most sensitive and best calibrated radiometer ever flown for land remote sensing. Post launch analysis of Landsat-4 and 5 data has revealed radiometric effects in TM not present in MSS that contribute to minor systematic radiometric variability. These effects are being analyzed and are fundamentally understood. Recommendations are being formulated for implementation of calibration and correction methodologies addressing this variability.

Clearly, the design approach for the TM Image Processing System (TIPS) was strongly influenced by the stringent geometric and, to a lesser degree, radiometric performance requirements. There were, however, other principal contributors that are briefly summarized below. Collectively they defined the need for new processes, special purpose hardware, new correction techniques, flexibility, and new processing control and data management techniques. Funding and schedule constraints demanded use of available technology.

Even though the TM is an R&D instrument, the TIPS was not conceived as an R&D system (although the program includes an R&D period). From its inception the technical approach to the design and implementation of the TIPS was dominated by the end requirement for a high volume, quick turnaround, production processor for TM image products. The primary technical contributors to the design of the TIPS were:

- The stringent geometric and radiometric performance requirements, already discussed.

- The throughput, or volume requirements. The final system is required to have a daily production capacity of 100 archival scenes, 50 241mm film products and 10 digital products on CCT. Meeting this requirement is especially challenging due to the sheer volume of data in a TM scene, an increase of almost 9 to 1 over MSS, and the TM data rate of 84.903 mbps versus 15.06 mbps for MSS. This in itself all but precludes the MIPS approach of disc buffering the image data and drives the design to a "pipeline" process. It also emphasizes the need for special purpose hardware to synchronize, demultiplex, geometrically correct and interface the video data.

- The corresponding complexity of new special purpose hardware, dictated by the complex raw video data format and data rate and volume considerations. The inherent unreliability of such hardware requires redundancy. It also dictates the need to produce an archival product in an intermediate format. The archival product format also allows the desirable capability of offering various product options such as different map projections and uncorrected digital product without reverting to reprocessing of raw video data.

- The TIPS requirement to produce all film and digital products. Imagery ordered by users has to be processed to product format on reproducible media for use by the NOAA DDC for generation and distribution of data products to the user community.

The Landsat-4/5 data processing system was originally conceived to be a combined MSS/TM processor. However as the complexities and uncertainties of the TM increased and development schedules diverged , this approach became impractical. MIPS would clearly be an operational system. TIPS, in its early stages, would be an experimental R&D system that would initially be used in characterizing the TM instrument performance as well as providing benchmarks for its own processing and performance capabilities. It also became clear that a phased development for MIPS and TIPS was appropriate. Emphasis could be placed on developing and having in place to support Landsat-4 launch a fully operational MIPS. This would facilitate the turnover to NOAA of an operational MSS capability (dictated by Congressional mandate). An interim TM processing system, with a limited one scene per day capability, was developed to provide early access to TM data and remove the initial uncertainties regarding the TM on-orbit performance. This would allow the TIPS development and implementation to proceed based on demonstrated performance rather than "hoped for" or specified performance. This also eliminated the very real problem of resource contention within a single system for MSS operations, TM development, and TM R&D.

DATA PROCESSING FOR THE THEMATIC MAPPER: PROCESS FLOW

Once the decision to separate the MIPS and TIPS was made, the design of TIPS could proceed in earnest. Great success was achieved in adapting the MIPS approach. To minimize development time and take advantage of proven processes and approaches, those that had worked well for MSS and that could be adapted to TIPS were used. Where necessary, new processes or approaches were defined. However, it will be seen later that the basic technical approach and process flows are quite similar. In a simplified form, this can best be illustrated by a comparison of the MIPS with the TIPS. Each system can be viewed as a series of functions or processes. These are summarized in Figure 11 and further described in the text. The image generation process flow for MSS and TM are also illustrated in Figure 11. Input and process control, data base management elements, and processes of the ground system common to both MSS and TM processing are not shown.

Since the MIPS produces no user products, the fundamental output of the MIPS is an uncorrected Archival High Density Tape, HDT_A. As described earlier, the contents of these tapes are transmitted from GSFC to the NOAA DDC at EDC daily via a domestic communications satellite. At the NOAA DDC the data are re-recorded in archival form and all subsequent MSS user products are produced at EDC by the EDC Digital Image Processing System (EDIPS) and product generation subsystems.

