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PLACE

POST LANDSAT D
ADVANCED CONCEPT EVALUATION
FINAL REPORT

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Prepared for

The National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland 20771

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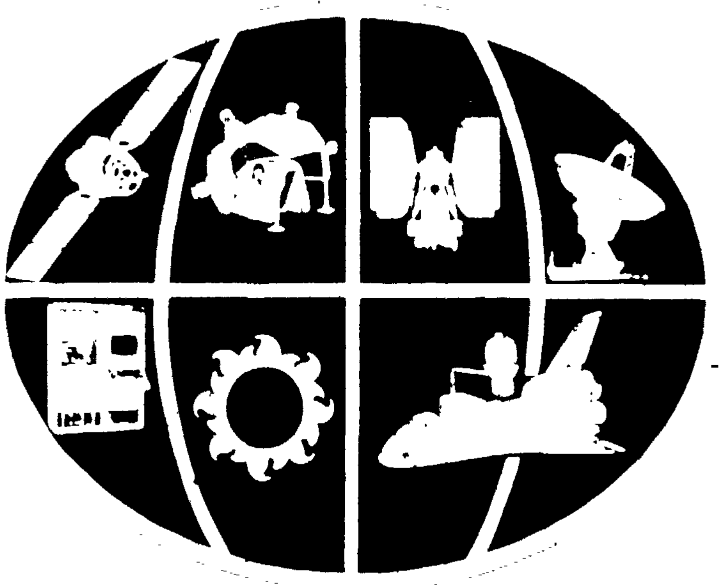

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PREPARED FOR:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND 20771

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1.0 INTRODUCTION

Every society, company and organization has groups of people that perform three kinds of functions: (1) the implementing and running of today's programs; (2) the planning and budgeting of tomorrow's programs; and (3) the long-range speculation about what may happen next week, or may not happen at all. The PLACE Study is of the third kind.

It is an imaginative look at what the future of earth resources could be in the 1985-2000 time period. We have sought to stretch our minds in this examination, to go beyond the credible to an area called the semicredible; to ask what is possible in the future, and what it will take to achieve it; to identify those technology seeds which should be planted now.

The principal objective of the PLACE Study is the identification of key technology requirements of earth resources satellite systems toward the end of the century. The study is based on previous looks to the future, yet contains several new, innovative future system concepts. The full technical breadth of the General Electric Company was employed in the formation of the system concepts and in the subsequent technology forecasts. Although a specific set of system concepts was used to drive the technology requirements, it is likely that an independent set would pose similar technology requirements.

This report is intended to be a complete documentation of the performance and results of the PLACE Study. The reader is invited and urged to challenge, modify, or carry on any of the results presented herein.

2.0 STUDY RESULTS AND CONCLUSIONS - A SUMMARY

The principal objectives of the PLACE Study were (1) to create a Space Systems Technology Model, and (2) to identify the key technology requirements posed by this model in the 1985-2000 time frame. Secondary objectives were (1) to examine future mission objectives; and (2) to develop a tool to assist in the priority structuring of the technologies. The results of the PLACE Study which satisfy these objectives are (1) the key-set of mission objectives; (2) the Space Systems Technology Model; (3) the key technology areas; and (4) the priority structuring methodology (PRISM), which are summarized in Section 2.1 below. In achieving these results, the PLACE Study attempted to be imaginative, to go beyond what is entirely credible to an area called the "semicredible" (see Section 3.3). Presented in Section 2.2 are the conclusions which were drawn from the analysis and several recommendations for further study, based on those conclusions.

2.1 SUMMARY OF RESULTS

2.1.1 KEY-SET OF MISSION OBJECTIVES

In examining a range of 91 possible earth resources mission objectives which may be desirable in the 1985-2000 time frame, a key-set of eight objectives was selected in order to focus the study. The key-set of mission objectives and their corresponding mission categories are presented in Table 2-1.

Table 2-1. Key-Set of Mission Objectives

AGRICULTURE	- Crop Production Forecasting
RANGE MANAGEMENT	- Grazing Potential Determination
FORESTRY	- Timber Stand Volume Estimation
GEOLOGY	- Geological Resources Location
LAND USE	- Land Use and Census Enumeration
WATER RESOURCES	- Watershed Monitoring
ENVIRONMENTAL QUALITY	- Water Pollution Detection
DISASTER ASSESSMENT	- Abrupt Event Evaluation

The selection, for the purposes of this technology study only, was based on two criteria: (1) economic and other societal importance and (2) the diversity of the objectives and the perceived diversity of the resultant technology requirements. The key-set of mission objectives initially drove the system conceptualization process. In addition, at the conclusion of the study, the priority structuring methodology related the system concepts and the technology requirements back to the key-set of mission objectives.

2.1.2 SPACE SYSTEMS TECHNOLOGY MODEL

The Space Systems Technology Model or the list of PLACE future system concepts is presented in Figure 2-1. It contains 12 future earth resources systems concepts, a comprehensive future ground processing concept and an assumed Advanced Tracking and Data Relay Satellite capability. It contains geosynchronous, intermediate and low earth orbit spacecraft, optical and microwave spacecraft, quick-look and mapping spacecraft, passive and active spacecraft, and single and multiple spacecraft systems. It contains extensions of present-day or perceived near-term capabilities and new measurement concepts not widely thought of before such as measurements of texture, ellipsometry, holography and microwave ground penetration. It contains a number of systems which exploit the potential of large structures in space including the texturometer, microsat, parasol, ferris wheel and the ellipsometer.

A complete description of the Space Systems Technology Model is presented in Section 6. A list of each system concept and an accompanying short description of each follows:

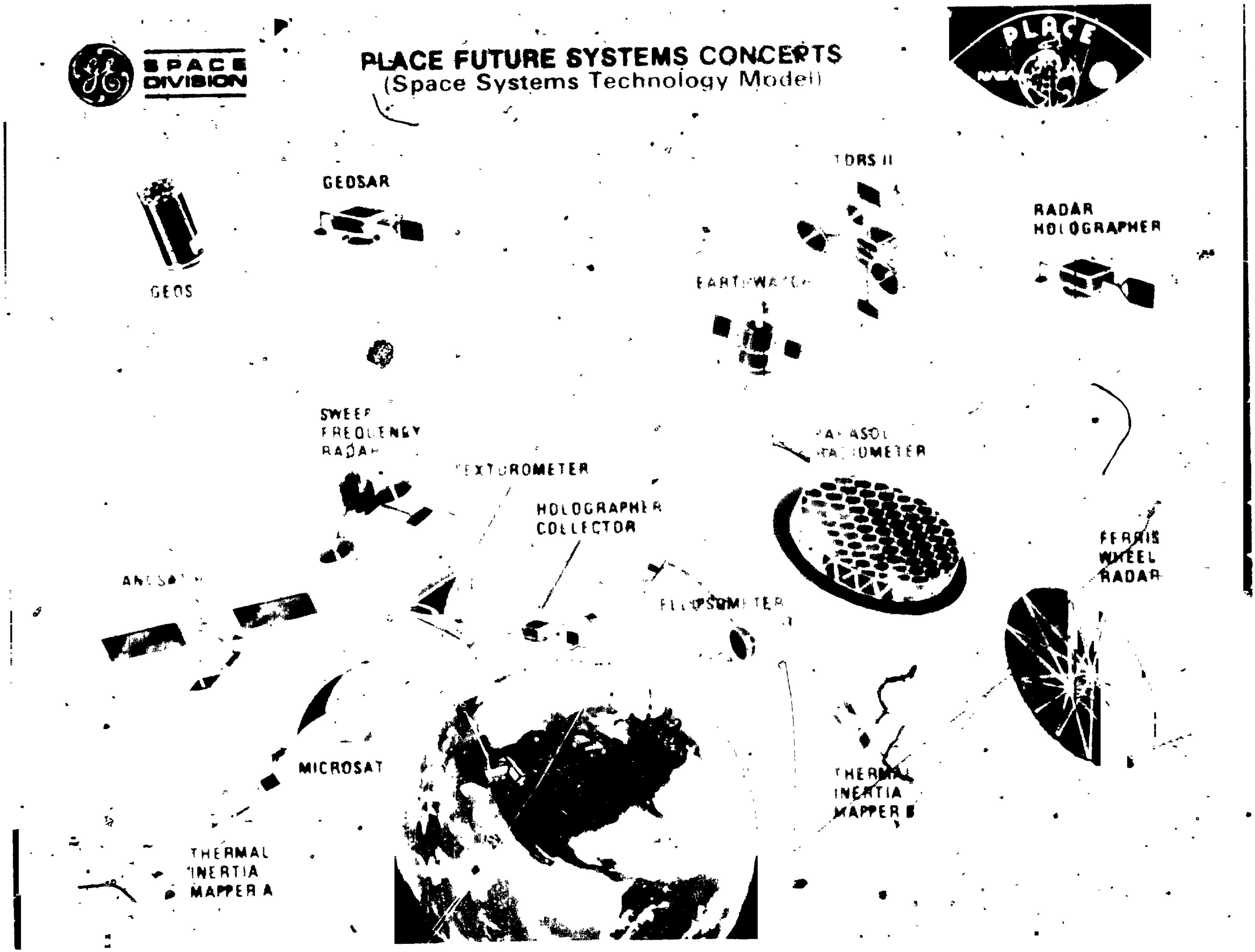

Figure 2-1. PLACE Future System Concepts

1. GEOS - Geosynchronous Earth Observation System - a large earth-looking telescope providing a quick-look imaging capability at 3m resolution for disaster assessment in optical wavelengths.

2. GEOSAR - Geosynchronous Synthetic Aperture Radar - uses the north-south drift of the geosynchronous orbit to provide range-rate measurements required by synthetic aperture. It can provide daily microwave coverage of its viewing area which can be used for disaster assessment, monitoring soil moisture, and many other uses.

3. Radar Holographer - a bistatic microwave measurement system with geosynchronous illuminator and low earth orbit collector(s) which provides a true hologram of the earth's surface. This microwave omnidirectional view may be useful for a number of classification objectives.

4. Earthwatch - a subsynchronous (6000 nautical mile) multisensor vehicle which could provide both mapping and quick-look capabilities for earth resources observation.

5. Landsat-H - a possible future Landsat system incorporating a "smart" pushbroom scanner and a synthetic aperture radar for earth resources observation.

6. Thermal Inertia Mapper - two spacecraft which measure the thermal emissivity of the ground at 10 meter resolution at pre-dawn and post-dawn opportunities.

7. Sweep Frequency Radar - a microwave texture measuring system which investigates the resonant backscatter of the ground at 10 discrete frequencies for identification and classification of ground materials.

8. Microsat - a large (600 x 1200 meter) passive L-band radiometer which provides soil moisture measurements at 1 Km resolution.

9. Texturometer - an optical ground texture measuring device that employs complex processing and optics to provide point measurements of spatial energy from 1 mm to 1 m, which could be useful for classification of ground materials.

10. Ellipsometer - a bistatic radar system that measures the ellipticity of the reflected wave and calculates soil moisture, vegetation moisture and vegetation height.

11. Parasol Radiometer - a larger (10 Km) version of Microsat employing a phased array concept.

12. Ferris Wheel Radar - a large (30 Km diameter) low frequency (30-300 MHz) ground penetrating radar that is spin-supported and provides measurements of subsurface boundary layers for geological investigations.

2.1.3 KEY TECHNOLOGY AREAS

Following completion of the Space Systems Technology Model, the technology requirements of each system were identified and technology forecasts were performed to determine whether the technologies would be mature enough when the various systems needed them. External technology drivers which could influence the development of a technology area were identified and the expected resultant technology stimulation, required by NASA, was characterized. A summary of the technology requirements of the PLACE system concepts is presented in Figure 2-2. In the figure, black dots depict enabling technologies and white dots enhancing technologies. Enabling technologies must be funded prior to implementation of a system concept. Enhancing technologies merely reduce implementation costs. Complete statements of the technology requirements and technology forecasts are presented in Section 7.

	LANDSAT H	EARTHWATCH	GEOS	TEXTUROMETER	THERMAL INERTIA MAPPER	MICROSAT	PARASOL	ELLIPSOMETER	FERRIS WHEEL	SWEEP FREQ. RADAR	GEOSAR	HOLOGRAPHER
SOLAR ARRAYS	○	○	○	○	○	○	○	○	○	○	○	○
BATTERIES	○	○	○	○	○	○	○	○	○	○	○	○
CRYOGENICS	○	○			○	●	●			○		
LARGE STRUCTURES			○	●		●	●	●	●			
2-POL. N-FREQ. ϕ ARRAYS		○				○	○	○	○	●		
RADIATION RESISTANCE		●	○								○	○
POINTING	○	●	●		○						○	
EPHEMERIS	○	●	●		○						○	○
LO-NOISE μ-WAVE REC'VR						●	●	○		○		
LARGE OPTICS			●	●								
ADAPTIVE OPTICS			○	●								
IONOSPHERE MODEL								●	○	○		●
STABLE OSCILLATORS	○	○	○							○	●	
RANGING SYSTEM				●		○	○	○	○			
DISSEMINATION CONCEPTS	○	○	●		○	○	○	○		○	○	○
ON-BOARD STORAGE	○	○	○							○	○	○
GROUND STORAGE	○	○	○	○	○	○	○	○	○	○	○	○
ON-BOARD PROC.	○	○	○	○							○	○
GROUND PROC.	○	○	○	○	○	○	○	○	○	○	○	○
D.B.M.S.	○	○	○	○	○	○	○	○	○	○	○	○
SOFTWARE ADVANCES	○	○	○	○	○	○	○	○	○	○	○	○
SOLID STATE SENSORS	●	●	●	●	○							
FERRIS WHEEL CHIP							●		●			
EXTRACTIVE PROC.	●	●	●	●	●	●	●	●	○	●	●	●
LASER SYSTEMS	●	●			●							

ENABLE = ●

ENHANCE = ○

Figure 2.2. Technology Requirements Posed by System Concepts

2.1.4 PRIORITY STRUCTURING METHODOLOGY (PRISM)

In order to tie together the mission objectives, system concepts and technology requirements and forecasts, a priority structuring methodology was developed. This methodology, embodied in a software program called PRISM, allowed for the examination of the complex interrelationships and interdependencies inherent in the set of mission objectives, system concepts and technology gaps.

A representative output of the PRISM program is presented in Figure 2-3. The reader is urged to fully understand the assumptions (Assumption Set A), methodology and inputs presented in Section 8, before drawing conclusions with respect to a particular technology being funded or not funded. The costs of each technology are representative and are for research only over a 15-year time period. Given a 15-year research budget level for earth resources technologies of 900 million dollars, all technologies would be funded and all programs enabled. On the other end of the scale, given $300 million, only extractive processing should be funded and no programs are enabled. Intermediate levels of funding reflect several or all of the large structures not being enabled. One clear insight, gained from the analysis, is that the cost and benefit of extractive processing and large structures dominate the technology requirements of future earth resources systems.

2.2 CONCLUSIONS AND RECOMMENDATIONS

It is difficult to perform a study within the semicredible. One has to walk a fine line between "being written off as a fake" on the one hand and being too conservative (ho-hum) on the other. Time will be the judge of whether the PLACE Study maintained that precarious line. The results, however, are worth the risk. By participating in such a study, one gains insight into what potential the future holds in store in future technology

*ASSUMPTION SET A

☐ = FUNDED
▨ = NOT FUNDED

PROGRAM KEY:

1. LANDSAT H
2. EARTHWATCH
3. GEOS
4. TEXTUROMETER
5. THERMAL INERTIA MAPPER
6. MICROSAT
7. PARASOL
8. ELLIPSOMETER
9. FERRIS WHEEL
10. SWEEP FREQUENCY RADAR
11. GEOSAR
12. HOLOGRAPHER

BUDGET	SOLAR ARRAYS	BATTERIES	CRYOGENICS	LARGE STRUCTURES	2-POL. N-FREQ. ø ARRAY	RADIATION RESISTANCE	POINTING	EPHEMERIS	LO-NOISE RCVR	LARGE OPTICS	ADAPTIVE OPTICS	IONOSPHERE	STABLE OSCILLATORS	RANGING SYSTEM	DISSEMINATION CONCEPTS	ON-BOARD STORAGE	GROUND STORAGE	ON BOARD PROC	GROUND PROC	D.B.M.S.	SOFTWARE ADVANCES	SOLID STATE SENSORS	FERRIS WHEEL CHIP	EXTRACTIVE PROC	LASER SYSTEMS	AM'T. SPENT	PROGRAMS ENABLED
$900M																										$898.5M	ALL
$750M	▨	▨							▨							▨			▨	▨	▨		▨			$745.5M	NOT 6, 7, 9
$750M	▨	▨									▨			▨			▨	▨	▨	▨						$750.0M	NOT 4 (HIGHER $/UTILS)
$600M														▨									▨			$588.0M	NOT 4, 6, 7, 8, 9
$500M		▨	▨	▨					▨		▨			▨			▨		▨		▨		▨			$495.0M	NOT 4, 6, 7, 8, 9
$300M	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		▨	$300.0M	NONE

Figure 2-3. Representative PRISM Output

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challenges and in the rewards of meeting those challenges. The following are conclusions and recommendations which we offer, based on our "trip" into the semicredible.

2.2.1 CONCLUSIONS - SYSTEM CONCEPTS

A number of imaginative system concepts have been proposed for this future time frame which demonstrate new measurement capabilities, which exploit the potential of large structures in space, or which simply present a glimpse of possible future avenues of growth.

A number of new measurement capabilities have been suggested that could enhance our ability to remotely sense earth resources in the future. These new measurement parameters include texture as an aid to identification and classification; ellipsometry for assessment of vegetation status; holography for its omnidirectional view, and microwave ground penetration for its subsurface mapping capabilities.

Two of the system concepts investigated are especially attractive due to their "nearer" term implementation prospects. These are the Earthwatch system concept and the GEOSAR system concept. Earthwatch, primarily for its dual potential for quick-look and mapping capabilities, presents an interesting alternative to the current Landsat/GEOS ideology, GEOSAR for its unique capabilities in rapid microwave mapping.

In the Landsat H system concept, a glimpse has been presented of how the Landsat program could grow to a fuller capability.

A number of programs have exploited and demonstrated the potential of the use of large structures for future earth resources systems. These large structures include the Texturometer, Microsat, Parasol, Ferris Wheel, and Ellipsometer system concepts.

2.2.2 CONCLUSIONS - TECHNOLOGY AREAS

Rather than look at individual technologies that were and were not funded in the exercising of the PRISM software, it is more instructive to step back and look at some of the insights gained in working with the technologies.

The major conclusion drawn is that the cost and the benefit of extractive processing and large structures dominate all future earth resources technology requirements in the time frame of interest. It is hoped that individuals interested in more specific go/no-go type decisions would put their own values into the PRISM program, in order to help them make these decisions. The real value of the PRISM program is the insight one gains while using it, and not in looking at the results of others.

During the performance of technology forecasts, a number of exciting and controversial projections were derived. Aside from the key areas of large structures and extractive processing mentioned above, these include forecasts for the 1995 time frame in the areas of on-board processors, ground storage systems, solid state sensors, multifunction sensor chips and laser systems. The on-board processor forecast indicated the early availability of powerful heterogeneous arrays of processors. The ground storage forecast indicated a preference for improvements in present tape cartridge and optical disk storage systems rather than some of the new memory technologies for extremely large data bases. In the area of solid state sensors, the projection indicated that current device problems would be overcome to allow 1 micron spacing between detectors. Multifunction sensor chips, as exemplified by the Ferris Wheel chip, will enable a new generation of phased arrays using large structures. Laser systems for atmospheric calibration and night imaging will be made possible by the development of long life laser systems.

One generality which can be stated as a result of the analysis is, given that (1) the expected benefits of a program or system concept are greater than the expected costs, and (2) the sum of the potential savings due to technology enhancements is generally a small fraction of program costs, then enabling technologies become much more important than enhancing technologies. This may be an obvious conclusion to some; however, often enabling and enhancing technologies compete for the same research dollars without this fact being noticed.

2.2.3 RECOMMENDATIONS

Five recommendations are made for future work based on the performance of the PLACE study.

1. The Earthwatch and GEOSAR system concepts appear to merit an immediate closer look due to their potential for nearer term implementation.

2. Research is recommended to evaluate the feasibility of those new measurement concepts suggested by the PLACE Study including measurements of texture, microwave holography, ellipsometry and microwave ground penetration. This fundamental research is needed now, so that the concepts may be implemented towards the end of the century, if the measurement principles are validated.

3. Increased emphasis must be placed on those enabling technologies identified in order to realize the full potential of future earth resources systems. The most important of these have been identified as the areas of large structures and extractive processing. Other key areas include on-board processors, solid state sensors and laser systems.

4. The Priority Structuring Methodology (PRISM) software developed has demonstrated potential for use as a decision support tool and should be further developed and used.

5. The PLACE methodology should be applied to a combined set of future earth resources, weather and climate missions with a view toward combining several types of sensors on common platforms.

3.0 STUDY METHODOLOGY

The methodology employed in the PLACE Study evolved during the early performance of the study and is presented in the subsequent sections. Prior to a discussion of the study methodology, definitions of some of the terms used in the study will be presented to avoid possible semantic confusion.

Mission Category - the major areas within Earth Resources to be included in the PLACE Study, e.g., Agriculture, Forestry, etc.

Mission Objective - goals which may be partially or fully satisfied under the major mission category headings, e.g., global crop production forecasting, water availability forecasting, etc.

Mission Subobjectives - subgoals required to fulfill the needs of one or more mission objectives, e.g., soil moisture monitoring, plant stress determination, etc.

System - a combination of hardware, software and people required to provide data for the various mission objectives, e.g., Earthwatch, Geosynchronous SAR, etc.

Program - the effort and resources that go into the development of a system.

Exploratory Technology Forecasting - a method involving examining technology trends to indicate the levels of technology that may be available in some time frame. This creates the situation of a "solution looking for a problem."

Normative Technology Forecasting - a method involving an examination of future technology needs and the projection of technological solutions to satisfy these needs. This technique relies on the old adage,"necessity is the mother of invention."

3.1 STUDY OBJECTIVES

The PLACE study objectives are listed in Table 3-1. The principal objective of the PLACE Study is the identification and forecasting of the "most important" technology requirements of earth resources satellite systems in the 1985-2000 time period. (The criteria for importance will be discussed at length in Section 8 of this report.)

Table 3-1. PLACE Study Objectives

PRIMARY

- Identify the key technologies of Earth Resources Satellite Systems of the 1985-2000 time period
- Provide a comprehensive 'Space Systems Technology model' for Earth Resources programs for this period

SECONDARY

- Identify and categorize future Earth Resources mission objectives
- Develop a tool to examine the key interrelationships of an assumed set of mission objectives, system concepts and projected technology gaps

Since the critical technology areas are to be based on potential earth resources satellite systems, a second primary objective of the study will be the creation of a plausible scenario of these future system opportunities, referred to as a "Space Systems Technology Model." Based on the primary objectives, then, the two principal outputs of the PLACE Study are (1) the future system concepts which make up the "Space Systems Technology Model" and (2) the technology forecasts in the identified "key" areas.

Two secondary objectives of the study, which support the primary objectives, are also identified. In order to provide a basis for the Space Systems Technology Model, an investigation of future mission objectives in the areas of earth resources was conducted. This may be regarded as an analysis of the "kinds of things we will want to be doing in earth resources toward the end of the century." The final objective arose from the need to examine the interrelationships and interdependencies of the aforementioned sets of mission objectives, system concepts, and technology areas. The two outputs of the study which satisfy the secondary study objectives are (1) the specification and analysis of a key set of mission objectives and (2) a priority structuring methodology, embodied in a computer program called PRISM, which may be employed as a decision support tool.

3.2 STUDY APPROACH

The overall approach employed in the performance of the PLACE Study is depicted in Figure 3-1. Groundwork for the system concepts was performed in three areas: (1) Mission analysis, (2) Exploratory technology forecasting, and (3) Examination of future system elements. The mission analysis involved an investigation of future earth resources applications objectives. The exploratory technology forecasting was an attempt to identify future technology solutions, looking for problems to solve. In several key system and subsystem areas, future technology tradeoffs were performed to indicate probable system elements to be used in the 1990-1995 time frame.

The method of combining the results of these three areas into system concepts is presented in Figure 3-2. The top horizontal flow, labelled "User Driver" is the optimal "systems analysis" approach to the construction of system

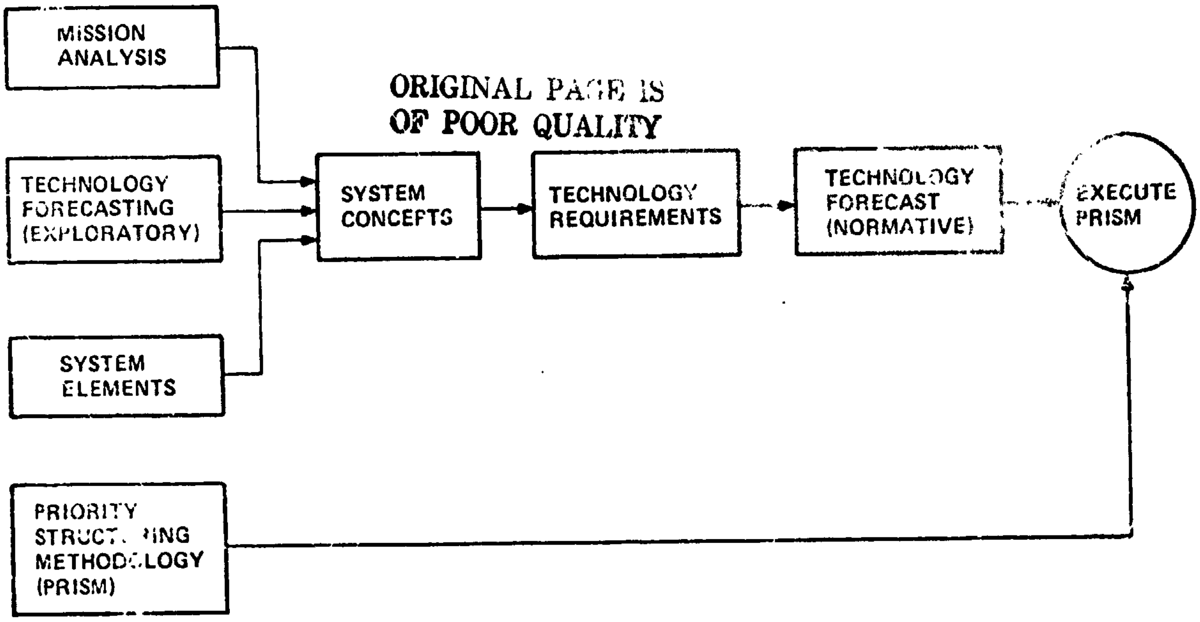


Figure 3-1. Place Study Methodology

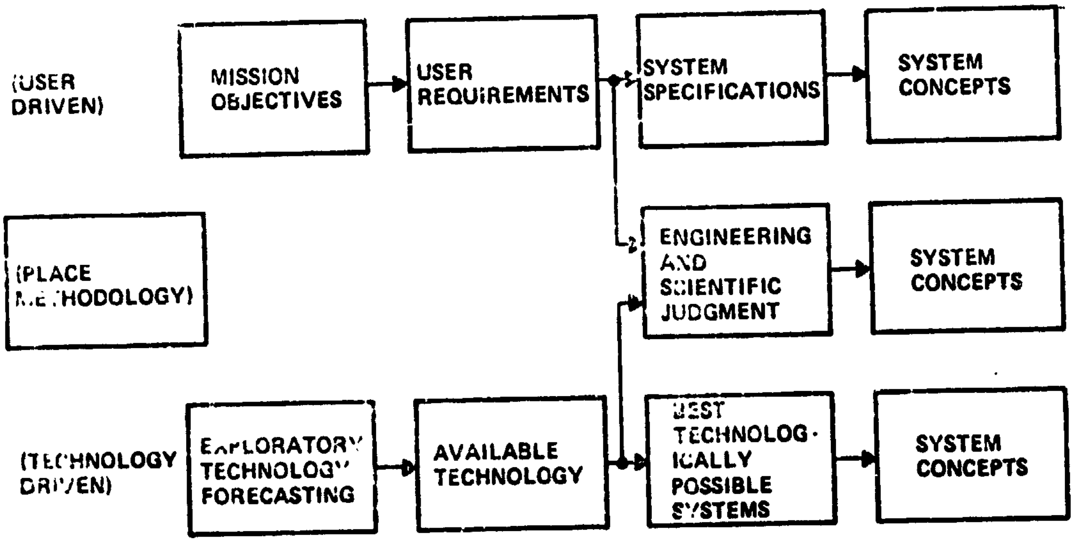


Figure 3-2. Formation of System Concepts

concepts. One starts with a stated need, quantifies the need, relates the need to a set of system specifications, and then combines all the specifications into a resultant set of system concepts. However, we did not feel that it was possible to pursue this approach in the PLACE Study. The reason for this is that the required links relating mission objectives to user requirements and user requirements to system specifications are not even known for today's systems, not to mention systems 20 years in the future. To illustrate the problem with the first link given the mission objective of grazing potential determination, one has a difficult task determining a consistent set of user requirements for such parameters as precision (accuracy), observation frequency, response time, etc. However, the difficulty with the first link pales when compared with the difficulty in specifying the second link. That is, given the user requirements, what are the system specifications. As an example, given the desire for 98% accuracy in a crop production forecast, optimum system specifications for the required spectral bands (.4μm-10m) and instantaneous field of views (IFOV's) are not known. In a study published by the National Research Council in October 1977 (Ref. 3-1), a conclusion reached was that not enough is currently known about passive and active microwave responses in order to specify such system parameters. That is, the relationship between phenomena and observables is not well enough understood.

The bottom horizontal flow of Figure 3-2 represents an alternate method of construction of system concepts. This involves a forecast of the technology that will be available in the time frame of interest, and putting together the technologically best possible systems independent of application. However, this would be begging the question of the study since the study's principal objective is to identify key technology areas for earth resources. That is, one wouldn't start with key technologies in a study to identify key technologies.

The procedure employed in the PLACE Study, as shown, was to employ both of these methodologies combining the needs and solution trends with engineering and scientific judgment, to arrive at the system concepts to be employed. Referring back to Figure 3-1, once the system concepts have been obtained, identification of their "key" technology requirements and the (normative) forecasting of the state of the art in each of these technology areas then follows.

A separate portion of the study involved the construction of a priority structuring methodology to assist in examining the interrelationships of the mission objectives, system concepts and projected technology gaps. The heart of this methodology was a computer program called PRISM which was successfully used to analyze the intricate set of interrelations and interdependencies.

3.3 NASA MANDATE FOR VISION

NASA has requested that the PLACE Study be imaginative and innovative in its forecasts of what is possible in the 1985-2000 time frame. Also, by disregarding political and institutional constraints, the study was to investigate what "can be" rather than what "will be." The application of this charge is illustrated in the "credibility continuum" presented in Figure 3-3. More specifically, it illustrates the tentative bounds of an area that we call the semicredible, within which the PLACE Study was performed. That is, in its forecasts, the study went beyond the entirely credible, to an area called the semicredible, yet (hopefully) stopped short of concepts which may be deemed incredible.

The first thing that one notes in looking at the credibility continuum is that the border between the semicredible (what could happen) and the incredible (what could not happen) is a subjective one. For different observers, this line will move to the right or to the left. For this reason, examples of mission objectives, system concepts and technologies are presented in each region to illustrate where the authors' borders lie. The two system concepts that lie in the semicredible region in the figure are described in Section 5. Note that some of the applications models that will be required to support operational systems objectives do fall into the incredible region.

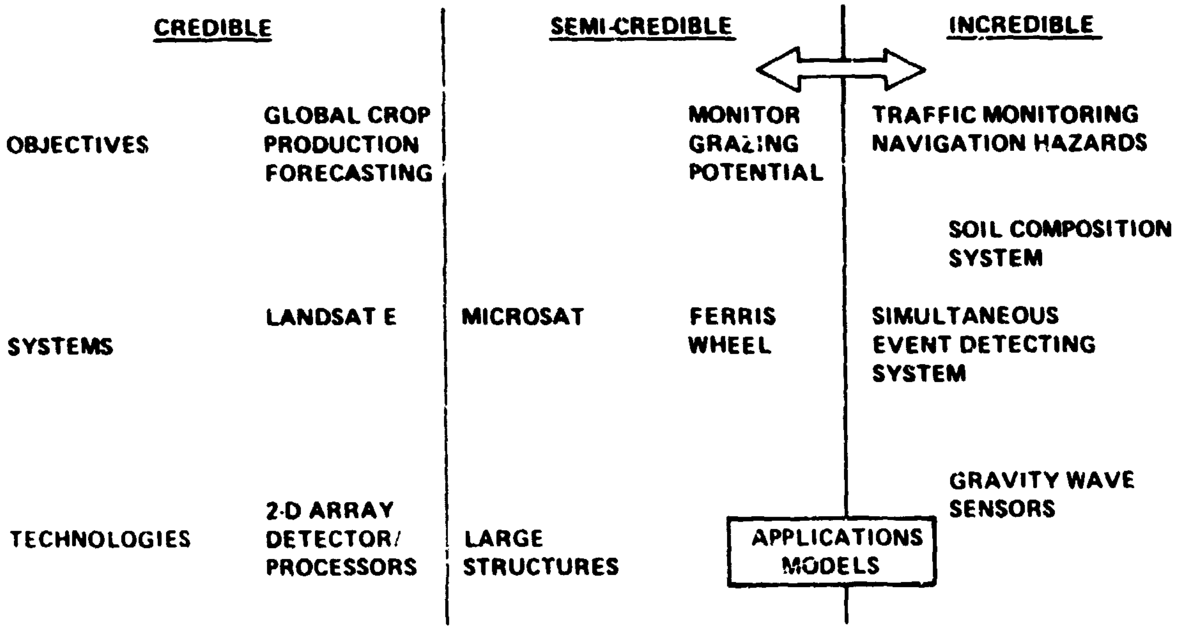


Figure 3-3. Credibility Continuum

There are several significant implications of working in this area called the semicredible which will be discussed at this point. The first is that the PLACE results and conclusions have neither the official approval nor the official endorsement of NASA or the General Electric Company, but rather represent the opinions and views of the authors of this study. At the present, the system concepts do not appear in any NASA future plan.

The second significant implication is that the future system concepts suggested could not be fully evaluated for technical or economic feasibility, and therefore may be vulnerable to fatal flaws. It is expected that as the various concepts are investigated more fully, their technical and economic feasibility will continue to be evaluated.

Finally, it must be noted that all forecasts for mission objectives, system concepts and technologies are based on projections of current trends and perceptions of future needs. They are therefore limited in not being able to take unforeseen events into account. That is, some new discovery could turn up in 1985 which changes the whole picture.

One final word concerning the assessment of the semicredibility of the system concepts, is illustrated by an observation by Sir Arthur C. Clarke: "Any sufficiently advanced technology is indistinguishable from magic." Initially, many of the PLACE system concepts appeared incredible. However, as the study progressed and the technology requirements of each system concept became better understood, the system concepts became more and more credible.

REFERENCES

3-1 Committee on Remote Sensing Programs for Earth Resources Surveys, Microwave Remote Sensing from Space for Earth Resources Surveys, Commission on Natural Resources, National Research Council, October 1977.

4.0 MISSION ANALYSIS

The initial task in the study was an investigation of future earth resources applications objectives. The procedure followed in performing this investigation is illustrated in Figure 4-1. The initial step was to set the bounds of earth resources for this study and to construct a complete list of possible earth resources objectives for the 1985-2000 time period. This list was narrowed to a key set of mission objectives and the inclusiveness of the key set was then evaluated. Finally, the implications of the key set objectives in terms of user requirements and trends toward system specifications were investigated. The selection and prioritization of future mission objectives is discussed in Section 4.1. An analysis of the interrelationships of the selected set of mission objectives is presented in Section 4.2. Finally, Section 4.3 contains a discussion of the implications of the selected (key) set of mission objectives for future system specifications.

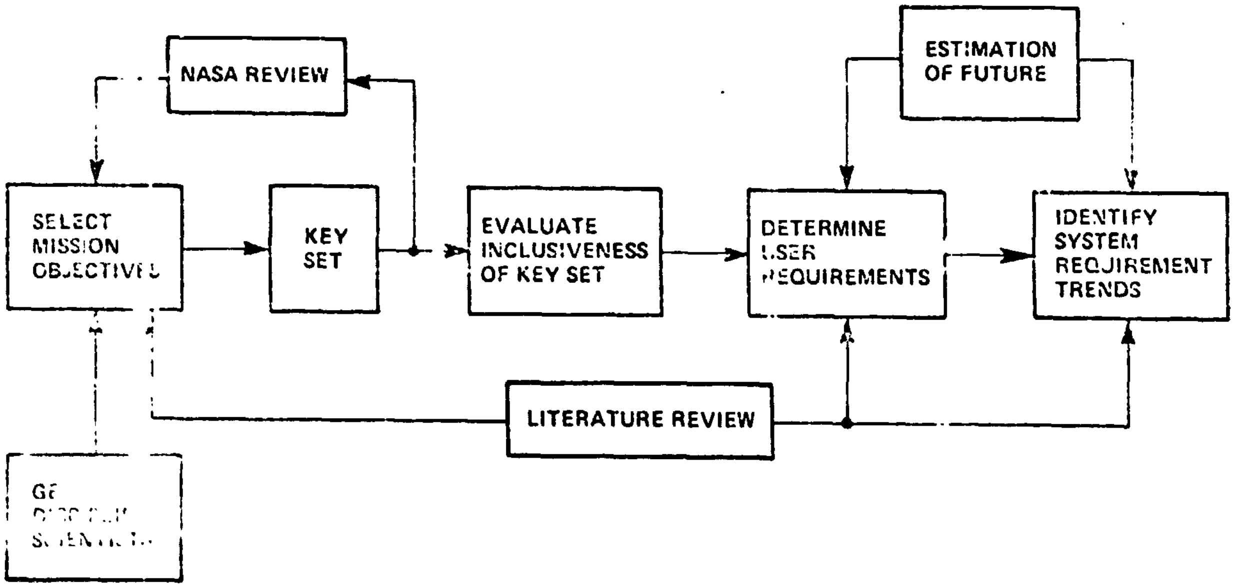


Figure 4-1. PLACE Mission Analysis Methodology

4.1 MISSION OBJECTIVES

The analysis of future earth resources objectives begins with setting bounds on what is included in earth resources for this study. It then goes on to the identification of possible future objectives in earth resources or "what are the kinds of things we will want to be doing in earth resources towards the end of this century". At this point, a key set of mission objectives was selected in order to focus the study.

4.1.1 BOUNDS OF EARTH RESOURCES

In order to gain an understanding of the limits of earth resources as used in this study, it is instructive to examine what was not included as well as what was included, as shown in Table 4-1. It was difficult to exclude Weather and Climate missions because of their close ties to many of the included Earth Resources missions, but this was necessary due to the limited resources of the study. Therefore, any weather and climate parameters required in the processing chain for the earth resources mission, were assumed to be available as needed. The remainder of the excluded list was either determined for similar reasons or was initially "ground-ruled" out of the study.

Table 4-1. PLACE Mission Categories

Included	Excluded
Agriculture	Weather and Climate
Range Management	Atmospheric Sensing (Except Calibration)
Forestry	Earth and Ocean Dynamics
Geological Resources	Energy/Comm/Nav
Land Use	Military Applications
Water Resources	Aircraft/D.C.P.'s
Environmental Quality	Extraterrestrial
Disaster Assessment	Criminal Activities (Except Pollution)

This study considers only spacecraft sensors. Information relayed from ground-level or atmospheric sensors, via Data Collection Platforms or transponders will be assumed to be available from other sources. Furthermore, historical records of weather, land use, images, and the like, have been assumed to be available in data banks. Remote sensing from aircraft is also outside the scope of the study. This has made subtle changes in approach for the reasons outlined in Table 4.2.

Table 4-2. Remote Sensing from Spacecraft
(as opposed to aircraft)

Advantages:

Rapid total-system response time (delay between requesting an image, of any random point, and receiving it)

Rapid scanning of a large area gives an instantaneous synoptic view (correlate separated but time-varying phenomena)

Ability to sense in remote areas

Less affected by political boundaries

Low mechanical stress environment allows large, stable structures

Scintillating atmosphere is distant from sensor.

Neutral:

Lower relief displacement in images

Sensor controlled remotely from human operator.

Disadvantages:

Low redundancy of spacecraft and sensors

Poorer spatial resolution for a given angular resolution; larger apertures are required

Cloud occlusion affects some sensors

Earth surface measurements are affected by entire atmospheric path

Time delay, due to finite speed of light, is greater

More difficult to repair sensors

Ionizing radiation more intense.

Although the applications are intended to be world-wide, there is a bias toward USA goals simply because it is more difficult to know of international requirements.

Also, while the time of consideration is the last 15 years of this century, it can more accurately be described as "future indefinite", simply because prognostication is so unreliable. A number of sources were examined (Ref. 4-1-27) in a search for inspiration on the general future of the world. Although this was of little use, one of the foundations of this study is the belief that technological achievement can influence the future toward the direction of predetermined goals. In that sense these goals or objectives "could happen" in the time frame of interest.

4.1.2 SELECTION OF MISSION OBJECTIVES

These requirements, needs, and goals have been obtained from two sources. The first has been the estimates of earlier published studies (Ref. 4-28-60). The second major source has been from meetings with General Electric personnel; key ideas have been received from those listed below.*

The aggregation of these mission objectives is given in Table 4.3. At the level of generality chosen for this list, there are 82 different objectives. This compilation has emphasized primary needs and goals; an example would be monitoring estuaries. Secondary, or sub-goals, such as determining land-water boundaries, are listed only if they are not covered by a previous goal, or if they better define the goal. Many of these needs overlap somewhat, but they are often repeated in a different context in order to help insure that few important goals are forgotten.

---

*Arch Park, Bill Needham, Ralph Baker, Ron Fries, Ned Buchman, Al Smith, Dottie Schultz, Dave Dietrich, and Dick Porter, all GE; also, Fred Flatow of GSFC.

Table 4-3. Future Earth Resources Mission Objectives

AGRICULTURE

1. Identify crops (this includes fruit trees and cotton) to level of species and variety
2. Measure their acreage and location
3. Estimate their yield from: vigor and stress factors (soil moisture, chemistry and fertilizer, and physical structure; plant disease, insect infestation, and weed encroachment; soil temperature; water and air pollution), planting time, and damage (frost or wind)
4. Determine production and food reserves from stockpiles and areas which have been harvested; forecast production from acreage and yield for each crop
5. Optimize Crops: Type of crop for each area, planting time, and soil amendments
6. Predict onset of insect and disease attack
7. Design irrigation projects, given water needs and resources; determine the need for and timing of irrigation
8. Map soil types and distribution and determine their productivity capability
9. Measure soil moisture and salinity
10. Measure soil radioactivity and pesticide residue
11. Map soil erosion, by wind and water, and deposition
12. Monitor desertification and drought.

RANGE MANAGEMENT

13. Inventory rangeland and classify vegetation
14. Determine potential for grazing, in animal unit months
15. Monitor status of forage: Palatability, range readiness, population pressure, and stress
16. Predict carrying capacity of range, and inventory livestock
17. Estimate grasslands fire potential.

Table 4-3. Future Earth Resources Mission Objectives (Cont'd)

FORESTRY

18. Create type stand classification by species

19. Measure stand area and density distribution of species group

20. Detect timber stress: Drought, insect, disease

21. Estimate stand volume and grade (Factors: Diameter, maturity, age, height, and density)

22. Predict seed-bearing years

23. Monitor and measure production

24. Inventory the understory

25. Estimate forest fire potential.

GEOLOGICAL RESOURCES

26. Map Geology (Morphology, Lithology, Structure) and verify or revise existing maps

27. Locate Geological Resources: Underwater, beneath vegetation, or deeply buried

28. Correlate resources with their surface expressions (anomalous colors, textures, patterns, and vegetation and its stress)

29. Locate metallic mineral deposits (see GEOSAT Committee Report, Ref. 4-41)

30. Explore for nonmetallic minerals and construction materials (for example, evaporites, phosphate, limestone, clay)

31. Locate fossil fuels: coal, petroleum, and gas

32. Locate radioactive ores: Uranium and Thorium

33. Explore for Geothermal and Geopressure resources

34. Detect river migration and delineate flood plains

35. Determine susceptibility for landslides, subsidence, and mine cave-in

LAND USE

36. Produce land use maps to level III Classification

37. Generate thematic maps and orthophoto maps

38. Detect change in land use (agricultural land conversion, for example)

Table 4-3. Future Earth Resources Mission Objectives (Cont'd)

LAND USE (Cont'd)

39. Determine land capability (potential for a given use)

40. Perform global demographic census

41. Map settlement patterns and transportation nets

42. Determine optimum routes for transportation, communication, and pipelines, and optimum sites for building and industry

43. Evaluate construction characteristics at a location as determined by geology, soil, and topography

44. Monitor housing and industrial heat loss

45. Monitor recreational, archaeological, and historical areas.

WATER RESOURCES

46. Forecast regional water balance

47. Determine water availability and consumption

48. Monitor snowsheds and water content of snow

49. Monitor watersheds: Forecast regional runoff and detect incipient floods

50. Identify areas suitable for aquaculture, both vegetation and fish

51. Inventory water bodies, including reservoirs

52. Select reservoir sites and detect reservoir seepage

53. Locate groundwater resources

54. Monitor glaciers and lake and river ice

55. Monitor sea ice: Drift velocity, extent, thickness, leads, age, salt content, temperature

56. Detect hazards to navigation in the ocean and inland waterways: Location of shoals and their depth, ice bergs

57. Route and monitor shipping: Weather, waves, and currents

58. Monitor fishing fleet and its catch

59. Monitor marine and fresh water plants and animals (plankton, fish, red-tide mammals)

Table 4-3. Future Earth Resources Mission Objectives (Cont'd)

WATER RESOURCES (Cont'd)

60. Determine ocean water temperature and composition (chlorophyll, gelbstoffe, salinity, dissolved oxygen, nutrients)

61. Measure coastal zone conditions (erosion, dredging, dune migration)

62. Monitor estuaries (salt-fresh water interface, pollution, vegetation)

63. Locate sites for marine construction and mining (ports, pipelines, power plants).

NOTE: It is recognized that several of the secondary goals (requirements), of the primary goals listed here, will be outside the scope of the PLACE Study and therefore assumed available.

ENVIRONMENTAL QUALITY

64. Evaluate quality of life indicators

65. Monitor changes in cities (urban blight and population density)

66. Analyze urban heat islands

67. Detect oil spills on land

68. Monitor waste disposal on land: Sewage sludge and land fill

69. Monitor radioactive waste storage

70. Monitor wildlife, its habitat areas and migration

71. Detect pollution of fresh water; map its dispersion and locate its source (chemical, oil, and thermal pollution)

72. Monitor quality of fresh water bodies: Salt water incursion; entrophication; water suspended solids, their particle size and constituents.

DISASTER ASSESSMENT

Detect, monitor, assess damage, and plan relief from natural and man-induced disasters:

73. Fires

74. Landslide

75. Subsidence

76. Earthquakes and Tsunamis

Table 4-3. Future Earth Resources Mission Objectives (Cont'd)

DISASTER ASSESSMENT (Cont'd)

77. Volcano eruptions
78. Explosions
79. Radioactivity dispersal
80. Violent storms (hurricane, tornado, wind, snow, and ice)
81. Floods
82. Frost.

There are two interesting points to be noted about these projected needs. First, all needs of today will still exist toward the end of this century, however the emphasis will shift toward achieving higher accuracies through improved performance. Secondly, no new goals will appear; society will just grow more capable of doing things that should be done today.

Are there any requirements which remote sensing from spacecraft cannot solve? There are some specific tasks for which no general and effective technique has been found. One example is the monitoring of radioactive materials in transport, storage, and use, for nuclear reactors, or perhaps the mapping of disease, such as that of hens in a poultry "Factory".

4.1.3 SELECTION OF A KEY SET

The original list of mission objectives has been analyzed in order to determine those mission objectives which were considered most critical. This key set of mission objectives includes one from each of the eight mission categories. The eight members of the key set have been selected because of their diverse requirements and their importance in the economic and social sense.

The philosophy of selecting a key set is related to that of determining experimental test sites: both utilize a representative sample. The system concepts that were constructed attempted to fulfill the requirements imposed by the key set as a minimum. It was felt that most non-key set objectives would be fulfilled automatically by these same system concepts. The following paragraphs outline the goals of the eight missions in the key set. While not always stated, all objectives are global in nature.

1. Crop Production Forecasting

This goal requires the prediction of the world's future production of all crops, excluding timber and forage. In addition to grain and vegetables, other crops included are: cotton and other fibers; orchard produce; and fuel crops, which may be important in the future. Crops will be given emphasis in this study in proportion to their aggregate value, and minor crops (greenhouse, uncultivated) will be given less consideration. The forecasts will be updated during the crop growing season; forecasts, however, will not be made for over a year in the future. The major aspects of production forecasting are the identification of crops, the measurement of their acreage and location, and the estimation of their yield as determined by vigor and stress factors. Furthermore, the production itself is later determined in order to improve the accuracy of future predictions. Economic constraints, which may leave crops unharvested, must be considered in order to correlate potential and actual production.

Key Set Subobjectives

Identify crops

Measure acreage

Estimate yield

Determine production and reserves.

2. Grazing Potential Determination

The current status of the range is evaluated and then its carrying capacity is estimated in animal unit months. The response time of this evaluation must be fairly short relative to any significant change in rangeland potential within different areas of the range. While there will be no need to enumerate the livestock and wildlife on the range, their presence will be indicated by the grazing pressure. An important, but difficult to evaluate, parameter which should be measured is the palatability of the forage. This can be estimated by the type of vegetation, its moisture content, and physical condition, such as dust cover. Additionally, the condition of the soil affects the potential for grazing; standing water, salt buildup, and bearing stress are important factors. Weather conditions and snow cover are important, too.

Key Set Subojectives

Inventory rangeland
Determine grazing potential
Monitor forage status
Predict range capacity
Inventory livestock
Estimate fire potential.

3. Timber Stand Volume Estimation

A number of different factors must be determined in order to evaluate the quantity and quality of timber in an area; some of these are: tree diameter, height, age, maturity, and density. The primary economic importance of these measurements is the estimation of the value of the lumber which could be logged in an area. Stand volume is also important for evaluating the water balance in a watershed, for monitoring reforestation after logging, and as an indicator of the recreational value of the land. Implicit in these evaluations is the identification of the species distribution of timber stands.

Key Set Subobjectives

Create type stand classification

Measure stand area and density

Detect timber stress

Estimate stand volume and grade

Monitor production and regrowth

Inventory understory

Estimate fire potential.

4. Geological Resources Location

To the extent that it is possible with remote sensing, surface, buried, and underwater geological resources must be located and identified. These resources include economically extractable minerals, metallic and non-metallic, also construction materials, fossil fuels, and geothermal resources. However, the location of geologically suitable construction sites is not a part of this objective. While some buried geological resources might be indicated at the surface by vegetation stress, anomalous colors, or geological structure, many valuable resources are without surface expression.

Key Set Subobjectives

Map geology

Locate hidden resources

Correlate surface expressions

Locate metallic minerals

Locate nonmetallic minerals

Locate fossil fuels

Locate radioactive ores

Explore geothermal resources

Determine landslide susceptibility.

5. Land Use and Census Enumeration

It is desirable to apply satellite remote sensing to the need for creating thematic and land use maps to a classification depth of Level III (Ref. 4-61). After these maps have been created once, the requirement is then for the detection and identification of changes in land use. Since there is no conceivable way of counting people directly from a satellite, indirect indicators of population must be used. Since these are much the same parameters which make up a thematic map, this goal will also include the enumeration of the global population. Furthermore, this demographic census will be periodically updated and will indicate changes in population density.

Key Set Subobjectives

Produce land use maps

Generate thematic maps

Generate orthophoto maps

Detect land use change

Determine land capability

Perform demographic census

Map settlement patterns

Determine optimum routes

Evaluate construction characteristics

Monitor recreational areas.

6. Watershed Monitoring

The aim of this mission objective is one of monitoring the earth's surface supply of fresh water. This also includes snow and ice cover on the land; however, icebergs as water supplies are not included. The flow and storage of water on the land's surface are the two fundamental parameters; the flow in streams and rivers and the storage of snowfields and reservoirs. The entire water cycle is not considered; rainfall and evaporation and also groundwater flow are excluded from this objective. While much of this mission could also be accomplished with Data Collection Platforms, only direct satellite approaches will be studied.

Key Set Subobjectives

Determine water availability

Monitor snowsheds

Monitor watersheds

Forecast runoff

Detect incipient floods

Inventory water bodies

Select reservoir sites

Detect reservoir seepage

Locate groundwater resources

Monitor glaciers

Monitor estuaries.

7. Water Pollution Detection

Inland water bodies are subject to a wide variety of pollutants; chemical, oil, and thermal pollution are the major types. Additionally, salt water incursion and eutrophication can degrade the quality of fresh water. Some water-suspended solids are pollutants also, and it would be valuable to know the particle size and constituents of these solids. The objective of satellite remote sensing will be four-fold: detecting, identifying, monitoring, and, if possible, tracing fresh water pollutants to their source.

Key Set Subobjectives

Monitor fresh water quality

Detect fresh water pollution.

8. Abrupt Event Evaluation

There are two types of abrupt events or temporal discontinuities which can be monitored with remote sensing: man and natural disasters and also short lived events. While disasters are human calamities, short-lived events such as some glacier bursts or the flocking of birds can cause no harm and can provide valuable scientific information. Both types of events can have similar sensing requirements: the primary need is for an any-time, fast-response remote sensor. Some of the disasters to be monitored could be fires, explosions, radioactivity dispersal, severe pollution, landslide, avalanche, subsidence, earthquakes and tsunamis, volcano eruption, violent storms (hurricane, tornado, wind, snow, and ice), floods, and frost. The aim is not to predict these disasters, nor is it to detect them; these require a different operational system and sometimes different sensors. Instead, the goal will be that of monitoring known disasters and also, to the extent that remote sensing can help, aiding the relief planning for these disasters. The short term aspect of disaster assessment, determining the extent of damage, is included within this mission; the longer term aspects, evaluating financial loss and planning reconstruction, are more suitable for another mission.

Key Set Subobjectives

Monitor, assess damage, and plan relief for

- Fires,
- Explosions
- Radioactivity dispersals
- Severe pollution
- Landslide and avalanche
- Subsidence
- Earthquake and tsunami
- Volcano eruption
- Violent storm
- Flood
- Frost
- Short-lived phenomena.

4.2 ANALYSIS OF THE KEY SET

By meeting the requirements for a given mission objective from the key set, many other objectives are at least partially fulfilled. Table 4-4 and Figures 4-2 through 4-9 gives an estimate of the minimum extent to which the 82 mission objectives will also be met when each of the eight objectives of the key set are satisfied. Note that these figures do not indicate the extent to which the final system which meets the requirements for satisfying a key set mission objective could also satisfy another objective; they are only based on the inherent requirements of each objective and have made no assumptions about specific systems. Furthermore, the figures do not indicate the proportion of information, which is generated by satisfying a key set objective, which could be applied to another objective; again, this slightly different concept would change the table.

Under the category of Disaster Assessment, each of the four separate functions (detect, monitor, assess damage and plan relief) apply to a different extent to each of the types of disasters. However, to simplify the figure, each of the four functions was included in each type of disaster indicated.

From the point of view of the end user of information from remote sensing, there are four major requirements. These are: (1) accuracy, which can be either identification accuracy, measurement accuracy (area, position, velocity, thickness, volume, height, moisture content, temperature), or detection probability; (2) the parameter range to be measured; (3) the frequency of successful observation; and (4) the response time, or the delay between sensor observation and user information. From these requirements, certain system specifications can form.

Table 4-4. Secondary Benefits of the Key-Set Missions

- o Indicates minimum extent to which the 82 mission sub-objectives will be satisfied by the 8 objectives of the key set
- o If all systems were used to try to satisfy all objectives (key set and non-key set), almost all objectives would be satisfied
- o The following tables assume that systems are operated only to satisfy the key set objectives.

	◔	◑	◕	●
NONE	SOME	MUCH	MOST	ALL

→ INCREASING PROPORTION

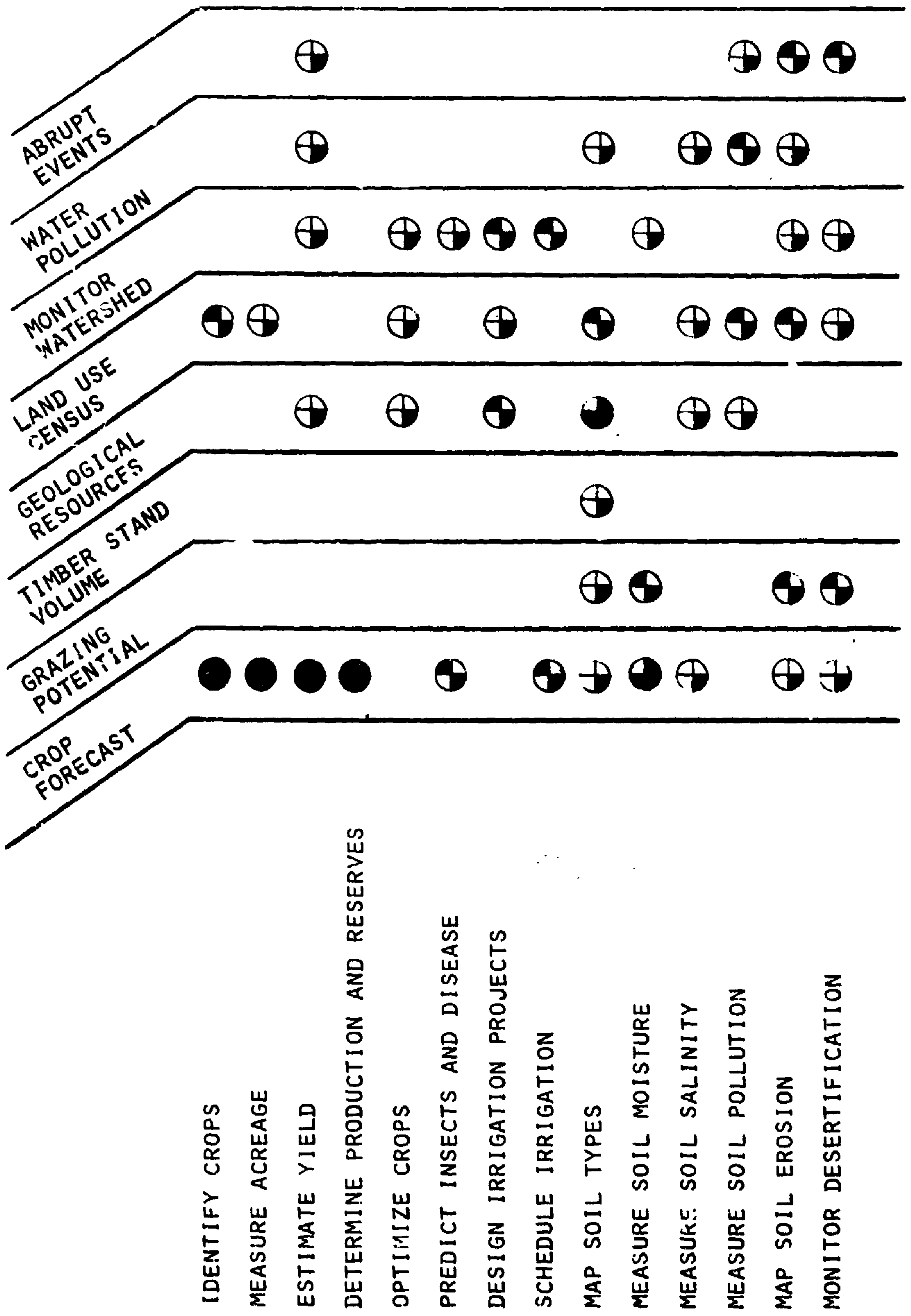


Figure 4-2. Key Set Suppo.t For Agriculture Objectives

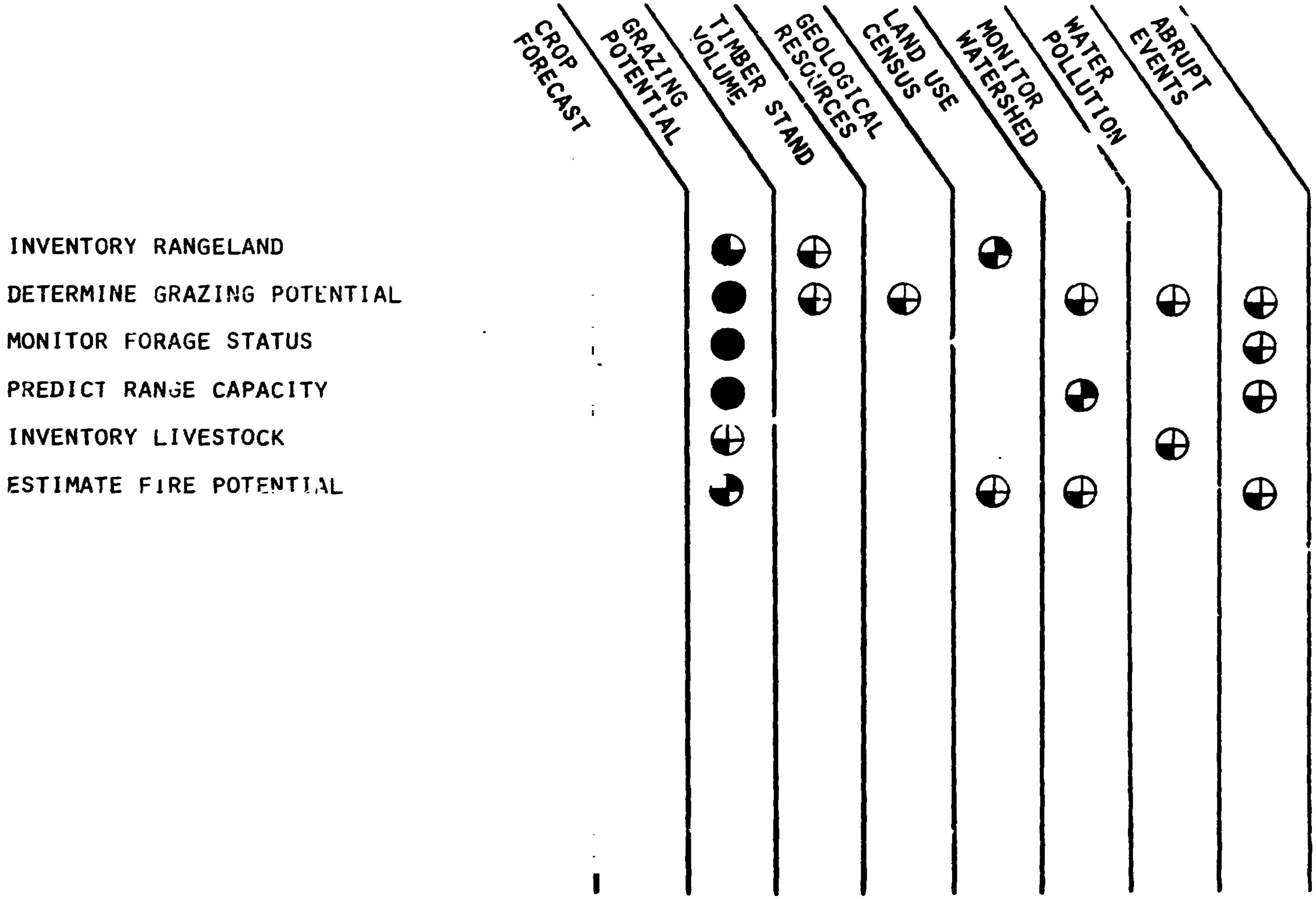


Figure 4-3. Key Set Support for Range Management Objectives

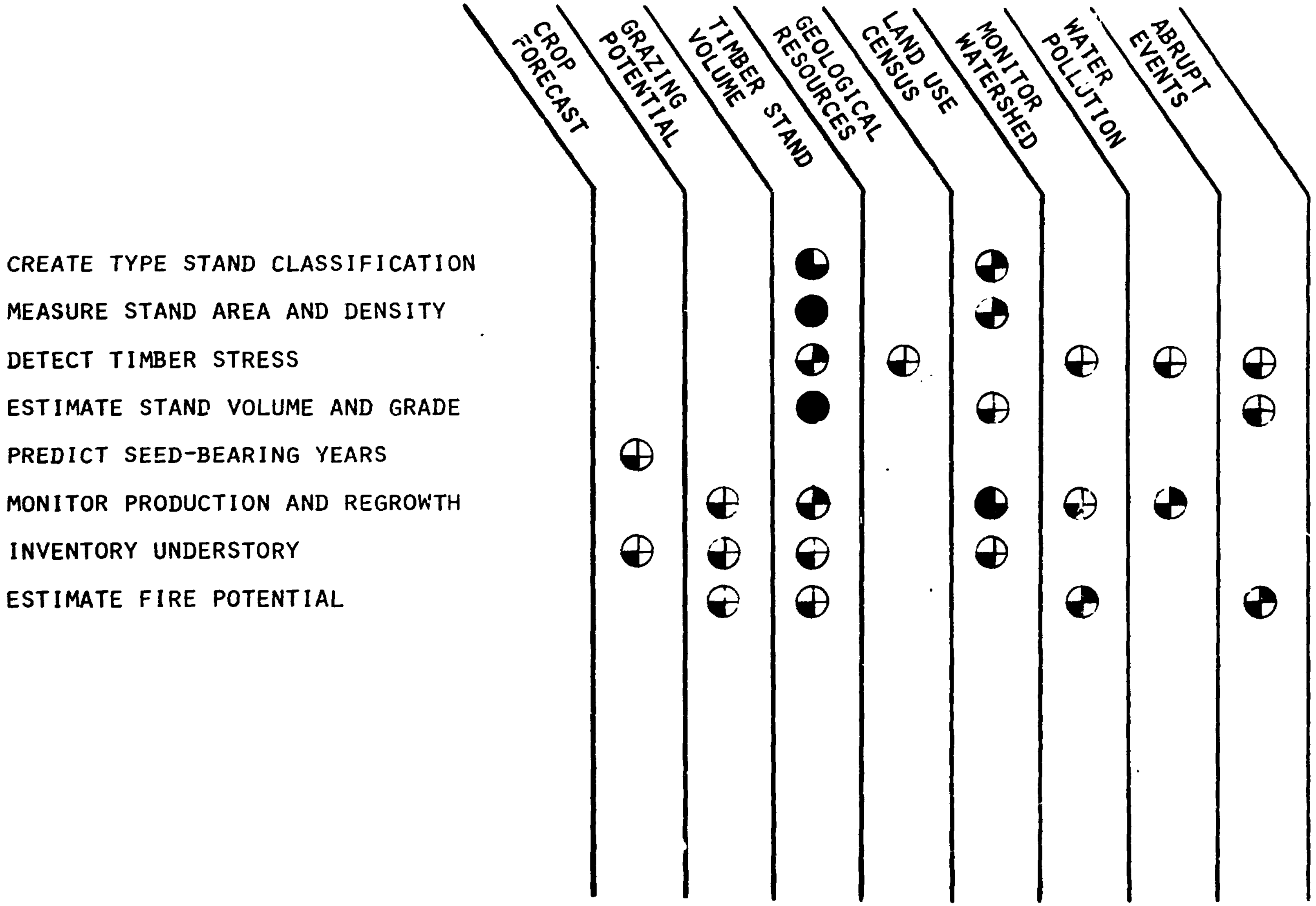


Figure 4-4. Key Set Support for Forestry Objectives

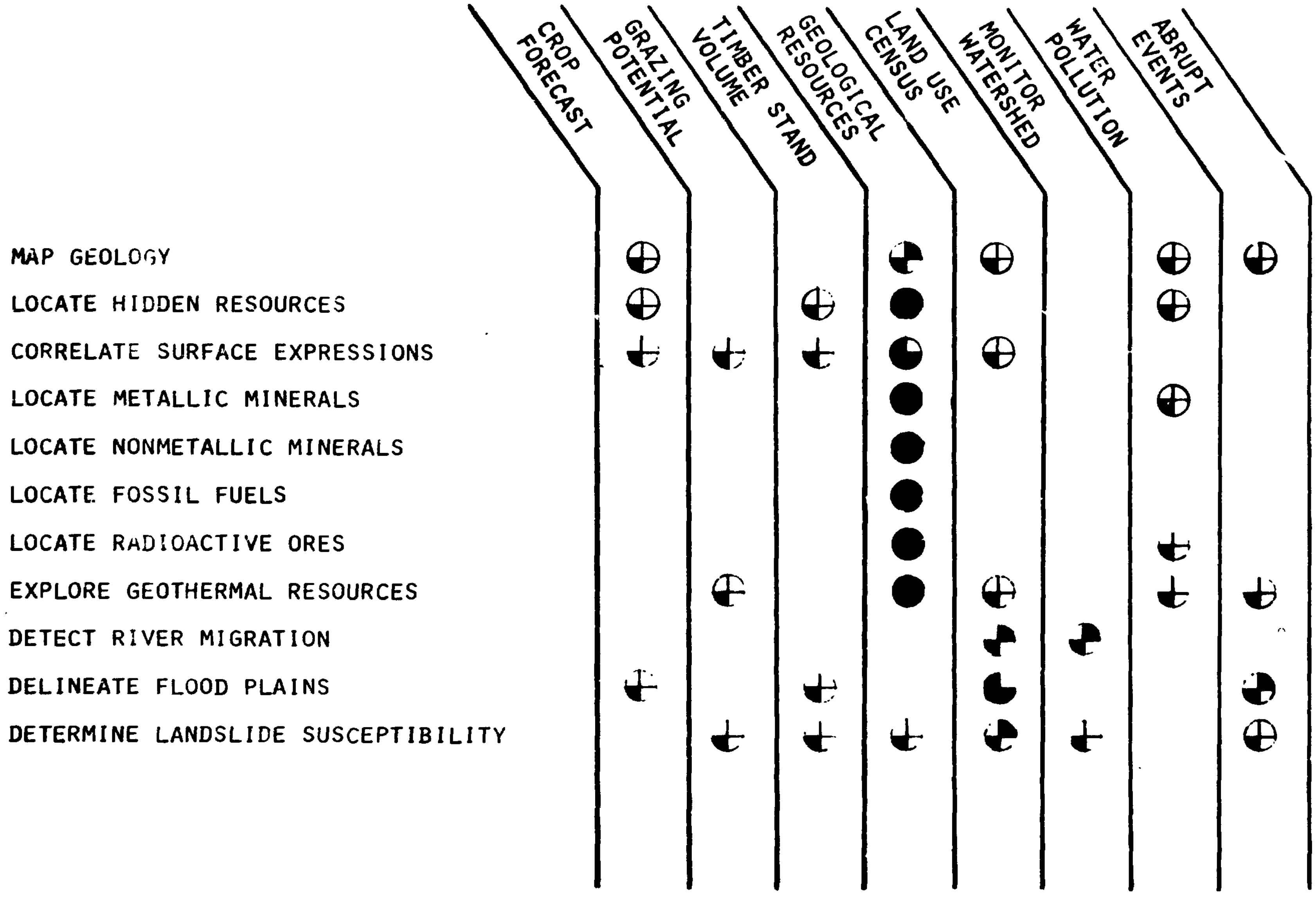


Figure 4-5. Key Set Support for Geological Resources Objectives

	CROP FORECAST	GRAZING POTENTIAL	TIMBER STAND VOLUME	GEOLOGICAL PESOURCES	LAND USE CENSUS	MONITOR WATERSHED	WATER POLLUTION	ABRUPT EVENTS
PRODUCE LAND USE MAPS	◔	◔	◔	◔	●			
GENERATE THEMATIC MAPS	◔	◔	◔	◔	●			
GENERATE ORTHOPHOTO MAPS					◔			
DETECT LAND USE CHANGE		◔			●			◔
DETERMINE LAND CAPABILITY	◔	◔		◔	◑	◔	◔	
PERFORM DEMOGRAPHIC CENSUS		◔			●			
MAP SETTLEMENT PATTERNS					◕			
DETERMINE OPTIMUM ROUTES			◔	◔	◑	◔		
EVALUATE CONSTRUCTION CHARACTERISTICS				◕	◔			
MONITOR HEAT LOSS					◔			
MONITOR RECREATIONAL AREAS		◔	◔		◔	◔	◔	◔

Figure 4-6. Key Set Support for Land Use Objectives

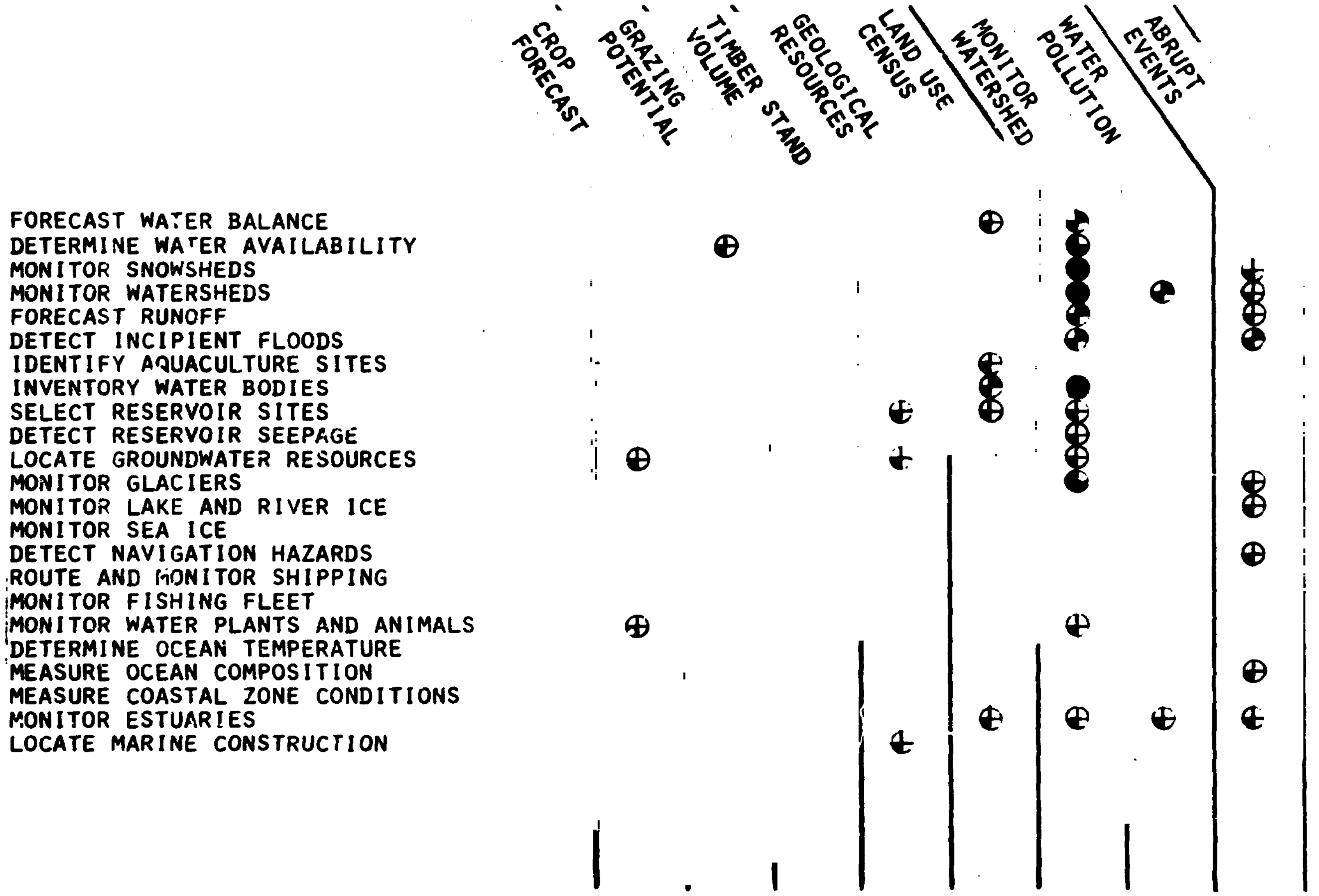
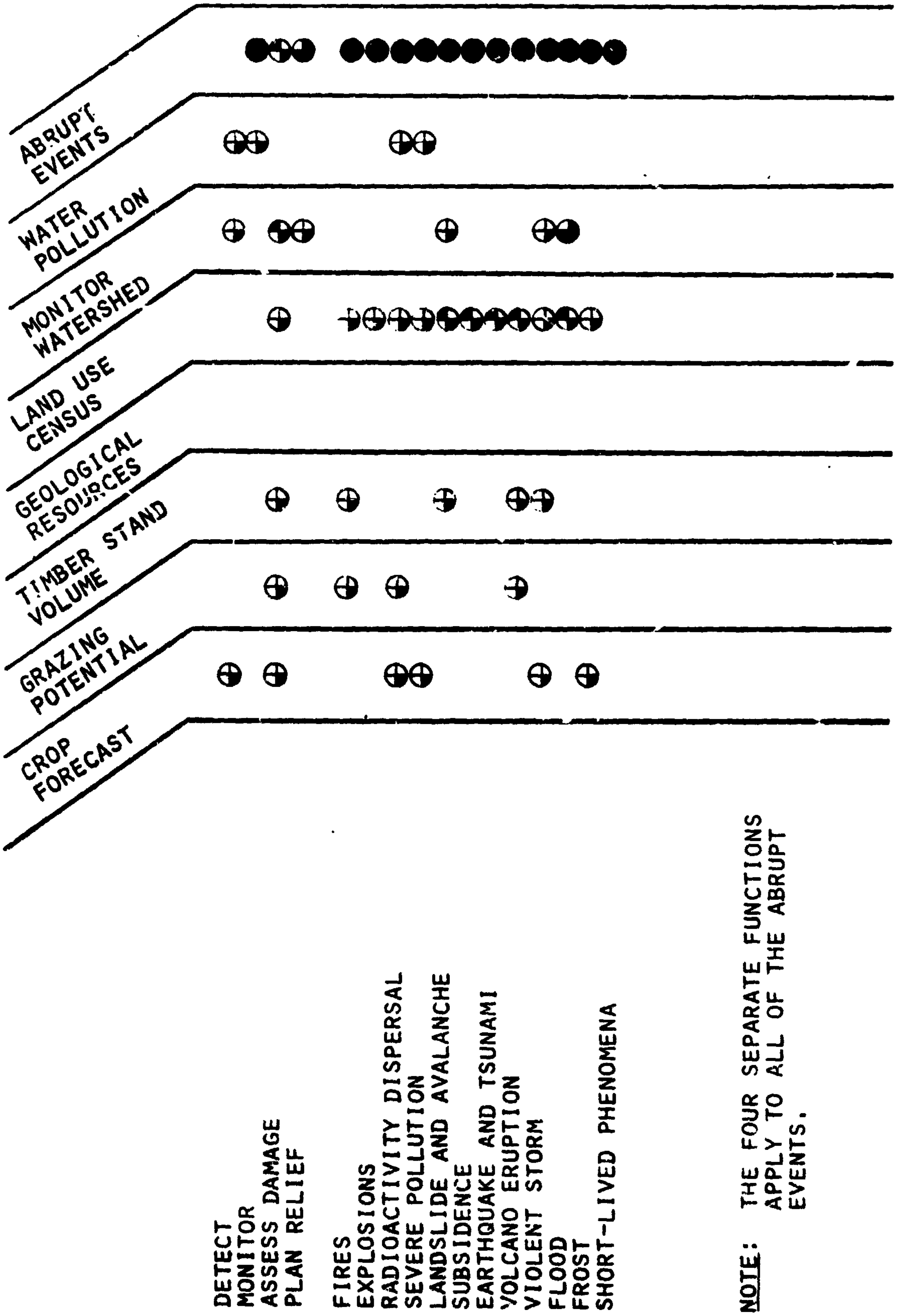


Figure 4-7. Key Set Support for Water Resources Objectives

	CROP FORECAST	GRAZING POTENTIAL	TIMBER STAND VOLUME	GEOLOGICAL RESOURCES	LAND USE CENSUS	MONITOR WATERSHED	WATER POLLUTION	ABRUPT EVENTS
EVALUATE QUALITY OF LIFE					◕		◕	
MONITOR URBAN CHANGES					●			
ANALYZE HEAT ISLANDS								
DETECT LAND OIL SPILLS				◔			◔	◑
MONITOR LAND WASTE DISPOSAL					◔		◔	
MONITOR RADIOACTIVE WASTE					◔		◔	◔
MONITOR WILDLIFE		◔	◔					◔
DETECT FRESH WATER POLLUTION		◔		◔	◔		●	◑
MONITOR FRESH WATER QUALITY	◔	◔				◔	◕	◔

Figure 4-8. Key Set Support for Environmental Quality Objectives



NOTE: THE FOUR SEPARATE FUNCTIONS APPLY TO ALL OF THE ABRUPT EVENTS.

