A REVIEW OF LANDSAT-D AND OTHER ADVANCED SYSTEMS RELATIVE TO IMPROVING THE UTILITY OF SPACE DATA IN WATER-RESOURCES MANAGEMENT

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ABSTRACT

Substantial progress has been made in applying remote sensing data from spacecraft to water-resources management and hydrologic problems. Landsat-D and the primary instrument, the thematic mapper, offer substantial potential for providing improved information for a wide range of applications. In particular, significant technological advantages are: (1) the spatial resolution (30 meters in the reflected solar-radiation bands) and the greater spectral coverage (seven bands) and narrower bands relative to previous Landsat instruments and (2) the radiometric resolution (256 versus 64 levels over the sensor dynamic range). Technological advances such as that typified by Landsat-D and planned microwave sensors indicate that significantly more applications to water-resources studies are possible. This growth in the use of remotely sensed data from spacecraft must be closely coupled to advances in data processing and delivery technology and methodology before routine and widespread use of the information observations is possible.

INTRODUCTION

The use of remotely sensed data, particularly from spacecraft, in activities related to water-resources management and studies of the hydrologic cycle is continuing to grow. The launch in the early 1970's of the Landsat series of satellites by the National Aeronautics and Space Administration (NASA) and the flight of the Very High Resolution Radiometer (VHRR) on the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting, operational, environmental satellite series are examples of space missions that have provided useful data to hydrologists and water-resources managers (Salomonson, et.al., 1979).

The observations provided from space have, nevertheless, gained rather slow acceptance because they are still lacking in several respects. For example, they may not have the spatial resolution or spectral resolution necessary for identifying key hydrologic features. The processing of the high volumes of data provided by remote sensors is often too expensive or too difficult to make their use attractive. Finally, the use of remotely sensed data has often been limited by the speed with which it can be ordered from a data archival center and applied by a water-resources manager. Although progress has been made in each of these areas, much remains to be done before the application of satellite data will become "routine" and widespread.

It is believed that a need exists and that there are substantive reasons for making substantive efforts to improve the utility of satellite data. The need arises from the perception that water resources and the associated hydrologic processes must be managed in an increasingly effective manner and must be better understood over larger and larger areas or regions because of expanding populations and increased industrial and agricultural activity, both in the United States and abroad. A key reason for attempting to better apply satellite data is that satellites and the associated sensors are particularly suited for providing repetitive, high spatial density, uniform observations over large areas. It is believed that these observations have and can be increasingly used to most effectively augment or complement conventional observation networks and data-gathering techniques.

The purpose of this paper is to review systems that NASA is now implementing or developing and to briefly consider other systems or approaches that may substantially affect the frequency of use and effective application of satellite data in hydrology and related fields.

LANDSAT-D

A new experimental Earth-resources monitoring system, Landsat-D, is scheduled for launch in the third quarter of 1981. Landsat-D includes several technological advances over the capabilities provided by Landsats 1, 2, and 3. In essence, the Landsat-D system is designed to be a complete, highly automated, data-gathering and processing system that should substantially contribute to more effective remote sensing of Earth resources and to the management of these resources, including water resources, on a local, regional, continental, and global basis.

The four major objectives of the Landsat-D project and program are:

1. To assess the capability of the thematic mapper (TM) to provide improved information for Earth-resources management.

2. To provide a transition for both domestic and foreign users from multispectral scanner subsystem (MSS) data to the higher resolution and data rate of the TM.

3. To provide system-level feasibility demonstrations in concert with user agencies to define the need for, and characteristics of, an operational system.

4. To encourage continued foreign participation in the program.

Flight Segment

The two major segments of the overall Landsat-D system are the flight segment and the ground segment. The flight segment (Figure 1) is being configured for compatibility with the operations of the Shuttle Transportation System (STS). A backup spacecraft, including sensors, is being planned that is called Landsat-D′ (D-prime). It is to be prepared for launch, as needed to ensure continuity of data, by the second quarter of 1982.

The launch vehicle for Landsat-D will be a Delta 3910 rocket. It will carry the Landsat-D payload to an orbital altitude slightly above 700 km. This altitude is compatible with the retrieval and replacement capabilities planned in conjunction with the STS during the Landsat-D project timeframe. The Landsat-D payload, including the spacecraft, instruments, and other equipment, is expected to weigh nearly 1630 kg (3600 lb). The present launch capability of the Delta 3910 is 1723 kg (3800 lb). This leaves a weight margin of approximately 5 percent.

