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Resource and Environmental Surveys from Space with the Thematic Mapper in the 1980's

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Committee on Remote Sensing For Earth Resource Surveys

Commission on Natural Resources

Resource and Environmental Surveys from Space with the Thematic Mapper in the 1980's

A report prepared by the
Committee on Remote Sensing Programs
for Earth Resource Surveys

Commission on Natural Resources

National Research Council

NATIONAL ACADEMY OF SCIENCES
Washington, D.C., 1976

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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NATIONAL RESEARCH COUNCIL
COMMISSION ON NATURAL RESOURCES

2101 Constitution Avenue Washington, D. C. 20418

COMMITTEE ON REMOTE SENSING PROGRAMS
FOR EARTH RESOURCE SURVEYS

September 24, 1976

Dr. Gordon J. F. MacDonald
Chairman, Commission on Natural Resources
National Research Council
Washington, D. C. 20418

Dear Dr. MacDonald:

The Committee on Remote Sensing Programs for Earth Resource Surveys, CORSPERS, has completed a review of the Thematic Mapper, proposed by NASA as the follow-on sensor to the present multispectral scanner (MSS) carried in the LANDSAT 1 and 2 spacecraft.

The Committee has been repeatedly impressed by the significant resource and environmental information that investigators were able to extract from the LANDSAT data. This is in spite of the fact that the MSS and the data handling facilities now in use are not representative of what could be done with current technology. As the Committee concluded in its 1974 study (Remote Sensing for Resource and Environmental Surveys), the present study confirms that the technology used in the LANDSAT program is readily extendable to operational systems that can satisfy major data requirements of many different categories of resource managers and environmental monitors. The Thematic Mapper is such an extension which can make significant contributions in an Earth Resources Satellite operational system.

I am pleased to transmit to the Commission on Natural Resources the Committee's report, "Resource and Environmental Surveys from Space with the Thematic Mapper in the 1980's".

Sincerely,

Arthur G. Anderson
Arthur G. Anderson,
Chairman

COMMITTEE ON REMOTE SENSING PROGRAMS FOR EARTH RESOURCE SURVEYS (CORSPERS)

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Preface

The U.S. Department of Agriculture, National Oceanic and Atmospheric Administration, U.S. Geological Survey, National eronautics and Space Administration, Environmental rrotection Agency, and the Civil Works, U.S. Army Corps of Engineers requested the National Academy of Sciences to review the adequacy of the NASA proposed Thematic Mapper to provide a basic land cover information matrix and the degree to which this sensor system can satisfy the information requirements of all elements of the natural resource applications community. The National Academy of Sciences/National Research Council assigned this study to the Committee on Remote Sensing Programs for Earth Resources Surveys (CORSPERS) in the Commission on Natural Resources. CORSPERS had previously completed an 18-month progress review of the LANDSAT (ERTS) Investigator Program. This review was reported in a National Academy of Sciences Report issued in August 1974.

The Committee's approach to the present study was first to summarize current research experience in different applications of remote sensing of electromagnetic radiation from a variety of terrestrial features. This formed a basis for specifying what sensor, orbit, and data-processing parameters, within the range of technical feasibility, would be useful to each applications group interested in future operational satellite systems. As expressed in its progress review of August, 1974, the Committee was acutely aware that the technical literature is limited in terms of repeatable experimental results. Most of the published studies were performed by remote sensing technologists with only scattered participation by operational managers.

The Committee also received briefings from the federal agencies with operational interests in data from orbital remote-sensing systems. With these briefings as background, the Committee drew upon its own experience and judgment to establish those data characteristics it considered optimal for operational use in different applications.

The Committee then reviewed the proposed Thematic Mapper mission as compared to the current LANDSAT/MSS in terms of satisfying the requirements for land cover data. Possible modifications that could expand its utility for other applications without significantly jeopardizing the primary objective were then considered.

Finally, the Committee made recommendations that it believes will enhance the performance of the Thematic Mapper system, not only for observation of vegetation but also for the collection of highly useful data required by the wide range of other interested users. The Committee also pointed out where additional studies should be conducted before the mission characteristics are completely finalized. In these recommendations, CORSPERS departed significantly from some specific aspects of the baseline proposal. However, the Committee maintained close contact with NASA to ensure that these modifications were compatible with technical system constraints and would not cause damaging delays in the program timetable. In several cases NASA was able to modify its baseline design as the Committee evolved its position. The "baseline mission" referred to in this report is the original proposal presented to the Committee by NASA during the initial meetings in November 1975 and January 1976 as described in the Appendix.

The Committee wishes to thank all those representatives of federal agencies who gave so freely of their time to assist the Committee in the study. CORSPERS acknowledges the substantial contribution provided by their experience and perspective to the successful completion of this evaluation. The Committee also wants to thank David S. Bartlett, a graduate student in Marine Studies from the University of Delaware, who joined the National Research Council staff from June through August to assist in the writing and to integrate the contributions of each Committee Member into the final report. He deserves a "well done" for an outstanding job.

Arthur G. Anderson, Chairman
CORSPERS

Contents

Action Summary

Orbital earth resources data have been available on a regular basis since July 1972 when LANDSAT-1 was launched. Since that time applications and technical evaluation of the data returned by LANDSAT's 1 and 2 have given the scientific and potential user community confidence that significant information on the natural resources of the earth's surface can be obtained by remote sensing from orbital platforms. The United States has scheduled the launch of LANDSAT-C when the useful operation of LANDSAT-2 ends, now estimated in 1977-78. NASA has proposed a follow-on program to extend the flow of orbital data well into the 1980's and to significantly upgrade the quality of data provided. (See the Appendix for a description of the proposed program.)

The principal component of the follow-on program is an improved multispectral scanner - the Thematic Mapper. The Committee on Remote Sensing Programs for Earth Resource Surveys (CORSPERS) of the National Research Council has studied both the proposed Thematic Mapper sensor and the mission characteristics to determine the adequacy of the design for a variety of earth observation applications.

The Committee concurs with the selection of observation of vegetation as the primary optimization objective in mission design. However, during its analysis, the Committee explored the possibility of extending the design to enhance the utility of the Thematic Mapper data for other applications without endangering the primary objective.

The Committee is in full agreement with and strongly endorses the following aspects of NASA's plans for the Thematic Mapper mission as presented to CORSPERS in November 1975 and January 1976:

1. To include an appropriately modified first generation MSS in the Thematic Mapper mission to provide

- a reliable back-up to the new Thematic Mapper;

- a continuation of the current LANDSAT MSS data for those users who either do not need improved Thematic Mapper data or do not have the necessary facilities to handle these data.

- precursor data to assist the user in selecting only good coverage before processing the more expensive Thematic Mapper data.

- transitional data to aid users phasing in the improved Thematic Mapper data.

2. To provide assured coverage for a minimum of 6 years to give agencies and other users an opportunity to justify the necessary commitment of resources for the transition into a completely valid operational phase.

3. To provide for global, direct data read-out, without the necessity for on-board data storage or dependence on foreign receiving stations.

4. To recognize the operational character of the Thematic Mapper after successful completion of its experimental evaluation.

5. To combine future experimental packages with compatible orbits as part of the operational LANDSAT follow-on payloads.

6. To provide for the inclusion of a seventh spectral channel on the Thematic Mapper if it becomes feasible and operationally useful.

The Committee also agrees that the improvements in ground instantaneous field of view (IFOV) and radiometric sensitivity (see definition, page 34) will produce substantially increased capabilities for virtually all applications.

The Committee wishes to recommend changes or express concern in the following eight areas:

1. Spectral Bands

The Committee carefully studied analyses of the Thematic Mapper Technical Working Group that led to the selection of the six spectral bands in the proposed NASA design. (See Table A.1 for proposed bands.) At the request of the Committee, additional analyses were conducted by NASA. After reviewing this work, CORSPERS recommends that the spectral bands be changed to the following:

- Band 1: 0.47μm to 0.52μm

In this band, the short wavelength limit is most critical and its position is based upon marine bathymetry requirements. The long wavelength limit is positioned by chlorophyll discrimination requirements. A long wavelength cut-off at 0.52μm is preferred, but extension to 0.53μm is acceptable.

- Band 2: 0.53μm to 0.58μm

The short wavelength limit is most critical from the standpoint of terrestrial vegetation discrimination. This limit should not be shorter than 0.53 micrometers. The long wavelength limit is positioned by both oceanographic and vegetation discrimination requirements. A 0.59μm long wavelength cut-off would be acceptable if signal strength requirements cannot be met with a 0.05μm band width.

- Band 3: 0.62μm to 0.68μm

The long wavelength limit is the most critical with plant species discrimination and vigor determination being the driving uses. Experience has shown that reflectance cross-overs in the 0.68 to 0.75 micrometer region confuse spectral signatures and reduce the accuracy of plant vigor determinations. The short wavelength limit is not critical as long as it is 0.60 micrometers or longer.

- Band 4: 0.76μm to 0.90μm

Neither limit is critical as long as the short wavelength limit is 0.75 micrometers or longer.

- Band 5: 1.55μm to 1.75μm

This band, in which foliar reflectance is strongly dependent upon foliar moisture content, should prove very useful in plant vigor determination. The exact wavelength limits are not critical and should be based upon atmospheric transmission and band width requirements.

- Band 6: approximately 8.8μm to approximately 12.6μm

The increased bandwidth is recommended for vegetation analysis purposes and to allow an improvement in spatial resolution. This wider band would permit reduction of thermal IFOV to 90m with a small (from 0.5°C to 0.64°C at 300K) degradation in sensitivity. The advantages of 90m thermal IFOV would seem to outweigh the sensitivity lost.

- Band 7:

The Committee also recommends, should a seventh spectral channel be included, that it cover the region from 0.58μm to 0.63μm. Measurements in this band are useful in vegetation species discrimination and disease detection. If a second cooled-detector channel (longer than 2.5μm) becomes feasible, the most valuable band would be in the 4.5μm to 5.5μm region.

In reviewing the spectral responsiveness of the Thematic Mapper bands, the Committee was convinced that present technology can produce filters with sufficiently sharp cut-offs and cut-ons to provide the needed spectral performance. The Committee considers a filter slope that drops from 85 percent of full response to 5 percent of full response within a 10 nanometer interval to be technically feasible and recommends that these specifications be used in filter design.

2. Equatorial Crossing Time

The NASA proposed mission and sensor design calls for an equatorial crossing time of 1100 hrs. The available evidence was not persuasive in convincing the committee that a change from the 0930 hrs LANDSAT 1, 2, and C crossing time is warranted. If vegetation classification with primary dependence on machine processing were the sole purpose, the near-noon orbit might be preferred, since it provides a minimum shadow effect and a better view of the plant canopy. Unfortunately, the small zenith angle associated with the near-noon orbit seriously limits the sensor over water surfaces; sun glitter is a problem when wind speeds rise above 5 meters/second. After reviewing the available calculations on sensor sensitivity and signal levels at crossing times of 0930 hrs and 1100 hrs, the Committee feels that while the later crossing time might be favored for automated vegetation classification, the probable gain in this area does not appear great enough to offset losses in other applications.

Another factor that must be considered in the selection of the optimum crossing time is cloud cover interference, which is both statistically variable and location-specific.

The Committee feels that it is important to continue the present LANDSAT crossing time in the follow-on program in order to take full advantage of the classification experience gained during the present experimental program. A change in crossing time could significantly alter the classification signatures and would probably cause a major perturbation in this background experience. On the basis of these considerations, the Committee recommends that the 0930 hrs crossing time of LANDSAT 1, 2, and C be retained. A more detailed study of all the relevant factors, particularly the statistical probability of cloud cover in critical areas, is recommended to refine this crossing time.

3. Frequency of Coverage

The Committee has deliberated at considerable length on the frequency of coverage question. There is little doubt that some users will find eighteen-day repetitive coverage more than adequate, even with the expected cloud coverage interference. Other major users require more frequent coverage during certain crucial times of the year but could accommodate to data gaps of several months at other times. Crop forecasting in the U.S. is a good example of this variable-coverage frequency requirement. Requirements for global crop forecasting data are even more complex due to the diverse growing seasons and agricultural practices. Other important users need more frequent coverage throughout the year, sometimes as often as daily. While this latter frequency is obviously not technically or economically feasible for a global, high data-rate system such as is envisioned in the LANDSAT follow-on, less frequent coverage can still be of significant value to many of these users. Even when individual users can specify their own coverage requirements, experience is inadequate to determine the optimum compromise between multiple users with different frequency requirements. In view of these highly subjective factors including the variable cloud cover probability, the Committee can assert that a system with a coverage interval of longer than every nine days will have a definite drop-off in value to many users interested in dynamic processes. The

Committee therefore recommends that a nominal nine-day coverage interval be accepted as the maximum interval between observations by the LANDSAT-follow-on spacecraft.

4. Ground Data Handling System

The Committee did not perceive that NASA or the user agencies had performed thorough analyses of the impact of the high data rate of the Thematic Mapper on the Ground Data Handling System. Since the high data rates will provide many more choices for data analysis, the potential data processing and storage loads will be far beyond current LANDSAT experience. Thoughtful, vigorous, and extensive analysis, along with an early commitment, is required to thoroughly understand the issues and to design the required systems. Such analyses should start now.

5. Data Archiving

Imbedded in the Ground Data Handling System analysis is the general question of data archiving. The Committee does not believe that all data must be preserved. The operational user community and NASA should proceed promptly to analyze their requirements and the technical alternatives, and to make the preliminary policy and design choices for long-term archiving. These choices can have a significant impact on the overall design of the Ground Data Handling System.

6. Supporting Research and Development

In reviewing the analytic work that had been done in preparation for the LANDSAT follow-on, as presented to CORSPERS, the Committee felt that many of the longer-term issues requiring research and development were inadequately treated. These include studies on changes in signature with variations of sun angle, viewing altitude, gray scale, and cloud cover. In the Committee's view, NASA is the only agency that has the broad range of competence required for such studies and therefore should assume the responsibility to initiate and lead them.

7. Impact of the Manned Reusable Space Shuttle

Another concern of the Committee is the apparent linkage between the continuity of the LANDSAT follow-on program, and the on-schedule success of the Manned Reusable Space Shuttle Program. NASA is planning to use the shuttle both for the initial launch operation and subsequent retrieval for refurbishment or in-orbit maintenance. While the Committee does not consider itself competent to evaluate either the firmness of the shuttle schedule or the performance of the shuttle when it is ready for operational service, it voices concern that NASA keep open its options to ensure that the continuity of the remote sensing program is not jeopardized by potential changes in the shuttle schedule or in its performance.

8. Data Gap

Finally, the Committee wishes to express its concern over the potential data gap that may confront the world-wide user community after LANDSAT C completes its useful life. The seriousness of this potential gap became apparent during the Committee's evaluation of the Thematic Mapper. Such a gap is likely to disrupt and disperse the capability of the present user community to use the data. The Committee urges that NASA and the user agencies take every action within their authority to reduce the possibility of a gap and to minimize the duration and the effects of such a data gap if it cannot be prevented.

In making the above recommendations and endorsements, the Committee considered trade-offs between the impact of the changes on land-cover data and the enhancements achieved in the data of interest to geology, oceanography, coastal processes, hydrology, and cartography. The Committee concluded that only minor compromises in land-cover data are required in order to gain significant increases in utility of the data for the other applications. The Committee is firmly convinced that the Thematic Mapper, as modified by the changes recommended above, can provide a major step forward in our capability to manage our natural resources and significantly assist in monitoring major environmental factors.

Chapter I

Introduction

Since 1967, NASA has collaborated with other interested federal agencies in developing the use of spacecraft as sensing platforms for the collection of useful earth resources survey data. Aircraft were used as experimental sensing platforms to provide an understanding of the radiation characteristics of terrain features, land cover, and water. These early experiments led to the design of the Multi-Spectral Scanner (MSS) and the Return Beam-Vidicon (RBV) carried on the ERTS (now LANDSAT) spacecraft and the Earth Resources Experiment Package (EREP) carried on SKYLAB. An extensive investigator program, with scientists and potential users in federal, state, and local governments, at private institutions, at academic institutions and in foreign countries, was conducted. Investigators determined the information content of the data collected and the relevance of the information to the requirements of resource managers. Data processing techniques were developed and design options identified for future operational remote sensing systems. These investigations have provided information on the differences in spectral profile between different plant species, surface features, and water characteristics; the effects of atmospheric perturbations; and detection of direct and indirect evidence of man's activities. With repetitive satellite coverage available at nine to eighteen-day intervals, seasonal variations and phenological changes in the spectral profile provided an additional dimension of considerable significance to the data. Experience with the LANDSAT MSS data has also demonstrated that because of its high radiometric precision, automatic data processing techniques can be used in analysis of individual picture elements for image content identification and mensuration. This technique has provided major increases in the utility of the data.

In parallel with the flight program, NASA has also sponsored a continuing space research and technology program to develop improved sensors and data processing systems. This work has greatly expanded the technological options now available to the system designer. Technology of orbital MSS's is now adequate to increase the number of spectral channels to six or seven and decrease the ground resolution to about 30m. Advances in data processing capability make it possible to handle the corresponding increase in data rate.

Remote sensing and its supporting technologies have advanced to the point where intelligent choices can now be made in designing orbital system capabilities to respond specifically to many selected information requirements. Costs, complexity, and technological and operational constraints, however, limit the span of applications that can be accommodated within a single spacecraft configuration and orbit. Trade-off choices have to be made in order to maximize the usefulness of a sensor system for the largest number of users while trying to maintain the quality of the data well above the usability threshold for each user. The approach adopted by NASA in the LANDSAT follow-on program is to develop a sensor configuration, the Thematic Mapper, that can provide a high quality matrix of repeatable land cover information. This matrix would provide basic data that can be used by many earth resource managers and environmental monitors. For some selected users, it may be necessary to supplement this information with data from Application-Specific Missions in different types of orbits and designed for the particular user. Examples of these Application-Specific Missions include the Heat Capacity Mapping Mission (HCMM), the Seasat Mission, the Coastal Zone Color Scanner scheduled for flight on NIMBUS-G, small Applications Explorer Satellites, and aircraft overflights.

In May 1975, NASA convened a Thematic Mapper Technical Working Group[1] to undertake a review of the follow-on LANDSAT program and to define an appropriate sensor configuration that could be ready for launch in the early 1980's. The specific recommendations on sensor designs and orbit characteristics made by the Thematic Mapper Technical Working Group were used by NASA as a basis for an initial "baseline mission" design (See Appendix). This baseline design established the initial specifications for breadboard engineering models developed by three different contractors to verify that the specifications were feasible from an engineering point of view. NASA reported all three models were able to satisfy the initial specifications.

