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DESIGN REQUIREMENTS FOR OPERATIONAL EARTH RESOURCES GROUND DATA PROCESSING

NAS 9-12336

12 MAY 1972

DRA

MID-TERM REPORT

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

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Prepared by
Earth Resources Technology Office
Applied Technology Laboratory
Houston Operations

TRW
SYSTEMS

16P

This document describes mid-term progress under contract NAS9-12336, "Space Station Experiment Data Ground Processing Study". Period of performance under this contract is 12/6/71 - 9/6/72. NASA/MSC contract Technical Monitor is G. R. Kimball (FS52), Flight Support Division, MSC.

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1.0 SUMMARY

This study effort evolves from a recognition that earth observations data processing will represent the predominant workload for ground based computational facilities in the era of Space Shuttle. Coupled with this recognition is a concern that too little is known about quantifying the volume of data to be processed, and the techniques to be employed, for potential operational dependence upon the remotely acquired data. This latter concern, of course, implies that the earth observation projects of NASA, USDI, USDA, etc. do, in fact, move from purely applied experimental research to operational utility.

In addressing the problem of preliminary conceptual design for future ground processing facilities, the obvious question is how much of what type of processing is anticipated? In short, the design problem is relatively straightforward once a projected workload can be established with some confidence. For this reason, the current study has emphasized devising a methodology for determining user requirements that attempts to utilize the limited information available from would-be users, but yet is not severely constrained by this limitation. The essence of the selected approach is to primarily talk to user agencies only in terms of things they fully understand (i.e., what is your job, what type of information would be an aid in performing this job?, as opposed to what processing algorithms and devices are required to convert what volume of raw data to usable information?). The approach selected is, consequently, replete with assumptions and subjective estimation. It is, however, stepwise logical and, as of this report, documented to the extent that the next critical steps may occur. These steps are verification with key user organizations and continued iterative refinement of the volumetric and frequency estimates.

The remainder of this report of mid-term progress attempts to define and characterize sensor capabilities projected into the Shuttle/Station era; identifies the problems, techniques, and equipment required to convert data to information; and describes a simulation technique intended as a design evaluation tool to permit quantitative comparison of differing design approaches. Finally, a tentative method is presented by which the candidate ground processing concepts will be synthesized. The report, taken in total, is intended to provide insight into the overall design problem and to provide an initial framework of tradeoffs necessary for the subsequent conceptual design of earth observations ground processing facilities.

2.0 STUDY OVERVIEW

The primary goal of this study is to develop realistic trade-off data and evaluation techniques that permit conceptual design of operational earth resources ground processing systems. The time frame of interest begins with post-Skylab activities and extends for approximately ten years into the Shuttle and Space Station era. Study emphasis is on developing a "unified" concept for the required ground system(s) capable of handling data from all viable acquisition platforms and sensor groupings envisaged as supporting operational earth survey programs (the term "operational" is used throughout this report to denote a balanced environment in which there is actual dependence by a user agency(ies) on remotely sensed data in performing a necessary and/or repetitive job, as well as ongoing research and development activities.) The platforms considered include both manned and unmanned spacecraft in near earth orbit, and continued use of low and high altitude aircraft. The sensor systems include both imaging and non-imaging devices, operated both passively and actively, from the ultraviolet to the microwave regions of the electromagnetic spectrum.

Motivation for performing the current study is provided by consideration of the following problems:

- first - in the area of manned systems, the post-Skylab "experiment" data processing is loosely defined
- second - in spite of considerable interest and activity on the part of would-be users of earth survey data, the requirements for data supporting operational activity are poorly identified and rarely quantified
- third - automated and man-assisted techniques for converting remotely sensed data to information are primarily topics of research (this situation essentially explains the existence of the first two problems)
- fourth - design and development of a "unified" ground processing system for operational programs requires lead time of approximately 3 to 5 years
- fifth - evaluation tools do not exist to rapidly assess the impact on ground systems of evolving processing requirements for earth resources data.

Specific study objectives derived from the above motivation are:

- survey, catalogue, and analyze output data characteristics of sensors expected to be flight qualified in the time frame of interest
- define preprocessing requirements generally attributed to unique characteristics or anomalies associated with the sensors of concern
- structure a method for defining realistic operational user requirements for various remotely sensed data products
- relate required data products to a set of modular processing functions to be performed by the ground system (onboard processing is considered only as it may impact the ground workload)
- relate the set of modular processing functions to equipment types by which implementation of the functions may be obtained (equipment types considered include off-the-shelf and anticipated devices based on digital, electronic analog, photo-optical, and electro-optical principles)
- develop a method for synthesizing candidate ground processing systems
- develop a simulation tool to evaluate competing candidate systems
- select promising concept(s)
- identify logical and cost-effective roles for NASA in processing operational data.

Figure 2-1 illustrates the overall study flow which is directed at satisfying the above objectives.

FOLDOUT FRAME 1

FOLDOUT FRAME 2

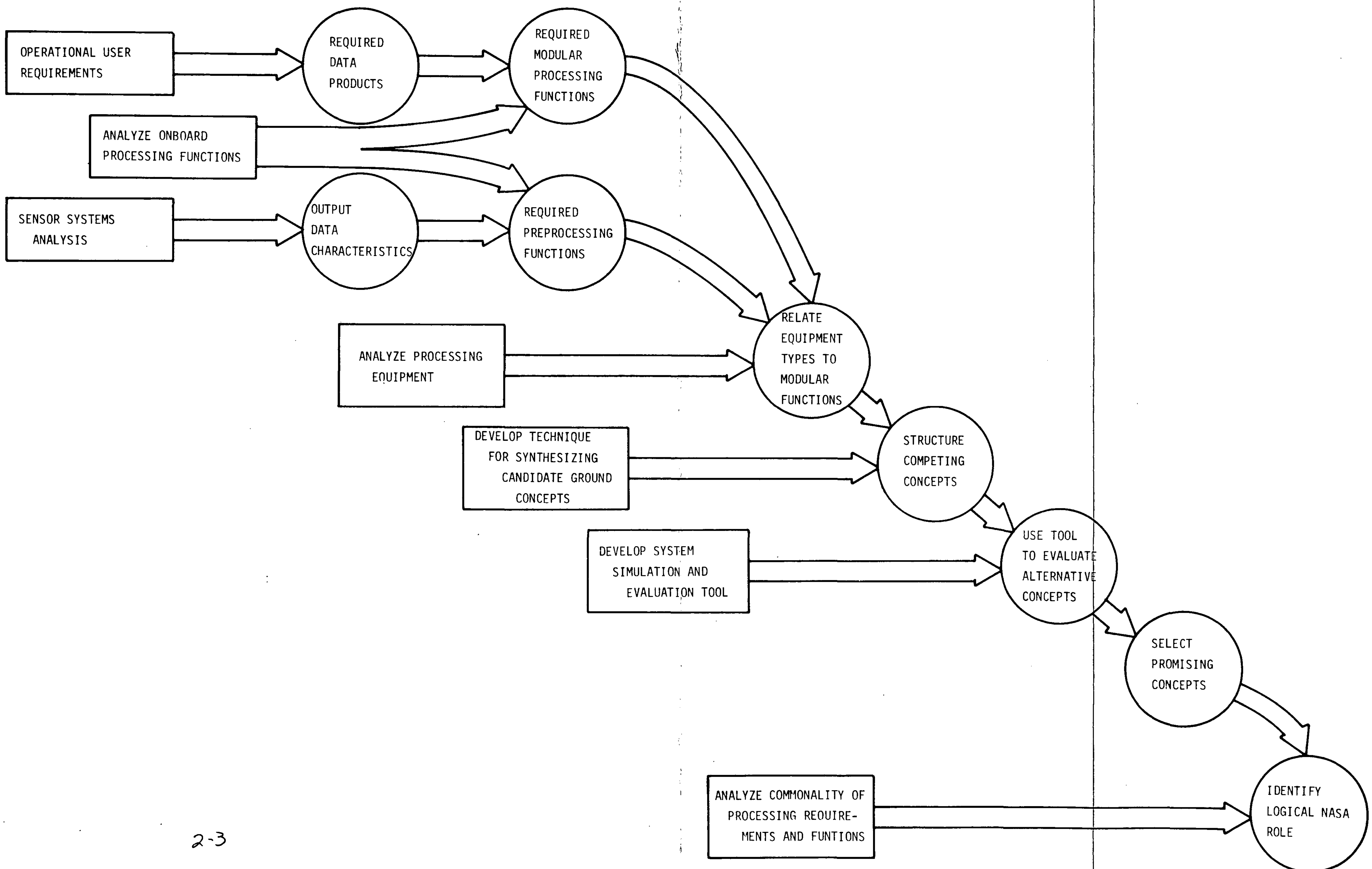

Figure 2-1. Study Flow and Objectives

3.0 OPERATIONAL USER REQUIREMENTS

In the time frame of interest it is assumed that an earth resource survey program will have moved from the current experimental stage to a situation characterized by a mix of operational, prototype, and experimental applications of remotely sensed data. "Operational," as used here, is taken to imply that there is dependence on the data to support critical activities. This section presents a methodology for projecting user requirements and provides preliminary assessments of processing requirements for various remote sensing mission characteristics.

3.1 Objective

The primary objective of this task is to develop use patterns for a set of modular processing functions. These functions (described in Section 5.6) are the discrete processing steps required to convert raw data to usable information. Use patterns are determined by developing a model of the user community for data products. These data products (i.e., thematic maps, statistical summaries, etc.) are then related to the modular processing functions, and ultimately to specific equipment types (Section 7.5).

The desired characterisitics of the user community model are:

- The model should be rooted in a projection of the actual use of remotely sensed data rather than the capabilities for acquiring data.
- The model should have the inherent flexibility of adapting to changes in sensors, mission configurations, and data analysis capabilities.
- The model should provide an upper bound for data processing consistent with the first objective.
- The model should provide an understanding of the temporally distributed nature of data processing requirements.
- The model should comprehensively account for data products to be delivered without an a priori decision of the processing roles of various agencies.

The model which has been developed meets these objectives. Consistent with these objectives, the data processing load of a center can be sized; even more importantly, the model facilitates parametric studies of the implications of various levels of technology availability on the processing load. At this stage of the study, a decision has been made to absorb the risks associated with subjective judgement to essentially "push through" the requirements definition process and to illustrate the adaptive nature of the model with refinement to follow as a result of user contacts and verification.

3.2 User Definition Process

The basic problems with choosing to concentrate upon operational applications of remotely sensed data are that the sensors, the data reduction techniques, and the applications are currently all in an experimental stage. Furthermore, there is a significant problem in defining the dynamics of the user community; i.e., the manner in which data are distributed among researchers, government agencies, and the "man on the street". Beyond these problems there are few definitive guidelines available to describe the amount of processing which would be considered appropriate for a "distributor" to perform; this problem is further intensified by the fact that confusion exists concerning who this distributor(s) is. Assuming that these problems are overcome or circumvented, there is a marked lack of information on how much data would be used by a given user. All of these problems are critical aspects of the ground data handling system design process, and before systematically describing the requirements definition process, the decisions and assumptions made to work around them will be discussed.

Ideally, all of the problems which have been described could be solved by going to selected users and asking for guidance; indeed, this was done early in this study. However, the current experimental status of the earth resources survey must be continually kept in mind. There is great hope for the new technology but, due partially to budgetary constraints, the users must defer quantitative answers to the questions which are relevant to defining processing requirements. Therefore, the approach taken in this study is to systematically develop processing requirements based upon subjective assessments of user needs. Then, users can be questioned with respect to the reasonableness of the assessments rather than placing the burden on the user to develop a list of requirements.

Although the sensors, data analysis techniques, and applications are areas of research, this research is well documented and it is possible to identify research endeavors which show operational promise. In this study the concentration is upon identifying the types of phenomena and the relevant spectral bands which could be accommodated by remote sensing in a multilevel system in which spacecraft, aircraft, and ground sensors are used to obtain increasingly precise measurements; i.e., the spacecraft data is being used largely to determine where to obtain precision data. Furthermore, an examination of current resource concerns permits a rather simple assumption that there are national priorities, the projected criticality of which, in the time frame of interest, will require the use of all available information, including remotely sensed data.

Relative to the structure of the user community to be considered in determining requirements, the decision was made to concentrate on the earth resource management community and, in particular, federal agencies. Bill Fisher of the USGS/EROS project office has divided the users of remotely sensed data into several categories[(1)], as described below:

Table 3-1. User Community Structure

User	Time Frame Within Which Data is Needed	Type and Format of Data Needed	Suggested Method of Dissemination
Scientists	1 week to 1 year	Raw data, data in map format, specially processed data	Mail
Resources - Managers and Planners	1 day to 2 months	Interpretative data, data in map form, extracted information	Telephone, Jet Plane, Mail
Policy People	1 month to 1 year	Synthesized interpretative data, data in map form	Mail
Resources - Public	1 to 2 days	Raw data supplemented by quick interpretations, comparisons of sequential coverages, and extracted information	Established media: TV, newspapers, radio, etc.
Educators	1 year	Data in map format and data supplemented in some cases by interpretations and explanations	Mail

(1) Fisher, William A., "Projected Uses of Observations of the Earth from Space," AIAA 70-332.

Most of the current confusion in describing the user community is between the "Resource Managers and Planners" and the "Resources Public" categories. Using the information in Table 3-1, two conjectures can be made.

First, the time frame requirements of the Resources Public are satisfied by either a synchronous satellite or an integrated large set of low altitude satellites.

Second, the dissemination methods for the Resources Public are similar to the APT capability of meteorological satellites in which no (or little) ground processing is done prior to transmission to the users.

Both the required frequency and the inherent processing requirements precluded direct consideration of the Resource Public in determining processing requirements at this point in time.

NASA has presented six alternatives for management of the Earth Resources Survey Program(1). These alternatives are generated by various allocations of the roles of sensor development, launch, on-orbit control, data acquisition, and data reduction among the government agencies. This is indicative of the uncertainty which exists with respect to the level of processing to be performed by any agency (including NASA). For the purposes of this study, consideration of agency roles is deferred until after the processing requirements have been identified at all stages, from delivery of data to a ground data handling system, to the delivery of a useful product to the user.

Finally, the problems associated with quantitatively describing the processing load must be addressed. Actually, two general types of problems confront this activity. There are problems related to a given phenomenon (e.g., areal extent, frequency of observation, resolution) but beyond these are the problems of "acceptance". Acceptance as used here is related to assessing the amount of data to be used at a given level of state-of-the-art and given data availability. For this study, the processing load is assumed to be proportional to the areal extent and frequency of observation associated

(1) "Report of the Interagency Ad Hoc Study Group on the Earth Resources Survey Program," William A. Anders, Chairman, March 1971.

with a given phenomenon. Reduction of the total processing load will be accomplished by consideration of cloud statistics for the locale of the phenomenon. Consideration is then given to the variety of data products required to effectively manage the phenomenon. An attempt is made then to parameterically describe agency acceptance for various levels of technology development. A summary of these assumptions is presented in Figure 3-1. The overall user definition process is outlined in Figure 3-2.

3.3 The Management Programs

The basic criteria for selection of earth resource management programs to serve as a baseline for systems requirements assessments were:

- They should represent national priorities.
- They should contain problem areas amenable to remote sensing.
- Based upon results of current research, there should be demonstrated feasibility of remote sensing aspects.
- The processing requirements of the selected programs should "exercise" the ground processing system.

The first criterion is rather straightforward; i.e., national priorities are obvious from reports and forecasts published in the popular literature.

The second criterion requires a survey of the current data gathering activities and the objectives of the various government agencies. This survey must then be considered against the backdrop of remote sensing technology to determine which of the conventional data gathering functions could potentially be replaced by remote techniques and which management objectives could be furthered by these techniques (even if there is not currently a counterpart in conventional techniques). An obvious problem is introduced at this point; only with blatant naivity could it be assumed that every potential application of remote sensing technology would be utilized to the fullest possible extent. In the present study this problem is addressed principally through the concept of "acceptance modeling" discussed in Section 3.5. However, it is recognized that the acceptance concept used here is not totally adequate; final consideration of the potential application of remote sensing technology will depend heavily upon econometric considerations. Within the scope of this study, econometric aspects are

"BEST OF ALL POSSIBLE WORLDS"	REAL WORLD	ASSUMPTION MADE TO PUSH FORWARD
LIST THE SENSORS AND APPLICATIONS FOR OPERATIONAL SYSTEMS	SENSORS AND APPLICATIONS ARE CURRENTLY AREAS OF EXPERIMENTATION	CONCENTRATE ON OBSERVABLE PHENOMENA AND SPECTRAL BANDS
IDENTIFY TIMING AND FORMAT REQUIREMENTS OF USERS	THE USER COMMUNITY IS POORLY DEFINED	CONCENTRATE ON EARTH RESOURCE MANAGEMENT COMMUNITY. ORGANIZE PHENOMENA INTO PROGRAMS WHICH ADDRESS NATIONAL PRIORITIES
DETERMINE LEVEL OF PROCESSING FOR EACH USER SERVED	THERE ARE SEVERAL MANAGEMENT ALTERNATIVES FOR REMOTE SENSING ASPECTS OF THE ERS PROGRAM	CONCENTRATE UPON IDENTIFICATION OF REQUIRED PROCESSING FUNCTIONS TO PROVIDE DATA TO FACILITATE DIVISION OF LABOR DECISIONS
SIZE SYSTEM REQUIREMENTS BASED UPON EXPECTED LOAD	VOLUMETRIC REQUIREMENTS HAVE NOT BEEN STATED FOR THE ACTUAL USE OF DATA	THE PROCESSING REQUIREMENT CAN BE DEFINED IN TERMS OF DATA PRODUCTS REQUIRED FOR ANALYSIS, AREAL EXTENT AND FREQUENCY

Figure 3-1. Methodology Assumptions

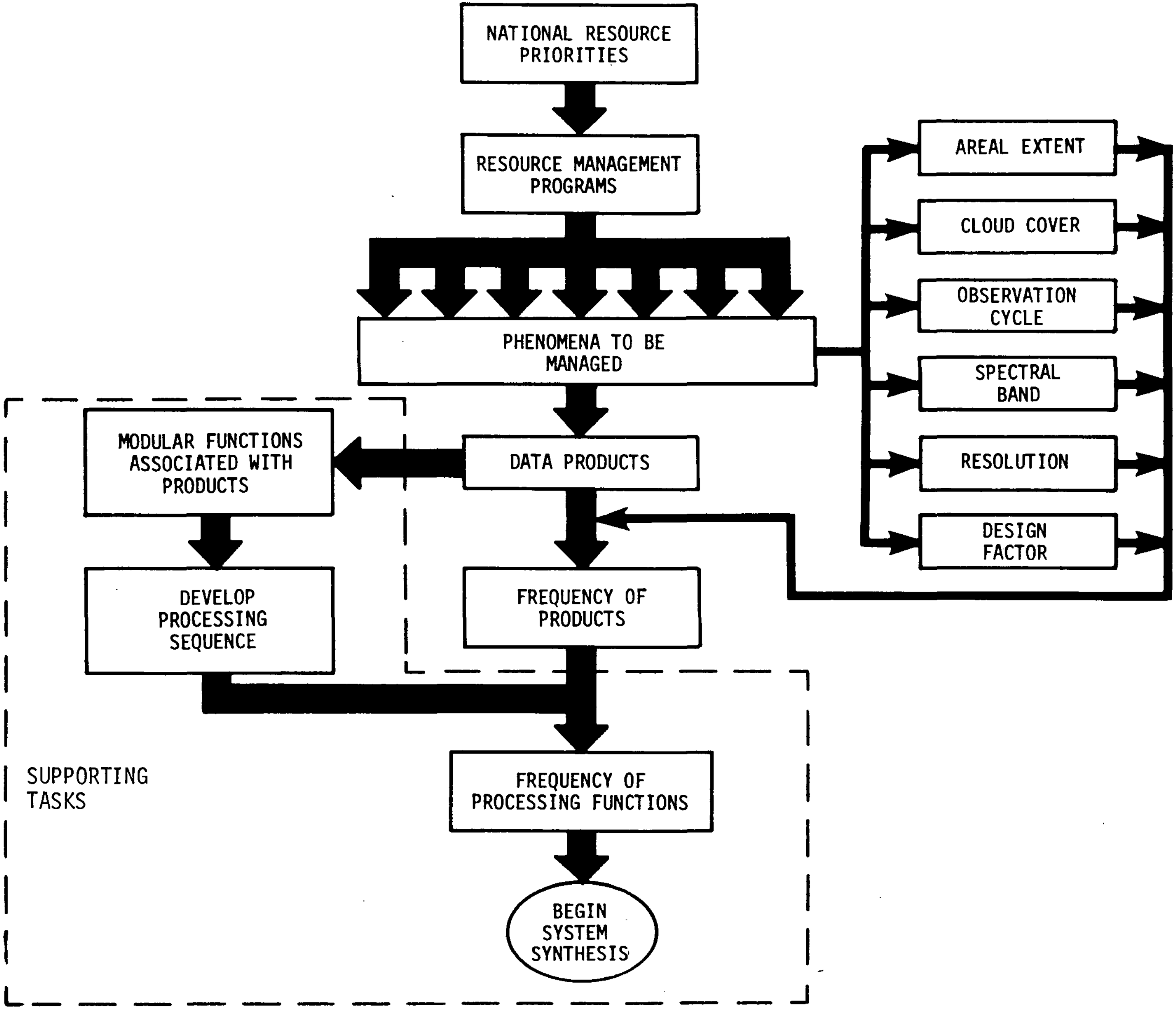

Figure 3-2. User Requirements Definition Process

considered only to the extent that the user requirements model includes parameters required for future econometric studies. An approach to such studies is outlined in Section 3.7.

The last criterion of programs which exercise the ground processing system is obviously arbitrary. However, the desire was to not expend any significant effort on applications such as the APT capability of meteorological satellites which, even though interesting from a communications viewpoint, impose little, if any, requirements on ground processing functions.

One of the first activities of this study was to investigate the flow of data among the various federal agencies involved in the management of the Nation's resources. One result of this study was the realization that there is a large amount of crossover in the data collection activities. For example, the responsibility for the management of the Nation's water resources resides within the USDI, but the USDA and U.S. Army Corps of Engineers are involved in major data collection and management activities directly related to water resources. Similarly, the USDI has considerable interest in vegetation cover--the nominal area of interest of the USDA. Further study indicates that while there is functional crossover between agencies, in most cases there is actually little redundancy in data collection activities.

The above situation precluded the development of programs specifically tailored to individual federal agencies. The programs are essentially described independently of the roles of the various federal agencies.

In the selection of remote sensing programs, the two obvious areas of meteorology and oceanography have been excluded from consideration. This was done for the following reasons.

- NOAA, under whose purview these areas would obviously fall, has an operational Environmental Satellite Center (ESC) encompassing all functions from preprocessing to delivery of a final product.
- The global nature of the problems, the low resolution of the sensors, and the high frequency of observation required tend to dictate a "tailor made" system (i.e., geosynchronous platforms).

- While the NOAA center is currently devoted primarily to meteorology, the global aspects of oceanographic applications tend to indicate that the ESC could be the logical choice for reduction and dissemination of this data.

Even though the USGS has begun operations of the Sioux Falls facility for providing ERTS data to the geological community, a geological management program is included for the following reasons:

- The Sioux Falls facility currently does not provide preprocessing functions nor is there provision for Level 3 products (discussed in Section 3.4).
- Conceivably, the Sioux Falls facility is the first of several regional centers; therefore, useful information can be generated on the possible distribution of functions, even if Sioux Falls serves as a major precursor or ultimate nucleus.

The following are descriptions of the resource management programs selected for study.

<u>Hydrological Resources Management</u>

The primary objective of the Hydrological Resources Management Program presented here is to achieve refinement of hydrological parameters on a synoptic scale. Of all the programs presented, hydrology uses, to the greatest extent, mathematical models. The primary objective of these models is to predict how much water will be available to a watershed as a function of precipitation. Model types include:

- Models which use an aggregate coefficient obtained as a function of ground slope, soil types, humidity, vegetation cover, etc., to calculate water output as equal to this coefficient multiplied by water input.
- A model developed by NOAA which correlates rainfall with water flow, predicts the time behavior of the flow (hydrograph), and predicts the overall behavior.
- An input/output model developed by Stanford which attempts to mathematically describe all interactions of pertinent factors in the watershed.

All of the models are obviously highly sensitive to basic information about the topography and geology of the watershed. The following management functions could conceivably the accommodated from space.

- Classification of ground cover
- Classification of soil types
- Determination of ground slope
- Inventory of primary and secondary streams
- Measurement of soil humidity
- Measurement of reservoir and river boundaries
- Mapping of acquifers
- Snow accumulation/snow melt assessments
- Flood movement
- Average precipitation
- Stream flow
- Arctic Ice movement

Geological Resources Management

The primary objectives of the geological resources management program presented here are to provide data pertinent to the location of mineral bearing regions and to recognize potential geological hazards. The geological processes are relatively static compared with dynamic processes such as agriculture. The basic requirement is for information displayed in map format. The USGS plans to update many of its maps in the form of photomaps and as increased resolution becomes available, it may be anticipated that the trend will be to generate photomaps series of correspondingly increasing scale. The Sioux Falls facility of USGS is gearing to provide the general user community with maps, including thematic maps, based on ERTS imagery. The mapping applications of remote sensing generally are best supported with large swath widths (up to 100 miles which is about the maximum size which can be imaged orthographically without being affected by earth curvature from ERTS altitude) since many features of geologic interest are confused with inter-photograph lines in photo mosaics. The following are the functions of the Geological Resources Management program.

- Mapping of lineaments, folds, outcrops, and alluvial deposits
- Mapping of soil types
- Surface texture and apparent color maps
- Mapping of vegetation cover
- Distribution of favorable lithological structures
- Location of offshore placers in shallow water
- Location of geothermal sources
- Mapping of faults and fissures
- Status of open pit and strip mining activities
- Monitoring of mine waste disposal activities
- Location of regions suitable for waste disposal

Agricultural Resources Management

The management processes related to agricultural resources may be considered to involve cycling through inventory, analysis, and operations functions[(1)]. For example, in the inventory phase it may be estimated that a given commodity will be produced at a certain level. In the analysis phase it could be determined that continued production at this level would reduce the price of the commodity below an acceptable value and, controls should be exercised to reduce planting in the operations phase. In the next cycle the inventory and analysis processes would concentrate on compliance.

The large volume of data which must be analyzed generates the desire for automation of the inventorying process. The volume is created by the large areal extent of the resource and the need for repetitive viewing (many plant types are differentiated only by examination of differences between fields of various stages of the growth cycle). The inventorying process requires extensive use of multistage sampling techniques in which progressively more detailed information is obtained for progressively smaller subsamples of the area being studied. It should be noted that the emphasis on inventorying exists whether the desire is to increase or reduce production. The management functions for agricultural resources include:

- Inventory of crop types

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(1) Colwell, Robert N., "The Future of Remote Sensing of Agricultural, Forest, and Range Resources," Presentation to Committee on Science and Astronautics, U.S. House of Representatives, January 26, 1972.

- Compliance monitoring
- Stress (moisture, disease, entomological) determination
- Soil classification
- Crop damage assessment
- Land erosion
- Irrigation project planning
- Agricultural land use
- Yield forecasts

Forestry and Rangeland Resources Management

Many of the comments made about Agriculture Resources Management hold true for forestry and rangelands. Like agriculture, they are renewable resources and, as such, their management is a dynamic process. To a certain extent, frequency of observation requirements is somewhat relaxed relative to agriculture since, in the main, the results of exercising controls are manifested more slowly. Most of the forest and rangeland resources of the nation are part of watersheds of the various rivers. Therefore, there is a certain portion of the areal extent of the two management purviews which must be considered in common. The primary objectives of this management program are an understanding of present and future timber stands, the carrying capacity of rangelands, and a knowledge of threats to either of these resources. Management functions within this program include:

- Timber inventory
- Forest stress detection
- Forage inventory
- Forage stress detection
- Easement and firelane maintenance
- Wildlife environment
- Monitoring of flammatory conditions
- Plant species migration and encroachment
- Entomological migration
- Air and water quality/plant health relationship
- Fire damage assessment
- Cutting/replanting compliance

Coastal Zone Management

The Coastal Zone Management Act introduced in 1969 created the framework for establishment of Coastal Zone Authorities. This Act is recognition of the diverse problems and opportunities associated with the Coastal Zone. This zone encompasses many aspects of agricultural, forestry, urban development, hydrology, and environmental quality, as well as the obvious areas of fisheries and oceanography. The basic aim of the Coastal Zone Management Program described in this section is to provide data of sufficiently synoptic scale to yield insight into the complex interactions of phenomena within the Coastal Zone. An interesting aspect of coastal zone applications is that there is a rather open field for remote sensing since the coastal zone management will be new authorities and, to a great extent, without elaborate conventional data gathering systems. Management functions of the Coastal Zone Management Program are:

- Erosion of shoreline
- Effect of structures on bug circulation
- Estuary dynamics
- Chlorophyll distribution
- Thermal distribution
- Effluent plume dynamics
- Turbidity
- Dredging compliance
- Storm damage assessment
- Shipping lane traffic
- Shipping hazards
- Wind/water relationships

Urban Dynamics Management

The applications of remote sensing to city planning have received considerable attention in research activities. Indeed, imagery obtained from aircraft have provided an important tool to city planners for noting changes in land use and detecting population shifts. Preliminary indications are, however, that the primary technology area for this program is information management for the diverse sources of data. The following are functions which in a multistage management system could be accomodated from space:

- Monitoring of population trends
- Urban hydrology
- Water utilization
- Urban blight
- Land use

Environmental Quality Management

The area of environmental quality will obviously rank high in national priority for some time to come. However, this area poses basic problems to developing a management program involving remote sensing, primarily due to the fact that gaseous pollution detection from space has not been established as clearly feasible. Current research does hold promise, however, for meaningful air pollution monitoring from space in the not to distant future.(1) The applications listed below are potentially feasible water quality management functions:

- Detection and monitoring of oil spills
- Suspended sediment
- Chemical and toxic wastes
- Thermal effluents
- Nutrient wastes

3.4 Data Products

The primary emphasis throughout this task is on identifying the requirements of the user community in terms which directly impact the design of a ground data handling system. Basic to this emphasis is an understanding of the data products to be delivered. Before describing these products generically, some observations on the analytical modes used in the earth sciences are in order.

There is a considerable amount of work in the field devoted to developing mathematical models. However, many more activities depend upon what may be termed "subjective modeling". This term is used to describe analytical processes which depend heavily upon the intuition (derived from experience) of the analyst. Thus, the tools used by the analyst are those which

(1) "Remote Measurement of Pollution," NASA SP-285, dated 1971

provide data in a form which complements intuitive processes. The following are brief descriptions of these generic data products.

Photomap - In its simplest form this product is merely a photograph, but it may include superimposed gridding and annotation. Typical uses of photomaps would include:

- Aid in planning construction
- Assignment of work crews in remote areas (USGS studies have shown marked improvement in the ability to determine exact location with photographic aids instead of traditional maps.)
- The basic information source for visual detection of plant stresses, fault lines, etc.

Overlay - This is a general description of a technique in which more than one image is adjusted in scale and orientation. Thus, an overlay could consist of simultaneous CRT images, prints, or transparencies. This is the primary information source for visual change discrimination. Typical applications of overlays would include:

- Studies of changes in land use
- Monitoring movement of insect infestation
- Changes in mine waste disposal activities

Thematic Map - Thematic maps are maps upon which geographically distributed attributes are described by visual aids such as contours and color differentiation. The plotting base may either be photographs or maps and plots are often made on transparent material. The information sources could simultaneously include conventional data sources and remotely sensed data. Typical applications of thematic maps would include:

- Contours of concentrations of various minerals displayed on a photograph of a region
- Known wind shears displayed on photograph of estuary to study wind/water relationships

Geometrically Referenced Spatial Measurements - Measurements of spatial relationships within imagery are obviously important for locating objects geographically through photogrammetric processes. Additionally, certain applications require rate of movement information. Typical applications include:

- Mapping of tectonic features
- Detection of surface thermal anomalies

Input to Mathematical Models - This category of data products is generated using spectral and spatial measurements discussed above. However, it is introduced as a separate type to account for the facts that conversion to model parameter units and generation of computable input media and format may be required. Typical applications include:

- Calculation of ground slope for input to hydrological models
- Determination of coefficient describing porosity of soil

Statistical Summaries - This data product is useful for determining trends and characteristics for use in automated processes. Typical applications include:

- Averaging of pixels to dampen high frequency effects
- Calculation of mean and covariance within an homogenous region for use in maximum likelihood classification schemes

Automated Inventory - This process involves recognition of signatures of certain ground objects and the compilation of the associated areal extent. Various schemes are currently under study including maximum likelihood techniques and clustering techniques. Typical applications include:

- Calculation of the acreage of blighted corn based upon multispectral data
- Acreage of selected crops for forecasting purposes

Automated Change Discrimination - For situations in which either the subtlety of changes in spectral responses from a region at different times or the volume of such data preclude manual interpretation, automated change discrimination techniques may be employed. Many of the functions required to generate this product are similar to those used in automated inventorying; however, the requirement of the availability of, and comparison with, additional images and the inherent registration problem introduces a considerable additional processing burden. Typical applications include:

- Detection of spreading of agricultural blight
- Detection of changes in land use

In later sections reference will be made to "Level of Processing". This refers to the following groupings of data products:

Level 1
- Photomaps
- Overlays

Level 2
- Thematic Maps
- Geometrically Referenced Spatial Measurements
- Geometrically Referenced Spectral Measurements
- Inputs to Mathematical Models
- Statistical Summaries

Level 3
- Automated Inventory
- Automated Change Discrimination

As an example, Level 1 represents only a small extension of current ERTS GDHS capabilities; Level 2 is typical of activities currently performed by various user agencies; and Level 3 represents realization of the goals of much current data processing research. Preliminary assessments of requirements for data products for the management programs are presented in Figures 3-3 through 3-9.

3.5 Acceptance Modeling

The concept of "substitution rate"[(1)] has been used to describe quantitatively the manner in which the Bureau of Public Lands would replace its conventional data gathering activities with remotely sensed data. The argument centered about ground resolution capability; it was conjectured that if data of 300 feet resolution were available to the Bureau, then there would be a willingness to replace perhaps 5% of the conventional activities. However, were data of 20 feet resolution available, then the Bureau would replace perhaps 90% of conventional data acquisition activities. Resolution between these values would have an appropriate substitution rate. Figure 3-10 is a summary of spatial resolution ranges developed for various applications.[(2)] This figure tends to verify the rather large range over which substitution must be considered.

(1) "Management of Grazing Lands," Charles E. Frank, Princeton University Conference, Sept. 1969.

(2) "Remote Sensing of Earth Resources," A. K. Thiel, C. D. Graves, Presentation to the House Committee on Science and Astronautics, 25 January 1972.