It is expected that the Landsat-D flight segment will be placed into one of two Sun-synchronous orbits. Figure 2 shows the coverage patterns for these orbits. The orbit described in Figure 2a is the closest approximation permitted by orbital mechanics to the "minimum-drift" orbit associated with Landsats 1 through 3. It is essentially an "inventory" type of orbit that, pending minimum cloudcover, can permit large areas to be observed and image mosaics to be prepared with minimum surface-cover change during the observing period. The orbit described in Figure 2b is more what is termed as "skipping or sampling" orbit. It permits samples of observations (scenes) over very large areas to be acquired in a minimum amount of time.

The advantages of the orbit in Figure 2a are most realizable in the lower latitudes in which clear skies tend to persist for longer periods of time (e.g., areas within large semipermanent atmospheric high-pressure regions). The advantages of the orbit described in Figure 2b are most realized in the higher latitudes (above 45 degrees) because of the orbit sidelap coverage. Barring cloudcover, observations would be available at least every 9 to 11 days at latitudes higher than 45 degrees in the Figure 2b orbit. This attribute makes this orbit attractive for monitoring snowcover variations and other dynamic features that occur at the higher latitudes. The decision of which orbit to use should be made by the summer of 1979 so that complete systems and error-budget studies can be completed..

The spacecraft component of the flight segment will be the Multimission Modular Spacecraft (MMS). This spacecraft will perform the basic functions of providing power, altitude control, and the command and data-handling systems. The MMS has improved attitude-control capability over previous systems. The pointing accuracy is specified to be 0.01 degrees (1-sigma value), and the stability is 10^{-6} degrees/second (1-sigma value). To appreciate the advantages afforded by the MMS in this area, one can compare these performance values to the 0.7-degree pointing accuracy and 0.01-degree/second stability values associated with Landsats 1 through 3.

The solar panels shown in Figure 1 will provide ample power. The individual outboard panels are approximately 1.5 by 2.3 meters in dimension. The solar array

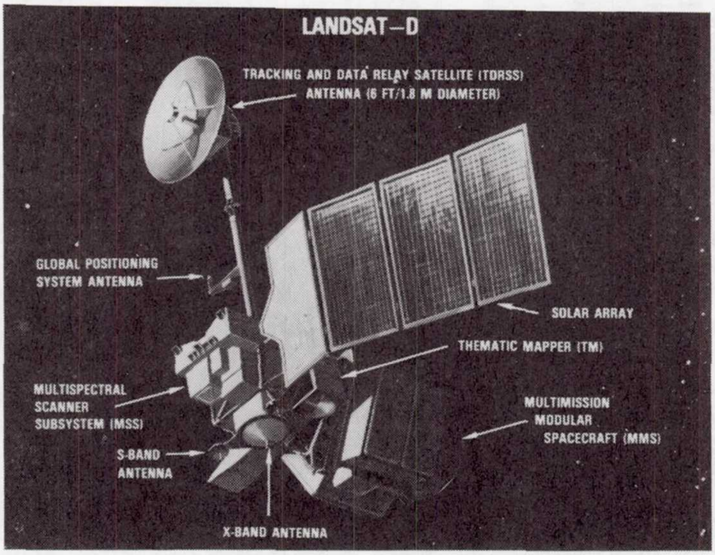


Fig. 1–Landsat-D flight segment

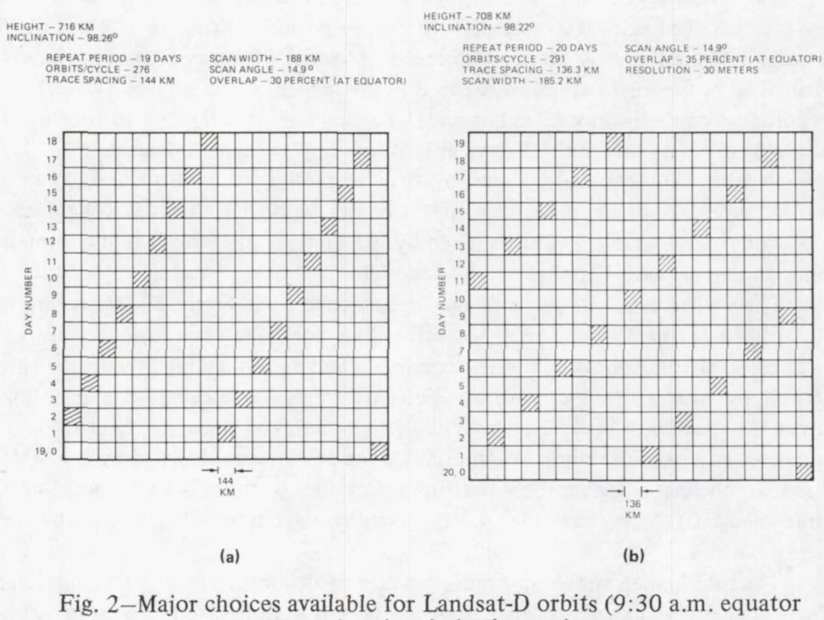


Fig. 2–Major choices available for Landsat-D orbits (9:30 a.m. equator crossing time in both cases)

will be capable of providing 790 watts of average power at the end of the Landsat-D mission, in contrast to the conservative estimate of 760 watts of average power that may be needed to sustain the operations of the various components, including the Earth-observing instruments.