The TIPS, on the other hand, ingests raw sensor data on high density tape (HDT_R) and produces not only the archival product HDT_A but all reproducable master products as well (CCT and 241mm film). The CCT and film products are then mailed to the NOAA DDC where they become a TM product master archive. The NOAA DDC is responsible for archiving, final product generation and distribution of MSS and TM products.

The similarities and differences of TIPS and MIPS processing can be seen through comparison of individual functions within their respective process flow. Certain of these functions within TIPS and MIPS are analogous: Payload Correction, Archive Generation, Performance Evaluation and Control Point Library Build.

Payload Correction. These functions are analogous for TM and MSS in that each function ingests spacecraft telemetry (attitude, ephemeris, instrument parameters) and produces scene correction data. The similarity ends, however, when the extent of the processing required to produce TM scene correction data compared to that of MSS is examined. The outputs of the MSS Payload Correction

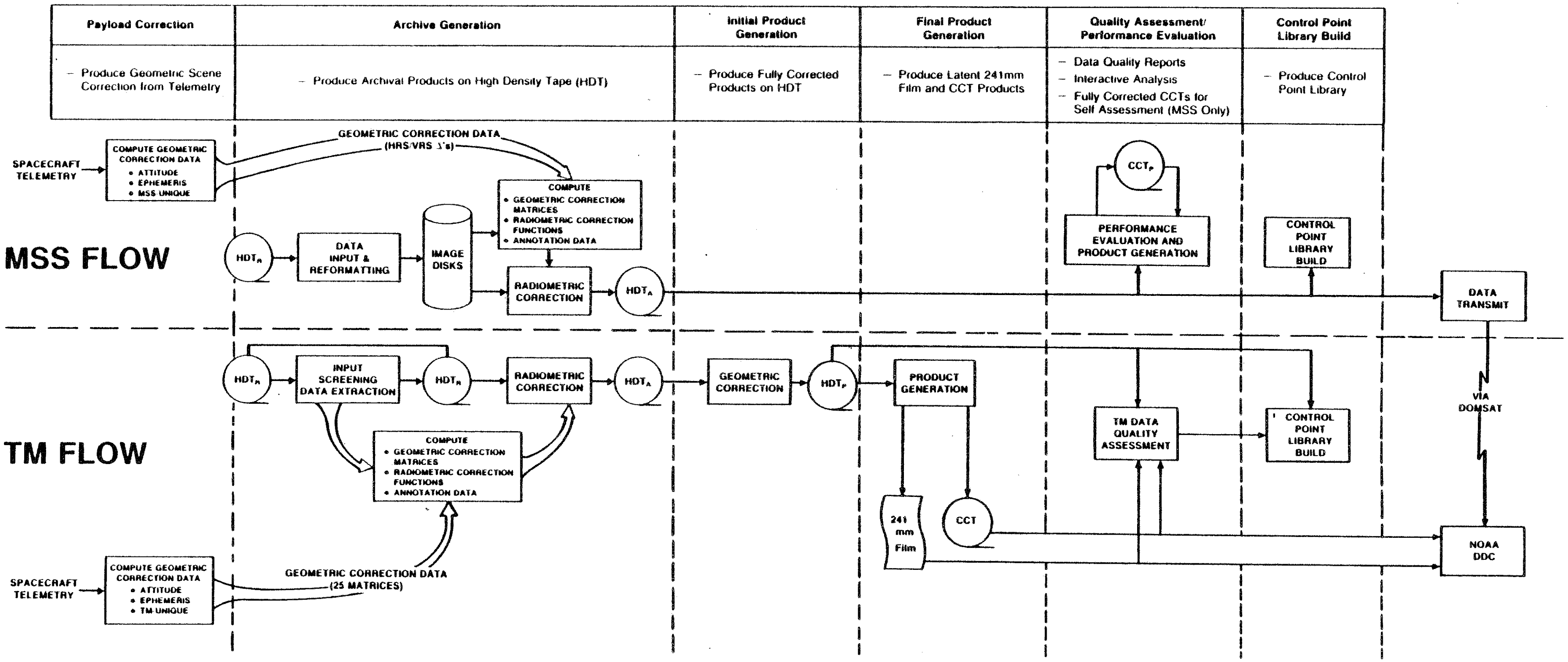


FIGURE 11. LANDSAT-4/5 MSS AND TM PROCESSING FUNCTIONS AND PROCESS FLOWS

Function are scene correction data in the form of perturbations to the nominal horizontal resampling (HRS), vertical resampling (VRS) correction matrices stored in the MIPS. The output of the TM Payload Correction Function is a set of 25 correction matrices for each scene, two of which are high frequency matrices that provide corrections for the effects of jitter and TM scan mirror and scan line corrector nonlinearity on a scan basis. Figure 12 summarizes the content of these matrices.