Figure 4-9. Key Set Support for Disaster Assessment Objectives delay between sensor observation and user information. From these requirements, certain system specifications can follow; the four principal ones are: sensed parameter (or wavelength or spectrum); spatial resolution (horizontal and vertical); radiometric (or parametric) accuracy; and the orbit and number of satellites required.

The user requirements are ideally the starting points for system design. A parameter such as resolution should not be listed as a user requirement because it pre-supposes too much about the system configuration; the user is interested in the result and not necessarily how it is achieved. An example of this dichotomy is shown in Figure 4-10. It is instructive to examine this dichotomy because it points out the difference between a user requirement and a system specification quite clearly. One often feels that there is a gray area in between what a user can tell you about his needs and what an engineer requires to shape a systems concept. The diagram illustrates that the gray area is, in fact, black magic.

To the extent that it is possible, Figures 4-11 and 4-12 list guesstimates for the user requirements of the key set of objectives. These numbers are, furthermore, attempts to define what might be needed in the year 2000.

4.3 TRENDS TOWARD FUTURE SYSTEM SPECIFICATIONS

In the ideal world, systems can be designed from the quantitative requirements of the users of remote sensing. In Figure 3.2, the design flow is along the User Driven line. In actual practice, however, many of these linkages are not known and systems must be specified with the help of estimates of future technology and the thinnest skeletons of systems concepts.

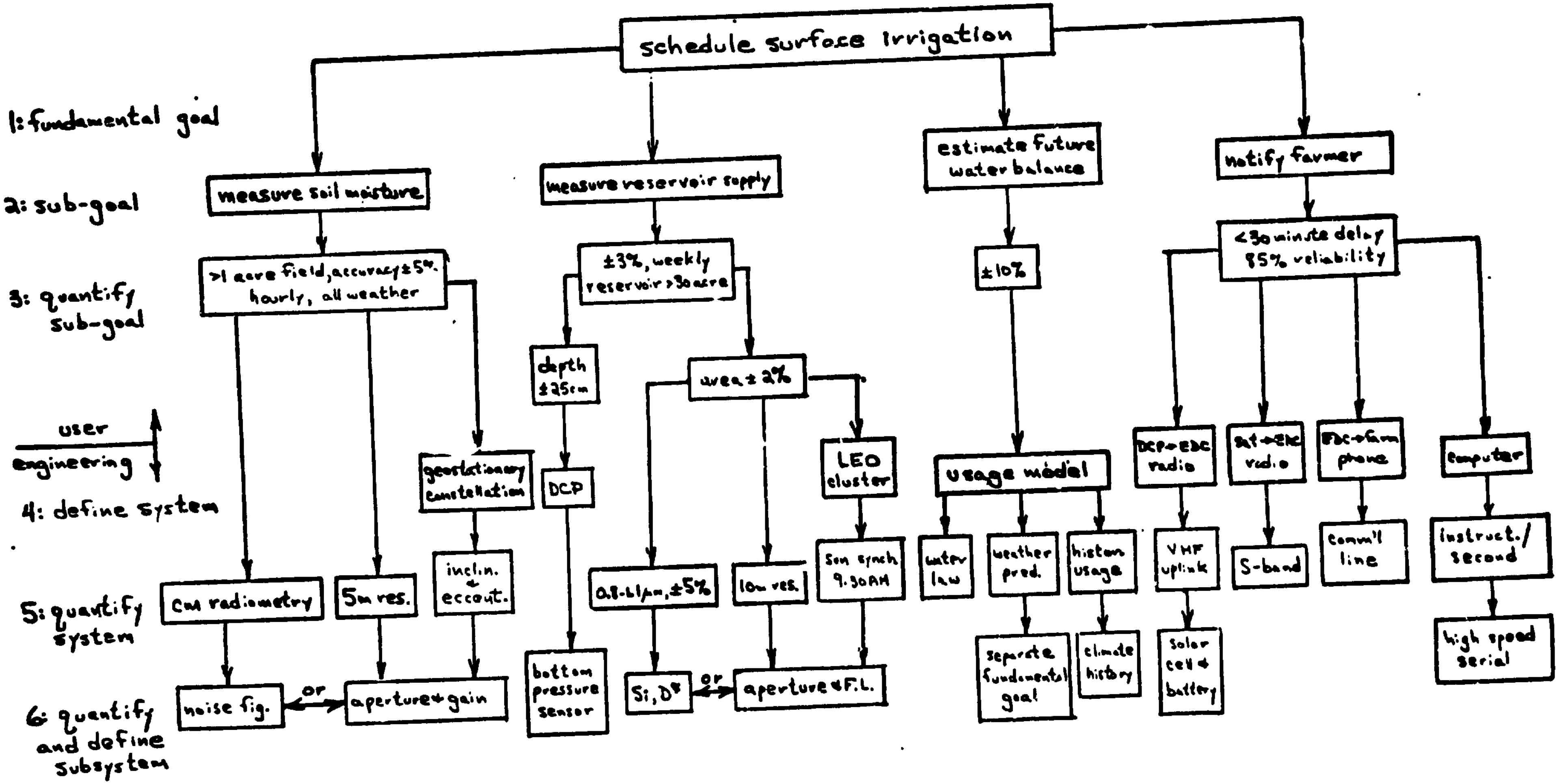


Figure 4-10. User/Engineer Specification Dichotomy

	ACCURACY	PARAMETER RANGE	OBSERVATION FREQUENCY	RESPONSE TIME
CROP PRODUCTION FORECASTING				
IDENTIFY CROPS	93%	ALL	3 DA	2 WK
MEASURE ACREAGE	93%	> 1 HA	3 DA	2 WK
ESTIMATE YIELD	95%	ALL	3 DA	1 WK
DETERMINE PRODUCTION	90%		8 DA	3 WK
GRAZING POTENTIAL DETERMINATION				
IDENTIFY VEGETATION	90%	ALL	1 MO	3 MO
ESTIMATE PALATABILITY			1 WK	3 DA
MEASURE FORAGE BIOMASS	90%		4 DA	4 DA
EVALUATE RANGE PHYSICAL CONDITION			1 DA	6 HR
TIMBER STAND VOLUME ESTIMATE				
IDENTIFY TREES	90%	ALL	1 YR	1 YR
DETERMINE DENSITY DISTRIBUTION	95%		1 YR	1 YR
MEASURE HEIGHT AND DIAMETER	90%	ALL	1 YR	1 YR
DETECT INSECT AND DISEASE ATTACK	80%		1 MO	2 WK
GEOLOGICAL RESOURCES LOCATION				
LOCATE ORES	90%	$\geq 10^7$ KG	SEASON	1 YR
LOCATE CONSTRUCTION MATERIALS	70%	$\geq 10^3 M^3$	SEASON	1 YR
LOCATE FOSSIL FUELS	95%	$> 10^4 M^3$	SEASON	1 YR
LOCATE GEOTHERMAL RESOURCES	75%		1 YR	1 YR
LAND USE AND CENSUS ENUMERATION				
MAP LAND USE TO LEVEL III	98%		1 YR	6 MO
DETECT CHANGE IN LAND USE	95%		2 MO	4 MO
PERFORM DEMOGRAPHIC CENSUS	95%		2 YR	1 YR

Figure 4-11. Requirements to Satisfy Subobjectives of Key Set in 2000

	ACCURACY	PARAMETER RANGE	OBSERVATION FREQUENCY	RESPONSE TIME
WATERSHED MONITORING				
MEASURE SNOW AND ICE VOLUME	80%	$>100\text{M}^3$	3 DA	1 DA
MEASURE STREAM AND RIVER FLOW	90%	ALL	3 HR	1 HR
MEASURE LAKE AND RESERVOIR VOLUME	95%	$>100\text{M}^3$	1 DA	1 DA
WATER POLLUTION DETECTION				
DETECT, IDENTIFY, AND MONITOR POLLUTANTS	85%		2 HR	30MN
MONITOR EUTROPHICATION			2 WK	1 MO
MEASURE SALT WATER INCURSION			3 DA	1 DA
ABRUPT EVENT EVALUATION				
MONITOR AND ASSESS DISASTERS	95%		DEMAND	1 MN
MONITOR NON-CALAMITOUS ABRUPT EVENTS	90%		DEMAND	1 HR

Figure 4-11. Requirements to Satisfy Subobjectives of Key Set in 2000 (Cont'd)

Many previous studies (Ref.$^{4-1-27}$) have listed estimates of the requirements for certain parameters. Figure 4-4 shows the distribution of four of these parameters. For these graphs, all mission objectives have been lumped together. Furthermore, the different studies may each give different estimates for a given need; all of these are included. The parameters which were specified by ranges are entered on the distribution for their entire length. The data are "noisy" because of the tendency to estimate with round numbers. The broken lines are only free-hand approximations to the trend of the data points. The mode of each curve is marked and Landsat-D capability is indicated.

In one distinction, there are two types of remote sensors: those which map particle or photon flux and those which measure scalar or vector fields. The former are much more common; most system requirements are based on optical or microwave solutions to user's needs. While resolution is one of the most important parameters for these electromagnetic systems, there are many others. Table 4-5 lists some of the other parameters which must eventually be specified; few of these can even be estimated now.

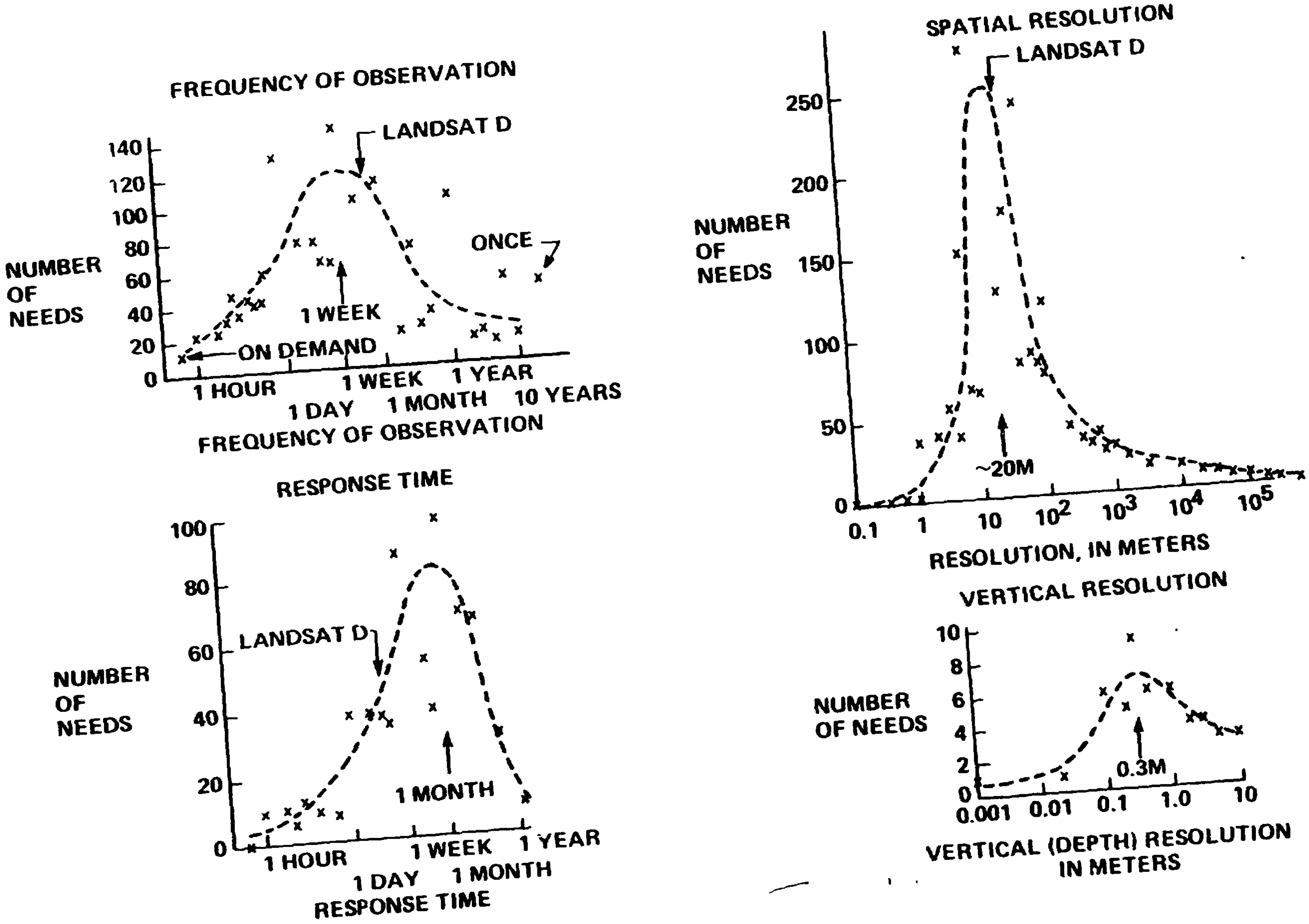


Figure 4-12. User and System Requirements: Some Distributions

Table 4-5. EM Sensing Requirements

Time of year
Time of day; solar angle relative to view angle
Frequency of observation
Time duration for one observation

Location or region; accuracy of location
Area to be surveyed; geographic scale

Detect, map, or sample
    if sample: pixel cluster size and spacing
    if detect: threshold criterion
Probability of successful observation per attempt
Stereo; required parallax angle; depth resolution
Obliquity

Format of output; correlation with earth coordinates
Response time
Radiometric correction
Geometric correction

Spectral band of sensor
Amplitude resolution; shape of IFOV
Polarization of sensor

Spectral band of active source
Polarization of source
Pulse frequency of source; synchronization with sensor
Power output of source; angular coverage.

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5.0 EXPLORATORY TECHNOLOGY FORECASTING

Exploratory technology forecasting is a projection method which involves estimation of the current state of the art and examination of technology trends in order to estimate the level of technology that may be available in a future time frame. This creates the situation of "a solution looking for a problem."

In the PLACE Study, projections of future technology drivers were arrived at via a number of routes. Future system building blocks were then used in the creation of system concepts, as discussed in Section 3.2. The inclusion of this activity in system conceptualization tasks allows for a balance between needs driven and technology driven systems.

The methodology employed in the exploratory technology forecasting activity is illustrated in Figure 5-1. "Blue sky" sessions were held which included GE's Space Systems personnel in an attempt to broaden our technological horizons with respect to future system elements. The results of these sessions were combined with recent literature on technology forecasting and interviews with select technology experts in several fields to yield a list of future technology options. This list was then modified by the "imagineering" of the study team to broaden its content. The resulting concepts in the areas of sensors, platform and support subsystems and data systems provided a firm base of technology drivers for the creation of the future system concepts.

The list of possible future system elements that resulted from the exploratory technology forecasting exercise is discussed in Section 5.1 The results of several specific "future technology trade studies" are presented in Section 5.2.

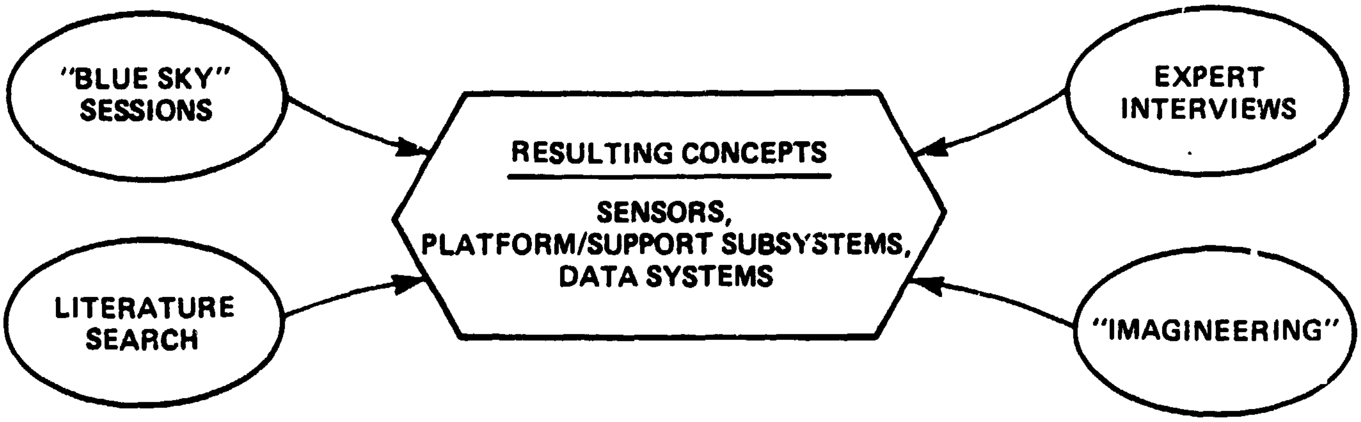

Figure 5-1. Exploratory Technology Forecasting Methodology

5.1 POSSIBLE FUTURE SYSTEM ELEMENTS

The discussion of possible future system elements will be divided into sensing concepts, orbits, platform concepts, support subsystems, and data system concepts. A description of the future space transportation and communication systems assumed to be available is presented in Section 5.2.

Each of the future system concepts will be an end-to-end system, as illustrated in Figure 5-2.

Division into this form highlights the concept of required data processing moving more and more towards the sensor in future system concepts. It also allows the discussion of the possible future system elements presented below.

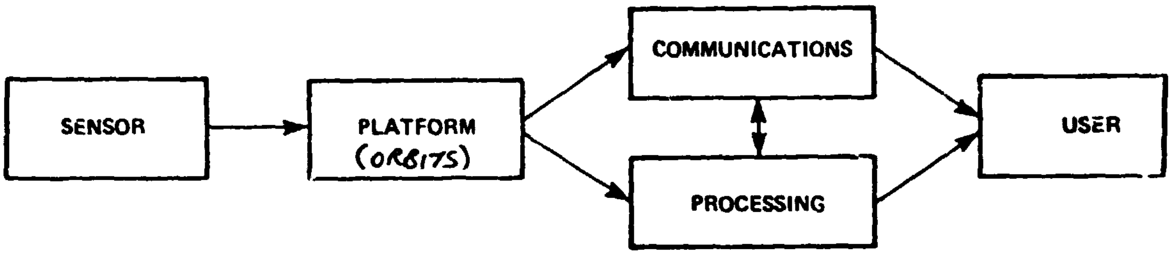

Figure 5-2. PIACE End-to-End System Concepts

5.1.1 EXPLORATORY SENSING CONCEPTS

Visible and infrared (IR) imaging sensors, of the type currently being flown and developed, were proposed. Passive multispectral sensors including push broom arrays (also called multilinear arrays), whisk broom arrays (of the MSS and TM type) and solid state cameras all were considered obvious candidates for future use. Less obvious was the proposed use of active visible and IR sensors using lasers that would provide capabilities for atmospheric calibration, detection of luminescence conditions (both fluorescence and phosphorescence) and night imaging. Finally, the concept of a "smart" visible/IR sensor that could edit its own data, or perhaps modify its acquisition programming based on the data content, was proposed. This concept was incorporated into the Landsat-H system concept and will be discussed in greater detail in Section 6.2.1.

A number of imaginative microwave sensors were proposed for possible future use. Aside from the contemporary synthetic aperture radar (SAR) in low earth orbit, the use of a SAR in geosynchronous orbit was proposed and was eventually developed into the GEOSAR system concept (see 6.1.12). A number of kinds of real aperture radars was proposed including large structures, bistatic radars employing principles of holography and ellipsometry, and the notion of a "swarm" of small satellites acting in unison as a phased array. Several of these ideas were developed into PLACE system concepts, while the last was deferred to a later time due to currently insurmountable technical problems (Section 6.2). Passive microwave radiometers employing apertures of various sizes were proposed and finally an accurate off-nadir altimeter was suggested. Each of these ideas was investigated further and either was developed into one of the PLACE future system concepts or was deferred until a later time.

A new concept in remote sensing measurement from space proposed was that of quantifying ground resource spatial frequency or texture. Both optical and microwave measurement techniques were suggested. These suggestions were later developed into the texturometer and sweep frequency radar system concepts.

Finally, gravity and magnetic field measuring spacecraft were proposed to assist in the global minerals exploration task. A tether satellite concept and a Faraday rotation magnetometer were analyzed; however, the systems were deferred to later study because of insufficient measurement precision (see Section 6.2).

5.1.2 ORBITS

In addition to the familiar Landsat class of low, near polar sun synchronous orbits, the PLACE Study was intended to explore the utility of any other orbits that might be found to have significant benefits for earth resources missions. The initial investigations were not in any way constrained, except by the laws of orbit mechanics; nevertheless, it quickly became clear that the orbits with significance for future earth resources fall neatly into about four loosely defined groups, as follows:

- Sun synchronous, Landsat group
- Space Shuttle sortie group
- Earthwatch group*
- Twenty-four hour period group

The ground coverage characteristics of low-earth sun-synchronous orbits have been well documented by J. C. King (Ref. 5-1), so no effort was spent in exploring them further. For a specific future mission requirement with short access requirements, given sensor characteristics and transportation/propulsion parameters, some detailed comparison of this orbit group of "high" altitudes with others, such as the Earthwatch group, will be needed to define optimal cost/coverage parameters. For example, daily (once per day) coverage of the earth using present Landsat sensors and orbits would require eighteen satellites. The same number of spacecraft in an "Earthwatch" orbit constellation could provide <u>continuous</u> coverage, but with either lower resolution or much larger sensor optics. Further, the Earthwatch constellation would require more orbit-to-orbit transportation.

Similarly, no effort was expended to define the earth resources observations that could be made from Shuttle sortie orbits. In the first place, the properties of these orbits are well known, and second, no missions were included in the final set that required sortie flights.

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* Medium altitude (6000 n. mi) inclined orbit suggested by Pogue (ref. 5-3).

The variety of ground traces that can be made available from a one day period satellite has long been recognized. An early, but comprehensive, description of the effects of orbit inclination, eccentricity and argument of perigee was presented by Stafford, et al, in Ref. 5-2. A good example of the adaptation of daily orbits to a specific mission purpose was done by Pogue, in Figure 2 of Ref. 5-3.

This shaping of a daily orbit to suit a mission purpose was used in the PLACE Study to favor the geometry of a ground trace for a geosynchronous synthetic aperture radar concept. A "circular" ground trace was judged to be most suitable for this mission concept. Figure 5-3 shows the general shape of the ground trace favored. This orbit is inclined one degree, has a period of 1436.078 minutes, an eccentricity of 0.008, and an argument of perigee of -90 degrees. Data on the ground trace, and the elevation, azimuth and range to a typical ground target in the central U.S. (longitude 100 W and latitude 40 N) are shown in Table 5-1. These data have been used to show the technical feasibility of synthetic aperture imaging from 24 hour orbits.

The "Earthwatch Concept" by William Pogue referred to earlier also pointed out the advantages of medium altitude orbits inclined to about 55 degrees as a means of providing frequent global coverage. A particular orbit configuration suggested by Pogue (Figure 5, Ref. 3) was a six hour period (technically, 1/4 of a sidereal day) at an inclination of 55 degrees (.96 rad). The resulting ground trace for this orbit for one day is shown in

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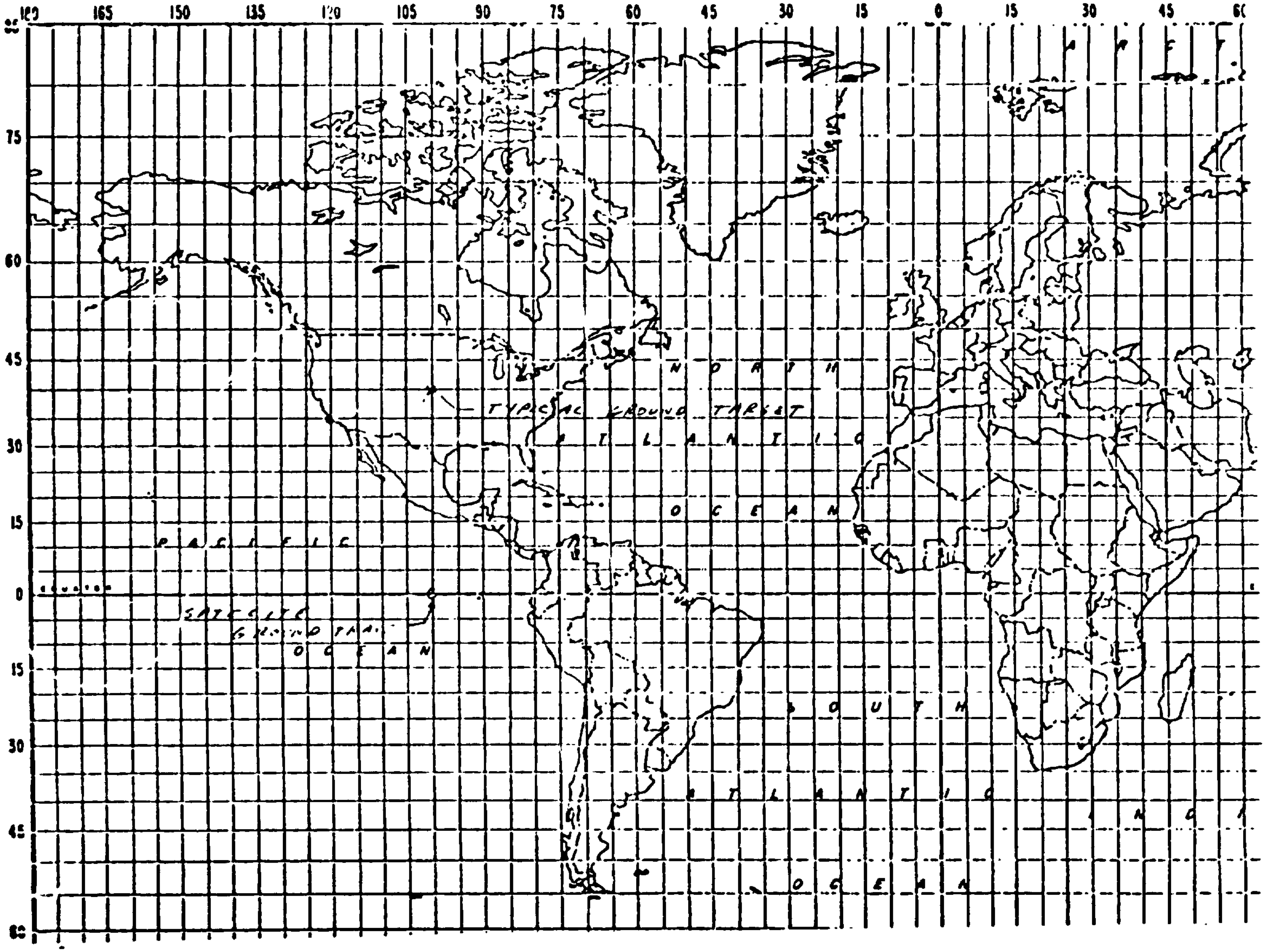

Figure 5-3. Geosynchronous Ground Trace

Table 5-1. Geosynchronous Orbit with Circular Ground Trace

```
 T  (MIN)          OMGDOT(DEG/DAY)   WPDOT(DEG/DAY·
 0.14360781E 04 -0.13414638E-01   0.26823147E-01


T(MIN)          LAT      LONG     ELEV       AZ       RANGE
  0.            1.00   260.00   44.79    179.99   20025.96
 14.36          1.00   260.06   44.78    179.91   20026.41
 28.72          0.99   260.12   44.73    179.82   20027.76
 43.08          0.98   260.18   44.77    179.72   20030.[illegible]
 57.44          0.97   260.23   44.75    179.63   20033.14
 71.80          0.95   260.29   44.73    179.54   20037.15
 86.16          0.93   260.34   44.71    179.46   20042.02
100.53          0.90   260.40   44.68    179.37   20047.72
114.89          0.87   260.45   44.65    179.28   20054.23
129.25          0.84   260.50   44.61    179.21   20061.53
143.61          0.80   260.55   44.57    179.13   20069.58
157.97          0.76   260.59   44.53    179.06   20078.36
172.33          0.72   260.64   44.49    178.99   20087.82
186.69          0.68   260.68   44.44    178.93   20097.93
201.05          0.63   260.72   44.38    178.87   20108.64
215.41          0.58   260.75   44.33    178.81   20119.91
229.77          0.52   260.78   44.27    178.77   20131.70
244.13          0.47   260.81   44.21    178.72   20143.96
258.49          0.41   260.84   44.15    178.69   20156.63
272.86          0.35   260.86   44.09    178.65   20169.67
287.22          0.29   260.88   44.03    178.62   20183.03
301.58          0.23   260.89   43.96    178.60   20196.64
315.94          0.17   260.91   43.90    178.58   20210.46
330.30          0.11   260.91   43.83    178.58   20224.43
344.66          0.05   260.92   43.76    178.56   20238.49
359.02         -0.02   260.92   43.70    178.57   20252.59
373.38         -0.08   260.92   43.63    178.57   20266.68
387.74         -0.14   260.91   43.56    178.58   20280.69
402.10         -0.20   260.90   43.50    178.61   20294.58
416.46         -0.26   260.89   43.43    178.63   20308.28
430.82         -0.32   260.87   43.37    178.66   20321.75
445.18         -0.38   260.85   43.31    178.69   20334.93
459.55         -0.44   260.83   43.25    178.73   20347.77
473.91         -0.49   260.80   43.19    178.77   20360.23
488.27         -0.55   260.77   43.14    178.82   20372.25
502.63         -0.60   260.74   43.08    178.87   20383.78
516.99         -0.65   260.70   43.03    178.92   20394.80
531.35         -0.69   260.66   42.98    178.99   20405.24
545.71         -0.74   260.62   42.94    179.05   20415.08
560.07         -0.78   260.58   42.90    179.11   20424.27
574.43         -0.81   260.53   42.86    179.18   20432.79
588.79         -0.85   260.49   42.82    179.26   20440.59
603.15         -0.88   260.44   42.79    179.33   20447.65
617.51         -0.91   260.39   42.76    179.41   20453.94
631.88         -0.93   260.34   42.73    179.49   20459.45
646.24         -0.95   260.28   42.71    179.57   20464.14
660.60         -0.97   260.23   42.70    179.64   20468.00
674.96         -0.98   260.17   42.68    179.73   20471.02
689.32         -0.99   260.12   42.67    179.82   20473.19
703.68         -1.00   260.06   42.67    179.90   20474.48
718.04_        -1.00   260.01   42.66    179.99   20474.92
```

Table 5-1. Geosynchronous Orbit with Circular Ground Trace (Cont'd)

T(MIN)	LAT	LONG	ELEV	AZ	RANGE
732.40	-1.00	259.95	42.67	-179.93	20474.48
746.76	-0.99	259.89	42.67	-179.84	20473.19
761.12	-0.99	259.84	42.68	-179.75	20471.01
775.48	-0.97	259.78	42.70	-179.68	20467.99
789.84	-0.95	259.73	42.71	-179.58	20464.13
804.20	-0.93	259.67	42.74	-179.50	20459.43
818.57	-0.91	259.62	42.76	-179.42	20453.93
832.93	-0.88	259.57	42.79	-179.35	20447.63
847.29	-0.85	259.52	42.82	-179.27	20440.57
861.65	-0.81	259.48	42.86	-179.19	20432.77
876.01	-0.78	259.43	42.90	-179.12	20424.25
890.37	-0.74	259.39	42.94	-179.06	20415.06
904.73	-0.69	259.35	42.98	-179.00	20405.22
919.09	-0.65	259.31	43.03	-178.94	20394.77
933.45	-0.60	259.27	43.08	-178.88	20383.76
947.81	-0.55	259.24	43.14	-178.83	20372.22
962.17	-0.49	259.21	43.19	-178.78	20360.20
976.53	-0.44	259.18	43.25	-178.74	20347.74
990.90	-0.38	259.16	43.31	-178.71	20334.90
1005.26	-0.32	259.14	43.37	-178.67	20321.72
1019.62	-0.26	259.12	43.44	-178.65	20308.25
1033.98	-0.20	259.11	43.50	-178.63	20294.54
1048.34	-0.14	259.10	43.56	-178.61	20280.66
1062.70	-0.08	259.09	43.63	-178.59	20266.65
1077.06	-0.02	259.09	43.70	-178.59	20252.56
1091.42	0.05	259.09	43.76	-178.58	20238.46
1105.78	0.11	259.10	43.83	-178.59	20224.40
1120.14	0.17	259.10	43.90	-178.60	20210.43
1134.50	0.23	259.12	43.96	-178.62	20196.61
1148.86	0.29	259.13	44.03	-178.64	20183.00
1163.22	0.35	259.15	44.09	-178.66	20169.64
1177.59	0.41	259.17	44.15	-178.70	20156.60
1191.95	0.47	259.20	44.21	-178.74	20143.93
1206.31	0.52	259.23	44.27	-178.78	20131.68
1220.67	0.58	259.26	44.33	-178.83	20119.89
1235.03	0.63	259.29	44.38	-178.89	20108.61
1249.39	0.68	259.33	44.44	-178.94	20097.90
1263.75	0.72	259.37	44.49	-179.01	20087.80
1278.11	0.76	259.42	44.53	-179.07	20078.34
1292.47	0.80	259.46	44.57	-179.15	20069.56
1306.83	0.84	259.51	44.61	-179.22	20061.51
1321.19	0.87	259.56	44.65	-179.30	20054.21
1335.55	0.90	259.61	44.68	-179.38	20047.70
1349.92	0.93	259.67	44.71	-179.47	20042.00
1364.28	0.95	259.72	44.73	-179.56	20037.14
1378.64	0.97	259.78	44.75	-179.65	20033.14
1393.00	0.98	259.84	44.77	-179.74	20030.00
1407.36	0.99	259.89	44.78	-179.83	20027.76
1421.72	1.00	259.95	44.78	-179.93	20026.40
1436.08	1.00	260.01	44.79	179.98	20025.96

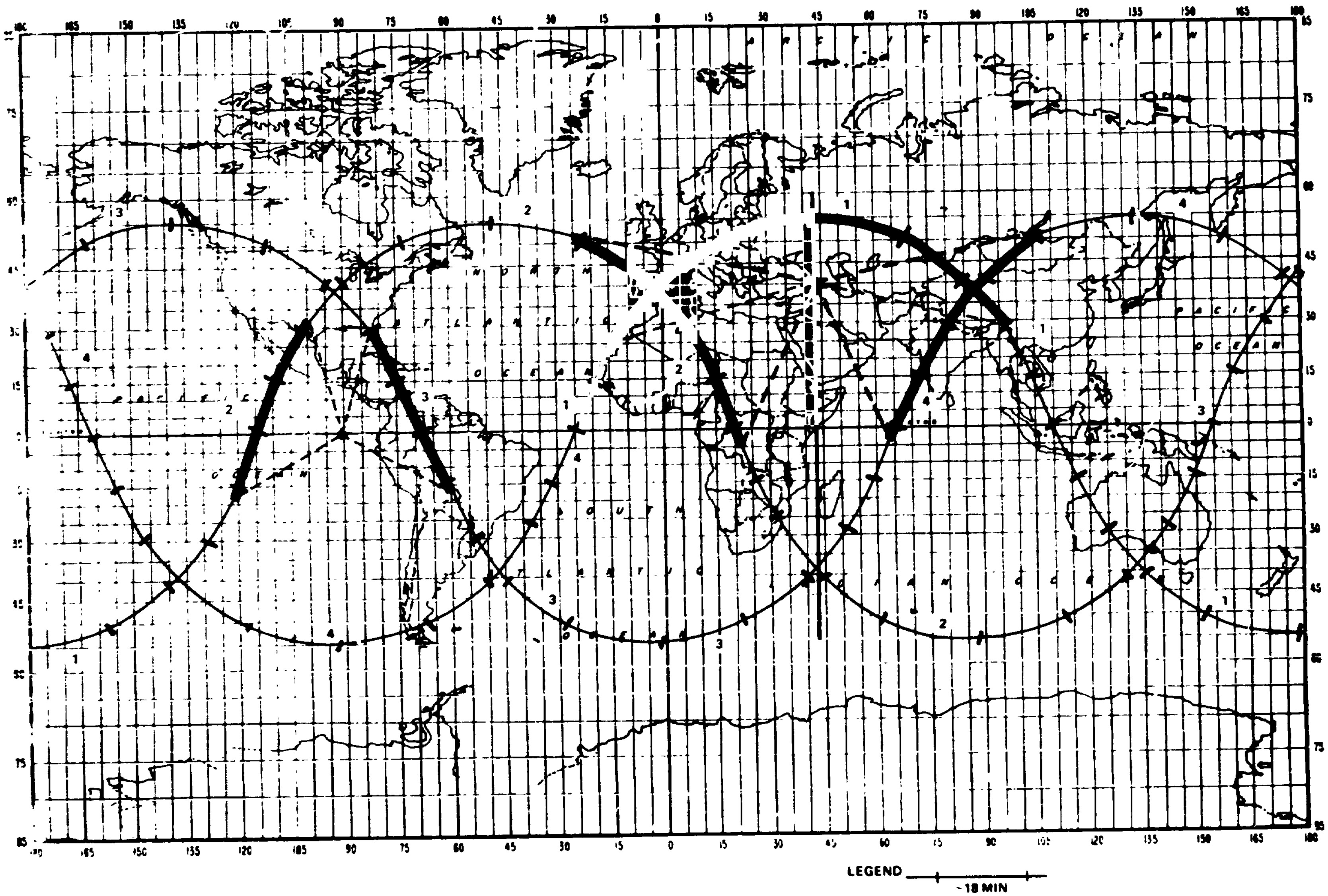

Figure 5-4. Earthwatch - Inclined Repeating Orbits

This figure also shows how the visibility of a given target varies as a function of its location and the desired viewing elevation angle. For example, point "A" (latitude 0, longitude 92.5°W) can be seen twice a day with an elevation angle of 40 degrees, with each viewing period being 60 minutes long. It should be noted that target A is simply typical of eight equatorial longitudes, spaced equally between ascending and descending ground tracks. Each of these points could be seen for two hours every day by a single Earthwatch satellite at a very favorable viewing inclination ot 40 degrees.

For a more favorable choice of parameters, Figure 5-4 shows how a target, "B", can be seen three times a day by a single satellite at a viewing elevation of 20 degrees, for a total view time of 283 minutes. Again, target "B" is a typical one of eight, four at 40 degrees N latitude and four at 40 degrees S latitude.

Table 5-2 presents more complete Earthwatch view times for the "worst case" longitude for a six hour 55 degree inclined orbit. "Worst case" longitude is half-way between ground traces - the hardest place to see. Note that cases A and B are simply two cases from Table 5-2. They have been underlined so that the correlation between Figure 5-4 and Table 5-2 is clearly delineated.

Figure 5-5 is a more graphic representation of the data for the six hour orbit, with a 20 degree viewing elevation requirement. Note that a single satellite can see every point on the globe two to four times per day. This is a capability not available to either low sun-synchronous orbits (Landsat group) or geosynchronous orbits.

Table 5-2. Earthwatch View Times - Six Hour Orbit Case

LATITUDE	VIEWING ELEVATION	VIEWING TIME			TOTAL
		ORBIT 1	ORBIT 2	ORBIT 3	ALL ORBITS
0	10°	96	130	130	356
	20	0	104	104	208
	30	0	81	81	162
	40	0	60	60	120
	50	0	36	36	72
20	10	142	120	120	382
	20	106	96	96	298
	30	64	70	70	204
	40	0	42	42	84
	50	0	0	0	0
30	10	143	115	115	373
	20	114	90	90	294
	30	87	62	62	211
	40	59	32	32	123
	50	17	0	0	17
40	10	140	108	108	356
	20	115	84	84	283
	30	94	54	54	202
	40	75	20	20	115
	50	53	0	0	53
	60	30	0	0	30
50	10	136	106	106	348
	20	115	78	78	271
	30	96	52	52	200
	40	78	6	6	90
	50	61	0	0	61
	60	46	0	0	46
55	10	146	104	104	354
	20	114	78	78	270
	30	95	51	51	197
	40	77	0	0	77
60	10	133	103	103	339
	20	110	77	77	264
	30	92	49	49	190
	40	76	0	0	76
	50	58	0	0	58
	60	42	0	0	42
70	10	123	100	100	323
	20	103	79.5	79.5	252
	30	83	46	46	175
	40	65	0	0	65
80°	10	113	99	99	311
	20°	91	73.5	73.5	238
	30	69	45	45	159
	40	56	0	0	56
90°	10°	99	99	99	297
	20	73.5	72.5	72.5	220.5
	30°	44.5	44.5	44.5	133.5
	40°	0	0	0	0

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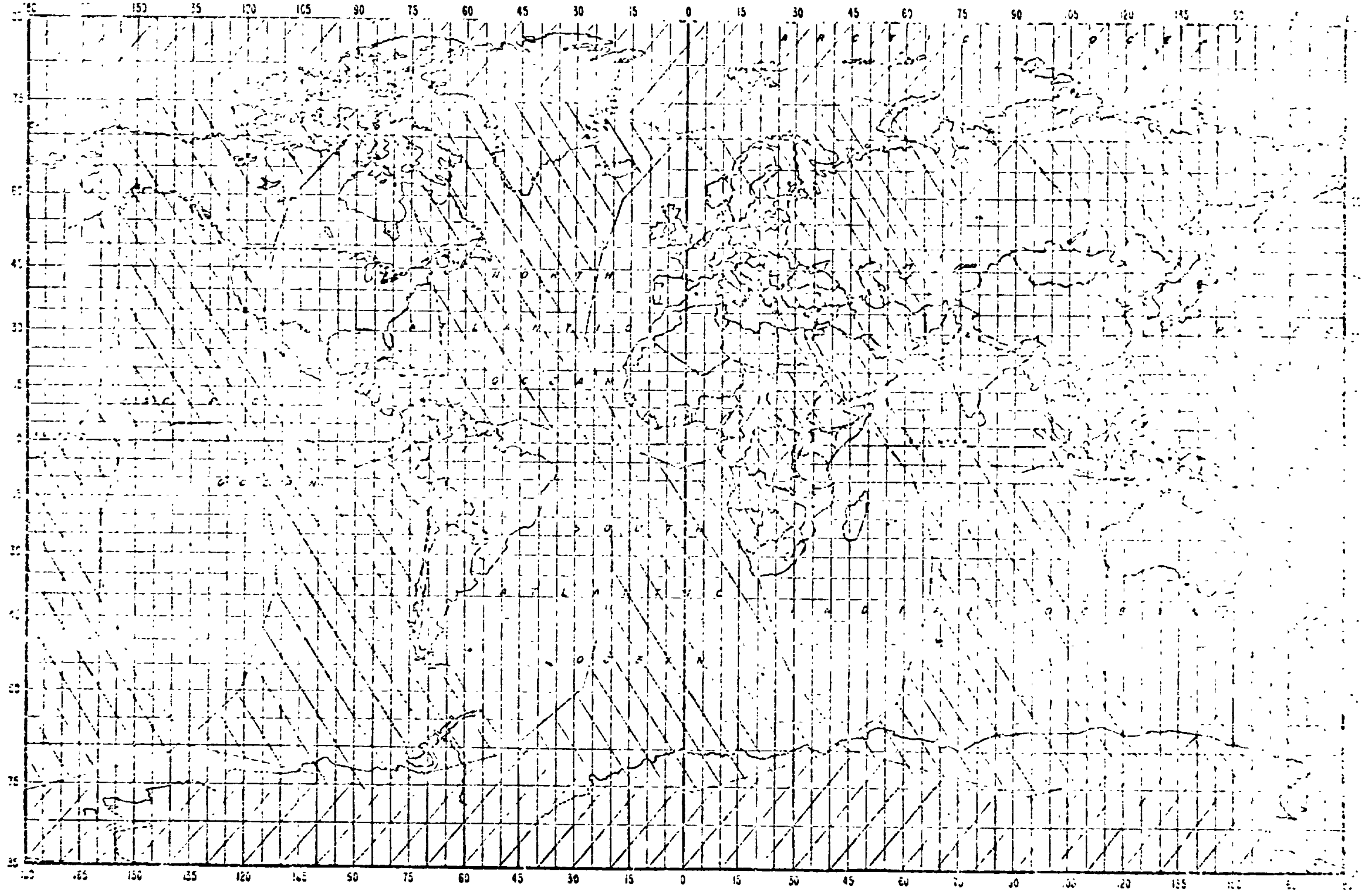

ε = 20°

Figure 5-5. Frequency of Earthwatch Viewing - Six Hour Orbit

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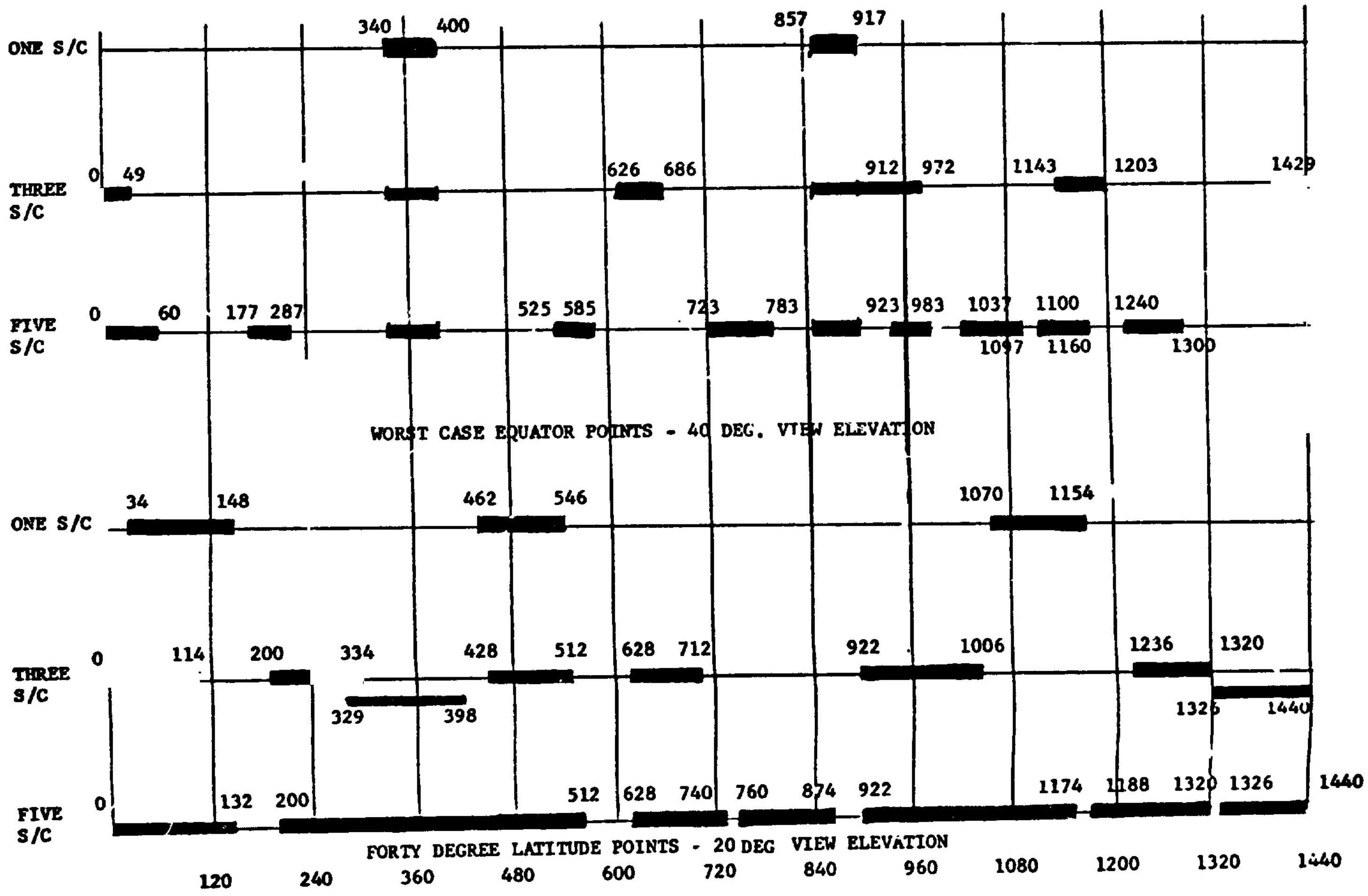

Figure 5-6. Earthwatch Viewing Intervals - Six Hour Case

Unfortunately, the viewing periods are not uniformly spaced during the day, so the determination of the number of satellites required to maintain a specified frequency of observational opportunity becomes complex. This is illustrated in Figure 5-6. The top of the figure shows how one, three, and five satellites can provide "fill-in" coverage at the worst case places on the equator (Target A) for a specified 40 degree viewing elevation. For the three constellations of satellites specified, the possible daily viewing of the equator (minimum) is two, six, and ten hours; and the maximum "outage" (non-viewing) times are 863 minutes, 291 minutes, and 150 minutes respectively.

The bottom half of Figure 5-6 shows the improved situation for target "B," a worst case 40 degree latitude point with a 20 degree elevation requirement. Again, the cases shown are for one, three and five satellites. The total potential viewing times at the worst 40 degree latitude points are 4.7 hours, 14.1 hours, and 23.5 hours. The maximum "outage" or non-view times for these three cases are 524 minutes, 226 minutes, and 116 minutes, respectively.

These initial viewing conditions were manually extracted from computer printouts of the form of Table 5-1, but for lower orbits, and with much finer time resolution used to define elevation limits. To expedite the evaluation of alternative orbits - specifically five, five and a half, and six revolutions per day - the computer program was modified to summarize the pertinent contact data needed for analysis. A sample of the resulting format is shown in Table 5-3.

Figure 5-7 shows the ground traces for a four hour orbit (more precisely, six revs per day), together with the ground targets examined. From the computer data it was concluded that selection of "best" and "worst" cases

Table 5-3. Computer Summary of Earthwatch Viewing Conditions

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                              STATION CONTACT SUMMARY
PERIOD=  359.017                  LATITUDE   0.050        LONGITUDE    42.500

ELEV      START          END            DELTA    AZSTART    AZEND
   5.00     15.94        161.59         145.65   -75.31     73.52
   5.00    480.59        622.99         142.41   -38.57    156.71
   5.00    992.26          0.             0.    -156.75      0.
   5.00      0.         1134.62         142.36     0.       38.77
   5.00   1452.56       1598.21         145.64   -74.70     74.12
  10.00     40.61        136.11          95.50   -50.95     48.33
  10.00    486.26        616.04         129.78   -40.12    160.92
  10.00    999.26          0.             0.    -161.02      0.
  10.00      0.         1128.94         129.68     0.       40.36
  10.00   1477.49       1573.01          95.52   -50.08     49.22
  15.00      0.            0.             0.       0.        0.
  15.00    491.79        609.42         117.63   -41.99    165.06
  15.00   1005.91          0.             0.    -165.22      0.
  15.00      0.         1123.39         117.48     0.       42.28
  15.00      0.            0.             0.       0.        0.
  20.00      0.            0.             0.       0.        0.
  20.00    497.21        603.08         105.87   -44.22    169.26
  20.00   1012.28          0.             0.    -169.48      0.
  20.00      0.         1117.96         105.67     0.       44.57
  20.00      0.            0.             0.       0.        0.
  25.00      0.            0.             0.       0.        0.
  25.00    502.53        596.97          94.43   -46.89    173.62
  25.00   1018.43          0.             0.    -173.92      0.
  25.00      0.         1112.61          94.18     0.       47.30
  25.00      0.            0.             0.       0.        0.
  30.00      0.            0.             0.       0.        0.
  30.00    507.80        591.02          83.22   -50.14    178.29
  30.00   1024.42          0.             0.     -31.79      0.
  30.00      0.         1107.31          82.89     0.       50.60
  30.00      0.            0.             0.       0.        0.
  35.00      0.            0.             0.       0.        0.
  35.00    513.08        585.17          72.09   -54.10   -176.52
  35.00   1030.32          0.             0.     176.05      0.
  35.00      0.         1102.00          71.68     0.       54.66
  35.00      0.            0.             0.       0.        0.
  40.00      0.            0.             0.       0.        0.
  40.00    518.45        579.31          60.86   -59.04   -170.51
  40.00   1036.23          0.             0.     169.91      0.
  40.00      0.         1096.58          60.35     0.       59.74
  40.00      0.            0.             0.       0.        0.
  45.00      0.            0.             0.       0.        0.
  45.00    524.07        573.28          49.21   -65.47   -163.15
  45.00   1042.35          0.             0.     162.36      0.
  45.00      0.         1090.89          48.53     0.       66.39
  45.00      0.            0.             0.       0.        0.
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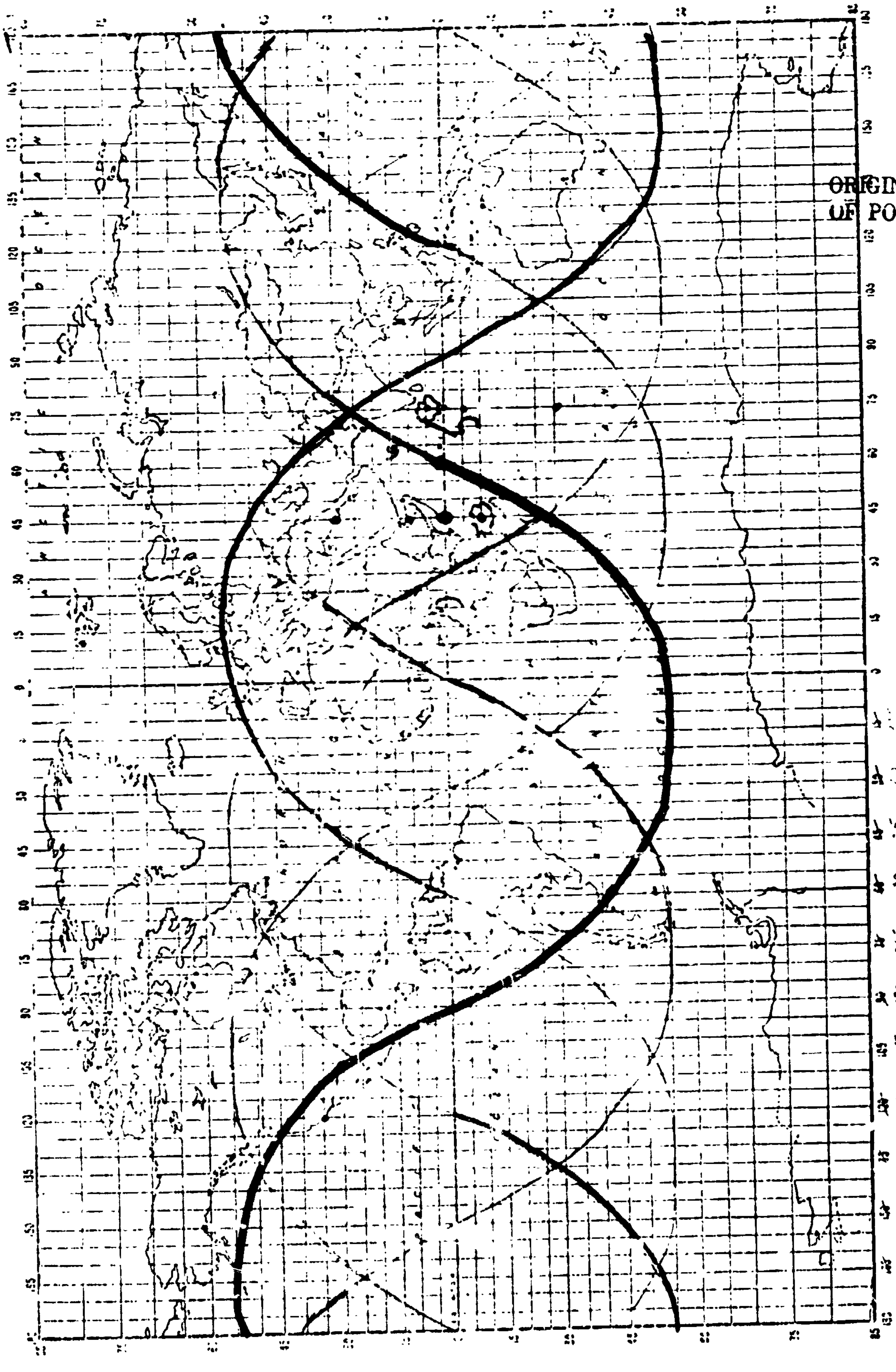

Figure 5-7. Sub-Satellite Trace for Four Hour Orbit

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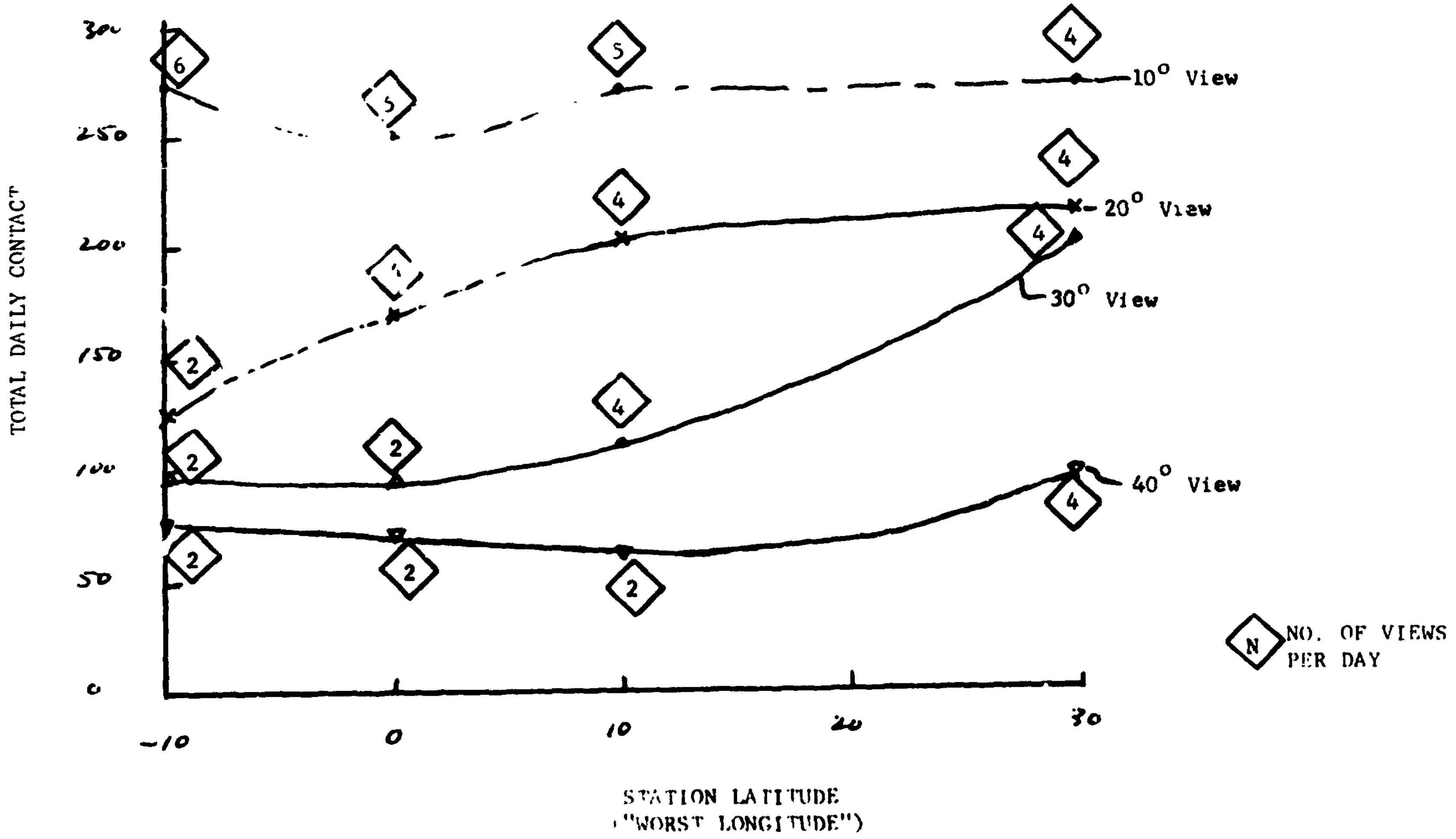
Figure 5-8. Station Contact Profiles for Four Hour Orbits



was not simple. Figure 6 illustrates how the total viewing time from a single Earthwatch satellite is a function of both desired view angle and target latitude (at the "worst" longitude). Further, the choice must be made between maximum total viewing time as an optimizing parameter versus minimum non-contact time as the desired goal. In general, it was concluded that lower orbits provide less total viewing time per satellite day, but more frequent observational opportunities.

A useful summary of the PLACE orbit selection parameters based on the difficulty of attainment is shown in Table 5-4. All launches are via space Shuttle, to the nearest standard Shuttle orbit. Hence, sun-synchronous orbits are attained by onboard propulsion from a 300 kilometer altitude 104 degrees STS orbit, and so on. Any required plane changes from the Shuttle orbit are made by the satellite propulsion system.

The relative Shuttle usage (the last column) is a measure of the cost of achieving mission orbit for each orbit class (per cent Shuttle usage/1000 Kg payload). This does not reflect the size of sensor systems needed to provide the desired ground resolution, nor the number of spacecraft needed to attain a desired contact frequency.

5.1.3 EXPLORATORY PLATFORM CONCEPTS

During the early exploratory technology forecasting phase of the PLACE Study, some attention was given to possible "platform concepts" (read: spacecraft, less sensors) that might enable earth resources missions that are not yet feasible within the present limitations of spacecraft capabilities.

A fundamental premise of the study, of course, is that launch from earth to low orbit will be via the Space Transportation System (Shuttle). Hence, it

Table 5-4. Earth Resources Orbit Comparison

ORBIT CLASS	SHUTTLE LAUNCH ORBIT			MISSION ORBIT PARAMETERS					RELATIVE SHUTTLE USAGE
	ALF. (KM)	INCL. (DEG)	PAYLOAD (KG)	ALT. (KM)	INCL. (DEG)	DELTA VEL (M/S)	MASS RAT RATIO (ISP=300)	NOTES	PER CENT USE FOR 1000 Kg
SUN SYNCHRONOUS	300	104	29,480	600	98	533	1.223	V=168 FOR NO MCL.	4.15
				900	99	736	1.322	V=325 FOR NO MCL.	4.48
EARTHWATCH (INCLINED-MEDIUM ALTITUDE)	300	57	25,850	6391	57	2085	2.265	6 REVS PER DAY	8.76
				7154	57	2230	2.407	5½ REVS PER DAY	9.31
				8042	57	2381	2.566	5 REVS PER DAY	9.93
				10366	57	2706	2.976	4 REVS PER DAY	11.51
GEO-SYNCHRONOUS	300	28.7	14,510	42164	0	4117	5.337	TWO STAGES	36.78
				42164	0	5241	TBD	SOLAR ELECTRIC Isp=2250 500 W/KG	TBD

is immediately evident that larger spacecraft are not only possible, but will be routine by the year 1985, the beginning of the PLACE era. Further, even early in the PLACE Study, there was considerable attention being given to the assembly of shuttle-sized payloads into very large structures in orbit. At the time of the exploratory forecasting work, most of this attention was focused on the Solar Power Satellite, large power modules to support Shuttle, and man-tended large space structures. Based upon any one of several concepts under active development, kilometer sized structures for PLACE missions were a distinct possibility by the late 1980's or early 1990's.

A very similar observation about Shuttle and standard spacecraft was made early in PLACE exploratory forecasting. The essence of this idea was that the combination of low launch cost per kilogram, via STS, and low spacecraft unit cost, via standard modules, could easily lead to the use of constellations of multiple spacecraft for a single mission. This suggestion took root in the Earthwatch concept, where five to ten (or more) identical vehicles provide the temporal access needed by a variety of earth observation programs.

This idea of multiple satellites was pushed to its limit with the suggestion of a constellation of a thousand or more small satellites, each weighing but a few kilograms, and costing only a few thousand dollars each. The enormous reduction in cost per function of electronic circuits, large emphasis upon low cost solar arrays, and the emergence of high strength aramid polyamide composite plastics were all noted as important indicators that simple and low cost space platform could be made.

Enough effort was devoted to this concept of a "satellite swarm" that the feasibility of building many spacecraft of this class was shown to be well within the bounds of the semicredible that had been set for the study. This concept resulted in the SATCLOUD system which is discussed in Section 6.2. Although the platforms concept seemed workable, it did not result in a usable system because sensor problems could not be solved.

In the future technology trade studies described in Section 5.2, the analysis of future space transportation trends concludes that technological capability and economic necessity would result in the use of solar electric ion engine propulsion systems, at least by the late 1980's, as a means of reducing the cost of space operations in high orbits; e.g., geosynchronous. This view was predicated upon: (a) the present (and projected) high cost of expendable stages to reach geosynchronous orbits; (b) the very high cost in both initial development and Shuttle launch mass for a reusable chemical system; and (c) the projection that means of avoiding or repairing (e.g., annealing) the solar array damage resulting from extended travel through the Van Allen belts would be available in the early 1980's. Hence, it is expected that high orbits will be relatively less expensive in the future than they are at present.

It was also noted that previous studies of SEPS (Solar Electric Propulsion Stages) had suggested the use of a "sortie" mode for short missions, much as Spacelab uses a dedicated Shuttle flight to achieve a set of mission objectives. This capability may be useful for PLACE development missions, but none of the final set of PLACE systems adopted this operating mode.

Another platform concept suggested was that of satellites which could be made to "fly formation," i.e., side by side, or one above the other. These orbits are clearly "impossible" in the sense that nearly continuous thrusting is needed to overcome gravitational forces and maintain these positions. For an orbit altitude of 1000 km, a one km side by side separation requires an out-of-plane thrust that varies between zero and about 10^{-4} g. A one km above-below formation would take a continuous thrust (applied to either satellite) of about 2×10^{-4} g. The conclusion drawn was that either arrangement could be maintained for days or weeks using advanced ion thrusters and lightweight solar arrays. None of these "impossible" orbit constellations were adopted in the final set of systems concepts.

5.1.4 EXPLORATORY DATA SYSTEM CONCEPTS

A number of exploratory data systems concepts were discussed as part of the exploratory technology forecasting exercise. The prime motivation for advances in this area may be regarded as an explosion of data processing requirements and capabilities. These driving forces are illustrated in Figure 5-9. We see the ground processing requirements increasing dramatically in the short term. However, a corresponding increase in capability is also taking place, as exemplified by GE's Federation of Functional Processors (FFP) and the Goddard Massively Parallel Processor (MPP) concept.

A number of technology advances are taking place in this area. In microcircuits, for example, chip size is increasing, cost is decreasing, and speed is increasing with no leveling off of these phenomena projected for the near term.

Multifunction chips which both remotely sense and process data are being developed. Current work is being done on a concept of imaging on a charge injection device focal plane, taking the Hadamard transform of the image on the same chip and reading the transform out in parallel from the sense/process

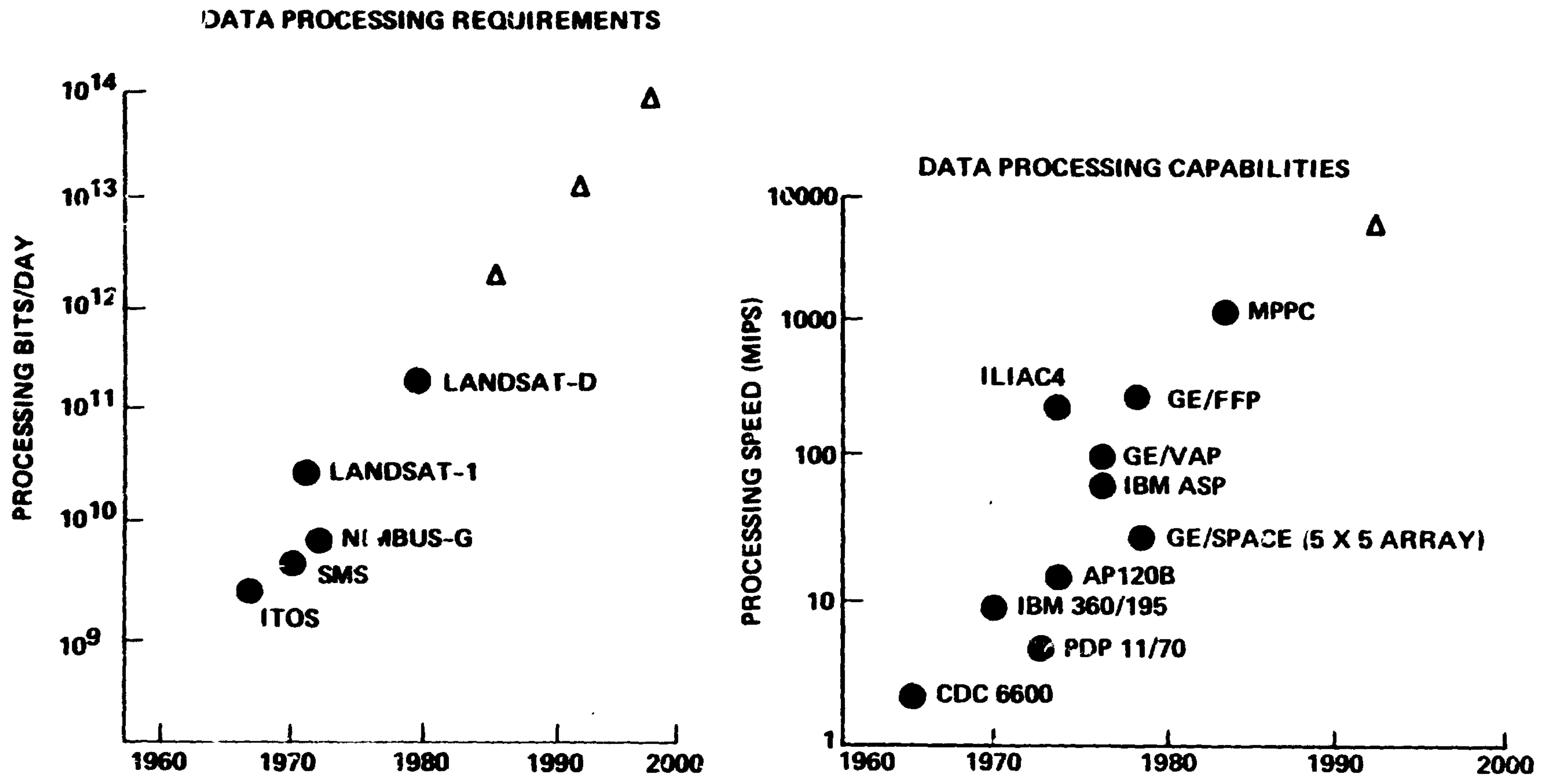


Figure 5-9. The Data Processing Explosion

chip. Another example of the use of multifunction chips is the insertion of logic into memory to allow for faster accessing of data.

Research is now being conducted to investigate the values of epitaxially depositing lithium niobate onto Silicon in order to be able to perform acoustical, optical, and electronic processing, all on the same chip.

Finally, the use of Gallium Arsenide to replace Silicon in LSI technology holds promise. The potential here is for infrared sensing and more rapid processing (than Silicon) on one chip.

A number of concepts for large storage and management of data are also being investigated. A viable solution for a Data Base Management System is the design of a highly parallel and pipeline oriented computer - a data base machine. By incorporating basic data base management functions (retrieve, insert, delete) into hardware, not only can more reliable basic functions be provided but software reliability will also be improved since the S/W requirements will be less complex and the system S/W will be smaller in size. Conventional von Neuman type computers are not designed for data base management. They spend much of the time interpreting data base management calls instead of executing them.

Device technology advances primarily in the following areas will increase the data transfer rate: processors, semiconductor random access memory and all electronic bulk memories. The cost-to-performance ratio of central processing units will decline rapidly over the next ten years. It is safe to assume all electronic systems will replace fixed head disks in the 1980's. Presently, electron beam accessed memories are only feasible in large sizes and they could provide capacities of 10^7-10^8 bytes and block access time of 5 μsec. Mostek has a 65 K bit RAM with an approximate 150 nsec access time and a projected 50 nsec by the 1980's. Semiconductor researchers have applied the Josephson junction to memory. IBM has demonstrated a 16 K bi RAM with 15 nsec access time. However, this operation is only achieved at cryogenic temperatures.

Moving head disks will probably continue to be the mainstay of data base bulk storage. Density improvements should allow at least 10^9 bytes per drive in the '80's. Very large, on-line archival systems should also be available with capacities exceeding 10^{12} bytes.

Another attractive concept is to separate the structural information of the data base (e.g., indices) from the data base itself to minimize the number of accesses to the data base. The amount of mapping information such as pointers in the storage device should be made as small as possible, clustering the contents of the data base, such that data likely to be simultaneously accessed will be placed physically close together.

Since mapping information would be accessed frequently to process queries, this information should be kept in a fast, functionally specialized "structure memory," (for our application, 10^{13} bits). A data base computer conceptualized by Hsiao (1) contains specialized components for the storage of directory information, for the processing of directory information, for the storage of the data base and for security enforcement.

Presented in Figure 5-10 is Hsiao's concept of a data base machine (ref. 6-4). A typical geographic-based information management system data set is presented

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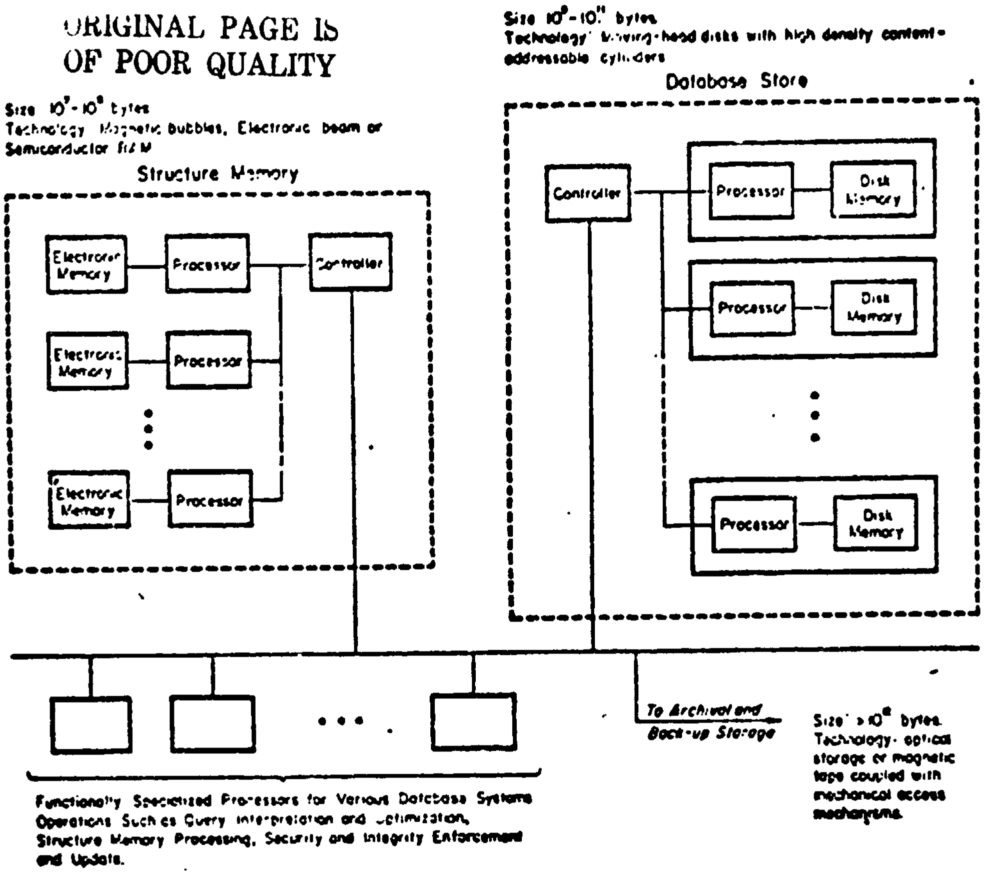

Figure 5-10. Future Database Machine

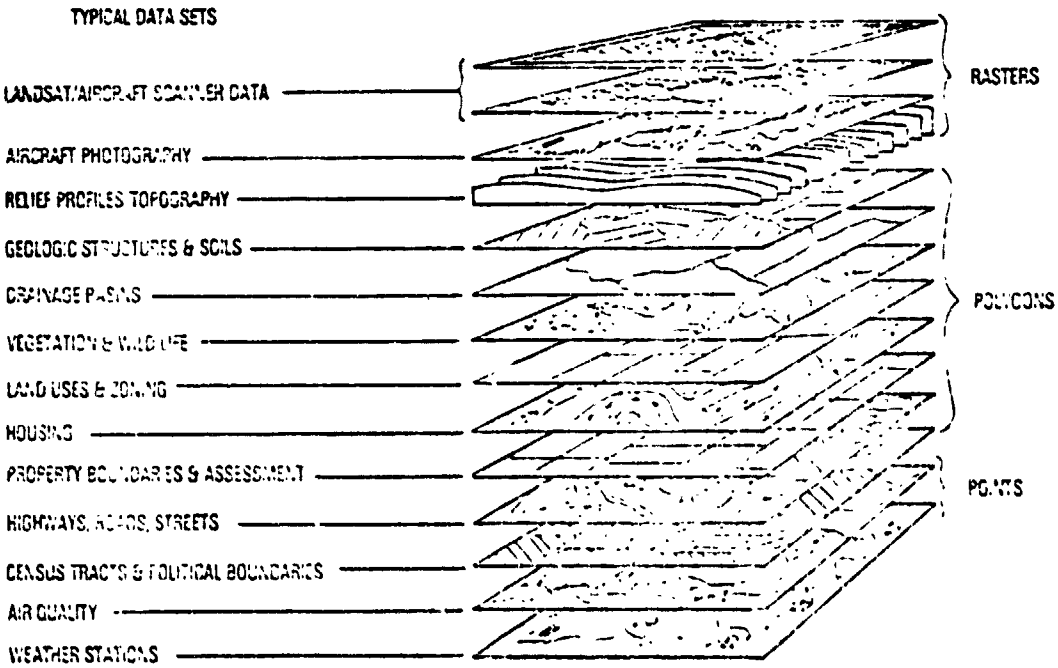

Figure 5-11. Data Sets

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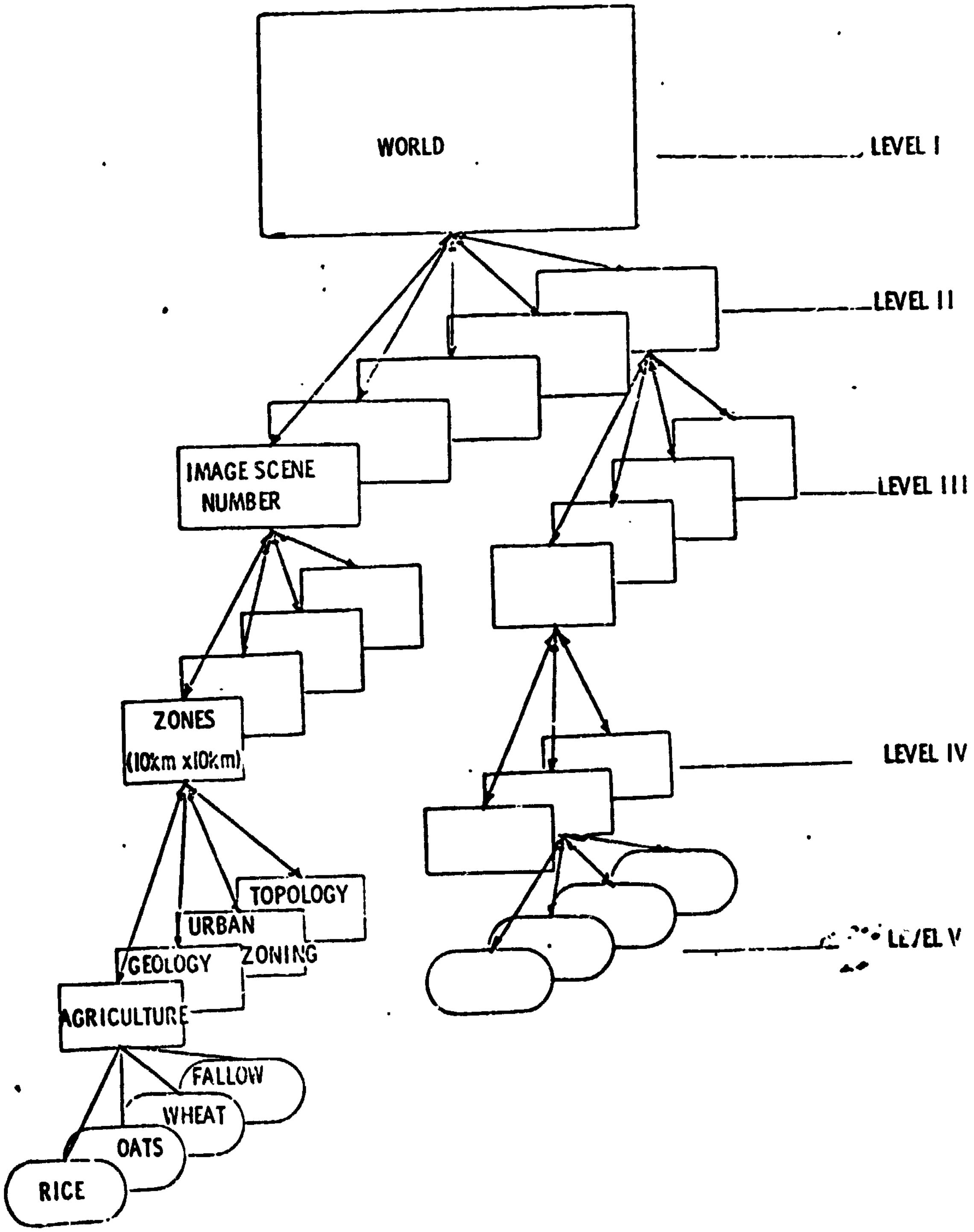

Figure 5-12. Hierarchical Pointer Structure in the Structural Memory

in Figure 5-11. Finally, the hierarchical nature of the structure of such a data set is illustrated in Figure 5-12.