One of the major aspects of the Landsat-D system and the subsequent operations is the compatibility with and use of the Tracking and Data Relay Satellite (TDRS) system. The use of this system will eliminate the need to rely on tape recorders. This is a positive step forward in concept because tape recorders have frequently been one of the satellite subsystems that have failed earliest in past Earth-observing space missions. Certainly, previous Landsat missions have had this problem.

The TDRS antenna shown in Figure 1 will permit command signals, telemetry signals, and sensor observations to be relayed to data-processing centers through one of two geosynchronous satellites in the TDRS system placed at 41° and 171°W. Data from these satellites will be received at White Sands, New Mexico, and relayed to the Landsat-D data-processing center at the Goddard Space Flight Center (GSFC) by a communications satellite. Figure 3 gives an overall view of the communications process for Landsat-D. To handle the high data rates associated with Landsat-D, the STS, and other space missions, the TDRS system uses a Ku-band ($\approx$15 GHz) frequency for communications. Because this frequency is somewhat more affected by atmospheric conditions than previously applied communications links, a relatively cloud-free location (White Sands, New Mexico) was chosen as the point for receiving TDRS information.

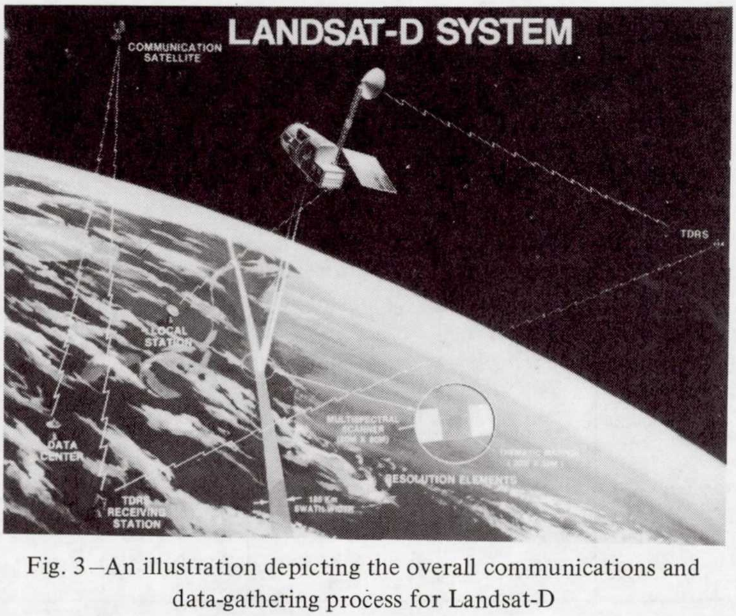


Fig. 3—An illustration depicting the overall communications and data-gathering process for Landsat-D

Landsat-D will also be able to directly communicate with and send data to ground receiving stations. For this purpose, X-band (8.025 to 8.4 GHz) and S-band (2206 to 2300 MHz) frequencies will be used. Although S-band has been used for previous Landsat missions, a high-frequency X-band link is required for handling the TM data stream. As a result, stations that intend to receive TM data must add some capabilities that were not previously required for receiving Landsat MSS data.

Landsat-D will fly a position-location device that receives and processes data from the Global Positioning System (GPS) (Fuchs and Pajerki, 1978). The GPS experiment is expected to provide a very accurate position location, nominally 10 meters for the portion of the orbit when Landsat-D is in view of the GPS satellites that are now available. The complete GPS will eventually employ 24 satellites, using doppler techniques to provide the 10-meter accuracy on a global basis. In the initial stages, Landsat-D will be able to use only six of the 24 satellites. Because these six are more or less in a cluster, they will be in view for only part of the orbit. GPS should provide more accurate data than standard tracking networks and contribute substantially to more autonomous operations of satellites and improved onboard data processing in the future.