Archive Generation. These functions are analogous for TM and MSS in that each ingests raw video (HDT_R) and outputs archival data (HDT_A) that have been radiometrically corrected and has the geometric correction data appended. The dissimilarity is in the methodology of the process, the processing rates and the special purpose hardware required for TM.

MSS archive generation is a buffered process. Raw video data (HDT_R), up to a maximum of approximately 35 scenes, are ingested and stored on disc. A data extraction and calculation phase is executed. Upon completion, the MSS data are radiometrically corrected, ancillary (geometric correction) and annotation data are appended and output from disc to the archival product (HDT_A). The ingest and output process for MSS executes at 1/4 MSS real time ($\approx$ 4Mbps). The complete MSS archive generation process takes between 6 and 7 minutes per scene.

TM archive generation is a staged pipeline process. The first stage is an ingest/data extraction phase where only selected portions of the raw scene data are ingested (calibration lamp data, control point neighborhoods, etc.). The second stage is a calculation phase. The third stage is an output phase, but is a pipeline process in that raw TM video are being ingested (HDT_R) and radiometrically corrected archival data, with ancillary and annotation data appended, are being output (HDT_A) simultaneously. A key feature of this process is that the video data never enter the computer bus. The interface device is a high speed array processor that also acts as a scan buffer and provides alternate scan reversal and reformatting for TM data. This allows the pipeline ingest/output process to execute at 1/2 TM real time ($\approx$ 42 Mbps). The complete TM archival generation process takes between 4 and 5 minutes per scene. Another key contributor to the processing speed is the special purpose hardware developed to synchronize, demultiplex, extract, buffer and reformat the high rate TM video.

