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definition of the

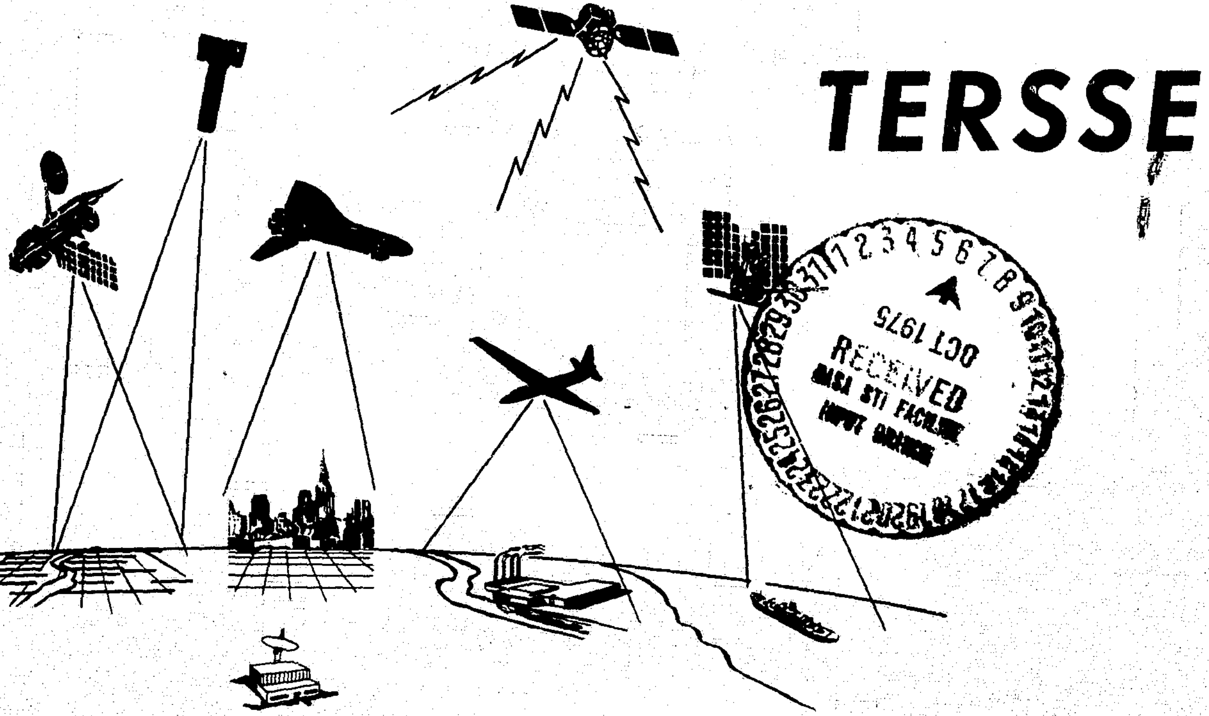
TOTAL EARTH RESOURCES SYSTEM

FOR THE

SHUTTLE ERA

VOLUME 2

AN ASSESSMENT OF THE CURRENT STATE-OF-THE-ART



GENERAL ELECTRIC

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TERSSE

DEFINITION OF THE
TOTAL EARTH RESOURCES SYSTEM
FOR THE
SHUTTLE ERA

VOLUME 2

AN ASSESSMENT OF THE CURRENT STATE-OF-THE-ART

PREPARED FOR

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PREFACE

The pressing need to survey and manage the earth's resources and environment, to better understand remotely sensible phenomena, to continue technological development, and to improve management systems are all elements of a future Earth Resources System. The Space Shuttle brings a new capability to Earth Resources Survey including direct observation by experienced earth scientists, quick reaction capability, spaceborne facilities for experimentation and sensor evaluation, and more effective means for launching and servicing long mission life space systems.

The Space Shuttle is, however, only one element in a complex system of data gathering, translation, distribution and utilization functions. While the Shuttle most decidedly has a role in the total Earth Resources Program, the central question is the form of the future Earth Resources system itself. It is only by analyzing this form and accounting for all elements of the system that the proper role of the Shuttle in it can be made visible.

This study, entitled TERSSE, Total Earth Resources System for the Shuttle Era, was established to investigate the form of this future Earth Resources System. Most of the constituent system elements of the future ER system and the key issues which concern the future ER program are both complex and interrelated in nature. The purpose of this study has been to investigate these items in the context of the total system utilizing a rigorous, comprehensive, systems oriented methodology.

The results of this study are reported in eight separate volumes plus an Executive Summary; their titles are:

Volume 1	Earth Resources Program Scope and Information Needs
Volume 2	An Assessment of the Current State-of-the-Art
Volume 3	Mission and System Requirements for the Total Earth Resources System
Volume 4	The Role of the Shuttle in the Earth Resources Program
Volume 5	Detailed System Requirements: Two Case Studies
Volume 6	An Early Shuttle Pallet Concept for the Earth Resources Program
Volume 7	User Models: A System Assessment
Volume 8	User's Mission and System Requirement Data

Executive Summary.

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SECTION 1

INTRODUCTION

Many studies have been performed in the recent past to assess current state-of-the-art (SOA) of various technologies and project it into the future. It was the specific intent of this study not to recreate these existing assessments, but to utilize them as basic study input. The objective of Task 2 was to pull existing study results together to develop a comprehensive state-of-the-art assessment of all technology areas which affect the Earth Resources Program.

The initial portion of Task 2 concentrated on extensive literature searches in the various technology areas. A significant amount of state-of-the-art assessment results were identified for spacecraft flight hardware, and sensors in particular. Broad data processing SOA assessments have received considerably less attention, although a wealth of papers exist on specific techniques and hardware. Major effort was required here to compile and comprehend data processing SOA. In the areas of distinguishing characteristics, user models and operations technology, no SOA assessments have been identified; in these areas, the study outputs are completely original work.

The volume is organized first to present a concise summary of the results of the SOA assessment (Section 2). The remaining sections provide supporting detail and are ordered by major elements in the Earth Resources system. Specifically, the section contents are:

- Section 2. Begins with a functional description of the basic Earth Resources system, then provides a concise SUMMARY of the significant conclusions of Task 2 by functional area with emphasis on the significance of these conclusions; identifies key areas requiring development and summarizes potential key issues derived from the state-of-the-art assessment.
- Section 3. Describes the state-of-the-art of DISTINGUISHING CHARACTERISTICS, including the radiance, and the temporal and spatial signatures which permit the discrimination of parameters in remotely-sensed data. Provides summary tables, descriptions of current activity and an extensive bibliography.
- Section 4. Describes the state-of-the-art of FLIGHT HARDWARE, including subsections on sensors, launch vehicles, attitude control, electrical power, on-board storage, on-board processing, and communications equipment, plus aircraft capabilities. Each subsection provides current and near-term state-of-the-art plus long-term implications where appropriate. Selected references are identified.
- Section 5. Describes DATA SYSTEMS state-of-the-art including preprocessing, extractive processing, storage, reproduction, and distribution. Hardware, algorithms and techniques are discussed. Summary descriptions are provided on both primary (e.g., ERTS, JSC) and secondary (e.g., LARS, ERIM) processing facilities.
- Section 6. Describes the state-of-the-art of USER MODELS; i.e., the models which convert remotely-sensed data into parameters useful to resource managers. Contains descriptions of seven models typical of the state-of-the-art plus references.
- Section 7. Describes OPERATIONS TECHNOLOGY state-of-the-art. Covers user interfaces, data processing production control and management, spacecraft and aircraft mission planning (scheduling), data retrieval, command and control, and system-level management. A potential key issue is identified.

- Appendix A. Contains comprehensive tables showing the applicability of the various distinguishing characteristics to the parameters required by the user discipline areas identified in Task 1.

- Appendix B. Describes methods of laser sensing of the atmosphere and oceans.

SECTION 2

SUMMARY

The objective of Task 2 is to provide a realistic, confident assessment of the state-of-the-art of all technologies affecting the Earth Resources program. The 1972-75 period is essentially the unchangeable near-term future which will serve as the basis for technology developments in the 1978-82 time frame. Task 2 was not intended to answer the many questions concerning the configuration, development, costs and timing of the Earth Resources program. Its primary objective is to assess the current state-of-the-art and determine those technologies which are lagging. In addition, there was a serious effort to gain insight into the overall workings of the program itself, such that this insight could be used in later tasks of the study where answers to the many program questions would be derived.

The methodology involved first an identification of the key elements in todays Earth Resources system and a breakdown of these elements into basic functional areas. The technological accomplishments in each of the functional areas was then determined and evaluated versus our understanding of eventual program needs or ultimate capability. The assessment has demonstrated that the major state-of-the-art problems in the near future are inaccuracies of radiometric measurements caused by atmospheric effects, a gross imbalance between sensor technology and all other parts of the Earth Resources system, and the almost total lack of developing operational applications of remotely-sensed data.

Following the state-of-the-art summary is a discussion on several of the system-level observations that grew out of the assessment effort. These observations in general involve the interrelationship of several of the technology areas.

At the end of this section is a discussion of the potential key issues derived from the state-of-the-art assessment. These key issues will be further developed and analyzed in later tasks.

2.1 <u>SUMMARY BY TECHNOLOGY AREA</u>

Initial efforts at assessing the state-of-the-art (SOA) encountered widely varying opinions of what constitues SOA and what SOA means to Earth resources. Research and Development (R&D) oriented personnel tend to view SOA as what has been demonstrated, either theoretically or in the laboratory. Operational people tend to view SOA as the newest item on the shelf, ready to be put into operational use. There are other views on SOA which are between these two extremes.

The progression from "theoretically possible" to "operational" is, however, representative of the orderly development of technology. Since one of the long-term goals of the Earth Resources program is to develop operational systems, depicting the SOA on a scale ranging from "theoretically possible" to "operational" not only resolves the question of what does SOA mean but provides an excellent way of showing the relative advancement of the specific technologies in question. Hence, six stages in the progression from "theoretically possible" to "operational" have been identified as shown in Figure 2-1. They are used throughout the detailed discussions later in this volume to identify SOA relative to this scale.

In general, progression down the scale implies there is a need for the technology in question, otherwise it wouldn't (or shouldn't) be developed. In addition, there is normally an increasing dollar investment as the technology develops.

It is interesting to note also that the R&D developer and the paid user (e.g., ERTS/EREP investigators) receive funds from the government to both aid in technology development and show its utility whereas the operational user pays into the system for a product from which he expects some economic benefit.

The SOA assessment has addressed all portions of the Earth Resources system. The vari[illegible] collection and processing functions have been grouped into five basic areas as illustrated in Figure 2-2:

1. Distinguishing Characteristics. The radiance, spatial and temporal characteristic which we desire to measure with remote sensors.

2. Flight Hardware. Primary emphasis on sensors but includes other platform-related functions which affect the ability to operate the sensor; i.e., power, attitude control and measurement, on-board data storage and processing, communications, launch vehicles and aircraft.

	EXAMPLES					
	NUCLEAR POWER		METEOROLOGICAL SATELLITES		MULTISPECTRAL ANALYSIS	
1. THEORETICALLY POSSIBLE	EINSTEIN	1905	RAND STUDY	1946	WRL	1960
2. FIRST EXPERIMENTAL DEMONSTRATION	FERMI	1942	TIROS 1	1960	WRL	1964
3. REGULAR EXPERIMENT	ARCO, IDAHO	1951	TIROS/NIMBUS	1961/66	LARS	1966
4. PROTOTYPE OPER/PROD.	CALDER HALL, ENGLAND	1956	ESSA 1	1966	ERTS	1972
5. INITIAL OPERATIONAL	SHIPPINGPORT, PA.	1957	ITOS 1	1970	IOS	1976
6. OPERATIONAL	USA	1960	ITOS/GOES	1974	IOS	1977

- DEFINITION OF SOA DEPENDS ON WHO YOU ARE!
- DEVELOPER AND USER SEE SOA DIFFERENTLY
- SOA ACHIEVEMENT DEPENDENT ON NEED AND $

Figure 2-1. State-of-the-Art Definition

3. Data Systems. Includes all those functions required to both preprocess (calibrate and correct) the data to recover the distinguishing characteristics and to extract from the characteristics those parameters of interest to users.

4. User Models. User models which convert parameters extracted from the remotely-sensed data into specific kinds of information directly useful to resource managers. These models may use ancillary data not supplied by the remote sensing systems. It is in user models that the interface between the remote sensing system and the user occurs.

5. Operations Technology. The collective set of functions required to make the Earth Resources System work. Includes the well known functions of command, control, orbit determination and telemetry processing as well as spacecraft and data processing facility scheduling and management, user services and overall system management.

2.1.1 DISTINGUISHING CHARACTERISTICS

- General Assessment. With the exception of spectral and spatial characteristics, primarily in the visible and near IR, the technology is in its infancy.

- Use of Multiple Characteristics. The imbalance between spectral/spatial and all other characteristics within the technology area is key since the use of combinations of characteristics over different parts of the electromagnetic spectrum (e.g., spectral with temporal or spatial/visible with scattering/microwave) holds great promise in the future to significantly improve the information yield from remotely-sensed data. Few studies have addressed this interdependence.

- Atmospheric Effects. Distinguishing characteristics development and measurement are being hampered by the effects of the intervening atmosphere.

2.1.2 FLIGHT HARDWARE

- General Assessment. Flight hardware state-of-the-art is well ahead of all other Earth Resources technology areas. The ability to gather data is far in advance of the capacity to process and utilize it.

- Sensors. No major breakthroughs or advances are foreseen in optics, scanning mechanisms or spectral separation mechanisms. Of all contributing technological areas, detector technology is the key which will permit improvements in sensor performance. A key factor in future sensor development will be to marry sensor technology to the particular needs for data.

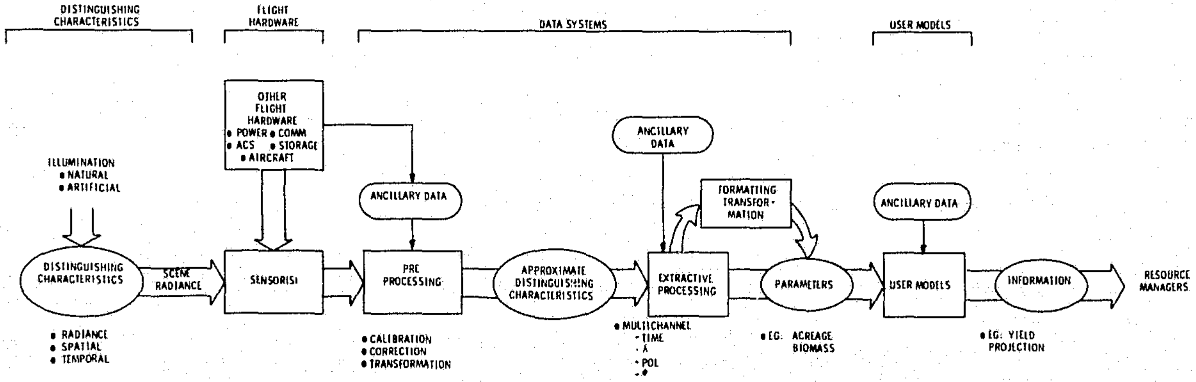

Figure 2-2. Earth Resources Data Collection and Processing - Scope of SOA Assessment

Radar requires special emphasis to understand the distinguishing characteristics in this portion of the spectrum, their relationship to other distinguishing characteristics, the users of this kind of data, and the processing techniques along with the sensor technology.

- Attitude Control and Electrical Power. Well developed technologies and are today sufficient to support the Earth Resources program throughout at least the next decade.

- Launch Vehicles. Conventional launch vehicles are a mature technology. Small (compared to shuttle) conventional launch vehicles generally justify a system optimization point involving small volume, low weight, low power, high cost, densely-packed instrumentation on spacecraft with few launch opportunities. Shuttle capability will require designing to a new system optimization point allowing major tradeoffs between volume, weight, power, cost, packing density and launch opportunities.

- On-board Processing. This is in its infancy. Many general-purpose processors are available and algorithm development is feasible. The questions of what data to process and how to process it have yet to be adequately addressed. Very high data rate processors require development.

- On-board Storage. Magnetic tape recorders will continue to predominate over the next ten years. When mass storage is needed, bubble memories, when fully developed, may be the only serious competition. Reliability of tape recorders continues to be a problem.

- Communications Technology. Well developed in S-band and rates to 60 Mbps are possible for Earth Resource missions. Higher rates require X- or K-band systems. Although the use of X-band or higher frequencies for Earth Resources data transmission is new, many of the components are already space-proven for other applications such as communications satellites. Development is underway on techniques and components required for transmission at rates up to 1000 Mbps. Communications is not a limiting technology.

- Aircraft. The aircraft hardware for data gathering is a mature technology. The use of aircraft will continue and expand as a key element in the Earth Resources program. Their effective use will require development of a command and control capability integrated with the rest of the Earth Resources system.

- Aircraft Data. This has been primarily on film in the past. Anticipated high-accuracy digital processing systems implies the use of digital electronic sensors with reduced emphasis on film.

2.1.3 DATA SYSTEMS - PREPROCESSING

- Atmospheric Effects. Radiometric measurements are now limited by atmospheric effects. Models of the atmosphere can enhance accuracy but may never be sufficient. Concurrent measurements with sounders/probes are required to accurately determine and correct for atmospheric effects. This is a key development area.

- Radiometric Calibration. Functions for line scanners and camera systems can be implemented today with either general-purpose or special-purpose machines in realtime in a production environment.

- Radiometric Accuracy on Film. Limited to 5-10% and is not sufficient for accurate multispectral analysis purposes.

- Geometric Correction. Geometric correction to sub-pixel accuracies is potentially achievable using ground control points. This accuracy is not currently achievable using other techniques because of ephemeris uncertainties.

- Correction of All Data. Correction of all data to the same absolute reference grid appears to be the only technique which will assure effective use of all distinguishing characteristics during extractive processing.

- Speed and Accuracy. Speed and accuracy during the rectification or rubber sheet stretching function is the limitation on the correction of all data to an absolute reference grid. Present state-of-the-art requires the rectification function to be implemented on special purpose hardware for production systems. All other geometric correction functions can be performed on a general-purpose machine and are not technology limiting.

2.1.4 DATA SYSTEMS - EXTRACTIVE PROCESSING

- Feature Selection. Feature selection has been concentrated in the visible and near IR, primarily spectral analysis. Spatial and temporal techniques are lagging. Spatial feature extraction requires considerable computation time; special-purpose hardware now in development should be available by 1975.
- Feature Reduction. Maximum likelihood techniques are well into development. Estimation techniques are relatively undeveloped.
- Feature Classification/Estimation. Classification algorithms and well-developed and special-purpose hardware permits classification at near realtime rates. Estimation techniques are relatively undeveloped. Training the classifiers is currently the most time consuming function.
- General Questions. General questions are what characteristics are to be processed and what parameters needed for resource management are desired as outputs? These are fundamental questions which must be addressed.
- Digital Processing. Digital processing using combinations of general-purpose machines and special-purpose hardware appears to be the near-term solution to todays data processing speed and accuracy problems.
- Parallel Processing. Parallel processing, both optical and electronic digital, is the long-term solution for both on-board and ground data processing.
- Data Storage Need. Data storage need in the Earth Resources system is for a new standard high density, ready access storage medium which is computer compatible. Current mass storage systems have long (tens of seconds) access times and are not universally available. Advanced magnetic and optical techniques are in development.
- Data Transformation/Reproduction. Hardware and technique state-of-the-art is well developed. The major question is what array of products are needed for operational use? Expect continued need for film, increase in the need for other (digital tapes, maps of many varieties, statistics, listings, etc.) products.
- Distribution. Distribution of original data is slow and cheap or fast and expensive. Timely bulk transfer of data between centers needs investigation; timely delivery to users of only necessary information as opposed to masses of data, is an important development area.

2.1.5 USER MODELS

- User Models. User models are the translater between the remote sensing system which acquires the data and the resource managers who use it.
- Operational Models. Used in many resource management areas, however, few models use remotely-sensed data as inputs.
- ERTS-1 Investigations. Not concentrating on model development.
- Current Model Development. Involves resource specialists with no remote sensing systems orientation. In addition, remote sensing people are not heavily involved in model development - NASA effort is of relatively high quality but minor in scale.

- Operational Model Development. A significantly lagging technology.

2.1.6 OPERATIONS TECHNOLOGY

- Hardware/Software. Not technology limiting.
- Major Technology Advance. Needed in concepts, philosophy and approach to the operation and management of large multi-element Earth Resources systems. Development effort is currently non-existent.

2.2 SOME SYSTEM LEVEL OBSERVATIONS

Throughout the state-of-the-art assessment an awareness was maintained for significant interrelationships between system elements which have either affected Earth Resources technological development in the past or may influence the development of the system in the future. Of particular interest was the gleaning of insights pertinent to the definition of system requirements for the total Earth Resources system of the future. The following paragraphs summarize the more important of these insights.

2.2.1 INTERRELATIONSHIP OF SYSTEM ELEMENTS

The most significant observation is that of the fundamental interrelationship between distinguishing characteristics, sensors, data processing and user models in the Earth Resources system. The need to perform a particular resource management task creates a need for input information. Where this information is to be obtained from remotely-sensed data, the needs must be related to parameters directly or via a user model. As Figure 2-2 shows, parameters (e.g., acreage) are an output of extractive processing, while information (e.g., yield projection) is an output of user model. The parameters in turn define the distinguishing characteristics which must be measured by the remote sensing system in order to successfully perform the resource management task. The distinguishing characteristics influence the choice of sensors which make the measurements. The output of the sensors are inputs to the data system which closes the loop by reducing the data and extracting the parameters to be used as inputs to the user models. The development of the Earth Resources system must insure uniform and coordinated progress in all these areas since it is apparent that lagging technology in any one area will seriously impede the progress of the entire system.

Historically, the Earth Resources program has been driven by sensor development with the objective of demonstrating that a given sensor can measure certain types of distinguishing characteristics. Relatively smaller emphasis has been given to the employment of these sensed characteristics operationally in the performance of resource management tasks. The program has been spearheaded by sensor development and not by the real needs of the resource managers, resulting in the program being at a point today where:

1. There exists a wealth of sensors which can collect great quantities of data.
2. The data system is not sufficiently advanced to process all the data that can be collected.
3. The users are even less advanced in that only a limited understanding exists as to just how to utilize the data. This is emphasized by the almost total lack of user models and the limited work to date on distinguishing characteristics.

Several possible paths of action over the next several years include:

1. More emphasis on expanded or new processing systems.
2. A major effort on research in the entire area of distinguishing characteristics.
3. A major effort to develop user models and operational procedures for applications of the data to operational problems.
4. Less emphasis on sensor development.

It is important to note that these are not necessarily mutually exclusive alternatives.

An interesting parallel can be drawn between the Earth Resources system and the historical development of the meteorological program. The meteorological program is not unlike the Earth Resources program in that it also requires measurements of characteristics by remote sensors, data processing, and modeling. The capsule history, given in Table 2-1, shows that as one major problem area was solved by a technology advance, the program expanded until limited by another problem which then impeded the entire program. The problem areas and technology advances involved all parts of the system, sensors, spacecraft, data processing and modeling, at one time or another.

Table 2-1. Capsule History of the Meteorological Program

Time Period	Technology Advance	Problem Area
• Prior to WW II	Hydrodynamics applied to atmosphere	Data severely lacking
• During WW II	Surface and upper air observations expanded	Data couldn't be assembled and processed in timely manner
• In '50's	Digital computers became available	Data sparse areas limit forecasts
• In early 60's	Satellites begin to fill data voids	Models inadequate to accommodate available data.
• In early 70's	Sophisticated global atmospheric models developed. Satellites begin to provide full global quantitative data.	Inadequate operational computers

Radiometric errors caused by atmospheric effects is a major problem area in the Earth Resources system. Atmospheric effects limit the ability to accurately determine the distinguishing characteristics of scenes sensed from high altitude aircraft and spacecraft which in turn impede research in the distinguishing characteristics area. Even more important is the fact that atmospheric effects also limit the radiometric accuracy of the corrected and calibrated data resulting from preprocessing which in turn limits the accuracies which can be obtained from extractive processing. This has a direct effect on the ability of the processing system to identify, classify and derive accurate parameters from the sensed data. Current technology suggests that atmospheric models may never be accurate enough to predict atmospheric effects and that measurements of the atmospheric will have to be made concurrently with operation of the Earth Resources data sensors.

2.2.2 EFFECTIVE UTILIZATION OF THE DATA

The state-of-the-art in the collection and processing functions permits a glut of data to pour out of today's Earth Resources system. Today's system, however, effectively stops at the output of the preprocessing (correction and calibration) function. Examples of today's system are the ERTS NDPF, the Sioux Falls Data Center, and EREP processing at JSC. Each of these facilities produce images and magnetic tape, i.e., data; they produce almost no information directly useful in a resource management task. Since resource managers are generally not aerospace or even remote-sensing oriented, the effective utilization of the data will be seriously impeded until the gap between data from preprocessing and resource management information is bridged. The bridge involves extractive processing (data converted to parameters), user models (parameters converted to information), and operations technology (the managment of the system which extracts varied information from masses of source data for a multiplicity of users).

The development of this bridge must integrally consider the:

- Information needed for the resource management tasks.
- Extractive processing algorithms which will supply the parameters.
- Availability of extractive processing equipment both for internal system and user utilization.
- User models which convert the parameters to information.
- Cost and timeliness of the above.
- Understanding and skill levels of the people involved, especially the resource managers who may be unfamiliar with the remote sensing system.

Until the above are systematically developed, the effective utilization of the data will be severely hampered.

On-board processing will affect the overall concept and configuration of the system. On-board processing has the potential to at least reduce data rates, making possible the direct transmission of either raw or preprocessed data to low-cost local ground stations. The Earth Observatory Satellite, to be launched in 1978/79, may be the first spacecraft to utilize on-board processing to reduce data rates. On-board processing has further potential to permit direct readout of either parameters or information to local stations which in turn can be used with minimum additional computation directly in resource management tasks.

In either case, the inclusion of on-board processing function will greatly influence the configuration of the ground systems. It permits the ground system to be distributed and local whereas the lack of on-board processing requires the use of a limited number of large central facilities. There appears to be at least a gross relationship between the on-board processing functions performed, the transmission data rates and the complexity, cost and distribution of ground stations. This relationship is illustrated in Table 2-2.

Table 2-2. Effects of On-Board Processing on Ground Station Complexity

Type of On-Board Processing	Data Rate	Potential Ground Station
None	High - Transmit all data	Few large complex central stations which process all data.
Reduced data rates	Lower - Transmit all or selected data	Limited number of lower cost ground stations - perhaps regional.
Preprocess all data	High - Transmit all data	Few large central stations with reduced complexity (no correction or calibration functions required).
	Lower - Transmit selected data	Limited number of lower cost ground stations with reduced complexity (no correction or calibration processing functions required).
Selective extractive processing	Lower Still - transmit selected parameters	Large number of low cost stations with minimum processing capability. Processing consists primarily of user model implementation.

The Titan series of launch vehicles are a very strong competitor to the Shuttle for unmanned Earth Resources missions, at least into the early 1980's. Its payload capabilities exceed those postulated for all spacecraft launches in the Earth Resources program during this time period. Its shroud diameter and payload-to-orbit capability are sufficient to launch spacecraft carrying the largest and heaviest postulated sensors (e.g., side-look radar: 27 foot antenna, 144 cubic foot; thematic mapper: 600 pounds; pollution monitoring package: 600 pounds; SEOS sensor package: 1144 pounds). This, coupled with the unavailability of Shuttle polar launch facilities and the Tug until 1983, implies that the Titan series will be the primary large launch vehicle for unmanned Earth Resources satellites at least until 1983.

The "heavy lift" capability of the Titan also suggests that the Shuttle advantages in the area of relaxed weight and volume constraints can be applied to Earth Resources satellites which are non-Shuttle launched. The Shuttle, in the unmanned area, may bring to the Earth Resources program a gross change in scale in launch capability but not necessarily any breakthroughs.

TDRS current design recommendations from the Phase B studies is for a 25 Mbps data rate at K-band. With this data rate, the relay satellite, planned for launch in 1978/79, is sufficient to support Earth Resources missions based on 1972 data gathering technology, i.e., ERTS at 15 Mbps. The ERTS technology is expected to be utilized in initial operational satellites in the 1977-78 time period; hence, there is consistency with the TDRS design. However, 1978 collection technology, typified by EOS, has data rates currently planned in the 200 Mbps range which is totally inconsistent with the vintage 1979 TDRS capability.

2.3 POTENTIAL KEY ISSUES

A key issue is a theme which cuts across many program elements and which impacts the form, growth rate, and direction of the Earth Resources program. They may be intuitively obvious, especially after they have been discerned and described, or they may be difficult to describe quantitatively and to isolate from the system situation which surrounds them. They can be identified anywhere in the study; Task 5 has been specifically created to define and analyze the key issues in appropriate depth.

The following are the potential key issues which have been identified during the Task 2 state-of-the-art assessment:

2.3.1 VALUE OF DATA

Value of data is related to the time interval between event and availability to the user in a useful form. The management of resources is a dynamic process; hence, the information used in this process must be current with respect to the task at hand. "Current" in the Earth Resources program can, depending on the task, mean anything from hours to months between the event observation and the utilization of the data. In general, the utility or value of the data decreases as this interval increases.

The need for timely data has been widely recognized and was reinforced in the Task 2 effort during evaluation of today's state-of-the-art in distribution systems. The ERTS system, with time between event occurrence and data delivery on the order of 30 to 60 days, represents today's technology.

Concurrent analysis in Task 1 demonstrated that there are many potential users who require data with time intervals of between 1 and 30 days.

Where data is not delivered within the necessary time frame the following consequences are likely to occur.

- The application may never even develop.
- R&D in that resource management area will be slowed.
- The coordination of ground measurements or verification becomes difficult or impossible.
- The difference between feasible and practical may be difficult to show.
- The operational utility of the application cannot be effectively demonstrated.

Timeliness of data has been identified as a potential key issue because the design; and, hence the cost of the total system is directly influenced by the timeliness requirements. For example, areas affected are:

- Scheduling of flight systems to acquire the data.
- Storage and communications/data return delays.
- Data processing and analysis throughput rates and delays.

- Preparation of information in useful formats.
- Delivery times from processing facility to user.
- The readiness and ability of the user to utilize the data.

2.3.2 DATA PROCESSING COST IS A KEY FACTOR IN SENSOR SELECTION

The interrelationship of distinguishing characteristics, sensors, data systems, and user models was discussed earlier. It is clear that no one part of the Earth Resources system can be independently developed without considering its effects on all other portions of the system. This is especially true in the area of sensors and data systems, the two most expensive and currently better-developed areas in the system. The design of the data system, in particular the preprocessing portion, is heavily dependent on the structure and content of the incoming data. Preprocessing includes radiometric correction of the data which removes the effects of sensor banding, quantization, shading, gain and offset, plus applies pre- and in-flight calibration. Preprocessing also includes geometric correction which removes the effects of sensor non-linearities, scan effects, misregistration and projection. Hence, the techniques to be employed, and therefore the cost of the processing system, are dependent on the sensor data to be processed. This has been identified as a potential key issue because:

- The ability to accurately reproduce the distinguishing characteristics of the scene for use by the rest of the system is directly a function of the capabilities of the sensor and preprocessing elements.
- Sensors and data processing facilities are high cost items in the Earth Resources system.
- The influence of data processing on sensor selection has been largely ignored in the past.

2.3.3 MULTI-SENSOR DATA CORRELATION

The evaluation of distinguishing characteristics state-of-the-art identified the multiple use of characteristics (e.g., spatial/visible with scattering/microwave) as potentially the most promising area for information extraction. In order to do this, however, one must be able to correlate the data taken at different times from the various sensors on a pixel-by-pixel basis. This correlation occurs in extractive processing. This means that all elements in the system up to and including extractive processing must obtain and manipulate data in formats such that correlation can be maintained. Areas affected include:

- Registration between spectral bands within a sensor.
- Time correlation of data between sensors.
- Attitude and ephemeris accuracies to permit proper geometric corrections.
- On-board and ground storage devices.
- Geometric and radiometric preprocessing hardware and algorithms.
- Extractive processing hardware and algorithms.

The large number of system elements affected plus the depth which must be considered in each of these elements (every implementation technique) makes this a potential key issue.

2.3.4 DEVELOPMENT OF RADAR SENSING TECHNOLOGY

The state-of-the-art assessment has demonstrated that of all sensing technology areas, radar systems are least understood in terms of distinguishing characteristics that should be measured, correlation with other distinguishing characteristics, sensor design, missions to fly, extractive processing techniques to use, and readiness of the users to accept and utilize the data. To date, the advantages of radar have been discussed largely in terms of its all weather capability. It appears however, from the comparatively limited research done in the distinguishing characteristics area, that radar sensing technology has the potential to be a major contributor to the multi-spectral sensing of the Earth in its own right, just as is multi-spectral IR sensing technology. The potential benefits plus the major additional efforts required to realize these benefits make radar sensing technology a potential key issue.

2.3.5 MANAGEMENT OF MULTI-ELEMENT SYSTEMS

Between 1975 and the mid 1980's, a major change will occur in the Earth Resources program in that every element will be multiplied both in size and complexity. Where today we have only one unmanned and one manned satellite in orbit, in the early to mid-eighties there may be EOS, IOS, SEOS, and Shuttle sorties. The number of Earth Resources aircraft will increase. There will be additional ground facilities, both domestic and international. Activities will be carried out on the federal, regional, state and local levels. There will also be a dramatic increase in the number of users.

The major question which must be addressed is: how to manage this complex, multi-element system? The state-of-the-art assessment has demonstrated that today's operations technology is not adequate to perform this management task. Even more important is the fact that almost no development effort is being expended in the operations technology area. The magnitude of the management task plus today's lack of emphasis require the operations technology area to be identified as a potential key issue.

SECTION 3

DISTINGUISHING CHARACTERISTICS

In examining the body of technology which constitutes the state-of-the-art for the total Earth Resources system, first consideration must be given to the characteristics of the resources of interest which permit the system to obtain useful information about them. These resource "signatures," or distinguishing characteristics, are the sensible properties of the resources which permit discrimination among, or quantification of, such resource parameters as species, acreage, or quality.

Distinguishing characteristics include sensible properties which permit discrimination in several diminsions: radiance, spatial properties, and time. In the process of obtaining information from raw Earth resources data, the distinguishing characteristics play a dominant role in the end-to-end definition of the system - from the selection and operation of sensors to the processing and distribution of the final system data.

In assessing the current state-of-the-art, distinguishing characteristics have been subdivided into six subclasses reflecting the focus of research groups involved in distinguishing characteristics and signature research to date. These subclasses are spectral signatures, spatial signatures, temporal-spectral signatures, polarization signatures, multiaspect-spectral signatures, and scattering cross section signatures. Obviously, some of these areas are interdependent, e.g., polarization signatures and spectral signatures, but few studies to date have fully addressed this interdependence.

The state-of-the-art for the six subclasses is summarized in Table 3-1. One additional entry is included at the end of the table and is the use of multiple types of distinguishing characteristics in the discrimination process. This area has been largely unexplored but shows great promise and is included here to emphasize its importance.

Distinguishing characteristics research has, to some extent, fused the characteristics of the parameters being sensed with the effects of the atmosphere and/or water through which a sensor must look to make basic measurements. To illustrate this point, sea surface temperatures may be estimated by single band radiance measurements in the thermal IR. Even by selecting optimum spectral regions, however, the effects of intervening atmosphere on temperature are too large to be ignored. Distinguishing characteristics research then turned to multispectral thermal IR signatures as a means of compensating for unknown atmospheric effects Ref. 1].

Table 3-1. Distinguishing Characteristics State-of-the-Art

Characteristics	State-of-the-Art
Spectral	
Visible	3-6
Near IR	2-3
Thermal IR	2-3
Microwave	2
Spatial	2-6
Temporal	2-3
Polarization	1-2
Multiaspect	1
Scattering	2
Use of Multiple Types	1

Work on distinguishing characteristics has generally followed two courses - the empirical approach and the signature studies or modeling approach. As an example of the former, there have been a number of studies where the investigator has stated, "I can discriminate corn from wheat on color IR photography." Something about the spectral-spatial-temporal signature of corn and wheat, as registered by the film, allowed him to discriminate. Proper detective work is then required. By contrast, the signature studies approach is exemplified by, "The spectral reflectance of corn canopy and wheat canopy differ enough in the green-red-near IR region that I can discriminate them with a three band sensor operating in this region."

Several criteria were used in evaluating the state-of-the-art of distinguishing characteristics. First, had basic laboratory measurements been performed? Second, had a modeling structure been evolved to relate the laboratory measurements of scene components to what might be logically viewed by the remote sensing data collector? Third, had empirical or theoretical attempts been made to verify these distinguishing characteristics? Using these criteria, a detailed review of the state-of-the-art was performed for each parameter of the list developed in Task 1. The results are included as Appendix A. The information is organized by discipline and numbered according to which information type and parameter is assessed. A four level rating system is used:

1. Characteristic contributes directly to the assessment of the parameter. Documented evidence of some feasibility.
2. Characteristic is useful only in a supporting way to the assessment of the parameter. Other measurements required to obtain a complete picture.
3. No documented evidence of the study or use of this characteristic to assess this particular parameter. Use of this characteristic cannot be rejected on theoretical grounds.
4. Characteristic not useful in assessing the parameter.

Thus, the state-of-the-art in distinguishing characteristics is relatively advanced if many levels 1 or 2 occur in a particular row of the charts. Level 3 indicates a relatively immature state-of-the-art.

Similarly, the status of work on distinguishing characteristics in a particular discipline can be assessed by how many parameters have levels 1 or 2, as opposed to level 3. It is from these lists that the statements in the state-of-the-art summary of Table 3-1 were derived. The remainder of this section elaborates on the summary with reference to some of the more important work going on today.

3.1 SPECTRAL DISTINGUISHING CHARACTERISTICS

This area of research is relatively mature with empirical work having been complemented by signature and model studies. Extensive empirical studies with photography and, to a lesser extent, with multispectral scanners have been conducted. A number of laboratory and field measurements of particular crops and rocks have been made. Some modeling efforts for crop canopy reflectance are being conducted. Visible and UV signatures for some atmospheric pollutants have been obtained.

Much of the empirical photointerpretation work in the visible and near infrared has been summarized in various journals [Refs. 2, 3, 4, 5]. No attempt to be detailed about this great bulk of work will be made for this report. Some investigators [e. g., Refs. 6, 7] have delineated the physical or radiometric basis for discrimination of categories on film.

In the scanner area many empirical signature studies are being conducted in agronomy [Refs. 8, 9, 10] using airborne scanner data. Applications to forestry, geology, hydrology, geography have also been discussed in general References 4 and 5. Environmental quality empirical studies have also been summarized [Ref. 11]. Oceanographic empirical studies have also been reported in general References 4 and 5.

The status of laboratory and field measurements of terrestrial targets is well-summarized in References 12, 13, and 14. For this data bank, nearly all known sources of information were canvassed. Questionable laboratory or field measurements were omitted from the library. The library shows heavy concentration on vegetation and rock spectra which has characterized the laboratory and field measurement program. Measurements on soils and water of various quality are needed.

The spectra of a number of atmospheric pollutants have been measured for many years. Some operational systems using spectrum matching to detect and measure these pollutants (e. g., LOPAIR) have been constructed.

Fewer empirical studies than in the visible have been carried out because of the need for scanner data to cover the entire range. (Color IR film has sensitivity out to only 1.1 μm - the near IR range extends from 1-2.6 μm.) Laboratory and field measurements of crops and crop components and rocks have been made to 2.6 μm, although the number of near IR measurements is less than for the visible. Models for crop canopy reflectance can be extended to the near IR region from the visible.

There have been some visible-near IR crop canopy models constructed to relate the basic laboratory measurements of leaf spectra to the crop canopy which the scanner views [Ref. 15]. Other models for grassland reflectance have been derived from the Suits model. In the water quality area, models for the reflectance of water containing different amounts of suspended sediment have been constructed [Ref. 16].

In the thermal region, much of the laboratory measurements, empirical work, and modeling have been done in the disciplines of geology, air environmental quality, and oceanography (sea surface temperature). The basic emissivity spectra of silicate materials has been measured in the laboratory [Ref. 17] and the field [Ref. 18]. Work on models relating the reststrahlen spectra of rocks (as viewed by a field radiometer or scanner) has begun [Refs. 19, 20]. Empirical measurements of rock emissivity structure in the thermal region (8-14 μm) has been reported [Ref. 21].

In oceanography, the use of multiple channels of thermal data to more accurately measure sea surface temperatures has been studied and modeled [Ref. 1].

The passive microwave area has been largely unexploited, perhaps because of the relative lack of equipment for measurements and of human intuition about microwave spectral signatures. The Fresnel theory is well established (relating reflectance and emission to properties of the medium) but has not been extensively applied. There have been empirical studies relating the microwave brightness temperature to the water content of snow [Ref. 22] and in relating microwave brightness temperature to water salinity [Ref. 23] .

Field measurements of the microwave spectra of moist soil, sea ice and the ocean surface have been presented by various investigators [Refs. 24, 25, 26, 26A] . In the Eighth Symposium on Remote Sensing of the Environment, papers were presented by German [Ref. 26B] and Russian [Ref. 26C] investigators on the microwave properties of terrain types.

In the modeling area of signatures for the microwave region, a model for the brightness temperature of the ocean under different wave states has been discussed [Ref. 26D] .

3.2 SPATIAL DISTINGUISHING CHARACTERISTICS

The large spread in state-of-the-art is between the photointerpretation empirical studies and optical character recognition, where texture and/or shape are used routinely in analysis, to level 2-3 for machine processing low contrast scanner data. The discrepancy in state-of-the-art is in part caused by the difficulty of implementing many of the algorithms on computers and in extraction of suitable features.

A large number of empirical photointerpretation studies have been done using texture and shape as keys and are reported in general Reference 2-5. Similarly, optical character recognition techniques have been established [Ref. 27] . In the latter, spatial processing of a binary scene (black-white) consisting of constrained shape, alphanumeric characters is used operationally.

In the earth resources area, some empirical studies have been done with photos and scanner data and coherent optical data processing (spatial filtering). Attempts to do similar processing with scanned photographic (or scanner) data in computers have run into limitations of speed and cost in implementing the fast Fourier transform. Some texture and shape empirical studies have been done with scanner data.

There have been applications of optical data processing to the automatic extraction of linear structures in geology [Ref. 28] and to studies of wave refraction and wavelength change (as a result of shallow water [Ref. 29]). Within the SR&T program, Haralick has used some texture features to classify data [Ref. 30] . Two investigators within the ERTS program are known to be working with machine-implemented spatial pattern recognition [Refs. 31, 32] . Shapes of ponds are being automatically calculated from airborne scanner data in a program addressing waterfowl management [Ref. 33] .

Modeling and laboratory signature measurement work have been done for a few cases of wave refraction and ocean sea state but not enough of this work has been done in general.

3.3 TEMPORAL DISTINGUISHING CHARACTERISTICS

Photointerpreters have conducted multitemporal photos surveys. The results of these empirical studies are reported in References 2 through 6. The general conclusion is that for vegetation mapping, the use of temporal information can improve the accuracy of photointerpretation classification.

In the scanner area, there have been attempts made to use or explore the utility of temporal information for crop surveys [Refs. 34, 35] . The multitemporal thermal signature has been found useful in mapping rock types by deducing thermal inertia, and from that deducing rock type [Ref. 36] . Attempts to do further experiments with scanner data have been hindered by the relative difficulty of overlay of two or more data sets collected at different times.

In the thermal region, temporal signature models have been developed to a useful state for predicting the temporal variation of target temperature [Refs. 36, 37] . Some crop calendars have been constructed for multitemporal agronomic signatures, but the work has not progressed far enough. Basic measurements to characterize temporal signatures seem to be lacking. In the ERTS program, there is at least one experiment looking at the temporal signature for vegetation (phenology) [Ref. 38] .

The periodic coverage of the ERTS-1 satellite should foster more temporal signature studies because repetitive data are routinely collected. The data are more easily overlaid than the airborne scanner data since ERTS is a relatively more stable platform.

3.4 POLARIZATION SIGNATURES

Work in this area has been rather limited in the visible to near-infrared region of the spectrum. Most empirical work has been done in the microwave region of the spectrum and associated with radar and scatterometry work. The photographic experiments have generally been concerned with haze or water penetration.

In the visible region, an empirical study of the relationship between polarization of reflected radiation and soil moisture has been reported [Ref. 39] . Theoretical studies of the polarization of reflected energy from surfaces [Ref. 40] and of emitted energy from rock samples [Ref. 41] have been made.

There have been few measurements of the polarizing properties of materials in the laboratory or field. The soil moisture measurements are a notable example. Goniometers now operational at ERIM are capable of making polarization measurements of samples at selected wavelengths from visible through thermal IR. A number of such measurements have been made [Ref. 42] .

As part of microwave scatterometry and radar measurements, data are usually taken at cross and like polarization [e. g., Ref. 43] . Agricultural crops have been measured this way. Also empirical experiments relating like and cross polarized returns to sea state have been conducted [Ref. 44] .

3.5 MULTIASPECT SPECTRAL SIGNATURES

Since little work has been done in this area, there are no specific references to empirical results. The basis for multiaspect spectral signatures is in the bidirectional reflectance variations of certain materials. Such bidirectional reflectance variations can be measured in the field, or in the laboratory with a goniometer. While the bidirectional reflectances of many materials have been measured [Ref. 42] , there needs to be more analysis of the data and more measurements made to establish a good theoretical basis for multiaspect spectral signatures.

Recently, the ERIM multispectral scanner has been modified to collect multiaspect data over the visible, near infrared, and thermal regions of the spectrum [Ref. 45] . Some data have been collected with this instrument at two different view angles - nadir and looking forward at 45 degrees and these data are currently being processed.

3.6 SCATTERING DISTINGUISHING CHARACTERISTICS

Practically all the scattering work done to date has been restricted to the microwave region of the spectrum. With the coming of optical laser scanner systems (optical radar systems), there may shortly be some results in the optical portion of the spectrum. The scattering signature of agricultural crops has been measured on the ground in the 4-8 GHz range [Ref. 46] , and agricultural crops classified using like and cross polarized radar data [Ref. 47] . An experiment to detect oil slicks on the ocean using a dual polarized 13.3 GHz radar scatterometer, and in so doing obtain some knowledge of the scattering signature of oil on water, was discussed by Krishen [Ref. 44] . With the advent of the X-L band dual polarization radar system, it should be possible to get some empirical data on microwave scattering signatures. These signatures will undoubtedly be augmented by results obtained from the S-193 scatterometer on Skylab.

Many of the cartographic or geologic mapping projects using radar data have not specifically addressed the question of scattering signatures.

3.7 JOINT USAGE OF SEVERAL TYPES OF DISTINGUISHING CHARACTERISTICS

With the exception of the photointerpreters who routinely use spectral and spatial distinguishing characteristics jointly in their analysis, there has been very little joint use of two or more types of distinguishing characteristics for machine analysis. In the ERTS program, two investigators [Refs. 32 and 48] have reported using both spectral and spatial information for processing, and noted improved classification results of forest types and agriculture types as a result. These and other unreported preliminary analyses suggest that this is potentially the most fertile ground for advances in the distinguishing characteristics/feature extraction area.

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SECTION 4

FLIGHT HARDWARE

Flight hardware today is further along in state-of-the-art development than any other segment of the Earth Resources system. The technology available for launching and controlling spacecraft, gathering data from space-borne and air-borne sensors and the transmission or return to earth of large quantities of data are comparitively well developed.

This section describes the current state-of-the-art of all hardware which has an effect on the ability to collect and return remotely sensed Earth Resources data. Primary emphasis has been given to sensors since they have the most direct effect on the system's ability to sense the distinguishing characteristics of the scene and to ultimately process this data into useful information in the data system. Supporting subsystems on board the spacecraft are also described including attitude control and measurement, electrical power, communications, on-board storage, on-board processing and launch vehicles. The section concludes with a description of the current state-of-the-art of aircraft programs.

4.1 SENSORS

In the Earth Resources program, sensors are used to detect the distinguishing characteristics of the observed scenes and convert these characteristics into signals suitable for permanent recording and return to a data processing facility. The Earth Resources program is concerned in particular with electromagnetic sensors which detect radiance in the frequency range from the visible to the microwave.

In the discussion that follows, the primary emphasis has been placed on the evaluation of a generic sensor on a component-by-component basis, considering both the theoretical limits and the actual performance of that component in current sensors. This evaluation is given in Section 4.1.1. The approach to defining the state-of-the-art of remote sensors in a general sense, without reference to specific detectors, optics, etc., designs is unique and should be of value in synthesizing requirements for future sensor systems later in the study. The specific component breakdown for the generic sensor is given in Table 4-1.

In addition, sensors have been categorized into types based upon the unique characteristic of the sensor. Their general performance, problems, and areas of development are discussed in Section 4.1.2. Table 4-2 defines the classes of sensors with sub-classes also indicated.

A third method is sometimes used to classify sensors based upon the designation of the particular scene parameter it is designed to measure. A summary of the scene parameter and sensor nomenclature is given in Table 4-3.

Table 4-1. Generic Sensor Components

Energy Collection Mechanism	Spectral Separation Mechanism
Scan Mechanism	Polarization Mechanism
Detecting Mechanism	Electronics
Detector Cooling Systems	Processing
Active Sources	Calibration

All remote electromagnetic sensors are basically radiometers. That is, a device which collects electromagnetic radiation and transduces it into an electrical signal (photo detector), a mechanical deviation (Golay cell), or a chemical change (film). A spectrometer is a radiometer plus a device which disperses the incoming energy into its spectral components and presents an output which is a function of both frequency and amplitude. An imager is a radiometer that produces a two-dimensional radiance spatial distribution as an output. This sensor is classified as either a mechanical, electronic, or film camera depending on the specific mechanism used to transduce the spatial radiation pattern. A polarimeter is a radiometer which measures not only the amplitude of the electromagnetic energy, but also parameters related to the polarization of the incoming wave. A sounder is an instrument which measures the vertical distribution of a parameter (i.e., atmospheric temperature profile) and is generally of the non-imaging classification. A scatterometer is a radiometer which measures the scattered energy from the atmosphere rather than the direct reflection or emission from the earth's surface. These sensors are generally in the active sensor classification.

Thus, by synthesizing sensor components as defined in Table 4-1, one can arrive at a sensor classification as applied to the measurement of specific scene parameters. For example, the multispectral scanner flown on ERTS is a mechanical imager by classification and an "imaging spectral radiometer" by application.

Table 4-2. Sensor Classifications

Classification	Sub Classes
Mechanical Imager	Image Plan Scanner Object Plane Scanner Multi-Feed Antenna
Electronic Imager	Vidicons "Push Broom" Arrays Phase-Array Radar Dielectric Tape Camera Image Dissector Phased-Array Radiometers Multifeed Radiometers
Film Camera	Panoramic Multispectral
Non-Imager	Sounder Atmospheric Profile Non-Scanning Radiometer
Active	Microwave Radar Laser Audio Wave

Table 4-3. Sensor Nomenclature by Application

Parameter Measured	Sensor Nomenclature
Radiance	Radiometer
Radiance Spectral Distribution	Spectrometer
Radiance Two-dimensional Spatial Distribution	Imager
Radiance Polarization	Polarimeter
Vertical Distribution	Sounder
Scattered Radiation	Scatterometer

4.1.1 SENSOR COMPONENTS STATE-OF-THE-ART

Remote sensors can be described by the model shown in Figure 4-1. Some sensors will not have all the components indicated, but all sensors will consist of a combination of some of these components. The theoretical performance, current state-of-the-art and projected improvements for each of these components are summarized in Table 4-4 and are discussed in this section. In theory, one could take the performance of each component and synthesize a

Table 4-4. Sensor Component State-of-the-Art

COMPONENT	THEORITICAL LIMIT	ACHIEVED - TO DATE	MAJOR PROBLEMS	CURRENT DEVELOPMENT AREAS
Energy Collection Mechanism				
Refractive Optics	Entrance aperature diffraction	Near diffraction limit	Limited multispectral use due to spectral transmission; Chromatic abberation	No major improvements expected
Reflective Optics	"	"	Wide image plane angle	One axis all reflective schmidt design; Post conical scan correction systems recently flown; 20° systems available 1980
Phased Array	"	"	Limited multispectral use. Useful only at descrete frequencies. Fabrication & mechanical tolerances	No major improvement expected 37 GHz achieved; 100 GHz by 1980 Rate of improvement unknown.
Dish	Entrance aperature diffraction	Near diffraction limit	Multifrequency feed horns. Image plane scanning	Designs just starting; available ~ 1980
Scanning Mechanisms				
Mechanical - Object Plane	Scan Efficiency = 100%	Less than 50% wide angle	Large size & weight	No major improvements expected.
Mechanical - Image Plane	"	80% narrow angle	Off-axis resolution Spectral separation	See reflective optics. Not a problem for reimaged optics (conical scan). Requires a separate array for each spectral interval. No improvement expected.
Electrical - Visible & IR	"	90-95%	Electron beam and photo surface, Limited spectral response. Large heat load for cooled tubes.	No significant improvement expected.
Electrical - microwave	See collection systems			
Detection Mechanisms				
Visible	Photon noise	Very near limit	Multielement arrays	Integrated arrays have been built, cost is a factor.
IR	"	Near limit	Multielement arrays Cooling	Radiative cooler/detectors have flown; solid cryo coolers to be flown ~ 1977.
Microwave	Photon noise	Near limit	Para-amp cooling	Maser para-amp cooling on spacecraft
Detector Cooling System				
Radiative	Space Temperature	100°K	Limited low temperatures due to size and parasitics	Minimization of heat leaks for large area coolers. 60-80°K possible
Stored solid/liquid cryogen	4°K	4°K	Open cycle systems life limited by amount of cryogen	Solid cryogen at 65°K with one year life to fly on Nimbus-F. Stored gas J-T cooler at 25°K on MARS fly-by mission.
Active Sources				
Lasers	No limit	---	Limited wavelength. Heavy power demand. Solar energy interference	Tunable dye lasers under development Applications need definition
Microwave	No limit	---	Spatial resolution as frequency Multifrequency Heavy power demand	Synthetic aperature device flown in aircraft See feed problem in collection systems
Spectral Separation	No limit	---	Spectral separation not a problem for Earth resources	Very narrow spectral widths for meteorology and air pollution have been achieved with gas cells. Even narrower widths can be achieved with up conversion from the IR.
Polarization Mechanism				
Visible	No limit	---	Materials for polarizer	Not many sensors use polarization. Much work to be done across the board.
IR	No limit	---	Materials for polarizer	Double reflection prisms possible. Use questionable since self emitted energy is not polarized.
Microwave	No limit	---	No major problems	Flight instruments under construction
Electronics				
Processing	No limit	---	Sampling methods, algorithms, fault immunity	Definition of basic approachs and requirements for on-board processing.
Calibration	No limit	1% Radiometric Accuracy	Correlation between spectral intervals. Large area, low radiance sources for visible & IR and tracability to a standard.	No major effort underway.

total sensor system with a performance determined by either the theoretical or practical limitations of the individual components. However, in practice, this is not generally achieved due to economic considerations and the practical problems of component integration. Therefore, a discussion of sensor systems as classified by type is presented in Section 4.1.2, to complete the overview of sensor state-of-the-art evaluation.

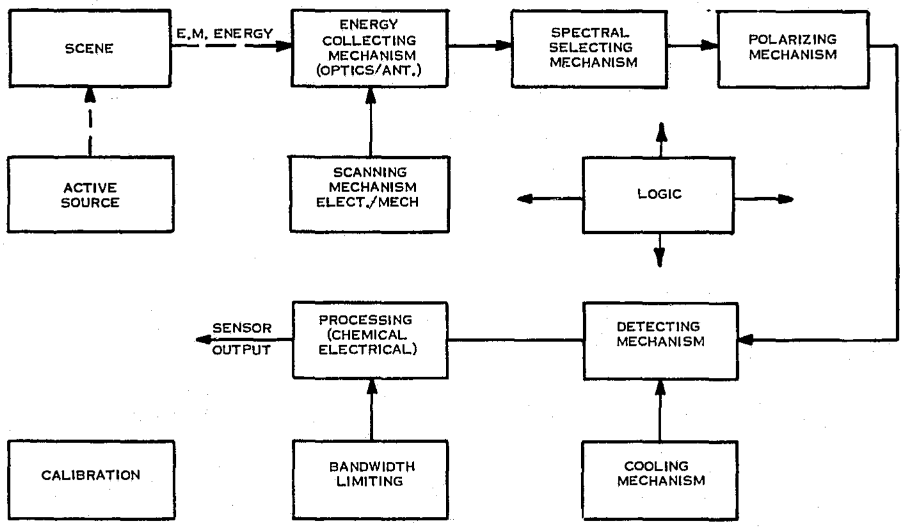


Figure 4-1. Remote Sensor Block Diagram

4.1.1.1 Energy Collection Mechanism

4.1.1.1.1 Resolution

Optical systems for visible and IR, and antennas for the microwave region have reached quite a high degree of sophistication, except perhaps in the area of materials for refractive IR systems. A true multispectral sensor should be able to collect energy from 0.5 to 20 micrometers and then again in the microwave spectrum. To collect visible and IR requires an all reflective optical system since no one refracture material is suitable for the total spectrum. Reflective systems are now being designed to have wide image plane angles with good resolution which will allow for image plane scanning. The art of telescope mirror fabrication is well in hand, and near diffraction limit can be achieved even with large diameters (1 meter and larger).

Most sensors employing single detectors in the visible and IR have the optics and detectors sized by the energy requirements; i.e., the detectivity for a given scene radiance. Thus, the resolution is generally poorer than the diffraction limit. Diffraction plus aberations is the limit for microwave and film sensors. When the transducer bandwidth is small as in the case of two-dimensional arrays/surfaces (e.g., vidicons), especially in the visible where the energy level is high and the device has integration, then the diffraction limit may be approached. The RBV is an example of such an instrument.

To date, unclassified mechanically scanned (visible and IR) single detectors or linear arrays typically have IFOV's ten times the diffraction limit. In two of the microwave instruments flown, the FOV was sized by energy limitations for one (NEMS) and for the second by physical limits of the spacecraft size. In this latter case the main lobe of the antenna pattern is actually smaller than the diffraction limit. Integrating the entire pattern would probably indicate operation at or at least very near the diffraction limit.

4.1.1.1.2 Mirror Materials and Coatings

When mirror blanks have been ground and polished to the correct figure, some sort of highly reflective coating is usually evaporated on the surface. In general, all of these metallic surfaces have increasing reflectivity with wavelength, so it is conservative to assume that a reflectivity of 95 percent or better is available with silver, gold, or aluminum for wavelengths greater than 1μm (Figure 4-2). The choice is generally made based on whether 0.8-0.9 μm operation is important and the extent to which the surface can be protected from the atmosphere. Gold and silver are relatively inert but aluminum is attacked, and oxides form. A variety of overcoats have been used to protect these surfaces from the atmosphere. Their chief requirements include imperviousness, adhesion, and relatively low absorption. Chief among those tried is MfF_2, though SiO_2 rates a good second. The primary disadvantage of these coatings is additional scatter and loss in reflectivity (about 5%).

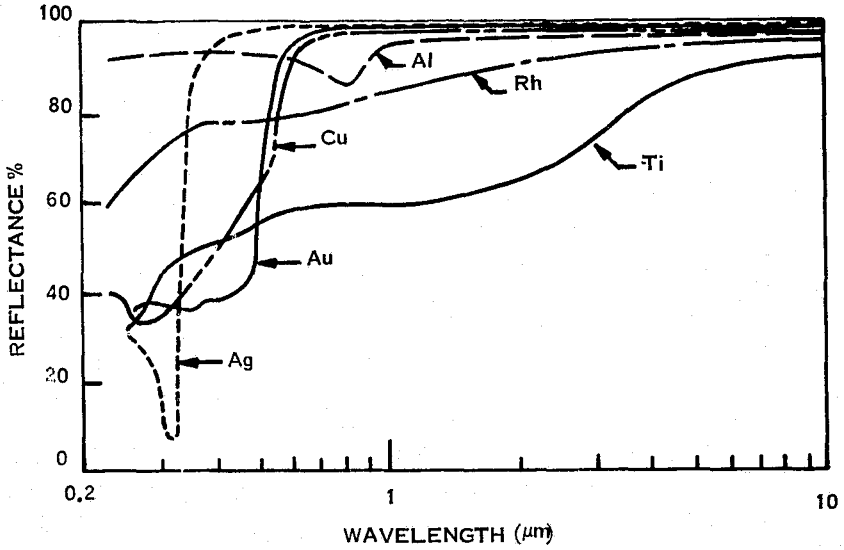


Figure 4-2. Reflectance of Various Films of Silver, Gold, Aluminum, Copper, Rhodium and Titanium

It has been well established that Pyrex, fused silica, Cervit and ULE quartz can be coated with electrolysis nickel and aluminum. Aluminum mirrors can be also stably coated with aluminum, sometimes with a nickel layer. Such systems can be used in all Aluminum mountings to maintain focus over wide temperature ranges. The Cervit and ULE materials have very low coefficients of thermal expansion so that they can remain stable over broad temperature ranges. In this case the mount must be made of a similar material or partly with Invar. In theory at least similar things can be done with beryllium and done with less weight because it has a higher strength to weight ratio. There have been some difficulties encountered, however. Beryllium is usually formed by a directional casting process and is, in a detailed sense, anisotropic. The difference between the coefficient of linear thermal expansion of nickel and that of beryllium as well as this anisotropy can cause rippling of the mirror surface. Efforts have been expended on isostatic casting and other methods of manufacturing the material.

4.1.1.1.3 Size/Weight Considerations

The increase in both the aperture diameter and the number of detectors required to achieve increased resolution, translates directly into increased sensor weight. Figure 4-3 represents an extrapolation of the weight of a VISSR-type scanner to larger aperture values, without the consideration of increased weight due to increase in number of detectors. The weight indicated refers to an all-beryllium system, and includes only the primary and secondary mirrors, support assemblies and tube. In this figure the present weight of the VISSR scanner is indicated by a circle, while the improved-resolution values are represented by crosses. For a 10-fold increase in resolution (always maintaining the same coverage, S/N, etc.) it is seen that the weight of the telescope alone would have to be increased to more than 1363 Kg (3000 pounds.)

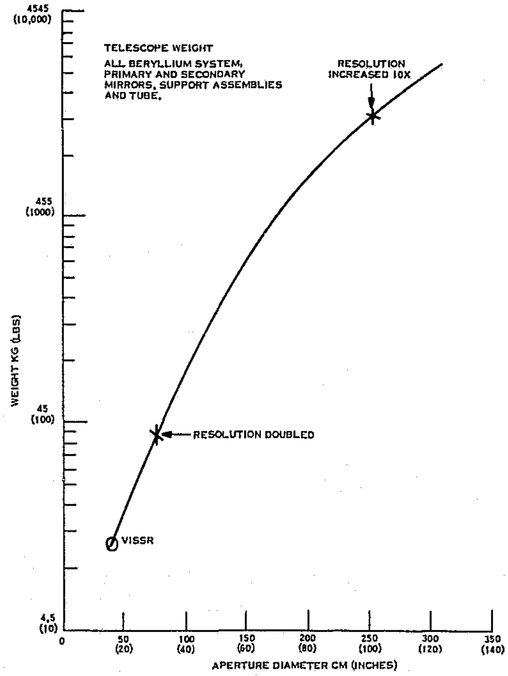


Figure 4-3. Weight vs. Diameter for VISSR-Type Scanner

4.1.1.2 Scan Mechanisms

A mechanical scanner is an imaging sensor in which the image of the scene to be mapped is physically scanned by a detector or detector array by means of mechanical motion. These scanning systems can be broadly classified as object plane and image plane scanners.

4.1.1.2.1 Object Plane Scanning

This was the earliest approach to imaging wherein the detector(s) are on (or nearly on) the optical axis and the IFOV of the instrument is pointed in different directions (i.e., scanned) by an external plane mirror. For wide angles of scan, such as horizon-to-horizon from spacecraft, this was easily accomplished by placing the plane mirror at 45 degrees on a rotating shaft. This had the advantage of having only rotary motion but many disadvantages. For large scan angles the scan efficiencies were reasonable (0.3 to 0.5) but could never be improved as they are inversely proportional to the scan angle. For narrow angle systems, such as were used on ERTS, this would result in large bandwidths and poor signal-to-noise ratios. A further problem is that this scan technique is not ameanable to detector arrays. When the array is arranged to scan adjacent lines at nadir, by the time the mirror has rotated 90 degrees, they will all be scanning the same line.

Many other object plane scan techniques have been studied such as:

- Multifacet Wedge Mirrors
- Inside-Out Polygons
- Refractive Polygons
- Oscillating Mirrors
- Polygons
- Split-Field Polygons
- Refractive Wedges

All of these systems suffer one or more major defects such as size, complexity, alignment, etc., which in most cases outweighs the advantages of increased scan efficiency.

The oscillating mirror technique used in the MSS for the high-speed scan direction and on VISSAR for the low-speed scan direction are two examples of instruments using different object plan scanning techniques with relatively high scan efficiency (~.5). However, since the scan mirror must be at least $\sqrt{2}$ larger than the collector, the use of large collectors for higher resolution data and hence higher scan rate is a self-defeating proposition.

It is a safe conclusion that there is a very low probability of any significant improvement in object plane scanner efficiencies.

4.1.1.2.2 Image Plane Scanning

Image plane scanning requires an optical system that covers the full field of view with the required resolution. The image is then scanned either by a single detector scanned mechanically to sequentially cover the total field element by element, or a linear array of detectors scanned to cover the field in groups of elements.

The advantages of image plane scanning are obvious in that the scanning mechanisms are smaller and hence lighter, the resolution or signal-to-noise ratio can be increased by the use of detector arrays, and the scan efficiency improved to very close to the ultimate. Spectral separation is a bit more difficult since it must occur after scanning or have separate scanning mechanisms for each spectral interval.

The primary disadvantage of image plane scanning is the requirement for a wide field of view optic. This can be achieved quite readily with refractive optics because it is possible to (a) shape both surfaces of a lens differently, and (b) use multiple lenses of different shapes and different indices of refraction. Using these techniques, lenses can be designed to be near diffraction limited with relatively wide view angles (e.g., RBV lens). In reflective telescope design, the off-axis aberrations are large primarily because most systems (Cassegrain, Dall-Kirkam, Newtonian, etc.) have only two curved surfaces and these in general are surfaces of rotation. The Schmitt system does have a fairly wide field of view, but the classical design requires a refractive corrector plate. Refractive elements are undesirable because of chromatic aberration and their limited spectral transmission. This latter problem makes simultaneous and registered multispectral imaging over the visible to infrared spectrum impossible. Several three-element, all-reflective systems have been proposed and some have been built and tested with varying degrees of success. It does appear that a high-throughput-efficiency, all-reflective system which has appropriate corrections in one axis rather than both is now feasible. This would allow for multi-detector linear array image plane scanning.