MANAGEMENT FUNCTION / INFORMATION REQUIREMENT	OVERLAYS	THEMATIC MAPS	STATISTICAL SUMMARY	AUTOMATED CHANGE REPORTS	AUTOMATED INVENTORY	SPATIAL MEASUREMENTS	GEOMETRICALLY REFERENCED SPECTRAL MEASUREMENTS	INPUT TO MATHEMATICAL MODELS	PHOTOMAP
CLASSIFICATION OF GROUND COVER		X			X		X		
CLASSIFICATION OF SOIL TYPES		X			X		X		
DETERMINATION OF GROUND SLOPE		X	X			X		X	
INVENTORY OF PRIMARY AND SECONDARY STREAMS					X	X		X	X
MEASUREMENT OF SOIL HUMUDITY		X	X				X	X	
MEASUREMENT OF RESERVOIR AND RIVER BOUNDARIES	X			X		X			
MAPPING OF ACQUIFERS	X	X				X			X
SNOW ACCUMULATION/ SNOW MELT	X			X	X	X		X	
FLOOD MOVEMENT	X			X		X			
AVERAGE PRECIPITATION	X	X	X	X	X			X	
STREAMFLOW	X			X		X		X	
ARCTIC ICE MOVEMENT	X	X		X	X	X			

Figure 3-3. Hydrological Resources Management

MANAGEMENT FUNCTION \ INFORMATION REQUIREMENT	OVERLAYS	THEMATIC MAPS	STATISTICAL SUMMARY	AUTOMATED CHANGE REPORTS	AUTOMATED INVENTORY	SPATIAL MEASUREMENTS	GEOMETRICALLY REFERENCED SPECTRAL MEASUREMENTS	INPUT TO MATHEMATICAL MODELS	PHOTOMAP
MAPPING OF LINEAMENTS, FOLDS, OUTCROPS, ALLUVIAL DEPOSITS	X					X			X
MAPPING OF SOIL TYPES	X	X			X		X		
SURFACE TEXTURE MAPS	X	X					X		
MAPPING OF VEGETATIVE COVER	X	X					X		X
DISTRIBUTION OF FAVORABLE LITHOLOGICAL STRUCTURES	X	X							X
LOCATION OF OFFSHORE PLACERS IN SHALLOW WATER		X		X			X		X
SURFICAL THERMAL ANOMALIES	X	X		X			X		
MAPPING OF FAULTS AND FISSURES	X	X							X
STATUS OF OPEN PIT MINING AND STRIP MINING ACTIVITIES	X				X				X
MONITORING OF MINING WASTE DISPOSAL ACTIVITIES	X								X

Figure 3-4. Geological Resources Management

MANAGEMENT FUNCTIONS / INFORMATION REQUIREMENTS	OVERLAYS	THEMATIC MAPS	STATISTICAL SUMMARY	AUTOMATED CHANGE REPORTS	AUTOMATED INVENTORY	SPATIAL MEASUREMENTS	GEOMETRICALLY REFERENCED SPECTRAL MEASUREMENTS	INPUT TO MATHEMATICAL MODELS	PHOTOMAP
INVENTORY OF CROP TYPES			[illegible]		X		[illegible]		X
COMPLIANCE MONITORING	X			X	X				X
STRESS DETERMINATION				X	X		X		
SOIL CLASSIFICATION		X			X		X		X
CROP DAMAGE ASSESSMENT	X	X	X	X	X				X
LAND EROSION	X	X	X	X		X			X
SOIL MOISTURE		X					X		
IRRIGATION PROJECT PLANNING	X					X			X
AGRICULTURE LAND USE		X	X	X					X
YIELD FORECASTS			X	X	X			X	

Figure 3-5. Agricultural Resources Management

MANAGEMENT FUNCTION / INFORMATION REQUIREMENT	OVERLAYS	THEMATIC MAPS	STATISTICAL SUMMARY	AUTOMATED CHANGE REPORTS	AUTOMATED INVENTORY	SPATIAL MEASUREMENTS	GEOMETRICALLY REFERENCED SPECTRAL MEASUREMENTS	INPUT TO MATHEMATICAL MODELS	PHOTOMAP
STRESS DETECTION	X	X	X	X	X		X		
TIMBER INVENTORY			X	X	X				X
FORAGE INVENTORY			X	X	X				X
ROAD AND FIRELANE MAINTENANCE						X			
WILDLIFE ENVIRONMENT	X	X			X				X
MONITORING OF FLAMMATORY CONDITION	X			X	X		X	X	
PLANT SPECIES MIGRATION AND ENCROACHMENT	X	X		X					
ENTOMOLOGICAL MIGRATION	X		X	X			X		
AIR QUALITY/ WATER/PLANT HEALTH RELATIONSHIP	X	X	X		X		X		
FIRE DAMAGE ASSESSMENT	X	X	X	X	X	X			X
CUTTING/ REPLANTING COMPLIANCE	X			X	X				X

Figure 3-6. Forestry and Rangeland Resources Management

MANAGEMENT FUNCTION / INFORMATION REQUIREMENT	OVERLAYS	THEMATIC MAPS	STATISTICAL SUMMARY	AUTOMATED CHANGE REPORTS	AUTOMATED INVENTORY	SPATIAL MEASUREMENTS	GEOMETRICALLY REFERENCED SPECTRAL MEASUREMENTS	INPUT TO MATHEMATICAL MODELS	PHOTOMAP
EROSION OF SHORELINE	X			X		X			
EFFECT OF STRUCTURES ON BAY CIRCULATION	X			X		X		X	X
FRESH/SALT WATER INTERFACES	X	X		X			X		
CHLOROPHYLL DISTRIBUTION		X	X	X			X		
THERMAL DISTRIBUTION	X	X					X	X	
EFFLUENT PLUMES	X					X			
TURBIDITY				X			X		
DREDGING COMPLIANCE	X					X			X
STORM DAMAGE ASSESSMENT	X			X		X			X
SHIPPING LANE TRAFFIC		X	X						
SHIPPING HAZARDS	X			X					X
WIND/WATER RELATIONSHIP	X	X							

Figure 3-7. Coastal Zone Management

MANAGEMENT FUNCTION / INFORMATION REQUIREMENT	OVERLAYS	THEMATIC MAPS	STATISTICAL SUMMARY	AUTOMATED CHANGE REPORTS	AUTOMATED INVENTORY	SPATIAL MEASUREMENTS	GEOMETRICALLY REFERENCED SPECTRAL MEASUREMENTS	INPUT TO MATHEMATICAL MODELS	PHOTOMAP
POPULATION TRENDS	X	X	X						X
URBAN HYDROLOGY		X		X		X		X	
WATER UTILIZATION	X	X	X				X	X	
BLIGHT		X	X						X
CLASSIFICATION OF STRUCTURES		X	X		X				

Figure 3-8. Urban Dynamics Management

MANAGEMENT FUNCTION / INFORMATION REQUIREMENT	OVERLAYS	THEMATIC MAPS	STATISTICAL SUMMARY	AUTOMATED CHANGE REPORTS	AUTOMATED INVENTORY	SPATIAL MEASUREMENT	GEOMETRICALLY REFERENCED SPECTRAL MEASUREMENTS	INPUT TO MATHEMATICAL MODELS	PHOTOMAP
BACKGROUND RADIATION BUDGET		X	X	X					
OIL				X			X	X	
SUSPENDED SEDIMENT	X				X		X		
CHEMICAL AND TOXIC WASTES	X				X		X		
SOLID WASTES	X				X		X		
THERMAL EFFLUENTS	X	X					X		
NUTRIENT WASTES		X					X		

Figure 3-9. Management of Environmental Quality

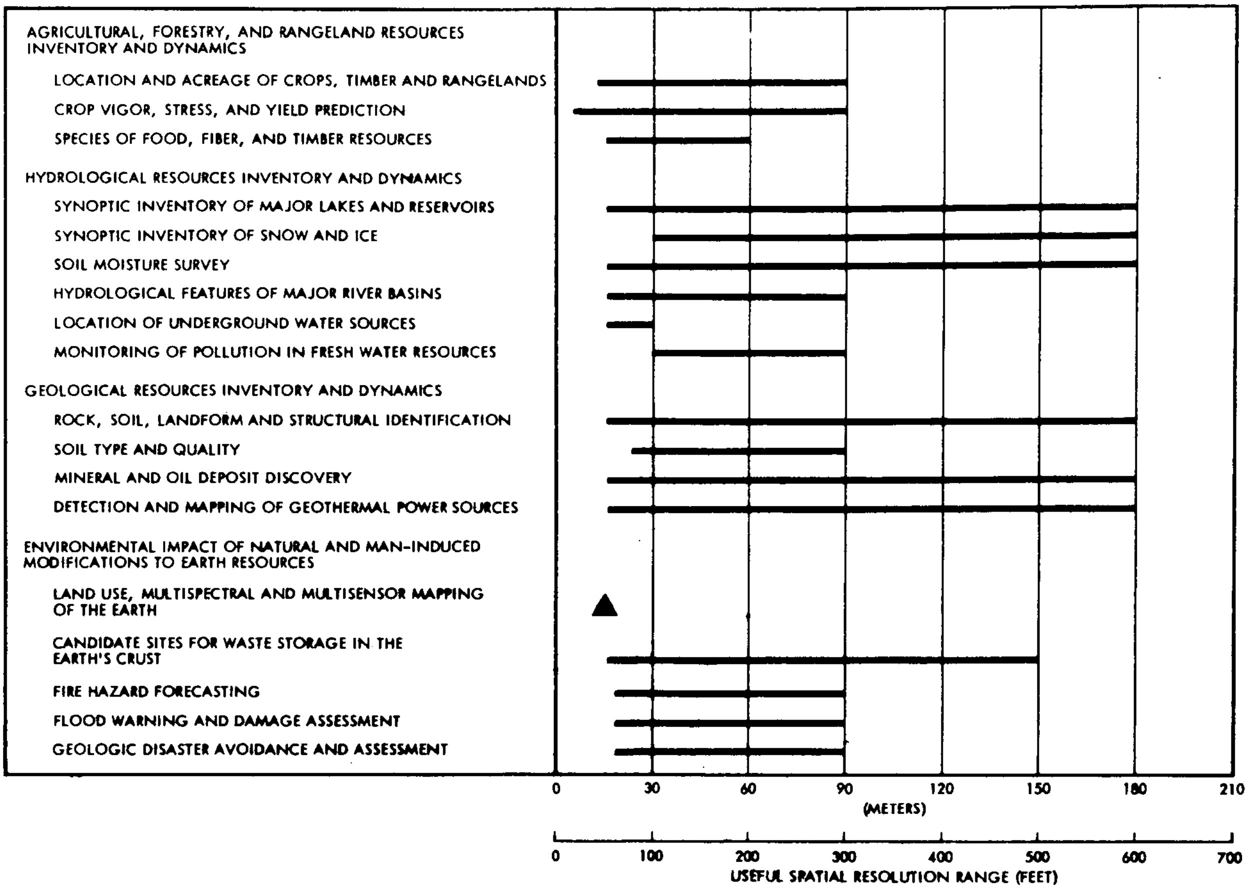

Figure 3-10. Spatial Resolution Requirements

In this study the concept of substitution rate has been extended to "acceptance rate". This permits consideration of management functions which are intractable with conventional data sources. Furthermore, it is necessary to consider the acceptance on the part of the user relative to the inherent user requirements; i.e., within the period of year of interest for a management function, what portion of the data available in that period would be of use. In an evolving remote sensing program, the following parameters influence the willingness of a user to accept the data as part of a management function:

- Resolution
- Observation Frequency
- Swath Width
- Spectral Regions
- Requirements for Automatic Processing

In effect, parametrically describing acceptance rate in this manner permits sizing of ground data handling requirements at any given level of technology development. Figure 3-11 illustrates the overall role of acceptance modeling in determining processing requirements.

Relative to a set of earth resource management programs, the following cases are examples of those which can be studied.

- If all desires of the user community are met with respect to the acceptance parameters, what is the processing load?
- If one satellite with 50-feet resolution is available in an ERTS-type orbit with 100-mile swath carrying sensors in the visible and near IR regions of the spectrum, what is the load?
- What impact does the deployment of multiple satellites similar to that above providing weekly coverage have?
- What happens to the processing requirements with the addition of a microwave radiometer?
- For a given mission configuration, what is the impact on processing requirements if the development of data processing techniques continues to lag the ability to collect data and automated inventory and change discrimination techniques are not available?

Preliminary assessment of percentage acceptance at various levels of technology development are presented in Figures 3-12 through 3-18 for the management programs. These figures also contain information on areal extent and period of the year for observation. The geographical region is presented for use in determining cloud cover statistics. However, for spaceborne applications cloud statistics must be used with care; if the frequency of passage of the spacecraft over a region is higher than the required observation frequency, then the increased number of viewing opportunities must be considered. The entries in the figures for "Region" refer to the information in Figure 3-19 and Table 3-2.[1] The "Areal Extent" values contained in Figures 3-12 through 3-18 are based upon information contained in the National Atlas. These values are considered preliminary and will be refined as study progresses.

[1]"World Wide Cloud Cover Distributions for Use in Computer Simulations," Paul E. Sherr, et al, NAS 8-21040, dated 14 June 1968.

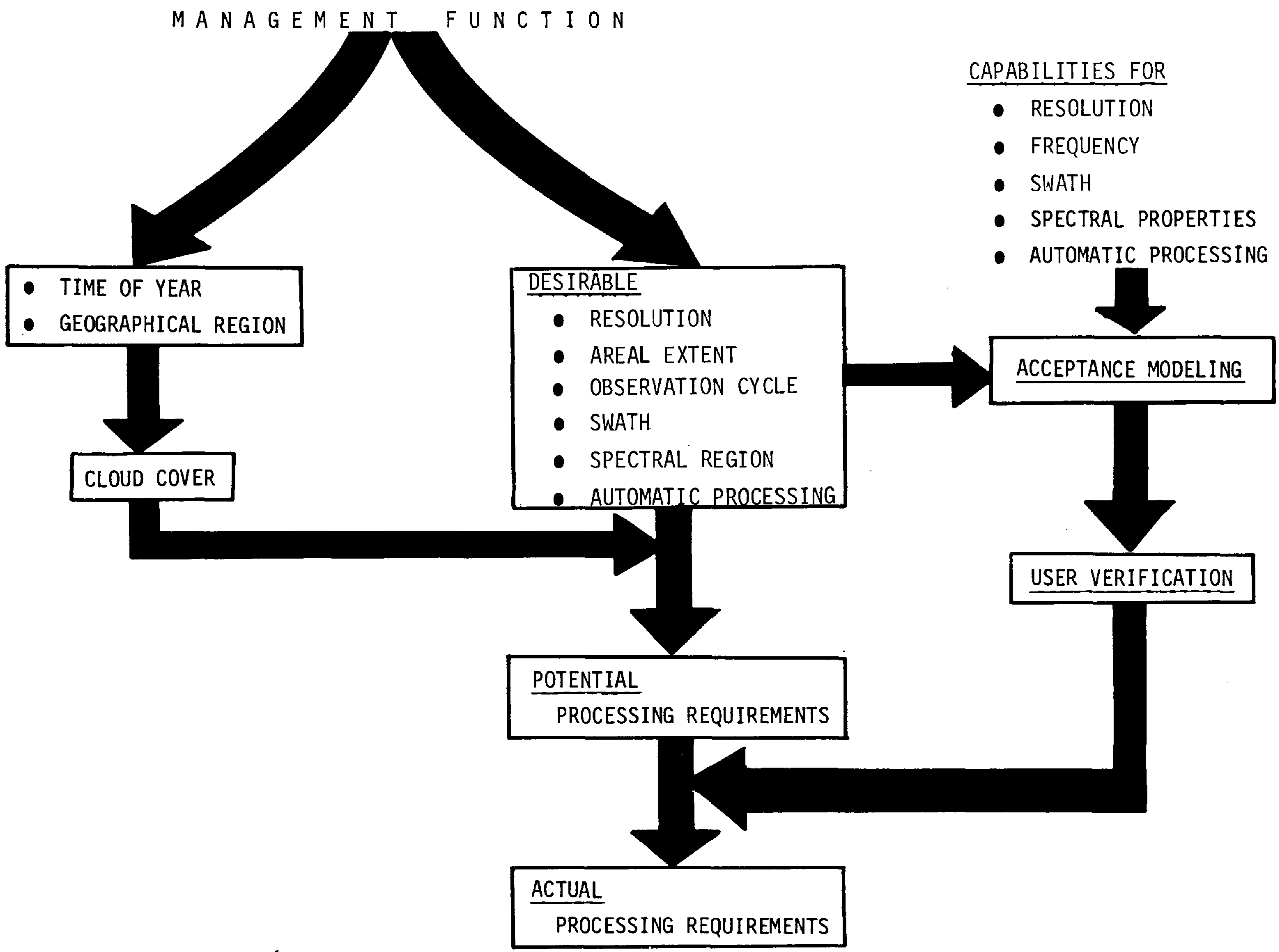

Figure 3-11. Role of Acceptance Modeling

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Management Function	Optimum Resolution (ft)	Optimum Frequency*	Optimum Swath (mi)	Optimum Spectral Region**	Processing Level (Section 3.4)	Resolution Acceptance (ft) 50	Resolution Acceptance (ft) 100	Resolution Acceptance (ft) 300	Frequency Acceptance Daily	Frequency Acceptance Weekly	Frequency Acceptance Biweekly	Swath Acceptance (mi) 10	Swath Acceptance (mi) 50	Swath Acceptance (mi) 100	Spectral Acceptance Visible	Spectral Acceptance Near IR	Spectral Acceptance Thermal IR & Microwave	Processing Acceptance Level 1	Processing Acceptance Level 2	Processing Acceptance Level 3	Geographical Regions	Time of Year	Areal Extent (sq. mi)
Classification of ground cover	100	3M	50	NIR	3	0.9	0.9	0.7	0.9	0.9	0.9	0.9	0.9	0.9	0.7	0.9	0.9	0.2	0.5	0.9	All	April - Aug	750,000
Classification of soil types	100	Y	50	TIR MW	3	0.9	0.9	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.4	0.4	0.9	0.2	0.5	0.9	All	Aug	750,000
Determination of ground slope	50	Y	50	V	2	0.9	0.8	0.7	0.9	0.9	0.9	0.7	0.9	0.9	0.9	0.9	0.9	0.4	0.9	0.9	All	Aug	650,000
Inventory of primary and secondary streams	50	M	50	NIR TIR	3	0.9	0.7	0.5	0.9	0.9	0.9	0.8	0.9	0.9	0.7	0.8	0.9	0.5	0.5	0.9	All	April - Aug	650,000
Measurement of soil humidity	5000	W	100	MW	2	0.9	0.9	0.9	0.9	0.9	0.8	0.9	0.9	0.9	0.0	0.1	0.9	0.7	0.9	0.9	All	April - Aug	750,000
Measurement of reservoir and river boundaries	50	W	50	NIR TIR	3	0.9	0.7	0.4	0.9	0.9	0.7	0.9	0.9	0.9	0.1	0.5	0.9	0.5	0.7	0.9	All	April - July	750,000
Mapping of acquifers	50	4M	100	NIR TIR	2	0.9	0.8	0.7	0.9	0.9	0.9	0.7	0.9	0.9	0.1	0.5	0.9	0.7	0.9	0.9	All	June - Sept	650,000
Snow accumulation/snow melt	100	W	50	V MW	3	0.9	0.9	0.5	0.9	0.9	0.8	0.9	0.9	0.9	0.5	0.5	0.9	0.4	0.7	0.9	All	Feb - June	750,000
Flood movement	50	E	50	V	3	0.9	0.8	0.7	0.9	0.5	0.1	0.7	0.9	0.9	0.9	0.9	0.9	0.4	0.4	0.9	All		
Average precipitation	5000	W	50	MW	3	0.9	0.9	0.9	0.9	0.9	0.7	0.7	0.9	0.9	0.0	0.1	0.9	0.5	0.7	0.9	All	Mar - Sept	300,000
Arctic ice movement	50	W	100	V MW	3	0.9	0.8	0.7	0.9	0.9	0.7	0.5	0.7	0.9	0.5	0.5	0.9	0.7	0.8	0.9	10	All	1,000,000

Legend

*W - Week
M - Month
Y - Year
E - Episodic

**V - Visual
NIR - Near Infrared
TIR - Thermal Infrared
MW - Microwave

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Figure 3-12. Data Acceptance for Hydrological Resources Management

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Management Function	Optimum Resolution (ft)	Optimum Frequency*	Optimum Swath (mi)	Optimum Spectral Region**	Processing Level (Section 3.4)	Resolution Acceptance (ft) 50	Resolution Acceptance (ft) 100	Resolution Acceptance (ft) 300	Frequency Acceptance Daily	Frequency Acceptance Weekly	Frequency Acceptance Biweekly	Swath Acceptance (mi) 10	Swath Acceptance (mi) 50	Swath Acceptance (mi) 100	Spectral Acceptance Visible	Spectral Acceptance Near IR	Spectral Acceptance Thermal IR & Microwave	Processing Acceptance Level 1	Processing Acceptance Level 2	Processing Acceptance Level 3	Geographical Regions	Time of Year	Areal Extent (sq. mi)
Mapping of lineaments, folds, outcrops, and all alluvial deposits	50	Y	100	V	2	0.9	0.6	0.2	0.9	0.9	0.9	0.2	0.8	0.9	0.9	0.9	0.9	0.4	0.9	0.9	1, 2, 3, 5, 6, 9, 10	Aug	1,500,000
Mapping of soil types	50	Y	100	MW	3	0.9	0.7	0.4	0.9	0.9	0.9	0.9	0.9	0.9	0.2	0.2	0.9	0.2	0.7	0.9	All	Aug	1,500,000
Surface texture maps	50	Y	100	MW	2	0.9	0.4	0.0	0.9	0.9	0.9	0.9	0.9	0.9	0.2	0.2	0.9	0.4	0.9	0.9	All	Aug	3,000,000
Mapping of vegatative cover	50	3M	100	NIR	2	0.9	0.7	0.4	0.9	0.9	0.9	0.9	0.9	0.9	0.6	0.9	0.9	0.7	0.9	0.9	All	April - Aug	3,000,000
Distribution of favorable lithological structures	50	Y	100	V MW	1	0.9	0.4	0.1	0.9	0.9	0.9	0.2	0.8	0.9	0.5	0.5	0.9	0.9	0.9	0.9	1, 2, 3, 5, 6, 9, 10	Aug	1,500,000
Location of offshore placers in shallow water	50	4M	100	V	1	0.9	0.7	0.5	0.9	0.9	0.9	0.5	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1, 4, 10	All year	530,000
Location of geothermal sources	50	3M	100	TIR	3	0.9	0.8	0.7	0.9	0.9	0.9	0.9	0.9	0.9	0.0	0.0	0.9	0.2	0.7	0.9	5, 11, 12	Aug - Mar	300,000
Mapping of faults and fissures	50	Y	100	V MW	2	0.9	0.7	0.4	0.9	0.9	0.9	0.4	0.7	0.9	0.6	0.6	0.9	0.2	0.9	0.9	1, 2, 3, 5, 6, 9, 10	Aug	1,500,000
Status of open pit mining and strip mining activities	30	M	100	V	3	0.6	0.3	0.1	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.5	0.5	0.9	2, 5, 7		100,000
Monitoring of mine waste disposal activities	10	2W	100	V TIR	1	0.2	0.1	0.0	0.9	0.9	0.9	0.9	0.9	0.9	0.5	0.5	0.9	0.9	0.9	0.9	2, 5, 7, 12		100,000

Legend

*W - Week
M - Month
Y - Year
E - Episodic

**V - Visual
NIR - Near Infrared
TIR - Thermal Infrared
MW - Microwave

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Figure 3-13. Data Acceptance for Geological Resources Management

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Management Function	Optimum Resolution (ft)	Optimum Frequency*	Optimum Swath (mi)	Optimum Spectral Region**	Processing Level (Section 3.4)	Resolution Acceptance (ft) 50	100	300	Frequency Acceptance Daily	Weekly	Biweekly	Swath Acceptance (mi) 10	50	100	Spectral Acceptance Visible	Near IR	Thermal IR & Microwave	Processing Acceptance Level 1	Level 2	Level 3	Geographical Regions	Time of Year	Areal Extent (sq. mi)
Inventory of crop types	100	M	100	NIR	3	0.9	0.9	0.7	0.9	0.9	0.9	0.9	0.9	0.9	0.6	0.9	0.9	0.5	0.5	0.9	2, 5, 6, 7, 12	April - Aug	603, 325
Compliance monitoring	300	M	100	NIR	3	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.7	0.9	0.9	0.5	0.7	0.9	2, 5, 6, 7, 12	June - Oct	603, 325
Stress determination	50	6W	50	NIR	3	0.7	0.5	0.1	0.9	0.9	0.9	0.8	0.9	0.9	0.7	0.9	0.9	0.7	0.7	0.9	2, 5, 6, 7, 12	May - July	603, 325
Soil classification	300	Y	100	MW V	3	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.4	0.4	0.9	0.7	0.7	0.9	2, 5, 6, 7, 12	Sept - Oct	300, 000
Crop damage assessment	50	E	50	NIR	3	0.9	0.7	0.5	0.9	0.7	0.5	0.9	0.9	0.9	0.7	0.9	0.9	0.7	0.7	0.9	2, 5, 6, 7, 12	Apr - Aug	60, 000
Land erosion	50	4M	50	V	3	0.9	0.5	0.7	0.9	0.9	0.9	0.8	0.9	0.9	0.9	0.9	0.9	0.7	0.7	0.9	2, 5, 6, 7, 12	Mar - June	300, 000
Soil moisture	1000	W	100	MW	3	0.9	0.9	0.9	0.9	0.9	0.8	0.6	0.9	0.9	0.0	0.0	0.9	0.4	0.7	0.9	2, 5, 6, 7, 12	Mar - May	603, 000
Irrigation project planning	50	Y	50	V	2	0.9	0.7	0.5	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.7	0.9	0.9	2, 5, 6, 7, 12	Oct - Mar	100, 000
Agriculture land use	50	4M	100	V NIR	3	0.9	0.7	0.5	0.9	0.9	0.9	0.5	0.9	0.9	0.7	0.9	0.9	0.4	0.7	0.9	2, 5, 6, 7, 12	Mar - Sept	603, 000
Yield forecasts	100	M	100	NIR	3	0.9	0.9	0.5	0.9	0.9	0.9	0.5	0.7	0.9	0.7	0.9	0.9	0.2	0.7	0.9	2, 5, 6, 7, 12	April - Aug	603, 000

Legend

*W - Week
M - Month
Y - Year
E - Episodic

**V - Visual
NIR - Near Infrared
TIR - Thermal Infrared
MW - Microwave

Figure 3-14. Data Acceptance for Agricultural Resources Management

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Management Function	Optimum Resolution (ft)	Optimum Frequency*	Optimum Swath (mi)	Optimum Spectral Region**	Processing Level (Section 3.4)	Resolution Acceptance (ft) 50	100	300	Frequency Acceptance Daily	Weekly	Biweekly	Swath Acceptance (mi) 10	50	100	Spectral Acceptance Visible	Near IR	Thermal IR & Microwave	Processing Acceptance Level 1	Level 2	Level 3	Geographical Regions	Time of Year	Areal Extent (sq. mi)
Stress detection	50	M	100	NIR	3	0.9	0.3	0.1	0.9	0.9	0.9	0.6	0.9	0.9	0.7	0.9	0.9	0.5	0.7	0.9	5, 8, 11, 12	Mar - Sept	780,774
Timber inventory	50	6M	100	NIR	3	0.9	0.5	0.1	0.9	0.9	0.9	0.9	0.9	0.9	0.7	0.9	0.9	0.2	0.7	0.9	5, 8, 11, 12	Mar - May Sept - Nov	780,774
Forage inventory	50	M	100	NIR	3	0.9	0.7	0.1	0.9	0.9	0.9	0.9	0.9	0.9	0.5	0.9	0.9	0.2	0.7	0.9	2, 5, 7, 12	Mar - May Aug - Sept	1,490,564
Road and firelane maintenance	50	Y	100	NIR	2	0.8	0.2	0.1	0.9	0.9	0.9	0.8	0.9	0.9	0.7	0.9	0.9	0.7	0.9	0.9	5, 8, 11, 12	May - Aug	780,774
Wildlife environment	300	M	100	NIR	3	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.9	0.7	0.9	0.9	0.6	0.7	0.9	2, 5, 6, 7, 8, 11	Aug - Mar	500,000
Monitoring of flammatory conditions	300	W	100	TIR	3	0.9	0.9	0.9	0.9	0.9	0.6	0.8	0.8	0.9	0.2	0.3	0.9	0.2	0.7	0.9	2, 8, 11, 12	May - Aug	780,774
Plant species migration and encroachment	50	3M	100	NIR	3	0.9	0.5	0.1	0.9	0.9	0.9	0.9	0.9	0.9	0.7	0.9	0.9	0.6	0.8	0.9	2, 8, 11, 12	Apr - July	100,000
Entomological migration	50	2M	100	NIR	3	0.9	0.7	0.1	0.9	0.9	0.9	0.9	0.9	0.9	0.7	0.9	0.9	0.5	0.5	0.9	2, 8, 11, 12	Mar - Nov	780,774
Air and water quality/plant health relationships	50	M	100	NIR	3	0.9	0.6	0.4	0.9	0.9	0.9	0.9	0.9	0.9	0.7	0.9	0.9	0.6	0.8	0.9	2, 8, 11, 12	May - July	375,000
Fire damage assessment	100	E	100	NIR	3	0.9	0.9	0.7	0.9	0.7	0.5	0.8	0.9	0.9	0.7	0.9	0.9	0.6	0.8	0.9	2, 8, 11, 12	May - Aug	
Cutting/replanting compliance	50	M	100	NIR	3	0.9	0.7	0.2	0.9	0.9	0.9	0.7	0.9	0.9	0.7	0.9	0.9	0.5	0.5	0.9	2, 8, 11, 12	Mar - Oct	75,000

Legend

*W - Week
M - Month
Y - Year
E - Episodic

**V - Visual
NIR - Near Infrared
TIR - Thermal Infrared
MW - Microwave

3-3)

Figure 3-15. Data Acceptance for Forestry and Rangeland Resources Management

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Management Function	Optimum Resolution (ft)	Optimum Frequency*	Optimum Swath (mi)	Optimum Spectral Region**	Processing Level (Section 3.4)	Resolution Acceptance (ft) 50	Resolution Acceptance (ft) 100	Resolution Acceptance (ft) 300	Frequency Acceptance Daily	Frequency Acceptance Weekly	Frequency Acceptance Biweekly	Swath Acceptance (mi) 10	Swath Acceptance (mi) 50	Swath Acceptance (mi) 100	Spectral Acceptance Visible	Spectral Acceptance Near IR	Spectral Acceptance Thermal IR & Microwave	Processing Acceptance Level 1	Processing Acceptance Level 2	Processing Acceptance Level 3	Geographical Regions	Time of Year	Areal Extent (sq. mi)
Erosion of shoreline	50	3M	100	V TIR	3	0.9	0.5	0.2	0.9	0.9	0.9	0.7	0.9	0.9	0.8	0.8	0.9	0.5	0.7	0.9	1,4,7,8,12	All year	530,000
Effect of structures on tidal circulation	50	1M	100	V	3	0.9	0.5	0.2	0.9	0.9	0.9	0.5	0.9	0.9	0.9	0.9	0.9	0.7	0.9	0.9	1,4,7,8,12	All year	530,000
Fresh/salt water interfaces	100	2W	100	V	3	0.9	0.5	0.2	0.9	0.9	0.9	0.5	0.9	0.9	0.9	0.9	0.9	0.5	0.7	0.9	1,4,7,8,12	All year	265,000
Chlorophyll distribution	300	M	100	V	3	0.9	0.9	0.9	0.9	0.9	0.9	0.3	0.9	0.9	0.9	0.9	0.9	0.5	0.7	0.9	1,4,7,8,12	All year	530,000
Thermal distribution	300	2W	100	TIR	2	0.9	0.9	0.9	0.9	0.9	0.9	0.3	0.9	0.9	0.0	0.0	0.9	0.2	0.9	0.9	1,4,7,8,12	All year	530,000
Effluent Plumes	100	2W	100	V TIR	2	0.9	0.9	0.5	0.9	0.9	0.9	0.7	0.9	0.9	0.3	0.3	0.9	0.5	0.7	0.9	1,4,7,8,12	All year	153,000
Turbidity	100	2W	100	V	3	0.9	0.9	0.5	0.9	0.9	0.9	0.8	0.9	0.9	0.9	0.9	0.9	0.5	0.7	0.9	1,4,7,8,12	All year	530,000
Dredging compliance	50	W	100	V	2	0.9	0.5	0.2	0.9	0.9	0.7	0.5	0.9	0.9	0.9	0.9	0.9	0.7	0.9	0.9	1,4,7,8,12	All year	53,000
Storm damage assessment	50	E	100	V	3	0.9	0.5	0.2	0.9	0.8	0.5	0.5	0.9	0.9	0.9	0.9	0.9	0.7	0.8	0.9	1,4,7,8,12	All year	
Shipping lane traffic	50	W	100	V	2	0.9	0.5	0.1	0.9	0.9	0.7	0.5	0.9	0.9	0.9	0.9	0.9	0.7	0.9	0.9	1,4,7,8,12	All year	530,000
Shipping hazards	50	W	100	V	3	0.9	0.1	0.0	0.9	0.9	0.7	0.5	0.9	0.9	0.9	0.9	0.9	0.5	0.7	0.9	1,4,7,8,12	All year	530,000
Wind/water relationship	50	W	100	V MW	2	0.9	0.5	0.2	0.9	0.9	0.7	0.5	0.9	0.9	0.4	0.4	0.6	0.9	0.9	0.9	1,4,7,8,12	All year	530,000

Legend

*W - Week
M - Month
Y - Year
E - Episodic

**V - Visual
NIR - Near Infrared
TIR - Thermal Infrared
MW - Microwave

Figure 3-16. Data Acceptance for Coastal Zone Management

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FOLDOUT FRAME 1

FOLDOUT FRAME 2

Management Function	Optimum Resolution (ft)	Optimum Frequency*	Optimum Swath (mi)	Optimum Spectral Region**	Processing Level (Section 3.4)	Resolution Acceptance (ft)			Frequency Acceptance			Swath Acceptance (mi)			Spectral Acceptance			Processing Acceptance			Geographical Regions	Time of Year	Areal Extent (sq. mi)
						50	100	300	Daily	Weekly	Biweekly	10	50	100	Visible	Near IR	Thermal IR & Microwave	Level 1	Level 2	Level 3			
Population trends	50	Y	50	V	2	0.9	0.7	0.5	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.9	0.9	1, 7, 8, 11, 12	Sept	250, 000
Urban hydrology	50	4M	50	V NIR	3	0.9	0.7	0.5	0.9	0.9	0.9	0.8	0.9	0.9	0.5	0.7	0.9	0.5	0.7	0.9	1, 7, 8, 11, 12	All year	250, 000
Water utilization	50	2W	50	TIR	2	0.9	0.7	0.5	0.9	0.9	0.9	0.9	0.9	0.9	0.0	0.1	0.9	0.7	0.9	0.9	1, 7, 8, 11, 12	June - Sept	250, 000
Blight	50	Y	50	V	2	0.9	0.7	0.2	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.7	0.9	0.9	1, 7, 8, 11, 12	Sept	250, 000
Classification of structures	50	Y	50	V TIR MW	3	0.9	0.7	0.2	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.9	0.3	0.5	0.9	1, 7, 8, 11, 12	Sept	250, 000

Legend

*W - Week
M - Month
Y - Year
E - Episodic

**V - Visual
NIR - Near Infrared
TIR - Thermal Infrared
MW - Microwave

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Figure 3-17. Data Acceptance for Urban Dynamics Management

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Management Function	Optimum Resolution (ft)	Optimum Frequency*	Optimum Swath (mi)	Optimum Spectral Region**	Processing Level (Section 3.4)	Resolution Acceptance (ft)			Frequency Acceptance			Swath Acceptance (mi)			Spectral Acceptance			Processing Acceptance			Geographical Regions	Time of Year	Areal Extent (sq. mi)
						50	100	300	Daily	Weekly	Biweekly	10	50	100	Visible	Near IR	Thermal IR & Microwave	Level 1	Level 2	Level 3			
Oil spills	100	W	100	TIR MW	2	0.9	0.9	0.7	0.9	0.9	0.2	0.7	0.9	0.9	0.4	0.7	0.9	0.7	0.9	0.9	4, 7, 8, 12	All	500,000
Suspended sediment	50	W	100	TIR	2	0.9	0.7	0.3	0.9	0.9	0.7	0.7	0.9	0.9	0.4	0.6	0.9	0.7	0.9	0.9	4, 7, 8, 12	All	500,000
Chemical and toxic wastes	50	W	100	NIR	2	0.9	0.7	0.5	0.9	0.9	0.7	0.7	0.9	0.9	0.7	0.9	0.9	0.7	0.9	0.9	4, 7, 8, 12	All	500,000
Thermal effluents	100	W	100	TIR	2	0.9	0.9	0.7	0.9	0.9	0.7	0.7	0.9	0.9	0.0	0.0	0.9	0.7	0.9	0.9	4, 7, 8, 12	All	500,000
Nutrient wastes	50	W	100	V	2	0.9	0.7	0.3	0.9	0.9	0.7	0.7	0.9	0.9	0.9	0.9	0.9	0.7	0.9	0.9	4, 7, 8, 12	All	500,000
Solid wastes	50	W	100	NIR	2	0.9	0.7	0.3	0.9	0.9	0.7	0.7	0.9	0.9	0.7	0.9	0.9	0.7	0.9	0.9	4, 7, 8, 12		

Legend

*W - Week
M - Month
Y - Year
E - Episodic

**V - Visual
NIR - Near Infrared
TIR - Thermal Infrared
MW - Microwave

Figure 3-18. Data Acceptance for Management of Environmental Quality

FOLDOUT FRAME 1

FOLDOUT FRAME 2

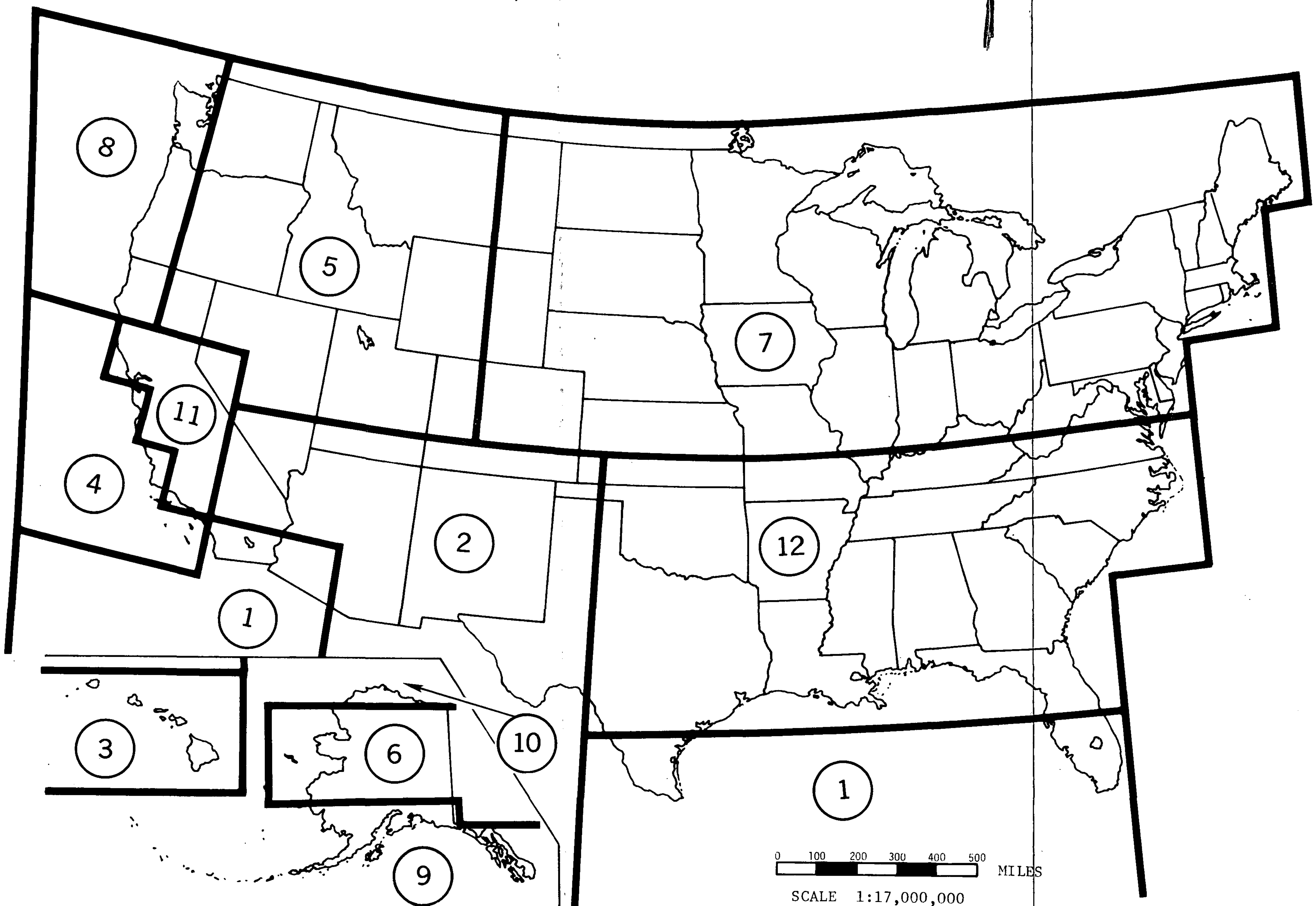

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Figure 3-19. Cloud Cover Regions

Table 3-2. General Description of Climatological Regions

Region Number	General Description	Location	Seasonal Change in Cloud Amount	Mean Monthly Cloud Amount Jun-Aug (in Percent)	Mean Monthly Cloud-Amount Dec-Mar (in Percent)	Predominant Cloud Type	Diurnal Variation in Cloud Amount	Hour of Maximum Cloud Amount (Local Time)
1	Essentially Clear	Major Desert Area	Small	<20	<20	--	Small	----
2	Little Cloudiness	Sub-Desert Areas	Small	<40	<40	--	Small	----
3	Tropical Moderate Cloudiness	North or South of Region 03	Small	~50	~50	Convective	Large	1600
4	Desert Marine	Over Ocean - off West Coasts	Small	50	50	Stratiform	Large	0800
5	Mid Latitude - Clear Summer	North America	Extreme	<40	~70	Synoptic Scale	Small	----
6	High Latitude - Cloudy Summer	North America, Asia	Moderate	~70	~50	Synoptic Scale	Small	----
7	Mid Latitude - Land	Northern Hemisphere	Moderate	~50	~70	Synoptic Scale	Small	----
8	Mid Latitude - Ocean	Northern Hemisphere	Moderate	~60	>70	Synoptic Scale	Small	----
9	High Latitude - Ocean	Northern Hemisphere	Moderate	>80	~70	Synoptic Scale	Small	----
10	Polar	Northern Hemisphere	Small	~60	~60	Synoptic Scale	Small	----
11	Mediter-ranean	Northern Hemisphere	Extreme	~30	--	Convective	Small	----
		Europe, Western North America		--	~60	Synoptic Scale	Small	----
12	Sub Tropical	Northern Hemisphere ~30N	Moderate	<50 --	-- ~60	Convective Synoptic Scale	Large Small	1600 ----

3.6 Preliminary Assessments of Volumetric Requirements for Data Products

This section contains preliminary assessments of processing requirements for the earth resource management programs described in Section 3.3. No attempt has been made to factor in the effects of cloud cover, nor has consideration been made of common data product requirements among the various management functions.