The instrument payload (Table 1) consists of the familiar MSS of Landsats 1 and 2; that is, it is the four-band instrument and does not have the fifth band (thermal infrared) that was included on Landsat-3. The TM provides narrower bands similar to those on the MSS and adds 0.45 to 0.52, 1.55 to 1.75, and 2.08 to 2.35 μm bands, plus the thermal band (10.5 to 12.5 μm). Table 1 lists the spectral intervals and radiometric sensitivity of each of the sensors. Table 2 provides the radiometric

Table 1
Landsat-D Earth-Observing Instrumentation
(March 1979)

	THEMATIC MAPPER (TM)		MULTISPECTRAL SCANNER SUBSYSTEM (MSS)	
	MICROMETERS	RADIOMETRIC SENSITIVITY (NEΔP)	MICROMETERS	RADIOMETRIC SENSITIVITY (NEΔP)
SPECTRAL BAND 1	0.45 - 0.52	0.8%	0.5 - 0.6	.57%
SPECTRAL BAND 2	0.52 - 0.60	0.5%	0.6 - 0.7	.57%
SPECTRAL BAND 3	0.63 - 0.69	0.5%	0.7 - 0.8	.65%
SPECTRAL BAND 4	0.76 - 0.90	0.5%	0.8 - 1.1	.70%
SPECTRAL BAND 5	1.55 - 1.75	1.0%		
SPECTRAL BAND 6	2.08 - 2.35	2.4%		
SPECTRAL BAND 7	10.40 - 12.50	0.5K (NEΔT)		
GROUND IFOV		30M (BANDS 1 - 6) 120M (BAND 7)	82M (BANDS 1 - 4)	
DATA RATE		85 MB/S	15 MB/S	
QUANTIZATION LEVELS		256	64	
WEIGHT		227 KG	68 KG	
SIZE		1.1 X 0.7 X 2.0M	0.35 X 0.4 X 0.9 M	
POWER		320 WATTS	50 WATTS	

Table 2
Radiometric Performance Requirements

BAND	SPECTRAL WIDTH (μM)	DYNAMIC RANGE (MW/CM^2 – STER)	LOW LEVEL INPUT (MW/CM^2 – STER)	SNR
1	0.45 – 0.52	0 – 1.00	0.28	32
2	0.52 – 0.60	0 – 2.33	0.24	35
3	0.63 – 0.69	0 – 1.35	0.13	26
4	0.76 – 0.90	0 – 3.00	0.16	32
5	1.55 – 1.75	0 – 0.60	0.08	13
6	2.08 – 2.35 μM	0 – 0.43	0.05	5
7	10.40 – 12.50	260K – 320K	300K	0.5K (NET D)

- ABSOLUTE CHANNEL ACCURACY $<$ 10% OF FULL SCALE
- BAND TO BAND RELATIVE ACCURACY $<$ 2% OF FULL SCALE
- CHANNEL TO CHANNEL ACCURACY $<$ 0.25% RMS OF SPECIFIED NOISE LEVELS

performance requirements for the TM. A more in-depth description of the TM is provided by Blanchard and Weinstein (1979)

In terms of basic design, there is at least one fundamental difference between the two instruments (TM and MSS). The MSS scans and obtains data in one direction only. The TM, however, scans and obtains data in both directions. The TM approach is necessary for reducing the scan rate for providing the dwell time needed to produce improved radiometric accuracy. Figure 4 illustrates the scanning strategy of the TM. Figure 5 sketches the optics configuration for the TM. The potential applicability of the TM for various applications with emphasis on water-resources management and hydrology is discussed in a later section.

Fig. 4–A sketch illustrating how the thematic mapper will scan the Earth

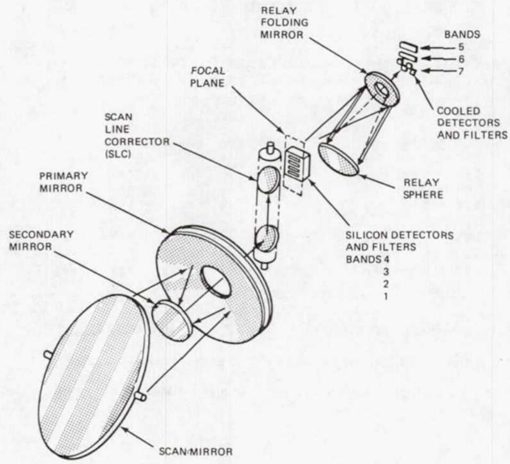


Fig. 5–Thematic mapper optical system

Ground Segment

The ground segment, a major part of the overall Landsat-D system, is being assembled for NASA by the General Electric Company. The ground system faces substantial challenges that are largely a function of the high data rate of the TM and MSS combined (≈100 megabits/second) that must be rapidly processed. The ground segment of the Landsat-D system consists of three major subsystems. The Operations Control Center (OCC) handles all communications with the flight segment, including the commanding and scheduling of the various subsystems of the flight segment and the monitoring of their performance. The Data Management System (DMS) processes all the data from the TM and MSS into final products. The Landsat-D Assessment System (LAS) is a facility in which TM and MSS observations will be analyzed to quantify the advantages for Earth observations and applications afforded by these systems and other related components of Landsat-D. Smith and Webb (1979) have made a more complete review of the Landsat-D ground segment.