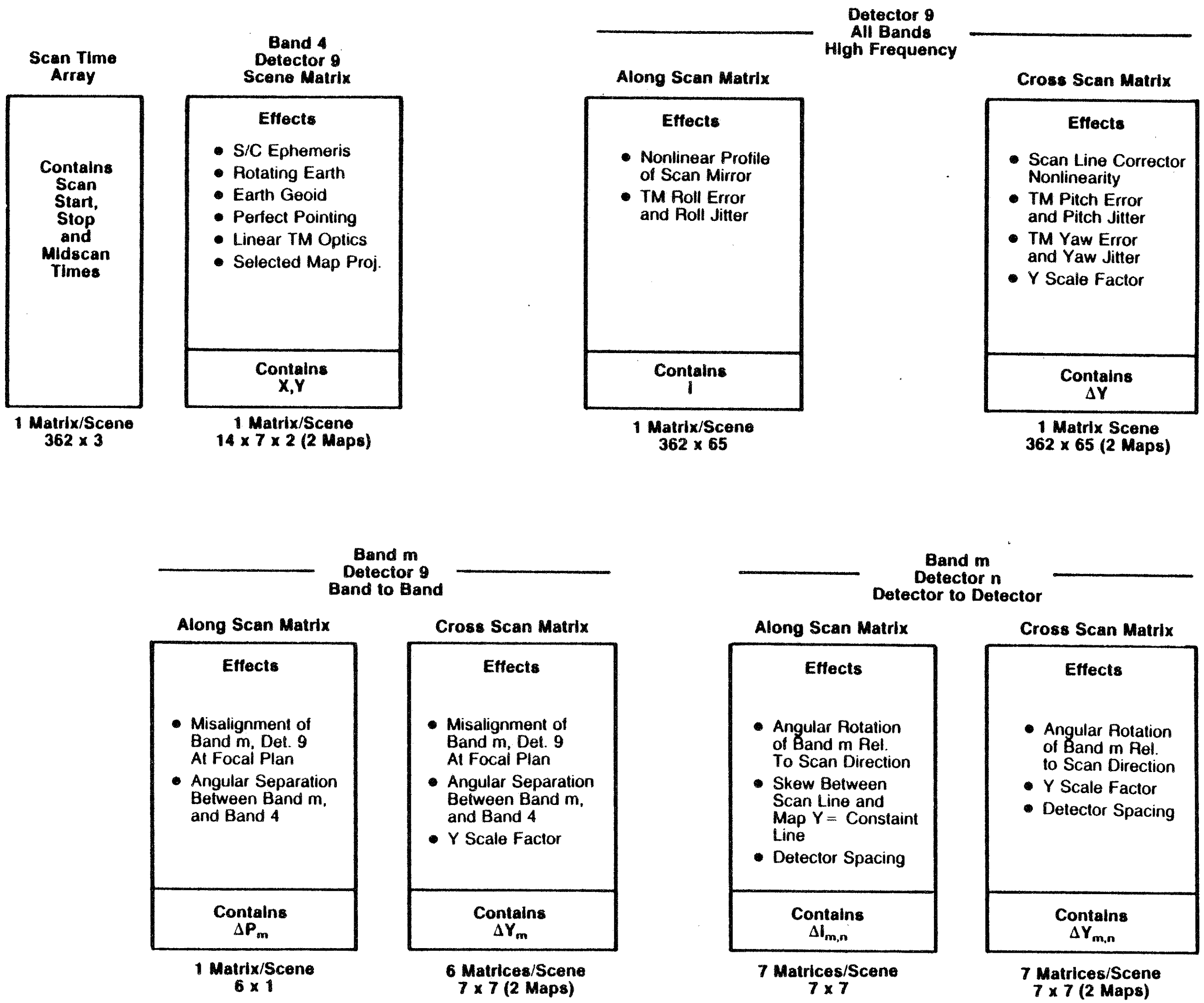


FIGURE 12. SUMMARY OF TM GEOMETRIC CORRECTION MATRICES

Performance Evaluation. Continuing with the functions that are analogous for the TM and MSS are Data Quality Assessment for TM and Performance Evaluation Product Generation for MSS. Each function provides a comprehensive analysis capability in the form of statistical and performance reports, formatted and unformatted dumps, and interactive display and manipulative capability. The TM function is more complex simply because of the additional complexity of the TM instrument and the TM calibration/correction processes. The TM function can also ingest data from HDT and CCT and provide full assessment capability for all products. The reports provide the detailed data necessary to assess the performance of the TIPS correction process and to provide some insights into instrument performance.

Additionally, since the MIPS has no product generation capability, the MSS function can also create a fully corrected CCT digital product for analysis of its own geometric correction performance.

Control Point Library Build. Each system has a complete Control Point Library Build (CPLB) function. They are dissimilar only in that the TM CPLB system was designed to model and build a library of geodetic control points on a swath, rather than a scene basis. The error modeling and blunder checking are correspondingly somewhat more sophisticated in the TM function, also having taken advantage of lessons learned in the MSS system.

The two remaining processes, Initial and Final Product Generation, are unique to TIPS.

Initial Product Generation. Archival data (HDT_A) are ingested and corrected to produce geometrically corrected product (P) imagery on High Density Tape (HDT_P). This process also requires special purpose hardware, for example the high speed array processor (shared with archive generation) in which the data is actually corrected (resampled) and special purpose input/output (I/O) devices. This is also a pipeline process but since scene buffering is required, the data must be stored on computer discs so the process is disc I/O limited and executes at 1/16 real time (≈ 5 Mbps).

Final Product Generation. This function ingests data from either HDT_A or HDT_P and produces high resolution 241mm latent film or digital products on CCT. The latent film is processed at GSFC, assessed for quality (density range, geometric scale, cosmetics, and video quality) and the first generation film master is shipped to the NOAA DDC to serve as the archival film product for subsequent generation of user film products. CCT masters are also shipped to the NOAA DDC to serve as archival masters for user digital products. Products produced by TIPS are determined by user acquisition and product orders placed by NOAA or the Landsat Science Office at GSFC.

TM SYSTEM PERFORMANCE

The following statement of TIPS performance is based upon an analysis of TM data from Landsat-4 processed to final products by the TIPS. Geometric correction accuracy was determined by direct measurement of errors in corrected imagery using control points. The results of the evaluation are summarized in Table 3. The range of 90% geodetic accuracy and temporal registration errors in the cross track and along track directions are shown. The results indicate that the TM data can meet the temporal registration and geodetic specifications. During the Research and Development phase the geometric correction system will be further calibrated and performance improvements are expected.