The manner in which commonality of requirements is to be treated is presently under study. However, there are strong indications that while there may be considerable commonality with respect to input data, there may be rather little commonality with respect to output information requirements.

Three cases are presented for each of the management programs:

Case 1 - The case in which all the requirements of the postulated management functions are met optimally with respect to the acceptance factors.

Case 2 - An ERTS spacecraft (sensing in the visible and near IR range of the spectrum, 300 ft. resolution and an observation frequency of approximately two weeks, actually 18 days).

Case 3 - An extension and improvement of ERTS; two spacecraft providing approximately weekly coverage, 100 ft. resolution and the spectral range extended into the thermal IR and microwave regions.

An assumption was made that the frequency, resolution and spectral band capabilities would be available on a progressively inclusive basis, e.g. if 100 ft. resolution is available and the optimum level of acceptance for a management function is 300 ft. then for this management function 100 ft. resolution is equally acceptable. Furthermore, the lowest acceptance value for multiple parameter cases is taken to be the determining value for requirements. Thus, for the single ERTS (Case 2 above) if the acceptance levels for resolution, frequency, and spectral band are 80%, 90% and 10% respectively, the data product assessment is that only 10% of the data would be used.

The estimates for data products are presented in Tables 3-3 through 3-9. The numbers in these tables represent square miles of viewed area (scaled by 10^{-6}) which form the basis for a given data product.

3.7 User Validation

Throughout this discussion emphasis has been placed on the admittedly subjective nature of the estimates provided in this mid-term report. The purpose of this discussion is to discuss the role of user contacts in the work to date and the work to follow. This section concludes with a very general discussion of econometric considerations.

Visits were made early in the study to headquarters of several federal agencies involved with the management of the Nation's resources. Individuals were interviewed in the following areas:

- The USDA Committee on Remote Sensing
- The Mineral and Land Resources Working Group of the USGS EROS Program
- The Environmental Satellite Service of NOAA
- EPA

The purposes of these interviews were

- To acquaint these agencies with the goals of the study
- To outline the methodology to be used in defining user requirements
- To obtain names of individuals within the agencies who could aid in refining assessments of the user requirements.

This latter objective is with respect to the subjective estimates generated in the study. The basic aim is to be in a position to discuss requirements on the working level with respect to what the resource manager uses to perform his function, how often he needs this information, and how much he needs. The idea is that the user should not be concerned at this stage with processing details.

This manner of use of federal agency contacts has a significant implication in the area of econometric studies which are beyond the scope of the present study. Often, the econometric aspects of the Earth Resources

Table 3-3. Data Products Volume for Hydrological Resources Management
($Miles^2 \times 10^{-6}$)

	JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
Photomap	--	--	--	0.58	0.58	1.17	0.58	0.58	0.58	--	--	--
Overlay	3.60	6.30	7.38	10.08	10.08	7.06	7.38	4.68	5.26	3.60	3.60	3.60
Thematic Map	3.60	3.60	4.68	8.05	7.38	7.96	8.05	5.94	5.26	3.60	3.60	3.60
Spatial Measurement	3.60	6.30	6.30	9.58	9.58	10.17	6.88	4.77	4.18	3.60	3.60	3.60
Spectral Measurement	--	--	--	3.37	2.70	2.70	3.37	3.37	--	--	--	--
Math Models	--	2.70	3.78	7.06	7.06	7.06	4.36	4.95	1.08	--	--	--
Statistical Summary	--	--	1.08	3.78	3.78	3.78	3.78	4.36	1.08	--	--	--
Automated Inventory	3.60	6.30	7.38	8.64	7.96	7.99	5.94	5.94	4.68	3.60	3.60	3.60
Change Discrimination	3.60	6.30	7.38	10.08	10.08	10.08	7.38	4.68	4.68	3.60	3.60	3.60
Case 1 - All Requirements Met												
Photomap	--	--	--	0.32	0.32	0.64	0.32	0.32	0.32	--	--	--
Overlay	2.00	3.50	3.62	4.82	4.82	5.14	3.32	2.12	2.44	2.00	2.00	2.00
Thematic Map	2.00	2.00	2.12	2.94	2.42	2.74	2.94	3.17	2.44	2.00	2.00	2.00
Spatial Measurement	2.00	3.50	3.50	5.02	5.02	5.34	3.52	2.77	2.32	2.00	2.00	2.00
Spectral Measurement	--	--	--	0.82	0.30	0.30	0.82	0.60	--	--	--	--
Math Models	--	1.50	1.62	2.24	2.24	2.24	0.74	1.19	0.12	--	--	--
Statistical Summary	--	--	0.12	0.42	0.42	0.42	0.42	0.87	0.12	--	--	--
Automated Inventory	2.00	3.50	3.62	4.46	3.94	3.94	2.96	2.74	2.12	2.00	2.00	2.00
Change Discrimination	2.00	3.50	3.62	4.82	4.82	4.82	3.32	2.12	2.12	2.00	2.00	2.00
Case 2 - Single ERTS												
Photomap	--	--	--	0.45	0.45	0.97	0.45	0.45	0.52	--	--	--
Overlay	3.20	5.90	6.98	9.08	9.08	9.60	6.38	4.28	4.80	3.20	3.20	3.20
Thematic Map	3.20	3.20	4.28	7.65	6.98	7.50	7.65	8.17	4.80	3.20	3.20	3.20
Spatial Measurement	3.20	5.90	5.90	8.45	8.45	8.97	5.75	4.17	3.72	3.20	3.20	3.20
Spectral Measurement	--	--	--	3.37	2.70	2.70	3.37	3.37	--	--	--	--
Math Models	--	2.70	3.78	6.93	6.93	6.93	4.23	4.75	1.08	--	--	--
Statistical Summary	--	--	1.08	3.78	3.78	3.78	3.78	4.30	1.08	--	--	--
Automated Inventory	3.20	5.90	6.98	8.10	7.43	7.43	5.40	5.40	4.28	3.20	3.20	3.20
Change Discrimination	3.20	5.90	6.98	9.08	9.08	9.08	6.38	4.28	4.28	3.20	3.20	3.20
Case 3 - Two Improved ERTS												

Table 3-4. Data Products Volume for Geological Resources Management
(Miles^2 x 10^{-6})

	JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
Photomap	0.74	0.27	0.27	2.97	0.74	0.27	2.97	4.32	0.74	0.27	0.27	0.27
Overlay	0.27	0.54	0.27	2.97	0.27	0.27	2.97	8.64	0.27	0.27	0.54	0.27
Thematic Map	0.47	0.27	--	2.70	0.47	--	2.70	7.02	0.47	--	0.27	--
Spatial Measurement	--	--	--	--	--	--	--	2.70	--	--	--	--
Spectral Measurement	0.47	0.27	--	2.70	0.47	--	2.70	4.32	0.47	--	0.27	--
Math Models	--	--	--	--	--	--	--	--	--	--	--	--
Statistical Summary	--	--	--	--	--	--	--	--	--	--	--	--
Automated Inventory	--	--	--	--	--	--	--	--	--	--	--	--
Change Discrimination	0.56	0.36	0.09	0.09	--	0.09	0.09	0.36	0.56	0.09	0.36	0.09

Case 1 - All Requirements Met

	JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
Photomap	0.27	0.01	0.01	1.21	0.27	0.01	1.21	1.06	0.27	0.01	0.01	0.01
Overlay	0.01	0.01	0.01	1.21	0.01	0.01	1.21	1.36	0.01	0.01	0.01	0.01
Thematic Map	0.26	--	--	1.20	0.26	--	1.20	1.05	0.26	--	--	--
Spatial Measurement	--	--	--	--	--	--	--	0.90	--	--	--	--
Spectral Measurement	0.26	--	--	1.20	0.26	--	1.20	0.30	0.26	--	--	--
Math Models	--	--	--	--	--	--	--	--	--	--	--	--
Statistical Summary	--	--	--	--	--	--	--	--	--	--	--	--
Automated Inventory	--	--	--	--	--	--	--	--	--	--	--	--
Change Discrimination	0.27	0.01	0.01	0.01	0.27	0.01	0.01	0.27	0.27	0.01	0.01	0.01

Case 2 - Single ERTS

	JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
Photomap	0.42	0.05	0.05	2.15	0.42	0.05	2.15	2.60	0.42	0.05	0.05	0.05
Overlay	0.05	0.29	0.05	2.15	0.05	0.05	2.15	5.09	0.05	0.05	0.29	0.05
Thematic Map	0.27	0.24	--	2.10	0.37	--	2.10	4.14	0.37	--	0.24	--
Spatial Measurement	--	--	--	--	--	--	--	1.95	--	--	--	--
Spectral Measurement	0.37	0.24	--	2.10	0.37	--	2.10	2.49	0.37	--	0.24	--
Math Models	--	--	--	--	--	--	--	--	--	--	--	--
Statistical Summary	--	--	--	--	--	--	--	--	--	--	--	--
Automated Inventory	--	--	--	--	--	--	--	--	--	--	--	--
Change Discrimination	0.40	0.27	0.03	0.03	0.40	0.03	0.03	0.27	0.40	0.03	0.27	0.03

Case 3 - Two Improved ERTS

Table 3-5. Data Products Volume for Agricultural Resources Management
($Miles^2 \times 10^{-6}$)

	JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
Photomap	--	--	0.90	0.54	0.54	1.35	1.62	1.08	0.54	0.81	--	--
Overlay	--	--	0.36	--	--	0.81	0.54	0.54	0.54	0.54	--	--
Thematic Map	--	--	2.97	2.16	2.16	0.27	0.54	--	--	0.27	--	--
Spatial Measurement	--	--	0.36	--	--	0.27	--	--	--	--	--	--
Spectral Measurement	--	--	2.16	2.70	3.24	0.54	1.08	0.54	--	0.27	--	--
Math Models	--	--	--	0.54	0.48	0.48	0.48	0.48	--	--	--	--
Statistical Summary	--	--	0.81	1.08	1.08	1.35	1.62	1.08	--	--	--	--
Automated Inventory	--	--	--	1.08	1.62	1.62	2.16	1.62	0.54	0.81	--	--
Change Discrimination	--	--	0.81	0.54	1.08	1.35	2.16	1.08	0.54	0.54	--	--
Case 1 - All Requirements Met												
Photomap	--	--	0.38	0.42	0.42	0.99	1.26	0.96	0.54	0.66	--	--
Overlay	--	--	0.08	--	--	0.57	0.54	0.54	0.54	0.54	--	--
Thematic Map	--	--	0.33	--	--	0.03	0.30	--	--	0.12	--	--
Spatial Measurement	--	--	0.08	--	--	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Spectral Measurement	--	--	--	0.42	0.48	0.42	0.48	0.42	--	0.12	--	--
Math Models	--	--	--	0.30	0.30	0.30	0.30	0.30	--	--	--	--
Statistical Summary	--	--	0.33	0.72	0.72	0.75	1.02	0.72	--	--	--	--
Automated Inventory	--	--	--	0.72	0.78	1.26	1.32	1.26	0.54	0.66	--	--
Change Discrimination	--	--	0.33	0.30	0.36	0.87	1.20	0.84	0.54	0.54	--	--
Case 2 - Single ERTS												
Photomap	--	--	0.64	0.54	0.54	1.23	1.50	1.08	0.54	0.81	--	--
Overlap	--	--	0.22	--	--	0.69	0.54	0.54	0.54	0.54	--	--
Thematic Map	--	--	2.73	2.16	2.16	0.15	0.42	--	--	0.27	--	--
Spatial Measurement	--	--	0.22	--	--	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Spectral Measurement	--	--	2.16	2.70	3.00	0.54	0.84	0.54	--	0.27	--	--
Math Models	--	--	--	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
Statistical Summary	--	--	0.57	1.08	1.08	1.23	1.50	1.08	1.08	1.08	1.08	1.08
Automated Inventory	--	--	--	1.08	1.38	1.62	1.92	1.62	0.54	0.81	0.81	0.81
Change Discrimination	--	--	0.57	0.54	0.84	1.23	1.80	1.08	0.54	0.54	--	--
Case 3 - Two Improved ERTS												

Table 3-6. Data Products Volume for Forestry and Rangeland Management
(Miles^2 x 10^{-6})

	JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
Photomap	0.45	0.45	1.85	2.10	1.40	0.07	0.07	1.85	1.85	1.22	0.45	0.45
Overlay	0.45	0.45	1.92	0.86	4.61	3.91	4.70	4.03	1.92	0.52	1.15	0.45
Thematic Map	0.45	0.45	1.15	0.79	1.04	1.04	1.13	1.15	1.15	0.45	0.45	0.45
Spatial Measurement	--	--	--	--	--	--	--	0.70	--	--	--	--
Spectral Measurement	--	--	1.40	0.70	4.55	3.85	4.55	3.51	1.40	--	0.70	--
Math Models	--	--	--	--	2.80	2.80	2.80	2.80	--	--	--	--
Statistical Summary	--	--	2.74	2.74	3.07	1.04	1.74	2.04	2.74	0.70	0.70	--
Automated Inventory	--	--	2.10	2.80	2.10	0.77	0.77	2.10	2.10	0.77	--	--
Change Discrimination	--	--	2.80	2.89	5.61	3.58	4.37	4.91	2.80	0.77	0.70	--
Case 1 - All Requirements Met												
Photomap	0.45	0.45	0.60	0.22	0.15	0.01	0.01	0.60	0.60	0.53	0.45	0.45
Overlay	0.45	0.45	0.60	0.09	1.23	1.16	1.24	1.46	0.60	0.46	0.52	0.45
Thematic Map	0.45	0.45	0.52	0.08	0.22	0.22	0.23	0.52	0.52	0.45	0.45	0.45
Spatial Measurement	--	--	--	--	--	--	--	0.07	--	--	--	--
Spectral Measurement	--	--	0.14	0.07	1.22	1.15	1.22	1.00	0.14	--	0.07	--
Automated Inventory	--	--	0.22	0.29	0.22	0.08	0.08	0.22	0.22	0.08	--	--
Change Discrimination	--	--	0.29	0.30	1.22	1.01	1.09	1.15	0.29	0.08	0.07	--
Case 2 - Single ERTS												
Photomap	0.45	0.45	1.54	1.48	1.09	0.05	0.05	1.54	1.54	0.89	0.45	0.45
Overlay	0.45	0.45	1.27	0.33	3.84	3.30	3.89	3.53	1.27	0.50	0.99	0.45
Thematic Map	0.45	0.45	0.68	0.28	0.45	0.45	0.50	0.68	0.68	0.45	0.45	0.45
Spatial Measurement	--	--	--	--	--	--	--	0.15	--	--	--	--
Spectral Measurment	--	--	0.77	0.23	3.79	3.25	3.79	3.03	0.77	--	0.54	--
Math Models	--	--	--	--	2.80	2.80	2.80	2.80	--	--	--	--
Statistical Summary	--	--	1.81	1.66	2.03	0.45	0.99	1.27	1.81	0.39	0.54	--
Automated Inventory	--	--	1.32	1.71	1.32	0.28	0.28	1.32	1.32	0.44	--	--
Change Discrimination	--	--	1.86	1.76	4.66	3.08	3.67	4.12	1.86	0.44	0.54	--
Case 3 - Two Improved ERTS												

Table 3-7. Data Products Volume for Coastal Zone Management
($Miles^2 \times 10^{-6}$)

	JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
Photomap	4.29	4.29	4.29	4.29	4.29	4.29	4.29	4.29	4.29	4.29	4.29	4.29
Overlay	8.20	7.73	7.73	8.20	7.73	7.73	8.20	7.73	7.73	8.20	7.73	7.73
Thematic Map	5.72	5.72	5.72	5.72	5.72	5.72	5.72	5.72	5.72	5.72	5.72	5.72
Spatial Measurement	2.96	2.48	2.48	2.96	2.48	2.48	2.96	2.48	2.48	2.96	2.48	2.48
Spectral Measurement	2.86	2.86	2.86	2.86	2.86	2.86	2.86	2.86	2.86	2.86	2.86	2.86
Math Models	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43
Statistical Summary	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38
Automated Inventory	--	--	--	--	--	--	--	--	--	--	--	--
Change Discrimination	2.86	2.38	2.38	2.86	2.38	2.38	2.86	2.38	2.38	2.86	2.38	2.38

Case 1 - All Requirements Met

	JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
Photomap	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
Overlay	1.17	1.07	1.07	1.17	1.07	1.07	1.17	1.07	1.07	1.17	1.07	1.07
Thematic Map	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Spatial Measurement	0.65	0.55	0.55	0.65	0.55	0.55	0.65	0.55	0.55	0.65	0.55	0.55
Spectral Measurement	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
Math Models	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Statistical Summary	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68
Automated Inventory	--	--	--	--	--	--	--	--	--	--	--	--

Case 2 - Single ERTS

	JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
Photomap	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53
Overlay	4.15	3.89	3.89	4.15	3.89	3.89	4.15	3.89	3.89	4.15	3.89	3.89
Thematic Map	3.80	3.80	3.80	3.80	3.80	3.80	3.80	3.80	3.80	3.80	3.80	3.80
Spatial Measurement	1.67	1.41	1.41	1.67	1.41	1.41	1.67	1.41	1.41	1.67	1.41	1.41
Spectral Measurement	2.63	2.63	2.63	2.63	2.63	2.63	2.63	2.63	2.63	2.63	2.63	2.63
Math Models	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21
Statistical Summary	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53
Automated Inventory	--	--	--	--	--	--	--	--	--	--	--	--
Change Discrimination	2.20	1.94	1.94	2.20	1.94	1.94	2.20	1.94	1.94	2.20	1.94	1.94

Case 3 - Two Improved ERTS

Table 3-8. Data Products Volume for Urban Dynamics Management
(Miles^2 x 10^{-6})

	JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
Photomap	--	--	--	--	--	--	--	--	0.45	--	--	--
Overlay	--	--	--	--	--	1.80	1.80	1.80	2.02	--	--	--
Thematic Map	0.22	--	--	--	0.22	1.80	1.80	1.80	2.70	--	--	--
Spatial Measurement	0.22	--	--	--	0.22	--	--	--	0.22	--	--	--
Spectral Measurement	--	--	--	--	--	1.80	1.80	1.80	1.80	--	--	--
Math Models	0.22	--	--	--	0.22	1.80	1.80	1.80	2.02	--	--	--
Statistical Summary	--	--	--	--	--	1.80	1.80	1.80	2.47	--	--	--
Automated Inventory	--	--	--	--	--	--	--	--	0.22	--	--	--
Change Discrimination	0.22	--	--	--	0.22	--	--	--	0.22	--	--	--

Case 1 - All Requirements Met

	JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
Photomap	--	--	--	--	--	--	--	--	0.17	--	--	--
Overlay	--	--	--	--	--	0.20	0.20	0.20	0.32	--	--	--
Thematic Map	0.12	--	--	--	0.12	0.20	0.20	0.20	0.54	--	--	--
Spatial Measurement	0.12	--	--	--	0.12	--	--	--	0.12	--	--	--
Spectral Measurement	--	--	--	--	--	0.20	0.20	0.20	0.20	--	--	--
Math Models	0.12	--	--	--	0.12	0.20	0.20	0.20	0.42	--	--	--
Automated Inventory	--	--	--	--	--	--	--	--	0.05	--	--	--
Change Discrimination	0.12	--	--	--	0.12	--	--	--	0.12	--	--	--

Case 2 - Single ERTS

	JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
Photomap	--	--	--	--	--	--	--	--	0.34	--	--	--
Overlay	--	--	--	--	--	1.40	1.40	1.40	1.57	--	--	--
Thematic Map	0.17	--	--	--	0.17	1.40	1.40	1.40	2.08	--	--	--
Spatial Measurement	0.17	--	--	--	0.17	--	--	--	0.17	--	--	--
Spectral Measurement	--	--	--	--	--	1.40	1.40	1.40	1.40	--	--	--
Math Models	0.17	--	--	--	0.17	1.40	1.40	1.40	1.57	--	--	--
Statistical Summary	--	--	--	--	--	1.40	1.40	1.40	1.91	--	--	--
Automated Inventory	--	--	--	--	--	--	--	--	0.17	--	--	--
Change Discrimination	0.17	--	--	--	0.17	--	--	--	0.17	--	--	--

Case 3 - Two Improved ERTS

Table 3-9. Data Products Volume for Environmental Quality Management
(Miles^2 x 10^{-6})

	JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
Photomap	--	--	--	--	--	--	--	--	--	--	--	--
Overlay	7.20	7.20	7.20	7.20	7.20	7.20	7.20	7.20	7.20	7.20	7.20	7.20
Thematic Map	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6
Spatial Measurement	--	--	--	--	--	--	--	--	--	--	--	--
Spectral Measurement	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80
Math Models	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
Statistical Summary	--	--	--	--	--	--	--	--	--	--	--	--
Automated Inventory	5.40	5.40	5.40	5.40	5.40	5.40	5.40	5.40	5.40	5.40	5.40	5.40
Change Discrimination	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80

Case 1 - All Requirements Met

	JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
Photomap	--	--	--	--	--	--	--	--	--	--	--	--
Overlay	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20
Thematic Map	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Spatial Measurement	--	--	--	--	--	--	--	--	--	--	--	--
Spectral Measurement	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20
Math Models	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Statistical Summary	--	--	--	--	--	--	--	--	--	--	--	--
Automated Inventory	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.60
Change Discrimination	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40

Case 2 - Single ERTS

	JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
Photomap	--	--	--	--	--	--	--	--	--	--	--	--
Overlay	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
Thematic Map	2.80	2.80	2.80	2.80	2.80	2.80	2.80	2.80	2.80	2.80	2.80	2.80
Spatial Measurement	--	--	--	--	--	--	--	--	--	--	--	--
Spectral Measurement	9.20	9.20	9.20	9.20	9.20	9.20	9.20	9.20	9.20	9.20	9.20	9.20
Math Models	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
Statistical Summary	--	--	--	--	--	--	--	--	--	--	--	--
Automated Inventory	4.60	4.60	4.60	4.60	4.60	4.60	4.60	4.60	4.60	4.60	4.60	4.60
Change Discrimination	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80

Case 3 - Two Improved ERTS

Survey are couched in terms of national income concepts. While this is certainly a desirable approach, the results, almost as often, are questionable. The value of analyzing user requirements in the context of federal agencies is that the contributions of remote sensing to the management efficiency of the agencies is more directly measurable. Furthermore, the agencies are in the best position of estimating the value of the new technology to their activities. Basically then, the approach would be to consider two "tiers" of benefits--contributions to management efficiency and national income concepts. There are rather strong indications that viable programs can be formulated on the basis of the former tier (the most directly estimable). Figure 3-20 outlines a concept of how the methodology of the present studies and experience soon to be gained from ERTS and EREP experiments could be combined to approach econometric studies.

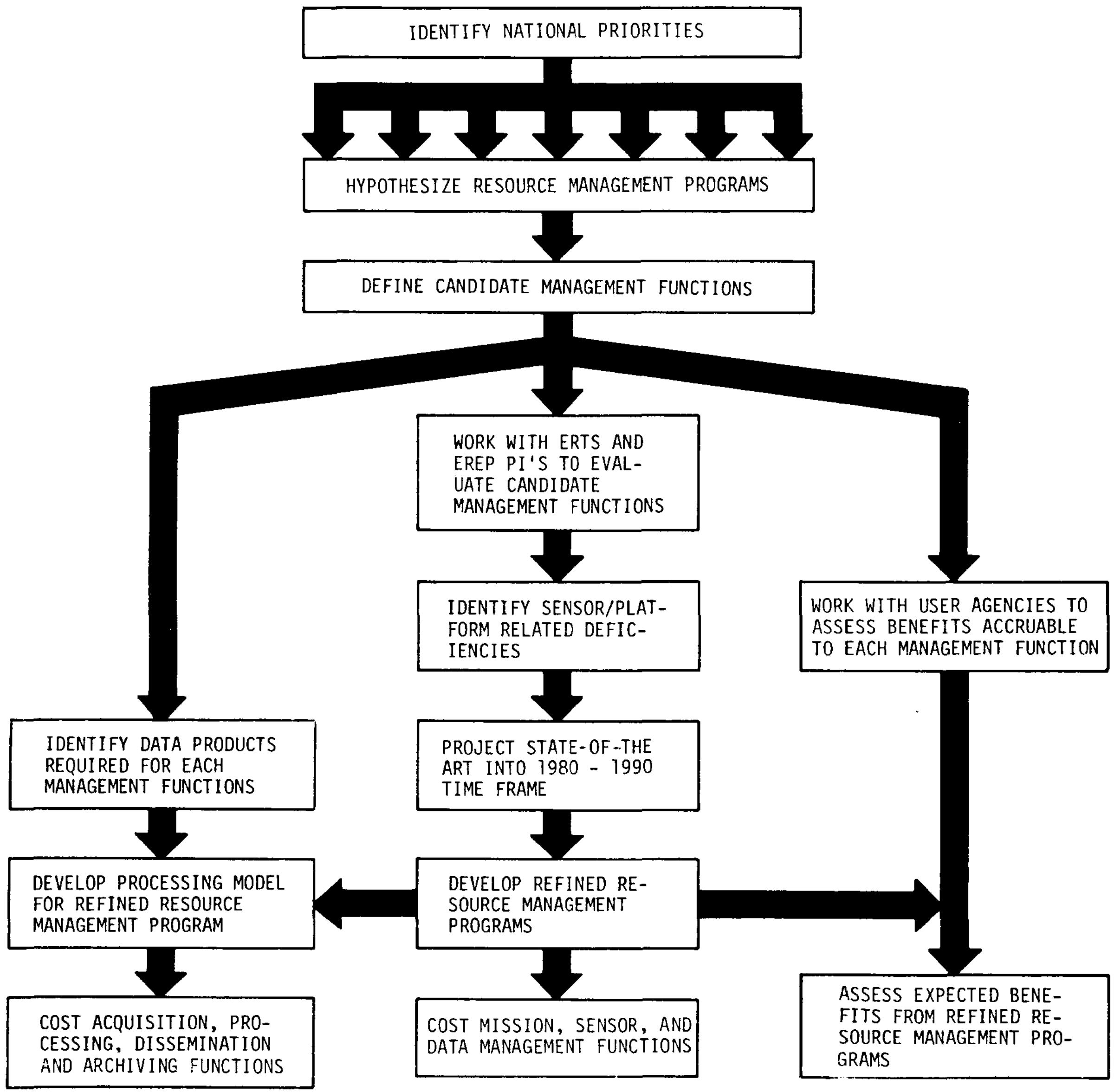

Figure 3-20. Concept of Econometric Studies

4.0 SENSOR CHARACTERISTICS

In this section the estimated state-of-the-art for sensor technology and the implications for use in spacecraft are discussed for the 1975-1885 time period. Since the emphasis in this study is on processing requirements and not on sensor capabilities per se, certain guidelines are followed in the discussion. These are:

1) Only imaging sensors (giving large data loads) or those with major processing requirements are considered.
2) Sensors are considered by generic type rather than as individual detailed instruments.
3) Output data loads are based on applicability to an earth resources observation program as well as on absolute sensor capabilities.
4) Preprocessing requirements prior to analytically oriented user processing are considered for each sensor type.

4.1 Background

4.1.1 The Electromagnetic Spectrum

All the remote sensors with application in earth resources observations involve the measurement of electromagnetic radiation received at the sensor. The source of this radiation may be reflected or scattered sunlight, thermal emission from the earth or from the atmosphere, or, for active systems, energy returned to the sensor by the reflection or scattering of radiation emitted from the sensor itself. A convenient classification of sensor types can be made on the basis of the portion of the electromagnetic spectrum in which they operate with further subdivisions within each spectral region.

Some of the pertinent characteristics of that portion of the electromagnetic spectrum which is useful for remote earth observations are illustrated in Figure 4-1. The usable region begins at a wavelength of about 0.3μm (equivalent to 10^{15} Hz in frequency) in the ultraviolet, since the atmosphere is opaque for shorter wavelengths. The visible region is shown to start at this wavelength, 0.3μm, and to extend to about 0.9μm. This is a somewhat greater range than that of the human eye, but for sensors

F

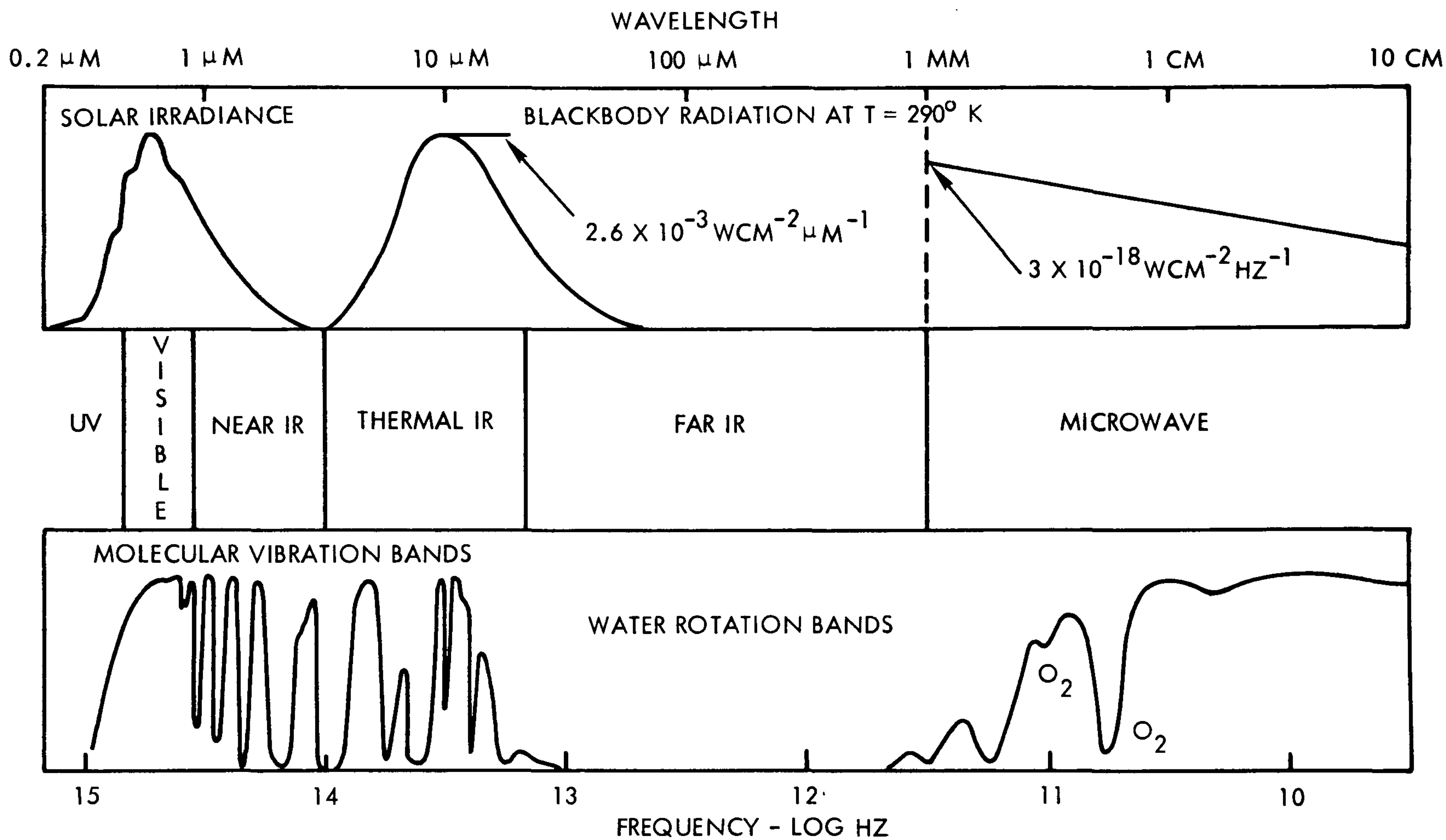

Figure 4-1. The Electromagnetic Spectrum

it represents a single region. The source of radiation is reflected sunlight, which peaks in intensity at about 0.55μm, in the middle of the region. The atmosphere is nearly transparent, as far as molecular absorption is concerned, but these wavelengths are noticeably scattered by small atmospheric particles in dust, haze, or smoke. Scattering by clouds (not absorption) makes even moderately thin clouds essentially opaque. Photographic films and the photosensitive surfaces of TV imaging tubes are characteristic detectors providing high-density two-dimensional arrays of resolvable imaging areas which are not available for other wavelength regions. Many single element detectors, such as photomultiplier tubes, are also sensitive in this region.

The near infrared extends from the visible to about 3.75μm. The cutoff point is chosen as the wavelength at which radiation from reflected sunlight drops to the level of thermal emission which is rapidly increasing with wavelength at this point. The exact wavelength of the crossover, of course, depends on reflectivity values on the one hand, and surface temperatures on the other, but the slopes of the two curves are so steep that it does not vary significantly for commonly occurring conditions. Characteristic detectors for this region are uncooled semiconductor devices. Atmospheric gases have a number of absorption bands arising mostly from molecular vibration modes in the near infrared, so observations are restricted to a few narrow "windows" between them.

The thermal infrared region begins at the end of the near infrared, 3.75μm; i.e., at the wavelength where thermal emission begins to predominate over reflected sunlight. Earth surface temperatures range from about 250^{o}K to 300^{o}K (about -10^{o}F to 80^{o}F) giving a peak blackbody radiation at around 10μm. There are strong molecular vibration bands, due principally to H_2O and CO_2, which restrict observations of the surface to windows at about 3.5 to 5.0μm and at 8.0 to 14.0μm. Some of the absorption bands result in emission from different effective altitudes within the atmosphere and can be used for vertical atmospheric profile measurements. Typical detectors are doped semiconductors or ternary mixtures requiring cooling to temperatures from 10^{o}K to 80^{o}K depending on the particular detectors.

The far infrared extends from about 15.0 to 20.0μm to about 1.0mm. This entire region is characterized by almost complete opacity of the atmosphere because of water rotation bands. Moreover, there are no really satisfactory detectors with sensitivities at these wavelengths. Consequently, the far infrared region, as here defined, is useless for earth resources observations.

The microwave region starts at a wavelength in the order of 1mm or, since frequency units are convenient to use here, about 300 GHz (300×10^9 Hz). The source of natural radiation for passive microwave sensors is thermal emission and it is very much weaker than in the thermal infrared near the peak of the blackbody curve, but electronic detectors (receivers) with very high sensitivities are available. Controllable coherent sources (transmitters) are also available, making active systems practical.