The DMS, the major subsystem of the ground segment, faces the major challenge of processing the high data rates noted previously. A related and key performance requirement for the DMS is to produce output products within 48 hours after receipt of TM and MSS data at GSFC. To do this, the DMS is utilizing advanced data-processing technology. For example, key components of the DMS will be two pipeline processors that are in the 10-megainstructions/second class, along with advanced minicomputers. Advanced digital-tape read-and-record devices will also be used in the DMS to receive, store, and record output from the data stream generated by the TM and the MSS. For example, 42-track, 20,000-bits/inch tape recorders will be used to handle the data rate (≈85 megabits/second) and to record multiple scenes from the TM that involve approximately 250×10^6 bytes per scene. Use of this technology in the DMS will continue the primarily digital approach (as opposed to film) to processing and archiving data established with Landsat-3 and will maintain or improve the total processing and output production time even in the face of the increased data rates.

Table 3 summarizes the input and output products of the DMS as of March 1979. The output products will be put into a long-term archive facility that will produce and deliver products on order to the general public. The long-term archive facility is expected to be the EROS Data Center in Sioux Falls, South Dakota, operated by the U.S. Department of Interior.

The LAS and OCC will also make use of the data-processing technology used in the DMS. The OCC will use three advanced minicomputer systems to perform its functions. The LAS will use one advanced minicomputer and one pipeline processor to analyze TM and MSS data. As in the DMS, high-speed, very high-density multitrack tape recorders will record and store data and output results.

As already indicated, the DMS is the key component of the ground segment in that it produces the major output products going to the long-term archival facility and eventually to the user community and the public at large. The four major components of the DMS are: (1) the information management subsystem (IMS), (2) the data receive, record, and transmit subsystem (DRRTS), (3) the image-processing subsystem (IPS), and (4) the product generation subsystem (PGS).

Table 3
Data-Management System

INPUT	OUTPUT (PUBLIC DOMAIN)
• 100 TM SCENES (IMAGE DATA) PER DAY – ALL SCENES PARTIALLY PROCESSED (RADIOMETRICALLY CORRECTED) – PUT ON HIGH DENSITY TAPES (HDT_A) – HDT_A ARCHIVED FOR SIX MONTHS AT GODDARD SPACE FLIGHT CENTER	• 200 MSS SCENES –FULLY CORRECTED (RADIOMETRICALLY AND GEOMETRICALLY) TAPES (HDT_P) – ALL SCENES TRANSMITTED TO EROS DATA CENTER SIOUX FALLS, SOUTH DAKOTA FOR LONG-TERM ARCHIVING
• 200 MSS SCENES (IMAGE DATA) PER DAY – ALL SCENES PARTIALLY PROCESSED (RADIOMETRICALLY CORRECTED) – PUT ON HIGH DENSITY TAPES (HDT_A) – HDT_A ARCHIVED FOR SIX MONTHS AT GODDARD SPACE FLIGHT CENTER	• 50 SELECTED TM SCENES – FULLY CORRECTED (RADIOMETRICALLY AND GEOMETRICALLY) TAPES (HDT_P) – ALL SCENES TRANSMITTED TO EROS DATA CENTER FOR LONG-TERM ARCHIVING – FIRST GENERATION FILM MASTERS (241 MM X 241 MM, ≈ 1:10^6 SCALE) SENT TO EDC – 10 TM SCENES PER DAY CAN BE PRODUCED ON COMPUTER COMPATIBLE TAPES (CCT'S)
• ANCILLARY DATA – SPACECRAFT EPHEMERIS AND ALTITUDE – RADIOMETRIC CORRECTION DATA – GEOMETRIC/GROUND CONTROL POINT DATA	
• PROCESS CONTROL DATA – PROCESSING, CONTROL, AND OPERATIONAL COMMANDS	
• DATA BASE UPDATES – AGENCY AND USER FILES, ETC.	

Data processing in the DMS is performed in these four subsystems through five fundamental steps (Figure 6). In steps 1 and 2, raw sensor data are accumulated from the spacecraft through the communications links already discussed and are processed to produce radiometrically corrected data that are stored on high-density tapes that are designated HDT-A tapes. In these same steps, computations are performed in preparation for making the sensor data compatible with map projections and a ground-control point (reference location) library is developed. In step three, the sensor data are processed and stored on high-density tapes that are designated HDT-P tapes, indicating that they have been fully processed and geometrically and radiometrically corrected. The sensor data are geometrically compatible with map projections such as the universal transverse mercator (UTM) projection, the space oblique mercator (SOM), or the lambert conformal conic (LCC) projections. Here, the data are to be processed to meet goals such as a geodetic accuracy for TM observations of 15 meters (90 percent of the time) and registration of observations from different times to each other of 9 meters (90 percent of the time). In step 4, the output products described in Table 4 will be produced in the PGS. In step 5, the HDT stored data are transmitted to the archival facility at Sioux Falls, South Dakota, by a communications satellite. Images or other products are mailed to this facility.