Although the concept of optical processing onboard a spacecraft appears remote at the present time, one could envision it eventually taking place due to the tremendous potential for parallelism, inherent in the process.

5.2 FUTURE TECHNOLOGY TRADE STUDIES

Early in the PLACE Study, it was decided that some of the exploratory technology forecasting efforts would be aimed at an area identified as future trade studies. Their purpose was to break away from "conventional" habits of thought, acquired over years of designing weight/volume limited spacecraft to be launched by expendable boosters.

To illustrate, when a spacecraft designer begins a "new" design in 1978, he has many "givens." The new spacecraft will collect power with silicon solar cells, store it in nickel-cadmium batteries, have an attitude control system using four momentum wheels (three if the mission is short and weight is very tight), etc. Things were always so, and things will continue this way, unless:

- we think of a better way, and
- the new way is a dramatic improvement.

The first point should be obvious, but the second is not. Unlikely as it sounds, outer space is now ultraconservative. Spacecraft customers, quite properly, want to buy what they know will work. There is serious doubt that one could ever sell to anyone, a spacecraft containing a subsystem whose principal claim to fame was that it cost half as much as the old way, provided (1) there was a flight proven alternative way to do the function, and (2) the subsystem function was essential to mission success.

An expensive subsystem which could reduce cost by an order of magnitude, possibly could be sold, preferably if it has had a flight test first.

In order to break new ground in thinking about satellite design, it seems important that the focus be far enough into the future that change from present practice seems assured. Hence, the effort was to "think 1992," which is 15 years away. Then we can go back 15 years in the space business for a mental comparison.

The basic presumption of this effort was that economics will dominate future decisions, i.e., the lowest price for an equivalent solution will prevail, provided that the price is truly lowest and the functions really equivalent. However, no cost/benefit ratio study could predict the magnitude of CB radio sales, or the instant popularity of pocket calculators, as soon as the technology permitted. Hence, the future trade study effort tried to recognize any special restraints or forcing functions outside of technology, that seemed likely to affect the course of future developments. Finally, a basic economic premise for future trade study analysis was that costs should be compared in mission orbit, i.e., including space transportation costs, both surface-to orbit, and orbit-to-orbit.

5.2.1 FUTURE SPACE TRANSPORTATION

In the past, launch costs and the envelope limitations imposed by payload fairings have been crucial design considerations, often dominating all others, even to the point of compromising reliability by limiting design margins (or redundancy) or by imposing complex deployments. In the Shuttle/PLACE era - 1985 and beyond - both weight and volume constraints will become much less important. In order to define some cost/mass ratios for PLACE systems, transportation to mission orbit was addressed.

Before projecting into the future, consider the present STS costs. The non-DOD government use cost for STS, fixed for three fiscal years, will be about $18 million 1975 dollars (Ref. 6-18). It will deliver 29,500 Kg to LEO at 28.5° inclination, or 18,000 Kg to low sun-synchronous orbit. Thus, on a dedicated basis, the 1980-83 cost is $610 per Kg to low inclination, or $1,000/Kg to sun-synchronous, in 1975 dollars. However, for less than a full load, 133% of these prices will apply, to allow for a 75% load factor. Hence, most payloads will pay $814, or $1,333 per Kg.

The first question is, "What cost can be expected in the last half of the decade?" There are numerous suggestions to convert the boosters to winged flyback, or hydrocarbon engines, or both (Ref. 6-10,11). It does not appear at all likely that NASA will invest the necessary billion dollars or so to develop these options unless the traffic is substantially greater than planned. However, if the planned traffic develops, there are two mechanisms for cost improvement: payload growth and cost learning.

Table 5-5 shows a simple breakdown of STS cost elements (Ref. 6-11).

C-2

Table 5-5. Shuttle Operating Costs

	Per Cent	$ Based on $18M Cost
Orbiter	15	$ 2.70 M
Solid Rocket Booster	40	7.20 M
External Tank	23	4.14 M
Facilities	22	3.96 M
		$18.00 M

In each cost area there are activities where, historically, cost learning occurs. In the orbiter area there is both maintenance and launch preparation; in the booster there is propellant manufacture, recovery operations, and refurbishment. The external tank is a big airframe production line, and facilities operations are good candidates for learning. After considering all the combinations of learning curves and fractions of the cost subject to learning, it turns out that either a 98% learning curve on all costs, or a 95% learning curve for half the costs, gives the expectation that the per flight cost should be down to about $15 million per flight (1975 dollars) in the second half of the 1980's.

There is bound to be some growth in the orbiter payload capability with time. Every booster and airplane experiences this. In addition, there is already some margin in the system design which may not be used in the development phase. It seems reasonable to project about a 20% growth by the second half of the decade. This would allow for a payload of about 35,000 Kg (35 Mg) for low inclination, or 21,600 Kg for sun-synchronous orbits.

The combination of these factors leads to a "what is likely" cost of $571 and $926 per Kg (75% load factor) in the mid-to-late '80's, given adequate traffic. These results are summarized in Table 5-6.

Table 5-6. Launch Cost Comparison (75% Load Factor)

Inclination	Present	Late 1980's
28.5°	$814/Kg	$571/Kg
90°	$1333/Kg	$926/Kg

The cost to achieve geosynchronous earth orbit (GEO) is now an order of magnitude more than for low earth orbit (LEO). There are at present two upper stage designs being pursued to take spacecraft from LEO to GEO. The first is the Spinning Solid Upper Stage (SSUS). This design is intended to place a spacecraft containing its own apogee kick motor (AKM) into a transfer orbit, starting from the STS orbit. This design is being developed in two sizes, one suitable for Delta-class payloads (SSUS-D) and the other for Atlas-Centaur (SSUS-A) class payloads. The second design is the Interim Upper State (IUS), which is being developed by the USAF. It is a 3-axis stabilized design and provides all of the functions needed to move any payload from STS orbit to GEO.

The price and performance has not been announced for any of these designs yet, (circa mid-1978) but enough is known to provide some informed speculation on GEO costs. Since the upper stage cost data is so sketchy it is considered to be the same for both early and late 1980's. Table 5-7 shows the projected costs. It must be noted that the cost per Kg in this table is constructed by allocating an STS cost based upon the number of upper stages that orbiter can provide.

Table 5-7. Expected GEO Transportation Cost

Item		Early 1980's	Late 1980's
STS Launch Cost		$18. M	$15 M
IUS	No./Launch	2	2
	Useful Payload-Kg	2250	2400
	Cost-each	$15 M	$15 M
	$ per Kg	$10,667	$9375
SSUS-A	No./Launch	2	3
	Useful Payload-Kg	1100	1300
	Cost-Each	$ 5 M	$ 5 M
	$ per Kg	$12,727	$7692
SSUS-D	No./Launch	4	5
	Useful Payload-Kg	550	700
	Cost-each	$ 3 M	$ 3 M
	$ per Kg	$13,636	$8571

In considering what new transportation system elements might become available in the late 1980's and in the 1990's, three principal data sources were consulted. These were the technology forecasts done in the NASA "Outlook for Space" study (Ref. 5-16), the NASA/AIAA symposium on space industrialization (Refs. 5-11, 14, 15, 21), and the Boeing study on Solar Power Satellites (Ref. 5-17).

The first topic to consider is what can be done to reduce the very high cost of getting spacecraft to geosynchronous orbit. NASA did have plans to develop a cryogenic space tug to perform this function. It would have taken one STS to LEO orbit to launch and return it, ready for re-use. It was projected to have the capability to take 1090 Kg round trip to GEO, or 3600 Kg up only, or other combinations of up and down. It required very high technology to achieve this performance, so it would cost a few billion dollars to develop. Neglecting operating or amortization costs, it could reduce GEO transportation to \$15 M/3600 Kg or \$4,167 per Kg. Since this is only a factor of two better than the expendable systems, it does not seem likely that NASA will fund this concept at least until there is a firm need for returning things, such as men, from GEO.

A more promising candidate is the aeromaneuvering tug (Ref. 5-21). This vehicle uses upper atmosphere braking on the return leg to minimize propellant consumption. Its delivery capability is projected to be nearly 50% greater than tug (which implies delivery costs of about \$2900 per Kg), while the round trip capability is expected to be 2.6 times that of tug (or 2850 Kg). Since the needed technology is easier, and the design sensitivities to component performance are reduced, it will be cheaper than tug to develop. Still, it will probably cost a billion or two, and NASA is not expected to spend that in the near future. This appears to be a good candidate for manned operations in GEO in the early 1990's, but it was not forecast as a cargo carrier in this century.

There is a third candidate for the LEO-GEO mission. This is the Solar Electric Propulsion Stage (SEPS). A year ago the SEPS study by Boeing did not project any capability for SEPS to do a LEO-GEO mission (without an awkward mid-orbit transfer from IUS) because of Van Allen belt radiation damage (Ref. 5-23). Recent results from the Boeing Solar Power Satellite

(SPS) study have shown (Ref. -17, 22) (a) that annealing of silicon solar cells can be done to remove most of the radiation damage; (b) that Ga As cells are much more radiation resistant and may be usable in SEPS; and (c) that thin-film silicon cells are more radiation resistant.

These results lead to the possibility of a very attractive LEO-GEO transfer system. Since it is also useful in several LEO missions as well, it is seen as "what is likely" that SEPS will be developed. Once this is done, it is a small step to outfit it with radiation resistant solar cells and use it in LEO-GEO mode. Boeing has not made any calculations about trip time LEO-GEO for an unassisted SEPS, since they only quite recently considered that possibility. However, some calculations about transporting SPS modules from LEO-GEO using the power it provides, give enough data to assure that there is an attractive system here (Ref 6-17). A 50 Kw SEPS, which is now being planned, would have a thrust of about 2 Newtons. A self powered solar cell SPS module with a thrust to mass ratio of 5 x 10^{-5} can go from LEO to GEO in 200 days (Ref. 5-17). On this basis, a 2 Newton SEPS can take 4180 Kg from LEO to GEO in the same time. Of this, 2000 to 2500 Kg would be useful payload.

A SEPS is functionally much simpler than a $10M comsat of 1977 vintage, so the unit cost should be less. It does have much more array, but even at $10 a watt (believed to be high for 1985), 50 Kw is only $0.5 M. STS transportation to LEO is below $1.0M, so a $10M unit cost in LEO seems reasonable. Based on that, 2500 Kg payload, and amortization over seven years with seven per cent money, the "likely to be" cost is $1200 per Kg delivered to GEO. Note that nearly half of that is the LEO delivery cost. Table 5-8 shows the variance around this value for different payloads and payback periods.

Table 5-8. SEPS to GEO Transportation Cost
(Late 1980's)

	PAYBACK PERIOD		
	5 YRS	7 YRS	10 YRS
Annual Charge[1] (7% Interest)	$2.44 M	$1.85 M	$1.42 M
Cost per Trip[2]	$2.3 M	$1.55 M	$1.19 M
STS Charge[3]			
2000 Kg payload	$1.428 M	$1.428 M	$1.428 M
2500 Kg payload	$1.142 M	$1.142 M	$1.142 M
Cost per Kg			
2000 Kg	$1383 M	$1191	$1047
2500 Kg	$1586	$1346	$1161

1) For $10 M SEPS
2) 200 days up, 100 days down, 1.2 trips per year (believed very conservative)
3) $571 per Kg

In considering the transportation costs to LEO in the 1990's, it turns out that the two central issues are the amount of traffic to be carried and whether the non-recurring cost is to be recovered as payload charges, or whether the government will make another ten billion dollar investment to "open up space."

At the Space Industrialization Symposium referred to earlier, several single stage-to-orbit (SSTO) concepts were presented. They were all Shuttle-class (30 Mg) payloads, and the gross liftoff weight was also comparable to Shuttle or less. It was the consensus that such a vehicle could be built by 1990 for something less than $10 billion. The technology forecast of "Outlook for Space" showed several projections of a two stage vehicle. Finally, the Boeing SPS Study showed two fully reusable designs capable of 380 Mg payloads, both for less development cost than $10 billion. Evidently size is not a major factor in development costs for new boosters. Assuming that investment payback is required, Table 5-9 shows the effect of best and worst case amortization and effect of traffic.

Table 5-9. Transportation Amortization Cost - $10 Billion Program

35,000 Kg Single Stage to Orbit Design		
Term	10 Yrs	15 Yrs
Interest	7%	6%
100 flight/yr	$407/Kg	$294/Kg
200 flight/yr	203/Kg	147/Kg
365 flights/yr	111/Kg	80.6/Kg
180,000 Kg Two Stage Design		
100 flights/yr	$79/Kg	$57/Kg
200 flights/yr	40/Kg	28/Kg
365 flights/yr	22/Kg	16/Kg
380,000 Kg Reusable (SPS Case)		
1875 flights/yr	$ 2/Kg	$1.44/Kg
3125 flights/yr	1.20/Kg	0.87/Kg

Based upon this look at investment, it is apparent that a new SSTO design will not be attractive in comparison with an uprated Shuttle until the traffic is well over 200 Shuttle flights per year. That is, for one tenth of this investment (∼ $1 billion) a flyback booster can be developed in the 1990's that would cut the Shuttle per flight cost to about $12 million. By using more composites, lighter avionics, etc., the Shuttle payload can go up to 50 Mg, so the cost per Kg to LEO would be $240 operations for a full orbiter, plus investment recovery. (Note that at 50 Mg, Shuttle is definitely volume constrained.)

Most projections of operations costs circa 1990-2000 are in the $50-100 per Kg range (e.g., Ref. 5-16). This seems extremely high for a fully reusable system. Consider the airline analogy. This assumes that one can learn to run a spaceline as efficiently as one can now run an airline. At present fuel is between 35-40% of total direct aircraft operating costs over the range of aircraft from DC-9 to 747 (Refs. 5-25, 26). Based on this analogy, one might expect total operating costs for a spaceline to be three times propellant costs, to be slightly conservative. If maintenance costs are much higher for a space vehicle, the maintenance factor can be quadrupled and space operations are projected to cost six times the propellant cost.

In the references surveyed, the mass of propellant per kilogram of payload ranged from below 30 Kg to over 50 Kg (e.g., some SSTO's had less propellant per Kg than two stage designs, etc.). Based on that survey, a value of 50 Kg per payload Kg looks fairly conservative.

A 1974 article in Astronautics and Aeronautics considered the price and availability of large quantities of liquid hydrogen (for aircraft) in the 1990's (Ref. 3). That article projected costs of $0.29 per Kg of liquid hydrogen (LH) made from coal, or $0.55 per Kg for LH from electrolysis of water using nuclear energy rates. Since in the later case oxygen is derived essentially free, as a byproduct, costs were based on the electrolysis method. If a mixed mode system is selected using kerosene/oxygen as the boost propellants, kerosene costs of $0.375 per gallon ($0.11 per Kg) must be included. Using free oxygen, $.55/Kg hydrogen and $.11/Kg kerosene, and assuming a 50 Kg/Kg load factor, the total propellant cost is $2.22 per Kg of payload. Thus we might project mature spaceline operations to cost between $6.65 per Kg and $13.30 per Kg of payload.

As another data point, consider the Boeing SPS study. Although it contemplates two or three thousands of flights per year of a reusable vehicle, there are no evident economies of scale that suggest that the operations cost cannot be scaled down by an order of magnitude with little effect. (Note that this system is operating to 477.5 km altitude at 31° inclination, a somewhat more demanding orbit than STS). Table 5-10 gives a summary of the Boeing cost study results and provides a hint of the detail to which the study was pursued. The total cost projection comes to about $20 per Kg, but adjustments must be made to the numbers before they can be used for a more modest program of a few hundred flights per year.

First, note that this $20 per Kg provides not only for running the spaceline, but for buying it; e.g., the production, spares, and tooling items provide for the acquisition of 626 airframes and some 15,400 engines over the 14 year life of the program. These items amount to about 45% of the $20 per Kg, leaving $11.22 or $10.86 per Kg for operations, depending on recovery mode. Of this $10 balance, nearly half is propellant cost. The Boeing propellant costs appear to be high by a factor of about four. They used $0.095 per Kg for oxygen, $0.214 per Kg for RP-1 and $2.623 per Kg for liquid hydrogen. If we use the prices quoted earlier, the propellant cost for winged recovery would go from $5.28 to $1.21. This leaves $5.94 for ground operations, direct and indirect manpower and program support.

The head count in the Boeing study is very high, as they freely acknowledge. They estimate a force of 148,000 people working to turn around 36 vehicles at any given time. This is a count of 4100 people per vehicle, while United Airlines has a total head count per vehicle (including flight attendants, counter personnel, etc.) of 125, of which 22 are in maintenance.

Even if spaceline is allowed one order of magnitude more people per vehicle, the manpower costs have been inflated by a factor of 3.28, e.g., $4.46 per Kg should be only $1.36. Now, for a 400 Mg class booster there are three operating cost elements:

TABLE 5-10 BOEING SPS TRANSPORTATION COST ESTIMATE

WBS ELEMENT	WINGED RECOVERY		BALLISTIC RECOVERY	
	$ PER KG	%	$ PER KG	%
OPERATIONS COST	20.82	100	19.48	100
PROGRAM DIRECT	17.10	82.1	15.85	81.4
PROGRAM SUPPORT	0.74	3.5	.72	3.7
PRODUCTION AND SPARES	8.50	40.8	7.64	39.2
STAGE 1	4.13	19.9	4.67	24.1
AIRFRAME	2.62	12.6	2.41	12.4
ENGINES	1.51	7.3	2.28	11.7
STAGE 2	4.37	21.0	2.53	13.0
AIRFRAME	2.37	11.4	1.32	6.8
ENGINES	2.00	9.6	1.21	6.2
PAYLOAD SHROUD	NA	NA	.41	2.1
TOOLING	1.10	5.3	.98	5.0
STAGE 1	.68	3.3	.66	3.4
STAGE 2	.43	7.0	.27	1.4
PAYLOAD SHROUD	NA	NA	.05	0.2
GROUND OPS/SYS	6.76	32.5	6.52	33.5
GROUND OPS	.93	4.5	.97	5.0
GROUND SYS	.13	.6	.13	.7
GSE SUSTAINING ENGR	.12	.6	.12	.6
GSE SPARES	.28	1.3	.23	1.2
PROPELLANT	5.28	25.2	5.02	25.8
OTHER	.04	.2	.04	.2
DIRECT MANPOWER	1.79	8.6	1.74	9.0
CIVIL SERVICE	.94	4.5	.91	4.7
SUPPORT CONTRACTOR	.85	4.1	.83	4.3
INDIRECT MANPOWER	1.93	9.3	1.88	9.7
CIVIL SERVICE	1.05	5.0	1.02	5.3
SUPPORT CONTRACTOR	.88	4.2	.86	4.4

Ground operations	$1.48 per Kg	(36.5%)
Propellant	$1.12 per Kg	(29.9%)
Manpower	$1.36 per Kg	(33.6%)

The ground operations and manpower per flight are roughly independent of launch vehicle size, so to go to smaller launch vehicles, the cost per Kg will increase; e.g., for a 100 Mg size the costs per Kg would be $5.92, $1.21, and $5.49 respectively, for a total of $12.57. This is ten times the propellant cost, vs. two and half for airlines.

The key question is whether there will be enough demand for space transportation in the 1990's to induce anyone to spend $10 billion dollars to develop and deploy a new, fully reusable earth-LEO transportation system. It is possible that there will be enough world-wide demand for such things as picture phone conferencing, direct TV broadcasting, space manufactured products, pocket telephones, free-fall laboratories, fire alarm satellites, ozone replenishment, etc. to make such a system attractive. Further, the export of satellites, delivered in orbit, is likely to be as important to the U.S. economy and balance of payments in the 1990's as the export of commercial jets was during the 1960's.

In summary, the "what is likely" forecast is for a new and reusable transportation system having operating costs in the mid-90's of $10 to $20 per Kg, and with amortization costs of $50 to $100 per Kg. Based upon that, the array size on SEPS is doubled (keeping weight and costs the same via solar cell progress) and the "what is likely" cost to GEO falls from $1200 per Kg to $250 per Kg if amortization is not charged, or $300-$350 per Kg if it is.

5.2.2 TDRSS II

In order to approximate the communications requirements of post 1990 PLACE systems, it is necessary to make several assumptions about the performance of a second generation TDRSS. This section will make such assumptions for a "baseline" case.

The most basic need is for a higher data rate, i.e., more bandwidth. The present TDRSS is limited to a TDRSS-ground link between 13.4 GHz and 14.05 GHz. After this spectrum is allocated to the several services involved, 225 MHz bandwidth is available for high data rate service. By using quadraphase modulation, a 300 M bps data rate is packed into this spectrum. It seems unreasonable to expect to get close to a gigabit per second into the present frequency allocation unless multiple access and S-Band single access services are completely eliminated, which is not considered reasonable. Consequently, a new (higher) frequency band will be considered. The only plausible band (based on the 1975 Office of Telecommunications frequency allocation plan) would be (space to earth) between 17.7 GHz and 21.2 GHz, which is 3.5 GHz wide, or more than five times the present TDRSS allocation. Within this band, still assuming several types of service, a 1 Gbps or more link should be possible. Note that there is no other spectrum presently allocated that is nearly as wide until over 100 GHz, where a 3 GHz slot is open (102-105 GHz). For purposes of this analysis, it will be assumed that to use the 102 GHz band would require technology enhancement, so the 18 GHz band will be postulated.

Assuming a frequency plan not grossly different from TDRSS, the space-to-space PLACE user to advanced TDRSS will be just slightly lower than the space-to-earth link. For purposes of link guesstimates, a 17 GHz return link will be assumed.

For present purposes, it will be assumed that the principal improvements that are reasonable to expect for a follow-on TDRSS would be a larger user-to-TDRSS antenna, with pointing improved so that the pointing loss would remain the same, and a lower noise temperature receiver. All other losses will be assumed to be the same. The effect of these assumptions is shown in the column "TDRSS II in Tables 5 - 11, 12 and 13 for MA, SSA and KSA services (Ref. 5-47). Footnotes to these sheets explain the detailed assumptions.

This improvement in TDRSS II capability implies that a user satellite wishing to return 1 Gbps to earth via TDRS II would need to have EIRP of 59.2 dB at the return link frequency of 17.7 GHz. This could be accomplished by a 40 W transmitter on the user (PLACE) system with a one meter antenna and an antenna pointing error of about 10 arc seconds.

If still higher data rates are required by PLACE systems, then spacecraft-to-spacecraft laser links can probably provide up to 3 Gbps in the post 1990 era. Return of this data to the ground could be a problem. However, if the frequency slot between 102-105 GHz were dedicated to high data rate service (i.e., no MA or SSA service), this return could probably be accomplished under most weather conditions. New facilities would be required for such a service.

A capability for onboard storage and bandwidth reduction processing is also assumed. This will allow for callup and retrieval of sampled data from the TDRSS as an alternative to ground storage. Estimates of the data storage and computational power available on board will be discussed as technology forecasts in Section 7.

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Table 5-11. MA Return Link Budget - User to TDRS

BER User EIRP (dBW)	10^{-5} EIRP	TDRSS II 10^{-5} EIRP
Space Loss (dB)	-192.2	-192.2
Polarization Loss (dB)	0.0	0.0
TDRS Antenna Gain (dB)**	29.6	29.6
Antenna Pointing Loss* (dB)	-1.3	-1.3
P_s at Output of Antenna (dBW)	-163.9 + EIRP	-163.9 +EIRP
T_s (Antenna Output Terminals) (°K)	615	300
T_i (Due to Direct Other User Interference) (°K)	295	295
$K (T_s + T_i)$ (dBW/Hz)	-199.0	-200.8
$P_s/K (T_s + T_i)$ (dB) (Hz)	35.1 + EIRP	36.9+EIRP
Spurious and IM Degradation (dB)	-0.5	-0.5
Tandem Link Loss (dB)	-0.2	-0.2
$P_s/(N_0 + x)$	34.4 + EIRP	36.2+EIRP
Antenna Beam Forming Loss (dB)	-0.5	-0.5
Link Margin (dB)	-2.3	-2.3
Required E_b/N_0 (dB-Hz) ΔPSK	-12.4	-12.4
Achievable Data Rate (dB)	19.2 + EIRP	21.0+EIRP
FEC Gain, R = 1/2, K = 7 (dB)	5.2	5.2
Achievable Data Rate (dB)	24.4 + EIRP	26.2+EIRP

Table 5-12. SSA Return Link Budget - User to TDRS

BER User EIRP	10^{-5} $EIRP_{DG2}$	TDRSS II 10-5 $EIRP_{DG2}$
Space Loss (dB)	-192.2	-192.2
Pointing Loss (dB)	-0.7	-0.7
Polarization Loss (dB)	-0.0	-0.0
TDRS Antenna Gain (dB)	36.9	42.9
P_s at Output of Antenna (dBW)	-156.0 + $EIRP_{DG2}$	-150.0+ $EIRP_{DG2}$
T_s (Antenna Output Terminals) (°K)	450	300
KT_s at Output of Antenna (dBW/Hz)	-202.1*	-203.8
P_s/KT_s (dB-Hz)	46.1 + $EIRP_{DG2}$	53.8+ $EIRP_{DG2}$
Spurious and IM Degradation (dB)	-1.0	-1.0
Tandem Link Loss (dB)	-0.5	-0.5
$P_s/(N+X)$	44.6 + $EIRP_{DG2}$	52.3+ $EIRP_{DG2}$
Link Margin (dB)	-1.9**	-1.9
Required E_b/N_o (dB-Hz)	-11.9**	-11.9
Achievable Data Rate (dB)	30.8 + $EIRP_{DG2}$	38.7+ $EIRP_{DG2}$
FEC Gain, R = 1/2, K = 7 (dB)	5.2	5.2
Achievable Data Rate (dB)	36.0 + $EIRP_{DG2}$	43.7+ $EIRP_{DG2}$

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Table 5-13. KSA Return Link Budget - User to TDRS

BER User EIRP (dB)	10^{-5} $EIRP_{DG2}$	TDRSS II 10^{-5} $EIRP_{DG2}$
Space Loss (dB)	-209.2	-210.3
Pointing Loss (dB)	-0.2	-0.2
Polarization Loss (dB)	-0.0	-0.0
TDRS Antenna Gain (dB)	52.7	58.7
P_s at Output of Antenna (dBW)	$-156.7 + EIRP_{DG2}$	$-151.8 + EIRP_{DG2}$
T_s (Antenna Output Terminals) (°K)	579	350
KT_s at Output of Antenna (dBW/Hz)	-201.0	-203.1
P_s/KT_s (dB-Hz)	$44.3 + EIRP_{DG2}$	$51.3 + EIRP_{DG2}$
Spurious and IM Degradation (dB)	-0.5	-0.5
Tandem Link Loss (dB)	-1.0	-1.0
$P_s/(N+X)$ (dB)	$42.8 + EIRP_{DG2}$	$49.8 + EIRP_{DG2}$
Link Margin (dB)	-1.3**	-1.3
Required E_b/N_o (dB-Hz)	-12.9**	-12.9
Achievable Data Rate (dB)	$28.6 + EIRP_{DG2}$*	$35.6 + EIRP_{DG2}$
FEC Gain, R = 1/2, K = 7 (dB)	5.2	5.2
Achievable Data Rate (dB)***	$33.8 + EIRP_{DG2}$*	$40.8 + EIRP_{DG2}$

5.2.3-A POWER SOURCE OPTIONS TRADE STUDY

The first step in considering future technology trades was to consider the power source. For long life, free flying spacecraft, as contemplated for most PLACE systems, only solar or nuclear energy sources are competitive.

Nuclear sources were considered, but not found to be attractive for any PLACE mission that we could envision. First of all, reactors were not regarded as suitable for PLACE missions. Their use has been projected only for very large power requirements. With 50 to 100 kilowatt (or more) solar arrays now considered feasible, no requirements larger than possible from solar arrays were foreseen. No space reactor is presently under development, and no PLACE need for one could be visualized which would justify a program of such a magnitude.

Secondly, with the PLACE emphasis on spacecraft economy, it does not appear that isotope systems are applicable to PLACE systems, even though the economics of future isotope systems is projected to be greatly improved for two reasons. First, dynamic systems are under development which produce much more electrical power from a given amount of isotope. Secondly, some DoE projections for the cost of isotope fuel suggest that future prices may be significantly lower than at present. Even with the most optimistic projections, however, isotope costs are almost certain to remain far above future solar array costs. Hence, isotope systems will not have an economic benefit, and appear to remain limited to applications such as outer solar system exploration, lunar surface applications (long night duty), or where environmental hardness is essential. Since none of these conditions apply to PLACE missions, nuclear systems were not considered further.

Several choices need to be made in the utilization of solar energy. The most basic is the form of conversion. These are several possibilities: Photovoltaic, Thermoelectric, Thermionic, and Dynamic (Ranking, Brayton, or Stirling). Of these possibilities, only photovoltaic conversion is considered to have any significant potential for PLACE missions by the year 2000. All the other candidates have serious handicaps relative to solar cells.

Thermoelectric conversion requires a hot side temperature of many hundreds of degrees C. A large area ratio solar concentrator of accurate figure must be quite accurately pointed at the sun to achieve the necessary temperatures. Even after this is done, the thermal to electric conversion efficiency is quite low; well below ten per cent. Then sizable radiators are needed to reject the large amounts of heat not converted into electricity. This combination of disadvantages appears to put solar thermoelectric space systems permanently out of the competitive range unless some breakthrough in technology not now in sight occurs, or some very specialized mission requirement offsets these major problems.

Solar thermionic systems are in only a slightly better competitive position. Very high concentration ratios (with very accurate solar pointing) are needed to achieve temperatures of a couple of thousands degrees celsius. Heat is rejected at rather higher temperatures, so the radiators are small. Conversion efficiency is potentially quite good, but the technology for building thermionic converters of high efficiency and long life in quantities at low cost is far from demonstrated. There is no apparent system advantage to PLACE to justify development of solar thermionic technology.

Solar dynamic systems seem to be the nearest competitor to the solar array. Early in the space program, when solar cell efficiencies were in the ten per cent region and costs high, solar dynamic systems with potential efficiencies of perhaps 30% looked attractive by comparison, and development efforts were started on kilowatt size units. As solar array sizes and efficiencies increased, and cost and mass decreased, and as the inevitable development pains of solar dynamic systems occurred, the kilowatt class solar dynamic systems lost their competitive advantage and the development program was discontinued.

For very large power systems of the future, specifically the Solar Power Satellite (SPS), solar dynamic systems have been re-examined. Multi-megawatt turbogenerators are a frequent item of commerce, whereas the largest solar array ever flown is only a few kilowatts. So in that sense, solar dynamic conversion is a more proven technology for large sizes than solar arrays. However, the huge solar concentrators for megawatt systems have never been built in space either. For SPS size sub-units, radiator size and mass considerations limited solar dynamic conversion efficiency to about 25%, only slightly better than projected solar cells. All things considered, the Boeing study team (Ref. 5-17) selected solar arrays in lieu of solar dynamic systems as the currently preferred power generation means for SPS.

Solar dynamic systems could readily be developed for a few kilowatts, based on the rotating machinery developed by the Department of Energy (DoE) for their isotope programs. However, the long life, unattended operation of light speed rotating machinery remains an unanswered question. Overall, no basis could be found to include solar dynamic power systems in the list of technologies needed for PLACE.

The remaining questions for solar cells are whether they should be used in a central or distributed manner, and whether it would be more economical to use more (increasingly cheap) cells to eliminate expensive orientation mechanisms. As the next section shows, an oriented concentrating array was found to be very attractive for small satellites, while an unoriented distributed array was preferred for a very large system (Ferris Wheel).

5.2.3 SOLAR ARRAY TRADE STUDY

A key consideration for solar arrays for earth orbit missions is how light weight and low cost should be traded to minimize system cost. The following reasoning is suggested. If the transportation cost to mission orbit is $1000 per kilogram, and the array specific power is 25 watts per kilogram (representative of current state of the art for rigid panels), then a one kilowatt array would weigh 40 kilograms, and the associated transportation cost would be $40K. Improving the array specific power to 100 watts per kilogram would reduce array weight and transportation cost to 10 kg and $10K respectively, the saving of $30K in transportation cost - equal to $30 per watt - is the even trade value of lighter weight. In other words, with array costs at the present level of several hundred dollars per watt, a ten per cent reduction in array cost is about equivalent to a four to one weight reduction. If future array costs are less, weight decreases will be of relatively greater value. However, as future transportation costs are reduced, weight savings will be corrsspondingly of less value. The weight cost trade is presented in Table 5-14 for various orbits, transportation costs, cell costs and cell performances. Future transportation costs were discussed in Section 5.2.1.

Since weight and power are the basic parameters in most subsystem trade studies, the cost and mass of power subsystems was the second topic to be investigated in the area of future trades.

Table 5-14. Cost/Mass Trades in Space Shuttle Era

ARRAY POWER COST PER KILOWATT		NOW		FUTURE CHOICE		
		STD CELL	THIN CELL	STANDARD OR CONCENTRATING		THIN PLANAR
	COST/W	300	1000	50	25	300
	W/KG	25	200	25	50	300
LEO $1000/KG	ARRAY TRANSP. TOTAL	300 K 40 K 340 K	1000 K 5 K 1005 K	50 K 40 K 90 K	25 K 20 K 45 K	300 K 3 K 303 K
GEO $5000/KG	ARRAY TRANSP. TOTAL	300 K 200 K 500 K	1000 K 25 K 1025 K	50 K 200 K 250 K	25 K 100 K 125 K	300 K 17 K 317 K

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The solar array trade study showed that by using a concentration ratio of about a hundred to one (on Ga As cells), we can reduce solar array panel costs by more than an order of magnitude compared to today, while reducing weight for a rigid panel by a factor of about four. This result was implicit in a study of Space station-solar array system started by GE for Grumman, but not carried to completion. The hundred to one reduction in cells was duly noted, but the configuration development stopped with a circular concentrator nested in a maze of framing. The central result that makes such an advanced array possible was the thermal analysis. This showed that a temperature of 125°C was consistent with 100:1 concentration ("century class") and a modest amount of aluminum cooling fins; specifically, six square inches of 0.020 inch aluminum (39 cm^2 x 0.5 mm). Simple checks of this calculation support the general conclusion.

The remaining step is to combine the elements of concentrator, cell and fin into a more elegant combination to reduce space, weight and cost. The evolution of these elements into a basic concentrator module is shown in Figure 5-13. The first transition is to go from the deep parabolic concentrator (F/O - 0.5 shown) at the lower right of Figure 5-13 to the Fresnel reflector at the upper right. The second transition is to go from a circular shape, which packs poorly, to a hexagonal shape, which packs well. The third transition is to add the solar cell, fins, and structure as shown at the lower left.

In this module configuration, the concentrator could be pressed into plastic, like pressing a record, but a better approach is believed to be a molded engineering foamed plastic. On the reflecting surface, aluminum or silver is deposited. Since the α/ϵ of bare metal could be poor enough to overheat the plastic, a thin film of transparent plastic is deposited on top of the metal to get better emissivity. Six aluminum arms of a spider serve both as radiators and structural support. A conical cup at the center supports the solar cell and its cover glass and conducts the heat from the cell to the radiator fins. A plug of insulation fills the cup to eliminate insulation on the back of the solar cell.

The configuration does not show as many concentric grooves as would be desirable in an actual concentrator; more grooves would lead to less shading by the adjoining ridges. A solar array panel is formed by joining numerous modules. The sketch at the lower left of Figure 5-13 suggests a method of spot-welding support fins on adjacent modules to form a truss structure. Since the resulting structure is composed of triangular trusses, as seen in Figure 5-14, it is thought to be stiff enough for most applications.

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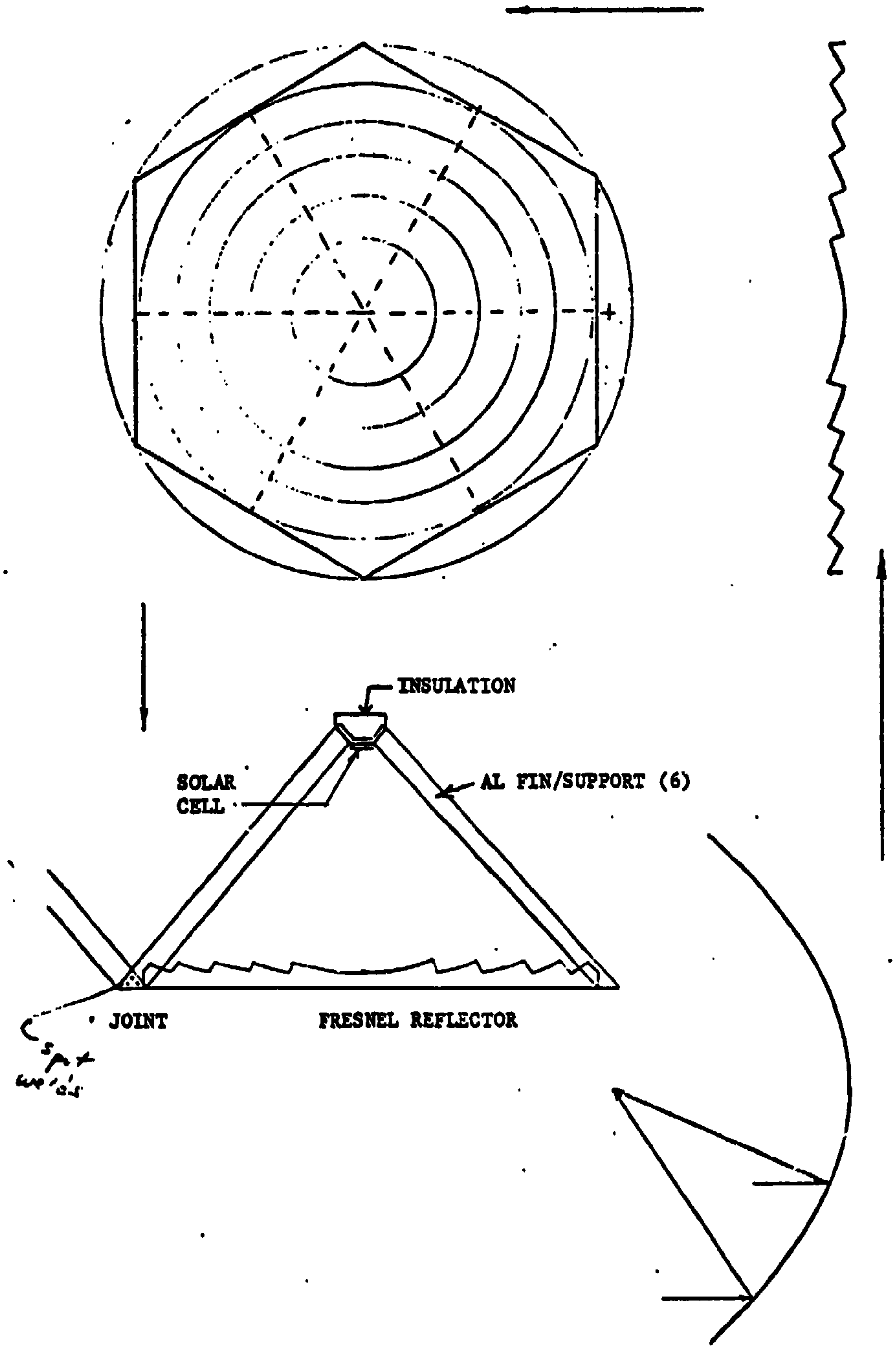

Figure 5-13. Evolution of "Century" Concentrator Module

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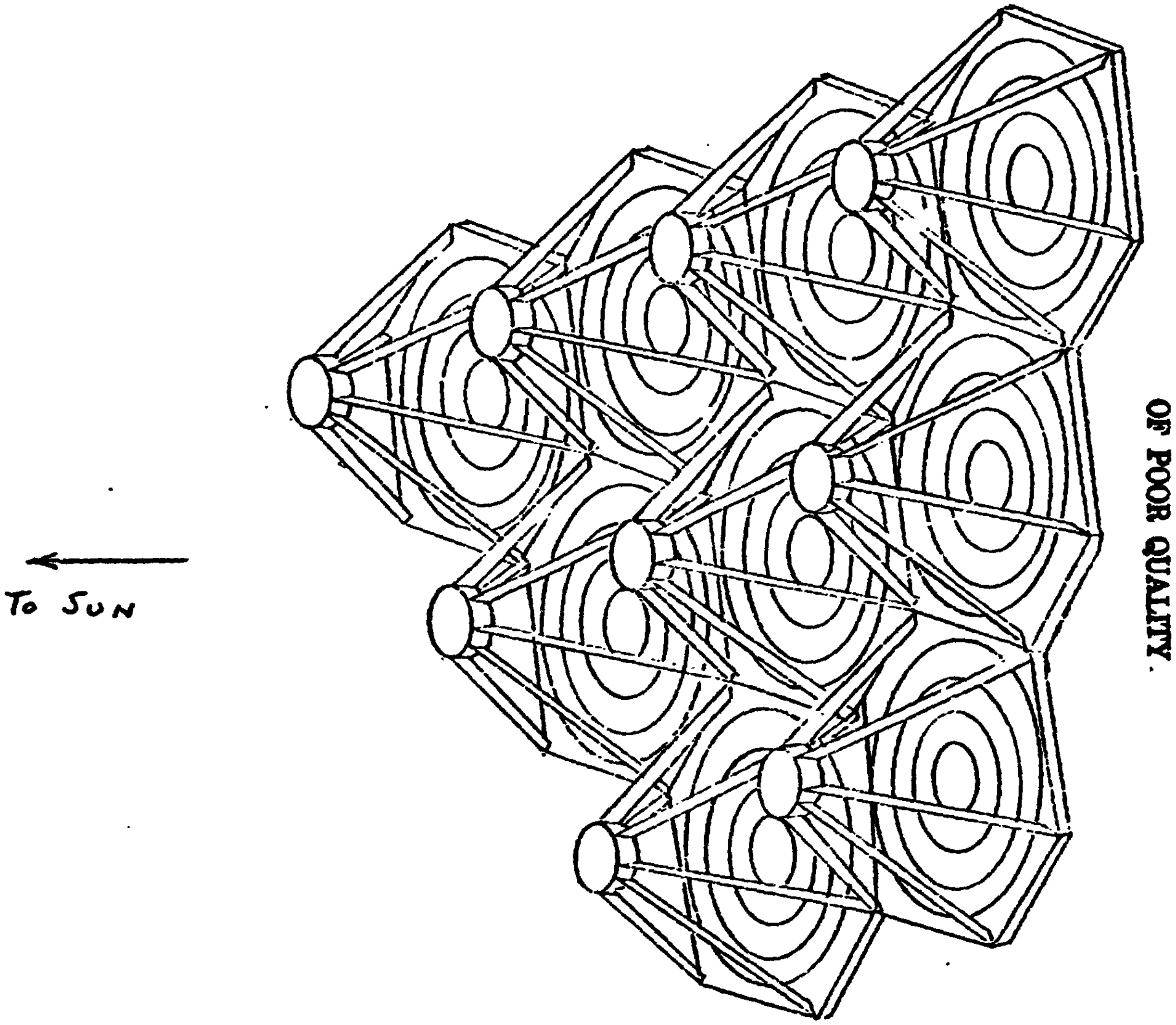

Figure 5-14. Fresnel Concentrating Solar Array

The same conceptual result is obtained if a transparent Fresnel refracting lens is substituted for the reflector. The reflector was conceived first, and was preferred for more detailed analysis because of uncertainty about the possible UV darkening of plastic Fresnel refractors over a period of years in space. This mirror/lens trade is an area where additional study is recommended.

It is clear at this point that a reasonable configuration for century class concentration ratios can be devised. The principal drawback of such an array is that it must be pointed to the sun more accurately than a flat panel. Only cursory attention has been given to this requirement, since it is clear that the requirement is on the order of a degree, and hence readily do-able without difficulty. At present, in kilowatt class arrays, the panels cost much more than the solar array drive and slip rings to provide 360° motion. Achieving one degree precision in this axis will add little or nothing to the cost of that drive.

The other question is the second sun pointing axis. Most spacecraft fly with array rotational axis POP (perpendicular-to-orbit plane). Either this must be changed to sun normal orientation, or a second solar array drive added. The latter is almost certain to be the choice. Fortunately, all this second drive must do is to accommodate the seasonal variation in Beta angle, if any. Consequently, slip rings are not needed, and a rather simple drive can be provided. This drive should certainly cost much less than the 360° type, so the conclusion is that less cost is added than can be saved by going to a high concentration ratio.

A preliminary effort was made to estimate the weight and cost of such a concentrator module. A 2 cm cell and CR 100 was selected as baseline. The results are shown in Table 5-15. Both the density and thickness are itemized so that the reasonableness of the mass estimate can be tested against other judgments. The output of such a module, at 19 per cent cell efficiency, is 8.3W, or about 110 W/Kg. This is not as good as the 200 W/Kg blanket under development, but is about four times better than the rigid panels now being used.

Table 5-15. Concentrator Design Parameters

Element	Thickness	Density g/cm^3	Mass grams	Cost $
Solar Cell	.15 mm	2.3	.110	$15.00
Cover Glass	.75 mm	2.5	.589	.50
Foam Insulation	15 mm	0.025	.200	-
Al Support Cup (1)	1.2 mm	2.7	7.968	.88
Al Support Fins (1)	.7 mm	2.7	31.752	
Concentrator				
- IR Coating	8 um	1.2	.762	.05
- Silver	1 um	10.5	.834	10.72
- Skin	.15 um	1.2	14.292	
- Foam	15 mm 0.	0.025	12.938	1.11
- Skin	.15 1	1.2	6.210	
Wire				
- Copper	30 gauge	8.94	.0003	.02
- Insulation	50 u	1.2	.0002	
			75.66	$28.29

(1) Radiator surface 168 cm^2. Increase of 4.3 from design study for Grumman using 1 cm cell diameter. Fin is about 40% longer, so was made 40% thicker.

The price, which works out to be $3.40 a watt, is very low compared to the $500 a watt we now pay for space solar power. Fortunately, as can be seen from Table 1, this cost can be off an order of magnitude on anything but costs for cell and silver, and not affect the total by fifty per cent. The estimate of $15 for a solar cell was taken from an earlier study as the 1982 expectation for a gallium arsenide cell. As used here, this has been taken to be the installed cost of one cell, for the late Shuttle era. The aluminum structure was taken as $4 per pound for simple fabricated aluminum. Similar molded structural foam plastic was taken as $15 per pound, which is probably high.

The choice of silver reflector coating vs. aluminum is not obvious. Aluminum would be lighter and much cheaper. However, it has poorer reflectivity, about .83 vs. .95 for silver. Based on silver costing $200 per troy ounce ($6.50 per gram), the silver for coating a reflector (one micron thick) costs $5.36. This was doubled to cover the cost of application. If aluminum coating costs $1.00, nearly all for application, and transportation to orbit costs $1300 per kilogram (see Section 5.2.1), then silver is slightly cheaper per watt in orbit. If transportation were slightly cheaper, aluminum would be cheaper. As it is, the choice is so close, the decision will probably be made on initial investment, or radiation resistance, etc.

So far, we have not considered the cost of assembling the cells into an array. Postulate a machine to align the module optical axis, and then spot weld the fins together when the alignment is correct. Assume such a machine were to cost $100K and assemble one module a minute, while being tended by one operator earning $6 an hour. Then if the machine were amortized over ten years with a ROI of 20% while being used two shifts a week, then the cost to assemble each module is 10¢ for machine time and 10¢ for operator time. If any of the parameters are low by a factor of ten, then the cost is low by a dollar a module. If two of them are low by ten, the cost goes up a dollar a watt.

One other topic needs to be considered. If transportation cost drives the trade from aluminum to silver for reflector coating, what about the 200 or 300 W/Kg blanket design? The earlier study cited also gave prices for thin silicon solar cells expected for 1982. The prices were $7 for a 2 x 4 cm cell six mils thick and $12 for a 2 x 2 cm cell two mils thick. Corresponding efficiencies are 14% and 11%. This amounts to $45 and $200 per watt for the six mil and two mil cell. At 200 W/Kg, transportation is still $6.50 per watt, and at 300 W/Kg it is $4.33. Hence, without any study of the cost of a complete array, it is clear that the concentrated array will be cheaper than very thin silicon unless cell prices get below $1 per cell, mounted.

There are several subsidiary advantages to high ratio concentrators. Since the cell and its cover glass are such a small fraction of the total mass, cover glass (and aluminum on the back) can be made thick to minimize radiation damage. Also, the cost of a spacecraft becomes rather insensitive to its power level since power is cheap and light. Finally, if Ga As anneals between 125°C and 150°C, as some data presently shows, the design is almost self-annealing. By stopping the withdrawal of power from a module, the cell temperature goes to 143°C on a fourth power basis.

There are a couple of disadvantages to this concept, compared to present design. One is that the panel is much more bulky than present flat panels. This could be a large problem for current payloads that have to fit expendable boosters, but should be less of a problem for Shuttle optimized PLACE systems. Also, the solar cell design for a concentrated array will be different from a flat array. Since fewer are needed, they might remain more expensive than otherwise. Overall, however, a confident projection can be made that solar array power will be much cheaper for PLACE systems.

5.2.4 POWER STORAGE TRADE STUDY

This future trade study was directed at the subject of what will be the optimal means of electric power storage in spacecraft ten to fifteen years from now. The size of the spacecraft power supply was not explicitly defined, but up to ten kilowatts load was the range in mind. Low, medium and geosynchronous altitudes were considered in the trade. Three basic storage techniques were considered in this trade study: advanced electrochemical batteries, fuel cells, and composite flywheels.

The major design parameters for low mass energy storage devices are the usable energy density in watt hours per kilogram (which is the product of name plate capacity times the usable depth of discharge DOD for specified conditions) and the charge to discharge efficiency - usually expressed as a ratio of charge energy input to discharge energy output, or "C/D." The relative importance of these parameters is a function of both the mission orbit and the specific power density of the solar array. Table 5-16 shows the relative importance of these parameters for the three classes of orbits considered for PLACE automated systems. This table shows that the C/D ratio is relatively more important in LEO, and usable energy density is relatively more important at GEO. This is fortunate, since the fewer battery cycles encountered in GEO generally permits a higher DOD, which gives the greater energy density desired.

Current generation spacecraft have the power storage function supplied by Ni-Cd batteries. Nickel-hydrogen batteries of somewhat improved properties are being developed, primarily by Hughes, for aerospace applications (Ref. 5-28). Both couples can offer near-term prospects of significant improvement (e.g., around 50 per cent) in energy storage density. However, neither of these

Table 5-16. Relative Importance Of Space Power System Parameters

PLACE ORBIT CLASS	ECLIPSE TIME (MIN)	RECHARGE TIME (MIN)	USABLE BATTERY ENERGY DENSITY (w-hr/kg)	SMALL(RIGID) SYSTEMS MASS (KG/KW)			LARGE (FLEXIBLE) SYSTEMS MASS (KG/KW)		
				C/D=1.3	C/D=1.5	C/D=2	C/D=1.3	C/D=1.5	C/D=2.0
LEO SUN-SYNCHRONOUS	36	60	100	37.5	39.0	42.0	24.9	25.5	26.4
	36	60	150	35.5	37.0	40.0	22.9	23.5	24.4
	36	60	200	34.5	36.0	39.0	21.9	22.5	23.4
55^o INCLINED INTERMEDIATE ALTITUDE(15000 Km)	45	312	100	31.9	32.3	33.1	23.5	23.6	24.0
	45	312	150	29.4	29.8	30.6	21.0	21.1	21.5
	45	312	200	28.2	28.6	29.4	19.8	19.9	20.3
GEOSYNCHRONOUS	60	1374	100	32.8	32.9	33.2	25.3	25.4	25.5
	60	1374	150	29.5	29.6	29.9	22.0	22.1	22.2
	60	1374	200	27.8	27.9	28.2	20.3	20.4	20.5

batteries compare with the almost order of magnitude improvements that are possible with more exotic cells now in advanced development for both utility peaking and automotive type applications (Ref. 5-38). For utility peaking the main design driver is cost per kilowatt - hour of storage. For automotive applications, energy density (watt - hours per kilogram) also becomes a major parameter , along with cost. Although the storage cells now being developed are not optimized for space use, they have potential energy densities ranging to over 300 w-hr per kg.

One of the highest energy density couples available is the sodium-sulphur battery being developed at GE-CRD for utility peaking. The prospects for space application of this technology were discussed with S.P. Mitoff of CR&D in late August 1977. It was concluded that, although the cell in development would not be suitable for space, there is no apparent reason - such as free fall - which would make it basically unsuited for space application. A new design would be needed for space use.

At present CR&D is working with 16 A-hr cells, trying to establish performance parameters, refine operating hardware, and reduce the cost of Beta alumina for separators. They expect to have a 250 A-hr cell ready for a several megawatt demonstration in the BEST facility by about 1981.

Based upon this information, and the results of the literature search, it seems entirely reasonable to conclude that some type of space battery of 200 to 300 hr per kg and depth of discharge of 50 percent or better should be available by the late 1980's or early 1990's. The relative cost of such a battery is totally speculative, but it is believed that they will not differ substantially from today's prices for long life aerospace secondary batteries, which is of the close order of $300 per watt-hour.

Table 5-17. Future Energy Storage Mass Comparisons

	SUMMARY - MASS OF ARRAY PLUS STORAGE					
	TOTAL STORAGE				LEO 3000 w-hr	GEO 6000 w-hr
Case	Element	Energy Density w-hr/Kg	DOD	C/D Ratio	System Mass	System Mass
1.	Battery plus Array	200	50%	1.4	126.7 Kg	114.2 Kg
2.	Battery plus Array	300	60%	1.25	108.4 Kg	97.0 Kg
3.	H_2O_2 fuel cell plus array	(note 6)		2.0	161.5 Kg	100.3 Kg
4.	HCl fuel cell plus array	(note 6)		1.25	137.3 Kg	96.9 Kg
5.	Flywheel plus array	150	90%	1.11	109.2 Kg	97.7 Kg

Assumptions:

1. 5 KW constant load
2. DC-DC power conversion efficiency = 90% (mass not included in comparison.)
3. Solar array mass, 100 w/kg. (Ref. 19)
4. Low earth orbit (LEO); 0.6 hr eclipse, 1.0 hr recharge.
5. Geosynchronous orbit (GEO); 1.2 hr eclipse, 22.4 hr recharge.
6. Fuel cell or electrolyzer is 4 kg/kw; Kevlar-49 tanks (Ref. 18)

It is interesting to compare this independent projection with the results in the "Outlook for Space", Ref. 6-41. Under energy storage, "thermal cells'" are projected to have energy densities of from 92-231 w-hr per kg in 1982 and 2000 respectively, at costs of $1200 to $300 per watt-hour.

The next candidate for PLACE era energy storage is fuel cells. It can readily be shown (Ref. 5-39) that for large power storage applications in the early 1980's - i.e. 100 kw power module - that H_2O_2 fuel cells are far superior in mass to any secondary batteries likely to be then available for space application. For application later in the 1980's, hydrogen-halogen fuel cells would be preferred, both because of a lower charge to discharge ratio requirement and since a single unit can serve as both electrolyzer and fuel cell. A hydrogen-chlorine system is lighter than a hydrogen - oxygen system, and is generally competitive with the advanced batteries described earlier. A summary of the data that supports this conclusion is given in Table 5-17. Based upon some projections from DECP, the storage costs might be slightly lower for a fuel cell system.

The final candidate considered for on-orbit energy storage was a flywheel-alternator combination. Based upon the strength/density ratio of recent composite materials, this possibility is attracting considerable interest. (Ref. 5-38, 41, 42, 43, 44). Estimates of the possible energy density for composite flywheel systems are in the general range of 150-200 w-hr per kg for composite designs in the early conceptual stage. Although this storage density is appreciably lower than that projected earlier for advanced batteries, this does not immediately put flywheels out of contention. Well over 90 percent of the energy stored in the wheel should be available (20-100 percent operating speed range; $E=KW^2$). For utility operation, depths of discharge for advanced batteries up to 90 percent are being forecast, but for space application with many more cycles and much higher charge/discharge rates it is at least questionable that such deep cycling will be possible. If depth of discharge for is to be limited to 50 percent or 60 percent, the flywheel is competitive in weight with batteries as shown in Table 5-17, since flywheels also have an efficiency edge. The input to output energy ratio can be made 90 percent or greater, while for batteries an 80 percent efficiency is about the best that can be expected. Hence, it is too early in the development of either advanced batteries or flywheels to call the contest on the basis of weight.

The major apparent advantage of flywheel systems compared to batteries is lower cost per kilowatt - hour stored, especially in large sizes. For a 10 MW-hr utility unit, with a rotor diameter of some four meters, a mass of 90 metric tons, and a full charge speed of 3600 RPM, and with possible preventive maintenance (Ref. 6-42), conventional bearing and rotating machinery technology is adequate and available. For a space application of a unit a thousand times smaller, higher rotational speeds and long life unattended reliability will require more sophisticated technology, such as magnetic rotor suspension which is still in the development stage. Consequently, space units will probably enjoy little or no cost advantage relative to batteries or fuel cells.

There appears to be a major disadvantage to flywheels for space application. Since the charge/discharge processes for flywheels involve the conversion of electrical energy into angular momentum (and vice-versa), flywheels must be used in counter-rotating pairs in stabilized spacecraft, and the energy transfer must be closely balanced. Consequently, a failure in either flywheel or the control elements is a catastrophic single point failure resulting in the loss of either attitude stability or power storage.

This discussion leads to the expectation that the most likely power storage element in PLACE era spacecraft (circa 1990) will be advanced (high temperature) chemical batteries, with an energy storage density of 200-300 w-hr per Kg, depths of discharge of 50-60 percent, and DC-DC efficiencies of 75-80 percent. Values in this range will be used in the conceptual spacecraft design of PLACE systems. However, fuel cells are closely competitive, and could become the preferred system. They will definitely be considered if there are PLACE systems with longer duration storage requirements. Flywheels, though weight competitive, present such development and operational problems that they do not seem likely to be used for space systems.

5.2.5 POWER DISTRIBUTION TRADE STUDY

In considering space power distribution options for future satellites, two recurrent issues were address; AC vs DC distribution, and the selection of distribution voltage. Two more detailed issues, the type of load fault protection devices, and the use of central vs. distributed voltage regulation were not treated. Both were considered to have adequate technology, both now and for the future, and the detail choice was not seen as having any measurable impact on the PLACE Study objectives or systems design.

The concept of using AC for spacecraft power distribution has been advocated for many years. JPL has used 100V, 2400 Hz power distribution on their planetary spacecraft ever since Mariner 1969. Since the wave form used is almost a square wave, this form of power can readily be transformed, rectified and filtered to provide DC voltages of any desired level. The 2400 Hz can also readily be converted into 400 Hz either single or three phase, for operating motors. This versatility has been the major reason for advocating this form of power distribution.

There are several countervailing arguments. Most space equipment has been designed to operate from a 28 V DC supply, so this is a reasonable distribution source. True, many components use DC-DC conversion to supply other internal operating voltages. This was a major basis for advocating a 2400 Hz AC supply. However, especially with the recent advanced in integrated circuits, DC-DC conversion, at much higher frequencies, has become both lightweight and very efficient. Since both transportation costs (the importance of mass) and solar array cost (the importance of high conversion efficiency) are projected to be lower in the PLACE era, the argument for AC distribution has even less significance in the future. Since almost all NASA programs are now standardized on 28 VDC, we relied on the principles mentioned earlier to "don't change anything that works well."

A slightly different argument must be considered concerning the distribution voltage. 28 VDC is a holdover from the aircraft industry of many years ago, when engine driven generators supplied only small amounts of power to operate the radio and gyrocompass. Clearly, at some increased power level in the space industry, a higher operating voltage will be needed to minimize conductor weight. The conclusion of our trade study was that for multi-kilowatt spacecraft in the PLACE era, the changeover point to a higher distribution voltage has not been reached. Even for several kilowatts, distributed over a twenty meter long vehicle, the power wiring is still only a fraction of a percent of the total vehicle weight. It could be made even smaller by using aluminum wire, and/or by accepting voltage losses greater than one percent. So far, we have more mass invested in connectors than we do in conductors, so arguments for a higher voltage are not yet very persuasive for PLACE vehicles. The clinching argument was that the space shuttle, which had the opportunity to set new precedents, if needed, continues to supply many kilowatts to a very large vehicle at 28 VDC.

The change to high voltage distribution will come some day, but on a program that uses a large block of power at a relatively high voltage. A likely candidate is SEPS, which uses perhaps 50 kilowatts, mostly at 600-1000V. The solar power satellite (SPS) is expected to distribute its several gigawatts at the Klystron Tube voltages needed; e.g. 30,000 VDC.

The only PLACE system that needed to use large blocks of power in a large structure was the Ferris Wheel Radar. In this system conceptual design, the suggested power system was a distributed solar array, which neatly avoided the distribution problem.

5.2.6 FUTURE TORQUER TRADE STUDY

The basis for this trade study was that the progress that could be expected to occur in advanced thruster subsystems during the PLACE era warranted a complete re-examination of the role of reaction wheels and jet thrusters for attitude control and orbit attainment and maintenance. In particular, if ion thrusters were to be used to raise spacecraft from Shuttle orbits to low sun-synchronous orbits, then reaction wheels might be eliminated in favor of doing all attitude control torquing with ion engines, using common tankage, solar array, and power conditioning shared among all of the thrusters needed. It can easily be shown that the propellant expenditure needed to remove cyclical torques (which is what momentum wheels do) amounts to only a fraction of a kilogram per axis per year. On this basis it might be very reasonable to substitute jets for wheels (each of which weigh several kilograms). <u>If</u> ion engines were used for orbit raising, a good case could be made for all jet systems, <u>provided</u> that no disturbance torques were very large. However, as discussed earlier, it was found that for reasonable estimates of time value, it was substantially more cost effective to go from shuttle orbit to low sun-synchronous orbit using on-board chemical (i.e. hydrazine) propulsion. This means that there would already be an on-board propellant tank and enough jet thrusters and control electronics to do orbit maneuvers. Hence, for a complete long life three axis control system, either ion engines or momentum wheels would need to be added.

In the PLACE era, almost all data links will be via TDRSS, and most earth observation satellites will use such a high data rate that steerable antennas will be needed to complete the data link through TDRSS. The reaction torque required to maintain satellite stability while these antennas seek to acquire a TDRS can easily be provided by reaction wheels, but are beyond the reasonable capability of ion engine torque couples unless the thrusters are greatly oversized. Hence the conclusion is reached that for PLACE sun-synchronous systems, attitude control torques will continue to be supplied by momentum wheels, as in present spacecraft. Wheel unloading could be accomplished with chemical thrusters using the hydrazine supply already on-board, or by using magnetic torques interacting with the earth field.

For very large structures, such as Microsat, ion thrusters might be needed to overcome large secular torques resulting from gravity gradient torques. It is not projected, however, that ion thrusters would play any role in the shape control of large structures, simply because their force levels are so very low.

For PLACE systems in geosynchronous orbit (GEO), the situation is only slightly different. As described earlier, it is projected that electrical propulsion will be used to attain GEO by the 1990's. However, none of the PLACE systems thus far visualized for that orbit have high enough electrical power requirements that they would be self-propelled to GEO; instead, a SEPS type operation is contemplated.

All of the PLACE systems in GEO have relatively large torque requirements for pointing sensors (and perhaps the whole spacecraft) to selected ground targets. Hence, momentum wheels will be needed in GEO systems. How these wheels will be unloaded is open to some question. The expected performance of a SEPS is that it could place a geosynchronous satellite in precisely the orbit desired; i.e. there would be no need to employ a chemical system to get quickly to the operating station and "stop" there. If this is so, then the system may use either chemical or ion thrusters for station keeping. Because of the high specific impulse of ion engines, North-South station keeping, if it is required by the mission, would preferably be done by ion engines. The same engines could then be used, in part, to unload momentum wheels. This would probably be chosen, for at least some wheel unloading. Ion engines could also be used for East-West station keeping, which requires much less velocity change, provided that rapid station relocations are not required. To illustrate, the 8 cm mercury ion thrusters under development at Lewis are nicely sized to handle the N-S station keeping requirements for a 1000 kg satellite. (Larger satellites, obviously, could be controlled by multiples of these thrusters.) These 8 cm thrusters would have more than ample velocity change capability to undertake E-W station keeping. However, such a thruster would require over a week to accelerate a 1000 kg satellite to a drift rate of one degree per day. Hence, a 60 degree longitude change could require about two and a half months. If faster changes are needed, chemical systems (possible augmented with electrical heating for higher performance) would likely be used. In that event, wheel unloading would probably be partly by ion and partly by chemical thrusters. In the absence of more definite system requirements, it does not seem possible to make any more definite statements about torque trade-offs.

For the Earthwatch orbit, the same reasoning applies as for geosynchronous orbits. However, this orbit class has not been studied as thoroughly, so less in known about the relative magnitude of "N-S" and "E-W" station keeping requirements. (Strictly, we are talking about orbit normal and orbit period adjustments in both cases.)

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6.0 SPACE SYSTEMS TECHNOLOGY MODEL

Presented in Table 6-1 and Figure 6-1 are the PLACE future system concepts. Each of these is not possible to be implemented today because of one or more enabling technologies which are lacking. As discussed in Section 3, they could, however, be implemented by the year 2000, given a desire to do so. Some of these system concepts are extensions of current capabilities, while others are entirely new methods of making remote sensing measurements from space. Their names are in some cases related to the sensor, in some cases the orbit, and in some cases the physical process which makes the measurement possible. All twelve of the system concepts and the ground processing concept that interfaces with all of them are considered to be operational systems. By this we specify that information derived from the system concepts is guaranteed to be available to users. We have the luxury in this study of disregarding the institutional and political implications of this assumption. The order in which the systems are discussed has no meaning, as will become clear later when the commonality between systems is discussed. Some of the system concepts were subjected to more in-depth analysis than others because of their novel implementation concepts, questionable feasibility, or general requirement for deeper investigation.

Table 6-1. PLACE System Concepts

Landsat H
Earthwatch
GEOS
Texturometer
Thermal Inertia Mapper
Radar Holographer

Microsat
Parasol Radiometer
Radar Ellipsometer
Ferris Wheel Radar
Sweep Frequency Radar
Geosynchronous SAR

Ground Processing Concept

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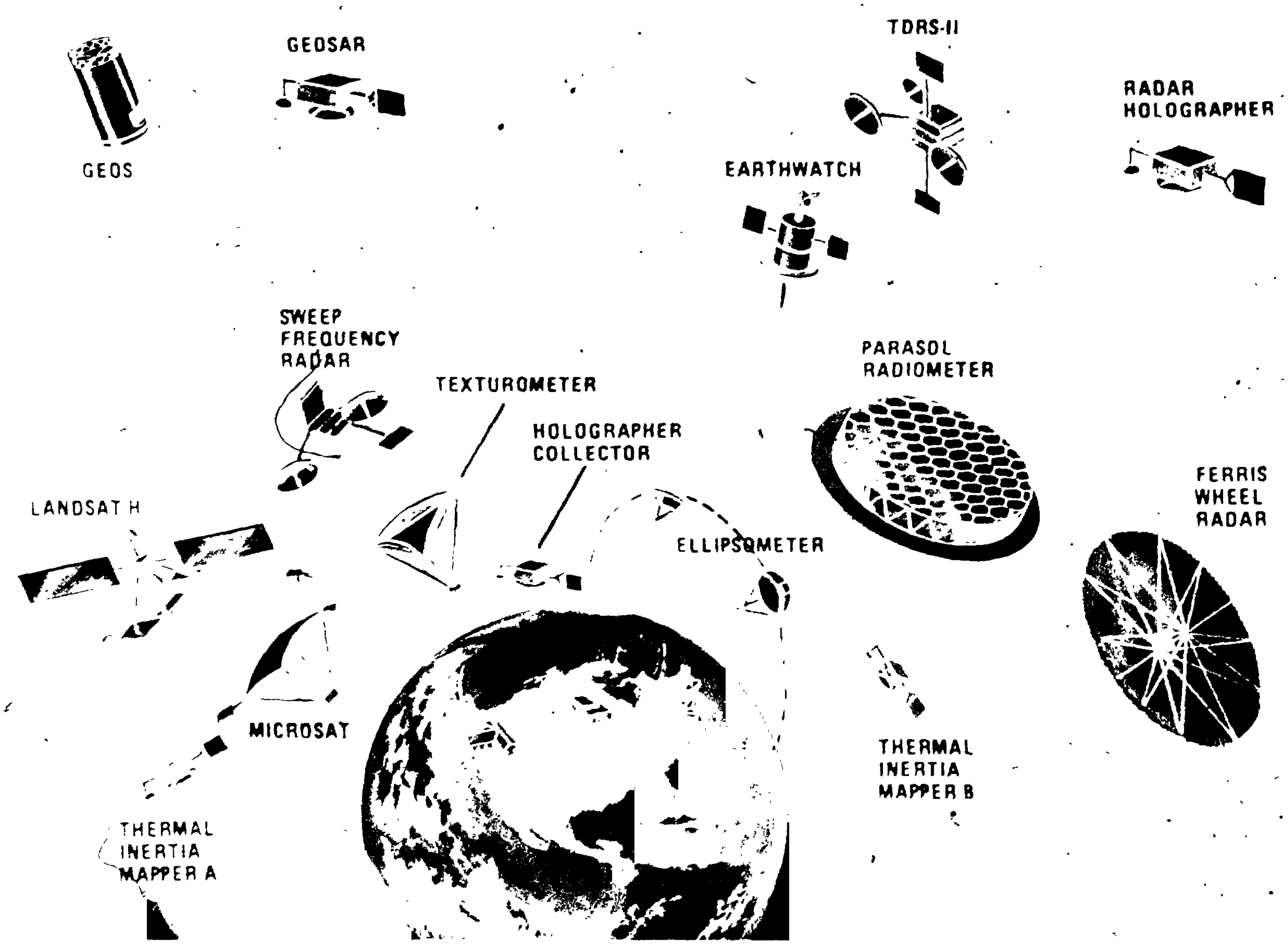
SPACE DIVISION

PLACE FUTURE SYSTEMS CONCEPTS
(Space Systems Technology Model)



6.1 PLACE SYSTEMS CONCEPTS DESCRIPTIONS

The development of each system concept proceeds through the characterization of the system as a concept and stops well short of even a preliminary design of each system. Many of the initial feasibility analyses and trade-off studies necessary to more positively establish the system concepts as legitimate candidates for future consideration were deferred. The system concepts, then, are presented as ideas, which will grow into designs or be discarded on their own merit.

6.1.1 LANDSAT H

The Landsat H system concept is presented as a possible extension of the current Landsat program to the 1995 time frame. It assumes the prior existence of Landsat E, an operational version of Landsat D, and Landsats F and G, optical and synthetic aperture radar developmental spacecraft, respectively.

Landsat H is a constellation of three multi-sensor spacecraft which contribute to all of the key set mission objectives. Its measure of semi-credibility, as defined in Figure 3-3, is medium. It is nominally located in the current Landsat 700 km sun-synchronous orbit. A cartoon rendition of the concept is presented in Figure 6-2, and some of the pertinent performance parameters are presented in Table 6-2. Some rough-order-of-magnitude (ROM) estimates of size and weight are 12 x 3 x 4 meters (without solar panels) and 2000 kg.

One of the unique features of Landsat H is its "smart " optical sensor, which allows for intelligent on-board data editing and data reduction. This is accomplished using one forward and one rearward-looking push broom array

Table 6-2. Landsat H System Concept

- Smart optical sensor allows for intelligent on-board editing/data reduction
  - Forward/backward looking
  - 10 M. Res., 10 bands, 185 km swath
  - HRPI - 5 M res. $(5\ \text{km})^2$ targets
- SAR provides all-weather imaging capability
  - 25 M res., L, C, X-band
- Active, visible sensor provides atmos. cal., luminescence, and night imaging
  - Selectable 3 km swath
  - Requires 300 KW Av. power during operation
- On-board processing and storage allows for change detection and/or information extraction
- 3 spacecraft - 6 day repeat cycle

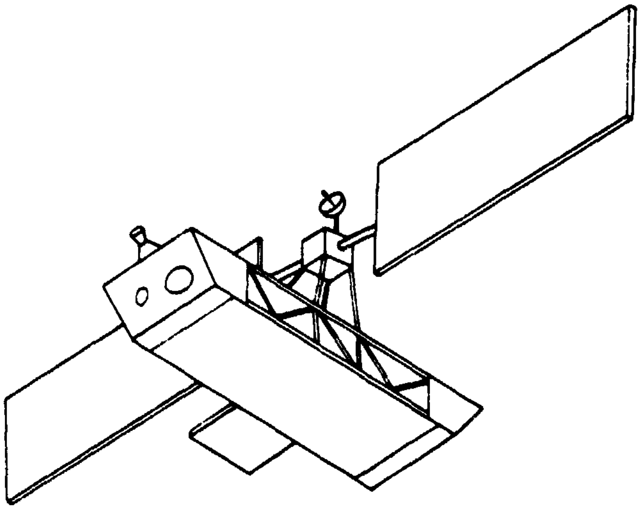


Figure 6-2. Landsat H System Concept

(also called multi-linear array). This push broom array is a one-dimensional array of solid state sensors which use the spacecraft motion to trace out the second dimension of the image. The forward looking sensor nominally looks 50 km "ahead" of the spacecraft in three spectral bands at either full (10 meter) or reduced (30 meter) resolution. Based on the information acquired from this data through on-board data processing, the rearward locking sensor operates at either full (10 meter, 10 spectral bands, 185 km swath width) or reduced capability. This on-board data processing may be as simple as cloud cover or haze detection for data editing or may be much more sophisticated, involving information extraction and change detection (requiring ancillary data uplink) for data reduction.

A second optical sensor on board Landsat H which may be controlled either by the forward-looking sensor or the ground (preprogrammed) is a high resolution pointable imager. This provides high resolution (5 meter) targets or segments which are nominally 5 km square.

Landsat H will have an L, C and X-band synthetic aperture radar to provide an all-weather imaging capability. The bottom of the spacecraft shown in Figure 6-2 is a 2 x 12 meter antenna for L and C bands with the additional smaller antenna for X-band. Nominal power levels are 500 W (L-band), 1000 watts (C-band) and 1500 watts (X-band). Each frequency has an approximate ground resolution of 25 meters.

One of the unique new sensors placed on the Landsat H vehicle is an active visible imaging system called "nite-lite". This sensor will be used to provide atmospheric calibration of the push broom scanner, to investigate luminescence phenomena (both fluorescence and phosphorescence), and to allow for night imaging with the push broom scanners.

Active illumination from a satellite in the visible or IR spectrum could be applied in three ways: allowing night-time imaging, enhancing surface discrimination by luminescence, and ranging with a LIDAR. This preliminary analysis emphasizes the "nite-lite" function of Landsat H, whose push broom scanner images a 185 km swath. While the design has assumed a laser source, an incoherent illuminator is possible, as is a passive reflector of solar radiation if the earth's shading does not limit timeliness. One major limitation of monostatic, active illumination is that the lack of shadows in the scene lowers the contrast of its image and makes relief-aided identification more difficult; backscattering could be reduced with a LIDAR approach, but the photon count rate would be reduced also.

The parameters derived during the design of "nite-lite" are given in Figure 6-3 the following notes match this sequence.

The design equation summarizes the parametric influence on the prime variable, signal-to-noise ratio. Note that there are usually implied dependencies among the sensor element size, the instantaneous field of view, and the relative aperture of the optics.