4.1.1.3 Detecting Mechanisms

Table 4-5 lists the sources and frequencies of electromagnetic energy and some of the kinds of detectors that are used to detect this energy. It has been demonstrated that in the visible and IR the detectors themselves are virtually background photon noise limited. For example, when the measured signal-to-noise ratio of the ERTS MSS was compared to the theoretical limits, it was found to be a factor of approximately two smaller. It should be noted that this was a laboratory measurement and does not include noise due to atmospheric scattering, which could be the real limit for instruments operating in the near IR and visible.

Table 4-5. Sources of EM Radiation and Methods of Detection

Kinds of Waves	Usual Source	Usual Method of Detection
Gamma Rays	Atomic explosions	Fluorescence, Chemical effect, Ionization
X-rays	Cathode ray impacts	Same as above, NaI crystals
Ultra-violet	Disturbances of intermediate electrons	Fluorescence, Chemical effect
Light	Disturbance of valence electrons Laser	Eye, Chemical effect, Photodetectors
Infrared	Disturbances of atoms and molecules (thermal sources) IR lasers	Thermopile, Bolometer, Radiometer, Photodetectors
Microwaves (EHF)	Short oscillations, high frequency discharge	Diodes, Bolometers
Microwaves (SHF)	Electrical resonance in tuned circuits, Thermal generated IR, Solid state devices	Solid state crystals diodes, tubes
UHF	Short oscillations klystrons, magnetrons, triodes, solid state devices	Electrical resonance in tuned circuits, diode detectors
Radio (10^3 -10^6 cm)	Circuits including large capacitors and inductors	Electrical resonance, Electromagnetic induction
VLF	Alternating current generators, solid state vacuum tubes	Oscillographs, diodes, heterodyne receiver
ELF	Alternating current generators, solid state vacuum tubes	Oscillographs, diodes, heterodyne receiver

Source: R.G. Reeves (ed.), 1968.

Evidence on other instruments indicates that in the visible and IR one can approach within a factor of 3 to 5 of the theoretical limit. Further, it is improbable that this can be improved greatly in the future, unless a new device type (e.g., the IR analog of a photomultiplier) is invented in the next several years.

Microwave detectors are technology limited. That is to say with an appropriately cooled MASER and parametric amplifiers they can achieve background-limited performance. However, there are several practial problems. First, they must be cooled to very low temperatures (20° to $4^\circ K$). MASERS have not been built to operate much above 4 GHz where Earth Resources applications may require frequencies to 100 GHz. Similarly in parametric amplifiers, the ratio of the pump frequency to the signal frequency determines the system noise. Varactor diodes have been made in the laboratory which allow for pump frequencies of 150 GHz which limits the upper frequency at which background limited measurements can be made. More work is needed in this area. Of the microwave instruments flown to date, background-limited performance has not been achieved because the instruments were equipped with conventional semiconductor components.

4.1.1.4 Detector Cooling Systems

Future infrared sensors for NASA applications will utilize cooled quantum or photodetectors. These detectors require cooling to cryogenic temperatures. For remote sensing applications, future imagers and scanners, particularly those operating in the 8-13 μm region, will utilize intrinsic photodetectors cooled to 100 degrees kelvin. Within the next decade, it is anticipated that detector cooling requirements for airborne and spaceborne infrared systems will generally lie in the 50-120 degree kelvin region with perhaps a few applications requiring temperatures as low as 20 degrees kelvin. The cooling capacity requirement at these temperatures will range from a few milliwatts for a single photovoltaic detector to perhaps a watt for large arrays of photoconductive detectors.

4.1.1.4.1 Cooling System Design Criteria

The basic design parameters for a cryogenic detector cooling system are: the required operating temperature and temperature stability; heat load at the operating temperature; the alignment requirements of the cooled detector(s) relative to the optics; and, the reliability and operating life of the system.

For spaceborne systems where weight and power are usually limited, the selection of a cooling system involves a detailed trade-off between the detector and cooling system parameters for a given mission duration. Furthermore, the configuration and orbital parameters of the spacecraft have an influence on the selection of a cooling system.

The reliability and operational lifetime of spaceborne cooling systems are determined by both the degradation or failure of mechanical and electronic parts, by potential long-term degradation from contaminants which may be cryo-deposited on critical optical and thermal surfaces, and by the system mass.

At present, the technology associated with airborne detector cooling systems operating at 20 degrees kelvin and above is well-advanced as a result of DOD programs. Low-cost, closed-cycle refrigerators with maintenance intervals of 1,000 hours or more are currently available on an "off the shelf" basis. Size, weight, and power consumption are of secondary importance. This existing technology, coupled with future developments being undertaken by DOD for advanced airborne reconnaissance missions, should provide an adequate technology base for future NASA airborne infrared imagers and scanners.

The current technology status for spaceborne cryogenic cooling systems is less advanced than in airborne systems. While airborne systems have been in use for nearly ten years, the first spaceborne system for providing continuous cryogenic cooling by use of a passive radiator was flown in 1972.

For space application, the important design parameters are: system reliability based on maintenance-free operation for periods up to 20,000 hours, electrical power consumption and system weight and size, launch environment; and, operation at zero "g". These factors preclude the direct use of airborne cryogenic cooling technology in spaceborne systems.

4.1.1.4.2 Description of Cooling Systems

There are three basic types of cooling systems:

1. Passive radiators for spaceborne systems which cool detectors by direct radiation to the low-temperature sink of deep space;
2. Open cycle systems which use fluid or solid cryogens stored in a dewar; or, stored, high-pressure gas which provides refrigeration by the Joule-Thomson effect. Solid cryogens are only applicable to spaceborne systems;
3. Closed-cycle systems employing a mechanical refrigerator using helium gas as the working fluid or closed-cycle Joule-Thomson systems.

In addition to these systems, solid-state thermoelectric devices can be used for detector cooling. Multiple-stage thermoelectric coolers are, however, limited in application to systems requiring cooling above 150 degrees kelvin. Some of the salient characteristics of passive radiators, open-cycle and closed-cycle systems suitable for spaceborne cooling are summarized in Table 4-6.

Passive Radiators. Conceptually, the simplest way of developing cryogenic temperatures in space is to radiate power to the low-temperature heat sink of space by use of a suitably sized emitting surface. This concept is particularly attractive since such a system is completely passive, requires no continuous electrical power, and is potentially capable of high reliability for extended periods.

Although passive radiators are simple in principle, there are several important design problems associated with the development of flight hardware. The design of the support system is critical since it must support the low-temperature stage with an extremely low thermal conductance yet, in many cases, it must maintain the detector in precise alignment with the room temperature optical instrument. Another fundamental design problem is that of preventing contamination of low-temperature optical surfaces by outgassing from either the spacecraft or the radiator itself. Contaminants can influence the detector operating temperatures by altering the emittance, solar absorptance or specularity of critical thermal control surfaces.

Several passive radiators have been flown on spacecraft and approximately ten additional units of various designs will be flown in the 1972-1975 time period.

Table 4-6. Characteristics of Spaceborne Cooling Systems

	Passive Radiators	Open-Cycle Systems	Closed-Cycle Systems
Characteristics	Simple and lightweight No continuous power requirement Limited temperature and heat load capacity Require proper orbit orientation and spacecraft location Indefinite life possible Prone to contamination degradation No detector microphonics	Wide temperature range (10-50° kelvin) Relatively simple High weight and volume; limited in watt-hours of refrigeration No power required No detector microphonics Systems vent gas continuously No attitude control, orbit or location constraints Safety must be considered Detector alignment dependent on low-conductance supports	Complete coverage of temperature and heat load range Complex Require power and heat-rejection system May introduce detector microphonics System weight and power strong functions of load temperature
Applications	Temperatures above 50° kelvin Geosynchronous or sun-synchronous orbits Heat loads 100mW (present technology) Long missions	Low heat loads Short to intermediate length missions Non-oriented vehicles	Low temperatures with relatively large loads Long missions (to 3 years) Provide refrigeration at 2 temperature levels

Open-Cycle Systems. There are three types of open-cycle systems which can be considered for space cooling: Joule-Thomson (J-T) systems using stored-gas, stored-liquid systems and stored-solid systems.

An open-cycle, J-T system consists of a counterflow heat exchanger, an expansion valve (or throttling orifice) and a gas bottle containing high-pressure gaseous refrigerant. It is one of the simplest systems for cooling detectors. The optical device can also be mounted at a distance from the gas-storage bottle and articulated with respect to this bottle.

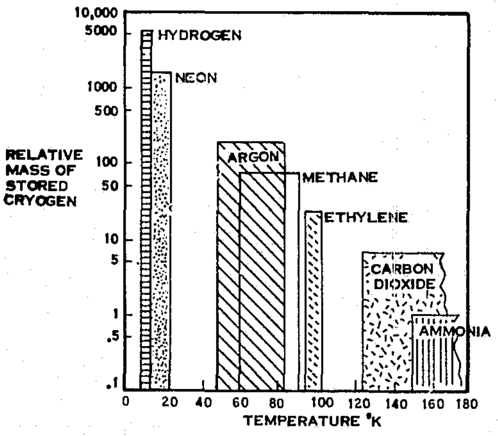
Two-stage J-T coolers using stored gas were flown on two Mariner spacecraft to cool infrared detectors to below 25 degrees kelvin. One system worked successfully and one system failed.

Open-cycle systems using liquid cryogens stored in conventional dewars have been used to cool infrared optical instruments in aircraft, sounding rockets, and balloons to temperatures below 4 degrees kelvin using liquid helium. Liquid neon and liquid nitrogen systems operating at 27 and 77 degrees kelvin respectively, have also been successfully utilized. For spaceborne use it appears that stored cryogens in liquid form will, in the near future, be restricted to missions where the refrigeration is required for short periods of time immediately following launch.

In a solid-cryogen, the detector is usually mounted on a pedestal which is thermally connected to a vacuum-insulated dewar containing a solidified cryogen. The ullage space above the stored solid is evacuated to maintain the cryogen in its solid state. Heat entering from the detector and the surroundings causes the cryogen to sublime, and the resulting vapor is vented.

The relative mass* for stored solid cryogens is shown in Figure 4-4. It can be seen that as the required cooling temperature decreases, the mass of stored solid cryogen for an equal mission length increases rapidly.

Closed-Cycle Refrigerators. At the present time, there are a number of DOD and one NASA program underway to develop closed-cycle refrigeration systems suitable for space applications. These systems require significant power and are certainly more complex than either passive radiators or open-cycle systems; but they will be necessary for higher heat load applications.



ITEMS HELD CONSTANT:
MISSION DURATION
SHELL TEMPERATURE
EFFECTIVE EMMITANCE OF INSULATION

Figure 4-4. Relative Mass of Cryogen for Solid Cryogen Coolers

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*The relative mass of stored cryogen is derived for a spherical vessel and accounts for density and heat of sublimation. The relative masses have been normalized using ammonia as a basis.

There are two general classes of cryogenic refrigerators. The first are the so-called intermittent flow types, which use regenerative heat exchangers. There are three types in this class. Identified by the thermodynamic cycle on which they operate, they are Stirling cycle refrigerators, Gifford-McMahon cycle refrigerators, and Vuilleumier cycle refrigerators. Stirling cycle and Gifford-McMahon cycle refrigerators have been developed for ground-based and airborne applications, where they are presently being used in operational systems. The maintenance intervals of these systems are from 500 hours for the former up to several thousand hours for the latter. It is doubtful whether these devices, as they are presently constructed for airborne use, can be made reliable enough to satisfy the requirements of space missions having durations of a year or more. At present, no effort is being made to develop a refrigerator utilizing either of these two cycles for extended space missions. However, several Stirling cycle refrigerators for infrared detector cooling will be flown on the Skylab program where the required operational time is less than 500 hours.

The development of Vuilleumier (VM) cycle refrigerators for ground-based, airborne and spaceborne use has been underway for the past five years. VM cycle refrigerators are heat-driven derivatives of the Stirling cycle refrigerators. The cycle is attractive for space use because of the potential for using solar or isotope thermal energy to drive the thermal compressor directly thereby minimizing the electrical power input.

Current developmental programs in VM refrigerators indicate the potential for longer life than the Stirling or Gifford-McMahon systems currently used in airborne applications. Since VM refrigerators employ bearings and seals, they are wear-limited. It is anticipated, however, that continued development will lead to maintenance-free operation exceeding 5,000 hours.

The second general class of closed-cycle refrigerators, the continuous-flow type, use counterflow heat exchangers. These units operate on the reversed Brayton thermodynamic cycle or derivatives of it. Refrigerators operating on the reversed Brayton cycle have been used in ground-based equipment for a number of years - mostly in relatively large-scale systems. Recently, efforts have been devoted toward developing reversed Brayton cycle refrigerators suitable for long-term space missions. The effort in these programs has been to scale down the size of existing systems, using an approach to the design of the mechanical elements which is inherently very reliable. There are several programs underway to develop refrigerators of this type. One refrigeration system uses rotary-reciprocating machinery, and the other uses turbomachinery.

Extensive effort has been devoted to developing gas-bearing-supported machinery for these refrigerators, resulting in equipment which is inherently capable of extremely long life. The units must be considered developmental at this time-but they appear to be the only ones which are capable of meeting the life requirements of extremely long-term space missions; i.e., up to three years of unattended operation. Therefore, in spite of the rather wide range of cryogenic refrigerators used today, the number of systems which can meet the requirements of a long-term space mission is extremely limited.

The approximate input power requirements for various types of refrigerators are shown in Figure 4-5 for a heat load of 1 watt at various temperature levels. The data show the strong influence of load temperature on input power requirements. Stirling cycle refrigerators are efficient at higher temperature levels. At the 20 degree kelvin temperature level the Stirling and VM cycles become inefficient due to regenerator losses. The reversed Brayton cycle systems utilizing high-speed turbo-machines are inherently inefficient at the relatively small heat load level of 1 watt.

4.1.1.5 Active Sources

Active sensors have a role in remote sensing although it is not as well defined as passive sensors simply because there has been much less work done with them. Their principal advantage is to be able to illuminate the target with monochromatic energy and observe either the reflected return or some stimulated emission, usually at a different frequency (i.e., flouresence, Ramanshifted emission). Some of their drawbacks are unwanted illumination such as the sun in the visible or self-emission in the IR and microwaves; limited frequencies in the IR and visible; and their heavy power demand.

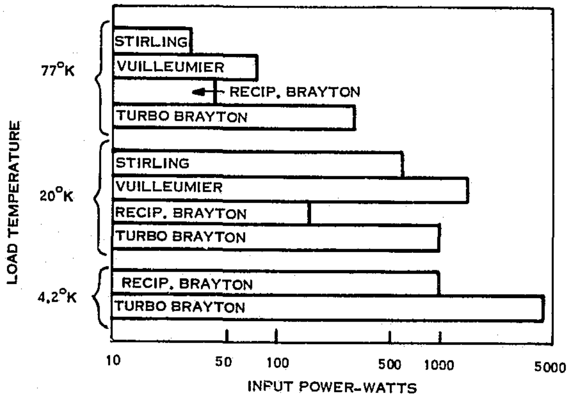

Figure 4-5. Refrigerator Power Requirements - Load Capacity 1 Watt

While there is no theoretical limit against which to judge the performance of onboard sources, there are several parameters which require further discussion.

4.1.1.5.1 Pulsed Systems

The energy from the source can be either c.w. or pulsed. With a pulsed system the peak power can be made larger than the average power of a c.w. system by an amount directly related to the duty cycle. Neglecting for a moment the bandwidth requirements of the receiver due to scanning or vehicle motion, it can be shown that there is an increase in receiver bandwidth needed to accept short duty cycle pulses. This increase in bandwidth (approximately the second power of the duty cycle) will increase the noise by the same amount as the signal.

Pulsed systems can be of two basic types; one in which the pulse width and repetition rate is such that the pulse of energy has time to travel to the scene and return before the next pulse (conventional radar), and the second mode is where the pulse is long with respect to the transit time (microwave scatterometers). This latter is done primarily to decrease the bandwidth and increase the integration time to improve the signal-to-noise ratio. However, one loses the ability to obtain range information that can be provided by short pulse technique. Range information is probably only of importance in two areas: atmospheric profiling in the visible and near IR, and height measurements in the microwave region (microwave altimeters).

4.1.1.5.2 Safety

One of the biggest problems in the visible and near IR is eye safety on the ground. Some work has been done to determine the tolerance level of human being to flux densities of varying wavelengths. However, there is not now an accepted and agreed upon level as there is for x-ray radiation (dosage level).

4.1.1.5.3 Beam Width and Scanning

The maximum utilization of source energy would have the beamwidth equal to the IFOV of the instrument. This can be more easily done in the microwaves with a common antenna and feed than in the IR. Scanning of the illumination beam must be object plane scanning.

4.1.1.5.4 Coherent Active Sources

The use of coherent sources such as laser and radar permits special measurements to be made which involve the phase of the electromagnetic energy. This of course is not true with thermally-generated energy such as reflected solar and earth self-emitted radiation. These special measurements such as holography and synthetic aperture are in a fairly early state of development, not so much in the technology of the hardware as in utilization of received signals.

4.1.1.6 Spectral Separation Mechanism

There are many techniques to separate the spectrum into its components, such as:

Interference Filters

Prisms

Gratings

Etalons

Selective Absorption

Intrinsic Absorption

Interferometers

Spectroscopy is a fairly old science and has a well developed technology. While each of the above techniques has its own advantages and disadvantages, (i.e., selectivity vs. throughput or transmission), there is little reason to believe that there will be a significant improvement in the next few years. The most important thing to remember concerning spectral selection is that there is a direct trade-off between energy and spectral bandwidth, i.e., as the spectral interval is made smaller, for a given sensor, the signal-to-noise decreases. (This makes the assumption that for earth resources purposes the energy received is incoherent.)

4.1.1.7 Polarization Mechanism

All wavelengths of electromagnetic energy can be polarized but the techniques and hardware are different for the three major spectral intervals. The majority of work to date has been in the visible and microwave regions, although polarizers have been made to operate in the IR.

4.1.1.7.1 Visible Polarizers

A relatively large number of techniques are available such as:

- Brewster Angle Reflection
- Dichroism
- Double Refraction
- Scattering
- Electro-optic

Some of these techniques can be arranged to obtain two planes of polarization which are at right angles. It is also possible to obtain the component at 45 degrees required by the Stokes equations in one device by the use of beam splitters and 1/4 wave plates. The intensity of the energy in all planes can be measured by rotating a mirror at the Brewster angle about the axis of the incident radiation but this requires a 360 degree detector array and the measurements are sequential. The principal area of development lies not so much in the fabrication of a polarizer as in the specific design of the instrument with adequate throughput.

4.1.1.7.2 IR Polarizers

Wire grid polarizers are made for polarizing IR energy by evaporating a metal grid and an appropriately transmitting media. They are used in IR spectroscopy, particularly the analysis of crystal materials. Application to earth resources is not currently envisioned.

4.1.1.7.3 Microwave Polarizers

Since microwave (and other) antennas and their feed systems are intrinsically polarized, there is no particular polarizing device per se. No particular improvements are expected in this area.

4.1.1.8 Electronics

The critical design parameters for the electronics used to amplify and band limit the detector signal are the amplifier equivalent input noise voltage (e_{na}) and series input resistance (R_i).

Three types of noise are generally associated with solid state amplifiers; thermal noise, shot noise and excess noise. Thermal noise results from the random motion of free carriers in a medium caused by thermal agitation. Shot noise is produced by rapid changes in the charge of free carriers with respect to circuit current. Excess noise usually occurs at low frequency and is also known as 1/f noise. The exact mechanism of excess noise is not known but is thought to be associated with carrier "traps" within semiconductor depletion layers.

Semiconductor amplifier noise is generally combined and presented as a noise figure (F), which is a function of source resistance ($R_s + R_i$) and frequency. Noise computations are accomplished as if the noise were thermally generated. The equivalent rms noise voltage (e_{na}) at the amplifier input is expressed:

$$e_{na} = 4\,KT\,(R_s + R_i)\,\Delta f$$

where: K = Boltzmann's Constant (1.38×10^{23} joule/^{o}K)

T = Equivalent amplifier Temperature (degrees kelvin)

$R_s + R_i$ = Total source resistance

Δf = Bandwidth increment in which the noise is measured

The equivalent amplifier temperature is expressed by the noise figure (F):

$$T = 290\,(F-1)$$

Figure 4-6 illustrates the noise figure of "state-of-the-art" solid state amplifiers as a function of frequency. The amplifier equivalent input noise in a band between F1 and F_2 is:

$$e_{na} = \sqrt{\int_{F_1}^{F_2} 290\,(F-1)\,4K\,(R_s + R_i)\,df}$$

Modulation/demodulation techniques such as "chopping" are often employed to translate sensor output spectrum to more optimum frequencies, for example higher than the 1/f noise region.

Figure 4-7 illustrates the noise figure as a function of source resistance for both state-of-the-art junction and field effect (FET) devices. The FET amplifier is practical for sensors with source resistance up to 100 megohms; vacuum tube amplification is superior in the case of extremely high impedance sensors (example, the photomultiplier tube provides both the high impedance sensor and amplifier).

4.1.1.9 Processing

On-board processing of the information obtained by the sensor system can be categorized into film processing and read-out techniques, optical data processing and digital electronic processing. Digital processing techniques are discussed in Section 4.7.

On-board film development and readout systems are current state-of-the-art and have previously flown on spacecraft. The readout system on Lunar Orbiter was a flying spot scanner. This technique utilizes a Cathode Ray Tube as a scanning light source focussed on the film. A photomultiplier detects the modulated light energy transmitted through the film transparency and converts it to an electrical signal. Another more recent technique

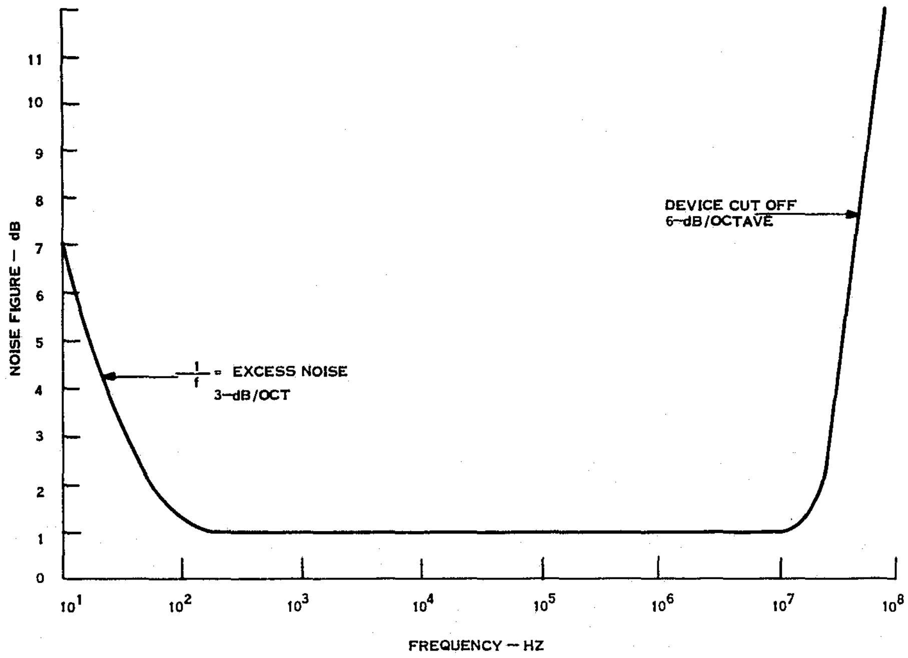

Figure 4-6. Noise Figure of Solid State Amplifiers

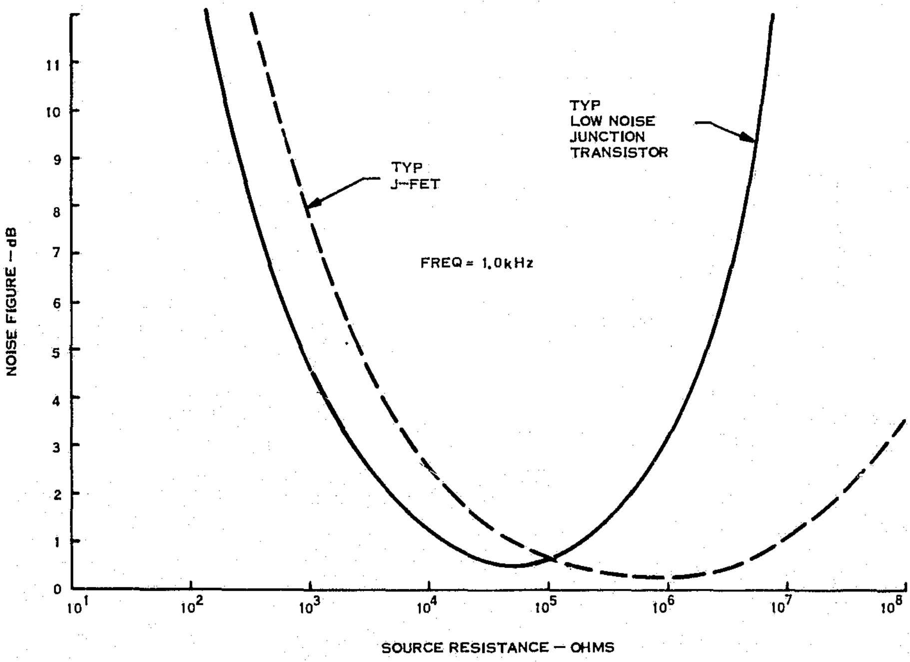

Figure 4-7. Noise Figure for Junction and FET Devices

developed for film readout is a laser scanner. The unique properties of the radiation from a laser are its monochromaticity and coherence, high energy level, and highly collimated beam. When this energy is focussed to a spot on the film, power density, bandwidth, and resolution capabilities are very high. Scanning of the beam can be accomplished with either electro-optical devices or by mechanical methods. Electro-optical devices are, at present, limited as to the number of spot diameters of deflection, so that mechanical techniques are currently used to scan large film formats.

Parallel on-board optical processing techniques are in a state of research and advanced development. Most proposed techniques would be used for either multispectral analysis or spatial frequency analysis or possibly a combination of both. These techniques would be a form of data compression and could greatly reduce the data rate requirements for satellite-to-earth data transmission and also reduce the earth-based data processing requirements.

Parallel optical processing is defined as techniques where each element in a two-dimensional input array is processed simultaneously as contrasted to sequential processing of scanned images.

Most of the techniques for parallel processing involve the application of non-linear optical or electro-optical components. Typical multispectral analysis will require obtaining images which are "intensity slices" in multispectral feature space. This can be accomplished by use of image threshold devices and image reversal devices. An image threshold device is one which produces a binary (i.e., no gray scale) image with "white" areas corresponding to areas in an input image having an intensity level above some specified threshold value. Image reversal devices provide a black-white reversal for binary images. The achievement of these multispectral data processing functions by parallel optical techniques will require near "real time" components of an advanced nature. The application of such components as liquid crystals, ferro-electric ceramics, image intensifiers and non-linear phosphors are under investigation and have promise for meeting these needs.

Parallel optical spatial frequency analysis of sensed images also appears applicable to on-board processing. This technique can provide textural analysis for general recognition and classification or, alternatively, matched spatial frequency filtering for specific recognition of observed scenes.

Parallel optical spatial frequency techniques will generally require the application of a laser and a real time "optical-to-optical" interface device. This function may be provided by advanced techniques utilizing liquid crystals or photo-plastic recording.

4.1.1.10 Calibration

Calibration problems can be divided into several categories and subcategories. While the list presented here is not necessarily all inclusive nor even agreed upon by the industry it does provide an attempt to classify the area of calibration. The classification is given in Table 4-7. Because of the nature of the hardware involved there can be a further subclassification by spectral interval; i.e., visible, IR and microwave.

4.1.1.10.1 Radiometric Calibration

While this is the one calibration which has received the most attention, it still requires additional work. The problem of certification and calibration of the myriad of sources designed by the instrument manufacturers is probably the most serious problem in IR sources. The sources themselves are probably fairly good, but it is doubtful that IR sensors are calibrated to better than 1-3% at a subsystem level and a 3-5% at a vehicle level. In the visible region, the major problem is the spectral distribution of the energy and the exact monitoring of the radiant flux. The latter can be inferred in the IR and microwave region, by the measurement of temperature. In the microwave region the sources are quite often coated with a loaded dielectric (Eccosorb), which causes problems of temperature measurement and temperature gradients. Further, since the emissivity of these sources is a subsurface phenomenon and geometry plays only a secondary role, the value of emissivity can only be inferred from measurements of reflectivity.

Table 4-7. Calibration Classification

- Radiance Related Calibrations
    - Radiometric
    - Spectrometric
    - Polarometric
- Instrument Related
    - Alignment
    - Field of View
    - Scan Linearity (or other)
    - Scan Repeatability and Jitter
    - Transfer Function
    - Modulation Transfer Function
- Systems Related
    - Vehicle/Instrument Alignment
    - Vehicle Attitude and Location
    - V/H Ratio
    - On Board Radiometric
    - Time

4.1.1.10.2 Spectral Calibration

Sophisticated spectrometers and the means to calibrate them in wavelength are in existance so that transmission and reflectance of sensor components can be easily and accurately measured. The major problem in this area is the measurement of relative spectral response of the assembled sensor, which in some instances, differs from the product of the spectral responses of the components (this is not a well-understood phenomenon). The measurement of reflectivity and transmission on a double beam spectrometer takes the difference in signal between the sample under test and an open path, thus cancelling changes in detector sensitivity, amplifier gain, source radiance, and spectral transmission of the spectrometer itself. When calibrating a sensor, a single beam must be used and these latter two problems affect the radiance to the sensor. Further, in many cases, the throughput (optical efficiency) and low flux sources of standard laboratory spectrometers do not provide sufficient energy to the sensor being measured.

4.1.1.10.3 Polarization Measurement

Little work has been done in this area with regard to calibrating visible and IR sensors because (a) there have been few polarimeter sensors, and (b) polarizing light in the IR region is a difficult task. In the microwave region, the use of waveguide and phase shifters makes these measurements more tractable.

4.1.1.10.4 Alignment, Field of View and MTF

Alignment of the optical axis is quite often defined in terms of the field of view (e.g., midway between the half power points). The difficulty here is in knowing whether this chosen optical axis lies on or near to the true optical axis defined by the figure of the optics, wherein misalignment could cause some blurring or loss of resolution.

The MTF can be calculated from the field of view measurement, but this would not include the effects of the electronics or the scan mechanism. Improper low and high frequency response in the electronics can phase shift the signal to produce smearing, overshoot, and ringing. Jitter in the scan mechanism can cause mis-registration, and reduced MTF. Line scanners are most susceptible to this sort of problem, because they are rarely tested on the ground to give an image. This requires providing an artificial motion to simulate the vehicle motion and, in most cases of fixed focus sensors, a distant target. (This can also be accomplished with a moving target in a collimator.) While no particular improvement is required in the state-of-the-art, more emphasis is required in building test fixtures, either universally applicable or specifically tailored to an instrument.

4.1.1.10.5 On-Board Calibration

Particularly in satellite sensors, where the instruments are not recoverable, on-board calibration is mandatory to maintain radiometric (and perhaps spectrometric) fidelity and it has been used in all spectral regions. Recently, problems have been found in using the sun as a calibration source in the visible, probably due to UV degradation of optical surfaces.

4.1.2 SENSOR SYSTEM CLASSIFICATIONS

A classification of sensors based upon a unique, distinguishing characteristic of one or more of its components was given in Table 4-2. In this section a description of each class, particular measurements for which they are used, current development status and practical performance limitations will be discussed. Table 4-8 summarizes the capabilities and characteristics of the classes of electromagnetic sensors.

4.1.2.1 Mechanical Imager

This class of sensor is by far the largest in number of instruments developed to date and has most of the sensor components discussed in Section 4.1.1, lacking only a polarization mechanism. Their major purpose is to obtain two dimensional radiance maps of the earth in a number of spectral regions. These radiance maps are used for virtually every scientific discipline. In this sensor a portion (either a single element or line) of the scene is imaged on the detection mechanism, and scanning is accomplished by changing the portion of the scene viewed by mechanical means. Both object plane and image plane scanning techniques have been used. As previously indicated, the state-of-the-art of each of the components is virtually at the theoretical limit so that the performance of these devices is limited primarily by size, weight, power and cost. This is not to imply that all of the components of any given instrument are at, or near, the theoretical limit. For example, in Section 4.1.1 it was pointed out that many mechanically-scanned imaging radiometers in the IR and visible have spatial resolutions far below the theoretical diffraction limit due to limited energy considerations.

Table 4-8. Capabilities and Characteristics of EM Sensors

Sensor Class	Sensor Nomenclature	Spectral range of operation (wavelength)	Day	Night	Clear	Haze	Clouds	Rain & Snow	Active/Passive	Imaging/ Non-imaging	Instantaneous/ sequential	Reflected/ emitted/trans-mitted radiation
Mechanical Imager	Mech. scanners with photomultipliers	10 - 400 nm	+	-	(+)	-	-	-	P	I	S	R
	Mechanical scanners	1 µm - 3.5 µm	+	-	+	+	-	-	P	I	S	R
	with photodetectors	3.5 µm - 1 µm	+	+	+	+	-	-	P	I	S	E
	Scanning MW radiometers	1 - 10 cm	+	+	+	+	(+)	(+)	P	I	S	E
Electronic Imager	Image tubes (vidicon, orthicon	290 - 900 nm	+	(+)	+	(+)	-	-	P	I	I	R
	Microwave Radiometer											
	Image dissector tubes	290 - 900 nm	+	-	+	(+)	-	-	P	I	S	R
Film Camera	Phtotgraphic cameras & film, conventional	290 - 900 nm	+	-	+	(+)	-	-	P	I	I	R
	Film camera with artificial illumination	290 - 900 nm	-	+	+	(+)	-	-	A	I	I	R
Non-Imager	Photometers	400 - 700 nm	+	-	+	(+)	-	-	P	N		R
	Spectrometers	3 pm - 10 cm	capabilities and characteristics according to spectral region and technique of detection									
	IR Radiometers	3.5 µm - 1 mm	+	+	+	+	-	-	P	N		E
	Radiophase/E-Phase	± 1.5 km	+	+	+	+	+	+	P	N		T
	MW Radiometers	1 mm - 1 m	+	+	+	+	(+)	(+)	P	N		E
Active	Side-looking radars	0.8 cm - 1.4 m	+	+	+	+	+	(+)	A	I	S	R
	Radar altimeter/ profilers	1 cm - 1 m	+	+	+	+	+	(+)	A	N		R
	Impulse radar (ice)	1 - 10 m	+	+	+	+	+	+	A	N		R
	Radar scatterometers	1 mm - 10 m	+	+	+	+	+	(+)	A	N		R
	Laser beam scanners	400 nm - 13 µm	+	+	+	+	-	-	A	I	S	R
	Laser altimeter/ profilers	400 nm - 13 µm	+	+	+	+	-	-	A	N	N	R

Sources: G.A. Rabehevsky 1970, R.G. Reeves (ed.) 1968 and others.

The technology developed in the long history of radar has made it unlikely that there will be any major improvement in the antenna, scan mechanisms, or electronics of purely passive systems. The mechanically scanned system offers the possibility of using multiple feeds for multiple frequencies. This area of multi-feeds does require additional effort. Adjacent feeds at the same frequency allows the scanning of multiple lines similarly to the IR and visible multi-line scanners. As in the case of visual/IR sensors, microwave sensors can be scanned in the object plane with reflectors or by moving the whole antenna (e.g., radar) or in the image plane by moving feeds. They can also have linear, sinusoidal, or conical scan similar to photon imaging sensors.

For mapping or surveying purposes one must assume a vehicle-mounted radiometer and hence a limit on the size of the antenna. Thus, there exists a trade-off between IFOV and frequency, because of the diffraction limit.

This trade-off is not currently evident in the IR and visible because of the energy limit, but will become more important as large linear array systems come into greater use.

4.1.2.2 Electronic Imagers

This class is a series of devices that use electronic scan techniques to read out the latent electron charge image of a scene imaged on a detection mechanism. Included in this class are devices such as:

- Image Orthicons
- Vidicons
- Image Isocons
- Image Dissectors
- Microwave Radiometer
- Dielectric Tape Cameras
- "Push Broom" Arrays
- Phased Array Radar

This class of sensor (vidicon camera) was one of the first to be used in remote sensing of the environment primarily in meteorology. The characteristics of the various kinds of electron beam readout sensors in this class are well known and the diversification of kind can be attributed in part to efforts to overcome difficiencies in an existing kind (e.g., image isocon using scattered return beam electrons rather than reflected return beam electrons as in the orthicon to reduced beam current noise).

In general terms the visual/near IR electron beam readout sensors have higher sensitivities (because of inherent integration and low photoconductor/emitter bandwidths) than single element scanners, but if one were to compare them to an equivalent two-dimensional array of solid state detectors (which is probably not a practical device to build) they would in general be less sensitive because of their lower quantum efficiencies. The negative electron affinity concept* shows great promise for increasing the effective quantum efficiency and hence an ultralow light level detection.

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*R.E. Simon, Quarterly Report No. 17, Contract DA 36-039-AMC-02221 (E).

The disadvantages of these devices are the requirement for a filament and cathode, and intrinsically a two-dimensional imager has shading, blemishes, poor radiometric calibration, poor geometric fidelity (compared to a rotary motion mechanical imager), limited spectral response and difficult spectral separation. It is important to note that each of the above objections have been overcome in given systems, but no one system has overcome them all simultaneously.

In summary, the state-of-the-art of these devices is progressing but is probably near its ultimate limit. However, for applications where a two-dimensional framing imager is needed (geography, cartography, etc.) or ultra-low-light-level capability is required such as in flourescence measurements, this class of sensors still is the simplest and most effective device.

In "push broom" array sensors, a detector array is located orthogonal to the vehicle velocity vector, with the width of scan angle being determined by the length of the detector array. The principal advantage of this arrangement is that there are no moving parts required for scanning since readout along the array is accomplished electronically. Further, the spectral separation mechanism is much simpler. This technique is dependent on large (many thousands of elements) linear array and proper wide field-of-view optics. The technology for these components exists, but the design has not yet been started (unclassified). It is therefore improbable that such an instrument will be available before 1981.

Phased array antennas and orthomode transducers have been developed to operate at frequencies up to 40 GHz with antenna beam efficiencies of up to 90%. Antennas have been made in the size range of 30 meters, for lower frequency arrays.

The principle limitation for larger arrays or operating at higher frequencies is one of mechanical tolerances in the fabrication and assembly of the mechanical parts. To what degree this can be improved in the next few years is uncertain.

One of the drawbacks of electronically scanned phased array antennas is the inability of a given array to operate at more than one frequency at a time. Thus, multispectral sensing requires a separate antenna for each wavelength.

Analogous to a multi-detector array, phased array antennas can also scan a multiple number of beams at one time. This technique has all the advantages of the analogous linear array in visual/IR sensors.

4.1.2.3 Film Cameras

Film sensors will undoubtedly be used extensively over the next few years for earth resources observations, because of a) very high resolution, in essence diffraction limited; b) simple and fast processing to achieve hard copies for the users; c) ease of storage of high density information; and d) relatively low cost.

Film cameras have developed over a very long time, have achieved a very high degree of sophistication and are not likely to see any significant improvement in the next few years. They suffer from many drawbacks such as radiometric accuracy and the difficulty of extracting radiometric data (scanning microdensitometer). Probably the most significant observation is that electronically scanned photosensors are rapidly approaching the resolution of film cameras, and already have achieved their sensitivity.* It is therefore probable that film cameras may be superseded by electronic systems within the next 5-10 years for a large portion of the Earth Resources missions.

4.1.2.4 Non-imagers

This class of sensor has basically the same characteristics as the mechanical imager class (both active and passive) with the exception that there is no scan mechanism. This sensor is generally represented by the early atmospheric profile and heat balance instruments.

Because of the relatively fixed field of view, the data rate requirement is not severe. Therefore, they have been used as spectrometers where the input energy is dispersed into spectral components in a continuous fashion and the output is a function of both frequency and incident amplitude. Spectrometers have been under development for many years and cover virtually the whole spectrum from x-ray to DC. There is little reason to expect a major improvement in the state-of-the-art.

A special type of non-imaging sensor is one that detects audio waves of very low frequency (VLF) and extreme low frequency (ELF) radiation passively.

The short wave part of the VLF region is one of the frequency bands allocated primarily for communication services. Until recently, it was used little for remote sensing purposes. Unlike other spectral regions, this band has received almost no attention from the military. However, rapidly expanding civilian research in this area has lead to operational passive systems already. VLF sensing makes use of frequencies around 20 kHz emanating from distant artificial sources (radio stations). In this spectral region, radiation propagates as ground waves, i.e., it penetrates several hundred meters into the ground and can be picked up again at locations several thousand kilometers distant from the source. The degree of penetration depends not only on the frequency of radiation, but also on the ground conductivity. Low conductivity means deeper penetration.

A system called "Radiophase" (developed by Barringer Research) uses the vertical component of the electric field as a phase reference against which to measure phase changes in the magnetic field. This is based on the fact that the magnetic component is far more affected by the underlying terrain (as a result of eddy currents induced in conductive bodies which in turn produce secondary magnetic fields) than the electric component. Orthogonal receiving coils detect the electric field phase reference. A still more recent development, a spinoff from the above,

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*Note: The sensitivity comparison must be made with same time base; i.e., film camera to a 2 dimensional array with the same exposure time. Film will always be more sensitive than a scanned linear array or point detector.

is called "E-Phase." It operates on the electrical field components. Again the vertical electrical field is used as a phase reference against which the out-of-phase component of the horizontal electrical field is measured. The two systems complement each other in that the former maps effectively ground conductivity, the latter apparent ground resistivity. Surveys are conducted from low altitudes (60-300 m) and applied to ore prospecting, differentiation of rock types, and the analysis of geological structures.

Another system called AFMAG (Audio Frequency Magnetic) used ELF (100-500 Hz) natural EM fields generated by lighting discharges. These discharges behave as vertical antennae and radiate energy over great distances (several thousand kilometers) and with high ground penetration. Similar to the above technique, receiving coils measure the resultant magnetic field.

4.1.2.5 Active Sensors

Active sensors are composed of any one of the other sensor classes and a self-contained source of illumination such as radar, lidar, and flash bulb cameras.

Their application is varied and they are probably the best candidate for the next generation of sensors. One of the more important applications will be the measurement of the scattering in the atmosphere, particularly in the visible spectrum. By time-gating the receiver (radiometer), a profile of scattering versus altitude may be obtained; or by integrating the signal for the entire light travel time to the ground, total backscatter may be obtained, although there is a problem of energy from the earth's surface. Much work is needed in designing specific experiments to determine the best means of making this atmospheric measurement; i.e., pulse durations, angles, IFOV, use of Raman shifted scatter, etc. Tunable sources in both the visible and IR are still in the status of a growing technology and further work is needed in this area.

It should be noted that peak-emitted power systems, such as Q switching, do not improve the S/N of the received signal because as the peak energy is increased, the pulse duration is shortened. Thus, the electrical bandwidth of the radiometer is increased and the integration time decreased.

Holography and synthetic aperture radar are applicable with coherent sources. While the hardware is not technology-limited, it can be complex, heavy and consume much power. Furthermore, there is considerable work to be done in discovering how coherence and the ability to measure phase of the incoming wave can best be applied to Earth Resources Signatures.

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4.2 ATTITUDE CONTROL AND MEASUREMENT

The requirements for attitude control and measurement originate from several characteristics which involve not only the platform and sensors but the ground data processing system as well. Attitude control affects the ability to determine the absolute location of the sensed data. Attitude rate contributes to image smear, and hence affects resolution, particularly in imaging sensors. Control and rate both affect the internal geometry of the sensed data. Attitude control also influences the accuracy of repeat coverage and both rate and attitude are key variables in the ability to point off-nadir and track ground scenes. Off-nadir pointing and tracking includes both entire vehicle slewing as well as the steering of an attached gimballed platform. Hence, selection of attitude control and measurement requirements influence not only the platform/sensor design but also the design of image location and correction techniques in the on-board and ground data processing systems.

Attitude control system design today is a maturing technology providing pointing accuracies to fractions of arc-seconds and rates approaching zero if so desired. The availability of different types of ACS and the wide range of accuracies available permit the ACS on any platform to be selected individually from tradeoffs of system performance versus cost.

Attitude control systems consist of four basic elements:

1. Attitude Sensing Device. Measures errors caused by all disturbance torques and is the major determining factor in ACS accuracy, i.e., systems using earth sensors are inherently less accurate than those using star trackers.

2. Processor. Converts the sensed data into attitude corrections. Either a special purpose device or general purpose computer can be employed and imposes no limits on ACS performance. In systems using general purpose computers, the computer may also be used for other platform functions such as onboard processing, or telemetry formatting. In future systems this approach may have increasing application.

3. Torquing Device. Imparts corrections to the platform. This is a variable in tradeoffs of control, initial stabilization, reacquisition, orbit adjust, and offset pointing.

4. Measuring Device. Measures and reads out the attitude values, usually to telemetry. Many times this is an integral part of the sensing device, although it may be completely separate in certain missions. Measurement accuracy has impact on ground processing.

Figure 4-8 shows the functional relationship of these elements and the various types of hardware devices used in each element.

4.2.1 ATTITUDE CONTROL

Attitude Control systems with pointing capability from 0.03 arc-seconds to 5 degrees have been flight proven, with a wide range of complexity, reliability, flexibility, and therefore cost. Typical systems and missions are identified in Table 4-9. Also listed in the table are some systems which have yet to be flight proven, including Advanced ERTS, which is a paper design indicating how improved pointing could be obtained using much ERTS hardware with minor modifications; a "planned" system with potential for TIROS-N, which is also a paper design with good potential for a low-cost system in that accuracy regime; military Met Sat, which is scheduled to be launched in 1974, and ATS-F, scheduled for 1973 or 1974 launch. In addition, two synchronous orbit communication satellites, SAS A and B, using the biased momentum approach, are planned for launch late in 1975. The tabulation is not intended to be all inclusive, but rather to provide a general overview of available systems.

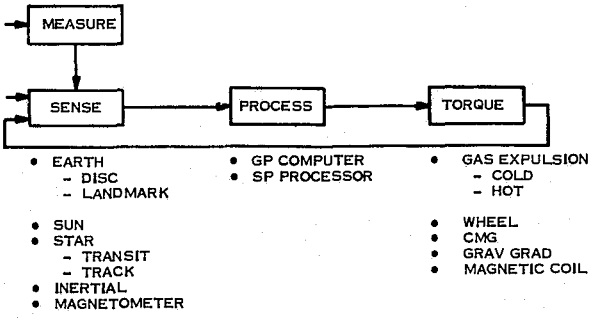

Figure 4-8. Attitude Control Functions and Components

Typical costs and weights of the various systems vary substantially with the life requirement and therefore the redundancies included. They also vary with the operational capabilities provided such as orbit adjust, offset pointing, slewing, handling of disturbances such as solar pressure and on-board uncompensated momentum, orbit eccentricity, initial stabilization and reacquisition capability, orbit injection methods, and mass properties of the vehicle.

Table 4-9. Attitude Control System - State-of-the-Art

Typical System	Type	Sense	Process	Torque	Pointing	Rate	Mission	Status
NRL	Gravity Gradient	Grav	N/A	Grav	<0.09 rad (5 deg) 80% of the time		Military	Flown
Technology	Gravity Gradient	Grav	N/A	Grav	0.009-0.17 rad (5-10deg)		Synch Comm	Flown
Intel Sat IV	Dual Spinner	Sun, Earth	SP	Gas	0.004-0.009 rad (0.25-0.5 deg)		Synch Comm	Flown
ITOS	Biased Momentum	Earth	SP	Wheel, Mag Coil	0.006-0.01 rad (0.35-0.64 deg)	0.0017 r/sec (0.1 deg/sec)		
Planned	Biased Momentum	Earth, Magnet	SP	Wheel, Mag Coil	0.003 rad (0.2 deg)	0.00009 r/sec (0.005 deg/sec)	Earth Obs	Paper Design
SAS A, B	Biased Momentum	Sun, Magnet	SP	Wheel, Mag Coil	0.09 rad (5 deg)	0.00006 r/mm (0.003 deg/min) Avg	ASTRO	Flown
ERTS	Zero Momentum	Earth, Inertial	SP	Gas, Wheel	0.009 rad (0.5 deg)	<0.00017 r/sec (0.01 deg/sec)	Earth Obs	Flown
Adv. ERTS	Zero Momentum	Earth, Inertial	SP	Gas, Wheel	0.003 (0.2 deg)	0.0009 r/sec (0.005 deg/sec)	Earth Obs	Paper Design
OGO	Zero Momentum	Earth, Inertial	SP	Wheel, Gas	0.017 rad,roll,pitch;0.09 rad, yaw 1.0 deg.R,P; 5 deg V)	0.002 r/sec (0.12 deg/sec)	Earth Obs	Flown
Military MetSat	Zero Momentum	Star, Inertial	GP	Wheel, Mag	0.0002 rad (0.01 deg)	0.009 r/hr (0.5 deg/hr) avg	Military	Sched 1974
OAO	Zero Momentum	Sun, Star, Inertial	SP	Gas, Mag	5×10^{-7} rad (0.1 sec);0.0003 rad (1 min)		ASTRO	Flown
ATS-F	Zero Momentum	Earth, Star	GP	Gas, Wheel	0.0017 rad (0.1 deg)		Synch Comm	Sched 1974
Skylab	Mass Expulsion, CMG	Earth, Sun, Star, Inertial	GP	CMG, Gas	0.009 rad (0.5 deg)		Earth Obs/ ASTRO (manned)	Flown

The various types of systems are briefly described in subsequent paragraphs.

4.2.1.1 Gravity Gradient Systems

These systems operate on the principle that point masses closest to the earth will experience a stronger gravitational actuation than those further removed. A dumbbell-shaped vehicle will then tend to be aligned with the major dimension along the local vertical. Dampers enclosed at gravity-gradient rod tips damp out oscillatory motions. Semi-active systems include a momentum wheel at constant speed, which tends to align the axis parallel to the momentum vector with the orbit normal.

These are the least complex systems in hardware (but are complex to analyze). They provide limited capabilities in terms of pointing with accuracies of approximately ± 0.09 rad (5 deg) and no capability for orbit adjust or other maneuvers. Circular orbits are required since orbital ellipticity causes oscillations in attitude. Long settling time constants are typical.

4.2.1.2 Dual Spinners

For roll-yaw stabilization, this system depends on the gyroscopic action of a large drum-shaped section, spinning with the momentum vector norminally normal to the orbit plane. A de-spun section, mounted on a bearing, allows pointing of this section to the earth (or elsewhere). Attitude of the spin section is determined from fixed earth and/or sun sensors, and is corrected after ground determination, by ground control of mass expulsion thrusters. The de-spun section attitude is autonomously controlled (about the bearing axis). Some form of damper (active or passive) is required for damping out nutational motion. Although capable of controlling orbit adjust disturbances, no capability exists for north-south off-vertical pointing. Mass properties must be closely controlled, and power (derived from solar cells mounted on the periphery of the drum) is limited by shroud volume limitations. While relatively simple in concept, the bearing is a source of potential single point failures, and the mass property requirements often make the basic system inherently unstable. This is the least complex of the active satellite attitude control systems but only of moderate accuracy with pointing in the range of 0.004 to 0.009 rad (0.25 to 0.5 deg.)

4.2.1.3 Biased Momentum Systems

As a class, these systems are similar mathematically to the dual spin systems, with an internal momentum wheel replacing the drum of the dual spinners.

The ITOS system uses a relatively large, low speed wheel, which has optical devices attached to facilitate earth horizon scanning for attitude determination. Modulation of wheel speed controls pitch error, while precession to correct roll error, and momentum unloading, are accomplished by ground controlled magnetic coils. A fluid damper reduces nutation to a threshold value. The system is relatively simple, but incorporates no mission flexibility for such requirements as orbit adjust or slewing. Acquisition and local vertical pointing capability is provided, with some roll offset capability.

The Planned Bias Momentum System refers to a proposed scheme similar in a sense to ITOS, using two small scan wheels, which provide improved horizon sensing as well as momentum bias and pitch control. Closed loop magnetics, using a magnetometer for field sensing, provide momentum unloading, roll precession, nutation damping, and autonomous initial stabilization. While limited orbit adjust capability is inherent, the system, like any biased momentum system must be carefully designed to assure adequate pointing accuracy in the presence of external and internal disturbances. Limited acquisition, local vertical pointing and limited orbit adjust capability is provided.

The SAS series of small astronomical satellites use a single wheel with ground controlled magnetics. Attitude is remotely determined from magnetometers and a digital sun sensor. The spacecraft is operated in a scan mode, with magnetic control of scan rate. As in each of the biased momentum systems discussed, no expendables are required. This is a very simple system, providing adequate accuracy for the mission at low complexity and weight costs. The orientation of the momentum vector may be precessed to any inertial direction.

Other biased momentum systems are in development which will operate at synchronous altitude, where magnetic control is deemed unproven. These systems must depend on mass explusion for momentum unloading, and various means are proposed for nutation and precession control, including the use of an additional wheel and gimballed wheel configurations, as well as pure mass explusion. They are obviously more complex than the magnetic systems, but offer somewhat more flexibility in terms of mission functions. The pointing accuracy of all biased momentum and dual spin systems is dependent on the amount of stored momentum versus the disturbances and is typically in the range of 0.003 to 0.09 rad (0.2 to 5 deg.) When very accurate pointing is required, the weight of the wheel becomes excessive as compared to the nominally zero momentum systems.

4.2.1.4 Zero Momentum Systems

These systems are characterized by the use of three orthogonal reaction wheels, which store the integrated disturbance torques until unloaded through some external torquing device. Each of the three axes requires attitude sensing capability. In storing the momentum, no error buildup is necessary, as opposed to the biased momentum systems, where roll and yaw disturbances generate a yaw error proportional to the ratio of the integrated disturbances to the momentum bias. The additional control functions required for the zero momentum system introduce a higher complexity factor; however, when acquisition functions are considered, the complexity tends to equalize with that of biased momentum systems. Since this class of system is chosen to meet both stringent accuracy requirements and maneuvering requirements, the total complexity depends on the mission assignment.

The ERTS control system consists of a pair of roll scan wheels for pitch and roll attitude sensing and roll momentum storage, a gyrocompass for yaw sensing, pitch and roll reaction wheels, 3-axis mass expulsion capability for momentum unloading and initial acquisition, a yaw rate gyro to facilitate initial rate removal, and the necessary signal processing. Acquisition capability removes initial rates up to 0.09 rad (5 deg) per second, from any attitude. Oriented solar arrays provide maximum efficiency in power collection. Local vertical pointing, orbit adjust, and aceuisition from relatively large initial conditions are provided.

Advanced ERTS is a proposed system, similar in many ways to the ERTS system, but including an improved horizon sensor and processing to provide a more stringent accuracy of 0.0035 rad (0.2 deg.)

The OGO system is quite similar in nature to ERTS. Used in a highly elliptical orbit, a more sophisticated earth sensor is required.

ATS-F is a synchronous orbit communication satellite, whose control system is capable of operating with a number of experimental sensors. In addition to local vertical pointing, offset pointing, slew capability, and tracking of a lower altitude satellite is accommodated. Orbit adjust capability is included. The system is quite complex (includes a general purpose computer) due to the many operational modes required. Basic sensing includes an earth sensor for roll and pitch error determination, and a Polaris sensor for yaw control. Monopulse and interferometer inputs provide control to RF sensors. Both digital and analog processing is used.

OAO is an inertially-oriented system providing the most stringent accuracy performance ever obtained, and requiring the most complex control system orbited to date. Accuracies of 5×10^{-7} rad (0.1 arc-seconds) have consistently been maintained for up to one-half-hour intervals. The sensor complement includes four sets of sun sensors of three types, up to six star trackers (of both the mechanically and electrically gimballed types), three sets of gyros, complex digital as well as analog processing, and six reaction wheels in two sizes. Inertial, star, and sun controlled modes are available, as well as slewing capability. Both mass expulsion for initial stabilization and momentum dumping, and magnetic control for dumping, are included.

4.2.1.5 Military Met Sat

The control system for this highly accurate local vertical pointing system depends on a star detector and a strapped down inertial reference unit for attitude sensing. Translation of the reference from inertial to a rotating orbital reference is accomplished in a general purpose digital computer. Magnetic torquing provides the momentum unloading function. Full acquisition and reacquisition capability is included. Aside from the computer, the system is of medium complexity, since many functions (such as stored magnetic field data and control law implementation) are accomplished in the computer.

4.2.1.6 Mass Expulsion, CMG Control

Two basic types of control devices are combined in this paragraph only because they are exemplified by a single system - Skylab. (An additional example of a purely mass expulsion system is the Mariner series of planetary missions.) The Skylab system uses earth, sun, and star data to update an inertial reference stored in a general purpose computer, with short-term reference supplied by an inertial reference unit. The basic control loop uses hot gas mass expulsion in a limit cycle mode. CMG devices provide a precise control. Illustrating the dependence of weight on mass properties, the system includes three gimballed CMG's, which each weigh on the order of 300 pounds. Being man-rated, the system is complex in terms of the number of redundancies and work-arounds provided to preclude failure. Accuracy is within ± 0.009 rad (0.5 deg) in all three axes.

4.2.2 ATTITUDE MEASUREMENT

The several attitude determination systems listed in Table 4-10 are representative of the current state-of-the-art. ERTS provides ground attitude determination in 3-axis by telemetry of yaw sensor outputs as well as the pitch and roll error signals of an attitude measurement system. After ground processing, these data yield attitude determination to an accuracy of ± 0.0017 rad (0.1 deg) (3σ).

Table 4-10. Attitude Measurement Systems State of the Art

Typical System	Measurement Method	Typical Accuracy	Status
ERTS	Pitch/Roll - passive Horizon Sensor Yaw = Roll	±0.0017 rad ($\pm 0.1^\circ$)(3σ)	Flown
SAS	Star sensors scanned by S/C Rotation	±0.0052 rad ($\pm 0.3^\circ$)(3σ)	Flown
OAO	Star trackers, sun sensors, magnetometers	$\pm 5 \times 10^{-7}$ rad (± 0.1 Sec) (1σ)	Flown
PADS	Star tracker with strapped down inertial meas. unit	> $\pm 1.7 \times 10^{-5}$ rad ($\pm 0.001^\circ$)(1σ)	Eng Devel. Available post 1975
MIL. METSAT	Strapped down inertial meas. unit with strapped down star detector	$\pm 1.7 \times 10^{-5}$ rad ($\pm 0.001^\circ$)(1σ)	Available 1974
—	Strapped down star sensor with gimballed platform mounted set of gyros	$\pm 1.7 \times 10^{-5}$ rad (0.001°)(1σ)	Not under Development

The SAS and OAO systems utilize data from on-board sensors for attitude determination, the former from star sensors scanned by spacecraft rotation, and the latter from a variety of sources including star trackers, sun sensors, magnetometers, and experiment pointing error data.

The PADS system is in the engineering development stage. Using a highly accurate gimballed star tracker together with a strapped down inertial measurement unit, data is obtained which allows attitude determination to a projected accuracy of about 1.7×10^{-5} rad (0.001 (1σ) deg). The system will not likely be flight demonstrated by 1975.

The attitude sensing of the Military MetSat is a derivative of the Air Force sponsored SPARS system. A strapdown inertial measurement unit together with a strapped down star detector, operating in a space platform which rotates in inertial coordinates at a rate on the order of one cycle in 120 minutes, provides data which could be used to determine spacecraft attitude to about 1.7×10^{-5} rad (0.001 (1σ) deg). Although the system is scheduled to be launched in 1974, it is not presently known whether its attitude determination capability will be tested. This is the nearest system to production but the least likely to meet the accuracy goal of 1.7×10^{-5} rad (0.001 deg).

A conceptual system has been identified as potentially the most accurate of those discussed, but which is not currently under development. It consists of a strapped down star sensor and a gimballed platform-mounted set of advanced gyros.

Each of the latter three systems achieves attitude knowledge based on stellar information, which yields excellent results for inertial orientation. When translated to Earth-referenced attitude, the direction of pointing may be determined accurately. However, relating the direction of pointing to geographical coordinates depends on accurate knowledge of spacecraft location (ephemeris), which, with these determination accuracies, becomes the limiting factor in determining absolute location of the spacecraft.

4.2.3 REFERENCES

1. The stellar inertial reference information is based on MIT-Draper Labs Reports E-2630 and E-2651, by Ogeltree, Coccoli, McKern, Smith, and White.

4.3 ELECTRICAL POWER

The electrical power system, a major support element on all earth resources platforms, is a relatively mature technology area, adequate for today's missions. Its importance in the state-of-the-art assessment is because many of the 1978-82 vintage sensors, especially radars, will require power levels considerably in excess of today's sensors.

The Shuttle System Payload Data (Ref. 1) was used as the primary guide to future spacecraft power levels with reference also made to the NASA Mission Model (Ref. 2). Table 4-11 summarizes the power needs as extracted from the Shuttle payload data with the needs ranging from 140 to 2600 watts. All of these requirements can be met with today's technology; hence, the selection of power systems for any given platform will be primarily a performance/cost trade for that particular mission. It must be recognized, however, that the size of the power system necessary to satisfy future requirements may create problems in areas other than in the electrical power system itself, such as:

1. Deployment Mechanism. The mechanical devices necessary to deploy large arrays.
2. Large Arrays Plus Large Antennas. Arrangement on the platform plus the effects on the attitude control system of disturbance torques (drag, solar pressure) created by these large appendages.
3. Obscuration. Obscuration of fields of view of sensors or coolers by the large arrays.
4. Large Battery Banks. Location and balance on the spacecraft of large battery banks to support peak power demands of sensors.

The basic functions of the power system are shown in Figure 4-9. Subsequent paragraphs describe the methods of implementation of the first two of these functions, source and process/control. The third function, distribution, is unique to the given platform and is not described.

Table 4-11. Summary of Future Earth Observation Power Requirements

	Beginning of Life Power (w)	End of Life Power (w)	Average Power (w)
Geosyn Oper. Meteor. Sat. (GOMS)	-	140	-
Foreign Synch. Meteor. Sat. (FSMS)	-	140	-
Earth Res. Survey Oper. Sat. (ERSOS)	550	-	-
Synch Earth Obs. Sat. (SEOS)	557	402	-
Earth Obs. Sensor Dev. Lab	-	-	2600 (4600 W peak)
Tracking & Data Relay Sat. (TDRS)	466	400	
Earth Observatory Sat. (EOS)	-	-	1000
TIROS O			1000
Environ. Monitoring Sat.	-	-	1000
Synch. Met. Sat. (Advanced) (SMS)	900	650	-
Small Applic. Tech. Sat. (SATS)	-	-	490 (1000 W peak)

4.3.1 SOURCES

The available basic sources for spacecraft power are nuclear, solar, radioisotope, or reactant chemicals (battery or fuel cells). All but nuclear are viable contenders to power long-life, durable, space-qualified power systems on earth observation platforms. A representative state-of-the-art summary is given in Table 4-12 for RTG, battery/solar cell, and fuel cell systems.

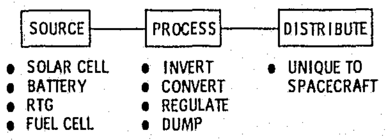

Figure 4-9. Electrical Power System Functions

4.3.1.1 Solar Cell/Battery Power Systems

The battery in a combination solar power/secondary battery energy system provides power during peak demands and during orbital night. The life of the system is limited by the cyclic life capability of the battery which is a

Table 4-12. Power Systems State-of-the-Art Summary

Type	Typical Systems	Mission	Status	Power Capability
Battery/	Fixed Array	Skylab	Flown	7.2 kw
Solar Cells	Rotating Arrays	ERTS	Flown	250 Watts
RTG	SNAP-19	Nimbus III	Flown	25 Watts
	SNAP-27	Apollo	Flown	70 Watts
	Multi-Hundred Watt	LES 8 Mariner Jup/Sat	In Development Available 1975	150 Watts
	Brayton, Rankine Sterling, Thermal Electric	Advanced	Paper Studies Available 1977	400 Watts
	Multi-Kilowatt	Station Base	Paper Studies Available Post 1980	1000 Watt Modules
Fuel Cells	One Stack H_2O	Biosatellite	Flown	0.3 kW
	Three Stack H_2O	Gemini	Flown	1.0
	Seven Stack H_2O	Apollo	Flown	2.5

function of the type of battery, the thermal control, and the depth of discharge. The solar power conversion mechanism which provides the highest efficiency is the semiconductor solar cell which converts the light photons of solar energy via the photovoltaic effect to provide 100 to 140 watts per square meter of solar cells. Inefficiencies and periods of eclipse reduce the orbital average power to only about 30 to 50 watts per square meter. Power subsystem technology is available to build larger array/battery systems to provide the power needs of several kilowatt systems if not constrained by weight or volume. This technology has reached maturity and only minor refinements in the materials area are anticipated.

Photovoltaic power sources (solar cells) are typically a group of thin, rectangular, light converting semiconductor elements which produce dc power at a fraction of a volt and tens of milliamperes per square centimeter of illuminated cell. The individual cells are matrixed into an array to supply the spacecraft power needs.

The power output per square meter of sun oriented solar array is given by:

$$P = SZ\, N_{sc}\, N_t\, N_c\, N_u\, N_m\, N_{me}\, N_s\, N_{rd} \cos\theta$$

Where:		Typical Values
$P =$	Power Output, Watts/m^2 = $(22.9 - 0.247T)\ 10.76$	= 96.8 Watts/m^2
$S =$	Solar Intensity, Watts/m^2	= 1399

Z = Packing Factor = 0.9

N_{sc} = Efficiency of Bare Cell (Free Space + 85°F) = 0.11

N_t = Temperature - Efficiency Dependence of Solar Cell = 2.417-0.0026T (T is in °R)

N_d = Actinic Transmittance of Filter = 0.92

N_u = Ultraviolet Degradation Factor = 0.95

N_m = Manufacturing Loss Factor = 0.97

N_{me} = Micrometeorite Loss Factor = 0.95

N_s = Solar Constant Variation Factor = 0.966

N_{rd} = Radiation Degradation Factor = 0.95 (185 Km 1 year life)

θ = Array Tilt Angle (Measured from perpendicular to sun's rays) = 0 (θ assumed to be 0° for solar array drives)

Solar cells are susceptible to damage by several hazards of the space environment. Micrometeorite impact will degrade individual cell performance, but this could be protected against by increasing the cell cover glass thickness.

Ultraviolet discoloration of cements used to attach sapphire or quartz type cover glasses to cells cause some output power degradation, although these materials show high resistance to darkening under strong ultraviolet light.

Solar cells are affected by temperature, but at 25°C about ten percent of the 1400 watts per square meter of solar energy can be converted directly to electrical energy. Higher temperatures yield substantially lower output from each cell as shown in Figure 4-10.

Solar cells are sensitive to nuclear radiation, experiencing typically a 0.2 percent or less loss of available current per day. For missions in radiation belts in excess of fifty days, solar cells must be protected by glass or other filter material to reduce degradation to acceptable levels. Protective coatings also can be used to reduce by reflection thermal energy otherwise absorbed from the sun. However, these filters restrict the useful operating range of the panel to incident angles more nearly normal to the cell surface, and protected cells have a fall-off of available current that is higher than predicted by a simple cosine function.