Advances in Application Using TM Data

Tables 1 and 2 compare the characteristics of the TM and the MSS. In essence, the TM offers advantages over the MSS in terms of spatial resolution, spectral resolution and numbers of spectral bands, and radiometric resolution.

In quantitative terms, the TM resolution element ("pixel" instantaneous field-of-view) covers 0.09 hectares on the ground. For mensuration and classification, several pixels must fall within a field or feature. If one assumes that 25 pixels are necessary for accurate work, then the field size involved is approximately 2.5 hectares. The corresponding figure for the MSS is over 16 hectares. For example, in urban situations in which stormwater management and watershed planning are activities for which satellite data have proved to be useful (Ragan and Jackson, 1975), the TM spatial resolution is roughly equal to the standard lot size (30 by 30 meters or approximately 100 feet by 100 feet). The identification of urban features, therefore, should be markedly facilitated by the use of TM data.

The TM spatial-resolution advantage and the attendant data processing for geodetic accuracy of pixel location should also produce map products from satellite imagery that are satisfactory or applicable at larger map scales than are possible with MSS data. Landsat 1, 2, and 3 MSS data can be used to compile a planimeter map that meets map accuracy standards at scales of 1:500,000 to 1:250,000. For Landsat-D, maps at 1:100,000 scale should be possible.

Figure 7 shows the spectral and radiometric capability of the TM relative to some typical spectral reflectivity curves. The new TM bands will enhance spaceborne remote sensing capability for mapping both surface and subsurface water

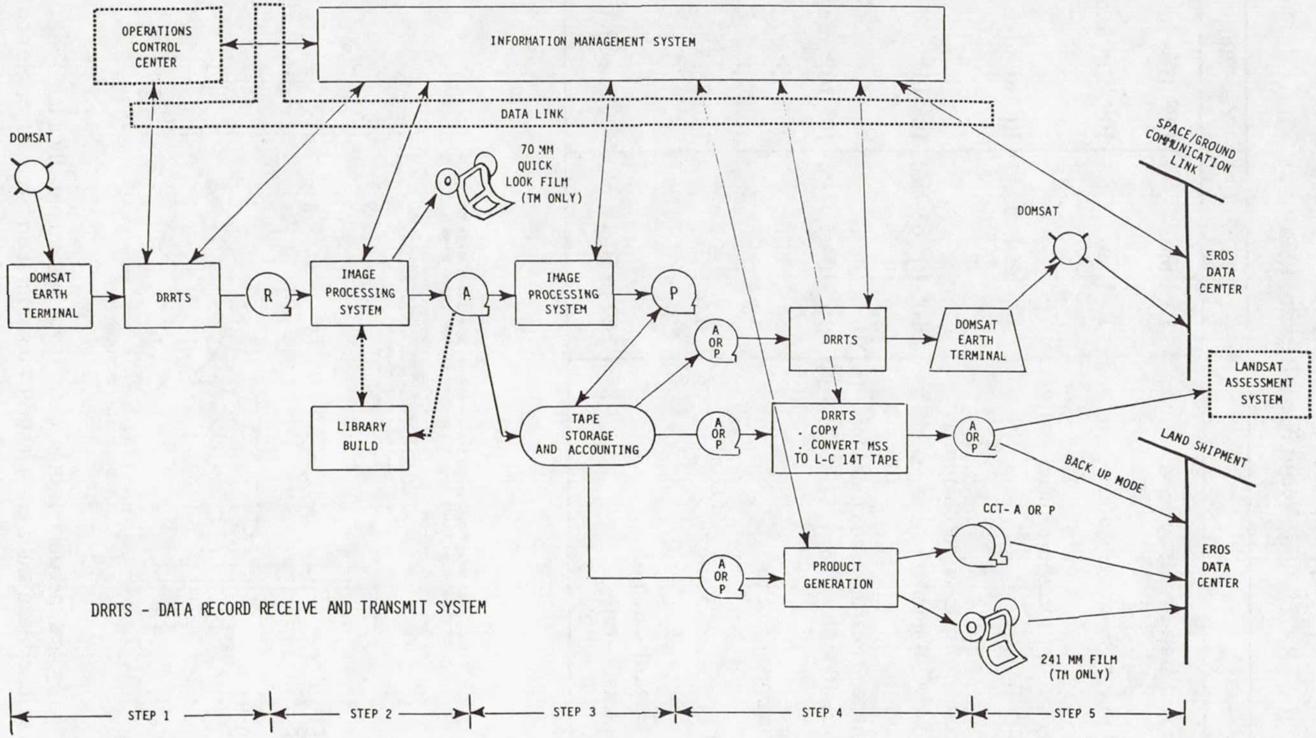


Fig. 6–Data flow within the Landsat-D data-management system

Table 4
Apparent Prognosis for Relevant Technologies
Versus Needs (Hearth, 1976)