The sensors discussed in later subsections are for ultraviolet/visible/near infrared wavelengths, film cameras, TV cameras, multispectral scanners, and imaging spectrophotometers. Thermal infrared types include spectrometers and radiometers, both imaging and non-imaging, as well as some of the channels of multispectral scanners. In the microwave region, passive radiometers and synthetic aperture side-looking radars are considered.

4.1.2 Data Volume

Estimation of the data volume is particularly difficult because of the interaction of sensor acquisition capabilities, storage and transmission limitations, and user requirements. Any one of these may prove to provide the limiting conditions. Once a set of coverage requirements has been established, on whatever basis of requirements or limitations, the instantaneous data rate can be expressed by the following:

$$D_R = \frac{K_s}{d_c} \frac{SV_g}{R^2} n_b n_c \tag{1}$$

where

S = Swath width

V_g = Speed of ground trace

R = Length at side of pixel on the ground

n_b = Number of bits per pixel

n_c = Number of channels per pixel

d_c = Duty cycle

K_s = A sensor constant, usually nearly equal to unity.

The interpretation of this equation is quite straightforward. The swath width times the ground speed gives the area covered per unit time. This divided by R^2 gives approximately the number of pixels per unit time; the exact number is found by multiplying by K_s, which accounts for special sensor factors such as scan overlap or frame overlap. (It is assumed that the resolution is the same along track and cross track; if not, R^2 should be replaced by $R_a R_c$.) The number of pixels per unit time multiplied by the number of bits per pixel and by the number of channels then gives the data rate, averaged over a cycle of operation. If, however, the duty cycle is less than one (e.g., a scan efficiency less than one), then the instantaneous data rate is higher by the factor $1/d_c$.

The amount of data acquired over an extended period of time is obviously the average data rate (given by Equation (1) without the duty-cycle factor) multiplied by the total time the sensor is operated. This depends on the area of interest and the frequency of repetitive coverage. Typical requirements might be imaging of the United States once every 14 days, or of the global ocean once each day (with greatly different resolutions, of course). If the coverage is fairly efficient, this means the U.S. imager would be operated about 2 percent of the time, since the U.S. area is about 0.02 of the total earth area, while the ocean sensor would operate 60 to 70 percent of the time.

The orbital characteristics, the swath width, and the length of time that the sensor is on determine the coverage, while the resolution, the number of channels, and the number of quantization levels determine the amount of detail obtained. For the same total data volume, tradeoffs can be made between coverage and detail. Also, tradeoffs can be made in the nature of the detail, such as more intensity levels at the cost of increased pixel size, or vice versa. Limitations on the extent to which these kinds of tradeoffs can be made are imposed by the characteristics of the individual sensors.

4.1.3 Orbital Effects on Sensors

Sensor performance is affected by the orbital characteristics in a number of ways. The scale is directly proportional to altitude so that if all other parameters are held constant, the size of the IFOV and the width of the swath increase directly with height above the surface. The effect of altitude on the speed of the subsatellite point along the surface is somewhat more complicated. The period of an earth satellite in a circular orbit is, except for perturbation effects,

$$P = P_o \; (a/a_e)^{3/2} \tag{2}$$

where

P_o = period at zero altitude = 84.4857 minutes

a_e = radius of earth

a = distance of satellite from center of earth = $a_e + h$

The speed of the ground trace is given by

$$V_g = \frac{2\pi a_e}{P} = \frac{2\pi a_e}{P_o} \left(\frac{a_e}{a}\right)^{3/2} \tag{3}$$

For low orbits, this can be approximated by

$$V_g = \frac{2\pi a_e}{P_o} \left(1 - \frac{3h}{2a_e}\right) \tag{4}$$

Thus the speed of the subsatellite point decreases slowly with altitude. The effect of this is to change the required scan rate or the rate at which image frames must be taken.

For definiteness, the orbit implied in the subsequent sensor discussions will be a 235nm (435km) circular orbit, giving V_g = 3.73nm/sec = 6.9km/sec. The inclination and other characteristics are assumed to be appropriate to the particular sensor and mission involved.

4.2 Ultraviolet/Visible/Near Infrared Sensors

Sensors for the wavelength region from about 0.3μm to a little over 3.0μm measure energy primarily from reflected or scattered sunlight, although some thermal radiation is available at the long wavelength end of the range. The devices considered in this section are all imaging sensors. For the region from 0.3μm to 0.9μm, photographic films and TV image tubes can be used as detectors. They have high sensitivity and excellent resolution and provide the equivalent of a large number (up to 10^9 or more for film) of individual detectors in a two-dimensional array. Photomultiplier tubes provide high sensitivity detectors for the UV and visible, but are single image element devices. A number of semiconductor devices, most of which can be used at ambient temperatures, are useful through the near infrared. They are basically point detectors, but many of them can be configured in usable linear arrays of up to several thousand individual detectors.

4.2.1 Film Cameras

Film cameras are those in which an image of the scene produced by an optical system is recorded by a silver halide emulsion. The original information is in the form of a latent image which must be made visible and permanent by chemical processing. A number of materials and techniques have been developed for producing images which can be processed by "dry" methods, such as the application of heat. Without practical exception, these all have little or no sensitivity in the visible region of the spectrum, so while they find applications in duplication or in data recording, they are not suitable for taking pictures in natural light. Thus, silver halide emulsions are the only photographic materials which will be available in the time period of interest (through 1985). The requirement for "wet" processing of silver halide film is not as restrictive as is often thought, however. Several methods are applicable to onboard processing and can be quite rapid (a few seconds) if necessary. The best known and only space-proven method in this category is the Eastman Kodak "Bimat" technique used, for example, in the Lunar Orbiter photographic system.

The useful wavelength range for film cameras is about 0.3μm to 0.9μm. The emulsions have sensitivity for ultraviolet radiation of wavelengths shorter than 0.3μm; the lower useful limit is set by the ozone in the atmosphere which absorbs radiation of wavelengths shorter than this. On the long wavelength end, emulsions are available for laboratory use out to 1.1μm or a little more, but these require hypersensitization just prior to use and need very careful handling, so the practical long wavelength limit for remote sensing applications is only 0.9μm as stated above.

Film Characteristics

A very large number of film types are available, each intended for a particular use or class of uses. They arise, however, from various combinations of a relatively small number of emulsion types, sensitization classes, and film bases. The emulsion types represent tradeoffs between sensitivity and resolution; high sensitivity is obtained at the expense of resolution and vice versa. This can be illustrated by considering the most frequently used panchromatic reconnaissance film types and calculating the product of Aerial Exposure Index (AEI), a measure of "speed" or sensitivity, and the square of the resolution (giving the number of resolution elements per unit area). This is shown in the following table.

Table 4-1. Speed and Resolution of Panchromatic Films

Film Type	AEI	Resolution @ 1.6:1 Contrast	(AEI) R^2
Tri-X	250	22 ℓpm	1.2×10^5
Double-X	125	38	1.8×10^5
Plus-X	80	50	2×10^5
Panatomic-X	20	65	8.5×10^4
SO-206	6	112	7.5×10^4
SO-243	1.6	205	6.7×10^4

From this table it can be seen that although the speeds vary by a factor of more than 150, and the resolutions by over 9, the product $(AEI)R^2$ varies by only a factor of 3. Panchromatic sensitizations cover the wavelength range from the ultraviolet to about 0.7μm and are generally the most useful for aerial or space photography. The most commonly used infrared film is Kodak Infrared Aerographic Film 5424, which is sensitive out to 0.9μm, with a resolution of 28ℓpm at 1.6:1 contrast. Color films are available either over the visible range or in a false-color version sensitive out to about 0.9μm. They are less sensitive and have lower resolutions than the black and white panchromatic emulsions (they range from AEI = 25 and resolution = 28ℓpm to AEI = 6 and R = 80ℓpm) as would be expected from the division of the incident radiation into what amounts to three channels. If, however, they are compared with black and white films filtered for the corresponding color bands, they have $(AEI)R^2$ products only about a factor of two less than for black and white.

Data Volume

For most earth resources applications, optical systems and exposure times can be used which are adequate for the slower films, such as SO-206 and SO-243, and thus take advantage of their higher resolution capabilities. Considering the effects of the imaging optics and image motion smear, system resolution imagery, with a picture area of 57 x 57mm, contains 3.25×10^7 resolution elements. To compare this with electro-optical devices, consider the imagery to be scanned by a flying spot scanner at 2.8 scan lines per line pair and quantized at 6 bits/pixel. This gives about 1.56×10^{10} bits per frame. Photography is often related to electrical image data by a ratio of two TV lines per optical line pair, but several effects, particularly the spot shape and intensity profile, result in some degradation so an additional factor called the Kell factor must be applied. A reasonable value for the Kell factor gives about 2.8 TV lines per optical line pair, as used above, in order to retain the original photographic resolution.

Camera Types

Film photography can be obtained as separate frames, continuous strips, or panoramic strips. Frame photography, and particularly vertical frame photography, is by far the most useful. The vertical frame picture has its principal point (the image point on the optical axis) at the nadir. With a well corrected lens, the geometric fidelity of the image is very high and any distortions which do exist can be determined by preflight calibration and are time-invariant. Photometric corrections needed can be determined from known camera characteristics and from sensitometric strips providing information on film properties.

The oblique frame format differs from the vertical format in that it exhibits the well known "keystone" effect, or perspective distortion of the image with respect to the original scene. This distortion can be removed by purely optical techniques; i.e., by reimaging in an optical rectifier; its mathematical determination is also quite straightforward. In addition, extremely oblique photographs from satellite altitudes will show distortions arising from the mapping of the curved earth surface on a flat film plane. This effect may also be perceptible even for vertical photography, depending on altitude, resolution, and angular field of view.

A continuous strip camera exposes the film through a narrow slit oriented normal to the direction of flight. The film is moved at the same rate as the imagery moves so that as time proceeds a continuous swath of imagery of width equal to the length of the slit is produced. If the motion of the film is not just right, there will be a difference of scale in the along-track and cross-track directions. With a narrow instantaneous field of view, this may not be accompanied by an appreciable image smear. Oblique slit camera photography is rarely used; it results in an increasing scale away from the nadir and considerable slurring at the outer edge but with constant scale in the along-track direction.

Panoramic photography uses a slit oriented along-track and swept across-track by a mechanical motion. This gives a wide swath (up to 180°) with an instantaneous FOV only as great as that subtended by the slit. Thus, very great coverage can be obtained with modest optical requirements. However, the image distortion is very pronounced. The scale at any point is the same in both directions but it increases with increasing nadir angle, θ, varying as $\sec^2\theta$. Special viewers and viewer-printers have been developed by several manufacturers (e.g., Itek and Fairchild) to correct this distortion.

Multispectral capabilities for film camera systems are obtained by the use of color film or by using a set of boresighted cameras, both used in the Skylab S190 experiment, or by wavelength-selective beam splitting from a single optical system, as in a camera developed for the Army by Perkin-Elmer. In general, the different channels are on different film rolls and inter-channel registration must be accomplished by some technique such as used in the ERTS data handling system.

Preprocessing Requirements

After imagery has been exposed in a camera, there are two options for getting the data to earth. The exposed but undeveloped film may be returned physically, either by an ejectable capsule from an unmanned spacecraft, or with the return of the astronauts from a manned spacecraft. Subsequent processing then follows conventional procedures. Alternatively, the film may be processed on board and read out over a data link in a manner similar to that used for Lunar Orbiter photography. On the ground, the image data may be recorded directly on film (Lunar Orbiter) or may be recorded on tape and subsequently transformed to hard copy. The result is a more or less faithful reproduction of the original imagery with some degradation and distortion introduced by the scanning, transmission, and reproduction cycle. If the data are recorded on magnetic tape, they are available for the application of digital or hybrid data processing techniques which would require a similar scanning process if they were to be applied to original photography.

Film photography has the unique characteristic, compared with all other imaging sensors, of being able to acquire and store a tremendous amount of data. Frame photography, moreover, results in far better geometric fidelity in the original record than can be achieved with any other device. On the other hand, the photometric accuracy is fundamentally limited to about $\pm$ 5 percent by the nature of the process and of the materials used. In addition, it does not readily lend itself to analysis on an element by element basis. These considerations indicate that it should be used in applications that exploit its advantages and in which the shortcomings are not important. Specifically, frame photography should be used primarily for return to the ground for development. This does not preclude selective onboard processing for examination by an astronaut to verify attainment of mission objectives and to permit the modification of experiment procedures if necessary.

The spacecraft ephemeris and attitude data, camera constants (e.g., focal length, pointing offset, etc.) must be related to the time of exposure to obtain and record the geographic location of the imagery. This includes scale and orientation as well as the coordinates of the principal point; i.e., the data for a geographic grid overlay.

The conditions of observation, such as sensitometric data (e.g., a density wedge, pre-exposed or exposed through a standard source at the time of image exposure, with or without a derived "H & D" curve relating density to exposure), should be given, along with identification of the spacecraft, camera, etc.

Both preprocessing and analytically oriented processing (Section 5.0) functions must be selected as most suitable to photography, permitting the achievement of useful earth observation products from the equivalent of a data volume which it would be completely impossible to handle on a pixel-by-pixel basis in a digital computer facility. However, this does not mean that selected photography could not be scanned and put into a serial data stream in which case it could be treated in limited amounts just like the data from any electro-optical sensor.

S190 - A Representative Camera System

The capabilities of a photographic camera system are evidently more dependent on mission requirements and experiment design than on ultimate camera limitations. The Skylab S190 Multispectral Photographic Facility may be taken as fairly typical of the more complex camera systems which may be used on aircraft or spacecraft within the next 10 to 15 years. In the following discussion the effects of likely variations from S190 design details will be indicated as well as the particular S190 characteristics. The Multispectral Photographic Facility has been developed by the Itek Corporation for the Skylab Program. It consists of a six-channel camera system (i.e., six individual cameras boresighted together) with forward motion compensation for measuring energy in the visible and photographic infrared regions reflected from earth features. It has four black and white channels covering the region from 0.5 to 0.9μm in 0.1μm wide bands, one regular color channel and one color-infrared (false-color presentation) channel. The individual cameras all have 6-inch focal length f/2.8 maximum aperture lenses, each appropriately corrected for the wavelength band with which it will be used. Seventy mm film is used with each camera having its own cassette containing 400 frames worth (approximately 100 feet) of film. This is an experimental camera system intended to allow studies of the utility of various film/filter combinations for earth observations. It is likely that most photographic systems used in later experimental or operational payloads will use fewer channels; applications involving a large number of narrowband channels are better instrumented by other devices. The film supply is probably less than later cameras will employ, and even in this system there is provision for replacement of the cassettes by the onboard experimenters.

The ground resolution of a camera (or any imaging sensor) is given by the size of the individual resolution element times the scale, which in turn is the ratio of the altitude to the focal length. That is,

$$R_g = R_s \frac{H}{f} \qquad (5)$$

where R_s, the sensor resolution, is the reciprocal of the resolution in ℓpm; i.e., it is given in millimeters per line pair or equivalent units. Thus, if the focal length is expressed in millimeters, R_g is given in the same units as H, the altitude. For 6-inch (305mm) focal length lenses, a camera resolution of 100ℓpm, and a spacecraft altitude of 435kw, this gives a ground resolution of about 29m. It is evident from Equation (5) that if the system resolution is kept constant in terms of the size of the resolution element in the image plane, the ground resolution is inversely proportional to the focal length.

The angular coverage of each camera is given by

$$\alpha = 2\tan^{-1} \frac{w}{2f} \qquad (6)$$

where w is the format width. In this case w = 57mm, so $\alpha = 21^{\circ}\ 15'$. The width of the ground area imaged is 163km. Comparison of Equations (5) and (6) shows that for a given inherent sensor resolution and format size, higher resolution is always obtained at the expense of coverage.

Three of the cameras, the black and white visible channels, have a resolution of about 100ℓpm while the other three, the b and w IR channel and the two color channels, have resolution capabilities of about 50ℓpm. The values just given, it may be noted, are about two times as great as the expected resolutions generally given in the S190 literature. This is because the values above are given for high contrast targets rather than for low contrast. With film camera and TV cameras particularly, and to a lesser extent with other imaging sensors, this kind of apparent discrepancy will always arise (but it is only apparent, being caused by two different points of view). If one is concerned with the performance which is to be guaranteed, or at least have a high probability of being achieved, then a worst-case, low contrast resolution is appropriate. On the other hand, many important features such as land-sea or snow-soil boundaries have fairly high contrasts and one should not eliminate the chance of exploiting these; so for the estimation of maximum data rates or data volumes, the high contrast resolution is appropriate to use. Using then the higher values, the number of bits per frame for the high resolution cameras is 1.56×10^{10} and one-fourth of this, or 3.9×10^9 bits per frame, for the low resolution cameras. The total for a set of six frames is 5.85×10^{10} bits. A full cassette, 400 frames, for each camera then gives 400 sets or a total data volume of 2.34×10^{13} bits. This is a thoroughly impractical quantity of data for digital manipulation; hence, the conclusions reached in the previous section that primarily analog processing methods are appropriate. With such processing, the significant measure of data volume is the number of frames which must be handled; i.e., 2400 frames.

To estimate whether the one cassette per camera S190 operation represents a large or small mission, consider the rate at which sets of pictures might be taken. A 10 percent overlap should be allowed for successive frames along a satellite track; that is, a set of frames should be taken every $0.9 \times 163 = 146$km, or with a ground trace speed of 6.9 km/sec, about every 20 seconds. This translates into an equivalent data bit rate of 2.9×10^9 bits/sec or an average of about one frame every 3.3 seconds. The total take could be accomplished in a little over two hours. However, the desired targets would not always be available so the elapsed time would probably be at least several days. Another way to estimate the mission size is to observe that this amount of photography would just about cover an area equal in size to that of the United States.

4.2.2 Television Cameras

TV cameras have been the backbone of spaceborne imaging systems up to the present. The high sensitivity, good resolution and coverage capabilities, relatively light weight and low power requirements, and reliable performance which characterize these sensors have made them especially attractive for use in unmanned spacecraft with limited payload capabilities. Examples include the Advanced Visible Camera Systems (AVCS) on ATS, Nimbus, and ESSA satellites, the Automatic Picture Transmission (APT) cameras, and the ERTS return beam vidicon (RBV) camera system, all on earth-orbiting spacecraft as well as systems used on Ranger and Mariner spacecraft and in the Apollo program.

The heart of the TV camera system is the electro-optical image tube. There are several kinds of image tubes; they include image orthicon types, vidicons using a variety of photoconductive materials giving spectral sensitivities from the near ultraviolet through the near infrared, secondary electron conduction (SEC) vidicons, return beam vidicons, and image dissectors. All of these perform three essential functions although by different methods: 1) creation of a pattern of electrons corresponding to the incoming distribution of light intensities in an optical image, 2) temporary storage of the electron pattern as a charge distribution over a suitable target, and 3) readout of the charge distribution with an appropriately focused and deflected scanning electron beam. All the image tubes except the image dissectors are integrating devices; that is, they continue to build up the charge pattern during the interval between readout scans (for continuous operation as in normal TV) or during the exposure time controlled by a shutter (for intermittent operation). Most of the tubes can be coupled to an image intensifier to give greater sensitivity.

Although TV cameras have been used more than any other imaging sensors in spacecraft payloads, they have several fundamental limitations which will reduce their applications in future earth resource observation missions. Their high sensitivity is now approached or equaled by other sensors with other better characteristics, except when the image tubes incorporate or are coupled with an image intensifier section. The sensitivity is then orders of magnitude better than that of any other imaging device; in fact, low light level TV cameras can be used with only moonlight or even starlight for the illumination of the scene. This capability is achieved only at the cost of greatly reduced resolution and/or field of view, however, and is generally not useful for earth resource observations. The electron optics of TV image tubes introduce serious distortions in the output image data, some of which depend on operating conditions and hence cannot be handled by calibration techniques. Photometric variations over the image are also very pronounced. In principle, these can be compensated in the data processing to a greater extent than in photographic film cameras but still leaving much to be desired for spectral signature recognition. TV imagery is similar to, but somewhat worse than, film imagery in the lack of a true multispectral capability. Color TV suffers relatively more in resolution compared with black and white than does color photography, and the registration of spectrally filtered multiple camera images is more difficult because of the geometric distortions present in the TV image data. Finally, the lack of an inherent storage capability (though not unique to TV cameras) restricts the amount of data that can be obtained to that which ancillary storage devices can handle, or to real-time transmission.

A TV Camera Mapping System

In view of the foregoing, the most likely application of a television camera system for earth resources observations is for mapping. For this purpose the return beam vidicon (RBV) is the best choice; it provides the best resolution along with other characteristics substantially the same as for other image tubes. It was chosen for the mapping sensor in the ERTS A and B payloads. RBV's have been made as large as 4.5 inches in outside diameter providing a 50 x 50mm useful image format. The projected state-of-the-art is undoubtedly adequate for the production of tubes with a useful faceplate area of 100 x 100mm, but such tubes would entail a number of difficulties in their use, probably the most serious being a readout rate in excess of 200 MB/sec. Actually, a system representative of a realistic and useful mapping sensor for earth resources can be configured with three 2-inch RBV's each having a useful format of 25 x 25mm. This is a system similar to the one used on ERTS. The ERTS RBV's are scanned at 4125 TV lines, which is consistent with their high contrast target resolution capability. These tubes have been under development for several years and it is not reasonable to expect dramatic improvements in their performance in the future. However, a resolution of 100 TV line pairs/mm; i.e., 5000 lines total, can be postulated as achievable.

The three cameras all have a 6-inch focal length lens and are bore-sighted to view the same area. Each is filtered to receive light from an approximately 0.1μm wide spectral band within the visible and very near infrared. The angular coverage across the format (refer to Equation 6) is $\alpha = 9^{o}\ 34'$, and for a 435km orbit the width or length of ground area imaged is 72.6km. With a 10 percent overlap of the frames along track, a set of images must be taken every 9.4 seconds. The true optical ground resolution, using a Kell factor of 2.8 TV lines per optical line-pair, is (from Equation 5) 40m. The RBV has a fairly slow-scan target but the image does degrade with time and should be read out in not more than 10 seconds. Here the limit is imposed by the time between frames and must, in fact, be reduced considerably from 9.4 seconds to allow time to erase and prepare for the next picture. It is practical and convenient to allow one-third of the interval; i.e., 3.13 seconds for each camera, thus providing a continuous data rate into the transmission line or onboard tape recorders. The data rate is 48 MB/sec, from 2.5×10^7 pixels/frame and 6 bits/pixel in 3.13 seconds. It is continuous, since data from one camera is started just as another stops. This just matches the capability of the Ampex AR 1700 video tape recorder (VTR), a 28-channel digital recorder capable of 2 MB/sec per channel on 24 data channels. The other channels are used for timing, housekeeping, etc. A pass over the U.S. takes about 400 seconds, so 1.92×10^{10} bits are acquired per pass. The total capacity of the AR 1700 is 6.2×10^{10} bits, or a little over three U.S. passes.

RBV Error Characteristics

The RBV video data are subject to a number of geometric errors arising from the characteristics of the electromagnetic beam focusing and deflection system. The ERTS RBV design specification values for these errors are representative; better laboratory performance can be achieved but at the expense of size, weight, and complexity unsuitable for spacecraft payload applications. The specifications are given in Table 4-2, in which the image positional effect has been calculated for the system described in the foregoing section; e.g., A TV Camera Mapping System.

Table 4-2. RBV Internal Geometric Errors

Error Type	ERTS Specification	Image Positional Effect $1\ \sigma(m)$
Magnetic Lens Distortion	1% max	170m
S curve	0.2mm at corners	165
Skew	3.5% max	149
Raster Rotation	1 degree	298
Scale	± 1%	170
Centering	± 1% each axis	578
Non-linearity	± 1% each axis	205

These errors are about four to ten times the optical resolution and hence require correction if the sensor performance is not to be seriously degraded. It should be noted that the first four error types are the results of the tube design and fabrication and hence are nearly time invariant, while the last three are strongly affected by operating conditions and can vary rather quickly with time.

Radiometric errors arise from shading; i.e., fairly slow variations in responsivity over the target, which can amount to more than 50 percent including the effects of optical vignetting. There are also a few spots or blemishes in which the responsivity varies by up to 10 or 15 percent over a small region. In addition, of course, the overall responsivities of the different tubes will differ markedly, both because of individual tube variations and because of the different spectral bands to which they are exposed and, moreover, the responsivity varies with exposure level. These radiometric error sources are to a considerable degree determined by the camera design and construction and can, therefore, be calibrated and compensated for. However, they may change slowly with time (aging) and to some extent are the result of operating conditions. Thus, periodic inflight calibration procedures are desirable.

The signal-to-noise ratio at 100 percent highlights should be better than 30db, but there are two other effects which may contribute noise. One is the result of external disturbances such as transient stray electromagnetic fields. These can produce more or less structured noise patterns, some of which are amenable to removal in the processing. Another is the phenomenon of "beam-bending," the electron beam strikes the target at very low velocities and may be attracted (bent) toward highlights, which are regions of relatively high positive charge. This is a systematic effect in terms of the image charge pattern, but in the absence of prior knowledge of that pattern it is very difficult to identify and correct and in this sense may be considered a form of noise.

<u>Preprocessing Requirements</u>

Annotation: The annotation requirements are similar to those for film camera imagery. The sensitometric data are derived from inflight calibration procedures, if available, and from monitoring of operating conditions.

However, once the imagery has been put into hard copy form, sensitometric wedges must be included to track the effects of subsequent reproduction steps. The annotation data in general may be included in the video signal stream at the time visible imagery is produced, becoming an integral part of the format.

Geometric Corrections: The geometric errors arising from internal RBV effects are only partly precalibratable. Therefore, a reseau of known geometric properties (as nearly regular as possible) is etched on the faceplate. Identification and location of the reseau marks, typically small crosses, then permits the construction of a transformation relating the output imagery to the image received on the faceplate. This transformation can then be applied by hybrid analog/digital means as developed by Bendix for ERTS or by purely digital operations. The latter provide the maximum potential for geometric error correction but can be very time consuming. Satisfactory methods of treating blocks of pixels over which the required corrections do not vary more than the acceptable residual error limits are being developed which promise to make digital manipulations feasible. Externally caused geometric errors, such as those caused by altitude variations (scale), departure of the line-of-sight from the nadir (keystoning), and earth curvature effects, can be corrected at the same time as the internal errors or separately. Both analog and digital methods can be used.

Radiometric Corrections: Radiometric correction procedures must include as a minimum the application to the video data from each camera of the appropriate responsivity values including shading variations to get from voltage signals (or the equivalent) to scene brightness units. This can be done on geometrically uncorrected data, since the shading is not a rapid function of position. Blemish correction is possible but might be done only on a selective basis. It must be performed after geometric correction because the spot size is comparable to internal geometric errors. Optionally, corrections for atmospheric effects and sun-scene-sensor angle variation over the format could also be made.

4.2.3 Multispectral Scanners

Multispectral scanners may cover the wavelength range from the visible through the thermal infrared since they have separate detectors for each channel and the type of detector can be chosen separately for each wavelength interval of interest. They may have a large number of channels, in fact, as many as, or more than, some imaging spectrophotometers and atmospheric profilers. These instruments are also multispectral scanners but their typical modes of operation and the applications of their data are sufficiently different to warrant separate treatment in later sections. Multispectral scanners can use either mechanical or electronic scan techniques; the two types are characterized by quite different design and data handling problems.

Mechanical Scanners

Mechanical scanners have usually only one detector per channel. Cross track coverage is obtained by sweeping the instantaneous field-of-view (IFOV) of each detector in a line or scan across the vehicle track with a moving mirror. In some cases, such as the ERTS MSS (Multispectral Scanner), more than one detector per channel are used, but this is to obtain several scan lines with one mirror sweep and thus reduce the rate at which the mirror must be moved. There is still only one detector per scan line per channel. Along track coverage is obtained by the forward motion of the vehicle so that successive scan lines cover adjacent strips of the surface. Many infrared imagers have been designed for use in aircraft to provide considerable overlap of the scan lines, giving redundant data by as much as a factor of four. However, for high performance operation of multichannel sensors in spacecraft, the scan rate is almost always adjusted to give essentially contiguous scan line coverage with perhaps a small overlap of the order of 10 percent.

The scanning may be accomplished in either the object plane or the image plane. Object plane scanning is achieved with a rotating or oscillating mirror located ahead of the optical system of the sensor. This makes the total field-of-view (FOV) which the optics must accept no greater than the IFOV of the detectors and greatly reduces the problems associated with the imaging system. This results in a rather large mirror, since it must illuminate the entire aperture of the optics at all times during the active scan period. A rotating mirror gives good scan linearity since the rotation rate can be held constant to a high degree of accuracy, but the scan efficiency or duty-cycle is very low. For example, a single-sided rotating mirror, rotated about an axis perpendicular to the line of sight, gives a scan efficiency of only 0.125 for a 90° scan. Rotating a mirror oriented at 45^{o} to the optical axis of the sensor about an axis along the optical axis doubles the efficiency but it is still quite low. Indeed, for most spacecraft applications the scan is much less than 90^{o} giving even lower efficiencies. An oscillating mirror is used in the ERTS MSS giving an efficiency of about 65 percent, but serious difficulties have been encountered with scan non-linearities and variations from scan to scan and this technique is not likely to be used in the future. Another method is to use a conical scan; i.e., the scanning mirror is oriented and rotated in such a manner that the sensor line of sight (LOS) traces a circle on the ground. Up to about 120^{o} of the circle can be used giving an efficiency of 0.33 and this is independent of the width of the swath. A further advantage for some applications is obtained in that the angle between the LOS and the ground is constant throughout the scan. Some difficulties arise, however, in the display of imagery using scan lines which are arcs of circles.

In image plane scanning, the optics must accept the entire FOV covered by a scan, resulting usually in larger and more complex imaging systems. However, the scanning mirror, or mirrors, are placed within the optical system at a location where they can be made quite small. The resulting scan is almost always conical, both for higher efficiency and because the variations of image quality over the scan can be reduced in this way. The EREP S192 Multispectral Scanner experiment is a good example of this type of scan.

The spectral separation of the channels can be accomplished by filters, as in the ERTS MSS; by a prism, used in the EREP S192, which also uses one filter; or by one or more gratings, as in the ERAP Multispectral Scanner and Data System (MSDS). Detectors are typically photomultiplier tubes for the visible, silicon detectors for the near IR, and doped semi-conductor or ternary semi-conductor mixtures for the thermal IR region.

Two examples of mechanical scanners may be considered to get an idea of the current and projected state-of-the-art. One is the ERAP MSDS, intended for use in a C-130 aircraft and currently being evaluated. It is a 24-channel system with channels ranging from 0.34 - 0.4μm in the near UV out to 12.0 - 13.0μm in the thermal IR. Since one of its objectives is to establish the utility of various spectral bands for providing earth observations in disciplines such as geology, hydrology, oceanography, and agriculture, it is not likely that more operationally oriented scanners will use any more and probably will use fewer channels. The IFOV of each detector is 2 milliradians. The cross-track scan uses a single mirror rotating at up to 100 revolutions per second giving a linear cross-track scan of $\sim 80^{\circ}$ (1.4 radians) for 700 pixels per scan and an efficiency of 0.222. Temporary buffer storage is provided to even out the data rate over each cycle of operation; the data are recorded at two channels per track on 12 channels of a 14-channel digital tape recorder with the analog data converted to 8 bits per pixel. This gives a data rate including calibration signals of 1.25×10^{6} bits/sec/track or 15×10^{6} bits/sec total data plus timing and housekeeping data on the other two tracks.

The EREP S192 Multispectral Scanner is being developed for Skylab. It is a 13-channel sensor covering overall about the same spectral range as the MSDS. The IFOV of each detector is 0.182 milliradians. It uses an image plane conical scanner covering 120° of the scan motion for an efficiency of 0.33. There are 1100 pixels per scan; this translates into an angular scan width of $9^{\circ}3'$ or a width on the surface of 71.5km from an altitude of 435km. There are 100 scans/sec and the data are buffered to average out the data rate giving, with calibration signals and quantization at 8 bits/pixel, about 10^{6} bits/sec/channel. One channel is recorded redundantly so there is a total of 14×10^{6} bits/sec plus timing and housekeeping.

The designs and performance characteristics of the two scanners just described appear to be widely divergent, particularly in the angular size of the IFOV's which differ in solid angle subtended by a factor of 120; i.e., $(2 \times 10^{-3} \text{ rad})^2/(1.82 \times 10^{-4} \text{ rad})^2$. However, the S192 has a considerably larger aperture and greater spectral bandwidths in the critical wavelength regions. These factors, plus a few other design details, indicate that, in fact, they both just about fully exploit the state-of-the-art in both detector technology and optical and mechanical system limitations, although applying different tradeoffs appropriate to their different applications.

Mechanical Scanner Preprocessing Requirements

Since the data from multispectral scanners are received in the form of a digitized serial video data stream (although the individual channels can be received in parallel), the general methods of handling the data are similar to those for TV data. In particular, the annotation requirements are about the same and the presentation in hard copy form requires the use of image recorders such as the LBR or the EBR. There are, however, significant differences in the error characteristics and in some of the desired output products.

The MSDS and the S192 scanner both represent the current state-of-the-art. No significant basic improvements are foreseen in the next decade, so their performance characteristics are probably fairly close to those of scanners employed in the next few years. Moreover, their capabilities seem to be consistent with the measurement requirements likely to be levied on this type of sensor for earth observations. An overall increase in data rates by a factor of two or so might represent a reasonable growth, say to 20 to 40 megabits/second. The number of channels is not likely to increase.

Geometric Error Correction: The internal geometry of the individual scan lines should have a fidelity consistent with the basic information contained in the data. However, the relationship of one scan line to the next can vary markedly over a period of time resulting in considerable picture distortions. The most pronounced effort will arise from the rotation of the earth. This results in an effective progressive cross-track displacement of successive scan lines, an effect giving as much as a 7 percent skew near the equator. This must be compensated in the processing to preserve true angle and distance relationships. An error in yaw angle of the spacecraft will produce a skew along track. Constant pitch and roll errors will displace but not appreciably distort the imagery, but attitude rates in these axes will cause a varying scale along track from a pitch rate and a varying cross-track skew from a roll rate. A yaw rate results in a varying along track skew. These distortions are all amenable to correction to the extent that the attitude values and rates can be determined and, hence, modeled into a geometric correction transformation. In addition, for conical-scan sensors, it may be necessary to transform the data format so that it corresponds to a rectilinear scan format. One great advantage that multispectral scanners have over film or TV data is that regardless of image distortions, the data from the different channels are inherently in register. It is this characteristic that makes such data much more suitable for spectral signature analyses than the film or TV data.

Radiometric Error Correction: Since each scan line involves only a single detector, the pixel-to-pixel radiometric values are quite uniform within a channel. Some variations in the relationship to surface radiance values can occur, however, because of different angles between the surface and the line of sight for linear scans. For conical scans, this difficulty is not present for thermal radiation but there remain variations in the sun-surface-sensor angles which may be important for reflected radiation. The detectors are calibrated frequently (every scan in both the MSDS and the S192 scanner) since their responsivities are sensitive to operating conditions, notably temperature. The calibration signals must be used to update the factors for converting from electrical signals to radiance units and this is usually a function performed on the ground.

Data Media: The multispectral scanners are basically imaging devices so some hard copy imagery will be required, perhaps in a few selected channels, and maybe in one or two false-color composite presentations. Data tapes will probably be organized by spectral signatures per pixel, rather than by channels, to facilitate exploitation of the inherent registration of the data from different spectral channels. Routine preparation of all the data in this form would represent a formidable volume of magnetic tape or even of some more exotic recording medium, such as LBR digital recording. It is likely that users will screen the hard copy image data and request data tapes of selected material. For conical scan sensors, the data may have to be converted to a rectilinear raster format on output data tapes.

Electronic Scan Sensors

Recent developments in micro-electronics technology have made possible the fabrication of linear arrays containing an almost unlimited number of detectors. Arrays of this type can be used in a "push-broom" configuration; i.e., there is a separate detector for each pixel along a cross-track line, and a swath is imaged by progression of the strip of surface imaged along this line as the vehicle moves forward. Arrays of up to 25,000 detectors, spaced 6 x 10^{-4} inch apart; i.e., 25,000 detectors in an array 15 inches long are currently feasible. The detectors are either silicon photodiodes or phototransistors, both of which give about equal performance. Their spectral sensitivity can be adjusted to peak from about 0.4μ to about 0.9μm. They operate by collecting a charge induced by and proportional to the incident radiation, the signal resulting from the discharge of the capacitance associated with the detector by electronic interrogation (i.e., appropriate switching). The scan along the array is thus electronic rather than mechanical and can be accomplished at rates of the order of a microsecond per detector. Up to saturation, they are integrating devices in much the same way as a vidicon is; typical usable integration times range from a fraction of a millisecond to several milliseconds. Detectors known as charge coupled devices (CCD's) have even more recently been announced and they offer some promise of simplified circuitry and in the fabrication of two-dimensional arrays. It is not to be expected that they will be markedly different in their applications in electronic scanners from the photodiode and phototransistors, however. Developments in the fabrication of arrays of infrared detectors indicate that push-broom sensors sensitive to infrared wavelengths may also be feasible within the next few years.

Eastman-Kodak has recently completed a study for NASA-GSFC (Contract NAS5-21595) for a multispectral imager using photodetector arrays. They postulate a 6-foot focal length f/5 optical system; the focal length must be quite long to get good optical performance with a 15-inch long array. Four channels are proposed; the image from the single optical system is split by dichroic mirrors to send different wavelength bands to four separate 25,000 detector arrays. If this sensor were used in a spacecraft at 435km altitude, the IFOV of each detector would be 3.62m on a side giving an optical resolution of 10.2m (using a Kell factor of 2.8). The arrays would be interrogated every 0.525 millisecond; with a quantization of 8 bits/pixel, this gives a data rate of 381 megabits/sec/channel. Data compression techniques can reduce this by about a factor of 2.5, to about 150 MB/sec/channel, which is still very high. If the arrays were reduced to 12,500 detectors each and the focal length reduced to 3 feet, the resolution (pixel size) would be doubled and the data rate reduced by a factor of four, to 95.3 MB/sec/channel, or 38.1 MB/sec/channel with data compression.