As the angle of incidence of sunlight on a panel of solar cells increases, the power output decreases both as a function of the cosine of the angle (effective light intensity decrease) and also as a function of the reflectance increase of the cell coverglass (4 percent at small angles to 100 percent reflectance at grazing incidence). Since the angle of incidence changes throughout the orbit, the orbit average power is considerably less than maximum output power. Therefore, tradeoff studies must be performed for each mission to determine if a solar array drive is required to continually orient the solar cell panels during the sunlight portions of the orbit. For example, in a 9:00 a.m. sun-synchronous orbit a fixed array generates only 50-60 percent of the power available from an oriented array. For a given mission requirement the fixed array must be correspondingly larger.

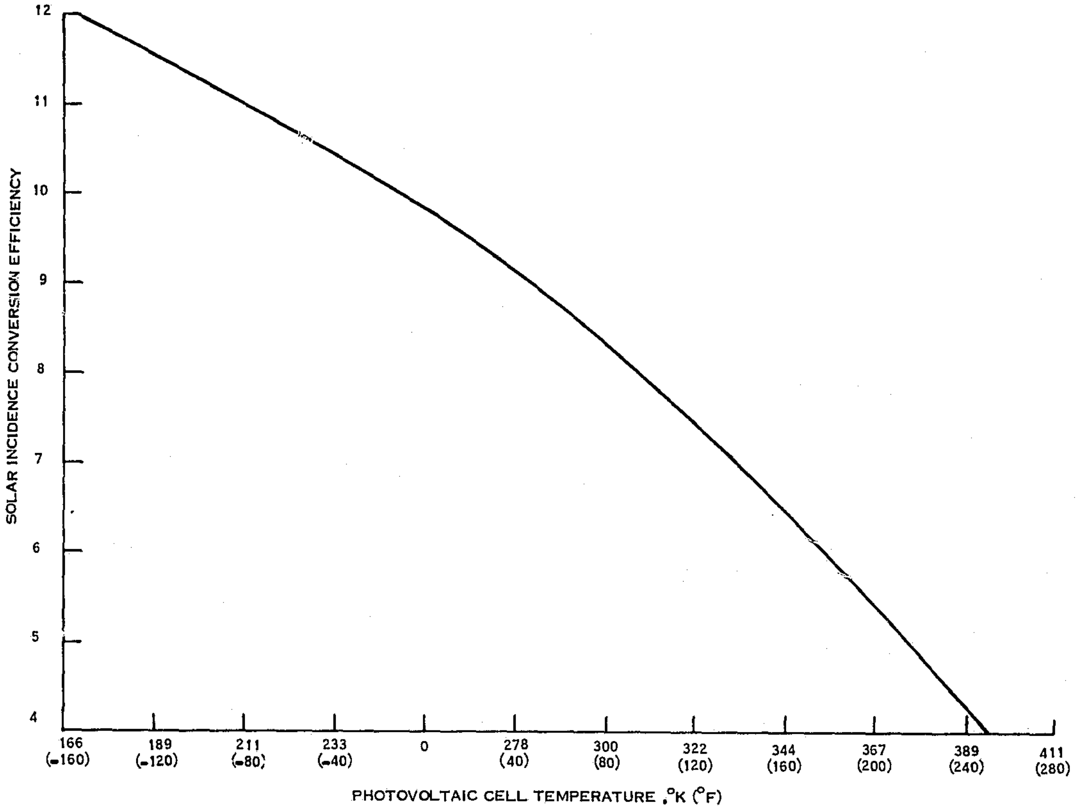

Figure 4-10. Thermal Degradation of Conversion Efficiency

Low inclination orbits would require constant reorientation of the solar panels through wide arcs to maintain orthogonality with the sun line. A circular sun-synchronous orbit permits the most efficient solar power/secondary battery system since the solar array can be maintained nearly orthogonal to the incident sunlight.

Weight is generally the forcing function of state-of-the-art solar array power systems. Costs can be reduced by approximately 25 percent for a 30 percent increase in weight by substituting standard solar cells for super premium cells, substituting a heavier, less complex array structure, increasing array thermal control, and increasing the solar cell cover glass thickness. However, this will not be the case through 1975 since platforms cannot afford the additional weight penalty.

Solar array costs vary somewhat, but studies have set the cost at $32,000 per square meter. This cost includes super premium cells, glass, and laydown at $27,000 per square meter and honeycomb substrate at $1100 per square meter. Array drive costs (if required) are approximately $100K. The array weight is 5.4 Kg/m^2 (1.1 pounds per square foot) and an array drive weights about 11Kg (25 pounds).

4.3.1.2 Radioisotope Thermoelectric Generators

The combination of a radioisotope heat source and a thermoelectric converter is referred to as a Radioisotope Thermoelectric Generator (RTG). An RTG has the capability to produce dc electric power continuously at a rate which is predicted from the radioisotope "fuel" decay rate and without either a continuous supply of consumables (reactants, fuel, etc.) or the removal of material wastes. A thermoelectric power supply utilizes a converter placed between a heat source and a heat sink to convert heat directly to electricity. The conversion device utilizes a series of thermocouples, usually of a semi-conductor material such as lead telluride or silicon germanium for high efficiency. The volume between thermocouples is filled with insulation to force most of the heat to flow through the thermocouples. The assembly of thermocouples, insulation, and their associated support structure is referred to as a thermopile. Normally the support structure doubles as the heat sink, or "waste" heat radiator, and is designed to maintain a specified temperature with a specific "waste" heat input. The thermoelectric power supply then has the capability of producing power whenever a heat source is present.

A logical combination with the static converter is a static heat source; specifically, a radioisotope heat source. Radioisotopes continuously generate heat due to the radioactive decay process. This process is governed by the particular radioisotope's half life and, thus, is completely predictable and solely a function of time. The heat source is formed by encapsulating the radioisotope in a manner so as to provide both a means for handling and effective utilization of the radioisotope heat and also protection to the environment in the event of an accident, since radioisotopes are basically toxic materials.

The RTG is generally characterized by both the radioisotope fuel and the type of thermoelectric material utilized. The radioisotopes which lend themselves to RTG applications are plutonium, polonium, curium, strontium, and cobalt; some of whose properties are provided in Table 4-13.

The Multi-Hundred Watt Radioisotope Thermoelectric Generator, presently under development for LES 8 and the Mariner Jupiter/Saturn missions, has a specific weight of 3.7 watts per Kg, provides approximately 150 watts, and measures approximately 30 cm in diameter by 51 cm long. This unit is today's state-of-the-art, will be available in 1975, and will be the basic workhorse for RTG systems for several years thereafter.

The RTG continually supplies full design power to the spacecraft irrespective of sun angle or spacecraft orbit and is very reliable since it is a static system. Solar array drives and paddles, batteries and much regulating equipment can be eliminated from the power subsystem. Spacecraft attitude control requirements are reduced due to the elimination of array drives and paddles. Power degradation is a gradual and predictable occurrence. Operational power is available from the RTG on-pad for systems checkout and during launch.

The RTG system is not without disadvantages, however, in that the system costs several times more than a solar cell/battery system. The Atomic Energy Commission is anxious to help fund and develop RTG's and individual system cost must be negotiated. The cost of a radioisotope thermoelectric generator is generally lumped into two subdivisions: radioisotope fuel costs and generator costs which includes thermopile, heat source capsule, and ground and checkout equipment. These two costs are interactive and are highly dependent on the radioisotope selected. Clean isotopes (plutonium) require less shielding and result in lower generator costs. If RTG systems could be recovered in space (e.g., shuttle mission), the higher initial cost could be amortized over several programs.

Table 4-13. Candidate Radioisotopes

Element	Mass Number	Half-Life -Years	Effective Power Density - watts/CM^3	Chemical Form	Approx. Fuel Cost Ratios
Cobalt	60	5.3	15.2	Metal	.015
Plutonium	238	87.0	4.0	Oxide	1.00
Curium	244	18.00	22.0	Oxide	.148
Strontium	90	28.8	1.5	Oxide	.022
Polonium	210	0.38	800	Rare Earth Polonide	.030

Other disadvantages are handling hazards, complex test procedures and stringent thermal controls. Additionally, the RTG is a power-limited source, and a battery may be required for widely varying loads or for pulse or transient conditions in excess of RTG steady-state capability.

R&D effort is currently being pursued by the AEC on several advanced isotope fueled systems including Rankine cycle, Brayton cycle, Sterling cycle and thermal electric type systems. These systems are expected to deliver 400 watts with a weight of between 80 to 90 Kg. Current planning is to narrow the choice to one type of system by mid-1975 and begin component development at that time. Flight unit availability would be in the 1977-78 time period.

4.3.1.3 Fuel Cells

A fuel cell is an electrochemical process to convert an inorganic consumable fuel to electrical power at a variable and controllable rate. There is a fixed installed capacity to do work with an initial weight penalty that includes the converter, the fuel and its tanks, and all the necessary circulatory and environmental controls. It is similar to an electrochemical battery, but in the fuel cell the chemical electrodes are constantly replenished from external storage, and the by-products are constantly removed. The useful life of the fuel cell is thus limited by the amount of chemicals in storage.

A typical fuel cell consists of a pair of electrodes and electrolyte, catalysts, fuel manifolds and electrical leads. Fuel cell efficiencies range from 20 to 80 percent, depending on the fuel and the design. For space applications, pure hydrogen and oxygen are fed to opposite sides of an electrolyte, and a reaction occurs which results in the formation of water and the generation of electrical power. Since typical operating voltages are 0.7 and 1.0 volt per unit cell, a number of them are connected in series and then enclosed in a case commonly called a stack.

The fuel cell is a relatively complicated system, requiring tankage, plumbing, regulator and relief valves, an active coolant loop, and cyclic purging to remove impurities. The disadvantages are the sophisticated ground tankage, cooling and loading problems involved with the liquid hydrogen and oxygen, pre-launch pressurization of tankage, continual topping or venting during on-pad hold, with venting, purging and cyclic reloading a possibility. There is a necessity for an active coolant loop to remove the thermal burden, although the water by-product can be used as an evaporative coolant. Tank heaters may be necessary to generate gas at the proper rates, or loss of fuel by venting might occur if the tank heat leak rate generates gaseous fuel faster than it is being consumed. The system has a high specific weight at high power levels, large volume and weight penalty for missions of greater than about one month, and may require micrometeoroid protection for the cooling system and its radiator. There is a minimum power point because of the minimum fuel flow rate that can be controlled by the regulator valves. A 1kW system weighs about 135 Kg plus about 0.7 Kg per kWh for fuel and tankage.

The integrated system requires no vehicle orientation and is relatively impervious to hazards of space environment such as Van Allen radiation, weapons effects, and solar flares. Fuel cells generating 2.5 kilowatts have recently flown on Apollo missions.

4.3.2 POWER PROCESSING/CONTROL

4.3.2.1 Processing

Power processing is a mature technology with fairly straight-forward design trade-offs required for each spacecraft configuration as a function of power levels, operating voltages, and duty cycles of the loads, plus orbit considerations (batteries required for night operations, etc.). The major emphasis in processing in the future will be modularization, optimization and standardization of components. NASA/Lewis, for instance, has just awarded a contract (NASA LRC 3-490720) to develop a Multi-Kilowatt Modularized Spacecraft Power Processing System.

Several choices are available for the arrangement and type of hardware used in power processing systems. Figures 4-11 through 4-14 are simplified block diagrams of alternatives for solar cell/battery power systems, and are typical of today's state-of-the-art. Table 4-14 indicates advantages and disadvantages of the various approaches.

1. Unregulated Bus (Figure 4-11). With this approach the distributed bus voltage varies over a considerable range, since it must be about 1.5 volts higher than the highest battery charge voltage at one extreme and about 0.5 volts lower than the battery discharge voltage at the other extreme. The user subsystems must perform any regulation required to utilize the distributed power, which can be a good approach if the major power loads require unique voltages or tight regulation. The early NASA Applications Technology Satellites used load switching devices successfully. Generally, however, the spacecraft service and payloads require some regulation, and most spacecraft have a 2 percent regulated bus with any special power processing required performed at the load, as described in subsequent paragraphs.

2. Buck-Boost Regulated (Figure 4-12). This alternative places a PWM buck-boost regulator in the line to the user loads providing a regulated distributed voltage. Thus, a centrally-located regulator provides this function for all user subsystems. Generally, the total system weight may be reduced since a single, large regulator may be built to be lighter and more efficient than many small regulators, and the voltage converters associated with the loads may be simplified depending on the individual load regulation requirements. Redundancy is also more easily applied to a central regulator.

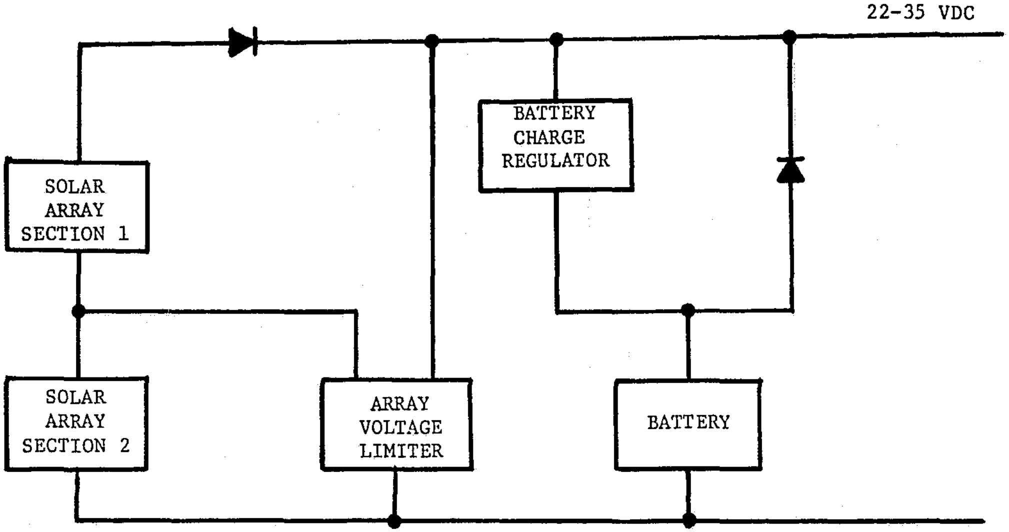

Figure 4-11. Unregulated Distribution Approach

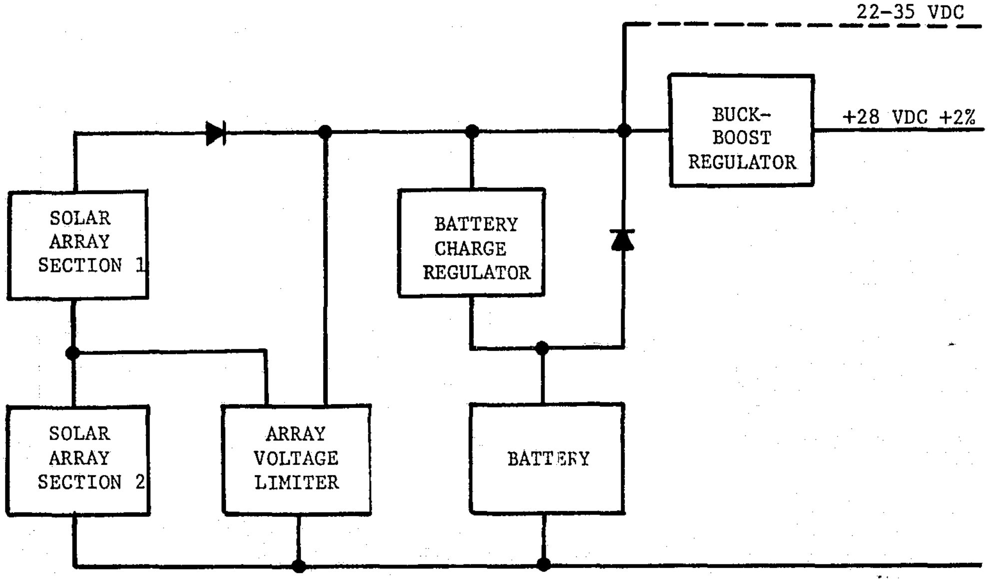

Figure 4-12. Buck-Boost Approach

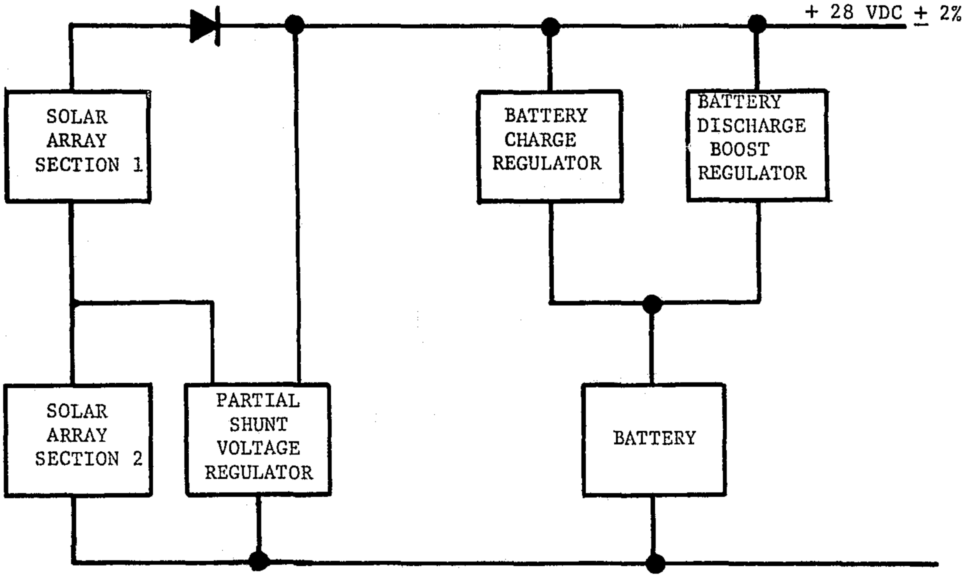

Figure 4-13. Shunt-Boost Approach

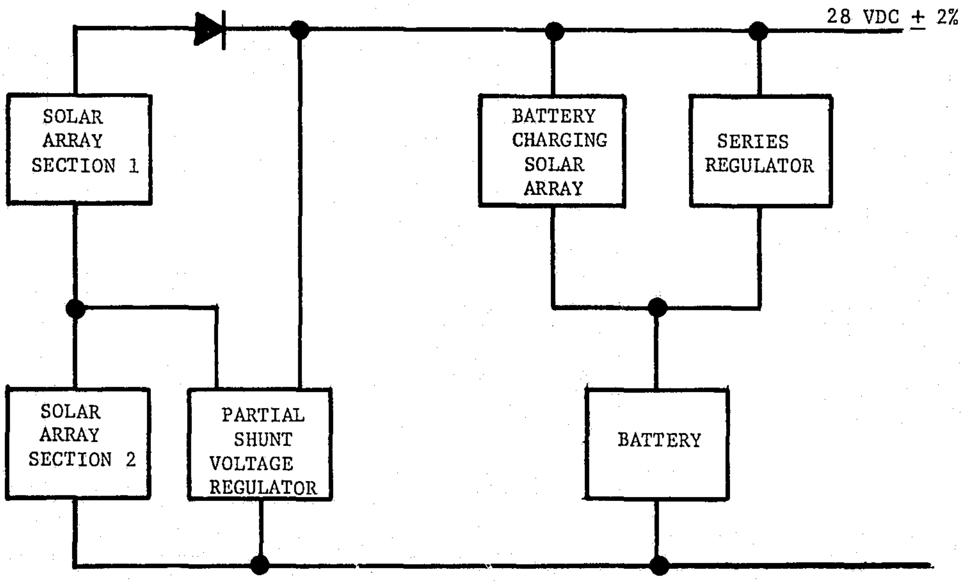

Figure 4-14. Shunt-Series Approach

Table 4-14. Comparison of Alternative Subsystem Implementation Approaches

Alternative	Advantages	Disadvantages
Unregulated	1. Lowest weight 2. Redundancy easily applied	1. Loads must provide own regulation 2. Overall power conversion efficience is lower than Alternative 3
Buck-Boost	1. Regulated bus + 2% 2. Able to operate with low battery discharge voltage	1. Overall power converions efficiency is lower than Alternative 3 2. EPS weight higher than Alternative 1 3. In-line regulation loss
Shunt-Boost	1. Regulated bus + 2% 2. Highest overall power conversion efficiency 3. Able to operate with low battery discharge voltage	1. EPS weight higher than Alternative 1
Shunt-Series	1. Regulated bus 2. Quieter bus than Alternatives 2 and 3	1. EPS weight higher than Alternative 1 2. Large number of series cells required in battery 3. Overall power conversion efficiency is lower than Alternative 3

3. Shunt-Boost (Figure 4-13). This alternative is a regulated direct energy transfer approach which utilizes a boost regulator between the battery and the regulated bus. The bus regulation is maintained within ± 2 percent by the controlled operation of the boost regulator, battery charge regulators, and the shunt regulator. This approach offers the advantages of a distributed regulated voltage without the in-line loss associated with the buck-boost configuration. The boost regulator represents a source of loss only during satellite night operation. During satellite day, the solar array power is transferred directly to the loads without an in-line regulation penalty. The shunt regulator operates only to dissipate excess power.

4. Shunt-Series (Figure 4-14). This alternative utilizes a small, separate portion of the solar array to charge the battery. The charging array adds to the main bus voltage to generate the battery charging voltage, and the inherent voltage-current characteristics of the array acts to limit the charge current. There would, in practice, be a separate set of charging arrays for each battery. The battery may discharge onto the main bus through either a switch or a series regulator. The series regulator would be the preferable choice, since the proper coupling of the series regulator with the partial shunt regulator will result in a regulated bus.

   One advantage of the shunt-series approach is a less noisy bus which results from the use of nonswitching (dissipative) regulators. Fewer parts are required since the battery charging arrays are self-limiting.

   Disadvantages are the large number of series cells required in the battery and the large losses in the series regulator. The use of a series regulator places an absolute lower limit on the allowable battery terminal voltage. Sufficient margin must be allowed for battery degradation, series regulator saturation voltage and diode voltage drop. When the battery is new, the dissipation in the series regulator is high and the regulator is inefficient.

Fuel cells would either be used as raw voltage with a wide variation, or with an in-line switching regulator for tighter regulation. A Radioisotope Thermoelectric Generator (RTG) degrades with increasing temperature and operates optimumly at constant power. The power processor selected to achieve the source conditioning is typically a transistorized shunt regulator which operates the RTG at constant voltage and, hence, constant power to maintain constant Peltier cooling for a variable real load demand.

4.3.2.2 Control

The power processing control category covers a wide range of functions, all within today's state-of-the-art. Bus voltage is sensed and compared with a stable reference. The error signal is then amplified and combined with other logic such as shunt current, load current, etc., for use to select modes of source operation, to control voltage regulating converters, and, in some cases, to assign critical user load sequencing as in the Fleet Satellite Communication System. In this program, the electrical system design requirement is to sense instantaneous source power capability and automatically cycle power amplifiers on a demand basis to provide the maximum transponder output power at all times for communications without jeopardizing the needs of the base load critical housekeeping subsystems. This technique provides automatic maximum use of available solar array power without endangering the minimum functions necessary to operate the spacecraft itself. Other processing control priorities are implemented to use constant power sources such as solar arrays, isotopes, and reactors first, to replace energy storage (batteries and fuel cells) if excess power exists, and to draw from energy storage when the constant power is inadequate for the load.

Battery charge and discharge monitoring functions are complex and require specialized treatment which is a function of orbit altitude, duty cycle, depth of discharge and battery characteristics.

A special-purpose or general-purpose On Board Computer (OBC) can be used to monitor and control the spacecraft energy balance when using a solar array and battery. The computer can calculate power usage for fault determination and telemetry warnings and status. General status monitoring of an array of switch positions or mode select indicators can also be assigned to the computer.

4.3.3 REFERENCES

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2. Tug Operations and Payload Support Study Contract NAS 8-28876.

3. U.S. Air Force Design Guide.

4. Notes from Big Meadows Workshop on Large Solar Cell Power System Technology, Oct. 5-9, 1969.

5. Subcommittee on Power Conditioning, NASA Research & Technology Advisory Committee on Power and Electric Propulsion - Report on Electric Power Processing Technology, August 1971.

6. RTG Handbook - Voyager Task C.

4.4 COMMUNICATION SYSTEM

The Communication System provides the satellite equipment for telemetry and command, and also provides the link for the return of sensor data to the ground stations. Although conventional system approaches can fulfill all of the anticipated telemetry and command needs, new satellite equipment and techniques as well as added ground station capabilities are required to satisfy the high data rate requirements well in excess of 100 Mbps expected in the Shuttle Era. The standard telemetry frequency bands at S-band and below do not provide adequate bandwidth for data rates in excess of about 60 Mbps so that antennas, power amplifiers and receiver preamplifiers at X-band or higher are required. The trade between transmitter power and antenna gain to achieve the high effective radiated power (ERP) needed to support high data rates will impact satellite power, thermal control and attitude control subsystems, and satellite and launch vehicle configuration. The potential use of the proposed Tracking and Data Relay Satellite (TDRS) would requ higher satellite ERP while giving the advantages of real time data return from beyond the continental U.S.

Although the use of X-band or higher frequencies for data transmission is new, many of the components required are already space-proven for other applications such as communication satellites, and development is underway of the techniques and components required for data transmission at rates up to the order of 1000 Mbps.

The Communication System, Figure 4-15, includes the telemetry subsystem for transmitting narrowband housekeeping and ancillary data and the command subsystem for receiving command data. The command receiver and telemetry transmitter also support the tracking function for satellite orbit determination. A broad beam, body-fixed antenna is preferred for the link with the ground network so that coverage is provided throughout the mission including orbit insertion and station keeping maneuvers, if called for by the mission profile, and in the event of abnormal attitude control operations. VHF and S-band frequencies are currently used, with changeover to totally S-band in the future now a firm goal. If real time relay through a TDRS is used, signals may share the high gain narrow beam antenna which supports wideband communications

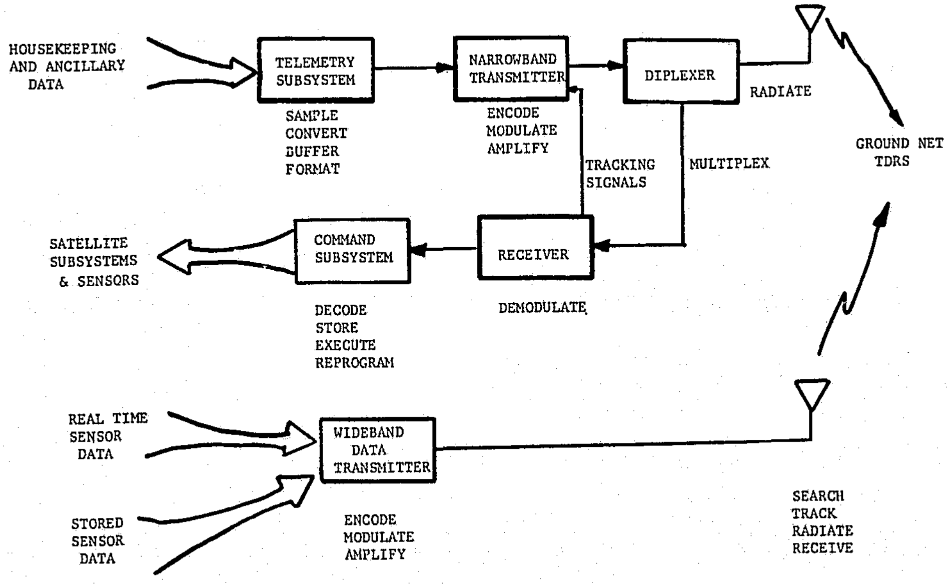

Figure 4-15. Communications System

The Wideband Data Subsystem accepts real time or stored data from the payload sensors and transmits the data directly to ground stations or relays it via the TDRS. Wideband data rates considered are in the range of 30 to 500 Mbps. X-band (8 GHz), Ku band (15 GHz) or even higher frequencies may be used. Optical links using lasers are being evaluated by NASA and the Air Force, primarily for satellite-to-satellite relay. The stringent pointing requirements of optical systems and the loss of communications to ground in cloudy weather conditions make the use of radio frequency systems the preferred approach for Earth Resources missions.

Telemetry and Command Subsystems for Earth Resources missions are not expected to require major changes in the capability afforded by current and planned systems. No large advance in telemetry data accuracy is foreseen; the planned growth in capability of the NASA Spaceflight Tracking and Data Network ground systems will accommodate expected telemetry and command data transmission requirements. Component technology advances will enable expanded performance and improved reliability without large size, weight and power penalties through the use of medium- and large-scale integrated circuitry. Increased power output and efficiency of solid state R. F. power sources will reduce the size and weight of S-band transmitters for narrowband telemetry.

On the other hand, increase in wideband data rates to the order of several hundred megabits per second requires new ground station capability as well as significantly affecting satellite equipments. The next section describes candidate approaches to the wideband data links to provide a basis for evaluating the state-of-the-art of the critical elements.

4.4.1 CANDIDATE WIDEBAND LINK APPROACHES

In order to provide data rates of up to 500 Mbps, frequencies higher than S-band must be considered. The maximum bandwidth that can be received by STDN is limited to 30 MHz by the new multifunction receiver. By dividing the sensor data into parallel data streams and using more than one S-band frequency channel, a bandwidth up to 100 MHz could be achieved by using the total allocated band. For wider bandwidths, higher frequencies can be used (Ref. 1). At X-band, the frequency range from 8.025 to 8.5 GHz may be used for space-to-earth communications. Bandwidths of about 1000 MHz are allocated at 14.4 to 15.35 GHz (Ku-band) and from 21.2-22 GHz (Kq-band).

The channel bandwidth required to transmit a given data rate is determined by the modulation method chosen and the channel signal-to-noise ratio (SNR). Current wideband digital data transmission systems use two-phase or four-phase shift keying (PSK or QPSK) because they are efficient in using satellite power and bandwidth. Both require an energy per bit to noise density ratio of 9.6 dB for a bit error rate of 10^{-5}. PSK requires a bandwidth to date rate ratio of about 2; QPSK required a ratio of about 1. The resulting data rates afforded by the candidate frequency bands are shown in Table 4-15.

Table 4-15. Data Rate Capability of Candidate Frequency Bands

Frequency Band	Bandwidth, MHz	Data Rate, PSK	Mbps QPSK
S	30	15	30
	100	50	100
X	475	237	475
Ku	950	475	950
Kq	800	400	800

At X- and K-bands, absorption in the atmosphere can severely increase the transmission loss under adverse weather conditions. Table 4-16 shows predicted path losses for different conditions.

Table 4-16. Atmospheric Losses, dB, at 5 Degree Elevation (Ref. 2)

Frequency, GHz	Clear	Clouds (Max.)	Rain	
			6 mm/hr	12 mm/hr
2.3	0.6	0.2	0.01	0.02
8	1	1.8	1.8	3.5
15	2	6	9	15
21	5	10	11	20

Measurements at 15.3 GHz with the ATS-V satellite indicate that at Rosman, N. C., losses greater than those predicted for cloudy weather (3dB at 40 degrees elevation) occur less than 1 percent of the time. If loss of data can be tolerated a small percentage of the time, it is valid to design the link from a low altitude satellite for operation at low elevation angles under clear weather conditions. For heavy clouds or rain, data will be lost at low elevation angles, but the reduced communication distance and lower absorption losses at higher elevation angles will permit data recovery on almost all station passes. Because Kq-band losses are higher than at Ku-band, and Ku-band appears to be adequate for all Earth Resources missions, Kq-band is not considered further.

In addition to data transmission direct to ground stations, the use of a geosynchronous TDRS to relay signals from low altitude satellites to a ground station is also considered for the Shuttle Era (Ref. 4). The TDRS would provide a 100 MHz bandwidth link at Ku-band.

Based on these considerations, Figure 4-16 was prepared to indicate the range of satellite equipment characteristics that would be needed to support the wideband data requirements. The figure shows the required satellite transmitter power as a function of data rate for a 925 Km (500 mile) altitude satellite. The ground and TDRS receiving characteristics assumed are representative of the type of capabilities that will exist (Table 4-17) in the Shuttle Era.

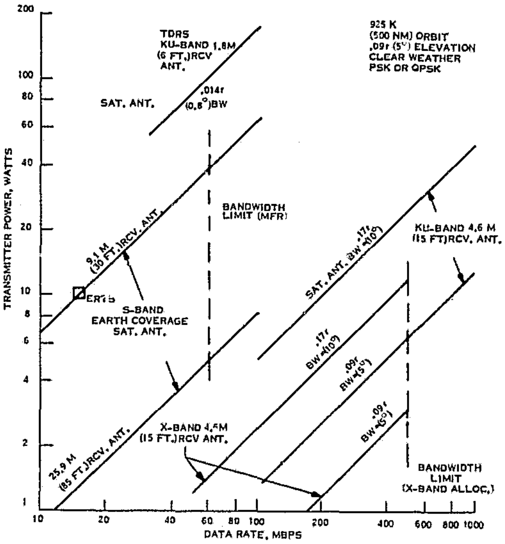

Figure 4-16. Typical Satellite Transmitter Requirements

Table 4-17. Ground Station and TDRS Characteristics

	Typical	Ground Stations		TDRS
Frequency	S-band	X-band	Ku-band	Ku-band
Bandwidth, MHz	30	500	1000	100
Antenna Size, Feet	30-85	15-30	15-30	6
Antenna Gain, dB	44-53	49-55	54-60	46.5
System Noise Temp., ^{o}K	150	300	500	2000

For data rates up to about 50 to 100 Mbps, a direct S-band link to ground stations is feasible with an earth coverage directional antenna on the satellite and transmitter powers of less than 70 watts for a 30 foot STDN antenna, and less than 9 watts for an 85 foot antenna. If a TDRS is used to provide real time return to the U.S., a narrow beam satellite antenna is needed and Ku-band transmitters in the 100-150 watt class are required. The 0.8 degree beamwidth satellite antenna assumed is the same design as the 6 foot antenna currently proposed for the TDRS.

For data rates up to 500 Mbps, X-band, and Ku-band systems require relatively narrow beam antennas on the satellite to allow-reasonable transmitter powers to be used for direct links to ground terminals. For 30 foot receive antennas, the satellite antenna beamwidth can be doubled compared to the beamwidth shown on the curves, for the same transmitter power. Transmitter power in the range of 3 to 12 watts is needed for 500 Mbps at X-band, compared to 6 to 25 watts at Ku-band. The increased power at Ku-band results from the higher propagation losses and somewhat higher receive system temperature.

The next sections discuss the state-of-the-art of the satellite components required to implement these typical systems.

4.4.2 SATELLITE ANTENNAS

Except for the narrow beam antenna required for the link to the TDRS, satellite antennas for wideband data transmission are readily achievable. As indicated in Table 4-18, the antennas for the links to ground stations are space proven or use standard techniques. Although the X-band and Ku-band antennas must be continuously pointed, the required accuracy is only on the order of 0.008 to 0.017 rad (0.5 to 1.0 deg), so that an open loop system is adequate.

Table 4-18. State-of-the-Art of Satellite Antennas

		S.O.A.	
S-band Earth Coverage	Turnstile	6	Existing units; e.g., ERTS wideband system antenna
Ku-band Antenna for TDRS Link	Parabolic Reflector	3	Same antenna used on TDRS. Monopulse tracking required
X-band 5° to 10° Beamwidth	Parabolic Reflector or Horn	6	0.6m reflector or horn. Open loop pointing by command. Simpler than spot beam antennas for communication satellites such as DSCS II, INTELSAT IV
Ku-band 5° to 10° Beamwidth	Parabolic Reflector or Horn	4	0.3m reflector or horn. Open loop pointing by command

The satellite antenna for the TDRS link is the same as the antenna that will be used on the TDRS itself. An autotracking system is required to achieve a pointing accuracy of 0.003 rad (0.15 deg).

4.4.3 TRANSMITTERS

Table 4-19 lists examples of power amplifiers that are candidates for the satellite transmitters. Traveling Wave Tube Amplifiers (TWTA's) are available for each frequency band having 20 watt output ratings and designed for space applications. TWTA's with 100 watt ratings have been space qualified at S-band. At the higher frequency bands, the TWTA efficiency decreases, but is generally better than can be achieved with solid state devices. Continual advances in output power and efficiency of solid state sources are being made, and the table lists examples of current laboratory device performance (not complete amplifiers).

Table 4-19. State-of-the-Art of Transmitters

Frequency Band	Power, Watts	Type	SOA	Remarks
S	20/10	TWTA	6	ERTS, eff. = 20%
	20	Solid State	4	ATS-F (1.8 GHz)
X	22	TWTA	6	Hughes 1202H, eff. = 20%
	5	IMPATT	2	Raytheon, eff. = 31%
	25	TWT	2	Hughes 219HX, eff. = 50%
Ku	20	TWTA	6	Hughes 1220H, eff. = 14%
	3	IMPATT	2	Raytheon, eff. = 20.7%

The powers required for wideband data transmission are currently available. Solid state amplifiers of adequate power may well be available in the Shuttle Era.

4.4.4 WIDEBAND MODULATORS

Several organizations are developing wideband modulators for data rates up to 1000 Mbps. Radiation, Inc. (Ref. 5) biphase modulates two orthogonal 1.56 GHz carriers at 500 Mbps in a 1 gigabit per second QPSK modulator for a laser communication system. Radiation, Inc. is also studying high data rate approaches for the GSFC Multi-Megabit Operation Multiplex System which combines the high data rate output of several sensors. Motorola (Ref. 6) has developed elements of a gigabit communication system using QPSK. Modulation is accomplished at L-band. Hughes Aircraft has developed components for a 500 Mbps data transmission system which phase shift keys a 60 GHz carrier directly (Ref. 5).

4.4.5 REFERENCES

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2. A. Benoit, "Signal Attenuation Due to Neutral Oxygen and Water Vapour, Rain and Clouds", The Microwave Journal, November 1968.
3. L. Ippolito, "Effects of Precipitation on 15.3 and 31.65 GHz Earth-Space Trnasmissions with the ATS-V Satellite", Proc. IEEE, February 1971.
4. "A Review of Satellite Systems Technology", IEE Aerospace and Electronic Systems Group, September 1972, pp. 109-114.
5. "Gigabit Data Rates", Microwave, May 1972, p. 34.
6. "Gigabit Communications", Motorola Engineering Bulletin, Fall 1970.

4.5 LAUNCH VEHICLES

Launch vehicle selection for unmanned earth observation satellites through the 1970's will continue to be made from a fairly small class of fully integrated launch vehicle/upper stage vehicle combinations. These vehicles are either presently operational or in the process of being uprated. Launch vehicles today are a well defined technology area, many years into the operational stage.

The Scout, Delta and Titan boosters with attendant strap-ons and upper stage combinations will be used for all missions ranging from low inclination, low altitude up to geo-stationary orbits. The major driving functions behind launch vehicle selection are orbit requirements and payload weight, although cost and shroud limitations also must be considered. The orbit requirements result from a complex tradeoff relating:

1. User and sensor requirements and constraints (i.e., field-of-view of sensors, illumination conditions, repeatability of coverage, allowable orbital eccentricity, and altitude/scale required)
2. Orbital mechanics (i. e., orbit decay rates, launch site constraints)
3. Vehicle design (drag coefficient, spacecraft power system, spacecraft thermal system, attitude control).

The orbit requirements and payload weight dictate the booster type and launch site. The Eastern Test Range (ETR) is used for easterly or low inclination launches where earth rotation can be used for velocity augmentation. ETR has facilities to launch Delta and Titan IIIC vehicles. The Western Test Range (WTR) is used for southerly launches - polar, sun-synchronous, and other high-inclination. WTR has facilities to launch Scout, Delta, and Titan IIIB boosters. Scout can also be launched from Wallops Island or San Marco.

Table 4-20 lists the current or near-term launch vehicles available for NASA programs and for each indicates payload capability to both a 925 Km (500 nm) circular sun-synchronous orbit and to a geo-synchronous orbit assuming a synchronous transfer orbit and spacecraft kickstage. Also shown are internal shroud diameter restrictions, and approximate per copy costs of the vehicles.

Table 4-20. Launch Vehicle Characteristics

Launch Vehicle	Payload Capability to:		Internal Shroud Diameter M	1973 per Copy Govt User Cost Est. (incl. Launch Costs $ x 10^6	Availability
	925 Km Kg.	Geo-Sync. Kg.			
SCOUT					
D (4 stage)	155	N/A	0.76	1.0	Now
E (5 stage)	N/A	28	↓	1.0	Now
ASLV (Adv. D)	310	N/A	↓	1.1	1975
DELTA					
2310 (3 Strap-ons)	727	N/A	2.13	7.9	Now
2610 (6 Strap-ons)	882	N/A	↓	8.2	Now
2910 (9 Strap-ons)	1100	N/A	↓	8.5	Now
2914 (3 stage)	N/A	352	↓	8.7	Now
3910 (2 stage)	1590	N/A	↓	10.5	1975
3914 (3 stage)	N/A	455	↓	10.7	1975
TITAN					
III B/Hydrazine	2180	N/A	2.74	9.0	Now
III B/Agena	2730	650	↓	15.0	Now
III C	9180	2100	↓	22.0	Now
III C/Centaur	N/A	3500	↓	27.0	Now
III D/Hydrazine	8650	N/A	↓	19.0	Now

The Scout D is a small, inexpensive, 4-stage solid propellant vehicle that is capable of orbiting only small observation payloads in near-earth orbits. Scout E has a fifth stage for higher energy/lower payload weight missions. No launches for earth observation missions are planned, using the Scout, through 1975. NASA is currently evaluating an improved version of the Scout referred to as Advanced Small Launch Vehicle (ASLV).

The Delta booster is generally used for NASA's near-earth launches. The first stage Thor booster can be complemented with 3, 6, or 9 strap-on Castor II solid rocket motors. The current second stage of the Delta vehicle is not capable of multiple burns and so payload capability decreases rapidly with altitude. A third stage is therefore used for medium altitude as well as geo-stationary missions. The major planned modification to the Delta is a multiple-start second stage (Titan transtage system).

The Titan IIIB is the basic 2-stage booster of the Titan series which is used in conjunction with a multi-burn third stage (hydrazine kickstage or Agena). The Titan IIIC is a IIIB with a solid rocket third stage designated Transtage. A fourth stage (Centaur) can be added to this combination if required for geo-synchronous missions. The proposed Titan IIIC7 and Titan IIID7 utilize additional solid rocket strap-ons. The Titan IIIC7 also includes a stretched transtage, sized for synchronous equatorial missions. The Titan IIID7 is a growth configuration of the Tital IIID, and will be used for future missions requiring payload capabilities in excess of those provided by the Titan IIID. It has a stretched core and seven-segment SRM's. A Titan IIIA configuration (a Titan IIIC without solids) has been resurrected recently for large low earth orbit missions.

The Titan series is particularly important in that it provides a heavy lift capability consistent with (or in excess of) the proposed requirements for earth observation satellites of the late seventies/early eighties time period. This time period is the beginning of the Shuttle Era. However, the proposed schedules for shuttle implementation suggest some incompatibilities with the launch requirements for both EOS and SEOS, i. e.:

1. EOS in 1978/9 requires a polar sun-synchronous orbit; no polar Shuttle capability is planned until 1983.
2. SEOS in 1981 requires a geo-synchronous orbit; the Shuttle/Tug combination will not be available until 1983.

The Titan can provide the interim launch capacity to support both of these missions:

1. EOS. The Titan can be used directly to provide polar launch capability and must be considered a worthwhile alternative to Delta (in fact, the only alternative for heavy spacecraft) for mission planning purposes.
2. SEOS. Either the Titan series alone or a Shuttle with a multiple-burn kickstage is a valid alternative to provide geo-synchronous launch capability.

The launch vehicle considerations for both of these missions will be examined further in Task 3.

Generalized vehicle performance curves can be generated (Ref. 1) to provide payload weight capability at a designated altitude for a particular booster/upper stage combination after orbit inclination and launch site (ETR or WTR) have been specified.

Figure 4-17 indicates the weight growth of unmanned earth observation satellites over the past several years. No significant increases are planned through 1975.

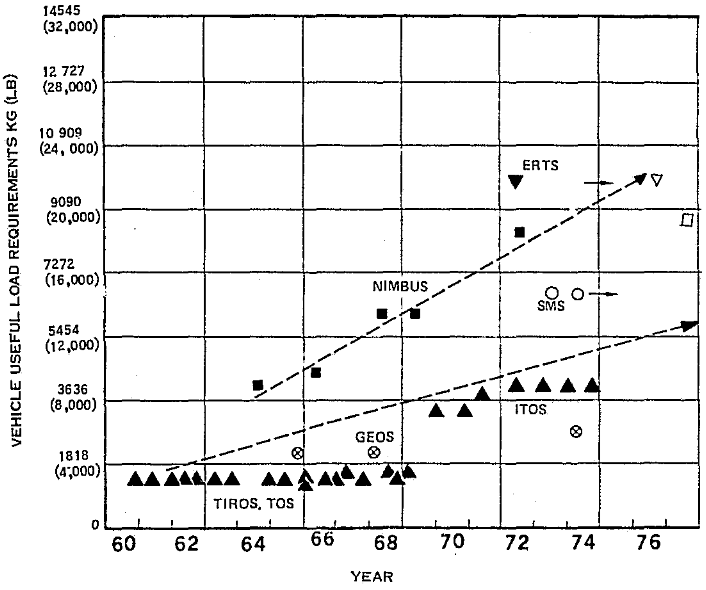

Figure 4-17. Launch Vehicle Payload Requirements Meteorological and Earth Observation Satellites

Typical vehicle performance curves are given in Figure 4-18 and show the payload capability available to launch into sun-synchronous circular orbits such as planned for future earth resources platforms.

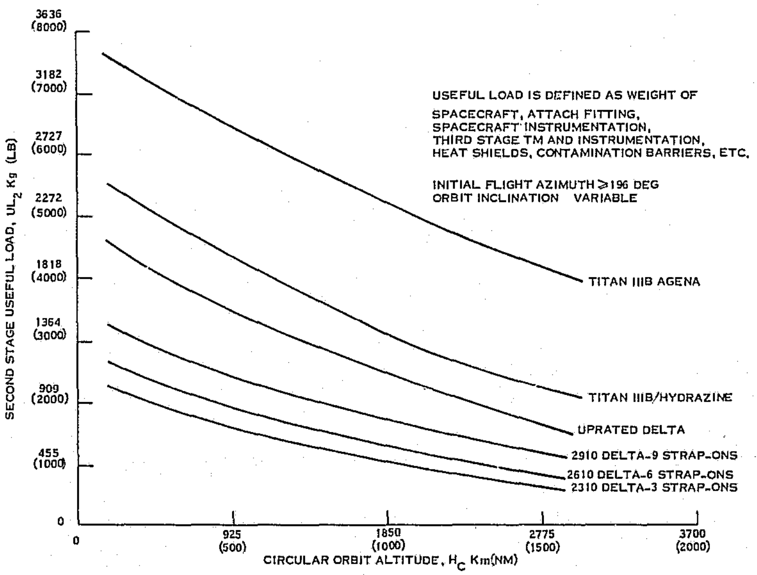

Figure 4-18. Useful Payload to Sun-Synchronous Orbit Capability-WTR

REFERENCES

1. Launch Vehicle Estimating Factors for Advanced Missions Planning, NASA NHB 7100.5B, 1973 Ed.
2. Delta Spacecraft Design Restraints, Aug. 1972 Revision.
3. Titan III Performance Handbook, Aug. 1970.
4. Space Planners Guide, U.S. A.F., 1965.
5. Data Acquisition Systems for Operational Earth Observation Missions, NASA-OART Working Paper MO-71-2, 8 November 1971.

4.6 ON-BOARD DATA STORAGE

Spacecraft data storage systems serve several functions: data rate buffer, data transmission delay device, and on-board computer peripheral adjunct. Data rate buffering includes accumulating either slow or varying rate data or bursts of high rate data for later uniform data rate playback matched to use the telecommunications link efficiently near its threshold. Data transmission delay (non-real time data) may be necessary to augment the communications system when sensor data is taken during periods when the spacecraft is not in view of the ground receiving station network. This condition can be eliminated by proper selection of receiving stations and relay communication satellites, but at the expense of increased communication system complexity and cost. As an On Board Computer (OBC) peripheral adjunct, the data storage system can be used for interim storage during computations or it can be used to store programs or archival data for reprogramming or data refresh of the OBC.

On-board data storage devices (DSS's) have historically tracked the developments in ground-based storage mediums. Today there are four basic types of spacecraft DSS's in use:

1. Shift Register
2. Solid State Memory
3. Photochemical Storage (Film)
4. Magnetic Tape Storage

In addition, there are several other data storage techniques that are in development but not flown yet on a major spacecraft program: bubble memory, plated wire, and beam metal oxide semiconductor (BEAMOS). The relative state-of-the-art of these techniques is summarized in Table 4-21.

Shift registers can be used for low storage capacity applications ($<10^3$ bits), and are usually associated with interim storage or data buffering prior to insertion into a larger storage system (e. g., magnetic tape) or insertion into the telecommunication system. Solid state memories are used in conjunction with controllers and sequencers where total storage capacity is low ($<10^6$ bits) or where quick random access to data blocks is required. Solid state memories can also be used as input buffers to magnetic tape or telemetry links. Photochemical storage (film) provides compact high data volume storage but has inherent pre-Shuttle Era disadvantages of limited mission life due to consumables and data recovery complexities (film canister re entry or on-board film readout devices).

Table 4-21. On-Board Data Storage: State-of-the-Art

Storage Type	State-of-the-Art	Major Function	Practical Limiting Capacity
Shift Register	6	Low Volume Interim Storage Data Buffering	10^3 bits
Solid State Memory	6	Moderate Volume Rapid Random Access Storage, (cheap)	10^6 bits
Photo Chemical Storage	6	High Volume Storage (Uses Expendables)	10^{12} bits/kg
Magnetic Tape	6	High Volume Storage (Mechanical Complex)	2×10^{10} bits/kg
Bubble Memory	3	High Volume Storage (Slow Access)	2×10^7 bits/kg
Plated Wire	4	Moderate Volume Storage (Excellent Parameters)	10^6 bits/kg
BEAMOS	2	High Volume Storage (Electronically Complex)	10^{10} bits/kg

Magnetic Tape Recorders have been used for all high volume data storage spacecraft applications. Table 4-22 is a data sheet listing most known recorders and characteristics. Of the 13 companies listed who have shown past expertise in building spacecraft tape recorders, only five are still market contenders: Odetics, Lockheed Electronics Corp., RCA, Borg Warner Corp., and Echo-Science.

The data was extracted from that prepared by the Tape Recorder Action Plan (TRAP) committee. The committee is comprised of recorder experts from NASA centers and the Air Force who met for the first time in 1972 and documented (Ref. 1) state-of-the-art in spacecraft data storage subsystems. The committee evaluated the various data storage mediums and concluded that tape recorders are much superior to all other techniques in cost, density, size, weight and maturity. In addition, tape recorders have a potential for improvement by several orders of magnitude. The tape recorder, however, is not without problems - the major drawback being reliability and life. The failure rate has remained nearly constant for the last ten years at about one failure every 10,000 hours of operation with the major problems being bearings, lubrication, tape and heads. Even though tape recorders have been operational for many years, development efforts will continue in the reliability area. In addition, the TRAP committee has recommended that NASA develop standardized components (bearings, tape, heads, motors, and even the entire transport unit) for tape recorders.

Table 4-22. Tape Recorder Data

													GSFC										
Parameter	UK 1	UK 2	EGO	POGO 1	POGO 2	OAO	AE 2	AE's C, D	AVCS	MRIR	MRIR-IM	HRIR	OSO's 1 to 4	OSO's 5, 6	OSO 7	OSO's I, J	RAE 1	RAE B	PCM	AVCS R	Tiros wide	SR	ITR increments
Manufacturer[a]	Raymond	Lockheed	RCA	RCA	RCA	RCA	Lockheed	Odetics	RCA	Lockheed	Lockheed	RCA	Raymond	Raymond	Raymond	–	Lockheed	Lockheed	Raymond	RCA	RCA	RCA	RCA
Mission	UK 1	UK 2	OGO's 2, 3, 5	OGO's 2, 4	OGO 6	OAO 2	AE 2	AE's C, D	Nimbus 1, 2, ESSA 1, 3, 5, 7, 9 AIS	Nimbus 2	Nimbus 3	Nimbus 1, 2	OSO's 1 to 4	OSO's 5, 6	OSO 7	OSO's I, J	RAE 1	RAE B	Tiros 2, 3, 4, 7, Nimbus 1, 2, B	ITOS 1, NOAA 1	Tiros 1 to [illegible]	ITOS 1, NOAA 1	ITOS 1, NOAA 1
Launch date	1963	1964	1964, 66, 68	1965, 67	1968	1967	1965	Future	1966-69	1966	1969	1964-66	1963, 65, 67	1969	1971	Future	1968	Future	1960-67	1970	1960-66	1970	1970
Number of recorders per spacecraft	1	1	2	2	2	1	1	1	2	1	2	1	2	2	2	–	1	1	1	2	2	2	1
Number of recorders of type launched	1	1	6	4	2	1	1	–	13	1	2	2	8	4	2	–	1	1	7	4	22	4	2
Capacity bits	N/A	N/A	43×10^6	43×10^6	43×10^6	43×10^6	2×10^6	11.8×10^7	N/A	6×10^6	6×10^6	8×10^5	2.4×10^5	4.8×10^4	5.2×10^6	E5 $\times 10^6$	5.8×10^4	2.25×10^4	6×10^6	N/A	N/A	N/A	10^6
Data rate, bits/sec (or Hz if so labeled)																							
Record	0-300 Hz	0-300 Hz	1K	4K	8K	1042	8.6K	16.4K	0-60 kHz	2K	1K	2.5K	400	800	800	6.4K	400	200	1K	60 kHz	60 kHz	0-450 Hz	45
Playback	0-15 kHz	0-15 kHz	64K	128K	128K	66.7K	8.6K	131.1K	0-60 kHz	52K	26K	20K	7.3K	14.6K	14.6K	–	10K	1K	30K	60 kHz	60 kHz	0-7.2 kHz	6K
Power, W																							
Record	0.25	0.25	7	7	7	7	0.23	5.5	11	2	2	7.5	1.3	1.3	1.3	5	0.75	1.1	2	19.8	19	7.5	2.4
Playback	–	1.5	14	14	14	14	0.30	7.7	18	8	8	10	5.5	5.5	5.5	12	1.25	1.6	5	16.1	19	10	5
Weight, lb	–	3.25	17	17	17	17	–	17	18	10	10	17	9.5	9.5	9.5	14	8	8	10	18.7	10	18.7	5.25
Volume, in.^{3}	–	–	1080	1080	1080	3500	–	600	1000	310	310	1000	211	211	211	580	170	170	320	1200	400	1155	336
Bit error probability	N/A	N/A	10^{-5}	10^{-6}	10^{-6}	10^{-6}	2×10^{-5}	10^{-6}	N/A	10^{-5}	10^{-6}	–	10^{-5}	10^{-5}	10^{-6}	10^{-6}	–	–	10^{-5}	N/A	–	10^{-6}	10^{-6}
Type of transport[b]	EL	EL	C-N	C-N	C-N	C-N	EL	C-N	C-N	EL	EL	C-N	EL	EL	EL	–	EL	EL	EL	C-N	C-N	C-N	C-N
Tapes																							
Manufacturer[c]	3M	3M	MEM	MEM	MEM	MEM	3M	–	3M	3M	3M	3M	3M	3M	3M	–	3M	3M	3M	3M	3M	3M	3M
Type	LR 1220	LR 1220	62L	62L	62L	62L	LR 1220	–	591	22049	22760	591	8998	8998	8998	–	1220	156	LR 1220	551	592	551	590
Length, ft	126	130	1200	1200	1200	1200	180	1200	1200	350	350	1200	300	300	300	–	240	240	250	1360	[illegible]	1360	90
Width, in.	1/4	1/2	1/2	1/2	1/2	1/2	1/4	1/4	1/2	1/4	1/4	1/2	1/4	1/4	1/4	–	1/4	1/4	1/4	1/4	3/8	1/4	1/4
Number of tracks	1	1	9	9	9	9	2	2	4	8	1	4	1	1	1	–	1	1	1	3	2	3	3
Track density, tracks/in.	4	4	18	18	18	18	8	8	8	8	1	4	4	4	4	–	4	–	1	12	8	12	12
Packing density, bits/in./track	1300 cycles/in. PFM	1300 cycles/in.	3390	3390	3390	3390	960	4000	670 cycles/in.	250	1000	670	670	1340	1340	–	2000	1000	1250	670 cycles/in.	–	2000	300
Tape speed, in./sec																							
Record	0.25	0.25	0.296	1.18	2.36	0.296	9	4	30	0.45	0.45	3¾	0.6	0.6	0.6	–	0.2	0.2	0.4	30	50	1.875	0.05
Playback	12.0	12.0	18.96	37.9	37.9	18.96	9	32	30	11.7	11.7	30	11	11	11	–	5	1.0	12	30	50	30	6.67
Head material	Brass/μ	Aluminum/μ	Brass/μ	Brass/μ	Brass/μ	Brass/μ	Alum/Alfesil	Alum/Alfesil	Aluminum/μ	Aluminum/μ	Aluminum/μ	Aluminum/μ	Brass/μ	Brass/μ	Brass/μ	–	Aluminum/μ	Aluminum/μ	Brass/μ	Brass/μ	Aluminum/μ	Brass/μ	Brass/μ
Bearing lubricant	GE F50 oil	MIL-L-6085	MIL-L-6085	MIL-L-6085	MIL-L-6085	MIL-L-6085, Andok C motor	MIL-L-6085	Andok C grease	Silicone grease	MIL-L-6085	MIL-L-6085	Silicone grease	MIL-L-6085	MIL-L-6085	MIL-L-6085	–	MIL-L-6085	Andok C grease	MIL-L-6085	Andok C grease	Silicone grease	Andok C grease	–
Gas fill	90% N_2, 10% He	90% N_2, 10% He	Ar	Ar	Ar	Ar	..	90% N_2, 10% He	90% N_2, 10% He	90% N_2, 10% He	90% N_2, 10% He	90% N_2, 10% He	70% N_2, 10% He, 20% Freon	70% N_2, 10% He, 20% Freon	70% N_2, 10% He, 20% Freon	–	90% N_2, 10% He	90% N_2, 10% He	90% N_2, 10% He	90% N_2, 10% He	90% N_2, 10% He	–	–
A/D cost	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None
Project costs	–	50K	2M				100K	750K	3M	300K	60K	300K	800K			–	250K	200K	500K	1M	1M	800K	200K
Cost per recorder flight unit	–	40K	150K	150K	150K	210K	50K	83K	100K	31K	31K	100K	70K	80K	80K	–	75K	100K	30K	200K	50K	200K	75K
In-house manpower, my	–	0.5	2				0.5	1	0.5	0.5	2	0.25	3			–	0.5	0.5	1	0.5	1	0.25	None
Project cost per in-house manpower, ks/my	–	100	1000				200	750	6000	720	2	1200	270			–	500	400	500	2000	1000	3200	N/A
Contract type	CPFF	FP	CPFF	CPFF	CPFF	CPFF	CPFF	CPIF	CPFF	FP	FP	CPFF	FP	FP	FP	–	CPFF	CPFF	CPIF	CPIF	CPFF	CPIF	–
Total mission life, hr	2160	0	44 000, 30 600	17 500	28 600	30 600	2200	12 000	6 months to 2 yr	2400	3250	3940	11 436, 4036	26 496, 21 648	2976	N/A	2200	N/A	625, 6000, 2400, 100, 0, 2000, 30 000	13 100, 6000	–	13 000, 6500	7200, 3600
Operational life,[d] hr	2160F	0F	2720, 7760, 5700, 3441, 1547F, 5700	4852F, 8293F, 4269, 4445F	7600, 7600	28 000F	150F	N/A	300, 200F, 400, 400, 600F, 400, 400, 400, 400, 400, 400, 0F, 400	2400F	0F, 3250F	300, 3000F	600F, 948F, 900F, 10 455F, 6000, 1536F, 0, 3500F	13 248, 13 248, 10 824, 10 824	0F, 2976	N/A	2200F	N/A	6000, 625, 100F, 2400F, 2000F, 0, 30 000	900 ITOS, 900, 450 NOAA, 450	150 each	6500 ITOS, 6000, 3500 NOAA, 3000	7200F ITOS, 1460F NOAA
Failure rate, failures/operational hours	1/2160	1/0	1/26 868	3/21 859	0/15 200	1/28 000	1/180	N/A	3/4700	1/2400	2/3270	1/3300	4/16 472	0/48 144	1/2976	N/A	1/2200	N/A	3/41 125	0/2700	0/3300	0/18 000	2/8660
Failure rate, failures/10^6 hr	463	∞	37	137	0	36	5555	N/A	638	417	612	303	243	0	336	N/A	454	N/A	73	0	0	0	231
Failure mode	Radiation damage	Motor driver phase shift circuit	Motor bearing lube	Motor bearing lube	Still running	Old age	Loss of phase relation data clock	N/A	Capacitor, silicone oil used	Tape jam or motor bearing lube	Tape jam or lube failure	Bearing lube silicone oil instead of grease	Tape pack (3), bearing tape pack (4)	Still running	Spilled tape, launch vehicle still running	N/A	Flutter	N/A	Bearing or tape pack, clutch, unknown	S/C failure, S/C turned off	N/A	S/C failure, S/C turned off	Head/tape dropouts
Recorder type	Analog	Analog	Digital	Digital	Digital	Digital	Digital	Digital	Analog	Digital	Digital	Digital	Digital	Digital	Digital	Digital	Digital	Digital	Digital	Analog	Analog	Analog	Digital

K = 10^3; M = 10^6.

[a] TI = Texas Instruments Inc.; SUI = State University of Iowa.

[b] C = coaxial; 3C = 3 capstan; CP = coplanar; EL = endless loop; N = negator; P = peripheral; RH = rotary head; RR = reel-to-reel.

[c] MEM = Memorex.

[d] F = time to failure.