	Now	Year 2000
Earth-based mass-storage systems	10^{12} bits	10^{17}-10^{21} bits
Spaceborne mass-storage systems	10^{11} bits	10^{14}-10^{15} bits
Transfer rate for spaceborne mass-storage systems	10^{7} bits/sec	10^{9}-10^{10} bits/sec
Performance of spaceborne computers (Navy AADC Computer)	10^{6}-10^{7} ops/sec	10_{8}-10^{9} ops/sec
Performance of earth-based computers (CDC Star-100, Illiac IV)	10^{8}-10^{9} ops/sec	10^{9}-10^{10} ops/sec
Data compression ratio		
Exact reconstruction	4 to 5:1	7 to 8:1
Reconstruction of thematic map	60 to 60:1	300 to 400:1

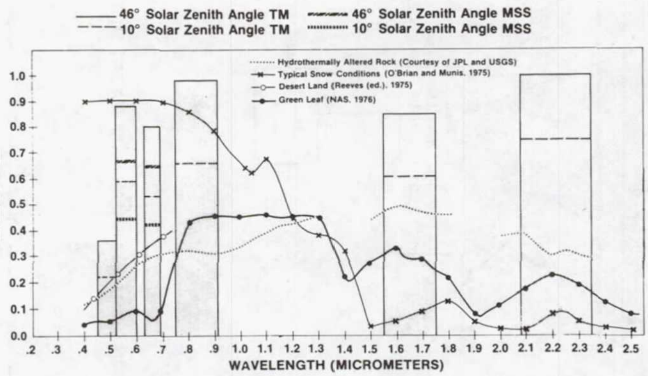


Fig. 7–Typical spectral reflectance curves for hydrothermally altered rock, snow, desert land and a green leaf showing saturation levels for visible and near-infrared bands of the thematic mapper (saturation of bands)

features. TM bands 5 and 6 should be useful in geological studies related to groundwater exploration. TM band 1 should be useful in bathymetry studies. Previous work (Barnes and Bowley, 1977) indicates that TM band 5 will be useful in objectively separating snow from clouds in monitoring regions. In comparison with the radiometric resolution, the TM suite of bands should permit more classes of land cover to be effectively delineated for urban hydrology studies or should be helpful in situations in which detection of moisture stress of crop is the objective, such as for irrigation efficiency studies. Overall, it is projected that the TM spectral capabilities should provide a basic dimensionality of at least 4 in the data compared to the dimensionality of 2 generally experienced in Landsat 1 and 2 MSS data.

Figure 7 also illustrates that the dynamic range of the TM data is larger in some key spectral intervals than that of the MSS. The TM will be less prone to saturate in the 0.63- to 0.69-m and 0.52- to 0.60-m region than the MSS. For example, saturation over clouds and snow, a common occurrence with the MSS, should happen less frequently in TM observations.

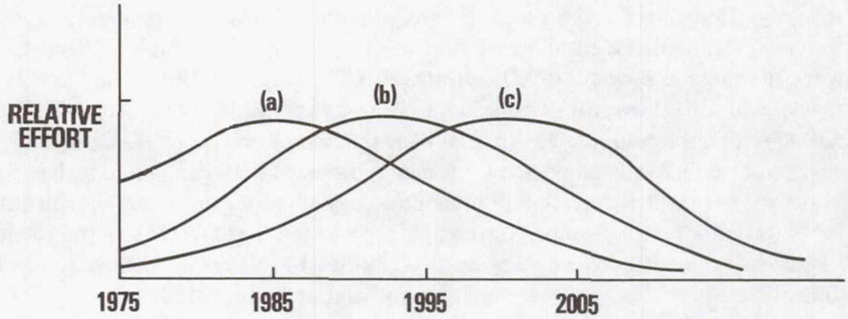
One of the major challenges in the Landsat-D timeframe is the high data rate associated with the TM. This high data rate conflicts with the need for rapid turnaround of data and ease in data processing. The Landsat-D ground segment, particularly the DMS and LAS, will be testing data-processing equipment and procedures to ease the problems associated with the TM data rates that arise from desirable increases in spatial resolution and spectral capabilities. From the viewpoint of water-resources management, the 48-hour turnaround goal is very desirable and needs to be improved whenever possible. The following section addresses some of the studies that are in progress to better handle the increased data rates and data-processing complexity associated with remote sensors and, thereby, to improve the utility of this type of data.