Future improvement of the technology in this area can be expected to reduce the size of the detectors by at least 50 percent; thus, sensors of this type have the capability for gathering data which is limited primarily by storage capacities, data links, processing requirements, and/or user capabilities to digest the data, and not by the sensors.

The processing requirements are similar to those for mechanical scanners. The image data exhibit essentially perfect scan linearity and inter-channel registration but are subject to the same externally induced distortion from earth rotation and vehicle attitude rates as are other scanners. The current detector arrays show large variations in responsivity from detector to detector up to a factor of two. Improvements in fabrication techniques can be expected to reduce these variations considerably and onboard compensation schemes seem to be feasible. However, for really satisfactory radiometric fidelity, the ground data processing will probably have to address the problem of applying detector-by-detector calibration compensation to the data stream.

4.2.4 Imaging Spectrophotometers

Imaging spectrophotometers are closely related to the multispectral scanners discussed in Section 4.2.3; in fact, they might be considered a subclass of those instruments. They are, however, characterized by a large number of narrow bandwidth, essentially contiguous spectral channels, all in the visible region, to be used in distinguishing subtle color differences in the ground scene, especially of the ocean surface. The interest is not so much in imaging, per se, as in getting spectral signatures related to specific locations. Under these circumstances, it is really the individual pixel size (the IFOV of the sensor) which is important rather than the optical resolution, since it contains the spectral information desired.

Instrument Characteristics

Both mechanical and electronic scanning sensors can be used. A mechanical scanner, the Oceanic Scanning Spectrophotometer, has been proposed for consideration in the EOS (Earth Observation Satellites) program. It is still in the conceptual stage; design details have not been worked out but a feasibility study has indicated an achievable set of design parameters. An IFOV of 2 milliradians is proposed, with a linear mechanical scan implemented by a four-sided mirror, covering $\pm 19^{o}$ from the nadir. This results in 332 pixels/scan, each of which is 0.87km on a side at a spacecraft altitude of 435km. Spectral channels 0.015μm wide within the visible region from 0.4 to 0.7μm are specified. Although the number of channels is still to be determined, it would take 20 channels to completely cover the wavelength interval. The method of isolating the radiation in the different channels has not been decided upon. Photomultiplier tubes are to be used for the detectors. The pixel size implies a scan rate of 8 scans/sec for continuous along-track coverage; with a quantization of 8 bits/pixel, and buffering to average the data over a complete cycle, the data rate is 4.22×10^{5} bits/second.

A different approach is embodied in the Multichannel Ocean Color Sensor (MOCS) under development by TRW Systems for NASA LRC under the AAFE program. It is an electronic-scan device using an image dissector tube for the light detection. A slit in the image plane of an objective lens defines the instantaneous sensor field of view. A collimating lens directs the light passing through the slit to a transmission diffraction grating which disperses it into a spectrum. A reimaging lens focuses the light on the face of the image dissector tube. The resulting two-dimensional pattern gives the spectral signature, in one direction, of each pixel in a cross-track strip positioned along the other direction. The tube is then scanned along the spectral direction so that each scan line gives the spectrum of the light from one pixel, while the set of scan lines in a complete raster covers all the pixels in the cross-track strip. Successive raster scans then provide spectral data for a continuous swath.

In the current design, the IFOV is 2 milliradians over a total strip of 0.3 radians, or 150 pixels/scan line. This gives a ground size of 0.87km for the IFOV and implies a scan (raster) rate of 8 raster scans per second. Quantization of 8 bits/pixel/channel is desirable. One of the advantages of the MOCS approach is that it gives an essentially continuous spectrum over the visible range for the light from each elemental area. Adjustment of the grating dispersion, raster dimensions, and image dissector internal aperture can provide the division of the spectrum into any number of desired intervals, subject to a nearly linear tradeoff between S/N and number of channels chosen. Definitive data on the number of channels needed for satisfactory spectral signature identification are not yet available but tentative indications are that 20 spectral channels are both feasible and adequate. The data rate is given by

$$D_R = n_p \, n_c \, n_b \, S_r \tag{7}$$

a modification of Equation (1), in which n_p = number of pixels per line and S_r = number of scans per second. This gives $D_R = 1.92 \times 10^5$ bits/sec for the MOCS, exclusive of timing and housekeeping data.

An image dissector is used in this application rather than a vidicon because of its superior radiometric properties. Electrons from the photocathode are directed through an internal aperture to be detected by what is essentially a photomultiplier tube. The electrons in the beam are only those generated during the effective dwell time on the internal aperture; for this reason the image dissector is a non-integrating device. Its sensitivity is, therefore, less than that of a vidicon but there is no lag; i.e., no residual effect from incomplete erasure of a previous charge (image) distribution. Although there can be variations over the photocathode, the detector is the same for all pixels and, hence, the responsivity is much more uniform than in a vidicon.

The typical requirement for an imaging spectrophotometer is for relatively modest resolution over a broad swath to obtain frequently repetitive coverage. A proposed configuration employs three MOCS sensors, aligned to cover a swath 0.9 radian wide, or 450 pixels over a swath width of 425km from an altitude of 435km. The data rate for the three-sensor system is 5.76×10^5 bits/sec.

The MOCS sensor, and imaging spectrophotometers in general, are still in a rather early stage of their development; considerable improvement in their performance characteristics can be expected. For about the 1980 time period, a MOCS-derived sensor giving 3000 elements across a swath can be postulated. This might in part be achieved by the use of multiple units as described above; there are some merits to the multiple unit approach in addition to relieving the S/N problem. Isolation of different parts of the field is achieved so that if one part suffers from some interference, like a sun-glitter pattern, the others are not affected. Also, a less than complete degradation of performance arises from the failure of one unit. The 3000-pixel sensor, used over a swath width of 0.9 radian, would have an IFOV of 0.33 milliradian or 145m on the surface, and operate at 48 raster scan/second. The data rate would then be 2.3×10^7 bits/sec, plus timing, etc.

Preprocessing Requirements

The processing of imaging spectrophotometer data prior to analytical processing differs from that required for other multispectral scanner data in several important respects. Geometrically, the mechanical scanner versions will have the same internal geometric fidelity as other scanners and the same effects from external sources with one addition. The swath width will be markedly greater than for previously discussed applications and, as a result, the effects of earth curvature will be significant and probably require some correction. However, since the emphasis in the data analysis is not on geometrical relationships, a much larger degree of residual image distortion will be acceptable in the output products. In fact, it may be sufficient to provide imagery in which very little geometric correction has been made but where the geographic grid presentation is distorted to permit fairly accurate location of points. The lower resolution of the imagery will also tend to relax geometric correction requirements.

The electronic-scan (MOCS-type) sensors will show some non-linearities along scan lines because of the electron optics; these, however, can probably be held to acceptable limits in the sensor design. Otherwise, the geometric properties will be like those of the mechanical versions.

One of the attractive characteristics of the mechanically-scanned spectrophotometers is the ease and stability of radiometric calibration. The electronic-scan devices are somewhat less straightforward but when carefully calibrated are capable of much higher radiometric fidelity than film or TV cameras. In either case it is important that the residual radiometric

C-2

uncertainties be made as small as possible. Both versions share the high degree of inherent registration among spectral channels that is characteristic of all multispectral scanners.

The color differences (i.e., the differences in spectral signature) which are of importance in the interpretation of imaging spectrophotometer data are in many cases very subtle. If the spectral data are treated on an absolute basis, variations arising not only from residual sensor errors but more significantly from atmospheric transmission and scattering effects may completely mask the information sought. One approach to coping with this problem is to determine from auxiliary data the precise magnitude of atmospheric effects and to apply the appropriate radiometric corrections. This is extremely difficult because of fundamental problems in getting the requisite atmospheric data. A much more promising approach is being investigated at TRW and elsewhere. It consists of determining the first and/or second derivatives of the spectral curves (apparent radiance versus wavelength for each pixel) and examining these. Not only are subtle differences between channels enhanced by this procedure, but the effects of both atmospheric transmission and systematic instrument errors, both of which vary only slowly with wavelength, are almost completely eliminated. It is expected that this kind of processing will be required before utilizing automatic information extraction. It is a completely routine operation not involving interpretive elements and, hence, is appropriately accomplished by the central data processing facility. It may be that not all the data will need to be treated in this way. Color composites involving selected channels might be sent to the users for screening and the differentiation of the spectral curves accomplished only on special request for a limited amount of the total data.

4.3 Thermal Infrared Sensors

A large and important class of infrared sensors has already been discussed as multispectral scanners, many or all of the channels of which may lie in the thermal infrared region. This section is concerned with other kinds of infrared sensors classified somewhat arbitrarily as spectrometers and radiometers. They differ from the multispectral scanners in that they are primarily not imaging devices, providing data on various observational parameters associated with more or less well defined points on the earth's surface or along the sensor line of sight. They may look only in a fixed direction or at a small number of discrete angles. They are characterized by data rates many orders of magnitude lower than those associated with imaging devices. On the other hand, the computational requirements involved in manipulating the data to extract the desired information may impose significant loads on the data processing facility. Although much of the data reduction may be done by the users, particularly in the more experimental programs, a large amount will eventually become the responsibility of the central data processing facility.

4.3.1 Infrared Spectrometers

The infrared spectrometers discussed in this section are used to obtain atmospheric profiles, especially values of temperature and water vapor concentration as functions of height. The data for atmospheric profiling are obtained from radiance measurements taken in very narrow spectral intervals at various spectral distances from the center of a strong infrared emission band of some atmospheric constituent. Radiation from near the center of the band comes mostly from high in the atmosphere, since the strong absorption makes even a low density of the gas appear opaque with a corresponding effective emissivity of unity. Near the edge of the band, where the absorption and emission are weaker, a greater density of gas is required to give an emissivity of unity, and the effective height in the atmosphere from which the radiation comes is much lower. The exponential relationship of absorption to path length (Beer's Law) and the decrease of density with altitude (also approximately exponential) result in very sharp weighting factors for the effective heights of the radiation; this is important for stable mathematical inversion techniques.

Two CO_2 bands are particularly useful for temperature profiling. The mixing ratio of CO_2 in the atmosphere is very nearly constant both vertically and horizontally so a priori pressure-density relationships can be used. The CO_2 bands centered at about 4.3μm and 15.0μm are both strong and are relatively free from interference from other atmospheric absorbants. In general, it is practical to get temperature measurements from lower in the atmosphere using the 4.3μ band rather than the 15μ band.

Water vapor concentrations, in the lower atmosphere particularly, vary widely both vertically and horizontally as functions of time. When the temperature profile has been obtained from CO_2 band measurements, the water vapor concentration profile can be determined from measurements in an H_2O band. The water vapor profile can, in turn, be used to improve the temperature profile, since neither CO_2 band is entirely free from H_2O interference.

Two infrared sensors which have demonstrated the feasibility of remote profiling of the atmosphere are SIRS and IRIS, flown on satellites of the Nimbus series. SIRS (Satellite Infrared Spectrometer) uses an Ebert type grating spectrometer to disperse the radiation, while IRIS (Infrared Interferometer Spectrometer) uses a Michelson interferometer. Both operate in the 15μm CO_2 band. A more advanced instrument, TOVS (TIROS Operational Vertical Sounder), is scheduled for inclusion in TIROS payloads. This sensor has 17 infrared bands from 3.7μm to 29.4μm with IFOV's of 1 and 10 degrees. There are also bands at 53.40 and 53.88 GHz in the microwave region. It is intended to provide temperature to $1^{o}K$, relative humidity to 10 percent, and total ozone content to $\pm$ 0.01cm. The data rate is approximately 3 kilobits/second.

Although the volume of data involved is very small compared with that produced by imaging devices, the data processing required is quite complex. The basic mathematical problem is that of inverting a set of radiance measurements at different wavelengths to obtain temperatures at different heights in the atmosphere through the use of radiative transfer equations involving the Planck blackbody function and the hydrostatic equation. Since the equations are highly non-linear, the stability of the inversion process is quite sensitive to both instrumental errors and to uncertainties in the atmospheric transmissivity constants involved. With careful conditioning of the data, Hanel and Conrath, and Wark and Hilleary have succeeded in obtaining temperature profiles using matrix inversion techniques. A more promising approach using the iterative application of non-linear relaxation equations has been developed by M. T. Chahine (Journal of Atmospheric Sciences, 27, 960, September 1970). This method produces satisfactory results with about 5 to 10 iterations taking a substantial fraction of a second on a CDC 6600 computer. The straightforward application of this or any other inversion algorithm is not sufficient, however. Serious ambiguities can arise from the presence of clouds in the field of view. The resolution of these ambiguities requires comparison with other data intended to determine the amount of cloud coverage with associated modification of the inversion procedures. The effects of water vapor in the atmosphere need also to be factored in. Cases involving either clear conditions or complete cloud cover appear to be amenable to satisfactory solutions, but intermediate conditions may still result in situations when the uncertainties cannot be resolved. In any event, the computer capacity and throughput time requirements are established more by the logical data flow complexity than by the inversion algorithms themselves.

It is evident that much work yet needs to be done in establishing the most effective mathematical and logical manipulations required. Moreover, improvements are required in the data on atmospheric transmissivities as functions of atmospheric constituent concentrations. Development efforts to solve these problems will, of course, be pursued by the principal investigators associated with the experimental sensors. In time, however, the procedures and atmospheric data will be established to give a fully automatic set of operations which will then become the appropriate responsibility of a central data processing facility. It should be observed that as a completely routine and automatic function, from sensor operation through the preparation of output information, atmospheric profiling does not seem consistent with manned earth observation spacecraft programs. However, the atmospheric data obtained are so fundamental to the refined interpretation of many other observations that vertical profilers are likely to be incorporated in many payloads as auxiliary sensors.

4.3.2 Infrared Radiometers

A variety of infrared radiometers have been flown on previous spacecraft or are proposed for EOS payloads. Most of them obtain point data rather than image type data and observe in a small number of distinctly separated, relatively broad spectral channels.

The radiometers which have been included in spacecraft payloads to date are all fairly unsophisticated instruments. A number of devices of much greater complexity in both design and application are being developed as AAFE experiments and/or proposed for future use in observational satellites. These include the Visible/Infrared Polarization experiment of Dr. Sekera at UCLA. This experiment is intended to investigate the feasibility of determining the Stokes parameters associated with particulate matter in the atmosphere by measuring the amount of atmospheric attenuation as a function of wavelength, look-andle, and polarization, for visible and near infrared wavelengths. The concentration of atmospheric particles can have a significant effect on atmospheric transmission, especially in wavelength regions which are relatively free from molecular absorption. The experiment is a difficult one, particularly because of the variations in the source intensity, since the radiation source is sunlight reflected from the surface. However, no better method is currently available.

Another experiment is the Cloud Physics Radiometer proposed for EOS, which observes both reflected and thermal infrared radiation in five channels chosen to exhibit different effects from cloud characteristics such as height, thickness, droplet size distribution, and phase (ice particles or water droplets). The procedure for determining the values of essentially five variables from five measurements, each of which is to some degree influenced by all the variables, is essentially one of matrix inversion and is probably less difficult than atmospheric profiling inversions, but the details have not yet been worked out.

A Sea Surface Temperature Imaging Radiometer has been proposed for EOS. It is based on a study by Anding, Kauth, and Turner (Final Report on Contract NAS12-2117, 1970) in which the feasibility of eliminating most of the atmospheric effects from infrared measurements of sea surface temperature is demonstrated theoretically. The technique involves the use of radiometric measurements in three spectral bands; it will be augmented by two more bands to sort out the effects of cloudy atmospheres as well as those of water vapor absorption. The SSTIR is a scanning device which can produce a temperature map in quasi-image form. It is hoped to provide temperatures with an NEΔT (noise equivalent temperature difference) of 0.83^{o}K, with a data rate of 3.3×10^{5} bits/second.

An instrument for measuring the concentration of certain pollutants in the atmosphere, the Remote Gas-Filter Correlation Analyzer, is another infrared radiometer experiment being developed as an AAFE experiment. It observes infrared radiation in fairly broad spectral bands, with very fine discrimination of atmospheric trace constituents being accomplished by the use of absorption cells containing the gas being investigated. Its operation is based on the fact that the difference signal between a path containing the sample gas cell and one which does not is very sensitive to the presence of the sample gas in the atmosphere and relatively insensitive to all other constituents for properly chosen wavelength intervals. As with the other devices discussed, many of the details fo the data reduction are yet to be determined.

In summary, infrared radiometers as a class represent low to moderate data volumes and uncertain but presumably not excessive data handling requirements. Moreover, most of them are more likely to be used in unmanned vehicles than in manned spacecraft, except that the data obtained may be needed as auxiliary information in support of manned space experiments.

4.4 Microwave Sensors

The electromagnetic spectrum from about 20μm wavelength to about a millimeter (a frequency of ~300 GHz) is unusable for earth resources observations because the atmosphere is practically opaque in this region, primarily because of absorption by water vapor rotation bands. At longer wavelengths (lower frequencies) the atmosphere rapidly becomes clearer than it is in any shorter wavelength region of the spectrum. Also, electronic (i.e., coherent or phase-sensitive) methods of detection and production of the radiation are readily available. These result in very much higher sensitivities than are possible in the visible or infrared regions and make the use of active as well as passive sensors practical. Thus, the microwave region (frequencies from about 1 GHz to 300 GHz) is very useful for remote sensing applications.

4.4.1 Passive Microwave Radiometers

The energy measured by passive microwave radiometers arises from thermal emission from the surface of the earth and from atmospheric constituents including clouds, raindrops, and dust, with thermometric temperatures usually about 200°K to 300°K. Thermal microwave radiation from a surface follows Planck's equation, just as thermal infrared radiation does. However, the microwave region is far removed on the long wavelength side from the blackbody radiation peak for terrestrial temperatures. Therefore, microwave blackbody radiation is proportional to the first power of the temperature and is orders of magnitude weaker than thermal infrared. Typical microwave receivers, however, are so much more sensitive, in terms of absolute power levels, than infrared detectors that usable signals are obtained.

Typical emissivities range from 0.85 to 0.98 for most solid terrain materials and are not strongly temperature dependent. However, for water the emissivities are quite low, in the range of 0.3 to 0.5, and do vary markedly with temperature, frequency, and physical conditions (surface roughness and/or droplet size particularly) so the blackbody temperature dependence can be masked by other effects for sea surface measurements. Over a considerable range of microwave frequencies, at temperatures around 250 to 300°K, the emissivity decreases as the temperature increases; at about 20 GHz it is proportional to 1/T, so the radiation per unit area (i.e., the "brightness temperature") is practically independent of actual (thermometric) temperature. At somewhat higher frequencies the inverse emissivity/temperature relationship is even stronger, resulting in an actual decrease of microwave emission with an increase in temperature.

Surface roughness and particle size are diffusing parameters and, therefore, always tend to produce an increase in the effective emissivity; sea foam, for example, can exhibit an effective emissivity of 0.8 or more. Since microwave wavelengths are in the same size order as many surface roughness parameters, the increase of microwave emission with surface roughness is also frequency dependent becoming less pronounced at longer wavelengths. The scattering by water droplets is also very frequency dependent. The index of refraction of water is of the order of 10 in the microwave frequency range, so radiation of about 1cm wavelength in air has a wavelength of about 1mm inside water droplets; this is the same order of magnitude as droplet sizes in rain. Thus, scattering effects are in the transition region between

Rayleigh and Mie scattering and show marked frequency variations in effective emissivities and extinction coefficients.

The emissivities of fairly smooth surfaces are also dependent on the angle of observation and on the plane of polarization. These variations can be exploited in the observation of water surfaces but are usually much too complex to be helpful in observations over land.

The Rayleigh diffraction criterion applies to microwave just as to other electromagnetic frequencies; i.e., the resolution of an antenna is about $R = 1.22\ \lambda/D$. For example, to obtain 1^{0} resolution with 1cm (30 GHz) waves, an antenna must be about 70cm in diameter. Thus, for high resolution instruments, rather large antennas are inevitable.

At frequencies lower than about 10 GHz the atmosphere is very transparent to microwaves. However, there is a very strong O_2 absorption line at about 60 GHz and a water vapor band at about 22.3 GHz. These can be used to obtain temperature profiles and atmospheric water vapor content profiles, probably with less precision than in the infrared but with more nearly all-weather capability; i.e., less interference from cloud cover.

A representative example of a microwave radiometer is the PMMR (Passive Multichannel Microwave Radiometer) proposed for EOS. This sensor uses five microwave channels, each in both horizontal and vertical polarizations, centered at about 5, 10, 18, 21.5, and 37 GHz. With these choices of frequencies it is expected that the effects of sea surface temperature, atmospheric water vapor, water droplets in light and heavy rain, and surface roughness can be distinguished. The roughness data hopefully can provide near surface wind speeds over water and sea ice characteristics over ice fields.

The antennas are sized to give resolutions ranging from 10km (37 GHz) to 80km (5 GHz) at an altitude of 435km and are conically scanned to give a swath width of about 600km. The weight is estimated at 233kg and the power requirement 355 watts. The data rate will be 10^4 bits/second.

Projections of the future state-of-the-art indicate very little improvement in weight and size because of the fundamental relationships between antenna size and resolution. Some reductions in power requirements may be achieved with increased design experience. Of course, increased payload allotments could result in higher performance radiometers, probably in terms of resolution, in which improvement by a factor of five or even more could be valuable to some of the user community.

Processing requirements are similar to those of corresponding infrared sensors, both as to data volume and data reduction requirements. The likelihood of the inclusion of microwave radiometers on manned spacecraft is probably fairly high in experimental programs in which flexible operation and coordination with other observations both from the spacecraft and from aircraft or ground based sensor are desirable. In more operational programs the use of the sensors will become more routine and automatic and, hence, less applicable to manned programs.

4.4.2 Active Microwave Systems

Active microwave sensors consist of scatterometers and radars. Scatterometers typically have resolution requirements similar to those for radiometers; in fact, a scatterometer may be combined with a radiometer in a hybrid sensor in which both active and passive modes share the same antenna. The microwave pulse emitted by a scatterometer is detected on its return after being either scattered by atmospheric particles or reflected from the surface. The information obtained is, thus, a measure of particulates in the atmosphere or of surface conditions.

Not only is the atmosphere free of molecular absorption for frequencies below about 10 GHz, but at moderately lower frequencies even the attenuation caused by scattering from heavy rain drops becomes negligible. For example, at 3 GHz (10cm wavelength) the attenuation from a two-way vertical path through the atmosphere is less than 1 db, even if the path includes an intense tropical thunderstorm. Imaging radar, therefore, offers the potential of all-weather operation and, because it provides its own illumination, observations can be obtained both day and night. In addition, the reflection coefficients of the surface vary differently with different substances and physical conditions than they do in either the visible or infrared wavelength regions. High resolution radar, thus, can provide a valuable adjunct to other types of imaging.

Ordinary radar is constrained by the same resolution limitations as passive microwave radiometers, so brute-force methods are not feasible for high resolution imaging. Synthetic aperture side-looking radar, however, provides a practical solution. A radar of this type uses a fairly long (perhaps up to 15m) narrow ($\sim$1m) antenna oriented with the long dimension along-track providing a fan beam pointed to the side of the suborbital trace. Cross-track resolution is achieved by correlating the return signal with time; i.e., the reflections from increasing distances from the nadir will arrive back at the antenna at later times because of the increasing length of the two-way path. It is necessary only to make the pulse-length short enough to obtain the necessary time-discrimination in order to achieve any desired cross-track resolution. The practical limitation to this procedure arises from the fact that the power requirement is inversely proportional to the resolution length. Resolutions as small as 10m can be achieved, however.

Along-track resolution is achieved by the synthetic aperture principle. As the vehicle moves forward, the physical antenna occupies progressive positions along the line of flight and, if the returns from successive pulses emitted about twice for each antenna-length of forward motion are remembered and correlated with one another, the result is similar to that which would be achieved by a very long physical phased array. The theoretical limit to the effective along-track resolution which can be achieved is one-half the antenna length and, in practice, a resolution twice this (or equal to the antenna length) is readily obtained. The physical basis for this capability is the fact that any reflecting element either forward or aft of the nadir has a component of motion in the line of sight of the radiation and, thus, the return signal exhibits a Doppler shift which is a function of along-track location relative to the spacecraft at the time the pulse was sent out.

The synthetic aperture raw data volume is quite large, often greater than that of corresponding optical image data, since the potential along-track resolution is usually better than the cross-track resolution and the data containing this information must be retained during the initial processing, even if the output is presented, as is customary, with equal resolution in both directions. Thus, the data rate is given by

$$D_R = \frac{S}{R_C} \frac{2V_g}{L} n_b \qquad (8)$$

where S/R_C, the swath width divided by the cross-track resolution, gives the number of pixels across the swath. $2V_g/L$, the ground speed divided by half the antenna length, gives the number of pulses emitted per second. n_b is the quantization level, 8 bits/pixel usually being adequate. For a synthetic aperture side-looking radar on a spacecraft at 435km altitude (V_g = 6.9km/sec), with an antenna 10m long, a cross-track resolution of 30m per pixel, and a swath width of 100km, $D_R = 3.68 \times 10^7$ bits/sec. The output image data rate, with the along-track resolution 30m, equal to that across-track, would be 6.14×10^6 bits/sec. An imaging radar with this performance is probably representative of typical applications in the 1980-1985 time period. The state-of-the-art, however, would permit a resolution of 10m and over twice the swath width, giving a raw data rate perhaps 10 times as great and an image data rate approximately half the raw data rate.

The raw data must undergo initial processing to get the output in the form of imagery. The Doppler-shift information is mathematically equivalent to the Fourier transform of the imagery in the along-track direction, and it can be handled by coherent optical processing techniques. These have been well developed for military aircraft applications over several years. The image data resulting from the optical processing are then basically the same as those obtained from any electronically-scanned line imager. The same geometric corrections for spacecraft altitude variations and earth rotation must be applied. Earth curvature effects will also be observed because of the rather wide swath width and made even more pronounced because the sensor is looking well to the side of the nadir. The cross-track scale may also vary across the swath, unless this has been compensated for in the cross-track range timing.

Radiometric corrections for atmospheric effect will not be required, but it may be necessary to make some compensation for the varying angle at which the line of sight intersects the earth's surface.

5.0 IMAGE DATA PROCESSING

This section treats the handling of imagery data by considering a comprehensive set of processing functions which could possibly be performed. These "modular functions" range from the initial reformatting, data compression and encoding type of functions to the analytically oriented functions directed at extracting information from the image data (i.e., automatic classification, feature identification, thematic mapping, etc.). Once this set of possible modular functions has been established, it is then incumbent upon the results of the user requirements analysis (Section 3.0) to define the required sequence of modular functions for a given workload profile (i.e., the demand for data products stemming from selected management programs). Once these function sequence alternatives have been established, it then remains to relate specific equipment types to the functions with the resulting output describing conceptual processing system designs.

5.1 Error Sources

A significant part of the overall required image processing deals with data correction or the compensation for errors. Earth observation experiments are predicated on the assumption that the geometrical and photometric/radiometric relationships in the object space can be faithfully reproduced through the data acquisition and processing system. In those cases in which spectral response is significant, there is the further requirement that these same relationships be maintained at all wavelengths of interest. Typical error sources introduced in earth observations from orbit are depicted in Figure 5-1.

These error sources are in general applicable to all sensors, although the magnitudes of certain errors, particularly those associated with atmospheric effects, are highly variable. Atmospheric effects are time, location, and frequency dependent and, therefore, are of particular concern when absolute radiance data or spectral signatures from land or ocean surfaces are desired.

5.2 Geometric Corrections

All sensors require the correlation of spacecraft location and pointing direction of the sensor with time of observation in order to specify the

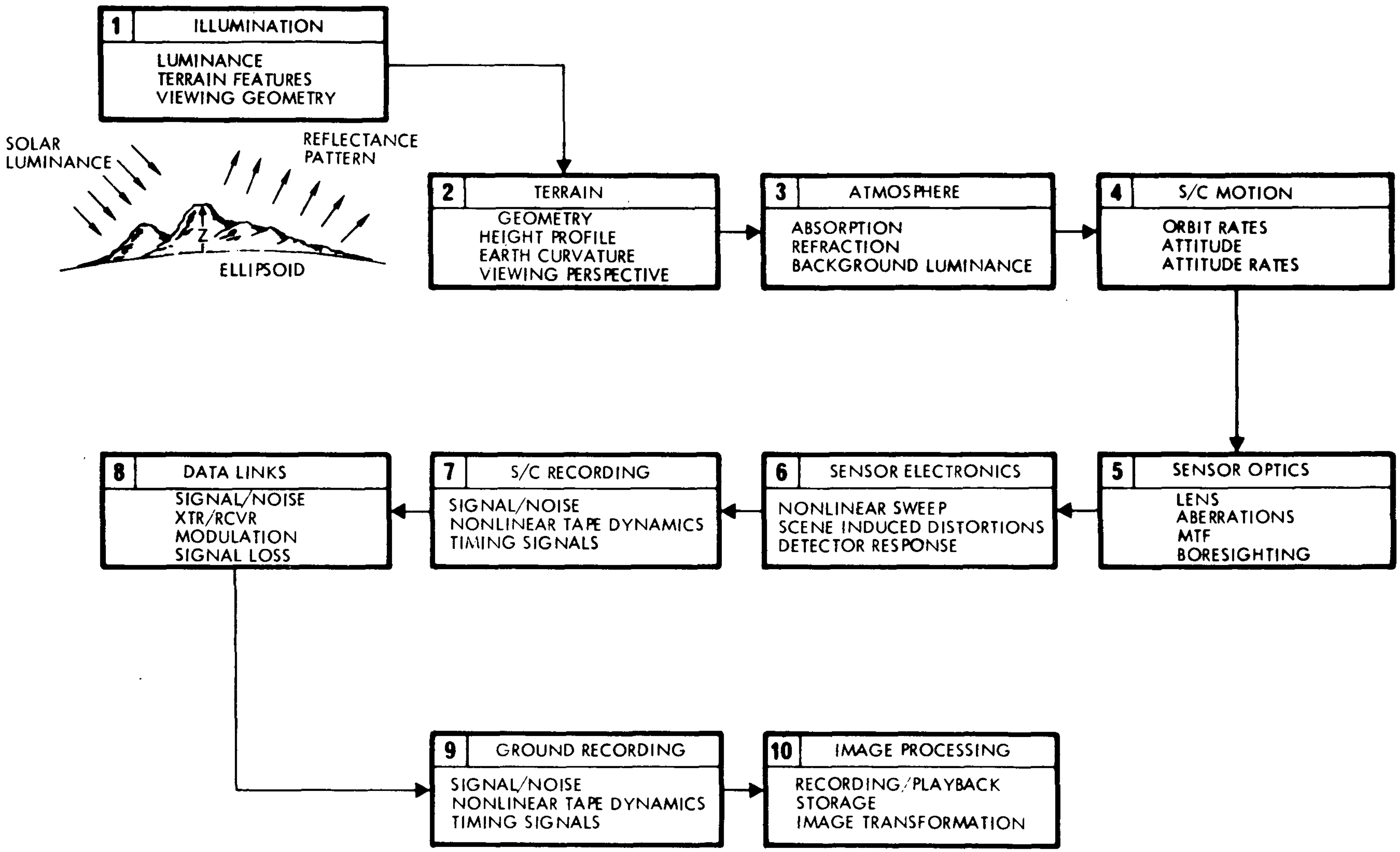

Figure 5-1. Image Error Source Sequence

location of the data with respect to the surface of the earth. In most cases the pointing direction is specified relative to the spacecraft so spacecraft attitude is also needed. For framing imagers (film cameras, RBV's) and point observation sensors such as vertical sounders and most radiometers, spacecraft orbital and attitude rates enter in only indirectly in that they affect the instantaneous values. On the other hand, all line-scan imaging devices have an effective scale in the along track direction determined by the velocity of the sub-orbital point and, in addition, distortions in the imagery arise directly from attitude rates in all three coordinates. Furthermore, the rotation of the earth beneath the satellite can produce a skew in the image of as much as about 7 percent.

Another geometrical distortion occurs in the data from most imaging sensors because the curved surface of the earth is, in effect, mapped on a flat image plane. This distortion is detectable in the ERTS RBV imagery with frames 100 nmi across and becomes very pronounced for imagery with wider cross-track coverage.

The RBV's and electronic imaging tubes in general exhibit distortions of the raster pattern because of imperfections in the electronic deflection section. The principal effects are pincushion distortion, skew, and size and centering errors. The first two are typically 1 to 2 percent in magnitude and are fairly constant in time for a given tube. The size and centering errors, of about the same magnitude, depend on operating conditions and thus vary with time. A reseau pattern on the tube faceplate is usually employed to give a measure of the distortions which are present in any frame of imagery.

Multispectral frame cameras, whether electro-optical or film cameras, consist essentially of separate cameras for each spectral channel, matched in focal length and boresighted as well as possible, but never perfectly. This is true even of cameras using a single aperture and beam splitters to separate the wavelength bands, since all the path lengths are not identical. Thus special measures must be taken to achieve an adequate degree of registration among spectral channels. The problem is much more serious with electronic cameras than with film cameras because the raster distortions differ noticeably from one image tube to another.

Multispectral line scan imagers are designed to produce inherently almost perfect registration among the spectral channels, since the detectors for different bands are offset a small, fixed, and known amount from one another, so any distortions in the imagery are faithfully reproduced in all wavelengths.

The problem of registration of imagery becomes particularly acute when the concept of "multistage" sampling is introduced. In this case correlation of disparate data sets arises through a desire to utilize broad coverage, low resolution imagery (spacecraft in near earth orbit) with high resolution, narrow coverage imagery (low altitude aircraft). In order to have these data sets complement one another in adding to the total information content of a scene of interest, they must be geometrically scaled (and in some cases warped) to bring about spatial coincidence. This general problem of processing multistage imagery is thoroughly described by Reference 1.

Mechanical scan mechanisms produce some special problems in addition to those already mentioned. The oscillating mirror scan mechanism (ERTS Multispectral Scanner) is subject to variations in scan speed and start time because of difficulties in timing and sizing the driving impulses. Conical scan mechanisms can be made much more uniform, but they do present some problems in recording them as hard copy imagery.

5.3 Radiometric Corrections

All remote sensing devices used in spacecraft operate basically by measuring incident electromagnetic flux as a function of direction from the sensor in one or more wavelength regions defined by optical filters, spectral dispersing elements, and/or detector spectral sensitivity ranges. Thus the overall instrument responsivity, which depends on the spectral response of the optical system, optical filters, and detectors including the modulation transfer functions which define the spatial frequence response, must be known and applied to translate the output electrical signal into equivalent values of incident radiation. The film camera is a partial exception in that the output signal consists of density variations in the photographic emulsion.

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1 - "General Questions on Requirements for Processing of 'Multistage' Image Data," NASA/MSC Memo FS52-72-46, 6 March 1972, G. R. Kimball.

Here the "H and D" curve, log density versus log exposure, corresponds to the detector/amplifier part of the other electronic system.

The determination of the sensor responsivity is the principal element of its calibration. The sensor can be calibrated prior to flight; it will also probably require some degree of recalibration during flight by measuring the response to a known input. This is often a formidable requirement, but the difficulties involved fall within the scope of sensor design rather than data handling. In general, calibration signals are handled almost the same as any others, except that the output is analyzed to provide corrections to the calibration functions instead of (or in addition to) being sent to the users. The calibration functions and their applications vary in complexity with different sensors. Almost all detectors, including film, are non-linear in their output versus input characteristics. Line scan sensors with the single detector per channel represent the simplest case, since the output of each channel is dependent only on a single calibration curve. The linear array of detectors in the push-bloom line-scan imager requires a calibration curve for each detector. Although future developments may greatly reduce the considerable variations from detector to detector which characterize the present state of the art, it is unlikely that sufficient uniformity to allow use of a single calibration curve for all detectors will be achieved for some time to come, at least for accurate radiometric measurements. There is a strong possibility, however, that compensations can be made in real time within the sensor electronics, thus effectively reducing the ground data processing requirements and providing a high-fidelity quick-look capability. The framing sensors, film cameras, and RBV cameras use a two-dimensional surface over which responsitivity can vary. Film is sufficiently uniform to permit moderately accurate photometric measurements, but there is no way to calibrate the non-uniformities which exist. RBV targets are far from uniform; they exhibit both shading (fairly slow changes of responsivity over the surface) amounting to 10 to 15 percent, and localized spots differing from their surroundings by similar amounts. Calibration of these variations can be made and compensation introduced to reduce the variations to about 1 percent or so. This can represent a considerable data processing load, however.

Sensors with image elements covering different parts of the instantaneous field of view, framing cameras and linear array scanners, may show some variation in radiation reaching the detectors as a function of distance from the optical axis; i.e., vignetting. Another angle effect, more difficult to treat because it is to some extent scene dependent, is the variation in brightness with angle from the local vertical, since most surfaces depart considerably from being perfectly diffuse reflectors. Sun glitter patterns over the oceans are an extreme example of this effect.

The atmosphere introduces radiometric errors because of wavelength dependent attenuation and radiance (veiling glare). Corrections for atmospheric effects are probably best left for the user to perform in R&D oriented programs, although for fully operational systems, appropriate atmospheric corrections should be performed during preprocessing of data.