Table 4-22. Tape Recorder Data

					MSC								JPL							LaRC		ARC		
HDRSS	SAS	SCMR	WBTV	NSTR	Gemini biomedical	Gemini PCM	MTR-1200	10-126B/TE-2	CM FOR	CM DSE	LM DSEA	ERKF	MM 64	MVM 67	MM 69 digital	MM 69 analog	MM 71	MVM 73	VO 75	Injun	Viking lander	Biosatellite	Type 28	--
RCA	GSFC	Odetics	RCA	Leach	Cook	RCA	Leach	Genisco	Leach	Leach	Leach	Ampex	Raymond/TI	Raymond/TI	Lockheed/TI	Lockheed/TI	Lockheed/ Motorola	Lockheed/TI	-	[illegible]	Lockheed	Cook	Kinelogic	Odetics
Nimbus 3, 4	SAS 1	Nimbus ~~E~~ 5	ERTS-1	ERTS	Geminis 1 to 12	Geminis 1 to 12	Apollo	Apollo	Apollo	Apollo	Apollo	Skylab	Mariners 3, 4	Mariner 5	Mariners 6, 7	Mariners 6, 7	Mariners 8, 9	Mariner J	Viking	Injuns 4, 5	Viking	Bios 1 to 3	-	--
1969, 1970	1970	Future 73	~~Future~~ 72	~~Future~~ 72	1964-66	1964-65	1963-65	1965-66	1966-68	1966-71	1969-71	~~Future~~ 73	1964	1967	1969	1969	1971	Future	Future	1964-6?	Future	1966-67	-	-
2	1	-	-	-	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	-	-
4	1	-	-	--	12	12	4	2	5	13	7	-	2	1	2	2	2	N/A	N/A	2	N/A	3	-	-
1.4×10^8	6×10^6	N/A	3×10^{10}	1.2×10^9	N/A	7.5×10^7	N/A	N/A	N/A	1.2×10^9	3.6×10^6	2.2×10^{10}	5.2×10^6	4.8×10^5	2.3×10^7	N/A	1.8×10^8	1.8×10^8	1.3×10^9	4×10^7	4×10^7	N/A	1.73×10^8	3.24×10^5
4K	1K	0-60 kHz	15M	1K	0-100 Hz	5.12K	100 Hz-50 kHz	100 Hz-50 kHz	50 Hz-50 kHz	50 Hz-12.5 kHz	300 Hz-3 kHz	125K, 1000K	10.7K	66.7	16.2K	8.5 kHz-30 kHz	132.3K	117.6K, 2.4K	331.7K, 16K, 4K, 1K	810	4K, 16K	0-100 Hz	10K	60
130K	30K	0-60 kHz	15M	24K	0-100 Hz	112.63	100 Hz-50 kHz	100 Hz-50 kHz	50 Hz-50 kHz	400 Hz-100 kHz	300 Hz-3 kHz	125K, 1000K	8.3	8.3	270	1.23 Hz-4.3 kHz	1K-16K	22K, 7.4K	1K-16K	32.4K	250-16K	0-100 Hz	50K	1380
8	0.8	14.5	~~95~~ 91	7.4	1.2	12.5	73	93	45	40	2.1	175, 140	3	7	20	23	22	27	100	3.4	10	2	20	3
15	4.0	15.5	~~98~~ 99	14.2	N/A	-	N/A	N/A	N/A	40	N/A	175, 140	4	6	18	19	18	16	20	5	10	2	30	7
31	6	21.4	~~[illegible]~~ 79.8	13	4	14.5	35	53	40	40	2.2	48	17	17	21	21	24	24	50	7.5	19	5.2	15	10
1510	220	774	3400	432	100	431	480	950	1425	1250	50	2182	481	541	532	532	770	770	2000	270	660	N/A	540	364
10^{-6}	10^{-4}	--	10^{-5}	10^{-4}	N/A	10^{-5}	N/A	N/A	N/A	10^{-7}	3×10^{-5}	5×10^{-6}	10^{-6}	10^{-5}	10^{-5}	N/A	10^{-5}	10^{-5}	10^{-6}	-	10^{-6}	-	10^{-6}	10^{-4}
C-N	EL	C-3C	CP-RH	C-RR	RR	C-RR	RR	RR	RR	RR	RR	RR	EL	EL	EL	EL	CP-P	CP-P	CP-P	C-N	CP-RR	RR	CP-P	C-N
RCA	3M	3M	3M	3M	3M	3M	3M	3M	3M	Kodak (CEC)	Ampex	3M	3M	3M	3M	3M	3M	3M	3M	3M	Univac	3M	3M	3M
617	LR 1220	900	MTA 20237	551	888	490	999	999	2261	216687	143	888	MT 1353	MT 1353	MTA 22760	MTA 22760	MTA 20250	MTA 20250	MTA 20250	551	Phosphor bronze	LR 1411	MTA 20250	951
800	300	1770	2000	1550	880	2300	750	2250	2250	-	450	7000	330	50	370	370	550	550	1000	1800	650	880	1100	180
1/2	1/4	1/4	2	1/4	1/2	1/4	1	1	1	1	1/4	1	1/4	1/4	1/4	1/4	1/2	1/2	1/2	1/4	1/2	1/2	1	1/4
5	1	3	1 transverse, 3 longitudinal	1	7	2	14	14	14	14	4	28	2	2	4	4	8	8	8	2	4	7	5	2
10	4	3	100	1	14	8	14	14	14	14	16	28	8	8	16	16	16	16	16	8	8	14	5	8
3100	1667	6300 Flux reversals per inch	7500	700	3400 cycles/in.	2730	3333 cycles/in.	3333 cycles/in.	3333 cycles/in.	8500	160	16 700	833	833	1500	1500 cycles/in.	3400	3400	6667	1000	1300	3400 cycles/in.	2600	150
1.3	0.6	42	12	1.43	0.0293	1-7/8	15	15	15	1-7/8, 7-1/2	0.6	60, 7 1/2	12.8	0.08	12.0	12	19.4	17.3-0.37	47.5-0.15	0.8	12.3, 3.075	0.0293	3.56	0.4
42	18	42	12	34.3	N/A	41-1/4	N/A	N/A	N/A	7-1/2, 60	N/A	N/A	0.01	0.01	0.2	1.71	2.4-0.15	2.9-1.1	2.4-0.15	32	12.3-0.19	0.0293	19	9.2
Brass/μ, alum/Alfesil	Alum/Alfesil	Alum/Alfesil	Alfecon-II	Havar/Alfesil	-	Alum/Alfenol	-	-	Alum/Alfesil	Alum/Alfesil	Alum/Alfesil	Soft	Brass/μ	Brass/μ	Brass/μ	Brass/μ	Brass/μ	Brass/μ	Havar/Alfesil	Aluminum/μ	Havar/Alfesil	-	-	Ferrite/Alfesil
Andok C grease	MIL-L-6085	Andok C grease	Andok C grease	Andoc C grease	FS1265 F44	Barden grease, G8, oil G-11	-	Barden grease, G-14	Versilube, F-50, VV545	NPT 3, Aeroshell 15	NPT 3, FS 1281	Nydgel 816, Aeroshell 7A, MIL-L-6085	MIL-L-6085	MIL-L-6085	MIL-L-6085	MIL-L-6085	MIL-L-6085	MIL-L-6085	-	Bray NPT-3	Wet vac-coat	FS 1265 F44	-	Andok C grease
Air, 20% Rh	-	-	Air, 50% Rh	90%N_2, 10%He	N/A	-	-	-	Vented	Vented	Vented	Vented	90% N_2, 10% He	90% N_2, 10% He	90% Ar, 10% He	90% Ar, 10% He	90% Ar, 10% He	90% Ar, 10% He	-	-	-	-	-	-
100K	None	N/A	475K	None	200K	None	None	None	None	None	None	--	524K	None	None		959K	0	0	None	None	-	-	-
8M	300K	500K	7M	590K	1.2M	2.7M	330K	590K	1.4M	8.3M	2.6M	4M	1035K	250K	4330K		3166K	1200K	-	68K	2.2M	-	-	48K
250K	19K	125K	450K	100K	20K	40K	17K	40K	60K	80K	40K	300K	100K	50K	200K		250K	-	-	25K	275K	-	-	24K
3	8 (all labor done in house)	1	9	0.5	4	6	7.5	10	4.5	7.5	4.3	5	6.8	3	17		22	4	--	0.5	2	1	--	-
2700	75	500	780	1100	300	452	44	59	302	1102	617	800	152	84	255		144	300	--	136	1100	-	-	
CPFF	All in house	CPFF	CPFF	CPFF	-	-	-	-	-	-	-	CP, FP	CPFF	CPFF	CPAF	CPAF	CPFF	CP/F-AF	-	FP	-	CPAF	-	--
23 700, 15 100	-	-	-	-	0.3-100 each	0.3-20	0.4 each	0.5 each	0.5 each	0.5-237	0-10	--	0, 26 000	4300	3600	3600	0, 5800	N/A	-	10 800, 30 000	-	100	-	-
3000F, 3000F 4000F, 8500	1008F	-	-	-	0-100 each	0.3-20	0.4 each	0.5 each	0.5 each	0.5-237	0-10	34	0, 221	38	49	27, 31	0, 640	N/A	-	1000, 2000	-	100	-	
3/18 800	1/1008	N/A	N/A	N/A	1/803	2/836	0/1.6	0/1	0/2.5	1/1481	0/55	--	0/221	0/38	0/98	0/58	0/640	N/A	--	0/3000	--	0/300	-	--
160	992	N/A	N/A	N/A	1245	2392	0	0	0	675	0	--	0	0	0	0	0	N/A	-	0	--	0		--
Tape debris, bearing failure	Tape jam or bearing	N/A	N/A	N/A	Improper loading of tape	Bearings	N/A	N/A	N/A	Case design, vent valves	N/A	-	Launch vehicle failure	N/A	N/A	N/A	Launch vehicle failure	-	-	N/A	--	N/A	--	--
Digital and analog	Digital	Analog	Digital	Digital	Record only; analog	Digital	Record only; analog	Record only; analog	Record only; analog	Analog and digital	Record only; analog and digital	Record only; Miller code, digital	Digital	Digital	Digital	Analog	Digital	Digital	Digital	Digital	Gear driven; sterilizable, digital	Analog	Digital	Digital

Figure 4-19 indicates weights versus storage volume of five types of data storage mediums: core memories, plated wire, beam metal oxide semiconductor (BEAMOS), magnetic bubble, and tape recorders. Also indicated are near-term practical limits of maximum packing densities. Note that the tape recorder curve seems to be approaching its practical limit curve asymtotically as the tape transport and electronics (fixed weights) become smaller compared to tape weight. The tape recorder appears to have a limitation of two orders of magnitude above the magnetic bubble. For lower storage requirements (less than 10^8 bits), however, the bubble memory can be competitive except that there is an inherent frequency limitation of about 2 MHz which eliminates bubble memory from high data rate applications.

Plated wire and bubble memories can be produced to occupy less than 2800 cm^3 compared to 14,000 to 60,000 cm^3 for similar storage capacity tape recorders, but volume constraints generally have not proved to be critical in trade-off studies in the past.

The BEAMOS data storage system currently in the early development stage, uses an electron fly's eye lens to provide high resolution read/write access to the semi-conductor target in a storage tube. Storage densities of one bit per micron are expected and data rates are limited by energy available to the beam (typically 50 Mbps). The early problem of volatile storage has been partially overcome and several days of unpowered storage is possible. The major problem is electronic complexity (hence weight) required for signal conditioning, beam control, etc. A major advantage is lack of mechanically moving parts.

Costs of storage devices include three major variables: data volume, data rates, and amortized development costs for the storage device class. Discrete core and plated wire memory costs are proportional to storage volume, but the constant of proportionality (gain) is a non-linear function of data rate (slower cycle time devices are larger dimensionally, require less care in production and thus cost less). The cost per bit approaches $ .018 asymtotically for access times of one microsecond. A near term practical limit of $ .01 per bit can be assumed. A JPL study (Ref. 4) has concluded that the tape recorder cost trend line is:

$$\text{cost per bit} = \$\ \frac{10^4\ \text{(BITS)}}{10^4}\ \frac{1}{25}$$

The same JPL report concluded that tape recorder cost per bit is presently (and will continue to be) less than core costs except for low data rate, low total volume storage systems. Very little cost data is available on bubble memories, but many believe that this technology, when fully developed, may prove to be the only tape recorder competition.

REFERENCES

1. "Report of the Tape Recorder Action Plan Committee", NASA SP-307, 21 March, 1972.

2. "Design Study for a High Reliability Five Year Spacecraft Tape Transport", IITRI, Report No. E6179 (Contract NAS 5-21556).

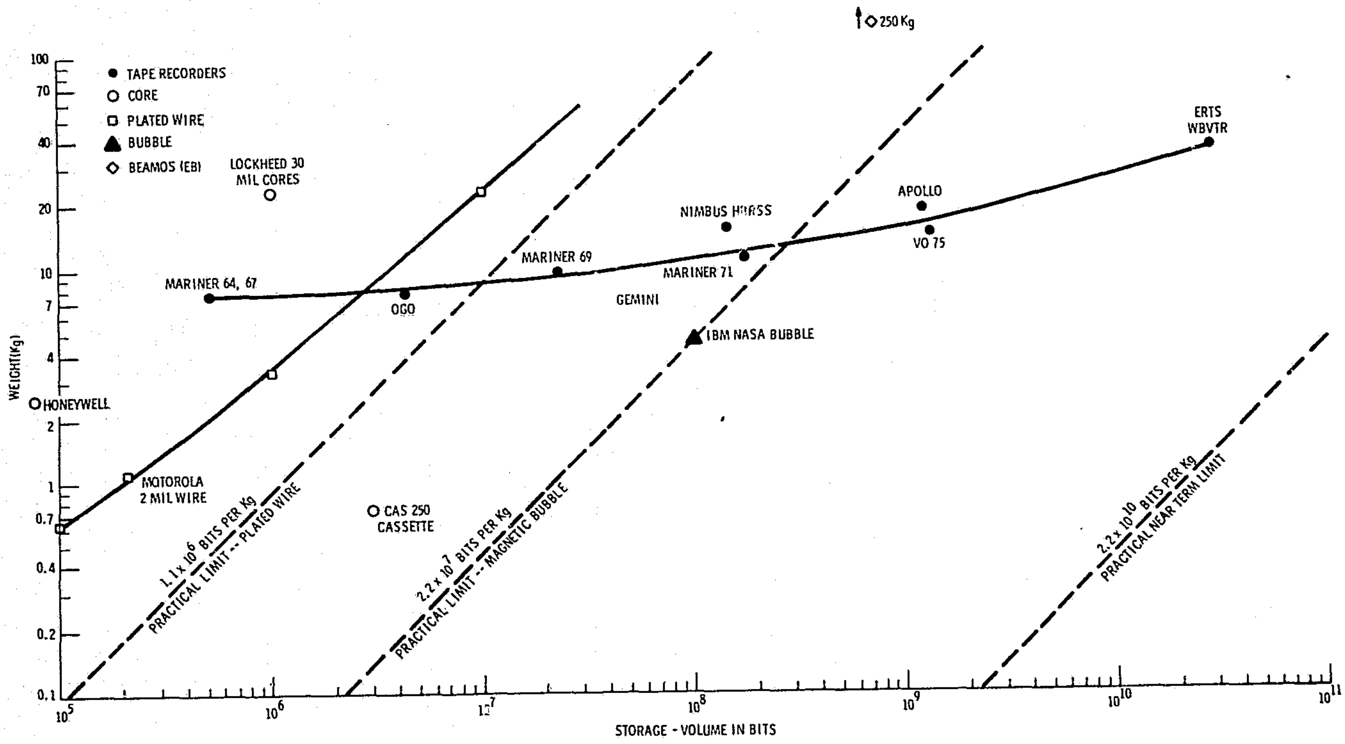

Figure 4-19. Data Storage System Weights vs. Storage Capacity

3. "Study of Reliability Data From in-house Spacecraft", NASA CR-84628.

4. Technology Review of JPL Data Storage Subsystem, Feb. 29, 1972.

5. Military and Space Mass-Memory Trends, GE TIS R71ELS-8, Jan. 1971.

6. "Review of Current Proposed Technologies for Mass Storage Systems", Proc. IEEE, Vol. 60, No. 3, March 1972, pp. 266-290.

4.7 ON-BOARD PROCESSING

Future data collection platforms and sensors will be under increased pressure to provide higher spectral and spatial resolution, increased accuracy, and wider area coverage. A prime example of this is evidenced by the proposed EOS satellite system which has output data rates of more than an order of magnitude greater than the ERTS satellite system. Of great concern are the related requirements placed on bandwidth of platform to earth data links and the ability to effectively manage and process the data to provide useful information to ultimate users.

One consideration for minimizing the amount of data to be handled, while not reducing the available information, is real time on-board data processing. Table 4-23 lists some of the typical functions where an advanced on-board data processor might be utilized. These represent only a small sample of the types of operations that would be performed. A major deficiency in the area of developing on-board processing equipment and techniques is that the ultimate problem to be solved is not well-defined. The type of on-board computations to be performed will ultimately be determined by the characteristics of the data, the availability of ground processing equipment and the information requirements of the users. Ultimate benefits of such a processor would include:

1. Simpler and less expensive ground stations.
2. Lower downlink bandwidth and, consequently, lower power required on-board the vehicle.
3. More rapid data availability in more convenient form.
4. Better utilization of vehicle, including all of its sensory capacity, as a result of self-adaptation to the stimuli of the sensed data.

On-board processing state-of-the-art is summarized in Table 4-24.

As presently conceived, an ultimate on-board data processor would be an integrated entity which performs many interrelated functions. It is conceptually convenient to think of a typical on-board data processing system as consisting of two interrelated parts: a "high data rate processing section" (e. g., parallel data processor), and a "low data rate processing section".

The high data rate processing section will operate in a parallel data processing mode, to reduce the very high data rate sensor outputs to more meaningful, lower data rate outputs. The high data rate processor receives the data from the external sensors and processes it in accordance with a program as directed by the controller function of the low data rate processor.

Table 4-23. Typical Objectives and Examples of the On-Board Data Processing

Objectives	Typical Example
Image data compression	Instead of sending pictures of corn fields, transmit the number of acres of corn together with the percentage of healthy corn.
To transform the primary data into a form more readily useful to the practical data user.	Instead of displaying cloud and ocean patterns, interpret the high probability of fish concentration areas for commercial fisherman.
To make on-board use of some of the sensed data to modify the mission program.	To interpret some pre-selected outputs of certain key earth observation sensors to turn on other sensors, or to change spectral sensitivity, or to change field-of-view, or to change the mode of data processing, or to program a sensor or vehicle roll search, etc.
Image enhancement	Based on deterministic or self-adaptive functions; select certain images for enhancement on-board the vehicle by optical means.
To perform real-time "generic" pattern recognition	The detection of a spiral formation might provide an on-board detection of a tornado and might be used to trigger detection search and automatic alarms.
To perform real-time specific recognition	On-board automatic recognition of specific earth surface features might provide navigation as well as relative location of other observed phenomena.
Real-time spatial frequency analysis of images	Determination by spatial frequency analysis of sea state, cloud and weather patterns, patterns associated with certain geological formation, etc.
Real-time spectral analysis	Agricultural crop conditions. Nature of air and water pollutants.
Image change detection	Sampled observation or change detection of major time'varying events (e.g., monitoring progress of forest fire or flood on successive orbits).

Table 4-24. On-Board Processing State-of-the-Art

Processing Type	State-of-the-Art	Summary Status
Low Rate		
Processors	6	Operational on many programs. Includes digitizing, formatting, multiplexing, calibration and storage. Used for command storage/execution, telemetry processing, attitude control and housekeeping. Fault tolerance is key development area.
Algorithms	4-6	
High Rate		
Processors	2-3	Both processors & algorithms in very early development stage. Goal is to reduce amount of data return, both quantity and rate. Functions include data compression, preprocessing, enhancement, and information extraction.
Algorithms	2	

The low data rate section will accept these outputs plus stored and transmitted commands. It will serve as a logic module to control the operation of the high rate processing section and also to control other related vehicle subsystems and will select and encode the desired compressed data to be transmitted to earth.

4.7.1 LOW DATA RATE PROCESSING SYSTEM

The present SOA of hardware and software for performing the low data rate control and output data functions aboard a spacecraft is fairly well advanced. Some typical functions that would fall into this low data rate category that are within the present state-of-the-art are digitizing, formatting and multiplexing, radiometric calibration and correction, and storage. The low data rate system would most likely act as the nerve center for the entire processing system and its main component would be an on-board computer, probably digital.

An On Board Computer (OBC) can be selected off-the-shelf for almost any application from among the 80 or more OBC's that are currently manufactured or in development (Refs. 10, 16). Spacecraft OBC's have excellent performance characteristics and in many applications are as capable as sophisticated ground based computers. In addition to numerous spacecraft applications over the last several years, OBC's have been used in other related areospace applications such as aircraft programs and ballistic missile systems.

The OBC has to date been mostly used for spacecraft service subysystem control, but has the ability to be used for on-board data processing and compaction. The Microwave Automatic Temperature Sounder (MATS) instrument, for instance, was proposed by NOAA as a candidate sensor for Nimbus-G to demonstrate the operational utility of providing meteorologists in the field with real-time vertical temperature soundings. An eight channel microwave radiometer in the 50 to 60 GHz band was to be used to provide inputs to an OBC which would compute the vertical temperature profile using statistical regression algorithms and then transmit only the profile at 100 BPS to receiving stations. Many similar applications will be found as the Earth Resources program evolves from the experimental phase to the operational phase.

Every spacecraft service subsystem listed in Table 4-25 requires some form of decision logic and/or control capability. This data processing can be performed as an integral part of the specific subsystem, on the ground, or with an integrated OBC for multiple subsystems. The need for on-line, real-time decision and control are very amenable to OBC's.

Table 4-25. Spacecraft Subsystems Requiring Decision Logic and Control

Command Storage/Execution/Sequencer
Telemetry Data Processing
Attitude Control
Payload Control
Image Data Processing
Navigation - Guidance Control
Housekeeping Management
Power Thermal Propulsion

OBC's to date have generally been in support of a specific service subsystem (attitude control) with other processing performed as capacity allows. One notable example of such use in the ANS Satellite which is a European (Dutch National Government) program for x-ray ultraviolet measurement.

In this program the OBC is used principally to integrate and control the attitude control subsystem elements. Additionally the OBC is used to control the payloads, process telemetry, process commands and perform spacecraft housekeeping (power, thermal, momentum) functions.

The state-of-the-art characteristics of OBC's presently are:

1. Less than 1 μ sec add times
2. Data rate up to 20 Mbps
3. Up to 262-K core, 32 bit words
4. Over 100 instructions
5. Multi-processor configurations
6. Using LSI technology
7. MTBF of greater than 10,000 hours

In addition to continued effort to improve performance in the areas of computational speed, reduced power, size and weight, the major problem area being pursued is fault tolerance.

Since the use of an OBC in spacecraft systems and subsystems is characterized by on-line continuous real-time data processing the following fault tolerance problems are inherent:

1. How are computer failures handled; how are faults detected and corrected; what are back-up modes of operation, dynamic reconfiguration, architectural features which provide fault detection and recovery at a low element level?
2. Can the OBC be reprogrammed from the ground, and what ground facilities are needed to checkout program mods before they are transferred to the OBC?

C-2

3. How is recovery and restart achieved if the system does momentarily stop due to power, parity or other problems?

These questions are at the core of utilization of an on board computer due to its on-line nature, and its remoteness from hands-on modification, reconfiguration and repair.

4.7.2 HIGH DATA RATE PROCESSING SYSTEM

On-board parallel data processing is a promising approach to the high data rate processing necessary for solving the data reduction and handling problems associated with advanced earth resources missions. In order to achieve the anticipated requirements for high data rate processing, both the spatial and optical frequency domain are presently being studied. The state-of-the-art in these systems is not advanced and it will be at least 1980 before these will approach the operational stage.

NASA/Goddard has a research and development program to develop parallel image processing systems to accept a "real" image input, handle it as an entity in real time, and generate information out of the system. Their interest in this area stems from the belief that, in the long run, only parallel image systems will be able to meet the very stiff speed and reliability requirements that will be demanded for image data processors aboard advanced spacecraft.

Under the NASA Goddard program, an attempt is being made to bring all parallel processing techniques together including electronic, non-coherent, and coherent optical methods. They envision hybrid on-board processors using a combination of techniques to solve the problem at hand. Their program is dedicated to developing a variety of automatic parallel processing techniques including theory, technology and methods, so that by the proper use of all techniques, the necessary image processing functions can be carried out on board a spacecraft.

The most near-term sophisticated high data rate processing system is one proposed for the Earth Observatory Satellite scheduled for launch in 1978/9. The processor is to accept 120 Mbps data from a Thematic Mapper and operate on the data to provide significantly reduced bit rates. The methodology and implementation methods are in a very early study phase and potentially include reduced resolution, reduced area coverage and modified sampling techniques. The EOS processor is representative of the state-of-the-art in on-board image processing technology.

4.7.3 REFERENCES

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4.8 AIRCRAFT

The use of aircraft in remote sensing has a long and productive history. Current practice for their use in Earth Resources as elements of the data acquisition system function is to adapt existing hardware to fill a need, as contrasted to the relatively unique satellite designs fabricated for such purposes. The collection of capabilities which the aircraft industry (both manufacturing and operating) offers has made it possible to select cost effective airframes and tailor them to a wide variety of applications. In addition, the employment of military reconnaissance aircraft originally designed for purposes very similar to Earth Resources imaging has provided the Program with unique capabilities at zero development cost. The state-of-the-art of aircraft as remote sensing platforms may be said to be mature-operational. Continued technological advances will occur into the foreseeable future without the expenditure of significant Earth Resources Program resources.

Several fundamentally different classes of aircraft exist, which are useful to the Program: light aircraft; facility aircraft; high altitude aircraft; and helicopters and balloons.

4.8.1 LIGHT AIRCRAFT

This category of platform includes single and twin engine aircraft up to 5682 Kg (12,500 lb) gross weight. Use of aircraft in this category for remote sensing is widespread. Many private, governmental, and academic institutions currently employ light aircraft with relatively simple sensor installations; the maximum operational complexity usually associated with this platform class is large scale aerial mapping of small areas. Light aircraft have been and will continue to be the first choice of the small user as a result of their low cost, immediate availability, and his ability to unilaterally control them.

Table 4-26 illustrates a typical sample of light aircraft characteristics relevant to their use as remote sensing platforms.

Table 4-26. Typical Light Aircraft Characteristics

	Sensor Payload Kg	Purchase Price	Operating Cost $/hr	Seats	Fuel Consumption e/hr (gal/hr)	Block Speed Km/hr (nm/hr)	Range Km (nm)	Cruise Alt m (Ft.)
Twin Commander	680 (1500)	$ 100,000- 130,000	48	6	83 (22)	296 (160)	1850 (1000)	1500-5000 (5000-17,000)
Cessna 182	135 (300)	$ 23,000- 30,000	18	4	49 (13)	222 (120)	925 (500)	1500-3650 (5000-12,000)

4.8.2 FACILITY AIRCRAFT

Use of the heavy multi-engined aircraft as flying laboratories has been the primary means of sensor development and, prior to the ERTS and EREP programs, for prototype project operations. These aircraft, outfitted by the government or at government expense, provide generous space and facilities for remote sensing payloads and investigator/operators. The success of such aircraft in accomplishing development objectives has been mixed, but it is fair to say that any shortcomings have not been primarily the result of an inadequate aircraft state-of-the-art. Operations and management of facility aircraft programs, and the technology development activities which they support appear to be much more important variables. Table 4-27 describes several typical facility aircraft.

The programs using such aircraft have, to date, been largely decentralized. The aircraft itself is typically the focal point of the operation for the group of pilots, maintenance personnel, and scientists or development engineers who operate it; missions change but the aircraft remains constant. NASA has taken steps to centralize overall management of its aircraft by establishing a Program Office at Ames Research Center. Evidence of the benefits of this approach is already visible in the greater ease and flexibility with which the needs of ERTS and EREP data users are being met.

4.8.3 HIGH ALTITUDE AIRCRAFT

The archetypes of this category of aircraft are the USAF U-2 and WB-57F which exhibit sensor platform capabilities unmatched by any other available aircraft (the SR-71 is not yet available to non-military users). Precise navigation, high area coverage efficiency (due to the high altitude) and transcontinental range are all characteristic of this category. The use of these aircraft, with available sensors, fills an important gap in the range of user requirements which lie between that ecomomically possible from satellites and that available from light aircraft, e.g., the region of 1-3 meter resolution and a few hundred square miles per frame. Table 4-28 summarizes the characteristics of typical aircraft in this category.

Table 4-27. Characteristics of Typical Facility Aircraft

	NOAA C-130	NASA/MSC C-130	NASA/AMES CV-990
Mission Manager	Yes, liaison with pilot and among experimentors but very informal.	Yes, liaison with pilot and among experimentors.	Yes, (several) liaison with pilot among experimentors.
Scheduling	Moderate delay. Reasonable change of flight if joint mission plans possible.	Highly utilized; 6-9 mo. advanced notice or joint flight plan, currently dominated by ERTS underflight reqmts.	Equipment at plane 1 month prior to flight. 3 weeks to install. No information on adv. notice. 3-4 flts per year, 1 month per flight.
Experiment Space	Camera ports, ramp/tail area, also cargo area of aircraft available.	Camera ports, ramp/tail area; some external mounting areas.	Optical windows, camera ports in cargo area, upward viewing ports; some external mtg., also aft opening.
Operator Convenience	Relatively inconvenient, few seats, little desk space, noisy, windy with ramp down.	Finished, sound proofed interior; 5 seats, 1 desk plus console seats and writing surface.	Very comfortable, passenger seats. Good rack access from seats.
Rack Space	One or two general purpose racks.	Well organized consoles with adequate rack space when unused instruments have been removed.	Std size racks. Many experimenters at same time. 30- -1.2 x 1.2 m bays.
Data Recording	Data station with time, position info. No recorder Altitude included. Supplementary TV camera	Data station with time position, A/C parameters available. Multichannel recorder available, supplementary TV camera/photography.	On board computer available for data processing and recording. Line printer/sample may be available. Supplementary TV camera; video recorder/photography.
Navigation/Position	Rent LTW-51 Inertial System upon demand.	LTN-51 Inertial system installed -- prime navigation aid.	TV display at each rack showing position roll, pitch, yaw - inertial navigation
Installation Interfaces	Informal, minimal, only normal safety requirements observed.	Formal relatively non-flexible interface drawings, electrical load analysis and QA documentation required.	Adaptable but need prior approval for mod's to aircraft.
Power Interface	110-120 60 Hz 110-120 400 Hz 28 VDC	110-120 60 Hz 110-120 400 Hz 28 VDC	60 Hz 110-120 VAC 400 Hz 110-120 VAC Ample power (28 VDC not available to experimentors).
Information Booklet	Not available; verbal discussion only.	NASA/JSC C-130 "Earth Observations Aircraft Remote Sensing Handbook", April 1972.	Experimentors Handbook available, describes location of windows, support equipment available, etc.
Other Instrumentation/Experiments	Generally oceanographic experiments. Laser profilometer predominates. General temperature profiles available.	ERTS mission/instrum. Current priority: other experiments on a non-interfering basis. Thermal photographic profile available. Other instrumentation upon request. (Laser, MSS)	Generally a coordinated experiment package is flown each time. Thermal, photo, and video tape recording data available.
Repair and Instrument Accessibility	In general no wiring changes, soldering, etc. Modular replacement only - most other maintenance done on ground. Modular design concepts recommended. Remote control of instrument in equipment bay generally advised.		

Table 4-28. High Altitude Aircraft Characteristics

	Operating Altitude Km (Ft.)	Range at Altitude Km (nm)	Airspeed Km/hr (kt)	Crew	Operating Cost ($/hr)
WB-57F	18.2 (60,000)+	4625 (2500)	740 (400)	2	1000
U-2	19.8 (65,000)+	5550 (3000)	740 (400)	1	1000

Two major observations must be made concerning high altitude aircraft. First, their use in an operational sense has been advocated, in some cases, as a substitute for satellites. It is becoming increasingly evident that the operational use of such aircraft on a large scale is warranted, and technoeconomically possible, not as a sole replacement for satellites but as an important complementary system element.

The second observation derives from the first: the U-2 and WB-57F must, in the final analysis, compete with lower altitude (but less expensive) aircraft (e.g., the Learjet) in an operational system. It has been convenient in the current era to exploit existing military aircraft in an adjunct role for the Earth Resources Program. The operational use of aircraft on a large scale will necessarily be done in the most cost effective way.

An area not currently receiving attention in the Earth Resources Program is that of real time data transmission of the data from aircraft to a processing facility. Film cameras are the primary sensors and the R&D user must await the retrieval, processing, and distribution of the images. This delay is acceptably small if the aircraft base and the user are co-located. But operational demands upon the system may dictate widely scattered basing arrangements if aircraft are to be effectively utilized. The use of electronic sensors and wideband communications (via TDRS, other satellites, or ground microwave links) may be indicated to provide timely data while at the same time effectively using the aircraft on a large-area basis.

4.8.4 HELICOPTERS AND BALLOONS

For the sake of completeness, helicopters and balloons are briefly mentioned. The helicopter as a category of platform, exhibits many of the characteristics of light aircraft, both in performance and in current utilization by the Earth Resources program. Because of their relatively higher operating cost, helicopters are restricted to situations where vertical flight, hovering, or operation from unprepared sites is required.

Balloons, either tethered or free-flying, have been used occasionally for observations at altitudes up to 30 Km (100,000 feet.) The operational problems associated with balloons constrain their usefulness to areas such as atmospheric sampling similar to that now performed by the National Weather Service.

SECTION 5

DATA SYSTEMS

As Earth Resources remote sensing data acquisition techniques have developed over the years, the technology for processing this data has also advanced, but at a relatively slower rate than that of the collection systems. Today, we are in a period where the ability to collect meaningful data greatly exceeds our ability to process and utilize it effectively. The portion of the Earth Resources system that performs the processing function is the Data System. It begins with input of raw sensor and ancillary data received from the Communications System and ends with the output of parameters which are either directly useful to resource managers or serve as inputs to resource management oriented models.

Data systems consist of two primary functions: preprocessing, and extractive processing, plus the auxiliary functions of storage, reproduction and distribution. Figure 5-1 depicts the generic Earth Resources data system and illustrates the flow of sensor data through the system.

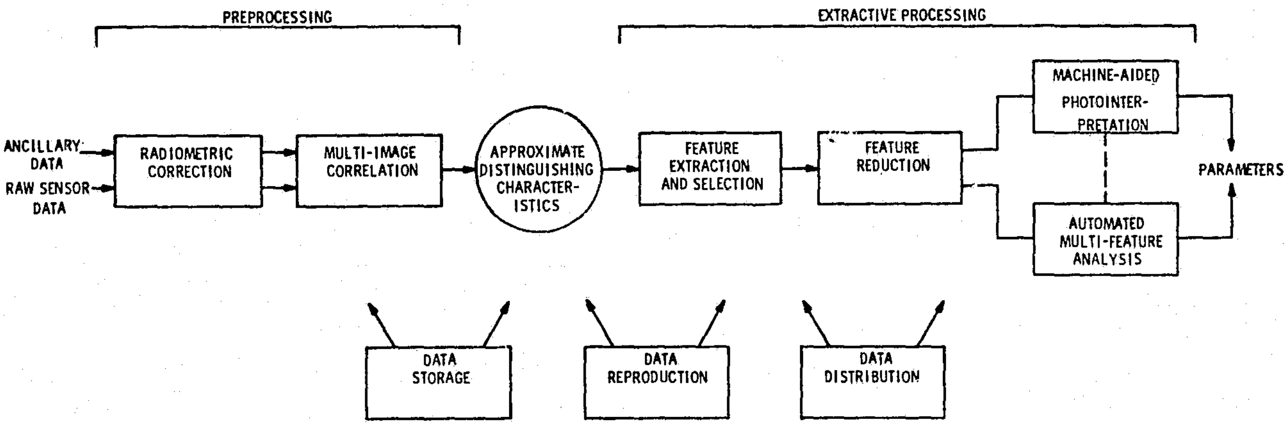


Figure 5-1. Earth Resources Data System

Preprocessing includes all those operations which are necessary to retrieve the desired information (i.e., approximate distinguishing characteristics) from data which has been radiometrically and geometrically contaminated by "noise" during the collection process. Extractive processing includes all those operations which convert the approximate distinguishing characteristics to user-oriented parameters and themes. The auxiliary functions of data storage, reproduction and distribution occur throughout pre- and extractive-processing and greatly affect their manner of implementation.

Information contained in this section was assembled from a comprehensive survey of applicable study reports, published research papers, symposia proceedings, personnel conversations, and IR&D activity. The report includes state-of-the art assessments (current and through 1975) of the hardware, software and techniques for the various data system functions, as well as discussions of key areas/limitations foreseen during the future decade.

5.1 PREPROCESSING

The preprocessing subsystem receives multi-dimensional raw data from the data acquisition subsystem (i.e., sensors) and performs those functions which are necessary to quantitatively restore the original fidelity to the data and produce sufficiently accurate approximations to the desired distinguishing characteristics of the sensed materials.

It cannot be emphasized too strongly that the function of image preprocessing is to retrieve desired information from data which has been contaminated, radiometrically and geometrically, by "noise" introduced during the collection process so as to make the data intelligible and useful for the user. No amount of processing can increase the information content of the data; it can only make the information that is already there more usable.

Images, in an earth resources context, are arrays of data elements (pixels or resels) which represent a record of events or conditions on the earth at a given instant of time. This data is generally used in one of two ways:

1. Inspection and analysis of the data (i.e., in photographic format) with the eye, where the precision of the radiometry and gemoetry is secondary. In fact, distortion of these quantities may enhance the capability of the eye/brain system to perform data extraction.

2. Automated numerical analysis and data extraction where the precision of the geometry and/or radiometry may be of paramount importance.

It is likely that a given set of data may be collected for several diverse purposes so that the data must eventually be presented in several different ways to satisfy all the requirement objectives. Therefore, it is expected that requirements for image preprocessing will be varied but the variations will be of benefit in optimizing the utilization of the data.

Potential techniques for image preprocessing fall into the following three categories:

1. Digital Techniques. The modern digital computer technology has made practical the processing techniques for handling non-linear operations in both the geometric and radiometric domain. The state-of-the-art evaluation of digital preprocessing techniques must include hardware (e.g., special purpose versus general purpose) and software (e.g., preprocessing algorithms) considerations. Successful utilization of these techniques does not require the presentation of the data in photographic format which makes them very applicable to the subsequent digital extractive processing of multispectral data.

2. Parallel Data Processing Techniques. Parallel data processing includes image processing techniques where all pixels in a two dimensional array of data (an image) are simultaneously operated upon in a desired fashion. Parallel data processing includes optical processing as a subset but it also includes electronic methods. For example, Large Scale Integration (LSI) holds much promise to allow data sensed by a large matrix of photo diodes to be entered directly into a matrix of digital logic to perform "parallel" processing. In addition, the conversion of an array of data into a modulated beam of electrons to allow manipulation with the techniques that are possible with electron optics also falls into this category.

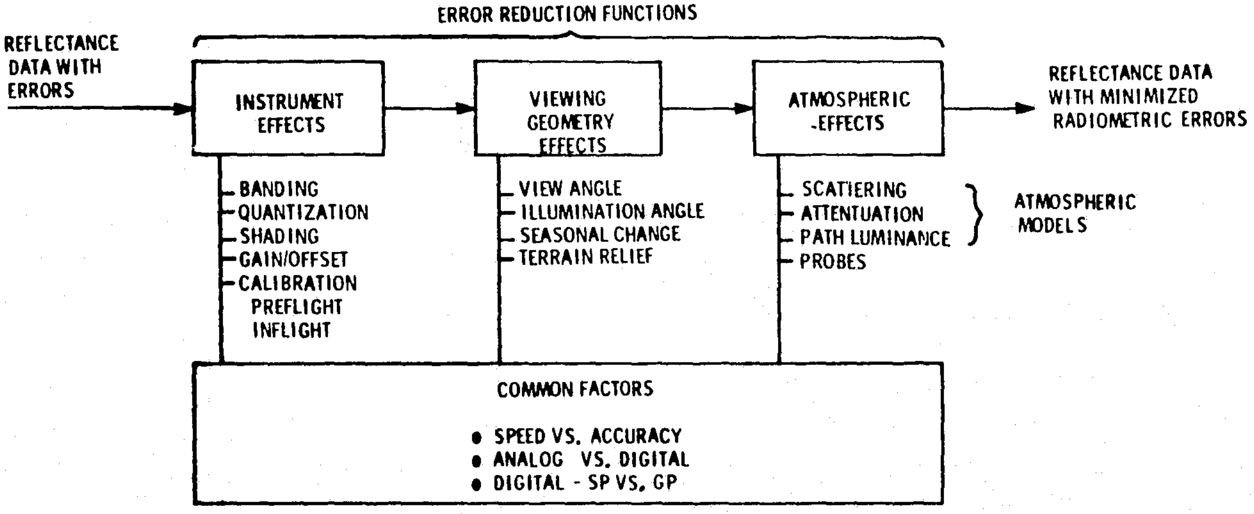
3. Hybrid Data Processing Techniques. Present hybrid data processing techniques utilize film as an intermediate recording medium to minimize the amount of digital data handling required to preprocess Earth Resources data. Necessary corrections are calculated using digutal techniques, however, corrections are applied by modulating the position and intensity of a reading and/or recording beam in the analog domain. A prime example of such a hybrid system is the present ERTS-1 data processing correction facility.

The present state-of-the-art will allow for processing earth resources data generated at ERTS-1 rates (15 megabits/second) at 2 to 2-1/2 times slower than this collection rate. This, however, is sufficiently fast to provide fully corrected data with about a one day delay.

Preprocessing functions for conventional imaging sensors can be grouped into two major categories, viz., radiometric correction and geometric correction.

5.1.1 RADIOMETRIC CORRECTION

The purpose of the radiometric correction function is to remove errors and anomalies in received radiance to allow the recovery of the reflectance distinguishing characteristics. As shown in Figure 5-2 radiometric correction functions can be grouped into three general areas dealing with the removal of the effects from (1) the data collection instrument, (2) the viewing and illumination geometry; and (3) the atmosphere (down and up). The state-of-the-art related to performing these correction functions is also shown in Figure 5-2.



CORRECTION FOR	State of the Art
Instrument	5
Viewing Geometry	3
Atmosphere	2

Figure 5-2. Radiometric Correction

5.1.1.1 Atmosphere

At present the radiometric quality of multispectral sensor data is limited not by sensor technology, or available flux, but rather by the degradation caused by the atmosphere. As spacecraft sensors become operational and the volume of data increases, it is important that suitable algorithms be developed which can be used to correct remotely-sensed data for atmospheric effects.

Absolute radiometric accuracy necessary for automated multispectral analysis can be obtained only by correcting spacecraft data radiance measurements for variable target irradiance, atmospheric attenuation and atmospheric backscatter. Such corrections should greatly enhance the usefulness of the data by extending the range of applicability to a variety of weather conditions. The atmospheric effect on the data depends on the type of remote sensing problem. In some cases, the effect is weak, as in the detection of fault lines; in other cases the effect is strong, as when measuring the chlorophyll content of water.

Major improvements must be made in consideration of atmospheric effects on multispectral images. Classical methods of image restoration depend, by and large, on nothing more complicated than some form of contrast amplification to make the image more interpretable. This does not solve the problem of determining absolute reflectance. Methods are required which attempt to model the nature of this atmospheric "noise" that degrades the image and develop signal processing techniques to achieve the best possible representation of the original object space.

Feasibility of such sophistricated techniques depends on the fact that atmospheric turbulence and other degrading influences have identifiable characteristics which, together with known characteristics of the original object, can be utilized to optimize image radiance. Implementation depends on the availability of high speed digital computers with large memories.

There are two possible approaches to eliminating the degradation effects of the atmosphere. The first, a preprocessing function, is to apply corrections to the data based on atmospheric models and ancillary data to enhance its absolute accuracy. The second, an information extraction function (see Section 5.2) is to process the data in such a way as to minimize or eliminate the effects of the atmosphere (e.g., ratioing) and allow information retrieval. Actual data systems must provide for an optimal utilization of both techniques to insure that atmospheric effects are minimized.

Several models (Refs. 4, 5) have been developed over the years, based on measured and calculated atmospheric data, which attempt to define those properties which interact with electromagnetic radiation - necessary for remote sensing of the Earth's surface. Some of the many properties considered in the atmospheric model are attenuation, refraction, multiple scattering, transmittance, path luminance, and background albedo. Even though much work has been done on modeling the atmosphere, relatively little work has been done to apply these results to an operational Earth Resources data correction function.

Research has been done (Ref. 12) to estimate the effects of the atmosphere on multispectral Earth Resources data from aircraft or spacecraft sensors. The ultimate objective of this work has been to determine the ability to correct the data and allow the extraction of absolute reflectivity. Results to date (Ref. 8) have indicated that the ERIM atmosphere radiative transfer model provides good to excellent agreements between experimental and theoretical results for wavelengths between 0.45 and 3.0 μm. Turner (Ref. 2) has developed the correction algorithms necessary for spacecraft-gathered remote sensing data and concludes that one should be able to correct spacecraft acquired data for atmosphere effects arising from multiple scattered radiation. The absolute accuracy with which this could be accomplished has not been determined. However, it is predicted that model calculations will permit optical parameter prediction to an accuracy of 30 to 50 percent of actual value. Further improvements will require that concurrent measurements be performed with either ground-based instruments or active onboard probes. A discussion of laser atmosphere probes is included as Appendix B.

Rogers (Ref. 3) discusses an approach to absolute ground reflectance determination using a Radiant Power Measuring Instrument (RPMI) to make direct measurements of atmospheric transmission, target irradiances, and sky radiance. The RPMI has been developed for NASA and is calibrated (5% absolute) to measure down welling and reflected radiance in four spectral bands corresponding to those of the ERTS-1 Multispectral Scanner. Research to date has not progressed to the point of providing procedures and/or techniques for obtaining the needed solar and atmospheric parameters.

5.1.1.2 Viewing and Illumination Geometry

The effect of viewing and illumination geometry on the calculation of multiplicative and additive correction functions to spectral reflectance has been shown to be very important under some circumstances. The solar altitude, elevation and azimuth look angle, as well as average background albedo have a significant effect on absolute reflectivity determination of an object. Egbert (Ref. 10) has shown, for example, that for one target-background pair (asphalt and grass), the contrast can vary from 2:1 to 0.5:1 for different angular conditions. He projects that inclusion of known information about illumination and viewing geometry can significantly improve the absolute accuracy of remotely sensed data and can aid in the planning of data gathering missions.

Corrections for viewing and illumination geometry may be made with a considerable degree of ease and accuracy. Many of the thrusts to arrive at the determination of atmospheric effects on remotely-sensed Earth Resources data have included the effects of viewing geometry.

Effects of terrain relief to date have been considered secondary and have not been removed from remotely-sensed Earth Resource data. Initial investigations have been conducted to determine the ability to determine the relief profile of an area from remotely sensed data to allow terrain mapping as well as to provide radiometric correction data. However, little success has been achieved to date.

5.1.1.3 Instrument Effects

The state of the art has advanced considerably in the area of correcting for radiometric errors in the data due to instrument effects. Removal of errors due to the instrument requires that extensive pre-flight calibration measurements be carried out. In certain instances periodic inflight calibration measurements are made and used to update corrections applied to the data. Camera calibration laboratories (Refs. 12, 13) perform radiometric calibration and mdoulation transfer function definition of optical systems (e.g., lenses, filters, detectors, etc.) in order to reduce the residual error in resulting radiometric data. The calibration functions required vary considerably in both nature and complexity for different types of sensors.

Framing cameras record an image over a two dimensional surface which can have a varying response. The return beam vidicon camera target exhibits a very nonuniform shading characteristic (25 to 50%) which can be measured and corrections applied to achieve radiometric accuracies from 3 to 5 percent. Periodic updates are required during RBV sensor operation due to the temporal variation of its spatial responsivity (electrical signal vs. incident illumination). Implementation of this correction can be accomplished several ways. A digital approach is to establish sets of spatially dependent tables to look up the actual radiance based on a measured electrical signal. For a typical ERTS-1 RBV camera, up to 27,000 different tables may be required to reduce shading effects to an acceptable level. An optical approach is to synthesize a film transparency spatial filter whose spatial density variation is a function of the camera spatial shading. This may then be applied to correct the shading optically.

Line scan sensors provide better radiometric fidelity than do framing camera sensors. Most scanners have multiple spectral bands and multiple detectors per band so several calibration curves are required. In addition, the gain and offset of typical sensors (i.e., photo multiplier tubes) vary as a function of time due to temperature or average scene radiance so provision must be made to update the sensor calibration curves during the imaging process. This detector calibration problem is very severe for large linear arrays of detectors in a push-broom line-scan imager since present state of the art of such sensors shows a very severe variation in responsivity from detector to detector. Radiometric calibration of line scan sensor data cannot be accomplished optically, but can be corrected in real time using digital techniques. Absolute calibration (to 2 or 3%) of each sensor is accomplished with a predetermined or periodically updated calibration table. Relative calibration (to about 1%) between detectors is determined per scan to eliminate banding which has an adverse effect on both photographic and digital data.

5.1.2 GEOMETRIC CORRECTION

The key requirement of an automatic multidimensional analysis system is the availability of a set of congruent measurements for each resolution element in the image. Multiple measurements from each image resolution element offer a means of improving the accuracy of recognition of the properties of the scene over that attainable using one dimension. Measurements of reflectance and radiance from microwave, thermal, and reflective infrared, through the visible wavelengths and into the ultraviolet region, can be utilized for analysis of each image point if congruence of these measurements can be achieved.

The necessity for geometric correction is generated primarily due to uncertainty in platform position and motion (ephemeris, altitude and altitude rates), sensor induced distortions (aberrations, smear, boresighting, etc.) and geometry of the imaging process (rotation of the earth, terrain elevation, viewing perspective). Many of these sources of geometric error can be minimized by calibration measurements of the sensors and associated electronics prior to and during the flight, measurement and/or control of platform dynamics and knowledge of the viewing geometry. In many remote sensing systems, measurement of the internal distortions related to the sensor is easily accomplished.

The requirement for ground registration accuracy is determined by the application of the data. A user who wishes to do only manual photo interpretation for purposes of change detection or geologic applications does not require very stringent absolute geometric accuracy. However, for mapping purposes or for automated information extraction, the geometric accuracy of the preprocessed data should be at least to within a picture element and probably to sub-pixel accuracy. This requires either very accurate knowledge of the parameters which affect geometric accuracy or the use of ground references. If the data system concept is to preprocess, store and correct all data from a given source or sensor to a single geometric accuracy, then the most stringent requirement will determine that accuracy.

In order to accomplish the task of being able to precisely register to sub-pixel accuracies data from different sensors, time periods and sources, the data must fit to some absolute reference grid or projection (e.g., the latitude/longitude grid using a specific reference spheroid, the UTM projection, etc.). This requires that the position of each point with a given radiance value be precisely determined and then moved to that point (hybrid approach) or the radiance value for a specific location on the reference be determined from a knowledge of adjacent radiance values from the data (digital approach).

The accuracy of applying geometric correction without ground control is primarily limited by the platform position and dynamics, and the geometry of the imaging process (e.g., curved earth, terrain elevation, viewing perspective). Sensor induced errors due to observatory, non-linear sweeps, boresighting, etc. can generally be minimized by measurement and calibration of the sensors and associated electronics. In most remote sensing systems, this is easily accomplished.

Some examples of this are the geometric measurements made for ERTS-1 prior to launch to define the RBV camera reseau mark locations and to specify the MSS mirror velocity non-linearities. The state of the art is such for both the measurement techniques and the inherent stability of cameras and scanners that this does not represent a limitation to geometric accuracy.

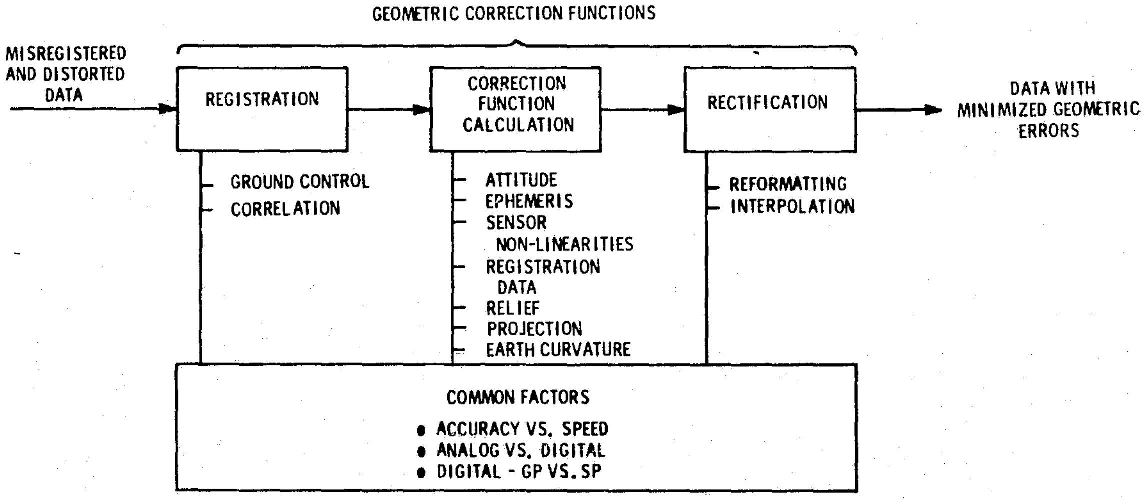
Effects of viewing geometry on image geometric fidelity can be considerable. As an example, Colvocoresses (Ref. 14) has calculated the impact of external viewing geometry on the geometric accuracy of ERTS-1 imagery. His results, summarized in Table 5-1, show that to meet stringent accuracy requirements for mapping, these effects must be considered.

The state-of-the-art in spacecraft attitude control systems for pointing to the Earth was discussed in Section 4.2 and assessed to be on the order of one arc second. The state-of-the-art in spacecraft ephemeris determination is predicted to be 50-70 meters along track and about 30 to 40 meters cross track and radially. For typical state of the art sensors for earth resources applications, the resolution element size is such that the effect of the ephemeris error is in excess of the acceptable misregistration. Therefore, some additional information must be utilized to perform the registration and correct functions.

The geometric correction process, regardless of the method of implementation, involves the completion of three basic functions which are: registration, correction function calculations, and rectification. These are depicted in Figure 5-3 along with summary state of the art assessments.

Table 5-1. Summary of Maximum Possible Displacements (Errors) in ERTS-A Imagery Due to External Conditions

Condition	Maximum Possible Uncorrected Displacement (meters)	Maximum Possible Displacement After Proper Scaling and Rectification to $\pm 0.14^{\circ}$		Nature of Final Displacements
		At Ground Scale (meters)	At 1:1,000,000-scale on 7.3" X 7.3" Format (millimeters)	
Earth Curvature	200	50	0.05	determinable
Atmospheric refraction	0.34			
Obliquity of 1°	440	53	0.05	not determinable
Terrain relief (for point 1,000 meters above or below control	160	160	0.16	determinable in well mapped areas
Map projection (UTM in U.S.)	42	42	0.04	determinable but of insignificant size.
Apparent combined error	840	300	0.30 mm	highly improbable



FUNCTION	STATE OF THE ART
Registration	3
Corr. Fcn. Calculation	3
Rectification	2

Figure 5-3. Geometric Connection

The registration function involves the identification of reference or control points or areas in the data and the measurement of their location to sub-pixel accuracy.

The correction function calculation process involves the determination of the x and y correction necessary at every point in the data in order to remove the distortions present and fit it to the actual location in some desired projection or reference grid system.

The retification process implements the calculation correction fit by reformatting the individual pixels (i.e., rubber sheet stretch) to make them correspond to their actual location.

5.1.2.1 Registration

The key process in the x, y measurement of a point in the input data to a sub-pixel accuracy is the two-dimensional correlation of the data with the reference area.

5.1.2.1.1 Optical Techniques

The simplest and oldest optical correlation technique involves an operator and a precision optical correlation measurement stage. The data in photographic form is visually compared to an image of the desired reference area to obtain its x, y location in the image. Measurement accuracies of available manual optical correlators are limited to 5-10 micrometers so the scale of the input data must be adjusted to provide the required sub-pixel measurement accuracy. This technique, although relatively easy to implement, is very slow and requires the reduction of the data to photographic form.

Optical correlation theory and techniques are also well developed for both non-coherent and coherent processing. The key to this technique is the development of a real time reusable recording medium.

Images of the reference point and its surrounding area are used to construct appropriate spatial filters which are recorded on film. Storage capability of film is such that thousands of such filters could be indexed and stored on one roll of film to give a mass storage capability. Optical processing systems are inherently parallel processors capable of performing operations on large arrays of data (i.e., images) containing millions of pixels in extremely short periods of time.

The throughput is limited by peripheral devices and not by the processing speed of the optical system itself. However, the fundamental limitations do not appear to impose any limitations on real time processing capability in an operational system.

The optical system can be illuminated with either coherent or incoherent light, each having advantages and/or disadvantages depending on the particular application at hand. The major advantage of coherent optical processing is that the Fourier transform of the data can be operated upon allowing two dimensional spatial filtering operations to be performed in parallel. The basic theory of optical spatial filtering is well developed and has been used operationally in many areas not related to Earth resources data processing.

Unfortunately, before coherent processing can be performed, the original data must be converted into a coherent optical wavefront. The most commonly used technique is to modulate a coherent beam using a non-diffuse transparency. However, no good, convenient, real-time method exists at this time for preparing transparencies. Research is being done to advance this technology and techniques applicable to coherent real time, optical processing. These include liquid crystal non-coherent to coherent image converters (Hughes), electronically alterable filters (ITEK), electronic Fourier transform plane sensors (Westinghouse), parallel optical spectral analysis techniques (Yale), and advanced spatial filtering techniques.

Incoherent optical data processing has been utilized in the information extraction function for many years. Some examples include dark room techniques of contrast manipulation, density slicing, dodging, photogrammetric rectification and the like. In recent years, however, optical processing techniques using incoherent light have been developed which are capable of performing many of the desirable filtering functions accomplished with systems using coherent light. Incoherent techniques allow processing of self-luminous data sources (i.e., oscilloscope presentations) for real time processing. The Fourier transform is not obtainable in an incoherent system and the inability to perform high-pass filtering precludes contrast enhancement functions (Ref. 15).

Materials used in optical interface devices for coherent optical systems such as liquid crystals or ferro electric ceramics have time constants of 50 to 2000 milliseconds. Considering resolutions of 10 to 35 lp/mm, this represents a processing rate of approximately 5×10^6 elements per second per square millimeter of area (or 3.2×10^7 elements/sec/square inch). Devices used for incoherent optical processing systems (image intensifiers or phosphorous) posses time constants one or two orders of magnitude shorter so that their data handling speed is larger by 1 to 2 orders of magnitude.

In certain, special cases where the signal (i.e., the reference area in a correlation process) is essentially noise free and of limited dynamic range, the non-coherent correlation has the advantage of requiring an optical system which is relatively simple. However, the desired correlation integral appearing in the output plane of this optical system is accompanied by additional bias terms that cannot be removed and tend to corrupt the desired correlation-function output and limits its accuracy. On the other hand, in a coherent-optical system, the unwanted terms can be physically separated from the desired correlation term. Thus, the accuracy and dynamic range of the coherent optical "computer" are limited only by the coherent energy level obtainable, the quality of the optical system and the noise in the output transducer.

5.1.2.1.2 Digital Techniques

Recently a great deal of effort has been spent on the application of fast digital transform techniques to image processing (Ref. 16). Several of these have useful application in calculating the cross correlation function between portions of two images for the purpose of registering the reference point to its exact location in an image.

The algorithms developed to implement the Fourier Transform have been successfully employed in this capacity and until recently provided the fastest registration method. In this procedure a normalized cross-correlation surface is calculated which is inspected for a maximum that is taken to represent the translation shift. For images which are not exactly the same (i.e., due to effects of noise, temporal changes, rotation, scale, etc.) this maximum is quite sensitive to these changes and there is always some probability that the correlation produced will produce an incorrect result. These effects of these changes can be minimized by enhancing both the references and image window area (e.g., spatial gradient, edge enhancement) prior to correlation. The resulting errors have been shown to be sub-pixel (Economy, Ref. 18) and meet the requirements of the data system.

A new method of image registration discussed by Silverman and Bernstein (Ref. 17) speeds up the process by at least a factor of 50. This registration technique, using sequential similarity difference algorithms is well suited for digital similarity techniques, but it suffers due to effects of magnification, rotation, noise, etc. Table 5-2 compares the direct Fourier Transform implementation, the discrete transform and the sequential similarity difference algorithms for various search area sizes and reference area window sizes.

Table 5-2. Number of Equivalent Integer Adds for Various Algorithms for Several Values Search and Window Sizes

Search & Size	Window Size	Direct Method $4.5M^2(L-M+1)^2$	FFT Correlation $200 L^2 \log_2 L$	Algorithm A $4 (1 + 10(M/32)^{1/2})(L-M+1)^2$
128	32	4.4 x 10^{7}	2.25 x 10^{7}	4.2 x 10^{5}
256	32	2.47 x 10^{8}	1 x 10^{8}	2.2 x 10^{6}
512	32	1.1 x 10^{9}	4.6 x 10^{8}	1.05 x 10^{7}
1024	32	4.5 x 10^{9}	2 x 10^{9}	4.35 x 10^{7}
2048	32	1.85 x 10^{10}	8.8 x 10^{9}	1.75 x 10^{8}
128	64	8.15 x 10^{7}	2.25 x 10^{7}	2.5 x 10^{5}
256	64	6.9 x 10^{8}	4.6 x 10^{8}	2.2 x 10^{6}
512	64	3.7 x 10^{9}	4.6 x 10^{8}	1.2 x 10^{7}
1024	64	1.7 x 10^{10}	2 x 10^{9}	5.5 x 10^{7}
2048	64	7.4 x 10^{10}	8.8 x 10^{9}	2.4 x 10^{8}
256	128	1.15 x 10^{9}	1 x 10^{8}	1.37 x 10^{6}
512	128	1.1 x 10^{10}	4.6 x 10^{8}	1.25 x 10^{7}
1024	128	5.8 x 10^{10}	2 x 10^{9}	6.7 x 10^{7}
2048	128	2.5 x 10^{11}	8.8 x 10^{9}	2.9 x 10^{8}
512	256	2 x 10^{10}	4.6 x 10^{8}	7.5 x 10^{6}
1024	256	1.8 x 10^{11}	2 x 10^{9}	7 x 10^{7}
2048	256	1 x 10^{12}	8.8 x 10^{9}	3.7 x 10^{8}
1024	512	2.7 x 10^{11}	2 x 10^{9}	4.1 x 10^{7}
2048	512	2.6 x 10^{12}	8.8 x 10^{9}	4 x 10^{8}
2048	1024	4.5 x 10^{12}	8.8 x 10^{9}	5.7 x 10^{8}

Implementation of image registration techniques must consider very strongly the computation time involved. Correlations of even very small arrays (32 x 32) of elements can take several seconds in a general purpose digital computer.

Special purpose computers can considerably reduce these computation times at the expense of losing flexibility of the equipment. Digital processors capable of operating at a speed equivalent to 3 x 10^{6} six-bit adds per second have been built and speeds up to 1 to 2 x 10^{7} are within the state of the art. This would provide a correlation surface for a 32 x 32 window and a 128 x 128 search area in 1 to 2 seconds using the digital filtering techniques or 30 to 40 milliseconds using the sequential similarity difference approach. Furhter increases in speed can be obtained by duplicating hardware and parallel processing to register images.

5.1.2.1.3 Hybrid Techniques

Hybrid correlations are, in general, improved versions of the manual optical correlation technique with the function of the man being partially replaced by a computer algorithm. Using this type correlation, an inexperienced operator grossly locates the reference area in an image of the input data. The area is digitized and its x, y location can then be found to sub-element accuracy using any of the digital correlation algorithms previously described.

5.1.2.2 Correction Function Calculation

The correction function may be viewed as a transformation which maps a distorted image space into a corrected image space. In general, a single composite transform is derived which incorporates the necessary corrections for sensor and spacecraft errors, input and output projections, and scale. The general form of the transformation will be based on a knowledge of the system geometries, and on empirical functions. The derivation of the transformation for a specific image will require satellite ephemeris and camera system calibration data to match the given points in either a best fit sense, e.g., least square error, or exactly using smooth interpolation techniques.

The calculation of the correction function is generally a very straight forward mathematical computation which is most easily performed using a general purpose digital computer. Care must be exercised in selecting and/or designing the correction algorithms to insure, not minimum computation time, but minimum implementation (e.g., rectification) time of the results.

5.1.2.3 Rectification

In general, an output grid point will not coincide with an input point and some algorithm is required for assigning a radiometric value based on values at neighboring input points. Interpolation algorithms based on values at neighboring points may readily be derived but imply some degree of smoothing and, therefore, loss of high spatial frequencies. An alternative approach, suitable for images with slowly varying distortions, is to assign the value of the nearest neighbor; i.e., the Point Shift approach. The error in each coordinate will be ± 1/2 picture element; for slowly varying distortions a number of consecutive output points will be assigned the values of a series of consecutive input points; this occurs in two dimensions. Thus the output image has the same spatial frequency characteristics over these sequences, with one picture element phase discontinuities at the boundaries. Experiments have shown that these discontinuities are in general not visually detectable.

The state-of-the-art of Optical Rectification of aerial photography is well established since this technique has been used for many years by cartographers to remove image distortion due to tilt and topography. The conventional procedure for the production of rectified photographs (using any of the several available rectifiers) is time consuming, laborious and requires a well trained technician to operate the rectifier and perform the required calculations. Considerable improvement in speed and reductions in cost have been made through more effective utilization of computers to calculate the necessary corrections.

The accuracies obtainable are excellent using applicable rectifiers for aerial or space photography. However, this approach is not feasible for handling the vast quantities of data as is necessary in an Earth Resources data system. Also, the techniques and equipment are not applicable to the rectification of scanner data since the corrections that can be made optically remove only camera distortions, viewing geometry, x and y translation, rotation, and a scale change. The internal distortions present in scanner data due to attitude variations during the collection process cannot be easily removed using optical rectification.

At present, most earth resources data systems use hybrid rectification systems in geometric correction of data. This can be done basically in one of two ways:

1. Utilize photographic data format input, scan the photo with a reading beam, modulate the position of the reading beam to a sub pixel accuracy based on the correction function, produce rectifier data in digital and/or photographic format.
2. Utilize photographic and/or digital data input, modulate the position of the writing beam to sub-pixel accuracy based on correction function, produce rectified data in photographic format only.

The state-of-the-art of electro-optical or hybrid geometric rectification of earth resources data is also well advanced. Several types of systems have been developed for rectifying various types of imagery which are applicable to earth resources data systems. The disadvantage of a hybrid system is that the data must appear in photographic form at either the input or the output of the processing system. The overall result is an enhancement in the system at the cost of severely degrading the radiometric accuracy of the data as well as causing a reduction in resolution of the data.

At present, much research is going into the area of all digital processing of Earth Resources data, since it holds future promise for very fast processing to reduce geometric errors and at the same time, does not reduce resolution or radiometric fidelity of the data. This technique utilizes the calculated correction function to determine what fraction of individual data pixels in the input space are required to establish the radiometric value associated with a specific element in a predetermined array (usually rectangular) of elements in the output space. At the present time, it appears that the state-of-the-art in the rectifier or the rubber sheet strecher is limited in realizing all digital pre-processing in an earth resources data system.

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5.2 INFORMATION EXTRACTION

Information extraction can be defined as the process of converting image data into parametric information such as the identification and classification of wheat fields from a multi-spectral image. Specifically it is the process of converting n-channel spatial array data (i.e. an image from any sensor in any spectral band) into user-oriented parameters. The spatial array can vary from a point reading to a spatial sample to a complete raster sampling of the scene. The sequential functions in information extraction are shown in Figure 5-4. They include:

1. Feature selection/extraction: obtaining the features or characteristics of the scene which can be used to identify points or objects in the scene.
2. Feature reduction: a linear transformation of the features obtained above to gain, hopefully, a minimum optimal set of features which will be sufficient to identify objects or points in a scene.
3. Feature classification/estimation: the conversion of feature measurements into user oriented parameters (i.e., corn yield, soil moisture, etc.)

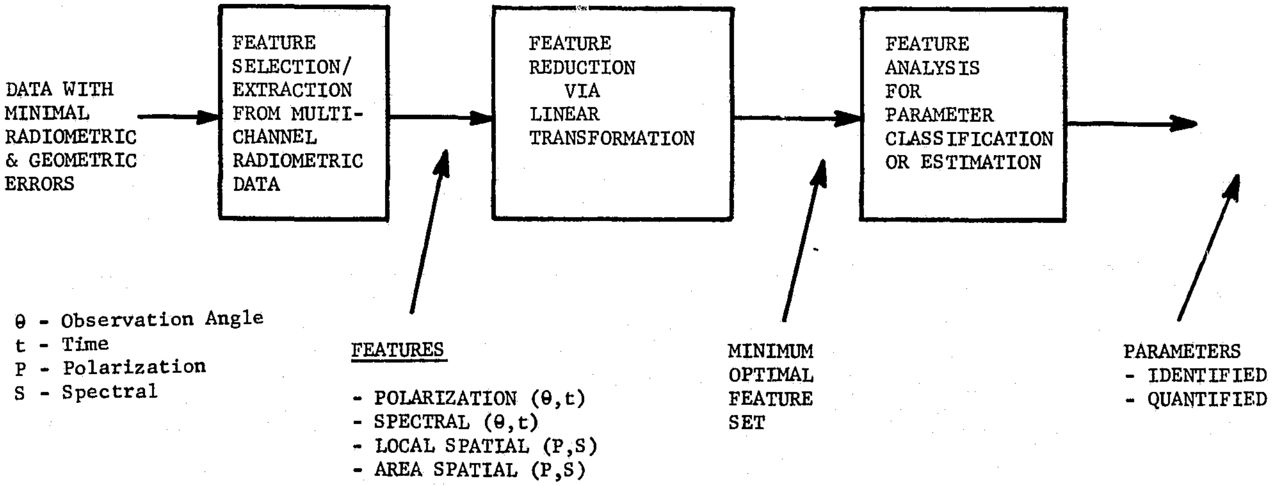

Figure 5-4. Information Extraction Functions

These functions and their states-of-the-art are described in subsequent paragraphs.

5.2.1 FEATURE SELECTION/EXTRACTION

Feature selection/extraction is the initial and most critical step in any machine-aided information extraction approach because subsequent extractive processing functions must utilize these features to achieve the desired result. Table 5-3 summarizes the state-of-the-art in feature selection/extraction. The four major categories of techniques are discussed in the following paragraphs.

5.2.1.1 Discrete Point Features

The radiometric image data that is recorded in a spectral channel is a function of (1) the energy in a spectral band; and (2) the energy with a particular polarization as received by the sensor. If during the preprocessing the illumination, atmosphere and sensor radiometric errors have been reduced or eliminated, then the intensities in

Table 5-3. Feature Selection/Extraction State-of-the-Art

Selection/Extraction Techniques	SOA
Discrete Point Measurements	
• Polarization	3
• Spectral Band (X-ray to Radar)	5
• Spectral and Polarization	3
- Combinations vs. Observation	
- Angle and Time	
Local Spatial	
Features Derived From the Above Measurements	
• MxM Window Filters (M~5-10) Operating on Each Pixel Smoothing, Laplacian, Gradient, Correlation Filter & Filter Sets	2
• Bilevel Image Extraction Via Thresholding	5
Spatial Measurements on N x N Gridded Areas	
• Transformation (Hadamand, Fourier, Karhune Loeve)	3
• Geometric Measurements Area, length, perimeter, aspect ratio, Spatial moment, texture measurements	2
• Radiometric Measurements (Expected valve, variance)	2
Function of Discrete Point Measures	
• Ratioing	5
• Normalization	5
• Ratio of Ratios	3

the data are a function of the properties of the object in the scene. Thus the radiometric intensities in a channel can be considered a feature which is useful in identifying points or objects in the scene. The n-channel radiometric image data can be considered as n-feature where each feature channel can have a different value for each point in the image.