The principal controlling variable is the allowable energy density on the ground. Many earlier studies have helped to define suitable safety limits (Refs. 6-1-6-4). For the USA, safety requirements for personnel in the vicinity of possible laser radiation are codified in 21 CFR 1040. The full name of this is Code of Federal Regulations, Title 21 (Food and Drugs), Chapter 1 (FDA and HEW), Subchapter J (Radiological Health), Part 1040 (Performance Standards for Light-Emitting Products). This law began its application on August 2, 1976. This satellite system must meet the most strict of the requirements, the Class I

Design equation: $S = \frac{d}{100AF}\left(\frac{I}{V_g}\right)^{\frac{3}{8}}\sqrt{\frac{7\rho T_a \lambda}{\pi hc}}$

D = satellite altitude = 800 km

G = gravitational constant = $6.67(10^{-11})\ \mathrm{N \cdot m^2 \cdot kg^{-2}}$

M_e = earth mass = $5.98(10^{24})$ kg

$GM_e = 3.99(10^5)\ \mathrm{km^3 \cdot s^{-2}}$

R = earth radius = 6378 km

V_o = orbital velocity = $\sqrt{\frac{GM_e}{D+R}}$ = $7.46\ \mathrm{km \cdot s^{-1}}$

V_g = ground track velocity $\approx \frac{RV_o}{S+R}$ = $6.65\ \mathrm{km \cdot s^{-1}}$

I = pixel or IFOV size = 10m

t = illumination period = $\frac{I}{V_g}$ = 1.50 ms

E = 21 CFR 1040 laser energy limit = $7(10^{-4})\,t^{\frac{3}{4}}$ = 5.38 μJ

A = possible telescope aperture directed at laser = 6 inch = 15.2 cm

E_g = permissible energy density on ground = $\frac{4E}{\pi A^2}$ = $0.297\ \mathrm{mJ \cdot m^{-2}}$

H_g = irradiance on earth = $\frac{E_g}{t}$ = $0.198\ \mathrm{W \cdot m^{-2}}$

T_a = atmospheric transmittance = 0.65

L_p = laser power per pixel = $\frac{H_g I^2}{T_a}$ = 30.5 W

W = swath width = 185 km

L_m = laser power for full swath scan = $\frac{L_p W}{I}$ = 563 kW

ρ = earth reflectance = 0.25

f = relative aperture (f/#) of optics = 2

H_s = sensor irradiance = $\frac{\rho T_a H_g}{4f^2}$ = $2.02\ \mathrm{mW \cdot m^{-2}}$

d = sensor element size = 25 μm

F = focal length of optics = $\frac{Dd}{I}$ = 2m

a = aperture of optics = $\frac{F}{f}$ = 1 m

P_s = power on each sensor element = $H_s d^2$ = 1.26 pW

E_s = energy on sensor element during integration = $P_s t$ = $1.90(10^{-16})$ J

h = Plank's constant = $6.625(10^{-34})\ \mathrm{J \cdot s}$

c = speed of light = $3.00(10^8)\ \mathrm{m \cdot s^{-1}}$

λ = wavelength of laser = 600 nm

N = number of photons per sensor element integration = $\frac{E_s \lambda}{hc}$ = 5730

S = signal to noise ratio, if quantum-limited = $\sqrt{N}$ = 75.8

$\Delta\rho$ = reflectance resolution = $\frac{\rho}{S}$ = 0.33%

Q = binary quantization level = $\log_2 S = \frac{\log_{10} S}{\log_{10} 2}$ = 6.25 bits

D^* = effective system detectivity = $\frac{dS}{\sqrt{t}\,P_s}$ = $3.88(10^{12})\ \mathrm{cm \cdot Hz^{\frac{1}{2}} \cdot W^{-1}}$

α = angular size of optics as seen from ground = $\frac{a}{D}$ = 1.25 μrad = 0.258"

R_g = diffraction-limited resolution of optics = $\frac{\lambda}{\alpha}$ = 0.48 m

B = radiance of laser source as seen from ground = $\frac{4H_g}{\pi\alpha^2}$ = $1.61(10^{11})\ \mathrm{W \cdot m^{-2} \cdot sr^{-1}}$

m = magnification of observer's 6" telescope = 360

α_T = angular size of laser source as seen through telescope = $m\alpha$ = 1.55'

Figure 6-3. Analysis of Nite-Lite

Accessible Emission Limits. For visible light, the laser radiation must not exceed an energy level which is dependent on the exposure time of 1.5 ms. This law defines this limit by the amount of energy passing through a circular aperture stop which has a diameter of 80 mm. However, since it is possible that amateur astronomers could be observing the night sky, at the point at which the satellite is, at the instant in which it is illuminating that region of the ground, a stricter requirement of a wider aperture has been assumed for this analysis. With most of these amateur telescopes being 6 inches or less in aperture diameter, this value has been chosen here. The problem of larger telescopes must be studied separately. This design also meets the similar requirements of Part 1040.11 on surveying, leveling and alignment laser products.

Table 6-3 lists approximate values for the radiance and irradiance of several natural luminants; blue sky has a radiance about ten times that of the full moon. For this system, the irradiance on the ground is about 200 times that of the full moon.

The earth is assumed to be a diffuse reflector. While a specific wavelength has been chosen for the laser in this example, other values might be more suitable from a conversion efficiency point of view or for luminenscence applications.

The analysis, shown in Figure 6-3 which has neglected thermal and other device noise sources, shows the nite-lite concept to be feasible given certain advanced in laser technology which will be discussed in Section 7.4.2.5. The quantum efficiency has been assumed to be unity; an efficiency of 10% causes a loss of 1.7 bit in quantization capability.

Table 6-3. Radiance and Irradiance of Natural Luminants*

	sun	full moon	Sirius stel. mag. = -1.6
H, irradiance, $\frac{W}{m^2}$ (on horizontal plane at earths surface)	10^3	10^{-3}	10^{-7}
R, radiance, $\frac{W}{m^2 \cdot sr}$ (as seen from earths surface)	10^7	10	10^7
α, angular diameter	$\frac{1}{2}^\circ$	$\frac{1}{2}^\circ$	$\frac{1}{100}''$

for small sources, $H = R\,\Omega$

for circular sources, $\Omega = \frac{\pi}{4}\alpha^2$ = cone angle of source

* Radiance and irradiance of some natural sources at the meridian integrated over the visible spectrum

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The optic aperture of the illuminator has been set at the same value as the sensor optics; it is possible that the same reflector could be used for both. The 1 m aperture is sufficient from considerations of both light-gathering ability and also resolution. A possible design of the laser system could illuminate just 3 km out of the 185 km swath. At approximately 30w/pixel, this leads to an average power output of the laser of 3 kw. The selected portion of the swath could be illuminated by a defocussed scanning mirror to prevent overheating.

Since the resolving power of the human eye is about 1' of arc, this illuminator will still appear to be a point source even through a telescope. Because of its high radiance and short duration, this might appear to be like a photographer's flash at a distance of 2 km.

6.1.2 EARTHWATCH

The Earthwatch system concept is based on the use of an inclined (about 55 degree), intermediate (subsynchronous) orbit, originally suggested by former astronaut William Pogue (Ref. 6-5,6). From one of these repeating orbits, nominally a 10,000 km 6 hour orbit, a constellation of 8-12 spacecraft could provide near continuous coverage of the earth with a minimum elevation viewing angle of 20°. A preliminary analysis of the orbit potential is presented in Section 5.1.2. Although this constellation of Earthwatch spacecraft potentially can see any point on the earth at all times, this is not to say that it can see all points at any time. The chief advantage of the Earthwatch orbit, then is that it could potentially provide both the earth resources management information (mapping) of a lower orbit spacecraft such as Landsat, and the quick-look capability (disaster assessment) of a synchronous orbiter. It is perhaps a concept which could replace two other concepts of future satellite systems. Two immediate disadvantages of the orbit are: (1) the Van Allen radiation belt; and (2) the resultant variable look angle for its mapping performance.

The first disadvantage led to a very stringent requirement on radiation resistance (Section 7.4.6). It is not clear at this time but it may be possible to modify the orbit slightly to relax this requirement. The variable look angle, however, will be something that future users of the Earthwatch system will have to learn to overcome.

The sensor complement provides a multifunction capability of passive and active visible and microwave measurements. As configured, the spacecraft is assigned a medium-level on the semi-credibility continuum of Figure 3-3 and would contribute to all of the key set of mission objectives. A possible configuration of the spacecraft is presented in Figure 6-4. The spacecraft would contain two pointable optical sensors, one with moderate ground resolution (30 meters) for mapping and one with high ground resolution for a quick-look capability. The moderate resolution sensor would nominally acquire 90 km square segments or targets while the high resolution sensor would nominally acquire 5 km square segments. The two microwave sensors on board, a synthetic aperture radar and a microwave radiometer, would frequency share the same 15 meter antenna. The synthetic aperture radar operating at L, S and X-bands and providing 10-25 meter ground resolution would require less than 5 K watts. The microwave radiometer at the same frequencies would provide ground resolution ranging from 12-120 Km. A "nite-lite" system, similar to that discussed in the Landsat H system concept (Section 6.1.1) would also be feasible although the implications of the higher orbit altitude have not been determined.

6.1.3 GEOS

GEOS, or Geostationary Earth Observation Satellite, is an advanced version of SEOS, the Synchronous Earth Observatory Satellite, which has been pursued in the past by M. Ritter of NASA's Goddard Space Flight Center and others (Ref. 6-21). As indicated in Figure 6-5, its prime distinction is the 8 m diameter of the

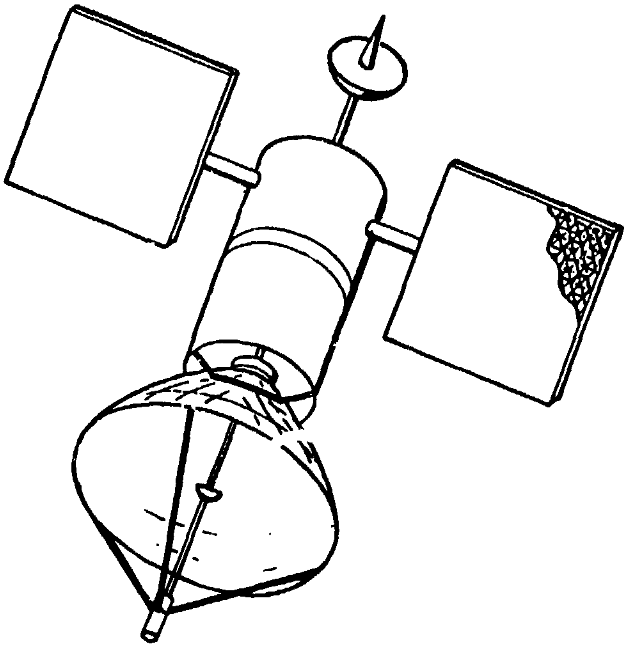
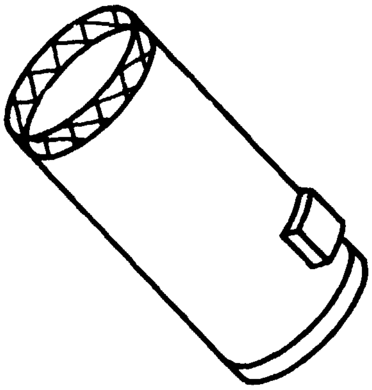


Figure 6-4. Earthwatch System Concept

main reflector. This will allow a 3M IFOV of the earth in the visible spectrum. As with SEOS, this satellite will be particularly suited to monitoring abrupt events (Ref. 6-23).

Many of the design requirements will be extrapolations of earlier designs for space telescopes (Refs. 6-20,22). The large reflector will present new problems, however. It will have to be segmented for transport to orbit and adaptive control of the mirror surface will be necessary for controlling thermal warp resulting from uneven solar heating. This requirement is discussed in Section 7.4.10, Large Optics. Estimations of weight and power requirements are listed in Table 6-4.

The image plane will have a large, two-dimensional array of Charge Injection Devices. While a 5 Km square area could be imaged without repointing the telescope, the CID's will allow a readout of selected, smaller areas for faster response. They will also allow for an instantaneous geometric correction of a subimage from computer distortion values.



- Large earth-looking telescope
  - Short-lived events, constant perspective
- 8 m diameter primary optics
  - Mirror segmented, adaptive controls
- Sensor images from visible to thermal IR
  - 3 M IFOV in visible
- $(1650\text{ element})^2$ 2-D focal plane array
  - 2 μm element spacing
  - CID's allow selective readout
- Focal length of mirror is 24M

Figure 6-5. GEOS System Concept

6.1.4 TEXTUROMETER

The texture of the ground surface, measured at scales between about 1 mm and 1m, can aid in the distinction of objects by remote sensing. Specific applications might be the identification of vegetation, particularly conifers, and the measurement of the particle size distribution of exposed sediments such as those on ocean beaches.

The human eye has a resolution of 1mm for objects which are about 3.5 cm away; to get this resolution from a spacecraft requires an optical aperture of about

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Table 6-4. Approximate Weight and Power for GEOS

Base Plate	3000 kg
Mirror	200 kg
Supports and Actuators	300 kg
Barrel (f-3)	500 kg
Secondary Supports	200 kg
Focal plane detectors, etc.	300 kg
Total Weight	4500 kg
Power - adaptive optics	200 W
- thermal control	1400 W
- focal plane sensors	400 W
Total Power	2000 W

300 m. A possible design is illustrated in Figure 6-6.

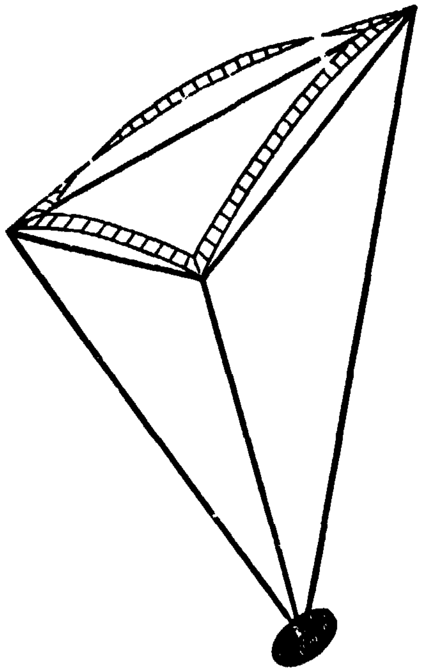

Figure 6-6. An Oblique View of the Texturometer

Since a true image is not necessary, three lines of mirrors provide the required resolution in only three directions, each 60° apart. Each line is composed of segmented mirrors, each one having a spherical surface; all of the segments for the three lines are arranged to form a nearly spherical cap in the shape of an equilateral triangle. A tetrahedral frame supports the mirrors and the sensors.

Figure 6-7 gives a schematic drawing of the three independent, linear arrays of sensors associated with the mirrors. Each sensor in the arrays has a diffraction-limited field of view of about 1 mm by 10 cm; the pattern of these is shown in the drawing.

The thousand sensors in each line may give an output such as in Figure 6-8. This high resolution linear image may be mathematically transformed in order to indicate the ground texture more clearly.

An approximate analysis of a possible optical system, which indicates preliminary system feasibility, is given in Figure 6-9. This initial analysis assumes an orbital altitude of 300 km; the results of the analysis, with a 600 km altitude are summarized in Figure 6-10. Many factors are not considered; some of these are: The precise diffraction limit equation, the efficiency of the detectors, and the resolution loss due to aberration of the mirrors. The three pairs of mirrors and sensor arrays are baffled so that no light mixing is possible; photon isolation prevents an unwanted diffraction pattern in the form of a six-rayed star. However, all mirrors could be aligned so that their linear images have a common midpoint on the ground as shown in Figure 6-7.

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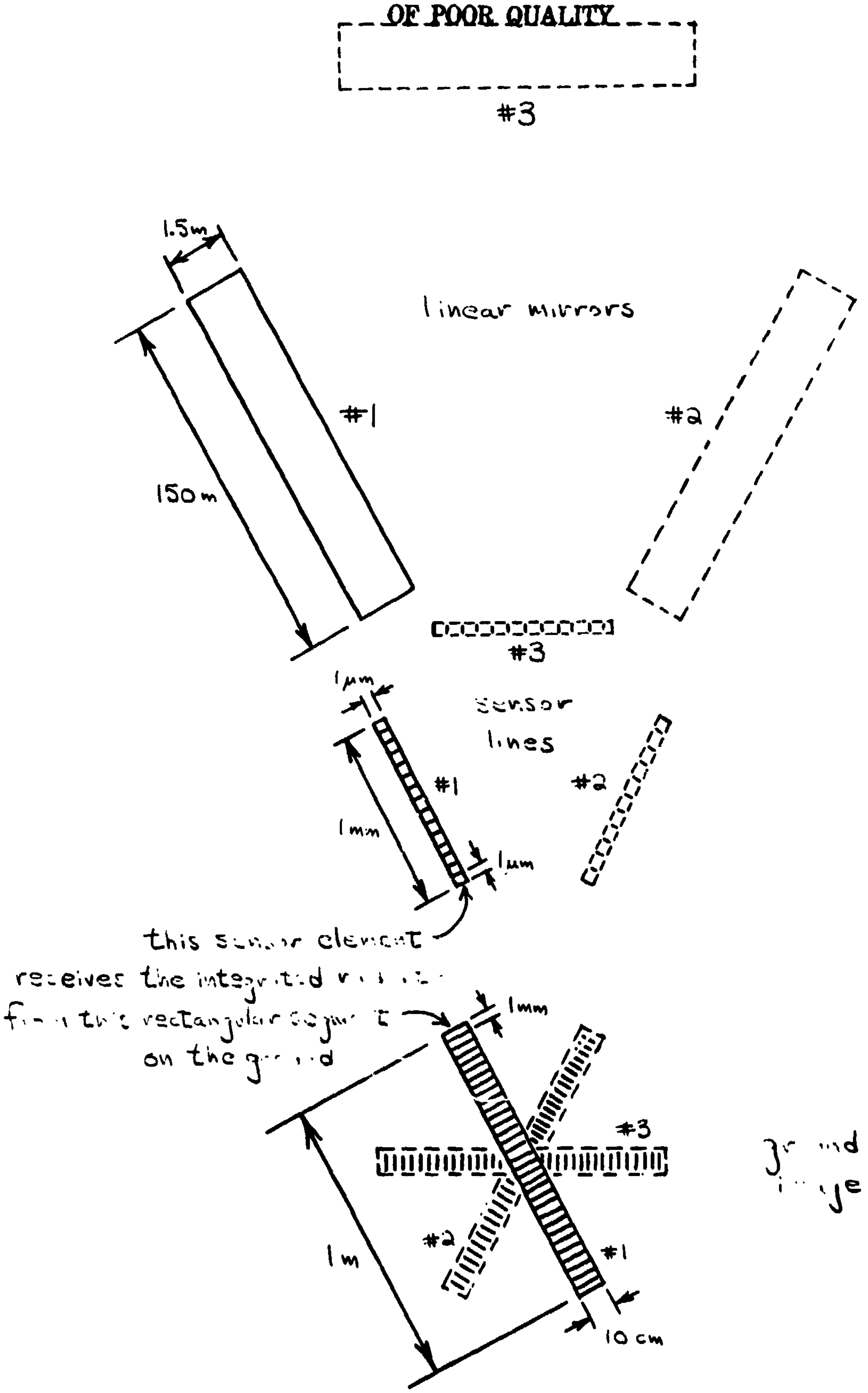


this sensor element receives the integrated radiation from this rectangular segment on the ground

Figure 6-7. A Schematic View

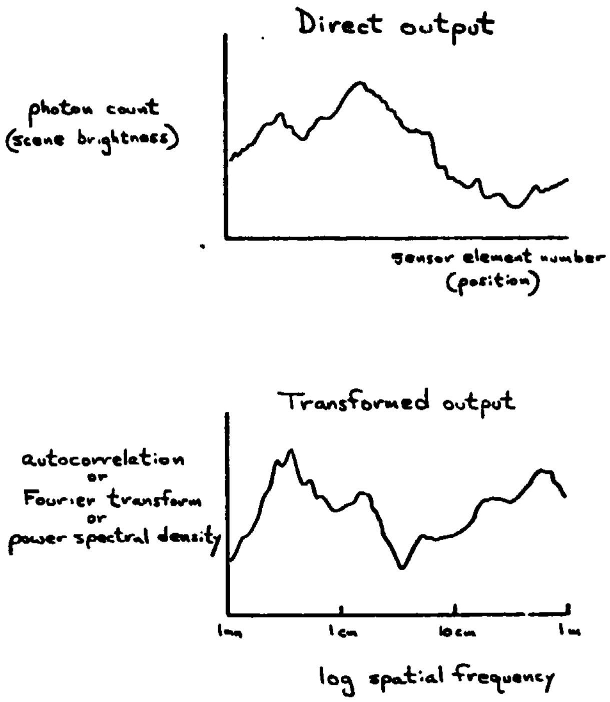


Figure 6-8. Data Transformations

S = orbital altitude = 300 km
T = required ground resolution = 1 mm
λ = wavelength of operation = 500 nm
D = aperture diameter = $\frac{\lambda S}{T}$ = 150 m (diffraction limited)

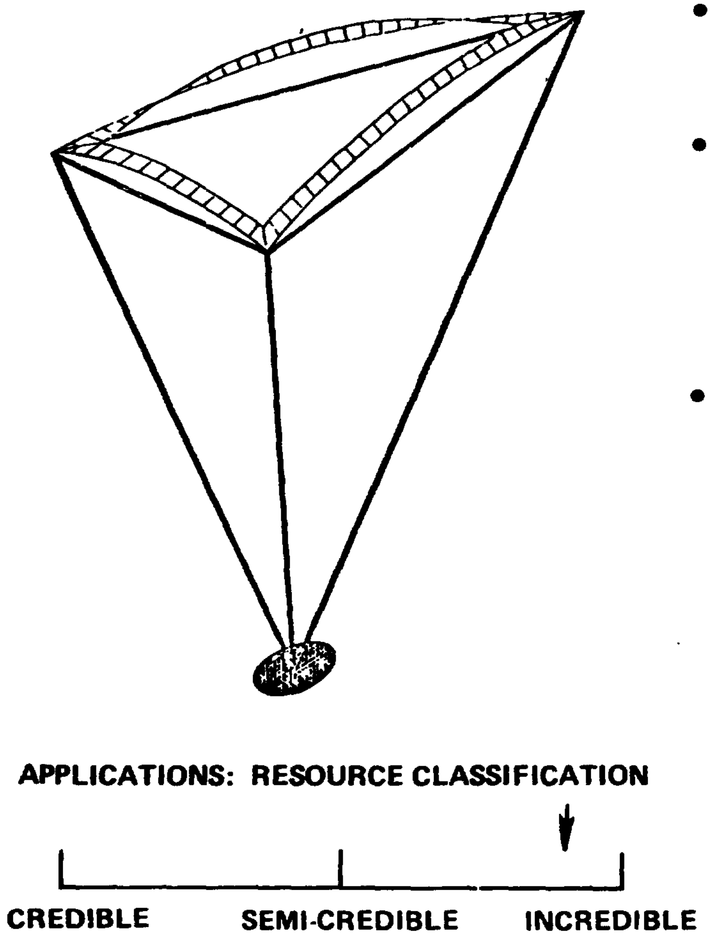
G = image or sensor element size = 1 μm
F = focal length of mirror = $S\frac{G}{T}$ = 300 m ; R = mirror radius = $2F$

W = width of mirror = 1.5 m ; L = segment length = 1.5 m
A = surface area of one linear mirror = WD = 225 m^2
f = f/# or relative aperture of mirror = $\frac{F}{2}\sqrt{\frac{\pi}{A}} = 10\sqrt{\pi} = 17.8$

H_e = solar radiation incident on earth at 500nm = 1.21 $W \cdot m^{-2} \cdot nm^{-1}$
ρ = average earth reflectance, assume diffuse = 0.25
$\Delta\lambda$ = sensor bandwidth = 25 nm
H_s = radiation incident on sensor = $\frac{H_e \Delta\lambda \rho}{4f^2} = 6.05(10^{-3})\ W \cdot m^{-2}$

h = Plank's constant = $6.625(10^{-34})$ J·s ; c = speed of light = $3.0(10^8)\ m \cdot s^{-1}$
E_p = photon energy = $h\frac{c}{\lambda} = 3.98(10^{-19})$ J
$H_s = 6.05(10^{-3})\ W \cdot m^{-2}\left(\frac{10^{19}}{3.98}\right)$ photon·$s^{-1} \cdot W^{-1} = 1.52(10^{16})$ photon·$s^{-1} \cdot m^{-2}$
I_d = detector flux rate = $H_s G^2 = 1.52(10^4)$ photon·s^{-1} (square detector)
t = count time = 0.05 s
P = photon count = $I_d t$ = 608 photon
with Poisson statistics, noise = $\sqrt{P}$, therefore $P = 608 \pm 24$; 4% noise

Figure 6-9. Optical Design Approximations



- MEASURES VISIBLE TEXTURE FROM 1 MM TO 1 M FROM 600 KM
- MIRROR FOCAL LENGTH = 600 M – 100, 3 M MIRRORS/LINE
  - C.I.D. ARRAYS IN FOCAL PLANE
  - ADAPTIVE OPTICS FOR ATMOSPHERIC CORRECTION, FOCUS, POINTING
- COMPLEX PROCESSING REQUIRED
  - TOMOGRAPHIC APPROACH TO PIXEL SYNTHESIS
  - DATA TRANSFORMED TO SPATIAL FREQUENCY DOMAIN

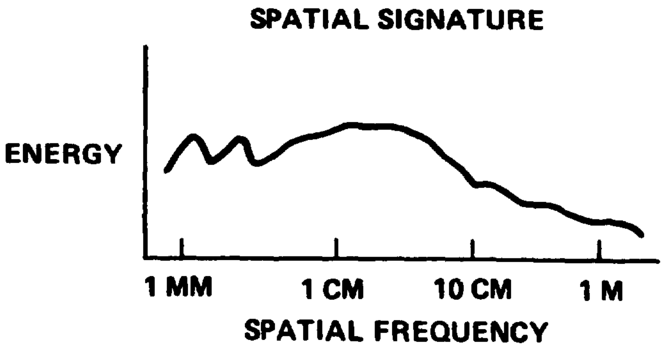


Figure 6-10. Texturometer-System Concept

The diffraction-limited field of view is rectangular because of the narrow mirror width, only 1% of the length.

Some aspects of the design requirements are being investigated by workers in the field of "synthetic aperture" optics (Refs. 6-8-13). This term indicates the tailoring of the diffraction pattern of the optical summation from a possibly sparse array of telescopes; therefore, the idea is different from SAR. The Multi-Mirror Telescope of the Optical Sciences Center of the University of Arizona may be operational in a year; this telescope is composed of six 1.8 m diameter reflectors in a 6.9 m diameter hexagonal array (Ref 6-18). However, this telescope is intended to be a "light bucket" for spectrometers and therefore the six optical paths will not be phase precise.

A major requirement of the Texturometer will be for small sensors suitable for the quantum-starved image. An introduction to photon-counting semi-conductor sensors has been given by Rose (Ref. 6-17). The integration time of these sensors could be either short or long compared to the photon flux rate. The total photon count could be increased with a greater mirror width, sensor spectral bandwidth, or count time.

Some optical and mechanical considerations for this satellite are given in Figure 6-11. However, the attitude control system, whether gravity gradient or active stabilization, has not yet been investigated. Atmospheric drag has not been studied, but could be reduced with the greater orbit altitude of the final design. Some aspects of the required shape control for the vehicle are discussed in Section 7.4.4.

Each of the mirror segments, possibly 1.5 m square, must have its angle and distance from the sensor plane independently controllable. Adaptive optics will allow reduction of the effects of atmospheric scintillation.

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G = gravitational constant = $6.67(10^{-11})\ N\cdot m^2\cdot kg^{-2}$; M_e = earth mass = $5.98(10^{24})\ kg$

E = earth radius = 6378 km; $GM_e = 3.99(10^5)\ km^3\cdot s^{-2}$

V_o = orbital velocity = $\sqrt{\frac{GM_e}{S+E}}$ = 7.73 $km\cdot s^{-1}$

V_g = ground track velocity = $\frac{EV_o}{S+E}$ = 7.38 $mm\cdot \mu s^{-1}$ (neglect earth rotation)

V_s = sensor velocity for image motion compensation = $\frac{FV_g}{S}$ = 7.38 $m\cdot s^{-1}$

M_s = sensor travel during photon count = $V_s t$ = 0.275 m

T = orbit period = $\frac{2\pi(S+E)}{V_o}$ = 5440 s = 91 min

N = samples per sensor per orbit $\leq \frac{T}{t}$ = 136,000

b = allowable blur diameter due to misfocus, in object [illegible] = 0.5 mm

d = maximum object distance shift before refocussing = $b\frac{S}{D}$ = 1 m

Θ = angular width of swath which can be sampled = 20°

X = swath width on ground = $2S\tan\frac{\Theta}{2}$ = 106 km

ΔS = object distance shift across swath = $\frac{S}{\cos\frac{\Theta}{2}} - S$ = 4.6 km (neglect [illegible])

$\frac{dF}{dS}$ = incremental focal length change with object distance = $\left(\frac{F}{S+F}\right)^2 = 10^{-6}$

ΔF = focal length shift $\approx \frac{dF}{dS}\Delta S$ = 4.6 mm

ΔR = mirror radius shift = $2\Delta F$ = 9.2 mm

e_r = radial motion of mirrors required for focal shift = ΔR [illegible]

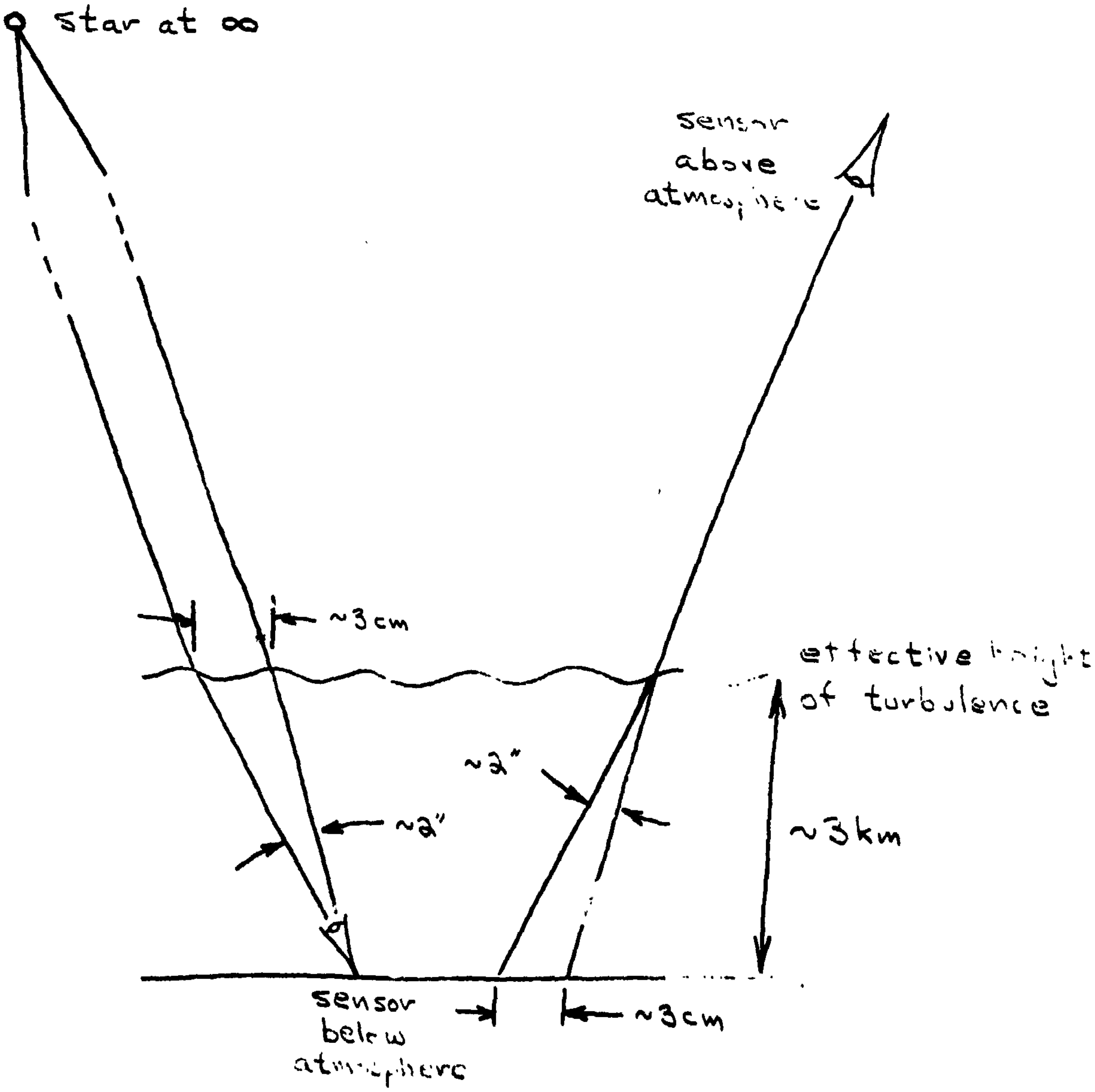
if tangential motion of mirrors (linear expansion) is possible,

e_t = tangential elongation between mirror segments = $\frac{\Delta R}{R}L$ = 23 μm

Figure 6-11. Opto-Mechanical Design Calculations

Atmospheric turbulence, primarily due to vertical thermal convection, affects the wavefront of an electromagnetic wave passing through it; this is due to the presence of air cells having slightly different density and therefore refractive index. Near the source of turbulence, phase shifts along the wave front occur; a spherical wavefront would change to a more irregular figure. Farther from the turbulence, both phase and amplitude (due to interference) changes will be found along the wavefront. Random polarization shifts will also occur. These factors degrade the resolution of an optical system imaging through the atmosphere. The average direction of wavefront propagation at one moment merely causes a displacement of the image; degradation due to this effect can be minimized by giving the imaging sensor a very short exposure time. However, the small perturbations on the wavefront and also the amplitude shifts (which have an effect like random apodization) are much more difficult to correct. Active or adaptive optics, employing deformable mirrors, can help, but correction for more than one image point at a time presents special problems (Refs. 6-28, 33).

One can estimate the resolution degradation of the atmosphere with a simple analysis based upon two facts. The first is that, with optical sensing through the entire atmosphere, the scintillation due to atmospheric turbulence can be assumed to have its source at an effective height of 3 km. The second fact is that astronomers consider the atmosphere to be capable of average good seeing when the blur diameter of a point object, such as a star, is 2" of arc. This is illustrated in Figure 6-12. These facts can then be applied to the case where a sensor is above the atmosphere and is observing the earth's surface. Ground resolution is then seen to be about 3 cm. Adaptive optics will therefore be needed for the higher ground resolution of Texturometer; an adaptive system might also be desirable for correcting the thermal warping of a space optical system even if the resolution was not as critical as this.



turbulence cell size ~ 1-75 m
fluctuation period or life time ~ 1ms - 1s

Figure 6-12. Atmospheric Turbulence

Because of the large aperture, only about 1 m of shift in subject distance will require refocusing of the mirror. This will also be accomplished with the adaptive optical system. Focusing algorithms have been well investigated and are sometimes based on the maximization of the amplitude of the high spatial frequencies in an image. Furthermore, fast optimum search techniques, such as the Fibonacci search sequence, are directly applicable. Mechanically, the mirror could be focused by radial motion of individual segments or by expansion between segments.

It may be more practical to focus the reflector by range measurement with a LIDAR than by searching for maximum high spatial frequency. Once the range is determined, it might be possible to focus with a radial translation of the image plane rather than by reconfiguring the mirror to a different radius. Another possibility is that of using a material whose refractive index can be varied electronically; this could be placed over the sensor plane, or over the mirrors for adaptive optical control.

It is probably not feasible to rotate the entire tetrahedral frame in order to select a point for a texture measurement. More likely, this could be done with a combination of three approaches: rotating the mirrors as a unit with one actuator at each of the upper corners of the tetrahedron; employing multiple and separated arrays of sensors on the sensor plane; and moving the sensor arrays on the sensor plane.

The focal plane could include many islands of sensor clusters. It would possibly be easiest if image motion compensation were achieved by electronic switching between sensors in an island rather than by physical motion. If the flight direction could be accurately compensated, a CCD sensor matrix would be ideal; electronic IMC would require an extremely large number of elements, however.

While the sensor plane might be made large enough for a suitable swath width, further off-nadir points might be imaged by rolling the entire satellite. If this would be too slow, an alternative would be that of rotating each individual mirror of the triple linear arrays. Then the mirror surfaces would be stepped like a Fresnel lens; except for the monochromatic case, coherent summation would be impossible at the image plane.

One important point deserves further consideration: since most surfaces will be randomly-textured, it will be very difficult to get the radiance of a 1 mm square pixel from a 1 mm by 10 cm rectangular diffraction-limited, effective IFOV (see Figure 6-7). That is, in general ground objects will not line up with the three mirror directions.

One possible way out of this problem would be active illumination. Rather than having three linear mirrors in an equilateral triangle, a pair of orthogonal mirrors would be employed. One mirror would be a reflector for the illumination source and the other would be a 1 mm square on the ground. While the ground irradiance from the illuminator could probably be higher than for Nite Lite, it could still be less than sunlight so that daytime measurement would be impossible.

A better solution is possible. Tomography has recently become well developed as a technique for reconstructing two-dimensional scenes from one-dimensional profiles, its primary application has been for biological X-rays. A 100 by 100 matrix of sensor elements would be needed to measure a 1 cm square with 1 mm resolution. In one direction, the diffraction patterns of adjacent sensors will overlap by 99%; the tomographic approach will be required to separate these. Because of the photon-limited noise of each measurement, many additional measurements might be required to get adequate radiance precision at the 1 mm level.

Photon statistics and the Hanbury Brown and Twiss effect might also be applied to the design of this Texturometer; however, a careful study of the physics and technology is required (Ref. 6-7, 9 , 10, 14, 16).

Since it is the spatial perodicities which are most valuable for comparing texture measurements, mathematical transforms will be required in order to convert the linear radiance values from the sensor arrays. One of three related transforms might be suitable: the autocorrelation function, the Fourier transform, or the power spectral density. These transforms might also be accomplished optically.

It may not be necessary to transmit the complete spatial frequency function to earth for each texture sample; certain spatial bands may be found to be adequate.

Textural analysis for earth resources applications is receiving increasing attention; several authors have reviewed different aspects of this work (Refs. 6-11, 12, 19).

6.1.5 THERMAL INERTIA MAPPER

Thermal inertia can provide an additional parameter for identifying and quantifying terrain. For hydrology, it is an indicator of the moisture content of the soil (Ref. 6-38). For geology, rock types can be contrasted; sometimes rocks covered by a thin layer of dust or vegetation, such as lichen, can be more readily distinguished by their thermal properties than in the optical spectrum.

The principle and practice of thermal inertia or heat capacity mapping has been outlined before (Refs. 6-34, 35). A spacecraft has recently been launched for the Heat Capacity Mapping Mission (Ref. 6-36). While the Heat

Capacity Mapping Radiometer will have a resolution of about 600 m in the thermal IR band, around 11 micrometers, the Geosat Committee has suggested that a higher resolution will eventually be necessary (Ref. 6-37).

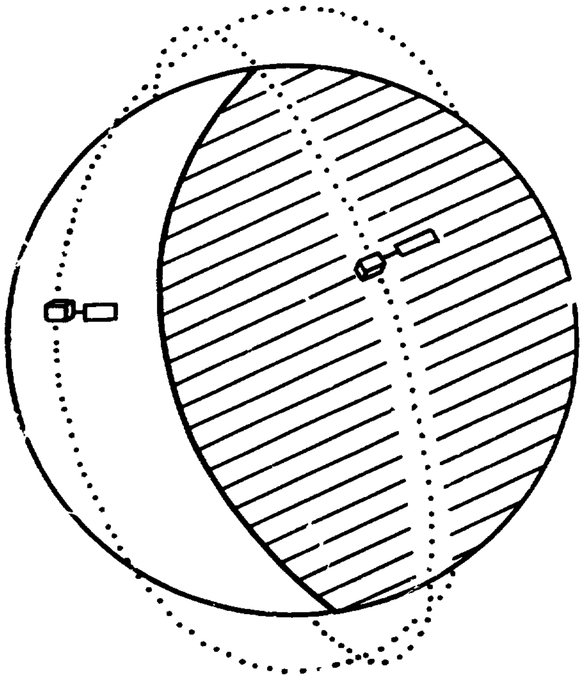
Therefore, the Thermal Inertia Mapper will have a resolution of about 10 m. Except for having an optical aperture of 0.6 m or larger, the TIM will be quite similar to the HCMR. Both will have a 600 km sun synchronous orbit and employ the 10.5 to 12.5 micrometer band. This system is summarized in Figure 6-13.

The estimates of future needs indicate that a temperature precision of 0.1°C would be desirable. For a temperature range between -10°C and 40°C, a data precision of 9 bits is required. It might also be valuable to trade off precision for dynamic range; a 1°C precision between -50°C and 450°C would allow better quantification of extreme conditions in particular, fires and volcanic eruptions. Both of these approaches will have a data rate of about one gigabit per second with a 100 km swath width.

Just as with the HCMM, the TIM will acquire thermal radiance images, in sunlight and darkness of the same scene, with about a 12 hour time separation; the difference in radiance allows an approximation to thermal inertia. TIM would probably operate in conjunction with another imaging system or spacecraft in order to get visible spectrum images.

6.1.6 RADAR HOLOGRAPHER

It would be desirable to generate a true radio frequency hologram of the earth from a spacecraft. This would be particularly valuable for those applications requiring topographic information and a variable perspective; in addition, this radar hologram could allow imaging through cloud cover.



- THERMAL MAPPER AS FOLLOW ON TO HCMM
- MEASURES THERMAL INERTIA OR HEAT CAPACITY OF TERRAIN
- SEQUENTIAL PASSES OVER SAME AREA
  - 4 A.M./10 A.M. – 4 P.M./10 P.M. LOCAL CROSSINGS
- 10 M RESOLUTION IN 8-13 μm BAND
  - 600 KM ORBIT
  - 0.6 M DIAMETER PRIMARY OPTICS

APPLICATIONS: WATER POLLUTION DETECTION
GEOLOGICAL RESOURCES LOCATION

CREDIBLE SEMI-CREDIBLE INCREDIBLE

Figure 6-13. Thermal Inertia Mapper - System Concept

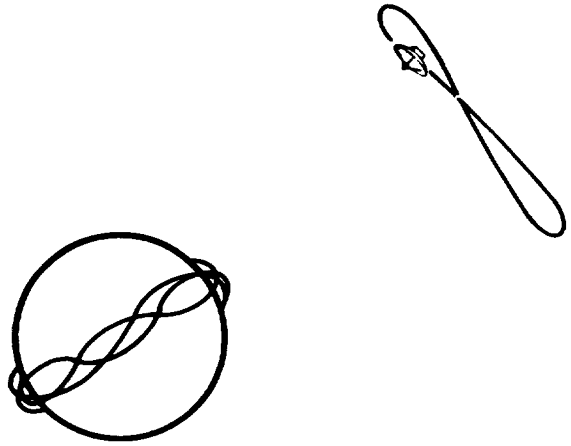
The radar holographer is not a quasi-holographic system such as SAR or "hologram radar" (Ref 6-41) but is instead a true holographic system. Most techniques of microwave holography employ a stationary illuminator and a receiver which acquires a dense two-dimensional array of samples.

An alternative approach has been tested by Hayward, Rope, Tricoles, and Yue (Ref 6-40); with their technique, only a pair of one-dimensional lines needs to be sampled. Their system employed a line of transmitter antenna perpendicular to a line of receiver antennas. All possible combinations of transmitter-receiver parts provide measurement samples; this quantity is the product of the number of transmitter and receiver points.

This approach could be accomplished with spacecraft. A stable CW transmitter operating at a frequency of 300 MHz is in a geosynchronous orbit. Its antenna illuminates the area for which a hologram is desired; this could be a 6000 km square. The satellite would have an orbital inclination to yield a drift of about 60° north and south of the geostationary point on the equator.

A number of simple receiver satellites would be in LEO; they only measure the phase and amplitude of the earth return relative to the direct illuminator signal. Their altitude might be around 900 km and the orbits could be equatorial or inclined. The antennas on each of these receivers receive the scattered radiation from the entire 6000 km area. The sampled information could be transmitted to earth; the position of the satellite for each sample must be known. The key parameters of this system are summarized in Figure 6-14.

When the array of samples is dense enough, a hologram can be generated (Ref. 6-39). The time required to generate a hologram is inversely proportional to the number of receivers in orbit. The generation time is also inversely proportional to the sample spacing required; this is dependent



- SYSTEM GENERATES TRUE VHF HOLOGRAM
  - PROVIDES VARIABLE PERSPECTIVE
  - DIFFERENT THAN HOLOGRAM RADAR OF LARSON ET AL
- GEOSYNCHRONOUS CW 300 MHz ILLUMINATOR
  - DRIFTS 60° N AND S OF EQUATOR
- MULTIPLE LEO PHASE AND AMPLITUDE RECEIVERS
  - IONOSPHERE PHASE SHIFT
- HOLOGRAM ACCURACY (CONTRAST) INCREASES WITH SAMPLING TIME
  - GROUND RES INCREASES WITH ACCURACY

APPLICATIONS: ABRUPT EVENT EVALUATION
GEOLOGICAL RESOURCES LOCATION
LAND USE AND CENSUS

CREDIBLE SEMI-CREDIBLE INCREDIBLE

Figure 6-14. Radar Holographer - System Concept on the finest order of Fresnel zone which must be recorded and therefore the "noisiness" of the hologram. Using three low earth orbit receivers the Fresnel pattern can be adequately sampled in about 2 months time.

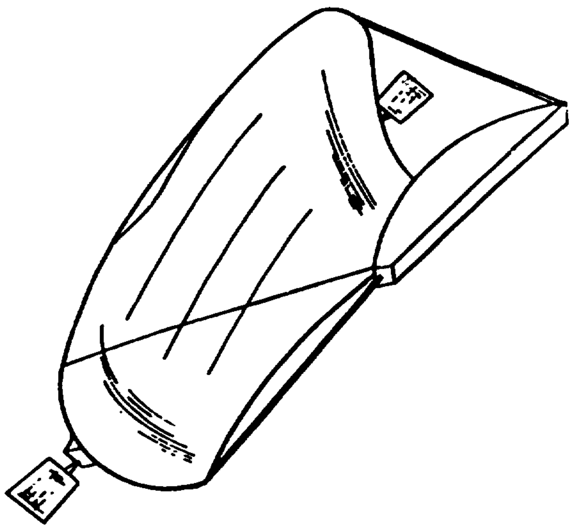
As with all of these techniques, scaling from microwave to optical frequency for viewing will reduce the size of the hologram. Phase shift in the ionosphere must also be considered (See Section 7.4.12).

The idea for this system benefits from the earlier work of Nabil Farhat, Professor of Electrical Engineering at the University of Pennsylvania.

6.1.7 MICROSAT

The Microsat system concept is based on an earlier General Electric study performed for the Large Space System Technology (LSST) program office centered at Langley Research Center. The original antenna design, presented in Figure 6-15, was developed by Messrs. Allen, Foldes and Tomiyasu of the General Electric Company and was adopted for use in this study. (Ref. 6-43).

The prime function of the Microsat system concept is a soil moisture sensor (L-band radiometer) with about 1 km ground resolution and radiometric temperature resolution of 1°K at an orbital altitude of 1000 km. A number of alternative designs were considered, with the selected antenna design being a parabolic torus with a cluster of feed horns arranged in a focal arc to provide simultaneous beam forming. The nominal reflector size is 600 meters x 1300 meters with 60 simultaneous beams, each scanning 81 cross track beam positions. In the preliminary design, the focal length was about 680 meters providing a 20 dB beamwidth of 1.07 milliradians. An estimate of the time of implementation of the system would be approximately 1988-1990.



- PRIMARILY SOIL MOISTURE SENSOR
- L-BAND PASSIVE RADIOMETER
- PARABOLIC TORUS ANTENNA WITH CLUSTER OF FEED HORNS IN A FOCAL ARC
- FREQUENCY IS 1.4 GHZ (L BAND)
- ANTENNA SIZE APPROXIMATELY 600M X 1300M
- GROUND RESOLUTION – 1KM, ORBIT – 1000KM, REPEAT CYCLE – 3 DAYS (2 SPACECRAFT), RADIOMETRIC TEMP. RES. – 1^{o}K

APPLICATIONS: WATER POLLUTION DETECTION
WATERSHED MONITORING

CREDIBLE — SEMI-CREDIBLE — INCREDIBLE

Figure 6-15. Microsat System Concept

Four different structural designs were considered (Ref. 6-43) for implementation of the parabolic torus antenna. These included (1) a tetrahedron truss mesh planform reflector, (2) a dual rim truss mesh planform reflector, (3) a drum mesh planform reflector and (4) a deployable ring mesh planform reflector. Analysis of the four configurations indicates that the drum with mesh reflector was the "best" erectable configuration. The deployable configuration was the preferable implementation design but "may suffer significantly in design and development complexity".

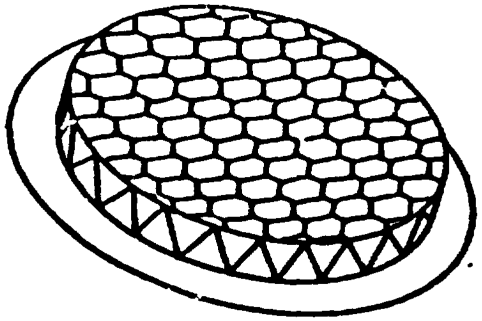
6.1.8 PARASOL RADIOMETER

In the PLACE era, it is possible that active microwave earth-viewing imagers may not provide the data required for soil moisture measurements. Passive microwave radiometry may be necessary to provide these measurements. For this reason, a high resolution radiometer must be closely studies, even though extremely large apertures are required.

The parasol radiometer of Figure 6-15A is one approach. While this final design employs a phased array, the original structure was a reflector; this is the reason for the retained name, "Parasol".

The advantages of the phased array are electronic control of structural warping and the possibility of nulling out interference sources. The disadvantage is that a sparse distribution of receiver elements will be necessary, and antenna side lobe problems must be carefully considered, even with random spacing.

The design suggested is a 10 km circular phased array which would employ individual transmit/receive elements on integrated circuit chips. A complete description of these elements, which were also employed in the design of the Ferris Wheel radar is presented in Section 7.4.23.



- HIGH RESOLUTION SOIL MOISTURE SENSOR WITH ADDITIONAL MAPPING APPLICATIONS
- PASSIVE 10 KM MICROWAVE RADIOMETER
- FROM 1000 KM ORBIT — 10 M RES AT λ = 10 CM
- IC CHIPS FORM ELEMENTS OF A PHASED ARRAY
- RIGID STRUCTURE HAS ACTIVE SHAPE AND ATTITUDE CONTROL SYSTEM

APPLICATIONS: WATER POLLUTION DETECTION
WATERSHED MONITORING

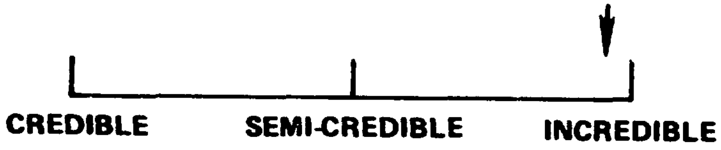


Figure 6-15A. Parasol Radiometer - System Concept

From an altitude of 1000 km, the system will have a resolution on the ground of 10 m at S-Band (10 cm). The detailed operation of the distributed element phased array concept will be discussed under the description of the Ferris Wheel Radar (Section 6.1.10).

Since the Parasol Radiometer is the largest solid structure of the PLACE system concepts (the Ferris Wheel is larger but is not a solid structure), the key feasibility question is whether it will be possible to build a 10 km structure by the year 2000. The promoters of the Solar Power Satellite obviously think so. Reference is made to Section 7.4.4 where the detailed requirements of large structures are investigated.

6.1.9 RADAR ELLIPSOMETER

Optical scientists have developed three related techniques for measuring the thickness and/or refractive index of thin, transparent films. In each of these, the specular component of reflected light is measured; two fundamental parameters are the angle of reflection and the frequency of the light. One technique employs a constant frequency and measures the change in reflectance as a function of angle, with the light source and sensor angles kept equal for specular reflection. The reflectance changes with angle because of interference between the light reflected from the upper and lower surface of the thin film.

A second technique keeps the angle of incidence and reflectance at a constant value; the frequency of the incident light is varied. Again, the changes in reflectance indicate the optical thickness and refractive index of the dielectric film. Dispersion, however, adds another variable.

The third technique is that of ellipsometry; here, both the angle and frequency of the light are constant. Instead, it is the change in the polarization of the reflected light which is measured. Ellipsometry is based on the principle that the reflection of light at an interface is different for the two cases of polarization: parallel to the plane of incidence and perpendicular to the plane of incidence. If the incident light is plane or circular polarized, the reflected light will, in general, be elliptical polarized. Three separate parameters describe elliptical polarization. While these parameters can be considered from the amplitude and phase of electromagnetic waves, they can also be thought of as the three geometric variables which describe an ellipse: its area, the ratio of the lengths of its major and minor axes, and the angle of its major axis. As one might expect, these three independent variables allow one to determine three properties of the thin film. These can be: its thickness (with an ambiguity if the film is thicker than the wavelength of the light in the film), its refractive index or dielectric constant, and also the refractive index of the medium below the thin film.

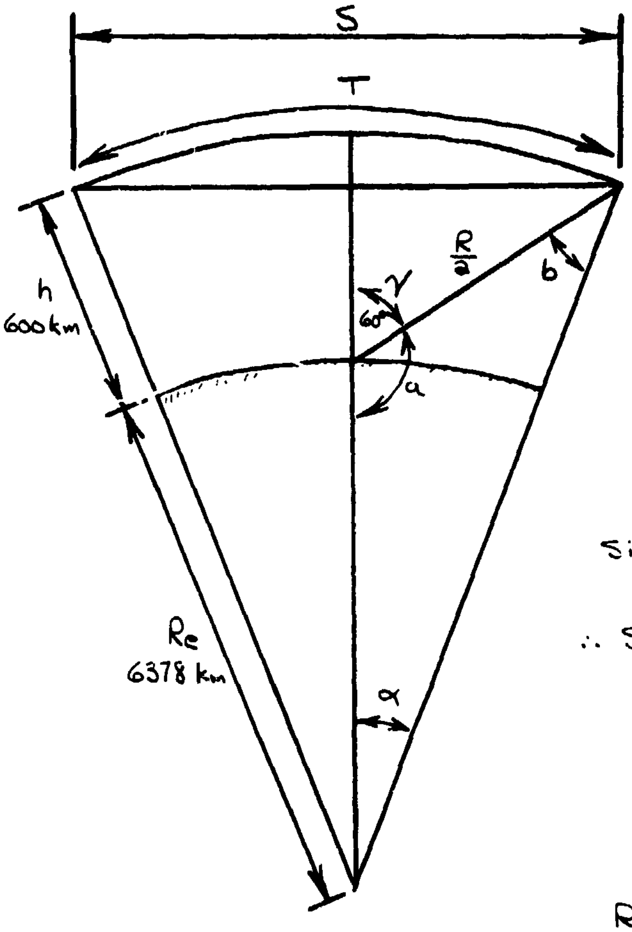
The three separate techniques for measuring layer thickness are equally valid for radio frequencies; furthermore, they can all be employed from spacecraft. The first two have specific disadvantages, however. It is difficult to provide the variable angle function because of the great distances involved at spacecraft altitude, and a variable frequency system can require excessive bandwidth.

The ellipsometry approach appears to be practical as a spacecraft radar system. The method has been conceived and developed by Siegfried Auer and John Schutt (Refs. 6-44,45). Its prime application is to agriculture. The "thin film" in this case is a crop growing in soil. The thickness or height measurement can aid the identification of the crop or its stage of growth. The dielectric constant of the crop layer indicates the density of the crop and its moisture content; these are good variables for quantifying potential yield. The measurement of the dielectric constant of the medium below the interference layer might provide a good indicator of soil moisture content.

In their analysis, Auer and Schutt have determined that the optimum radar frequency for the agricultural applications is about 300 Mhz, and the best angle of incidence and reflectance is around 60° from the normal. As Figure 6-15B indicates the range, via reflection, between two satellites in this configuration would be about 2200 km if the altitude of the pair was 600 km; the two satellites follow the same orbital path (see Figure 6-16). Auer has also suggested that the effect of Faraday rotation in the ionosphere could be corrected with ground patches having known reflectance and dielectric constant, such as desert regions and bodies of water. The lateral homogeneity of the ionosphere might be adequate to apply these rotation calibrations many kilometers from their source.

The spatial resolution or footprint of the radar ellipsometer must be about 100 m or better in order to increase the likelihood that the crop has a uniform thickness within it. A real aperture radar system would then require an antenna with dimensions of about 11 x 22 km; there would also be the further complication that both transmitter and receiver antennas must be beamed to the same 100 m diameter area on the earth.

An alternative concept, suggested by K. Tomiyasu of the GE Space Division has been analyzed. Each antenna could be a long, linear phased array with dimensions of 11 km x 4 m; the fan beans of the two would be oriented so that their footprints on the earth would intersect at about a right angle and the



$$\frac{\sin b}{R_e} = \frac{\sin a}{R_e + h}$$

$$\therefore \quad \sin b = \frac{R_e}{R_e + h} \sin a$$

$$\cos b = \sqrt{1 - \left(\frac{R_e}{R_e + h}\right)^2 \sin^2 a}$$

$$\sin \alpha = \sin(a + b) = \frac{\frac{S}{2}}{R_e + h}$$

$$\therefore \quad S = 2(R_e + h)(\sin a \cos b + \cos a \sin b)$$

$$= 2 R_e \sin \gamma \left[\sqrt{\left(\frac{R_e + h}{R_e}\right)^2 - \sin^2 \gamma} - \cos \gamma \right]$$

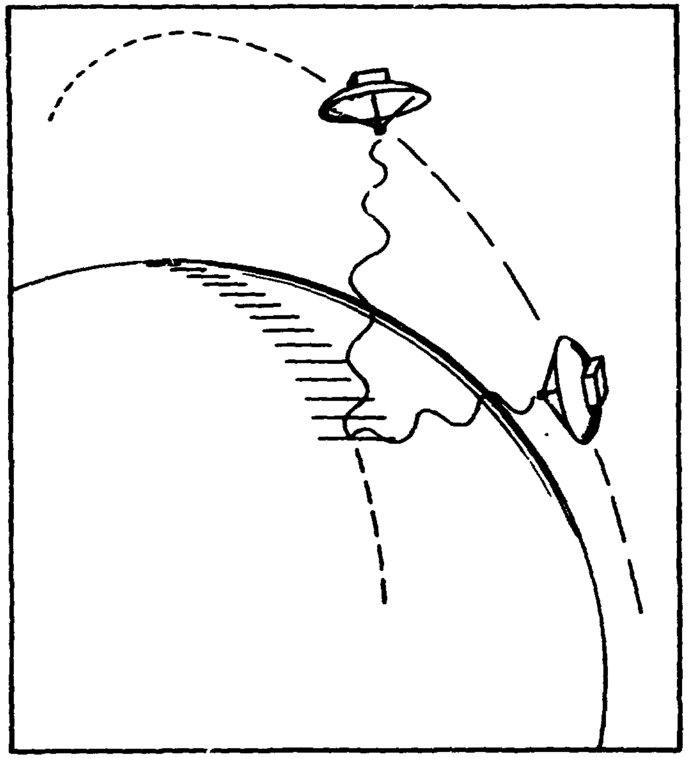
$$= 1885 \text{ km}$$

$$R = \frac{S}{\sin \gamma} = 2200 \text{ km}$$

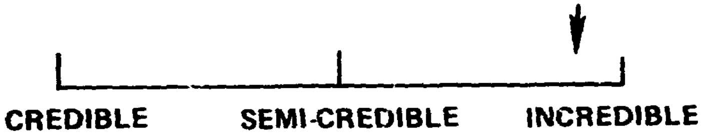
$$\alpha = \gamma - \sin^{-1}\left(\frac{R_e}{R_e + h} \sin \gamma\right) = 8^\circ$$

$$T = \pi (R_e + h) \frac{\alpha}{90^\circ} = 1940 \text{ km}$$

Figure 6-15B. Geometry of the Radar Ellipsometer



APPLICATIONS: AGRICULTURE, RANGE, FORESTRY



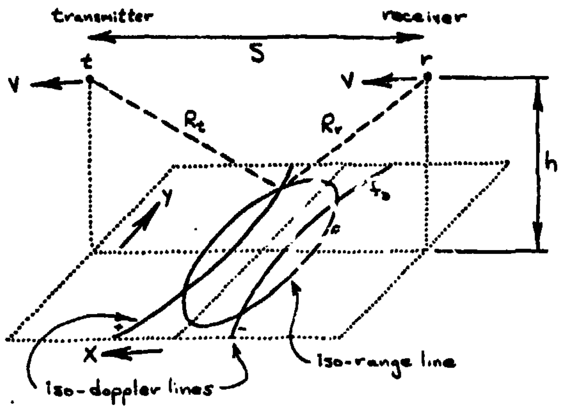
- BASED ON EARLY WORK BY SIEGFRIED AUER AND JOHN SCHUTT
- BISTATIC RADAR APPROACH EMPLOYS ONE SPACECRAFT FOR TRANSMITTER AND ONE FOR RECEIVER (SPECULAR REFLECTION ONLY)
- SYSTEM WILL MAP DIELECTRIC CONSTANT OF THE SOIL, DIELECTRIC CONSTANT OF VEGETATION, AND HEIGHT OF VEGETATION
- MEASURES EFFECT OF REFLECTION ON POLARIZATION OF WAVES (3 MEASUREMENTS OF ELLIPTICITY)
- BISTATIC SAR APPEARS TO BE MOST PRACTICAL SYSTEM
- 600 KM ALTITUDE - 1900 KM SEPARATION
    - 100 M RES
    - 300 MHZ OPERATING FREQUENCY – IONOSPHERE

Figure 6-16. Radar Ellipsometer - System Concept area of intersection would be the 100 m square. The length of the footprint would be about 270 km on the ground; this would be the available swath width. By steering the two phased arrays, any spot within a 270 Km square could be sampled. The maximum swath width is also dependent on the slope of the land surface and the suitability of non-specular returns.

Assuming a normalized scattering coefficient of 0.01, an effective system temperature of 1000°K, and system losses and antenna efficiencies each of 3 dB, a peak power of about 1 kW is required for a SNR of 20 dB. The average power is only 75 mW. Additional analysis is needed to investigate the effect of noise sources filling most of the received beam.

Another implementation possibility is that of employing smaller antennas, with greater beam width. While the specular return (from a smooth earth) is from the point of minimum range, the range gating precision which is required is about 5 mm for a 100 m cell around the specular point.

Finally there remains the possibility of implementing the ellipsometer with non-real or synthetic aperture. An analysis of the isodop (constant Doppler frequency) and isodel (constant time delay between transmitter and receiver) contours indicates potential problem areas, as shown in Figure 6-16A. Note that there are four indistinguishable range-doppler cells symmetrically left and right of the ground track. The isodel contours are quite sensitive to the tilt and elevation of the local scene to be imaged. A concave scene surface which is tangent to an isodel ellipsoid cannot be imaged because of a vanishing isodel gradient. (Ref 6-79). It is left as a future challenge to overcome these fundamental problems so that the radar ellipsometer may be implemented with smaller apertures.



$$R_t = \sqrt{h^2 + (X - \tfrac{S}{2})^2 + Y^2} \qquad R_r = \sqrt{h^2 + (X + \tfrac{S}{2})^2 + Y^2}$$

iso-range lines: $R = R_t + R_r$

$$Y^2 + X^2\left(1 - \frac{S^2}{R^2}\right) = \frac{R^2 - S^2}{4} - h^2$$

since $R > S$, these are ellipses

iso-doppler lines: $f_D = \frac{V}{\lambda}\left(\frac{X - \frac{S}{2}}{R_t} + \frac{X + \frac{S}{2}}{R_r}\right)$

not a conic; up to 8th degree in X

for $X = 0$, $f_D = 0$

Figure 6-16A. Range and Doppler Curves for a Bistatic Radar

6.1.10 FERRIS WHEEL RADAR

Perhaps one of the most imaginative and challenging of the PLACE systems concepts (with all due respect to the Texturometer) is the Ferris Wheel Radar. Described as a geologist's dream, this real aperture radar (summarized in Figure 6-27), is intended to map subsurface materials through the identification of boundary layers.

The Ferris Wheel Radar system could be constructed as a phased array radar with the individual elements distributed over the structure. While airborne radars have been used for profiling ice for over a decade, and a spaceborne radar was employed on Apollo 17 (Refs. 6-56, 58, 65) the Ferris Wheel ground-penetrating radar will require considerably more power and size than these earlier radars.

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Structural considerations will be discussed first. For economical construction, including material and transportation costs, it may be best to minimize the number of compressional and torsional elements in the structure. Tensional structures may have a lower mass for a given size of structure; thin cables can replace thicker beams. The cable tension can result from the rotation of the entire structure.

An oblique view of a possible structure is given in Figure 6-17. A flat, circular net of cables is supported in the midplane of a rotating structure much like a bicycle wheel with spokes. The cross section of the supporting structure, shown in Figure 6-18, is triangular; its only purpose is the prevention or control of possible waviness in the cable net out of the desired flat plan; it may not be necessary. A pillar capable of supporting the triangular frame's compressional load is coincident with the axis of rotation. The circular net, illustrated in Figure 6-19, could support the plane of the phased array radar of Ferris Wheel. Its parallelogram or diamond cell could be made arbitrarily smaller with a denser net of cables, and a different number of sectors could be chosen rather than the dozen shown.

This particular cell shape has the advantage of adjusting for dimensional errors in the fabrication of the net and also for in-plane waves in the rotation of the structure. The symmetrical balance of forces tends to keep the diamond mesh uniform and undistorted. The cell pattern also simplified the construction of the cable net in space; a possible approach is illustrated in Figure 6-20. A long, temporary extension is given the compressional pillar. The cable mesh is fabricated on this supporting staff, forming the "bud" of the resulting "flower" or wheel. The diamond cell insures that none

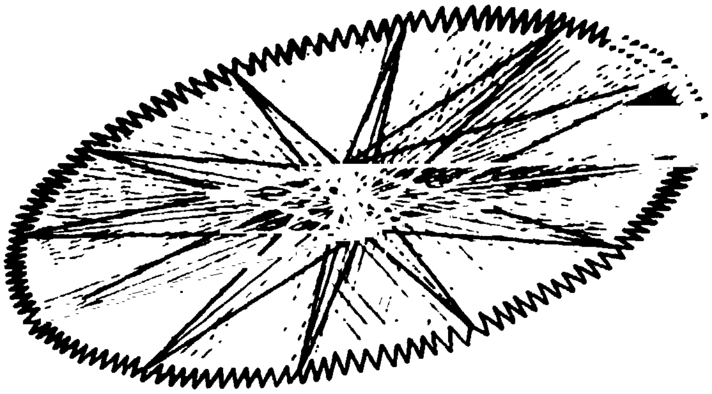

Figure 6-17. An Oblique View of the Roto-Tensile Structure

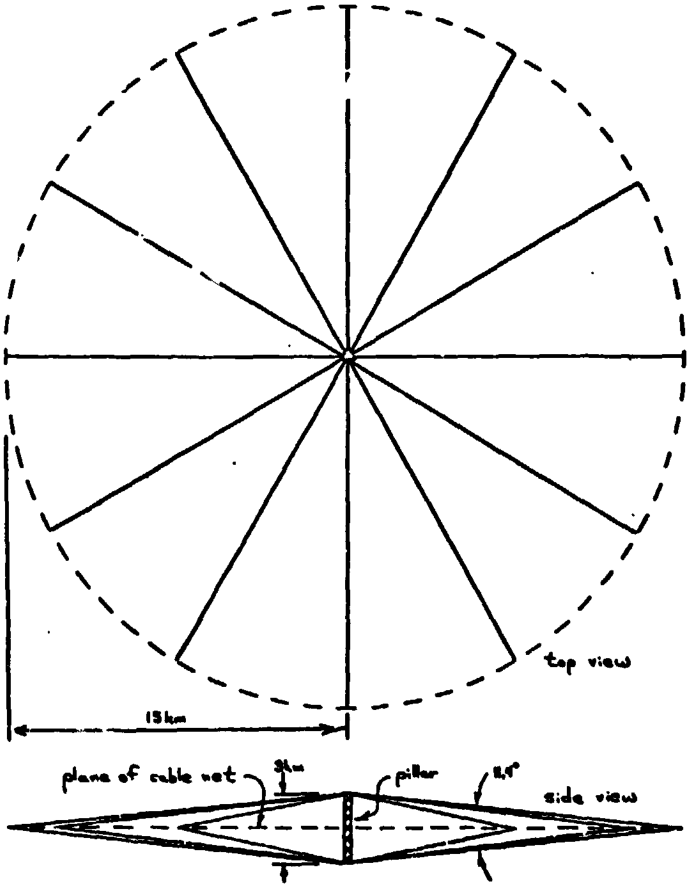

Figure 6-18. The Support Structure for the Planar Cable Net

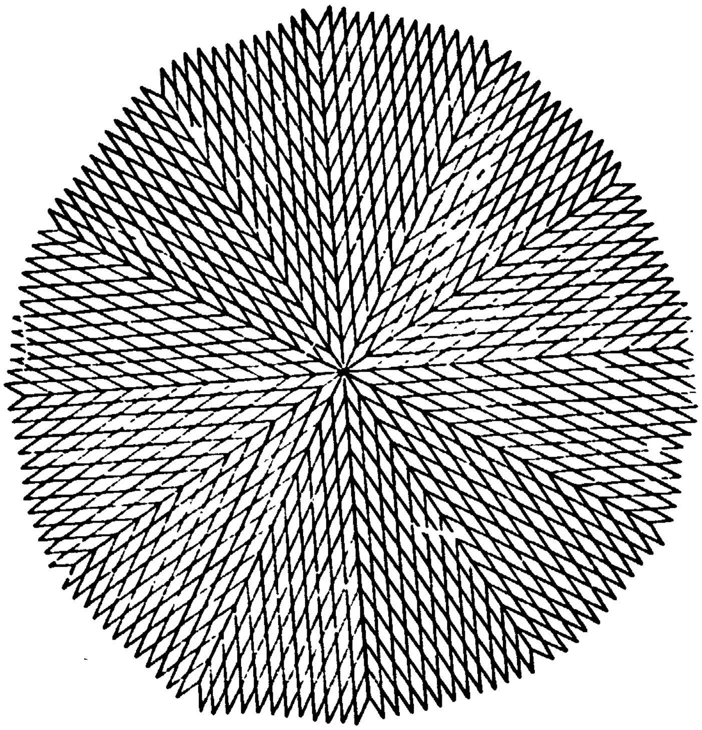

Figure 6-19. The Primary Structure Plane: A Web Composed of Cables, Forming Diamond-Shaped Cells

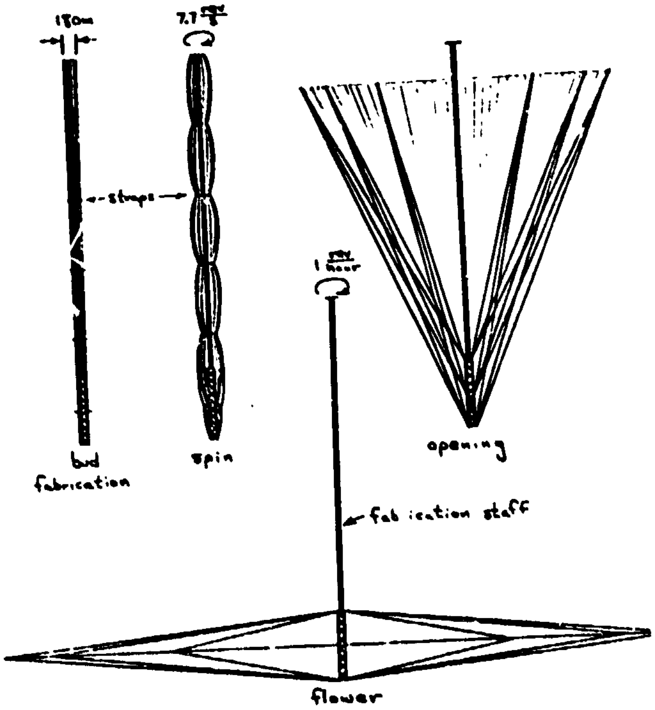

Figure 6-20. The Axial Opening Method of Deployment

of the cables in the bud will be slack; that is, the net can be deformed and all cables will remain in tension.

If several temporary straps are tied around the cable net or bud, the entire structure can be spun around its long axis. When the straps are released, the bud will open into the desired flower configuration. Figure 6-21 gives approximate calculations of the spin parameters required in order that axial opening will yield a spin rate of the flower of one revolution per hour.

After opening, the temporary staff can be removed. In a different configuration, this staff could also be used to support a parabolic reflector, although elaborate guying would be required. During opening from this fabrication and deployment configuration, the triangular framing cables must have their lengths changed. This might be accomplished with a continuous cable passing over pulleys at each end of the compression column and extending from the rim of the wheel through the column, and then back to the rim. During opening, a length of cable equal to about 1/80th of structure's diameter must be added to this loop.

While this axial deployment configuration is particularly easy to fabricate, it has the disadvantage of requiring very large spin energy, most of which must be dissipated during opening. If this is not done, the flower will reclose into a bud pointing in the opposite direction. For the structural dimensions given in Figure 6-21, over one megajoule must be wasted for each kilogram mass in the structure.

The radial opening configuration given in Figure 6-22 will improve this situation. The cable net is fabricated while spinning about an axis per-

Deployment Approximations

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r_o = radius of flower = 15 km
height of axial pillar = 3 km
angle between opposing guy lines = $2 \arctan \frac{1.5}{15} = 11.4°$
ω_o = rotation velocity of flower = $1 \frac{rev}{hour} = 1.75(10^{-3})\ s^{-1}$
m = mass of structure, kg
I_o = moment of inertia about rotation axis $\approx \frac{1}{4} m r_o^2$
E_o = kinetic energy of flower = $\frac{1}{2} I_o \omega_o^2$
A_r = radial acceleration at rim = $r_o \omega_o^2 = 0.046\ m \cdot s^{-2} \approx \frac{G_{earth}}{200}$

Axial Opening: see Figure 4

r_c = radius of cable bud during fabrication and spin = 90 m
I_c = moment of inertia of bud (longitudinal axis) $\approx \frac{1}{2} m r_c^2$
ω_c = rotational velocity of bud = $\frac{I_o}{I_c}\omega_o = \frac{1}{2}\left(\frac{r_o}{r_c}\right)^2 \omega_o = 24.3\ s^{-1} = 7.7\ \frac{rad}{s}$
E_c = kinetic energy of bud = $\frac{1}{2} I_c \omega_c^2$
$\frac{\Delta E}{m}$ = change in kinetic energy on flowering (per unit mass) = $\frac{1}{m}(E_c - E_o) =$
$\approx \frac{1}{4}\left[(r_c\omega_c)^2 - \frac{1}{2}(r_o\omega_o)^2\right] = 1.20(10^6) - 43 = 1.20 \frac{MJ}{kg}$
$\frac{E_c}{E_o} = \frac{I_c}{I_o} = \frac{1}{2}\left(\frac{r_o}{r_c}\right)^2 = 10^6/72$

Radial Opening: see Figure 6

I_r = moment of inertia of bud (normal to length, at center) $\approx \frac{1}{12} m r_o^2$
E_r = kinetic energy of rotating bud = $\frac{1}{2} I_r \omega_r^2$
ω_r = rotation velocity = $\frac{I_o}{I_r}\omega_o = 3\omega_o$
$\frac{\Delta E}{m} = \frac{1}{m}(E_r - E_o) = \frac{1}{2}\left[\frac{r_o^2}{12}(3\omega_o)^2 - \frac{r_o^2}{4}\omega_o^2\right] = \left(\frac{r_o\omega_o}{2}\right)^2 = 171 \frac{J}{kg}$
$\frac{E_r}{E_o} = \frac{I_o}{I_r} = 3$

Figure 6-21. Rotation Velocity and Energy Calculations pendicular to its bud length; no temporary staff is used. Again, straps hold the cable mesh together. When these straps are released, the net will fan out into the desired circular flower. During opening, the center of rotation of the structure will, of course, move to the pillar axis. As Figure 6-22 indicates, there is still excess spin energy in the bud as compared to the flower; this energy must be dissipated during opening in order to prevent the fan from opening more than 360°, resulting in an overlapping mesh. This deployment configuration wastes much less energy than the prior configuration.

In both configurations, the forces which initiate the opening of the bud are proportional to the diameter of the bud. As for electronics, the individual transmitter-receiver elements of Ferris Wheel are integrated circuit chips, which will be discussed in a later section; a more general electronic analysis is considered next.

The following parametric analysis of the Ferris Wheel's power requirements assumes an AM pulse radar, although a CW scatterometer is a possible alternative (Ref 6-66). While the indicated precisionis greater, this design only aims to be accurate to within a factor of ten. Since many of the parameters will change with further evolution of the design, these factors only indicate one possibility: a nominal design.

The particular form of the radar equation which was applied to this analysis is given in Figure 6-23; several auxiliary equations are listed also. The symbols are defined in the numerical evaluation of Figure 6-24. Explanatory notes on Figure 6-24 follow; these notes follow the order of the discussion of the parameters in Figure 6-24.

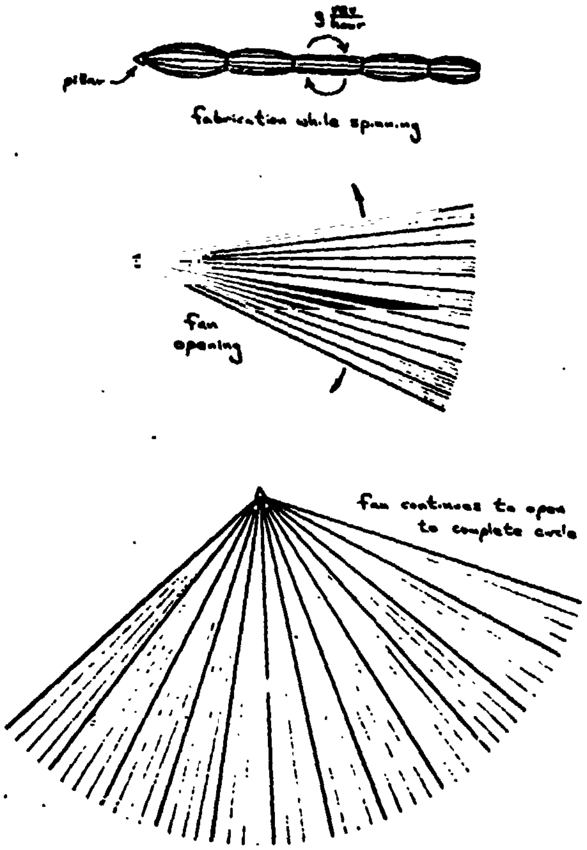

Figure 6-22. The Radial Opening Method of Deployment

Radar Equation

$$S = \underbrace{\frac{P_t U G}{4\pi R^2 L_i L_s}}_{P_d} \frac{\sigma_r G \lambda^2}{(4\pi)^2 R^2 L_g L_i L_s N}$$

PRF	$U = \tau F = \frac{c}{2BE}$
cross section	$\sigma_r = \sigma^\circ I^2$
IFOV	$I = \Theta_3 \approx \frac{\lambda}{D} R$
antenna gain	$G = \pi n \eta$
ground loss	$L_g = e^{4\alpha d}$
attenuation	$\alpha \approx 60\pi \frac{\sigma}{\sqrt{\epsilon_r}}$
noise power	$N = kTB$

Figure 6-23. Radar Equation Used in Ferris Wheel Radar Analysis

f = center frequency of radar = 30 MHz

c = speed of light in vacuum = $3(10^8)\ \mathrm{m \cdot s^{-1}}$

λ = wavelength in free space = $\frac{c}{f}$ = 10 m

D = antenna diameter or aperture = 30 Km

θ_3 = half power beam width of antenna = $\frac{\lambda}{D} = \frac{1}{3}$ mrad

n_2 = number of elements in phased array for $\frac{\lambda}{2}$ rectangular spacing $= \frac{\pi}{\theta_3^2} = 28.3\,(10^6)$

n = actual number of elements = $5(10^7)$

η = antenna efficiency of each element = $\frac{1}{2}$

G = antenna gain = $\pi n \eta = 7.85(10^7)$

B = half power bandwidth = $\frac{f}{10}$ = 3 MHz

τ = width of rectangular pulse = $\frac{0.89}{B} \approx \frac{1}{B} = \frac{1}{3}(10^{-6})$ s

E = terrain relief = 100 km

F = PRF maximum = $\frac{c}{2E} = 1500\ \mathrm{s^{-1}}$

U = duty cycle of pulse = $\tau F = 5(10^{-4})$

R = range to reflector $\approx h$ = satellite altitude = 900 km

L_s = transmitter or receiver system loss factor = 2

L_i = one way ionospheric loss factor = 2

P_d = maximum allowable average (6 min.) power density on earth $= 100\ \frac{\mathrm{W}}{\mathrm{m}^2}$

P_t = peak transmit power = $\frac{4\pi R^2 L_i L_s P_d}{G U} = 1.04(10^{11})$ W

P_{te} = peak power per element = $\frac{P_t}{n}$ = 2.08 kW

P_{ave} = average power per element = $P_{te} U$ = 1.04 W

I = ground spot size or resolution diameter = $\theta_3 R$ = 300 m

σ° = radar cross section per unit area = 0.1

σ_r = radar cross section = $\sigma^{\circ} I^2 = 9(10^3)\ \mathrm{m}^2$

k = Boltzmann's constant = $1.38(10^{-23})\ \frac{\mathrm{J}}{\mathrm{K}}$

T_e = effective system noise temperature = $3(10^4)$ K

N = system noise power = $k T_e B = 1.24\,(10^{-12})$ W

S = SNR per pulse = 10

L_g = two way propagation loss in ground (amplitude attenuation factor) $= \frac{P_d \sigma_r G \lambda^2}{(4\pi)^2 R^2 L_s L_i N S} = 1.12(10^{12})$

r = dynamic range required in receiver = $10 \log_{10} L_g$ = 120.5 dB

Figure 6-24. A possible parametric design of the Ferris Wheel Radar

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μ = permeability of free space and ground = $4\pi(10^{-7})\ \frac{H}{m}$

ϵ_o = permittivity of free space $\approx \frac{10^{-9}}{36\pi}\ \frac{F}{m}$

ϵ_r = dielectric constant of ground ≈ 6

ϵ = permittivity of ground = $\epsilon_r \epsilon_o = 5.32(10^{-11})\ \frac{F}{m}$

ω = angular frequency = $2\pi f = 1.88(10^8)\ s^{-1}$

K_o = lossless propagation constant = $\omega\sqrt{\mu\epsilon} = \frac{\omega\sqrt{\epsilon_r}}{c} = 1.54\ m^{-1}$

σ = conductivity of ground = $10^{-3}\ \frac{\mho}{m}$

$\tan\delta$ = loss tangent of ground = $\frac{\sigma}{\omega\epsilon} = 0.1$

α = amplitude attenuation of ground = $K_o\sqrt{\frac{\sqrt{1+\tan^2\delta}-1}{2}}$
$\approx 60\pi\frac{\sigma}{\sqrt{\epsilon_r}} = 7.7(10^{-2})\ m^{-1}$

A = power attenuation of ground = $20\alpha\log_{10}e = 0.664\ \frac{dB}{m}$

d = maximum depth of reflector in ground = $\frac{\log_e L_g}{4\alpha} = 90.2\ m$

β = propagation constant = $K_o\sqrt{\frac{\sqrt{1+\tan^2\delta}+1}{2}}$
$\approx K_o\left(1+\frac{\tan^2\delta}{8}\right) \approx K_o = 1.54\ m^{-1}$

V = propagation velocity in ground = $\frac{\omega}{\beta} \approx \frac{c}{\sqrt{\epsilon_r}} = 1.22(10^8)\ \frac{m}{s}$

R_r = range resolution in ground = $\frac{V\tau}{2} = 20.3\ m$

R_a = range accuracy in ground = $\frac{R_r}{\pi\sqrt{5}} = 2.03\ m$

Q = number of range cells = $\frac{d}{R_a} = 44$

G_c = gravitational constant = $6.67(10^{-11})\ N\cdot m^2\cdot Kg^{-2}$

M_e = mass of earth = $5.98(10^{24})\ Kg$

R_e = radius of earth = $6.378(10^6)\ m$

V_o = orbital velocity = $\sqrt{\frac{G_c M_e}{R_e+R}} = 7.42\ km\cdot s^{-1}$

V_g = ground track velocity (neglect earth rotation) = $\frac{R_e}{R_e+R}V_o = 6.50\ km\cdot s^{-1}$

V_s = scan velocity = $IF = 450\ km\cdot s^{-1}$

W = number of samples per swath = $\frac{V_s}{V_g} = 61.5$

Z = swath width = $IW = 20.8\ km$

Figure 6-24. A possible parametric design of the Ferris Wheel Radar (Cont'd)

The usable frequency range is between about 30 and 300 MHz; a polychromatic radar is possible also. Frequency allocation in this high frequency band presents difficult conflicts.