In the case of both radiometric and geometric corrections, both digital and analog approaches are feasible. Geometric manipulation in the digital domain involves the determination of new intensity values at a grid of sample points representing the corrected image. In general, the new values sought will lie between existing or uncorrected samples and thus a strategy for establishing the new value is required. Selecting the value of the nearest neighbor is one approach, while developing in interpolation function is another; the former being less accurate and the latter requiring more computer time. Point-by-point photometric corrections can also easily be made as the image is being geometrically processed.

Geometric manipulations in the analog domain usually involve either all optical or electro-optical approaches. The all optical approach starts with an uncorrected transparency and images a small section of it through a special optical train onto an unexposed film. The optical train permits small translations, rotations, and anamorphic scale changes, and thus warps the uncorrected image in small increments to produce an exposed corrected film. Making point-by-point photometric corrections with this process is difficult.

Electro optical processing involves scanning the uncorrected image and then laying the video signal back down on unexposed film in altered positions. Here point-by-point photometric correction can simultaneously be made. A variation of the above starts with a video signal and creates a corrected image through control of the sweep as it is reproduced.

5.4 Special Preprocessing

The corrective manipulations discussed above were somewhat arbitrarily defined as those required to obtain radiance values from output electrical signals. Most sensors require somewhat more computation than this, and three types of sensors require significantly more. Thematic mappers require the radiance values to be interpreted in terms of some derived quantities, such as surface temperature, soil moisture, etc., and isopleths pertinent to these quantities determined and plotted. The decision as to what should constitute preprocessing and what should be user analysis may be somewhat arbitrary. However, routine automated procedures in operational programs (e.g., sea surface isotherms from an operational oceanographic satellite) would definitely be included in preprocessing, while thematic maps requiring considerable judgement and expertise in the users discipline (e.g., delineating agricultural areas by type) would probably not be.

Atmospheric profilers and similar sensors require the inversion of sets of radiance measurements taken under different conditions (e.g., different wavelengths or nadir angles) to obtain atmospheric parameters such as temperature or humidity as functions of altitude. Moreover, cloud cover or surface characteristics can introduce complications in the data interpretation which require sophisticated logical correlation among several types of measurements. All these requirements can result in large data processing loads even for relatively low data-rate sensors.

Synthetic aperture radar has another special computational requirement. The raw data may be thought of as containing along-track resolution information in the Fourier transform domain. The transformation to recognizable imagery is usually accomplished by optical processing techniques. These are well developed and quite satisfactory for ground or aircraft operation, but not for spacecraft. However, since the amount of data needed to specify the SAR imagery is typically some two orders of magnitude less than the raw data, onboard processing would greatly reduce transmission requirements. All-electronic techniques for this type of preprocessing are being developed; it is to be expected that they will be suitable for space applications at least by the 1980 time period.

5.5 Automatic Information Extraction

The classical photo interpreter's art of extracting information from imagery deals principally with a process of visual inspection and analysis by a trained human observer. This process, while being predominately a set of manual operations, has been greatly enhanced by a variety of instruments and machines (i.e., stereo viewers, microdensitometers, autoplotters, etc.). The human's role in this overall task is to subjectively combine visually acquired inputs relating to spatial properties, coloration, texture, and temporal phenomena to identify and classify objects in a ground scene(s). In performing this task the human exercises a sophisticated ability to combine various types of data and draw conclusions as to information subtleties present. The most obvious shortcoming in manual photo interpretation lies in the human's inability to rapidly process a large number of frames of imagery. This latter problem is of major concern with the synoptic capabilities and requirements of operationally oriented remote sensing and the resultant high volume of imagery to be processed.

To date the emphasis in research leading to automated techniques for information extraction has been in exploiting the spectral information content of imagery or spectroradiometer data. Simply stated, the theory depends upon an assumed uniqueness of spectral "signatures" for a given object on the ground (the "object" being an area of sufficiently small dimensions to be considered essentially homogeneous). The spectral signatures are produced by recording the returned energy (combined reflected and radiated electromagnetic energy) in each of a number of narrow and discrete wavebands. Attempts to classify objects based on their signatures would then depend on prestored, empirically derived, statistics on signatures of known objects (or alternatively, an ability to model and analytically calculate what a given signature should be) coupled with classification and decision logic implemented by digital, analog, or hybrid computation. Such a scheme for signature recognition is illustrated in Figure 5-2.

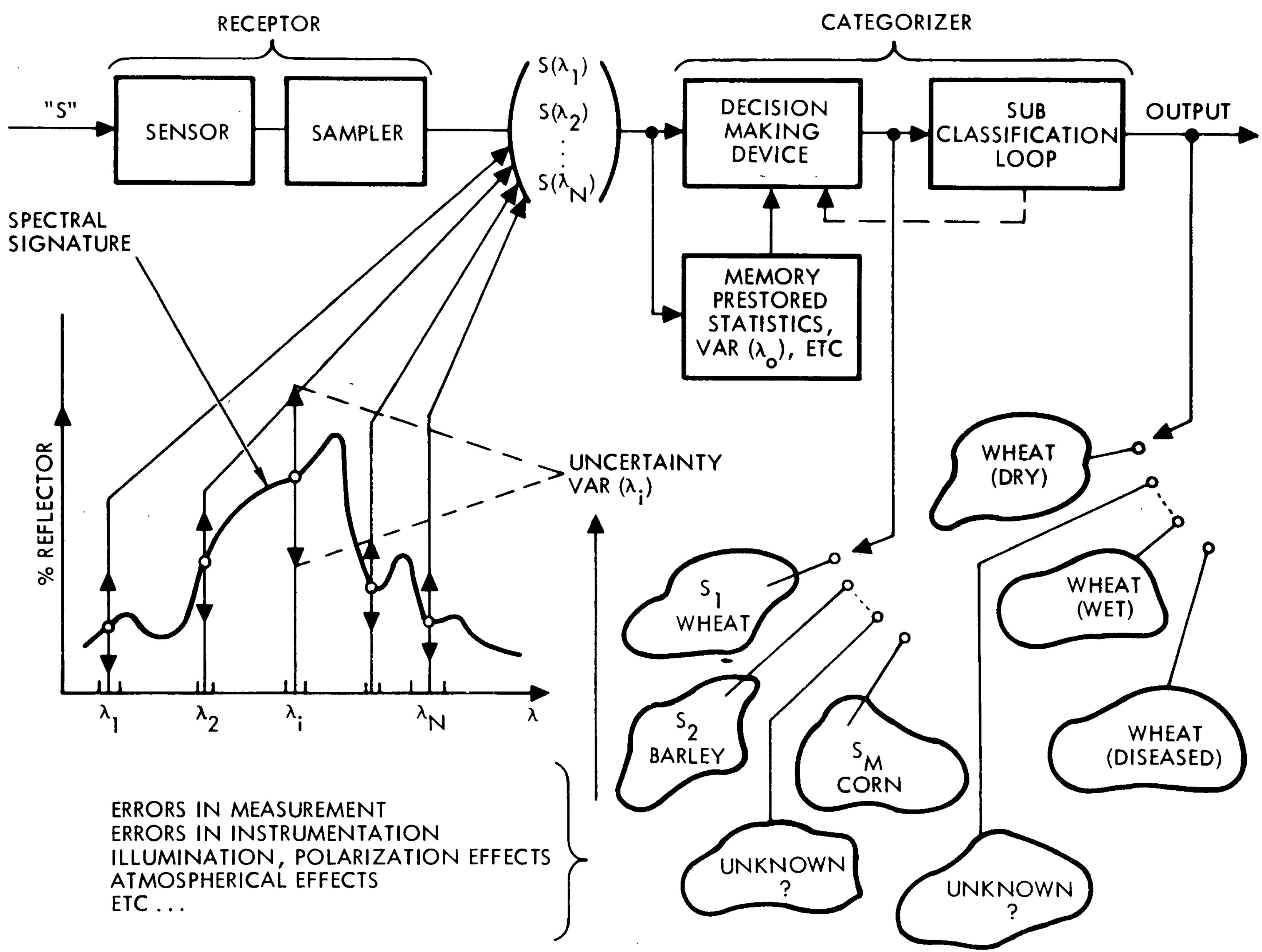

Figure 5-2. Spectral Signature Recognition

The real difficulty with the above technique lies in the fact that there exists appreciable variability in these would-be unique signatures and the problem becomes one of modeling (Reference 1) or empirically deriving the expected variability (this phenomena holds true even for repeated observations in which great care is taken to maintain constant sun angle, viewing angle, cloud cover, ambient temperature/humidity, instrument calibration, etc., and can be attributed in large to a lack of macroscopic homogeneity between identical objects/species in two different ground scenes; i.e., no two leaves of diseased corn appear exactly the same, and no two rows of perfectly healthy corn will be arrayed exactly the same or have exactly the same amount of the same color dirt exposed between rows, etc.)

There are applications in which it would be desirable to automatically extract spatial relationships. Techniques for automatically identifying and locating features of interest have been developed in which scanning of the imagery and a pixel by pixel investigation is required. Digital techniques are usually based on highly machine time consuming step-by-step testing of the distance and direction of a neighboring pixel from a reference pixel. Less flexible, but considerably faster feature extraction may be done by various optical and electronic analog techniques.

In practice neither spectral signature recognition or feature extraction tend to be truly automatic. Most current implementation techniques depend upon the use of "training" sets and a man-assisted calibration of the classification algorithms employed.

5.6 Modular Processing Functions

In general, image processing techniques exist for: altering the geometry and photometry of images (includes most of the above data corrections); image enhancement and spatial filtering; and monitoring or interpreting images and abstracting information from them.

It is useful to divide the above techniques or functions into three broad categories: preparation, conversion, and manipulation. Preparation includes auxiliary tasks such as reseau abstraction, locating ground control

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1 - "A Model for Spectral Signature Variability," TRW IOC 4913.7-71-193, dated 12 November 1971, D. M. Detchmendy, W. H. Pace.

points, etc. Conversion includes the simple functions in which the basic information is not altered, such as reproduction of multiple copies or transfer between analog and digital domains. Manipulation on the other hand includes the more sophisticated operations in which the data or their representation basis are altered. Manipulation can be further divided into basic operations, such as geometric correction, photometric alteration, and spatial filtering, and into information abstraction or interpretive operations such as screening, spectral signature analysis, pattern recognition, etc.

In Table 5-1, these categories have been subdivided into a set of modular processing functions which become the basic building blocks for synthesizing processing systems. This set of functions is the basis for individual subsystem models which are to be included in the System Performance Simulation (Section 8.0).

Table 5-1. Modular Processing Functions

Preparation Functions		
RESEAU	-	Abstracting calibration fiducials
GNDCØN	-	Measuring control-point coordinates
SCREEN	-	Screening for further processing
GEØCAL	-	Calculating geometric transformations
DEMØDE	-	Demodulating/Decompacting/Demultiplexing
ATTEPH	-	Attitude/Ephemeris calculations
ARCHIV	-	Information archiving support
Conversion Functions		
SCANIM	-	Convert transparency to video signal
RESCAN	-	Convert video to hard copy
A-TØ-D	-	Convert video to byte sequence
D-TØ-A	-	Convert byte sequence to video
Basic Manipulations		
GEØMCØ	-	Alter image geometry
PHØTØM	-	Alter image photometry
SPAFIL	-	Spatial filtering of image
ZØØMIN	-	Select geographical region
TRANSF	-	Functional transformation
Interpretive Manipulations		
SIGREC	-	Signature recognition
CHADIS	-	Change discrimination
GRIDIM	-	Superimpose grid
ANØTAT	-	Add annotation
MØSECT	-	Mosaicing
ENHANC	-	Image enhancement
CØNTUR	-	Abstract contours
ADDCØL	-	Color display from B&W negatives
CØLDIS	-	Volatile color displays
STATIS	-	Statistical summary
SUBADD	-	Subtract/Add images
SCALIM	-	Image enlargement

6.0 ONBOARD PROCESSING FUNCTIONS

Between the time that ground phenomena is remotely sensed and the time at which the data become user oriented information, a variety of processing functions will of necessity be performed. Of those modular functions identified in the previous section, those dealing with sampling, digitizing, compressing, multiplexing, calibrating, correcting, and storing are strong candidates to be performed onboard. Some must be performed onboard to prepare data for transmission to the ground, while others may optionally be done onboard or on the ground with the decision resting on considerations of need, cost, spacecraft subsystem weight, volume, power, etc.

Usually one would prefer to put on the ground all functions not required on board. However, certain functions, if done on board, can ease other onboard functions or substantially ease a ground problem. Examples of the latter include data compression which could substantially ease a communication problem or data calibration and correction for APT type transmission to minimize such functions at hundreds of small ground reception sites.

This section discusses those functions which could most probably be performed in an unattended or automated mode on board a spacecraft. The more difficult issue of defining appropriate onboard manned, analyst-in-the-loop and/or onboard maintenance functions is deferred till later phases of this study when better definition of the distinctions between experimental and operational data acquisition become available.

6.1 Image-to-Data-Stream Conversion

The ability to convert two dimensional image intensity to a time-sequenced data flow has existed for several decades. Television accomplishes this on a frame-after-frame basis by electronically scanning the image plane with a series of horizontal sweeps. Thus, even though the (analog) transmitted wave form is a continuous function of the intensity along a specific horizontal line, the intensity along any vertical line has discrete jumps. Where purely digital communication systems are to be used, it is necessary to also introduce discrete jumps in both the horizontal and the intensity directions. While such techniques are well known and have been employed widely, other techniques can be used to digitally represent images.

The amount of information a sensor can collect is directly related to the total energy which enters the system during a measurement time and how this energy is distributed over the various possible degrees of freedom of the image. In traditional sensors, each sampled picture element becomes a degree of freedom. Thus, the degrees of freedom are spatially distributed. The same image could (through coherent light techniques) be represented by its Fourier transform and in this case the degrees of freedom are spectrally distributed. The amount of information is essentially the same in either case since conversion from one to the other is possible with little loss.

Future sensors using advanced optical techniques could, in fact, digitize an image in the Fourier domain rather than with spatial sampling. Furthermore, any system of orthonormal functions can be used as a basis for digitization. As an example, the main reason over sampling an image is required with present-day sensors is to deal with the gradual fall-off of the sensor modulation transfer function (MTF). A more nearly optimum sample shape (something more nearly approaching a two-dimensional $\frac{\sin X}{X}$ function could substantially reduce the data required to represent an image of given resolution. Such a sample shape cannot be easily constructed with a single detector but a group of smaller detectors weighted and phased properly could simulate the desired detector and thus produce an improved ratio of number of resoluble elements to number of sample values.

6.2 Data Compression

For any sampling strategy there remains a wide variety of possible means for associating a binary sequence with an image. The usual way is to express each sample magnitude as a binary number of, say, 7 bits and then sequence these numbers according to the sampling plan. Using this sampling strategy, the average number of bits required to represent an image can be reduced by using the statistical distribution over the class of possible images. In essence, highly likely images are coded with fewer bits and less likely ones with more bits in accord with Huffman coding practice.

For practical reasons one would prefer to apply this statistical approach over many local regions rather than over an entire image, but compressibility suffers as the unit which is compressed becomes smaller and smaller. This is so because one ignores more and more point probability between units as they become smaller. Thus, there is a practical limit to how small a unit should be individually compressed. For example, no gains can be made in trying to compress one bit at a time and even with one picture element at a time; round off errors alone (we cannot use 3.4 bits per picture element so we round off upward to 4) can account for an increase in the amount of data by 20 to 50 percent. On the other hand, if a sensor is simultaneously producing four registered spectral bands and 7 bits represent the sample amplitude in each band, the round-off penalty would not exceed 5 to 15 percent.

For a four-spectral band sensor whose amplitudes are quantized to 7 bits, 28 bits characterize the "color" at each pixel. If a probability of occurrence is assigned to each of the 2^{28} possible "color" combinations, a Huffman code can be created which reduces the average sequence length an amount which depends on the specific probability distribution.

The probability distribution can be assigned absolutely or conditionally. An absolute assignment takes no account of the "color" already observed in adjacent samples, while a conditional assignment can depend on as many of the previously sampled values as one desires and considers practical. TRW's IR&D studies indicate that average compression ratios of 2 to 5 can be expected with practical conditional assignment strategies depending on the terrain type and the quality of the sensor.

The approach to image data compression discussed above is called information preserving because the transmitted (and usually shorter) digital representation of the image can always be expanded to yield the original representation without ambiguity. Another class of data compression techniques produces non-reversible (but subjectively acceptable) representations and with proper caution can also be used.

Inherent in data compression is the need for buffering. This buffering permits the averaging of data peaks and valleys as a compression over local regions varies. As compression techniques become more effective, the amount of buffering required to prevent over or under flow grows. To be effective, however, the buffer must be able to accept variable input rates and yield a constant average output rate. Variable speed tape recorders working with solid state memories show the greatest promise in this area.

The relationship and derivation of several candidate data compression techniques is presented in Figure 6-1. This type of summary is useful for identifying potential applicability of various techniques but provides no information regarding the performance and complexity.

One of the difficulties in this field is the great diversity of specialized techniques coupled with fact that there is at present no universally applicable measure of the effectiveness of a given technique. As a result, it is difficult to make any tradeoff of effectiveness versus complexity without reference to a particular communication system. Steps in this direction are being taken, but it may be some time before the theoretical analysis of data compression systems is sufficiently well developed to be effective. For a given source and error criterion, the minimum possible transmission rate is found in the rate distortion function of Shannon.[1,2] Except for simple cases such as the mean square error criterion, the mathematics is formidable. However, the concept of rate distortion is of considerable value due to the generality of its definigion, potential application, and because it offers a yardstick by which the effect of many of the various data handling operations can be measured. Briefly, the rate distortion function R(d) is defined as the minimum information rate required to transmit information from a given source to a receiver with average distortion no greater than D. A typical presentation of the rate distortion function together with the comparative rate versus distortion performance of several competing sampling schemes for transform compression techniques is shown in Table 6-1. The concept of distortion can be made to fit any fidelity criterion and any information processing system. Applications include sampling, quantization, coding, estimation, dimensionality reduction, pattern recognition, data compression, modulation; in fact, any process that lends itself to characterizing information generated by a source

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1. Shannon, C. E., "A Mathematical Theory of Communications," Bell System Technical Journal, Vol. 17, October 1948, pp. 623-656.
2. Shannon, C. E., "Coding Theorems for a Discrete Source With a Fidelity Criterion," in Information and Decision Processes, R. E. Machol, Ed. New York, McGraw-Hill, 1960, pp. 93-126.

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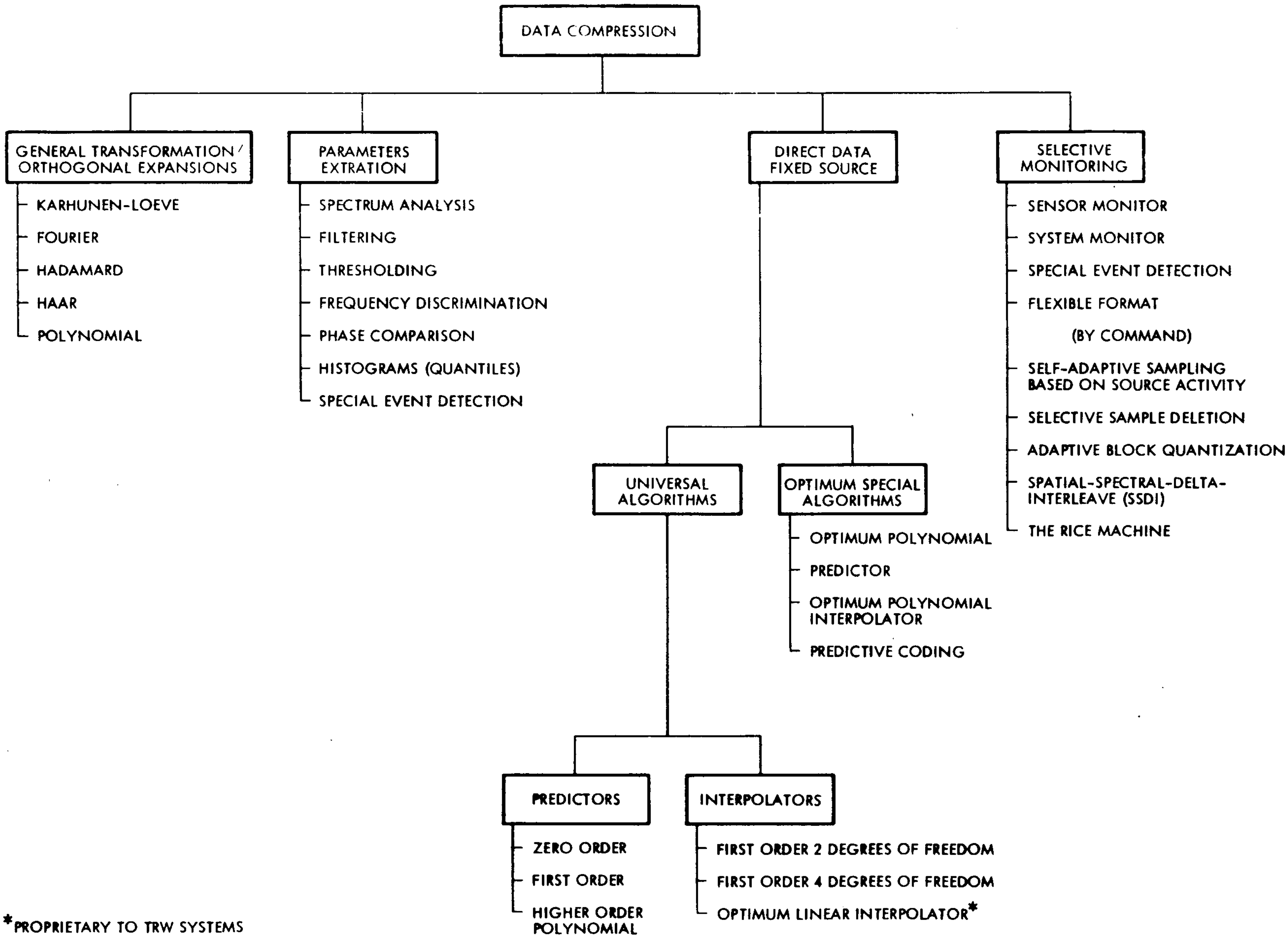

*PROPRIETARY TO TRW SYSTEMS

Figure 6-1. Data Compression Techniques

Table 6-1. Information Preserving Data Compaction Techniques

TECHNIQUES	REMARKS
STATISTICAL PREDICTION	
• Zero-order prediction • Spectral-Spatial-Delta Interleave (SSDI) and Shell Code Algorithm	In a predictive scheme, past values are used to predict future values. A predictive compressor removes the redundancy in a message by exploiting the probability constraints within a message ensemble. Both zero-order predictor and linear approximation techniques are sub-classes of the general class of DPCM or predictive coding techniques, the differential information between adjacent pixels is determined and suitably coded. SSDI, developed by TRW, is an algorithm based on delta modulation with differences taken spatially and across the spectral bands.
• Huffman and Shannon-Fano Coding	This class of coding matches the source statistics. As an example, knowing the probability of occurrence of each quantized amplitude. Huffman coding (optimum comma free code) can be used to minimize the average word length. Here the high probability sequences use long codes.
• Run-length Coding	Useful when strong correlation between adjacent sequences exist.
• Subsection Processing and Coding	Mean level of a small block of pixels is determined. This mean level along with the difference levels are optimally coded so as to reduce the average output code length.
• Rice Algorithm	A compressor using concatenated codes which adapts to rapid changes in data activity by deciding which code to use.
• Adaptive Compression	Adaptive compression is a compromise between exact coding where the exact statistics are known and straight transmission. Here the past meassage statistics are measured and used to encode the subsequent message interval. While this procedure is in progress, the efficiency of the coding presently in use is monitored and in addition new statistics are measured. If the compression efficiency falls below a given level, the newly measured statistics are used, i.e., the coding is updated. Erroneous statistics used for coding can lead to message expansion i.e., the encoded message contains more bits than the original message.
POLYNOMIAL CURVE FITTING	
• Contour Coding Algorithm	The algorithm locates and curve traces all equal magnitude elements of two dimensional picture arrays. The output is a sequence of integers describing amplitude, location and shape of these contours.
• Modified Transform Coding	Two dimensional transform of the digitized image is taken and all co-efficients in the transform domain are transmitted. Coefficients which lie below a predetermined threshold can be transmitted by variable length coding (Huffman Code).
• Bit Plane Encoding	In this method a group of bits are divided into subgroups so that some of the subgroups can be summarily described. Kanefsky has investigated the application of this method to two dimensional pictorial data.

with a probability distribution. For example, in signal coding, the rate distortion function is just the capacity of the binary symmetric channel with transition probabilities D and (1-D).

The recent upsurge of interest as evidenced by activity in the literature indicates a concentrated effort to develop bounds and approximations to extend the range of application of the rate distortion function. An entire book devoted to rate distortion theory has appeared[1] in which important new results are collected and presented and classical results are presented tutorially. Andrews[2] has published a bibliography on rate distortion theory and Tasto and Wintz have published their results on a Bound on the Rate Distortion Function and Its Applications to Images[3]. O'Neal has recently published results on the Bounds on Subjective Performance Measures for Source Encoding Systems[4]. This last author has included results on the application of rate distortion theory with a frequency-weighted mean-square error criterion.

There are three other figures of merit in common use in describing data compression systems, as discussed in detail by Davisson[5]. These are:

- The Data Compression Ratio (DCR)
- The Bit Compression Ratio (BCR)
- The Energy Compression Ratio (ECR)

Their definitions are summarized in the following table.

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1. Berger, T., Rate Distortion Theory: A Mathematical Basis for Data Compression, Englewood Cliffs, N.J., Prentice-Hall, 1971.
2. Andrews, H. C., "Bibliography on Rate Distortion Theory," IEEE Transactions on Information Theory, Vol. IT - 17, No. 2, March 1971, pp. 198-199.
3. Tasto, M. and Wintz, P. A., "A Bound on the Rate Distortion Function and Application to Images," IEEE Transactions on Information Theory, Vol. IT - 18, No. 1, 1 January 1972, pp. 150-159.
4. O'Neal, J. B., "Bounds on Subjective Performance Measures for Source Encoding Systems," IEEE Transactions on Information Theory, Vol. IT - 17, No. 3, May 1971, pp. 224-231.
5. Davisson, L. D., "The Theoretical Analysis of Data Compression Systems," Proceedings of the IEEE, Vol. 56, No. 2, February 1968, pp. 176-186.

Table 6-2. Data Compression Figures of Merit

Figure of Merit	Definition
DCR	The ratio of generated sample values to the transmitted values. This figure of merit can most easily be applied to the sampling and zero order or fan prediction and interpolation data compression techniques, with fixed PCM word lengths.
BCR	The ratio of the information bits for transmission of the original sample values to those required in the system with data compression including all reconstruction information in addition to the transmitted sample values. The effect of channel transmission errors is to make the received reconstructed data of generally lower quality than in the straight transmission of the sample values.
ECR	The energy compression ratio is defined as the energy required per sample to transmit the data uncompressed divided by the energy when compressed under the same noise conditions and transmission scheme for the same reconstructed "quality," such as mean square error or probability of error.

Generally, these measures of effectiveness are less informative than the rate distortion bound, but they can still be useful in comparison of competing systems. A preliminary analysis of compression techniques for earth resources survey data is shown in Table 6-3.

6.3 Data Formatting and Multiplexing

The use of data multiplexers to gather information from many different sources within a spacecraft for subsequent downlink transmission over a single (or several) communication channel has become a classical design task that must be addressed in virtually every spacecraft design. The design approach taken is highly dependent upon the nature and quantity of the various information sources and the available communication channel bandwidth. Usually there is a mixture of analog and digital signals to be multiplexed. Depending upon the various speed requirements, the spacecraft multiplexer may be required to operate at several speeds and in many cases the multiplexing task is divided between separate high and low speed multiplexer designs. Again, requirements may dictate a time or a frequency division multiplexer.

Table 6-3. Candidate Information Preserving Compaction Algorithms and Their Relative Performance

Coding (Compression) Techniques	Number of Bits/Pixel*	Approximate Compression Ratios**	Implementation Complexity for Near-Real-Time Output
PCM (reference)	6-8	1:1	(reference)
Differential PCM (DPCM), predictors interpolators, etc.	3	2:1 or higher	Simple to moderate
Adaptive DPCM (e.g., Rice Machine)	2-5	3:1	Simple
Adaptive 2-dimensional DPCM (e.g., Shell Coding) Spectral-spatial delta interleave and their modifications	2-2.5	higher than 3:1	Simple to moderate
1-dimensional transform techniques (e.g., Fourier and Hadamard	2.5-3	3:1	Moderate
2-dimensional transform	2-2.5	higher than 3:1	Moderate to Complex
Adaptive 2-dimensional transform	1-1.5	5:1 and higher	Complex

*Approximate number of bits/pixel required for same quality picture produced by 6-8 bit PCM.

**Compression ratios achievable with non-information preserving techniques (NIP) are much higher than that achieved with information preserving (IP) techniques. An error fidelity criterion (e.g., mean square error) suitable to the user is desired. Most of the compression techniques, such as delta modulation, linear interpolation, and transforms are based upon mean square error.

Techniques for accomplishing the multiplexing at the very high bit rates will require further effort. Read only memories have proven satisfactory for establishing one of several multiplex formats at rates up to 10^9 bits/sec and within the next 5 to 10 years this rate should increase by a factor of 10. Where alternate formats are possible, it is, of course, necessary to ensure that the ground demultiplexing is using the same format as the onboard multiplexer. This is accomplished by inserting the format code in a fixed position in the telemetry frame.

Another aspect of data formatting which may ease the data rate problem is adaptive multiplexing. By careful consideration of the purposes of a mission and the characteristics of the payload members, one can establish a priority schedule for the assignment of such limited resources as spacecraft power and data bandwidth. This priority schedule should deal with the end utility of each sensor's data both along and combined with data from the other sensors. It should also include such factors as terrain being observed, lighting conditions, cloud cover, perishability of data, and the nearness to readout, sensor health, and other factors. Some inputs to the priority decision model can be automatic, while others must be entered manually through the command system. The consequence to the data handling system in any event is a division of the available bit rate between sensors in a more or less optimum fashion for each measurement interval.

6.4 Coding

The application of redundancy-reducing data compression techniques places increased value and importance on each data bit because it represents a distilation of the raw data and will require a greater reliability in the communications channel. Coding tends to make the channel performance less sensitive to the effects of occasional large noise bursts, since each of the digital words is reconstructed at the receiver from the observation of many signal-plus-noise samples rather than just one. A complete analysis of any modern communication system performance, particularly one incorporating data compression, must therefore consider the effect of coding on performance.

The nine categories of algebraic codes commonly used in communication and data transmission systems are identified and briefly described in Table 6-4.

6.5 Onboard Correction and Calibration

Practical sensors introduce various geometric and photometric distortions into the data produced. Thus, correction may be required before the data become useful. Normally such corrections would be accomplished in ground processors. For small APT type users, however, simplicity and cost savings would result from transmitting fully corrected images. In addition, onboard

Table 6-4. Binary Code for Error Correction and Detection

ALGEBRAIC CODES

CODE	DESCRIPTION
• Cyclic	• Systematic group codes for coding blocks of k binary information symbols into blocks of n binary symbols by adding n – k parity checks
• Fire	• A class of cyclic codes that correct or detect errors in a single block. A fire code corrects any single burst of length b or less, and detects errors in any single burst of length $d \leq b$. The length of the code must not exceed the least common multiple of $2^m - 1$ and $b + d - 1$, where m is an arbitrary parameter relating the length of the code (n) and the number of parity bits (n – k, which equals m + b + d – 1).
• Hamming	• Based on the theory that, for any m, there is a code of length $2^m - 1$ that has m parity bits and $2^m - 1 - m$ information symbols and can correct any single error. One parity bit can be added to permit double-error detection as well as single-error correction; or alternatively the correction of adjacent double errors as well as of single errors.
• Bose-Chaudhuri	• Based on the theory that for any m and t, there is a code of length $n = 2^m - 1$ that will correct all combinations of t or fewer errors. The number of parity bits never exceeds mt.
• Fixed-Count	• Error-detecting codes in which all blocks contain the same number of ones. An undetectable error occurs only when the number of erroneous ones is the same as the number of erroneous zeros, which is unlikely.
• Simple-Parity Check	• A single parity bit is appended to each information block for error detection. Additional error detection and even error correction can be achieved by arranging the information in a rectangular array and adding parity bits to every row, every column, and even every diagonal.
• Reed-Muller	• Based on the theory that, for any m and r (where m exceeds r), there is a code that can correct any combination of $2^{m-r-1} - 1$ or fewer errors. For this code: $n = 2^m, \quad k = \sum_{i=0}^{n} \binom{n}{i}$ information symbols. where n is the number of coded words. The Digilock telemetry system uses this kind of code. The decoding equipment is quite complex.
• Low-Density Parity-Check	• Each parity bit checks only a few symbols in each coded block.
• Recurrent	• Non-block codes in which the check bits are inserted at intervals among the information bits. Particularly well suited to burst-error correction.

SEQUENTIAL CODES

Non-block codes developed by J. M. Wozencraft, of MIT for probabilistic decoding involving a moderate amount of computation. Seco, a sequential coder developed recently by Lincoln Lab, basically is a two-way system with feedback. A varying amount of redundancy is used to adapt the signal to the channel condition at the time of transmission. As the channel capacity varies, the redundancy varies so as to insure the transmission of as much data as possible. The receiver senses changes in channel capacity and uses feedback to command the appropriate changes in channel redundancy.

correction can be designed to minimize noise introduced by the correction process (that is, corrections can be made before they are conditioned for optimum communications).

The feasibility of such onboard corrections depends on algorithm and equipment practicality and on the availability of the information needed to make the corrections. The development of simple algorithms and the application of LSI techniques definitely renders onboard processing feasible by 1985 as far as the equipment is concerned. Obtaining the information needed for making the corrections may be more difficult. The principal contributors to geometric errors are satellite position and attitude, sensor scan irregularities, and the earth's rotation and curvature. The principal contributors to photometric errors are detector quantum-efficiency variations and atmospheric conditions. To remove geometric errors, use of ground control points is frequently involved. If required, this could prove very difficult in an onboard processor because of the large file of reference images required. It might be possible, however, to use a dedicated real-time ground station to receive transmission of small image requirements containing known ground control point, process this data, and retransmit to the satellite the coefficients needed to complete the onboard processing of the entire image.

6.6 Satellite Data Storage

There are two separate aspects of the data storage problem, one being the rate at which one can insert data, and the second, the gross capacity. If the satellite's data storage facilities are not capable of absorbing the combined data rate due to the sensor payload, real-time transmission must be adapted or data will be lost. If a sophisticated system capable of recording at a rate appreciably greater than that at which data is being collected is available, then a store and dump mode can be adopted.

To establish the data storage requirements, needed inputs include:

- What sensors are used?
- For what periods are the sensor outputs of interest (each sensor)?
- How many ground stations are used?

- What are the ground station locations?
- What assumptions are to be made on ground station capability?

Several applicable data storage techniques for ERS onboard storage applications have been examined with anticipated state-of-the-art in 1975 and beyond. These techniques include magnetic tape recorders, plated wire, bubble memory, ferrite core, semiconductor memory, optical memory, etc. Figure 6-2 shows a tree configuration of various memory alternatives.

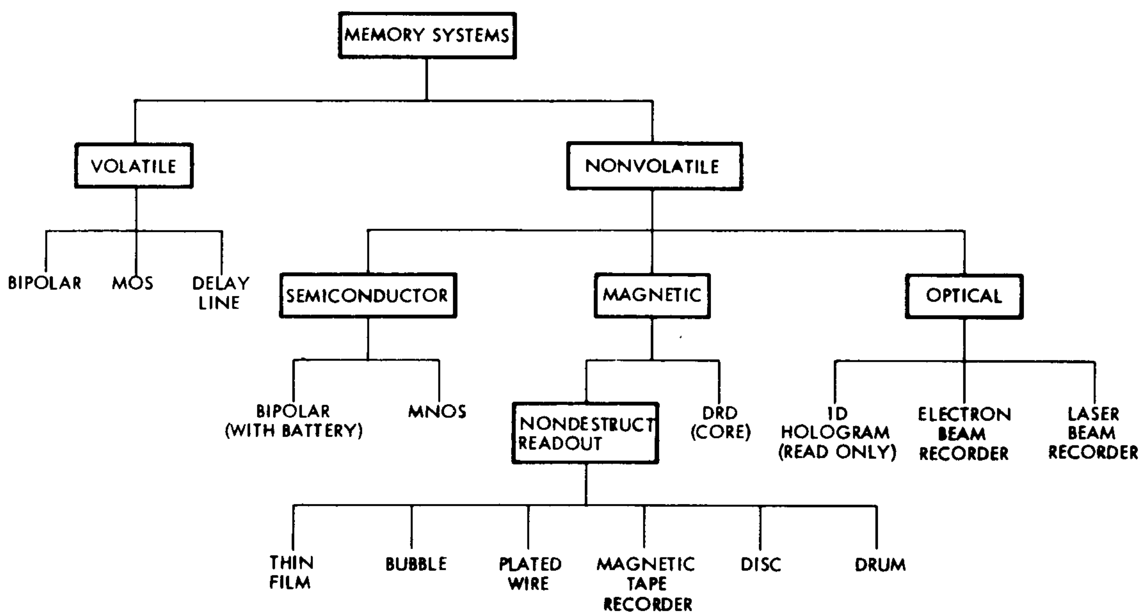

Figure 6-2. Candidate Onboard Data Storage Techniques

The several data storage technologies for spaceborne applications shown in Figure 6-2 are compared in Table 6-5 based on individual performance, susceptibility to environmental conditions, and physical configurations. Table 6-5 also summarizes the advantages, disadvantages, and the development status of each technology.