FUTURE THRUSTS

The application of remotely sensed information acquired by spaceborne sensors is growing, and future growth may be expected for reasons indicated in the introduction. This growth, however, will come about and arrive at the point where this type of data are routinely and conventionally applied in water resources, depending on the success achieved in developing sensors that provide information that meets user requirements and the progress made in simplifying and expediting the processing of remotely sensed data and delivering it in optimally usable form to water-resources managers and hydrologists.

Figure 8 shows curves of relative effort versus time that represent the views of the authors as to how progress and timing in the areas noted previously may be achieved on the basis of current NASA planning and modest optimism as to the evolution of technology related to remote sensing and data processing.

The information extraction curve in Figure 8 addresses not only sensor development but also interpretation technique development that must be applied to remotely sensed data. Landsat-D represents technology that extracts new spectral information and spatial resolution by using sensors that respond to reflected solar



a) INFORMATION EXTRACTION
b) DATA PROCESSING/FORMATTING AND DELIVERY
c) ROUTINE APPLICATION IN RESOURCES MANAGEMENT AND SCIENTIFIC RESEARCH

Fig. 8–Technology development and applications development

and emitted thermal infrared radiation. However, work needs to be done on these data to determine how to extract the maximum information in an efficient manner. Information in the reflected and thermal infrared will probably be further exploited in the next few years by using mechanical scanners or, more likely, solid-state technology and the development of pointable sensors that will permit temporal changes in selected areas or situations to be observed at resolutions higher than the thematic mapper while, at the same time, controlling or keeping the data within the 10 megabits/second order of magnitude.

The microwave portion of the electromagnetic spectrum will also be, or should be, exploited further because of the more nearly all-weather capability of these sensors and their greater sensitivity to variations in the moisture contained within the atmosphere (e.g., cloud liquid-water content and precipitation), the snow pack (e.g., moisture equivalent and wetness), and the upper layers of the soil surface or within vegetation (e.g., soil moisture). The possibility of extracting information related to fundamental flux and storage terms in the hydrologic cycle, such as precipitation and soil moisture, makes research and development of microwave systems and interpretation techniques appear to be very attractive, if not imperative, given the increasing need to better manage water resources and understand climatic processes that either are strongly related to or impact hydrologic processes. The factors noted previously indicate that effort and support for information extraction efforts must continue to grow into the mid-1980's and comprise a substantive portion of technology and applications development into the 1990's.

The sensors mentioned previously will not only provide new information in themselves but, in order to extract the most pertinent and useful information, will most likely necessitate the combining of data from different sensors on the same space vehicle and also different vehicles. In addition, high data volumes will be produced by these sensors that will be in the 10^7 to 10^8 bits/second orders of magnitude and the 10^{11} to 10^{12} bits/day range. To make these data volumes at all tractable for application to water-resources management and hydrological studies, considerable emphasis must be placed on developing data processing, formatting, and delivery technologies and methodologies. This is suggested in the second curve of Figure 8. This problem has been likened to "learning to drink water from a fire-hose."

There is considerable hope that the challenges associated with data processing and applications of remotely sensed data will be met. Table 4 shows the expected growth in ground-based and spaceborne computer systems and mass-storage systems (Hearth, 1976). The steps forward suggested in Table 4 appear to be promising in terms of handling the data volumes previously suggested.

Specific efforts in the near term include the Global Positioning System noted earlier. This is a step toward the autonomous operation of spacecraft. This capability, accompanied by improved onboard computers and storage, may possibly lead to the onboard processing of data so as to include not only reformatting and calibration, but also the geographic location of each observation so that minimal processing would be required on the ground at receiving stations before having applicable results.

Studies that are evaluating the various methods and alternatives to expedite and simplify the use and processing of satellite data both in conjuction with and independently of conventional data sources include the NASA end-to-end data systems (NEEDS) study (Sos, 1979) and the Applications Data Service (ADS) (Brown, 1979) concept. These efforts are not only assessing the volumes of data involved and the technologies needed, but also studying and developing strategies and approaches to formatting and assessing data so as to simplify its use and diminish costs involved as much as possible.

It appears certain that an increasing effort to develop the data-processing and delivery techniques alluded to previously will be necessary before routine and continued use of remotely sensed data over a wide spectrum of activities occurs. Figure 8 suggests that the peak in this kind of effort may be projected into the 1990's time frame with routine use occurring by the 21st century. It is clear that this schedule could be different, depending on a host of development and alternatives. However, the main point is that routine use of remotely sensed data will occur pending the joint development of accurate information that is expeditiously delivered to the user community.

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