Because of the large number of phased array elements, the radar transceiver IC chip design developed later (See Section 7.4.23) will be necessary for weight reduction. The average element spacing will be less than a half wavelength because the diamond web will not readily allow a square lattice arrangement.

The pulse length is ten cycles at 30 MHz.

The effective terrain relief is determined by the variability in range which is possible during the 10 ms delay for an echo; a higher PRF could probably be selected.

Ionospheric attenuation varies considerably with angle of incidence, location, time of day, and solar activity. Since this system will operate at nearly normal incidence, and since a slow survey rate is acceptable for geologic exploration, the 3 db value selected here is probably typical (Refs 6-51,53,54,55) Ionospheric absorption increases at frequencies lower than 30 MHz and is almost complete at 5 MHz; at 300 MHz, ionospheric loss is essentially always negligible.

The primary design factor for this radar system is the limit on the maximum allowable electromagnetic power density on the earth's surface. The value selected is that for the USA, which is based on the human health allowances for thermal heating; the limit for the USSR is based on neurological factors and is a thousand times lower (Ref. 6-47). The U.S. limit for reduction exposure is determined by an average power density over a six minute period; while this radar system would probably never illuminate an area for this long, the analysis has assumed that it would. In practice, probably only a single pulse, or possibly a few, would be needed for each ground pixel or IFOV. An additional factor which must be considered is resonance absorption, which is maximum at a wavelength 2.5 times a person's height; this frequency is about 70 MHz.

This design indicates an average power requirement in excess of 50 MW; while this could be received from on-board solar cells, a Solar Power Satellite could also furnish it.

The high system noise temperature results from galactic noise reflected from the earth, or possibly entering the back of the antenna. This noise is greatly reduced at higher frequency.

The radar receiver must have a high dynamic range in order to separate the ground surface echo from the echoes of buried interfaces.

The design given in Figure 6-24 assumes some approximate values for the propagation constants of some typical materials. A more detailed look at this is given below.

Range resolution specifies the minimum detectable spacing between vertically separated interfaces; range accuracy indicates the higher precision to which the absolute depth to a single interface can be measured.

This analysis has assumed only a single pulse per pixel. By increasing this number, the power requirement can be reduced; however, the scan rate will be reduced also.

The electromagnetic parameters for earth materials vary over many orders of magnitude. The range of variation for some materials is illustrated in Figure 6-25. These data are for a frequency of 30 MHz. The parameters for soil are from Von Hippel (Ref 6-63) and those for sand are from Shahidi (Ref 6-60). As this figure indicates, maximum echo depth is very dependent on the moisture content of the ground. The salinity of the moisture in the soil samples was unspecified; attenuation increases rapidly with salinity also. In this high frequency band, it is found that the dielectric constant of many ground materials is approximately constant while the conductivity is directly proportional to frequency; therefore, the depth of penetration of the radar is linearly proportional to the radar wavelength.

In general, it is found that ground conductivity decreases in regions of geologically older rocks; while more detailed maps are now available, the generalization of Figure 6-26 illustrates the main trends. The result is that greater depth penetration should be possible on the east coast as compared to mid-continental USA.

Electromagnetic parameters for different materials and conditions have been given by a number of authors (Refs. 6-48, 49, 50, 52, 57, 59, 61, 62, 62), however, much more data of this type are needed.

A summary of the Ferris Wheel Radar is given in Figure 6-27.

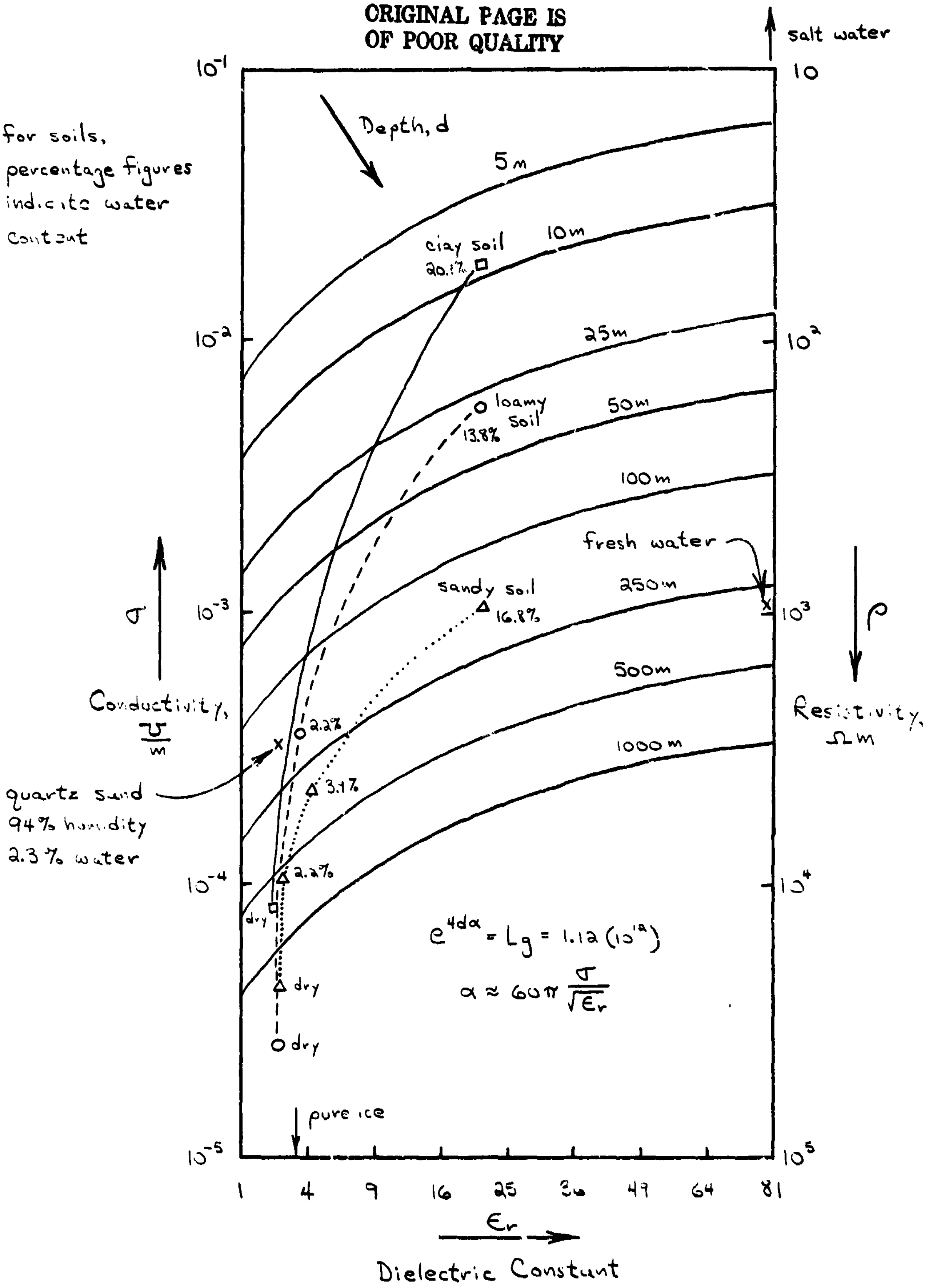


Figure 6-25. Maximum echo depth for a number of different ground materials.

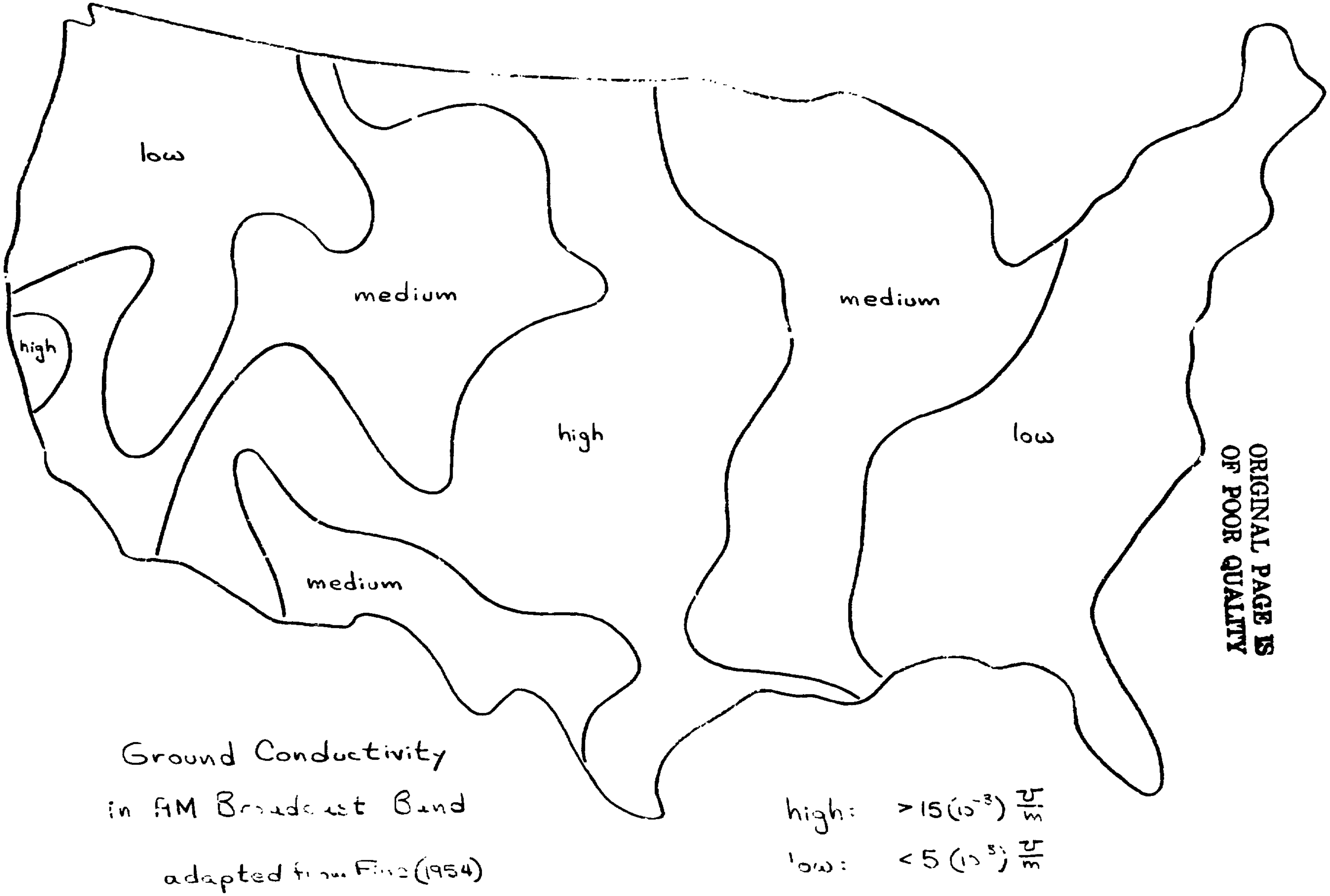
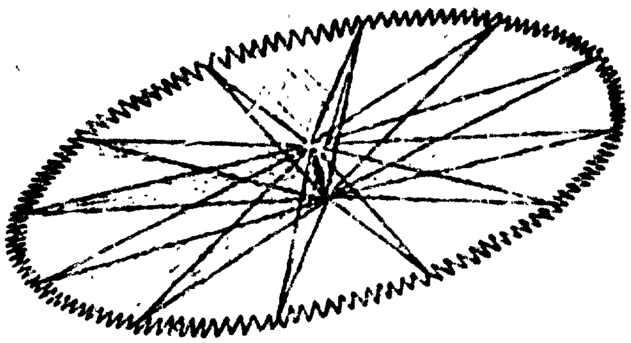


Figure 6-26. A generalization of ground conductivity at about 1 MHz.



- LARGE (30 KM DIAMETER) ROTATING (1 REV/HR) CABLE STRUCTURE THAT RELIES ON CABLE TENSION FOR SUPPORT
- REAL APERTURE RADAR OPERATES AT LOW FREQUENCY (30-300 MHZ) FOR GROUND PENETRATION
- RESULTANT RETURN SIGNAL CAN MAP MATERIALS (BOUNDARY LAYERS AND GROUNDWATER) TO A DEPTH DEPENDENT ON SOIL MOISTURE AND SALINITY
- SPACECRAFT SPIN VECTOR IS FIXED IN INERTIAL SPACE
- 50 MW AVERAGE POWER KEEPS POWER DENSITY ON EARTH BELOW 100 W/M^2
- IC CHIPS FORM ELEMENTS OF A PHASED ARRAY
- 900 KM ORBIT — 300 M GROUND RES

APPLICATIONS: GEOLOGICAL RESOURCE LOCATION

CREDIBLE SEMI-CREDIBLE INCREDIBLE

Figure 6-27. Ferris Wheel Radar - System Concept

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6.1.11 SWEEP FREQUENCY RADAR

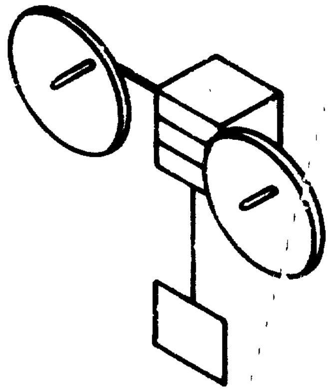
The basic parameters for the Sweep Frequency Radar System Concept are presented in Figure 6-28. While it would be most desirable to sweep the radar frequency through a broad range, it is necessary to make a compromise with spectral utilization by selecting ten discrete frequencies for simultaneous mapping. The ten representative frequencies proposed for use on the Sweep Frequency Radar system are presented as follows:

	Frequency (GHz)	Wavelength ( )
1	0.03	10 meters
2	0.3	1 meter
3	1	30 cm
4	3	10 cm
5	10	3 cm
6	20	1.5 cm
7	30	1 cm
8	100	3 mm
9	200	1.5 mm
10	300	1 mm

The frequencies were selected from the transparency characteristics of the earth's atmosphere and ionosphere as shown in Figure 6-29 (Ref 6-78). A SAR approach will allow a reasonably sized antenna throughout the spectrum; exact frequency selection would depend on a study of their relative utility for contrasting texture.

This system will give results similar to those from the Texturometer. The main difference is that the Texturometermeasures periodicity primarily in the range direction over a 10 m area on the ground. The Sweep Frequency Radar searches for a resonant backscatter condition exhibited by a ground material and uses this as a characteristic of the ground texture. Also, the former is a sampler, while Sweep Frequency Radar is a mapper.

The System utilizes synthetic apertures to achieve it's desired ten meter ground resolution and 100 km swath width at each frequency. The average power requirements range from 1 watt to 30 MHz to over 64 KW at 200 GHz.



- RESULTANT TEXTURE IS ADDITIONAL PARAMETER FOR IDENTIFICATION AND CLASSIFICATION
- POLYCHROMATIC SCATTEROMETER FROM 30 MHZ TO 200 GHZ
- RESONANT BACKSCATTER INDICATES TEXTURE AT DISCRETE MEASUREMENTS FROM 1.5 MM TO 10 M
- 600 KM ORBIT – 10 M RES – 100 KM SWATH
- POWER VARIES FROM 1 W (AT 30 MHZ) TO 64 KW (200 GHZ)
- FREQUENCY ALLOCATION CONSIDERATIONS

APPLICATIONS: ALL DISCIPLINES


CREDIBLE SEMI-CREDIBLE INCREDIBLE

Figure 6-28. Sweep Frequency Radar - System Concept

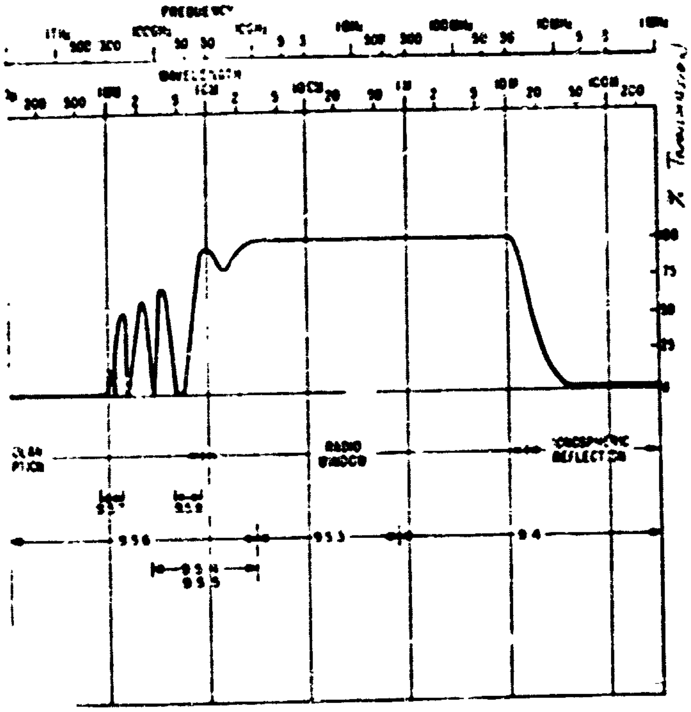


Figure 6-29. Partial electromagnetic spectrum showing relative transparency of the Earth's atmosphere and ionosphere.

6.1.12 GEOSAR

The concept of a synthetic aperture radar in geosynchronous orbit was jointly developed by Dr. Tomiyasu and Mr. Chestek of the General Electric Company.

High-resolution radar images of the earth can be taken with a synthetic aperture radar (SAR) from geosynchronous orbital ranges by utilizing satellite motion relative to a geostationary position. (See Figure 6-30). A suitable satellite motion can be obtained by having an orbit plane inclined relative to the equatorial plane and by having an eccentric orbit. Potential applications of these SAR images are topography, water resource management and soil moisture determination. Preliminary calculations show that the United States can be mapped with 100-m resolution cells in about 4 hours. With the use of microwave signals the mapping can be performed day or night through clouds and during adverse weather.

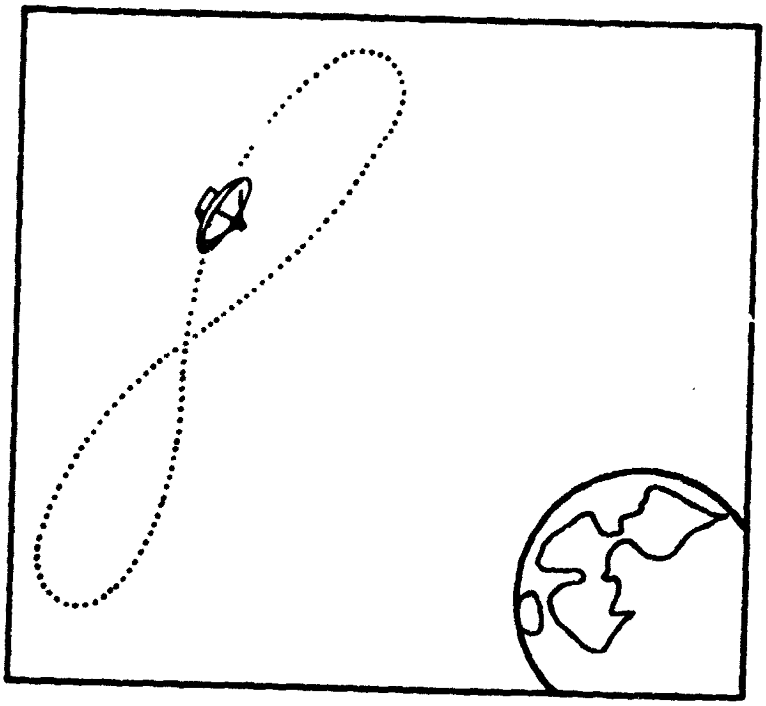


Figure 6-30. SAR Geometry

Synthetic aperture radars have been flown in aircraft (Ref. 6-67) and are scheduled to be flown in a low orbit satellite (Ref 6-68). To produce the images the antenna beam is usually oriented broadside (normal) to the radar platform velocity vector, although the beam can also be oriented at other oblique angles (6-69). The SAR image plane is defined by the platform velocity vector and radar antenna beam axis. A geometrical contraint requires that the normal of the object scene plane must not lie in the SAR image plane. In vector notation, *

$$(\bar{v} \times \bar{R}) \cdot \hat{n} \neq 0$$

where $\bar{v}$ = radar platform velocity vector

$\bar{R}$ = radar range vector along antenna beam axis

n = object scene plane normal.

---

*Other identities are $\bar{v} \cdot (\bar{R} \times \hat{n})$ and $\bar{R} \cdot (\hat{n} \times \bar{v})$.

The subsatellite track of a satellite in geosynchronous orbit depends on the orbit inclination angle and orbit eccentricity. In Figure 6-31A a track is shown for an example of orbit inclination angle only. The long dimension is oriented in the north-south direction. If a small amount of orbit eccentricity is added, the track will tilt as shown in Figure 6-31B. With an inclination angle of ±1°, an orbit eccentricity of 0.009, and an argument of perigee of 90°, a near circular subsatellite track (Ref. 6-70) can be produced, as shown in Figure 6-31D, and the relative satellite scanning speed is about 48 m/sec with reference to a nominal geostationary position. The maximum range rate is about 30.4 m/sec to a 40° latitude ground location at the same longitude. A radar frequency of 2450 MHz, an antenna beamwidth of 1° and a ground resolution of 100 meters are assumed.

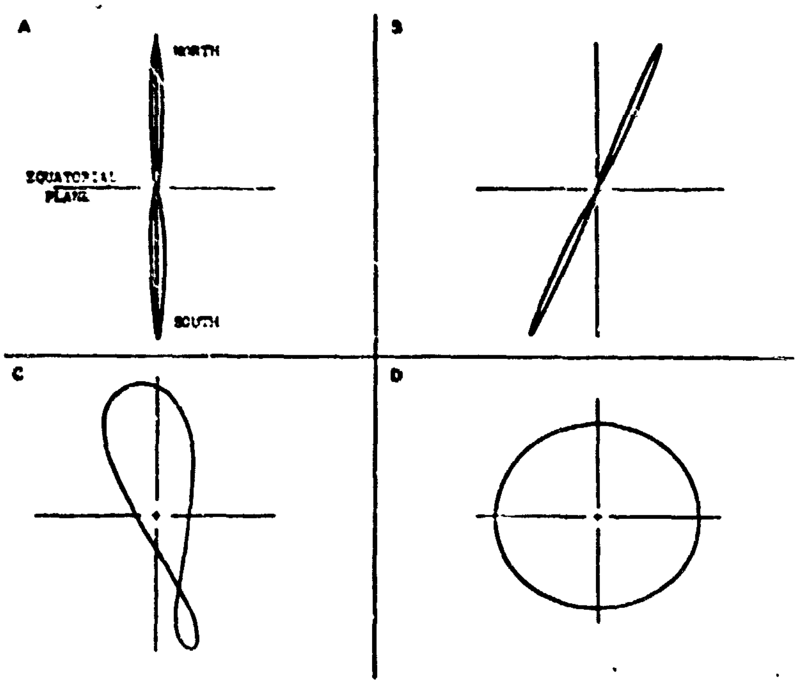


Figure 6-31. Subsatellite Track

The following values were computed:

Antenna diameter	7.3 m
Incidence angle	46.3°
Beam Footprint	1063 km N-S by 654 km E-W
Differential slant range across footprint	690 km
Range ambiguity	217 pulses/sec. max
Azimuth ambiguity	13 pulses/sec. min
Radar PRF	54 pulses/sec. nominal
Integration time	476 secs. minimum
Radar bandwidth	2.08 MHz
Radar Doppler shift	500 Hz, max

Depending on the viewing angle, an integration time of up to 700 seconds per beam footprint may be required. To cover the United States, three east-west rows and seven north-south columns of footprints will be required and this will take about four hours of total integration time. The number of pixels is 10^9. The potential ambiguity caused by the radar Doppler shift of 500 Hz can be removed by ground processing which relies upon accurate ephemerides data. An oscillator stability of better than one part in 10^{11} is required over the integration time. The time-delay Doppler shift signal processing technique used here to produce images is quite similar to that used in radar astronomy (Ref. 6-71).

The power required was calculated assuming a system noise temperature of 600°K, a system loss of 6 dB and a resultant S/N = 10 dB. The average powers required as a function of normalized radar cross section σ^{o} are:

σ^{o}, dB	P_{ave}, Watts
0	80
-10	800
-20	8000

Other sets of parametric values can be assumed to achieve different performance characteristics.

6.2 SENSOR SYSTEM CONCEPTS DEFERRED

During the investigation of these PLACE systems, a number of other sensor and system concepts were studied. This section outlines a few problems for which we found no solutions. These are described here in the belief that it is valuable to mark one's failures as well as successes. Also, these are given in the spirit that another investigator will get around the difficulty we found and will develop a practical solution to these remaining valuable requirements.

Already, much work has been accomplished toward the location of geological resources with the help of satellite imagery. While the present optical and future radar techniques can give many clues to the location of buried ores, it would be valuable if additional evidence could be found using the classical geophysical tools of gravitational, magnetic, and radioactivity sensing. We could not find a way to detect a reasonably small ore body; the following analysis indicates the order of magnitude of the geophysical effects.

The characteristics of a hypothetical ore body are listed in Figure 6-32. Ore bodies of this size can readily be detected by near-earth aerial sensing and can usually be economically mined. The only unusual feature is the existence of the stated gamma ray emission and magnetization contrast in one ore body.

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Ore body characteristics

m = mass = 10^{9} kg (compact, near earth's surface)

ρ = density = 2.5 $g \cdot cm^{-3}$ = 2.5 (10^{3}) $kg \cdot m^{-3}$

V = volume = $\frac{m}{\rho}$ = 4 (10^{5}) m^{3}

r = radius = $\sqrt{\frac{3V}{4\pi}}$ = 46 m

$\Delta\sigma$ = density contrast with surroundings = 0.5 $g \cdot cm^{-3}$

ΔM = magnetization contrast (remanent + induced) = [illegible] $nT \cdot m^{3} \cdot kg^{-1}$

ν_e = effective gamma [illegible] = 0.[illegible] $s^{-1} \cdot g^{-1}$

Earth parameters

R_e = radius = 6.38 (10^{3}) km

m_e = mass = [illegible] (10^{24}) kg

G = gravitational constant = 6.67 (10^{-11}) $m^{3} \cdot kg^{-1} \cdot s^{-2}$

Gm_e = [illegible] (10^{5}) $km^{3} \cdot s^{-2}$

M_e = relative magnetic moment of dipole field = [illegible] $nT \cdot m^{3} \cdot kg^{-1}$

d_0 = atmospheric density at sea level = 1.22 $kg \cdot m^{-3}$

H = scale height of atmosphere = 8 km

u_m = [illegible] = [illegible] (10^{-3}) [illegible]

Orbital parameters

h = altitude = 500 km

v = orbital velocity = $\sqrt{\frac{Gm_e}{R_e + h}}$ = 7.64 $km \cdot s^{-1}$

time to travel 10 m on ground ≈ 1.3 ms ([illegible])

Figure 6-32. Sensing Parameters

Gravitational detection

a_e = acceleration due to earth, at satellite altitude

$= \frac{G m_e}{(R_e + r)^2} = 8.4 \ m \cdot s^{-1}$

Δg = gravitational anomaly due to [illegible] body

$= \frac{G m}{h^2} \frac{\Delta \rho}{\rho} = [illegible] (10^{-3}) \ m \cdot s^{-1}$

SOA (state of the art) = $10^{-7} \ m \cdot s^{-1}$

(now being [illegible] and measurements [illegible])

Magnetic detection

H_e = earth's magnetic field at satellite altitude

$= \frac{M_e m_e}{(R_e + h)^3} = [illegible].4 ([illegible]) \ nT$

ΔH = magnetic anomaly due to [illegible] body

$= \frac{\Delta H \, v_m}{h^3} = [illegible] ([illegible]) \ nT$

SOA = 10^{-3} nT (ground-based instrument), M[illegible] ≈ 5 nT

magnetic field [illegible] ≈ [illegible] nT

Radioactivity detection

T = transmittance of gamma radiation through [illegible] = $e^{-\mu_m d r}$

where d = atmospheric density; [illegible] $= d_0 e^{-r/H}$

integrating [illegible] T_a = 0.04

SOA - NaI detector area is A_d = 0.46 m²

Y = gamma ray count rate at satellite [illegible]

$= Y_s \, m \frac{A_d}{4 \pi h^2} T_a = 2.6 (10^{-2}) \ s^{-1}$ (or 38 s per count)

for a count of [illegible], [illegible] required

for 100 m resolution, ultimate detection [illegible]

Figure 6-33. Anomaly Calculations

Figure 6-32 also tabulates the orbital parameters of the satellite carrying the geophysical sensors.

The fundamental equations which indicate the maximum geophysical anomalies are indicated in Figure 6-33. The gravitational anomaly is inversely proportional to the square of satellite altitude; the calculation of this is given in Figure 6-33. Current technology is far from being able to detect this anomaly.

From satellite altitude, the ore body will appear to be a magnetic dipole. While the spatial pattern of the anomaly is dependent on the orientation of the magnetic vector of the ore body, the maximum difference in the amplitude of the magnetic intensity which the body causes is calculated in Figure 6-33. Even if an instrument had the sensitivity to detect this anomaly, it would be difficult to correct for changes in the magnetic field caused by ionospheric currents. An additional factor is the computational problem of extracting ground-referenced measurements from the satellite data (Refs. 6-72, 73, 75).

While MAGSAT will have a sensitivity of about 5 nT from its altitude of 400 km (Ref. 6-74), this will be valuable primarily for the study of global geophysics (Ref. 6-77). Mineral exploration would require a sensitivity which is a million times greater than this.

These problems might be alleviated if the measurement of magnetic intensity could be made closer to the earth. This would be possible if the magnetic field altered an observable parameter which could be remotely sensed without the inverse cubed loss of the magnetic field from a small source.

The spaceborne radar ellipsometer has a considerable noise component due to the Faraday rotation of the EM wave through the ionosphere. This rotation is proportional to the intensity of the magnetic field in the ionosphere. While this could yield a lower magnetic measurements plane, it would not be good enough.

Another magneto-optic dependency which could be considered is that of the Kerr Effect: the polarization direction of light is rotated on reflection from a magnetization of the reflecting body; the measurement of the magnetic field at the earth's surface with an active optical system is conceivable. Unfortunately, the effect is extremely small. Even with a magnetic field 1700 times the earth's normal value, the angle of rotation of linearly-polarized light reflecting from an iron surface is only 20 minutes of arc (Ref. 6-76).

Ore bodies can also be detected by the gamma radiation emitted by the decay of daughter products in the uranium and thorium chains and also by the decay of radioactive potassium. The gamma ray emission value which has been assumed could be composed of contributions from any of these three reactions; the mass absorption coefficients for the three energies are very similar, and an average was made for this calculation. Figure 6-33 gives the determination of atmospheric transmittance and the geometric loss factor. While a detector could be collimated to give adequate ground resolution, it may not be practical to make a reflection concentrator large enough for an acceptable count rate.

Another system concept for which we had great hope but could not get around some fundamental design problems, was called SATCLOUD. The concept involved the construction of a small ($< (20 \text{ inch})^3$), cheap ($\sim \$2000$), light "daughter" spacecraft using mostly plastic and integrated circuits. Many (10^3-10^4) of these spin-stabilized daughter spacecraft would then be launched in geosynchronous orbit to provide a real aperture radar. The system would function as a random, sparse phased array and would require one or more "mother" satellites for station keeping and command and control. There would be a number of difficult, but solvable, problems in deployment, surveillance and control. The problem that ultimately could not be solved, even after range gating and fitting a PN code, was too high a sidelobe level. The concept is illustrated in Figure 6-34.

These four system concepts (SATCLOUD, MAGSAT II, GRAVSAT II, and RADSAT), which we pass on to future investigators, are summarized in Figure 6-35. Presented in Figure 6-36 are still other systems which were initially considered and then later deferred.

6.3 GROUND PROCESSING CONCEPTS

Normally, in a discussion of future space system opportunities, the ground processing required by the systems is either deemphasized or deleted. In the PLACE future scenario of combinations of these systems performing operationally, the ground processing is extremely important. A ground processing system that all PLACE space systems could use in common is illustrated in Figure 6-37.

Note that all data from all earth resources systems initially enter the global data base. It may reside there for a long or very short time, depending on a user's throughput requirements for that data. A number of global data base configurations were considered as being possible in the 1995 time frame, as are illustrated in Figure 6-38. Based on a perception of how a future global data base concept would evolve, a decision was made. The data base used in the PLACE Study is decentralized and may be made up of a combination of regionalized multi-data centers and discipline-specific global centers. It is assumed that the data base as a whole is geographically based to a 10 meter grid of the land area of the world and nominally contains 300 overlays for each grid cell. This leads to the requirement for a ground storage system

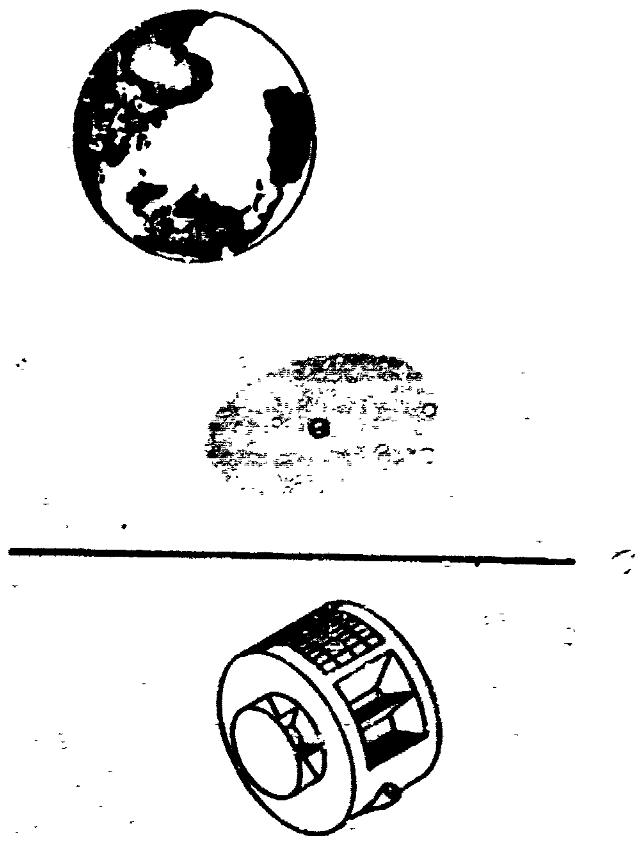


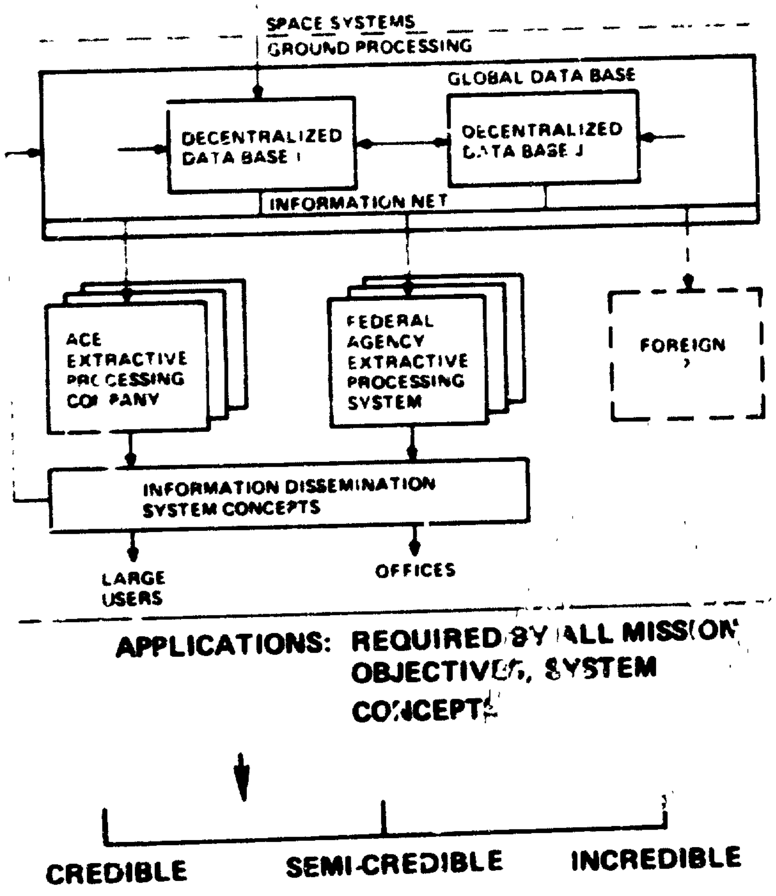
Figure 6-34. Satcloud - System Concept

NAME	APPLICATION	OPERATION	APPARENT FLAW
SATCLOUD	1M RESOLUTION FOR ALL-WEATHER DAY-NIGHT REAL APERTURE IMAGING	• 10^4 SMALL, CHEAP S/C • RANDOM SPARSE PHASED ARRAY • 100 KM DIAMETER AT GEO	INTEGRATED SIDELOBE LEVEL TOO HIGH
MAGSAT II	DETECT 10^9 Kg ORE BODY HAVING MAGNETIZATION CONTRAST OF $0.05 nT \cdot m^3 \cdot Kg^{-1}$	MEASURE FARADAY EFFECT IN IONOSPHERE OR KERR ROTATION AT EARTH'S SURFACE	MAGNETO-OPTICAL EFFECTS ARE TOO SMALL.
GRAVSAT II	DETECT 10^9 Kg ORE BODY HAVING DENSITY CONTRAST OF $0.5 g \cdot cm^{-3}$	HIGHER SENSITIVITY VERSION OF PRESENT DESIGNS	THE IMPROVEMENT WHICH IS REQUIRED IS A FACTOR OF A MILLION
RADSAT	DETECT 10^9 Kg ORE BODY HAVING EFFECTIVE GAMMA RAY EMISSION OF $100 S^{-1} \cdot Kg^{-1}$	LARGE NaI DETECTOR ON GAMMA RAY SPECTROMETER	GEOMETRIC LOSS CAUSES LOW COUNT RATE; COLLIMATION REQUIREMENTS ARE SEVERE

Figure 6-35. Future System Concepts Deferred

SYSTEM	APPLICATION	IMPLEMENTATION CONCEPT	APPARENT FLAW
RADAR ALTIMETER	2 CM _ HEIGHT AT OBLIQUE ANGLES	CHIRP RADAR OR LIDAR	EPHEMERIS REQUIREMENT NO STRONG MOTIVATION
SHUTTLE CALIBRATION FACILITY	CALIBRATION OF FREE FLYERS	SHUTTLE UNDERFLY WITH CALIBRATING SENSOR	TECHNOLOGY AVAILABLE FROM PROGRAM DEVELOPMENT
OPERATIONAL SHUTTLE FLIGHTS	PERIODIC URBAN CENSUS, TIMBER INVENTORY, ETC	CUSTOM SENSORS	OPTIMISTIC FUTURE SCENARIO HAS ALL FREE FLYERS REQ'D
LARGE INFLATED STRUCTURES	REAL APERTURE MICRO WAVE ANTENNAS	10 KM DIAMETER LENS-LIKE BALLOON IS INFLATED TO LOW PRESSURE	MASS OF INFLATION GAS EXCEEDS 10^7 KG
LUNAR BASED SYSTEMS	RIGID, LOW VIBRATION SURFACE FOR LARGE STRUCTURES	ARECIBO IN A CRATER	INAPPROPRIATE FOR EARTH VIEWING
GRAVITATIONAL RADIATION DETECTORS	DETECTION OF ACCELERATING MASSES SUCH AS TORNADOES OR VOLCANOES	ARRAY OF MASSES WITH STRAIN GAUGES LOCATE SOURCE OF ACCELERATION	FUNDAMENTAL PRINCIPLE UNPROVEN

Figure 6-36. Future System Concepts Deferred



APPLICATIONS: REQUIRED BY ALL MISSION OBJECTIVES, SYSTEM CONCEPTS

GLOBAL INFORMATION SYSTEM

REGIONALIZED & DISCIPLINE-SPECIFIC DATA BASES
NOMINAL 10 M GRID – 300 OVERLAYS
NETWORK PROVIDES NON-LOCAL ACCESSING

EXTRACTIVE INFORMATION PROCESSING SYSTEMS

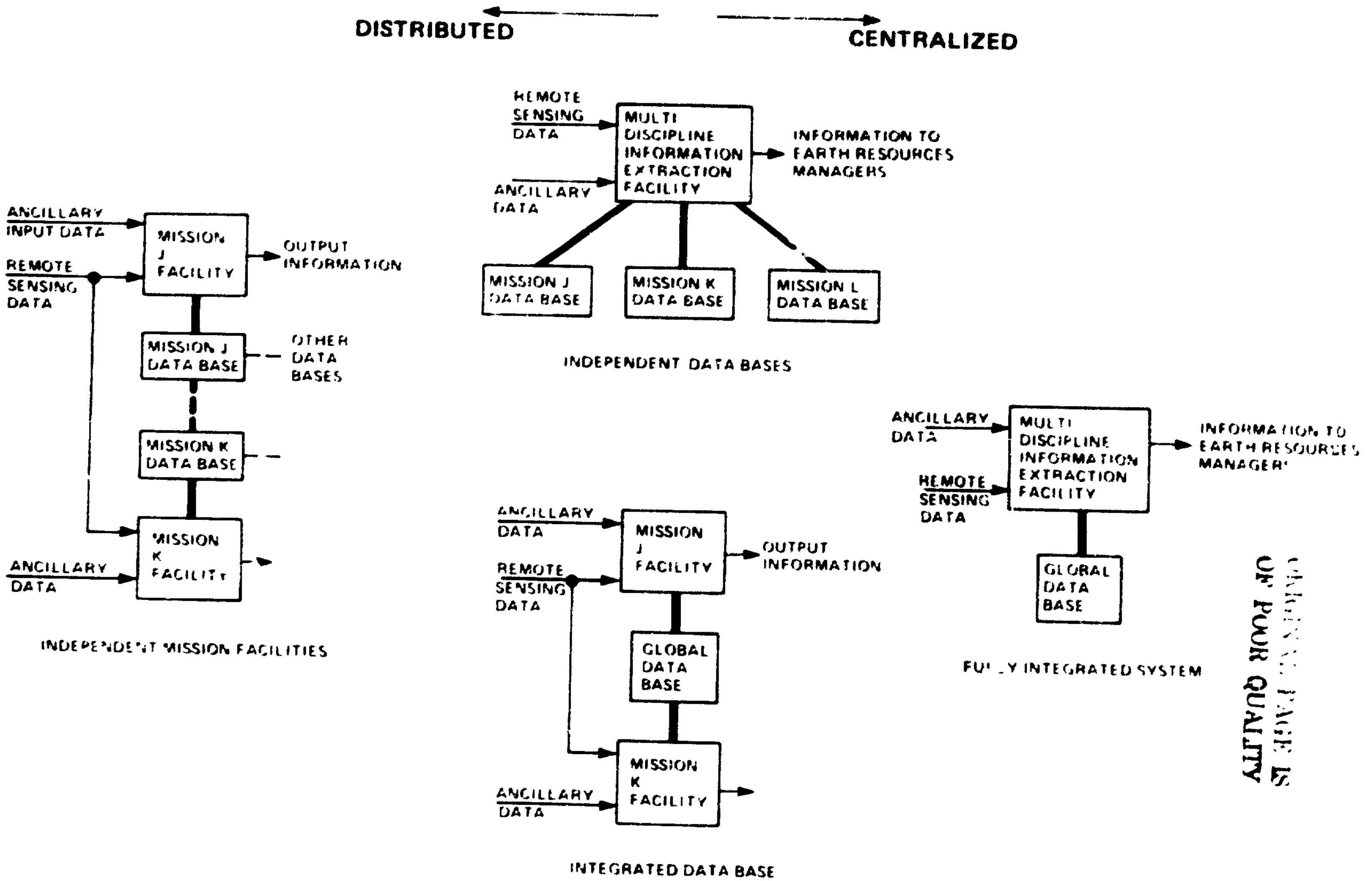
EXISTING SIGNATURE BANK
LIMITS OF SIGNATURE EXTENSION DEFINED
MODELS – FORECASTS
REMOTE SENSING DATA INCLUDES:

VISIBLE-I.R.
MICROWAVE
TEXTURE
LUMINESCENCE

INFORMATION DISSEMINATION SYSTEMS

- COMSAT LINK TO LARGE USERS
- DIGITAL GROUND LINK TO OFFICES
  - INITIALLY VIA TV CABLE
  - LATER (1995) VIA PHONE LINK

Figure 6-37. Future Ground Processing Concept



INDEPENDENT MISSION FACILITIES

INDEPENDENT DATA BASES

INTEGRATED DATA BASE

FULLY INTEGRATED SYSTEM

Figure 6-38. Global Data Base Alternatives that could accommodate approximately 3.5 x 10^{15} bits and a data base management system to control the information within it. These requirements are addressed in Sections 7.4.17 and 7.4.20, respectively.

The next stage in the ground processing concept is the extractive information processing system. This is really a large number of processes, operating on the data, as is illustrated in Figure 6-39, for the land use mission objective. The computational power required to perform these processes is illustrated in Figures 6-40 and 6-41 for a number of mission objectives. These requirements are posed for potential on-board and ground processors as described in Sections 7.4.18 and 7.4.19, respectively. Typical of the extractive information processing systems of the future is the generic system illustrated in Figure 6-42. However, the key developments which must be realized in order for these extractive processing systems to be successful, are advances in signature extablishment, signature extension, discipline models and resultant forecasts. These requirements, which must take advantage of future forms of remote sensing data, are discussed in more detail in Section 7.4.24.

The final stage in the ground processing concept, once the desired information has been extracted from the data, is dissemination of the information to the users. Future methods of providing this information dissemination are discussed in Section 7.4.15. Finally, it is noted that the derived information itself is then returned to the data base to aid in future extractive processing activities.

6.4 INTERRELATIONSHIPS OF SYSTEM CONCEPTS

Many of the PLACE system concepts are overlapping in function, and a brief analysis of their interrelationships will be presented in this section. A

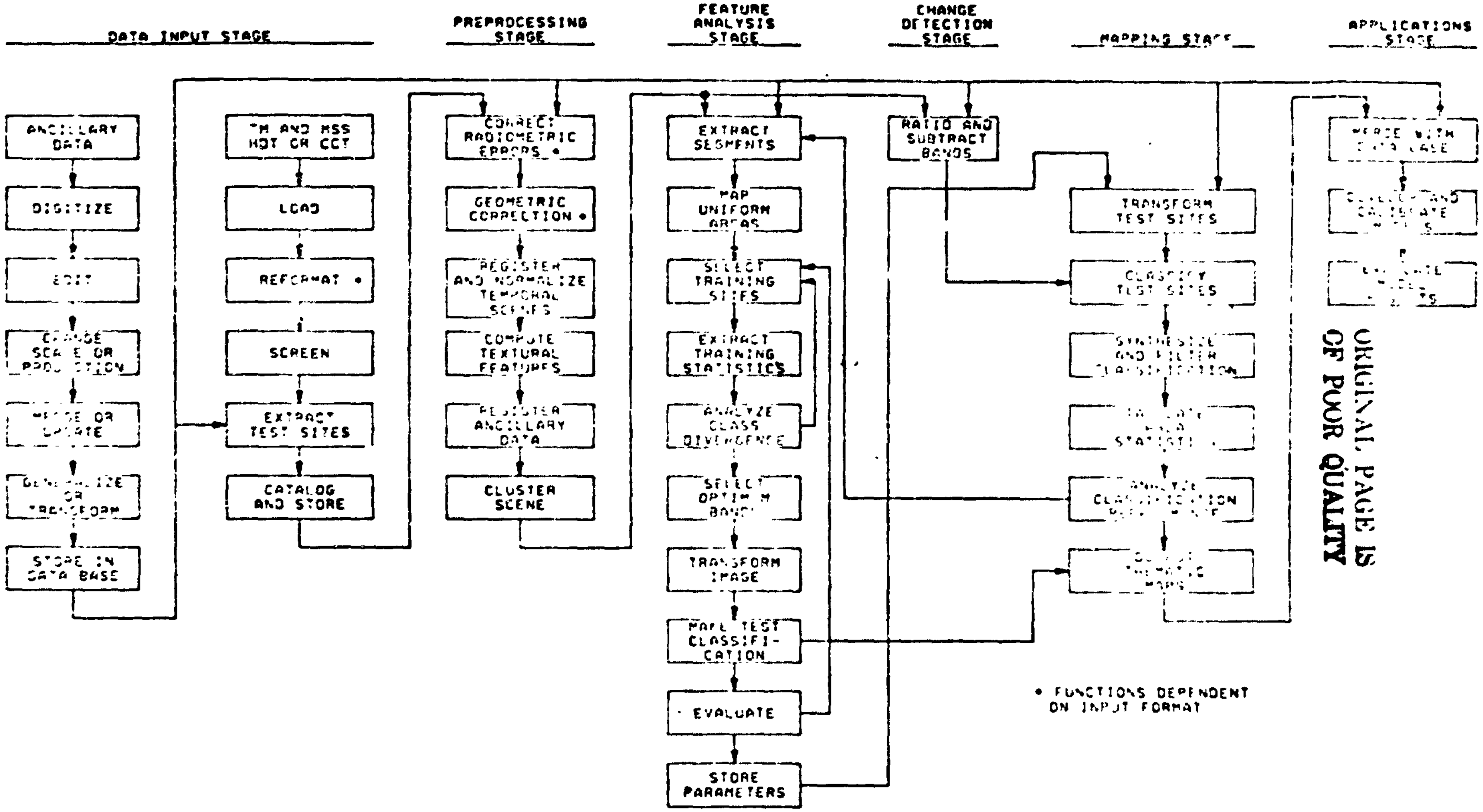


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Figure 6-39. Processes Performed on Input Data

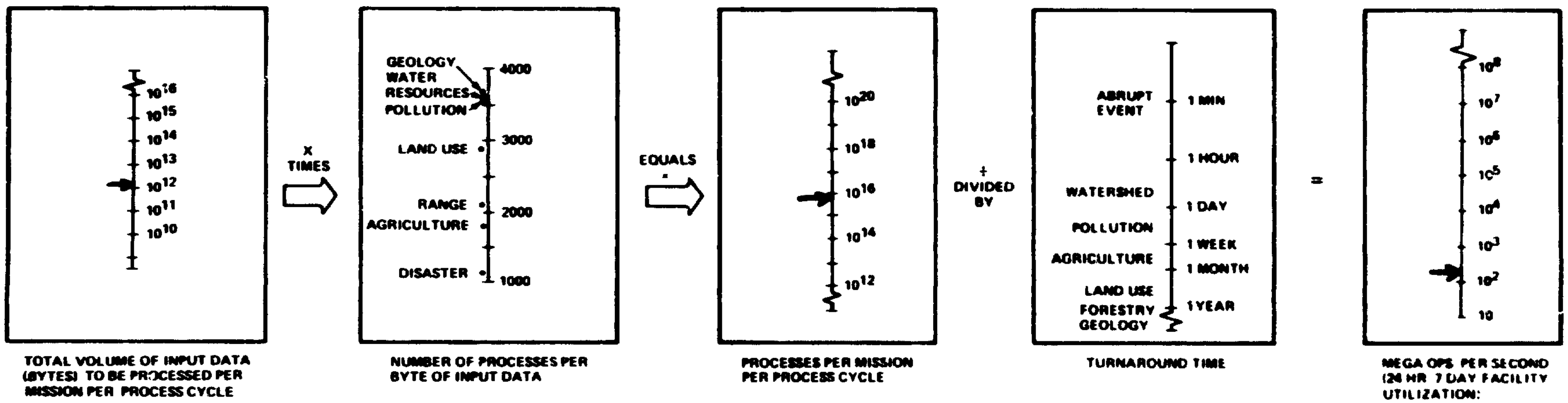

Figure 6-40. Computational Power Requirements

	CROP PRODUCTION	WATERSHED MONITORING	GEOLOGY	DISASTER ASSESSMENT
AREA IN $10^6 M^2$	5.9×10^6	.188 (U.S.) $\times 10^6$	59×10^6	510×10^6
SAMPLING STRATEGY	1	1	1	10^{-6}
PIXELS IN $10^6 M^2$ (30 METER)	10^3	10^3	10^3	10^3
NO. OF SPECTRAL CHANNELS	10	10	10	10
NO. OF LOOKS	1	1	2	2
SUM + ANCILLARY EQUIVALENT	2	2	1	1
BYTES	1.2×10^{11}	4×10^9	1.2×10^{12}	10^{13}
OPERATIONS PER BYTE	1.8×10^3	3.8×10^3	3.7×10^3	1.1×10^3
TOTAL OPERATIONS	2.2×10^{14}	3.7×10^{12}	8.1×10^{15}	1.1×10^{10}
÷ TURNAROUND TIME	1.2×10^6 (2 WK.)	8.6×10^4 (1 DAY)	3.15×10^7 (1 YR.)	600 (10 MIN.)
MOPS/SEC	180	43	260	18

Figure 6-41. Examples of Extractive Processing Requirements

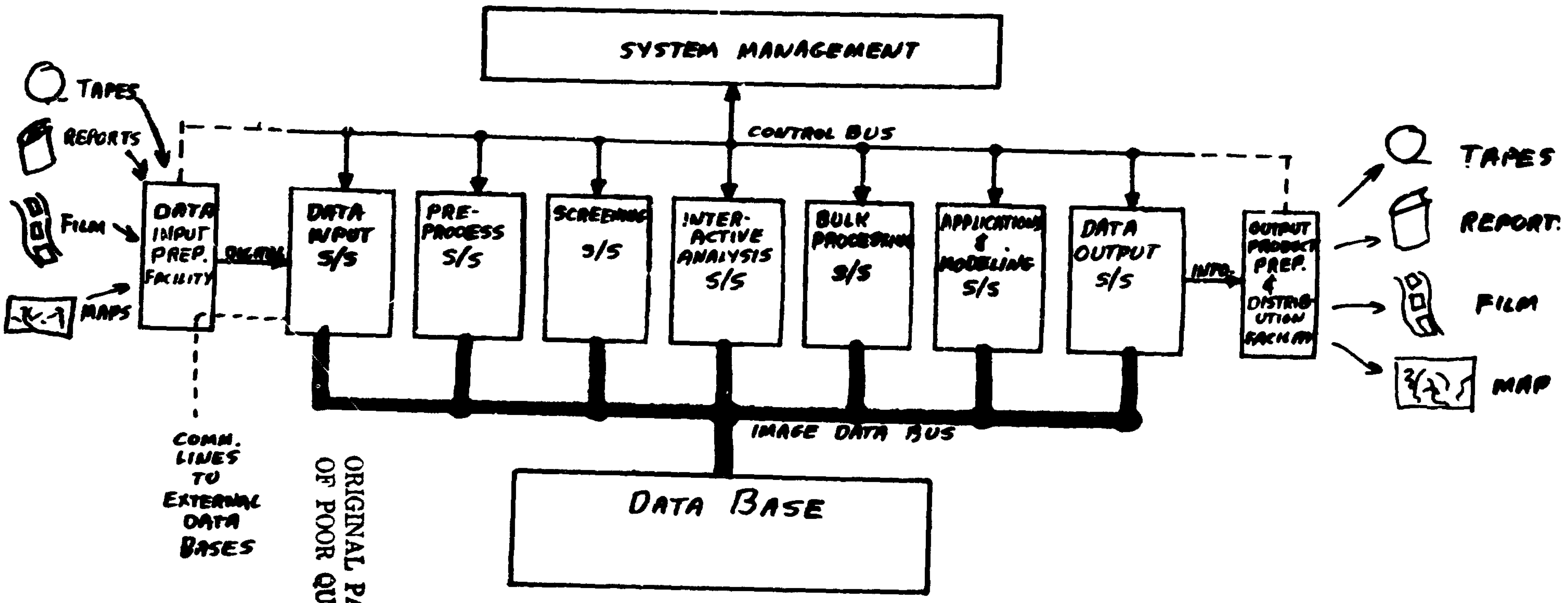

Figure 6-42. Generic Information Extraction System

look at the overlap between systems is shown in Figure 6-43, the PLACE system concepts menu. Representing the choice of system concepts as a Chinese menu illustrates the point that common groupings do exist in the system concept output products. For example, there are two methods of observing a measure of ground texture, the sweep frequency radar and the texturometer, but the methods of implementation, and the frequencies, are different; even the uses for the data may be different. In the area of quick-look capability, the different PLACE system concepts offer different relative advantages with respect to different missions. The PLACE Study has chosen to pursue all of the twelve operational system concepts, rather than attempt to select preferred system concepts at this preliminary point. It is felt that by pursuing the technology requirements of all of these concepts, that later on, in the mid to late '80's when the hard choices have to be made to pursue one system and not the other, the choice will be made on benefit and cost and not on the fact that a particular enabling technology had not been developed sufficiently 5-10 years earlier.

Referring again to Figure 6-43, one notes a preponderance of microwave systems. The grouping here of both passive and active systems with the primary system goal of soil moisture mapping deserves comment. In a study of NASA's Microwave Remote Sensing Program Five Year Technical Plan (Ref. 6-80) by CORSPERS dated 10/31/77, it was concluded that not enough is currently known concerning the relative abilities of passive and active microwave systems to measure soil moisture at the present time to recommend the exclusive use of one over the other. This is a key point for future systems designers because of the large structure requirements associated with passive systems with even modest ground resolution figures.

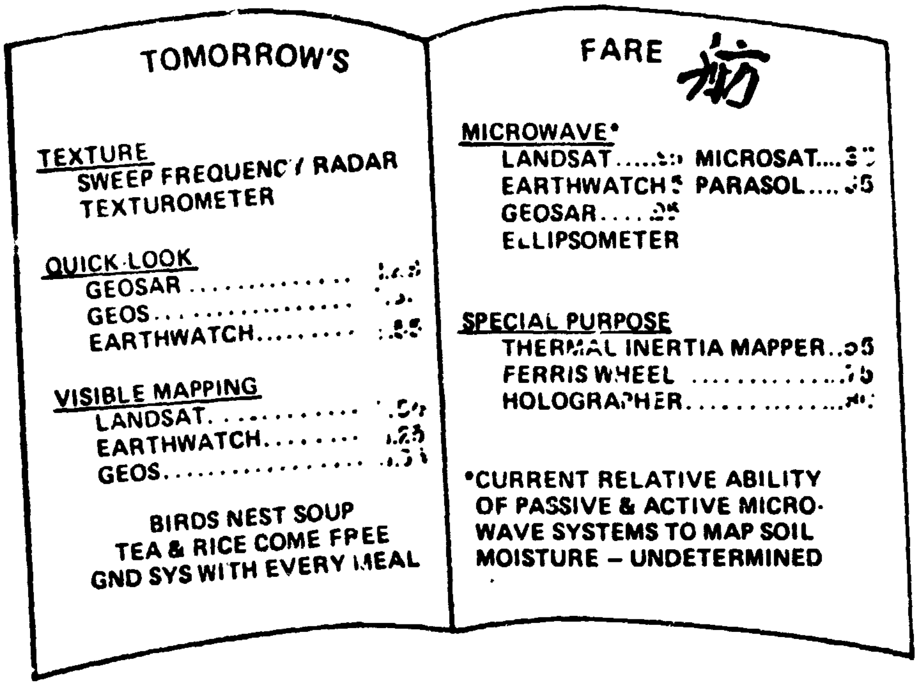

Figure 6-43. PLACE System Concepts Menu

A second view of the interrelationships between the PLACE system concepts is presented in Figure 6-44, where the systems are clustered functionally. In general, microwave systems are located to the left, optical systems to the right, and the distance between any two systems is a relative measure of their dissimilarity. Systems which provide a quick-look capability or active systems which provide their own illumination (either visible or microwave) are specially marked. In addition, strong similarity ties between systems such as thermal emission sensing are marked.

A different aspect of examining the interrelationships between the PLACE system concepts is presented in Figure 6-45, a time phasing of the system concepts. These time estimates represent a view of when these systems could happen, keeping in mind the technology requirements and "semi-credibility measure" of each system concept. The developmental period for each spacecraft represents a time associated with construction (for large structures) and sensor and processing development. An operational system is one in which information from a system is guaranteed to be available to users. The political and institutional implications of a system being operational were not taken into account. The projections assume that the SEOS program, which has been considered by NASA, will be the developmental portion of the GEOS program. It also assumes that the MICROSAT program will be developmental for the Parasol Radiometer.

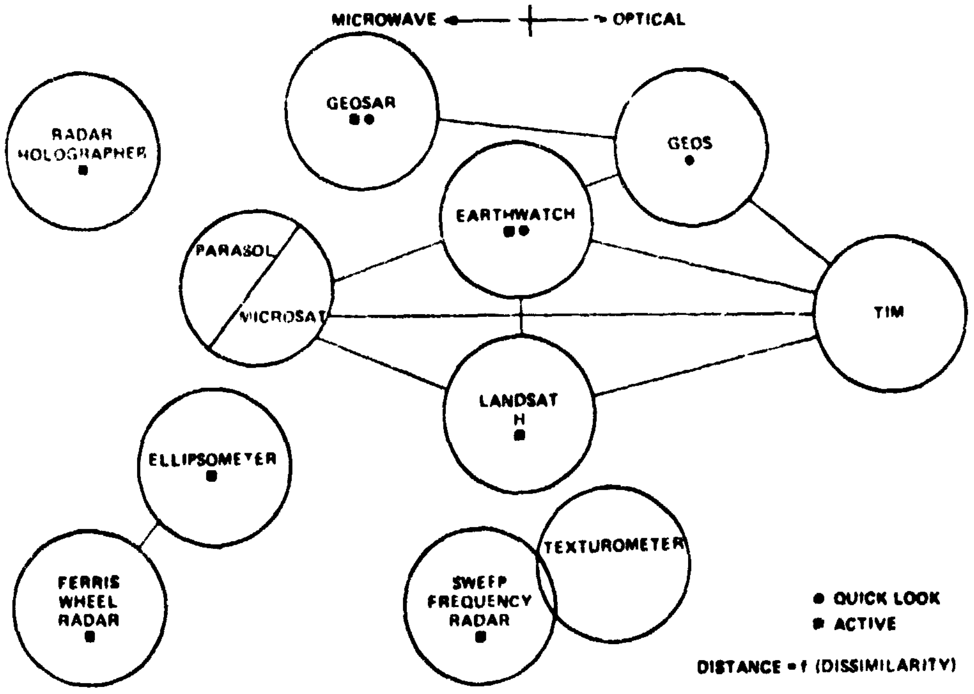

Figure 6-44. System Functional Similarity Clusters

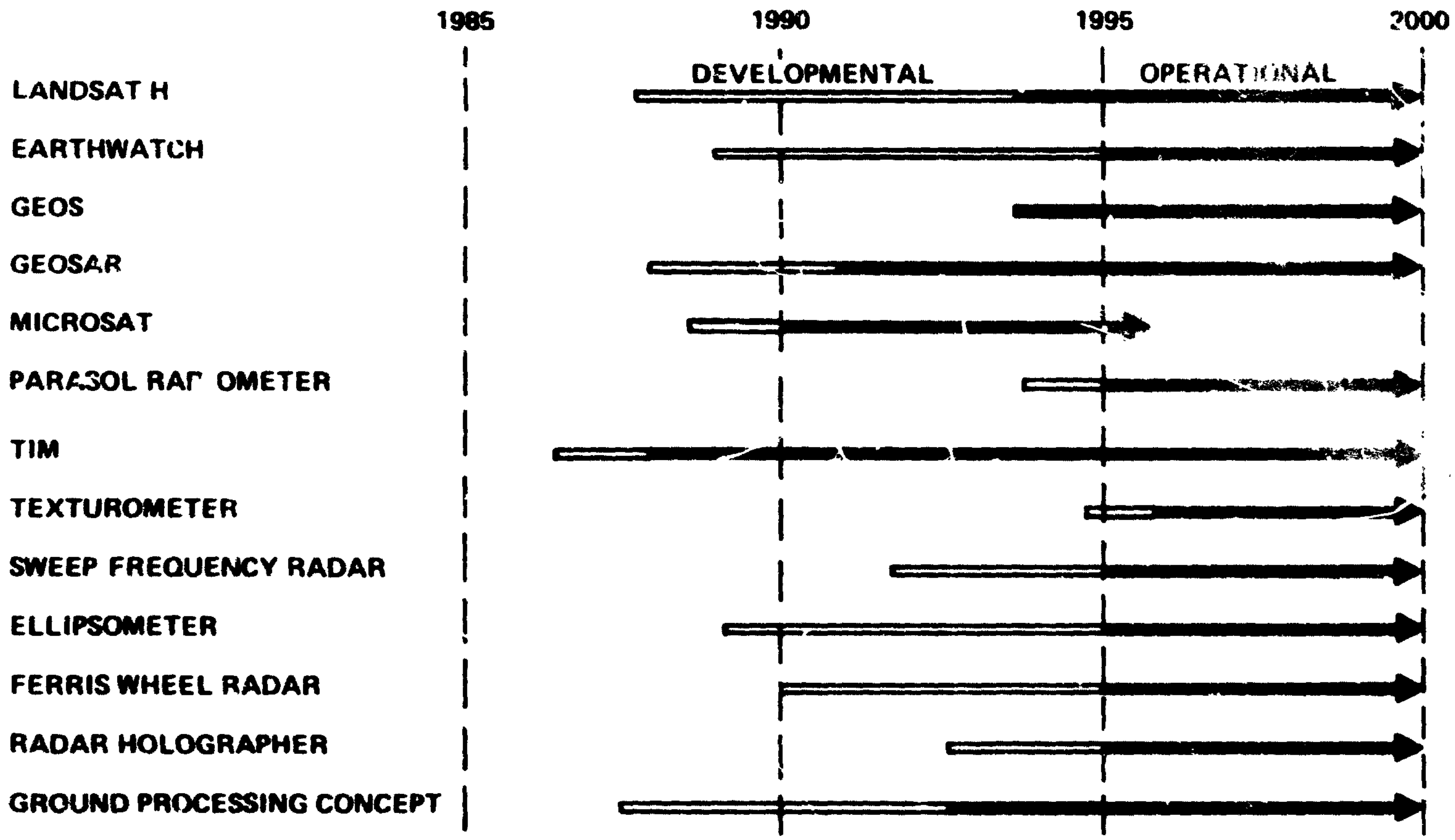

Figure 6-45. Time Phasing of System Concepts

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7.0 TECHNOLOGY REQUIREMENTS AND FORECASTS

This section presents the methodology, assumptions and results of the definition of Earth Resources technology requirements and the forecasting of technology advances for the latter part of the century. Some of the more critical technology areas received more in depth analysis than others due to their widespread application and/or controversial forecasts.

7.1 METHODOLOGY

The general flow of activities related to this task is shown in Figure 7-1. Initially, a candidate set of technology categories relevant to the Earth Resources discipline was assembled, based on the results of similar studies and our previous experience. This candidate set was used as a check list to ensure that the major technologies are considered in the analysis of each system concept in the Space System Technology Model as described in Section 6.0. The analysis involved the examination of each system concept to identify those hardware, software, and operational development needs that are not within the current state of the art (S.O.A.).

An initial technology requirement definition was made by establishing the specific aspect of the non-S.O.A. development which is required for the applicable system(s). For instance, the Advanced SEOS (GEOS) requirement for high resolution during earth scanning from geosynchronous orbit results in an attitude control system that is outside the current technological capability. Further inspection of the various elements in this technology indicated that the significant technology advances within the time frame in question were: (1) knowledge of pointing accuracy relative to the sensors' axis andthe local vertical; (2) vibrational stability at the telescope focal plane.

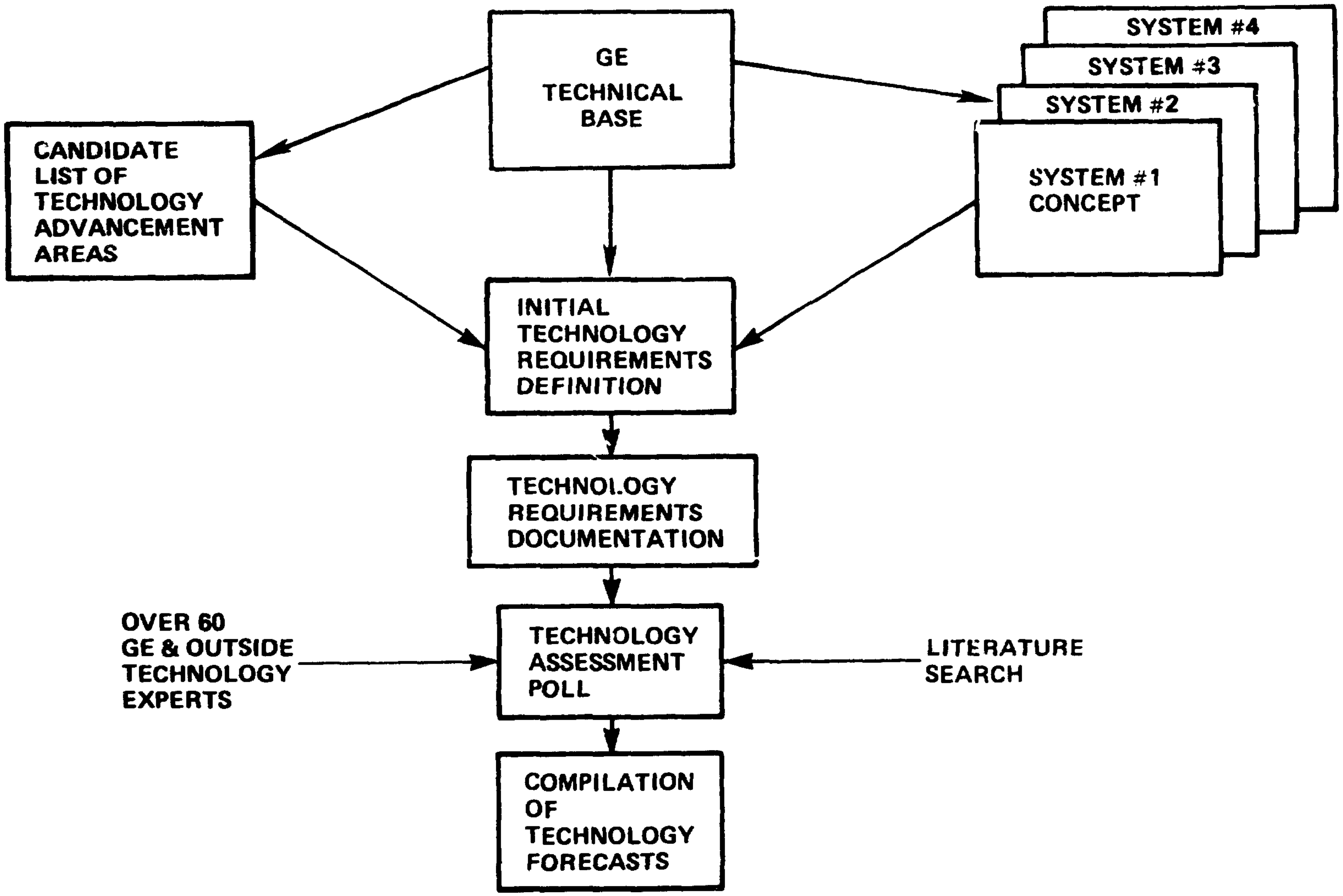


Figure 7-1. Technology Requirements/Forecasts Task Flow

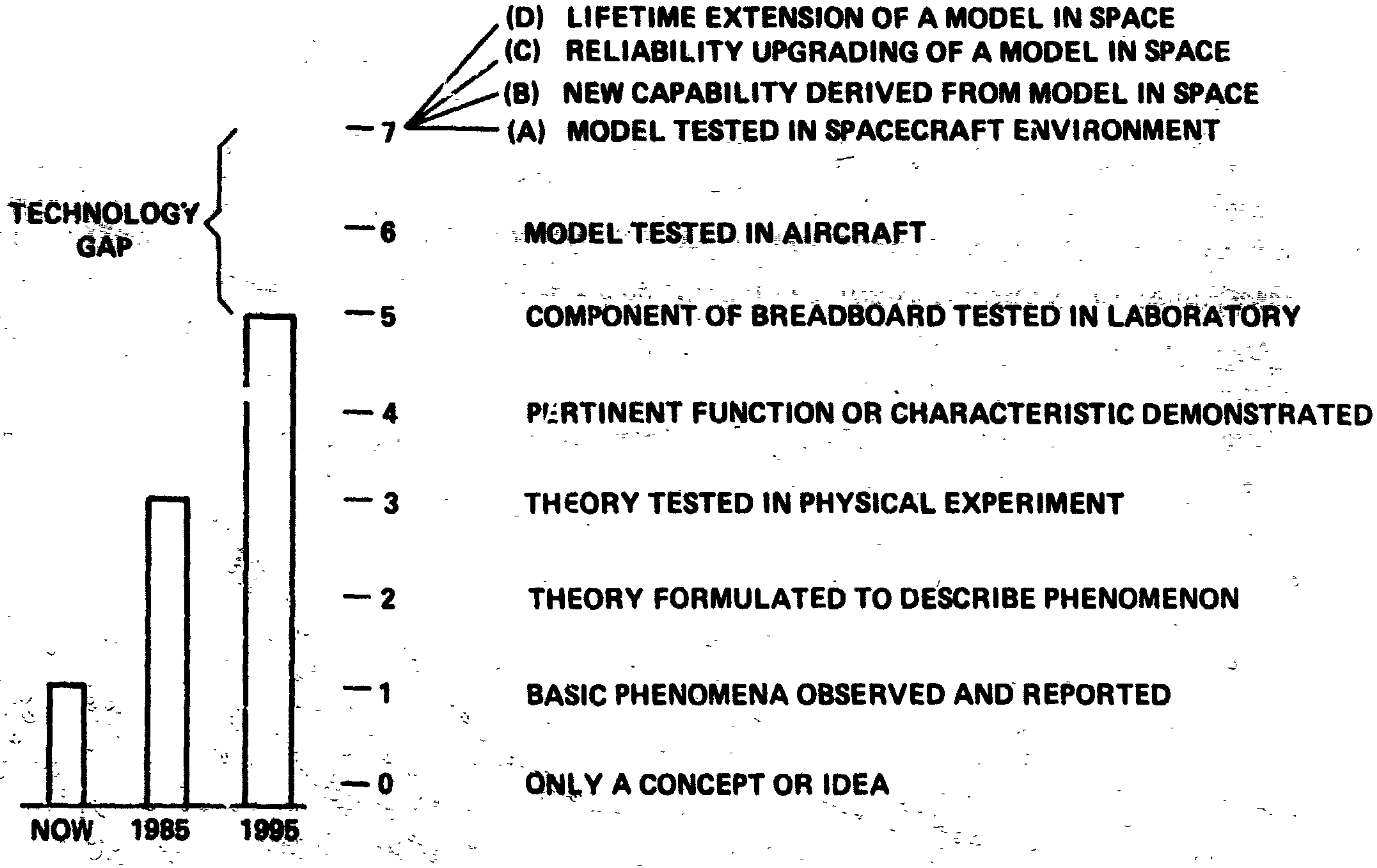
Once the specific technology requirement was established, those technologies which obviously could not be attained in the near-term (i.e., within 2 to 3 years) were documented in a Technology Requirements Document, a brief summary of the following types of information:

- o Overall description of the requirements
- o State of the art overview
- o Major requirements
- o Desirable features
- o Needed forecast

This document was used to communicate with over sixty technology experts from GE and outside consultants, during the Technology Assessment Poll.

This poll requested that each expert in a given technology area make the projection in terms of current , 1985, and 1995 states of the art. The rationale for these projections was solicited, as well as an estimate of the technology level to be attained in each time frame, following a scale which was developed in conjunction with NASA-OAST during the Future Payload Technology Requirements Study (FPTR), as shown in Table 7-1. On the scale, the lowest level of technological achievement is the concept or idea. It progresses through the observation of the basic phenomena and theory formulation to the various tests and demonstration stages. The highest level (7) is the space demonstration, which is categorized in four modes: A, B, C and D. Mode A is fulfilled when a prototype or engineering mode of the specific technology item is tested satisfactorily in space. An example of Mode A is a space demonstration of a LIDAR unit, using the Spacelab pallet as a test bed.

Table 7-1. Technology Achievement Levels



In Mode B, a capability existed for a ground-based version of the technology, but this capability is being enhanced by adapting the system to the space environment. Synthetic Aperture Radar is an example of a technology test that is well advanced using aircraft, but requires the solution of several space-unique problems prior to testing a model in space. When the desired degree of performance is reached in space, the Mode B level will be fulfilled.

Modes C and D relate to technologies which are already available in space systems, but which require better reliability and longer life in the space environment solar arrays and spacecraft betteries are in this category. In addition, the technologists were asked to estimate the amount of money required to close the technology "gap" by 1995. Referring to Table 7-1, the gap consists of the difference between the technological level estimated for 1995 and the "full attainment" of that technology, as characterized by Level 7, which has alternative modes designated A, B, C or D. During the course of the experts' reply period, representatives of the PLACE team had personal meetings with the experts and their associates, to ensure mutual understanding of the technical requirements, the overall study, and the poll information being submitted. The results of the technology assessment poll were compiled for inclusion in the final oral presentation and the final report.