Table 6-6 shows the projected characteristics of a number of candidate storage schemes for the next 15 years. At present, the tape recorder appears to be outstanding. Not only is it a highly developed technology, its performance and capability are also very impressive as compared to the

Table 6-5. Summary of Present Day Data Storage Technologies

DATA STORAGE TECHNOLOGIES	ADVANTAGES	DISADVANTAGES	STATUS
Tape Recorder	• Digital or analog data input • Multiple speed • Time compression or expansion • High packing density • Lightweight, small size • Rewrite capability	• Performance deterioration caused by Bearing, Tape and Headwear • Tape is susceptible to extreme temperature and magnetic field • Mechanical moving parts limit the lifetime	40, 000 BPI, 100 tracks on 1 inch tape is available. Tape speed 120 IPS, bandwidth 15 MHz
Bubble Memory	• Excellent resistance to vibration, shock and radiation • Good reliability (potentially) • Long lifetime (potentially) • Good packing density • Low power consumption • Lightweight, small	• Associated circuits sensitive to radiation • Sensitive to temperature change • Reqnire technology breakthrough • Poor output signal	Under development — available data 1975 or earlier
Optical Memory (Laser)	• Input/output completely isolated • Data readout in serial, in parallel or in block • High bit density	• Very high power consumption • Weight, volume excessive in associated equipment • Poor efficiency • Poor matching between laser pulse rate and data transfer rate • Short lifetime	Not available within the next five years
Sonic BORAM	• High data rate • Non-destructive readout • Low power consumption	• Low bit density • Fixed data rate • Require temperature compensation • Lifetime relatively short • Require asychronous IC buffer register • Large volume	Under development
DTPL	• Permanent bias field not required • Low power consumption • Good response to environment changes	• Poor linear bit density • Poor output signal • Low data transfer rate • Require series - parallel shift register at input and output • MTBF shorter than Bubble Memory	Under development - available date mid-70's
Ferrite Core	• Not recommended for spaceborne applications requiring over 2 Mbits data capacity	• Low bit density • Large volume • Heavy weight • Short MTBF • Poor response to atmospheric hazards • High power consumption	10^7 bit capacity late 1972
Plated Wire			10^7 bit capacity available late 1972, e.g., Minuteman, Poseden
Thin Film			Generally not used due to production problem

Table 6-6. Projected Characteristics of Various Data Storage Devices (1975-1985)

Data Storage Technologies	Performance: Packing Density Bits/In^2	Performance: Potential Capacity Bits	Performance: Write/Read Data Rate B/S (Serial Mode)	Performance: Energy/Bit J	Response to Environmental Conditions: Temp	Response to Environmental Conditions: Shock	Response to Environmental Conditions: Vibration	Response to Environmental Conditions: Radiation	Mean Time Between Hours	Max. Weight Lbs.	Volume In^3
Tape Recorders	5×10^7	10^{10}	$20\times10^6/20\times10^6$	10^{-4}	A	A	A	G	10^4	50	2, 000
Bubble Memory	10^6	10^8	$3\times10^6/3\times10^6$	5×10^{-5}	P	G	G	G	2×10^4	200	3, 000
Plated Wire	5, 000	10^7	$8\times10^6/8\times10^6$	10^{-3}	A	A	A	G	Depends on electrical connection	300	2, 000
Ferrite Core	2, 000	10^7	$2\times10^6/2\times10^6$	10^{-3}	A	A	A	G	5×10^3	400	10, 000
Thin Film	10^4	10^7	$2\times10^7/2\times10^7$	Not available	G	A	A	G	Not available	-	-
Sonic BORAM	3, 000	10^8	$10^7/10^7$	2×10^{-6}	A	A	A	G	10^4	450	7, 000
DTPL	2, 500	10^8	$5\times10^5/5\times10^5$	2×10^{-5}	A	G	G	P	10^4	100	2, 000

A – adequate
G – good
P – poor

forecasted performance of those still-to-be-developed memories. For example, the next most promising technology, the bubble memory, is 2 to 3 years away even for a prototype, and its performance improvements (large memory, etc.) require further major technology development. Plated Wire Sonic, BORAM, and Optical Memories appear to be in the same category; however, one should not rule out that the replacement of tape recorder by a totally non-mechanical device is possible within 1975-1985 period.

State-of-the-Art in Tape Recorders

Table 6-7 lists some of the pertinent characteristics of tape transports that are representative of state-of-the-art transports that could be considered because they are available or in development.

Electron/Laser Beam Recorder

These devices can be used with photographic, magnetic, or thermoplastic recording material. A related class of recording techniques uses a laser beam to provide the radiant energy or temperature change, as needed for those recording media. Photographic media, whether "exposed" by a radiation beam or by electrons, require processing which may be acceptable. These media are not reusable. If reusability is not important, then the so-called thermally (dry) processed photographic materials (Eastman Kodak and 3M Corp.) should be considered. Both magnetic and thermoplastic recording media are exposable by either radiation or electron beams and are reusable.

Magnetic materials are exposable by focussed energy beams through one of several thermomagnetic effects. These magnetic recording techniques have been pursued in a number of NASA contracts. A conventional magnetic recording results and so readout can be achieved with conventional magnetic heads. Electron beam readout has also been pursued, but the results have not been very promising so far.

Substantially more effort has gone into the use of thermoplastic materials in electron beam recorders. In this case, the incoming data modulates an electron beam current so that as the beam is scanned over the recording medium, a spatial charge image is painted on. In some cases, the thermoplastic medium is in the form of a film strip or reel and as it is transported from the

Table 6-7. Comparison Near-Term Magnetic Tape Transports

Contractor/Model	RCA/ERTS	RCA/ERTS	RCA/SH	Ampex/AR 700	Ampex/AR 1700	Ampex/AR 500	Leach/MTR 7000	Borg-Warner PERT
Number of tracks	1	100	1	28	28	One	12	30
Recorder Operation	helical scan	longitudinal	helical scan	longitudinal	longitudinal	rotary head	longitudinal	longitudinal Newell Drive
Tape Speed (IPS)	effectively 1964	40	effectively 1333	60	120	effectively 2000	120	Up to 1000
Tape Length (ft.)	2000	2000	2400	7200	9200	2200	9200	2400
Tape Width (inches)	2	2	1	1	1	2	1	1/2
Bandwidth (MB/Sec/T)	15-20	1	5	1.0	2.0	5.5	2.0	6-15
Packing Density (KB/I/T)	7.5-10	25	analog	20	20	analog	16.7	15
Weight (lbs.)	74	74	50	48	72	115	100	50
Size (cu. ft.)	2.3	2.3	1.0	1.3	1.5	2.6	3.7	1.0
Power (watts)	90	90	75	175	220	?	700	150
Signal/Noise (db)	42	30	38	20	20	22	22	24
Data Capacity (bits)	2.4×10^{10}	6×10^{10}	analog	4.8×10^{9}	6.2×10^{10}	analog	2.2×10^{10}	1.3×10^{9}
Availability	In development	In development	In development	Used on Martin Skylab program	In production not space qualified	In production not space qualified	Wright-Patterson AFB	In development
Estimated ROM Cost	180K per flight unit 800K development costs	180K per flight unit 800K development costs	80K per flight unit 650K for development	120K per flight unit 650K for development	120 per flight unit 650K for development	120 per flight unit 650K for development	60K per flight unit 600K for development	160K per flight unit 800K for development

recording station it passes over a heated platen. Upon reaching about 100°C, the electrostatic forces between the upper charged surface and the induced charge on the lower surface of the dielectric film deforms the material so that a relief image replica of the initial charge image is formed. Upon cooling, the image is fixed. Data recorded in this fashion has been read out by both optical (laser) techniques and by reflection of an electron beam from the fixed recording. The playback device used is the same as that used for recording, the thermoplastic or disk recording medium.

Much of the performance data on thermoplastic recorders is classified. It seems reasonable to expect that their performance would be about the same (perhaps better) as that of electron beam recorders using photographic type materials with the advantages of simpler material processing and a potentially very important reusability advantage.

It is reported that electron beam recorders can record serial data at rates between 100 and 200 M bits per second.

One Dimensional Holograms (Read-Only) Memory

This device stores information in the form of one dimensional Fourier holograms. The binary holograms consist of many parallel transparent apertures on an opaque background and are similar to general diffraction gratings. Readout is accomplished by deflecting a laser beam to a selected track and decoding the holograms using an optimal Fourier transform.

IBM has recently reported performance of an experimental model, including a storage density of 2.25M bits/in^2, a data rate of 2M bits/sec, and average access time of 8.5 msec. Test results indicate that it is feasible to extend the storage density to 6M bits/in^2, data rate to 20M bits/sec, and access time to 1.3 msec.

Performance of Current Bulk Memories and Future Predictions

Projected interest is in memories with a capacity of 10^6 to 10^8 bits and an access time of approximately 10 ns. From Figure 6-3, it can be seen that with commercially available memories only magnetic cores and plated wire meet both constraints. However, semiconductor memories of this capacity are within the capability of the existing technology if the penalty of a large parts count and high standby power are acceptable.

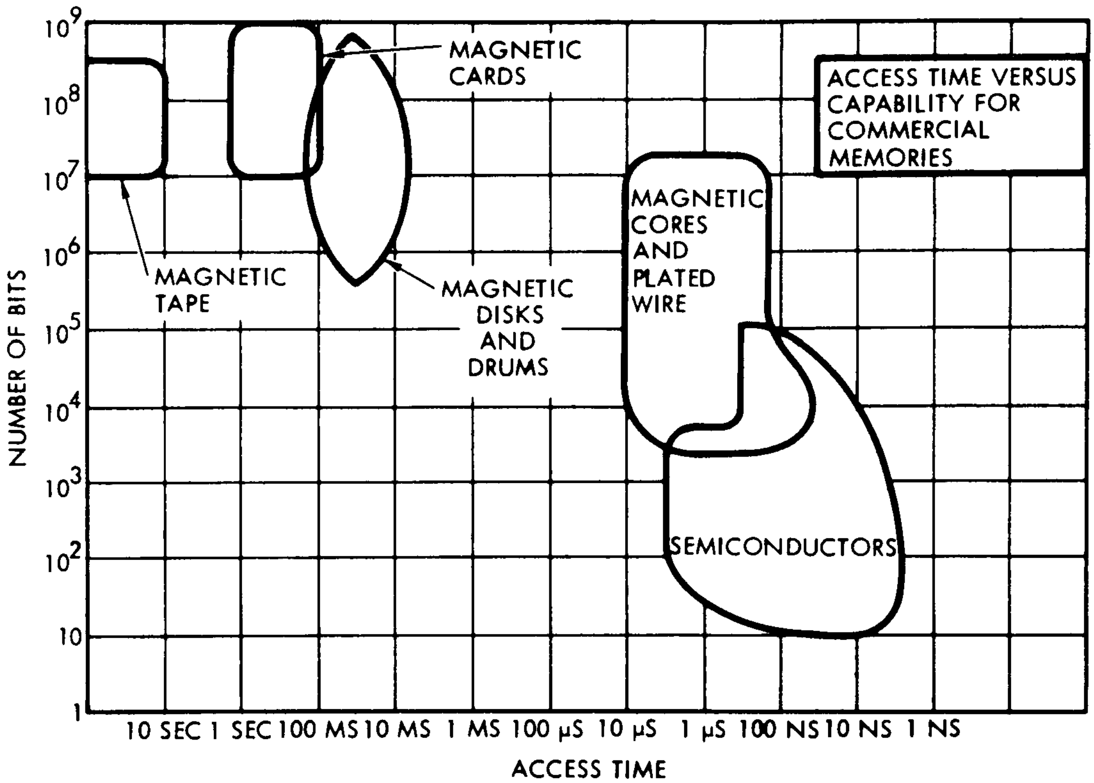

Figure 6-3. Access Time Versus Capacity for Commercial Memories

If random access is not required, magnetic tape, disks, and drums are available with relatively high data transfer rates (8M bits/sec for 8 bit parallel transfers). These devices are particularly useful where bursts of high-speed data are to be stored and read out of a slower rate. Data is written "on the fly" so that the search time of the memory is avoided. TRW has recently completed a data storage system consisting of 30,000 bits of semiconductor memory buffering bursts of data onto a 2.4 x 10^6 bit disk. The peak input data rate was 30M bs; the average input data rate was below that of the disk memory.

Random Access Memories (RAM's)

Random Access Memories consist of two types: magnetic devices and semiconductor devices. Table 6-8 gives a comparison of these types. It is expected that the major advances in this area will be in plated wire and complementary MOS.

Improvements in magnetic material parameter control and the capability to process smaller wire (2 mil wire) will increase the packing density and reduce the access time of plated wire memories.

	Ferrite Cores	Plated Wire	Bipolar	Dynamic MOS	Static MOS	Compli-mentary MOS
Cycle Time	600 ns	550 ns	150 ns	600 ns	300 ns	65 ns
Access Time	320 ns	200 ns	50-100 ns	300 ns	200 ns	15 ns
Total Power (MW/Bit	3. 6	2. 0	2. 4	0. 6	1. 2	0. 06
Word Drive Current	400 ma	800 ma	5-10 ma	100 ma	100 ma	100 ma
Word Drive Voltage	25 V		2 V	5-20 V	5-20 V	5-15
Sense Voltage	20-50 MV	10-30 MV	1-5 V	5-20 V	5-20 V	5-15
Cell Spacing	25 x 25 Mils	15 x 15 Mils	8 x 8 Mils	2 x 2 Mils	6 x 6 Mils	8 x 8 Mils
NDRO	No	Yes	Yes	No	Yes	Yes
Volatile	No	No	Yes	Yes	Yes	Yes

Table 6-8. Comparison of Random Access Memory Characteristics

Improved processes and controls will make large capacity C-MOS memories available with the access and cycle times of bipolar memories and significantly lower power consumption. In addition, it is expected that continued improvements will be made in the number of bits/chip for both MOS and bipolar memories. As an example, INTEL has just announced (see Table 6-9) a 4096 x 1 bit N-MOS chip to be available in late 1972. This is a factor of two improvements from currently available chips with equivalent access time. Figure 6-4 shows the expected improvement in price versus performance for semiconductor RAM's.

Serial Storage Devices

Where random access is not required, serial storage devices (delay lines) may offer some advantages. Table 6-10 lists some types of serial storage devices. The areas which will see significant improvement are capacity per unit and price/bit. Some improvements will be made in power consumption and bit density, especially for MOS shift registers and microwave acoustic delay lines.

Table 6-9. Semiconductor Random Access Memories

Manufacturer	Model Number	Size (Bits)	Organization (Words x Bits)	Access Time	Cycle Time (ns)	Max. Clock Freq. (MHz)	Power	Technology	Remarks
Advanced Memory Sys.	AMS 0328 E/T	256	32 x 8	15	20	100	0.2 W	Bipolar	Functional cards
American Microsystems	MB 52	2,048	2048 x 1	1000	1000	1	300 MW	P MOS	Fully decoded
	MA 52	2,560	256 x 10	700	700	1.4	350 MW		
COGAR Corp.	15C07	18,432	1024 x 18	125	250		45 W	Bipolar	Functional cards
	30C06	147,455	8192 x 18	250	300		51 W	MOS and Bipolar	Functional cards
Electronic Arrays	EA3300	4,096	512 x 8	1000	1200	0.850	100 MW	P MOS	24 Pin Dip
		1,024	1024 x 1	250	580			N MOS	Announced Feb. 1972
Fairchild	3580/84	2,048	512 x 4	750	1000	1.0	450 MW	P MOS	
General Instruments	MEM 2048	2,048	64 x 32	1000		1.25	150 MW	M TOS	24 Pin Dip
INTEL	1103	1,024	1024 x 1	600	600		150 MW	P MOS	
	3301	1,024	256 x 4	60	80		300 MW	Bipolar	
		4,096	4096 x 1	300	500		100 MW	NMOS	Available Late 1972
INTERSIL	1CM5008	512	256 x 2	350	400	3		N MOS	Static
Motorola	MC1036	16	16 x 1	17	50		25 MW	Bipolar (ECL)	
	MC4064	64	64 x 1	15	60		500 MW	Bipolar (TTL)	
	MC1170	64	16 x 4	200	1200		250 MW	P MOS	
Call	MCM1173	1,024	1024 x 1						
National Semiconductor	NM423	2,048	256 x 8	1500			350 MW	P MOS	Static
Philco Ford	PM2048C	2,048	1024 x 2	1000	2000		350 MW	P MOS	Statis
RCA	CD4003	16	16 x 1	15	65		0.0001 MW	C MOS	14 Pin flatpack
	CD4005D	16	16 x 1	15	65		0.1112 MW	C MOS	14 Pin Dip
Texas Instruments	TM540204	2,048	1024 x 2	320	640		350 MW	P MOS	24 Pin Dip
Standard Logic Inc.	RAMM 1024	10,240	1024 x 10	500	600			P MOS	Functional card

Table 6-10. Serial Storage Devices

Type	Capacity Per Unit (Bits)	Frequency Range	Temperature Range	Power MW/Bit	Bit/Density[1] (Bits/ft^3)	Price/Bit (Cents)
MOS Shift Reg	1,024	400 Hz to 5 MHz	-55°C to 85°C	0.5	4,000	1.0 - 2.0
Wire Sonic Delay Lines	30,000 8,000	1.5 to 2 MHz 1.5 to 2 MHz	15°C to 55°C -55°C to +75°C	0.6	333	0.5-0.6
Glass Delay Lines	5,000 2,000	20 to 40 MHz 20 to 40 MHz	15°C to 55°C -55°C to +80°C	1 to 5	3,000	2.0-3.0
Quartz Delay Lines	60,000 30,000	60 to 100 MHz 60 to 100 MHz	50°C to 100°C 15°C to 75°C	1 to 5	300 to 3,000	0.7-1.3
Microwave Acoustic Delay Lines	1,000	10 to 1,000 MHz	-54°C to 110°C	1 to 10	1,000	

(1) Includes packaging and associated circuitry.

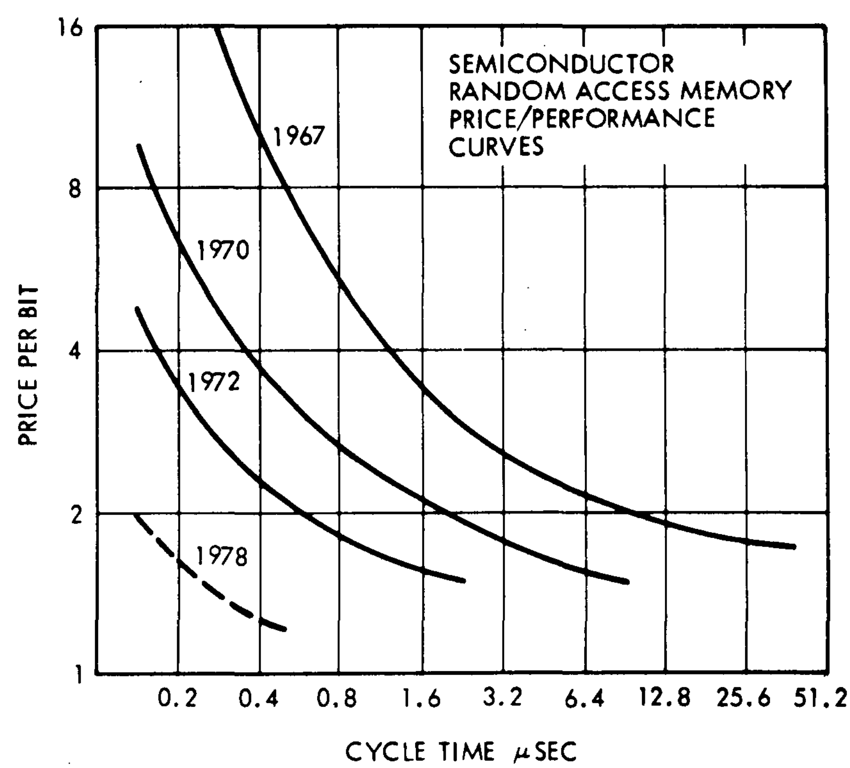

Figure 6-4. Semiconductor Random Access Memory Price/Performance Curves

7.0 IMAGE PROCESSING EQUIPMENT

This section summarizes operating characteristics of a number of the more significant types of special purpose, automatic, and semiautomatic image processing equipment. Devices considered are representative of those currently in use at existing facilities throughout the country and, for the most part, are state-of-the-art equipment. Classical, general purpose photo interpretive equipment has been excluded from this treatment as well as large scale general purpose digital and analog computers. General purpose computers, and their associated image processing programs, are considered in ongoing phases of the current study.

The equipment types considered may be divided into four basic categories:

Image Domain Conversion - generally relates to the image domain being converted from film to a digital or analog representation, or the reverse. Included are scanning image digitizers, electron and laser beam recorders.

Photo-Optical Devices - relates to sophisticated optical projection and manipulation generally based on film transparencies as the input media. Examples treated are an automatic map maker and an additive color viewer.

Electro-Optical Devices - including typically digital or analog manipulation with electronic display; such as the video input and digital image analysis stations and electro-optical correlation with an automatic image restituter.

Optical Computing - principally concerned with optical spatial frequency filtering devices.

7.1 Image Domain Conversion

7.1.1 Scanning Digitizer

This type of device is best typified by the Multiband Imagery Scanner Station (MISS) recently procured by NASA/MSC. This system is used to manually register, scan, and digitize up to four multiband camera images for multispectral data analysis. This device, like most scanners, passes intensity regulated, achromatic light through appropriate color filters and finally impinges on a photomultiplier tube.

Scanning motion is produced by moving the film transparency on a precision X-Y motor driven stage in the desired scan pattern. Scanning rates on the order of 30,000 microns/second are achievable with this type of system with the coordinate/density digitized data recorded on computer compatible magnetic tape. The density or transmittance of each scanned picture element may be encoded at any level desired with a typical level being 8 bits (i.e., $2^8 = 256$ density or grey scale levels).

7.1.2 Electron Beam Recorder (EBR)

The ERTS Ground Data Handling System (GDHS) uses an EBR to record imagery on 70mm photographic film for both RBV and MSS data. This recorder has a continuous film transport to minimize degradations at the corners of the image. By passing the film through the vacuum of an electron gun chamber, the direct writing beam spot size can be made very small ($\sim$2 microns) as compared to the CRT method where the beam spot is modified by the phosphor and glass interface (1 mil).

The electron beam recorder is a complete recording system in which the film is directly exposed by electrons striking a silver halide photographic material and producing a latent image. Basically, the EBR consists of a high resolution electron gun; an electron-optical system for focusing, deflecting, and otherwise controlling the electron beam; a film transportation mechanism; a vacuum pumping system which maintains the required vacuum in various parts of the recorder; a number of highly regulated power supplies; and other electronic circuits which control the operation of the recorder.

The electron-optical system for focusing and deflecting the electron beam consists of electromagnetic coils which are mounted on the outside of the vacuum section. The main vacuum chamber contains the camera and film. Thus, in effect, the film and camera are inside a picture tube and the writing beam falls directly upon the film. Figure 7-1 illustrates the EBR functional components.

Summary characteristics for the ERTS GDHS EBR manufactured by CBS are shown in Table 7-1.

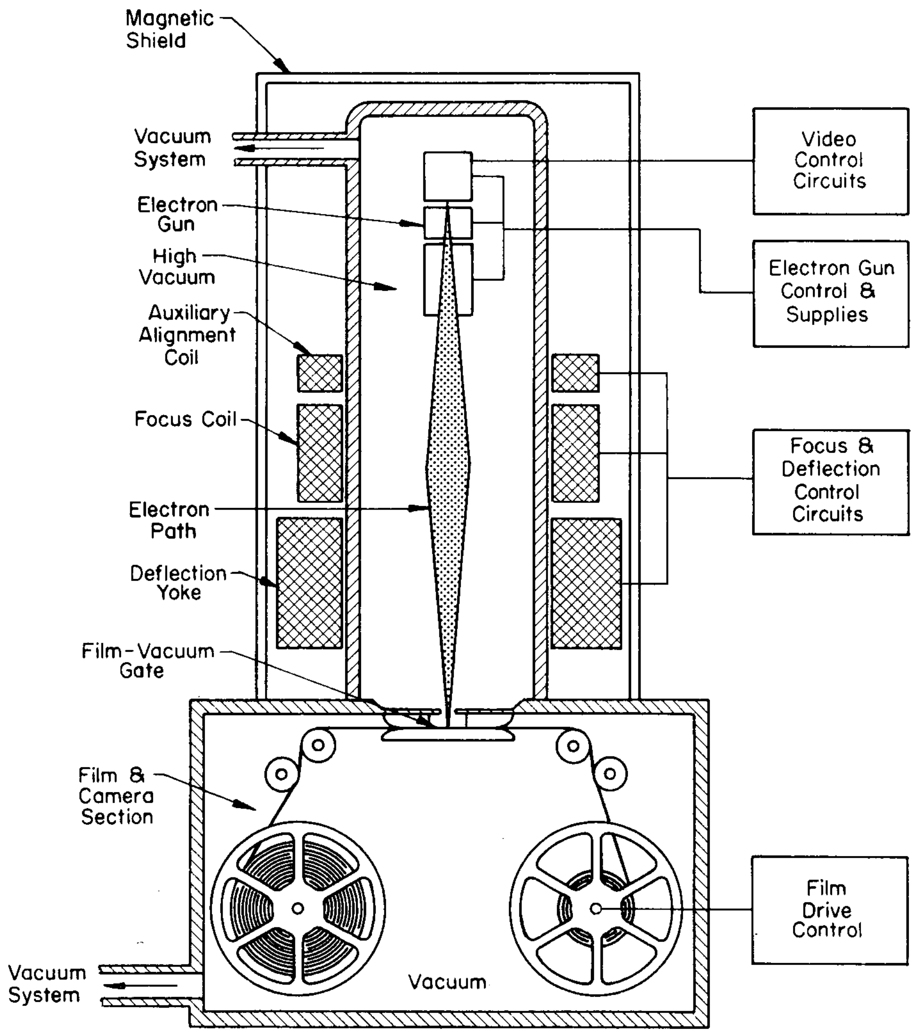

Figure 7-1. EBR Functional Components

Table 7-1. EBR Characteristics

Parameter	Data Mode RBV	MSS
Lines per Frame	4125	4312
Line Rate (lines/sec)	1250	163.44
Cells per Line	4003	3300 ± 300 ∓ 30
Active Line Time (μ sec)	720	2160
Band Width (MHz)	3.20	0.768
Active Writing Time per Frame (sec)	3.3	27.6
Framing Time (sec)	3.5	25
Film Speed (mm/sec)	18.286	2.380
Aperture Scanned (mm)	5.344 10.344 MAX	12.86 15.36 MAX

7.1.3 Laser-Beam Image Reproducer (LBIR)

The Laser-Beam Image Reproducer (LBIR) by RCA consists of a laser, light modulator, beam-enlarging optics, imaging lens, a four-sided mirror fastened to the shaft of an air-bearing-type hysteresis synchronous motor, and a film-transport table. The reproducer, which uses a high-intensity, Helium-Neon gas laser, has the necessary small spot size (~6 microns) and high writing rate needed to reproduce high-resolution, hard-copy pictures.

The laser beam is modulated by an incoming video signal and is then formed by optical components to provide a recording spot of high-energy intensity. The spot is deflected by a high-speed scanning mirror which produces the horizontal scan. Vertical scanning is accomplished by moving the film-transport table past the scanning beam. The scanner and film table motors are precisely locked to the video synchronizing signals for good geometric fidelity in the reproduced pictures.

The Laser-Beam Image Reproducer can be used with high-resolution TV sensors, such as the ERTS Return-Beam Vidicon Camera, and with high-resolution line-scanning systems, including those that observe the scene directly or those that scan an already exposed film (e.g., the Lunar Orbiter System).

The scanning velocity of the LBIR is ten times that possible with magnetic recorders. This feature, in conjunction with the available energy to record at these higher rates and the capability for wide-bandwidth modulation of that energy, enables a significant increase in signal recording bandwidths over those available from the most advanced magnetic signal recorders.

Table 7-2 gives performance characteristics of the RCA LBIR.

Table 7-2. LBIR Performance Characteristics

Image Characteristics:	
Size	9.0 inches x 9.0 inches, single frame
Horizontal Resolution	6000 TV lines at 75 percent response
Gray Scale	13 square-root-of-two (100:1 dynamic range, minimum)
Density Uniformity	Within 2 percent of maximum film density (in D No.)
Scanning Spot Size	0.8 mil
Recording Rates:	
Horizontal Line Rate	1200 lines per second
Video Bandwidth	DC to 10 MHz
Input Video Format	Separate video and sync inputs
Special Features:	
Calibration	Self-calibrating (Test Pattern Generator)
Video Processing	Gamma correction for sensor
Physical Configuration:	
Size	6 feet length x 2 feet width x 6.5 feet height
Weight	500 pounds
Power	20-amperes, 115-volts, 60-cycle, single-phase.

7.2 Photo-Optical

7.2.1 Automatic Map Making

Automatic map making equipment and related systems have been developed by a number of companies (e.g., Itek, Bunker Ramo, Bendix, Wild Heerbrugg, Raytheon, etc.). This type of equipment automatically obtains terrain altitude data from input aerial photographs and outputs orthographically correct photographs as a step in the map production process. The equipment uses a digital computer in a hybrid analog/digital configuration to perform the calculations and control functions required to solve the photogrammetric problem.

Accurate altitude mensuration from aerial photographs requires the use of stereo photographic pairs taken from widely separated positions, typically six tenths of the altitude. Altitude variations in the terrain show up on the resulting pair of photographs as large relative image displacements.

The computer calculates the position of images on the two photographs corresponding to a given horizontal geographic position in the terrain and at an estimated altitude, then directs analog elements to center image scanning on the calculated positions. Other analog elements measure any image displacement between the two scanned areas and report the results to the computer as height corrections. The computer is thereby able to correct its estimate and to make a reasonable height estimate for the next point to be measured in a closely spaced profiling sequence.

As the profiling operation progresses, the image of each small area is recreated on a cathode-ray tube and imaged at the correct X-Y location on the progressively exposed orthophoto negative. Concurrently, the computer outputs a coded signal to set the brightness of a cathode-ray tube to one of three levels (off, medium, full-on) to expose the corresponding element on the altitude chart.

The equipment has been demonstrated to operate as a convenient and accurate stereo comparator with an accuracy of better than 4 microns rms. As an automatic compilation instrument, it makes spot altitude measurements at up to 80 measurements per second and can compile conventional vertical stereo pairs in about 45 minutes for fairly complex terrain, or in about 1-1/2 hours for severe terrain character. The precision of altitude measurement of the equipment, working with f = 6 inches vertical photography, is better than 1/5000 of the flying altitude.

The equipment typically includes four identical precision scanning tables; a control console; a small digital computer with associated typewriter, paper tape, and magnetic tape units; and the various electronics required to obtain integrated operation of the elements.

7.2.2 Additive Color Viewer

An additive color viewer provides a means of analyzing and evaluating multispectral imagery. It is a multi-channel, optical projector, designed to accept either the positive roll film contact transparencies or individual cut film positive transparencies mounted in film holders.

The viewer superimposes up to four individual spectral images in registration on a high quality rear-projection screen at a fixed magnification to display a 9 by 9 inch composite image in natural or in false color. Each channel is equipped with X and Y movement controls to facilitate accurate multi-image registration and to compensate for any minor film-shrinkage effects should they occur. Each channel is also provided with individual illumination controls and filter selection controls. These controls are mounted on a convenient panel above the viewing screen.

The selective filter control provided for each of the four projection channels enables the operator to view each image in black and white or through a blue, green, or red filter. A wide range of natural or false-color effects can be created by varying filter combinations and illumination intensities.

7.3 Electro-Optical

7.3.1 Video Image Analysis Systems

Video image analysis systems use a black and white television camera, video recorder, or video film scanner to produce a standard television signal. A special digital video processor analyzes the shades of gray in the television signal. The gray scale levels are classified into ten or more categories. A different color is assigned to each category; the appropriate color television signal for the color is generated by the digital processor. The final result is a complete color signal suitable for operation of a color monitor unit.

When the system is used as a photometer, the television camera picks up the brightness levels directly from the scene or image. Cameras may be adapted to telescopes, microscopes, spectrographs, infrared image converters, and other optical instruments. When the system is used as a densitometer, the photographic transparency is placed in front of the light box viewed by the television camera.

The output of the system may be transmitted over color television systems for remote viewing. The color signal may be recorded on video magnetic tape or on color film. Systems are used typically to make quantitative readings of brightness or density by placing a calibrated photographic step wedge in the picture for reference. The steps of gray are then made to appear in different colors by adjustment of the color controls. An area in the image having a brightness corresponding to a step on the wedge will have the same color. The accuracy of a system is limited by the noise and shading in the television camera. Typically, twenty or more shades of gray may be resolved. Geometric resolution of a unit is comparable to that obtained in studio-quality 525 line color television systems.

7.3.2 Multispectral Scanner Data Analysis Station (DAS)

The DAS at NASA/MSC is designed to provide the scientific investigator with the capability of processing, displaying, screening, and recording data under the operation of a single person at the control and display console.

The station provides six principal functions:

- Data display and screening. This permits the investigator to view a color or black-and-white display of selected processed data, sections of which he may designate for transfer to computer tape or film.
- Data transfer from original tape recording to computer tape. This is affected in a format compatible with standard 9-track computer tape units.
- Data transfer from original tape recording to film, which may be done either in color or black-and-white.
- Data transfer from computer tape to film. This may be either color or black-and-white, following data processing by an off-line computer.
- Data processing for purposes of coloration or contrast enhancement. This is accomplished through application of algebraic functions or transforms to multispectral data as received, prior to data display or film-recording.

- Data search for a scanner recorded IRIG-A (Inter Range Instrumentation Group) time code to position the tape to a manually selected or computer-selected recorded time.

The ground station tape playback unit accepts data tape recorded in the airborne multispectral scanner and reproduces it at a playback speed controlled by the ground data station computer. Speed may vary from 1-7/8 to 120 in. per sec.

Principal interface with the system is the control and display console, through which the operator may screen enhanced or processed multispectral data on a "moving window" color display. Annotation data at the right-hand edge carry scan-line count in hundreds, aircraft site run number, and a symbol to indicate beginning and end of each data run. A line is included to show aircraft track.

Screening may be conducted in two modes, demand or search. In demand screening, the operator views a moving-window display of the processed data and selects those sections or areas that he wishes either film-recorded or transferred to computer tape for further analysis.

In search-mode screening, the entire tape is screened without interruption and tape coordinates for all data of interest, together with processing instructions, are stored in the computer.

7.3.3 Automatic Image Restitution

This geometric correlation technique involves scanning two input images, correlating the resulting signals in an analog processor, and then analyzing the product to develop error signals proportional to distortions and offsets in the two photographs. A typical correlation system for measuring zero and first-order distortions is shown in Figure 7-2. Zero-order errors are those contributing to X and Y displacement (parallax) while first-order errors include scale (magnification) and skew. Figure 7-3 shows the typical transformations involved in first-order and second-order distortions. Electronic scanning and correlation circuits can provide the zero, first, and if necessary, higher order error coefficients. These error signals then are used to provide corrections to the input imagery using either electronic or optical techniques.