Federal agencies anticipate that because of the extensive lead time required for the development of a new sensor system the Thematic Mapper configuration will probably be used throughout the 1980 to 1990 decade. Its design is therefore crucial to many different application groups and potential users. While supplementary sensors may be orbited on other spacecraft, the broad utility of remote sensing for resource management and environmental monitoring will, for the foreseeable future, have to depend on the success of the Thematic Mapper configuration. The quality of the land cover information derived from the Thematic Mapper data, the proper recognition and evaluation of potential user information requirements, and the adequate design of the ground data processing and information distribution network are significant elements that will bear heavily on the success of satellite remote sensing for resource management and environmental monitoring. The final design of the instrument and mission parameters of the Thematic Mapper will determine the burden on supplementary Application-Specific Missions or other data sources that need to be deployed in order to satisfy the total applications community.

In late 1975 the federal agencies requested the Committee on Remote Sensing Programs on Earth Resource Surveys, CORSPERS, of the National Research Council, to evalaute the proposed baseline design of the Thematic Mapper. CORSPERS had previously completed an extensive review of the LANDSAT 1 investigator results in six principal application areas. This review was reported in the National Academy of Sciences report, "Remote Sensing for Resource and Environmental Surveys - 1974." The Committee approached the evaluation of the Thematic Mapper by extending the earlier experience in each of the application areas to include LANDSAT 2 results and by actually analyzing the difficulties encountered in using the MSS data in each of the application areas. This analysis was then used as the departure point in evaluating the proposed Thematic Mapper design and in making recommendations to modify the design to increase its capability. The analysis was conducted from the perspective of the following seven major application areas:

- Cartography
- Vegetation inventory and assessment
- Land use management
- Geological applications
- Oceanography and coastal zone management
- Water resource management, and
- Environmental monitoring

The analysis in each of these application areas focussed on the data characteristics as determined by the design parameters of the sensor system used in collecting the data. This, then, provided a basis for evaluating the probable performance of the proposed Thematic Mapper. The sensor system parameters used in the analysis generally included the following:

- Number, spectral location and wavelength limits of the spectral bands.
- Instantaneous field of view of the sensor on the surface of the earth (IFOV).
- Dynamic range of the sensor (see definition, page 33).
- Radiometric sensitivity of the sensor (see definition, page 34).
- Equatorial crossing time of the spacecraft, i.e., the local time of observation.
- Frequency of coverage, i.e., the interval between successive observation opportunities.
- Data processing and management.
- Archiving considerations.

The lead-off discussion in Chapter 2 covers the experience of investigators working in the field of cartography. Since the cartography discipline is generally involved in presenting image-type information in nearly all the applications of orbital data, this discussion should assist the reader in the discussions of the other applications that follow. Definitions of selected technical terms are also included as footnotes at the first appearance of the term.

Most of the investigators working with LANDSAT data directed their research efforts to extracting information of interest to a specific discipline or application. As a convenience to the reader, this report has segregated the literature references relevant to each application to follow immediately after the discussion of the application.

REFERENCES

1) Harnage, J. and D. Landgrebe, LANDSAT-D thematic mapper technical working group, Final Report. NASA JSC-09797, Houston, Tex., June 1975, 156 pgs.

Chapter II

Analysis of LANDSAT 1 and 2 Experience

Cartography

Cartography (mapping and charting) is a supporting discipline in remote sensing, because cartographic data and cartographic presentations are required by all the other disciplines discussed in this report. The data from aerial and orbital sensors, after processing, are eventually presented to the user and employed in the form of an image, chart, or other type of area display.

The discipline of cartography is also a user of remotely sensed data, because the data are used in mapping and charting for general purposes. Therefore the discussion that follows is divided into two sections: namely, cartography in the user disciplines and cartography as a user discipline.

Cartography in the User Disciplines

The user of orbital scanner data derives information principally from an image or other type of area display that is an end product of the data processing. The usable information content of this product is obviously important to the user, and is a paramount concern of the designer of the satellite sensing system. Unfortunately, there is no single parameter or single figure of merit that can completely specify or describe the image quality and useful information content of imagery.[1] Detectability, discrimination, recognizability, and interpretability are perhaps the major characteristics of the display that are of concern to the user; but these characteristics are not in general quantifiable. Spatial resolution is often mistakenly used as a sole measure of these characteristics.[2]

The size of the satellite sensor's instantaneous field of view on the ground, ground IFOV, is used in this report as the figure of merit by which to judge the quality and usable information content of MSS imagery and displays. Ground IFOV has these advantages as a figure of merit: it is a concept that is clearly and unambiguously understood in all the user disciplines; these users are less likely to misinterpret the significance of ground IFOV than resolution; ground IFOV is derivable directly from the design parameters of the sensor system, and is a useful parameter for the designers of the system; ground IFOV comes close to being a valid single parameter to indicate the capabilities and usefulness of the sensor system.

Ground IFOV, or simply IFOV, is the area sensed and recorded instantaneously on the ground by the orbiting system. The size and shape of this area varies somewhat because: the viewing direction of the sensor system does not remain vertical throughout each line scan; the ground is not always flat and horizontal; and the detector-recording system has a finite response time. Nevertheless, for simplicity, the shape of the ground IFOV is assumed to be square and constant in size. The size of the ground IFOV is specified by the length of a side of the square. Ground IFOV is approximately equivalent to the smallest picture element (pixel) in the area display that is presented to the user discipline.

Ground IFOV is a major factor in determining a lower limit to useful pixel size in the image or display. The pixel size, in turn, is a major factor in determining the following: smallest recognizable object or feature; discrimination between objects or features; image interpretation; spatial texture; spectral texture and signature; accuracy of location of boundaries; accuracy of area measurements. For example, as the IFOV scans across the boundary between a cultivated agricultural field and a forest area, the change in signal strength, in an appropriate spectral band, will be gradual if the ground

IFOV is large, and sharp if the ground IFOV is small. The boundary between the two areas will therefore be diffuse and uncertain if the ground IFOV is large.

Ground IFOV, combined with area coverage and frequency of repetitive coverage, also determines the data rate of the system. The data rate in any one channel is inversely proportional to the square of the value of the ground IFOV, if the area of coverage and the frequency of repetitive coverage are constant. If the IFOV is too small, the data rate and system cost become unmanageably high. If the IFOV is too large, the usefulness of the system diminishes. Compromises and trade-offs must therefore be made.

Optimization of these compromises and trade-offs consists in maximizing the ratio of benefits to cost. This is shown diagramatically by the two curves in Figure 2.1 (not to scale). The abscissa for both curves is ground IFOV which increases from right to left; i.e., "resolution" increases from left to right. The broken curve represents the usefulness of the ground IFOV, in an arbitrary user discipline. For a very large ground IFOV, e.g., 1000 m, the usefulness of the system is judged to be very small. As ground IFOV decreases, usefulness rises; but the curve begins to flatten out and approach saturation as ground IFOV becomes very small, (e.g., 0.01 meter). The general form of this usefulness curve in Figure 2.1 is probably correct for all or most of the user disciplines; but its exact shape and its ground IFOV values undoubtedly vary from user discipline to user discipline. Some disciplines may have sharp bends or points of inflection in the usefulness curve. Nevertheless, the curves for all the disciplines can be said to have these two common characteristics: the curves are monotonic, i.e., usefulness always increases as ground IFOV decreases; and the curves flatten out to saturation for very small values of ground IFOV.

Distinction is made, of course, between the usefulness of a system for a particular user discipline, and the ratio of benefits to cost of the system. The benefits/cost ratio is illustrated by the solid curve in Figure 2.1. For very large values of ground IFOV (very poor "resolution"), the usefulness of the system is very small, and hence the benefits/cost ratio is small. For very small values of ground IFOV (exceedingly good "resolution"), the costs of the system become large and the data rate becomes unmanageable while the usefulness curve flattens out. Hence the benefits/cost ratio, again, is small for very small

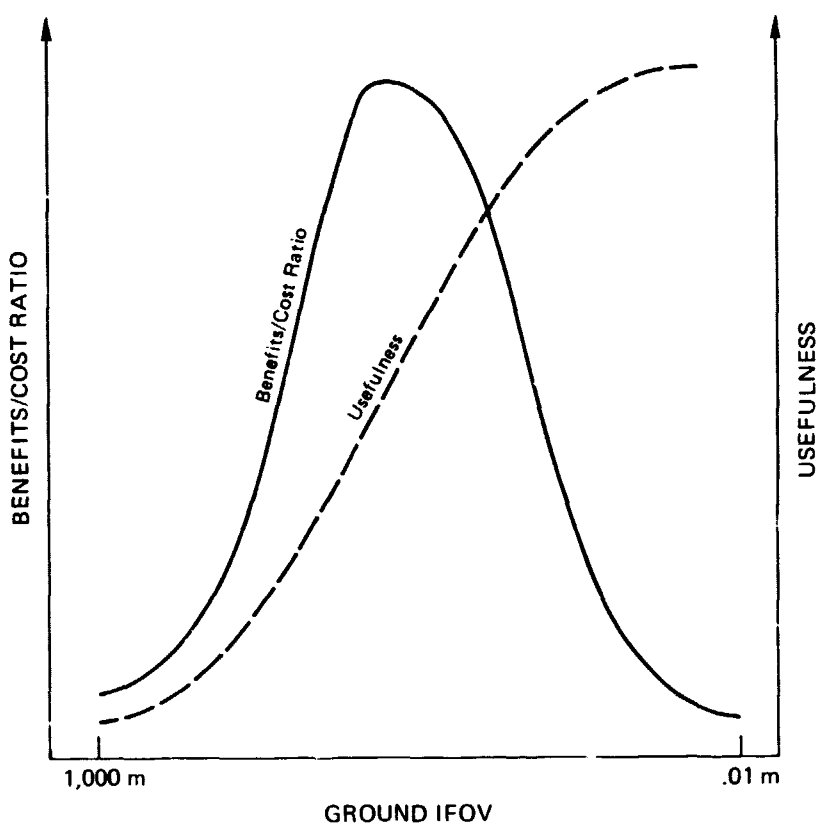

FIGURE 2.1 Schematic Graph of Relationship Between Data Usefulness, Benefit/Cost Ratio and Sensor Ground IFOV

values of ground IFOV (very fine "resolution"). Somewhere between the two regions of small benefits/cost ratio, the benefits/cost curve rises to a maximum. The optimum ground IFOV for the particular application lies at this maximum.

In general, each user discipline has its own curve of usefulness as a function of ground IFOV; and therefore each user discipline has its own curve of benefits/cost ratio as a function of ground IFOV. Consequently, each user discipline is likely to have its own optimum ground IFOV (at the maximum of the benefits/cost ratio curve).

The difficulty of quantifying usefulness in each user discipline has prevented the disciplines from constructing curves, such as Figure 2.1, with accuracy. Nevertheless, the methodology of Figure 2.1 serves as an intuitive guide in estimating the optimal value of ground IFOV for each user discipline.

The user community repeatedly expresses the desire for better and better resolution, i.e., for smaller and smaller ground IFOV. This desire stems from the tradition of relying upon spatial resolution in black-and-white images for recognition, discrimination, and identification. However, now that spectral and temporal signatures are available, and will become increasingly available with finer spectral resolution in planned sensors, emphasis should be directed toward developing the ability to recognize, discriminate, and identify by means of spectral and temporal data, as well as by means of spatial data.

Cartography as a User Discipline

This section discusses the uses of orbital scanner data for making general, conventional maps and charts, as distinguished from thematic maps and charts that have specialized applications in the other user disciplines. General cartography has data requirements that differ from the data requirements of thematic cartography for the other user disciplines.

In general cartography, the principal uses of data from current orbital systems are the following, listed approximately in order of importance:

1. Revision and updating of planimetry in maps of scale smaller than 1:250,000,

2. Charting remote or inaccessible areas at map scales smaller than 1:250,000,

3. Limited aid in revision of the planimetry of maps at scales larger than 1:250,000, and

4. Limited aid in compiling large scale orthophotomaps.

Scanner imagery from the LANDSATS's is not suited for compiling topographic maps (relief or contour maps) because this imagery is nearly orthogonal and the relief displacements are too small. Terrain elevations cannot be determined accurately enough for topographic maps from this imagery alone. Stereo data supplied by conventional aerial photography from aircraft altitudes is essential for topographic mapping at present. On the other hand, the near orthogonality of LANDSAT-type scanner imagery is a distinct advantage because it simplifies the compilation and revision of planimetric maps of small scale.

Ground IFOV

Conventional high resolution aerial photography from aircraft, with small ground IFOV, will continue to be available to the cartographer because he needs photography from aircraft altitudes for topographic relief information. Therefore the cartographer's need for small ground IFOV from satellite sensors is not acute. The present LANDSAT ground IFOV of approximately 80 m is effective for the general cartographic uses listed above. A 40 m ground IFOV would, of course, increase the usefulness of the data; but the improvement would not be dramatic and is not likely to introduce new uses of the data for general cartography. The benefits/cost ratio curve (Figure 2.1) is probably rising, but only slowly, in the region between 80 and 40 m (for general cartographic uses). Reductions of the ground IFOV of future sensors from 80 to 30 m, or to still smaller values. is justified principally by cartography in the user disciplines rather than by general cartography as a user discipline.

Frequency of Coverage

Unlike some of the other user disciplines, general cartography is concerned with relatively slow changes over long periods of time. Were it not for the interference of cloud cover, general cartography could be satisfied with coverage only four times a year, e.g., once each season. However, a shorter period of repetitive coverage is needed because of cloud cover. Approximately one year of continual operation of the MSS on LANDSAT 1 was needed to obtain complete cloud-free coverage of the U.S., with an eighteen-day period of repetitive coverage. A nine-day period would be acceptable as far as cloud cover and general cartography are concerned.

Equatorial Crossing Time

For purposes of general cartography, the 0930 hrs equatorial crossing time of LANDSATs 1 and 2 has had the following advantages which should be retained in future orbital programs:

1. The experience of practical aerial photographers indicates that in many areas cloud cover interference in general is more likely to be encountered in late morning than in early morning.

2. Reflected sun glitter over water surfaces, which will limit sensor operation, will be more pronounced with later morning orbits than with the 0930 hrs orbit.

3. A principal use of LANDSAT data in general cartography will be to detect planimetric changes for revision of small-scale maps. Some of these changes develop slowly, and can be detected only by comparing sets of MSS data over long periods, e.g., years. For accurate

comparisons of these sets of data, the equatorial crossing time of future sensors should remain the same as that of the predecessor LANDSATs, namely 0930 hrs.

4. The 0930 hrs orbit gives more pronounced shadows for assistance in surface contour analysis than a later orbit.

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Vegetation Inventory and Assessment

Analysis of vegetation cover is probably the dominant use to which remote sensing technology has been applied. The advantages of repetitive, large area coverage by remote sensors are particularly suited for use in agriculture, forestry, and rangeland management. Research has clarified many of the interactions of electromagnetic radiation with vegetation. In many cases, information about soil and subsurface characteristics, drainage patterns, and environmental impact of pollutants can be derived through the identification of the type and condition of vegetation coverage, thereby expanding the value of the analysis to users outside of agriculture and forestry. Therefore a sensor designed for analyis of vegetation can form a basis for a general purpose remote sensing system.[1]

Spectral Bands

While all significant aspects of the spectral response characteristics of vegetation are by no means clear, research has shown trends that have been used in designing remote sensor systems for analysis of vegetation. These trends allow relative evaluation of many plant characteristics. Coverage in several different spectral bands increases classification effectiveness for vegetation. It is also possible to specify with reasonable precision those spectral regions that are of particular use and those regions in which data may be less valuable, or actually counterproductive for certain applications. Figure 2.2 is a typical spectral profile curve for a green leaf. Figure 2.3 shows the effect of different levels of moisture content on the spectral profile. The following discussion suggests several refinements that may improve the utility of orbital data over that which has been attained by LANDSAT/MSS. It should be noted, however, that refinement of band location

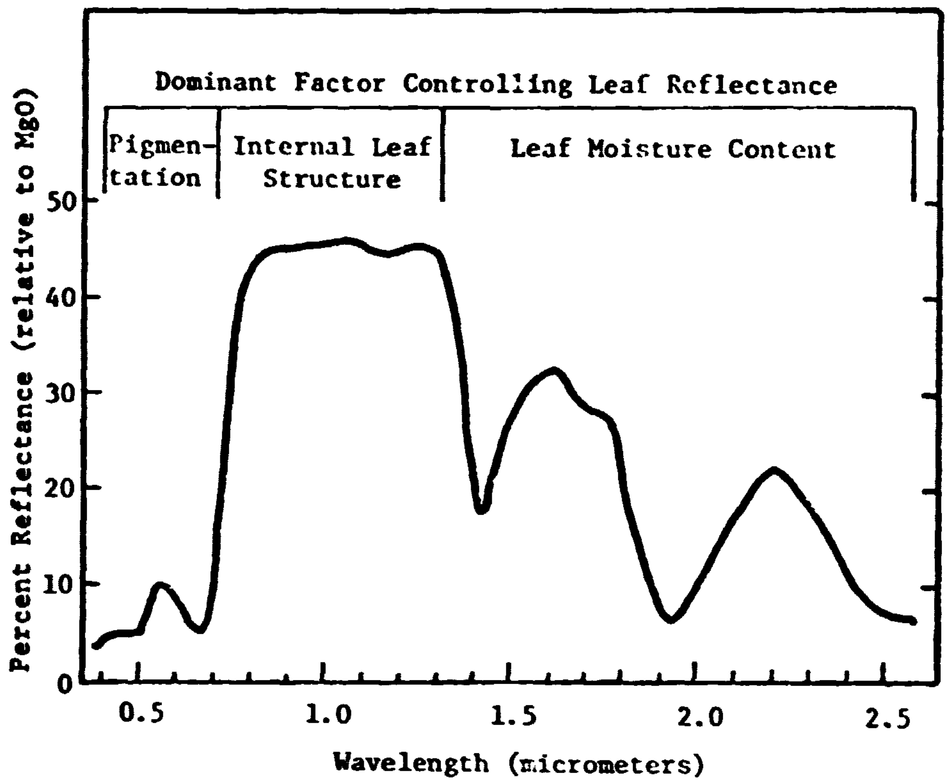

FIGURE 2.2 A typical reflectance curve for a green leaf.