7.2 GROUNDRULES AND DEFINITIONS

Certain groundrules were established during the analysis and technology assessment poll. These are important in understanding the results. Relative to the technology requirements definition task, the following was established:

1. The applicability of a technology to a given system can be assessed in two modes:

   a. An ENABLING technology is one that is necessary to permit the implementation of the system as conceived.

b. An ENHANCING technology is one that is desirable (but not mandatory) since it will reduce the cost of implementation significantly.

2. A technology requirement must require an advancement in the state of the art; that is, it should not be based merely on an engineering development where the techniques are available and proven.

3. The quantitative definition of the pertinent technology requirement parameters is based on the most demanding of all the requirements imposed by the systems enabled or enhanced by that technology.

Relative to the Technology Forecasting task, the following apply:

1. The technology projections assume no significant NASA technology effort between now and 1995.

2. The "technology gap" is defined as the technological deficiency between the projected 1995 technology achievement (assuming no significant NASA expenditures) and the maturing of the technology as evidenced by a space demonstration of the technology aspect.

3. The estimated cost of filling the "technology gap," as defined previously, assumes required expenditures for those specific and limited aspects of the developments which have a significant technology (i.e., s.o.a. advancement) content. Similarly, the in-space demonstration which constitutes the last step in technological maturity, is assumed to incorporate only the parts, components or sub-assembly portions related to that technological content. It is estimated that many of these space demonstrations will involve a space package constituting less than 1/2% of a Shuttle payload. Future derivatives of the Long Duration Exposure Facility are examples of the type of payload where the demonstration packages may be accommodated.

4. Cost of research required by NASA assumes funding from external sources has taken place.

7.3 IDENTIFIED TECHNOLOGY REQUIREMENTS

Twenty five technology requirements were identified as being required by the PLACE system concepts. The requirements, which were selected for further analysis in the study, are listed in Figure 7-2. Correlated with each requirement is the applicable PLACE system which utilizes the technology. The black dots indicate that the technology is enabling relative to that system, whereas the white dot indicates that the technology enhances the system from a cost point of view.

Several patterns are discerned through this matrix (Figure 7-2). For instance, while the number of enhancing technologies exceed that of the enabling technologies, all PLACE systems require more than one enabling technology. Technologies exhibiting a high degree of commonality among systems, such as solar arrays and batteries, ground and on-board storage, data processing, and data base systems, are generally enhancing. Extractive processing is the technology which enables the largest number of systems. A summary of the total number of systems enabled by the various technologies, listed in descending order is shown below:

EXTRACTIVE PROCESSING	11
LARGE STRUCTURES	5
SOLID STATE SENSORS	4
LASER SYSTEMS	3
CRYOGENICS	2
POINTING	2
EPHEMERIS	2
LOW NOISE M-WAVE RECEIVERS	2
LARGE OPTICS	2
IONOSPHERIC MODEL	2
FERRIS WHEEL CHIP	2
2-POL. N-FREQ. ARRAYS	1
RADIATION RESISTANCE	1
ADAPTIVE OPTICS	1
STABLE OSCILLATORS	1
RANGING SYSTEM	1
DISSEMINATION CONCEPTS	1

	LANDSAT	EARTHWATCH	GEOS	TEXTUROMETER	THERMAL INERTIA MAPPER	MICROSAT	PARASOL	ELLIPSOMETER	FERRIS WHEEL	SWEEP FREQ. RADAR	GEOSAR	HOLOGRAPHER
SOLAR ARRAYS	○	○	○	○	○	○	○	○	○	○	○	○
BATTERIES	○	○	○	○	○	○	○	○	○	○	○	○
CRYOGENICS	○	○			○	●	●			○		
LARGE STRUCTURES			○	●		●	●	●	●			
2-POL. N-FREQ. φ ARRAYS		○				○	○	○	○	●		
RADIATION RESISTANCE		●	○								○	○
POINTING	○	●	●		○						○	
EPHEMERIS	○	●	●		○						○	○
LO-NOISE μ-WAVE REC'VR						●	●	○		○		
LARGE OPTICS			●	●								
ADAPTIVE OPTICS			○	●								
IONOSPHERE MODEL								●	○	○		●
STABLE OSCILLATORS	○	○	○							○	●	
RANGING SYSTEM				●		○	○	○	○			
DISSEMINATION CONCEPTS	○	○	●		○	○	○	○		○	○	○
ON-BOARD STORAGE	○	○	○							○	○	○
GROUND STORAGE	○	○	○	○	○	○	○	○	○	○	○	○
ON-BOARD PROC.	○	○	○	○							○	○
GROUND PROC.	○	○	○	○	○	○	○	○	○	○	○	○
D.B.M.S.	○	○	○	○	○	○	○	○	○	○	○	○
SOFTWARE ADVANCES	○	○	○	○	○	○	○	○	○	○	○	○
SOLID STATE SENSORS	●	●	●	●	○							
FERRIS WHEEL CHIP							●		●			
EXTRACTIVE PROC.	●	●	●	●	●	●	●	●	○	●	●	●
LASER SYSTEMS	●	●			●							

ENABLE = ●

ENHANCE = ○

Figure 7-2. Technology Requirements Posed by System Concepts

7.4 TECHNOLOGY REQUIREMENTS/FORECAST RESULTS

7.4.1 LOW-COST SOLAR ARRAYS

Technology Requirements

Many PLACE systems require substantially more power than most contemporary systems, hence, an enhancing (cost saving) technology for most future missions is lower cost solar arrays. Since the goal is to optimize on the basis of minimum cost in mission orbit, light weight is also a part of the need, the importance of light weight being in inverse proportion to expected transportation costs. Radiation resistance and solar array dynamics are related aspects of this technology requirement which are covered in separate technology requirement definitions.

The present cost of solar arrays is of the order of $300 per watt, with transportation costs of typically another $20 per watt. No specific level is evident as a "must" for future system costs. However, analysis suggests that a 90% reduction, to ~ $30 per watt for array and transportation, is both quite feasible and of major benefit. Consequently, this level is suggested as the "requirement" for low cost space qualified solar array. This level of cost performance is desired with a rigid (natural frequency over one Hertz), multi-kilowatt, deployable array.

State-of-the-Art Overview: Three current development trends need to be recognized in making technology projections in this area. The first is the development attention being given to GaAs cells. These cells have the promise of potentially higher efficiency, greater radiation resistance, and greater ability to tolerate large concentration ratios. (See Table 7-2 for a comparison of efficiencies.) At present these cells are experimental and expensive, and projections indicate that future costs may remain significantly higher than silicon cells.

Table 7-2

Comparison of Present Levels of Efficiencies for Photovoltaic Materials

MATERIAL	EFFICIENCY
Si (single crystal)	19%
CdS - Cu_2S	8%
GaAs (single crystal)	23%
Si (polycrystalline)	10%
GaAs (thin film)	5%

In the area of silicon solar cells, much attention is being focused on thin solar cells and lighter substrates, in order to save array mass. Very thin solar cells, down to 50 μm thick, are being developed. Such cells have reduced efficiency (compared to "standard" cells), much higher specific power (watts per kilogram), improved radiation resistance, and higher costs per installed cell.

The third area to be recognized is the thrust toward reduced costs for terrestrial solar cells. Edge defined crystal growth, automated assembly, and other developments are aimed at a dramatic reduction in terrestrial solar array costs.

The reader is referred to section 5.2.3 in which the cost and the weight of future solar arrays are traded-off. In addition, the concept of the even trade value for solar array weight and cost is developed. Table 7-3 shows the even trade value of various array specific power goals as a function of transportation costs.

Table 7-3

Even Trade Values for Increasing Solar Array Specific Power - $ Per Watt

Transportation Costs $ Per Kg	$ WATT TO GO FROM 25 w/kg TO				
	100 w/kg	200 w/kg	300 w/kg	400 w/kg	500 w/kg
100	3.00	3.50	3.67	3.75	3.80
500	15.00	17.50	18.35	18.75	19.00
1000	30.00	35.00	36.70	37.50	38.00
2000	60.00	70.00	73.40	75.00	76.00
5000	150.00	175.00	183.50	187.50	190.00

Technology Forecast

The results of the technology assessments poll are summarized in Table 7-4 (Refs. 7-1, 2)

Technology Projection

Table 7-4. Solar Array Projection

	CURRENT		1985		1995	
	TERRESTRIAL	SPACE QUAL.	TERRESTRIAL	SPACE QUAL.	TERRESTRIAL	SPACE QUAL.
MFG. COST	$9.00/WATT	$300/WATT	$2.50/WATT	$70/WATT	$0.50/WATT	$15/WATT
POWER DENSITY	25 WATTS/Kg		150 WATTS/Kg		250 WATTS/Kg.	
TRANSPORTATION COST*	$20/WATTS		$1.6/WATT		$0.40/WATT	

Current cost of silicon cells for terrestrial applications is $8 to $9 per watt. The cost to space-qualify the arrays, along with the costs of adaptation to the launch and space environment bring the current cost to approximately $300 per watt (Refs. 7-1,2). This space-to-ground ratio of approximately 30:1 is seen as remaining fairly constant through 1995.

A Department of Energy goal of $0.50 per watt has been set for the latter half of the next decade. The experts consulted by PLACE agree that, technologically, this goal is attainable by 1986, however, it would require large scale production rates that are not foreseen until the 1990's. Based on reasonably conservative production projections, the 50¢ per watt goal would be attained in 1995; this leads to the projection of $15 per watt for space qualified solar arrays.

Concerning the reduction of transportation cost, the major thrust must be in the structure supporting the cells, and the deployment mechanism employed. Additional improvement beyond the current thickness of 250 microns will not reduce the weight of the total assembly as significantly as lightening of the supporting structures.

Required NASA Developments

The major portion of the technology development in silicon is foreseen to occur in ground-based applications. NASA development effort will be required to adopt this technology to the space applications, considering the special environments of space flight and the need for light weight. GaAs cells seem promising from the points of view of efficiency and radiation resistance; however, the required NASA involvement here would be much greater, since the GaAs technology development thrust by the private sector is relatively small.

7.4.2 HIGH ENERGY DENSITY SECONDARY BATTERIES

Technology Requirement

All PLACE systems included in the selected set include energy stored to permit collection and return of data during eclipse. Thus for all missions, a lighter energy storage subsystem would be an enhancing (cost saving) technology. Major progress is now being made in laboratories toward this goal of lighter secondary batteries. Most of this effort is focused on utility power peaking and automotive transportation applications. Most of this development effort appears to have potential for space applications in the post-1985 era.

The principle requirements for lightweight energy storage cells is a combination of high intrinsic energy density and a high useable discharge fraction. This must be met for enough charge/discharge cycles to meet system life requirements. The PLACE systems require a life capability of two years in low earth orbit and up to eight years ingeosynchronous orbit.

The estimates of enhancement benefit for PLACE missions has been generally based upon a usable energy density of 100 watt-hours per kilogram (w-hr/kg). This could be achieved, for instance, by a 200 w-hr/kg cell with a usable depth-of-discharge of 50 percent, or by any other combination of theoretical energy density and usable discharge fraction. The minimum design life, corresponding number of discharge cycles, and discharge/recharge time for the three classes of orbits considered for PLACE are summarized below:

	ORBIT TYPE	YEARS OF LIFE (YEARS)	DISCHARGE/ RECHARGE CYCLES (ESTIMATED)	DISCHARGE TIME (MIN)	RECHARGE TIME (MIN)
(1)	Low earth orbit; synchronous	2	11,000	30-50	60-70
(2)	Inclined (55^{o}) Intermediate Altitude (Earthwatch)	4	0-1000	0-50	240-360
(3)	Low Inclination Earth Synchronous	8	1,000	0-75	1350-1436

State-of-the-Art Overview

An energy storage future trade-study done earlier in the PLACE study concluded that new electrochemical couples, initially developed for terrestrial uses, would be adapted to spacecraft by 1992, and would have much higher energy densities than present cells. Fuel cells and flywheels were also considered (see Section 5.2.4), but not expected to displace chemical batteries.

Projected improvements in solar array power to weight ratio projected for the post-1985 period (Reference 2) means that, unless major improvements are achieved, energy storage mass will become an even larger fraction of the power subsystem total than at present. On the other hand, the reduced solar array mass means that charge/discharge efficiency is relatively less important than at present, although a good value is still desirable.

Technology Forecast

The current technology capability is for 60 watt hrs. per kilogram, based on terrestrial applications, using nickel-hydrogen cells. (Refs. 7-3,4). A number of storage cells currently under development are projected to meet the stated energy density requirement, for instance:

- o Link Chloride
- o Lithium - Aluminum/Fe
- o Lithium - Silicon/Fe
- o Lithium - Carbon Monofluoride
- o Lithium - Titanium Sulfide
- o Sodium Sulfur
- o Sodium Antimony Chloride

The capability projection is 180 watt hours/kg by 1985, and 250 watt hours/kg for 1995. The latter will be attained through the use of high temperature ("thermal") cells.

Required NASA Developments

The cell developments for ground applications such as vehicular propulsion and electrical load averaging will require adaptation to the specific needs of the space systems and missions. Primary among these considerations will be the adaptation of the cell design to the charge/discharge schedule as discussed in the Technology Requirement section. In addition, the long-duration application of the batteries in space missions will require extra counter measures against problems such as electrolyte loss and high pressure gas build-up.

7.4.3 ACTIVE CRYOGENIC REFRIGERATORS

Technology Requirement

Low temperature sensors are used in several of the PLACE system concepts to decrease the detector noise to acceptable levels. The requirement ranges from 25° to 100°K, which is beyond the capability of a purely passive radiator.

Cooling of earth observation infra-red detectors requires temperatures of 50° - 75° Kelvin. There is little benefit in lower temperatures for these missions since the fluctuations in the atmospheric background have larger contributions to the noise range level. At this temperature range, the cooling load is estimated to be one to ten watts, for the PLACE missions. The cooling load for infrared detectors included substantial contributions from radiation of elements in the optical path (e.g. primary mirror, baffles, steps), and from conduction through electrical leads and support members to the focal plane assembly. Consequently, it is useful and/or necessary to cool these elements to a lesser degree, i.e. 100K or so. At these temperatures rather substantial heat loads may be encountered. For example, the earth albedo input to a mirror of one square meter area could be of the order of 50 watts if the mirror absorptivity were 0.05. Consequently, cooling loads of a hundred to several hundred watts may be encountered in PLACE systems.

Cooled parametric amplifiers for microwave receivers would be useful for some PLACE systems. Since the atmosphere is transparent in this region, temperatures lower than needed for IR detectors would be useful. Nominally, 25K is taken as a requirement, although even lower temperature may have utility. Only a few watts of cooling would be needed at this temperature.

The major requirement for technology development is the achievement of reliable long life operation of refrigerators at these temperatures and loads.

Desirable features of future active cryogenic refrigerators are light weight, low power consumption, and low cost. To some degree all of these parameters must be met to enable the use of the technology; beyond that point improvements are simply enhancing. As a goal, the following performance is desired:

Temperature (K)	Efficiency (% of Theoretical)	Cooling Load (Watts)	Refrigerator Mass (Kg per watt cooling)
150	15	200 - 500	1.0
100	10	200 - 500	1.0
75	8	1 - 10	2.0
50	6	1 - 10	3.0
25	5	0.5 - 2.0	3.0

State-of-the-Art Overview

A review of cryogenic refrigeration literature indicates that substantial work has been accomplished for five closed cycle systems:

- o Vullenmeir (V.M.)
- o Revised Brayton/Claude (turbomachinery and Rotary-reciprocating (R^3)

- Stirling
- Gifford - McMahon
- Joule - Thompson

Much of the existing hardware designed for refrigeration applications are able to meet the load and temperature requirements of the PLACE systems.

Figure 7-3 through 7-6 show the current capabilities in terms of efficiency, volume, mass, and cost for terrestrial application refrigerators, according to a survey by the Cryogenics Division, Institute of Basic Standards, National Bureau of Standards. (Ref. 7-6)

The technology of large capacity helium refrigerators is quite mature, as exemplified by the list of units shown in Table 7-5 (Ref. 7-5), that were ordered between 1975 and 1977.

Technology Forecast

Table 7-6 shows the current and predicted performance characteristics for cryogenic refrigerators in the range from 25^{o}K to 150^{o}K. The "gap" between PLACE derived requirements and 1995 capabilities is in the area of mass-per-watt ratio and efficiencies. The Vullenmeir cycle, combined with a solar power system appears to have the highest potential for attaining the long-life required for PLACE-type missions.

Required NASA Developments

1. Significant development effort to reduce mass and size of refrigerators.
2. Improvement in the efficiency of units in the 25^{o}K region.

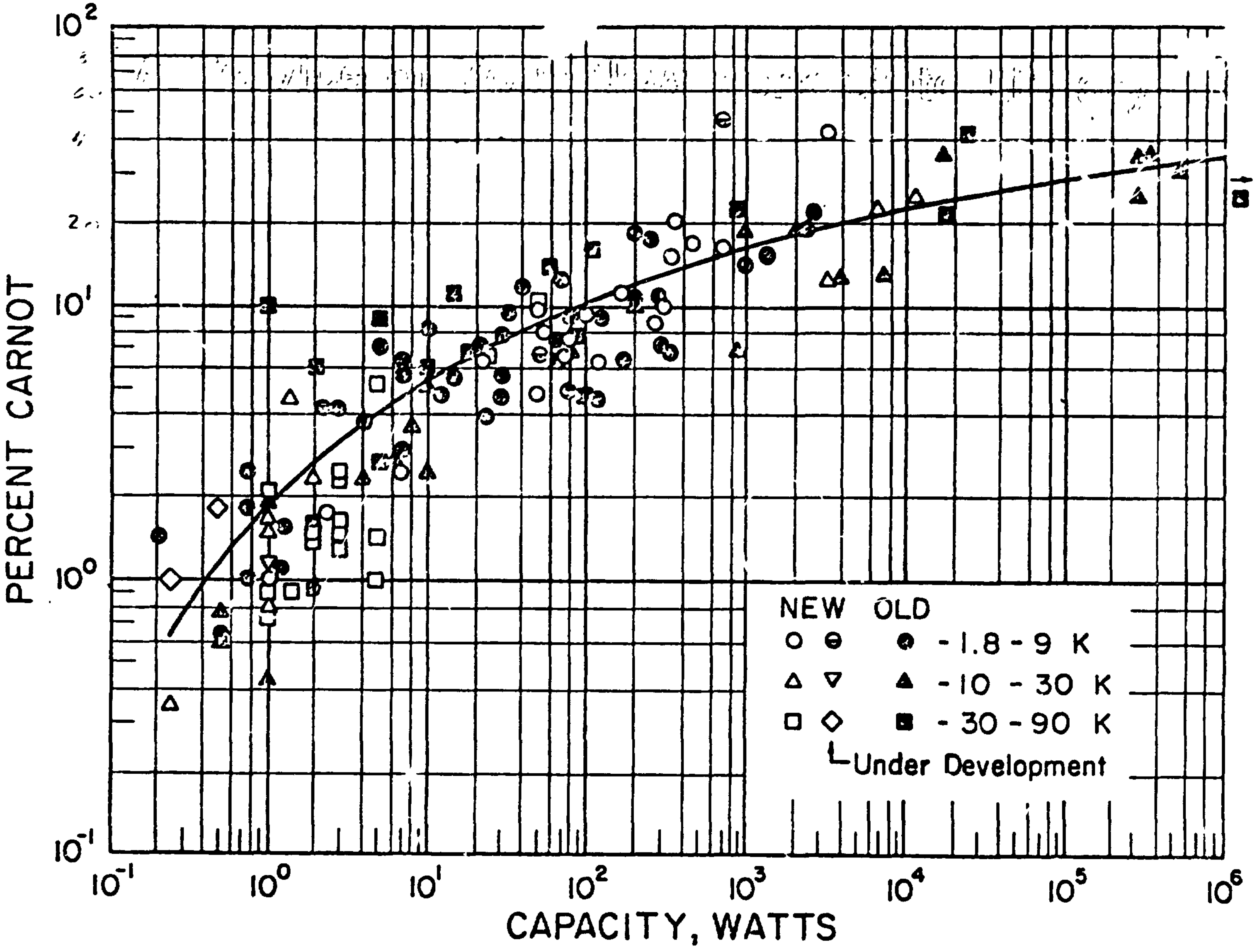


Figure 7-3. Efficiency of Low Temperature Refrigerators and Liquefiers as a Function of Refrigeration Capacity

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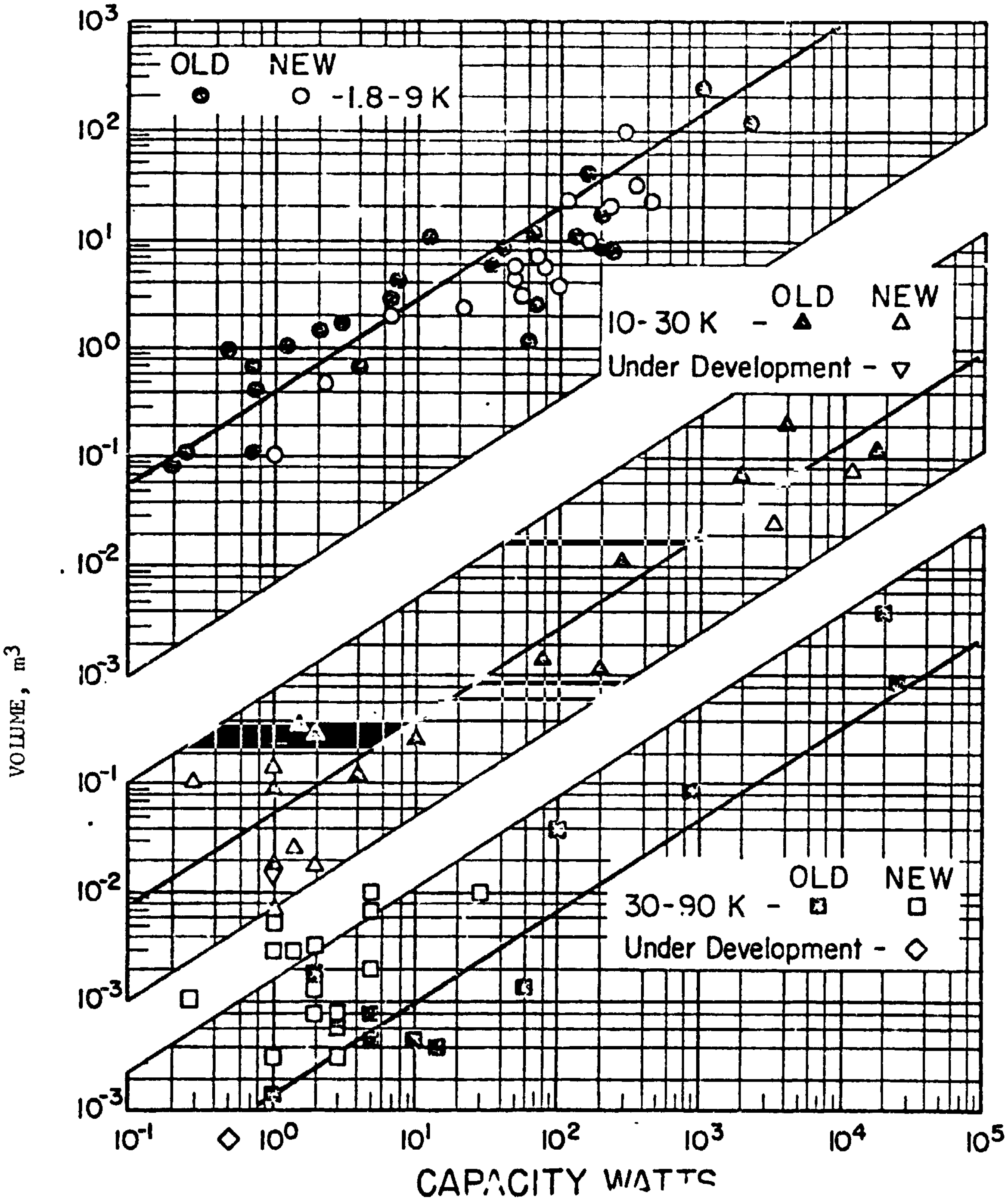

Figure 7-4. Volume of Low Temperature Refrigerators and Liquefiers as a Function of Refrigeration Capacity

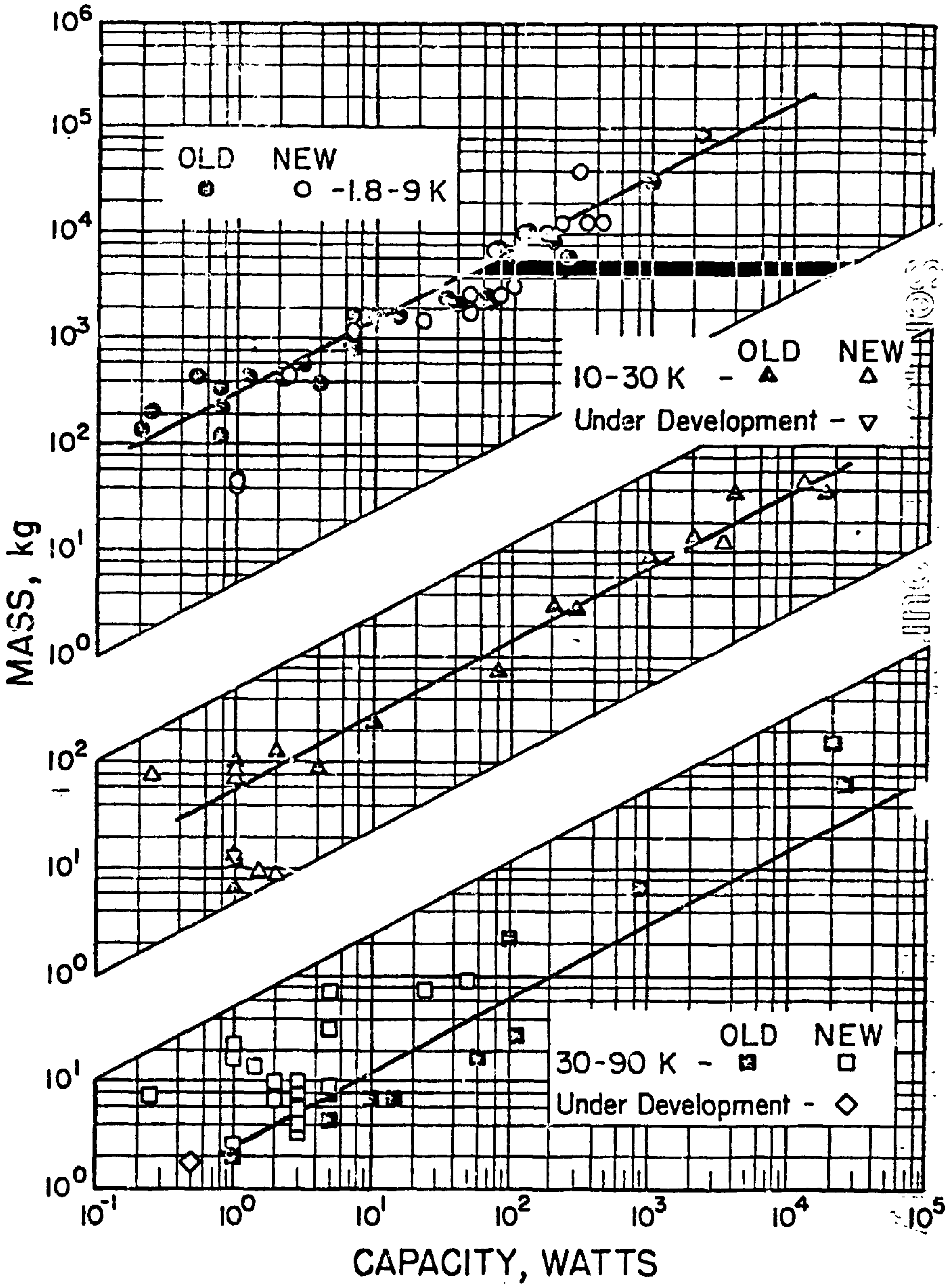

Figure 7-5. Mass of Low Temperature Refrigerators and Liquefiers as a Function of Refrigeration Capacity

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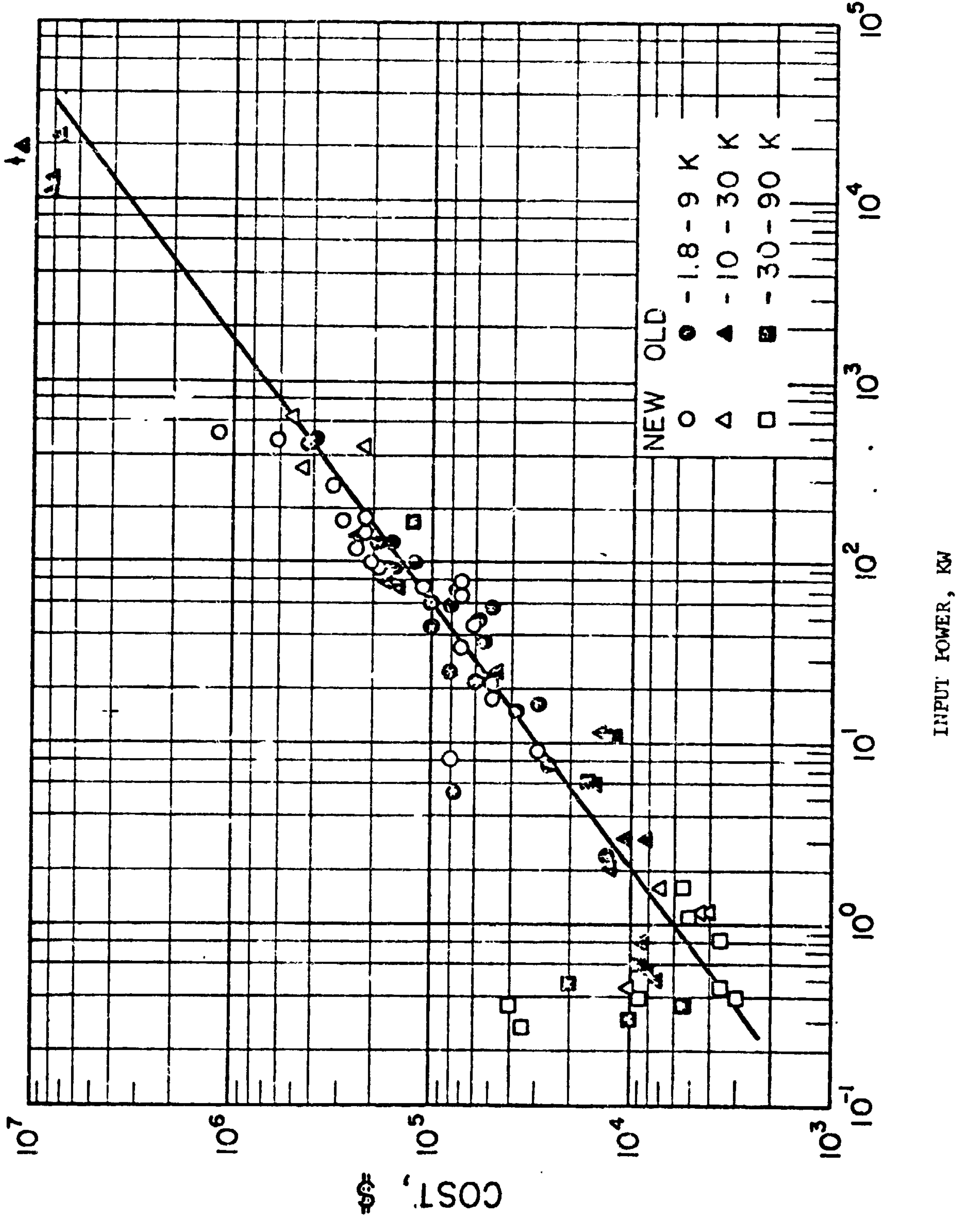


Figure 7-6. Cost of Low Temperature Refrigerators and Liquefiers

Table 7-5. Large Helium Refrigerators and Liquefiers Ordered Since 1975

Agency	Application	Nominal Capacity	Temperature K	Expander Type	Compressor Type	Liquid Nitrogen Precooling
LASL	Energy Storage	900 W	4.5	Turbine Gas bearing	Reciprocating	Yes
BNL	SPTL*	600 W plus 1.5 g/s lead cooling	6-8	Turbine (3) Gas Bearing	Screw	No
BNL	HEUB Beam Magnets	700 W	4.5	Reciprocating (2)	Reciprocating	Yes
FERMI	Energy Doubler	1500 W	4.5	Turbine (2) Gas Bearing	Screw	Yes
LBL	ESCAR	1500 W	4.5	Turbine (2) Gas Bearing	Screw	Yes
ORNL	MFE Magnets	1500 W or 900 W	4.5 or 3.5	Turbine (1) Gas Bearing	Screw	Yes
FERMI	Energy Doubler	4500 L/hr		Turbine (3) Oil Bearing	Reciprocating	Yes
ERDA	SPTL Russian Exchange	700 W plus 4 g/s lead cooling	4.5	Turbine (2) Gas Bearing	Screw	Yes
U.S. BUREAU MINES	Bulk Liquefier	500 L/hr		Turbine (2) Oil Bearing	Reciprocating	Yes

* Superconducting power transmission line.

TABLE 7-6

FORECAST - CRYOGENIC REFRIGERATION CHARACTERISTICS

	Current	1985 (SOA)	1995 (SOA)
Temp = $150^{\circ}K$			
Load, cooling	200-500 watts	200-500 watts	200-500 watts
Efficiency	15% Carnot	15%	15%
Design Life	3000 Hours (3)	6 years	10 years
Weight	1.4 kg/watt (3)	3 kg/watt	2 kg/watt
Comment (1)		Likely V.M. or R^3 (1) redundant	Likely V.M. or R^3 (1) redundant
Temp = $100^{\circ}K$			
Load, cooling	200-500 watts	200-500	200-500
Efficiency	10% Carnot	10%	10%
Design Life	3000 hours	6 years	10 years
Weight (2)	2 kg/watt	4 kg/watt	3 kg/watt
Comment (1)		Likely V.M. or R^3 (1) redundant	Likely V.M. or R^3 (1) redundant
Temp = $50\text{-}75^{\circ}K$			
Load, cooling	1-10 watts	1-10 watts	1-10 watts
Efficiency	8% Carnot	8%	8%
Design Life	5000 hours (3)	6 years	10 years
Weight (2)	5 kg/watt (3)	10 kg/watt	8 kg/watt
Comment (1)		Likely V.M. or R^3 redundant	Likely V.M. or R^3 redundant
Temp = $25^{\circ}K$			
Load, cooling	.5 to 2.0	.5 to 2.0	.5 to 2.0
Efficiency	3% Carnot	3%	3%
Design Life	5000 hours	6 years	10 years
Weight (2)	7 kg/watt	14 kg/watt	12 kg/watt
Comment (1)		Likely V.M. or R^3 redundant	Likely V.M. or R^3 redundant

7.4.4 LARGE STRUCTURES

The discussion of the technology requirements and forecasts associated with large structures will be divided into five areas: (1) Structural Analysis; (2) Attitude and Shape Control; (3) Materials; (4) Structural Elements and Joints; and (5) Orbital Assembly/Logistics. Each of these areas will be individually discussed in the following sections.

Technology Requirements

The major requirement for large structure analysis technology is development of the ability to translate mission requirements such as pointing accuracy and antenna surface tolerance, and environmental conditions such as orbit parameters and upper atmospheric density, into "conventional" design parameters, such as "the bending moment on this joint is...," "the bandwidth of this control element must be...," or "a damping coefficient of so much is required in this member." Two types of analytical techniques need to be developed for the analysis of large structures. One result needed is techniques that permit mission planners and system conceptual designers to perform the top level trades needed to define optimal programs, i.e., means of relating approximate system mass, number of launches, cost, construction time, andthe like, to requirements for accuracy, size, stability, control elements, and other mission parameters. The other result needed is detailed analysis procedures that yield stresses, deflections, frequencies, and the like with sufficient accuracy to permit successful structures to be constructed in space. Obviously the mission planning and conceptual design work precede the construction phase. However, it is not self-evident that effort should be focused on simple analysis techniques first; it may be, as has happened on other complex problems, that only detailed analysis of sample problems will lead to the insights that make simple approximations possible. Two major performance desires are immediately evident. The first is that the analysis techniques developed be capable of verification in free-fall through inexpensive tests that can be conducted early in the Shuttle era. The second desire is that the analyses lead to acceptably accurate and reliable results at a modest cost in analysis time and margin of safety.

Attitude and shape control sensors and actuators represent a new problem when applied to large structures. Attitude control is used to describe the orientation of the structure as a whole to an inertial or orbital coordinate frame. Shape control means the relative positioning of elements of the structure relative to each other. Obviously the two are related, and could be redefined as the attitude control (in some reference coordinate system) of each part of the structure. The distinction is made for convenience; for shape controlthe structure can be made to react against itself, i.e., no net external reaction must be provided, although that is one possible way to control shape. Attitude and shape sensors are discussed in the technology requirements on Pointing and Ranging (6. 7 and 6.14, respectively). The attitude and shape control actuators are discussed below. The attitude actuators are new in that they will be decentralized and optimally distributed throughout the structure. However, shape control sensors are a new class of device. So far, deployed shape has been a constant; space structures were assembled and tested on the ground. Their shape was predetermined and fixed, except for moving antennas and sensors. With space assembly, a new factor enters the configuration definition. The major requirement for control actuators is that they be available with the capacity to supply the required length (tension and compression), angle and rotation corrections needed by the large PLACE structures. The ability of a large structure to overcome some shape distortion by electronic means has been discussed in Section 5.2.6.

The major requirements in the area of materials is that the structural materials must withstand the natural and imposed environment without unacceptable deterioration of itself or damage to other parts of the system over lifetimes greater than ten years. This requirement includes the need for protection from several phenomena. The free-fall aspect is both obvious, and enables large structures. The vacuum environment not only imposes a material degradation concern, but implies that outgassing of condensible vapors which can contaminate neighboring optical surfaces must be avoided. Typical optical surfaces would include sensor optics and detectors, solar cells, thermal control coatings, cryogenic coolers, etc. In short, most surfaces of the satellite are susceptible to adverse effects from structural outgassing. Both UV and ionizing radiation effects are important at all altitudes, with trapped particle radiation especially important between 1000 Km and synchronous altitude. Almost all orbits, including all PLACE orbits, include an eclipse phase. This abrupt change in incident radiation often has a pronounced effect upon spacecraft structure, often leading to surface temperature decreases of 200 K or more in a matter of minutes for non-power dissipating elements. Any thermal contractions resulting from this sudden temperature change must be accommodated while meeting all functional requirements. The problem of charge build-up at geosynchronous altitudes has also begun to be investigated.

Future PLACE systems also pose challenging requirements on structural elements and joints. Classes of "building blocks" or geometries capable of withstanding to-be-designated levels of tension (rods and cables), compression (columns and arches), flexure (beams and trusses), torsion (shafts) and shear (webs and plates) must be developed. Although in terrestrial practice specialized forms have evolved for each primary load cateogory, in space, new forms for structures, tailored to space parameters, can be expected to evolve. The joints for large structures must withstand the loads applied - which are yet to be defined - within stress levels consistent with reliable long life. Further, the joints must provide rigid connections where required. Even a minute amount of play in a joint can lead to large deflections/misalignments in large structures. In some cases, the joints may be expected to supply structural damping. Finally, the joints must be capable of being assembled (and perhaps disassembled) in space.

The requirements involved in orbital assembly and logistics have been given some study, and concepts for in-orbit assembly may be divided into three major classes: manned, remote manned, and automatic or robotic. Manned orbital assembly operations on large structures generally envision significant limitations on human dexterity imposed by a need for space suits to overcome the environment. The other alternative, assembly in a large habitable space "hangar", has never been seriously advanced. This limit on manned capability has usually been considered to restrict assembly operations to fairly simple tasks on bulky objects. Further, such manned operations have been regarded as enormously expensive. In the past this has been valid, but with future prospects of $100 per kilogram transportation costs, and an "orbital bunkhouse" with geoponic life support, this situation may change. Remotely "manned" orbital assembly operations is another approach that has received substantial study. In low earth orbit, teleoperators with ground based control are communication limited. If direct communications to ground are used, the line of sight limitation limits use of the equipment to only a few minutes per orbit. If a geosynchronous communications relay link is used to solve this problem, then the radio propagation delay (which varies between 0.24 sec and 0.99 sec) seriously impedes the man-machine feedback loop, and limits the speed of operations. Further, for any orbit, the end effectors of the teleoperator are, in general, even less dexterous than the gloved hand. The communication dilemma can be solved by having the operator in the same orbit as the teleoperator. This approach compounds the problems of manned orbital operations and limited machine capability.

The third approach is to use automatic machines or robots to do the orbital tasks. Various forms of beam builders and assembly automators have been proposed. The concept usually includes manned machine tending and/or maintenance. Automatic machine repairing machines have not been encountered in concepts proposed to date.

TECHNOLOGY PROJECTION

An assessment of the current state of the art and in some cases a forecast of future capabilities follows for each of the following five areas: (1) Structural Analysis; (2) Attitude and Shape Control; (3) Materials; (4) Structural Elements and Joints; and (5) Orbital Assembly/Logistics.

The area of analysis of large space structures is quite young, with early analysis packages such as DYNAMO and SAGERT currently available. In the future, these programs will be improved and expanded to include temporal varying loads, non-linear transfer functions, etc. Associative efforts to correlate the results with empirical test data and reduce computer run time will also be ongoing.

The area of attitude and shape sensors is well established, with shape sensors based on ranging (see Section 7.4.14). The current relative capabilities of momentum storage vs. thrusters is discussed in Section 5.2.6. Of the candidate chemical, ion, electrothermal and colloid thrusters, NASA-Lewis is currently pursuing the ion engines and the INTELSAT V program is developing electrothermal thrusters. Other methods of attitude control including magnetic field interaction, solar pressure and gravity gradient will also be considered as correction forces in the future. Shape control devices that will be considered in the future include piezoelectric devices, magnetostructure devices and hydraulic actuators. Very little applications work has been initiated to date except for physical lab demonstration-type experiments.

The four areas that will be addressed under materials are metals, polymers, composite materials, and coatings. A comparison of the critical parameters of some representative structural materials is presented in Table 7-7 (Ref. 7-44). Metal structural materials such as aluminum and titanium have been used extensively and the technology is adequate. Of the polymers, Kevlon is degraded by ultraviolet radiation but materials such as dac[illegible] are attractive for mesh type surfaces. A significant amount of work on the use of composite materials has been performed (Ref. 7-8). Graphite epoxy has been extensively used and has excellent material properties but requires a UV shield for long life. Graphite polyimide, the most stable organic compound, is being marketed by DuPont as CAPTON. It has the property that

Table 7-7. Structural Material Status Estimate

Property (English Units)	Graphite Epoxy	Aluminum 6061-T6	Steel 1021	Titanium 6A1-4V	Carbon/Carbon HM (45° Wrap)
Youngs Modulus E (psi)	10×10^6	10×10^6	25×10^6	16.6×10^6	18×10^6
Density ρ (lbs in^3)	0.06	0.1	.275	.164	0.054
CTE (α) (in/in°F)	1×10^{-6}	13×10^{-6}	6.5×10^{-6}	5×10^{-6}	0.43×10^{-6}
Specific Stiffness (E/ρ)	16.6×10^7	10×10^7	9.1×10^7	10×10^7	33×10^7
Specific Thermal Expansion ($1/\rho\ \alpha$)	16.6×10^6	$.77 \times 10^6$	$.56 \times 10^6$	1.2×10^6	43×10^6
Radiation Resistance	Unknown	Excellent	Excellent	Excellent	Excellent
Space Use Compatability	Unknown	Excellent	Excellent	Excellent	Excellent
Manufacturing Maturity	Emerging	Established	Established	Established	Infancy
Cost	High	Low	Low	Moderate	Very High

its outer layer turns black after several years, providing a UV shield but creating thermal problems. Carbon-carbon composites are extremely difficult to manufacture but offer excellent structural properties. Metal matrix composites such as aluminum graphite and magnesium graphite are another attractive alternative, although they are not as developed as graphite epoxy. The material corrodes in the presence of water vapor, which prevents its use in the aircraft industry. However, it is an extremely stable compound that may be the answer to the long life, hi-energy radiation problem. A number of coatings have been investigated to prolong the structural life of materials. White paint which has been extensively used is heavy and is a poor UV shield, but has low absorptivity and high emissivity. A second candidate is a layered dielectric surface, perhaps of pure silicate. A third candidate which may prove effective would involve vapor deposition of metal coatings.

A number of concepts for structural elements and joints was discussed at the joint Industry/Government Seminar on Large Space Systems Technology held at NASA's Langley Research Center in January of 1978 (Ref. 7-7). The most actively pursued concept is the nestable column; however, work is also continuing on trusses, tetrahedral sections, the astromast concept, and the Buckminster Fuller truss. A comparable number of mesh and joint concepts was also presented.

The ongoing Solar Power Satellite conceptual studies provide some insight into the magnitude of the orbital assembly and logistics problem. As part of that investigation (Ref. 5-17), tradeoffs have been performed concerning optimal assembly procedures and techniques. Additionally, a new class of space tools which will facilitate in orbit assembly will emerge. These include concepts such as better gloves, smart screwdrivers that automatically feed, drive and torque threaded fasteners, and smarter, more dexterous robots and teleoperators, perhaps containing decentralized microcomputers.

NASA Development Required

In each of the pieces of the large structures problem discussed, it is perceived that NASA and the Department of Defense have a joint interest in promoting the required technologies. The extent to which the DOD will independently develop individual technologies is unknown. In specific areas such as materials development, related aircraft and miscellaneous commercial activities will also provide some impetus.

In the area of analysis of large structures, NASA must sponsor development of improved computer programs, simplifying techniques and corroborative test methods.

For attitude and shape control of large structures, NASA must initiate the development, standardization and simplification of attitude and shape actuators.

In the area of materials research, the optimum material to survive in a long-life hi-energy radiation environment must be determined and the advantages of the various coating alternatives must be parameterized. A specific recommendation for the continued development of metal matrix composites is also included.

In regard to the future use of structural elements and joints, the development of standards indicating the items which may be used in various requirement environments is required by NASA.

Finally, scenarios for implementation of classes of large structures must be developed. These scenarios should be based on manned, remote manned and robotic assembly tradeoffs and should include procedural standards such as the construction (weaving) of a large mesh or the alignment of subsection of a large structure.

7.4.5 DUAL POLARIZED POLYCHROMATIC PHASED ARRAYS

Technology Requirement

Several PLACE system concepts expect to utilize phased arrays for antennas. System cost, mass, and complexity are all expected to be favorable affected by having both polarizations and a range of frequencies available in the same antenna. The requirement then is for a microwave aperture that would operate over a 4:1 frequency range (L-band to S-band) with both vertical and horizontal polarizations. This antenna may operate with constant beamwidth thereby reducing the area of coverage with higher frequency.

Technology Forecast

The two highest potential implementation approaches, as shown in Figure 7-7 are the slotted waveguide approach and the printed element stripline approach (Ref. 7-12). A 10 M long waveguide has been constructed for operation at L-band (1.4 GHz). The implementation, which is generally heavier, but with less loss than the stripline, is constructed of a carbon fiber composite. It is estimated that the weight of a dual polarization waveguide would be 1.3-1.5 times the weight of a single polarization, with the basic problem associated with providing addition ground planes.

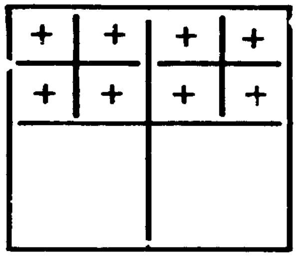
A 2-3 meter printed circuit stripline array has been constructed for operation at L-band. This approach is generally lighter but has more losses than the waveguide approach. The construction involves a multilayer sandwich-type layout with an air or foam dielectric layer. The

REQUIREMENT

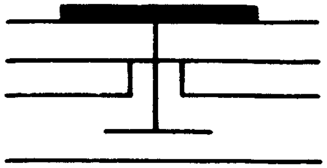
LARGE DUAL POLARIZED PHASED ARRAYS THAT OPERATE AT THREE DISTINCT FREQUENCIES IN THE 1.4–8 GHz REGION, USED IN BOTH ACTIVE AND PASSIVE MODE

CURRENT CAPABILITIES

SLOTTED WAVEGUIDE APPROACH
- 10M LONG (L-BAND)
- HEAVIER – LESS LOSS
- CARBON FIBER COMPOSITE
- FED BY TRAVELING WAVE



STRIPLINE – PRINTED ELEMENTS APPROACH
- 2–3M LONG (L-BAND)
- LIGHTER – MORE LOSS
- MULTILAYER SANDWICH CONFIGURATION
  - DIELECTRIC LAYER – RADIATING ELEMENTS PRINTED
  - CORPORATE NETWORK EXCITES ELEMENTS



NASA DEVELOPMENT REQUIRED

MAIN PROBLEM IS CONFIGURATION/MANUFACTURING

REPRESENTATIVE SHUTTLE EXPERIMENT – 2 POLARIZATIONS – 3 FREQUENCIES – 3 X 3 METER ARRAY

EXTERNAL TECHNOLOGY DRIVERS

DoD INTERESTED IN BOTH THE MULTIFREQUENCY PROBLEM AND THE MANUFACTURING PROBLEM

Figure 7-7. Dual Polarized Polychromatic Phased Arrays radiation elements are printed on the top surface and connected to ground by a coaxial cable.

NASA Development Required

The main problem associated with these large dual polarized polychromatic phased arrays is in the configuration and manufacturing. What is called for, is a series of clever production techniques that would allow for inexpensive mass production of the required radiating elements.

A representative Shuttle experiment which could test alternative implementations and manufacturing procedures could involve a 3 x 3 meter array with 2 polarizations and 3 frequencies.

NASA can expect to receive external assistance from the Department of Defense, which is interested in multifrequency arrays and in the associated manufacturing problem.

7.4.6 RADIATION RESISTANCE

Technology Requirement

A number of PLACE systems will be subjected to ionizing radiation levels high enough to damage spacecraft elements. Several systems are in geosynchronous orbits, where solar and galactic radiation is significant. One system, Earthwatch, is in an orbit (6-10,000 km altitude, at 55 degrees inclination) where Van Allen radiation is of major concern. For the geosynchronous, an increase of radiation tolerance above todays levels is mission enhancing, for Earthwatch it can be considered as mission enabling.

Preliminary estimates of ionizing radiation for the Earthwatch system is that the dose will be about 5×10^5 rad (Si) or more per year. A mission life of ten years at these rates will be required to enable deployment of the system. Components known to be susceptible to debilitating damage as these doses include CMOS, solar cells, and power semiconductors. These elements, and any others that are similarly vulnerable, must be made hard enough - either intrinsically or via shielding - to survive the postulated radiation dose.

Technology Forecast

A comparative view of the susceptibility of various semiconductors to radiation by D. Myers of Fairchild (Ref. 7-45) is presented in Table 7-8. Each area was individually examined for susceptibility to radiation at geosynchronous (neutrons) and Earthwatch (protons) orbit.

Table 7-8. Semiconductor Susceptibility to Radiation

	Radiation environment / Semiconductor technology	Discrete bipolar transistors and J-FETs	Silicon controlled rectifiers	TTL	Low-power Schottky TTL	Analog integrated circuits	C-MOS	n MOS	Light-emitting diodes	Isoplanar II ECL
	Neutrons (n/cm^2)	10^{10} – 10^{12}	10^{10} – 10^{12}	10^{13}	10^{14}	10^{13}	10^{15}	10^{15}	10^{13}	$>10^{15}$
Ionizing radiation	Total dose (rads (Si))	$>10^4$	10^4	10^6	10^6	5×10^4 – 10^5	10^3 – 10^4	10^3	$>10^5$	10^7
	Transient dose rate (rads (Si)/s) (upset or saturation)	-	10^3	10^7	5×10^7	10^6	10^7	10^5	--	$>10^8$
	Transient dose rate (rads (Si)/s) (survival)	10^{10}	10^{10}	$>10^{10}$	$>10^{10}$	$>10^{10}$	10^9	10^{10}	$>10^{10}$	10^{11}
	Dormant total dose (zero bias)	$\sim 10^4$	10^4	10^6	10^6	10^5	10^6	10^4	$>10^5$	$>10^7$

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Extensive use will be made of large-scale integrated (LSI) circuits using MOS technology in spacecraft memories and microprocessors. Current total dose susceptibility after screening is approximately 10^5 rads (Si), with

10^6 now available on a custom basis from several vendors. Current development is driving towards a 10^6 figure, with difficulties being encountered in establishment of a production line. It appears that this goal will be met in the 1985 time frame. Whether the industry will achieve the goal of 10^7 rads by 1995 is questionable.

LSI circuits will also use integrated injection logic (I^2L) in this time frame in microprocessors. The current level of susceptibility is 10^6 rads after screening. In this case the problem is mainly at intermediate altitudes, since the I^2L circuitry can handle the neutron radiation.

In the area of low power Schottky (TTL) devices, levels of 5 x 10^5 are available today with projections indicating susceptibility through 10^6 in 1985 and 10^7 in 1995.

Linear circuits, including components such as operational amplifiers and A/D converters, will be a problem area. In the Voyager program, a resistance to a level of 10^6 rads was not achieved and the program ended up shielding 10^5 level components. Continued development is required in this area.

It is estimated that the effects of radiation over ten years will cut silicon solar cell capabilities by 50% at Earthwatch altitudes, by 25% at 1000 mile altitudes and by 5-10% below 500 miles. The use of gallium arsenide cells will not provide a large improvement in this area. Continued development will result in an increased resistance by a factor of 2-5 in the 1995 time frame.

A related problem is the occurrence of spacecraft charging at geosynchronous altitudes. The dynamic solar environment creates regions of high concentrations of electrons which may damage items such as thermal blankets, solar cell covers, glass covers, etc. New materials must be developed to limit conductivity and prevent electron build-up. The Air Force is currently investigating this phenomenon with their Space Charging at High Altitudes (SCATHA) program.

NASA Development Required

Considerable effort is currently being expanded by DOD on the dose rate problem (high radiation concentrations over short periods of time) with less effort on the total dose problem. Support for a continuing program for long term survivability of components and subsystems is required by NASA.

7.4.7 POINTING OF OPTICS

Technology Requirement

Pointing of Geosynchronous Earth Observation System (GEOS) is accomplished through a scanning pattern (see Figure 7-8) in which the whole vehicle attitude slowly sweeps the "pushbroom detector" back and forth, until the desired field-of-view frame is covered. This method of pointing, coupled with the high resolution requirement of 3 meter IFOV from geosynchronous orbit in the system places a stringent system requirement on the knowledge of pointing. In addition, the structural deflections due to vehicle rotation and the vibrational environment must be controlled to prevent pointing errors.

Specifically, the requirement is for 0.008 arc-seconds accuracy of knowledge of pointing, which corresponds to 1/2 pixel from geosynchronous orbit. Pointing accuracies must be maintained during continuous attitude sweeps with angular rates up to 0.5 arc-seconds per second. Knowledge of local vertical must be known precisely, i.e., within 1.5 meter. Vibration stability of the focal plane and optics structure must be in the milli-arc second range.

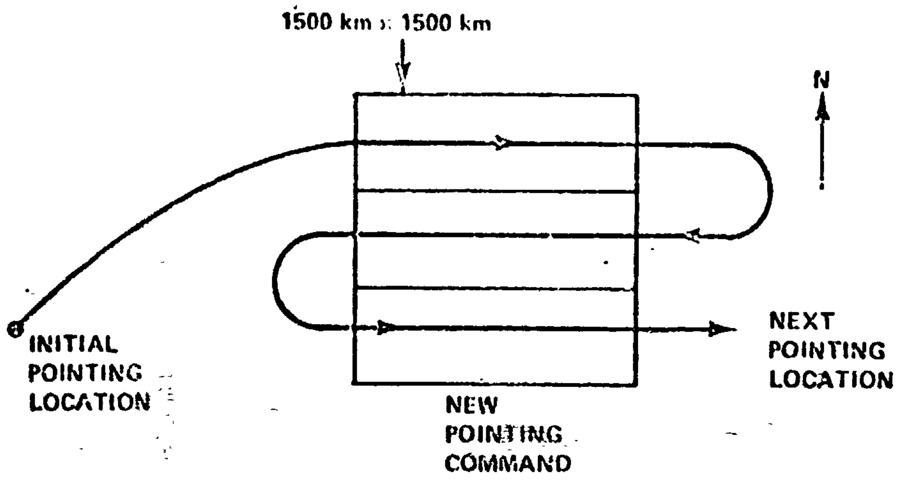

Figure 7-8. GEOS Scanning Pattern

State-of-the-Art Overview

Current capabilities are characterized by the Charged Coupled Device (CCD) Array or a stellar attitude sensor, and the Fiber Optics Rotation Sensor (FORS) as an gyro attitude rate sensor device. The capability of the CCD array is approximately one arc second.

Table 7-9 (Ref. 7-14) shows the performance characteristics of the FORS as compared with two other advanced rotation rate sensors, the Ring Laser Gyroscope (RLG) and the Dry Gyro Inertial Reference Unit (DRIRU).

The requirement of milli arc second stability is expected to be satisfied by 1995. With a structural resonance frequency of at least ten hertz, disturbances f as large as 10^{-4} ft. -lb. will still satisfy this requirement. Start up and turn around angular accelerations can be shaped through optimal filtering to avoid exciting particular structural modes. Low noise bearings or even magnetic bearings will provide adequate reaction wheel control.

Table 7-9. Rotation Sensors - Comparison of Performance and Characteristics

PARAMETER	FORS	RLG[1]	DRIRU[2]
LEAST DETECTABLE ANGLE	6×10^{-4} $\widehat{\text{sec}}$	1.57 $\widehat{\text{sec}}$	5×10^{-2} $\widehat{\text{sec}}$
DRIFT RATE	0	~ 1°/hr	0.5°/hr
DERIVED POSITION ERROR	$0.01\ ^{\circ}/h^{1/2}$	$0.007\ ^{\circ}/hr + .005\ ^{\circ}/hr^{1/2}$	0.02 °/hr
WARMUP TIME	<1 second	30 min.	4 hr.
VOLUME, 3-AXIS REDUNDANT	$300\ in^3/5000\ cm^3$	$350\ in.^3/6000\ cm^3$	$990\ in^3/16,000\ cm^3$
MASS, 3-AXIS REDUNDANT	12#, 5.4 kg	39#, 18 kg	25#/11.4 kg
POWER, 3-AXIS REDUNDANT	12 watts	18 watts	22-1/2 watts
LIFETIME	POTENTIALLY UNLIMITED	2 yr	2 yr
EXPECTED PRODUCTION COST	$150K	$200K	$300K

1. HONEYWELL RING LASER GYRO GG1300
2. NASA STD DRY GYRO INERTIAL REFERENCE UNIT.

Required NASA Developments

The "gap" in capabilities in 1995 suggests additional effort in the area of high precision attitude update systems. The more promising areas are CCD and CID arrays. Improved gyros will be required, however the trends show the likelihood that the rotation sensor capability will be met by 1995.

Technology Forecast

Figure 7-9 represents our estimate of the technology trend (Ref. 7-19), as characterized by systems from 1968 to 1995. The projection is an exponential extrapolation of current and near-term capabilities, and makes the assumption that all other error sources can be made near zero compared to the sensor errors at the time of attitude update. It can be seen that the projected capability is one order of magnitude below that required for the 1995 era.

The requirement for 1.5 meter knowledge of local vertical is projected to be met by 1995, based on advanced GPS system developments.

7.4.8 EPHEMERIS DETERMINATION

Technology Requirement

Earth resources systems of the future will have greater und resolution than today's sytems and hence will have more stringent requirements for position determination. The Landsat D system is expected to know position from predicted ephemeris to an RMS accuracy of 34 meters in track, 19 meters cross track and 16 meters radial.

The global positioning system which will be operational in 1985 will provide accuracies within 5M horizontal and 7M vertical 50% of the time and 8M horizontal and 10M vertical 90% of the time.

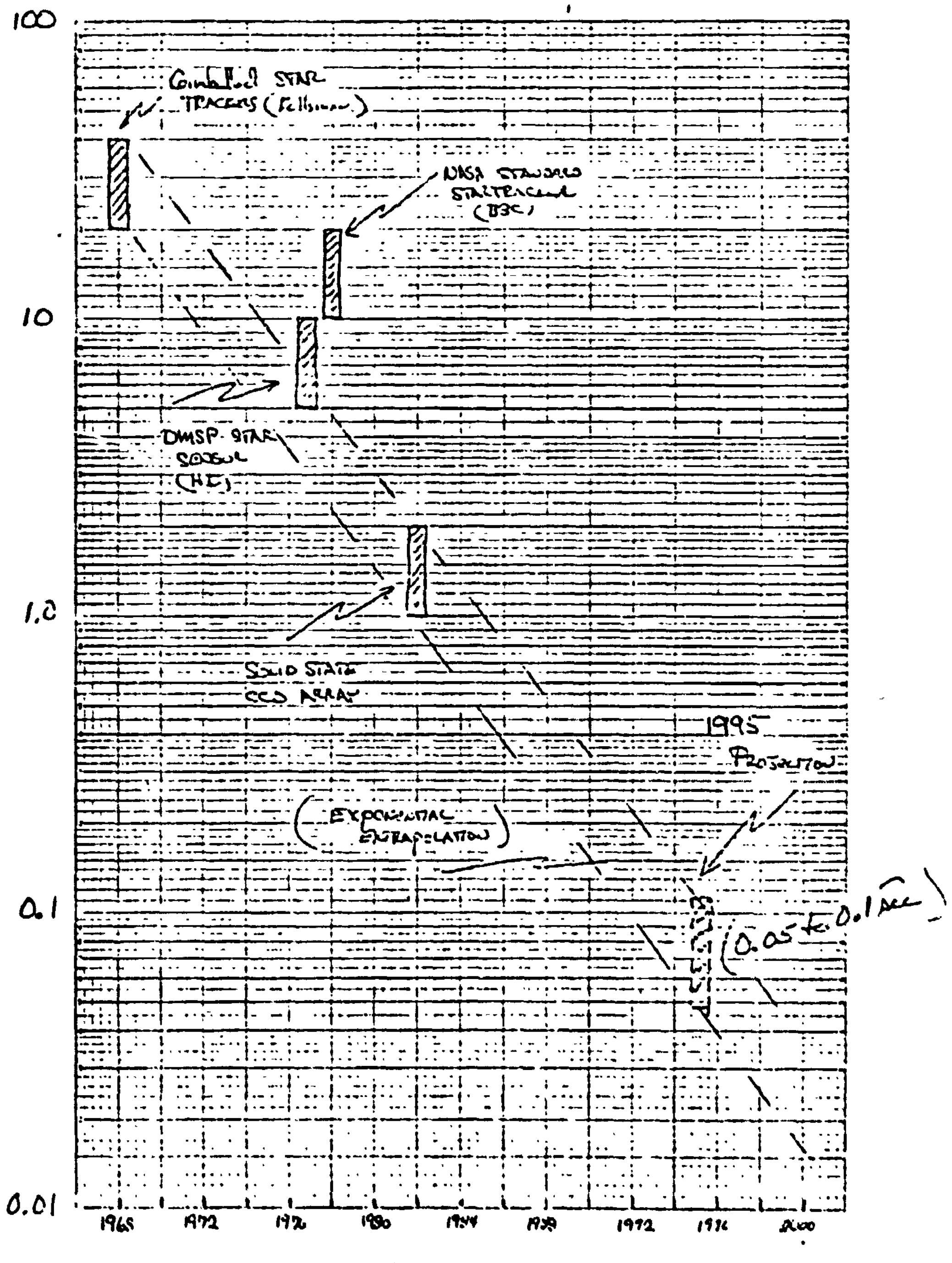

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Figure 7-9. Stellar Attitude References

As several of the PLACE future system concepts will have an instantaneous field of view of 3 meters, and since spacecraft position error is only one of several sources of image error, knowledge of spacecraft position to within 1-2 meters would be necessary to eliminate the need for geometric correction or the use of ground control points. A future system could, of course, use ground processing to relax this requirement, however, this would create some restrictions on the direct readout availability of the data to users.

Technology Projection

In the 1995 time frame, the global positioning system will provide the required measurements to low earth orbit data while geosynchronous satellites will utilize either radio triangulation or laser tracking to provide the required accuracy. The projection of satellite ephemeris error vs. time in Figure 7-10 (Ref. 7-15) indicates an expected error level 1.9 meters in track and 1.5 meters in the cross track and radial direction. In addition, as indicated by NASA's Outlook for Space (Ref. 7-11) the orbit determination will be deterministic in nature, using repeated multi-station measurements to uniquely determine the satellite position.

In an experiment performed by Dr. Roy Anderson of GE's Corporate Research and Development Center, the accuracy of an L-band trilateration method using the ATS-5 spacecraft was investigated (Ref. 7-16). The use of stations at Buenos Aires, Honolulu, and Schenectady, N.Y., indicated a capability for ±20 meter earth center distance accuracy and ±40 meter line-of-position error. The single measurement precision was about 10 meters.

NASA Development Required

Development required in two areas by NASA has been identified: (1) refinement of the Global Positioning System's equipment and techniques

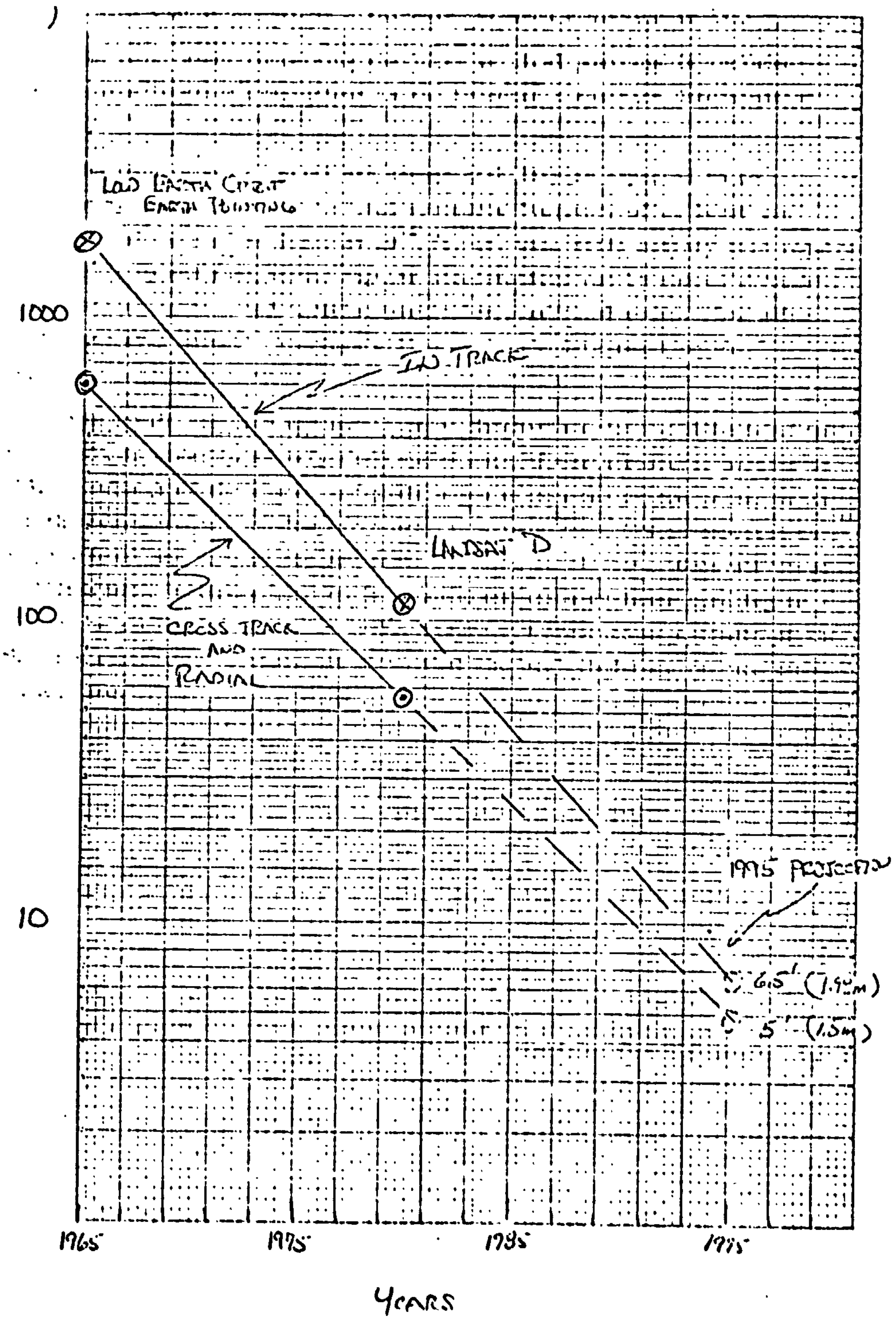

Figure 7-10. Satellite Ephemeris

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to allow for greater accuracy and (2) continued development of knowledge of ionospheric propogation factors to reduce the radio triangulation error.

7.4.9 LOW-NOISE MICROWAVE RECEIVERS

Technology Requirement

The Ellipsometer and Parasol exemplify active and passive microwave systems which demand high detector/receiver sensitivity. At the frequency range of 1.6 to 10 GHz where the instruments of these systems operate, thermal noise is the largest signal-to-noise ratio degrading factor. The requirement is for a noise temperature less than 20°K.

State-of-the-Art Overview

Six candidate amplifier types for achieving noise temperature of less than 20°K in the frequency range of 1.6 GHz to 10 GHz are:

1. FET Amplifiers
2. Tunnel diode amplifiers
3. Uncooled parametric amplifiers
4. Cooled parametric amplifiers
5. Masers
6. Super conductor - semiconductor Schottky barrier diode mixers.

Of these, the tunnel diode amplifiers offer the least prospect for improvement in noise figure. It is because the primary noise mechanisms in a tunnel diode is the shot noise resulting from the d.c. current flow through the degenerate p - n junction. The noise reduction by cooling, therefore, is not possible. Further, the shot noise is determined by the shot noise constant, a material parameter and no geometry or other technology related advances can significantly reduce the noise temperature.

The superconductor - semiconductor Schottky barrier diode mixers using lead Schottky on p - GaAs have demonstrated mixer noise temperature close to the bath temperatures (20^oK). However, realization of the low bath temperatures in satellite atmosphere with its weight and volume constraint is impossible within the time frame of this century and for a cost of less than $100M. (It may contribute about 2000 lbs. to the satellite weight). Other approaches offer more practical alternatives. Parametric amplifiers are the best alternative (next to Masers in performance) at the present time and the technology is improving. However, the ability and reliability of these amplifiers remains an important concern.

The present technology trends indicate that the advanced field effect transistors (FET) offer the best future promise for the required performance. Figure 7-11 shows the performance of state-of-the-art GaAs FET using the 0.5 μm long gate. The technology of these devices which started at about 2 μm long gates has reached a status of 0.5 μm today and is still progressing towards smaller gate lengths.

The drivers for the extremely small gate technology are not only the low noise figure requirements but also the high frequency potential of these very flexible, widely applicable devices. These requirements have already set the trends in the thinking in both industry and the government. Several of the specific technology required for lower noise figures have been defined.

Unlike the bipolar transistors and other devices, the noise in GaAs FETs is not completely dominated by the shot noise. This, then, leads to the possibility of realizing lower noise figures by cooling the devices below

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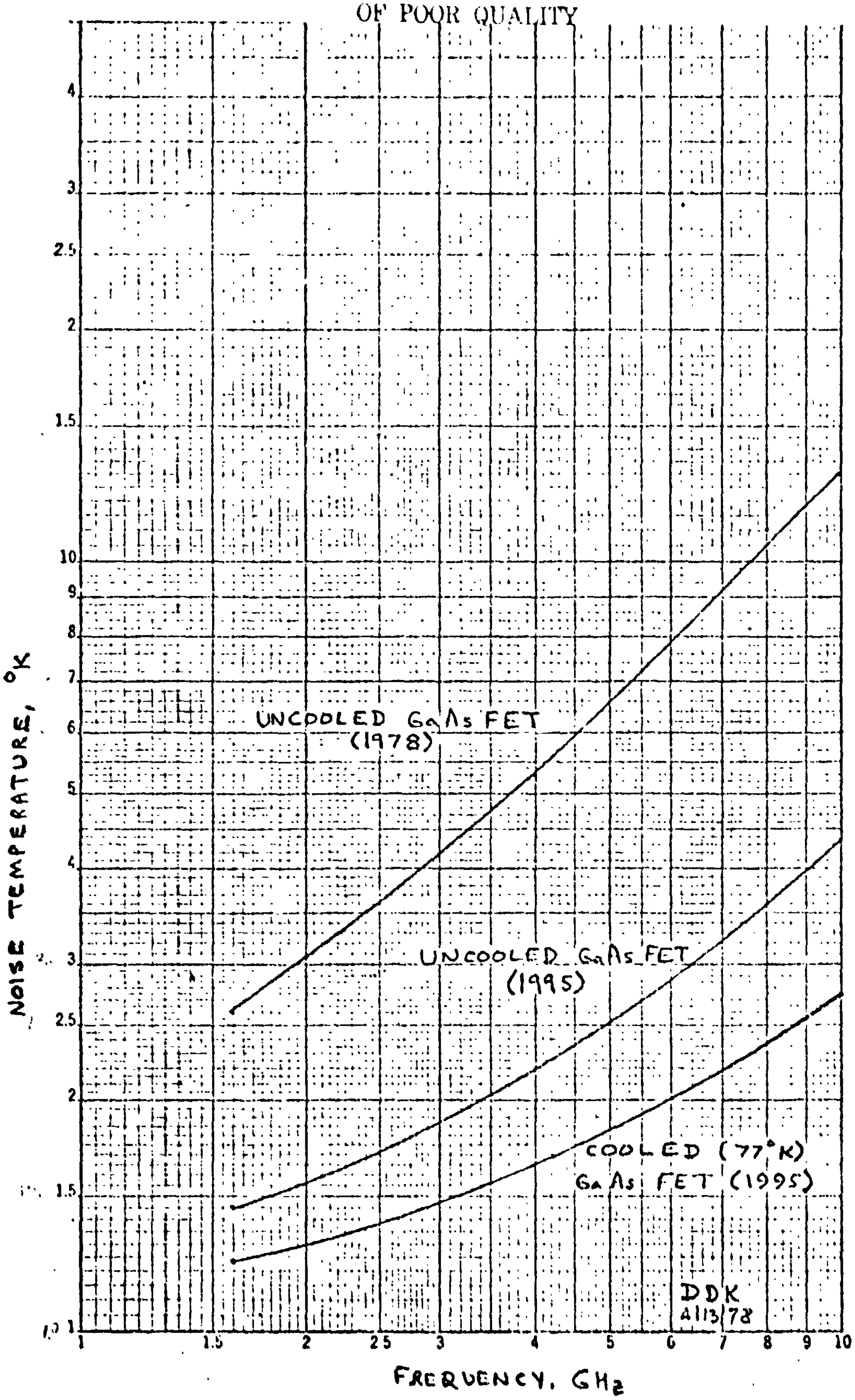


Figure 7-11. Low Noise GaAs FET Performance Trend

room temperature. Experiments demonstrating this potential have been conducted up to about 100°K by several laboratories. The results have shown a significant decrease in the device noise figure at lower temperature.

Technology Forecast

Advanced Field Effect Transistors, by 1995, are projected to have gate lengths of 0.2 micrometers or less and associated noise performance within the required 20°K region (Ref. 7-17). Figure 7-11 shows the projected 1995 performance of GaAs FETs both for uncooled and cooled detectors. The uncooled mode is more desirable from the points of view of cost and operational simplicity, however, the noise level exceeds the 20°K at frequencies of 3.5 GHz and is 115% higher than the required 20°K at 10 GHz. On the other hand, the projection for cooled (77°K) GaAs FETs indicates that temperatures below 20°K will be attainable at frequencies below 6 GHz, and the noise temperature at 10 GHz is only 27°K. This suggests that the systems may use passive cooling in a portion of the frequency spectrum (e.g. 1.0 to 3.5 GHz), and active cooling at higher frequencies, where the cooling temperature will be nominally 77°K except at frequencies around 6 GHz where lower temperatures will be required.

Required NASA Developments

The following technology areas are recommended for emphasis:

(a) Adaptation of passive cooling techniques to GaAs FETs applications.

(b) Investigation of alternative materials to GaAs, for advanced performance FETs.

(c) Amplifiers operating at lower frequencies, using short-gate devices.

(d) Device modeling and reliability/assessment predictions.

7.4.10 LARGE OPTICS

Technology Requirement

Telescopes for earth resources monitoring from geosynchronous orbit will require large aperture reflective elements. For instance, the primary mirror for the GEOS system (See Section 6.1.3) will require an aperture of 8 meters in order to satisfy the 3 meter ground resolution requirement for applications such as detailed disaster damage assessment. This technology requirement deals with the ability to manufacture, assemble, and control the contour of the large mirrors.

a. Optics must be segmented, mainly because the 8 meter diameter exceeds the 4.58M diameter capacity of the Shuttle Orbiter cargo bay.

b. Manufacture of the optical mirror requires precise contour over a large area. Typically, the surface figure will be accurate to at least 1/10 wavelength (600 Å), with the waviness of the surface controlled to 1/6 wavelength (1000 Å), per inch.

c. The mirror segments must be able to be assembled in orbit. Relative positioning between segments can be held within an even multiple of wavelengths, but the phase relationship must be maintained within 1/10 wavelength.

d. The contour of each segment must be controlled to compensate for inertial, thermal and launch-induced errors. A number of precision actuators, possibly ten per mirror segment, will be individually controlled through optical feedback servo loops.

An illustration of this concept of segmented optics is presented in Figure 7-12.

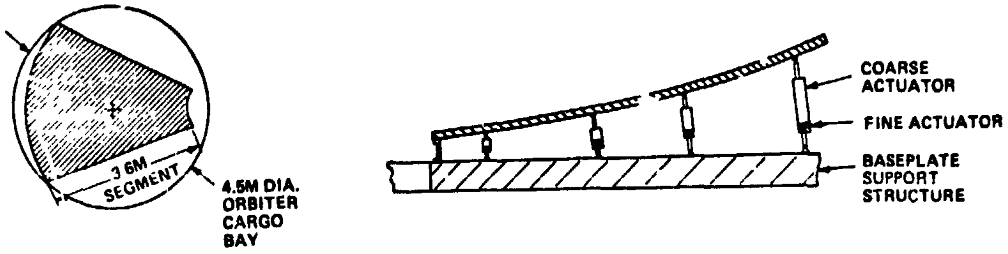


Figure 7-12. Large Optics

Desirable features for the large optics are light weight (e.g. 200 Kg for an 8 meter diameter primary mirror), and the ability to assemble the primary mirror in low earth orbit, prior to placement in geosynchronous orbit. The latter would greatly facilitate man's involvement in the construction process.

State-of-the-Art Assessment

Current state-of-the-art in optics size is approximately one meter diameter diffraction limited performance. Current activity in adaptive segmented optics include:

a) Wave-front, or figure sensing, which is part of the figure control systems' closed loop.

b) Software approach for closed loop control system

c) Countermeasures against optically disturbing vibrations (jitter) and particulate deposition on the mirror surfaces.

Technology Projection

The technology basis for 8 meter aperture, diffraction-limited, segmented, adaptive optics is projected to be met by 1995. However, the testing of a model in space by NASA, including man-attended assembly and calibration is not foreseen in the Pre-1995 era.

State-of-the-Art Overview

Several major optical companies are involved in the development of adaptive techniques requiring modification of the primary mirror contour to compensate for mirror structural deformation and atmospheric effects. The concepts summarized below are representative of the effort that is being entered in the laboratory and through computer simulation, in order to accomplish the stated objective.

Coherent Adaptive Optics

A coherent light technique determines the atmospherically induced phase distortions by means of laser scatterometry and establishes an optical phase shift on the transmitted (illuminating) beam wavefront (Ref. 7-18). The net result is a diffraction limited (undistorted) wavefront which compensates for the atmospheric effects. The optical phase shifter consists of a mirror (independent of the primary optical elements) upon which an array of actuating pistons or piezoelectric devices are acting segmentally to effect the necessary deformation.