So far the discussion considered features representing the scene spectral or polarization properties as recorded by an image taken at one time and observation angle. If images acquired at different times and observation angles for a given scene are corrected to the same reference frame via geometric preprocessing, then the polarization and spectral features can be a function of the observation time (t) and angle (θ). For each value of t and θ there are a new set of n-features (one for each channel of the n-channels of radiometric image data for a given time and observation angle). Hence the number of features expand rapidly as the spectral/polarization bands and the number of observation times/angles increase.

For example, if the four MSS bands from four ERTS passes over the same scene are geometrically registered, there will result 16 channels of radiometric image data (i.e., 16 features) which can be used to identify objects in the scene. If these 16 channels of data were put in film format, there would be 16 black and white photos all in registration for a particular scene.

A unique characteristic of the above features is that each feature or channel has a value for every point in the image which is only a function of the radiometry at that point. Hence polarization (t, θ) and spectral (t, θ) features are called discrete point features.

Presently polarization features are only semi-operational at radar frequencies, and are experimental at all other frequencies. Spectral features are near operational at frequencies down to radar; however, research is still required to define the best center and width of the spectral bands for a particular or group of applications.

From a sensor viewpoint the practical limitations of the radiometric accuracy of these features is 8 to 9 bits. However, because of the uncertainties in correcting for illumination and atmospheric effects across the image, present radiometry in the visible IR range is limited to about 6-7 bits. In addition the radiometric error due to interpolation between pixels (or positional error if nearest neighbor is used) can be of the order of 1-25 percent depending on the interpolation technique used and the local spatial gradient in the image. Thus desired point features with any radiometric correction are presently limited to about 6 to 6.5 bits of radiometric accuracy.

For observations taken at different times and angles, the primary problem presently requiring a research effort is the selection of the temporal and angular sampling intervals.

5.2.1.2 Immediate Neighborhood Spatial Features

The previous discussion was limited to those features (one channel of image data) which were a function of the radiometry at each point in the image, i.e., the spatial radiometric variations (variations between adjacent picture points in the image x-y plane) were not considered. The determination of variational characteristics between adjacent picture points for each point in an image is referred to as immediate neighborhood spatial feature extraction. These features are similar to the discrete point radiometric features in that each feature has a value for each point in the image. Examples of these features are spatial features derived from:

1. Spatial filtering of discrete point features, i.e., n-channel gradient, Laplacian, smoothing, high and low pass filter, match filter sects, etc.
2. Bi-level image obtained by thresholding the above features.

The gradient and Laplacian type operators followed by selected thresholding have recently been used to extract boundaries and homogenous training areas for both supervised and unsupervised learning. Matched filter sets have been used to extract line segment, arcs, and other simple geometric slopes from gray level images.

5.2.1.3 Area Dependent Spatial Features

The features discussed so far have the characteristic that the feature (channel) have a value at every point in the scene. Area dependent spatial features are different in that there are only feature values for each array of picture elements in the scene. The array can be a small segment of an image or the total scene. Arrays can be square (n x n pixels), polygons, or any arbitrary shape. The array can be pre-defined (i.e., n x n segment of an image) or derived from the descrete point features of the scene via spatial filtering and thresholding, classification, or other techniques. Examples of area dependent spatial features are:

1. Transformations (i.e., Fourier, Hadamard, Karhune Loeve) of n x n pixel arrays.
2. Area, length, perimeter, aspect ratio, expected value, variance, spatial moments, texture measurement, etc. of each array.

Most of the recent work with remote sensing applications has centered around transformation or texture measurement for predefined n x n pixel segments in a grided gray level image. The geometric features (i.e., length, area, perimeter, spatial moments) have mainly been applied in fields other than remote sensing (i.e., blood cell counts, aircraft identification).

5.2.1.4 Function of Descrete Point Measurement/Features

These functions consist of the rationing of features or the normalization of features. Normalization of features is used to represent the division of each feature by the average value of a feature for a given observation time or angle. These functions have several benefits: (1) they further reduce radiometric error not removed during the preprocessing step; (2) they can reduce the number of features by one; (3) most importantly, they can produce new features which are more representative of the object of interest in the scene. These functions have been incorporated into several multispectral analysis systems which are near operational on an experimental basis.

Most effort to date on feature selection/extraction has been concentrated in the visible and near IR and has been primarily spectral analysis. Additional development work is required to bring the spatial and temporal areas up to the current level of spectral techniques. Spatial feature extraction in general requires considerable computation time. Special hardware processing systems, which could be programmed to extract many of these spatial features on a cost effective basis, are presently under design and several such hardware systems should be available by 1975.

5.2.2 FEATURE REDUCTION

From the discussion on Feature Selection/Extraction it was shown that many features could be measured or derived for a particular ground scene. If the example of four ERTS overflights of a given ground scene is expanded to include spatial and ratioed features we could have the following situation:

16 Descrete point features - 4 bands, 4 overflights
x6 Spatial and ratioed features extracted for each descrete point feature
96 Features or Channels

Each of these 96 channels/features could consist of 10 million picture elements (pixels) of 6-16 bit dynamic range, and could be useful in identifying objects or points in the scene. To try to process the quantity of data would be very time consuming, even with high speed special purpose hardware. It is thus desirable to select the minimum subset of features or linear combination of features which will produce satisfactory object recognitions/classifications. The reason for using new features that are linear combinations (transforms) of the original features is that in most cases fewer transformed features are required to obtain the same degree of classification accuracy.

Ideally, the optimum set of new features would be obtained by selecting the minimum set of transformed features that would produce the desired classification accurately with the classification algorithm being used. However, this apparently straightforward method is usually not practiced because the time to select the optimum features would be longer than the time to classify using the original features. Thus a whole family of feature reduction algorithms have been developed which show some degree of optimality under certain conditions. These are listed in Table 5-4 in approximate order of increasing effectiveness and computation time.

Table 5-4. Reduction Techniques

	Technique	State of the Art
1.	Select input channel with largest variance	6
2.	Maximum or minimum eigen values of multi-class cluster	5
3.	Maximize (1) inter- to intra-class scattering or (2) distance - function using subset of original channels	4
4.	Minimize error using subset of original channels by use of a linear classifier	4
5.	Maximize (1) inter- to intra-class scattering or (2) distance - function using the best subspace of the original channels	3
6.	Minimize error using the subspace by use of a linear classifier	2
7.	Minimize error in subspace using the best available classifier	1

The final two methods are one function of the composite class distribution and as such do not guarantee an optimal separation of the classes. However, these are the only methods of feature reduction that can be applied prior to clustering type classification, because in the clustering approach no a priori individual class distributions are known. The remaining approaches can only be applied when a training site (supervised) machine training approach is used. In addition, approaches 3 through 7 utilize optimization techniques which require an interactive solution and as such can require a long solution time for the many channel, many class problem.

5.2.3 FEATURE CLASSIFICATION/ESTIMATION

Given an optimal set of spectral, polarization, temporal, angular and/or spatial features, these features must be used to classify or estimate points or objects in a scene in order to obtain user oriented parameters. The relation between the features and parameters can vary from deterministic to statistical. If this relationship is deterministic, i.e., the parameter is a monotonic function of the n-features, then the parameter can be estimated from the features. These functions are referred to as parameter estimation techniques and are in an early experimental state. Though the basic physics indicates that many of those deterministic relationships should exist, the models relating features to a particular parameter have been derived for only a few cases. These estimation models are very specific in that each model applies only to particular parameters (i.e., water depth for clean water).

On the other extreme, a statistical relationship may exist between the parameter and the features. In this case a given set of feature values will correspond to a given parameter. The process of determining a given parameter from one of a set of feature values is called classification. A graphic representation of estimation and classification is shown in Figure 5-5.

Between the above two extremes is a method which can be considered to be classification followed by estimates of the value of the classified parameter. This is shown graphically in Figure 5-6. From a classification viewpoint this method can be considered as a continuous subclassification of a particular class or mixture of classes. The complex mixture algorithm for subpixel intepolotion falls into this category.

Classification theory and algorithms are well developed. Whereas estimation algorithms are application specific, the classification algorithms are generic in that they can be applied to a broad range of classification problems. Algorithms are available which will produce linear, quadratic, and stair step decision boundaries. The state of the art of classification and estimation techniques is summarized in Table 5-5.

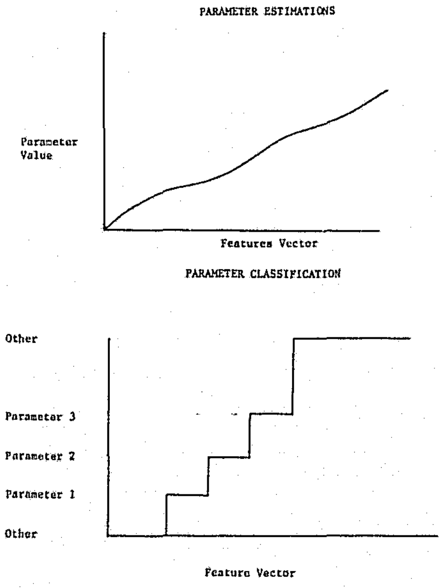

Figure 5-5. Example of Parameter Estimation and Classification

In the past, the selection of a particular classification algorithm was determined mainly by the level of computation cost one was willing to accept for the solution of a particular problem. Now, however, special digital hardware has been designed, and in some cases built, which can use any of the above algorithms and classify n-channel ($n \leq 12$) into ten classes in real time (i.e., at collection rates). For example, a 4-channel ERTS scene containing 10 million multispectral elements can be classified using quadratic or stair step decision boundaries into classes in about 25 seconds. This special hardware is about an order of magnitude lower in cost than a medium to large scale general purpose computer.

With the cost effective speedup of the solution of these previously time-comsuming algorithms by 2-3 orders of magnitude, the major time consuming classification activity has now become the process of training the classifier to recognize a given set of classes. The approaches that are presently being used to reduce the training time utilize the computer or machine to aid in its own training. This machine training can take two basic forms. In one form the machine aids the operator by enhancing and displaying the area containing the training sites. The machine can also store, recall and display the a priori training sites. The operator has only to register this training site data with the input image, evaluate this area in the input imagery and the training can be affected in a semi-automatic manner. If the input imagery is registered to a reference grid then the total process can be completely automated. In this automated mode it is still desirable to have the operator evaluate the a priori training area in the input imagery for artifacts, or significant changes (e.g., the field has burned after the ground truth was collected). The machine can also synthesize training sites utilizing theme data obtained in a previous classification (this is a form of unsupervised training). It can display each step of the classification process including the final results to the

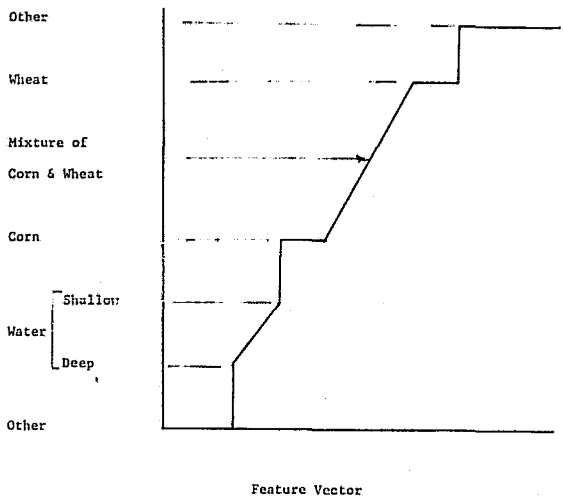

Figure 5-6. Continuous Subclassification of Particular Classes

Table 5-5. Classification and Estimation Technique State-of-the-Art

Machine Aided	
Gamma stretching	6
Color X-Function	6
Level slicing	6
Ratioing	4
Clustering	3
Local spatial operations	3
Area spatial operations	3
Supervised	
Training sites	6
Training sites plus unsupervised update	3
Unsupervised	
Spectral clustering	4
Spatial/spatial clustering	2
Spatial derived training areas	3
Estimation	3

operator so that he can assist the machine in its processing. Systems are now operating which can perform all of the above functions with a time lag between operator input and machine output in seconds (i.e., Image 100). Work now needs to be done to see how to utilize the interactive features to best minimize the machine training and classification times.

The other form of machine aided training is an elaborate form of image enhancement which is called feature space clustering. Cluster algorithms assume a nodulous feature space and they attempt to identify and represent these nodes by appropriate distributions. Using these distributions, either linear, quadratic or stair step decision boundaries are derived and the image points are classified. It is then assumed that these distributions and the corresponding spatial themes relate to object classes of interest in the scene. The classification results (themes) are displayed to the operator who then uses ancillary data to identify which clusters, groups of clusters, or subsets of a cluster correspond to the desired spatial feature. Since several passes through this man-machine loop are required to effect the final classification results, a fast effective interactive capability is required for efficient operation.

In the past, computer clustering algorithms utilized only spectral information and Euclidian distance as a closeness measure. The algorithm consistently produced results with accuracies lower than those obtained using the training site approach. Recently computer algorithms have been developed which utilize spatial continuousness and spectral homogeneity to identify initial nodal centers. The latter algorithms have produced results which are approximately equal to the training site approach.

A somewhat different cluster approach is being developed which will actually measure the spectral distribution by acquiring the histogram for a 250,000 pixel image area. By scanning the resultant histogram for high count cell, high density nodule regions can be identified directly. In addition a steepest descent technique can be used to find local high count nodes. Cells can be associated by various closeness criteria such as a common hyperface, hyperline, and hyperpoint and the resultant cluster of cells can be used to classify the pixel in the image. At each step of the process the intermediate results are displayed to the operator for his evaluation. This particular process should be operational in several months.

The same special purpose hardware which is used to speed up the classification based on training site learning can also be used to speed up the clustering/classification programs. The speed improvement of this hardware over a large general purpose machine is about 100 to 1 with the special hardware costing about one-tenth that of the general purpose machine. Presently, however, no effort to utilize special hardware to speed up cluster algorithms can be identified except for the case of the histogram clustering approach.

5.3 DATA STORAGE

The Data Storage and retrieval function occurs at many points in the flow of data through the processing system, beginning with the recording of raw data from the sensors and ending with the archiving of the pre- and/or extractive processed data. The major consideration in this function is to store large amounts of data in a relatively small volume while providing timely access, all for a low cost per bit. In addition, the storage medium must not degrade the radiometric and geometric accuracy of the data and must store the data in formats suitable for automatic extractive processing and analysis. Typically, the storage function must accept sensor data input at the rates of 15 Mbps today (ERTS) and up to 200 Mbps by 1980 (EOS). It must archive on the order of 5×10^{13} bits per year today (ERTS) and 4×10^{14} bits per year in 1980 (EOS).

The state of the art of storage media is summarized in Table 5-6. It is adequate today to support the high data rate recording required at the front end of the processing system. Video recorders such as the Ampex FR1928 and RCA TR70 readily record data at rates up to 15 Mbps. Recorders are in advanced stages of development, e.g., Ampex Electron Beam Recorder/Reproducer, to extend their rates to 200 Mbps. It is important to recognize that sensors of the future, with rates up to 200 Mbps, do not pose the high rate storage problems as may first be suggested. De-multiplexing of the data prior to storage greatly reduces the effective data rates and makes them compatible with current or near term magnetic tape recorders capable of rates of 30 to 50 Mbps.

Table 5-6. Data Storage Media - State-of-the Art

Media	Use	State of the Art	Earth Resources System Implications
Video Magnetic Tape	Raw Sensor Data Storage	6	Adequate
Computer Compatible Magnetic Tape	Mass Storage - Digital	6	Unsuitable for Mass Storage ● Large Volume ● Slow Access
Advanced Mass Storage Magnetic & Metalic Tape	Mass Storage - Digital	3-5	Acceptable for Mass Storage ● Moderate Volume ● Access Time: Seconds to Minutes
Optical - Digital	Mass Storage - Digital	Devices - 5 Systems - 3	Excellent for Mass Storage ● Small Volume ● Access Time: Microseconds
Optical - Analog	Mass Storage - Images on Film	6	Adequate with Limitations ● Radiometric Inaccuracy ● Retrieval Limitations

The significant state of the art questions involve the storage of extremely large quantities of data accumulated over extended periods of time. Currently, the primary medium for bulk storage of data is either magnetic tape for digital data or film for image data. These mediums are expected to predominate over the next several years. Currently both mediums have their disadvantages, specifically very high storage volume for magnetic tape and retrieval difficulty and poor radiometric performance for photographic film. These media, plus advanced mass storage systems, are described in subsequent paragraphs.

5.3.1 MAGNETIC TAPE

Magnetic tape systems such as the Leach MTR-7100, Honeywell 96, Ampex 1900 and Orion G-H307, are in operation and store large quantities of data at a low cost per bit. However, they require a large storage volume and do not provide a realtime access capability. They typically record 6.6 x 10^5 bits/m (16.7 x 10^3 bits/inch) on each of 14 to 30 tracks. Tape lengths vary from 2194 to 2926 meters (7200 to 9600 feet) giving a capacity of up to 70 x 10^9 bits per tape. It requires approximately 1000 reels of 35 cm (14 inch) diameter tape to store the typical EOS volume of 2 x 10^{13} bits. Tape speeds range from 9.5 to 305 cm/sec (3-3/4 to 120 in/sec) for a maximum output rate from all tracks exceeding 27 x 10^6 bps. In general, the large number of tapes involved with the associated handling problems preclude rapis access to the data, hence these systems must be considered unacceptable for Earth resources mass data storage applications.

5.3.2 ADVANCED MASS STORAGE

Several systems have been developed, or are in the advanced stages of development, which specifically address the rapid access high capacity storage problem. These systems are described in Table 5-7. The systems have capacities of 10^{12} - 10^{13} bits with access times ranging from a few seconds to several minutes. Their improved access time coupled with their much reduced volume, makes them attractive as interim storage systems over the next several years.

5.3.3 OPTICAL STORAGE SYSTEMS - DIGITAL

The current state of the art of digital optical memories is not well developed, however, they show promise of providing the large capacity, fast access time memory required by the Earth resources program of the shuttle era. The basis for advances in optical storage systems is the recent progress made in the areas of materials, optical phenomena and laser technology. Using an optic beam for addressing, the information bit size can be as small as the optical wavelength, resulting in a theoretical packing density of 10^7 - 10^8 bits/cm^2. The ability to focus a beam at a distance eliminates the problem of crash and wear between the read-write transducer and the storage medium as in conventional systems. With the introduction of inertialess beam deflectors, and the use of an array oriented technique such as holographic storage, the access time of such a large memory may be reduced to microseconds. Table 5-8 presents current device capabilities for various optical storage media. Much additional work is required before these devices can be incorporated into operational systems, particularly in the areas of laser heating requirements, depth of field for the processing optical systems, the practical packing density, access time, data rate and output signal to noise ratio.

5.3.4 OPTICAL STORAGE SYSTEMS - ANALOG

Present analog optical mass storage is accomplished by storing picture elements on photographic film. The advantages of image storage on film are its very high information storage capacity along with its sensitivity. Its major disadvantages are its incompatibility with digital extractive processing devices and techniques (retrieval) plus its inherent radiometric inaccuracy. Geometric errors are also a problem but to a lesser degree.

The unit of information storage on film is the grain which in terms of the illuminating light in an optical memory is basically a binary storage element. Because of the random nature of the photographic recording process and because the recorded signals appear as discrete opaque grains rather than a continuous tone, film creates noise which causes a degradation in the radiometric fidelity of the data. If the average grain diameter is known for a particular emulsion, it is possible to predict the number of detectable levels, or the number of bits, as a function

Table 5-7. Advanced Mass Storage Systems

COMPANY	MODEL	DEVICE TYPE	ORGANIZATION	MAX/MIN ACCESS TIMES	TRANSFER RATES	MAXIMUM STORAGE	COST	FIRST DELIVERY OR EXPECTED DELIVERY	REMARKS
AMPEX	TBM (Terabit) Memory System	Video tape; Rotary Head & 3 Long Head tracks on 2" wide video tape	Transport Drivers, Transport Moduel & Data Channels. Transport module has 2 transports; up to 32 modules/sys.	10 sec. Average access time	Each data channel read/write 750 Kbytes/sec up to 6 data channels /system with simultaneous read/write	11 billion bytes/transport module 400 billion bytes/system	Approx. .0001¢/bit	1972	Published info available; Selective block erase & upd Sys Cont & Fault Isola. by internal computers
GRUMMAN	Masstape	6x3" cartridge containing 260 ft. of ½" tape recorded at 8000 BPI; Data recorded in sections & blocks; each 130,880 bytes	11 cartridges housed in a quadrant-shaped "pac," 4 pacs are mounted on each drive to form a carousel; 8 carousels from a storage unit.		1.0 million bytes/sec plus	13.268 billion bytes/storage unit (useable); 8 mass tapes used together to form a 512 channel trillion bit system	.0001 to .0002¢ per bit	1973	No known users, Demonstrated at NJCC in May
IBM	Unannounced							1973	Nothing published
CDC	Tape Library (tentative)	3x100" tape cartridges in a 1700 cell storage: X-Y plot device access and loads Cartridges to a special tape transport	1 - 1700 cartridge system (may double in size) 1 - transport /controller (expanding to 4); several libraries possible.	7 secs. Max (if size doubles, this time doubles) Min. undertermined.	1 Mbytes/sec	8.25 M bytes/cartridge 14.025 x 10^9 Bytes/system 8 systems = 1.22 x 10^{12} byte bytes	Unknown	1974 (Late)	Nothing published; sys is in development stage; a working model or the concept has been built & tested
INTERNATIONAL VIDEO CORP.	Mass Memory Recorder MMR-1	Helical-Scan 1" video tape and rotating head; tape is 7000 ft. and enclosed in cartridge 8.5 x 10^{10} bits/car	MMR-1 is a device; not a mass storage system; Controllers must be built and possibly a system control computer incorporated in a system	3.5 minutes max; 45 seconds ave.; Random access time	8.1 x 10^6 Bits/sec	2 x 10^{12} bits; use 26 to 28 IVC MMR-1's to accomplish this storage	.000056¢/bit (not a system; system design & hardware extra)	1971	May meet TELOPS req'mts for mass storage. MMR is only a device and not a system
UNION DIVISION PRECISION INSTRUMENT	System 190 (Similar to UNICOM 690 Mass Memory Systems)	Laser read/permanent write system. Focused laser beam vaporize minute holes in metallic surface of a special recording medium - the data strip	31.25 x 4.75" data strip; up to ten data strips are contained in strip pack; data strip capacity is 275 x 10^6 user data bytes	Data strip load time is manual; select & load strip on drum is 10 sec; Max access time when strip is on drum 2 50 ms.	400,000 Bytes/sec - nominal	2.8 billion bits/strip 450 strips/system (Terabit Memory); one model 191 controller will manage 8 192's & 193's in any combination	.0001¢/bit	1972	System consists of 191 control units; 192 read/write units; or 193 read only units;

Table 5-8. Optical Storage Media Characteristics

	Silver Halide	Photochromic	Thermoplastic	Deformable Membrane	Elastooptic
Maximum linear storage density, cycles/mm	10^{3}	10^{3}	$3 \cdot 10^{2}$	10^{2}	50 (isotropic) $2 \cdot 10^{3}$ (crystal)
Energy required, J/cm^{2}	10^{-8} - 10^{-6}	10^{-2} - 10^{-1}	10^{-4}	10^{-4}	10^{-7} -10^{-5} (J/cm^{3})
Minimum record time, sec	10^{-9}	10^{-9}	10^{-8}	10^{-8}	10^{-8} (isotropic) 10^{-10} (crystal)
Development time, sec	1.0 - 10.0	n/a	1.0 - 10.0	n/a	n/a
Decay time, sec		10^{-3} -10^{-7}		n/a	n/a
Minimum erasure time, sec	n/a*	10	10 - 10^{2}	n/a	n/a
Life	Indefinite	Finite number of cycles	Finite number of cycles	10^{12}	Indefinite
Maximum linear space bandwidth product	10^{5}	10^{5}	10^{3}	10^{3}	10^{3}
Maximum area space-bandwidth product	10^{10}	10^{10}	10^{6}	10^{6}	10^{4}

*Not applicable

of recorded area. Figure 5-7 shows the relationship between number of recorded bits and grains per unit area while Figure 5-8 shows the number of delectable levels for two representative emulsions. In general, the resulting radiometric error for film systems can be made little better than 5 percent.

Image storage on photographic film is today a well advanced technology and will continue to be a major storage medium in the Earth resources system. No significant improvements are expected in the near future.

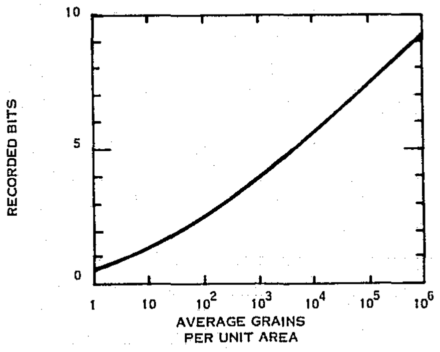

Figure 5-7. Information Storage Characteristics as a Function of Developed Grains

5.4 DATA TRANSFORMATION/REPRODUCTION

The transformation of data from one medium to another, including major reformatting (e.g. conical scanned data into raster format) and the reproduction or coyping of data, occur at several points in the Earth resources data system. Prior to preprocessing, the raw sensor data may be transformed from film density levels to digital bits or it may be converted from one digital format to another. Preprocessed data may be converted from film to digital prior to extractive processing and film or digital preprocessed data may be copied for distribution to users or other centers. Information derived from extractive processing can be in any one of several forms including film, digital image data, maps, statistics, etc. all of which must be reproduced for distribution to users or other centers.

In general all these transformation and reproduction functions have the same important system considerations of:

1. High speed
   a. Large volume throughput
   b. Minimum delay
2. High accuracy
   a. Minimize resolution loss
   b. Maintain geometric/radiometric accuracy
3. Low cost

The functions can be grouped and categorized as follows:

1. Digital/analog to film
2. Film to film
3. Digital to digital
4. Film to digital/analog

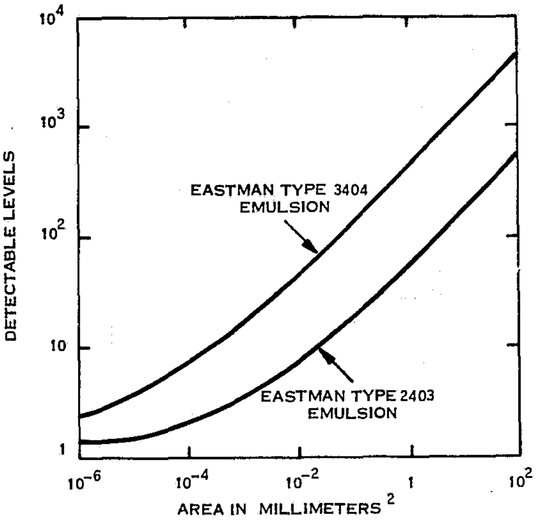

Figure 5-8. Information Storage Characteristics of Eastman Kodak Types 2403 and 3404 Emulsions

Table 5-9 summarizes the state of the art for these four categories. Subsequent paragraphs describe them in more detail.

5.4.1 DIGITAL/ANALOG TO FILM

The type of device utilized in the transformation of data from an electronic signal to film density is dependent upon the type of data being processed, the approach to data modification (e.g., correction) during the conversion process and the application of the resulting data. For example, if the data being processed is analog in nature and the facility chooses to use a hybrid approach where geometric corrections are applied during the writing on film, then the film recorder must have a spatial modulation capability (i.e., an electron beam recorder or a cathode ray tube). On the other hand, if the processing facility performs the geometric corrections while the data is in a digital electronic signal form, the recorder can be simpler (i.e., crater lamp drum recorder, laser beam recorder) because the spatial modulation requirement no longer exists.

For the requirements imposed by earth resources data in the areas of format size, quantity, radiometric accuracy, geometric accuracy and speed, the electron beam recorder and the laser beam recorder are the prime candidates for film recording of images in major processing facilities. Other types of devices such as drum recorders and CRT's do not meet the speed and flexibility requirements expected in a major earth resources data facility. A CRT is severely limited in its resolution, radiometric fidelity and geometric accuracy over large formats. A drum

Table 5-9. Transformation/Reproduction State of the Art

Transformation	State-of-the-Art	Summary Status
Digital/Analog to Film		
Electron Beam Recorder	5-6	Operational but expensive. Format size limited to 100-150 mm
Laser Beam Recorder	5-6	Operational, very high resolution capability formats up to 230 mm fast, expensive. Constrained to raster scan. Has color capability.
Cathode Ray Tube	6	Limited resolution, radiometric fidelity and geometric accuracy over large formats. Inexpensive.
Crater Lamp Drum Recorder	6	Accurate, inexpensive but slow. Suitable for low throughput systems
Film to Film		
Black & White	6	Fast, accurate equipment available. Throughput governed more by procedures and management than by equipment constraints. Further mechanization of equipment may enhance throughput and data quality
Color	6	
Digital to Digital		
800/1600 BPI Mag Tape	6	1-2 Mbps transfer rates. Accurate, operational
6250 BPI Mag Tape	6	10 Mbps transfer rate. Accurate,operational but not widespread availability
Advanced Storage Systems	4	10 Mbps transfer rate. Accurate, in development
Film to Digital	6	Multimegabits rates with electron beam or laser scanners.

recorder, while relatively inexpensive and very accurate in both a radiometric and geometric sense, is very slow and would require several units and operators to match the data handling capability of Laser Beam Recorders (LBR) or Electron Beam Recorders (EBR). They may, however, be adequate to meet the requirements of smaller facilities and users.

A major consideration for speed and geometric accuracy in both LBR and EBR devices is the film transport system. Those considered to meet the requirements for reproducing earth resources data fall basically into two categories: continuous motion transports and frame advance transports which accept roll film input.

In continuous motion transports, the reproduction systems depend upon a constant film velocity to produce the scan motion perpendicular to the beam velocity. This approach is most generally used in laser beam recorders, but may be used in EBR's for certain applications. Continuous motion transports require that data be printed in a raster format. Anomalies in film velocity (i.e., filter, biases, etc.) cause various kinds of geometric errors in the resulting two dimensional data; however, experience at the NASA ERTS data processing facility have shown those errors to be about the same as those introduced by along scan anomalies of the electronic beam.

In frame advance film transports, the film is advanced a given distance at a very rapid velocity between writing times. The writing area is usually one full frame of data so two dimensional writing beam deflection must be provided. This complicates the beam dynamics control, but eliminates the need for film velocity control, allows any data format to be utilized (e. g., spiral scan), and provides the capability of writing annotation and data separately.

5.4.1.1 Electron Beam Recorder

EBR's are currently operational and working well. The electron beam can be spatially modulated very accurately which allows a hybrid approach to geometric correction using a continuous framing technique. The dynamic focusing range presently limits the format size to less than 100 mm. To achieve the necessary spot size (3-4 mm) the electron path must be evacuated to at least 10^{-6} torr. A state of the art system has a 50% MTF response at 8000 lines along the format. Typical EBR characteristics are given in Table 5-10. The cost is relatively high, about $400,000 to duplicate the state of the art EBR used at the ERTS data processing facility and about $200,000 to duplicate the Brazilian EBR.

Table 5-10. EBR Performance Characteristics

Parameter	Performance
Video Bandwidth	0 to 8 MHz at 3 dB
Line Scan Rate	RBV: 1250 lines/sec MSS: 326 lines/sec
Dynamic Writing Area	63 x 16mm
Horizontal Frequency Response	
Center	8000 TV lines at 50% response
Edge	7200 TVL at 50% response
Vertical Lines per Frame	RBV: 4125 (55 mm frame) MSS: 4512 (53 mm frame; after line doubling)
Density Range	0.1 to 2.1
Transmission Range	100:1
Field Flatness	Max. density variation 1% of D_{max}
Scan Jitter	Peak-to-peak variation 0.01% of 63 mm
Film Transport Jitter	rms variations line-to-line (non-cumulative) < 20% raster pitch
Repeatability	Peak error < 0.03 mm

Minor improvements are probable through 1975 such as enhanced dynamic focusing to allow up to a 50 percent increase in format size and reduced spot size to 1.5 to 2 micrometers. Costs may be reduced if demand is sufficient to allow production runs instead of "one of a kind." Film for use in the EBR may be improved to minimize static buildup and reduce banding and geometric distortions.

5.4.1.2 Laser Beam Recorder

LBR's for earth resources applications are operational and provide extremely good resolution and high MTF response at spatial frequencies corresponding to 18,000 to 24,000 elements per scan line with very fast writing times (1000 to 2000 lines per second). A 20,000 x 20,000 pixel image can be reproduced in only 20 seconds. The format size of reproduced data can be made very large (230 mm or above) compared to that for an EBR. The LBR uses a continuous transport and is constrained to a raster scan which does not allow a hybrid approach to geometric correction. This also requires that annotation data be processed into the data stream prior to delivery to the LBR. A summary of published data on the present RCA black and white laser beam recorder characteristics is shown in Table 5-11. State-of-the-art improvements in black and white LBR's which can be expected include better spot shaping to enhance resolution and help to elimate banding. The cost of an LBR to function in a situation comparable to that for an EBR is slightly less (by a factor of 1.5) and ranges from $100,000 to $300,000.

An LBR also provides the capability of producing color imagery (as well as black and white.) CBS labs has built a three-color LBR which exposes 16 mm film at TV rates. Significant development efforts are still required, however, to upgrade color LBR's to large-format recording with high geometric precision.

5.4.2 FILM TO FILM

The state of the art in film to film reproduction is well advanced with little improvement expected through 1975. The technology and equipment are presently available to provide rapid, high quality photo copying of large volumes of data, both color and black and white. In addition, special processing techniques can be employed to enhance specific features within the image to facilitate extractive processing of the photographic data. Typical of today's state of the art are the ERTS photolab at GSFC and the EROS photolab at Sioux Falls, South Dakota.

Table 5-11. RCA LBR Characteristics

Characteristics	Present LBIR
Resolution:	18,000
Pixels per scan	18,000
Corresponding cycles/mm	39.5
MTF (with film)	56% (Kodak 3414)
MTF (electro-optics only)	75%
Gray scale:	
Dynamic range	250:1
Maximum film density	2.0 (Kodak 3414)
Video bandwidth	DC-10MHz (-0.5 dB) DC-25MHz (-3 dB)
Signal to noise ratio (electronics)	50 dB
Horizontal blanking	10%
Nominal line scan rate	1000 lines per second
Nominal scanner speed	15,000 rev/min
Scanner sync jitter	50ns p-p, 10Hz bandwidth
Scanner	1-inch diameter, air bearings
Number of facets	4
Line-to-line spacing	12.7 μm
Line-to-line jitter	± 0.3μm
Transport speed range	1 to 100 mm/sec
Recording gate	Air-guide curved plate
Film Supply capacity	240 mm wide by 76 m (3413)
Laser power	15 mw @ 632.8 nm

Original equipment selection and in-process quality control are the key factors in meeting specific requirements for geometric and radiometric accuracy, resolution and reliability. Throughput and cost of reproduction are also affected by equipment considerations, but operating personnel capabilities, indexing and cataloging techniques and photo facility management are equally, or perhaps more important, considerations in low cost high volume facility production. The ERTS system, with the requirements to provide multiple products to many users, has shown clearly that operating personnel and photolab management are more important state of the art considerations today than is the reproduction equipment itself. By way of example, the ERTS photolab has the capacity to produce 300,000 products per week with an average turnaround time of 5 days given that only multiple copies of every roll of film are produced. The scheduling, sorting, film shuttling and multiple handling problems associated with the making of single or limited copies of selected imagery for a multiplicity of users limits production to only 60,000 products per month with an average turnaround time in excess of 30 days. The equipment capability is adequate, the data management, i.e., operations technology state-of-the-art, is lagging. Future improvements in the state of the art must increase mechanization of photo processing to enhance quality and throughput.

5.4.3 DIGITAL TO DIGITAL

The state of the art of translating digital data to other formats or simply the copying of digital data, either from high density storage media or from conventional tapes or memories, is well defined and expected to advance very little over the next several years. For both reformatting and copying, where magnetic tape is utilized, the transfer rate is primarily governed by the inherent capability of the machines involved. Generally the process is done on a digital computer and for conventional 800 and 1600 bpi magnetic tape, the rate ranges from one to two megabits per second. Using high density, 6250 bpi, CCT's, the rate is about 10 megabits per second.

The translation/reproduction of data retrieved from the more advanced high capacity storage media (Table 5-7) will also involve a computer interface resulting in speeds on the order of 10 megabits per second. Improvements in digital translation/reproduction speed are expected to follow the developments in computer systems. Since the digital computer is inherently an accurate machine, accuracies are sufficient today with no improvements required.

5.4.4 FILM TO DIGITAL

The transformation of data from a photographic format to an electronic signal is a function which occurs frequently during extractive processing. Typical system operation involves the modulation of a light beam by the spatial transmittance variations on the recorded film. Motion of the film with respect to the beam may be accomplished by either scanning the beam or moving the film; an appropriate detector(i.e., photo multiplier tube) converts the transmitted light to an analog electrical output signal which may be sampled at the desired frequency and encoded at any level with typically 8 bits (256 density levels). Accurate synchronization of the scanning pattern and the electronic signal are required to allow identification of individual picture element characteristics.

The state-of-the-art of film to electronic data converters is well developed. Most devices are of the film scanning type and are thus severely limited in bandwidth. A typical example is the Multiband Imagery Scanner at NASA/JSC which is used to scan and digitize four multiband camera images for multispectral data analysis. Maximum scanning rates of 30 millimeters per second are achieved by moving the film transparency on a motor driven x, y platform in the desired pattern. Considering the information storage capacity of an ERTS-1 MSS color composite image (3 bands) this system is capable of a maximum output data rate of approximately 12 kilobits per second. The high scanning velocities capable with an electron beam allow output data rates of several megabits/sec to be easily achieved.

5.5 DATA DISTRIBUTION

The data distribution function in the Earth Resources system can be divided into three basic areas:

1. Distribution internal to a center
2. Distribution between centers.
3. Center to user distribution.

State-of-the-art considerations apply entirely to the distribution of sensor data and involve the transfer of large quantities of data in short time periods at reasonable cost. The current SOA in the three areas is summarized in Table 5-12. Through 1975 the primary method of data transfer from center to center and center to user will continue to be film sent through the U.S. mail. A limited increase in the use of Computer Compatible Tapes (CCT's) as a transfer medium will also occur. The high cost of wideband data links plus their relatively limited capacity will continue to inhibit their utilization. This situation is not expected to change significantly until such time as the Earth Resources system transitions from data (film) as primary outputs (with the user doing all the data reduction) to information (or parameters) as the primary output (with the Earth resources system providing the bulk of the data reduction function).

Table 5-12. Data Distribution - State of the Art

Distribution Area	State-of-the-Art	Summary Status
Internal Center		
Digital Computer to Anything else	6	Typical transfer rates = 1 Mbps
Special Purpose Hardware	3-5	Rate depends on application; rates essentially unlimited for parallel processes.
Between Centers		
CCT's	6	800 BPI packing density - 4 tapes required for one ERTS-type image Transfer requires mail or courier. 1-3 day delay over long distances.
High Density CCT's	4-5	6250 BPI packing density - 4 ERTS-type images per tape. Not available on many systems
Film	6	Essentially unlimited capacity
Data Links		
Wideband - 240 KHz	6	Cost is \$30K/month for 1850 Km (1000 mi). Requires 25 minutes to send one ERTS-type image
Narrowband - 3 KHz	6	In common use for low rate data - cost is \$1100/month for 1850 Km (1000 mi).
Center to User		
CCT's	6	Primary current distribution method. Uses U.S. Mail. 1-3 day delay is typical
Film	6	
High Density CCT's	4-5	Not available to most users
Data Links		
Wideband - 240 KHz	6	Not in general use
Narrowband - 3 KHz	6	Utilized by limited numbers of users for low rate data

5.5.1 DISTRIBUTION INTERNAL TO A CENTER

Sensor data transfer internal to a data processing center generally involves one or more of the following:

1. Video data to a processor.
2. Processor to processor transfer.
3. Processor to film writing device.
4. Processor to/from CCT.
5. Processor to/from HDDT.

In general all transfers involve some sort of processor. The processor can be either general purpose or special purpose, analog or digital, although the trend today is toward all digital systems. Where general purpose digital machines are involved the data transfer rates are on the order of one megabit per second. Special purpose processors have an essentially unlimited transfer rate using parallel techniques with the resulting data rate being largely dependent on the application. General purpose machines have been operational for many years in all kinds of earth resources applications; special purpose devices range from experimental to near operational in the Earth Resources area.

Other types of data transferred in the processing center, such as telemetry, calibration, correction, attitude, ephemeris and timing are orders of magnitude lower in rate, present no state of the art problems and have been operationally handled for years.

5.5.2 DISTRIBUTION BETWEEN CENTERS

The primary method of large volume data transfer between centers is currently, and will continue to be over the near term, the physical transfer of rolls of magnetic tape and film images generally via the mail. The cost is low but the delay time in transit is on the order of one to three days, a delay that will not be acceptable in systems that must respond to the near realtime needs of many users.

Data links are a potential solution to improving the delay time, however, they present capacity limitations and are costly. A standard commercial wideband channel with an approximate bandwidth of 240 kHz plus a service terminal costs $ 30,650 per month for the first 1850 Km (1000 mi). Interestingly enough, these wideband data channels are used all the time and are certainly "operational" from the telephone company's point of view. They appear, however, to be inadequate for the Earth resources system of 1980, hence requiring some state of the art developments. For example, it would take three such channels to keep up on a daily basis with the data being received from ERTS today. This is not to imply that all data will be transferred between centers all the time. On the contrary, it suggests that perhaps only carefully selected data be transferred raising questions of how to select the data to be transferred between centers. The mass data transfer between centers is an important element in the delivery of useful information to users in a timely fashion. Its relative lag in the state of the art makes it an important consideration in several key issues concerned with the value and accessibility of information to users.

5.5.3 CENTER TO USER DISTRIBUTION

Distribution of data to users is almost entirely done via shipment of film and magnetic tapes through the mail. Again the mails create a one to three day delay that may or may not be tolerable depending on the needs of the user.

A very limited number of users receive data (e.g., ERTS DCS) via narrowband telephone circuits. Data rate for an unconditioned 3 kHz voice circuit is 2400 bps. Cost for a dedicated line is $1100 per month for the first 1850 Km (1000 miles) (to transfer a full ERTS image over this line would take approximately 70 hours).

Either of the above state of the art (today) methods involve delays for any significant amount of data. Little change is anticipated in the near term. In addition, the high cost of wideband data links will continue to preclude their use by the average user. Hence the near realtime distribution of data (the equivalent of one or more images) represents a challenge to the present state-of-the-art.

The most attractive solution is to greatly limit the amount of data sent to the user, i.e., don't send data (e.g., film) for the user to reduce, send him reduced data - parameters or information. This permits the timely delivery of information via narrowband links, information limited to the specific needs of the individual user. This solution significantly affects the design of the data system - it's much easier on the data system to make multiple copies of images than it is to store, schedule and run specific algorithms for many different users. The question of timely distribution to users is another important consideration in the key issues involving the time value and accessibility of information. These key issues have been identified for further analysis in Task 5.

5.6 DATA PROCESSING FACILITIES

Several processing facilities are available which have various capabilities in the processing and analysis of earth science data. The totality of existing systems and facilities is far too vast to describe in this study. The purpose of this section is to describe the capabilities of a few selected facilities from government, industry and universities. These are only a small sampling of perhaps hundreds of such ongoing activities, but will give a clear understanding of the state-of-the-art.

The primary data processing facilities discussed in Section 5.6.1 were selected from among those U.S. and foreign government owned and operated facilities which are concerned with gathering, processing and disseminating data on a national scale. The secondary facilities discussed in Section 5.6.2 were selected from among those that are more discipline oriented and are concerned with extractive processing of data in both research and quasi-operational modes.

5.6.1 PRIMARY FACILITIES

5.6.1.1 NASA Data Processing Facility

The primary functions of the ERTS NASA Data Processing Facility (NDPF) are to receive telemetered sensor and ancillary data from the ERTS-1 spacecraft, preprocess this data to a specified radiometric and geometric accuracy, produce film and/or CCT recordings, and distribute them to specified users.

Spacecraft ephemeris, derived from tracking data acquired by STDN stations is provided to the NDPF. This, along with telemetry data containing spacecraft attitude and sensor operation information, is used to produce an Image Annotation Tape for identification, location and annotation of all imagery during image processing. There are three types of image processing performed in the NDPF: system correcting, scene correcting, and digital. All data is system corrected while only selected data is scene corrected and/or digitally processed. Inputs and outputs of the NDPF are summarized in Table 5-13.

Figure 5-9 illustrates the flow of data through the data processing facility. To accomplish the processing functions, the NDPF utilizes the following subsystems.

1. System Correction Subsystem.
2. Scene Correction Subsystem.
3. Digital Processing Subsystem.
4. Photographic Processing Facility.
5. Computing Services Subsystem.
6. User and Support Services Subsystem.

Table 5-13. NDPF Input/Output Summary

Subsystem	Input	Output/Destination
System Correcting Processing	-RBV and MSS Video Tapes -Image Annotation Tapes -High Density Digital Tape	-Exposed Black and White Film -Digital Image Data Tape
Scene Correcting Processing	-Work orders -Image Annotation Tapes -Master Image Film -Ground Control Point Film	-Exposed Processed Images -Processed, Digitized Image Data -Work orders -Master Film Images -Image Correction Outputs
Digital Processing	-Digital Image Data Tapes -Enhancement Analysis Tapes -Image Annotation Tapes -Work orders	-Computer Readable Tapes -Digital Image Data Tapes -Work orders
Photographic Processing Subsystem	-Exposed B&W Film; 70 mm and 9 inch by 9 inch -B&W and Color Film Images -Work orders	-B&W Film and Prints -Color Film and Prints -Image Assessment Data -Work orders
PCM Processing Subsystem	-Spacecraft Performance Tape -Spacecraft Orbit Data	-Image Annotation Tapes -Master Digital Data Tape
DCS Data Processing Subsystem	-DCS Data Tapes	-DCS Data Products
Support Services Subsystem	-Black & White and Color Film and Prints -Image Annotation Tapes -Master Digital Data Tapes -DCS Data Products -Digital Image Data Tapes -Data and Service Requests	-Work orders -Film and Print Imagery -Digital Data Tapes -Montage and Data Catalogs

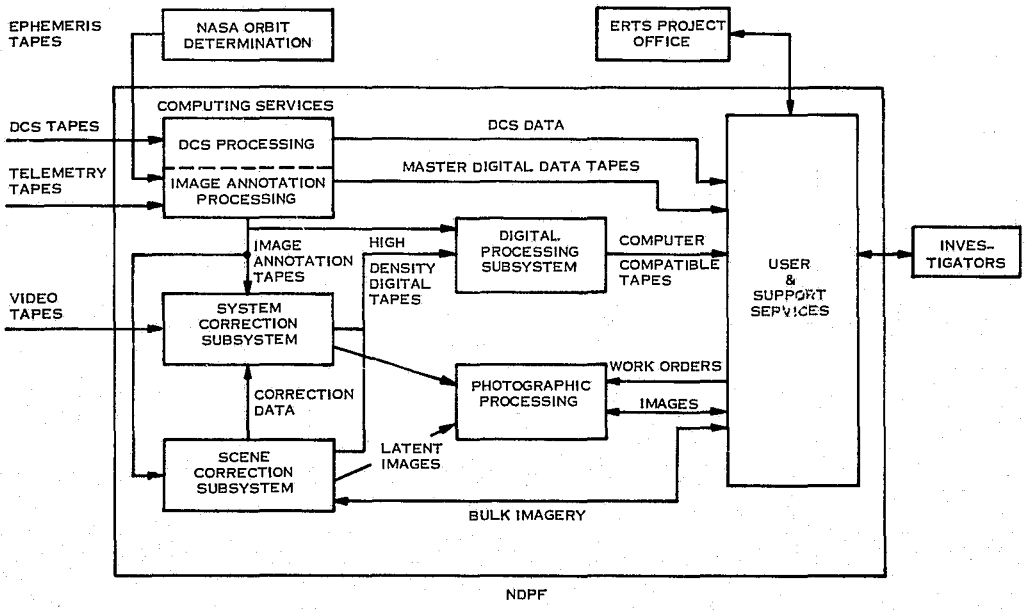

Figure 5-9. NDPF Data Flow

The System Correcting Subsystem processes all imagery data received at the NDPF. Data is accepted in the form of video tapes and transferred to film imagery using an electron beam recorder. Image annotation tapes produced by image annotation processing provide descriptive and positional data. User and Support Services determine and control the process flow through the system by means of work orders. The latent film produced is developed and transferred to the Photographic Processing Facility where multiple copies are made for distribution to investigators. Based on investigator requests, selected film images are input to the Scene Correction Subsystem, where their data contents are corrected both spatially and radiometrically. The corrected images are written out onto film which is also processed by the Photographic Processing Facility.

Both subsystems are capable of writing image data on High Density Digital Tape (HDDT). These tapes are used in the Digital Processing Subsystem to produce digital image data on computer compatible tapes (CCT). The CCT's are then duplicated by support services and distributed to the investigators.

Processing of Data Collection System information in the NDPF consists of editing and storing the data received on magnetic tape, and reformatting it into products suitable for distribution to investigators. This process is completely independent of image acquisition and processing.

5.6.1.1.1 System Correction Processing

The System Correction Subsystem, shown in Figure 5-10 produces latent images on 70 mm film from the data received for each spectral band of the RBV and MSS sensors. The data is also digitized, reformatted, and placed on high density digital tape. Certain corrections and annotations are applied to the data during the system correction processing operation and include:

1. Geometric correction for spacecraft platform instabilities.
2. Reduction of systematic errors caused by RBV camera distortion and image generation.
3. Radiometric correction for each RBV and MSS spectral band.
4. Framing of MSS data to be spatially coincident with RBV data.

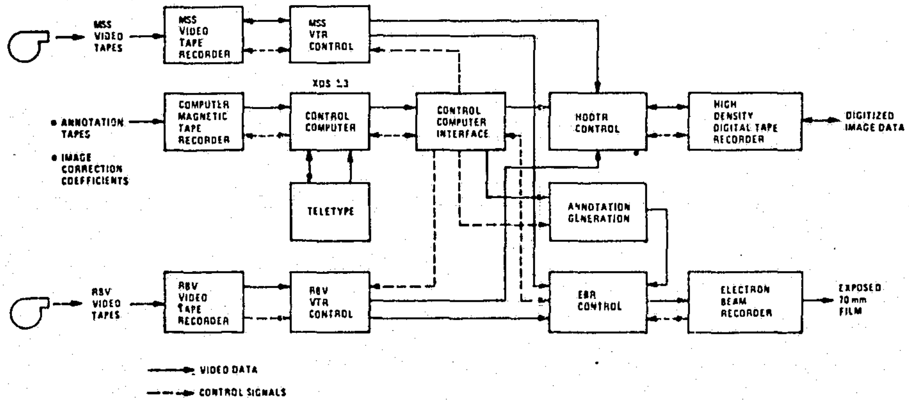

Figure 5-10. System Correction Processing Subsystem

The System Correction Subsystem equipment includes video tape recorders for handling input data, a computer digital tape recorder for input of annotation data, an annotation generator, high resolution film recorder, and a high density digital tape unit and associated control units. Operation of all of this equipment is controlled by the process control computer which is a small scale, dedicated computer providing control and timing of all hardware, formatting of annotation data, and computation of geometric corrections to be applied to imagery.

The high resolution film recorder is an Electron Beam Recorder (EBR), and all images are generated through this device. The recorder has a continuous film transport to minimize degradations at the corners of the image and to allow dynamic framing of the MSS data.

5.6.1.1.2 Scene Correction Processing

Scene correction processing is performed on a small quantity of data when requested by investigators. The 70 mm images produced by the System Correction Subsystem are processed by a hybrid analog to digital system, shown in Figure 5-11 to produce corrected film images on a 240 mm format. This process removes additional geometric and radiometric distortions not corrected in the bulk process and performs precision location and projection of the corrected image relative to Universal Transverse Mercator (UTM) and geographic map coordinates.

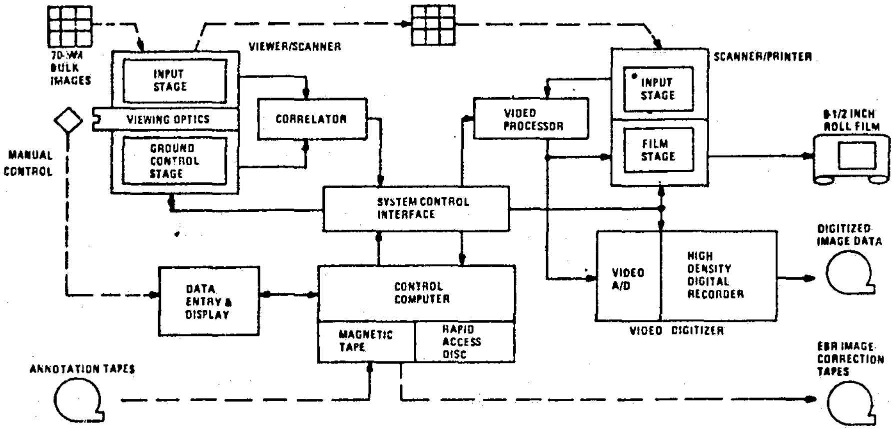

Figure 5-11. Scene Correction Subsystem

A key feature of the Scene Correction Subsystem is the use of ground control points to measure and correct positional errors in the MSS and RBV images. The ground control points used for precision location of imagery are objects having a known position on the earth's surface and which can be identified in an image. Data obtained from measurements of these control points are used to perform geometric corrections and provide data to the Scene Correction Subsystem for systematic error removal. This subsystem also has the capability to digitize the corrected data, and record it on high density tape for conversion to a computer compatible tape by the Digital Processing Subsystem.

The Scene Correction Subsystem consists of a viewer/scanner assembly which receives the 70 mm film input, a scanner/printer assembly to produce the 240 mm precision-processed film image, a high density digital tape recorder and a process control computer.

The image measurement functions are performed using the viewer/scanner. This instrument is basically a precision, two-stage image comparator with automatic and manual image-matching and coordinate-measuring capability. The operator station includes a data entry device, binocular viewing optics, X-Y handwheels, and a video monitor.

5.6.1.1.3 Digital Processing

Digital Processing is performed on a small quantity of image data when requested by investigators. Digital Processing edits, formats, calibrates and corrects high density data tapes produced from scene correction or system correction processing and outputs this data on a computer readable digital tape (CCT) for distribution to ERTS investigators. The equipment consists of a process control computer, five magnetic tape units, a data controller/corrector, and a High Density Digital Tape Recorder (HDDTR). These items and the subsystem's relationship to the system correction and scene correction subsystems are shown in Figure 5-12.

The High Density Digital Tape (HDDT) and associated HDDTR are essential to the efficient flow of data within the NDPF. The HDDTR provides high bit packing density and transfer rates during system and scene correction processing, along with playback at lower speeds to retain compatibility with the average recording rate on the computer compatible tapes.

The control computer is used in a process control mode whereby the digital image data is transferred to the memory modules and the main frame computer performs the data correction computation. The subsystem reads data into the control memory, accepts manual instruction inputs, operates on the stored data to correct, edit, reformat, and annotate it, and records the processed data on CCT.

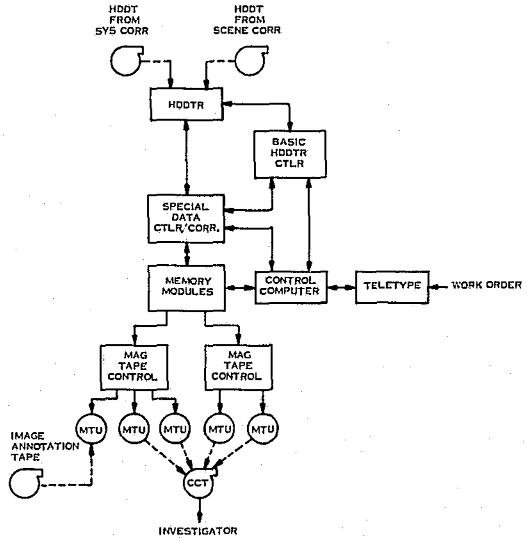

Figure 5-12. Digital Processing Subsystem

For MSS data, selected corrections are performed by the Digital Data Controller/Corrector consisting of line length adjust, radiometric calibration, and decompression.

5.6.1.1.4 Photographic Processing

The NDPF Photographic Production Facility (PPF) utilizes the images produced in system and scene correction processing to perform the following functions in accordance with user requests:

1. Develop 70 mm black and white negative and positive transparencies.
2. Produce 70 mm black and white transparencies from developed 70 mm transparencies.
3. Produce 242 mm (9.5 inch) black and white negatives from 70 mm transparencies.

4. Produce 242 mm (9.5 inch) black and white positives from 242 mm (9.5 inch) negatives.
5. Produce 254 mm (10 inch) color negative and positive transparencies and positive prints using 242 mm (9.5 inch) positives of 3 separate spectral photographs of an identical scene.

Equipment used to accomplish this includes continuous tone automatic black and white processors, automatic color film and paper processors, high speed strip printers, and step and repeat contact printers. Specialized equipment includes a photographic enlarger modified to a fixed focus enlargement of 3.37, a color composite printer, and microfilm copying, processing, and duplicating equipment.

The PPF also includes a centralized chemical mixing and storage facility incorporating a pollution abatement system consisting of electrolytic silver recivery units, black and white fixer recirculation, and color bleach regeneration and recirculation.

5.6.1.1.5 Computing Services Subsystem

A central computer system, utilizing a comprehensive data base and information storage and retrieval capability, provides control of NDPF operations. The NDPF Information System utilizes a dedicated Xerox Sigma-5 computer and provides the capability for production control, management reporting, data storage and retrieval, service to users, and preparation of digital products.

The Information System is built around a central data base providing support for computation and production control functions. It provides accurate accounting and storage of all data pertaining to observations, production schedules, and management control. All phases of operation are entered into the data base, including data received at the NDPF, conditions under which the observations were made, results of image quality assessment, results of cloud assessment, status of production, and status of shipment. All data is readily available for general searches, in addition to being available to satisfy the more specific requirements of production control.

DCS data transmissions are relayed by land lines from receiving stations to the Operations Control Center where the data is recorded on the Data Collection System Magnetic Tape (DCST). The DCST is forwarded to the NDPF where the data is edited, reformatted, and stored on disc for up to 48 hours. At the end of each 24-hour period, the preceding 24 hours of collected data is placed on a permanent archive tape. This transfer allows for retrieval of data at any time in the future, while permitting quick access to current (the most recent 24-48 hours) data.

DCS processing also prepares the platform data products for the DCS investigators. Capability is provided to produce on request, digital tapes, listings, and punched cards containing a selected subset of available, uncalibrated platform data. Means are also provided to accumulate and print summary data suitable for the DCS catalog.

5.6.1.1.6 User and Support

This section services investigators in a timely and selective manner by providing a full range of activities including:

catalogs, a comprehensive data retrieval system, microfilm services, dissemination of all imagery and DCS data, image descriptor maintenance, and the data ordering system. These services are summarized in Table 5-14.

Table 5-14. User Services Summary

Item	Summary Description
Standing Orders	Investigators may place a Standing Order for System Corrected, black and white imagery which has not yet been acquired by the Observatory. All data produced is matched against Standing Orders. Whenever an image is generated which satisfies a Standing Order, an internal NDPF request is generated to automatically reproduce and send the image to the requestor.
Data Requests	Investigators may place a Data Request for the reproduction of data already on file at the NDPF.
Standard Catalogs	Standard Catalogs announcing the images available are produced and sent to users. Separate catalogs for both U.S. and non-U.S. coverage are generated and contain data describing the images processed during the preceding month.
Image Descriptor Index	A cumulative catalog of image descriptors is produced once a month and distributed to the Investigators. This catalog is generated from a standard list of image descriptors supplied by individual Investigators based on their analysis of imagery.
DCS Catalog	A catalog summarizing all DCS transmissions is published once a month and distributed to the Investigators. Since the data content of the DCS messages are a function of the individual platforms which are owned by the Investigators, the catalog only summarizes the number of messages by platform and not the message content.
Microfilm Images	The Microfilm Images provide users with data which they can screen to select useful images. They grossly display what imagery is available and are not for data analysis. Each set of microfilmed images is in exact correspondence with the Standard Catalogs.
Browse Facility	The browse Facility in Building 23 at GSFC is available to assist visitors in their examination and selection of imagery data. Trained personnel are available to instruct and assist visitors to the facility.
Queries of the Data Base	User Services maintains an interactive information system which can query and search the computerized data base to identify images of interest to an investigator. Access to this system is available to visitors and via telephone and mail requests.

All of the NDPF equipment and processes are scheduled by work orders which are generated to match investigator requests against received data through the NDPF information system. The information system also serves as a data base to generate catalogs of image coverage, microfilm, abstracts, and DCS data for distribution to investigators.

It is anticipated that close to one-half million master images will be processed and stored at the NDPF each year. The storage and retrieval system aids the investigator to select only those images that are of significance to him. Investigators have access to all NDPF data through several files to provide efficiency in searching areas of interest. These aids include:

1. Browse Files. complete microfilm file of all available images arranged by date and location, with a data and location, with a data base query and search system and image viewing equipment.

2. Coverage Catalogs. listings in two separate catalogs of all U.S. and non-U.S. images that are returned over each 18-day coverage cycle. These catalogs are updated and distributed on a regular schedule.

3. DCS Catalog. listing of information available from the remote, instrumented data collection platforms.

Imagery requested by investigators is processed in either black and white or color from archival images stored in the master file. Samples of bulk and precision imagery and color composites are available to permit the investigator to select the material most useful for his purposes. Other material (such as DCS tapes and listings, digital image tapes, catalogs, and calibration data) are provided to investigators either to fill a standing order or specific data requests.

The User Support portion of the section was established early in 1972 after it became clear that there would be over 300 individual investigators using ERTS data. This organization:

1. Coordinates the establishment of contracts with all investigators - prepare the contract, negotiate it with the investigator, direct the contract through the NASA procurement system.

2. Accumulates requirements for ERTS data - solicit exact requirements for ERTS output products (when required, coverage area, cloud cover required, image quality, type of product, etc.), validate these requirements (assure that the products are really needed for experiment and that the system can supply them in a timely fashion) and enter them into the software system.

3. Plans the mission - since the requests for data oftentimes exceed the capacity of the system to supply it, plan the mission operation to best satisfy the most investigators at any given time.

4. Coordinates aircraft underflights - many investigators require the gathering of lower altitude data via aircraft, therefore schedule all aircraft flights to gather data when requested by the investigator (generally at or near the time the spacecraft is imaging the same area).

5. Performs investigator liaison as required - prepare and mail bulletins, instructions, special requests or information to investigators whenever necessary, e.g., notification of orbit adjust, new services available, addition or deletion of products, changes to formats, etc.

6. Coordinates ERTS-B proposal submission and evaluation - prepare proposal preparation instruction manuals, solicit proposals, establish procedures and criteria for evaluation, coordinate all evaluation committee activities, notify submitters of the results, coordinate contractual mechanisms.

5.6.1.2 EROS Data Center

The EROS Data Center (EDC) in Sioux Falls, South Dakota, is operated by the U.S. Department of Interior, Geological Survey, to provide access to remotely sensed imagery for federal, state, and local governments; the general public; and foreign governments. By 1975, it will represent the state-of-the-art in production multispectral analysis and theme extraction for users of earth resources data. In 1975, however, the EROS Data Center will still be relying on the NDPF at Goddard Space Flight Center to correct geometrically and radiometrically the remotely sensed data from the ERTS spacecraft. Present throughput is approximately 5,000 products per week and this will grow to about 30,000 per week in 1975.

The EROS Data Center (EDC) is divided into functional elements for servicing user queries; receiving, encoding and archiving agency imagery and data; photographic reproduction; and product dissemination. A computer facility provides the inquiry system data base access and control element of the facility. Figure 5-13 shows the functional interactions within and to the EDS.

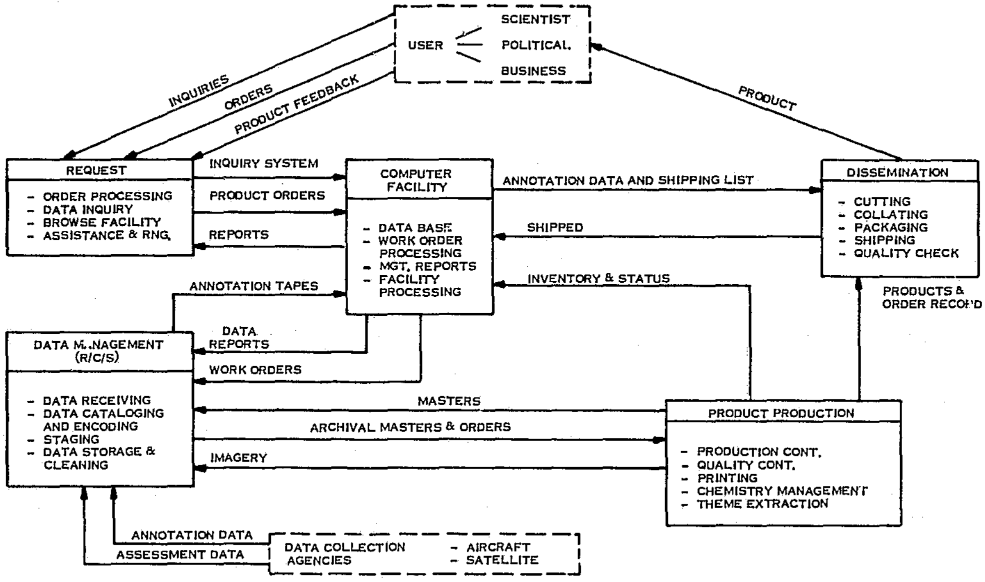

Figure 5-13. EROS Data Center-Functional Flow

The User Services or Request Function serves as the EDC primary interface with the user community. Here the response to user queries, the initial receipt and processing of customer requests, the required product research, the initiation of product work orders, and the dissemination of information about the EDC and its services are handled.

The user can communicate with the EDC by mail, phone or in person. All incoming requests are cataloged, uniquely identified and receipt is verified. A microfilm browse facility is available for both staff and customer use.

The EDC data base can be queried for product availability by geographic coordinates, source identification image, quality, cloud cover, and other vairables. The inquiry system will respond with the micro-film location of the requested imagery. The imagery can then be viewed and the required product types selected.