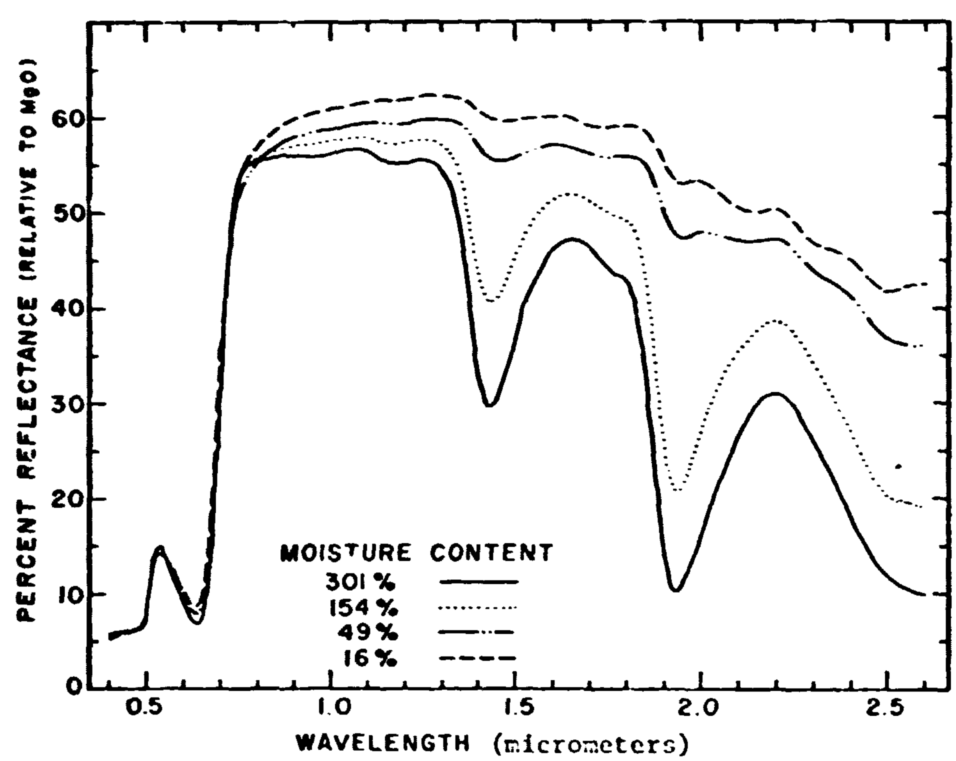

FIGURE 2.3 Reflectance of the upper surface of a sycamore leaf at different oven-dry-weight moisture contents.

and width is ultimately limited by the precision with which sensor technology can specify the boundaries of spectral coverage within a particular band. This depends upon a technology that can provide sharp filter response slopes to spectral regions; there is no advantage to specifying a 0.06μm band width if the filter design requires an interval of 0.03μm to reach its maximum response.

Attempts to identify and evaluate various types of vegetative cover using LANDSAT/MSS data have met with mixed results. Some investigators report good results in identification and mapping of forest and rangeland types with classification accuracies between 83 percent and 96 percent.[2-3-4-5] Similarly, inventories of total crop acreage and single crop (cotton) acreage have been produced with accuracies greater than 90 percent.[6-7] On the other hand some studies report lower accuracy of identification for forest types[8-9] or refer to LANDSAT-derived maps as "semidetailed."[10] Much of the reduced accuracy may be attributed to the large LANDSAT/MSS ground IFOV (approximately 80m); however, there are indications that refinement and expansion of spectral coverage would improve accuracy and provide more information on vegetation cover and stress identification.

Studies using sensors with finer spectral resolution than that provided by LANDSAT/MSS show that, for many vegetation discrimination tasks, the LANDSAT/MSS bands are too wide. Band 4 (0.5 to 0.6μm) incorporates a significant "hinge-point" near 0.55μm below which plant senescence (aging from full maturity to death) is accompanied by a reduction in reflectance (see NOTE) and above which an

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NOTE: "Reflectance - The ratio of the radiant energy reflected by a body to that incident upon it. The suffix (-ance) implies a property of that particular specimen surface."

Source: Reeves, R.G. ed., Manual of Remote Sensing. American Society of Photogrammetry, Falls Church, Va., 1975, p. 2101.

increase in reflectance is observed.[11] In the broad 0.5μm to 0.6μm band the two trends offset one another, and reduced sensitivity to senescence results. Similarly the difference in reflectance between hardwood trees and conifers is reduced below 0.53μm.[12] A short wavelength cutoff at 0.53μm would improve capabilities for vegetative species and stress determination. LANDSAT/MSS Band 5 (0.6 to 0.7μm) includes both the typically low "red" reflectance of plants and the beginning of the rapid rise in plant reflectance in the "near infrared" at wavelengths longer than 0.68μm. Again, averaging of the signal over this wide band may cause confusion, since vigor changes can cause opposite trends in the "red" and "near infrared" reflectivities of plants.[13] Therefore, a shortening of the long wavelength limit of the MSS Band 5 (0.60μm to 0.70μm) to 0.68μm would improve its utility for general vegetation studies.

Research in forestry has shown that a "yellow-orange" band (0.58μm to 0.63μm) measured by portions of two separate channels in the LANDSAT/MSS may have significant value in vigor, species, and yield determination for trees[14-30] and crops. This band would therefore be valued for vegetation analysis although little experience with this region on orbital scanners has been accumulated.

While there is little doubt that "near-infrared" reflectance is of significant value in identification of plant type and stress, there is some confusion about the relative utility of the two LANDSAT/MSS BANDS 6 and 7 (0.7μm to 0.8μm and 0.8μm to 1.1μm) which are located in this spectral region. Many investigators have found bands in these two regions to be interchangeable in vegetation analysis and can find no justification for differentiating them.[36-37] Some studies, however, indicate that MSS Band 6 (0.7μm to 0.8μm) may be slightly more useful than Band 7 (0.8μm to 1.1μm) in measurement of biomass,[15-16] and basic research indicates that the 0.7μm to 0.8μm band should be far more useful in estimation of above-ground plant biomass than is the 0.8μm to 1.1μm band.[17-18] Available field evidence is not conclusive, however, and biomass determination remains a promising potential rather than a present capability. The weight of available evidence supports a single band with coverage from 0.76μm to 0.90μm, deleting a water absorption area between 0.9μm and 1.1μm.

Experience with measurements in the "ultraviolet-blue" spectral region (approximately 0.3μm to 0.46μm) is limited since photographic data are adversely affected by atmospheric scattering at these wavelengths. Atmospheric perturbations can be filtered out of scanner measurements in this spectral region but little evidence is available as to the value of such a band in vegetation studies.

Evidence is available to evaluate use of spectral coverage at longer wavelengths than sensed by the current LANDSAT/MSS sensor system. In the spectral region beyond approximately 1.5μm, reflectance is sensitive to plant moisture content. A sensor band between 1.55μm and 1.75μm,[35] or between 2.0μm and 2.6μm,[14] would be useful for detection of moisture and disease stress.[19-20-21]

"Thermal-infrared" radiation is sensitive to temperature and emissivity (see NOTE) changes in plants under moisture stress[22] and can improve differentiation of crop types.[23] In general any measurements between approximately 4.0μm and 14.0μm may be related to surface temperature, if the emissivity is known, although there is some dispute as to whether the 4.5μm to 5.5μm or 8.0μm to 14.0μm band is preferable.

While identification of any particular cover type generally requires not more than four spectral bands (if it can be discriminated at all), multi-category classification tasks can beneficially use more than four bands from which to choose those best suited to discriminate each category.[24-25] The six bands shown in Table 2.1, covering a spectral range from the "green" (approximately 0.54μm) to the "thermal-infrared" (approximately 4.0μm to 14.0μm) would seem to represent those best suited for discrimination of vegetative cover types in support of a variety of applications.

NOTE: Emissivity - The ratio of the radiant flux emitted by a real body to the radiant flux emitted by a black body.

TABLE 2.1

Spectral Band Selection for Vegetation Analysis

Band	General Application
0.53 to 0.59μm	Discrimination of vegetation
0.58 to 0.63μm	Vigor determination, disease detection, forest type discrimination
0.62 to 0.68μm	Species discrimination, vigor determination
0.76 to 0.90μm	Species discrimination, vigor determination, biomass determination
1.55 to 1.75μm or 2.0 to 2.6μm	Detection of moisture stress
4.5 to 5.5μm or ∿8.0 to ∿14.0μm	Detection of moisture stress, soil moisture, some species discrimination

Ground IFOV

In general, it appears that the more successful LANDSAT vegetation discrimination studies[2-3-4-6-7] attempted only limited or simple cover-type identifications while the less successful inventories[8-9] were aimed at multiple-category, detailed classification or simple classifications in areas of heterogeneous cover types. These results are probably analogous to the inability of LANDSAT to provide adequate Level-II land use information (see Land Use Management - page 45) and indicate that a system incorporating smaller ground IFOV's is needed. Some investigators have responded by employing multistage, integrated approaches using aircraft as well as LANDSAT.[26-27-28] Improvements in resolution (smaller IFOV's) over the LANDSAT/MSS IFOV of 80m are expected to improve area determinations by reducing uncertainty of boundary locations. Smaller IFOV's also make classification more accurate by obtaining more independent spectral measurements per unit area and, as they approach small values of 10-30m, by detecting textural cues of value in the discrimination of vegetation.[29] These two factors, as they may generally affect agriculture, rangeland, and forestry applications, are related to incremental improvements in ground IFOV (see Table 2.2).

The accessibility of smaller and smaller fields with decreasing IFOV is of great importance to crop yield prediction. It is anticipated that the yield prediction capability under development through the joint NASA, NOAA, USDA Large Area Crop Inventory Experiment (LACIE)[34] will find greatest use in foreign areas where conventional agricultural data sources are poorly developed or inaccessible to the USDA. Many foreign agricultural systems, particularly in Asia, are based on smaller average field sizes than are observed in the U.S., Canada, and the U.S.S.R. In China and India, field sizes are often 20 acres or less.[34] Studies have shown that classification and mensuration accuracy is markedly improved if a field contains ≥ 60 pixels.[35] Thus approximately 40m IFOV is desired for 20 acre fields while 30m IFOV would allow measurement of fields ≥ 10 acres in size.

A useful improvement in automated discrimination of cover types will also result from reductions in ground IFOV by enhancing the quality of training samples (see NOTE).

NOTE: "Training Samples" - Selected spectral measurements, edited from scanner data, representative of known cover types and used to form spectral signatures for automatic extrapolation of cover type classification to other areas in the scene.

TABLE 2.2 Improvements in Vegetation Analysis with Decrease in Sensor IFOV from LANDSAT MSS 80m

Ground IFOV	Agriculture	Forestry
60m (.6 acre)	Small improvement in determination of field area by reducing uncertainty at field edge.	Little Improvement.
40m (.3 acre)	Continued improvement in determination of field area by reducing uncertainty at field edge, and improving detection of small fields.	Small improvement in ability to recognize some forest types (e.g. those in tropics with large crowns). Improvement in forest type area measurement.
30m (.15 acre)	Continued improvement in determination of field area and detection of small fields.	Textural differences should appear and aid in separating forest types and conditions, including diseases and insect attacks. Continued improvement in area determination.
20m (.07 acre)	Continued improvement in determination of field area and detection of small fields.	Textural differences further enhanced and forest type determination improved.
10m (.02 acre)	Detection of crop disturbances becomes possible on an actionable scale.	Saw timber sized trees distinguishable from smaller trees.
5m (.004 acre)		Forest size class should be determinable (e.g. saw timber, poles, samplings). Forest type discrimination much enhanced.

A statistically significant sample of spectral characteristics from which to derive a signature for automated analysis generally requires editing 20-50 independent measurements (pixels) from the scanned scene. As the size of the pixels are decreased, so is the size of the total sample area needed, and the probability of acquiring a discrete, homogenous signature is enhanced.

Dynamic Range and Radiometric Sensitivity

Spectral bands with locations and widths optimized for vegetation analysis will produce best results if their dynamic ranges (see NOTE) are adjusted to correspond to the range of typical reflectance values encountered over plant canopies. In the visible bands, a range of 0 to 30 percent is sufficient for vegetation. Soils have reflectance up to 60 percent and very reflective sand and bare rock may require even higher saturation thresholds. In the reflective infrared (approximately 0.7μm to 3.0μm), plant reflectances are much higher, and call for a dynamic range of from 10 to 65 percent. In the thermal infrared a temperature range of 270°C to 320°C will include normally encountered surface temperatures in vegetated areas.

NOTE: "Dynamic Range - The ratio of maximum measurable signal to minimum detectable signal." In this report it is specified as the reflectance or temperature values equivalent to the maximum and minimum detectable signals.

Source: Reeves, R.G., ed., _Manual of Remote Sensing_. American Society of Photogrammetry, Falls Church, Va., 1975, p. 2079.

Studies of radiometric sensitivity (see NOTE) requirements have expressed the need for NEΔρ's (Noise Equivalent increment of target reflectance) between 0.5 and 1.0 percent and NEΔT's (Noise Equivalent increment of target temperature) of 0.5°C to 1.0°C for agriculture, forestry, and rangeland uses.[25-35] The frequent use of automated digital analysis for vegetation studies increases the significance of sensitive radiometric measurements. As automated analysis usually relies on spectral information alone without spatial/textural cues, requirements for radiometric sensitivity and accuracy are more stringent than those for manual interpretation. Therefore, as more and more use is made of automated spectral analysis, more value will be attached to sensitivities in the 0.5 to 1 percent and 0.5°C to 1°C ranges.

Equatorial Crossing Time

Experience with LANDSAT's 1 and 2 indicates that the local observation time associated with approximately 0930 hrs equatorial crossing time encounters shadows caused by both terrain slope and plant canopy effects. These can have a significant effect on the spectral signature obtained for many targets. These effects tend to degrade the signatures. Some research has shown that tree signatures, for instance, are enhanced if only the sunlit portions of the crowns are sampled.[30-33] Thus, with higher sun angles, somewhat better vegetation signatures could be obtained in nearly all types of terrain.[30-31-32-33] Some concern has been expressed over the potential for specular reflection from terrestrial cover types if sun angles are too high; however, no studies have been encountered in which specular "glint" was a problem over vegetated land surfaces.

NOTE: Radiometric Sensitivity - In this report, used to denote th smallest detectable increment of radiance. Specified in units of reflectance (NEΔρ--Noise Equivalent increment of reflectance, %) or of temperature (NEΔT--Noise Equivalent increment of temperature, °C).

The probability of cloud cover during different portions of the day is another major factor affecting the selection of equatorial crossing time for cover analysis. Experience in many locations would seem to argue for early crossing times (before 1000 hrs) to minimize cloud interference. Since acquisition of repetitive coverage is highly important, avoidance of cloud cover would seem to take precedence over optimization of reflectance signatures through later crossing times, provided the available margin in reflectance signatures is adequate at the earlier crossing time.

Frequency of Coverage

The eighteen- and nine-day observation frequencies provided by LANDSAT's 1 and 2 are not completely adequate for all vegetation analysis applications. Crop-yield prediction requires repetitive measurements at short intervals during critical periods of the crop calendar. Unfortunately, the critical periods vary depending on crop type, planting time, geographical location and weather; thus frequent coverage is needed over periods longer than a month.[34] It is not entirely clear what the best observation frequency during such periods would be, but in some cases it is shorter than nine days, particularly if bad weather obscures one or more opportunities. Typical applications and the required observation frequencies are shown in Table 2.3.

In those cases where required observation frequencies may exceed the capabilities of orbital systems, specialized aircraft missions may have to be used as supplementary data sources.

TABLE 2.3

Observation Frequencies Requirements
For Typical Applications In Vegetation Analysis

Typical Application	Observation Frequency
Inventory of forest lands	yearly and
Inventory of land removed from or put into agriculture	occasionally seasonally
Inventory of total acreage in cultivation	seasonally
Rangeland assessment	
Yield estimates from crop calendar	3-9 days during growing season
Disease detection	
Moisture stress detection	

Data Processing and Archiving

Timely availability of data is a major requirement affecting operational crop management - detection of disease, irrigation management, etc. Rapid transmission of data to users is essential in order to respond to early detection by remote sensors. For irrigation management near-real time data would be highly useful. Data available within one to three days, however, is still of significant value. Crop yield forecasting does not require such rapid delivery and data delivered within a week would be adequate.

Retention of all usable data for 18 months would satisfy most users engaged in crop yield studies. Forestry, rangeland, and agricultural research needs would probably be satisfied through seasonal data stored for long periods to facilitate studies of long term climatic and ecosystem dynamics. A data screening system based on the careful selection of date of coverage for a particular vegetation type combined with degree of cloud cover and sensor performance might be developed to identify the "best" data for archiving beyond a one to two year initial storage period.

One specific concern expressed about data format for digital data processing is related to thermal data. Ground IFOV's for thermal data are typically larger than those for reflective data. The planned IFOV's for LANDSAT-C, for instance, are 78m for the reflective bands and 234m in the thermal channel. Even if the actual IFOV's are different it is important that the data sampling rate be the same in all channels in order to accommodate automated, multispectral processing using multidimensional signature analysis. If feasible, a uniform data sampling rate, with redundancy of area covered by thermal pixels, would simplify digital processing.

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Land Use Management

The inventory and management of man's use of land ultimately encompasses all of the other disciplines discussed in this chapter, including geology, agriculture, forestry, rangeland management, oceanography, and hydrology. Environmental monitoring attempts to identify the interrelationships of man's activities with his environment. Cartographic tools are used in planning, implementing, and monitoring virtually every human activity involving interaction with the physical environment. All are related to the use of land and adjacent waters and must be considered as central to concepts of land use management. In this respect the use of remote sensing technology in any of the applications discussed in this chapter may be considered as different facets of land use management.[1] Much of the data required for land use management, however, involves the inventory, monitoring, and planning of man's social and economic activities as reflected in patterns of urban and suburban development. It is this aspect of land use management that places some unique constraints and stringent requirements on the capabilities of remote sensing systems. Therefore, this section deals primarily with the use of remote sensing data in evaluating the distribution and dynamics of man's industrial, business, residential, and transportational structures and activities. Data characteristics required for other contributing observations such as vegetation analysis, hydrology, geological resources, etc., are discussed in sections dealing more specifically with these fields.