Atmospheric Compensation with Shearing Interferometry Phase Sensing Techniques

An image is formed of the entrance pupil on a phase correction array of individually adjustable piezoelectric phase actuators. A reference light beam is sent to a lateral shearing interferometer. Through this technique, all aberrations are greatly reduced in the light reaching the image plane.

Electrostatic Correction Technique

Electrostatic forces may be used in place of hydraulic or piezoelectric actuators for the corrector mirror. A suitable wavefront distortion sensor, such as the Hartman sensor is used to signal the actuation of an array of electrodes on the corrector mirror consisting of a metallic membrane a few microns thick.

Required NASA Developments

1. Development of a lightweight telescope system that minimizes the STS resources necessary to place it in geosynchronous orbit.

2. Coordination of advanced optics requirements with DOD for orbital demonstration test.

3. Development of large optics assembly techniques, using computerized ad neutral-buoyancy simulation.

7.4.11 ADAPTIVE OPTICS

Technology Requirement

Two of the future earth resources systems being examined show a need for adaptive optics, the GEOS and Texturometer system concepts. The purpose of the adaptive optics mechanism would be

(1) to compensate for slowly varying perturbations of the mirror figure, and

(2) to compensate for the rapidly varying effects of atmospheric turbulence.

The mechanism requires an actuation device with a time response sufficiently fast to prevent lag between the localized atmospheric change and the co[illegible] mirror form. In order to complete the servo loop, a highly accurate wavefront (contour) sensor is required. Examples of candidate sensors are Hartman sensors and Strehl ratio maximization sensors.

Assuming a two-phase actuation system, the coarse actuator range is 50 to 20,000 micro-meters, whereas the fine actuator must be capable of 0.1 to 100 micro-meters. The wavefront sensor must be accurate within 0.05 to 0.1 wavelength (e.g. ±300 Å to 600 Å, for a visible source of 0.6 micron wavelength).

Technology Forecast

Based on the progress achieved to date in the laboratory, the technology for adaptive optics as described in the technology requirements section will be available before 1995.

Required NASA Development

Initiate design of an adaptive optics system suitable for large segmented optics, and test the system in a Shuttle flight.

7.4.12 IONOSPHERE MODELING

Technology Requirement

The ionosphere is that part of the upper atmosphere which is sufficiently ionized by solar ultraviolet radiation so that the concentration of free electrons affects the propagation of radio waves. The PLACE study has identified two system concepts that can potentially be severely affected by the ionosphere. The Ferris Wheel Radar is a real aperture radar which operates at low frequency (30-300 MHz) to map subsurface boundary layers. The radar ellipsometer is a bistatic radar which measures the polarization of the reflected wave. The first system is affected by ionospheric absorption while the second is affected by the Faraday rotation effects of the ionosphere.

The atmosphere introduces little attenuation to radio waves above 50 GHz (Ref. 7-19-23). The ionosphere affects transmission severely below 10 MHz. At frequencies above 100 MHz the ionosphere has some effect on the speed of propagation and the polarization of radio waves. These effects decrease continually as the frequency increases. A major difficulty in the interpretation of Faraday rotation measurements at a single frequency is that the absolute number of rotations during a single or double passage thru the ionosphere cannot usually be determined (due to 2π ambiguity) and observations can only be made of variations in rotation over the passage of the satellite. Given an average ionosphere, the polarization vector may rotate 6.6 radians through one passage of the ionosphere at 100 MHz many tens of times at 40 MHz. The observed number of rotations is ambiguous by an additive constant $2n\pi$. The use of closely spaced frequencies on a single satellite eliminates this ambiguity. Regular latitude and local time gradients and large scale irregular gradients in electron density make significant contributions to the rotation rate at any instant.

An accurate daily forecast of the geographic and temporal variations in the ionosphere is required, the latter including regular diurnal, seasonal and sunspot cycle components and irregular day-to-day components associated mainly with variations in solar activity and atmospheric motion. For example, a direct correlation between sunspot activity and the F layer critical frequency has been observed.

Some key disturbances or periods of turbulence which occur in the ionosphere but which are not currently well understood include:

Sporadic E	Irregular and rapidly varying increases in the electron density of the E-layer
Spread F	Rapid changes of electron density which are fairly localized within the F_1 - layer
S.I.D.'s	Sudden Ionospheric Disturbances which occur shortly after a solar flare which increases attenuation for periods up to an hour
PCA's	One type of ionospheric storm called a polar cap absorption. It is a major, long-term period of turbulence primarily occuring within the D-layer and lasting for several days.

Technology Forecast

It would now appear to be unlikely that forecasts of the state and structure of the ionosphere in sufficient detail to allow a prior correction of spaceborne microwave measurements of the earth at frequencies between 30 and 300 MHz would be achievable in the foreseeable future. It is more likely that appropriate instrumentation will have to be carried along in parallel with such proposed space sensors so that simultaneous observations can be made of the ionosphere, to support the interpretation of the observed data.

Forecasting the gross features of the ionosphere in support of radio communications interests is routinely done today. According to John Lloyd (Ref. 7-24) of the Institute for Telecommunication Services in Boulder, Colorado, they do predict the electron density profiles in the atmosphere, as well as the total electron content, and the effective bending of radio waves as a function of frequency. The objective of these forecasts is to provide radio communicators with guidance as to optimum frequency. There are times when it is not possible to "see" through the ionosphere at frequencies of 30 to 50 MHz. Using a data base derived from ground-based measurements of critical frequency, they are able to discern the "sporadic E", the D, E, F_1 and F_2 layers, and to construct an electron density profile. In terms of gross features, or the "climatology" of the ionosphere, these forecasts are pretty good, though they are not perfect even for communications purposes. On any given day, there is a fairly large uncertainty with respect to the actual density of the F_2 layer, which is quite variable from day-to-day. If a real time measurement of the electron density of the F_2 layer could be made and combined with the gross ionospheric forecast, then a reasonable model of the overall features of the ionosphere would result. Lloyd pointed out, that they are also capable of forecasting the general occurrence of the phenomenon known as "spread F", but not the detailed ionospheric structure during such occurrences. However, it is still apparently a matter of debate as to whether or not this feature is directly relatable to "scintillation" effects that are frequently observed in signals passing through the ionosphere. It is this scintillation phenomenon that is the crux of the forecast problem of interest here.

Dr. Ben Balsley (Ref. 7-25) of the NOAA/Environmental Research Lab (ERL) in Boulder, Colorado has been concerned for several years with the study of irregularities in the ionosphere down to a scale of "meters". At frequencies in the range of 30 to 300 MHz, it would be essential to model what could be referred to as "ionospheric turbulence" in order to account for rapid variations or scintillation of signals passing through the ionosphere. These effects are particularly common over the polar and equatorial ionospheres, and are more disturbing to the interpretation of measurements made at frequencies closer to 300 MHz.

In the Equatorial E region, i.e., within 300 to 400 Km north and south of the equator (the half-power points of the phenomenon), the "Equatorial Sporadic E" or the "Equatorial Electrojet" occurs. This phenomenon causes a strong scintillation in intensity of radio waves. This effect strongly related to sunspots, is a maximum in the daytime, though it is present at night. A disturbance of the equatorial F-layer called the "Equatorial Spread F" usually has maximum effect in the period from just past sunset to midnight", and seems to occur mostly within ±20° of latitude of the equator. This phenomenon, according to Dr. Balsley, is known to cause deep scintillation of signals. As was indicated earlier, there is not a unanimity of opinion on that point.

In mid-latitudes, there is a phenomenon similar to spread-F which is known for certain to be present at night, but for which there is some uncertainty as to its daytime occurrence. Also, in mid-latitudes, there is a sporadic-E which causes a reflection and probably a diffraction of signals near 30-40 MHz. This phenomenon is known to occur in the daytime, though its occurrence after evening is uncertain.

In a review article (Ref. 7-26) on ionospheric irregularities, it was noted that the majority of mid-latitude F-region irregularities can be linked to the presence of acoustic-gravity waves. These waves show up as TID's - traveling ionospheric disturbances. The most prominant of these, the medium-scale TID's, have horizontal dimensions of 100-200 Km and move at speeds of about 100-200 m/s. It is easy to see how difficult it would be to anticipate the specific time and location where one of these would have an impact on a measurement of the earth from space.

In the auroral latitudes, there are a number of F-level and E-level irregularities. These occur primarily in the late afternoon and night and are related to the intensity of the geo-magnetic activity.

In summary, though the gross features of the ionosphere are predictable to a point, there are many highly variant irregularities of ionospheric structure that would preclude interpretable observations to be made of the earths' surface from space at frequencies between 30 and 300 MHz. In general, the scale of this ionospheric "turbulence" varies from "meters" to "10's of kilometers" and results in signal variations lasting over periods of hours to fractions of a second. If such measurements of the earth are to be made from space, it will probably be necessary to carry along an ionospheric sounding device on the measurement satellite so that the structure of the ionosphere over the area being observed, can be monitored. In this way, the validity of the measurements or an appropriate correction to them will be known. Since the terrestrial phenomena being sensed are not likely to be rapidly varying or transient, it should be possible to compile some sort of map over a period of time through integration of several sets of measurements from the same area, much as is done today in satellite mapping of sea ice or sea surface temperature. The technology for monitoring the structure of the ionosphere is available within NASA as this was done on several earlier satellites.

The use of the topside sounder on the Explorer program (as well as on other experimental spacecraft (Ref. 7-27-29) provided electron density measurements from the satellite position down through the F-2 layer. Such a system, when combined with the ground net measurements could provide the required accuracies in the 1995 time frame.

NASA Development Required

Two major areas will provide external support to this technology area. The first is the radio communications industry which uses ionospheric predictions to determine optimal frequencies of transmission. The second group is the Air Force due to their interest in communications and sensing.

The NASA development required is both in theoretical and instrument development areas. Continued research is needed in the understanding and modeling of ionospheric disturbances. Development effort is required to realize techniques (sensors, processing, etc.) for real-time calibration of the ionosphere, based on the previous work performed with the topside sounder.

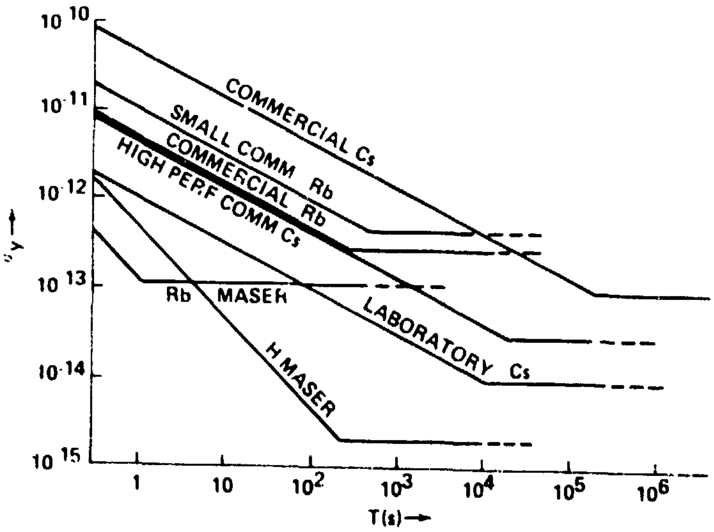
7.4.13 STABLE OSCILLATORS

Technology Requirement

Several of the PLACE system concepts have requirements for an extremely accurate oscillator/clock source. The geosynchronous SAR must "stare" at a "footprint" on the ground for 8-12 minutes in order to achieve a synthetic aperture. This may be regarded as a need to hold an accuracy of a fraction of an S-Band wavelength for 12 minutes. This translates to an oscillator with a stability of one part in 10^{13}, that can operate reliably in a space environment.

Technology Forecast

Mr. Helmut Helwig of the Time and Frequency Division of the National Bureau of Standards in Boulder, Colorado was contacted (Ref. 7-30-33). The current state-of-the-art is summarized in Figure 7-13, which shows the current frequency stabilities of oscillators vs. sampling times.



REF DR HELMUT HELWIG, N.B S.

Figure 7-13. Current Oscillator Frequency Stabilities

The highlight of the current work is a laboratory model of a hydrogen maser with an accuracy of three parts in 10^{15} over several days. The hydrogen maser is targeted for use in space by the Global Positioning System in the

1981-82 time frame. The development program, being run by the National Bureau of Standards includes the Naval Research Labs, the Smithsonian Astrophysical Observatory and a hardware competition between RCA and Hughes.

In the 1985 time frame, an order of magnitude improvement in the accuracy of crystal oscillators, hydrogen masers, cesium beam tubes and rubidium standards may be expected. In addition, four new promising devices including cesium gas cells, dual crystal oscillators, passive hydrogen masers and superconducting cavity oscillators may further improve performance. Other stability concepts which may be developed in the 1995-2000 time frame include microwave, infrared and optical beams, atom and ion storage, saturated absorption and two photon transitions.

NASA Development Required

These activities are all being carried out external to NASA and therefore the following two activities should be funded by NASA: (1) periodic studies to maintain awareness of National Bureau of Standards, the Department of Defense and the astronomy community's activities in the area of stable oscillators, and (2) periodic studies concerning the potential for improvements in the ruggedizing and packaging of new frequency standard techniques.

7.4.14 PRECISION RANGING SYSTEM

Technology Requirement

Future large space structures will require precise methods of monitoring large distances within a structure in order to maintain accurate reflector figures and vehicle shapes. By repeatedly measuring critical spacecraft distances over time, appropriate control mechanisms may be used in the correction process.

The precision ranging system required must be capable of measuring distances up to 10^4 meters with an accuracy of as much as 10^{-8} meters in a short period of time (1-10 m second). The capability of making 300 of such measurements simultaneously is also a desirable parameter. This requirement was treated separately from large structures due to the more stringent requirements of the texturometer for a ranging system.

Technology Forecast

Two 19 5 measurement concepts are presented which meet the stated technology requirements. The first concept involved the use of a heterodyne interferometer, originally suggested by Mr. Leo Davis of the Lockheed Corporation (Ref. 7-34). Using a modified Michelson interferometer technique, the phase of sequential range tones, reflected across the distance of interest, is measured. The system uses a CO_2 laser (10.3 μm) to provide the shortest wavelength, the beat frequency between this laser and another at 10.6 μm to derive two intermediate wavelengths (350 μm and 5.6 mm) and phase modulation of the laser to derive a 3 meter and a 300 meter wavelength.

A second method, conceived by Dr. Roy Anderson of GE's Corporate Research and Development Laboratory (Ref. 7-35) employs an optical alignment technique. An optical code or pattern is presented to a viewer; if the pattern is in focus and can be decoded properly, the measurement is correct, otherwise some distance error is noted. Using a feedback signal the optics are adjusted until the proper distance is measurable.

NASA Development Required

External technology drivers in this technology area include the ground based geodesy market and the large structure activity of the Department of

Defense. The NASA development required is a preliminary program to identify and develop the measurement technique that is most appropriate to the needs of NASA long-term large structures applications programs.

7.4.15 INFORMATION DISSEMINATION SYSTEMS TECHNOLOGY REQUIREMENT

In the PLACE era, rapid inexpensive means of delivering information to users will be required. The information may be in the form of an image, a thematic map, or simply statistics concerning a geographic area. This requirement includes transmission of information from the extractive processing center or global data base to a user's home, office, regional center, etc. This technology requirement also includes the display portion of the user's equipment.

Technology Projections

A number of imaginative information dissemination concepts are currently being developed which will lead the way toward accomplishment of the future requirements. These include the British Viewdata and Ceefax systems, the Qube system being tested in Colombus, Ohio, and the Japanese VISDA system.

Viewdata, which is the British Post Office Home Information Center Experiment involves the connection of a home TV set through telephone lines to a large computerized information data base which may be queried and interacted with for a fee. Originally developed for reference material, the system grew to include direct buying, voting, classified advertising, games, etc. Ceefax is a piece of the system (which may operate independently) involving minor modifications to a television set , which allow for display of textual data carried in the vertical interval of a TV signal. The system is aiming for an extensive market test in late 1978 and early 1979.

Qube, being developed by Warner Communications, is a revolutionary two-way cable television system that will allow subscribers to program and/or participate in a number of events including entertainment, education, catalog shopping, home fire and security protection, polling and others. As of 12/1/77, 13000 homes in Columbus, Ohio had subscribed to the Qube system.

Finally, the Japanese Ministry of International Trade and Industry (MITI) has begun test of a Visual Information System Development Association (VISDA) system, an interactive cable TV system that will include an optical fiber transmission system. The system, which offers services similar to the two systems described above, is undergoing a 2-year test.

In the 1985 time frame, the home data/video terminal market is expected to take off. This development, which will have had its roots in the present home-hobby computer and video game trends, will result in inexpensive home television/computer/telephone systems. The required modems, software and hardware add-ons will have been developed by industry. In addition, cable TV networks will flourish in this period, offering a wide range of interactive services.

In the 1995 time frame, cable TV will decline as dial-up video becomes available through the phone system. Digitization of the phone system is the key to this development. Pocket computers/terminals/transceivers such as Al Stringham's Visionizer (Ref. 7-46) or Peter Kurzhal's Portable User Transceiver (Ref. 7-47) will become the micro-terminals of this period.

NASA Development Required

As indicated above, a number of external technology drivers will carry the required advancement in this technology area. In the short term, it will be the video game, hobby computer and interactive cable TV market. In the long term, the consumer services/entertainment market will expand to include many other services and the home terminal concept will become more compact and more versatile.

The only resultant NASA development required will be periodic small studies to test the feasibility of new "terminal" type concepts and to test the compatibility of emerging output product format with information dissemination requirements.

7.4.16 ON-BOARD DATA STORAGE

Technology Requirement

Associated with the trend toward performance of more of the data processing on-board a sensing spacecraft is a requirement for greater storage capability. However, unlike previous requirements for storage, the primary purpose of the on-board storage will be as a working store for ancillary data, rather than just a "store and dump" mechanism. Projections indicate that bubble memories and perhaps CCD or NMOS could replace tape systems within the next ten years.

Two different PLACE future system concept, LANDSAT H and GEOSAR were examined for the on-board storage requirements that they posed. For Landsat H, the requirement was assumed to be pixel-by-pixel change detection of the high data rate sensor over an entire swath. The memory would then have to read out as fast as the sensor data rate for comparison purposes. The requirement for GEOSAR was assumed to be the need to store the entire footprint of data at 54 pulses/second for the maximum storing time of 12 minutes.

These worst case conditions resulted in an on-board storage capacity requirement of $5 \times 10^{12} - 10^{13}$ bits with a transfer rate requirement of 200 Mpbs to 1 Gbps.

Technology Projection

The transfer rate requirement of 200 mbps to 1 Gbps will be addressed first (Ref. 7-49). The need for increased commercial and military computational speed of electronic systems will cause equipment development with transfer rates in this range. The memory elements themselves won't need to inherently operate at these speeds. The speeds will be obtained by operating banks or blocks of serial memories in parallel and pingponging between two or more blocks into high speed temporary store and data multiplexing electronics. These high speed temporary storage and multiplexer electronics will have been developed to meet high speed commercial and military data handling requirements. Present day Emitter Coupled Logic, ECL, approaches these speeds and considerable development work is directed toward developing Galium Arsenide high speed logic circuitry which has an inherent speed/power advantage over the present day silicon circuits, (> 5 x faster).

Each of the leading candidate technologies, NMOS, CCD's and magnetic bubble memories are individually addressed.

NMOS - Write/read wear out mechanism, would use only in non-volatile systems.

- Relatively difficult manufacturing process to make hard to total dose radiation levels encountered in long life space missions.
- Insufficient development dollars being spent because other technologies look more promising.

CCD - Significant work on commercial devices 10^6 bits/chip projected for 1982. Very vulnerable to radiation.

MAGNETIC BUBBLES -

- Presently developing 10^6 bits/chip

C-4

- Considering the fact that bubble memories are a recent development and that between 1976 and 1978 bubble memory module capacity has increased from 10^6 to 10^8 bits, an increase of module capacity to 10^{13} bits in the 1990 to 1995 time frame is not unreasonable. The commercial market is the driving force and is very strong. TI, Rockwell, and others have strong committments to bubble memories. An additional advantage of bubble memories is their inherent total dose radiation hardness. The read/write circuits in bipolar form also offer some radiation hardness.
- Current state-of-the-art is at the 1 M bit/chip level. IBM is forecasting a potential 10^4 increase by the 1995 time frame. The forecast employed here is more conservative, that of reaching 100 M bits/chip by the 1995 time frame.

It should be noted that for solid state devices, more bits/chip are being forecast than in other projections. The primary reason is that chip sizes will be breaking their present bounds (presently around 200 x 200 mils) and approaching wafer sizes in the 90's for serial word memory chips. The reasons for this are the limited number of pins needed for this type of memory and the ability to by-pass inoperative bits and select only good bits on a chip. This will probably be accomplished in several ways such as by storing in an auxiliary memory all the bad mass memory locations and by-passing these or by discretionery masking or/and opening up tiepoints to groups of bits on a wafer. The increase in memory bits/chip has been increasing at the rate of about 10^4/year. Presently we are beyond 10^4 bits/chip in 1978. Even only allowing a 10^3 bits/chip increase/decade results in a 10^{10} chip in 1978. The use of 100 of these chips would then be required to achieve 10^{12} bits.

NASA Development Required

Assuming strong support from the military and commercial markets for computational speed of electronic systems and a strong commercial bubble market, NASA research activities for on-board storage systems could best be directed to bubble devices. The specific areas of development should be in radiation hardness evaluation and in serial read/write system and circuit designs.

7.4.17 GROUND DATA STORAGE SYSTEMS

Technology Requirement

The requirement for a large ground data storage system is based on the global data base proposed in the ground processing concept of section 6.3. The data base would be used by all PLACE system concepts as part of their ground processing activities. The size of the system is derived from the assumption of a data base which is geographically-based to a 10-meter grid of the land area of the world. It is further assumed that each grid would be described by 300 8-bit overlays, resulting in a total storage capability of approximately 3.5 x 10^{15} bits. This, then, is the requirement posed for the 1995 mass storage system.

Technology Forecast

A discussion of current capabilities would have to start with the IBM 3850 (TELOPS) magnetic tape cartridge system. The system employs an automated-access "wine rack" of 4720 magnetic tape cartridges, each capable of storing 50.4 million bytes of data for a total system storage capability of 1.9 x 10^{12} bits. A different mass storage concept of storing data as laser "etches" on an optical disk is being pursued by Phillips and Xerox.

A third possibility which has recently been pursued by the General Electric Corporate Research and Development Center involved destructive ion bombardment of a silicon diode (Ref. 7-49). The resultant ion implant "blemish" could then be precisely located and accessed. Continued research has indicated that the storage density hoped for (.1 micron) could not be achieved due to the dislocation not remaining confined to a small area and the project has been terminated.

Two systems are presented as being viable for meeting the requirement of 3.5 x 10^{15} bits by the 1995 time frame. These are developed versions of the tape cartridge system and the optical disc system mentioned above, and are based on the work of Dr. R. C. Raymond for DARPA (Ref. 7-50, 52).

The tape cartridge system is based on proposed improvements in bit density per track and in track density per tape. Projections of bit densities as high as 6-9000 bits/inch and track densities up to 1000 tracks per inch (or higher) are considered attainable in this time frame. An alternative design to the "wine-rack" concept employing a multi-layer carrousel store for a most-wanted file, besides the normal racks, tape mounters, exchangers and conveyors, has been proposed by Dr. Raymond.

The optical disk system involves a pulsed laser blasting small "pits" in the telluride surface of an optical disk. The system is precise enough to allow for storage of 3 or 4 bits over a 1 micron "pit" area, resulting in a potential storage capability of 3×10^{11} bits/disk. The resultant storage system would then have to accommodate approximately 10,000 phonograph-record-like disks. Again Dr. Raymond has proposed a multi-layer carousel and rack storage arrangement involving disc mounting units, exchangers and stackers.

NASA Development Required

There clearly will be an interest shown by DOD, the commercial library market, and possibly other government organizations in such a mass storage system. The current relationship between NASA, the Department of the Interior, the Department of Agriculture, and the State Department concerning ownership and operation of a global data base is unclear but evolving. Recommendations for NASA development are in two specific areas: (1) higher bit densities for both tape and disc products and (2) development of system concepts for mass storage systems involving tape and disc media.

7.4.18 ON-BOARD PROCESSORS

Technology Requirements

Future space systems in general show a trend toward moving more of the required data processing forward in the acquisition link towards the sensor. This tendency is based directly on the availability of increased capabilities for on-board processing. Projected technology advances such as the use of arrays of processors, the use of Josephson tunneling devices, and the development of Gallium Arsenide crystals for LSI chips, all offer tremendous opportunity for increased future system performance.

Three levels of data processing corresponding to three different levels of accomplishment of data processing and information extraction are presented. The first level of processing which corresponds to the performance of pre-processing only on-board leads to a requirement of 260 M operations/second. Carrying the processing through to the construction of thematic maps would require from 13-40 G operations/sec. An intermediate requirement of performing part of the extractive processing leads to a required capability of 1-3 G operations per second. These computations assume the data rate of the Landsat H multispectral sensor and a range of extractive processing operations, described in Section 6.1.1.

Technology Forecast

Currently the major functions of on-board processors are command and control functions with very limited data reduction processes. Typical of the data reduction complexity is the TIROS N averaging process to produce artificial lower resolution data. Today's on-board processors are generally capable of operating at up to 200,000 equivalent operations per second throughput speed.

In the 1985 time frame, it is felt that on-board processors will be capable of performing standard radiometric and geometric correction operations in real-time with operating speeds of 260 million equivalent operations per second. The processors will incorporate 20 logic (CSOS, NMOS, or GaAs) and will begin to employ heterogeneous arrays of processors (see NASA Development Required). Processing at these rates will also be used in some of the complex display processing that will be used on Shuttle.

In the 1995 time frame, it is felt that partial extractive processing will be within the scope of on-board processors, nominally operating in the 1-3 billion equivalent operations per second range. These processors will incorporate fast silicon or perhaps gallium arsenide logic operating at 200 Mbps. They will also incorporate a large increase in functional density.

<u>External Technology Drivers</u>

An extremely important external development in this technology area will be the availability of heterogeneous arrays of processors from more than one vendor in the 1980-1982 time frame (Ref. 7-36). The concept of a heterogeneous array of processors is made up of modular, cascadable processing elements which can be reconfigured electronically to form specific processing paths (pipelines). Each processing element in the matrix is specially designed to perform a certain operation. Simple elements or "operators" would perform algebraic, trigonometric or logarithmic functions while more complex operators could perform geometric correction or maximum likelihood classification. This projection is based on a perception of a "critical mass" gathering in the industry in this area. Such a development will essentially transform current computer hardware/design problems into operator/programming problems. An early example of this type of system was the GE Onboard Experiment Data Support Facility (OEDSF) Conceptual Design Study in which the concept of a macro processor was investigated (Ref. 7-37), as illustrated in Figure 7-14.

NASA Development Required

Given the availability of these heterogeneous arrays of processors, the major development item for their use will be the development of those special functions or operators needed. This falls into the gray area between hardware and software that will evolve in this time frame.

A second development area will be the addressing of problems associated with operation of these machines in a space environment such as qualification, nuclear hardness, temperature controls, packaging, etc.

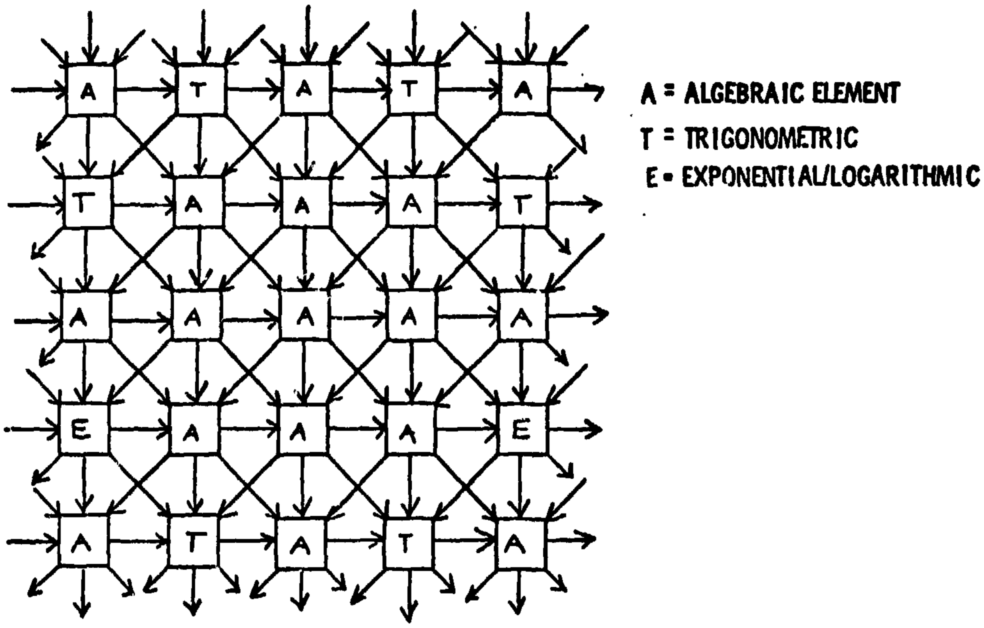


Figure 7-14. Heterogeneous Array of Processors

7.4.19 GROUND COMPUTERS

Technology Requirement

Requirements for future ground based computers are based primarily on projected preprocessing and extractive processing operations of the various future system concepts. The extractive processing seems to outweigh the preprocessing computation requirements. It may be argued that as we learn more about how to perform the extractive processing, we will also learn shortcuts in implementation. However, the following projections are based on current 'guesstimates' for processing requirements (see Section 6.3). The major requirement in extractive processing of classification and verification results in a processing requirement of 13-40 G operations/second for the operational performance of each of several earth resources mission objectives. In some cases, this requirement must be maintained for 24 hours a day, 7 days a week. Obviously, such a requirement calls for parallel processing on a major scale.

Technology Forecast

The forecast for ground computer technology closely parallels the developments for on board processors discussed in Section 7.4.18. Current general purpose machines are capable of operating at a rate of 200 million equivalent operations per second, primarily using 2 M bit logic and considerable parallelism.

Special purpose hardware is achieving much higher operating speeds at the present. Hardware which supports GE's computer generated imagery equipment currently operates at 15 billion equivalent operations per second.

In the 1985 time frame, use of 20 M bit logic will allow for operating speeds of up to 2.0 billion equivalent operations per second. This period will also mark the early use of arrays of processors for general purpose computing.

In the 1995 time frame, ground computers will achieve the desired goal of 40 billion equivalent operations per second. A continuum of flexibility will exist in computer architecture ranging from single function, very fast computers to completely general slower computers. Located in the center of this continuum will be the emerging class of heterogeneous arrays of processors containing some general purpose functions along with hardware and software operators. These capabilities will exist with or without the development of Josephson junctions.

External Technology Drivers

As in the case of on-board processors, the emergence in the 1980-1982 time frame of heterogeneous arrays of processors on the commercial market will support the achievement of the stated technology goals. It should be pointed out, however, that there will always be a general purpose market and that the development of special purpose hardware and software operators will only be a portion of the industry's goals.

NASA Development Required

Actual development of a number of these special purpose operators for (1) special control functions and (2) for extractive processing will have to be primarily supported by NASA.

7.4.20 DATA BASE MANAGEMENT SYSTEMS

Technology Requirement

In order to optimally utilize the data anticipated from the PLACE system concepts, an efficient geo-referenced land information data base management system (DBMS) must be conceived. If the entire land surface area of the planet were to be divided into 10 m grid cells with 300 overlays (8 bits/overlay) per cell; the storage requirement is approximately 3,565 Tera bits (3.5×10^{15}).

This poses enormous problems in the storage, retrieval and updating of the data base. Presently, mass storage is on magnetic tape. RCA has demonstrated a high density multi-track recorder with a capability of 240 Mbps. At this rate it would take 172 days to read the entire data base. Timeliness is of the utmost importance.

One can take several approaches in improving the response time:

1) Physically increase the speed at which data characters are transferred between primary and secondary memory. Hardware advances make this feasible.

2) Logically increase the information content of each data character transferred to main memory. (Data item encoding and data stream compression).

3) Selectively transfer only those data records which are actually required by an application. The development and refinement of record accessing techniques, such as multi-list and index sequential, have afforded a significant reduction in run time for applications requiring the retrieval of small subsets of records from large data bases.

4) Selectively transfer only those data items within a record which are actually required by an application.

5) The implementation of database computers. By relegating DBMS functions to specialized hardware, the response time can be improved.

One must have near real time accessing of the database (storage, retrieval, updating) within an hour as opposed to days. Timeliness is to be achieved through faster storage devices, sophisticated software or hardware advancements. Included in this requirement is a filing and indexing ability to handle unplanned uses of the data. For example, a federal agency might want to compare all U.S. roofs with an afternoon temperature over 50°C (solar heaters) for this year and last. Another point to keep in mind is an index of the type of information extracted; once the information has been derived, there is no need to do it again. The database should support several models - hierarchical, network and relational and may be required to interchange structures as needed.

Technology Forecast

The forecast of what will be available in the area of data base management systems in the 1995 time frame will be divided into seven topics (Ref. 7-36):

(1) Hardware - mass data storage systems
(2) Digitizing Techniques - construction of the data base
(3) Data Base Organization/Hardware Allocation - what should be stored in fast access memory
(4) Data Base Organization/Data Representation - Hierarchical vs. Relational vs. Networks.
(5) Access Control/Integrity of Data Base - User Synchronization
(6) Response Time - an inverse function of overhead.
(7) Networks - Decentralized data bases.

Hardware

As discussed in Section 7.4.17, the hardware that will be in use for large data base systems will be either tape forms or optical discs. The data base machine concept, which has been pursued for several years, will not gain wide acceptance. Although many universities and research centers have built or are building models, the concept breaks down when access control and update of the data base are considered. Data base management technology will probably remain serial in nature, with increases in execution speed and storage capacity as functions of the respective hardware.

Digitizing Techniques

In considering a geo-reference data base and DBMS, the original building and continual update of the data base must be considered, a la "how do we get the data into digital format" question.

- Raster data is normally already in digital format, or analog which can be digitized easily.
    - Landsat
    - Aircraft
- Consider the other data sources:
    - Photography
    - Topography
    - Geology
    - Land use and zoning
    - Housing
    - Property boundaries
    - Census and political boundaries
    - Air quality
    -
    -
    -

The generation of the data base from these data (which are not normally in digital format) must be planned. Automatic digitizing of map data may be possible -- semi-automatic (manual trace) are in experimental operation today. This applies to all <u>linear</u> and <u>polygon</u> data. Some <u>point</u> data is becoming available in digital format (cf. Census Bureau DIME maps).

A prediction is that a good deal of the data required in the 3 x 10^{15} bit data base capacity estimate will not be available from all the world by 1995, and even if it were, it will not have been digitized (that is, the technology will not have provided a way to digitize it all). The Defense Mapping Agency and the Air Force are working on semi-automatic and automatic digitizing techniques.

One of the original ground rules of the PLACE Study was that data required from external systems would be assumed to be available. This does not, however, make the problem go away.

DB Organization/Hardware Allocation

The executable code and data structures supporting access are typically kept in fast memory if fast time-response to a transaction is required, e.g., a typical sub-schema for PDP/11 size data base application would fit in the fast bipolar memory of an 11/55.

The Data itself will be kept on bulk random access storage such as disc or tape. Current applications of High Density Digital Tape (HDDT) have come up with devices which allow blocking and identification of data upon writing. This effectively makes the HDDT's record oriented like conventional magnetic tapes, and supports direct data access (+ tape spin time latency). The challenge here is a combination of the hardware problems discussed above, and the representation problems discussed below.

DB Organization/Data Representation

Organizations other than hierarchical have been the object of much study lately. Relational data base management system representations seem to hold some real promise for linear and polygon representations.

Network representations have the same features as relational, but are more suited to a read only environment. Hierarchical representations appear to be still the best for point specific data and attribute data. Several universities are working on, or have, operational systems which are entirely relational. A hybrid of hierarchical and relational would probably best serve the geo-reference need.

Access Control/Integrity of the Data Base

For a read only data base, this is generally not a problem if update is off-line.

When update of the data base is considered (on-line), users must be controlled (synchronized) through the read/modify/write sequence. Most formal DBMS packages provide this feature today.

With synchronization, "deadlocks" can occur and must be detected and arbitrated. This is also done in most DBMS today. However, with much larger DBMS's and data bases, the probabilities of synchronization enforcement and deadlocks increase, and affect timely response of DBMS to transactions. Universities are doing some work in this area.

Resiliency is a descriptor of a data base's capability to tolerate a detected error (work around it). It is a capability that all DBMS's have to some degree, but a must for a 10^{15} bit data base (e.g. who would want to rebuild it because an error ruined it).

Response Time

The response time of a data base is a function of the number of direct access paths you provide into the data base via the access sub-schema. This translates into data storage overhead in support of data retrieval. Normally, access structures are a small fraction of total database storage. Typical relationships are exponential or logarithmic, such as

$$\text{Data} = f\ (\#\ \text{access structures})^n$$

$$\text{or Data} = f\ (K)^{(\#\ \text{of access structures})}$$

It is possible to have uniform accessibility (in a real time sense) by vastly increasing access structures, e.g., linear constant relationship. This solves a retrieval response time problem and causes an update problem. That is, all of the overhead/access structure must be updated when the DB is updated. Some work is being done in this area in universities and industry. All data bases are organized toward some applications and not organized toward others. The probability of a transaction desiring to read the entire DB should be $\ll 1$. If this is not true, the database organization (hardware allocation and data representation) is very poor and should be reorganized for the specific application.

Networks

There is a significant amount of work being done in on-line networks (ARPA) and networked data bases.

Geo-reference databases will probably be networked with other data bases in the late 1980-1990's.

External Technology Drivers

Although there is a strong research effort in the area of networks, the activity in many areas of data base research is disjointed. A strong unifying and directional influence is needed. This would be expected to be provided by the organizers of a global data base. The relationship of NASA, the Department of Interior, the Department of Agriculture and the State Department is currently evolving with regard to this position of leadership.

NASA Development Required

Assuming that NASA assumes this position of leadership, the required development could be grouped into two phases. The first phase would involve the seeding of basic research in data base organizations to academic and research facilities. The second phase would involve development necessary to lead to a prototype system (for the global data base) and adaptation of the existing networks technology to the earth resources data base problem. Additional development in the areas of synchronization and resiliency as defined above would be required.

7.4.21 SOFTWARE ADVANCES

In the PLACE era massive software generation is anticipated in order to cope with the greater demand for earth resources' data applications. To handle this processing upsurge software technology advancements are therefore necessary. The technology requirements generated are based on a study by Mr. Preston Rose of M&S Computing, Inc. of Huntsville, Alabama (Ref. 7-51).

These Software advancements fall into broad, general improvement categories:

- methods for containing, controlling and reducing data rate and volume.
- methods of improving information content
- techniques to reduce the cost of Software development
- techniques for improving software reliability and simplifying verification/validation activity
- techniques to capitalize on the potential offered by break throughs in hardware (H/W) technology.

Shortcomings that crop up on specific missions, instruments or applications would be improved by one or all of the above categories.

To see significant improvement in these categories more research should be expended on software design engineering, software development by non-programmers and fault free software development. Without progression in these three areas other related software system architecture technologies such as efficient large array search, sort and manipulation, natural communications methods, high speed buffering techniques and software fault detection will be stunted because the associated software will be too costly and/or too unreliable.

Out of these five general areas of required development, the technology requirements which relate to the PLACE system concepts were identified. Specific technology requirements were identified for future earth resources systems in the following seven areas:

1. Software standardization
2. Automated translating aids
3. Fault detection and recovery techniques
4. Dynamic software restructuring
5. Adaptive search and sort procedures
6. Natural communication methods
7. On-board image processing/pattern recognition

The technology requirement in each area is briefly explained below along with an associated technology forecast. (Ref. 7-39).

7.4.21.1 Software Standardization

This requirement may be further subdivided into three areas (a) standardization, (b) requirements decomposition and structuring guidelines and (c) documentation methodology. Standardization of language, operating systems, interfaces between software modules and system management practices would help to eliminate redundant development and improve long-term software reliability. Development of proper guidelines for assisting in design (Case b) and documentation would lead to greater software efficiency and clearer and more concise documentation.

A technology forecast in the area of software standardization resulted in four specific conclusions:

- Although software standardization is only at the level of a generally-approved good idea (level 1 of Table 7-1), an operational environment will exist in the 1988-89 time frame with operational application of the principles in the 1990-92 time frame.

- Standardization will occur by 1987 without investment by NASA because of Air Force interest. However, if NASA does not participate their requirements may not be best met.

- There is good reason to go ahead and attempt stardardization to reduce redundant development.

- It appears that the decomposition and structuring guidelines for general class software problems will be 99 percent of the solution.

7.4.21.2 Automated Translating Aids

Development of automated aids for translating well defined payload software requirements into program code (in the desired language) is required. In effect the translation aids may be looked upon as a set of master programs which output specific program codes corresponding to a given input of software requirements. One specific example of this requirement in the field of earth resources is the requirement to write the required code automatically, given a sensor configuration and a desired function (e.g. geometric correction to Polar Stereographic projection).

The technology is currently at the experimental stage with ongoing research in a number of areas, specifically automatic compiler construction. Application of this technology in earth resources is not as well developed. Given the proper investment by NASA, the general technology can be operational in the 1990 time frame. Several approaches to higher order languages for earth resources operational use may be pursued. In particular, if the hardware is to be close to today's general purpose computers, architecture improved versions of languages such as Signal Processing Language (SPL) will evolve.

A second approach is to extend the macro capability used in many of today's assemblers. If the macro concept is extended so that the syntax of the macro is also subject to definition, then a library of macros paramaterized for complex signal processing functions could be developed. A higher order language might then be developed to assemble and define syntax and parameters for the required macro library modules to create very complex signal processing programs.

Similar approaches may also be used with other than general purpose hardware structures but there is always the risk of technology obsolescence through advances in signal processing hardware technology.

7.4.21.3 Fault Detection and Recovery Techniques

Development of fault detection and recovery techniques in real time space activity will be necessary. In the past this has been compensated for by using sophisticated redundant hardware systems. Such program organization methods would maintain status in a way to allow backup and recovery with minimum loss of data and control in real-time systems. This does not involve redundant hardware but rather it is the concept of a self-healing machine through dynamic reconfiguration.

The general current level of the technology is at the lab test level (level 5 of Table 7-1) based on a brassboard version of the Fault-Tolerant Spaceborne Computer (FTSC). The technology could be fully developed by the 1987-89 time frame, given the proper investment by NASA. Some key areas of reasearch are:

Error-detecting and correcting codes. Quad-redundant and triple module redundancy (TMR) for critical components and functions. Double storage of critical parameters. Use of multiple microprocessors for sensor processing with error detection and replacement by central fault tolerant computer.

7.4.21.4 Dynamic Software Restructuring

Control structures are needed to adaptively deploy available software to meet the requirements of the automated intelligence environments. This dynamic restructuring of the software to adapt it to the environment will enable NASA to plan and execute missions' involving autonomous capabilities. This would also include task control structures for distributed processor environments. System partitioning and interconnection techniques need to be developed for managing concurrent real time processing in space oriented distributed systems. This area may be regarded as the technology of high level software adaptively modifying a system's hardware and software configuration in response to environmental conditions. "High Level" software here refers to high in the hierarchy of control, not high level programming languages.

This technology finds application in two general areas: First, it provides a mechanism to "work around" failures, i.e., the system reconfigures so that failed elements are used less often (or never) to achieve fault-tolerance and graceful degradation; second it provides the means whereby a computer system can react to a wide dynamic range of operating conditions.

In the latter case the technology is relatively mature. Multi-tasking and multi-programming Operating Systems, their algorithms and implementations are fairly well understood. The extension to multi-processor distributed systems is progressing well. (i.e., TANDEM Non Stop T.M.)

In the former case, the technology to achieve system-level fault tolerance is not as advanced but is moving well. The primary problems lie in fault detection and isolation, rather than fault correction by system reconfiguration. Most fault detection and isolation schemes force a trade-off between "Speed of Detection" and interprocessor communications overhead.

The objective guidelines are therefore judged with respect to the "Fault-Tolerant" area of application rather than the "wide dynamic load range" area. Critical aspects of this technology have been demonstrated in the laboratory. It is expected that a fully operational system will be available in the 1988-1990 time frame, with or without investment by NASA. Other current activities in this area include the Raytheon Long-life spacecraft computer and the GE Distributed Control Kernel.

7.4.21.5 Adaptive Search and Sort Procedures

Adaptive search and sort procedures are required to ensure that the development of pattern recognition, image processing and related algorithms will be efficient and enable processing the high volume data in near real time.

In a similar vein, optimal large array partioning procedures offer a viable solution to the problems of large array manipulations such as matrix transpositions under the constraints of the processing system configuration expected onboard. Development of optimal procedures for large 2 and 3 dimensional arrays manipulations will meet the needs of data compression, image processing scene analysis problems. These routines should be adaptive to the data characteristics of the arrays being manipulated.

Current work in the fields of artificial intelligence and pattern recognition have demonstrated the feasibility of adaptive search and sort algorithms. Refinement and application of these principles to an earth resources environment will be an ongoing task through the year 2000.

7.4.21.6 Natural Communications Methods

It is essential for the efficient usage of available human resources onboard that natural communication methods be used. Accordingly it is necessary to evaluate their influence and potential impact on the supporting payload software system to thereby ensure the success of the development of such methods.

Development of natural communication methods for specific experimental tasks is required. The results of this development will be used to derive an overall assessment of the impact of natural communication on NASA payload software design. The key requirement for a voice recognition system is to have an extensive recognizable vocabulary with minimum required "training".

The forecast in this area assumes that a practical system will require the recognition of a multiple word string to achieve a correct response some percentage of the time in excess of 95 percent. The current state-of-the-art is such that critical aspects of the required technology have been demonstrated. Some examples are:

- o Devices are on the market - Threshold Technology, Inc. makes one. It can be trained to recognize single words from about a 30 to 100 word vocabulary.
- o GE Evendale is presently assessing the use of this device on their QC Line.
- o GE Pittsfield is considering one for a Navy application.
- o Other manufacturers are about to announce products.
- o Success rate for trained systems and operators with carefully considered vocabularies is about 90 percent.
- o Emory University is doing FORTRAN programming with voice recognition.
- o Carnegie-Mellon is doing work for ARPA in subject System is called HARPY.

With the proper investment by NASA an operational system with expanded vocabulary and success rate much higher than 95 percent is possible in the 1988-1990 time frame.

7.4.21.7 Onboard Image Processing/Pattern Recognition

Onboard image processing/pattern recognition can be enabled by restructuring the key software functions to achieve maximum parallel processing. This can be attained by identifying the parallelism in these functions not only in terms of parallel or concurrent identical processing on different pixels but also in terms of parallel execution of different computations on the same data. Suitable computer architecture will be adapted to take full advantage of the advancements in low cost hardware technology and parallel processing concepts.

Coupling this requirement with the technology forecast in the area of on-board processors, leads directly to the requirement becoming the efficient use of heterogeneous arrays of processors. Current work on application of these machines to image processing is in its infancy. Key developments which should be developed by NASA by the 1990 time frame are software aids to assist a programmer/designer in the optimal partitioning of these arrays, or allocation of a problem to hardware elements and in the challenging timing problems that future users of these machines will have to deal with.

7.4.22 SOLID STATE SENSORS

Technology Requirement

Future earth resources systems examined show the requirement for multi-element solid state sensors. This technology requirement will identify the need for two such sensors (1) A multi-channel push broom array and (2) A multi-channel solid state camera (2 dimensional array). The key to the technological feasibility of each of these sensors is the availability of the solid-state sensor devices. The approximate time requirement for these technologies is 1993-1995.

The push broom array will require approximately 18,500 detectors in a linear array. We envision 10 bands ranging from the visible through the thermal infrared. Our initial design calls for element size of ~.01 mm, a focal length of .8 meters, altitude = 800 km, IFOV = 10 m.

The 2-dimensional solid state camera would contain approximately 2.7 million elements (1650 x 1650 array). In order to have a reasonable focal length the spacing requirements of these elements are tighter - 1-3 micrometer separation.

Various detectors which have been considered are silicon doped with Indium or Titanium, Indium Antimonide, and Mercury Cadium Telluride. We would like to see D* values up around 10^{13} and need to know the cooling requirements of the various systems.

Technology Forecast

Silicon solid state detectors, operating over the visible range, have been produced with a detector spacing of 25 microns (Ref .7-40). It is projected that this figure could be lowered to 10 microns in the 1995 time frame.
A projection of this technology, based on the work of Gordon Moore (Ref. 7-41) is presented in Figure 7-15. The current technology of photolithography will be replaced by electron beam lithography to allow accuracies of 1 micron.
Device problems to be overcome. Defects in such multi-element chips are currently running at about 5-15/cm^2. Improvements in yield, however, are also expected.
It is questionable whether it will be possible to get an 8-bit reading out of a 1 micron spot without the use of a calibration wedge for each element.
It is possible that the spatial uniformity of the devices will be such that radiometric correction calibration over regions may be practical. The density projections also apply to the higher wavelengh materials discussed below.

Germanium detectors which operate over a range of 0.8-2.0 microns have been used in the construction of Charge Injection Devices (C.I.D.'s) with 50 micron spacing. Indium Antimonide (1.5-5.0 μm) is also under development for operation in the near infared.

In the thermal infared, work is ongoing in the use of mercury cadmium telluride and in the use of extrinsic silicon. Cooling becomes a major problem at this wavelength with temperatures of 20°-40° K being required. Dopants such as indium and titanium are being investigated at the present time.

NASA Development Required

There are a number of external technology drivers which will assist in meeting the requirements in this area. The commercial push for a 1000 element by 1000 line solid state television camera is carrying the research in solid state elements at the present. Even if the commercial push falls short because of an inability to mass produce a consistent product, the DOD may still sponsor development of the 1000 x 1000 camera. The commercial memory and microprocessor markets are also driving research into higher chip densities, are attacking device problems such as geometries, chip size, and defect levels, and are developing production aspects of electron beam lithography.

The resultant development to be attacked by NASA falls into three areas:
(1) techniques for interconnecting large numbers of chips into a single array,
(2) some basic research in the area of sensor physics, specifically into the problem of charge build-up on single elements, and (3) the use of processing "tricks" to assist in resolution. The third item could involve the use of dither, induced by piezoelectric devices, to achieve subelement image resolution (after processing).

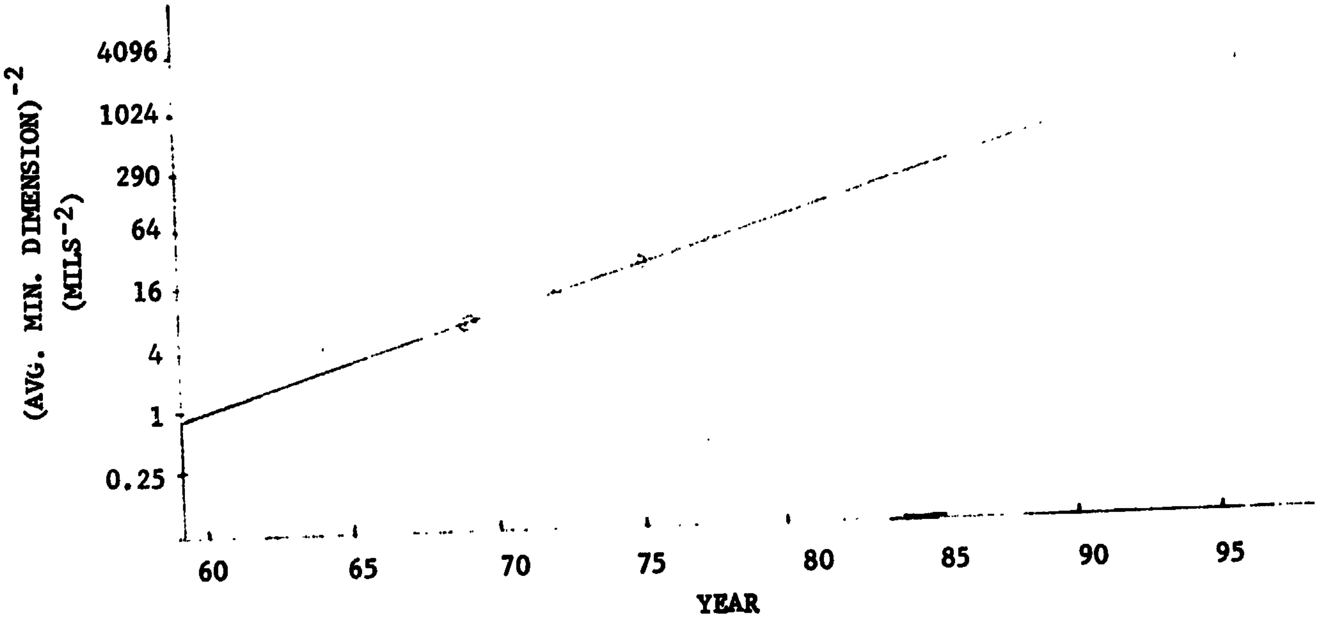


Figure 7-15. Device Density Projection

7.4.23 FERRIS WHEEL CHIP

Summary

To achieve the small ground resolution desired for some PLACE missions at low microwave frequencies (VHF to L-band, for example) giant antenna apertures are required - hundreds to many thousands of meters in extent. For many missions a phased array is more desirable than a parabolic reflector. Both passive and active systems are proposed, with most active systems being pulsed, not continuous wave. To form a tight coherent beam from the very many elements involved in a large array is a major problem, especially if the beam must be steerable. Mass

A corollary problem is the generation and distribution of power to drive the output RF amplifiers. (From the onset it was taken for granted that each radiating element would have a dedicated solid state RF amplifier.) The sheet mass of conductor alone to distribute pulses of several hundreds of kilowatts overdistances of kilometers would be a nearly prohibitive mass penalty.

The final part of the problem is the detection and characterization of the return pulse with return of the data to a central processor over large distances with the coherent phase information preserved.

Functional Requirements

In principle it is possible to perform all of the required functions in a single slice of silicon, and this is the way the proposed solution was conceived. In practice, there may be good reasons to use several interconnected chips, mounted on a light substrate; e.g. Mylar blanket. It should be noted that something like a million array elements are involved. Figure 7-16 is a schematic diagram of the required functions as they have been conceived.

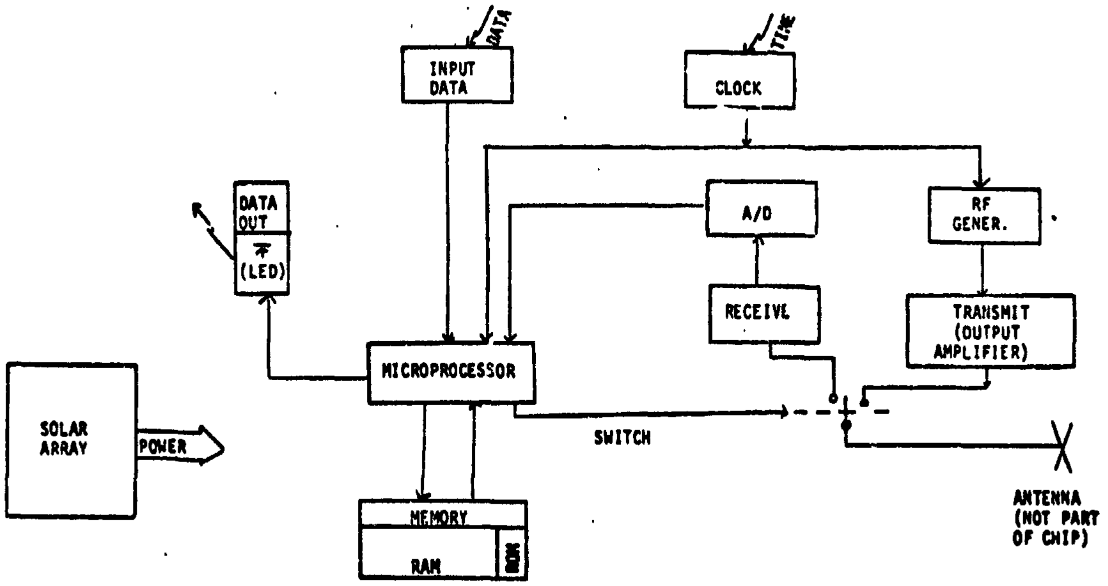


Figure 7-16. Ferris Wheel Radar IC Chip

of system and RF losses in waveguides or stripline are major factors limiting what can be done by present technology. A solution is proposed involving a single integrated microcircuit chip (presumably silicon) having solar cells, photodiodes, RF elements, and a microcomputer; and the requirements of this chip are defined.

Problem Statement

This technology requirement was first considered for the ferris wheel radar (See Section 6.1.10). The mission of Ferriswheel is to use ground penetrating microwave radar pulses to explore for sub-surface features (e.g. ore bodies). Hence the wavelengths must be long, one to ten meters at least (30 MHz to 300 MHz), and to achieve useful ground spatial resolutions a large aperture is required - sizes of twelve to thirty kilometers in diameter are being considered.

Because of the huge size, a slowly spinning structure of tension threads was considered to be the only structural approach that mass considerations would allow. A very preliminary structure mass estimate, which arrived at a guesstimate that such a structure could be carried in about two shuttle loads (volume permitting), was based upon tension members no larger than a quarter of a millimeter in diameter. On this basis, the coax/waveguide needed to distribute RF energy to a million ferrite phase shifters to feed the antenna array elements looms as an "impossible" mass problem. A lighter solution was clearly needed.

The crucial problem faced is the low speed of light. At 300 MHz, pulse widths of about five microseconds are wanted, but the time for light to travel from the center of a thirty kilometer wheel to the edge is fifty microseconds. Clearly, to form a coherent beam, the RF pulses to be radiated from elements near the center of the wheel need to be delayed (or stored) for up to several pulse lengths, or thousands of RF wavelengths.

A substantial part of the silicon area is dedicated to a solar array. The total power requirements could be met by a single small solar cell, but it is not clear that the voltage output from a single junction will be adequate for all of the rest of the circuitry. However, it should be possible to form a number of solar cells, connected in series, on the same chip, just as other circuit elements are formed in multiple units.

The major part of the circuitry on the chip is devoted to the process of timing the RF output pulse. The concept is that a central control unit (CCU), conceptually (but not necessarily) located at the center of the array, will notify each chip well in advance of the time a pulse is required, about 150 times per second. So there are several milliseconds to send a message to all chips that "we are all going to pulse together at some future time T." Each chip would know - stored in ROM - how far away from the CCU it was, so it could compute the number of clock pulses until time T, count them, and pulse in proper phase. The proposed concept uses a laser at the CCU to send clock pulses to a photo-receptor on each chip. A separate laser/receptor link on a different wavelength sends data, such as time T.

The clock pulses can be counted down (divided) to produce an RF frequency source at any convenient sub-multiple of the laser clock pulse rate. At the computed time, an RF switch is closed and thousands of nanoseconds of either CW or modulated RF are transmitted through an antenna element connected to the chip.

Several milliseconds after the RF wave front is launched, each microcomputer closes the RF receive switch, and the receive element amplifies and demodulates the return signal, and the phase and amplitude information is A/D converted and stored in RAM for later transmission to the CCU to be combined with the data from other elements in order to extract the desired information. Subsequently, in the milliseconds left before time for the next pulse, each chip (upon command) transmits the stored data about the return pulse to the CCU. It was visualized that this could be done by a light emitting diode on the chip, viewed by one of many optical receivers at the CCU.

In the initial visualization of this phased array concept, no provision was made for power storage. Daylight operation only was assumed, and since the peak RF power for each (of a million) elements was only several milliwatts, it was simply assumed that enough solar array would be provided for each element to supply the peak power, which is hundreds of times the average RF power. (Duty cycle is less than 0.08 percent at 300 MHz less than 0.8 percent at 30 MHz).

Subsequent analysis has indicated a major advantage for night-time operation; i.e. much reduced ionospheric attenuation at the most desirable (lower) frequencies at night. Hence, if a low cost light weight storage device would be added it would permit the desired night operation, and could probably be used to reduce the size of the solar array needed for each phased array radiator.

Because the ground penetrating radar will be operated at the lowest feasible frequencies, Faraday rotation in the ionosphere dictates that the antenna polarization be circular both on transmit and receive so that the desired measurements do not depend upon polarization data.

Further, since the ground penetrating radar is spinning, thus fixed in inertial space, half the time it is facing "away" from the earth. Thus it would be desirable for the antenna patterns to be the same in both directions along the axis to avoid this lost time. It is recognized that this will double the required power, but for a vehicle of this magnitude that impact is trivial.

Performance Requirements

Qualitative estimates have been made for some of the parameters of the IC projected for this application. For the 30 MHz ground penetrating array, preliminary calculation of the link parameters (see Figure 6-24) suggests an average RF power output per element of about 1.0 watt. The pulse repetition rate was 1500 pulses per second with each pulse of 0.3 microseconds duration.

DC power required for the transmitter depends upon the DC/RF efficiency that can be achieved on the chip, and upon whether peak power storage is available. These transmit powers were predicated upon an orbit altitude of 1000 kilometers, one million elements, and a receiver noise temperature of 4000°K - another technology requirement for a sensitive single chip receiver.

One crucial performance requirement is for a high speed clock. At 30 MHz, the duration of a cycle is 33 1/3 nanoseconds. If coherence to a tenth wavelength is needed, clock pulses of 3 nanoseconds or less are needed. This should be no serious problem for the laser clock pulse transmitter, but the photodiode receiver on the individual chip may present a technology challenge. The use of 300 MHz and/or greater coherence requirements will require even higher clock rates. By comparison, the data link speed requirements are modest.

The memory and processing speed requirements of the microcomputer have not yet been estimated but are expected to be rather modest. Because of the several milliseconds between pulses, computation of the phase delay required for steering does not appear to require very high speeds. Similarly, to characterize a return pulse microseconds long with range bins of 15 to 150 nanoseconds duration appears to require only kilobits of RAM memory.

The mass of this integrated circuit chip is not a major factor compared to the current estimate for structure mass, but should be kept reasonably small. On the basis of chips of five square centimeter size, .2 mm thick (density of silicon 2.42 g/cc), each chip would weigh less than a quarter of a gram, and a million of them would weigh 242 Kg. This number could increase an order of magnitude, if necessary, and not significantly affect the feasibility of the Ferriswheel system concept.

The primary technology requirements for energy storage relate to mass, operating voltage, and pulse discharge capabilities. Assuming one storage device (battery) per phased array element (a convenience, not a requirement), a mass of not more than a gram or so per battery is desired to keep the total system storage mass to a metric ton or so. The voltage requirement is not known at present - it is probably set by the RF transmitter need. The average energy per storage cell is 75 W (RF), increased by several times for DC-RF conversion plus microcomputer power, divided by a million units; that is, a part of a milliwatt for the minutes of night operation desired. At 200 watt-hours per kilogram projected for 1990 era space batteries, the mass to store a milliwatt hour would be only milligrams. Even after allowing for large penalties associated with very small scale, the mass requirement seems reasonable. A greater challenge may be to achieve low cost for these units.

The principal requirement identified to date is that of a low mass. A one mil copper plate on 38 gauge substrate (glass filaments) was used in the crude mass guesstimate. For 30 MHz crossed dipoles this led to a total mass of the order a metric ton; reasonable in comparison with other system elements.

Technology Projection

The requirements and operating environment for the Ferris Wheel chip were discussed with representative's of GE's electronics (LSI) Laboratory. It was their collective opinion that (1) the described requirements could be implemented on a single chip or wafer in the 1993-95 time frame and (2) that production technology will have advanced sufficiently to enable mass production of this chip.

NASA Development Required

The primary support required by NASA will be adaptation of the multifunction chip capability being developed by industry, to a space application. The commercial market will have developed many of the functions of the above requirements for commercial products such as wrist radio, microcomputer applications and for a host of other uses. It is expected that DOD will also jointly support this development in the area of compatibility with the operating environment, e.g. radiation hardening, packaging, etc.

7.4.24 EXTRACTIVE PROCESSING

Technology Requirement

For each of the key set objectives discussed in Section 4.1.3, the technology required to operationally transform remote sensing measurements into usable information must be achieved. Extractive processing (also called information extraction) includes the hardware, techniques and knowledge required to transform preprocessed data (radiometrically and geometrically corrected) into management alternatives or information which a resource manager can use. In this discussion, extractive processing assumes all collateral or ancillary data required to be available externally, in a data base of some kind. The organization and collection of that data is treated independently (see Section 7.4.20). Since extractive processing is considered an enabling technology for so many of the PLACE system concepts (see Figure 7-2), it will be shown to be (Section 8.0) one of the key technologies in the PLACE study. A characterization of the extractive processing interrelationships is presented in Figure 7-17.

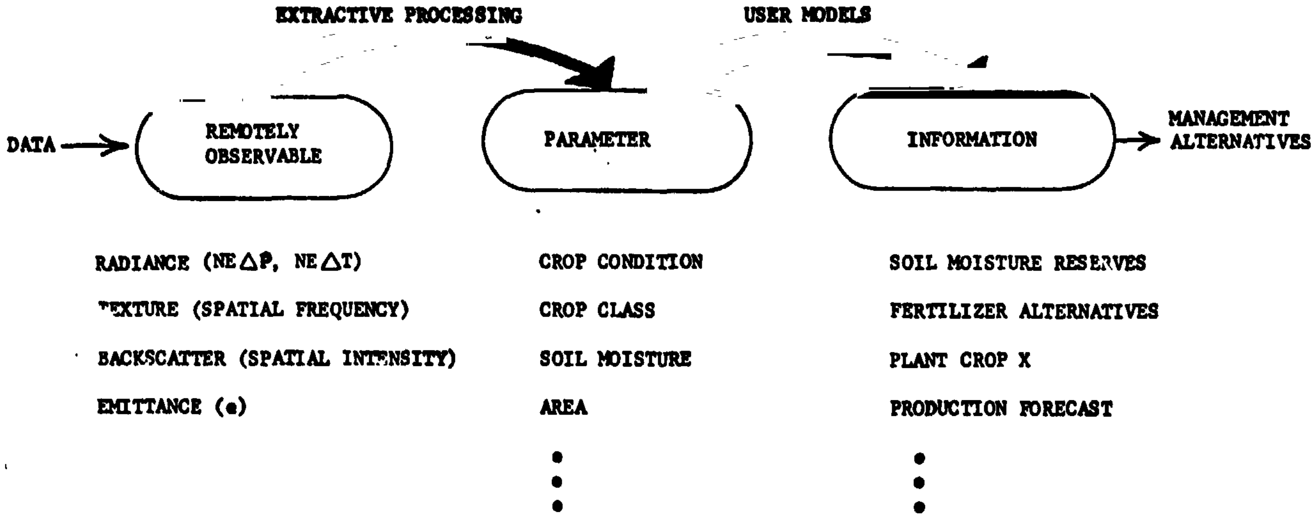


Figure 7-17. Extractive Processing Interrelationships

Table 7-10. Key Research Required

ITEM	SPECIFICS	COMMENTS
SCIENCE BASIS	● DETERMINE PHENOMENA-BASED REQUIREMENTS ● DETERMINE PHYSICAL/BIOLOGICAL BASIS FOR PHENOMENA MEASUREMENTS - RELATE MEASUREMENTS TO PLANT PHYSIOLOGY	
BASIC SIGNATURE RESEARCH	● CALIBRATED SENSORS ● SYSTEMATIC ACQUISITION PLAN - CLIMACTIC REGIONS - GROUND TARGETS - "TRUTH" REQUIRED - COLLATERAL DATA	WHAT ARE OPTIMUM MEASUREMENTS? OVERCOME PHOTON-LIMITED TECHNIQUES? MULTISPECTRAL (VISIBLE-μ WAVE)
ECOZONE MAPPING	● DEVELOP THE ZONE CRITERIA ● ORGANIZE EXISTING DATA ● PLAN FOR NEEDED ACQUISITION	PREREQUISITE TO SIGNATURE EXTENSION
USER MODELS	● RELATE MANAGEMENT NEED TO PARAMETERS ● EXTRAPOLATE TO TOMORROW	
HARDWARE MECHANICS	● ESTABLISH INTEGRATED LABORATORY ● LOW COST TOOLS ● COMBINED TECHNIQUES/ALGORITHMS (CASCADE) ● MORE SUPERVISED, MAN-MACHINE INTERACTION	

For the purposes of this discussion, extractive processing is divided (Ref. 7-42) into five areas, a science basis, basic signature research, ecozone mapping, user models, and hardware mechanics, as shown in Table 7-10. Although each of the five areas is discussed independently, they are all heavily interrelated and interdependent.

Establishing a science basis for extractive processing is equivalent to a basic understanding of the phenomena which are being observed and the measurements which are being made. This may be divided into two parts: (1) understanding the phenomena-based requirements; and (2) determining a physical/biological basis for phenomena measurements. The first area involves understanding the microprocesses of a phenomenon. The second is, for example, establishing a relationship between remote sensing measurements and plant physiology.

Basic signature research is a more empirical approach to establishing the "identifiability" of a phenomenon. Two tasks are envisioned in this area: (1) the specification and development of a standard set of calibrated sensors for use in field programs; and (2) construction and execution of a systematic plan for acquisition of basic signature data. As discussed herein, the term signature refers to measurements over time, over all sensible frequencies (.4 microns - 10 meters, active and passive), for each homogeneous ground region (ecozone) and for each identifiable species.

Ecozone mapping refers to establishment of those homogeneous ground regions (homologues) over which a signature is valid. This will then enable later work in the area of signature extension.

User models is the very broad area of relating intermediate parameters derived from remotely sensed data to management need. In some cases, the intermediate parameter, soil moisture or crop condition, for example, may in fact be the end item. In other cases, they will serve as one of many inputs in deriving a management alternative. Forecasts are treated as a special case of models in this discussion, since a forecast is an extrapolation of a condition over time.

The final area of hardware mechanics involves the required development of many of the hardware tools required by the technology. Specific aspects will be discussed below.

Technology Forecast

Establishment of a science basis for extractive processing and development of user models is an area that has long been considered the realm of the user. However, in the operational systems being considered, they are regarded as technology gaps to be closed, without ownership of the problem being an issue. There has in the past been a great deal of work in understanding the microprocesses of a phenomenon in a number of fields. Where the research has consistently fallen short is in further relating these microprocesses to what is actually measurable remotely. In the area of models, there has been extensive work performed in hydrologic models. There have been several crop models proposed and studied, and some work in the area of key census cities has been performed. In both the areas of establishment of the science basis and development of user models, it is projected that development will continue through the PLACE era with a continuing refinement and improvement of the understanding required. The required research in these two areas constitute some of the most difficult technology challenges in the PLACE study. As is indicated in Figure 3-3, then accomplishment may actually go beyond the "semi-credible" to the incredible.

In the area of basic signature research, there are a number of independent and somewhat disjointed field measurements programs ongoing. Oftentime, the data from different sites is not comparable or complementary. It is porjected that in the 1995 time frame, with the help of the work done in understanding the science basis and in ecozone mapping (see below) and with an appropriate investment by NASA, the empirical base for the establishment of a "signature bank" will have been established.

Little work is currently being done in ecozone mapping with the primary activity being centered at the Environmental Research Institute of Michigan in the area of signature extension. It is projected that in the 1995 time frame, a world ecozone map could be completed given the proper investment by NASA. In addition, research into the validity of signature extension will be continuing with uncertainties reduced.

Finally, in the establishment of the required hardware mechanics required to support the other areas, contributions made from advancements in processors and information dissemination systems will allow for sophisticated, low cost research tools in the 1995 time frame.

NASA Development Required

It is perceived that NASA can expect some assistance from external sources in attacking this technology area. Whatever federal agency or combination of agencies that operates the global data base (discussed in Section 6.3) and other "discipline" oriented federal agencies such as the Department of Agriculture and the Department of the Interior have a joint interest in extractive processing with NASA and should provide some support. In addition, assistance in user modeling and field measurement programs can be expected from international organizations such as the Food and Agriculture Organization (FAO), from private institutions such as the Rockefeller Foundation, and perhaps from large discipline-oriented business groups such as agribusiness.

The NASA portion of the required research and development will be described in each of the five mentioned areas. In the area of establishment of a science basis, it is the sponsoring of basic research to understand those aspects of the phenomena which should be measurable (observable) from remote sensing. In order to support the establishment of a signature bank, standard, calibrated sensors should be identified and developed and a systematic data acquisition plan must be constructed and put into operation. This plan should take into account the various climatic regions and ecozones, should identify required collateral data and take advantage of what already exists, and should identify and plan for acquisition of that "truth" or ground verification which is required. A three part effort is envisioned to accomplish the desired goals in ecozone mapping: (1) develop the criteria which will be used to identify a zone in each region; (2) organize existing data into a usable format; and (3) plan for acquisition of that data which is yet needed. Work in the area of user models should focus on identifying the benefits of using remote sensing in user models and in subsequently constructing/altering the models to allow for the inclusion of remote sensing inputs.

A number of programs must be undertaken to provide the hardware tools necessary to perform these tasks. The first is the establishment of an integrated laboratory for research in extractive processing. Within this environment, different classifiers, models and machines could be compared and evaluated. A key aspect of this concept would be the absence of short-term operational achievement-oriented goals placed on the laboratory. Rather, an environment conducive to research should be fostered. The second area of development is the establishment of low cost tools, processors, displays, etc., which would foster much more research in academia where there are a lot of hands and minds but few resources. For example, instead of a graduate student testing one algorithm in one area, he could perhaps test 100 algorithms in 10 areas. Thirdly, an investigation into the value of cascaded techniques (classifiers and models) which support the convergence of evidence theory should be made. This involves the argument that even if any one method does not work, a combination of methods over time will lead to the right answer. Finally, the use of more man machine interaction is recommended. Experience has shown consistently that better results are achieved in a supervised process, where a human's unique skills are taken advantage of.

7.4.25 LASER SYSTEMS

Technology Requirement

The PLACE laser technology requirements derive from two applications: a laser calibration technique for remote sensing and a laser illuminator of the ground scene (NITE-LITE). The required performance for these applications is as follows:

CALIBRATION	ILLUMINATOR
ENERGY: 3 JOULES/PULSE	ENERGY: 0.45 JOULE/PULSE
PULSE FREQUENCY: 1000 PPS	LIFE: 10^{11} PULSES
LIFE: 8000 HRS.	PULSE FREQUENCY: 700 Hz

The demand for high radiometric measurement precision in post-1985 sensors for Earth Resources will require advances not only in detector and signal processing technology, but also in techniques to factor-out the temporal and spatial variability in the atmospheric transmissibility. The subject technology requirement refers to obtaining atmospheric "calibration" data that would permit the correction of radiometric data obtained through the satellite sensors according to the actual atmospheric conditions prevailing over each site where radiometric data is taken. The use of lasers is indicated here, since the return beam undergoes attenuation in accordance with its interaction with the same atmospheric volume traversed by the signals to the passive sensor(s).

The laser calibration requirements fall in two major categories: technique development and laser system development. The basic calibration technique involves sending laser pulses parallel to the line-of-sight of the sensor(s) of interest, and measuring the gated signal resulting from the light scattering within the atmosphere.

The specific measurement techniques must consider the constraints imposed by possible health hazard due to eye damage from light levels exceeding safe limits. In addition, the signal strength must exceed the background radiation due, principally, to solar radiation during the daylight portion of the orbit. The laser signal must operate in a spectral region where the beam can penetrate the atmosphere down to the ground level, so that the effects of the entire atmospheric volume is measured. The laser wavelength and bandwidth must be selected to permit an accurate correlation between return signal energy level and the "extinction coefficient", a parameter which is essential in the determination of atmospheric transmissivity. Two principal groups of techniques are considered: (1) LIDAR and (2) Absorption. With LIDAR the concentration profile along the laser pulse path is measured by the signal intensity as a function of arrival time at the receiver; thus, atmospheric "soundings" are obtained at different altitudes. In absorption, the laser beam integrated attenuation resulting from traversing the entire path is measured.

A possible technique to alleviate the problem of high background due to daytime solar flux consists of selecting the laser wavelength in a narrow bandwidth coincident with a Fraunhoffer absorption line. For example, the Ca-K line at

3933.682 Å transmits only 5% of the continuum near the line center. Therefore, significant improvements in signal-to-noise ratio can be attained for daylight operation of the calibration system.

Regarding the laser system (hardware) development requirements, the type of laser selected will depend on the power levels, the wavelength range, the bandwidth and pulse width requirements. Gas lasers have the largest potential wavelength span (commercially 0.33 micrometer to 10.6 micrometer can be obtained). Solid-state lasers such as ruby and neodymium produce the most powerful pulses, in the realm of gigawatts. Liquid lasers such as dye lasers are also capable of high power, and are tunable over a wide spectral region. Semi-conductor injection lasers are of interest since they can be sun-pumped in space.

The laser receiver must have a sensitivity compatible with laser operation at energy levels that are safe from the point of view of eye damage.

The laser illuminator application consists of enhancing spatial and radiometric resolution through pulsed laser illumination. This system is discussed in Section 6.1.1. Special features of the laser apparatus for this application are as follows:

1. Array or single laser source.
2. Tunable lasers over the visible spectrum.
3. Optical system designed specifically for linear arrays or pushbroom scanners.

State-of-the-Art Assessment

The limiting parameter seems to be the laser life, in which the requirements are much greater than the projected capabilities. Several developments appear promising, among these are the Excimer and Dimer type lasers. CO_2 lasers will not be suitable in the visible and near IR range; Nd: Yag lasers are energy limited for this application, they cannot build energy sufficiently fast; Nd-Glass lasers cannot dissipate heat at a sufficiently high rate.

Technology Projection

The forecast, relative to the laser calibration application, is shown below (Ref. 7-43).

	Current Capability	1985	1995	
W-Length	0.53 Micron	0.53 Micron	0.53 Micron	
Energy	1 Joule	3 Joules	3 Joules	
Pulse Freq.	10 PPS	200 PPS	1,000 PPS	
Bandwidth	1-5 Å	1 Å	1 Å	Limiting
Life	<300 Hrs.	<300 Hr	1,000 Hrs	←

In the laser illuminator application, the forecast is as follows:

	Current Capability	1985	1995	
Power	10 - 25W	600 (Lab)	3KW	
Life	5 x 10^6 Pulses	10^8 Pulses	10^9 Pulses	↖ Limiting

Required NASA Developments

1. Develop long-life high-powered lasers.
2. Improve techniques for laser heat removal.
3. Develop data interpretation techniques to factor in particle size distribution in the calibration.

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8.0 PRIORITY STRUCTURING AND DECISION SUPPORT

The overall problem addressed in the priority structuring and decision support analysis was the understanding of the complex interrelationships and interdependencies inherent in the set of mission objectives, system concepts and technology gaps discussed in Sections 4, 6 and 7, respectively. The specific problem addressed was to allocate scarce resources (dollars) among the technologies in a way that will maximize the benefits produced.

The method of solution was the development of a decision support tool, called PRISM, which would assist in the analysis of the priorities of the various technologies. PRISM was developed to run in two modes, a Ballpark mode and a Goodness Measure mode, as will be discussed below.

The results of the analysis are twofold: (1) a flexible decision support tool (PRISM) has been developed and (2) a set of prioritized alternatives for technology funding has been computed, based on a stated set of assumptions.

A discussion of the priority structuring problem and an establishment of terminology will be presented in Section 8.1. The two modes of operation for PRISM, the Ballpark mode and the Goodness Measure mode, will be presented and compared in Section 8.2. The application of PRISM to the PLACE objectives, system concepts, and technologies and the resulting set of prioritized technology funding alternatives will be illustrated in Section 8.3.

Detail concerning the operation of PRISM is presented in Appendix A. Appendix A.1 reviews the methods of calculation. A detailed user's manual including representative inputs and outputs is contained in Appendix A.2. Finally, the complete listings and detailed flowcharts are presented in A.3 and A.4, respectively.

8.1 BACKGROUND DISCUSSION

Presented in this section will be a discussion of the overall problem scope. The terminology to be used and the assumptions inherently imposed by the PLACE structured approach will be presented in Section 8.1. The concept of relating technologies through systems or programs to benefits is discussed in Section 8.1.2. The special problems posed by the existence of enabling technologies is examined in Section 8.1.3.