Orders can then be placed (with proper payment) for imagery in the archival files or standing orders for imagery not yet in the archives (i.e., 10 percent cloud cover of Boston in the fall).

The User Services function is also responsible for maintenance of records regarding all user contacts and the status of each customer's query or order.

The Photo Order Processing System is a computerized system, designed to provide an interface between the User Services, Data Management and the Photo Lab for the purpose of processing orders for imagery. Orders are entered into the EDC computer via terminal. When all daily orders have been transmitted they are edited, corrected, and placed on file. The accepted images are compared with the Main Image File and work orders are generated. From this file the Photo Lab is given all the information it needs to produce orders. Data Management is told what film to send to the Photo Lab and Dissemination is informed about new orders in the system.

This system also provides other services to facilitate the processing of orders. It controls an Order Bin File for the placement of active orders until the whole order is complete and ready to be shipped. It tells Dissemination which orders are ready to be shipped and provides mailing labels for this purpose. It controls and order archive file where information about completed orders is stored. It also provides other listings to management for the purpose of monitoring the system. Orders are assigned different status codes depending on their completion status. The status codes include: order edited, order processed, financial processing, work orders generated, order produced, order approved for partial shipment and order shipped. This data is listed daily and given to the User Services area to provide a status of each element of each order for quick reference by the request clerks in answering customer order status queries.

Remote access to the EDC computer system is provided at several Regional Centers (MIO, MTF). Queries can be made and product orders placed from terminals located in these areas.

The Data Management or Receipt/Catalog/Store function is responsible for input data receipt, data encoding and cataloging, staging, and data storage and cleaning. Input imagery is received from several agencies (ERTS, NASA Ames, NASA-JSC, Aircraft, Skylab, USGS, etc.); inspected and stored.

Imagery is added to the Main Image File through several methods. ERTS imagery is accompanied by Annotation Tapes and assessment sheets and are entered into the data base after adding archival roll locations and merging annotation tape data with assessment data. Other imagery (USGS, Ames, etc) arrives without annotation data and is entered into the data base by roll identification from data on the file containers through the Minimum Data Entry program. The imagery cannot be accessed through the inquiry system, but orders for the imagery can be processed. As annotation data becomes available, either from the image supplying agency, or from manual encoding by the Data Management function, the imagery is added to the Main Image File for access by the user inquiry system. The Data Management function is responsible for film inspection and cleaning. The film is cleaned prior to being used and upon receipt from the supplying agency.

The Data Management function provides all interface with agencies furnishing photographic source material and associated general accession data. This interface also enables a communication with the source agency for replacement of damaged or defective material. For both ERTS and Skylab imagery, the EDC provides a "Public Domain" communication to NASA when the imagery is entered into the film archives.

The Data Management function also performs the microfilming task. Items which are microfilmed include photo indices, maps, and important EDC records. Copies of the generated cassettes are distributed among the Browse file, the User Services area, regional sites and the archieves for entry into the data base and for filing as a product source.

The Photo Lab interface is provided through a production staging function. The staging function collates the computer generated work/order cards with the required archival rolls. The archival imagery is retrieved for production and refiled after return from the staging area. The staging function, although conceptually simple, is one of the most critical functions in the facility in that it schedules and controls the production and dissemination of all products.

The Photographic Laboratory function is responsible for the reproduction of imagery from the archival source material and generation of special film products (i.e., color composites). The archival rolls and associated w/o cards are staged by required product type and assigned a machine. The Photo Lab can be divided into three major functions: printing, processing, and quality control. The printing and processing functions are performed in accordance with a machine/product type assignment schedule because the equipment can generally be used for more than one product type and one archival roll may be required for generation of several product types. When a production task is assigned, the machine operator transports the archival roll, the accompanying w/o cards, and the unexposed raw stock, if any to the assigned printer area. Sensitized strips are put on the material to verify product quality. Routine maintenance and quality control procedures are performed during production by the operators. When a printing task is completed the archival roll is returned to staging and all the exposed film material and associated w/o cards are staged for processing. The processor operator transports the exposed film and w/o cards to the assigned processor area. The operator then processes the exposed material. The task is monitored by the operator and an automatic chemical replenishment system. After processing, a densitometry run is made on the sensitized strips as a quality control check on machine performance and procedures validation. When the processing task is complete, the products are taken to the quality control station where an inspection is made of the finished product. If a product is rejected, the w/o cards are so annotated and returned to staging for rescheduling. The equipment performance data is checked and tests run if necessary. Satisfactory products and the accompanying w/o cards are sent to dissemination.

The Dissemination function prepares the orders for shipment to the customer. The activity includes cutting, collating, final quality check, packaging, and shipping. Output of the Photo Lab includes the rolls or sheets of imagery and the work order cards. The imagery is cut (if required), inspected, collated by user identification number and placed into the reserved bins for the customer until the order is complete. Shipping orders are sent from the computer for all completed orders or for partial shipments, which may be initiated by management decision. The orders are then packaged along with annotation data and shipped to the user.

The Autographic Theme Extraction function (Figure 5-14) provides a facility to extract selected themes for approved experiments within USDI. Four classes of extractions can be made with the existing system; open water, snow and ice, mass works of man, and infrared-reflective vegetation. Completed extractions are archived in Data Management to be available for reproduction upon request.

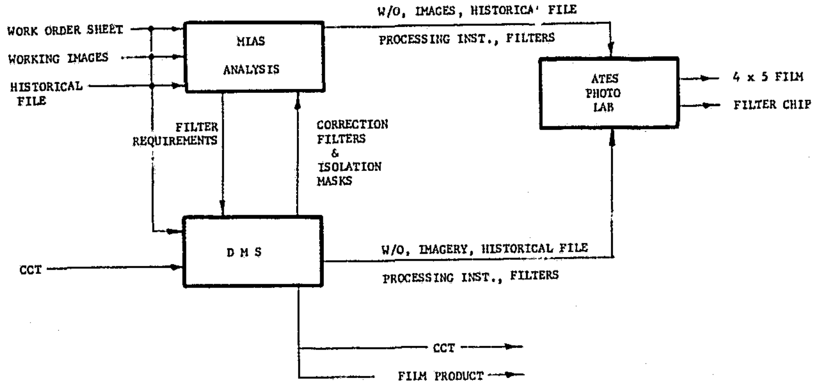

Figure 5-14. EROS Data Center Automatic Theme Extraction System

When completed, ATES will serve the needs of a wide spectrum of users and will accommodate a wide range of remotely sensed and ground truth input data. The block diagram emphasizes the overall concept of accepting a wide variety of input data for which geometric and densimetric corrections are applied in analog form and which are then submitted to theme-extraction analysis for the generation of detailed photoprocessing instructions. The photoprocessing is then accomplished by acting upon the original data by applying digitally generated analog rectification masks under detailed instructions developed as a result of thematic-content evaluation. The system responds to the time-critical data user by providing lower resolution graphics as a direct output from the thematic-content evaluation. The quantized version of the output is accomplished by binary-level raster scanning of the formated thematic map data, which results in a computer-compatible digital tape.

Development of the digital Density Manipulation system (DMS), which utilizes a PDP11 computer, has not been completed but it will be operational by 1975. The facility is presently supporting only approved experimenters in specific discipline areas, but will be in the production phase and supporting many users by 1975. The present theme extraction capability is primarily analog utilizing photochemical and video techniques.

In addition, by 1975 the LARSYS information extraction system will be available at the EROS data center, either by means of a remote terminal or the completed software package.

A Professional Services function is provided at the EDC for user assistance and training, and for scientific research. At this time the interactions between this function and the rest of the EDC are being defined.

A Browse facility is provided at the EDC to support drop-in customers. The facility is equipped with a terminal for access to the inquiry system, microfilm cassettes of available imagery (where available) microfilm and microfiche display units.

5.6.1.3 Canadian Data Processing Facility

The Canadian Data Processing Facility was designed in late 1971 and is presently phasing into an operational status. The three major functions of the facility are:

1. Process the data received from the Earth Resources Technology Satellite (ERTS) to produce corrected photographic images and computer-compatible digital representations thereof.
2. Process data remotely sensed by airborne sensors in a similar fashion.
3. Provide the tools required for research and development effort in automatic interpretation techniques.

Figure 5-15 is a block diagram of the data handling system. At the heart of this is a dual PDP-10 digital computer. The dual processor configuration was chosen primarily to handle the generally conflicting requirements of high system stability and reliability for the ERTS production function, and the high degree of flexibility in both hardware and software for the airborne and interpretation needs.

The equipment is normally operated as if it consisted of two entirely separate and independent systems. The first is the dedicated, on-line ERTS production facility, which is used to control the processing of the video data. The second is the utility system, used for all general software and hardware development in support of the airborne and interpretation requirements, as a research tool for the center scientists, and for the off-line data processing tasks which are necessary to prepare for the ERTS production runs. As experimental systems reach an operational status, they can be moved over to the production system.

The primary output product of the ERTS production system is a geometrically and radiometrically corrected photographic latent image of scene corrected quality. The National Air Photo Library has the responsibility for processing the photographic film, duplicating it and distributing it to the users. On request, the MSS data for a limited number of scenes will be made available on computer compatible, 9-track digital tape at either 2032 or 4064 characters per centimeter (800 or 1600 characters per inch) density.

The utility portion of the facility is operated under a standard time-sharing monitor system which allows a number of users simultaneous access to the system.

As a first step to providing support to the airborne programs, a high speed analog-to-digital converter will be added to the system. This will allow computer processing of data recorded on analog magnetic tapes from airborne sensors such as infrared line scanners. Eventually it is expected that other playback devices will be interfaced to the computer.

The first non-standard equipment to be provided to support the research and development effort into automatic interpretation techniques will be a high resolution, full color video display system. This system will be controlled by the computer and will operate in a time-sharing mode with the other activities.

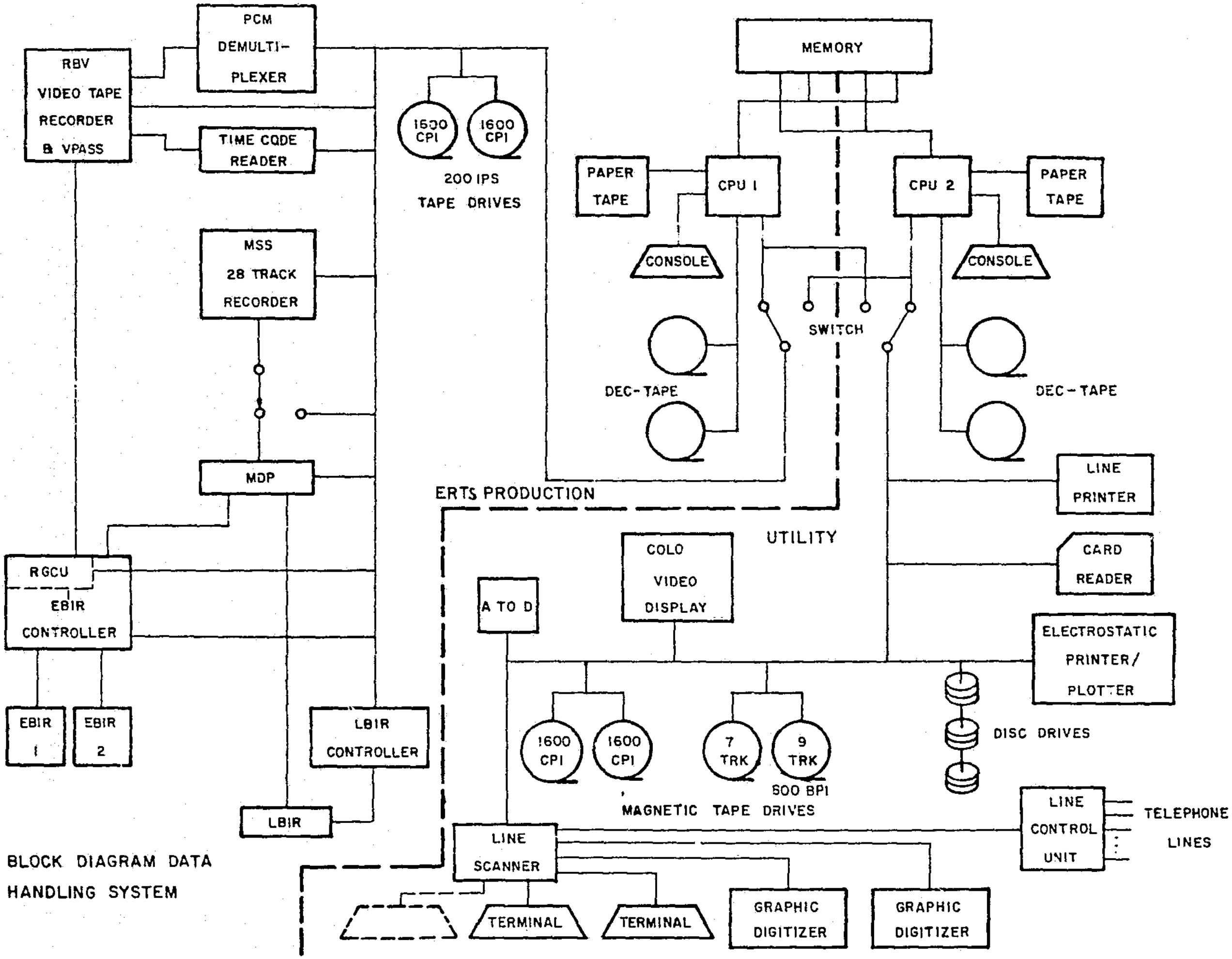

Figure 5-15. Block Diagram of Canadian Data Handling System

Many other general functions will be performed by the facility. A few examples of these are: reducing photographic images (color or black and white transparencies) to digital form with the aid of the LBIR in scanning mode; maintaining a library of references to remote sensing literature which may be accessed through the Technical Information Retrieval system; and maintaining an inventory of all remotely sensed data which is processed by the facility.

The Canadian DPF functional configuration is shown in Figure 5-16. The following three modes of operation are available:

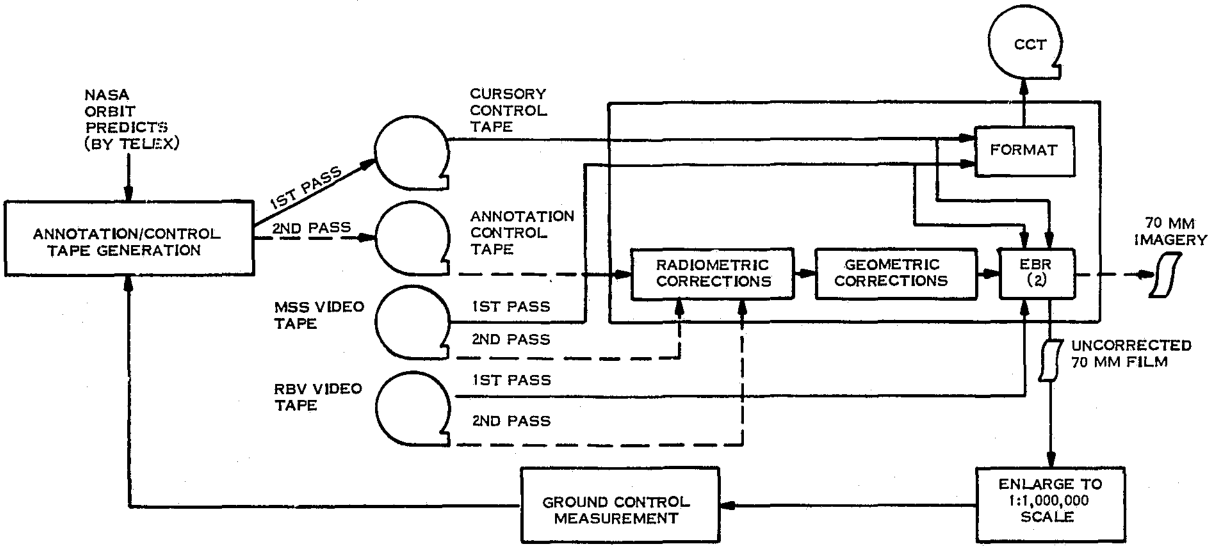

Figure 5-16. Canadian Data Processing Facility Functional Organization

1. MSS Video-to Film Conversion. Processing imagery requires two passes through the system. The first "system" pass requires four passes through the video tape, resulting in a one-fourth real time output rate on film. Two electron beam image recorders are used in a "ping pong" mode, taking turns printing images. This film is uncorrected and has only cursory annotation. Ground control points are read from an enlarged copy of this film and a final control/annotation tape is generated. The video tape is then re-run through the system (four passes at the real speed). Geometric corrections are performed in the electron beam image recorder controller with data from the control/annotation tape. Radiometric calibration is performed on a one sweep delay basis via look-up table.

2. RBV Video-to-Film Conversion. The RBV video-to film conversion mode is similar to that of the MSS. However, only one pass of the video tape is made for all bands. After the first film imagery is enlarged and returned to the x-y digitizer, the reseaus are measured as well as ground control points for the final "system" pass through the image processing system, using the final control/annotation tape with the video tape. The resulting electron beam recorder images are annotated and both geometrically and radiometrically corrected.

3. MSS Video-to-Tape Conversion. Scene data are transferred to the main frame core at one-fourth the real time rate. The data are then transferred to standard tape drives for preparation of computer compatible tapes. Each tape contains all four bands of a complete scene (1600 bpi tape).

5.6.1.4 Brazilian Data Processing Facility

The Brazil data processing facility was designed in Mid-1972 and is presently in a checkout phase. The image processing system, shown in Figure 5-17 will convert both MSS and RBV video tapes to images on 70 mm film using a framing electron beam recorder under computer control. Only MSS video data is converted to computer compatible tapes. The imagery produced is geometrically corrected for spacecraft altitude and attitude effects, earth rotation effects, sensor line length variations, and systematic image processing effects. The correction data for the spacecraft effects is derived from the recorded pulse code modulation (PCM) data and an ephemeris tape received from NASA. The system will make precision image measurements to remove systematic image processing effects and to correct selected images with respect to ground coordinates. Radiometric calibration is applied to the data to remove sensor response variations.

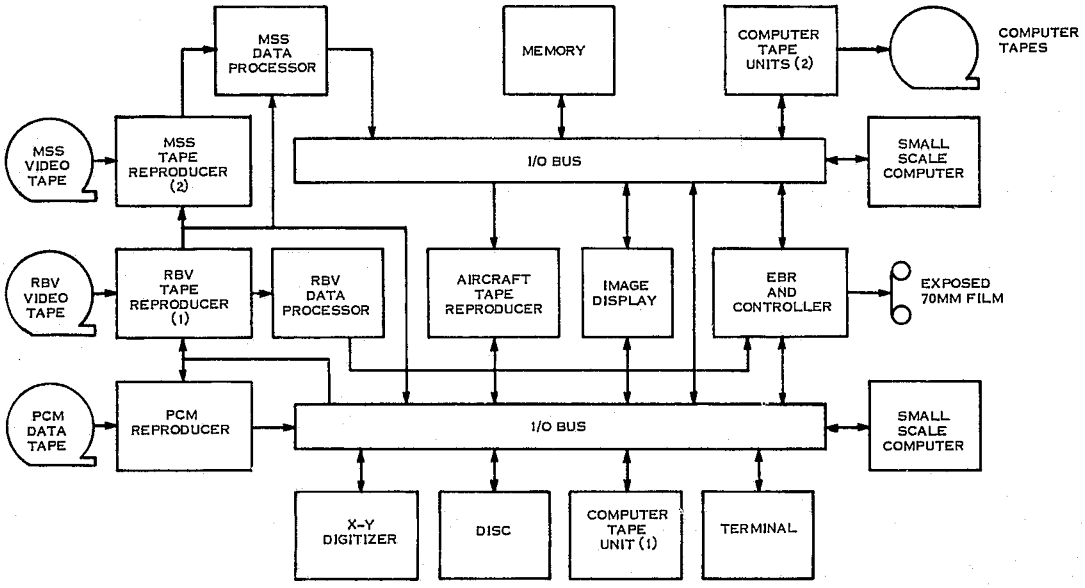

Figure 5-17. Brazilian Image Processing System Configuration

The IPS can display the MSS video data in color or black and white on a quick look cathode ray tube monitor. This data is displayed in a high or low resolution mode with the capability to edit data for transfer to computer compatible tape. The computer compatible tape data may also be displayed in color or black and white. The addition of aircraft input hardware will give the system a similar capability for the aircraft-acquired data.

The Brazilian functional configuration is shown in Figure 5-18. Eight modes of operation are available in the Brazilian system. The system is configured such that no two functions can be performed at the same time. The system extracts data from the telemetered PCM data tapes and merges these data with that contained on the ephemeris tape received from NASA, creating an image correction tape. This tape is used to provide corrected and annotated MSS and RBV film imagery.

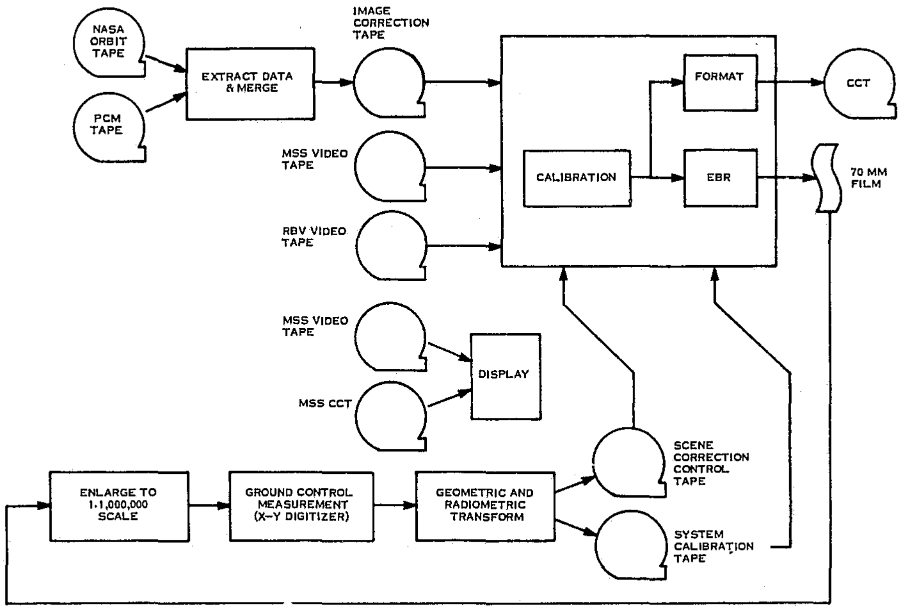

Figure 5-18. Brazilian System Functional Configuration

5.6.1.4.1 MSS Video-to-Film Conversion

This requires eight passes through the video tape (twice for each band; each pass through the tape picks up every other image). The data are run at the real time rate. This gives a one-eighth real time output rate for 70 mm imagery. Radiometric corrections are applied "on the fly" from calibration wedge data via a look-up table. Geometric corrections are performed under control of the image correction tape.

5.6.1.4.2 RBV Video-to-Film Conversion

This processing requires one pass through the video tape. The data are run at the real time rate, giving a real time output for 70 mm imagery. All corrections are performed via the EBR controller. The corrections are derived from the image correction tape and the system calibration tape.

5.6.1.4.3 MSS Video-to-Tape Conversion

Selected scenes or sections of scenes are converted to CCT format at one-fourth the record rate. Either one or two CCT's may be produced per pass through the video tape depending on the selected format. The position (byte and scan line number) of the start of a data swath is operator programmable. The length of the swath is variable by user choice. The swath width may be either 512 or 950 pixels (including 14 percent overlap in the latter case). Radiometric calibration corrections are applied on a one sweep delay basis and no geometric corrections are performed.

5.6.1.4.4 MSS Video Display Mode

Data from an MSS video tape may be displayed in black-and-white or color with both low and high resolution capabilities. The low resolution mode displays the full 185 Km (100 nm) swath width in a sampling mode. The high resolution mode displays any set of 640 contiguous elements at full resolution. The selection of data for enlargement is done by positioning a cursor symbol around the area of interest. This display is capable of providing annotation to identify the image segment being displayed in the low resolution mode.

5.6.1.4.5 Computer Compatible Tape Display Mode

Data from a computer compatible tape may be displayed in black-and-white or color. Any set of 640 contiguous elements may be displayed at full resolution.

5.6.1.4.6 MSS Scene Correction Film Mode

Internal and external geometric errors of each MSS scene are determined by measuring ground control points and corner points using an x-y digitizer. Using this information along with orbital position information, a prior calibration data, and gray scale measurements, a scene correction control tape is generated which is applied to the MSS video during a second video-to-film conversion.

5.6.1.4.7 RBV Scene Correction Film Mode

Using an x-y digitizer, internal geometric errors of each RBV image are determined by measuring the detectable reaseau positions in each image and comparing with the lens faceplate reseau calibration of the respective camera. External geometric errors are determined by x-y digitizer measurement of ground control points. Using these measurements plus focal length, boresight alignment, gray scale measurement and inflight radiometric calibration images, a scene correction control tape is generated which is applied to the RBV video during a second video-to-film conversion.

5.6.1.4.8 Scene Correction Calibration Mode

Measurements are made periodically to update the system calibration tape. This tape corrects for system drift, particularly in the EBR geometry.

5.6.1.4.9 Aircraft Video to Film Conversion

With acquisition of a suitable tape recorder, aircraft acquired digital scanner data can be processed to produce film images, CCT's and black-and-white film recording of one spectral band, for conversion to computer tapes to interleaved spectral data, or for black-and-white (or color) display of one or three spectral bands. The data recorded on film will be corrected for slant range geometry and intensity variations.

5.6.2 SECONDARY FACILITIES

5.6.2.1 Environmental Research Institute of Michigan

The Environmental Research Institute of Michigan (formerly Willow Run Laboratories of the University of Michigan) has two major divisions: the Radar and Optics Division, devoted to radar technology and the Infrared and Optics Division, devoted to infrared technology. Both divisions are actively exploring uses of their respective technologies in Earth Resources Applications.

Through contracts with DOD, NASA, and other sponsors, ERIM has developed hardware and analysis capabilities in a number of areas pertinent to the Earth Resources effort. ERIM currently maintains capabilities to collect and analyze airborne and spacecraft multispectral scanner and photographic data and SLAR radar data and to support these activities with a ground and laboratory measurement capability.

5.6.2.1.1 Ground Measurements

ERIM has assembled an array of spectral radiometers, micrometeorological equipment, and pyranometers to support aircraft and spacecraft data collection missions. A set of 20 x 40 foot canvass panels are also available as reflectance standards for low altitude aircraft missions (Ref. 1). A recent addition to the set of measurement hardware is an ISCO model spectral radiometer with chart recorder, automatic sequencer, and digital computer data reduction capabilities.

All hardware and canvas panel fit in a panel truck for easy deployment at remote sites.

A thermal region field integrating spectral radiometer (FISR) has been constructed to make spectral radiometric and emissivity measurements in the 3 - 5.5 and 8 - 14 μm regions (Ref. 2). Data from the instrument are processed on digital computers.

A device to measure the dielectric constant and conductivity of materials has recently been developed by the Radar and Optics Division (Ref. 3). It is portable and can be deployed at remote sites in support of Radar overflights.

5.6.2.1.2 Laboratory Measurements

In addition to the ground measurements, ERIM possesses laboratory measurement hardware--A Beckman DK-2, Cary 14, and Perkin-Elmer Model for making directional reflectance and transmittance measurements and two goniometer systems for making bidirectional reflectance measurements (Ref. 4). Data from these instruments are stored in a signature library. (The ERSIS system at NASA-Houston contains most of the signature information in the Michigan library (Ref. 5).

5.6.2.1.3 Airborne Measurement Capability

ERIM has C-47, C-46 and C-131 aircraft which can be outfitted with a variety of radar, photographic, UV-visible, and infrared multispectral sensors. The C-46 is capable of handling both infrared and radar sensors, the C-47 infrared and advanced development sensors, and the C-131 radar sensors.

The UV-visible infrared scanner at ERIM is the M-7 system (Ref. 6), a multiband UV-visible infrared line scan device with associated analog tape recorder and electronics. It is supported on the ground by various test and alignment gear and an imagery production/slicing facility.

The radar system in the C-46 aircraft has recently been modified to collect simultaneous cross polarized (H-H, H-V) imagery at X and L Bands (Ref. 7). The radar is supported on the ground by optical and optical-digital processing facilities (Ref. 3).

Both C-46 radar and C-47 multispectral aircraft have aerial camera capabilities. Current cameras include an RC-8 (on loan from NASA), K-17, and various P2, P220, and KB-8 cameras for black and white and color support photography.

Both C-46 and C-47 aircraft have collected extensive radar and multispectral data under sponsorship of NASA and other government and private contracts.

5.6.2.1.4 Data Processing Facilities

In addition to the scanner and radar support facilities, ERIM has analog, general purpose digital, and parallel digital data processing facilities for multispectral data. All facilities are compatible with data not only from ERIM aircraft, but also from other NASA aircraft and satellites through the medium of computer-compatible tape.

The ERIM analog processor is SPARC (Spectral Analysis and Recognition Computer), a seven year old special purpose analog computer designed to perform likelihood ratio pattern recognition studies at real time rates on multispectral data (Ref. 9).

General purpose digital facilities include IBM 7094 and 1401 and CDC 1604 computers, and a special purpose A/D - D/A interface (Ref. 10). A software package for analysis of multispectral data has been developed on both 7094 and 1604 computers.

Currently under construction is a parallel digital processor (tentatively named HYDRA). The effort is being supported by NASA-AAFE funds. Tentative completion data is October 1974, with an interim system in operation by October 1973 (Ref. 11).

Also available for radar and photographic processing are various coherent light optical processors and hologram processors. These are capable of being used for spatial processing of photographic and scanner data (Ref. 12).

5.6.2.1.5 References

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3. F. Thomson, et. al. "ERIM Progress Report on Use of ERTS-1 Data", Report 193301-1-P, ERIM, Ann Arbor, Michigan, January 1973.

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5.6.2.2 Center For Research Incorporated (CRINC) University of Kansas

The Center for Research Inc. (CRINC, formerly CRES) has digital and analog-digital data processing facilities associated with digital tape and photographic format data respectively. They have also constructed ground radar spectrometers and an airborne scatterometer. They have received support from NASA's SR&T program and other sponsors in the past and have ERTS-1 contracts.

5.6.2.2.1 Ground Measurements

CRINC has developed an octave bandwidth (4-8 GHz) scanning spectrometer operating from a "cherry picker" and truck. The system now has FM modulation and is capable of measuring H-H or V-V Returns from selected objects. A 3 foot dish and BWO are used. The spectra of a number of agricultural crops at various polarizations and orientations relative to two directions have been measured.

Under contract to the Naval Ordinance Laboratory, CRINC has developed a 9.3 GHz scatterometer which has been flown in their C-45 (Twin Beechcraft). CRINC have also participated in some of the checkout and experiments of the 13.3 GHz scatterometer mounted on the NASA aircraft.

5.6.2.2.2 Processing Facilities

CRINC has two ground data processing systems, IDECS and KANDIDATS. The IDECS system uses film transparency input and has a capability for user interaction. The KANDIDATS system is a set of digital algorithms programmed for a GE 635 computer.

IDECS (Image Discrimination, Enhancement and Combination System) is a near real time analog-digital processing system. Three flying spot scanners are available to scan photographic input data. An AGC system on the scanner CRT yields nearly uniform light level over the entire frame being scanned. Analog digital hardware performs linear combination, slicing in one or multiple hands, and color display and area counting. In the multiband slicing mode the operator can select the levels to slice each band or the levels may be set by reference to a rectangular training set. A PDP-15/20 computer is being interfaced to the IDECS system to calculate the decision rule parameters for IDECS.

KANDIDATS (Kansas Digital Image Data System) is a package of software routines with monitor, now implemented on the GE 635 computer. The routines perform clustering, feature extraction, multi-image registration and congruencing, histogramming texture analysis, and pattern recognition. Several decision rules, including Bages rules, nearest neighbor, and linear decision rules are available. The system requires digital tape input and has hard copy printed output as well as black and white and color TV displays.

The system has been used to remove the effects of radar antenna pattern variations in SLAR imagery. Also, a number of textural classification and other classification work has been done using multi-frequency, multi-polarization SLAR data.

5.6.2.3 University of Alaska

The University of Alaska is developing photo interpretation and digital processing capabilities for ERTS-1 data analysis. The current activity involves twelve ERTS-1 investigators, the Digital Data Processing Laboratory, and the University of Alaska Computer Facility. Emphasis to date has been on developing photo interpretation and duplication capability, along with those digital analysis tools needed by ERTS-1 investigators.

5.6.2.3.1 Processing Facilities

Photo interpretation equipment and digital processing capabilities have been developed to assist the ERTS-1 investigators. Four color additive viewers have been constructed for two facilities in Fairbanks and Palmer. The Fairbanks facility additionally has a Macbeth densitometer for density signature analysis and a good photo lab for duplicating imagery (Ref. 1).

The digital processing capabilities are implemented on the University's IBM 360/40 computer. Currently on order is a color display with interactive capability to be attached to the 360/40 through an interface PDP 11/20 computer (Refs. 2, 3, 4). The unit, when delivered, will permit the user to interact with the main 360 computer in the selection of training sets and in viewing the results of classification.

The digital computer software package is written for the IBM 360/40, which is supported by an IBM 1620 system and Calcomp plotters at the computing center and a NOVA 820 processor at the Digital Data Processing Lab. The software package now includes data conversion and listing programs, and programs for the display of data on the color digital display. A supervised pattern recognition program has recently been added (Ref. 4). Clustering, ratio of channels, histogram, and acreage tabulation programs are planned.

5.6.2.3.2 References

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5.6.2.4 University of California

The University of California-Berkeley group was formed in 1961 under the direction of Dr. Robert Colwell, and now consists of about 35 people under the direction of Donald T. Lauer. The group is subdivided into five functional units: Operational Feasibility, Automatic Image Classification and Data Processing, Imager Interpretation and Enhancement, Spectral Characteristics, and Training. Currently the group receives NASA funding through the ERTS and Skylab programs, and funding from other federal and state sources.

5.6.2.4.1 Ground Measurements

The Spectral Characteristics unit has merged two EG and G spectral radiometers into a van or helicopter mounted spectral radiometer covering the 0.1 to 1.2 um spectral range. An ISCO spectral radiometer is used to measure incoming solar and sky radiation. Supporting software for data reduction is available on the Livermore-Berkeley CDC 6600 computer.

5.6.2.4.2 Processing Capabilities

The data processing capabilities consist of software and hardware for analysis of digital format data, some hardware for photo interpretation and film scanning densitometers for digitizing photography. The group is linked to the Livermore-Berkeley CDC-6600 computer through a remote terminal. They have a modified LARSYS-A package of programs available for analysis of digital multi-spectral data. In the laboratory, a NOVA computer with black and white and color displays is available for editing data and display of classification results. A filmstrip printer is also available for printing classification results from the computer. A scanning microdensitometer may be used converting photographic data to digital form.

Photo interpretation facilities include the usual light tables, access to the VARISCAN, a lab constructed color optical combiner, and a Basch and Lomb Zoom Transfer Scope. Photointerpretation is done in the Image Interpretation and Enhancement unit by a number of trained photo interpreters.

5.6.2.5 Laboratory for Applications of Remote Sensing (LARS)

The Laboratory for Applications of Remote Sensing was formed in 1966 under the sponsorship of USDA, NASA, and Purdue University Research. It is currently organized in five work groups: Biogeophysical Research; Measurements; Data Processing; Agricultural Requirements and Applications; and Aerospace Systems. To support their research, this laboratory has ground measuring, airborne photographic, ground data processing, and laboratory measurement capability which is further described in the following sections.

5.6.2.5.1 Ground Measurements

LARS has constructed a field measurement capability housed in a trailer and supported by auxiliary power supplies and "cherry picker" for making remote measurements. The most recently installed ground measurement capability is an Exotech Model 20C spectral radiometer covering 0.4-15 μm. It is supported by a Barnes T-4 scanning thermal radiometer, a PRT-5 radiometer, and various other equipment. Output of the Exotech instrument is recorded on 7 track analog magnetic tape for further analysis by a component of the LARSYS software system.

5.6.2.5.2 Laboratory Measurement Capabilities

LARS possesses several laboratory instruments for making supporting measurements to remote sensing. A Beckman BK-2 hemispherical reflectance measurement device covers the range of 0.3 - 2.6 μm and can make spectral transmission as well as reflectance measurements. A recently constructed device is capable of measuring the spectral bidirectional reflectance or transmission of specimens in the range 0.35 - 1.2 μm. Data are recorded on digital paper tape for later machine analysis. A device for measuring soil permittivity has also been constructed.

5.6.2.5.3 Aerial Photographic Capability

LARS has available a Twin-Beechcraft and can rent several small Cessna aircraft for aerial photographic missions. Both hand-held 35 mm cameras and handmounted 70 mm Hulcher cameras are used for black and white, color, and color IR aerial photography from a variety of altitudes up to 6100 meters (20,000 ft.).

5.6.2.5.4 Processing Facilities

LARS possesses an IBM 360/67 digital computer with disk, real time display, and remote terminal capability for analysis of multispectral data in digital tape form. The LARSYS software system is capable of performing multispectral analysis, pattern recognition, and data correction and overlay. The IBM 360 system is supported by an off-time A/D conversion facility for converting analog tapes to digital format.

The real time display is an IBM 4507 display system which has been programmed to display a portion of multispectral data and to permit the operator to quickly select training sets for pattern recognition analysis.

An experiment in the use of a centralized processor with remote terminals for user access is now being conducted. Up to eight terminals may be connected to the IBM 360/67 at LARS through phone lines. At the present time, terminals are located at NASA-Goddard and NASA-Houston.

5.6.2.6 General Electric GEMS/Image 100

The General Electric Company manufactures, and rents services on, a multispectral extraction system which incorporates a unique combination of state of the art multi-dimensional analysis techniques, near real time operating speeds, and interactive features. These features allow the General Electric Multispectral Information Extraction System (GEMS/Image 100) to operate more than 100 times faster than computer-based systems. In actual use, the GEMS/Image 100 can perform digitally over 1.2 billion operations per second (i.e., adds, divides, limit checks, etc.) while under flexible interactive control of the user operator. By accepting photographic and/or digital image data as input and displaying analysis results in conventional image format, Image 100 enables the user interpreter to analyze his data via both conventional photographic interpretation of enhanced images and state of the art multispectral analysis techniques.

Features of the Image 100 system are:

1. Interactive training enables the user to interact with his data on realtime basis; optimum use made of capabilities of both man and machine to perform spatial and spectral analysis.
2. Multidimensional signature analysis performed utilizing user-selectable preprocessing and classification techniques.
3. Signature analysis performed for any number of thematic classes - up to nine themes can be displayed simultaneously.
4. Processed results (themes) displayed in enhanced form on color CRT within seconds.
5. User can easily modify discrimination technique to eliminate misclassifications.
6. Bulk processing mode allows rapid classification of total flight line on ERTS image from magnetic tape.

A conventional color CRT monitor serves as the principal display means, permitting the user to view both the input imagery and output results. User instructions are implemented via a simplified keyboard and joystick controls. Normally, analysis results for a 256K pixel scene are displayed two to five seconds after instructions are issued. Interactive provisions which enable the user to control and/or modify the analysis process based on his knowledge of the input imagery reduce training and theme extraction time from hours to minutes or seconds. The rapid response of the system coupled with user-oriented control functions and display formats provide a flexible tool for decision optimization. In addition, in the bulk processing mode, the Image 100 can classify a total ERTS 4-channel MSS image (5×10^6 pixels) into a 10 theme thematic map in about 8 minutes. The total Earth Resources Information Analysis Management System with GEMS interfaces is shown in Figure 5-19.

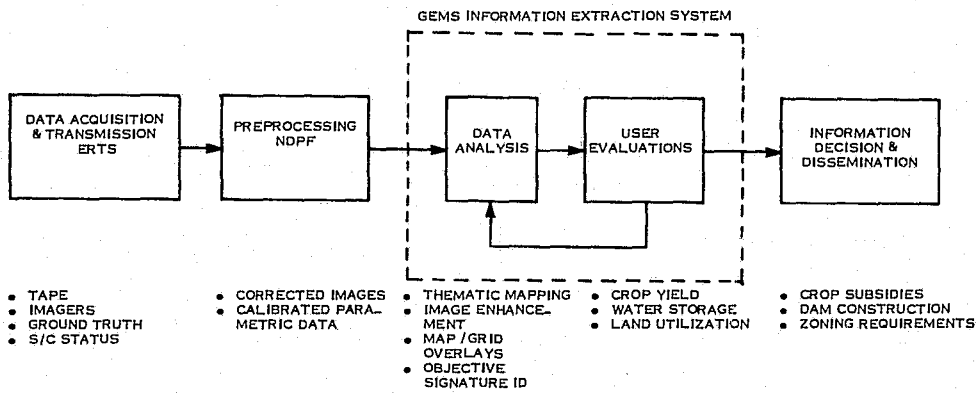

Figure 5-19. Earth Resources Information Management Systems

System Description

Figure 5-20 is a simplified block diagram depicting the basic GEMS configuration. As shown, principal system elements are the Input Scanner and Converter, Preprocessor and Signature Analyzer, Process Controller (with tape input and output), Color CRT Display, and System Controls.

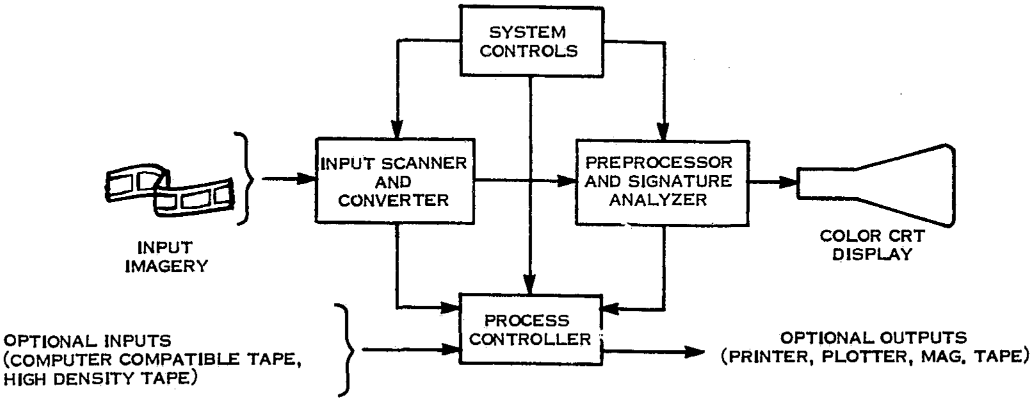

Figure 5-20. GEMS/Image 100 Configuration

The Input Scanner and Converter scans input imagery (photographs) and converts the resulting video into digital format for subsequent processing. The disc can also be loaded direct from magnetic tape. This digitized video then enters the Process Controller where point by point radiometric corrections are made, if required. The Process Controller then routes the data to the hardware Preprocessor and Signature Analyzer. Here, preprocessing in the form of normalization, ratioing, and/or transformation can be applied to each point in the image.

The preprocessed data is then subjected to interactive multidimensional multispectral analysis under software control. Thematic results of the analysis are displayed on the color CRT for user evaluation. The user can then modify the analysis via procedures such as identifying misclassified theme areas on the CRT and initiating corrective action.

GEMS/Image 100 is a user-oriented analysis tool which is easily operated with only a few hours of instruction. Typically, the user will proceed from simple, straightforward, machine-controlled analysis routines to more sophisticated, interactive analysis utilizing all the capabilities of both man and machine as experience is gained.

Two principal analysis functions performed in operating Image 100 are training and classification. These functions are defined as follows:

1. Training. Multispectral analysis is predicated on the fact that like objects in a scene usually have similar spectral properties. To effect analysis, the user must tell the machine which objects or features (water, soil, vegetation, man-made objects, etc.), are of interest. Given object positional information, the machine finds the four-dimensional spectral properties of the selected object.

2. Classification. Once the spectral properties of the object are found, the machine scans the total image (pixel-by-pixel) and determines if the spectral properties of each pixel correlate with those of the object of interest. The result of the classification process is a map in which each pixel is identified by a class type (or theme), rather than a gray level.

5.6.2.7 Philco-Ford Earth Resources Development Center

Philco-Ford Corporation has established an Earth Resources Development Center in Houston, Texas which is available, on a contract basis, to earth scientists and engineers in government, industry, and education. This system is one of many which is designed to allow for the application of the masses of remotely sensed data to specific environmental studies. Examples of possible applications include:

1. "Mapping" of specific phenomena.
2. Multispectral data classification.
3. Correlation of "ground truth" and spectral data.
4. Alphanumeric/graphic/photographic combinations of data output.
5. Photographic or spectral image enhancement.
6. Conversion of display data from one medium to another.
7. Mass data storage.

The Earth Resources Development Center will enable high speed, automatic analysis and visual output for applications which formerly required lengthy manual processing. In addition to a PDP-11/45 computer system, the following four devices are combined and comprise the image data processing system:

1. High Resolution Color Display. Capable of presenting 1024 x 1024 picture elements in both false color and multiple gray scale. Inherent in the design is literally perfect registration between the primary colors. Thus, no complicated optical or electrical convergence will be required.

2. Image Enhancement Console. Allows an investigator to perform color enhancement of film images in real-time and further allow quick evaluation of color enhancement for the patricular application. It will also permit the overlay of two film images of identical scenes taken in different parts of the electromagnetic spectrum.

3. Film Digitizer and Printer. Allows film images to be converted into digital data and recorded on magnetic tape or interfaced directly with applications programs; and digital data to be converted into film images. Thus, a wide variety of complex graphics can be created. Digital graphics, for example, may be overlaid onto film images.

4. High Density Storage System. Provides storage capacity of up to 9×10^{10} bits of information for each single reel of 1-inch tape, a potential improvement over conventional systems of up to 200:1. The unit will include a recorder and an interface controller equipped with a test control and status panel.

SECTION 6

USER MODELS

In the context of the Earth Resources Information System, models play two important roles. First, user models translate remote sensing technology parameters into information types which "users" can apply directly. The users may further apply resource management models to integrate the information from remote sensing and other sources to help manage a resource (Figure 6-1). For purposes of this discussion, a model is defined as a documented set of procedures for calculating or estimating information from parameter values (user model) or resource management guidelines from information (resource management model). Models need not be formally implemented in an operational agency program or on a digital computer to qualify - but the procedures must be programmable. Both classes of models typically make use of some parameters or information types which cannot reasonably be estimated from remotely sensed data (e.g., degree days in crop yield models) and source parameters or information types which can be estimated from remote sensing (e.g., number of ponds in migratory wildfowl productivity models). In many cases, models which use only ground measured or sampled data could equally use estimates provided by remote sensing.

Only user models - those which convert parameter values into information - are considered. The reason is partly practical and partly philosophical. Resource management models are properly the responsibility of the users and not many resource management models have been documented in literature available for this study. On the other hand, user models form the prime interface between the remote sensing system (NASA primary responsibility) and the user of the output (users) and thus are an important part of this study. They have been documented to a greater extent in the literature.

While some user models exist, they primarily utilize ground measured data. Few models exist which attempt to directly employ remote sensing derived parameters, but there are a few notable exceptions, e.g., Langley's multi-stage sampling model (Ref. 1). On the other hand, a number of models exist which could use remote sensing derived parameter values either directly or by simple modification.

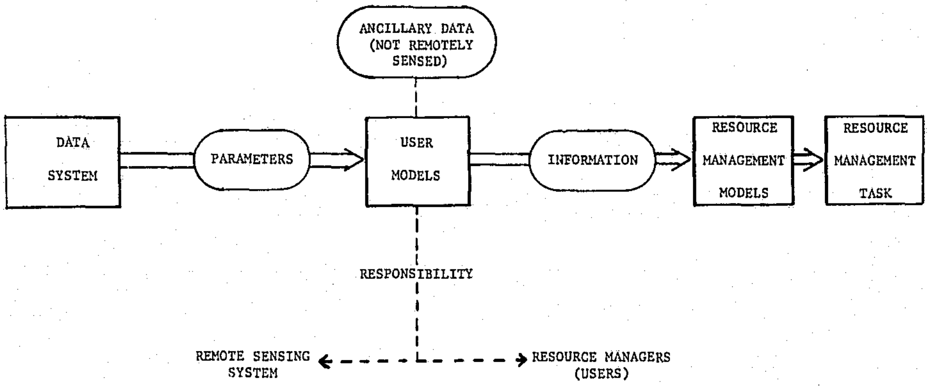

Figure 6-1. Earth Resources Information Models

There are two discipline areas where the development of models to estimate information types has been relatively well developed - in agriculture, for crop yield forecasting; and in hydrology, for basin water runoff and water balance. In the study of natural ecosystems, the modeling approach of the International Biological Program funded by NSF is comparatively far along, especially for the Grassland Biome. In general, however, models using remote sensing inputs must be considered in the very early experimental stage of development, as summarized in Table 6-1.

Table 6-1. User Models - State-of-the-Art Summary

Type	State-of-the-Art
Crop Yield	2
Watershed Hydrology	2
All Others	1-2

User models are of major importance to the successful development of the Earth resources system in that they represent the interface between remote sensing technology and the resource manager. The models convert remotely sensed parameters into information directly useful to the resource manager in terms applicable to him. In addition, successfully and consistently applied user models are indicative of systems that are or are near to being operational. Hence, careful coordination and joint study with the user agencies will be required in the development of these models so that (1) the models are in a form which is ultimately most useful to the resource manager, and (2) they maximize the cost effective contribution that remote sensing technology can make in the resource management function.

Seven models (Table 6-2) were selected for further exposition in this section. They were selected to span the discipline areas of Task 1 and also display a range of implementations. They are representative of today's state-of-the-art. For each model, the complete set of inputs required, the outputs generated, the status of implementation and the appropriateness of remote sensing inputs are described.

Table 6-2. Representative User Models

	Model Name	Discipline	State of Implementation	References
1.	Waterfowl Productivity Model	Hydrology (Wildlife Management)	Mathematics only	3, 4, 5
2.	Watershed Runoff Model	Hydrology	Implemented and updated on computer	6, 7
3.	Tampa Bay Circulation Model	Coastal Oceanography	Implemented on computer	8
4.	IBP Grassland Productivity Model	Agronomy (Rangeland Management)	Implemented on computer	9
5.	Multistage Forest Inventory Model	Forestry	Implemented on computer	1, 10, 11
6.	Crop Yield Impact Model	Agronomy	Mathematics only	12, 13, 14
7.	EPA Air Pollution Model	Environmental Quality (Air)	In use	15

6.1 WATERFOWL PRODUCTIVITY MODEL

Crissey (Refs. 3, 4) and Dzubin (Ref. 5) have suggested a model for estimating the number of mallard ducks produced in a given year in North America. The estimate is of crucial importance in setting hunting regulations for ducks each fall in both the United States and Canada.

Crissey has found a linear relationship between the number of potholes and ponds present in the Southern Prairie Provinces (Manitoba, Saskatchewan, and Alberta) in July and the number of new mallard ducks produced. The correlation coefficient is 0.89. Data from eleven years (1955-1966) were used to derive the model relationship.

The only input required for the model is the number of ponds in July in the Southern Prairie Provinces. This area produces about half the total number of mallard ducks produced each year, and is perhaps a quarter of the total mallard breeding area (Ref. 3). The input is the total number of ponds and the output is the number of young mallard ducks produced for the North American continent.

Remote sensing by visual observation is currently used to estimate the number of ponds. A stratified sampling scheme has been set up with sampling error less than 20% (Ref. 4). Remote sensing is being successfully applied to the problem of estimating the number of ponds (and automatically obtaining valuable area and perimeter information) in a cooperative program of the Bureau of Sports Fishery and Wildlife (BSFW) and the Environmental Research Institute of Michigan. Funding for this work comes from BSFW and NASA (Refs. 5a, 5b).

The current status of this model is not fully known. Crissey presented the basic mathematics four years ago, and publications at that time seemed to indicate that the technique was at least being used to check mallard production obtained by other means (Ref. 4).

6.2 WATERSHED RUNOFF MODEL

There are a great many watershed runoff models which have been developed both by USDA and USDI for specific purposes. A typical watershed model was developed at Stanford under NSF sponsorship by N. Crawford (Ref. 6). The goal of Crawford's model is to compute a stream hydrograph (flow rate of a stream as a function of time) as a function of water input to the watershed.

There are two classes of inputs to the watershed model - inputs characterizing the watershed and inputs characterizing the water input.

Watershed descriptive parameters consist of an identification of interception (how much input water is diverted directly to evapotranspiration), percentage of impervious area, potential evapotranspiration rate, and the amount of water stored in the upper soil (vadose) zone, the lower soil zone, and the deep (aquifer) zone. These are parameters which describe the land surface. Further parameters are required which describe the channel. These consist of channel time delay and routing showing the flow time from each channel segment to the output point.

Water input parameter description consists of the water input as a function of time and spatial variables. If snowmelt is a significant contributor to water input, additional radiation, albedo, and snow density and depth must be provided.

Model outputs consist of channel hydrographs at various points in the flow system, along with tabular summaries of the amount of water in storage (soil moisture).

The model has been implemented on a computer at Stanford University and been modified by Civil Engineering students over a four year period (NSF support). A number of calculations for different watersheds have been produced (Ref. 6).

The model is a rather sophisticated one, using a number of relationships for computing the interchange of water from upper to lower to deep water zones, for computing snowmelt rates, for calculating the potential evapotranspiration, and for calculations involving channel routing. The modelers have drawn on the work of other investigators to establish these relationships. (These other investigators are referenced in Ref. 6). The basic equation which the model attempts to solve is the water balance equation. This equation simply states that inflow of water to a watershed must be balanced by outflow plus storage. Storage can be in surface or ground water, while outflow can be evapotranspiration, stream flow or aquifer recharge.

More direct methods of estimating evapotranspiration are suggested by Dunin and Costin (Ref. 7). This term is a difficult one for hydrologists to measure. Of the required inputs, remote sensing seems able to supply land use information, from which the model calculates infiltration, impervious material percentage, and evapotranspiration terms directly. Some estimate of snow condition and of snow albedo and radiation input may also be obtainable from remote sensing products. Soil moisture information (upper level soil storage) may be estimable by remote sensing. Thus, many of the required model inputs could be supplied by remote sensing systems.

6.3 TAMPA BAY CIRCULATION MODEL

The U.S. Geological Survey and Tampa Port Authority have adapted a circulation model of Leendertse (Refs. 8, 8a, 8b) to study and simulate the flow of water in Tampa Bay. The Leendertse model was originally developed for Jamaica Bay, New York, and has been modified slightly for Tampa Bay. (The primary references (Refs. 8, 8a) were not available at the time of preparation of this symopsis).

The model inputs are bottom topography, wind speed and direction, rainfall and runoff amounts and tidal gage information. The model output is a plot of current flow in the bay as a function of time.

A great many of the circulation model inputs are not readily estimable from remote sensing information. However, the flow of water predicted by the model can be verified by remote sensing techniques using sediment or dye as tracers. Further, some of the water depth information required by the model could be obtained from bathymetry using scanner data. (Inputs of water depth must be made periodically because the currents redistribute sediments and sand.)

The model is currently implemented on a computer in Tampa. Tidal and bathymetry measurements are also recorded on computer tape for easy access by the model.

6.4 IBP GRASSLAND PRODUCTIVITY MODEL

The International Biological Program (IBP), sponsored by NSF, has taken a modeling and basic measurement approach to characterization of several of the world's important biomes (e.g., Northern Hardwoods, Tropical Rain Forest, Tundra, Grasslands). While the modeling approach is being used for all biome studies, the grassland biome model is most extensively developed, perhaps because of the relative simplicity of the biome. One of the general uses of the model is to calculate the present year's grassland condition (biomass as a function of time), using initial conditions of biomass and nutrients derived from the last year's field investigative work and the actual driving parameter information (rainfall, solar radiation) measured in the present year. Then model outputs are compared to actual field measurements and the model is updated (Ref. 9). The current model is basically a system of non-linear, first order, differential equations.

The grasslands biome model is a very sophisticated model with four main driving variables (solar energy, air temperature, wind speed, and precipitation), 40 system variables, 321 intermediate system variables, and 340 parameters. The model outputs consist of predictions of the state of abiotic (micro-climate, soil temperature, soil moisture), producer, soil microorganism, consumer, and soil mineral variables (Ref. 9).

The model is currently implemented, and being periodically updated, at Colorado State University. The latest reference on this work which was generally available is dated July 1971, so the present status of the model is not precisely known. The IBP program is still going on, and it is assumed that the model is still operational and advanced from its July 1971 state.

Remote sensing could supply many of the model inputs required, especially those initial conditions of standing biomass, and soil moisture now required. Further, some of the inputs now collected and used during the growing season could be obtained by remote sensing. Soil moisture, solar energy input, and soil temperature information could be readily supplied, and some information about plant species and biomass could be obtained.

6.5 MULTISTAGE FOREST INVENTORY MODEL

Philip Langley has proposed a multistage sampling model to use aircraft and spacecraft remote sensing data in timber volume estimation (Refs. 1, 10a, 10b). The model basically expands detailed forest yield data from small sample plots to large areas to obtain better estimates (lower variance) than by more conventional techniques. The model was originally proposed for forest yield prediction, but the mathematics are sufficiently general to fit other yield prediction situations (e.g., agriculture).

Model inputs are estimates of forest yield on small plots. The small plots are identified as elements of particular forest stands on medium scale imagery, and the stands identified as forest area on small scale spacecraft imagery. Additional information can be brought in at each stage of the sampling, and the mathematics are sufficiently general to include stratification (e.g., conifer and hardwood forest) at any stage. As Langley points out (Ref. 10) there is no "standard" sampling design for every problem, but the same theory can cover variations on the multistage sampling design.

The mathematics of expansion of local estimates of timber volume are those of multistage sampling, with or without stratification, with proportional probability of selection at all stages. (An excellent reference to the general theory of sampling is Cochran, "Sampling Theory," (Ref. 11). The mathematics permit calculation of a timber volume estimate and a variance of that estimate. Given certain information about the relative cost of various data collection and analysis steps, and some estimate of the benefit to the user of various precisions of information, it is even possible to optimize a sampling design for a particular problem.

The model has been tested in an analysis involving Apollo 9, high altitude aircraft, and ground measured data in the Southeast (Ref. 10). It is further being tested with ERTS and Skylab data replacing the Apollo photography (Refs. 10a, 10b). Model inputs are particularly appropriate for remote sensing; in fact, the model was designed to use these inputs in an efficient way. Certainly aircraft and, depending on the scale of the problem, spacecraft data would be useful in this model.

6.6 EPA AIR POLLUTION MODELS

Two models are currently in use by EPA and by state and local governments in complying with the provisions of the Clean Air Act of 1970. The models attempt to calculate the concentration of various pollutants in the atmosphere over large cities given data on the types and amounts of pollutants emitted by sources, and the meteorology over large cities (Ref. 12). The outputs are used to determine how much reduction in discharge of pollutants is required to meet the standards of the Clean Air Act of 1970.

In the simple model, the air over a city is considered well mixed, and the concentration of pollutants is calculated from the known inputs from sources and the assumed volume of air. (Some estimate of volume of air and a loss mechanism must be assumed, but these factors were not discussed in the reference available at the time of writing). In the more sophisticated model, the source dispersion is considered a function of meteorological conditions, and the dispersion of pollutants from each source calculated for each "significant" atmospheric state. The average pollutant concentration is then computed by weighing the concentrations under different meteorological conditions by the frequency of occurrence of those conditions (Ref. 12). (Again, some loss mechanism and air volume of interest must be assumed.)

The models are currently being used by large cities in preparing plans (to be approved by EPA) for compliance with the Clean Air Act of 1970. The simple model has been most often used, although there are cases where the more sophisticated model has been used. (It gives more realistic answers, and permits examination of the effect of reducing one type of pollutant, e.g., auto emissions.)

Some of the model inputs could be supplied by remote sensing, for example, the concentrations of various stationary pollution sources. Maps of particular pollutant concentration could be incorporated into the model, with revisions, as initial conditions. Finally, remote sensing derived meteorological data might be useful in documenting what meteorological conditions occur at a particular time. Maps of pollutant concentration would be useful for model updating and refinement.

6.7 CROP YIELD IMPACT MODEL

The impact of Southern Corn Leaf Blight (SCLB) on corn yield is being studied by Marvin Bauer of LARS, using data on blight severity derived from the Corn Blight Watch Experiment in 1971. Dr. Bauer attempted a correlation between severity of corn blight on various dates and corn yield as measured from sample plants (Refs. 13, 14, 15).

The inputs to the model were the severity of blight as a function of time (during the growing season), the cytoplasm type of the corn, and the yield of two plants within each of two sampling units in 1400 fields spread across 210 segments across the Corn Belt.

Dr. Bauer attempted to establish a correlation between SCLB severity and the average yield in a flight line, after making corrections based on row spacing to obtain corrected numbers of plants per acre and expanding the field measured yield data to the flight line through the use of standard formula. Although no formal correlation procedures were carried out, a good correlation was observed between the severity of blight on 23-26 August and the projected yield per flight line.

Remote sensing could provide some of the blight severity information for this suggested model especially since Dr. Bauer observed significant yield reductions only in fields with blight levels high enough to be mapped by MSS automatic analysis techniques. Corn productive acreage estimates could also be provided by remote sensing, but cytoplasm type probably could not.

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SECTION 7

OPERATIONS TECHNOLOGY

Up to this point the state-of-the-art assessment has considered rather specific functions or elements in the Earth resources system. An additional technology has been identified, one that ties all the other functions together and makes them work as a system. This technology in the operational phase of the program is analogous to the role of system engineering during the design and development phase. Many of the contributing functions to the "tie it together and make it work" technology are not recognized today, either as functions in themselves or their degree of importance to the successful operation of the system.

The "tie it all together and make it work" function has been designated Operations Technology and defined as the anagement function at the system level and extending down into all parts of the system to include those functions equired to schedule, control and monitor the flow of information throughout the system. Operations Technology includes the methodologies of:

1. Overall management of the system at all levels below that of policy-setting.
2. Acceptance and processing of user requests for data and information;
3. Scheduling the collection (spacecraft, aircraft, ground platforms), data processing and distribution systems.
4. Command and control of the collection systems.
5. Retrieval of data from all data sources.
6. Control of production flow during data processing.
7. Control of the archival/retrieval function.
8. Control of the data distribution systems.
9. Derivation of requirements for improvements to the system.
10. Generalized user support, training and assistance.
11. Advertising the system and its capabilities.

The breadth of operations technology is illustrated in Figure 7-1. The Earth resources system in the figure represents a composite of today's major systems - Skylab/EREP, ERTS and EROS and shows the extent to which operations technology applies to all parts of the system.

The state-of-the-art of the various functional areas has been summarized in Table 7-1. Each of the operations technology functional areas is described in Table 7-2 in terms of today's status and the current system which is representative of today's state-of-the-art. The table also contains the anticipated state-of-the-art advances through 1975 plus some observations on the long term implications of the 1972-75 state-of-the-art development trends.

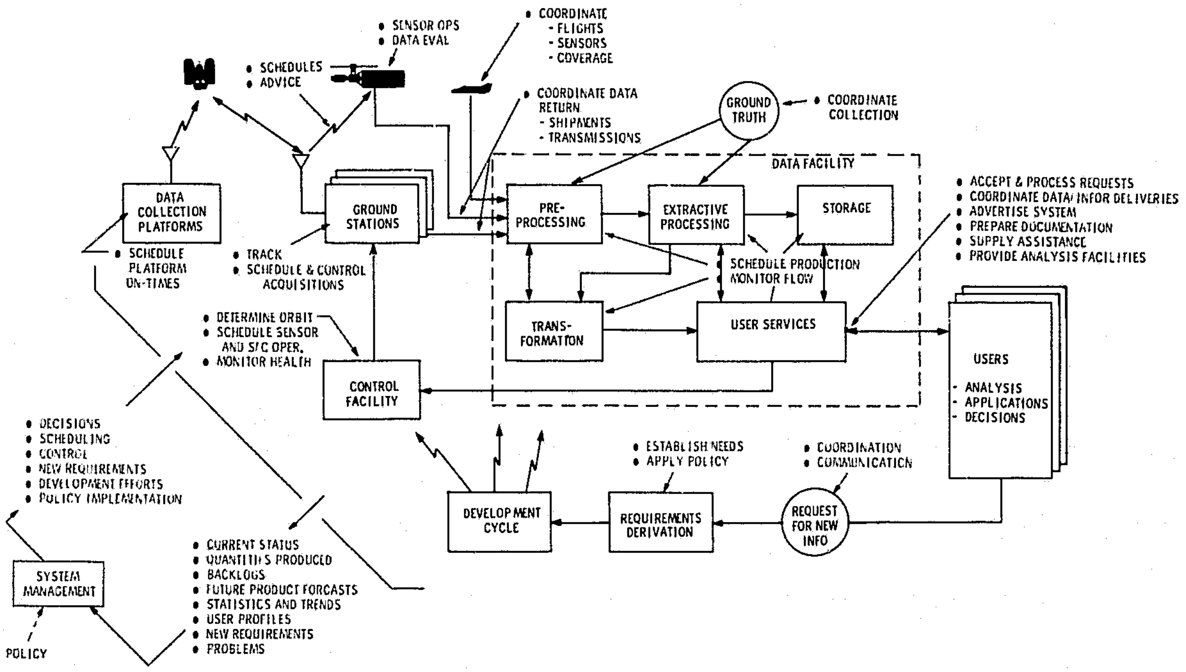

Figure 7-1. Today's Operations Technology

Table 7-1. Operations Technology Summary-State-of-the-Art

Functional Area	State of the Art	Summary Status
User Interface	2-4	Adequate in the acceptance and processing of user requests for data. Inadequate in areas of product delivery times, user assistance and consulting, provision of analysis facilities, providing reduced data (parameters) and advertising ER system capabilities.
System Management	2	Generally lagging in all areas dealing with management of multielement systems and high throughput subsystems.
System Scheduling	1-4	Adequate for spacecraft/sensor and aircraft mission planning/scheduling; less progress in scheduling pre-processing and distribution. Almost non-existent in extractive processing area.
Archival Storage	2-3	Recent progress in advanced mass storage systems. Adequate for near term needs. Requires application in ER area.
New Requirements Development	2	No easy route for user feedback. ERTS/EREP experiments or RTOP's route is arduous.
Retrieval of Payload Data	4-6	Space & Aircraft to ground is adequate; ground transmission/shipment involves several day delay.
Command & Control	6	Adequate.

Operations technology has until very recently been thought of primarily in terms of "flight operations" or command and control of spacecraft. ERTS was the first program which broadened the definition to include the scheduling and monitoring of large data processing facilities, an interface with many hundreds of users, detailed spacecraft sensor and tape recorder scheduling plus the overall management of a high throughput multi-element system. ERTS is most representative of today's unmanned operations technology state of the art, as is Skylab/EREP in the manned area.

In the broad sense, operations technology historically has developed as required by the needs of a given single program, many times almost as an afterthought. Very little development effort or long range planning has gone into this area, mostly because it really was not critical to the program at that time. Today this continues to be true and, coupled with the lack of any major Earth Resources program advances such as a new launch between now and 1975, means that operations technology in 1975 will be little different than today. The only exception is the improvement in services provided by the EROS data center as it matures from an interim facility to a full scale operation.