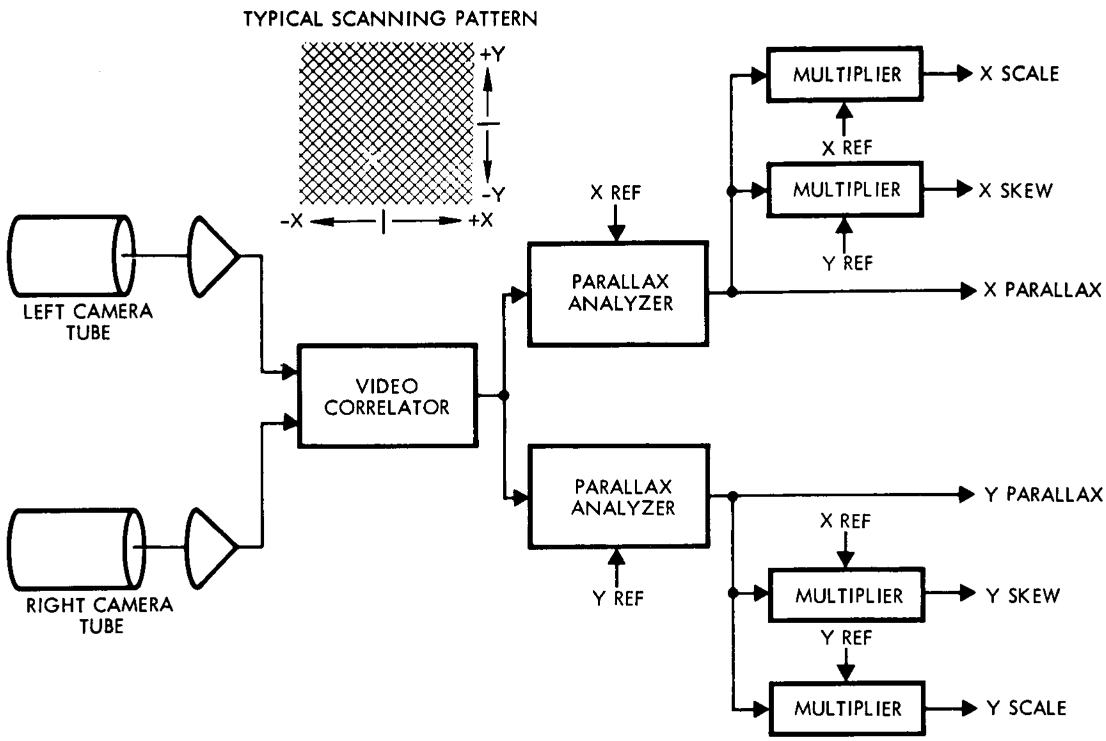

Figure 7-2. Image Scanning and Correlation

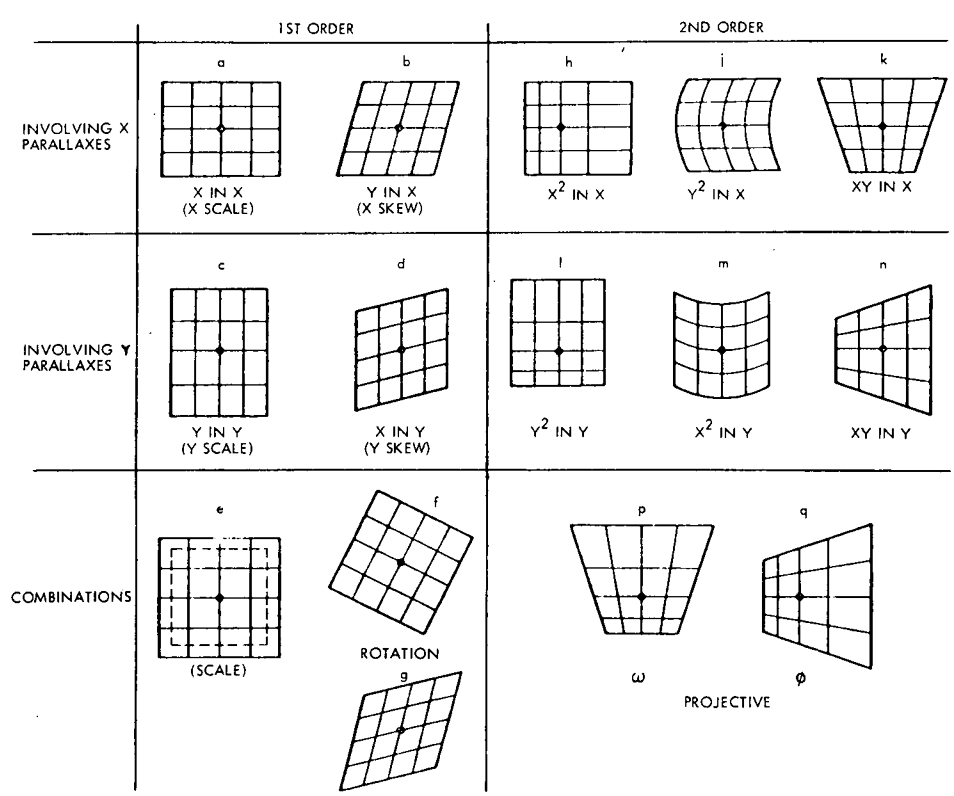

Figure 7-3. Image Transformations

With appropriate error signals representing the relative distortions between the two images, it is now possible to correct or restitute an output image. The two basic techniques which can be used to apply corrections to imagery for automatic registration and restitution are:

> Electronic, where transformations similar to those shown in Figure 7-3 are applied to a CRT raster scan. The resulting video signals from this scan are used to modulate a printing raster to restitute the image.
>
> Optical, using a combination of zoom, rotator, and anamorphic lenses along with translation, to provide zero and first-order corrections to the output image. Figure 7-4 shows typical optical transformations.

The correction process can be carried out either in parallel (transforming the entire image at one time) or serially (by segmenting the image and correcting incrementally).

For parallel electronic photorestitution (see Figure 7-5), an orthogonal raster is projected onto the input images from CRT scanners. The resultant video signals are correlated and analyzed to develop zero, first, and second order error signals which are used to transform both the scanning rasters in equal and opposite amounts. The scanning rasters are driven in closed-loop fashion to a state where best correlation is achieved. The resultant video signal from one scanning path can be used to modulate the intensity of a third CRT, which will print a corrected copy. A second copy from the other scanned image can now be exposed. Thus, the two images will register except for residual errors which would include local disturbances and high-order distortions. The two images are registerable between themselves with residual errors divided approximately equally between the two.

For parallel optical photorestitution (Figure 7-6), the optical train consists of a zoom lens to correct for magnification, a K rotator for rotation, and a pair of anamorphic lenses for skew and stretch corrections. A pair of image dissector tubes performs the image scanning. Video signals produced by the image tubes are correlated to produce error signals which are transformed in a small process-control computer to drive the optical transformations. Since the two output copies can be exposed simultaneously, this approach provides fast throughput.

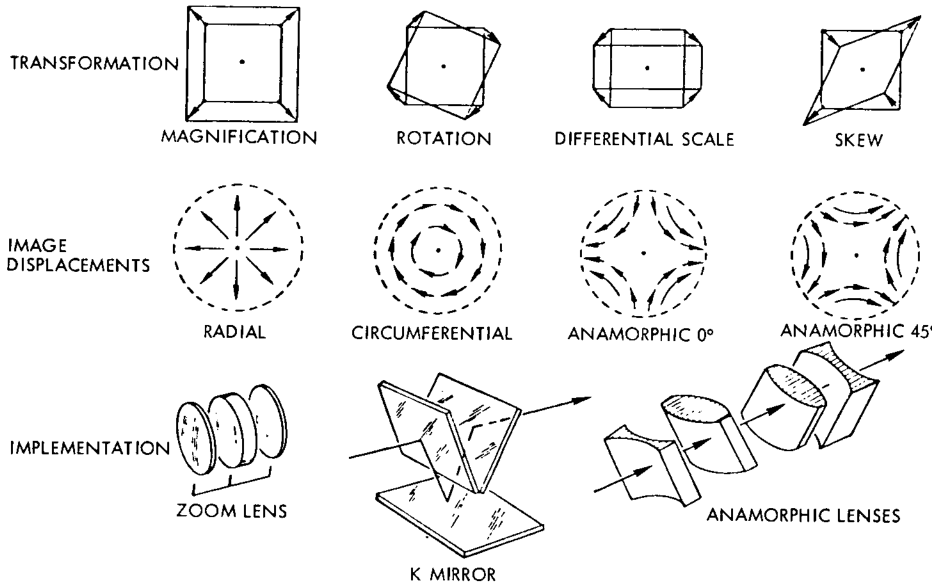

Figure 7-4. Optical Image Transformations

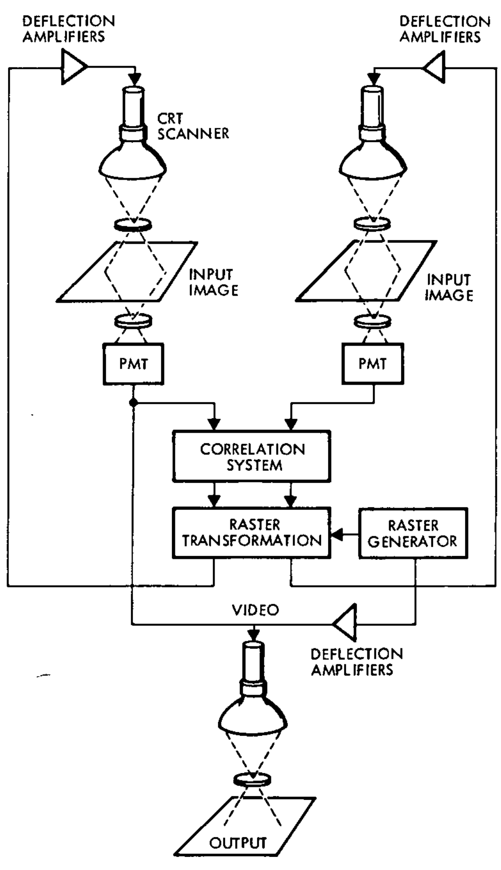

Figure 7-5. Electronic Method of Photorestitution

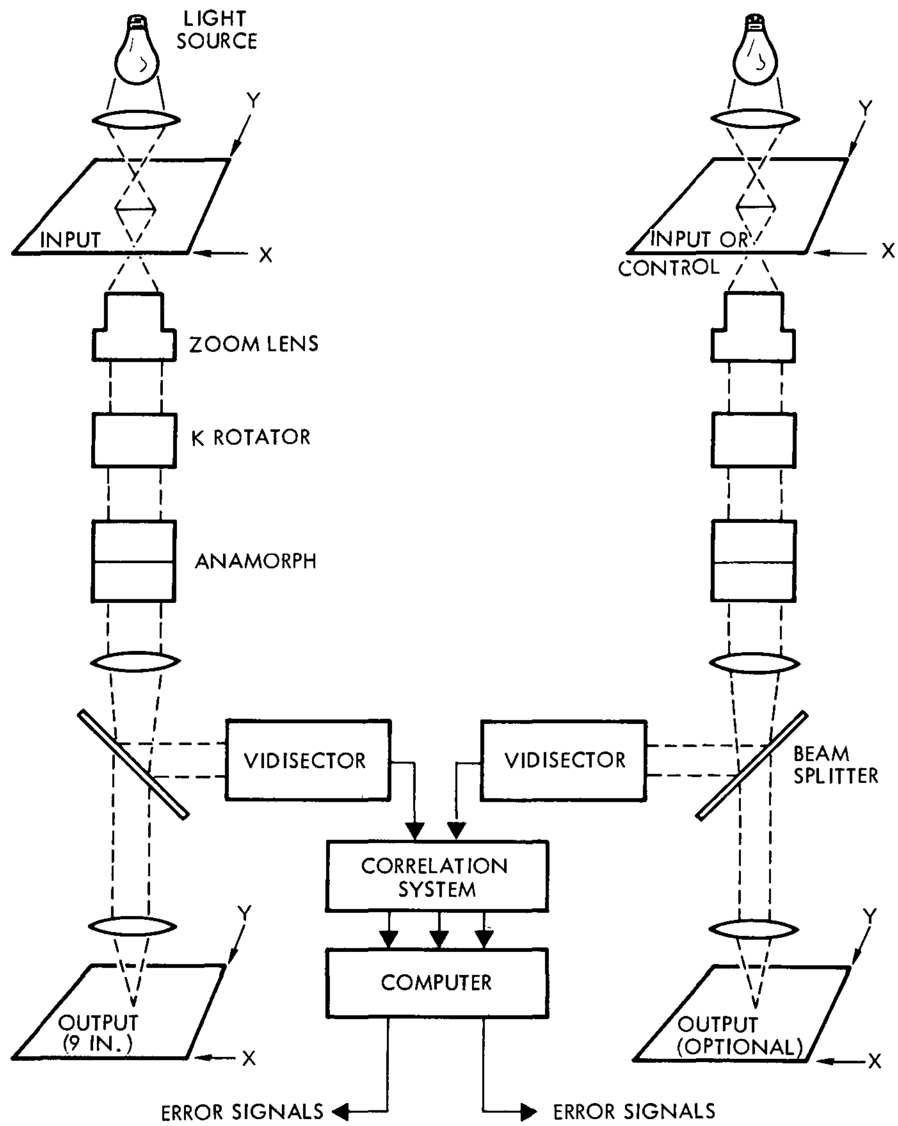

Figure 7-6. Parallel-Optical Method of Photorestitution

7.4 Optical Computing Technology

In electrical systems it is possible to separate signals of differing frequencies by a network of reactive components. The unique frequency dependent properties of capacitive and/or inductive reactance furnishing the desired discriminatory action.

Optical components such as the prism, diffraction grating, and thin film interference filter allow analogous separation between light constituents of differing frequencies. In addition, optical components can perform what has become known as spatial filtering.

The principle involved is that a simple convex lens spaced its own focal length from an object will produce in its image plane an intensity distribution that is the Fourier transform of the spatial frequency distribution (intensity) of the object, if the object is illuminated by a coherent light source.

If a second lens is positioned its own focal length from the image plane of the first lens, a second transformation will be affected resulting in an untransformed image of the original object appearing in the image plane of the second lens.

If opaque masks are placed in the image plane of the first lens (called the transform plane), the final image becomes a spatially filtered version of the original object. The general arrangement required to perform these operations is illustrated in Figure 7-7.

The information in the transform plane is contained in the combination of the phase relationships and the amplitude distribution. An elementary object such as a grid of orthogonal wires will result in a transform plane energy distribution of the form shown in Figure 7-8. The X and Y axis correspond to the horizontal and vertical dimensions of the object. Along the Y axis (at x = 0) we would obtain a series of intense spots corresponding to the first increasing orders of diffraction pattern peaks associated with the dimension for the vertical wire spacing of the object. Along the X axis (at y = 0) we would have the corresponding spots associated with various orders of diffraction maxima for the lateral dimension spacing in the object.

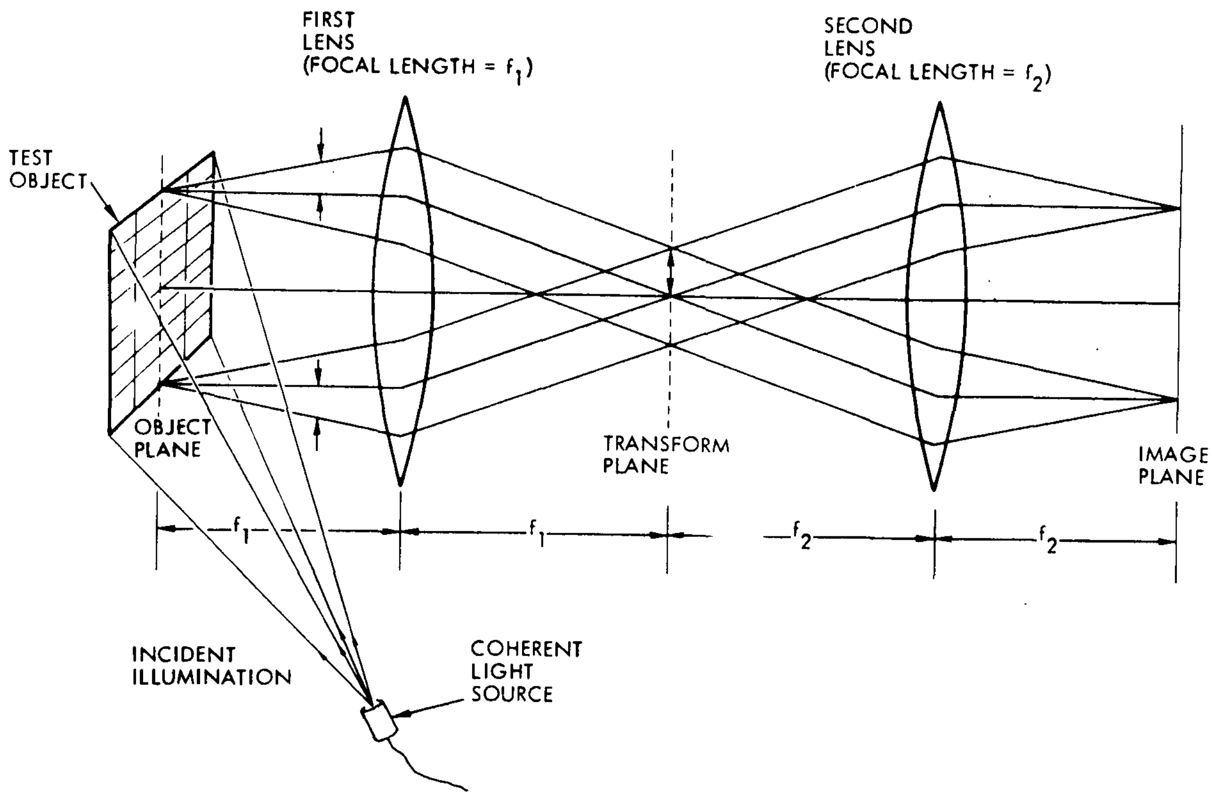

Figure 7-7. Optical System Arrangement for Spatial Filtering

The origin (y = 0, x = 0) corresponds to the non-frequency dependent, or d.c. term.

From the foregoing it will be evident that one can implement the optical equivalent of any of the familiar electrical filter types by an appropriately shaped mask in the transform plane. Some examples are shown in Figure 7-9.

The initial application of optical filtering was for processing of seismic geophone film records obscured by noise and strong spatial line patterns. This work culminated in the Conductron Corporation "Laser Scan" equipment, now widely used in seismic record processing.(1)

Examples of a spacecraft applications are the high pass optical filtering of satellite weather photos, to sharpen the boundaries of the sea, clouds, ice and shoreline, and resolution enhancement of the Surveyor VI moon photos.

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(1) M. B. Dobrin, A. L. Ingals' Velocity and Frequency Filtering of Seismic Data.

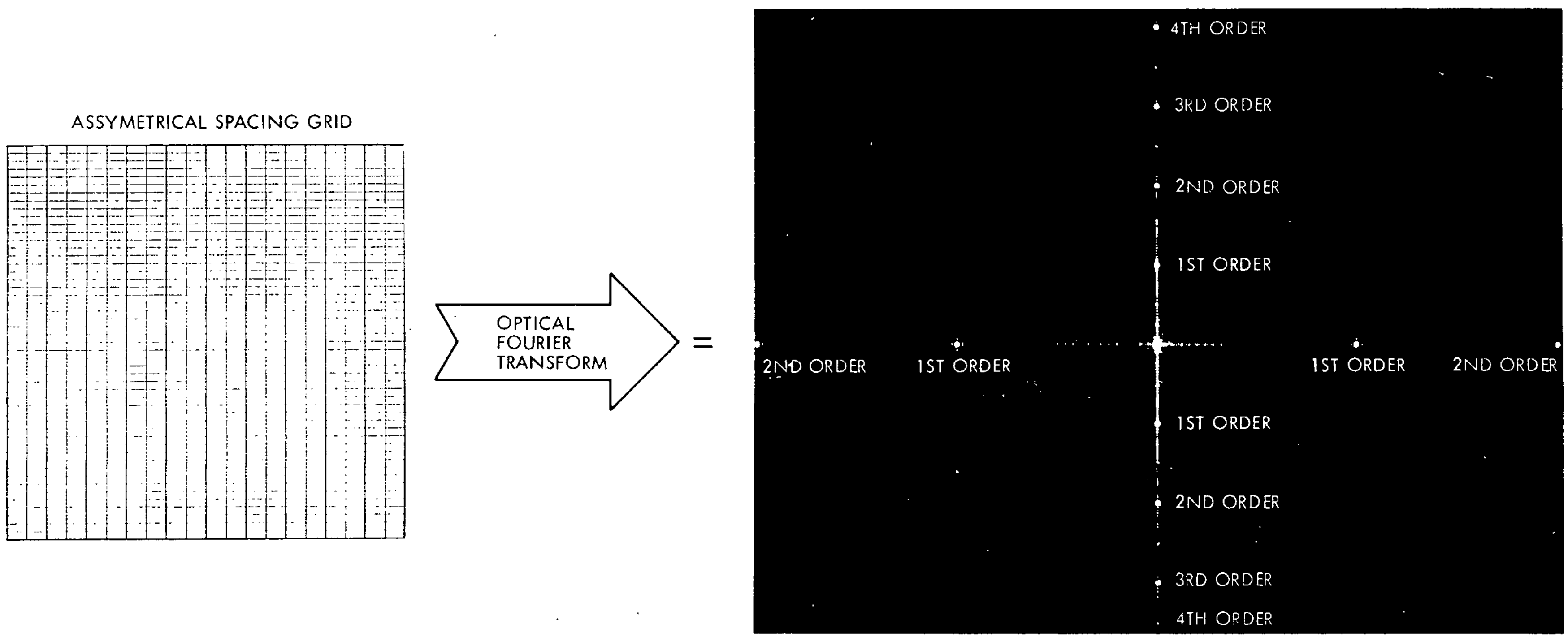

Figure 7-8. Example of Optical Transform

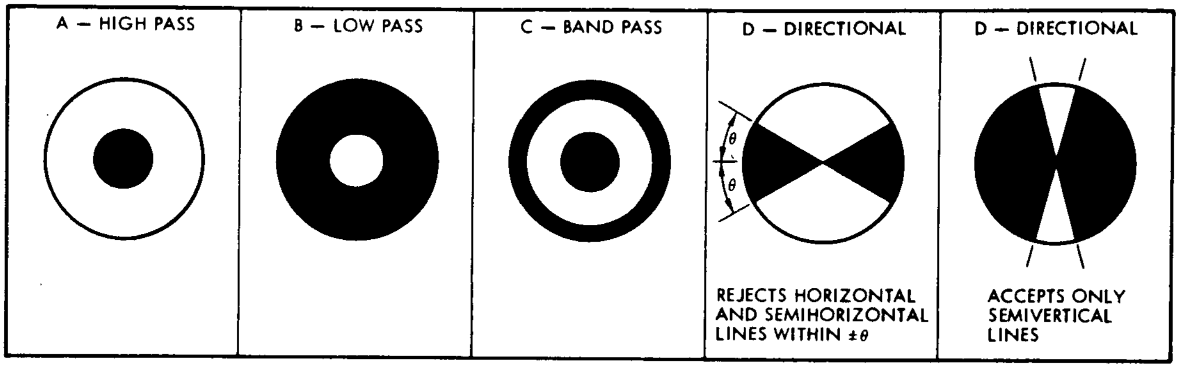

Figure 7-9. Typical Filters

Optical systems can perform a number of processing functions beyond simple spatial filtering. Examples are:

- Spectrum analysis
- Signal correlation and cross correlation
- Pulse shaping (compression/expansion)
- Pattern recognition
- Analog simulation
- Matched filtering
- Convolution

The optical spatial filtering and allied processing methods provide a potentially valuable fast technique for sifting large quantities of data. A key advantage lies in the basic holographic or whole scene nature of the process, as opposed to traditional electronic methods which are sequential.

7.5 Equipment Types and Modular Processing Functions

Figure 7-10 is an attempt to relate the limited set of equipments described in previous sections to the modular processing functions that they perform. In reviewing Figure 7-10, it is apparent that certain equipment types will perform more than a single function and that many functions are performed by more than one equipment type. This is, obviously, the essence of the overall system design problem and the basis for anticipating a number of unique and competing system concepts (a system concept being established when a number of the equipment types are selected, ordered, and possibly directly interconnected to process a prescribed flow of data).

Figure 7-10. Equipment Type Vs. Modular Functions

Equipment Types \ Modular Processing Functions	Preparation							Conversion				Basic					Interpretive											
	RESEAU	GNDCØN	SCREEN	GEØCAL	DEMØDE	ATTEPH	ARCHIV	SCANIM	RESCAN	A-TØ-D	D-TØ-A	GEØMCØ	PHØTØM	SPAFIL	ZØØMIN	TRANSF	SIGREC	CHADIS	GRIDIM	ANØTAT	MØSECT	ENHANC	CØNTUR	ADDCØL	CØLDIS	STATIS	SUBADD	SCALIM
Image Domain Conversion																												
Scanning Digitizer										1		2																
Electron Beam Recorder											1	2																
Laser Beam Recorder											1																	
Photo-Optical Devices																												
Automatic Map Maker	2			2								2											1					
Additive Color Viewer		1																2	2			2			1			2
Electro-Optical Devices																												
Video Image Analysis Station		1						1	2						2							1	2	1	1			2
MSS Data Analysis Station		1									1		2					2	2			2			1			2
Automatic Image Restituter	1			1						2		1	2															2
Optical Computing																												
Spatial Frequency Filter														1			1	2				2					2	

LEGEND: 1 - Primary Equipment Function
2 - Ancillary Function

The approach to modeling and simulation (Section 8.0) depends on a system-oriented description of the different equipment types (D/A converters, electron beam recorders, etc.) that varies depending on the different modular functions that each might perform. Each equipment type will be described by three basic sets of descriptors:

- throughout descriptors (volume/unit time, input/output formats, etc.)
- performance descriptors (measures of the quality of processing)
- interface/connector characteristics (i.e., required input/output media, number of channels, etc.)

These descriptors may vary for a given equipment type depending on the modular function that is to be represented (this might be viewed as switching a given device from one mode to another; i.e., a laser beam recorder being "switched" to function as a scanning digitizer.)

Of the above descriptors, those relating to performance or quality degradation are the more difficult to handle. Ideally, one seeks a criteria which has meaning to all of the modular functions and equipment types and includes well defined and relatively simple rules for deriving system performance from that of the subsystems. An overall rms (root mean square) measure meets the latter desire but is inadequate in dealing with the causes of poor fidelity and frequently fails to agree with intuition concerning the relative fidelity of images. A better approach is to use separate criteria for geometric fidelity, photometric fidelity, and resolution preservation. The latter can be accomplished practically by monitoring the spatial frequency response of system elements with a modulation transfer function (MTF) analysis, in which the overall system MTF is formed as the product of the element MTF's.

Geometric fidelity similarly can be reasonably characterized as an rms displacement error between system input and output. The system rms error then consists of the rss (root sum squared) of the errors of each element. Establishing a simple meaningful photometric fidelity criteria is perhaps most difficult of all. A tentative approach is taking the rms intensity uncertainty of each system element at high light and low light levels is probably adequate. Overall system performance, therefore, consists of computing the rss values of the individual elements for each level.

8.0 SYSTEM PERFORMANCE SIMULATION

The system performance simulation programs serve the purpose of providing a tool for the evaluation of data processing systems before a commitment to specific equipment has been made. The programs permit the interconnection of a chosen set of subsystems to provide a total system. The results of the simulation provide the information to monitor the throughput and the performance of the total system and each subsystem individually. Provision is made for evaluation of non-digital as well as digital subsystems. Man-in-the-loop operations are also included so that their impact upon the total throughput can be considered.

Two programs are provided to produce the systems simulations required for analysis of an earth resources ground data processing system. They are the Equipment Simulation Program (ESP) and the Computer System Simulation Program (COMPSIM). The former provides for simulation of a complete data processing center while the latter provides the detail simulation required for a modern complex digital computer. Both programs use the discrete event simulation library package, SALSIM, which provides the basic simulation capabilities required.

8.1 Simulation Technique

The system performance simulation programs use the SALSIM discrete event simulation package. This set of subroutines introduces a simulation capability to FORTRAN. It also eliminates the need for a special language and provides for unlimited expansion of capabilities by addition of new subroutines, called functional operators, as the requirement arises. Expansion of the capabilities of simulation languages is typically difficult, but addition of extra subroutines to SALSIM is made relatively easy through the functional operators.

Using a functional operator found in SALSIM, a programmer writes FORTRAN models of the equipment or process to be simulated. These models provide for a flow of activities and simulate all time delays encountered. Important statistics concerning the experiment or process is maintained and printed at the end of a simulation run. These statistics show the throughput, percent utilization, unit queues, and other data vital to the analysis of a system's capability to process a given workload.

SALSIM is currently operational on the 360/75 and is being used in the simulation programs described in the following two sections.

8.2 The Equipment Simulation Program

The Equipment Simulation Program was designed to provide a method for handling hybrid systems containing analog, digital, and man-in-the-loop elements in the overall ground processing system. The program uses SALSIM to simulate the movement of frames of data through a total system. It provides for the evaluation of any piece of equipment being considered in the ground data processing system. The program provides for input of both imagery and non-image data, or a combination of both, and simulates the processing of the data through devices selected by the user. The user also inputs all key parameters for each device, such as the delay time (mean and spread) required for an analyst to examine a picture and resolve if it is usable. Another possible input would be the probability that the picture, or a portion of the picture, will be rejected.

Input

The program inputs consist of three sets of cards:

1) Data Identification Cards. These three cards identify data as image, analog recorded, or digitally recorded. There must be one card for each type, even if there is no data of a given test type. The format is:

COL	CONTENTS
10	I = image data (i.e., photograph) A = analog recorded data D = digitally recorded data
15-20	Total number of frames of this type of data to be processed.
21-30	Time at which this data is to be introduced into the simulation.
31-40	Number of data points per frame (if digital)
48-50	Number for first piece of equipment to process this data. (See data flow cards.)

COL	CONTENTS
57-60	The total number of pieces of equipment used in first processing step.

2) Data Flow Cards. These cards tell the simulation the order in which frames of data flow through the various pieces of equipment. The format is:

COL	CONTENTS
1-5	Card number. All data flow cards are numbered 1-N. Each card represents an equipment station on man-assisted function in the total processing system.
13-16	The name of the device used by this step of the data reduction.
26-30	Next step card number. The next step to be used in the data reduction.
45-48	Normally blank. If this card represents the last step of the data reduction, this field contains an ENDb or FINI.

3) Equipment Parameter Cards. These cards contain the required parameters for each device. For example, the digitizing rate of an A-D converter, the probability of an on-line analyst rejecting a frame due to cloud cover, etc. The format is:

COL	CONTENTS
3-6	The name of this piece of equipment (same as col. 13-16 of the data flow cards). The last card contains ENDb in this field and all other fields are blank.
17-20	Total number of pieces of equipment of this type.
31-40 41-50 51-60 61-70	Parameters pertaining to operation of this piece of equipment. Parameters continue on the next card(s) in these fields (with col. 1-30 blank) until all required parameters are input.

The parameters to be used in these cards are currently being defined for all pieces of equipment described in Section 7.0, "Image Processing Equipment".

Output

The output of the Equipment Simulation Program consists of two lines of statistics for each type of equipment and each device of the same type given by the input parameter cards. The first line gives the equipment utilization for each equipment type. It contains:

1) Percent Utilization. The percent of the total simulation time during which the device is being used by a frame of data.
2) Total number of frames of data using the device.
3) The average time used by each frame.
4) A number identifying the user at the end of the run, if any.
5) The total number of interrupts which occurred, if the device is interruptable.

The second line gives statistics regarding the wait queues at each device:

1) The total number of frames which had to wait to be processed.
2) The total number of frames waiting to be processed at the end of the run.
3) The maximum number of frames waiting in the queue.
4) The average contents of the wait queue.
5) The average time per frame spent in the wait queue.

8.3 The Computer Simulation Program

Detail evaluation of complex, multiprocessing, multiprogrammable digital computers becomes difficult to accurately simulate by use of the Equipment Simulation Program. Other considerations play a key roll in the digital processing time required such as: executive overhead, program priorities, and possibly the sharing of computer(s) with other jobs not related to earth resources data reduction. To provide a detailed analysis of the highly interactive operation of a digital computer, COMPSIM is provided.

In order to simulate a given process on a particular computer, three things must be provided. First, input parameters describe the hardware configuration of the machine. The inputs define such things as device character transfer rates, the number of devices on a channel (if they are multiplexed), the CPU's cycle time, etc. The programs which perform the data processing are modeled by writing small FORTRAN subroutines which use the SALSIM functional operations to represent the delay operations which occur in the subroutine. These include such functions as read, write, and a process operator which represents the calculations and data manipulation involved. These program models tend to be short and easy to develop. Finally, the executive model must be written to represent the procedures used by the machine to schedule jobs and to route input/output messages.

Ongoing project work on this task is directed at developing detail descriptions of the input parameters and the procedures for modeling the executive and application programs including documentation of all of the required functional operators.

9.0 SYSTEM SYNTHESIS AND EVALUATION

This section is intended to provide insight into the method by which alternative ground processing concepts will be structured and the process of evaluation of these concepts. This particular area of study is yet to be initiated and, consequently, the discussion is brief and focuses on a proposed approach instead of study results.

Considering the diverse requirements of the various possible management programs and associated data products (Section 3.0), the number of modular processing functions (Section 5.0), and finally, the equipment alternatives (Section 7.0), it is clear that a number of distinctly different design concepts are possible. Consequently, a method is required to systematically generate and evaluate the possible concepts that offer some hope of being inclusive of all reasonable systems.

The approach to the problem of systematically identifying all viable system concepts and selecting a single best candidate is illustrated in Figure 9-1. This approach is as follows:

- step 1 - Utilizing the loading profiles developed in the user requirements analysis, select a minimum number of modular functions satisfying a specified number and mix of programs and management functions.
- step 2 - Define the realistic order or sequence of performing the modular functions (this may result in more than one sequence of functions).
- step 3 - Review the equipment types matrices illustrated in Section 7.5 and identify the equipment alternatives for each of the required modular functions.
- step 4 - For the sequences developed in step 2, generate candidate systems by alternatively considering the equipment types suitable for each modular function, according to several basic processing philosophies.

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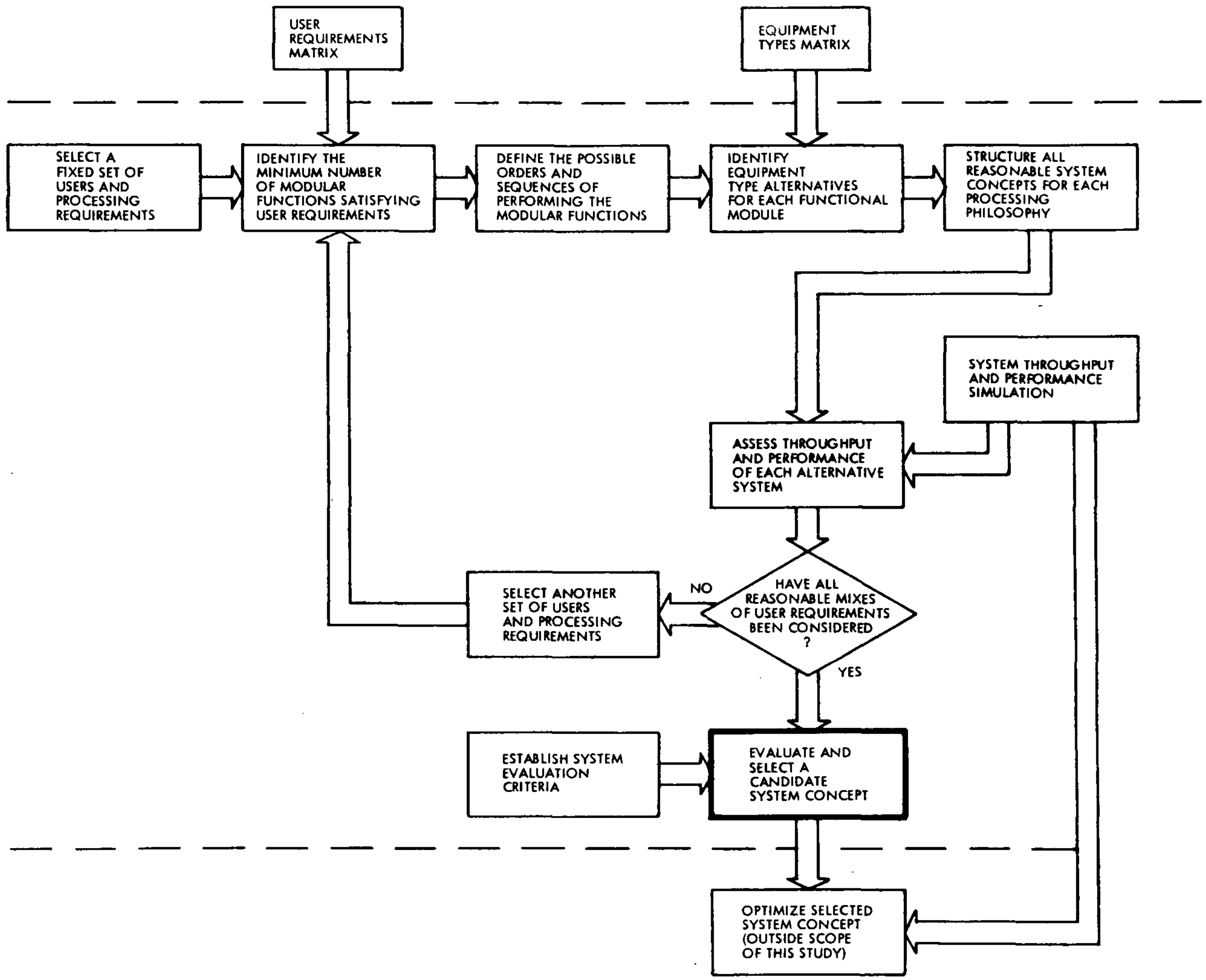

Figure 9-1. Methodology for System Synthesis, Evaluation, and Selection

step 5 - Using the system simulation described in Section 8.0, assess the throughput and performance of each alternative system against a volume workload representative of the user mix selected.

step 6 - Consider any other meaningful number and mix of users and return to step 1.

step 7 - After all viable candidate concepts have been established, evaluate each against predetermined evaluation criteria.

step 8 - Select a single most promising system concept.

A final step would be to refine and optimize the design of the selected concept. This process, again, would utilize the simulation tool and would consider a greater level of detail than previously.

It is clear that in practice the above method would not be as straightforward and as simple as it appears. The overall process is basically iterative in nature and will require a dependence on engineering judgement and experience. In particular, two areas are of special concern: the process of assigning equipment types by design philosophy and the establishment of evaluation criteria. These are discussed further.

By design philosophy, it is meant that a preference is postulated for one or more fundamental types of processing. Generally, this includes:

- photo-optical or photographic processing
- electro-optical processing
- electro-mechanical processing
- electronic analog processing
- digital processing
- a mix, or hybridization, of any of the above

Because the most general class of data inputs and outputs will include both photographs and magnetic tapes, it is not possible to consider a completely digital or completely analog system. Some means of going between the two will be required. If we limit ourselves, however, to the data manipulation functions, most processing can take place either entirely in the digital or entirely in the analog domain. However, efficiency suggests that the analog processors required are most efficiently controlled by digital computers and, therefore, in all probability, meaningful system configurations range from the all-digital to the hybrids in which processing is analog but control is digital.

The advantages of an all-digital approach in terms of flexibility, accuracy, and growth potential are well understood. Their disadvantage lies in the anticipated throughput limitations imposed by the serial nature in which computers operate and potentially in the necessary cost of equipment (microprogramming/hard logic approaches) and software development needed to overcome this difficulty. Thus, in synthesizing a primarily digital approach, it is necessary to focus on those techniques which minimize computational difficulty without sacrificing accuracy and flexibility. Hybrid systems are potentially faster than all-digital ones because parallel processing of many picture elements takes place. They suffer potentially, however, from inherent quality degradation, such as uncertain repeatability and grey scale reduction, which may or may not be injurious to the candidate application for which the data is intended. Consequently, when synthesizing hybrid systems, emphasis will be on those elements and techniques which minimize quality degradation whenever quality preservation is important.