Spectral Bands

In general, users of land use information are unlikely to provide definitive preferences as to the spectral location, width, and sensitivity of spectral bands in most remote sensing systems. Spectral response in any wavelength region is not uniquely sensitive to types or patterns of human activities. Multispectral analysis can enhance differentiation of developed areas from natural vegetation and, in some cases, detection of a mixture of vegetation and building materials characteristic of a particular type of development, i.e., the large trees, house roofs and lawns of established residential areas. For the most part, however, it is spatial distribution, size, and proximity to other features that characterize most types of development and allow their identification. Observation in the visible and near-infrared portions of the spectrum is generally adequate for land use applications with few experimental results supporting particular arrangements of bands within this region. Bands chosen to optimize analysis of vegetation, soil, and rock types, water resources, etc., can all contribute to effective land use inventory. Numerous studies cite the successful use of LANDSAT/MSS bands in differentiation of generalized land use types[2-3-4-5-6-7] with some indications of preference for bands 5 and 7 (0.6μm to 0.7μm and 0.8μm to 1.1μm).[2-4-7] Manual image interpretation is predominant in land use mapping: false-color composite images are often used (usually 3 bands: Band 4 - 0.5μm to 0.6μm; Band 5 - 0.6μm to 0.7μm and either Band 6 - 0.7μm to 0.8μm or Band 7 - 0.8μm to 1.1μm). In some cases thermal infrared sensing may also be helpful in identifying certain types of development, particularly industrial, and their interaction with adjacent water bodies.

A study using Skylab S-192 scanner data in land use discrimination established that spectral coverage over a broad range from 0.41μm to 12.50μm was useful. The wide spectral range was utilized because of the variety of urban, soil, and vegetative cover types of interest in a typical land cover detection task. It is of particular interest in this case that three of the six most useful bands in this study were located outside the range covered by the LANDSAT/MSS (0.5μm to 1.1μm). Use of "blue" (0.41μm to 0.46μm), "near IR" (1.55μm to 1.75μm) and thermal IR (10.2μm to 12.5μm) bands were all found productive in discriminating land use, including both urban and vegetative types.[8]

Ground IFOV

As the spatial dimensions and distribution of structures are most often used to identify types of urban and suburban land use, the geometric characteristics of remotely sensed data are of prime importance for many land use applications. Ground resolution, which for the purposes of this discussion is considered equivalent to ground instantaneous field of view (IFOV), is identified as the most critical single sensor parameter determining the detail and accuracy of classification of patterns produced by human activity. The ground IFOV required for discriminating a particular land use category is dependent upon the physical size and geometry involved. Classes of land use categories have been identified which, in general, may be related to the required ground IFOV. The categorization system most often used in connection with remotely sensed land use information was devised by Anderson et al. (1972)[9] and modified on the basis of testing in 1976.[10] Two levels of categories are distinguished hierarchically: Level-I consists of broad, general classes such as urban and built up land, agricultural land, forest land, etc.; while Level-II subdivides the Level-I classes into more detailed categories - for example, residential, commercial, industrial, etc. - within the urban and built-up class. In any particular region, classification at Level-I will generally result in five to ten categories being distinguished. Several investigations have found LANDSAT/MSS data adequate for such Level-I type mapping.[2-5-6-7-11-12] At scales of 1:125,000 to 1:1,000,000 Level-I classification can provide accurate, cost-effective information for many regional planning tasks.[2-6-11-12-13-14] Level-II mapping with LANDSAT/MSS data is not normally considered practical since some of the essential categories cannot be identified with the ground IFOV provided (approximately 80m).[11-12]

Similarly, Skylab S-192 scanner data (ground IFOV approximately 80m) were found to be generally inadequate for Level-II mapping.[8] The same study indicated that S-190B filmed data (ground resolution approximately 20m) provided significantly better discrimination, and were adequate for good Level-II mapping. It was clear that the finer resolution of this sensor was the primary reason for its success in Level-II mapping.

Experience indicates that complete Level-II mapping would require ground IFOV of roughly 10-20m. Therefore, most state and local programs using satellite data also employ high altitude aircraft for the high resolution data in an integrated approach to land use mapping. [4-15-16-17]

Scene-to-scene pixel registration (long term scan stability) is also a critical factor where multitemporal analysis is used in land use mapping. There are indications that misregistrations as small as 0.5 IFOV can significantly degrade accuracy of classification.[8]

Use of any type of remotely sensed information by urban land use planners is in a formative stage.[1] The state and local planners in whom virtually all current management responsibility is vested are understandably slow to substitute remotely sensed data for the extremely detailed conventional sources (tax and property maps, census data, administrative files, etc.) usually available to them. While land use dynamics, increased information costs, centralization of management authority, and experience with remotely sensed information are expanding the use of remote sensors, there is currently no large user demand for the regional, Level-I type maps typically produced from orbital data.[1-2-6-18] Several state and regional authorities including North Carolina, North Dakota, Ohio, Michigan, and Ohio-Kentucky-Indiana Council of Governments are using LANDSAT-derived land use maps in support of federally sponsored, regional water management programs and other large scale land and water use planning functions. As the need and federal support for such programs increase, so will the use of orbital platforms for data collection. Nevertheless, in most of the state and local management/planning functions, substitution of orbital data for aircraft film data will be slow until ground IFOV from orbital scanners can provide at least Level-II maps at reasonable costs.

Equatorial Crossing Time

Equatorial crossing time is not a critical parameter for most land use management applications. One exception is the Coastal Zone management program which requires data on a regional basis such as is provided by orbital sensors. The critical relationships between coastal land use and the adjacent aquatic environments may be obscured by sun glitter if crossing times are later than approximately 1000 hrs.[19] Regional water management programs have used data from LANDSAT primarily for land use and terrain analysis. However, because coastal waters, lakes and reservoirs are also of interest, glitter-free data are required. Avoidance of clouds is also of concern in determining utility of data.

Frequency of Coverage

Most land use management functions do not require frequent update of map data. At the small scales provided by current orbital data, some maps need be revised only every five to seven years. Higher resolution information may be used on a more frequent basis, ranging from hourly (for water pollution monitoring) to quarterly (for short term land use dynamics). In general, current LANDSAT nine- to eighteen-day frequencies would be adequate for virtually all land use applications *if* the IFOV were satisfactory.

Data Processing and Archiving

As remotely sensed land use data come into general use, extensive archiving systems with access to both historic and recent data will be required. The accuracy of automated classification of many land use categories varies considerably by season and/or month. Thus, the development of effective automated classification techniques, change-detection capability, and valid trend assessment is dependent upon easy access to all data on a seasonal and/or monthly basis. This capability should be available to each state and supplemented by state or regional browse facilities. Selective purging of historical data files could be tolerated if enough information were retained to record at least annual and long-term trends in land use dynamics.

Data delivery within one to two weeks of acquisition would be sufficient for most land use management functions. More rapid response is required, however, in enforcement of environmental regulations (See Environmental Monitoring - page 92).

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Geological Applications

Geologists have included remote sensing techniques in their repertoire of exploration and analytical procedures for many years. The availability of LANDSAT orbital data, beginning in 1972, has naturally drawn considerable interest from geologists. The mineral and petroleum exploration community is now the largest single group of LANDSAT data purchasers (Committee Briefing by W. Fischer, USGS, November 1975). While most of the specific interpretation techniques and geographical locations of interest to commercial exploration and extraction firms are proprietary and therefore not readily available for evaluation, the sheer volume of data purchases would seem to indicate that LANDSAT data may have considerable value. In general, orbital data are used as an adjunct to aircraft photo interpretation, geophysics, and other field survey techniques and are not expected to completely replace any of the proven procedures. However, the unique perspective provided by orbital sensors provides an added dimension and is a valuable reconnaissance tool that can enhance the productivity of geological exploration.

Other geological applications, e.g., groundwater hydrology, hazard detection and monitoring, and specialized soils mapping, can also derive benefit from orbital data and are described in the technical literature. Many of these users have requirements that are quite divergent from those of the exploration/extraction community. Thus, it is difficult to specify system capabilities required by "geological users" as a general category. In some cases, differing geological applications may place demands upon sensor design that cannot be reconciled in a single instrument.

With the understanding that divergent application requirements make optimal characterization of "geologic" sensor needs difficult, the following discussion is presented.

Spectral Bands

In general, the multispectral properties of rocks are poorly understood and are not presently used to identify rock types by means of remote sensing. Reflectance characteristics vary widely due to weathering conditions, moisture content, and vegetative and soil cover and are therefore only very generally correlated with the chemical (mineral) and physical properties of the subsurface rock. The relationship of "blue" (0.4μm to 0.5μm) to "red" (0.6μm to 0.7μm) reflectance is useful in characterizing the oxidation state of component iron[1] and may be useful in identifying some mineralized areas. In most cases, however, the relative spectral properties of rocks, soils, and overlying vegetation are used only to discriminate among different types; actual lithologic identification is accomplished through field observations.[1]

Multispectral imaging also allows observation of structural and topographic features that may be instructive in themselves or may provide a clue to the rock type in which they are found.[2,5] The four LANDSAT spectral bands have been found to be useful for observation of structural features, particularly large lineaments[2-3-4-5] and for some general discrimination of soil and rock types at small scales.[6-7-8-11] Most studies used visual interpretation of composite or single band imagery in different combinations, employing the four MSS bands.[3-5-8-11] Two studies indicated preference for Band 7 (0.8μm to 1.1μm) as the best single band for lineament detection.[2-4] In discriminating rock types, some investigators used ratioing or digital analysis techniques that made use of all four MSS bands (0.5μm to 0.6μm, 0.6μm to 0.7μm, 0.7μm to 0.8μm and 0.8μm to 1.1μm).[6-7] Published reports indicated that petroleum exploration groups use composite images, made from combinations of all four MSS bands to analyze physiography, rock type, and lineaments at small scales.[9-12-13]

Outside of the spectral range provided by the current LANDSAT/MSS there is good evidence that thermal infrared sensing (approximately 4.0μm to 14.0μm) can produce useful geological data. Volcanic and some geothermal phenomena are detectable in thermal data. The ground IFOV's of current orbital thermal sensors (Skylab S192, X-5 Thermal Sensor, IFOV approximately 80m) are inadequate to locate small geothermal (<400 m^2) areas unless their temperature is very high (360 to 480K).[10-14] More subtle temperature differences can be used to locate ground water discharge into surface water bodies.[15-16] Monitoring of rates of temperature changes at different times of day under uniform conditions have been used to differentiate rock types.[17] As mentioned earlier, measurements in the "blue" spectral region (0.4μm to 0.5μm) can be combined with data in the "red" (.6μm to 0.7μm) region for studies of iron oxidation,[1] and thus extension of coverage into the "blue" region is desirable. The 1.55μm to 1.75μm infrared band is sensitive to moisture stress in vegetation (see Vegetation Inventory and Assessment - page 29) and could be used as an indicator of the hydrologic characteristics of the underlying soil and rocks.

Ground IFOV

Ground IFOV is the sensor parameter of primary concern to most geologic users of remote sensor data. Through many years of exploration most large features of geologic interest indicating areas of mineral deposits, surface expression of geologic structures indicating possible accumulation of hydrocarbons, geologic hazards, etc., have already been identified. With the exception of the few remote and unexplored areas of the earth yet remaining, the major benefit to be derived from comprehensive world coverage of the type provided by orbital sensors is location of the smaller, more isolated, less prominent features that have escaped detection by past explorations. Thus the value of remote sensing systems, particularly in petroleum and mineral exploration, is heavily dependent on the size of the smallest discriminable feature.

The successful uses of LANDSAT/MSS 80m data have been in identification of large features such as ancient stream beds for potential ground water supply,[18-19] detection of lineaments 10 km to more than 100 km long,[2-9-20] and in soil and geologic mapping at scales of 1:250,000 or less.[8-10-11] LANDSAT/MSS data have not been adequate for some investigations in which smaller features or larger scales are involved.[3-21] As previously noted, Skylab thermal data also suffer somewhat from too large an IFOV (approximately = 80m).[14] Even S190A and B Skylab photographs (15m to 30m resolution) are not completely sufficient for many mineral exploration tasks.[3] One study of faulting found significantly more value in S190B photography (IFOV equivalent 15-20m) than in S190A photography (IFOV equivalent 30-40m) for mapping of faults, due to the approximately 20m difference in ground resolution.[22]

Generally, improvements in IFOV to 30-40m would increase the detectability of alteration aureoles and other indicators of mineralization. Structures in sedimentary rocks important to petroleum exploration would also be more identifiable with 30m to 40m IFOV. IFOV's of 15m or better would allow detailed fracture mapping with utility in hazard detection and petroleum and ground water exploration. Ultimately, there will always be a need for ground surveys, including subsurface investigations through drilling and geophysical studies. Some such tasks, particularly monitoring of tectonic activity such as tilting, swelling, changes in heat flow and other physical properties, could be aided by a system analogous to the LANDSAT Data Collection Platforms (DCP) in which data from instruments located in remote and inaccessible areas could be relayed to investigators at a central location.

The geological community has expressed a strong interest in the Synthetic Aperture Imaging Radar (IFOV = 25m) scheduled for flight on SEASAT (NASA oceanographic applications satellite planned for launch in 1978). If the radar is activated over land as well as water, these data can be invaluable in physiographic analysis, especially if made compatible with LANDSAT data.

The future of orbital data for geological exploration purposes seems to lie in their contribution to an integrated, ground-aerial-orbital system such as is already in use by some commercial exploration firms.[23] The magnitude of the orbital system contribution depends primarily on the adequacy of the ground IFOV of the sensor.

Frequency of Coverage

Most geological users are not particularly demanding in their requirements for frequent coverage. Discrimination of most features requires, at the most, seasonal coverage so that changes in vegetation can be observed and the topography can be viewed under different sun angles. Once the useful information has been extracted, further coverage is usually unnecessary, since temporal variation in most geological features is very slow. Monitoring of some seismic, glacial, hydrologic, and volcanic phenomena can benefit from data now available from LANDSAT's 1 and 2 (coverage every nine days) particularly if supplemented with data collected by in situ instruments and relayed via orbital platforms. A specialized use of thermal data in differentiating rock type through thermal inertia requires more than one measurement during a 24-hour period. Analysis of some geological hazards--landslides, mudflows, etc.--may require daily or more frequent coverage. These tasks are generally more compatible with suborbital sensing platforms.

Radiometric Sensitivity and Data Quantization

Most geologists interested in discrimination of rock and soil type (including the mineral and petroleum exploration communities) agree that the sensitivity of remote sensing instruments is of major importance. Increased sensitivity can discriminate small differences in ground cover reflectance that may indicate differences in underlying rock and soil type. The indirect effects of subsurface characteristics on surface soil and vegetation are usually quite subtle. High radiometric contrast associated with differing subsurface conditions is rarely noted. The sensor must be highly responsive to these small variations. Furthermore, the variability observed in many geological phenomena is transitional and it is important that the subtle gradations be preserved as much as possible in remote sensor data. The transitional lateral variations in sedimentary facies, for instance, may be important in petroleum exploration. If radiometric data are recorded in large steps (or quanta) these variations may appear to occur as sharp boundaries, and a very different conclusion will be drawn about the nature of the lithology. Thus, it is critical that the full radiometric sensitivity of orbital scanners be preserved in the data output through sufficiently fine grey level quantization in recording and transmission. Two studies of sensor parameters have indicated the need for $NE\Delta\rho$'s between 0.2 and 1.0 percent for rock and soil discrimination.[21-24] Desired $NE\Delta T$'s are between 0.5°C and 1.0°C.[21-24]

Bare soil and rock can exhibit much higher reflectances than vegetation in the "visible" portion of the spectrum and so it is important that these cover types be considered in setting dynamic range specifications. Reflectances up to 60 percent have been observed in soils in the visible spectrum, as compared to a maximum of 30 percent over vegetation. One study even recommends a 70 to 78 percent reflectance saturation threshold for geological studies in the visible spectrum.[24] In the reflective and thermal infrared, geological applications do not have dynamic range requirements significantly different from those needed by the other users discussed in this chapter. While volcanic and some geothermal phenomena do exhibit unusually high temperatures, orbital thermal sensors are, with few exceptions, used to detect such thermal anomalies and thus do not require detailed temperature differentiation within the observed range. It is not necessary to extend normal thermal sensing ranges to high temperatures (>330K).

Equatorial Crossing Time

Geological interests do not all agree on equatorial crossing time for orbital platforms. In flat terrain, typical of many petroleum-bearing provinces, low sun angles are desired so that subtle topographic expressions of structure and geomorphic features may be more readily observed. In areas of high relief where much mineral exploration is conducted, however, shadows can obscure significant spectral characteristics and so high sun angles are desirable. Because of this divergence of applications, no definitive preference can be expressed. Where possible, observation under different sun angle conditions would be preferred by geologists in orbital mission planning. Even with constant local observation time, seasonal variations in sun angle provide a useful dimension of topographic information.

Data Processing and Archiving

Geological demands on speed of data delivery are not particularly severe. With the exception of some hazard monitoring, data delivery within several weeks of acquisition is adequate.

Long-term archiving of historical data would be valuable for geologic processes with very slow rates of change, such as glaciation and erosion. As with current data, however, frequent coverage is not necessary - perhaps one data set per year is sufficient for those specialized uses requiring historical information.

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Oceanography and Coastal Zone Management

Coastal and oceanographic research programs have realized significant benefits from the application of spacecraft remote sensing, despite the fact that no existing sensor or mission has been optimized for marine uses. Marine programs may be divided into three groups of applications having different sensing requirements: coastal-terrestrial, near-shore marine (including lakes), and open ocean.

In general, sensor systems designed for application in inland areas are also appropriate for use in the terrestrial environments of the coastal zone, even where they are periodically influenced by the tides (e.g., coastal wetlands). The concentrations of population and industrial activity in coastal areas lend particular impetus to inventories of vegetation and land use with a scale and frequency of update compatible with orbital remote sensing.

In near-shore marine and lake environments sensor requirements may be quite different - particularly in the spectral range, resolution, and frequency of update needed.

In the deep waters of the open ocean, the large area coverage of spacecraft sensing is particularly advantageous, but ground resolution, frequency of update, and spectral range requirements are somewhat different from those in the other areas of marine concern.