TABLE 3

SUMMARY OF 90% ERRORS (PIXELS)

CASE	CROSS TRACK RANGE	ALONG TRACK RANGE	SPECIFICATION
Direct Measurement			
Temporal Registration:	.16 - .32	.25 - .32	.3
Geodetic Registration:	.46 - .52	.32 - .56	.5

Radiometric performance was evaluated by computing the range for each scan based on scan line means after variation due to scene content has been filtered out. The specified requirement calls for the scan range to be less than 2 (± 1) quantum levels. Table 4 shows a Radiometric Quality Index (RQI) for 9 areas, averaged over the number of scans indicated. Also indicated (in parenthesis) is the number of scans that exceed the 2 quantum level range, where applicable.

The system is correcting within specification, except occasionally for band 7. The band 7 problem is caused by an extremely noisy detector (detector 7) and solutions are under consideration.

TIPS is currently processing all TM data acquired, up to a maximum of 100 scenes per day (700 scenes per week) to archival product (HDT_A) and producing 12 film products and 2 digital products per day in preparation for ramping up to the specified production levels of 50 film products and 10 digital products per day by January 1985.

TABLE 4

OFF-LINE RADIOMETRIC QUALITY INDEX (RQI) FOR SEVEN BANDS
(Units are quantum levels. Numbers in parenthesis
indicate the number of scans that exceeded the
2 quantum level limit.)

Area	Number of Scans	BANDS 1	2	3	4	5	6	7
1	32	1.33	.60	.79	.38	.90	.23	3.95 (7)
2	26	1.21	.47	.79	.60	.61	.26	1.91 (6)
3	32	1.38	.65	.76	.35	.85	.22	3.60 (32)
4	32	1.30	.42	.64	.58	1.01	.24	.89
5	32	1.23	.45	.77	.54	.87	.30	1.33 (10)
6	32	1.21	.50	.79	.49	.85	.26	.97
7	32	1.21	.43	.70	.33	.69	.24	1.54 (2)
8	32	1.26	.52	.64	.33	.70	.23	.87
9	32	1.37	.65	.81	.37	.74	.31	.92

LESSONS LEARNED

Data processing system designers and implementers are always faced with some hard realities that can be expressed in many ways, but we will generalize as follows:

1. No matter how well you plan, you won't think of everything.
2. Whatever approach you select, it will require at least one major change.
3. You have to use what is available now, not what will be available in a year.

There are many more, of course, but the point we want to make is that the successful implementation of any processing system is likely to be an evolutionary process. This was especially true in the case of the TIPS.

In responding to the challenge of building a "production" data processor of data from an R&D instrument, the performance of which was undefined, an extraordinary amount of attention and planning was given to key processes and the way they would interact. TIPS was designed to be modular to facilitate the modification of major functions or processes with minimal impact to others, as instrument and ground processing performance became better understood and practical limitations defined.

A comprehensive engineering and interactive capability was included to facilitate development as well as data and process analysis. As system needs became clearer during TIPS implementation this capability was redefined and improved.

Because of the extreme complexity of the TIPS special purpose hardware, numerous device diagnostics and built-in test capabilities were provided. With operational experience this capability has been improved and expanded to provide more meaningful process and device diagnostics.

The importance of comprehensive reporting capability was recognized and provided for. As instrument and process performance have become better understood, the system reporting capability has also evolved so that now, detailed statistics on every key aspect of system performance can be routinely provided.

A need to modify some aspects of the TM R&D activity was dictated by operational experience and actual instrument and ground processing performance. The R&D period also pointed out several deficiencies in the TIPS design. As an example, the current design does not allow the implementation of scan level radiometric corrections.

Operational experience has identified deficiencies in process control and data management, particularly in the area of error handling, that are continually being refined to improve the system's operational efficiency.

This last item is important in achieving the final high volume performance requirement. TIPS has achieved the stringent geometric rectification, temporal registration and radiometric correction performance requirements placed upon it. It is consistently and routinely producing extremely high quality film and digital products at specific levels. While TIPS is currently an operational system, it is still evolving toward the final operational product levels. There is every expectation that the operational enhancements to be implemented over the next few months will enable that goal to be successfully achieved.

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