In general, operations technology state of the art is adequate to support today's systems - systems that involve single spacecraft and single ground processing facilities, and are primarily R&D or experiemental in nature. But between 1975 and the early eighties a major change will occur in the Earth resources program in that every portion of the system will be multiplied both in number and complexity. There will be additional platforms including R&D polar orbiters, operational polar orbiters, synchronous satellites, shuttles and aircraft. There will be additional ground stations, both domestic including regional and local, and international. There will also be a several orders of magnitude increase in the number of users. Not only will the number of users increase but their characteristic will change from R&D to operational. They will be both domestic and international and represent all segments of the population.

The major question which must be addressed in the future is how to manage this multiple element system. Examination of the "Long Range Implications" column in the table strongly suggests that the near term state of the art is not adequate to do this. The quantum jump in system complexity over the short period from 1978 to 1982 will no longer permit the historical "evolvement" of operations technology. This coupled with today's lack of emphasis on operations technology requires it to be identified as a potential key issue in the study and a subject for further study in Task 5.

FOLDOUT FRAME

Table 7-2. Operations Technology - State-of-the-Art

TECHNOLOGY AREA	CURRENT STATUS	TYPIFIED BY	ADVANCES BY 1975	STATE OF THE ART	LONG-RANGE IMPLICATIONS
USER INTERFACE					
Acceptance of data/ coverage requirements	Manual but adequate for 300 users	ERTS	Slight - may expand to support up to 500 users but will still use basic ERTS technology	4	Current technology adequate - requires effort to automate efficiently
Consolidation/tabulation of data req'ts	Partially automated for 300 users	ERTS	"	4	"
Acceptance/processing of requests for output products	Mostly automated	EROS	Limited improvement. Additional improvements expected post 1975 with acquisition of new computer	3	"
Providing output products (data)	ERTS - 30 to 60 days from acquisition to product delivery EROS - 14 days from request for standard product to delivery	ERTS/EROS	Only minor improvements expected- even these may be offset by more users	2-3	Long delivery times inadequate for many users and will eliminate them from use of the system for operational purposes.
Providing reduced information (parameters)	Non-existant	-	Minimal - pilot projects (e.g,, corn blight watch) may be only contributors in this area. Many developments occuring in algorithm mechanization but no effort in methodology of providing information to users.	1	No apparant development efforts in the methodology of providing reduced information. Since this is major system output, lack of development efforts will inhibit growth to operational systems.
Providing analysis facilities for users	Non existant in major facilities. Universities provide limited capability. NASA centers have facilities to support their own investigations	-	EROS Data Center Autographic Theme Extraction System and LARS terminal will be on line	2	Where do users go for facilities and assistance?
Consulting/assistance on data analysis problems	EROS Data Center User Assistance & Training provides limited capability	EROS	Some improvement as EROS matures. No other generally available capability.	2	
Advertising of system capabilities	Very limited - EROS training sessions educate selected groups. Inadequate to acquaint the general public with the system or encourage its use.	EROS	Some improvement as EROS matures. No major public relations effort planned.	2	Rate of growth of Earth resources system will be influenced by the demand.
Informative documentation for users	Adequate - handbooks, bulletins, letters,	ERTS	Minor improvements as EROS matures. Little change in ERTS approach.	4	Current technology adequate. Large increase in volume required.

	investigations				and assistance?
Consulting/assistance on data analysis problems	EROS Data Center User Assistance & Training provides limited capability	EROS	Some improvement as EROS matures. No other generally available capability.	2	
Advertising of system capabilities	Very limited - EROS training sessions educate selected groups. Inadequate to acquaint the general public with the system or encourage its use.	EROS	Some improvement as EROS matures. No major public relations effort planned.	2	Rate of growth of Earth resources system will be influenced by the demand.
Informative documentation for users	Adequate - handbooks, bulletins, letters, brochures.	ERTS	Minor improvements as EROS matures. Little change in ERTS approach.	4	Current technology adequate. Large increase in volume required.
SYSTEM MANAGEMENT					
Management Reports (Upward Reporting)	Partially automated reports on current production status. Reports on own internal center status plus limited information on interfaces with other centers.	ERTS/EROS	Additional automation; greater selectivity and more comprehensive reports. Still primarily reporting on internal center workings.	2	Other than existing interfaces, no effort under way to develop comprehensive, multi-element reporting systems.
Management Decisions (Downward direction)	Primarily oriented to internal center control. Limited communications to other centers/agencies where data exchange is required.	ERTS/EROS/ EREP	Little change anticipated. ERTS & EROS will continue to operate essentially independent of each other with ERTS data flow to Sioux Falls being the principal operational communication.	2	Other than existing interfaces no effort planned to coordinate operations and decisions between centers/agencies. Inadequate capability to manage multi-element systems.
Earth Resources Policy	NASA Headquarters/JSC for NASA programs. USDI - Washington, D.C. for USDI programs.	ERTS/EREP/ Aircraft, etc EROS	No change. Additional communication between NASA & USDI in areas of operational E.R. satellite (primarily in design area) and NASA mission sensor selection.	2-3	Complexity and extent of Earth resources program implies need for integration between all agencies at all levels to fully exploit the system capability.
SCHEDULING					
Optimize spacecraft payload operations	Partially automated. Uses actual user requests, a-priori priorities, past coverage history, spacecraft constraints, communications time and weather to optimize. Outputs are mission plans. Relatively complex approach, new to NASA programs, is required to support one spacecraft and 300 users. More users will require more bulk storage	ERTS	More automated, but little advance in concept - will use current ERTS technology for ERTS-B. USDI/Sioux Falls will likely draw on ERTS technology. Current ERTS system not readily expandable to multiple spacecraft system.	4	Generalized sophisticated Earth viewing mission scheduling algorithms have been developed by military and as propriatory by contractors. Technology exists but requires application.
Schedule preprocessing	Partially automated. Requires manual tape screening efforts to identify data not to be processed. All remaining data is then processed. Correction function computations are fully automated.	ERTS	Little change expected for ERTS-B at GSFC. USDI/Sioux Falls plans not yet clear but a system similar to GSFC's expected to evolve.	3	No effort currently being applied to this area outside of Sioux Falls for their own system.
Schedule Extractive Processing	Essentially non-existant. No earth resources oriented system exists where many and various processing techniques are regularly scheduled and applied for a multiplicity of users.	-	EROS data center Autographic Theme Extraction System plus terminal to LARS will be available and regularly scheduled for users.	1	Large scale scheduling and control of multiple extractive processing algorithms and hardware not currently under development.
Schedule data/information distribution	Standard products prepared and sent to users per their specific requests. Currently users get only data and must extract useful information on their own. Scheduling of specific product production and shipment is partially automated. Packaging and shipment is manual.	ERTS/EROS	Little change in ERTS system. EROS scheduling capability will (must) grow with increasing number of uers. Step function improvement with expanded computer capability in 1975.	3	Not a difficult scheduling technique assuming the adequate scheduling of pre and extractive processing

FOLDOUT FRAME

Schedule aircraft/ payload operations	Primarily manual. Scheduled in time increments of yearly basis. Current emphasis on sensor & signature development (R&D model). In flight rescheduling due to weather is common.	NASA/ University aircraft	Little change anticipated in scheduling techniques, or in method of flight operations. Technology adequate.	3	Current effort lacking in the scheduling of multiple aircraft on a nationwide, regular, operational basis, integrated with spacecraft operations.
Schedule aircraft data processing	Little scheduling involved. Data is processed on an as-required basis fit into other processing lab schedules.	JSC/Ames/ Univ. of Michigan	Some thought & planning given to through-put in processing labs as number of flights increase. Technology adequate.	3-4	Current technology adequate. Aircraft data must be integrated with other data being processed in the facility.
Schedule Manned spacecraft operation	Primarily manual. Scheduled 2 days ahead of time on a continuing basis. Inaccuracy of 2 day weather forecasts is major problem.	EREP	None - no manned Earth resources missions to be flown.	2-3	Scheduling of manned Earth resources missions not fundamentally different from unmanned missions. Technology exists but requires application.
MANNED FLIGHT OPERATIONS					
Use of man as realtime operator during data acquisition and processing	Executes preplanned timeline. Almost no realtime decision making by crew. Have demonstrated crew capability to locate ground scenes via viewfinder.	EREP	Minimal - no manned Earth resources missions to be flown. Simulator studies will be only contributor.	1-2	Many valuable crew contributions to target location, evaluation, data gathering and processing have been postulated in paper studies. Crew contribution demonstrated in solar telescope experiments. Requires implementation and verification. Not a technology problem.
ARCHIVAL (OFF-LINE) STORAGE					
Data Handling	Manual handling. Data on magnetic tape stored in warehouse. Tape tracking via computer listings.	ERTS	Little if any in operating programs. Advanced mass storage systems now available but require application to ER area.	3-5	Masses of data to be stored implies need for low cost, high volume, ready access systems.
Scheduling of data for storage	Fixed time period to keep active. At expiration, data is automatically archived	ERTS	Little if any. Time period may be variable as a function of data utility	3-4	Expected growth of temporal analysis techniques will require long active periods of selected data or rapid retrieval mass storage systems.
NEW REQUIREMENTS DEVELOPMENT					
Acceptance of user requests for new information/data	Long route through NASA or agencies via ERTS/EREP experiments or RTOPS	ERTS/EREP	No ERTS/EREP change. Minimal capability may exist at Sioux Falls data center via user training and assistance.	2	No clear path being established to permit user requests, comments and suggestions for new capability to be monitored and considered.
RETRIEVAL OF PAYLOAD DATA					
Transmit data from spacecraft to ground	Maximum rate = 15 Mbps. Total data return limited by the number of wideband receiving stations (3)	ERTS	240 Mbps systems in development	6	Anticipated technological growth adequate for future missions
Record data on ground	Maximum Rate = 15 Mbps	ERTS	240 Mbps systems in development	6	Anticipated technological growth adequate for future missions
Ground transmission to processing facility	Limited to 240 KHz bandwidth lines	AT&T	No significant improvement	3-4	Inadequate for high data rate/ quantity systems. Implies direct transmission to processing facilities or TDRS.
Ground shipment to processing facility	By airmail. Typical delivery time 1-2 days following acquisition.	ERTS	No significant improvement	3	Inadequate for selected user applications requiring near realtime data.
Deliver aircraft payload data to	Direct delivery. Typical times measured in hours	NASA Earth Resources Aircraft	No significant improvement	6	Technology adequate

Transmit data from spacecraft to ground	Maximum rate = 15 Mbps. Total data return limited by the number of wideband receiving stations (3)	ERTS	240 Mbps systems in development	6	Anticipated technological growth adequate for future missions
Record data on ground	Maximum Rate = 15 Mbps	ERTS	240 Mbps systems in development	6	Anticipated technological growth adequate for future missions
Ground transmission to processing facility	Limited to 240 KHz bandwidth lines	AT&T	No significant improvement	3-4	Inadequate for high data rate/ quantity systems. Implies direct transmission to processing facilities or TDRS.
Ground shipment to processing facility	By airmail. Typical delivery time 1-2 days following acquisition.	ERTS	No significant improvement	3	Inadequate for selected user applications requiring near realtime data.
Deliver aircraft payload data to processing facility	Direct delivery. Typical times measured in hours after acquisition	NASA Earth Resources Aircraft	No significant improvement	6	Technology adequate
COMMAND & CONTROL					
Convert mission plans to command lists	Automated	ERTS	Minimal - current technology adequate	6	Current technology adequate
Transmit commands to spacecraft	Automated through STDN. Command rate is one per second.	ERTS/ Others	Planned STDN system will provide adequate capability	6	IOS will provide additional ground station(s). Will be compatible with STDN.
Receive telemetry data	Automated through STDN	ERTS/ Others	"	6	"
Evaluate telemetry data	Automated	ERTS/ Others	Minimal - current technology adequate	6	Current technology adequate.
Tracking and Orbit determination	Automated through STDN. Done by NASA for all spacecraft	ERTS/ Others	Gradual improvement in ephemeris accuracy	6	Ephemeris errors will eventually limit the accuracies of non-ground reference type geometric correction algorithms.
Orbit Control	Orbit repeat within ± 10 nm every 18 days	ERTS	Minimal - current technology will allow ± 1 nm every n days with more orbit adjust maneuvers	6	Current technology adequate.

Table 7-2. Operations Technology - State-of-the-Art

FOLDOUT FRAME 2

APPENDIX A

STATE-OF-THE-ART ASSESSMENT FOR DISTINGUISHING CHARACTERISTICS ORGANIZED BY PARAMETER

INTRODUCTION

In this section, the results are presented of a detailed review of the state-of-the-art for distinguishing characteristics for each parameter of the list prepared in Task 1. The information was organized by discipline and numbered according to which information type (first number) and which parameter (second number was being assessed.

A four level rating system was used to assess the state-of-the-art in each area:

1. Characteristic contributes directly to the assessment of the parameter. Documented evidence of some feasibility.
2. Characteristic is useful only in a supporting way to the assessment of the parameter. Other measurements required to obtain a complete picture.
3. No documented evidence of the study or use of this characteristic to assess this particular parameter. Use of this characteristic cannot be rejected on theoretical grounds.
4. Characteristic not useful in assessing the parameter.

Thus the state-of-the-art in distinguishing characteristics is relatively advanced if many levels 1 or 2 occur in a particular row of the charts. Level 3 indicates a relatively immature state-of-the-art.

Similarly, the status of work on distinguishing characteristics in a particular discipline can be assessed by how many parameters have level 1 or 2, as opposed to level 3.

SUMMARIES OF STATE-OF-THE-ART

Two summaries were prepared of state of the art material in the sheets, one a discipline summary and the other an area of focus summary. The discipline summaries show, by discipline, the number of parameters at levels 1, 2, 3, and 4. The area of focus summaries show the same information for the categories of subdivision of distinguishing characteristics initially defined in Section 2. For the discipline summary, a parameter was classed as level 1 if there was a level 1 anywhere in the column for that parameter, as level 2 if only a 2 appeared in the column, as level 3 if only a 3 appeared and as level 4 if there was felt to be no way that remote sensing would measure the parameter.

DISCIPLINE - Agronomy

	1.1	1.2		2.1	2.2	2.3	2.4	2.5	2.6	2.7		
Spect. Signature												
Visible	1	1		1	1	1	2		1	1		
NIR	1	1		1	1	1	1		1	1		
Thermal IR	4	4		2	2	2	1		1	2		
μw	3	3		2	2	3	3		1	4		
Temporal Spect. Sig.												
Visible	1	1		1	1	1	2		1	2		
NIR	1	1		1	1	1	1		1	2		
Thermal IR	2	2		2	2	2	1		1	2		
μw	3	3		2	2	3	3		1	4		
Thermal Radiance												
Thermal IR	2	3		2	2	2	2		2	4		
μw	2	3		2	2	3	3		3	4		
Multiaspect Sp. Sig.												
Visible	2	2		3	1	1	1		3	1		
NIR	2	2		3	1	1	1		3	1		
Thermal IR	4	4		4	2	2	2		3	2		
μw	2	2		3	3	3	3		3	3		
Scattering Cross Section												
μw - 1 band	2	3		3	3	3	3		3	3		
μw - mult. bd.	2	3		3	3	3	3		3	3		
Optical	3	3		3	3	3	3		3	3		
Polarization Signature												
Visible	3	3		3	3	3	3		3	3		
NIR	3	3		3	3	3	3		3	3		
Thermal IR	3	3		3	3	3	3		3	3		
μw	2	3		3	3	3	3		3	3		
Spatial Signature												
Visible	1	2		2	2	3	1		1	2		
NIR	1	2		2	2	3	1		1	2		
Thermal IR	2	2		3	3	3	1		1	2		
μw	3	3		3	3	3	3					

DISCIPLINE – Agronomy

	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	3.10	3.11	3.12	3.13	3.14
Spect. Signature														
Visible	2	2		2	2	2	1	1		1	1	2	2	
NIR	4	2		1	1	2	1	1		2	1	1	1	
Thermal IR	2	2		4	4	1	4	1		2	4	4	4	
μw	2	3		3	3	3	4	3		3	3	3	3	
Temporal Spect. Sig.														
Visible	3	3		2	2	2	1	2		1	1	2	2	
NIR	3	3		1	1	2	1	2		2	1	1	1	
Thermal IR	1	3		4	4	1	4	2		2	1	1	1	
μw	3	3		3	3	3	4	3		3	3	3	3	
Thermal Radiance														
Thermal IR	2	2		2	2	1	4	4		4	2	2	1	
μw	3	3		3	3	3	4	4		4	3	3	3	
Multiaspect Sp. Sig.														
Visible	2	4		1	1	3	1	2		1	1	1	2	
NIR	2	4		1	1	3	1	2		2	1	1	2	
Thermal IR	2	4		2	2	3	4	2		3	4	3	4	
μw	3	4		3	3	3	4	4		3	3	3	4	
Scattering Cross Section														
μw – 1 band	3	4		3	3	4	4	4		2	2	1	2	
μw – mult. bd.	3	4		3	3	4	4	4		2	2	1	3	
Optical	3	2		3	3	4	2	4		3	3	3	3	
Polarization Signature														
Visible	3	3		3	3	4	3	2		1	3	3	3	
NIR	3	3		3	3	4	3	2		2	3	3	3	
Thermal IR	3	3		3	3	4	4	2		3	3	3	3	
μw	3	3		3	3	4	4	3		3	3	3	3	
Spatial Signature														
Visible	2	4		3	3	4	2	2		2	3	3	2	
NIR	2	4		3	3	4	2	2		2	3	3	2	
Thermal IR	2	4		3	3	3	4	2		3	3	3	3	
μw							4						3	

DISCIPLINE - Agronomy

	4.1	4.2	4.3		5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9
Spect. Signature													
Visible	1	1	1		2		1	1	2	2	2	2	2
NIR	1	1	1		4		1	1	2	2	2	2	2
Thermal IR	4	4	4		1		1	1	2	2	2	2	2
μw	3	3	3		1		3	3	3	3	3	3	3
Temporal Spect. Sig.													
Visible	1	1	1		2		1	1	2	2	1	1	1
NIR	1	1	1		4		1	1	2	2	1	1	1
Thermal IR	4	4	4		1		1	1	2	2	2	1	1
μw	3	3	3		1		3	3	3	3	3	3	3
Thermal Radiance													
Thermal IR	2	2	2		2		2	2	1	1	2	4	4
μw	3	3	3		3		3	3	2	2	3	4	4
Multiaspect Sp. Sig.													
Visible	3	3	3		4		2	2	2	2	2	3	3
NIR	3	3	3		4		2	2	2	2	2	3	3
Thermal IR	4	4	4		4		2	2	2	2	2	3	3
μw	3	3	3		4		3	3	3	3	3	3	3
Scattering Cross Section													
μw - 1 band	3	3	3		3		3	3	3	3	3	3	3
μw - mult. bd.	3	3	3		3		3	3	3	3	3	3	3
Optical	3	3	3		3		3	3	3	3	3	3	3
Polarization Signature													
Visible	3	3	3		2		3	3	3	3	3	3	3
NIR	3	3	3		4		3	3	3	3	3	3	3
Thermal IR	3	3	3		3		3	3	3	3	3	3	3
μw	3	3	3		2		3	3	3	3	3	3	3
Spatial Signature													
Visible	2	2	1		2		1	1	1	1	2	2	2
NIR	2	2	1		4		1	1	1	1	2	2	2
Thermal IR	3	3	2		4		1	1	1	1	2	2	2
μw											3	3	3

DISCIPLINE - Agronomy

	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	6.9	6.10		7.1	7.2	7.3
Spect. Signature														
Visible	2	2	2	1		1	1	4	1	4		2	2	4
NIR	2	2	2	2		1	1	4	1	4		2	2	4
Thermal IR	2	2	2	2		1	1	2	1	2		2	2	4
μw	3	3	3	3		3	3	2	3	3		3	3	4
Temporal Spect. Sig.														
Visible	1	1	4	4		4	4	4	4	4		2	2	4
NIR	1	1	4	4		4	4	4	4	4		2	2	4
Thermal IR	1	1	4	2		4	4	2	4	4		1	1	1
μw	1	1	4	2		4	4	2	4	4		1	1	1
Thermal Radiance														
Thermal IR	2	2	2	2		4	2	1	2	2		1	1	1
μw	2	2	2	2		4	3	1	3	3		1	1	1
Multiaspect Sp. Sig.														
Visible	4	4	4	4		4	4	4	4	4		4	4	4
NIR	4	4	4	4		4	4	4	4	4		4	4	4
Thermal IR	4	4	4	4		4	4	4	4	4		4	4	4
μw	4	4	4	4		4	4	4	4	4		4	4	4
Scattering Cross Section														
μw - 1 band	3	3	3	2		3	3	4	3	3		3	3	3
μw - mult. bd.	3	3	3	2		3	3	4	3	3		3	3	3
Optical	3	3	3	3		3	3	4	3	4		3	3	4
Polarization Signature														
Visible	2	2	3	3		3	3	4	2	4		1	3	3
NIR	3	3	3	3		3	3	4	3	4		3	3	3
Thermal IR	3	3	3	3		3	3	4	3	4		3	3	3
μw	3	3	3	3		3	3	4	3	3		3	3	3
Spatial Signature														
Visible	3	3	3	3		4	3	4	3	4		4	4	4
NIR	3	3	3	3		4	3	4	3	4		4	4	4
Thermal IR	3	3	3	3		4	3	4	3	4		4	4	4
μw	3	3	3	3		4	3	4	3	4		4	4	4

DISCIPLINE - Agronomy

	7.4		8.1	8.2	8.3	8.4	8.5	9.1	9.2	9.3	9.4	9.5	9.6	9.7
Spect. Signature														
Visible	1		1	1	1	2	4	2	1	1	1		1	1
NIR	2		4	4	4	2		2	1	1	1		1	1
Thermal IR	1		4	4	4	2		4	1	4	4		4	2
μw	3		1	1	1	3		4	4	4	4		4	4
Temporal Spect. Sig.														
Visible	2		2	2	2	1		1	2	1	1		2	2
NIR	2		4	4	4	1		1	2	1	1		2	2
Thermal IR	1		2	2	2	3		1	2	4	4		4	2
μw	1		2	2	2	3		3	3	4	4		4	4
Thermal Radiance														
Thermal IR	4		1	1	1	2		2	2	4	4		4	4
μw	4		1	1	1	2		2	2	4	4		4	4
Multiaspect Sp. Sig.														
Visible	4		4	4	4	4		2	2	4	2		1	1
NIR	4		4	4	4	4		2	2	4	2		1	1
Thermal IR	4		4	4	4	4		4	4	4	4		4	2
μw	4		4	4	4	4		4	4	4	4		4	3
Scattering Cross Section														
μw - 1 band	3		3	3	3	3		3	3	4	4		3	3
μw - mult. bd.	3		3	3	3	3		3	3	4	4		3	3
Optical	3		3	3	3	3		3	3	4	4		3	3
Polarization Signature														
Visible	1		2	2	2	2		3	3	2	2		3	3
NIR	3		3	3	3	3		3	3	2	2		3	3
Thermal IR	3		3	3	3	3		3	3	4	4		4	3
μw	3		3	3	3	3		3	3	4	4		4	3
Spatial Signature														
Visible	4		4	4	1	1		3	3	4	4		3	2
NIR	4		4	4	1	1		3	3	4	4		3	2
Thermal IR	4		4	4	3	3		3	3	4	4		4	3
μw	4		4	4	3	3		3	3	4	4		4	2

DISCIPLINE - Agronomy

	10;1	10.2		11.1	11.2	11.3	11.4	11.5		12.1	12.2	12.3	12.4
Spect. Signature													
Visible	1	2		1	1	2	1	2		2	2	1	
NIR	1	2		1	1	1	1	2		1	1	2	
Thermal IR	1	2		2	2	1	2	2		4	4	1	
μw	3	3		2	2	3	3	3		3	3	3	
Temporal Spect. Sig.													
Visible	4	1		1	1	2	1	1		2	2	2	
NIR	4	1		1	1	1	1	1		2	2	2	
Thermal IR	4	1		2	2	1	2	2		2	2	1	
μw	4	1		3	2	3	3	3		3	3	1	
Thermal Radiance													
Thermal IR	4	2		2	2	2	2	3		2	2	4	
μw	4	2		2	2	3	3	3		3	3	4	
Multiaspect Sp. Sig.													
Visible	4	1		2	1	1	1	2		3	3	4	
NIR	4	4		2	1	1	1	2		3	3	4	
Thermal IR	4	4		4	2	2	2	4		3	3	4	
μw	4	4		2	3	3	3	4		3	3	4	
Scattering Cross Section													
μw - 1 band	3	3		2	3	3	3	3		3	3	3	
μw - mult. bd.	3	3		2	3	3	3	3		3	3	3	
Optical	3	3		3	3	3	3	3		3	3	3	
Polarization Signature													
Visible	3	2		3	3	3	3	3		3	3	1	
NIR	3	3		3	3	3	3	3		3	3	3	
Thermal IR	3	3		3	3	3	3	3		3	3	3	
μw	3	3		2	3	3	3	3		3	3	3	
Spatial Signature													
Visible	4	2		1	2	1	3	3		3	3	4	
NIR	4	2		1	2	1	3	3		3	3	4	
Thermal IR	4	2		2	3	1	3	3		3	3	4	
μw				2	3	3	3	3		3	3	4	

DISCIPLINE - Agronomy

	12.5	12.6	12.7	12.8	12.9	12.10	12.11		13.1			
Spect. Signature												
Visible	2	1		1	1	3	4		2			
NIR	1	1		2	1	3	4		2			
Thermal IR	4	4		2	4	3	2		2			
μw	3	4		3	3	3	2		3			
Temporal Spect. Sig.												
Visible	2	1		1	1	3	4		1			
NIR	2	1		2	1	3	4		1			
Thermal IR	4	4		2	4	3	2		1			
μw	3	4		3	3	3	2		3			
Thermal Radiance												
Thermal IR	3	4		4	4	3	1		2			
μw	3	4		4	4	3	1		2			
Multiaspect Sp. Sig.												
Visible	4	4		1	2	4	4		2			
NIR	4	4		2	2	4	4		2			
Thermal IR	4	4		3	4	4	4		4			
μw	4	4		3	4	4	4		3			
Scattering Cross Section												
μw - 1 band	3	4		2	3	3	4		3			
μw - mult. bd.	3	4		2	3	3	4		3			
Optical	2	4		3	3	3	4		3			
Polarization Signature												
Visible	3	2		1	3	3	4		3			
NIR	3	2		2	3	3	4		3			
Thermal IR	3	4		3	4	3	4		3			
μw	3	4		3	3	3	4		3			
Spatial Signature												
Visible	4	4		2	2	1	4		2			
NIR	4	4		2	2	3	4		2			
Thermal IR	4	4		3	4	1	4		3			
μw	4	4		3	4	3	4		3			

DISCIPLINE - Forestry

	1.1	1.2	1.3	1.4	1.5	2.1	2.2	2.3	2.4	2.5	2.6		3.1	3.2
Spect. Signature														
Visible	1		2	2	2	4	2	2		1			2	2
NIR	1		2	2	4	4	2	1		1			1	1
Thermal IR	4		4	4	4	4	4	4		4			4	4
μw	3		3	4	4	4	4	3		3			3	3
Temporal Spect. Sig.														
Visible	1		4	1	1	4	4	2		2			2	2
NIR	1		4	1	4	4	4	2		2			1	1
Thermal IR	2		4	3	4	4	4	1		4			1	1
μw	3		4	4	4	4	4	3		4			3	3
Thermal Radiance														
Thermal IR	2		4	4	2	4	4	2		4			2	2
μw	2		4	4	4	4	4	2		4			3	3
Multiaspect Sp. Sig.														
Visible	2		2	2	4	1	1	2		4			3	3
NIR	2		2	2	4	1	1	2		4			3	3
Thermal IR	4		3	3	4	3	3	3		4			3	3
μw	2		3	3	4	4	4	3		4			3	3
Scattering Cross Section														
μw - 1 band	2		4	2	3	3	3	3		3			3	3
μw - mult. bd.	2		4	2	3	3	3	3		3			3	3
Optical	3		4	3	3	3	3	3		3			3	3
Polarization Signature														
Visible	3		4	3	4	4	4	3		4			4	4
NIR	3		4	3	4	4	4	3		4			4	4
Thermal IR	2		4	4	4	4	4	4		4			4	4
μw	2		4	4	4	4	4	4		4			4	4
Spatial Signature														
Visible	1		1	2	2	1	1	4		2			4	4
NIR	1		1	2	2	1	1	4		2			4	4
Thermal IR	2		2	3	4	3	3	4		4			4	4
μw	2		3	3	3	3	3	4		4			4	4

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DISCIPLINE - Forestry

	3.3	3.4	3.5	3.6	3.7	3.8		4.1	4.2	4.3	4.4	5.1	5.2	5.3
Spect. Signature														
Visible	2		1	1	1	2		1		2	4	3	3	3
NIR	1		2	2	1	2		1		2				
Thermal IR	4		2	3	2	1		4		3				
µw	3		3	3	3	3		3		3				
Temporal Spect. Sig.														
Visible	3		1	1	1	2		1		1				
NIR	1		2	2	1	2		1		1				
Thermal IR	1		2	3	2	1		2		3				
µw	3		3	3	3	3		3		3				
Thermal Radiance														
Thermal IR	2		4	3	4	2		2		4				
µw	3		4	3	4	3		2		4				
Multiaspect Sp. Sig.														
Visible	3		1	2	2	3		2		2				
NIR	3		2	2	2	3		2		2				
Thermal IR	3		3	3	3	3		4		3				
µw	3		3	3	3	3		2		3				
Scattering Cross Section														
µw - 1 band	3		2	3	3	3		2		3				
µw - mult. bd.	3		2	3	3	3		2		3				
Optical	3		3	3	3	3		3		3				
Polarization Signature														
Visible	4		1	4	4	3		3		4				
NIR	4		2	4	4	3		3		4				
Thermal IR	4		3	4	4	4		2		4				
µw	4		3	4	4	4		3		4				
Spatial Signature														
Visible	4		2	2	2	2		1		2				
NIR	4		2	2	2	2		1		2				
Thermal IR	4		3	4	3	3		3		3				
µw	4	3	4	3	3	3		3						

DISCIPLINE - Forestry

	5.4	5.5	5.6	6.1	6.2	6.3	6.4	6.5	6.6		7.1	7.2	7.3
Spect. Signature													
Visible	3	3		1	3	3	1	4	2		4	1	4
NIR	↓	↓		1	↓	↓	2	4	2		4	1	2
Thermal IR	↓	↓		2	↓	↓	3	2	2		2	2	2
μw	↓	↓		3	↓	1	1	1	1		3	3	4
Temporal Spect. Sig.	↓	↓			↓								
Visible	↓	↓		2	↓	3	2	4	2		4	1	4
NIR	↓	↓		2	↓	↓	2	4	2		4	1	2
Thermal IR	↓	↓		2	↓	↓	3	2	2		2	2	1
μw	↓	↓		3	↓	↓	2	2	2		3	3	4
Thermal Radiance	↓	↓			↓	↓							
Thermal IR	↓	↓		2	↓	↓	3	2	2		4	3	4
μw	↓	↓		3	↓	↓	3	2	2		4	3	↓
Multiaspect Sp. Sig.	↓	↓			↓	↓							
Visible	↓	↓		3	↓	↓	4	4	4		1	2	4
NIR	↓	↓		3	↓	↓	↓	↓	↓		1	2	↓
Thermal IR	↓	↓		3	↓	↓	↓	↓	↓		4	3	↓
μw	↓	↓		3	↓	↓	↓	↓	↓		2	3	↓
Scattering Cross Section	↓	↓			↓	↓							
μw - 1 band	↓	↓		3	↓	↓	3	2	2		2	3	3
μw - mult. bd.	↓	↓		3	↓	↓	↓	2	2		2	↓	3
Optical	↓	↓		3	↓	↓	↓	3	3		3	↓	3
Polarization Signature	↓	↓		↓	↓	↓	↓						
Visible	↓	↓		↓	↓	↓	↓	3	3		4	4	3
NIR	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓	3
Thermal IR	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓	3
μw	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓	3
Spatial Signature	↓	↓		↓	↓	↓							
Visible	↓	↓		↓	↓	↓	1	4	4		2	2	4
NIR	↓	↓		↓	↓	↓	1	↓	↓		2	2	2
Thermal IR	↓	↓		↓	↓	↓	2	↓	↓		3	3	2
μw	↓	↓		↓	↓	↓	2	↓	↓		3	3	3

DISCIPLINE - Forestry

	8.1	8.2	8.3	8.4	8.5	8.6	8.7	8.8		9.1	9.2	9.3	9.4
Spect. Signature													
Visible	4	4		4	4	1	1	1		2	4	3	3
NIR	4	2		4	4	1	1	1		2		↓	↓
Thermal IR	4	2		2	2	2	2	1		3		↓	↓
μw	4	3		1	3	3	3	3		3		↓	↓
Temporal Spect. Sig.													
Visible	2	4		4	4	4	4	1		1		↓	↓
NIR	2	2		4	4	↓	↓	1		1		↓	↓
Thermal IR	2	2		2	2	↓	↓	4		3	1	↓	↓
μw	3	3		1	3	↓	↓	4		3	3	↓	↓
Thermal Radiance													
Thermal IR	1	1		4	4	2	2	4		3	4	↓	↓
μw	3	1		4	4	3	3	↓		3	↓	↓	↓
Multiaspect Sp. Sig.													
Visible	4	4		4	1	4	4	1		4	↓	↓	↓
NIR	↓	↓		↓	1	↓	↓	1		↓	↓	↓	↓
Thermal IR	↓	↓		↓	4	↓	↓	3		↓	↓	↓	↓
μw	↓	↓		↓	2	↓	↓	3		↓	↓	↓	↓
Scattering Cross Section													
μw - 1 band	2	↓		↓	2	2	2	3		↓	↓	↓	↓
μw - mult. bd.	2	↓		↓	2	2	2	↓		↓	↓	↓	↓
Optical	3	↓		↓	3	3	3	↓		↓	↓	↓	↓
Polarization Signature													
Visible	4	↓		↓	4	3	3	4		3	↓	↓	↓
NIR	↓	↓		↓	↓	3	3	↓		3	↓	↓	↓
Thermal IR	↓	↓		↓	↓	4	4	↓		4	↓	↓	↓
μw	↓	↓		↓	↓	3	3	↓		↓	↓	↓	↓
Spatial Signature													
Visible	2	↓		↓	2	2	2	1		↓	↓	↓	↓
NIR	2	↓		↓	2	2	2	1		↓	↓	↓	↓
Thermal IR	1	↓		↓	3	2	3	3		↓	↓	↓	↓
μw	2	↓		↓				3		↓	↓	↓	↓

DISCIPLINE - Forestry

	9.5	9.6	9.7	9.8	9.9	9.10						
Spect. Signature												
Visible	1	4	1	1	2							
NIR	1	4	1	1	2							
Thermal IR	4	4	4	4	2							
μw	3	3	3	3	1							
Temporal Spect. Sig.												
Visible	4	4	1	1	2							
NIR	↓	4	1	1	2							
Thermal IR	↓	2	4	4	2							
μw	↓	3	3	3	1							
Thermal Radiance												
Thermal IR	4	4	4	4	4							
μw	4	4	↓	↓	↓							
Multiaspect Sp. Sig.												
Visible	2	1	2	2	3							
NIR	2	1	2	2	3							
Thermal IR	3	4	4	3	3							
μw	3	3	3	3	3							
Scattering Cross Section												
μw - 1 band	3	2	3	3	3							
μw - mult. bd.	3	2	3	3	3							
Optical	3	3	3	3	3							
Polarization Signature												
Visible	4	4	4	4	4							
NIR	↓	↓	↓	↓	↓							
Thermal IR	↓	↓	↓	↓	↓							
μw	↓	↓	↓	↓	↓							
Spatial Signature												
Visible	1	2	2	2	2							
NIR	1	2	2	2	2							
Thermal IR	3	3	3	3	3							
μw	4	3	3	3	3							

DISCIPLINE - Geography

	1.1		2.1	2.2	2.3	2.4	2.5		3.1	3.2	3.3	3.4	3.5
Spect. Signature	4												
Visible	↓						2		1	1	1	1	1
NIR	↓						2		1	1	1	1	1
Thermal IR	↓						4		4	4	4	2	2
μw	↓						4		3	3	3	3	3
Temporal Spect. Sig.	↓												
Visible	↓						2		1	1	1	1	1
NIR	↓						2		1	1	1	1	1
Thermal IR	↓						4		2	2	2	2	2
μw	↓						4		3	3	3	3	3
Thermal Radiance	↓												
Thermal IR	↓						4		2	2	2	2	2
μw	↓						4		3	3	3	3	3
Multiaspect Sp. Sig.													
Visible	3						3		3	3	3	3	3
NIR	3						3		3	3	3	3	3
Thermal IR	3						4		4	4	4	4	4
μw	3						4		4	4	4	4	4
Scattering Cross Section													
μw - 1 band	2						4		3	3	3	3	3
μw - mult. bd.	3						4		3	3	3	3	3
Optical	3						4		3	3	3	3	3
Polarization Signature													
Visible	4						3		3	3	3	3	3
NIR	4						3		3	3	3	3	3
Thermal IR	4						4		4	4	4	4	4
μw	4						4		3	3	3	3	3
Spatial Signature													
Visible	1						4		1	1	1	1	1
NIR	1						4		1	1	1	1	1
Thermal IR	3						4		2	2	2	2	2
μw	3						4		3	3	3	3	3

DISCIPLINE - Geography

	3.6	3.7		4.1	4.2	4.3	4.4	4.5	4.6		5.1		6.1
Spect. Signature													
Visible	1	1		1	1	1	1	1	1				
NIR	1	1		1	1	1	1	1	1				
Thermal IR	3	3		4	4	4	4	4	4				
μw	3	3		3	3	3	3	3	3				
Temporal Spect. Sig.													
Visible	1	1		1	1	1	1	1	1				
NIR	1	1		1	1	1	1	1	1				
Thermal IR	2	2		2	2	2	2	2	2				
μw	3	3		3	3	3	3	3	3				
Thermal Radiance													
Thermal IR	2	2		2	2	2	2	2	2				
μw	3	3		3	3	3	3	3	3				
Multiaspect Sp. Sig.													
Visible	3	3		3	3	3	3	3	3				
NIR	3	3		3	3	3	3	3	3				
Thermal IR	4	4		4	4	4	4	4	4				
μw	4	4		4	4	4	4	4	4				
Scattering Cross Section													
μw - 1 band	3	3		2	2	2	2	2	2				
μw - mult. bd.	3	3		3	3	3	3	3	3				
Optical	3	3		3	3	3	3	3	3				
Polarization Signature													
Visible	3	3		3	3	3	3	3	3				
NIR	3	3		3	↓	↓	↓	↓	↓				
Thermal IR	4	4		3									
μw	3	3		3									
Spatial Signature													
Visible	1	1		1	1	1	1	1	1				
NIR	1	1		1	1	1	1	1	1				
Thermal IR	2	2		2	2	2	2	2	2				
μw	3	3		3	3	3	3	3	3				

DISCIPLINE - Geography

	7.1	7.2	8.1	8.2	8.3	8.4		9.1	9.2	9.3	9.4		10.1
Spect. Signature													
Visible			1	1	1	1		1	1	1	1		1
NIR			1	1	1	1		1	1	1	1		1
Thermal IR			4	4	4	4		4	4	4	4		4
μw			3	3	3	3		3	3	3	3		3
Temporal Spect. Sig.													
Visible			1	1	1	1		1	1	1	1		1
NIR			1	1	1	1		1	1	1	1		1
Thermal IR			2	2	2	2		2	2	2	2		2
μw			3	3	3	3		3	3	3	3		3
Thermal Radiance													
Thermal IR			2	2	2	2		2	2	2	2		2
μw			3	3	3	3		3	3	3	3		3
Multiaspect Sp. Sig.													
Visible			3	3	3	3		3	3	3	3		3
NIR			3	3	3	3		3	3	3	3		3
Thermal IR			4	4	4	4		4	4	4	4		4
μw			4	4	4	4		4	4	4	4		3
Scattering Cross Section													
μw - 1 band			2	2	3	3		2	3	3	3		2
μw - mult. bd.			3	3	3	3		3	3	3	3		3
Optical			3	3	3	3		3	3	3	3		3
Polarization Signature													
Visible			3	3	3	3		3	3	3	3		3
NIR			3	3	3	3		3	3	3	3		3
Thermal IR			4	4	4	4		4	4	4	4		4
μw			3	3	3	3		3	3	3	3		3
Spatial Signature													
Visible			1	1	1	1		1	1	1	1		1
NIR			1	1	1	1		1	1	1	1		1
Thermal IR			2	2	2	2		2	2	2	2		2
μw			2	2	3	3		3	3	3	3		3

DISCIPLINE - Geography

	10.2	10.3		11.1	11.2	11.3	11.4		12.1	12.2	12.3	12.4	12.5
Spect. Signature													
Visible	1	1		1	1	1	1		1	4	1	1	1
NIR	1	1		1	1	1	1		1	↓	1	1	1
Thermal IR	4	4		2	2	3	4		4	↓	3	3	4
µw	3	3		3	3	3	3		3	↓	3	3	3
Temporal Spect. Sig.										↓			
Visible	1	1		1	1	2	2		1	↓	2	2	2
NIR	1	1		1	1	2	2		1	↓	2	2	2
Thermal IR	2	2		2	2	2	2		2	↓	2	2	2
µw	3	3		3	3	3	3		3	↓	3	3	3
Thermal Radiance										↓			
Thermal IR	2	2		2	2	2	2		2	↓	2	2	2
µw	3	3		3	3	3	3		3	↓	3	3	3
Multiaspect Sp. Sig.													
Visible	3	3		3	3	3	3		3	3	3	3	3
NIR	3	3		3	3	3	3		3	3	3	3	3
Thermal IR	4	4		4	4	4	4		4	4	4	4	4
µw	4	4		3	3	4	4		3	4	4	4	4
Scattering Cross Section													
µw - 1 band	2	2		2	2	2	2		2	2	3	3	2
µw - mult. bd.	3	3		3	3	3	3		3	3	3	3	3
Optical	3	3		3	3	3	3		3	3	3	3	3
Polarization Signature													
Visible	3	3		3	3	3	3		3	3	3	3	3
NIR	3	3		3	3	3	3		3	3	3	3	3
Thermal IR	4	4		3	3	4	4		3	3	4	4	4
µw	3	3		3	3	3	3		3	3	3	3	3
Spatial Signature													
Visible	1	1		1	1	1	1		1	1	1	1	1
NIR	1	1		1	1	1	1		1	1	1	1	1
Thermal IR	2	2		2	2	2	2		2	2	2	2	2
µw	2	2		2	2	2	2		2	2	2	2	2

DISCIPLINE - Geography

	12.6	12.7	12.8	12.9	12.10		16.1	16.2		17.1	17.2		18.1
Spect. Signature													
Visible	1	1	1	1	4								
NIR	1	1	1	1	4								
Thermal IR	4	4	4	4	3								
μw	3	3	3	3	3								
Temporal Spect. Sig.													
Visible	2	2	2	2	4								
NIR	2	2	2	2	4								
Thermal IR	2	2	2	2	1								
μw	3	3	3	3	3								
Thermal Radiance													
Thermal IR	2	2	2	2	1								
μw	3	3	3	3	3								
Multiaspect Sp. Sig.													
Visible	3	3	3	4	4								
NIR	3	3	3	4	4								
Thermal IR	4	4	4	4	4								
μw	4	4	4	4	4								
Scattering Cross Section													
μw - 1 band	2	2	2	3	4								
μw - mult. bd.	3	3	3	3	4								
Optical	3	3	3	3	4								
Polarization Signature													
Visible	3	3	3	3	4								
NIR	3	3	3	3	4								
Thermal IR	4	4	4	4	4								
μw	3	3	3	3	4								
Spatial Signature													
Visible	1	1	1	1	4								
NIR	1	1	1	1	4								
Thermal IR	2	2	2	2	1								
μw	2	2	2	3	3								

DISCIPLINE - Geography

	18.2		19.1		20.1							
Spect. Signature					4							
Visible					↓							
NIR					↓							
Thermal IR					↓							
µw					↓							
Temporal Spect. Sig.					↓							
Visible					↓							
NIR					↓							
Thermal IR					↓							
µw					↓							
Thermal Radiance					↓							
Thermal IR					↓							
µw					↓							
Multiaspect Sp. Sig.					↓							
Visible					↓							
NIR					↓							
Thermal IR					↓							
µw					↓							
Scattering Cross Section												
µw - 1 band					3							
µw - mult. bd.					3							
Optical					3							
Polarization Signature					4							
Visible					↓							
NIR					↓							
Thermal IR					↓							
µw					↓							
Spatial Signature												
Visible					1							
NIR					1							
Thermal IR					4							
µw					3							

DISCIPLINE - Geology

	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	1.10	1.11	1.12
Spect. Signature												
Visible	1	1	1	2	2	2			1	2	1	
NIR	1	1	1	2	2	2			1	2	1	
Thermal IR	1	1	1	3	2	2			2	2	2	
μw	3	3	3	3	3	3			3	3	3	
Temporal Spect. Sig.												
Visible	4	4	4	4	4	1			2	2	2	
NIR	↓	4	↓	4	↓	1			2	2	2	
Thermal IR	↓	2	↓	2	↓	1			2	1	2	
μw	↓	3	↓	3	↓	1			3	1	3	
Thermal Radiance	↓				↓							
Thermal IR	↓	2	2	4	↓	2			2	1	3	
μw	↓	3	2	4	↓	2			3	1	3	
Multiaspect Sp. Sig.	↓				↓							
Visible	↓	4	4	4	↓	4			2	4	2	
NIR	↓	↓	↓	↓	↓	↓			2	4	2	
Thermal IR	↓	↓	↓	↓	↓	↓			3	4	3	
μw	↓	↓	↓	↓	↓	↓			3	4	3	
Scattering Cross Section												
μw - 1 band	3	3	3	3	3	3			3	3	3	
μw - mult. bd.	3	↓	↓	↓	↓	3			3	3	↓	
Optical	3	↓	↓	↓	↓	3			3	3	↓	
Polarization Signature		↓	↓	↓	↓						↓	
Visible	3	↓	↓	↓	↓	2			3	1	↓	
NIR	3	↓	↓	↓	↓	3			3	3	↓	
Thermal IR	3	↓	↓	↓	↓	3			3	3	↓	
μw	3	↓	↓	↓	↓	3			3	3	↓	
Spatial Signature		↓	↓	↓	↓							
Visible	4	↓	↓	↓	↓	3			2	4	2	
NIR	↓	↓	↓	↓	↓	3			2	4	2	
Thermal IR	↓	↓	↓	↓	↓	3			3	4	3	
μw	↓	↓	↓	↓	↓							

DISCIPLINE - Geology

	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	2.10	3.1	3.2
Spect. Signature												
Visible	4	1	1	2	2	1		1	4		1	1
NIR	4	1	1	2	2	1		1	4		1	1
Thermal IR	2	1	4	2	2	2		2	2		2	2
μw	4	3	4	3	3	3		3	3		3	3
Temporal Spect. Sig.												
Visible	4	4	2	2	2	2		2	4		1	2
NIR	↓	4	2	2	2	2		2	4		1	2
Thermal IR	↓	2	4	2	1	2		2	2		2	2
μw	↓	4	4	3	3	3		3	3		3	3
Thermal Radiance												
Thermal IR	4	4	4	4	2	2		4	2		2	2
μw	4	4	4	4	3	3		4	3		3	3
Multiaspect Sp. Sig.												
Visible	2	3	2	4	4	4		2	4		2	2
NIR	2	3	2	↓	↓	↓		2	4		2	2
Thermal IR	3	3	4	↓	↓	↓		3	4		3	3
μw	3	4	4	↓	↓	↓		3	4		3	3
Scattering Cross Section												
μw - 1 band	2	3	4	3	↓	2		2	2		3	3
μw - mult. bd.	3	3	4	3	↓	3		3	3		3	↓
Optical	3	3	4	3	↓	3		3	4		3	↓
Polarization Signature												
Visible	3	3	3	3	↓	4		4	4		3	↓
NIR	↓	3	3	3	↓	↓		↓	↓		3	↓
Thermal IR	↓	3	4	3	↓	↓		↓	↓		3	↓
μw	↓	3	4	3	↓	↓		↓	↓		3	↓
Spatial Signature												
Visible	1	2	3	4	2	1		1	4		2	2
NIR	1	2	3	4	2	1		1	4		2	2
Thermal IR	3	3	4	4	3	2		2	4		3	2
μw	3	3	3	4	3	3		3	4		3	3

DISCIPLINE - Geology

	3.3	3.4	3.5	3.6	3.7	3.8	3.9	3.10	3.11	3.12	4.1	4.2
Spect. Signature												
Visible	4	2		2	1	1	1	4		1	1	2
NIR	4	2		2	1	1	1	4		1	1	2
Thermal IR	2	4		2	4	2	2	2		4	4	2
μw	4	4		3	4	3	3	3		4	4	3
Temporal Spect. Sig.												
Visible	4	4		2	2	2	2	4		2	2	2
NIR	↓	↓		2	2	2	2	4		2	2	2
Thermal IR	↓	↓		1	4	2	2	2		4	4	2
μw	↓	↓		3	4	3	3	3		4	4	3
Thermal Radiance												
Thermal IR	↓	↓		2	4	4	2	2		4	2	2
μw	↓	↓		3	4	4	3	3		4	3	3
Multiaspect Sp. Sig.												
Visible	2	↓		4	2	2	2	4		3	2	2
NIR	2	↓		↓	2	2	2	4		3	2	2
Thermal IR	3	↓		↓	4	3	3	4		4	3	3
μw	3	↓		↓	4	3	3	4		4	3	3
Scattering Cross Section												
μw - 1 band	2	↓		↓	4	3	3	2		4	2	1
μw - mult. bd.	3	↓		↓	4	3	3	3		4	3	3
Optical	3	↓		↓	4	3	3	4		3	3	3
Polarization Signature												
Visible	3	↓		↓	3	3	3	4		3	3	2
NIR		↓		↓	3	3	3	4		3	3	2
Thermal IR		↓		↓	4	3	3	4		4	3	3
μw		↓		↓	4	3	3	4		4	3	3
Spatial Signature												
Visible	1	2		2	3	2	2	4		4	2	1
NIR	1	2		2	3	2	2	4		4	2	1
Thermal IR	1	4		3	4	3	3	4		4	3	3
μw	3	4		3	4	4				4	2	4

DISCIPLINE - Geology

	4.3	4.4	4.5	4.6		5.1	5.2	6.1	6.2	6.3	6.4	6.5	6.6
Spect. Signature													
Visible	1	4	2	2		2	2	4	4	4	1	1	1
NIR	1	4	2	2		2	2	4	4	4	1	1	1
Thermal IR	2	4	4	4		3	4	2	2	2	2	4	2
μw	3	4	4	4		3	4	3	3	3	3	4	3
Temporal Spect. Sig.													
Visible	2	4	2	2		2	4	4	4	4	2	2	2
NIR	2	4	2	2		2	4	4	4	4	2	2	2
Thermal IR	2	2	4	4		3	4	2	2	2	2	4	2
μw	3	3	4	4		3	4	3	3	3	3	4	3
Thermal Radiance													
Thermal IR	2	1	2	2		2	4	1	1	1	4	4	2
μw	3	3	3	3		3	4	3	3	3	4	4	3
Multiaspect Sp. Sig.													
Visible	2	4	2	2		2	1	4	4	4	2	2	2
NIR	2	↓	2	2		2	1	↓	↓	↓	2	2	2
Thermal IR	3	↓	3	3		3	4	↓	↓	↓	3	4	3
μw	3	↓	3	3		3	4	↓	↓	↓	3	4	3
Scattering Cross Section													
μw - 1 band	3	↓	2	1		1	2	↓	↓	↓	3	4	3
μw - mult. bd.	3	↓	3	3		3	2	↓	↓	↓	↓	4	3
Optical	3	↓	3	3		3	3	↓	↓	↓	↓	4	3
Polarization Signature													
Visible	3	↓	4	4		4	4	↓	↓	↓	↓	3	3
NIR	3	↓	↓	↓		↓	4	↓	↓	↓	↓	3	3
Thermal IR	3	↓	↓	↓		↓	4	↓	↓	↓	↓	4	3
μw	3	↓	↓	↓		↓	4	↓	↓	↓	↓	4	3
Spatial Signature													
Visible	2		1	1		1	2	4	4	4	2	3	2
NIR	2		1	1		1	2	4	4	4	2	3	2
Thermal IR	3	2	3	3		3	4	1	1	1	3	4	3
μw	3	2	1	1		1	4	3	3	3	3	4	3

DISCIPLINE - Geology

	7.1	7.2	7.3	7.4	7.5	7.6	7.7	8.1	8.2	8.3	8.4	8.5	8.6
Spect. Signature													
Visible	1	1	1	2	2	2	4	4	1	1	4	4	1
NIR	1	1	1	2	2	2	4	4	1	3	4	1	1
Thermal IR	2	2	3	2	4	2	4	3	2	2	4	↓	2
μw	3	3	3	3	4	3	4	3	3	2	3	↓	3
Temporal Spect. Sig.												↓	
Visible	2	4	4	4	4	1	4	4	2	4	4	↓	4
NIR	2	4	4	4	4	1	4	4	2	4	↓	↓	4
Thermal IR	2	4	4	4	4	2	1	2	2	4	↓	↓	2
μw	3	4	4	4	4	3	3	3	3	4	↓	↓	3
Thermal Radiance												↓	
Thermal IR	2	2	2	2	4	2	2	1	2	2	3	↓	3
μw	3	3	3	3	4	3	3	3	3	2	3	↓	3
Multiaspect Sp. Sig.													
Visible	2	2	2	2	1	2	4	4	4	4	3	2	2
NIR	2	2	2	2	1	2	4	↓	↓	↓	3	2	2
Thermal IR	3	3	3	3	4	4	4	↓	↓	↓	4	3	3
μw	3	3	3	3	4	4	4	↓	↓	↓	4	3	3
Scattering Cross Section								↓	↓				
μw - 1 band	3	3	3	3	3	3	3	↓	↓	2	3	2	2
μw - mult. bd.	3	3	3	3	3	3	3	↓	↓	3	2	4	3
Optical	3	3	3	3	3	3	4	↓	↓	3	3	4	3
Polarization Signature								↓					
Visible	3	4	4	3	4	4	4	↓	3	3	3	4	4
NIR	3	4	4	3	4	4	4	↓	3	3	3	↓	↓
Thermal IR	3	4	4	4	4	4	4	↓	3	4	4	↓	↓
μw	3	4	4	3	4	4	4	↓	3	3	3	↓	↓
Optical Signature								↓					
Visible	2	1	1	2	2	2	4	↓	4	3	3	1	2
NIR	2	2	2	2	2	2	4	↓	4	↓	↓	1	2
Thermal IR	3	2	2	3	4	4	4	↓	4	↓	↓	2	3
μw	3	3	3	3	4	4	4	↓	4	↓	↓	3	3

DISCIPLINE - Geology

	9.1	9.2	9.3	9.4	9.5	9.6		10.1	10.2	10.3	10.4	10.5
Spect. Signature												
Visible	1	1	1	4	4	1					4	
NIR	1	1	1	4		1					4	
Thermal IR	2	2	2	3		4					3	
µw	3	3	3	3		4					3	
Temporal Spect. Sig.												
Visible	2	2	2	4	1	2					4	
NIR	2	2	2	4	1	2					4	
Thermal IR	2	2	2	2	3	4					2	
µw	3	3	3	3	3	4					3	
Thermal Radiance												
Thermal IR	2	2	3	1	4	4					1	
µw	3	3	3	3	4	4					3	
Multiaspect Sp. Sig.												
Visible	4	2	3	4	4	2					4	
NIR	4	2	3	↓		2					↓	
Thermal IR	4	3	3	↓		4					↓	
µw	4	3	3	↓		4					↓	
Scattering Cross Section				↓							↓	
µw - 1 band	2	3	3	↓	3	4					↓	
µw - mult. bd.	3	3	3	↓	3	4					↓	
Optical	3	3	3	↓	3	4					↓	
Polarization Signature				↓							↓	
Visible	4	3	3	↓	3	3					↓	
NIR	4	3	3	↓	3	3					↓	
Thermal IR	4	4	3	↓	4	4					↓	
µw	4	3	3	↓	3	4					↓	
Spatial Signature				↓							↓	
Visible	1	2	3	↓	3	3					↓	
NIR	1	2	3	↓	3	3					↓	
Thermal IR	2	3	3	↓	3	4					↓	
µw	3	3	3	↓	3	4					↓	

DISCIPLINE - Geology

	11.1	11.2	11.3		12.1		13.1	13.2	13.3	13.4		
Spect. Signature												
Visible	1											
NIR	1											
Thermal IR	3											
µw	3											
Temporal Spect. Sig.												
Visible	4											
NIR	↓											
Thermal IR	↓											
µw	↓											
Thermal Radiance												
Thermal IR	3											
µw	3											
Multiaspect Sp. Sig.												
Visible	4											
NIR	4											
Thermal IR	4											
µw	4											
Scattering Cross Section												
µw - 1 band	3											
µw - mult. bd.	3											
Optical	3											
Polarization Signature												
Visible	4											
NIR	↓											
Thermal IR	↓											
µw	↓											
Spatial Signature												
Visible	1											
NIR	1											
Thermal IR	3											
µw	3											

DISCIPLINE - Hydrology

	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8		2.1	2.2	2.3	2.4
Spect. Signature													
Visible	1	2		1	1	3	4	1		1	4		2
NIR	1	2		1	1	3	4	1		1	4		2
Thermal IR	4	4		4	4	3	4	4		4	3		4
μw	3	3		2	3	3	4	4		4	3		4
Temporal Spect. Sig.													
Visible	2	2		2	2	3	2	2		2	4		2
NIR	2	2		2	2	3	2	2		2	4		2
Thermal IR	4	4		4	4	3	3	4		4	2		4
μw	3	3		2	3	3	3	4		4	3		4
Thermal Radiance													
Thermal IR	2	3		2	2	3	3	2		2	1		3
μw	3	3		2	3	3	3	3		3	3		3
Multiaspect Sp. Sig.													
Visible	4	4		4	4	4	4	4		3	4		3
NIR	4	4		4	4	4	4	4		3	↓		3
Thermal IR	4	4		4	4	4	4	4		4	↓		4
μw	4	4		4	4	4	4	4		4	↓		4
Scattering Cross Section													
μw - 1 band	3	4		2	3	3	3	2		4	↓		4
μw - mult. bd.	3	4		3	3	3	3	3		4	↓		4
Optical	3	4		4	3	4	4	3		3	↓		3
Polarization Signature													
Visible	3	4		3	3	3	3	3		3	↓		3
NIR	3	4		3	3	3	3	3		3	↓		3
Thermal IR	4	4		4	4	4	4	3		4	↓		4
μw	3	4		3	3	3	3	3		4	↓		4
Spatial Signature													
Visible	2	4		2	4	4	4	2		2	↓		3
NIR	2	4		2	4	4	4	2		2	↓		3
Thermal IR	3	4		3	4	4	4	3		3	↓		3
μw	3	4		3	4	4	4	3		4	↓		

DISCIPLINE - Hydrology

	2.5	2.6	2.7	2.8		3.1	3.2	3.3	3.4	3.5	3.6	3.7
Spect. Signature												
Visible	1	2	3	1		4		2	1	2	2	1
NIR	1	2	3	1		4		2	1	2	2	1
Thermal IR	4	3	4	2		3		4	4	1	4	4
μw	4	3	3	3		3		4	4	3	4	3
Temporal Spect. Sig.												
Visible	4	1	4	2		4		2	2	1	2	2
NIR	4	1	4	2		4		2	2	1	2	2
Thermal IR	4	3	4	2		2		4	4	1	4	4
μw	4	3	3	3		3		4	4	3	4	3
Thermal Radiance												
Thermal IR	2	2	1	2		1		3	2	2	2	2
μw	3	3	1	3		3		3	3	3	3	3
Multiaspect Sp. Sig.												
Visible	3	4	4	4		4		3	3	4	4	4
NIR	3	4	4	4		↓		3	3	4	4	4
Thermal IR	4	4	4	4				4	4	4	4	4
μw	4	4	4	4				4	4	4	4	4
Scattering Cross Section												
μw - 1 band	4	3	4	4				4	4	4	4	3
μw - mult. bd.	4	3	4	4				4	4	4	4	3
Optical	3	3	4	4				3	3	4	3	3
Polarization Signature												
Visible	3	3	4	3				3	3	4	4	3
NIR	3	3	4	3				3	3	4	4	3
Thermal IR	4	4	4	4				4	4	4	4	4
μw	4	3	4	3				4	4	4	4	3
Spatial Signature												
Visible	2	2	4	2				3	2	2	2	2
NIR	2	2	4	2				3	2	2	2	2
Thermal IR	4	3	4	3				3	3	3	4	3
μw	4	3	4	3				3	4	3	4	3

DISCIPLINE - Hydrology

	4.1	4.2	4.3	4.4	4.5		5.1	5.2	5.3	5.4	5.5	5.6	5.7
Spect. Signature													
Visible	3	2	1	1	4		4	4		2	1	1	
NIR	3	2	1	1	4		4	4		2	1	1	
Thermal IR	4	2	2	2	2		3	3		4	4	1	
μw	3	3	3	3	3		3	3		4	4	3	
Temporal Spect. Sig.													
Visible	3	2	2	2	4		4	4		2	2	1	
NIR	3	2	2	2	4		4	4		2	2	1	
Thermal IR	3	2	2	2	2		2	2		4	4	1	
μw	4	3	3	3	3		3	3		4	4	3	
Thermal Radiance													
Thermal IR	4	2	2	2	4		1	1		4	4	1	
μw	↓	3	3	3	4		3	3		4	4	3	
Multiaspect Sp. Sig.													
Visible	4	2	4	2	1		4	4		3	3	3	
NIR	↓	2	4	2	1		↓	↓		3	3	3	
Thermal IR	↓	3	4	3	4		↓	↓		4	4	4	
μw	↓	3	4	3	2		↓	↓		4	4	4	
Scattering Cross Section													
μw - 1 band	2	1	2	3	2		↓	↓		4	4	4	
μw - mult. bd.	3	3	3	3	2		↓	↓		4	4	4	
Optical	3	3	3	3	3		↓	↓		4	4	4	
Polarization Signature													
Visible	4	2	4	3	4		↓	↓		3	3	3	
NIR	↓	2	4	3	4		↓	↓		3	3	3	
Thermal IR	↓	3	4	3	4		↓	↓		4	4	4	
μw	↓	3	4	3	4		↓	↓		4	4	4	
Spatial Signature													
Visible	2	1	1	2	2		↓	↓		4	4	4	
NIR	2	1	1	2	2		↓	↓		4	4	4	
Thermal IR	3	3	2	3	3		↓	↓		4	4	4	
μw	3	1	3	3	2		↓	↓		4	4	4	

DISCIPLINE - Hydrology

	6.1	6.2	6.3	6.4	6.5	6.6	6.7		7.1	7.2	7.3	7.4
Spect. Signature												
Visible		2	2	1	1		1		1	2	1	1
NIR		2	2	1	1		1		4	2	4	4
Thermal IR		2	4	4	4		2		4	2	4	4
μw		3	4	4	4		4		1	3	1	1
Temporal Spect. Sig.												
Visible		2	2	2	2		2		2	1	2	2
NIR		2	2	2	2		2		4	1	4	4
Thermal IR		2	4	4	4		2		2	3	2	2
μw		3	4	4	4		4		2	3	2	2
Thermal Radiance												
Thermal IR		2	4	4	4		4		1	2	1	1
μw		3	4	4	4		4		1	2	1	1
Multiaspect Sp. Sig.												
Visible		3	3	3	1		1		4	4	4	4
NIR		3	3	3	1		1		4	4	4	4
Thermal IR		4	4	4	4		2		4	4	4	4
μw		4	4	4	4		3		4	4	4	4
Scattering Cross Section												
μw - 1 band		4	4	4	3		3		3	3	3	3
μw - mult. bd.		4	4	4	3		3		3	3	3	3
Optical		4	4	4	3		3		3	3	3	3
Polarization Signature												
Visible		3	3	3	3		3		2	2	2	2
NIR		3	3	3	3		3		3	3	3	3
Thermal IR		4	4	4	4		3		3	3	3	3
μw		4	4	4	4		3		3	3	3	3
Spatial Signature												
Visible		4	4	4	3		2		4	1	1	4
NIR		4	4	4	3		2		4	1	1	4
Thermal IR		4	4	4	4		2		4	3	3	4
μw		4	4	4	4		3		4	3	3	4

DISCIPLINE - Hydrology

	8.1	8.2	8.3		9.1	9.2	9.3	9.4	9.5		10.1	10.2	10.3
Spect. Signature													
Visible	2	2	4		4	4	4		4		4	4	4
NIR	2	2	4		4	4	4		4		4	↓	4
Thermal IR	2	2	3		4	4	4		3		4	↓	2
μw	3	3	3		4	3	4		3		3	↓	3
Temporal Spect. Sig.													
Visible	1	1	4		4	3	4		4		4	↓	4
NIR	1	1	4		4	3	4		4		4	↓	4
Thermal IR	1	1	3		3	3	3		3		3	↓	2
μw	1	1	3		3	3	3		3		3	↓	3
Thermal Radiance													
Thermal IR	2	2	3		3	3	3		3		3	↓	2
μw	2	2	3		3	3	3		3		3	↓	3
Multiaspect Sp. Sig.													
Visible	4	4	4		4	4	4		4		4	↓	4
NIR	4	4	4		4	4	4		4		4	↓	4
Thermal IR	4	4	4		4	4	4		4		4	↓	4
μw	4	4	4		4	4	4		4		4	↓	4
Scattering Cross Section													
μw - 1 band	3	3	3		3	3	3		3		3	↓	3
μw - mult. bd.	↓	↓	3		3	3	3		3		3	↓	3
Optical	↓	↓	4		4	4	4		4		4	↓	4
Polarization Signature													
Visible	↓	↓	4		4	1	3		3		4	↓	4
NIR	↓	↓	4		4	1	3		3		4	↓	4
Thermal IR	↓	↓	4		4	3	4		4		4	↓	4
μw	↓	↓	3		3	3	3		3		3	↓	3
Spatial Signature													
Visible	↓	↓	4		4	4	4		4		4	↓	4
NIR	↓	↓	4		4	4	4		4		4	↓	4
Thermal IR	↓	↓	4		4	4	4		4		4	↓	4
μw	↓	↓	4		4	4	4		4		4	↓	4