Central to modern concepts of coastal zone management and ocean studies is perception of the complex interrelationships between the marine environment and the adjacent coastal zone with its human inhabitants. Results achieved with existing orbital sensors indicate considerable potential for satellite monitoring of the coastal and oceanic regions of the world. A significant aspect of this potential is the synoptic view of the entire marine and coastal system provided by spacecraft - a potential that can be considerably enhanced through consideration of marine problems in the design of comprehensive earth observation programs as well as through specific marine-oriented missions.

Spectral Bands

Applications of remote sensing in the terrestrial environments of the coastal zone do not require significantly different spectral coverage from that used for detection and monitoring of inland cover. The prime objectives in both cases are mapping of vegetation/land use and detection of surface water, bare soil and geologic features expressed directly in surface materials or indirectly through vegetation changes in response to subsurface features. LANDSAT/MSS data have been applied to regional inventory of coastal land use[1-2-3-4] and vegetation, particularly wetland plant communities.[4-5-6] Optimization of band selection for land use, agricultural inventory, and other terrestrial purposes should satisfy the coastal application requirements, and so further discussion is deferred to those disciplines primarily concerned with terrestrial areas (Vegetation Inventory and Assessment, Land Use Management, and Geology).

In near-shore marine and lacustrine areas, spectral requirements diverge from those over land. Some degree of water penetration is usually desirable, and requires extension of spectral coverage to shorter wavelengths than those usually used for terrestrial applications. In mapping of coastal bathymetry, LANDSAT/MSS Bands 4 and 5 (0.5μm to 0.6μm and 0.6μm to 0.7μm) have been used to measure water depths down to approximately 7.5m in clear coastal water and to approximately 2m in more turbid waters.[7] The optimum single band for bathymetry varies according to bottom reflectance, water clarity, and atmospheric conditions; however, a theoretical investigation indicates an optimal short wavelength cutoff for general bathymetry between 0.45 and 0.48μm and an optimum long wavelength cutoff between 0.55 and 0.58μm.[8] The LANDSAT/MSS "green" (0.5μm to 0.6μm) band appears to be suboptimal for bathymetry purposes because of less bottom contrast at the 0.5μm short wavelength cutoff and attenuation of signal in the 0.58 to 0.6μm region.[8-9] An empirical study using Skylab S192 scanner data in the 0.46μm to 0.51μm and 0.52μm to 0.56μm bands reported depth measurements accurate to within approximately 15 to 20 percent at depths down to 20m in clear, tropical water.[10] Therefore, extension of coverage into the "blue" region at approximately 0.46μm is indicated for maximum water penetration and bottom contrast in shallow water bathymetry studies.

Near-shore current circulation studies using natural water-mass tracers, especially suspended sediment, have successfully employed LANDSAT/MSS data.[11-12-13-14-15] Relatively low concentrations of suspended material may be observed in MSS Bands 4 and 5 (0.5μm to 0.6μm and 0.6μm to 0.7μm), while Band 6 is best for delineation of highly turbid water masses.[16-17] Some investigators have attempted quantitative assessment of suspended sediment concentrations either through regression with radiance in the 0.6μm to 0.8μm range[16-18] or through comparison of MSS measured spectra with reference spectra obtained by other instruments.[19] The results of the latter study have been incorporated into Corps of Engineers' operational inventorying and monitoring of estuarine and inland waters.[19] Thermal sensing in the 8.0μm to 13.0μm emmissive range has also been used from various platforms including spacecraft, to monitor currents and point-source thermal plumes.[20-21]

Detection and monitoring of photosynthetic productivity in the marine environment is a high priority endeavor with global implications. Attempts to quantify chlorophyll concentrations in aquatic suspension have met with mixed results. Inaccuracy is primarily due to the inability to discriminate between chlorophyll and inorganic sediment.[22] However, measurements of marine photosynthetic organisms show a "hingepoint" at approximately 0.52μm, below which chlorophyll in suspension reflects strongly and above which absorption is dominant (Committee briefing by J.W. Sherman III, NOAA Spacecraft Oceanography Project, January 1976). Sediment, on the other hand, acts as a broad-band backscatterer. Thus, the use of two bands, separated at approximately 0.52μm, may allow discrimination of chlorophyll from inorganic sediment. Separation of the "blue" from the "green" spectral bands at approximately 0.52μm would aid analysis of chlorophyll distribution.

Monitoring of polar region sea ice has applications in meteorology and navigation. LANDSAT/MSS spectral bands, particularly in the reflective infrared (0.7 to 1.1μm) region have been used to observe fracture and lead formation, shearing, freeze-thaw conditions and distribution of icebergs in arctic and antarctic seas.[23-24] Spectral coverage in the 1.55μm to 1.75μm region would allow effective discrimination of snow and ice from clouds, while temperature conditions at the snow/ice surface could be monitored in the thermal infrared region (8μm to 13μm).

Ground IFOV

For marine applications the maximum tolerable dimensions of the IFOV vary from approximately 10km for global current mapping and ecosystem analysis to 10m or less for monitoring of coastal processes and land use (Table 2.4).[25] Large IFOV's, even from orbital scanners, generally do not constrain open ocean studies in which the system is characterized by large expanses of water with very gradual horizontal variability. In observation of near shore and coastal processes, resolution becomes a more critical parameter.[25]

In coastal-terrestrial areas, IFOV requirements largely parallel those of the general vegetation mapping and land use management community. For these applications, the needs for IFOV and cartographic accuracy often exceed the capabilities of currently envisioned orbital sensors and will continue, for some time, to require aircraft or ground surveys. Small scale (1:250,000 to 1:500,000), regional inventories of coastal land-use have been accomplished using the LANDSAT/MSS 80m ground IFOV.[1-2-3-4] While such inventories are useful in regional planning and research directed at environmental trends, state and local authorities usually require much more detailed larger scale maps to support planning activities. (See Land Use Management - page 46.)

In the area of inventory of natural vegetation for management purposes, ground IFOV requirements are not as restrictive as when the activities and structures of man are the prime concern. Mapping of wetlands, in particular, has benefited from application of remote sensing, including LANDSAT data.[1-4-5-6] Legal mapping requirements (e.g., in support of legislation requiring permits for certain activities in tidal wetlands) are unlikely to be fulfilled in the foreseeable future by satellite data. However, improvements in ground IFOV of orbital scanners will be helpful in inventories for environmental impact and management purposes in two primary ways. Classification accuracy of wetland vegetation communities could be improved with smaller IFOV's by providing more homogeneous training samples for use in automated multispectral analysis. Mensuration could be improved with more precise location of class boundaries and more accurate and detailed delineation of species, or other classes. IFOV's between 30m and 50m have been indicated as desirable for wetlands inventories.[25]

The LANDSAT/MSS data have been applied by many groups to map coastal currents, shoals and detection of pollution.[7-9-11-12-13-14-15-16-17] However, both the detectability and accuracy of location would improve with smaller IFOV's. Again, IFOV dimensions of 30 to 50m are desired to produce useful results in a wide range of geographic areas and applications.[25]

TABLE 2.4

IFOV Requirements for Marine Applications

Typical Applications	IFOV
Mapping mean high/low water Coastal current measurement	<10m
Coastal pollution detection Shoreline mapping and shoals Wetlands inventory	30 - 50m
Sea ice surveillance	30 - 100m
Pollution/environmental impact	30 - 300m
Turbidity and sediment transport Bathymetry and bottom topography	50 - 100m
Biological assessment	1 - 2km
Global current mapping Global ecosystem analysis	1 - 10km

Source: Adapted from NASA Advanced Scanners and Imaging Systems for Earth Observations (1972), page 65.[25]

Radiometric Sensitivity and Dynamic Range

In coastal waters spectral radiance changes as low as 0.016 mw/cm^2-sr have been observed in LANDSAT/MSS Bands 4 and 5 (0.5μm - 0.6μm and 0.6μm - 0.7μm) across the boundaries of ocean currents. Effective measurement of such small variations in signal requires better sensitivity than is available in the normal LANDSAT/MSS gain mode. Improvements in sensitivity by a factor of 3x were obtained by operating the LANDSAT/MSS in the "high gain mode." Significant improvements for many oceanographic applications were observed.[7-9] Therefore, future sensors should incorporate improvements in sensitivity of at least 3x in the "blue-green" spectral region. NE$\Delta\rho$'s of 0.5 to 1.0 percent are desired by marine users in a five to seven band instrument.[25-26]

In thermal sensing, a dynamic range allowing measurement of temperatures between 240 K and 320 K is necessary to cover the widest range of oceanographic applications. The low temperature cutoff is determined by interests in snow and ice surface temperatures (Committee briefing by J.W. Sherman III, NOAA Spacecraft Oceanography Project, Jan. 1976). NEΔT's between 0.5°C and 1° C are needed within the above range.[25-26]

Equatorial Crossing Time

The time of equatorial crossing is of prime concern to investigators studying open water features, since sun-glint can obscure large portions of a scene over water if solar zenith angles are within a particular range of values. Calculations show that with a surface wind velocity of only 5 m/sec, a scanner sensing around the nadir at 1100 hrs will encounter a minimum sun glint zone 35° wide between 35° N and 35° S latitude.[27] During some seasons the entire image will be obscured by glint at 1100 hrs.[27] Both the LANDSATs 1 and 2 have an equatorial crossing time of 0930 hrs, which allows observation of all portions of the earth during all seasons without sun glint except where high winds produce wave slopes ≥15°.[27] Actual observations of serious glitter obscuration have been made by aircraft after 1030 hrs.[28] Crossing times before 1000 hrs are thus desired if a scanner is to have effective, continuous application in marine investigations (Committee Briefing by J.W. Sherman III, NOAA Spacecraft Oceanography Project, Jan. 1976).

As in any other nonmeteorological application, cloud cover is to be avoided for maximum utility in marine applications. If cloud buildup is found to be significantly related to time of day, this relationship should be considered along with sun glitter in planning the local time for observations.

Frequency of Coverage

Marine features vary much more rapidly than terrestrial phenomena, often approaching the variability of atmospheric conditions. The demands upon temporal sensor coverage become particularly severe if tidal effects are to be observed. Surface current circulation patterns can change significantly within an hour in a tidal estuary, within a day on the continental shelf, and over longer periods in the open ocean. Orbital platforms, such as the LANDSAT series, cannot be expected to meet all of these diverse coverage needs. Therefore, for the foreseeable future, aircraft will be needed to supplement satellite observations of short-term marine phenomena.

LANDSAT 1 and 2 coverage frequencies of eighteen and nine days have been used in a variety of marine applications, including some studies of short-term coastal phenomena. Long periods of data collection (one to four years) can be used to accumulate observations under realistically varied sets of meteorological and tidal conditions; for some applications this process roughly simulates more frequent coverage. Applications in coastal areas could be greatly expanded, however, with the capability for daily observation frequencies. At high latitudes, overlapping LANDSAT coverage has provided observation of sea-ice conditions in some areas for two consecutive days[23] and other high-latitude phenomena could benefit from the same capability. Consecutive-day overlap will only occur if the orbits of a two-satellite system are planned so that each satellite covers contiguous swaths on consecutive days. Collection of collateral data on the surface is simplified at any latitude if adjacent swaths are imaged on consecutive days, allowing stripboard teams to make data collection excursions of more than one day. Any swathing pattern, such as an interlaced arrangement, which does not provide consecutive coverage of adjacent swaths by each satellite is to be avoided.

Data Processing and Archiving

Experience with LANDSAT's 1 and 2 indicates that some marine applications could benefit from real-time data output. On one occasion, during a special experiment, near-real-time output was successfully used to direct oceanographic sampling.[29] In addition, research on living marine resources indicates that biological sampling and fishing activities could use orbital data if they were available in near-real-time. For the most part, however, data availability within two to nine days of acquisition would be sufficient for both operational and research uses of data obtained with LANDSAT 1 and 2 (nine-day) coverage frequency.

Data formats for the longer wavelength instruments planned for flight on the SEASAT mission (the NASA oceanographic applications satellite planned for launch in 1978) should be compatible with visible-IR sensors; correlation of ocean color and coastal features with sea state, surface winds, etc. would be of considerable value.

It is difficult to generalize desired archiving procedures for the wide range of marine applications. Land use and some vegetation studies certainly benefit from historical data, and long term data are also valuable in assembling observations of marine phenomena under many different conditions if daily, or more frequent, coverage is not available. It is difficult, particularly over water, to specify an interval beyond which data need not be stored nor is there any rational basis for choosing some data over others except by instrument performance and cloud cover. These experiences would seem to support the feeling that original data, no matter how old, should not be destroyed. One set of original data should, if feasible, be stored permanently on some reliable, economic medium at a central facility. Secondary and enhanced data products, such as film transparencies, film prints, computer compatible tapes and enhanced imagery for selected time periods (e.g., one to two years) should be accessible to users at central and various regional "browse" facilities.

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Water Resources Management

Water resources data are employed by a variety of users for a wide range of purposes. Because of such diversity, there can be no single characterization of "water user needs." However, broad categories of water data can be identified that are required by classes of users or by types of problems.[1] These data requirements can then be matched to existing or proposed water information systems or networks that use conventional, experimental, or a mixture of collection approaches.

In general, water resources problems can be classified according to time and space dependencies. Hydrologic time-dependent problems range from operational river forecasting of "flash floods" (critical time intervals may be less than one hour) to archiving of annual water resources data for each of the 50 states (USGS publications are usually issued about one year after the year of record). Hydrologic space-dependent problems can range from the design of an urban storm drainage system (a few acres in size) to water resources planning for large river basin projects of 100,000 mi^2 or more. Small areas and quick response times are usually associated, as are large areas and slow response times. However, small area/non time-dependent tasks (such as ordinary hydrologic design of small projects) are perhaps the largest single class of water resources problems in terms of annual expenditures. Data gathering costs usually are a very small fraction of the overall expenditures for most hydrologic projects.

Spectral Bands

The requirements for spectral resolution related to hydrologic purposes are not well established. Data are available from about 33 spectral bands (some are duplicates) from: U-2/Vinten multispectral cameras (4 bands), the RC-10 Wild framing camera (1 band), Skylab/Earth Terrain Camera (S190B-3 bands), Skylab/S-190A multispectral photographic camera (6 bands), Skylab/S-192 MSS (13 bands), LANDSAT/MSS 1 and 2 (4 bands), and the NOAA/VHRR (2 bands). In spite of the availability of measurements in many spectral bands, there is little in the hydrologic data gathering experience to form an adequate basis for optimal selection of band locations and widths. However, while sensing of hydrologic parameters has not strongly affected the selection of spectral bands for present instruments, useful data have been acquired from many of the available sensors.

LANDSAT/MSS data in the 0.8µm to 1.1µm (Band 7) region have been used to inventory surface water bodies by the State of Virginia[2] and the U.S. Army Corps of Engineers.[3] The high contrast of the land/water interface provided by the low signal over water in the 0.8µm to 1.1µm band has also lent itself to studies of flood extent.[4-5-6] In addition, flood mapping has been accomplished by using data in the thermal band (10.5µm to 12.8µm) of the NOAA/VHRR sensor.[7]

Surface (top 2.5cm) soil moisture can be effectively measured over sparsely vegetated areas in the 21cm (L-band microwave) spectral region of the Skylab/S-194 sensor.[8] The L-band imaging synthetic aperture radar, to be carried on SEASAT (the NASA oceanographic applications satellite planned for launch in 1978), may provide useful data in this spectral range if it is activated over land areas. There are also indications that data recorded in thermal wavelengths can be correlated with soil moisture.[9]

Several studies of snowcover have been made using available orbital sensors with encouraging results. Data from LANDSAT/MSS Band 5 (0.6µm to 0.7µm) have been used to monitor snowcover for correlation with subsequent melt runoff.[10-11] High correlation (r = .92) has been noted between runoff and snowcover, as measured by the LANDSAT/MSS in the 0.6µm to 0.7µm and 0.8µm to 1.1µm (MSS Bands 5 and 7) regions.[12] Extension of spectral coverage into longer wavelengths, as in the Skylab S-192 scanner, provides discrimination of snow from clouds in the 1.55µm to 1.75µm infrared region.[13]

In detection and monitoring of water quality, radiance in LANDSAT Bands 4, 5 and 6 (0.5µm to 0.6µm, 0.6µm to 0.7µm, 0.7µm to 0.8µm) has been correlated with chlorophyll and sediment concentration in lakes, reservoirs and rivers.[2-14-15] In general, spectral requirements for such applications are identical to those discussed in the Oceanography and Coastal Zone Management and Environmental Monitoring sections of this report (see pages 63 and 87).

In the light of the experience obtained in hydrologic data gathering from available orbital sensors, the following generalizations may be made:

- The four bands of LANDSAT/MSS (0.5μm to 0.6μm, 0.6μm to 0.7μm, 0.7μm to 0.8μm and 0.8μm to 1.1μm) have been demonstrated to be generally useful for hydrologic purposes, and
- Extension of spectral coverage into the blue (0.4μm to 0.5μm) and thermal infrared (8.0μm to 14.0μm) areas would be significantly useful.

Ground IFOV

For water resources purposes, the single most important specification for remote sensing systems is "ground resolution", or IFOV as used in this report.

A general scope of the hydrologic resolution requirements is presented in Table 2.5, in which an experienced panel of water engineers and managers attempted to summarize ground IFOV needs for hydrologic purposes.[1] As examples, the 12 hydrologic parameters of "land characteristics" vs. range of required ground IFOV are shown. The wide range of desired ground IFOV, even within a specific application such as flood delineation (1 - 100m), is notable and results from the extensive variability in both the size of hydrologic features of interest and in the accuracy of boundary determination and measurement required. Water resources management involves evaluation of such a broad continuum of feature size that virtually every available sensor IFOV (up to 900m from NOAA/VHRR) has found some use, and any incremental decrease in IFOV makes a new class of significant features accessible to analysis. Some specific examples of the utility of particular IFOV's follow.

TABLE 2.5

IFOV Requirements For Analysis of Some Hydrologic Parameters

Hydrologic Parameter	Ground IFOV
soil	
type	10-30m
infiltration	10-30m
areal extent	10-30m
salinity	10-30m
vegetation	
type	10-100m
moisture stress	10-100m
areal extent	10-100m
flood delineation	1-100m
storm damage	10-100m
waterworks	1-100m
impervious areas	10-100m
irrigation practices	10-100m

Source: NAS, 1975[1]

LANDSAT/MSS imagery has been used to delineate water bodies as small as 0.1 - 0.2 km^2.[16-17] This value of ground IFOV (approximately 80m) is useful for many water resources problems where supplemental interpretation of available maps is required or where map information at scales <1:250,000 is inadequate because of scale or lack of update. LANDSAT maps have been produced by computer techniques at scales of 1:62,500 and even 1:24,000. Such maps have been useful in some instances, even though they obviously do not meet national map accuracy standards. Other types of hydrologic mapping using LANDSAT/MSS imagery include: flood and flood plain mapping; hydrologic land use (to Level-I and sometimes Level-II of the classification system described by Anderson et al.[18]); and physiographic measurements such as drainage area, shape, and channel sinuosity.

The effect of incremental improvements in ground IFOV for the snow mapping problem is reported by Rango et al.[19] Simple regressions between snow cover and seasonal runoff showed significance at the 99 percent level for the Indus

River watershed (using NOAA/VHRR imagery of 900 meter ground resolution) and for watersheds in Wyoming (using LANDSAT/MSS, 80m ground IFOV) as small as 200 km^2. Improving ground IFOV to 30-40m is likely to allow assessment of drainage areas smaller than 200 km^2. This would be useful for regions characterized by small river basins typical in New England.

In reservoir management and operation, a study employing several orbital sensors concluded that the LANDSAT ground IFOV (approximately 80m) was "marginally useful" but that resolutions equivalent to those provided by the Skylab film cameras (approximately 10 to 40m) would be much better.[20]

Experience shows that there are certain fine ground IFOV requirements (<10m) that may require capabilities equivalent to aircraft photography.[1] Collection of in situ measurements in inaccessible areas can also be simplified in some cases by use of remote data collection platforms transmitting data via satellite links. LANDSATs 1 and 2 and geosynchronous meteorological satellites presently provide this communications capability and geosynchronous spacecraft are expected to continue to do so in the future.

Equatorial Crossing Time

The approximately 0930 hrs LANDSAT time of crossing has been adequate for hydrologic studies, although a later crossing time (1000 - 1100 hrs) might be better due to improved signal-noise ratio with higher sun angle. Crossing times for hydrologic applications should, of course, be sensitive to the statistical probability of cloud cover at various times of the day.[21] Sun glitter could affect those problems associated with open water if sun elevation at time of viewing is too high (see Oceanography and Coastal Zone Management - page 67), although the bulk of hydrologic problems do not involve areas of open water. Shadows enhancing terrain features for drainage basin analysis would be more evident with early crossing times, although in areas of high relief extensive shadows might also obscure significant features. While no studies have attempted to select optimal crossing time for hydrologic applications, indications are that doing so would be difficult and subjective and probably would focus on cloud cover as the principal consideration.

Frequency of Coverage

Frequency of coverage is an important characteristic for many time dependent water resources data problems. Present frequency of coverage experience with aircraft and satellite systems ranges from twice per day (NOAA-2,3,4, Nimbus, to once per 18 days (LANDSAT), to once per nine days (two LANDSATS), to variable coverage (U-2 aircraft). Experience has shown that the required frequency of coverage for hydrologic data varies greatly from operational high frequency requirements to analysis of long-term trends. Some general applications and the range of required frequencies are presented in Table 2.6.

The difference in usefulness due to the frequency of coverage between the 18-day LANDSAT-1 single satellite system and the nine-day two-satellite LANDSAT system is difficult to quantify. Many users of water data do not require frequently collected information. Hydrologic data for design, surveys, reconnaissance, planning, inventorying and research generally require long continuous and accurate years of records to perform statistical analyses for planning and design. For such time-independent problems, neither nine-day nor 18-day repeat coverage is significantly more useful than seasonal or even yearly coverage would be.[1-22]

Another type of problem concerns "pre- or post-hydrologic events"; for example, damage assessment after flooding and research or planning phase in assessing a situation before construction. Here, updated water information is required that can describe a particular situation at a particular time. High frequency coverage is not of primary importance except as it provides one set of recently updated information.[20] The nine to eighteen day coverage cycle of LANDSAT is adequate for this type of problem.

TABLE 2.6

Required Coverage Frequencies For Typical Applications In Hydrology

Application	Frequencies Needed
Evaluation of Surface Waters	Daily to weekly
Evaluation of Subsurface Waters	Daily to monthly
Glacial Ice Studies	Seasonally to yearly
Estuarine Studies	Seasonally
Wetlands Inventory	Yearly
Watershed Characterization	Yearly to one observation with no update
Land Characterization	Yearly to one observation with no update
Water Quality Assessment	Hourly to seasonally
Shoreline Studies	Hourly to monthly to yearly
Surface Radiation Studies	Daily to weekly

Source: NAS, 1975.[1]

Operational problems, as a class, are most time-dependent. As shown in Table 2.6, the required frequencies can vary from hourly to seasonal. The number of hydrologic parameters or events usefully sensed is not greatly increased when coverage drops from eighteen to nine days.[1] The nine-day repeat cycle is still too long for most hydrologically time-dependent problems where hourly, daily, or weekly coverage is required. Further, nine-day coverage offers little advantage over an 18-day cycle for seasonal or yearly requirements except for cases in which twice the coverage can effectively increase the chances for cloud-free viewing. For example, in the case of operational management of reservoirs by the New England Division Reservoir Control

Center, U.S. Army Corps of Engineers, the daily operations require critical information at least daily or marginally once each two days on a routine assured basis, especially during storm events.[20] Many water resources managers have provided for ground based real-time data communications networks to acquire timely data. The LANDSAT Data Collection Platforms (DCP) can provide near-real-time capabilities.[20] The U.S. Geological Survey, Water Resources Division currently has 200-300 operating data collection platforms and is in the process of converting some transmission equipment for use with existing or planned geostationary satellites for more effective continuous communication (personal communication, Mr. D. Anderson, USGS, July, 1976).

The nine-day frequency would appear more advantageous than an 18-day cycle for seasonal snow melt forecasting, for medium to large drainage basin reconnaissance where hydrologic response times are within the nine-day time frame; for lake ice monitoring; for some subsurface water survey problems; and for inputting data of slowly-changing parameters for some hydrologic models.[1]

In summary, the data suggest that the value of hydrologic information increases sharply if daily coverage is available. Applications not requiring such frequent coverage are largely insensitive to incremental changes in frequencies longer than approximately one week. Some benefits would accrue to a nine-day cycle when compared to an 18-day cycle. On the other hand, large classes of hydrologic problems exist which are insensitive to either a one or nine or eighteen day coverage, and require either continuous monitoring, near real-time data or seasonal-yearly data.

Data Processing and Archiving

The data handling issue is complex because of the large number of agencies with responsibility for accumulating hydrologic data. The Office of Water Data Coordination (OWDC) of the U.S. Geological Survey has lead agency responsibility for archiving water data; however, many other agencies are affected, including National Weather Service, U.S. Army Corps of Engineers, Environmental Protection

Agency, Soil Conservation Service, Bureau of Reclamation and others. Each has statutory responsibility and data requirements that are unique to its assigned operation.

Although NASA has the prime responsibility in orbital data acquisition research and development, it is recognized that archiving and dissemination of hydrologic earth resources data should be addressed through coordinated efforts of the operational agencies listed above. The Office of Water Data Coordination, for example, maintains a master water data index in digital form - the National Water Data Exchange (NAWDEX) system. This system is currently interfaced with the digital data storage systems of the Environmental Protection Agency (STORET system), Corps of Engineers, and many other federal and state agencies. LANDSAT data of hydrologic interest could also be included, but only if responsibility for screening, processing, and formating of that information is placed with a specific agency with water resource responsibilities and if raw data are provided to that agency in a time frame compatible with its operation.

In the case of the OWDC digital data file, known as WATSTORE, information is published on an annual basis, six to twelve months after the period of interest for use in planning flood protection projects, ground water reconnaissance, etc. The EPA digital system (STORET) primarily contains water quality data, and temporal sampling frequency and speed of data retrieval requirements are generally more severe. Designers of future earth observation systems must take an active role in formulating data formats and response times that are compatible with the wide ranging requirements of potential user agencies. Failure to do so may result in agency handling of LANDSAT data as a separate entity when it could more effectively be incorporated into the existing data systems. (See Environmental Monitoring - page 92.)

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Environmental Monitoring

The three major environmental concerns - air, water, and land quality - derive critical information from resource data in certain applications areas as shown in Table 2.7.

TABLE 2.7

Data Sources Used In The Major Areas Of Environmental Concern

Environmental Concern	Data Source
Air Quality	Weather and climate/atmospheric studies.
Water Quality	Water resources; oceanography and coastal studies; geology; agriculture and forestry.
Land Quality	Geology; agriculture and forestry; land use.

As the objective of environmental monitoring is to provide data to assist in the effective management of resource utilization, the compilation of resource inventory data, as collected by the other application groups contributing to this report, forms an essential part of the monitoring task. Environmental monitoring has its own specialized data requirements, however, derived primarily from the need to follow the dynamics of environmental processes: pollution dispersion and impact, and degradation of land, air and water resource potential. Further, the collection of this information is often tied to operational enforcement programs with specific and, in many cases, severe requirements as to the accuracy, timeliness, and reliability of the data.[1] These factors determine, in a unique way, many of the necessary characteristics of remote sensor systems as discussed below.

Spectral Bands

The use of remote sensing technology in environmental monitoring is in its initial stages and so experience related to selection of optimal spectral bands and other parameters for such applications is limited. However, research has indicated that measurements in several spectral regions are useful.

Assessment of land degradation usually involves evaluation of the type and condition of land cover, and so spectral coverage aimed at vegetation and soil analysis (see Vegetation Inventory and Assessment - page 25 and Land Use Management - page 43) is of value in these applications. An inventory of surface mined areas, for instance, used ratioed data from LANDSAT/MSS Bands 5 (0.6μm to 0.7μm) and 6(0.7μm to 0.8μm) to detect areas in which vegetation had been removed and resulted in 93 percent accuracy in measurement of the total area affected by current strip mining.[2] Several other investigations have employed LANDSAT/MSS spectral bands (0.5μm to 1.1μm) in small-scale environmental impact and ecosystem analysis by examining vegetation patterns in the areas of interest.[3-4 5-6]

Water quality information, particularly suspended sediment and algal concentration, has been derived from LANDSAT/MSS data[7-8-9-10] and, in at least one case, was included in the operational estuarine and inland water monitoring program of the U.S. Army Corps of Engineers.[11] Better spectral resolution would aid in such applications,[12] particularly lengthening the short wavelength "green" band cuton to approximately 0.52μm to allow possible differentiation of chlorophyll from suspended inorganic sediment.

Detection and tracking of oil spills have been attempted from LANDSAT and Skylab with generally poor results. One of the deficiencies of LANDSAT/MSS data noted was the spectral range covered (0.5μm to 1.1μm).[13] Studies using other sensors have shown that extension of coverage into the "ultraviolet-blue" (approximately 0.35μm to 0.50μm), "thermal infrared" (10.5μm to 12.5μm) and "microwave" (10μm to 30 cm) regions is needed for detecting oil on water.[14-15-16-17] "Thermal infrared" sensing would also be useful in detection and monitoring of thermal pollution sources on land and in water. The 4.0μm to 13.0μm region is sensitive to surface temperature and could be used to locate thermal effluents or their sources.[15-18]

In general, sensing in the "visible" and "near infrared" has been found to be useful in some environmental monitoring from space. Additional coverage in the "blue" and "thermal infrared" spectral regions would expand the number and type of orbital data applications. However, it seems likely that the factors limiting environmental monitoring from space will be available ground IFOV and frequency of coverage rather than spectral resolution.

Ground IFOV

Ground IFOV, or ground resolution, is an important factor determining the utility of remote sensor systems in various environmental monitoring applications. Ground IFOV requirements depend not only on the scale of the phenomenon of interest but also on the purpose for which the data are acquired. In general, use of data for enforcement of environmental regulations places the most severe requirements on the IFOV of the sensor since accuracy of measurements and location must often be comparable to that which is achieved by inspectors on the ground. While LANDSAT/MSS data (IFOV = 80m) have been found useful by experimenters investigating large area environmental degradation processes, studies aimed at analysis of water quality[12] and surface mining activities[19] have expressed the need for improved ground IFOV if operational monitoring and enforcement requirements are to be met. The general relationships between environmental monitoring tasks and IFOV's are illustrated in Table 2.8.

TABLE 2.8

Sensor Ground IFOV And Associated
Typical Applications In Environmental Monitoring

Typical Applications	Ground IFOV
Monitoring of surface mine features for compliance with regulations (e.g., high walls, haul roads, spoil piles and settling ponds); detection of small effluent plumes in water.	1 - 10m
Baseline environmental inventories (vegetation analysis, general land use, drainage characteristics); non point-source pollution detection; monitoring of strip mine reclamation.	30 - 40m
Detection and monitoring of dispersion patterns for large pollutant discharges (e.g., oil spills);estuarine dispersal patterns.	50 - 100m

This list is indicative that, for many enforcement uses, data having ground IFOVs equal to or smaller than 10m may be required. Environmental inventories, including some impact assessment, some routine monitoring, and many research activities connected with general environmental analysis could be performed using IFOVs of approximately 30m or larger.

Dynamic Range and Radiometric Sensitivity

Dynamic range requirements for environmental monitoring are probably not significantly different from those specified by other applications groups. However, as environmental analysis spans the entire range of observed reflective and thermal characteristics of natural and man-made targets, the required range is broader in every spectral region than for any other single application and should be taken into account in the design of any system to be used for environmental monitoring.

Sensitivity requirements depend not only on target characteristics but also on many other factors--atmospheric and background perturbations, IFOV, and spectral band-width. However, typical target reflective values can be used to specify the maximum required sensitivity expected. Concentrations of suspended solids varying by 5-30 mg/liter over a range from 20-70 mg/l produce reflectance changes in LANDSAT/MSS bands as low as 0.5 percent (Band 5, 20 mg/l vs. 25 mg/l).[20] Thus, remote sensor sensitivities should be capable of detecting these small reflectance changes in order to allow assessment of other factors contributing to the total signal received and, if these factors can be isolated, to discriminate the small real differences present. NE$\Delta\rho$'s in reflective bands should range between 0.1 and 1 percent for detection of solid materials in aquatic suspension and for examination of dissolved constituents.[15-16] NEΔT's in thermal sensing should be 0.25°C to 1°C for measurement of significant thermal pollutants and in tracing water mass movement and dispersal.[15-16]

Equatorial Crossing Time

Since much environmental monitoring is concerned with pollutants entering bodies of surface water, avoidance of specular reflectance is a prime consideration in system design. Experience with LANDSAT crossing times (approximately 0930 hrs) has shown little difficulty with sun glitter, but calculations indicate that crossing as late as 1100 hrs would encounter a serious glitter problem which would render sensing of surface water useless under ordinary wind conditions during most of the year.[21]

A somewhat related parameter involves the timing of adjacent sensing swaths for orbital systems. Simultaneous ground sampling in marine areas and large lakes is simplified by the current LANDSAT coverage of adjacent swaths on adjacent days since ships and water sampling teams can be deployed for more than one day at a time over large study sites. Alternative patterns, such as interlacing of multisatellite swaths which result in intermittent coverage of adjacent areas, would considerably reduce the efficiency of field data collection.

Frequency of Coverage

An important parameter (in addition to ground IFOV) determining the extent to which remote sensor data can be employed in operational environmental monitoring is the frequency of coverage. Routine inventories can employ low frequency data but enforcement of many regulations requires virtually continuous coverage with near-real time read out in order to detect violations. A summary of coverage frequency requirements for a variety of monitoring uses is shown in Table 2.9.

TABLE 2.9

Coverage Frequencies for Typical Applications in Environmental Monitoring

Typical Applications	Coverage Frequency
Monitor industrial stack emissions.	Hourly (or continuous)
Monitor landfills for regulation compliance.	Daily
Assess project boundaries for compliance (e.g., forest clear cutting and strip mining).	7 - 14 days
Routine sampling of point source discharges.	Monthly
Perform baseline inventories.	Seasonal - yearly

LANDSAT coverage frequencies (9 to 18 days) have been useful for certain applications such as those indicated previously. However, daily or shorter frequencies are required for many enforcement activities, indicating the need for specialized aircraft missions or geosynchronous orbital systems.[15] Variable or high frequency coverage could also be obtained, in some cases, through automated *in situ* sampling and telemetry systems analogous to the LANDSAT Data Collection Platform System (DCPS). Reliability of the sampling stations and security from vandalism, however, would have to be improved.[22]

Data Processing and Archiving

For many environmental monitoring purposes, speed of initial data formatting (correction, production of imagery, etc.) and delivery is crucial. As in the case of weather observations, daily analysis of data is important for many enforcement tasks, making near-real-time delivery of data necessary. Even if data is not acquired daily, 24-hour data delivery is desirable for some monitoring tasks. On the other hand, baseline inventory data and change assessment studies (e.g., change in surface mining areas) do not require near-real-time data. The EPA, for example, maintains a digital repository of water quality data from the entire U.S. - the STORET system. The system receives data from local sources from two weeks to several months after the actual sampling and updates its files weekly (personal communication, Mr. Conger, EPA, July 1976). Because of the delay between sampling and data availability through STORET, users of the data apply them primarily to assessment and regional studies. Such uses and the STORET system time frame would be entirely compatible with LANDSAT data. Compatibility with this and many other existing data bases must be the driving factor for design of future LANDSAT data receiving and processing facilities.

As with other applications, archiving needs for environmental monitoring vary. Permanent storage is desirable for some baseline inventory studies and in cases where analysis of long term trends is used in research. Retention of data for seven to ten years may be needed when they are used in lengthy legal proceedings connected with enforcement. By far the bulk of data, however, is needed only on a transient basis and original data could be discarded after being analyzed. Once an oil spill is cleaned up, for instance, there is no operational need to retain original data used in its detection.

Currently, agency data storage systems, such as STORET, archive all historical data on digital tape for research and assessment purposes and agencies may desire that the same procedure be followed with LANDSAT data, either at the agency or NASA.

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Chapter III

Analysis of the Thematic Mapper

The Committee evaluated the proposed Thematic Mapper mission in the light of the investigator experience in the various disciplines discussed in Chapter 2 of this report. Because of the constraints which necessarily had to be established by the baseline mission (see the Appendix for a description of the baseline mission) the Committee excluded from its consideration user requirements that obviously fell outside of the capabilities the type of spacecraft and mission under consideration.