DISCIPLINE - Hydrology

	10.4	10.5	10.6	10.7		11.1	11.2	11.4	11.5	11.3	12.1	12.2	12.3
Spect. Signature													
Visible		4	3	3		3	4	3	3	4	1	1	4
NIR		4	3	3		3	4	3	3	4	1	1	4
Thermal IR		3	3	3		3	3	3	3	3	4	4	4
μw		3	3	3		3	3	3	3	3	3	3	3
Temporal Spect. Sig.													
Visible		4	3	3		3	4	3	3	4	2	2	4
NIR		4	3	3		3	4	3	3	4	2	2	4
Thermal IR		2	3	3		2	3	3	3	3	2	2	4
μw		3	3	3		3	3	3	3	3	3	3	4
Thermal Radiance													
Thermal IR		1	3	3		2	3	3	3	3	2	2	3
μw		3	3	3		3	3	3	3	3	3	3	3
Multiaspect Sp. Sig.													
Visible		4	4	4		4	4	4	4	4	4	4	3
NIR		↓	4	4		4	4	4	4	↓	↓	4	3
Thermal IR		↓	4	4		4	4	4	4	↓	↓	4	4
μw		↓	4	4		4	4	4	4	↓	↓	4	4
Scattering Cross Section													
μw - 1 band		↓	3	3		3	3	3	3	3	3	3	3
μw - mult. bd.		↓	3	3		3	3	3	3	3	3	3	2
Optical		↓	3	3		4	4	3	3	3	3	3	3
Polarization Signature													
Visible		↓	4	4		3	3	4	4	4	4	4	3
NIR		↓	4	4		3	3	4	4	↓	4	4	3
Thermal IR		↓	4	4		4	4	4	4	↓	4	4	4
μw		↓	3	3		3	3	3	3	↓	3	3	3
Spatial Signature													
Visible		↓	4	4		4	4	4	4	4	4	4	3
NIR		↓	4	4		4	4			4	4	4	3
Thermal IR		↓	4	4		4	4			3	4	4	3
μw		↓	4	4		4	4			3	4	4	3

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	12.4	12.5	12.6	12.7	12.8		13.1	13.2	13.3	13.4	13.5	13.6	13.7	13.8
Spect. Signature														
Visible	4	2	3	2			1			1	2	2	1	2
NIR	4	2	3	2			1			1	2	2	1	2
Thermal IR	3	4	4	3			4			4	2	2	4	4
μw	3	3	2	3			3			4	3	3	4	4
Temporal Spect. Sig.														
Visible	4	1	3	2			2			2	1	2	2	4
NIR	4	1	3	2			2			2	1	2	2	4
Thermal IR	2	2	3	3			2			3	1	1	3	4
μw	3	3	3	3			3			3	3	3	3	4
Thermal Radiance														
Thermal IR	1	4	3	3			2			2	2	2	2	2
μw	3	4	3	3			3			3	2	3	3	3
Multiaspect Sp. Sig.														
Visible	4	4	4	4			3			3	2	4	3	2
NIR	↓	↓	↓	↓			3			3	2	↓	3	2
Thermal IR	↓	↓	↓	↓			4			4	4	↓	4	4
μw	↓	↓	↓	↓			4			4	3	↓	4	4
Scattering Cross Section														
μw - 1 band	↓	↓	3	3			3			4	3	3	4	3
μw - mult. bd.	↓	↓	3	3			3			4	3	3	4	3
Optical	↓	↓	4	3			3			3	3	3	3	3
Polarization Signature														
Visible	↓	↓	3	3			4			3	3	3	3	4
NIR	↓	↓	3	3			4			3	3	3	3	4
Thermal IR	↓	↓	4	4			4			4	3	3	4	4
μw	↓	↓	3	3			3			4	3	3	4	4
Spatial Signature														
Visible	↓	3	4	4			3			2	2	3	1	1
NIR	↓	3	4	4			3			2	2	3	1	1
Thermal IR	↓	3	4	4			3			3	3	3	3	2
μw	↓	3	4	4			3			4	3	3	3	4

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	1.1	1.2	1.3	1.4		2.1		3.1	3.2	3.3		4.1	4.2
Spect. Signature													
Visible	4	4	4	4		4		4	4	4		1	4
NIR	4	4	↓	↓		↓		4	4	↓		1	4
Thermal IR	1	1	↓	↓		↓		4	4	↓		1	1
μw	1	1	↓	↓		↓		3	3	↓		2	1
Temporal Spect. Sig.													
Visible	4	4	↓	↓		↓		4	4	↓		2	4
NIR	4	4	↓	↓		↓		4	4	↓		2	4
Thermal IR	4	2	↓	↓		↓		4	4	↓		2	4
μw	4	2	↓	↓		↓		4	3	↓		2	4
Thermal Radiance													
Thermal IR	1	1	↓	↓		↓		4	4	↓		1	1
μw	1	1	↓	↓		↓		3	3	↓		2	1
Multiaspect Sp. Sig.													
Visible	4	4	↓	↓		↓		4	4	↓		3	4
NIR	4	4	↓	↓		↓		4	4	↓		4	4
Thermal IR	4	4	↓	↓		↓		4	4	↓		4	4
μw	4	4	↓	↓		↓		4	4	↓		4	4
Scattering Cross Section													
μw - 1 band	4	4	↓	↓		↓		3	3	↓		3	4
μw - mult. bd.	4	4	↓	↓		↓		3	3	↓		3	4
Optical	4	4	↓	↓		↓		4	4	↓		3	4
Polarization Signature													
Visible	4	4	↓	↓		↓		4	4	↓		3	4
NIR	4	4	↓	↓		↓		4	4	↓		3	4
Thermal IR	4	4	↓	↓		↓		4	4	↓		4	4
μw	2	2	↓	↓		↓		3	3	↓		3	2
Spatial Signature													
Visible	4	4	↓	↓		↓		4	4	↓		3	4
NIR	4	4	↓	↓		↓		4	4	↓		3	4
Thermal IR	4	4	↓	↓		↓		4	4	↓		3	4
μw	4	4	↓	↓		↓				↓			

DISCIPLINE - Oceanography

	4.3	4.4		5.1	5.2	5.3	5.4	5.5		6.1	6.2	6.3	6.4
Spect. Signature													
Visible	4	1		2	4		4	1		2	4		1
NIR	4	1		2	4		↓	1		2	4		1
Thermal IR	4	2		2	4		↓	2		2	4		2
μw	3	3		2	4		↓	3		2	4		3
Temporal Spect. Sig.													
Visible	4	1		2	2		3	1		2	3		1
NIR	4	1		2	2		3	1		2	3		1
Thermal IR	4	2		2	2		3	2		2	3		2
μw	4	3		2	3		3	3		2	3		3
Thermal Radiance													
Thermal IR	4	2		2	4		4	2		2	3		2
μw	3	3		2	4		↓	3		2	3		3
Multiaspect Sp. Sig.													
Visible	4	3		4	4		↓	3		4	4		3
NIR	4	3		4	4		↓	3		4	4		3
Thermal IR	4	4		4	4		↓	4		4	4		4
μw	4	4		4	4		↓	4		4	4		4
Scattering Cross Section													
μw - 1 band	3	4		3	3		↓	4		3	3		4
μw - mult. bd.	3	4		3	3		↓	4		3	3		4
Optical	4	3		3	4		↓	3		3	3		3
Polarization Signature													
Visible	4	3		3	3		↓	3		3	3		3
NIR	4	3		3	3		↓	3		3	3		3
Thermal IR	4	4		4	4		↓	4		4	3		4
μw	3	3		3	3		↓	3		3	3		3
Spatial Signature													
Visible	4	3		3	3		3	3		3	3		3
NIR	4	3		3	3		3	3		3	3		3
Thermal IR	4	4		3	3		3	4		3	3		4
μw	4	3		3	3		3	3		3	3		3

DISCIPLINE - Oceanography

	7.1	7.2	7.3	7.4	7.5	7.6		8.1	8.2	8.3	8.4	8.5
Spect. Signature												
Visible	4	4	4	4	4	3		4	4	4	4	4
NIR	4	4	↓	↓	↓	3		4	↓	4	↓	↓
Thermal IR	4	4	↓	↓	↓	4		4	↓	4	↓	↓
μw	3	3	↓	↓	↓	3		3	↓	3	↓	↓
Temporal Spect. Sig.				↓	↓						↓	↓
Visible	4	4	3	↓	↓	4		4	3	4	↓	↓
NIR	4	4	3	↓	↓	↓		4	3	4	↓	↓
Thermal IR	4	4	3	↓	↓	↓		4	3	4	↓	↓
μw	3	3	3	↓	↓	↓		3	3	3	↓	↓
Thermal Radiance				↓	↓	↓					↓	↓
Thermal IR	4	4	4	↓	↓	↓		4	4	4	↓	↓
μw	↓	↓	↓	↓	↓	↓		↓	↓	↓	↓	↓
Multiaspect Sp. Sig.	↓	↓	↓	↓	↓	↓		↓	↓	↓	↓	↓
Visible	↓	↓	↓	↓	↓	3		↓	↓	↓	↓	↓
NIR	↓	↓	↓	↓	↓	3		↓	↓	↓	↓	↓
Thermal IR	↓	↓	↓	↓	↓	4		↓	↓	↓	↓	↓
μw	↓	↓	↓	↓	↓	3		↓	↓	↓	↓	↓
Scattering Cross Section												
μw - 1 band	2	2	3	3	3	3		2	2	3	3	3
μw - mult. bd.	2	2	3	3	3	3		2	2	3	3	3
Optical	3	3	3	3	3	3		3	3	3	3	3
Polarization Signature												
Visible	3	3	4	3	3	3		3	3	3	3	3
NIR	3	3	↓	3	3	3		3	3	3	3	3
Thermal IR	3	3	↓	4	4	4		3	3	3	4	4
μw	2	2	↓	3	3	3		2	3	3	3	3
Spatial Signature			↓									
Visible	2	2	↓	1	1	4		2	3	3	1	1
NIR	2	2	↓	1	1			2	3	3	1	1
Thermal IR	3	3	↓	3	3			3	3	3	3	3
μw	3	3	↓	3	3			3	3	3	3	3

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	9.1	9.2	9.3		10.1	10.2	10.3	10.4	10.5	10.6	10.7	10.8	10.9
Spect. Signature													
Visible	4	4	3		1				1				
NIR	↓	↓	3		4				2				
Thermal IR	↓	↓	4		4				3				
μw	↓	↓	3		4				2				
Temporal Spect. Sig.													
Visible	3	3	4		2				1				
NIR	3	3	↓		4				2				
Thermal IR	3	3	↓		4				1				
μw	3	3	↓		4				2				
Thermal Radiance			↓										
Thermal IR	4	4	↓		4				2				
μw	↓	↓	↓		4				3				
Multiaspect Sp. Sig.	↓	↓											
Visible	↓	↓	3		3				3				
NIR	↓	↓	3		4				3				
Thermal IR	↓	↓	4		4				4				
μw	↓	↓	3		4				3				
Scattering Cross Section													
μw - 1 band	3	3	3		4				2				
μw - mult. bd.	3	3	3		4				3				
Optical	3	3	3		2				3				
Polarization Signature													
Visible	4	4	3		3				3				
NIR	↓	↓	3		4				3				
Thermal IR	↓	↓	4		4				3				
μw	↓	↓	3		4				3				
Spatial Signature	↓	↓											
Visible	↓	↓	4		4				4				
NIR	↓	↓	↓		4				4				
Thermal IR	↓	↓	↓		4				4				
μw	↓	↓	↓		4				4				

DISCIPLINE - Oceanography

	10.10		11.1	11.2	11.3	11.4		12.1	12.2	12.3	12.4	12.5
Spect. Signature												
Visible			1	1	1	4		2	4	1		4
NIR			1	3	1	4		2	↓	p		↓
Thermal IR			1	2	1	4		3	↓	2		↓
μw			3	2	1	3		3	↓	3		↓
Temporal Spect. Sig.												
Visible			4	4	4	4		4	3	2		3
NIR			4	4	↓	4		↓	3	2		3
Thermal IR			4	4	↓	4		↓	3	2		3
μw			4	4	↓	4		↓	3	3		3
Thermal Radiance												
Thermal IR			2	2	2	3		2	4	4		3
μw			3	2	2	3		3	4	↓		3
Multiaspect Sp. Sig.												
Visible			4	4	4	3		4	4	↓		4
NIR			4	↓	↓	3		↓	↓	↓		↓
Thermal IR			4	↓	↓	4		↓	↓	↓		↓
μw			4	↓	↓	4		↓	↓	↓		↓
Scattering Cross Section												
μw - 1 band			2	2	2	3		2	3	3		↓
μw - mult. bd.			3	3	3	2		3	3	3		↓
Optical			3	3	3	3		3	3	3		↓
Polarization Signature												
Visible			3	3	4	3		4	4	4		↓
NIR			3	3	↓	3		↓	↓	↓		↓
Thermal IR			4	4	↓	4		↓	↓	↓		↓
μw			3	3	↓	3		↓	↓	↓		↓
Spatial Signature												
Visible			3	3	1	3		1	3	3		3
NIR			3	3	1	3		1	3	3		3
Thermal IR			3	3	2	3		2	3	3		3
μw			3	3	3	3		3	3	3		3

DISCIPLINE - Oceanography

	13.1	13.2	13.3		14.1		15.1	15.2	15.3		16.1	16.2
Spect. Signature												
Visible					4							
NIR					↓							
Thermal IR					↓							
μw					↓							
Temporal Spect. Sig.					↓							
Visible					↓							
NIR					↓							
Thermal IR					↓							
μw					↓							
Thermal Radiance					↓							
Thermal IR					↓							
μw					↓							
Multiaspect Sp. Sig.					↓							
Visible					↓							
NIR					↓							
Thermal IR					↓							
μw					↓							
Scattering Cross Section												
μw - 1 band					3							
μw - mult. bd.					3							
Optical					3							
Polarization Signature												
Visible					4							
NIR					↓							
Thermal IR					↓							
μw					↓							
Spatial Signature					↓							
Visible					↓							
NIR					↓							
Thermal IR					↓							
μw					↓							

DISCIPLINE - Oceanography

	17A.1	17A.2	17A.3	17A.4	17A.5	17A.6	17A.7	17A.8	17A.9	17A.10			17B.1
Spect. Signature													
Visible	1	1		4				1	4	1			1
NIR	1	1		4				1	↓	4			4
Thermal IR	2	2		2				4	↓	4			2
μw	3	3		3				4	↓	4			3
Temporal Spect. Sig.									↓				
Visible	2	2		4				2	↓	2			2
NIR	2	2		4				2	↓	4			4
Thermal IR	2	2		3				4	↓	4			2
μw	3	3		3				4	↓	4			3
Thermal Radiance													
Thermal IR	3	3		1				4	3	4			2
μw	3	3		2				4	3	4			3
Multiaspect Sp. Sig.													
Visible	4	4		4				3	2	3			3
NIR	4	4		4				3	2	4			4
Thermal IR	4	4		4				4	4	4			4
μw	4	4		4				4	4	4			4
Scattering Cross Section													
μw - 1 band	1	1		4				4	1	4			4
μw - mult. bd.	3	3		4				4	1	4			4
Optical	3	3		4				3	3	2			4
Polarization Signature													
Visible	4	4		4				3	3	3			3
NIR	4	4		4				3	3	4		4	
Thermal IR	4	3		4				4	4	4			4
μw	3	3		4				4	3	4			4
Spatial Signature													
Visible	4	1		4				4	3	4			3
NIR	4	1		4				4	3	4			4
Thermal IR	4	2		4				4	3	4			4
μw	4	2		4				4	3	4			4

DISCIPLINE - Oceanography

	17B.2	17B.3	17B.4	17B.5	17B.6	17B.7	17B.8	17B.9	17B.10		17C.1	17C.2	17C.3
Spect. Signature													
Visible	1	1			4	4		1	3				1
NIR	4	4			4			4	3				4
Thermal IR	2	4			2			4	4				3
μw	3	4			3			4	4				3
Temporal Spect. Sig.													
Visible	2	1			4			2	3				2
NIR	4	4			4			4	3				4
Thermal IR	2	4			2			4	4				3
μw	3	4			3			4	4				3
Thermal Radiance													
Thermal IR	2	4			1	3		4	4				4
μw	3	4			2	3		4	4				4
Multiaspect Sp. Sig.													
Visible	3	3			4	2		3	4				1
NIR	4	4			4	2		4	4				4
Thermal IR	4	4			4	4		4	4				4
μw	4	4			4	4		4	4				3
Scattering Cross Section													
μw - 1 band	4	4			4	1		4	3				3
μw - mult. bd.	4	4			4	1		4	3				3
Optical	4	4			4	3		2	3				3
Polarization Signature													
Visible	3	3			4	3		3	3				3
NIR	4	4			↓	3		4	3				3
Thermal IR	4	4			↓	4		4	4				3
μw	4	4			↓	3		4	3				3
Spatial Signature													
Visible	3	3			↓	3		4	3				4
NIR	4	4			↓	3		4	3				4
Thermal IR	4	4			↓	3		4	3				4
μw	4	4			↓	3		4	3				4

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	17C.4	17C.5	17C.6	17C.7	17C.8		18.1	18.2	18.3	18.4	18.5	18.6	18.7
Spect. Signature													
Visible	1	4	1	1	2		1	1	1	1	1	1	2
NIR	4	4	1	4	2		4	4	4	4	4	4	4
Thermal IR	4	2	1	4	2		4	4	4	4	4	4	4
μw	4	2	3	4	3		4	4	4	4	4	4	4
Temporal Spect. Sig.													
Visible	1	4	1	2	2		4	1	2	2	2	2	4
NIR	4	4	1	4	2		4	4	4	4	4	4	4
Thermal IR	4	4	1	4	2		4	4	4	4	4	4	4
μw	4	4	2	4	2		4	4	4	4	4	4	4
Thermal Radiance													
Thermal IR	4	1	1	4	2		4	4	4	4	4	4	4
μw	4	2	2	4	2		4	4	4	4	4	4	4
Multiaspect Sp. Sig.													
Visible	3	4	3	4	3		2	2	2	2	2	2	4
NIR	4	4	3	↓	3		4	4	4	4	4	4	4
Thermal IR	4	4	4	↓	4		4	4	4	4	4	4	4
μw	4	4	4	↓	3		4	4	4	4	4	4	4
Scattering Cross Section				↓									
μw - 1 band	4	4	4	↓	4		4	4	4	4	4	4	4
μw - mult. bd.	4	4	4	↓	4		4	4	4	4	4	4	4
Optical	4	4	3	↓	4		1	3	4	4	4	4	4
Polarization Signature													
Visible	3	4	3	3	3		3	3	3	3	3	3	3
NIR	4	4	3	4	3		4	4	4	4	4	4	4
Thermal IR	4	4	4	↓	4		4	4	4	4	4	4	4
μw	4	3	3	↓	3		4	4	4	4	4	4	4
Spatial Signature				↓									
Visible	3	4	1	↓	4		1	1	1	1	1	1	4
NIR	4	4	1	↓	4		1	1	1	1	1	1	4
Thermal IR	4	3	1	↓	4		3	3	3	3	3	3	4
μw	4	4	3	↓	4		4	4	4	4	4	4	4

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	19.1	19.2	19.3	19.4	19.5		20.1	20.2	20.3	20.4		21.1	21.2
Spect. Signature													
Visible	4	2	4	1	4		4	4	1			1	4
NIR	4	↓	↓	1	4		4	4	1			1	↓
Thermal IR	1	↓	↓	4	4		1	4	4			4	↓
μw	1	↓	↓	3	3		1	3	4			3	↓
Temporal Spect. Sig.													
Visible	4	↓	↓	2	4		4	4	2			2	↓
NIR	4	↓	↓	2	4		↓	4	2			2	↓
Thermal IR	4	↓	↓	2	4		↓	4	4			2	↓
μw	4	↓	↓	3	4		↓	4	4			3	↓
Thermal Radiance													
Thermal IR	1	↓	4	1	2		1	2	4			2	4
μw	1	↓	4	3	1		1	3	4			3	↓
Multiaspect Sp. Sig.													
Visible	4	4	3	3	4		4	4	3			4	↓
NIR	↓	↓	3	3	4		↓	4	3			4	↓
Thermal IR	↓	↓	4	4	4		↓	4	4			4	↓
μw	↓	↓	4	4	4		↓	4	4			4	↓
Scattering Cross Section													
μw - 1 band	↓	3	1	4	3		↓	3	4			3	3
μw - mult. bd.	↓	3	3	4	3		↓	3	4			3	3
Optical	↓	3	3	3	4		↓	4	3			3	3
Polarization Signature													
Visible	4	3	3	3	4		4	4	3			3	4
NIR	4	3	3	3	4		4	4	3			3	4
Thermal IR	4	4	4	4	4		4	4	4			4	4
μw	2	3	1	4	3		2	3	4			3	4
Spatial Signature													
Visible	4	3	1	1	4		4	4	4			1	1
NIR	4	3	1	1	4		4	4	4			1	1
Thermal IR	4	3	3	1	4		4	4	4			2	2
μw	4	3	3	2	4		4	4	4			3	3

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	21.3		22.1	22.2	22.3		23.1	23.2	23.3	23.4	23.5	23.6	23.7
Spect. Signature													
Visible	4		4	4	3			4					1
NIR	↓		4	↓	3			4					4
Thermal IR	↓		4	↓	3			1					4
μw	↓		3	↓	3			1					4
Temporal Spect. Sig.				↓									
Visible	3		4	↓	3			4					2
NIR	↓		↓	↓	3			4					4
Thermal IR	↓		↓	↓	3			2					4
μw	↓		↓	3	3			3					4
Thermal Radiance			↓										
Thermal IR	4		↓	4	3			1					4
μw	↓		↓	4	3			1					4
Multiaspect Sp. Sig.	↓		↓										
Visible	↓		↓	4	4			4					3
NIR	↓		↓	↓	↓			↓					4
Thermal IR	↓		↓	↓	↓			↓					4
μw	↓		↓	↓	↓			↓					4
Scattering Cross Section								↓					
μw - 1 band	3		3	3	3			↓					4
μw - mult. bd.	3		3	3	3			↓					4
Optical	3		4	4	3			↓					2
Polarization Signature													
Visible	4		4	4	3			4					3
NIR	↓		4	4	3			4					4
Thermal IR	↓		4	4	3			4					4
μw	↓		3	3	3			2					4
Spatial Signature	↓												
Visible	↓		4	4	3			4					4
NIR	↓		4		3			4					4
Thermal IR	↓		4		3			4					4
μw	↓		3		3			4					4

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	23.8	23.9	23.10	23.11	23.12	23.3	24.1	24.2	24.3	24.4		25.1	25.2
Spect. Signature													
Visible	4				2		2	2	2				
NIR	4				4		4	4	4				
Thermal IR	4				4		4	4	4				
μw	3				4		4	4	4				
Temporal Spect. Sig.													
Visible	4				1		2	2	2				
NIR	4				4		4	4	4				
Thermal IR	4				4		4	4	4				
μw	4				4		4	4	4				
Thermal Radiance													
Thermal IR	2				4		4	4	4				
μw	1				4		4	4	4				
Multiaspect Sp. Sig.													
Visible	4				3		3	3	3				
NIR	4				4		4	4	4				
Thermal IR	4				4		4	4	4				
μw	4				4		4	4	4				
Scattering Cross Section													
μw - 1 band	3				4		4	4	4				
μw - mult. bd.	3				4		↓	↓	↓				
Optical	4				2		↓	↓	↓				
Polarization Signature													
Visible	4				3		3	3	3				
NIR	4				4		4	4	4				
Thermal IR	4				4		4	4	4				
μw	3				4		4	4	4				
Spatial Signature													
Visible	4				4		3	3	3				
NIR	4				4		4	4	4				
Thermal IR	4				4		4	4	4				
μw	4				4		4	4	4				

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	25.3		26.1	26.2	26.3		27.1	27.2		28.1	28.2	
Spect. Signature												
Visible			1	1	1		1	2		1	1	
NIR			4	2	4		1	2		1	1	
Thermal IR			4	4	4		2	2		2	2	
μw			4	4	4		3	3		3	3	
Temporal Spect. Sig.												
Visible			2	1	4		2	1		2	2	
NIR			4	2	↓		2	1		2	2	
Thermal IR			4	4	↓		2	1		2	2	
μw			4	4	↓		3	3		3	3	
Thermal Radiance					↓							
Thermal IR			4	4	↓		2	4		2	2	
μw			4	4	↓		3	4		3	3	
Multiaspect Sp. Sig.												
Visible			3	3	2		4	4		4	4	
NIR			4	3	4		4	↓		↓	↓	
Thermal IR			4	4	4		4	↓		↓	↓	
μw			4	4	4		4	↓		↓	↓	
Scattering Cross Section								↓				
μw - 1 band			4	4	4		3	↓		3	3	
μw - mult. bd.			4	4	4		3	↓		3	3	
Optical			2	4	1		3	↓		3	3	
Polarization Signature												
Visible			3	3	3		4	3		4	3	
NIR			4	3	4		↓	3		4	3	
Thermal IR			4	4	4		↓	4		4	3	
μw			4	4	4		↓	3		3	3	
Spatial Signature												
Visible			4	1	1		1	3		1	1	
NIR			4	1	1		1	3		1	1	
Thermal IR			4	4	3		2	3		2	2	
μw			4	4	4		2	3		3	3	

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	1.1	1.2	1.3	1.4	1.5		2.1	2.2	2.3	2.4	2.5	
Spect. Signature												
Visible	4	4	4	3	1		3	3	3	2	?	
NIR	2	3	3	3	1		3	3	3	2		
Thermal IR	1	1	3	3	2		3	3	3	4		
μw	3	3	3	3	3		3	3	3	3		
Temporal Spect. Sig.												
Visible	4	4	4	3	2		3	3	3	2		
NIR	2	2	3	3	2		3	3	3	4		
Thermal IR	2	2	3	3	2		3	3	3	4		
μw	3	3	3	3	3		3	3	3	3		
Thermal Radiance												
Thermal IR	2	3	3	3	2		3	3	3	2		
μw	3	3	3	3	3		3	3	3	3		
Multiaspect Sp. Sig.												
Visible	4	4	4	3	2		3	3	3	2		
NIR	3	3	3	3	2		3	3	3	2		
Thermal IR	3	3	3	3	3		3	3	3	4		
μw	3	3	3	3	3		3	3	3	3		
Scattering Cross Section												
μw - 1 band	4	4	4	4	4		4	4	4	3		
μw - mult. bd.	4	4	4	4	4		4	4	4	3		
Optical	4	4	4	4	4		4	4	4	3		
Polarization Signature												
Visible	4	4	4	4	4		4	4	4	4		
NIR	4	4	4	4	4		4	4	4	4		
Thermal IR	4	4	4	4	4		4	4	4	4		
μw	4	4	4	4	4		4	4	4	4		
Spatial Signature												
Visible	4	4	4	3	2		4	4	4	4		
NIR	4	4	4	3	2		4	4	4	4		
Thermal IR	4	4	4	3	3		4	4	4	4		
μw	4	4	4	3	3		4	4	4	4		

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	3.1	3.2	3.3	3.4	3.5		4.1	4.2	4.3	4.4	4.5	
Spect. Signature												
Visible	1	3	1	2	? ↓		2	3	2	2	? ↓	
NIR	3	3	3	2			3	3	3	2		
Thermal IR	4	4	4	4			4	4	4	4		
μw	3	3	3	3			3	3	3	3		
Temporal Spect. Sig.												
Visible	2	3	2	2			2	3	2	2		
NIR	3	3	3	2			3	3	3	2		
Thermal IR	4	4	4	4			4	4	4	4		
μw	3	3	3	3			3	3	3	3		
Thermal Radiance												
Thermal IR	4	4	4	2			4	4	4	2		
μw	3	3	3	3			3	3	3	3		
Multiaspect Sp. Sig.												
Visible	3	3	3	2			3	3	3	2		
NIR	3	3	3	2			3	3	3	2		
Thermal IR	4	4	4	4			4	4	4	4		
μw	3	3	3	3			3	3	3	3		
Scattering Cross Section												
μw - 1 band	4	4	4	3			4	4	4	3		
μw - mult. bd.	4	4	4	3			4	4	4	3		
Optical	4	4	4	3			4	4	4	3		
Polarization Signature												
Visible	4	4	4	4			4	4	4	4		
NIR	4	4	4	4			4	4	4	4		
Thermal IR	4	4	4	4			4	4	4	4		
μw	4	4	4	4			4	4	4	4		
Spatial Signature												
Visible	4	4	4	2			4	4	4	2		
NIR	4	4	4	2			4	4	4	2		
Thermal IR	4	4	4	3			4	4	4	3		
μw	4	4	4	3			4	4	4	3		

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	5.1	5.2	5.3	5.4	5.5		6.1	6.2	6.3	6.4	6.5	
Spect. Signature												
Visible	1	2	1	2	?		1	3	1	?	?	
NIR	4	4	4	2	↓		3	3	3	↓	↓	
Thermal IR	1	2	1	4			2	3	2			
μw	2	2	2	3			3	3	3			
Temporal Spect. Sig.												
Visible	2	2	2	2			2	3	2			
NIR	4	4	4	2			3	3	3			
Thermal IR	2	2	2	4			3	3	3			
μw	2	2	2	3			3	3	3			
Thermal Radiance												
Thermal IR	3	3	3	2			3	3	3			
μw	3	3	3	3			3	3	3			
Multiaspect Sp. Sig.												
Visible	3	3	3	2			3	3	3			
NIR	4	4	4	2			3	3	3			
Thermal IR	3	3	3	3			3	3	3			
μw	3	3	3	3			3	3	3			
Scattering Cross Section												
μw - 1 band	4	4	4	3			4	4	4			
μw - mult. bd.	4	4	4	3			4	4	4			
Optical	4	4	4	3			4	4	4			
Polarization Signature												
Visible	4	4	4	4			4	4	4			
NIR	4	4	4	4			4	4	4			
Thermal IR	4	4	4	4			4	4	4			
μw	4	4	4	4			4	4	4			
Spatial Signature												
Visible	4	4	4	2			4	4	4			
NIR	4	4	4	2			4	4	4			
Thermal IR	4	4	4	3			4	4	4			
μw	4	4	4	3			4	4	4			

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	7.1	7.2	7.3	7.4	7.5		8.1	8.2	8.3	8.4	8.5	
Spect. Signature												
Visible	3	3	3	3	?		3	3	3	3	?	
NIR	3	3	3	3	↓		↓	↓	↓	↓	↓	
Thermal IR	3	3	3	3	↓		↓	↓	↓	↓	↓	
μw	3	3	3	3	↓		↓	↓	↓	↓	↓	
Temporal Spect. Sig.					↓		↓	↓	↓	↓	↓	
Visible	3	3	3	3	↓		↓	↓	↓	↓	↓	
NIR	3	3	3	3	↓		↓	↓	↓	↓	↓	
Thermal IR	3	3	3	3	↓		↓	↓	↓	↓	↓	
μw	3	3	3	3	↓		↓	↓	↓	↓	↓	
Thermal Radiance					↓		↓	↓	↓	↓	↓	
Thermal IR	3	3	3	3	↓		↓	↓	↓	↓	↓	
μw	3	3	3	3	↓		↓	↓	↓	↓	↓	
Multiaspect Sp. Sig.					↓		↓	↓	↓	↓	↓	
Visible	3	3	3	3	↓		↓	↓	↓	↓	↓	
NIR	3	3	3	3	↓		↓	↓	↓	↓	↓	
Thermal IR	3	3	3	3	↓		↓	↓	↓	↓	↓	
μw	3	3	3	3	↓		↓	↓	↓	↓	↓	
Scattering Cross Section					↓						↓	
μw - 1 band	4	4	4	3	↓		4	4	4	4	↓	
μw - mult. bd.	4	4	4	3	↓		↓	↓	↓	↓	↓	
Optical	4	4	4	3	↓		↓	↓	↓	↓	↓	
Polarization Signature					↓		↓	↓	↓	↓	↓	
Visible	4	4	4	4	↓		↓	↓	↓	↓	↓	
NIR	4	4	4	4	↓		↓	↓	↓	↓	↓	
Thermal IR	4	4	4	4	↓		↓	↓	↓	↓	↓	
μw	4	4	4	4	↓		↓	↓	↓	↓	↓	
Spatial Signature					↓		↓	↓	↓	↓	↓	
Visible	4	4	4	3	↓		↓	↓	↓	↓	↓	
NIR	4	4	4	3	↓		↓	↓	↓	↓	↓	
Thermal IR	4	4	4	3	↓		↓	↓	↓	↓	↓	
μw	4	4	4	3	↓		↓	↓	↓	↓	↓	

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	9.1	9.2	9.3	9.4	9.5		10.1	10.2	10.3	10.4	10.5	
Spect. Signature												
Visible	3	3	3	3	?		4	4	4	3	?	
NIR	↓	↓	↓	↓	↓		3	3	3	3	↓	
Thermal IR	↓	↓	↓	↓	↓		3	3	3	4	↓	
μw	↓	↓	↓	↓	↓		3	3	3	3	↓	
Temporal Spect. Sig.												
Visible	↓	↓	↓	↓	↓		4	4	4	3	↓	
NIR	↓	↓	↓	↓	↓		3	3	3	3	↓	
Thermal IR	↓	↓	↓	↓	↓		3	3	3	4	↓	
μw	↓	↓	↓	↓	↓		3	3	3	3	↓	
Thermal Radiance												
Thermal IR	↓	↓	↓	↓	↓		3	3	3	3	↓	
μw	↓	↓	↓	↓	↓		3	3	3	3	↓	
Multiaspect Sp. Sig.												
Visible	↓	↓	↓	↓	↓		4	4	4	3	↓	
NIR	↓	↓	↓	↓	↓		3	3	3	3	↓	
Thermal IR	↓	↓	↓	↓	↓		3	3	3	4	↓	
μw	↓	↓	↓	↓	↓		3	3	3	3	↓	
Scattering Cross Section												
μw - 1 band	4	4	4	4	↓		4	4	4	3	↓	
μw - mult. bd.	↓	↓	↓	↓	↓		4	4	4	3	↓	
Optical	↓	↓	↓	↓	↓		4	4	4	3	↓	
Polarization Signature												
Visible	↓	↓	↓	↓	↓		4	4	4	4	↓	
NIR	↓	↓	↓	↓	↓		4	4	4	4	↓	
Thermal IR	↓	↓	↓	↓	↓		4	4	4	4	↓	
μw	↓	↓	↓	↓	↓		4	4	4	4	↓	
Spatial Signature												
Visible	↓	↓	↓	↓	↓		4	4	4	3	↓	
NIR	↓	↓	↓	↓	↓		4	4	4	3	↓	
Thermal IR	↓	↓	↓	↓	↓		4	4	4	3	↓	
μw	↓	↓	↓	↓	↓		4	4	4	3	↓	

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	11.1	11.2	11.3	11.4	11.5		12.1	12.2	12.3	12.4	12.5	
Spect. Signature												
Visible	3	3	3	?	?		3	3	3	2	?	
NIR	↓	↓	↓	↓	↓		↓	↓	↓	2	↓	
Thermal IR	↓	↓	↓	↓	↓		↓	↓	↓	4	↓	
μw	↓	↓	↓	↓	↓		↓	↓	↓	3	↓	
Temporal Spect. Sig.	↓	↓	↓	↓	↓		↓	↓	↓		↓	
Visible	↓	↓	↓	↓	↓		↓	↓	↓	2	↓	
NIR	↓	↓	↓	↓	↓		↓	↓	↓	2	↓	
Thermal IR	↓	↓	↓	↓	↓		↓	↓	↓	4	↓	
μw	↓	↓	↓	↓	↓		↓	↓	↓	3	↓	
Thermal Radiance	↓	↓	↓	↓	↓		↓	↓	↓		↓	
Thermal IR	↓	↓	↓	↓	↓		↓	↓	↓	2	↓	
μw	↓	↓	↓	↓	↓		↓	↓	↓	3	↓	
Multiaspect Sp. Sig.	↓	↓	↓	↓	↓		↓	↓	↓		↓	
Visible	↓	↓	↓	↓	↓		↓	↓	↓	2	↓	
NIR	↓	↓	↓	↓	↓		↓	↓	↓	2	↓	
Thermal IR	↓	↓	↓	↓	↓		↓	↓	↓	4	↓	
μw	↓	↓	↓	↓	↓		↓	↓	↓	3	↓	
Scattering Cross Section	4	4	4	↓	↓		4	4	4		↓	
μw - 1 band	↓	↓	↓	↓	↓		↓	↓	↓	3	↓	
μw - mult. bd.	↓	↓	↓	↓	↓		↓	↓	↓	3	↓	
Optical	↓	↓	↓	↓	↓		↓	↓	↓	3	↓	
Polarization Signature	↓	↓	↓	↓	↓		↓	↓	↓		↓	
Visible	↓	↓	↓	↓	↓		↓	↓	↓	4	↓	
NIR	↓	↓	↓	↓	↓		↓	↓	↓	4	↓	
Thermal IR	↓	↓	↓	↓	↓		↓	↓	↓	4	↓	
μw	↓	↓	↓	↓	↓		↓	↓	↓	4	↓	
Spatial Signature	↓	↓	↓	↓	↓		↓	↓	↓		↓	
Visible	↓	↓	↓	↓	↓		↓	↓	↓	2	↓	
NIR	↓	↓	↓	↓	↓		↓	↓	↓	2	↓	
Thermal IR	↓	↓	↓	↓	↓		↓	↓	↓	4	↓	
μw	↓	↓	↓	↓	↓		↓	↓	↓	3	↓	

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	13.1	13.2	14.1	14.2	15.1	15.2	15.3	16.1	16.2
Spect. Signature									
Visible	2	3	4	4	2	2	2	4	4
NIR	1	3	2	2	2	2	2	↓	↓
Thermal IR	1	1	2	2	4	4	4		
μw	2	2	3	3	3	3	3		
Temporal Spect. Sig.									
Visible	2	3	4	4	2	2	2		
NIR	2	3	2	2	2	2	2		
Thermal IR	2	2	2	2	4	4	4		
μw	2	2	3	3	3	3	3		
Thermal Radiance									
Thermal IR	2	4	1	1	4	4	4		
μw	3	4	3	3	3	3	3		
Multiaspect Sp. Sig.									
Visible	3	3	4	4	3	3	3		
NIR	3	3	4	4	3	3	3		
Thermal IR	3	3	4	4	4	4	4		
μw	3	3	4	4	3	3	3		
Scattering Cross Section									
μw - 1 band	3	3	4	4	3	3	3		
μw - mult. bd.	3	3	4	4	3	3	3		
Optical	2	2	4	4	1	3	3		
Polarization Signature									
Visible	3	3	4	4	2	2	3		
NIR	3	3	4	4	2	2	3		
Thermal IR	3	3	4	4	4	4	4		
μw	3	3	4	4	3	3	3		
Spatial Signature									
Visible	4	4	4	4	2	4	4		
NIR	4	4	4	4	2	4	4		
Thermal IR	4	4	4	1	4	4	4		
μw	4	4	4	4	3	4	4	↓	↓

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	16.3	16.4	17.1	17.2	18.1	18.2	19.1	19.2	19.3
Spect. Signature									
Visible	4	4	4	4	4	4	3	3	3
NIR	↓	↓	4	↓	↓	↓	↓	↓	↓
Thermal IR	↓	↓	2	↓	↓	↓	↓	↓	↓
μw	↓	↓	2	↓	↓	↓	↓	↓	↓
Temporal Spect. Sig.									
Visible	↓	↓	4	↓	↓	↓	↓	↓	↓
NIR	↓	↓	4	↓	↓	↓	↓	↓	↓
Thermal IR	↓	↓	2	↓	↓	↓	↓	↓	↓
μw	↓	↓	2	↓	↓	↓	↓	↓	↓
Thermal Radiance									
Thermal IR	↓	↓	1	↓	↓	↓	↓	↓	↓
μw	↓	↓	2	↓	↓	↓	↓	↓	↓
Multiaspect Sp. Sig.									
Visible	↓	↓	4	↓	↓	↓	↓	↓	↓
NIR	↓	↓	4	↓	↓	↓	↓	↓	↓
Thermal IR	↓	↓	4	↓	↓	↓	↓	↓	↓
μw	↓	↓	4	↓	↓	↓	↓	↓	↓
Scattering Cross Section									
μw - 1 band	↓	↓	4	↓	↓	↓	↓	↓	↓
μw - mult. bd.	↓	↓	4	↓	↓	↓	↓	↓	↓
Optical	↓	↓	4	↓	↓	↓	↓	↓	↓
Polarization Signature									
Visible	↓	↓	4	↓	↓	↓	4	4	4
NIR	↓	↓	4	↓	↓	↓	↓	↓	↓
Thermal IR	↓	↓	4	↓	↓	↓	↓	↓	↓
μw	↓	↓	4	↓	↓	↓	↓	↓	↓
Spatial Signature									
Visible	↓	↓	4	↓	↓	↓	↓	↓	↓
NIR	↓	↓	4	↓	↓	↓	↓	↓	↓
Thermal IR	↓	↓	2	↓	↓	↓	↓	↓	↓
μw	↓	↓	2	↓	↓	↓	↓	↓	↓

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	19.4	19.5	19.6		20.1	20.2	20.3	20.4		21.1	21.2	21.3
Spect. Signature												
Visible	2	?	4		1	1	1	2		3	3	3
NIR	2	↓	↓		2	2	2	2		↓	↓	↓
Thermal IR	4	↓	↓		2	2	2	3		↓	↓	↓
μw	3	↓	↓		2	2	3	3		↓	↓	↓
Temporal Spect. Sig.												
Visible	2	↓	↓		2	2	2	2		↓	↓	↓
NIR	2	↓	↓		2	2	2	2		↓	↓	↓
Thermal IR	4	↓	↓		2	2	2	3		↓	↓	↓
μw	3	↓	↓		2	2	3	3		↓	↓	↓
Thermal Radiance												
Thermal IR	2	↓	↓		2	2	2	4		↓	↓	↓
μw	3	↓	↓		3	3	3	4		↓	↓	↓
Multiaspect Sp. Sig.												
Visible	2	↓	↓		2	2	3	3		↓	↓	↓
NIR	2	↓	↓		3	3	3	3		↓	↓	↓
Thermal IR	4	↓	↓		4	4	4	4		↓	↓	↓
μw	3	↓	↓		3	3	4	3		↓	↓	↓
Scattering Cross Section												
μw - 1 band	3	↓	↓		2	2	3	3		↓	↓	↓
μw - mult. bd.	3	↓	↓		2	2	3	3		↓	↓	↓
Optical	3	↓	↓		3	3	3	3		↓	↓	↓
Polarization Signature												
Visible	4	↓	↓		3	3	4	3		4	4	4
NIR	4	↓	↓		3	3	4	3		↓	↓	↓
Thermal IR	4	↓	↓		3	3	4	3		↓	↓	↓
μw	4	↓	↓		3	3	4	3		↓	↓	↓
Spatial Signature												
Visible	2	↓	↓		2	1	4	3		↓	↓	↓
NIR	2	↓	↓		2	1	4	3		↓	↓	↓
Thermal IR	4	↓	↓		2	1	4	3		↓	↓	↓
μw	3	↓	↓		3	3	4	4		↓	↓	↓

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	21.4	21.5	21.6		22.1	22.2	22.3	22.4	22.5	22.6		23.1
Spect. Signature												
Visible	3	2	?		3	3	3	3	2	2		4
NIR	↓	2	↓		↓	↓	↓	↓	2	2		↓
Thermal IR	↓	4	↓		↓	↓	↓	↓	4	4		↓
µw	↓	3	↓		↓	↓	↓	↓	3	3		↓
Temporal Spect. Sig.	↓		↓		↓	↓	↓	↓				↓
Visible	↓	2	↓		↓	↓	↓	↓	2	2		↓
NIR	↓	2	↓		↓	↓	↓	↓	2	2		↓
Thermal IR	↓	4	↓		↓	↓	↓	↓	4	4		↓
µw	↓	3	↓		↓	↓	↓	↓	3	3		↓
Thermal Radiance	↓		↓		↓	↓	↓	↓				↓
Thermal IR	↓	3	↓		↓	↓	↓	↓	2	2		↓
µw	↓	3	↓		↓	↓	↓	↓	3	3		↓
Multiaspect Sp. Sig.	↓		↓		↓	↓	↓	↓				↓
Visible	↓	2	↓		↓	↓	↓	↓	2	2		↓
NIR	↓	2	↓		↓	↓	↓	↓	2	2		↓
Thermal IR	↓	3	↓		↓	↓	↓	↓	3	3		↓
µw	↓	3	↓		↓	↓	↓	↓	3	3		↓
Scattering Cross Section	↓		↓		↓	↓	↓	↓				↓
µw - 1 band	↓	3	↓		↓	↓	↓	↓	3	3		↓
µw - mult. bd.	↓	3	↓		↓	↓	↓	↓	3	3		↓
Optical	↓	3	↓		↓	↓	↓	↓	3	3		↓
Polarization Signature			↓									↓
Visible	4	4	↓		4	4	4	4	4	4		↓
NIR	↓	↓	↓		↓	↓	↓	↓	↓	↓		↓
Thermal IR	↓	↓	↓		↓	↓	↓	↓	↓	↓		↓
µw	↓	↓	↓		↓	↓	↓	↓	↓	↓		↓
Spatial Signature	↓		↓		↓	↓	↓	↓				↓
Visible	↓	2	↓		↓	↓	↓	↓	2	2		↓
NIR	↓	2	↓		↓	↓	↓	↓	2	2		↓
Thermal IR	↓	3	↓		↓	↓	↓	↓	3	3		↓
µw	↓	3	↓		↓	↓	↓	↓	3	3		↓

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	23.2	23.3	23.4	23.5		24.1	24.2	24.3	24.4		25.1	25.2
Spect. Signature												
Visible	4	4	4	4		3	3	3	4		4	4
NIR	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
Thermal IR	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
μw	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
Temporal Spect. Sig.	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
Visible	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
NIR	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
Thermal IR	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
μw	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
Thermal Radiance	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
Thermal IR	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
μw	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
Multiaspect Sp. Sig.	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
Visible	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
NIR	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
Thermal IR	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
μw	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
Scattering Cross Section	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
μw - 1 band	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
μw - mult. bd.	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
Optical	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
Polarization Signature	↓	↓	↓	↓					↓		↓	↓
Visible	↓	↓	↓	↓		4	4	4	↓		↓	↓
NIR	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
Thermal IR	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
μw	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
Spatial Signature	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
Visible	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
NIR	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
Thermal IR	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓
μw	↓	↓	↓	↓		↓	↓	↓	↓		↓	↓

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	25.3	25.4		26.1	26.2	26.3	26.4	26.5	26.6		27.1	27.2
Spect. Signature												
Visible	4	4		4	4	4	4	4	4		4	4
NIR	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
Thermal IR	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
μw	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
Temporal Spect. Sig.	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
Visible	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
NIR	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
Thermal IR	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
μw	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
Thermal Radiance	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
Thermal IR	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
μw	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
Multiaspect Sp. Sig.	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
Visible	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
NIR	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
Thermal IR	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
μw	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
Scattering Cross Section	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
μw - 1 band	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
μw - mult. bd.	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
Optical	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
Polarization Signature	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
Visible	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
NIR	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
Thermal IR	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
μw	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
Spatial Signature	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
Visible	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
NIR	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
Thermal IR	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓
μw	↓	↓		↓	↓	↓	↓	↓	↓		↓	↓

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	28.1	28.2	28.3	28.4	28.5	28.6	28.8	29.1		30.1	30.2	30.3	30.4
Spect. Signature													
Visible	1	2	3	3	3	1	1	4		1	2	3	
NIR	2	4	4	4	4	4	4			4	4	4	
Thermal IR	4	4	4	4	4	4	4			4	4	4	
μw	4	4	4	4	4	4	4			4	4	4	
Temporal Spect. Sig.													
Visible	2	2	3	3	3	2	2			2	2	3	
NIR	2	4	4	4	4	4	4			4	4	4	
Thermal IR	4	4	4	4	4	4	4			4	4	4	
μw	4	4	4	4	4	4	4			4	4	4	
Thermal Radiance													
Thermal IR	2	4	4	4	3	3	4			3	3	4	
μw	4	4	4	4	4	4	4			4	4	4	
Multiaspect Sp. Sig.													
Visible	3	3	3	3	3	3	3			3	3	3	
NIR	4	4	4	4	4	4	4			4	4	4	
Thermal IR	4	4	4	4	4	4	4			4	4	4	
μw	4	4	4	4	4	4	4			4	4	4	
Scattering Cross Section													
μw - 1 band	4	4	4	4	4	4	4			4	4	4	
μw - mult. bd.	4	4	4	4	4	4	4			4	4	4	
Optical	3	3	3	3	3	3	3			3	3	4	
Polarization Signature													
Visible	3	3	3	3	3	3	3			3	3	4	
NIR	4	4	4	4	4	4	4			4	4		
Thermal IR	4	4	4	4	4	4	4			4	4		
μw	4	4	4	4	4	4	4			4	4		
Spatial Signature													
Visible	1	4	4	4	3	3	3			3	3		
NIR	4	4	4	4	4	4	4			4	4		
Thermal IR	2	4	4	4	4	4	4			4	4		
μw	4	4	4	4	4	4	4	↓		4	4	↓	

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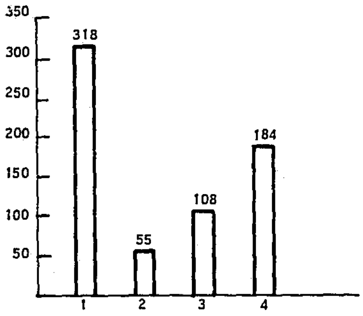
	31.1	31.2	31.3	31.4	32.1	32.2	32.3	32.4	33.1	33.2	33.3	
Spect. Signature												
Visible	1	1	3		1	1	3		3	3	3	
NIR	2	4	4		2	2	3		↓	↓	↓	
Thermal IR	4	4	4		4	4	4		↓	↓	↓	
μw	4	4	4		4	4	4		↓	↓	↓	
Temporal Spect. Sig.												
Visible	2	2	3		2	2	3		↓	↓	↓	
NIR	2	4	4		2	2	3		↓	↓	↓	
Thermal IR	4	4	4		4	4	4		↓	↓	↓	
μw	4	4	4		4	4	4		↓	↓	↓	
Thermal Radiance												
Thermal IR	2	4	4		3	3	4		↓	↓	↓	
μw	3	4	4		3	3	4		↓	↓	↓	
Multiaspect Sp. Sig.												
Visible	3	3	3		3	3	3		↓	↓	↓	
NIR	3	4	4		3	3	3		↓	↓	↓	
Thermal IR	4	4	4		4	4	4		↓	↓	↓	
μw	4	4	4		4	4	4		↓	↓	↓	
Scattering Cross Section												
μw - 1 band	4	4	4		4	4	4		↓	↓	↓	
μw - mult. bd.	4	4	4		4	4	4		↓	↓	↓	
Optical	3	3	3		3	3	3		↓	↓	↓	
Polarization Signature												
Visible	3	3	3		3	3	3		4	4	4	
NIR	4	4	4		4	4	4		↓	↓	↓	
Thermal IR	4	4	4		4	4	4		↓	↓	↓	
μw	4	4	4		4	4	4		↓	↓	↓	
Spatial Signature												
Visible	3	3	3		3	3	3		↓	↓	↓	
NIR	4	4	4		3	3	3		↓	↓	↓	
Thermal IR	4	4	4		4	4	4		↓	↓	↓	
μw	4	4	4		4	4	4		↓	↓	↓	

DISCIPLINE - Environmental Quality

	34.1	34.2	34.3		35.1	35.2		36.1	36.2	36.3	36.4	36.5
Spect. Signature												
Visible	2	4	4		1	1		4	4	4	4	4
NIR	2	4	↓		1	1		↓	↓	↓	↓	↓
Thermal IR	4	4	↓		2	4		↓	↓	↓	↓	↓
μw	3	3	↓		3	4		↓	↓	↓	↓	↓
Temporal Spect. Sig.												
Visible	2	4	↓		2	2		↓	↓	↓	↓	↓
NIR	2	4	↓		2	2		↓	↓	↓	↓	↓
Thermal IR	4	4	↓		2	4		↓	↓	↓	↓	↓
μw	3	3	↓		3	4		↓	↓	↓	↓	↓
Thermal Radiance												
Thermal IR	2	3	↓		2	2		↓	↓	↓	↓	↓
μw	3	3	↓		3	3		↓	↓	↓	↓	↓
Multiaspect Sp. Sig.												
Visible	4	4	↓		4	4		↓	↓	↓	↓	↓
NIR	4	↓	↓		4	4		↓	↓	↓	↓	↓
Thermal IR	4	↓	↓		4	4		↓	↓	↓	↓	↓
μw	4	↓	↓		4	4		↓	↓	↓	↓	↓
Scattering Cross Section												
μw - 1 band	4	↓	↓		3	3		↓	↓	↓	↓	↓
μw - mult. bd.	4	↓	↓		3	3		↓	↓	↓	↓	↓
Optical	4	↓	↓		3	3		↓	↓	↓	↓	↓
Polarization Signature												
Visible	4	↓	↓		4	4		↓	↓	↓	↓	↓
NIR	4	↓	↓		↓	↓		↓	↓	↓	↓	↓
Thermal IR	4	↓	↓		↓	↓		↓	↓	↓	↓	↓
μw	4	↓	↓		↓	↓		↓	↓	↓	↓	↓
Spatial Signature												
Visible	2	↓	↓		2	3		↓	↓	↓	↓	↓
NIR	3	↓	↓		2	3		↓	↓	↓	↓	↓
Thermal IR	3	↓	↓		2	3		↓	↓	↓	↓	↓
μw	3	↓	↓		3	3		↓	↓	↓	↓	↓

DISCIPLINE - Environmental Quality

	37.1	37.2		38.1								
Spect. Signature												
Visible	2	1		1								
NIR	2	1		1								
Thermal IR	4	4		4								
μw	3	3		3								
Temporal Spect. Sig.												
Visible	2	2		2								
NIR	2	2		2								
Thermal IR	4	4		4								
μw	3	3		3								
Thermal Radiance												
Thermal IR	3	3		2								
μw	3	3		3								
Multiaspect Sp. Sig.												
Visible	3	4		4								
NIR	3	4		4								
Thermal IR	4	4		4								
μw	4	4		4								
Scattering Cross Section												
μw - 1 band	3	3		3								
μw - mult. bd.	3	3		3								
Optical	3	3		3								
Polarization Signature												
Visible	4	4		3								
NIR	↓	4		4								
Thermal IR		4		4								
μw		4		3								
Spatial Signature												
Visible	2	1		1								
NIR	2	1		1								
Thermal IR	3	3		2								
μw	3	3		3								



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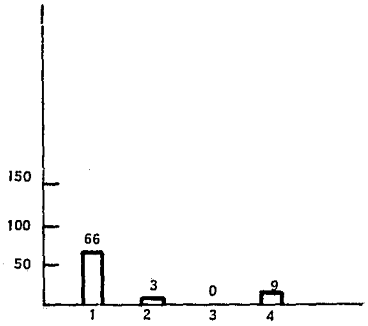

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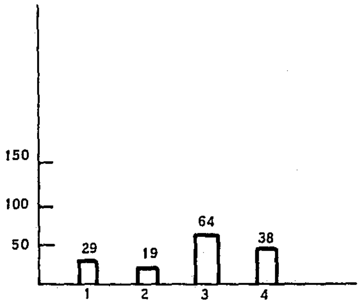

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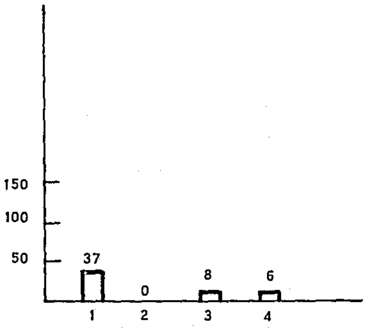

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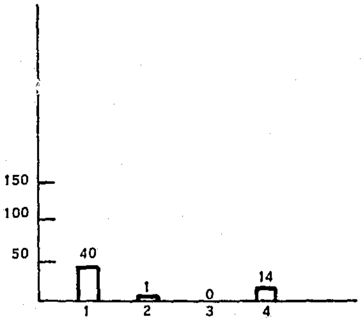
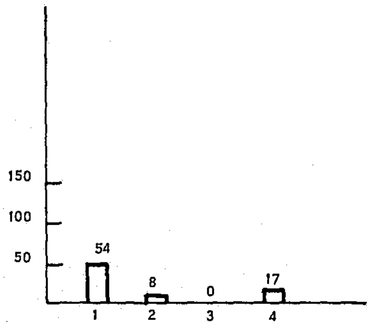


GEOGRAPHY



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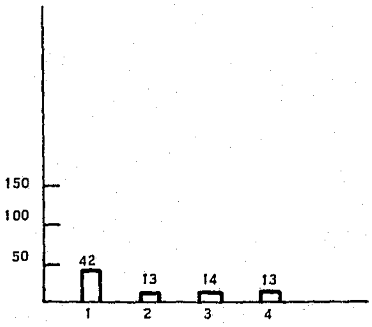

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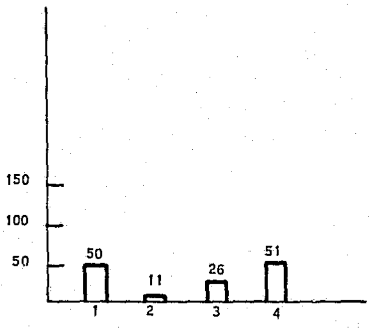
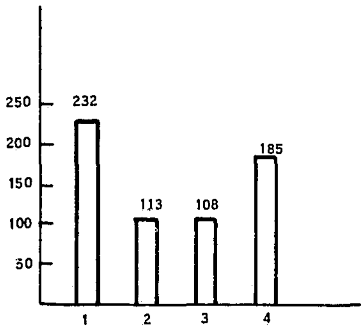


OCEANOGRAPHY



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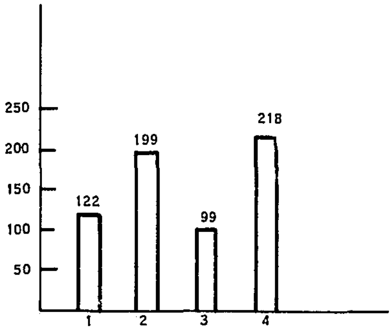
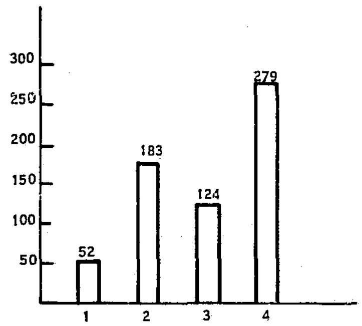
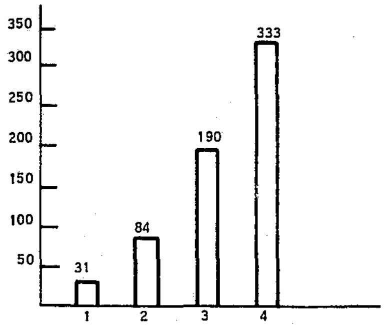


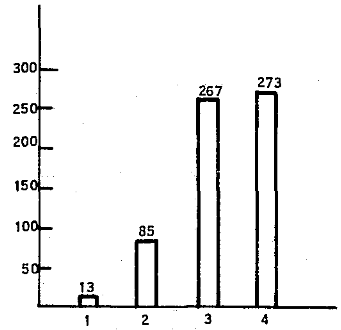
TEMPORAL SPECTRAL SIGNATURE



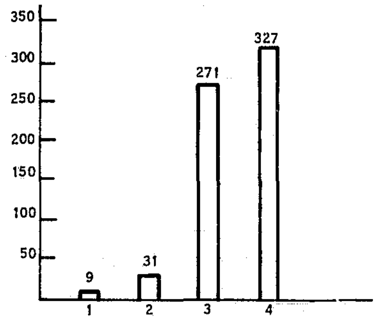
THERMAL RADIANCE



MULTIASPECT SIGNATURE



SCATTERING CROSS SECTION



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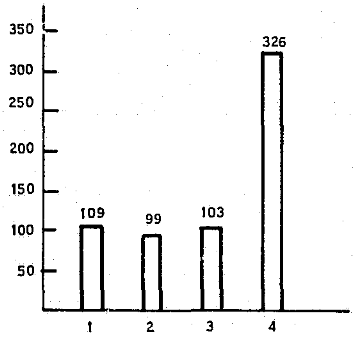
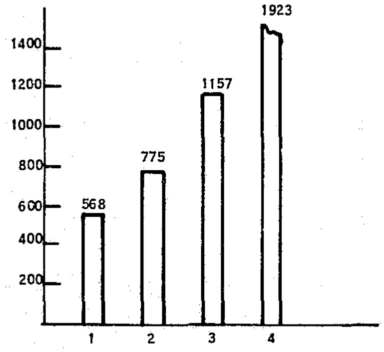


SPATIAL SIGNATURE



SUMMARY

APPENDIX B

ACTIVE OPTICAL SENSING OF THE ATMOSPHERE AND OCEAN

The remote optical measurement of atmospheric properties has been made practical by the development of pulsed lasers. Pulsed solid state lasers have been made with single wavelength outputs of > 10 joules lasting < 50 ns, while flashlamp-pulsed liquid dye lasers have been made with tunable outputs to ~ 10 joules lasting ~ 1000 ns. Such an optical source permits the construction of a laser radar or "lidar" (Light Detection and Ranging) system which is powerful and sensitive enough to measure back-scattering from the atmosphere to ranges of many miles and with range resolutions to < 3m if desired.

Basically a lidar system consists of a laser which emits a short pulse of high power light, plus a coaxial or adjacent parallel telescope which receives the light backscattered from the laser pulse by all the constituents in its path. This backscattered light is focused at a field of view-limiting aperture and then often recollimated before passing through a wavelength-selecting device to a fast response radiation detector. The brief laser light pulse is also short in length, such that range resolution is possible. Normally, the receiver field of view and alignment are such that the entire laser beam is viewed by the detector for all ranges of interest.

In the natural atmosphere, the emitted laser pulses will undergo Mie (aerosol) scattering, Rayleigh scattering, Raman scattering, and resonance Raman and/or resonance fluorescence. Both the Mie and Rayleigh processes scatter at the incident (laser) wavelength with scatter cross sections, typically 10^{-8} to 10^{-27} cm^2/sr and 10^{-27} cm^2/sr, respectively. Raman scattered radiation is shifted in wavelength by amounts which are characteristic of the scattering molecule, with cross sections of 10^{-30} cm^2/sr. The theoretical and experimental understanding of molecular resonance Raman vs. resonance fluorescence effects has not been reconciled; therefore, the practical utilization of such effects has not yet been fully proven for lidar measurements.

RAYLEIGH/MIE SCATTERING

The light emitted from a laser will be backscattered by both the gaseous molecules in the atmosphere (Rayleigh scattering) and by suspended particles (Mie scattering), of all types, including dust, small droplets, ice crystals, etc. The intensity of the backscattered laser signal is a function of the total mass concentration involved. Since both the Rayleigh and Mie scattered signals are at the incident light wavelength, it is difficult to separate the return from the gaseous atmosphere vs. the aerosol return. In cases where there is an obvious discontinuous and highly variable return, the magnitude of the larger Mie scattered signal above the background Rayleigh return can be determined especially if the atmospheric density can be estimated fairly closely. However, the Mie return itself does not yield a unique solution to question of the size and number density of the scatterers. However, the occurrence of significant concentrations of dust, water droplets, or ice crystals are fairly easily seen in lidar returns. In regions of the atmosphere fairly free of aerosols, it is possible to relate the backscattered signal simply to the Rayleigh scattered energy and hence to atmospheric density. This is always a somewhat uncertain measurement due to the high variability - both in time and space - of atmospheric aerosols.

The Mie scattered signal is a function of the wavelength being used as well as of the optical characteristics and size of the scatterers. In order to measure the particle size spectrum and number density of an aerosol target or cloud, multiple frequency lidar systems are being considered. Even a dual frequency measurement would be useful in deriving the desired information.

Simple lidar systems are also being considered for use as altimeters for very accurate measurements of the shape of the ocean surface. With the very short pulse lengths that can be generated and the accuracy achievable in gating circuits, very accurate, high resolution measurements can be made of the distance between the water surface and an aircraft or satellite platform.

DIFFERENTIAL ABSORPTION

Any time a lidar system emits and/or the radiation is subsequently scattered at a wavelength corresponding to absorption by an atmospheric or pollutant gas, the loss of energy from the received backscatter signal is a function of the absorption co-efficient and the integrated (total) amount of absorbing gas between lidar and scatterer. The magnitude of this integrated absorption effect is most easily determined by making a similar measurement at an adjacent wavelength where the absorption co-efficient is zero or at least significantly less.

For greater flexibility in application, a differential absorption lidar will usually employ a fixed frequency laser, such as a ruby, and a tunable laser, such as a dye laser. The output of the fixed frequency laser can be frequency doubled or tripled as necessary to reach a wavelength close to but outside of an absorption band of a gaseous constituent to be measured. The dye laser can then be tuned such that its output frequency, or its frequency doubled output falls precisely within an absorption band of the gas being measured. If the two output frequencies are relatively close, then it can be assumed that whatever backscatters them does so equivalently to both signals. The only difference in the received backscattered signals will be due to the absorption by the gas of interest in the distance between the scattering point and the receiver. By gating the pulsed output signals, the concentration with range of the absorbing gas can be measured. This technique has been used to measure water vapor in the atmosphere. Early experiments are now planned for the ground based measurement of ozone and SO_2 using this technique.

RAMAN SCATTERING

When light impinges on a scattering molecule, there is an energy exchange between some of the photons and the molecule. This results in these scattered photons undergoing significant shifts in spectral frequency that are specific to that molecule. Furthermore, the magnitude of this frequency shifted backscattered return is proportional to the mass of that specific substance present in the scattering volume. Since the spectral frequency of the Raman return is specific to the scattering molecule, it can be used to identify the scatterer as well as measure its concentration.

The major practical limitation to using Raman scattering for atmospheric and water surface measurements (it makes no difference where the scattering molecule may be), is the relatively small return. The typical Raman cross section of an atmospheric gas is about 1/500th that of the Rayleigh cross-section. So that when measurements of trace gases are concerned, the anticipated return signals are very difficult to detect, and are severely background limited. The use of very high powered lasers to overcome this difficulty other than in the laboratory, must be tempered by safety considerations.

RESONANT FLUORESCENCE

When the frequency of the incident light on a molecule is in resonance with a particular absorption line of that molecule, fluorescence can be initiated. This will result in a re-emission of photons from that molecule at the same frequency shifts as for the Raman scattered radiation, but with backscatter cross-sections for some molecules, possibly several orders of magnitude larger than for Raman scattering. The major difference between the Raman return and fluorescence is in the delay between absorption and re-emission of a photon. Whereas in Raman scattering, the process is essentially instantaneous ($\sim 10^{-14}$ sec) in fluorescence, the re-emission of a photon may take over approximately 10^{-9} sec. This "extended" return results in several disadvantageous effects including the loss of some ranging capability. It would appear for the measurement of some molecules, where range or profile information is not as important (perhaps a substance on a water surface) that resonant fluorescence might offer a strong possibility for detection and identification.