The initial Committee evaluation addressed the primary mission objective - observation of land cover. Every one of the applications areas represented derives substantial benefit from the observation of land cover. Inventories of land cover, particularly vegetation, form an essential part of surveys of earth resources. Further, land cover information can be used to differentiate, and in some cases identify, features such as topography, rock and soil type, environmental perturbations, and hydrologic conditions which indirectly affect the type, appearance, or condition of cover present. The multispectral characteristics of vegetation have been extensively studied and have been used for many years to derive information on natural and man-affected environments from remote platforms. Thus the sensing of land cover, particularly vegetation, offers substantial returns in many applications and is supported by technical expertise obtained through research and operational experience. The Committee therefore concurs in the selection of sensing of land cover as the primary mission objective.

After initially accepting land cover and vegetation as the optimization objective, the Committee temporarily set aside this objective and analyzed the design with the idea of satisfying as wide a spectrum of users as possible. The Committee then reviewed the effect of the resulting changes on the initial optimized design. The Committee accepted compromises where the impact on vegetation data was minor provided major advantages were achievable in other disciplines.

The Committee is in agreement with the NASA plan to propose the Thematic Mapper as an operational prototype in the transition from the present LANDSAT experimental sensors to an operational system. The Committee has observed that the present LANDSAT/MSS data, while indicating the feasibility of effective earth observation from space, have not been widely incorporated into operational processes as a replacement for more conventional forms of data collection.[1] With some specific exceptions, significant improvement over the present LANDSAT/MSS capability seems necessary before widespread user acceptance can be expected. The Committee is satisfied that the Thematic Mapper, with the modifications recommended in this report, will have the capability to serve as the basis for the initial operational sensor after it successfully completes the experimental phase. This operational context has associated with it the absolute requirement that the user community be assured continuity of data. Lacking this assurance, the user community probably will not commit its resources to use the data, and at the same time close out, reduce, or otherwise modify its conventional data sources even though they may be less effective.

Many users requiring data on dynamic processes such as crop growth and snow cover cannot tolerate a data gap during critical time periods. This requires a multiple satellite system in orbit that can continue the data flow, although at a lower rate, in case of a failure in one spacecraft or sensor. There must also be an adequate number of ready-to-launch spares available to be used while the failed spacecraft is either recycled through maintenance and refurbishment, as planned in the shuttle era, or a replacement is procured and launched. Until continuous data flow is assured, the principle users will probably continue to be those engaged in research or those whose interest is largely confined to static phenomena. While both of these are important, the Committee is convinced that the larger long-term benefits to be derived from remote sensing will come from monitoring dynamic processes.

The Committee also recognizes that the increased data rate associated with the improved sensor will initially stress the capabilities of the user community both in terms of available facilities and experience necessary to make full use of the data. This, however, should only be a temporary phase as the increased utility of the data will create its own motivation to improve these capabilities.

Several general aspects of the proposed follow-on program appeared to the Committee to have obvious broad merits which would be felt throughout all segments of the user community. While prolonged discussion should not be necessary, the Committee does wish to endorse the following six aspects:

1. The inclusion of an appropriately modified first generation multispectral scanner (MSS) in the Thematic Mapper mission in order to provide:

- a reliable, space-proven backup sensor to the new Thematic Mapper,
- a continuation of the current LANDSAT/MSS data for use by those who either do not need the improved Thematic Mapper data or do not have the necessary facilities to receive or analyze that data,
- precursor data to assist the user in selecting only good coverage before processing the more expensive Thematic Mapper data.
- transitional data to aid users in converting to the improved Thematic Mapper data.

2. The provision of assured coverage for a 6 year period to give agencies and other users an opportunity to justify the necessary commitment of resources for the transit. n to a valid operational phase.

3. The use of global, real-time direct data readout. This will eliminate the necessity of limited capacity on-board data recording, a historically unreliable operation, and the reliance on overseas receiving stations.

4. The recognition of the operational character of the Thematic Mapper after successful completion of its experimental evaluation.

5. The combination of future experimental sensor or component packages as part of the operational LANDSAT follow-on payloads in those cases where the experiment can be conducted in the same orbit.

6. The provision of space in the Thematic Mapper instrument design for a seventh spectral channel to be added when future research and technical development make it feasible and operationally useful.

Those features of the proposed follow-on program which could have specific and, perhaps, divergent impacts upon different members of the applications community have been examined in detail and compared with the applications requirements and preferences expressed in Chapter 2 of this report. In some cases this analysis has led the Committee to recommend specific changes to parameters in the proposed baseline mission design. In other cases, where a subjective judgement on the importance of one application versus another may be involved, the impact of a particular parameter is discussed without making specific recommendations for modifications. The Committee feels that some of these views may be relevant to future considerations of tradeoffs.

Spectral Bands

In the analysis of the spectral bands, the first consideration was to optimize the spectral resolution capabilities for observation of vegetation. While the proposed bands of the baseline design (see the Appendix, Table A.1) would provide improved capability in this area, the Committee feels that significant improvements can be achieved by making some adjustments in bands, band widths and filter cut-ons and cut-offs. In the Committee's judgment, present technology can produce filters with sufficiently sharp cut-ons and cut-offs to warrant the modifications called for below. These require a filter slope that goes from 85 percent of full response to 5 percent of full response in a 0.01μm interval. Discussion of each band and recommended modifications follow:

1. "Green" Band:
   Baseline proposed band - 0.52μm to 0.60μm
   CORSPERS recommended band - 0.53μm to 0.58μm

The short wavelength limit is most critical from the standpoint of terrestrial vegetation discrimination. This limit should not be shorter than 0.53 μm because of significant vegetation signature crossovers in the 0.50 - 0.53 μm region. The long wavelength limit is positioned by both oceanographic and vegetation discrimination requirements. A 0.59μm long wavelength cutoff is acceptable if signal strength requirements cannot be met with a 0.05μm bandwidth.

2. "Red" Band:
   Baseline proposed band - 0.63μm to 0.69μm
   CORSPERS recommended band - 0.62μm to 0.68μm

The long wavelength limit is the most critical, with plant species discrimination and vigor determination being the driving uses. Experience has shown that reflectance cross-overs in the 0.68 to 0.75 micrometer region confuse spectral signatures and reduce the accuracy of plant vigor determinations. The short wavelength limit is not critical as long as it is 0.60 micrometers or longer and was moved to 0.62μm only to maintain 0.06μm bandwidth.

3. "Near-infrared" Band(s):
Baseline proposed bands - 0.74μm to 0.80μm and 0.80μm to 0.91μm
CORSPERS recommended band - 0.76μm to 0.90μm

Recent research indicates that one band in this spectral region is probably sufficient unless future research indicates that an additional 0.70μm to 0.76μm band is valuable for plant biomass determinations. Neither limit is critical as long as the short wavelength limit is 0.75μm or longer and the long wavelength limit is not extended into the water absorption band at approximately 0.91μm.

4. "Long Wavelength, Reflective-infrared" Band:
Baseline proposed band - 1.55μm to 1.75μm
CORSPERS recommended band - no change

This band should prove very useful in plant vigor determination. In this wavelength region foliar reflectance is strongly dependent upon foliar moisture content. The exact wavelength limits are not critical and should be based upon atmospheric transmission and band width requirements. It should be noted that a 2.0μm to 2.6μm band would be an acceptable alternative for the same applications.

5. "Thermal-infrared" Band:
Baseline proposed band - 10.4μm to 12.5μm
CORSPERS recommended band - 8.8μm to 12.6μm

The wider "thermal-infrared" band is recommended primarily to increase signal strength, thus allowing for the possibility of improved spatial resolution in this band. Reducing ground IFOV from 120m to approximately 90m would be highly desirable. Calculations indicate that use of this wider band could reduce IFOV to 90m with a small degradation in NEΔT (from 0.5°C to approximately 0.64°C at 300 K) (O. Weinstein, NASA, unpublished data, Apr. 1976). In addition to providing better discrimination, 90m IFOV thermal data could be more easily registered with the 30m reflective radiance measurements, since it is an odd multiple (3x) of the reflective IFOV. This would allow registration of the high resolution pixel into the center of the lower resolution thermal pixel. In view of the small degradation in NEΔT produced and uncertainties concerning the utility of very sensitive thermal measurements integrated over large areas on the surface, reduction of thermal ground IFOV is recommended even with the associated degradation of NEΔT. The wider band limits do incorporate an ozone absorption band at approximately 9.6μm, but small horizontal variations in global ozone distribution would seem to mitigate any affect absorption would have on data quality.[2] In any case, the sharp limits of the ozone absorption band (see Figure 3.1) would allow effective use of a blocking filter if spatial or temporal variation in ozone absorption is shown to be a problem.[2]

6. "Blue" Band
   Baseline proposed band - none
   CORSPERS recommended band - 0.47μm to 0.52μm

The aggregation of the proposed two "near-infrared" bands into one band, from 0.76μm to 0.90μm, as recommended above, allows replacement of the deleted band by one in another spectral region. Oceanographic research has shown coverage in the "blue" region (0.4μm to 0.5μm) to be of considerable value when penetration of water is desired (as in bathymetry and studies of suspended and dissolved constituents). The Committee feels that extension of applications into the important fields of ocean and lake studies would greatly enhance the overall utility and cost-effectiveness of the system. The intimate connection between terrestrial land use and adjacent water bodies makes inclusion of a water penetration band on an instrument designed basically to analyze terrestrial cover especially important, even though other space programs may address oceanographic interests specifically. Further, some research indicates that this band may be useful for terrestrial studies, particularly land use. CORSPERS recommends adding a "blue" band covering the region between 0.47μm and 0.53μm. The short wavelength limit is the most critical and its position is based on bathymetry requirements. The long wavelength limit should be as close to 0.52μm as possible as chlorophyll and inorganic sediment

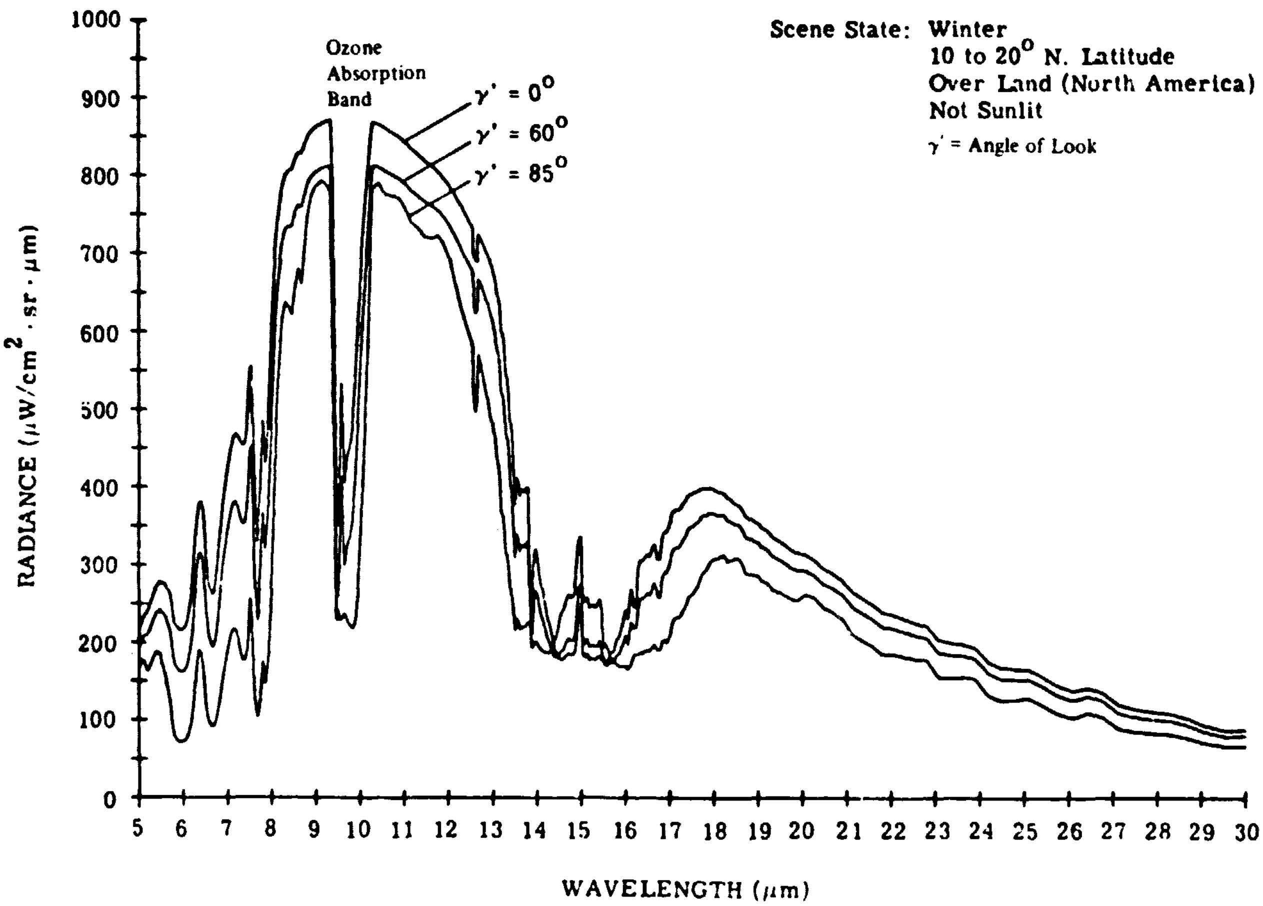

FIGURE 3.1 Expected Value of Spectral Radiance for Three γ Angles

Adapted from: Rose et al. (1973)[2]

reflectance crossovers with divergent slopes at longer wavelengths could complicate assessment of marine and lacustrine phytoplankton distribution. If necessary, extension of the long wavelength limit to 0.53μm would be acceptable.

7. Alternatives for Seventh Thematic Mapper Spectral Band

NASA has included in its proposed design of the Thematic Mapper room for including a seventh spectral channel. In the event that a seventh channel is added, the Committee wishes to express its preferences for the spectral region covered. The analysis of vegetation could be enhanced by the addition of a "yellow-orange" band (0.58μm to 0.63μm) for vigor and species differentiation. The accuracy and reliability of yield determination may be improved, particularly for forestry applications.

Either of two other bands, with slightly lower potential, might also be usefully considered as the seventh band of the Thematic Mapper currently proposed. While the loss of data utility incurred by aggregation of the two proposed "near-infrared" bands was considered to be small by comparison with the gains produced by adding the "blue" channel for water penetration, there are some indications that a 0.70μm to 0.75μm band may improve capabilities for determination of vegetative biomass. Therefore, coverage in this region would be desirable for experimentation in vegetative biomass determination.

There are also studies from both geology and land use mapping groups showing some improvements in rock type and land use discrimination through use of measurements in a 4.5μm to 5.5μm "thermal" band. The utility of this band is reduced for geological applications if twice daily coverage, at the high and low thermal peaks, is not available. However, thermal land use discrimination would be possible with a coverage frequency as is proposed for the Thematic Mapper. If a cooled-detector (i.e., thermal) channel were incorporated as the seventh spectral band, the 4.5μm to 5.5μm band should be given first priority.

8. Summary of Spectral Band Recommendations

The recommended CORSPERS band arrangements for a six and a seven band Thematic Mapper are:

	6 band TM		7 band TM (one cooled channel)
1)	0.47μm to 0.52μm	1)	0.47μm to 0.52μm
2)	0.53μm to 0.58μm	2)	0.53μm to 0.58μm
3)	0.62μm to 0.68μm	3)	0.58μm to 0.63μm
4)	0.76μm to 0.90μm	4)	0.62μm to 0.68μm
5)	1.55μm to 1.75μm	5)	0.76μm to 0.90μm
6)	8.8 μm to 12.6μm	6)	1.55μm to 1.75μm
		7)	8.8 μm to 12.6μm

Ground IFOV

There is little question that the proposed decrease in ground IFOV from 80m in the MSS to 30m for the Thematic Mapper will produce substantial gains in all applications areas. Even in cases where features of interest are sufficiently large to be adequately discriminated by the current LANDSAT IFOV, decreasing the ground IFOV will improve the accuracy of boundary location and thus of areal measurements. In addition, several application categories (Environmental Monitoring, Water Management, Vegetation Inventory and Assessment, and Oceanography) indicate that specific new clusters of features and phenomena which are largely inaccessible to the current LANDSAT/MSS could be resolved with a 30 - 40m IFOV. The benefits to be derived from analysis of smaller features and/or from continuous improvements in accuracy of mensuration and training set sampling with decreasing IFOV are difficult to quantify. The relationship is non-linear, as shown in Figure 2.1, and highly application-dependent. It is apparent that there is a significant group of applications which do not derive substantial benefits from remote sensing until IFOV's of ≤10m are available, just as there are certain problems which currently require *in situ* measurements.[3]

The performance trade-offs between the technical state of the art, quantity of data, cost, other system parameters (radiometric sensitivity, etc.) and ground IFOV cannot be quantified at this stage. It is, however, clear that substantial benefits in nearly all applications will be obtained with the proposed decrease in ground IFOV from 80m to 30m.

Radiometric Sensitivity and Dynamic Range

It is difficult to quantify the gains associated with increments of improvement in radiometric sensitivity. In some applications, however, there are definite indications that the sensitivity threshold below which significant increases in data quality do not occur has not been reached by the current LANDSAT/MSS. Oceanographic users, for instance, benefited from the "high gain mode" of operation of the first generation MSS and therefore desire sensitivity analogous to that achieved through this high gain (3x) restriction of dynamic range. Studies of sensitivity requirements for other applications areas produce a range of desired NE$\Delta\rho$'s from 0.1 to 1.0 percent and NEΔT's from 0.25°C to 1°C[3-4]. Most mimimum requirements expressed by these studies would appear to be met by an NE$\Delta\rho$ of 0.5 percent and an NEΔT of 0.5°C such as is proposed for the Thematic Mapper. As explained in the earlier thermal-infrared band discussion, small losses of thermal sensitivity would be acceptable if the IFOV of the thermal channel can be reduced to coincide more closely with the other channels.

In general, the saturation maxima in the reflective bands recommended by the Thematic Mapper Technical Working Group appear to be reasonable, although there is wide variation in the estimates of the individual Working Group panels contributing to that report and in the other sources examined by the Committee.[3-4-5] In view of this divergence, conservative (i.e., large) specified values of required dynamic range are advised at this stage. In the thermal band, dynamic range considerations are more easily grasped by applied users because of their connection with conventional measurements of temperature. The Technical Working Group recommended range of 270 K to 330 K is adequate for most applications, although NOAA has indicated it would prefer a colder low cutoff at 240 K for studies of snow and ice surface temperatures. If extension of sensitivity to this lower limit can be accomplished without degrading NEΔT to greater than 1°C, such a change should be considered, even though snow and ice studies probably will be only a small part of total applications of the thermal data.

Equatorial Crossing Time

The proposed baseline design calls for an 1100 hrs equatorial crossing time. Several factors persuaded the Committee that, at this stage, the earlier 0930 hrs LANDSAT 1, 2, and C crossing time should not be abandoned. If vegetation classification with primary dependence on machine processing were the sole objective, the near-noon orbit might be preferred, since it provides a minimum shadow effect and a better view of the plant canopy. Unfortunately, the small zenith angle associated with the near-noon orbit seriously limits the sensor over water surfaces with winds above 5m/sec because of sun glitter. After reviewing the available calculations on sensor sensitivity and signal levels at the 0930 hrs and 1100 hrs crossing times, the Committee concluded that while the later crossing time might be favored for automated vegetation classification, the advantage did not appear to be large. This assessment, however, should be analyzed in greater depth.

A potential major factor that must also be considered in the selection of the optimal crossing time is cloud-cover interference. By its nature, this interference is both statistically variable and location-specific. The differences noted in the data made available by NASA[6] on cloud cover interference between the present LANDSAT 0930 hrs and the proposed 1100 hrs. crossing times were not conclusive. A primary consideration for every earth resources application is the availability of cloud free data. The Committee's feeling is that, pending a thorough analysis of available meteorological data, current equatorial crossing times should not be changed to later in the day when intuition suggests that cloud build-up may appreciably reduce the number of cloud-free observations in many locations.

The Committee also feels that it is important to continue the present LANDSAT crossing time in the follow-on program in order to take full advantage of the classification experience gained during the present experimental program. The Committee is particularly concerned that a change in crossing time would add another variable to the comparison of Thematic Mapper classification signatures and shadow patterns with background experience obtained with the preceding LANDSAT's. The Committee therefore recommends that the 0930 hrs crossing time of the LANDSAT 1, 2, and C be retained for the LANDSAT-T/M mission. Further research on the probability of cloud-cover interference at different times of the day in critical areas along with the sun glitter factor should refine this crossing time.

Frequency of Coverage

The Committee has deliberated at considerable length on the frequency of coverage question. There is little doubt that some users would find 18-day repetitive coverage more than adequate even with the expected cloud coverage interference. There are other major users who require more frequent coverage during certain crucial times of the year but, at other times of the year, would not be distressed with data gaps of several months. Crop forecasting is a good example of this variable coverage-frequency requirement. There are other important users who need more frequent coverage throughout the year, ranging up to daily coverage. While this latter frequency is obviously not within technical or economic reach for a global high data rate system, such as envisioned in the LANDSAT follow-on, less frequent coverage can still provide significantly useful data to many of these users. Even though individual users may specify their own coverage frequency requirements, there is inadequate experience to determine the optimal compromise where multiple users are involved. This is further complicated by the variable cloud-cover probability. In the light of these highly subjective factors, the Committee can assert that a system with a coverage interval of longer than 9 days will be significantly less capable of satisfying the data requirements of many users interested in dynamic processes. The Committee therefore recommends that a nominal 9 day interval be accepted as the maximum interval between observations for the LANDSAT follow-on mission.

Ground Data Handling System

The Committee did not perceive that any of the agencies had performed thorough analyses of the impact of the high data rate of the Thematic Mapper on the Ground Data Handling System. Since the Thematic Mapper design will result in very much higher data rates and provide many more choices for data analysis, the potential data processing and storage loads will be far beyond current LANDSAT experience. The nominal four day turn-around cycle proposed by NASA will, if realized, satisfy most users. There are, however, significant applications (particularly in environmental monitoring) in which 24-hour or shorter data processing times are needed. Some provision for such special interests should be made in program planning. Thoughtful, vigorous, and extensive analysis is required to thoroughly understand the issues and to design the required systems. Such analysis work should start now.

Data Archiving

Imbedded in the Ground Data Handling System analysis is the general subject of archiving data. There is little experience on which to base a generalized, central archiving policy that can satisfy all the diverse users of the data. It seems likely that as user agencies develop operational programs, the responsibility for archiving of data will be dispersed to those groups having specialized requirements. Some might choose to store all data for particular geographical areas--a responsibility which NASA or EROS (USGS) will probably not undertake on behalf of all of the user groups. It is, however, incumbent upon NASA and/or EROS to maintain a central index of all data so that small users or scientific interests who do not maintain files of their own can have access to these data. Maintenance of the present system of central storage of selected data, supplemented by regional browse facilities is, of course, required. In addition, technical advice, particularly with regard to optimal storage conditions and specifications of data content decay rates, recording medium decay rates, recopying procedures, etc. should be made available to all groups undertaking data storage. It is essential that both NASA and the other agencies be aware of storage costs and incorporate them into their program budgets. Archiving costs for data on magnetic tape, for instance, can range from $2.00 to $10.00 per reel per year,[7] a factor which will certainly influence archiving policies and procedures as well as program budgets.

Related Concerns

In addition to specific considerations pertaining to the Thematic Mapper itself, several related concerns emerged from the Committee's deliberations.

1. Supporting Research and Development

Review of the analysis work that had been done in preparation for the LANDSAT follow-on as presented to CORSPERS left the Committee with the impression that many research and development issues related to future operational problems have been neglected. Studies such as signature changes with variations of sun angle and viewing altitude, gray scale and cloud cover appear to be sparse. In the Committee's view, NASA is the only agency that has the broad range of competence required to do these studies and therefore should assume the responsibility to initiate and lead these studies.

2. Impact of the Manned Re-usable Space Shuttle

Another concern that has troubled the Committee during this review is the apparent linkage of the continuity of the LANDSAT follow-on program, which is based on shuttle-supported maintenance and refurbishment, with the on-schedule success of the space shuttle program. While the Committee does not consider itself competent to evaluate either the firmness of the shuttle schedule or the performance of the shuttle when it is ready for operational service, the Committee is concerned that NASA leave alternate pathways open to insure that the continuity of the remote sensing program is not jeopardized by potential changes in the shuttle schedule or in its performance.

3. Data Gap

Finally, the Committee wishes to express its concern over the potential data gap that may confront the world-wide user community after LANDSAT-C completes its useful life. While the Committee was evaluating the Thematic Mapper, the severe impact of this potential gap became apparent. The Committee is greatly concerned that such a gap will disrupt and disperse the present user community's enthusiasm and capability to use the data. The Committee urges that NASA and the user agencies take every action within their authority to reduce the possibility or duration of a gap and, at the same time, to minimize effects of such a data gap if it cannot be prevented.

In summary, the Committee has considered the trade-offs between the original objective to obtain a matrix of high quality land cover data and the desire to broaden the capability of the system to satisfy the orbital data requirements of other applications including geology, land use, oceanography, coastal processes, hydrology, environmental monitoring, and cartography. The Committee is convinced that the changes recommended will provide better land cover data than the baseline design and, at the same time, provide greatly improved data for the remainder of the user community. Additional improvements in land cover data were possible but at the cost of seriously degrading or entirely foreclosing the use of the data by many of the other users. Other orbital sensor systems, such as the Seasat-1 and the Heat Capacity Mapping Mission, HCMM, can also have a very significant impact as complementary data sources for selected applications, provided the data format is compatible with the Thematic Mapper data. Inter-system data capability should, wherever possible, be a desired design policy for all earth resource observation systems. The Committee is f˙⁻ⁿly convinced that the Thematic Mapper, as modified by the ꞇommended changes, can provide a major step forward in ou˙ pability to manage our natural resources and significantly assist in monitoring the impact of man on the environment.

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6) NASA, Analysis of the Effects of Equatorial Crossing Times on Earth Resources Applications for LANDSAT Follow-on. Unpublished Report, NASA, Goddard Space Flight Center, Beltsville, Md., April, 1976, 168 pgs.

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Appendix

NASA Proposed Thematic Mapper Baseline Mission

NASA has proposed a program to extend the flow of orbital earth observation data into the mid-1980's and to upgrade the quality of that data consistent with advances in technology which have occurred since the initial LANDSATs were designed. Following the launch of LANDSAT-C, carrying a modified version of the MSS already flown with LANDSATs 1 and 2 and modular RBVs having 40m IFOVs, the proposed program calls for the development of an observation system incorporating the latest state of the art in visible-IR scanner, data processing, and spacecraft technology.

NASA has sought advice on the initial design of this system from outside groups and individuals with particular technical or applications expertise. Several studies related to design and performance specifications were undertaken with NASA support. A comprehensive "Thematic Mapper Technical Working Group" was convened to allow discussion and interchange between experts in NASA and the technical community on possible design options of the follow-on system.[1] The wide ranging recommendations of this group, encompassing instrument design, orbital parameters, and data formatting and handling considerations, formed the basis for a baseline mission design presented by NASA to the Committee at the beginning of this study in November 1975 and January 1976. This design, as described below, served as the point of departure in the Committee's deliberations.

The principal component of the mission is an advanced MSS - the "Thematic Mapper" (T/M). The design specifications for the T/M system call for extension of the capability of the present LANDSAT's in virtually every significant aspect - the range of spectral coverage, number and sensitivity of individual spectral bands, ground resolution, quantization, and geometric accuracy. The primary objective of the T/M program is observation of land cover characteristics - in particular, vegetation. While not excluding other compatible objectives, the observation of vegetation combines both techniques of multispectral analysis and the probability of extensive utility in a variety of applications. After an initial period of user adjustment and experimentation with the new system, the T/M is to provide the basis for transition to operational earth resource observation from space.

Included with the T/M on the same spacecraft will be an MSS essentially identical to that planned for flight on LANDSAT-C. Differing from the LANDSATs 1 and 2 MSS design only by the addition of a thermal channel and some minor modifications to compensate for the reduction in altitude from 900 km for the LANDSAT 1,2, and C to 705 km for the T/M, the MSS incorporated into the T/M mission will provide continuity with historical LANDSAT data and also serve as a proven backup sensor to the new T/M.

In order to eliminate the necessity for on-board storage of data, the T/M baseline mission calls for real-time global readout either directly to domestic and foreign receiving stations or through a planned network of two multipurpose communications satellites (TDRSS - Tracking Data Relay Satellite System) to a central receiving station in the U.S.

The expanded capability of the T/M sensor will produce nearly a tenfold increase in data rate over that encountered with the current MSS (Table A.1). Ground processing facilities must therefore be designed to handle the increased flow of data and provide products to users within a useful interval following actual acquisition of data. Current plans call for a 4 day "turn-around" time from data acquisition to availability of computer compatible data tapes.

The program timetable calls for launch in early 1981 by which time all the above elements of the complete system must be operating. Provision is planned for retrieval for repair and refurbishment of the spacecraft and sensors by means of the manned space shuttle. Two spacecraft are planned to be in orbit at all times with a third available for replacement during maintenance or repair periods. A

TABLE A.1 Main Characteristics of the Thematic Mapper

	TM			MSS	
	MICROMETERS	RADIOMETRIC SENSITIVITY (NE$\Delta\rho$) (1)	(2)	MICROMETERS	RADIOMETRIC SENSITIVITY (NE$\Delta\rho$)
SPECTRAL BANDS 1	0.52 - 0.60	.35%	.57%	0.5 - 0.6	.57%
2	0.63 - 0.69	.43%	.57%	0.6 - 0.7	.57%
3	0.74 - 0.80	.42%	.56%	0.7 - 0.8	.65%
4	0.80 - 0.91	.32%	.42%	0.8 - 1.1	.70%
5	1.55 - 1.75	.60%	1.68%		
6	10.40 - 12.50	0.5K (NEΔT)		10.40 - 12.60	1.4K (NEΔT)
GROUND IFOV	30 m (BANDS 1-5)			78 m (BANDS 1-4)	
	120 m (BAND 6)			234 m (BAND 5)	
DATA RATE	110 MB/S			15 MB/S	
QUANTIZATION LEVELS	256			64	
INTERBAND REGISTRATION	0.1 IFOV			0.25 IFOV	
LONG TERM SCAN STABILITY	0.5 IFOV			1.5 IFOV	
EQUATORIAL CROSSING TIME	1100 hrs. local			0930 hrs. local	
ALTITUDE	705 km			900 km	
WEIGHT	270 kg			54 kg	
SIZE	0.9 x 0.9 x 1.8 m			0.35 x 0.4 x 0.9 m	
POWER	250 WATTS			42 WATTS	

(1) OPTIMISTIC CASE

(2) WORST CASE

Source: NASA, Goddard Space Flight Center
CORSPERS Committee Briefing, Nov., 1975

period of 6 years of continuous data flow is planned for in the initial follow-on proposal. This should ensure data flow over a sufficiently long period of time to encourage users to commit resources to train and equip themselves to use the T/M data and should establish commitments for long-term operational use of the orbital data.

A significant aspect of the follow-on program is that future experimental sensors will, when orbital requirements are compatible, be combined on the same spacecraft with operational sensors such as the LANDSAT follow-on. This arrangement will allow experimental programs to be carried out at reduced cost and allow use of the experimental data in an operational environment. This will be greatly aided by the space shuttle capability to deploy and retrieve instruments in space.

In addition to the general program elements outlined above, the proposed follow-on program specifies the following baseline mission characteristics:

Spectral Bands

The design of the proposed T/M is planned to provide data in the six spectral bands shown in Table A.1. The proposed bands differ from the existing MSS design primarily by the addition of two bands in the longer wavelength regions of the spectrum: 1.55μm - 1.75μm (T/M Band 5) and 10.40μm - 12.50μm (T/M Band 6). The 1.55μm - 1.75μm band is very sensitive to plant moisture content and thus will find use in vigor determination and desiccation studies. Coverage in the thermal infrared region (10.40μm - 12.50μm) is a high priority feature for many applications including enhanced vegetation and land use discrimination and location and monitoring of geothermal activity, thermal effluents, and water mass circulation.

The spectral range covered by the other four proposed T/M bands (0.52μm - 0.60μm, 0.63μm - 0.69μm, 0.74μm - 0.80μm and 0.80μm - 0.91μm) is essentially equivalent to the existing MSS bands (Table A.1). They do differ somewhat in that advances in filter and detector technology have allowed narrowing of bandwidths and sharper cutoffs than were possible in the MSS, thus avoiding some reflectance crossovers and atmospheric perturbations which degrade the MSS data and target signatures derived from it.

Instrument contractors are being requested to provide, in their initial design, the capability to add a seventh spectral channel to the scanner. Technical and data management constraints combined with expressions of user needs presently indicate a six channel system; however, technical advancements along with strong user justification may lead to the future addition of a seventh channel.

Spectral Sensitivity and Dynamic Range

The specified spectral sensitivities for the proposed T/M are shown in Table A.1. Uncertainties about signal-to-noise characteristics of the final instrument have led to an estimated range of sensitivities rather than a particular value for most bands. In general, the design NE$\Delta\rho$ is 0.5 percent although problems may be encountered in achieving this sensitivity, particularly for the 1.55µm - 1.75µm band. The specified NEΔT value for the thermal band (10.40µm - 12.50µm) is 0.5°C. In every case the proposed T/M sensitivities match or exceed the LANDSAT/MSS characteristics, particularly in view of the narrower T/M band widths.

The recommendations of the Thematic Mapper Technical Working Group[1] concerning saturation thresholds for the seven bands they considered most useful are summarized in Table A.2.

For the LANDSAT/MSS equivalent bands (between 0.52µm and 0.91µm), the Working Group recommended ranges similar to those specified for the earlier instrument. Expected ranges for other bands (0.45µm - 0.52µm, 1.55µm - 1.75µm and 10.4µm - 12.5µm) were derived from other sources including the ERIM Multispectral Scanner Data Applications Evaluation[2] and the Working Group's judgment.

TABLE A.2

Saturation Thresholds of Spectral Bands
Recommended by T/M Technical Working Group

Band	Reflectance for Saturation
0.45μm - 0.52μm	20%
0.52μm - 0.60μm	58%
0.63μm - 0.69μm	53%
0.74μm - 0.80μm	75%
0.80μm - 0.91μm	75%
1.55μm - 1.75μm	50%
10.4 μm - 12.5μm	270 K - 330 K

Ground Instantaneous Field of View (IFOV)

The ground IFOV of the proposed T/M is 30m resulting in an approximately seven-fold decrease in the area of the scanner picture element (pixel) from that provided by the MSS. The reduction in ground IFOV is accomplished by a decrease in angular IFOV to 42 μrad and a lower spacecraft altitude of 705km. This "higher resolution" constitutes a significant improvement in the quality of data for almost every application; aiding detection, recognition and mensuration of earth resources features.

Geometric Accuracy

The band to band registration of the T/M data will be 0.1 IFOV which is 2.5x better than for the MSS. At 30m ground IFOV the interband registration will thus be ±3m. The characteristics of the instrument, spacecraft control, and data processing facilities are planned to provide long term scan stability that will produce scene to scene registration to within 0.5 IFOV, or 15m on the ground. Long term scan stability is important for registration of scenes in multi-temporal analysis and area measurement.

Quantization

The proposed T/M design calls for a quadrupling of the number of quantization levels to 256 in order to accommodate the sensitivity and dynamic range characteristics of the sensor.

Orbital Altitude

The provision of 30m ground IFOV with the design angular IFOV of 42μrad requires a spacecraft altitude of 705km. This altitude will also be compatible with the shuttle capability to service the T/M scanner and spacecraft. This is lower than the current LANDSAT altitude of approximately 900km. The lower orbit should also improve target radiance signal.

Equatorial Crossing Time

The proposed equatorial crossing time of the LANDSAT-1 spacecraft is 1100 hrs. This change from the approximately 0930 hrs crossing time of current LANDSATs is planned in order to improve the signal-noise ratio, enhance vegetation classification accuracy, and take advantage of higher solar elevation to reduce shadows in areas of high relief. This reduction in shadow effect is a disadvantage for some users.

Coverage Frequency

A two-satellite system providing coverage every nine days was recommended by the Thematic Mapper technical Working Group.[1] The nine day interval allows observation of many dynamic phenomena, particularly crop growth and phenological variations. It also increases the probability of obtaining cloud-free coverage. The proposed T/M mission calls for two-satellite, nine-day coverage. Two satellites would also provide a backup in case of failure of one sensor or spacecraft and thus assure continuity of coverage while repairs are made or replacements launched.

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