8.1.1 TERMINOLOGY AND ASSUMPTIONS

The PLACE Study took a highly structured approach inherent in the PRISM concept, to the priority analysis problem, as is illustrated in Figure 8-1. The items labelled T_i are technology gaps, identified in Section 7, which must be closed. The programs are the future system concepts which were discussed in Section 6. A technology may enable or enhance a program. An enabling technology is necessary to permit the implementation of the program

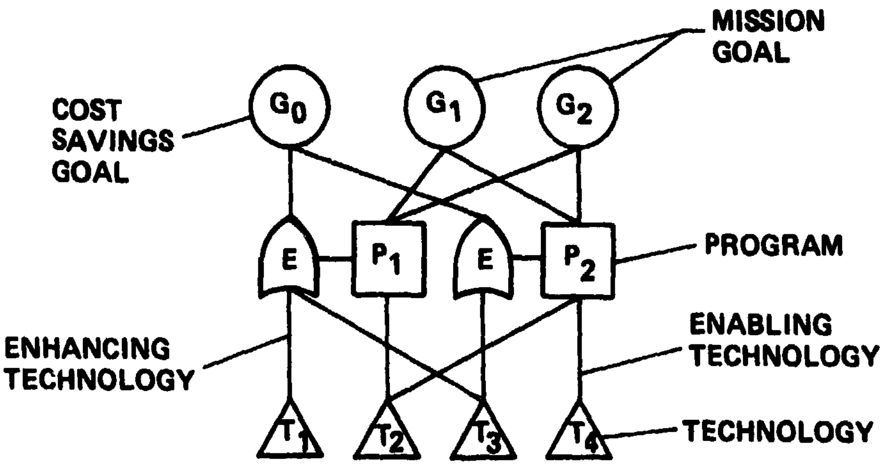


Figure 8-1. Structure of the Priority Analysis Problem

as conceived. An enhancing technology is desirable in that it will significantly reduce the implementation cost of the program. It should be noted in Figure 8-1, that enhancing technologies contribute to the cost savings goal by enhancing programs (E portion of each program). By enabling programs ($\boxed{P}$ portion of each program), a technology contributes to the mission goals, which are synonymous with the key set of mission objectives discussed in Section 4.1.3.

The allowable relationships or links are as follows. Technologies support (enable or enhance) programs. A single technology may enable some programs and enhance others. Technologies must be fully funded or not funded, there is no partial funding. Partial funding may, in essence, be achieved by dividing a single technology gap into a number of gaps, each successively more difficult (wide). The inclusion of technological risk, or a probability of success of closing a technology gap vs. increased funding, was considered early in the PLACE Study. This would then allow for the computation of the probability of enablement of a program as the product of the probabilities of success of the enabling technologies. A number of shapes for the probability of success vs. funding curves was examined, including linear, exponential and Rayleigh cumulative distribution function curves, in an unsuccessful attempt to find a reproducing shape (which would simplify calculations). Therefore, since the shape of the probability of success vs. funding curve is highly conjectural, and since seemingly minor differences in shape can lead to major differences in results, it was decided to eliminate technological risk from consideration.

In the assumed structure, all technologies that enable a given program must be funded if the program is to succeed. That is, a program is "completed" only if all its enabling technologies are funded. Subsequently, completed programs contribute to goals, both the cost savings goal and the mission goals. The technologies that enhance a program need not be funded, however, for the program to contribute to goals.

Goals or mission objectives may be fully or partially met since programs independently contribute to their accomplishment. In the structure defined, various benefit levels or weights may be assigned to each goal.

It should be noted that the analysis is evaluating the priorities for a fixed set of future system concepts and projected technology gaps, as described in Sections 6 and 7. For example, the relative benefit of the Earthwatch system concept using 1-3 μmeter spaced solid state detectors to the Global Crop Production Forecasting mission objective is estimated. No attempt is made to determine the incremental benefits which may be due to finer detector spacing.

8.1.2 TECHNOLOGY DOLLAR BENEFITS

The key problem in the priority analysis problem as structured is the interdependencies of enabling technologies. It is difficult to develop a single priority ranking of the technologies because the amount of benefit derived from a given technology depends on what other technologies have also been funded. Instead, one can develop optimal groups of technologies which should be funded at a given budget level. If the budget level is changed, the composition of the group changes. An example of this interdependency may be seen in Figure 8-1. Program 2 (P2) has enabling technologies T2 and T4. If neither technology is funded, one achieves no benefit (from program P2) for funding either.

A related problem is that of deciding the relative values of enabling and enhancing technologies, i.e., if an additional dollar is to be spent, should it be used to enable some new program or enhance (i.e., reduce the implementation cost of) some already enabled program A "right" answer could only be found if there were accurate dollar benefit estimates available for each program and each enhancement. But in general, such estimates either do not exist or are not very reliable. Thus, it is necessary for the decision maker to select an appropriate tradeoff between enhancing and enabling technologies. The two methods to be discussed implement these tradeoffs in slightly different ways, but both require the decision maker to weigh the relative importance of an implementation cost saving against the benefits derived from satisfying a given goal. That is, relative units of goal accomplishment (utils) are weighed against cost savings dollars.

8.1.3 THE VALUE OF ENABLING TECHNOLOGIES

It is important to consider carefully the value of enabling technologies. Suppose that the value of a program is V dollars. This means that a user would pay as much as V dollars to obtain the benefits of the program, but he would pay no more. He might, for example, have an alternative program that produces equivalent benefits but costs only V dollars. Thus, if the cost of the program were less than V dollars it would be employed; if it were greater than V dollars, it would not be. Now further suppose that there is a technology gap which, if closed, will reduce the cost of the program. One would like to determine the value of closing this technology gap. There are three possible cases in arriving at this value, as shown in Figure 8-2.

In the first case, A_1, the initial cost of the program is less than V, its value. If the technology reduces the cost to A_2, the value of closing the technology gap is just (A_1-A_2) dollars and the technology enhances the program. One assumes that the cost of closing the technology gap must be less than (A_1-A_2) or the required research would not be cost effective.

In the second case, B_1, the initial cost of the program is greater than V. The technology reduces the cost of the program to B_2, but this is also greater than the value of the program. Since the cost of the program, even with the advanced technology, is greater than its value, it will not be performed. Since the program is not performed, the technology results in no cost saving to the user, and its value is zero.

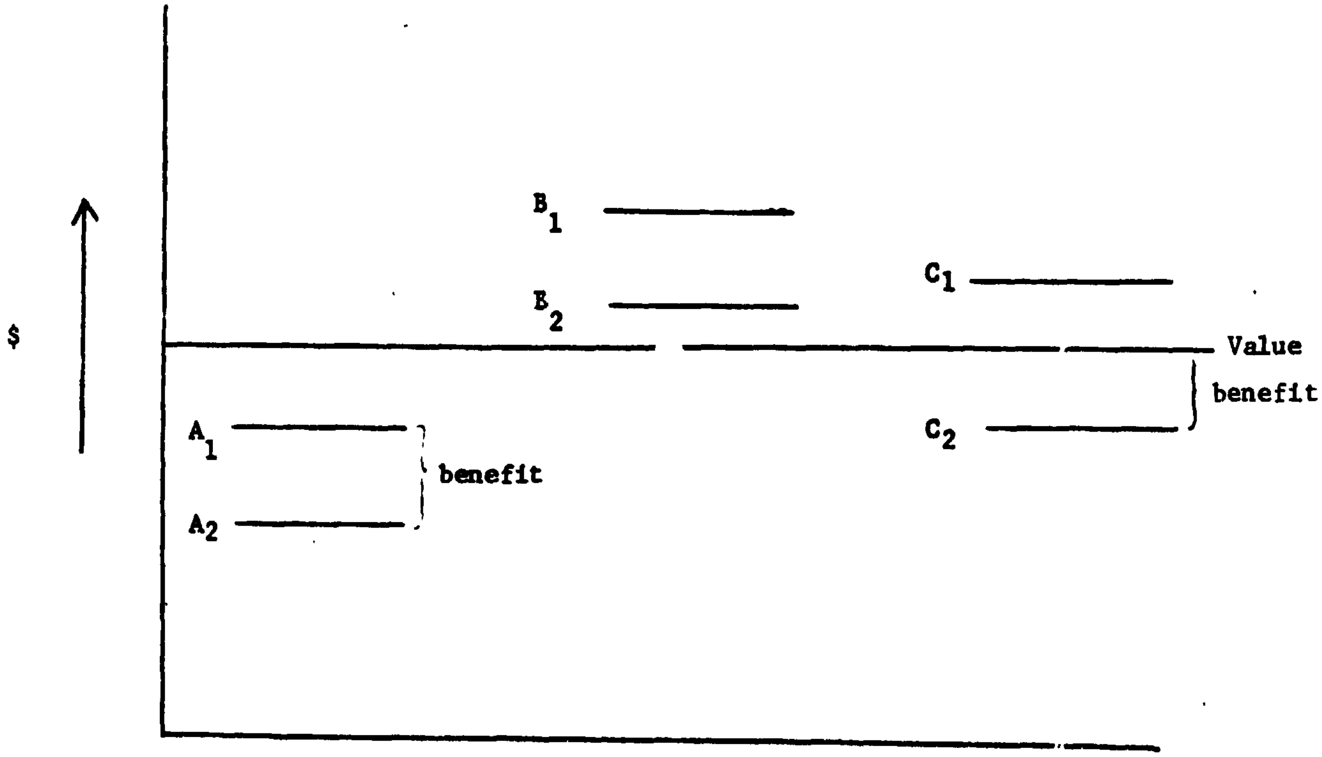


Figure 8-2. The Value of an Enabling Technology

In the third case, C_1, the initial cost of the program is greater than V, and C_2, the cost of the program after the technology advancement is less than V. While it is tempting to say that the value of the enhancing technology is (C_1-C_2) dollars, as in the first case, this is incorrect. No matter what the initial cost of the program, it would not have been implemented if its final cost were greater than V. Thus, the value of closing the technology gap to the user is only $(V - C_2)$ dollars. Closing this technology gap, then, financially enables the program. The key implication of this in the priority analysis is that if one assumes the rewards of closing an enabling technology gap in terms of increased relative benefits (utils = V), one must subtract the cost of the program (in dollars) from the cost savings goal. The value $(V - C_2)$ is then achieved.

The above discussion considers technologies which are financially enabling. One normally is used to working with technologically enabling technologies. For example, the Parasol Radiometer (a large passive microwave radiometer for measuring soil moisture) may not be implemented unless the technology gap posed by the requirements for construction of large structures is closed. It may be argued, however, that all technologically enabling technologies are really financially enabling ones. One could achieve the same performance with very many ground soil moisture measures but it would be prohibitively expensive. The large structure technology may be regarded then as reducing the system cost to a point less than the system value.

8.2 PRISM: A PRIORITY STRUCTURING AND DECISION SUPPORT TOOL

PRISM was developed as a software decision support tool to help examine the interrelationships among the goals, programs and technologies. It will be used in this study to allocate various budget levels to competing technologies in order to maximize the benefits produced.

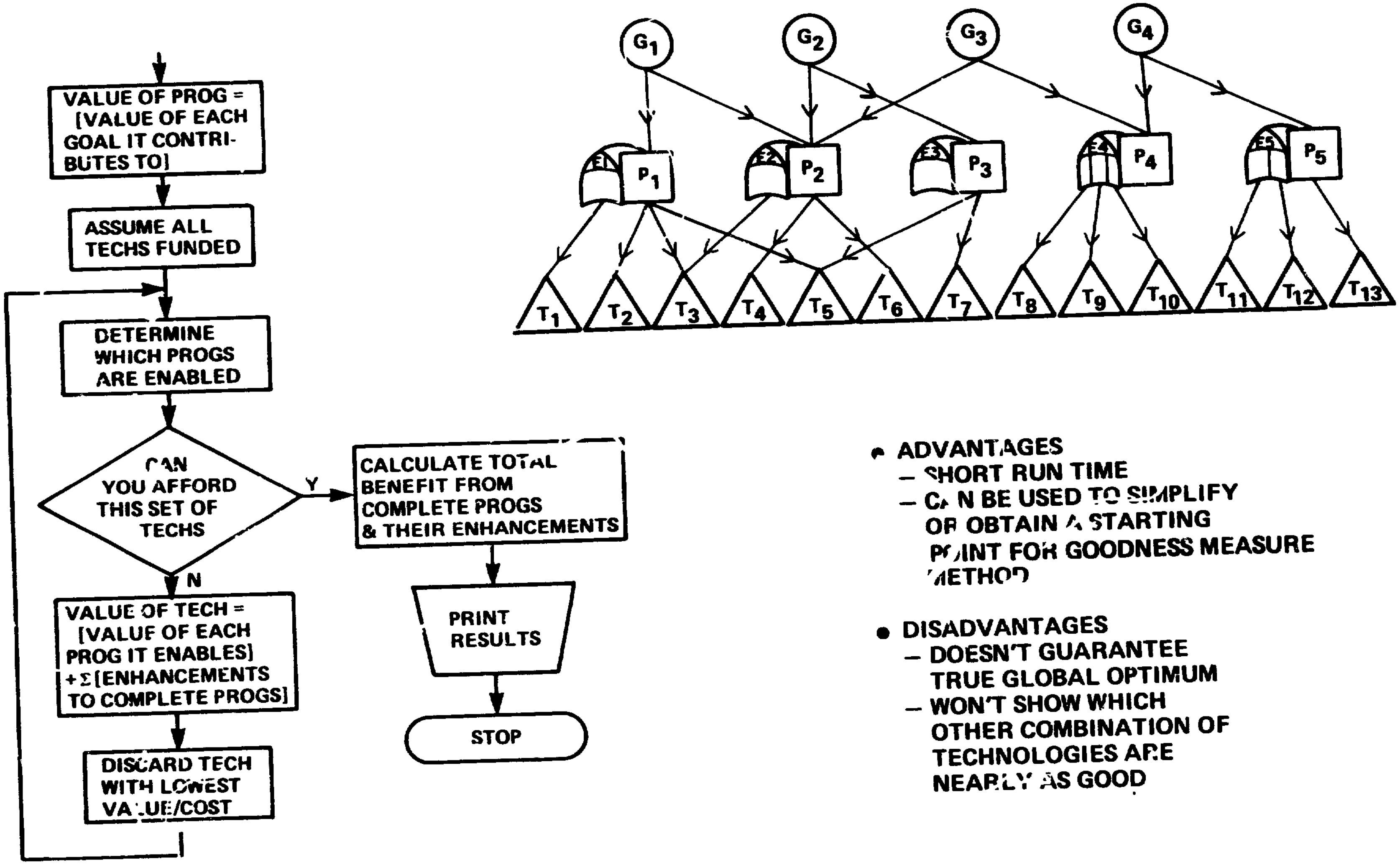
PRISM was developed to operate in two modes: the Ballpark mode and the Goodness Measure mode. The Ballpark mode, discussed in Section 8.2.1, is a heuristic method that tentatively ranks each technology according to benefit derived by assuming that all others are funded, then iteratively revises the rankings as technologies with low benefit/cost ratios are eliminated. The Goodness Measure mode, discussed in Section 8.2.2, treats the problem by examining groups of technologies rather than single technologies. The two methods of analysis are then compared in Section 8.2.3.

8.2.1 THE BALLPARK MODE

The operation of the Ballpark mode is summarized in Figure 8-3. The diagram's terms were described in Section 8.1.1, and the simplified flow chart will be traced in the following discussion.

The Ballpark mode starts by calculating for each program a score that is a weighted sum of the worth of each goal to which it contributes. It then calculates for each technology a similar score that is a weighted sum of the value of each completed program it enables and the value of each enhancement it produces.

The method initially assumes that all technologies are funded and, consequently, that all programs are enabled. If the total cost of the set of funded technologies is not within the budget, the technology with the lowest benefit/cost ratio (lowest benefit also used) is eliminated. If this technology enables any program, all benefits that these programs assigned to technologies are removed and the benefits produced by each technology



- ADVANTAGES
  - SHORT RUN TIME
  - CAN BE USED TO SIMPLIFY OR OBTAIN A STARTING POINT FOR GOODNESS MEASURE METHOD
- DISADVANTAGES
  - DOESN'T GUARANTEE TRUE GLOBAL OPTIMUM
  - WON'T SHOW WHICH OTHER COMBINATION OF TECHNOLOGIES ARE NEARLY AS GOOD

Figure 8-3. "PRISM" - Ballpark Mode

are recomputed. The process of eliminating the technology with the lowest benefit/cost ratio and recomputing the benefits of the remaining technologies is continued until the budget is met.

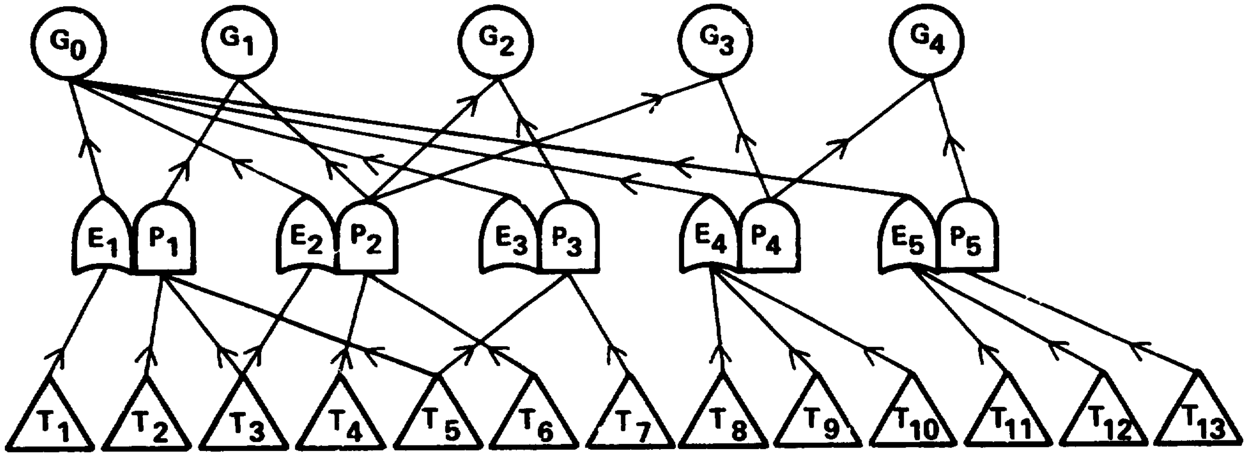
Figure 8-3 illustrates how the Ballpark mode handles enabling and enhancing technologies: a technology gets credit for enhancing a given program only if the program is completely enabled and the technology is funded. All benefits due to enablements are multiplied by a factor k; this factor, which is varied over a wide range, establishes the relative merit of enhancing and enabling technologies.

Detail on the Ballpark mode's methods of calculations, a user's guide containing sample inputs and outputs, complete software listings, and more detailed flowcharts are presented in Appendices A.1.1, A.2.1, A.3.1 and A.4.1, respectively.

8.2.2 THE GOODNESS MEASURE MODE

The operation of the Goodness Measure mode is summarized in Figure 8-4. This method calculates a score that indicates the total benefit that each goal derived from every possible combination of funded and nonfunded technologies. It then computes an overall sum or goodness measure as the weighted sum of the enhancements to enabled programs and contributions of completed programs to goals for each combination.

Figure 8-4 indicates the way enhancing technologies are handled: enhancements to a given program contribute not to the goals served by that program, but rather to a separate cost enhancement goal. If the relative weight given to the cost enhancement goal is increased, sets of technologies that emphasize cost saving will receive a higher score than those that enable many new technologies.



- ADVANTAGES
  - THOROUGH
  - ALLOWS HUMAN DECISION MAKER TO EXAMINE ALL COMBINATIONS THAT ARE NEARLY AS GOOD AS THE BEST
- DISADVANTAGES
  - LONG RUN-TIME — WITH 25 TECHS IT IS DIFFICULT TO EXAMINE EVERY COMBINATION

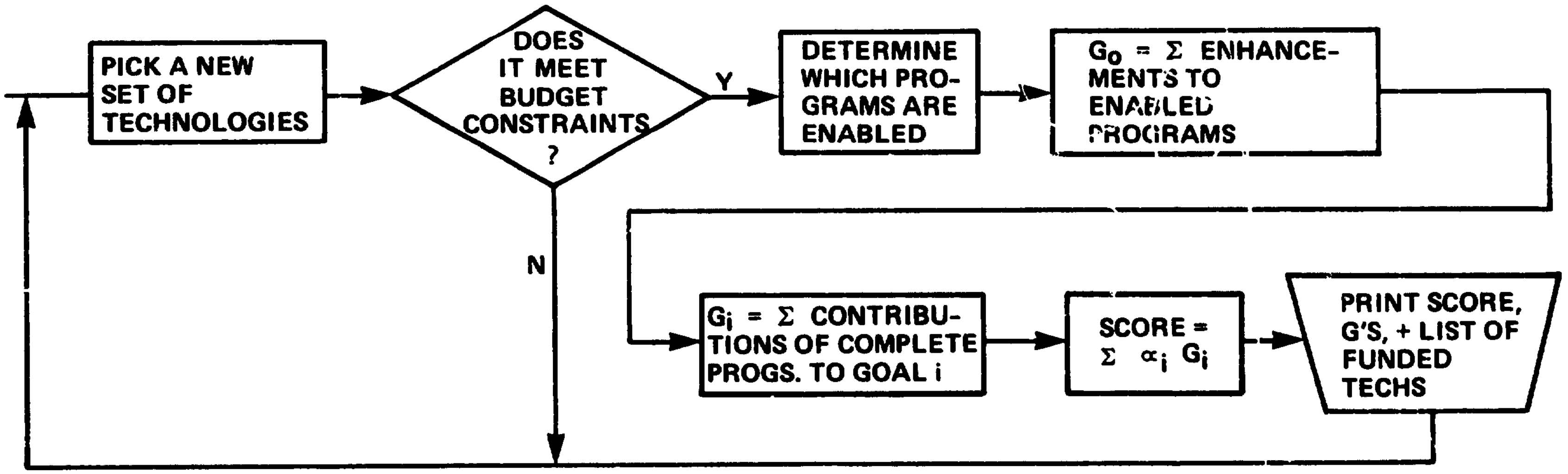


Figure 8-4. "PRISM" - Goodness Measure Mode

The enhancements associated with a given program are, of course, only added into the total if the program is enabled, i.e., if all technologies enabling that program are funded.

If there are not too many technologies, it may be possible to check every combination of funded and non-funded technologies. But this is not really necessary. If the total costs of many of the combinations of ten out of twenty technologies are in the neighborhood of the desired budget, it would probably be unnecessary to check combinations of fewer than five or more than fifteen. Eliminating these combinations from further consideration reduces the number of cases that must be considered - and consequently, computation time - by nearly 25 per cent.

To take advantage of such reductions in computation time, the program that performs these calculations first estimates the number of technologies that can be funded from the given budget. Call this number m. It first examines all combinations of m funded technologies, and compares the cost of each combination to the budget. If every combination of m technologies can be funded with enough money left over to fund the most expensive technology, the program automatically removes from consideration all combinations of (m-1) or fewer technologies. Similarly, if no combination of m technologies can be funded with enough money left over to fund the cheapest technology, all combinations of (m + 1) or more technologies are removed from consideration. When all feasible combinations have been checked, the program stops.

Detail on the Goodness Measure Mode's methods of calculation, a user's guide containing sample inputs and outputs, complete software listings, and more detailed flowcharts are presented in Appendices A.1.2, A.2.2, A.3.2, and A.4.2, respectively.

8.2.3 COMPARISON OF METHODS

The major advantage of the Ballpark Mode is its speed - its execution time is much less than that required for the Goodness Measure Mode. The major disadvantage is the fact that the Ballpark Mode does not guarantee an optimum solution. That is, the technique may find a local benefit maximum which is not the global maximum. It also will present a single combination of technologies as an output and will not permit examination of combinations of technologies which are almost as "good."

It is possible, however, to use any of several algorithms for computing the benefits of the technologies. If the results are different, the user can select that result yielding the highest total benefit.

Moreover, it will probably happen that certain technologies are always funded (or always eliminated) irrespective of the method of computation. The funding status of these can be fixed, yielding a reduced problem that may be solvable by the Goodness Measure Mode. The Ballpark Mode was used for this purpose in the PLACE Study. There were too many technologies identified (25) to evaluate all possible combinations (2^{25} cases). Therefore, the Ballpark Mode was employed to reduce the dimensionality of the problem.

While the Goodness Measure Mode will definitely identify the single "best" (producing highest benefit) combination of technologies, this is not its major advantage. Its major advantage is the fact that it will also print out all combinations of technologies that are nearly as good as the best one, and the user can specify how nearly. Thus, the program sifts out many worthless combinations and allows a human decision maker to concentrate on a relatively small number of worthwhile combinations.

The major disadvantage is the long run time. If there are n different technologies, there are 2^n different combinations of such technologies. Thus, if there are 30 technologies, there are over a billion combinations to investigate. Even if we restrict our attention to examining all possible combinations of ten of the thirty, there will be over 30 million combinations to investigate. Clearly, the Goodness Measure Mode is most useful if the Ballpark Mode can be used to reduce the number of technologies whose funding status is in doubt.

8.3 PRISM RESULTS

The results of the PRISM decision support tool being exercised will be discussed in this section. The results of a Delphi analysis which was used to establish the value of each program (system concept) to each goal (key set of mission objectives) will be presented in Section 8.3.1. The remaining required inputs including the costs of technologies will be presented in Section 8.3.2. Finally, the output of the PRISM software, both the Ballpark and Goodness Measure modes, will be discussed in Section 8.3.3.

8.3.1 DELPHI SURVEY DATA

The Delphi technique was utilized in PLACE as a systematic solicitation of expert opinion. Its purpose was to attain a group consensus on the contributions of the system concepts to PLACE's ket set objectives; a necessary input for both PRISM modes. This opinion took the form of answers in a written questionnaire. Included in the questionnaire was a brief description of each of the key set objectives and system concepts. From the onset, all the key set objectives were weighted equally. An important assumption made was that each mission objective was assumed to be independent, and the contributions of a system concept to a mission objective was independent of the contributions of other system concepts.

A sequence of three encounters was scheduled. To increase the reliability of the group estimates, a self appraised competence rating was used. These ratings were an attempt to evaluate the expertise of the group in each of the key set objective areas. The ratings ranged from expert through familiar in an area. An expert in any one of the objectives having worked more than three years in that field, ranked that objective in the expert box. Those familiar with the varied objectives, however, having no true indepth knowledge in a particular field, ranked this objective in the familiar box.

The Delphi technique was run as follows:

Round 1. Each group member initially ranked the systems in the order of importance to fulfill a given key set objective. For each response, the median and interquartile range (IQR) was determined. The IQR is the middle 50% of responses.

Round 2. Round 1 IQR's and medians were fed back to the respondents. They then reconsidered their previous answers in the light of the other participants' responses and then revised their answers if they wished to. If this response was outside the IQR, the respondent stated the reason his answer differed.

Round 3. Respondents were given the new IQR's, medians and a brief summary of reasons presented in support of extreme positions. The participants revised Round 2 responses if they so wished. If an answer was outside the IQR, the respondent was requested to state why he was unpersuaded by opposing arguments. The median of these final responses was taken as representing the group consensus.

The participants in the Delphi survey included eleven scientists and engineers with over 98 years of combined earth resources experience. Also included were six General Electric managers of earth resources programs, and the NASA PLACE Technical Officer.

Results of the Delphi analysis were observed to converge over the three rounds. That is, the interquartile range (a measure of the scatter) for the value of each program to each goal generally decreased with each round. The results of the Delphi analysis are presented in Table 8-1, the Goal Program Matrix. The table lists the contribution of each PLACE system concept

Table 8-1. The Goal Program Matrix

	CROP PRODUCTION FORECASTING	GRAZING POTENTIAL DETERMINATION	TIMBER STAND VOLUME ESTIMATION	GEOLOGICAL RESOURCES LOCATION	LAND USE AND CENSUS	WATERSHED MONITORING	WATER POLLUTION DETECTOR	ABRUPT EVENTS EVALUATION
Landsat H	0.14	0.13	0.13	0.12	0.13	0.13	0.13	0.11
GEO SAR	0.07	0.07	0.08	0.06	0.07	0.05	0.06	0.12
Parasol Radiometer	0.07	0.09	0.07	0.06	0.06	0.10	0.11	0.05
Radar Holographer	0.04	0.05	0.07	0.10	0.09	0.05	0.04	0.10
Earthwatch	0.14	0.13	0.13	0.11	0.13	0.13	0.14	0.15
Ferris Wheel Radar	0.02	0.03	0.04	0.14	0.05	0.07	0.04	0.04
Texturometer	0.08	0.08	0.09	0.08	0.07	0.04	0.05	0.04
Sweep Frequency Radar	0.08	0.07	0.07	0.05	0.08	0.06	0.08	0.07
Microsat	0.05	0.05	0.04	0.03	0.04	0.07	0.08	0.04
GEOS	0.12	0.11	0.11	0.07	0.12	0.12	0.13	0.14
TIM	0.08	0.08	0.07	0.11	0.10	0.09	0.11	0.08
Radar Ellipsometer	0.11	0.11	0.10	0.08	0.06	0.09	0.06	0.05

to each mission objective in the key set. The contributions to each mission objective have been normalized (all columns sum to 1.0).

Assuming that all goals are of equal value (an assumption that was carried throughout the PRISM analysis), that is, that crop production forecasting is equally as important an objective as grazing potential determination, the values may be summed horizontally to see a relative measure of the value of each program. This is illustrated in the nomogram of Figure 8-5. On this scale, the values have been normalized to a 0-100 rating. The parentheses indicate the actual values from the sums of Table 8-1. For example, if one sums the contributions of MICROSAT to each of the eight objectives, you arrive at .4, which is the lowest score of all the system concepts. In general, the multisensor system concepts, Landsat H and Earthwatch, scored quite well, while special purpose systems such as the Ferris Wheel Radar and the Texturometer were rated lower.

The data from the third round of the Delphi analysis is presented in Table 8-2. For each combination of a system concept and a mission objective, three values are presented: the interquartile range (middle 50% of re-

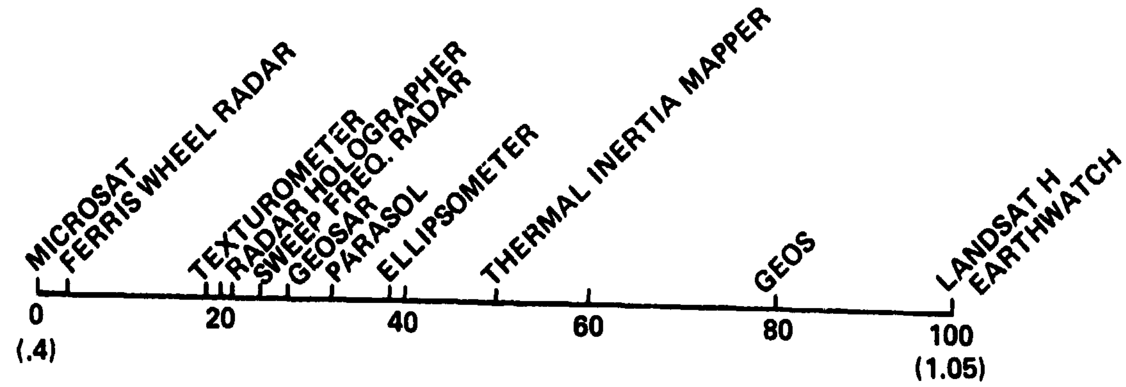


Figure 8-5. Relative Value of Programs

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Table 8-2. Delphi Analysis Third Round Responses

	CROP PRODUCTION FORECASTING			GRAZING POTENTIAL DETERMINATION			TIMBER STAND VOLUME ESTIMATION			GEOLOGICAL RESOURCES LOCATION			LAND USE AND CENSUS			WATERSHEı. MONITORIAC			WATER POLLUTION DETECTOR			ABRUPT EVENTS EVALUATION		
	IQR	MEDIAN	SCORE	IQR	MEDIAN	SCORE	IQR	MEDIAN	SCORE	IQR	MEDIAN	SCORE	IQR	MEDIAN	SCORE	IQR	MEDIAN	SCORE	IQR	MEDIAN	SCORE	IQR	MEDIAN	SCORE
LANDSAT H	14-15	14	.135	14-15	15	.134	15	15	.134	13-14	14	.120	14-15	15	.131	15	15	.134	13-14	14	.129	11-12	12	.114
GEO SAR	4-11	8	.070	4-11	6	.065	6-11	10	.076	6-7	6	.059	4-11	9	.073	5-8	5	.053	5-7	5	.056	12-13	13	.124
PARASOL RADIOMETER	6-10	7	.074	8-10	10	.086	7-8	7	.067	4-7	5	.055	5-8	7	.064	11-12	12	.103	11-12	11	.105	4-6	5	.054
RADAR HOLOGRAPHER	4-6	4	.043	4-5	4	.047	6-10	8	.072	10-12	10	.099	9-11	10	.093	4-6	5	.051	3-4	4	.035	9-11	10	.100
EARTHWATCH	14-15	14	.136	14-15	14	.133	14	14	.128	11-13	11	.112	14	14	.128	14	14	.128	15	15	.142	15	15	.146
FERRIS WHEEL RADAR	1-4	3	.024	3-4	3	.030	3-4	4	.038	15	15	.136	3-8	5	.047	6-10	8	.073	3-4	4	.035	3-6	4	.041
TEXTUROMETER	9	9	.082	9-10	9	.084	9-10	10	.087	5-8	8	.077	6-9	8	.067	3-4	4	.039	4-6	4	.047	3-5	4	.036
SWEEP FREQUENCY RADAR	7-10	8	.075	5-9	9	.072	8-10	8	.074	5-6	6	.052	7-10	9	.079	5-7	6	.057	7-10	9	.077	7-8	8	.074
MICROSAT	4-6	5	.048	4-6	6	.050	4-5	5	.044	2-5	4	.034	4-5	4	.040	4-10	7	.065	9-10	9	.080	4	4	.041
GEOS	12-13	13	.121	11-13	12	.112	12-13	12	.113	6-10	7	.072	13	13	.121	13	13	.118	13-14	13	.125	14	14	.137
TIM	5-10	8	.080	7-9	8	.081	5-8	6	.067	11-12	12	.108	10-12	10	.097	8-10	10	.088	11-13	12	.113	7-10	9	.082
RADAR ELLIPSOMETER	12-13	12	.112	11-12	12	.106	11-12	12	.100	5-10	7	.076	6-8	7	.060	9-11	7	.091	5-6	9	.056	4-6	6	.051

sponses), the median, and the score. The IQR and median are in the original ranking units (0-15) while the score has been normalized.

8.3.2 PRISM INPUTS AND ASSUMPTIONS

A number of inputs were required to run PRISM, including:

(1) Program Goal Matrix
(2) Technology Enablement Matrix
(3) Technology Enhancement Matrix
(4) Technology Costs
(5) Dollars/Utils Ratio
(6) Goal Weighting Vector
(7) Funding Levels

The Program Goal Matrix (1) was derived from the Delphi analysis as discussed in Section 8.3.1, and is presented in Table 8-2. The Technology Enablement and Technology Enhancement Matrices (2,3) identified technologies which were required by a program and those that reduced its implementation cost. This matrix was discussed in Section 7 and is presented in Figure 7-2. The Technology Costs (4) were estimates obtained from technology experts through a Technology Assessment Poll which is described in Section 7.1. The costs, which are presented in Figure 8-6, are for technology research only over a fifteen year period. They do not include any program development costs. They are costs to NASA and they assume additional funding from external sources such as private industry or the Department of Defense. The "guesstimates" are for research through a prototype flight (e.g., on Shuttle) or other suitable technology demonstration. A review of what is included in each technology area (Section 7) is key to an understanding of these cost estimates. The Dollars/Utils Ratio (5) was a factor that related dollar savings to the utils in the Program Goal Matrix. By raising or lowering it, one can make enabling or enhancing technologies more valuable. This ratio was varied over a wide range in the analysis. The Goal Weighting Vector (6) stipulates the relative values of each of the mission objectives in the key set. As was mentioned earlier, all goals were assumed to be of equal value for this exercise. The Funding Levels (7) used were fractions of the funding needed to support all technology areas. The above restrictions constitute assumption set "A".

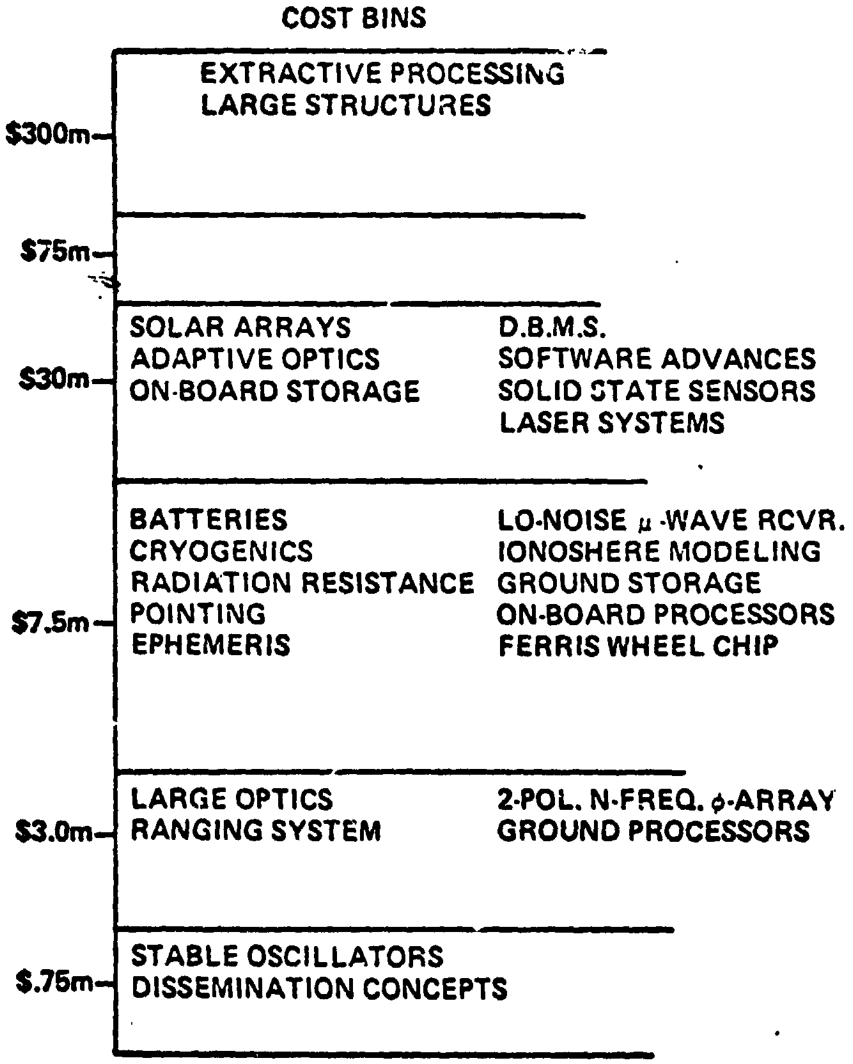

Figure 8-6. "Guesstimated" Technology Costs

8.3.3 OPTIMUM TECHNOLOGY RANKING/FUNDING FOR VARIOUS BUDGET LEVELS

With the inputs described in Section 8.3.2, PRISM was exercised in both Goodness Measure and Ballpark modes. This section discusses the results.

Ballpark Mode Results

To understand fully how the results listed in Figure 8-7 were obtained, it may be useful to follow the sample computer printout in the User's Guide of Appendix A.2.1 describing this mode. As previously discussed, for a given 15 year research budget, certain technologies were funded and subsequently programs were enabled. The benefit/cost algorithm was chosen to determine the criterion for technology funding.

It is obvious that if one has the money to fund all the technologies, all the programs are enabled. For the sample budget level of $900M, all technologies were funded since only $898.5M was spent. For the next budget of $750M, the benefit criterion was chosen for determining technology funding. That is, the technologies that produced the lowest benefit were iteratively eliminated until the budget was met. The Ballpark mode did not enable the Texturometer because the technology of adaptive optics produced low benefits. On the other hand, with the same budget level but using the benefit/cost criterion, this mode did not enable any of the large structure systems. The program could not justify spending $300M on large structures since its benefit/cost was low. Since the Ballpark mode independently and successively removes one technology at a time, until the budget level is met, a situation where budgets of $750M, $600M and $500M funded the same technologies arose. The program got to the point where the cost of the remaining technologies was $753M and had to get below $750M. Using the benefit/cost criterion, it then decided to eliminate the large structure technology which cost $300M.

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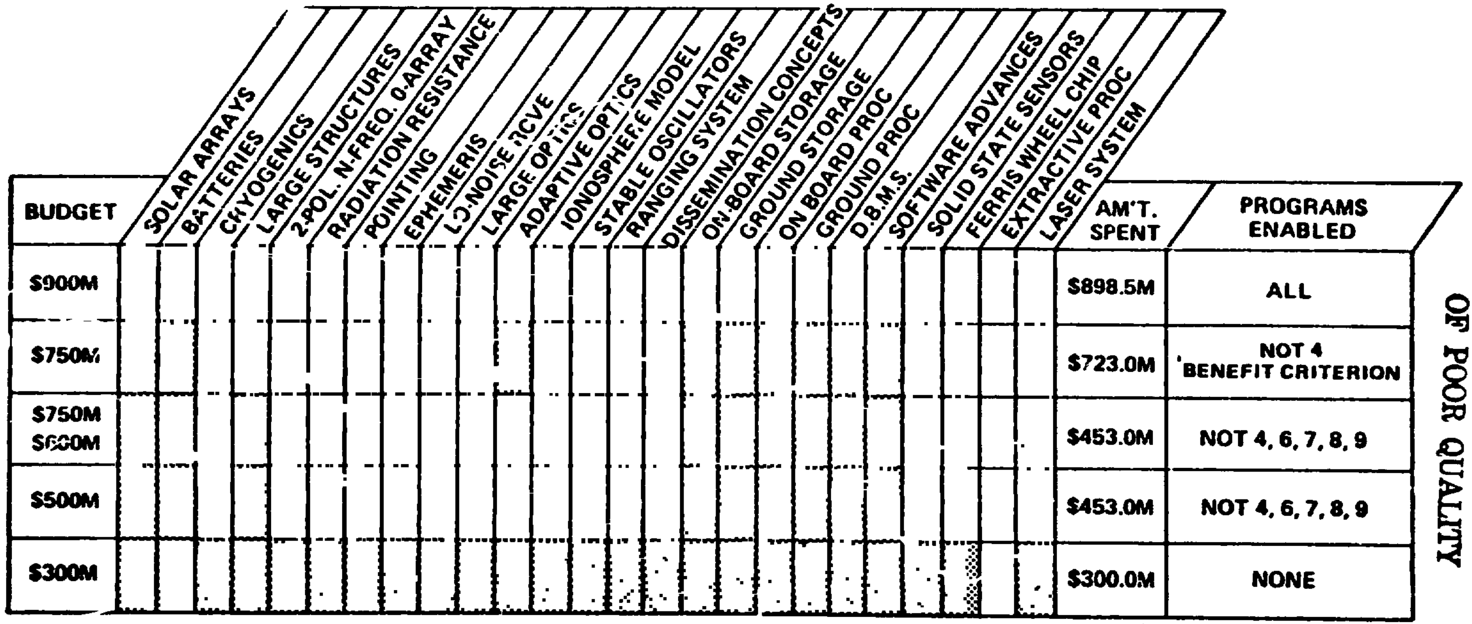
*ASSUMPTION SET B–(LOWER $/UTILS)

☐ = FUNDED
▨ = NOT FUNDED

PROGRAM KEY:

1. LANDSAT H
2. EARTHWATCH
3. GEOS
4. TEXTUROMETER
5. THERMAL INERTIA MAPPER
6. MICROSAT
7. PARASOL
8. ELLIPSOMETER
9. FERRIS WHEEL
10. SWEEP FREQUENCY RADAR
11. GEOSAR
12. HOLOGRAPHER



BUDGET	AM'T. SPENT	PROGRAMS ENABLED
$900M	$898.5M	ALL
$750M	$723.0M	NOT 4 'BENEFIT CRITERION
$750M $600M	$453.0M	NOT 4, 6, 7, 8, 9
$500M	$453.0M	NOT 4, 6, 7, 8, 9
$300M	$300.0M	NONE

Figure 8-7. "PRISM" - Ballpark Mode - Results*

This reduced the cost of the remaining technologies to $453M, which was then used for all three budget levels. As an aside, a budget of $300M was allocated to see what technologies Ballpark mode would fund. Only extractive processing (cost - $300M) was funded because it had the highest benefit/cost ratio; however, none of the programs was enabled because they required other enabling technologies and the budget had all been spent in one place.

Goodness Measure Mode Results

To understand fully how the results listed in Figure 8-8 were obtained, it may be useful to follow the sample computer printout in the User's Guide of Appendix A.2.2 describing this mode.

The results from the Ballpark Mode provided several alternative starting points for the Goodness Measure Mode. These starting points took the form of a group of technologies which were always funded and a group which were never funded, reducing the number of iterations to be evaluated. The combination with the highest Goodness Measure was then selected as the optimal funding allocation.

For 15 year research budget levels of $900M and $300M, results similar to those of the Ballpark mode were obtained. At the $300M funding level, the unique importance of extractive processing was again pointed out. Two cases were run at the $750M level, with different dollars/utils ratios. In the latter case, cost savings were weighted heavier, slightly favoring enhancing technologies. A reasonable limit was placed on this ratio by the assumption that a program's total implementation cost savings should not exceed half the program's cost. Funding allocations for the next two budget levels ($600M and $500M) are those that maximized the Goodness Measure as defined in Section 8.2.2.

*ASSUMPTION SET A

PROGRAM KEY:

1. LANDSAT H	7. PARASOL
2. EARTHWATCH	8. ELLIPSOMETER
3. GEOS	9. FERRIS WHEEL
4. TEXTUROMETER	10. SWEEP FREQUENCY RADAR
5. THERMAL INERTIA MAPPER	11. GEOSAR
6. MICROSAT	12. HOLOGRAPHER

☐ = FUNDED
▨ = NOT FUNDED

BUDGET	SOLAR ARRAYS	BATTERIES	CRYOGENICS	LARGE STRUCTURES	2-POL. N-FREQ. Ø ARRAY	RADIATION RESISTANCE	POINTING	EPHEMERIS	LO-NOISE RCVR	LARGE OPTICS	ADAPTIVE OPTICS	IONOSPHERE	STABLE OSCILLATORS	RANGING SYSTEM	DISSEMINATION CONCEPTS	ON-BOARD STORAGE	GROUND STORAGE	ON-BOARD PROC	GROUND PROC	D.B.M.S.	SOFTWARE ADVANCES	SOLID STATE SENSORS	FERRIS WHEEL CHIP	EXTRACTIVE PROC	LASER SYSTEMS	AM'T. SPENT	PROGRAMS ENABLED
$900M																										$898.5M	ALL
$750M	▨	▨	▨						▨							▨			▨	▨	▨		▨			$745.5M	NOT 6, 7, 9
$750M	▨	▨									▨			▨		▨	▨	▨	▨	▨						$750.0M	NOT 4 (HIGHER $/UTILS)
$600M				▨										▨									▨			$588.0M	NOT 4, 6, 7, 8, 9
$500M		▨	▨	▨					▨		▨			▨			▨		▨		▨		▨			$495.0M	NOT 4, 6, 7, 8, 9
$300M	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		▨	$300.0M	NONE

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Figure 8-8. "PRISM" - Goodness Measure Mode - Results*

REFERENCES

Greenberg, G.A. et al, Research on the Problem of Efficient R&T Program Formulation Under Conditions of Uncertainty and Risk, Princeton University, Contract No. NSG-7131, April 1976.

Appendix A - The Priority Structuring Methodology (PRISM)

Detail concerning the implementation and operation of the Priority Structuring Methodology, PRISM, is presented in this Appendix. Section A.1 contains more detail on the methods of calculation in each operating mode. Section A.2 contains a user's manual for PRISM with sample inputs and outputs. Contained in Sections A.3 and A.4 are complete listings for the program and detailed flow charts.

A.1 METHODS OF CALCULATION

After reading in the input data, the program multiplies the goal-program matrix by the vector containing the relative values of the goals. The resultant vector contains the relative values of the programs.

After printing out the input data and reading in the amount of funding available, the program calls the VERSUM subroutine, which counts the number of 1's in each column of the matrix. The results the vector, IPCRIT, records the number of enabling technologies required by each program.

The main program then fills the X vector (technology vector) with ones and calls the COMPRG subroutine. This subroutine multiplies the X-vector by the transpose of the c matrix and compares each element of the resulting vector to the corresponding element of the IPCRIT vector. Equality means that all the technologies that enable the corresponding program are funded, and the corresponding element in the Y vector is set equal to 1; otherwise it is set to zero.

The total cost of the X-vector is calculated by multiplying the X-vector and the transpose of the technology cost vector col. If the total cost is less than the amoung of funds available, the program calculater the total benefit of the completed programs, adds the benefits due to any enhancing technology, and then quits.

Otherwise the program calculates the benefits due to each technology by summing benefits of each complete program it enables and each complete program it enhances. If OPTION 1 is equal to 2 the benefit score for technology i is

$$\mathrm{BENEFIT}_i = k \sum_{j=1} \left[Y_j C_{ij} P_j / \mathrm{ICRIT}_j \right] + \sum_{j=1} Y_j \, B_{ij}$$

If option 1 = 1, the score is

$$\mathrm{BENEFIT}_i = k \sum_{j=1} Y_j C_{ij} P_j + \sum_{j=1} Y_j \, B_{ij}$$

If OPTION 2 - 1,

$\mathrm{Rho}_i = \mathrm{BENEFIT}_i / \mathrm{cost}\ i;$

if option 2 = 2,

$\mathrm{The}_i = \mathrm{BENEFIT}_i$

The subroutine LEAST finds the minimum rho and produces a vector 'LOWEST'. $\mathrm{LOWEST}_i = 1$ if Rho_i is within RHODEL percent of the minimum Rho and zero otherwise.

Another function, ISEL_2, selects the one of these minimum benefit technologies that represents the technology contributing to the fewest complete programs. This technology is defunded, and the resulting new X-vector is evaluated.

A.1.2 PRISM - GOODNESS MEASURE MODE - METHODS OF CALCULATION

This method requires three matrices: the G matrix gives the importance of each program to each goal; the Q matrix indicates which technologies enable each program, and the B matrix indicates the cost saving in each program due to each technology. The flow chart in Appendix C.4 indicates the sequence of calculations.

After reading in the input data, the program first allocates funds to the technologies that must always be funded. If there is no money left over, it stops.

If there is money left over, it assumes that the first m (where m is either a user-supplied estimate or the computed average number of technologies that can be funded with the given budget) non- fixed technologies in the technology vector are funded, and puts 1's in corresponding locations in the technology vector. If these m technologies are either too expensive (the total cost greater than the amount of funds left) or too cheap (total cost less than the budget less the cost of the most expensive technology) the program discards this collection, picks a new set of m technologies and continues the same process.

If the collection of funded technologies meets the budget constraints, the program looks to see which programs are enabled by this collection of technologies. It does this using the following method: wherever element q_{ij} of the IQ matrix equals zero, the program substitutes the value of tech$_i$, the corresponding element in the technology vector. If the sum of the elements in column j in this modified IQ matrix equals the number of technologies, program j is enabled and the jth element of the program vector is a one; otherwise the program is not enabled and the element is zero.

Next the program looks at enhancing technologies. If tech$_i$ equals one and $B_{ij} > 0$, B_{ij} is added to element G $(j,0)$ in the computer-supplied zeroth column of the g matrix. The jth element of this column indicates the dollar value of the total enhancements to the jth program. If there are any enabling technologies ($B_{ij} < 0$) in the jth column of the B matrix, the value COSPRG (j) is subtratacted from $G_{j,0}$).

The program vector is then post multiplied by the G matrix to produce a score vector, and the score vector is premultiplied by the transposed ALPHA vector to produce a score. If the score exceeds a user-specified threshold, the technology vector, score vector, cost and score are printed. The program then goes back and selects another combination of funded technologies.

When all combinations of M funded technologies have been examined, the program examines the most expensive and the cheapest of all the combinations of M funded technologies. If the cheapest of these was beyond the budget, no higher M's will be considered. From among the M's remaining to be tried, the program selects the smallest one that is larger than the current M. If there are no larger M's, it selects the largest remaining M. The program once more starts examining combinations of M technologies. When all M's have been tried or eliminated from consideration, the program prints the best score and technology vector, then stops.

A.2 OPERATOR'S MANUAL

A.2.1 PRISM - BALLPARK MODE USER'S GUIDE

Ballpark is an interactive program that uses a top down method to calculate a "heuristic" solution to the funding allocation problem.

The user can choose either of two ways to calculate the benefit, and can successively drop either the technology with the lowest benefit or the lowest benefit/cost rate.

Input Format:

The variable that the user must enter include:

NAME	TYPE	DESCRIPTION
NUMGOL	I	Number of goals
NUMPRG	I	Number of programs
NUMTEC	I	Number of technologies
IDGOL	I (numgol)	Set of one or two digit numbers used to identify goals
IDPRG	I (numprg)	Set of one or two digit numbers used to identify programs
IDTEC	I (numtec)	Set of one or two digit numbers used to identify technologies
A	R (numprg, numgol)	Goal-program matrix. A high number for A(i,j) means that program i contributes a lot to goal j.
G	R (numtec, numprg)	Program-technology enhancement matrix B (i,j) indicates the amount by which technology i enhances program j
IC	Z (numtec, numprg)	Program-technology enablement matrix. IC (i,j) = 1 means technology i enables program j
FUDGE	R	Enable-enhance fudge factor. Multiplies component of benefits due to enablements when benefits are summed
COSTEC	R (numtec)	costs of technologies
BENGOL	R (numgol)	relative benefits of goals
FUNDS	R	Amount of funds available. Funds = 0 brings end of run
OPTION 1	I	1: benefit of enabling tech $= \sum$ benefit of progs it enables 2: " " " $= \sum \frac{\text{benefit of prog. it enables}}{\text{\# of techs.}}$
OPTION 2	I	1: look only at benefit/cost ratio 2: look only at benefit

Output

The program reprints all input data so the user can check it for correctness. The values of each program are also calculated and printed. In the interaction matrices, zeros are suppressed.

For a given amount of funds and set of options the program prints out the list of funded technologies that will meet the budget the total cost, and the total benefit. The user can either enter a new level of funding, exercise other options, or quit.

SAMPLE PROBLEM BALLPARK MODE

INPUT:

```
          ALLOCATION OF FUNDS AMONG INTERDEPENDENT PROGRAMS


ENTER NUMGOL,NUMPRG,NUMTEC                          8,12,25
ENTER THE GOAL IDENTIFICATION VECTOR = IDGOL;       idgol;
ENTER THE PROGRAM ID VECTOR = IDPRG;                idprg;
ENTER THE TECHNOLOGY ID VECTOR = IDTEC;             idtec;
ENTER THE PROGRAM-GOAL MATRIX, INPUT=GMATRIX;       gmatrix;
ENTER THE B MATRIX,INPUT=BMATRIX;                   bmatrix;
ENTER THE C MATRIX,INPUT=CMATRIX;                   cmatrix;
ENTER THE ENABLE-ENHANCE FUDGE FACTOR               500
ENTER THE TECHNOLOGY COST VECTOR,INPUT=COSTEC;      cost;
ENTER THE GOAL BENEFIT VECTOR                        1,1,1,1,1,1,1,1
```

OUTPUT:

```
INPUT DATA:

GOAL #  DESCRIPTION                   RELATIVE VALUE
    1_____________________________    1.00
    2_____________________________    1.00
    3_____________________________    1.00
    4_____________________________    1.00
    5_____________________________    1.00
    6_____________________________    1.00
    7_____________________________    1.00
    8_____________________________    1.00
```

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PROG #	DESCRIPTION	RELATIVE VALUE
11		1.03
12		0.58
13		0.61
14		0.54
15		1.05
16		0.42
17		0.52
18		0.56
19		0.40
20		0.92
21		0.72
22		0.65

TECH #	DESCRIPTION	COST
1		30.00
2		7.50
3		7.50
4		300.00
5		3.00
6		7.50
7		7.50
8		7.50
9		7.50
10		3.00
11		30.00
12		7.50
13		0.75
14		3.00
15		0.75
16		30.00
17		7.50
18		7.50
19		3.00
20		30.00
21		30.00
22		30.00
23		7.50
24		300.00
25		30.00

```
INTERACTION MATRICES

GOALS AND PROGRAMS

            GOALS

                1       2       3       4       5       6       7       8

PROG ----------------------------------------------------------------------------
 11      !  0.14    0.13    0.13    0.12    0.13    0.13    0.13    0.11
 12      !  0.07    0.07    0.08    0.06    0.07    0.05    0.06    0.12
 13      !  0.07    0.09    0.07    0.06    0.06    0.10    0.11    0.05
 14      !  0.04    0.05    0.07    0.10    0.09    0.05    0.04    0.10
 15      !  0.14    0.13    0.13    0.11    0.13    0.13    0.14    0.15
 16      !  0.02    0.03    0.04    0.14    0.05    0.07    0.04    0.04
 17      !  0.08    0.08    0.09    0.08    0.07    0.04    0.05    0.04
 18      !  0.08    0.07    0.07    0.05    0.08    0.06    0.08    0.07
 19      !  0.05    0.05    0.04    0.03    0.04    0.07    0.08    0.04
 20      !  0.12    0.11    0.11    0.07    0.12    0.12    0.13    0.14
 21      !  0.08    0.08    0.07    0.11    0.10    0.09    0.11    0.08
 22      !  0.11    0.11    0.10    0.08    0.06    0.09    0.06    0.05



PROGRAMS AND TECHNOLOGIES:B-MATRIX

            PROGRAMS
              11      12      13      14      15      16      17      18      19      20      21      22

TECH -----------------------------------------------------------------------------------------
  1      ! 30.00    0.75    7.50    0.75    3.00    7.50    0.75    3.00    3.00    0.75    0.75    0.75
  2      !  0.75    0.30    3.00    0.30    0.30    3.00    0.30    0.30    0.30    0.30    0.30    0.30
  3      !  3.00                            3.00                    0.75                    3.00
  4      !                                                                         30.00
  5      !                  7.50            3.00    7.50                    7.50                    7.50
  6      !          0.75            0.75                                            0.75
  7      !  0.30    0.30                                                                    0.30
  8      !  0.30    0.30            0.30                                                    0.30
  9      !                                                          0.75                            0.75
 10      !
 11      !                                                                         30.00
 12      !                                         30.00            3.00
 13      !  0.30                            0.30                    0.30            0.30
 14      !                  3.00                    3.00                    3.00                    3.00
 15      !  3.00    3.00    0.75    0.75    3.00                    0.75    0.75            0.75    0.75
 16      !  7.50    7.50            3.00    7.50                    3.00            3.00
 17      !  3.00    3.00    3.00    3.00    3.00    3.00    3.00    3.00    3.00    3.00    3.00    3.00
 18      !  7.50    7.50            3.00    7.50            3.00                    3.00
 19      !  0.75    0.75    0.75    0.75    0.75    0.75    0.75    0.75    0.75    0.75    0.75    0.75
 20      !  7.50    7.50    3.00    3.00    7.50    3.00    3.00    3.00    3.00    7.50    3.00    3.00
 21      !  3.00    3.00   30.00    3.00    3.00   30.00    7.50    3.00    7.50    7.50    3.00    7.50
 22      !                                                                                  0.30
 23      !
 24      !                                          3.00
 25      !
```

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```
PROGRAMS AND ENABLING TECHNOLOGIES: C-MATRIX


        PROGRAMS
          11   12   13   14   15   16   17   18   19   20   21   22

TECH -------------------------------------------------------------
   1   !
   2   !
   3   !             1                             1
   4   !             1              1    1         1              1
   5   !                                      1
   6   !                       1
   7   !                       1                        1
   8   !                       1                        1
   9   !             1                             1
  10   !                                 1              1
  11   !                                 1
  12   !                  1                                       1
  13   !        1
  14   !                                 1
  15   !                                                1
  16   !
  17   !
  18   !
  19   !
  20   !
  21   !
  22   !   1                   1         1              1
  23   !             1              1
  24   !   1    1    1    1    1         1    1    1    1    1    1
  25   !   1                   1                             1


ENTER THE AMOUNT OF FUNDS AVAILABLE
=750

ENTER OPTION1: 1-NON-ALLOCATED COST;2-ALLOCATED
=1

ENTER OPTION2; 1-BENEFIT/COST;2-BENEFIT
=1
```

```
THE TOTAL FUNDING AVAILABLE IS  750.00 DOLLARS

FUNDED TECHNOLOGIES:
      3
      5
      6
      7
      8
      9
     10
     11
     12
     13
     14
     15
     22
     23
     24
     25

PROGRAMS COMPLETED:
     11
     12
     14
     15
     18
     20
     21

TOTAL FUNDS EXPENDED: 453.00 DOLLARS

total benefit from programs:    10855.60

ENTER THE AMOUNT OF FUNDS AVAILABLE
=750

ENTER OPTION1: 1-NON-ALLOCATED COST;2-ALLOCATED
=1

ENTER OPTION2; 1-BENEFIT/COST;2-BENEFIT
=2

THE TOTAL FUNDING AVAILABLE IS  750.00 DOLLARS

FUNDED TECHNOLOGIES:
      3
      4
      5
      6
      7
      8
      9
     10
     12
     13
     14
     15
     22
     23
     24
     25
```

```
PROGRAMS COMPLETED:
    11
    12
    13
    14
    15
    16
    18
    19
    20
    21
    22

TOTAL FUNDS EXPENDED: 723.00 DOLLARS

total benefit from programs:    15105.60

ENTER THE AMOUNT OF FUNDS AVAILABLE
=600

ENTER OPTION1: 1-NON-ALLOCATED COST;2-ALLOCATED
=1

ENTER OPTION2; 1-BENEFIT/COST;2-BENEFIT
=2

THE TOTAL FUNDING AVAILABLE IS  600.00 DOLLARS

FUNDED TECHNOLOGIES:
    22
    24
    25

PROGRAMS COMPLETED:
    11
    21

TOTAL FUNDS EXPENDED: 360.00 DOLLARS

total benefit from programs:     3496.30

ENTER THE AMOUNT OF FUNDS AVAILABLE
=1

ENTER OPTION1: 1-NON-ALLOCATED COST;2-ALLOCATED
=1

ENTER OPTION2; 1-BENEFIT/COST;2-BENEFIT
=1

THE TOTAL FUNDING AVAILABLE IS    1.00 DOLLARS

FUNDED TECHNOLOGIES:
    15

PROGRAMS COMPLETED:

TOTAL FUNDS EXPENDED:   0.75 DOLLARS

total benefit from programs:        0.
```

```
ENTER THE AMOUNT OF FUNDS AVAILABLE
=600

ENTER OPTION1: 1-NON-ALLOCATED COST;2-ALLOCATED
=1

ENTER OPTION2; 1-BENEFIT/COST;2-BENEFIT
=1

THE TOTAL FUNDING AVAILABLE IS  600.00 DOLLARS

FUNDED TECHNOLOGIES:
      3
      5
      6
      7
      8
      9
     10
     11
     12
     13
     14
     15
     22
     23
     24
     25

PROGRAMS COMPLETED:
     11
     12
     14
     15
     18
     20
     21

TOTAL FUNDS EXPENDED: 453.00 DOLLARS

total benefit from programs:    10855.60
```

```
=500

ENTER OPTION1: 1-NON-ALLOCATED COST;2-ALLOCATED
=1

ENTER OPTION2; 1-BENEFIT/COST;2-BENEFIT
=1

THE TOTAL FUNDING AVAILABLE IS  500.00 DOLLARS

FUNDED TECHNOLOGIES:
     3
     5
     6
     7
     8
     9
    10
    11
    12
    13
    14
    15
    22
    23
    24
    25

PROGRAMS COMPLETED:
    11
    12
    14
    15
    18
    20
    21

TOTAL FUNDS EXPENDED: 453.00 DOLLARS

total benefit from programs:     10855.60

ENTER THE AMOUNT OF FUNDS AVAILABLE
=500

ENTER OPTION1: 1-NON-ALLOCATED COST;2-ALLOCATED
=1

ENTER OPTION2; 1-BENEFIT/COST;2-BENEFIT
=2

THE TOTAL FUNDING AVAILABLE IS  500.00 DOLLARS

FUNDED TECHNOLOGIES:
    22
    24
    25

PROGRAMS COMPLETED:
    11
    21

TOTAL FUNDS EXPENDED: 360.00 DOLLARS

total benefit from programs:     3496.30
```

A.2.2 PRISM - GOODNESS MEASURE MODE USER'S GUIDE

GM is an interactive program that uses the Goodness Measure Mode to calculate value scores for every possible combination of funded and nonfunded technologies. As it is currently constituted it will handle a tree with up to nine goals, twelve programs, and twenty five technologies.

The program offers the following convenience features:

- If he wishes, the user can indicate that certain technologies are always funded.
- If the program stops before completion, the user can restart it where it quit without repeating combinations already checked.
- The user can either decide explicitly how many funded technologies there should be in the collection investigated or he can let the program decide. As calculations progress, the user can revise his initial estimate.
- The program only prints out combinations whose value scores exceed a user-provided threhold. This threshold can be changed as calculations progress.

Input format:

The variable that the user must enter include:

NAME	TYPE *	DESCRIPTION
NUMGOL	I	Number of goals (exclusive of the cost reducting goal)
NUMPRG	I	Number of programs
NUMTEC	I	Number of technologies
NUMFIX	I	Number of technologies whose funding status the users wishes to prespecify (must be less than numtec)
IDGOL	I (numgol)	Set of two-digit numbers used to identify the goals
IDPRG	I (numprg)	Set of two digit numbers used to identify the programs
IDTEC	I (numtec)	Set of two digit numbers used to identify the technology
G	R (NUMPRG, NUMGOL)	Goal-program matrix. A high number for G (i,u) means that program i contributes a lot to goal j
IQ	Ƶ (numtec, numprg)	Program-technology enabling matrix. NOTE: IQ (ij) = 1: technology i does not enable program j. IQ(i,j)=0: technology i enables program
B	R (numtec, numprg)	Program-technology enhancement matrix. B(i,j) > 0 technology i enhances program j = 0 technology i is irrelevant to program j < 0 technology i enables program j
Alpha	R (numgol + 1)	Weights on the goals. The first element is the weight on the cost-enhancement goal.

* I = Integer
R = Real
l = Logical

Ƶ = Integer, zero or 1 only
(n) = vector (order)
(i, j) = Matrix (rows, columns)

NAME	TYPE	DESCRIPTION
COSTEC	R(numtec)	costs of the technologies
COSPRG	R(numprg)	Costs of the programs - to be subtracted from enhanced programs (see "Technology Dollar Benefits", above).
*(Fixed tech)	L (numfix)	Fixed portion of technology vector T: this program is funded F: this program is not funded.
BUDGET	R	Amount of funds available to spend on technologies
IGUESS	I	An estimate of m, the number of technologies that can be funded with the given budget. Entering 0 causes the program to estimate IGUESS by taking the integer part of the number obtained when that portion of budget not used up by fixed technologies is divided by the average cost of the non-fixed technologies
* ITALLY	L)numtec)	A vector that keeps track of which M values should or should not be tried. ITally (I) = .true. means "don't bother to check M = I". The program automatically makes ITALLY (M). = .true. after all combinations of M funded technologies have been tested. It also makes M true for values that can't possibly meet the budget constraints.
* IADD	I (M)	A vector that indicates which M technologies are funded in the initial collection, e.g. 4,2,1 indicates that the first, second & fourth technologies are funded. NOTE: the numbers <u>must</u> be entered in descending numerical order.
THRESH	R	A value threshold. The program will not print results whose total value is less than THRESH. THRESH is initially zero; after 25 combinations have been printed out, the user enters a new value of thresh taking into account the score values produced by the first 25 combinations. After the program has printed 25 scores above this threshold, the user is once more asked to enter a threshold value. By properly specifying the threshold value, the user, can eliminate the time wasted by printing out many not-very productive combinations. NOTE: It is better to make "thresh" a little low rather than too high. If "thresh" is too low, the program prints out marginal combinations that can be ignored; if it is too high, the program does not print combinations which might be valuable, and there is no way these unprinted values can be recovered without rerunning the program.

* Entry of these variables optional

Output

The GM program reprints all input data so the user may check its correctness. Matrices are printed with the correct orientation (rows horizontal). In the interaction matrices, zeros are suppressed. The matrix relating programs to enabling technologies inserts the appropriate element of the technology vector in place of zeros in the original input data. In the enhancement matrix, asterisks indicate technologies enabling programs, real numbers indicate technologies enhancing programs, and blanks indicate technologies that are irrelevant to programs.

For each combination of technologies whose total score exceeds the threshold value and whose cost is neither too great nor too small, the program prints the score, cost, and a record of the technology vector. In this record, T's indicate funded technologies, F's indicate non-funded technologies'.

SAMPLE PROGRAM GOODNESS MEASURE MODE

INPUT:

```
*frun#easy4"41"
enter the number of goals,programs,technologies and the number of fixed techs.
enter the goal identification vector
enter the program id vector = idprg;
ENTER TECH ID S. REMEMBER THE FIRST  19 ARE     FIXED
enter the goal-program matrix , input=gmatrix;
enter the qmatrix, input=qmatrix;
enter the b matrix, input=matrixb;
enter the alpha vector
enter the technology cost vector = costec;
enter the program cost vector = cosprg;
ENTER FIXED PORTION OF TECH VECTOR. T = FUNDED,      F = NOT FUNDED


8,12,25,19
idgol;
idprg;
idtec;
gmatrix;
iqmatrix;
matrixb;
1.e-5,1. 1.,1.,1.,1.,1.,1.,1.
costec;
cosprg;
t,f,f,t,f,t,f,f,t,t,t,t,t,t,t,t,t,t,t
```

OUTPUT:

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```
INPUT DATA:

GOAL #  DESCPIPTION                         ALPHA
     1__________________________________    1.00
     2__________________________________    1.00
     3__________________________________    1.00
     4__________________________________    1.00
     5__________________________________    1.00
     6__________________________________    1.00
     7__________________________________    1.00
     8__________________________________    1.00

PROG #  DESCRIPTION                         PROG COST
    11__________________________________    300.00
    12__________________________________    300.00
    13__________________________________  10000.00
    14__________________________________    300.00
    15__________________________________    300.00
    16__________________________________  10000.00
    17__________________________________   2000.00
    18__________________________________    300.00
    19__________________________________   2000.00
    20__________________________________   2000.00
    21__________________________________    300.00
    22__________________________________   2000.00

TECH #  DESCRIPTION                         COST
     1__________________________________    300.00
     2__________________________________      7.50
     3__________________________________      7.50
     4__________________________________    300.00
     5__________________________________      7.50
     6__________________________________      3.00
     7__________________________________      3.00
     8__________________________________      7.50
     9__________________________________     30.00
    10__________________________________      0.75
    11__________________________________      0.75
    12__________________________________     30.00
    13__________________________________     30.00
    14__________________________________      3.00
    15__________________________________      7.50
    16__________________________________      3.00
    17__________________________________      7.50
    18__________________________________      7.50
    19__________________________________      7.50
    20__________________________________      7.50
    21__________________________________      7.50
    22__________________________________     30.00
    23__________________________________     30.00
    24__________________________________     30.00
    25__________________________________     30.00
```

INTERACTION MATRICES

G-MATRIX: GOALS AND PROGRAMS

GOALS

PROG	1	2	3	4	5	6	7	8
11	0.135	0.134	0.134	0.120	0.131	0.134	0.129	0.114
12	0.070	0.065	0.076	0.059	0.073	0.053	0.056	0.124
13	0.074	0.086	0.067	0.055	0.064	0.103	0.105	0.054
14	0.043	0.047	0.072	0.099	0.093	0.051	0.035	0.100
15	0.136	0.133	0.128	0.112	0.128	0.128	0.142	0.146
16	0.024	0.030	0.038	0.136	0.047	0.073	0.035	0.041
17	0.082	0.084	0.087	0.077	0.067	0.039	0.047	0.036
18	0.075	0.072	0.074	0.052	0.079	0.057	0.077	0.074
19	0.048	0.050	0.044	0.034	0.040	0.065	0.080	0.041
20	0.121	0.112	0.113	0.072	0.121	0.118	0.125	0.137
21	0.080	0.082	0.067	0.108	0.097	0.088	0.113	0.082
22	0.112	0.106	0.100	0.076	0.060	0.091	0.056	0.051

PROGRAMS AND TECHNOLOGIES: Q-MATRIX

PROGRAMS

TECH	1	2	3	4	5	6	7	8	9	10	11	12
1	Y1	Y1	Y1	Y1	Y1	1	Y1	Y1	Y1	Y1	Y1	Y1
2	1	1	1	1	1	1	1	1	1	1	1	1
3	1	1	Y3	1	1	1	1	1	Y3	1	1	1
4	1	1	Y4	1	1	Y4	Y4	1	Y4	1	1	Y4
5	1	1	Y5	1	1	1	1	1	Y5	1	1	Y5
6	1	1	1	1	1	1	Y6	1	1	1	1	1
7	1	1	1	1	1	1	1	1	1	1	1	1
8	1	1	Y8	1	1	Y8	1	1	1	1	1	1
9	1	1	1	1	1	1	Y9	1	1	1	1	1
10	1	Y10	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	Y11	1	1
12	Y12	1	1	1	Y12	1	1	1	1	1	Y12	1
13	Y13	1	1	1	Y13	1	Y13	1	1	Y13	1	1
14	1	1	1	1	1	1	1	Y14	1	1	1	1
15	1	1	1	Y15	1	1	1	1	1	1	1	1
16	1	1	1	1	1	1	Y16	1	1	Y16	1	Y16
17	1	1	1	1	Y17	1	1	1	1	Y17	1	1
18	1	1	1	1	Y18	1	1	1	1	Y18	1	1
19	1	1	1	1	Y19	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1	1	1	1	1
21	1	1	1	1	1	1	1	1	1	1	1	1
22	1	1	1	1	1	1	1	1	1	1	1	1
23	1	1	1	1	1	1	1	1	1	1	1	1
24	1	1	1	1	1	1	1	1	1	1	1	1
25	1	1	1	1	1	1	1	1	1	1	1	1

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```
PROGRAMS AND TECHNOLOGIES: B-MATRIX

                PROGRAMS

                1        2        3        4        5        6        7        8        9       10       11       12
TECH ------------------------------------------------------------------------------------------------------------------
     1   !  *        *        *        *        *        3.00     *        *        *        *        *        *
     2   !  0.75     0.30     3.00     0.30     0.30     3.00     0.30     0.30     0.30     0.30     0.30     0.30
     3   !  3.00              *                 3.00                       0.75     *                 3.00
     4   !                    *                          *        *                 *       30.00              *
     5   !                    *                                            0.75     *                          0.75
     6   !                    3.00                       3.00     *                 3.00                       3.00
     7   !  0.75     0.75     0.75     0.75     0.75     0.75     0.75     0.75     0.75     0.75     0.75     0.75
     8   !                    *                          *
     9   !                                                        *                         30.00
    10   !  0.30     *                          0.30                       0.30              0.30
    11   !  3.00     3.00     0.75     0.75     3.00                       0.75     0.75     *        0.75     0.75
    12   !  *                                   *                                                     *
    13   !  *                                   *                 *                          *        0.30
    14   !                    7.50              3.00     7.50              *        7.50                       7.50
    15   !                             *                30.00             30.00                                *
    16   !                                                        *                          *
    17   !  0.30     0.30              0.30     *                                            *        0.30
    18   !  0.30     0.30                       *                                            *        0.30
    19   !           0.75              0.75     *                                            0.75
    20   !  7.50     7.50              3.00     7.50              3.00                       3.00
    21   !  3.00     3.00     3.00     3.00     3.00     3.00     3.00     3.00     3.00     3.00     3.00     3.00
    22   !  3.00     3.00    30.00     3.00     3.00     3.00     7.50     3.00     7.50     7.50     3.00     7.50
    23   !  7.50     7.50     3.00     3.00     7.50     3.00     3.00     3.00     3.00     7.50     3.00     3.00
    24   !  7.50     7.50              3.00     7.50                       3.00              3.00
    25   ! 30.00     0.75     7.50     0.75     3.00     7.50     0.75     3.00     3.00     0.75     0.75     0.75


                ENTER THE AMOUNT OF FUNDS AVAILABLE
                =850


                THE TOTAL FUNDING AVAILABLE IS 850.00 DOLLARS

                Enter an estimate of the no of techs that will be needed in
                addition to the fixed techs. If you dont wish to guess enter 0
                =0


               THE FOLLOWING TECHNOLOGIES ARE ALWAYS FUNDED:
                     1
                     4
                     6
                     9
                    10
                    11
                    12
                    13
                    14
                    15
                    16
                    17
                    18
                    19
```

```
DO YOU WISH TO ENTER AN ITALLY VECTOR? T:YES;F:NO
=f
score      cost          20  21  22  23  24  25

GOAL VALUES
M=   4 DO YOU WISH TO ENTER A STARTING Y VECTOR ? T:YES;F:NO
=f
   5.86     828.00      T   F   T   T   T   F
              -5747.95      0.74       0.73       0.75       0.70       0.79       0.67       0.72       0.81
   5.86     828.00      T   F   T   T   F   T
              -5747.95      0.74       0.73       0.75       0.70       0.79       0.67       0.72       0.81
   5.86     828.00      T   F   T   F   T   T
              -5747.95      0.74       0.73       0.75       0.70       0.79       0.67       0.72       0.81
   5.86     828.00      T   F   F   T   T   T
              -5747.95      0.74       0.73       0.75       0.70       0.79       0.67       0.72       0.81
   5.86     828.00      F   T   T   T   T   F
              -5747.95      0.74       0.73       0.75       0.70       0.79       0.67       0.72       0.81
   5.86     828.00      F   T   T   T   F   T
              -5747.95      0.74       0.73       0.75       0.70       0.79       0.67       0.72       0.81
   5.86     828.00      F   T   T   F   T   T
              -5747.95      0.74       0.73       0.75       0.70       0.79       0.67       0.72       0.81
   5.86     828.00      F   T   F   T   T   T
              -5747.95      0.74       0.73       0.75       0.70       0.79       0.67       0.72       0.81
BEFORE GOING TO A NEW M, DO YOU WANT TO CHANGE ITALLY? T:YES,F:NO
=f
score      cost          20  21  22  23  24  25

GOAL VALUES
M=   5 DO YOU WISH TO ENTER A STARTING Y VECTOR ? T:YES;F:NO
=f
   5.86     835.50      T   T   T   T   T   F
              -5747.95      0.74       0.73       0.75       0.70       0.79       0.67       0.72       0.81
   5.86     835.50      T   T   T   T   F   T
              -5747.95      0.74       0.73       0.75       0.70       0.79       0.67       0.72       0.81
   5.86     835.50      T   T   T   F   T   T
              -5747.95      0.74       0.73       0.75       0.70       0.79       0.67       0.72       0.81
   5.86     835.50      T   T   F   T   T   T
              -5747.95      0.74       0.73       0.75       0.70       0.79       0.67       0.72       0.81
BEFORE GOING TO A NEW M, DO YOU WANT TO CHANGE ITALLY? T:YES,F:NO
=f
score      cost          20  21  22  23  24  25

GOAL VALUES
M=   6 DO YOU WISH TO ENTER A STARTING Y VECTOR ? T:YES;F:NO
=f
BEFORE GOING TO A NEW M, DO YOU WANT TO CHANGE ITALLY? T:YES,F:NO
=f
score      cost          20  21  22  23  24  25

GOAL VALUES
M=   3 DO YOU WISH TO ENTER A STARTING Y VECTOR ? T:YES;F:NO
=f
   5.86     820.50      F   F   T   T   T   F
              -5747.95      0.74       0.73       0.75       0.70       0.79       0.67       0.72       0.81
   5.86     820.50      F   F   T   T   F   T
              -5747.95      0.74       0.73       0.75       0.70       0.79       0.67       0.72       0.81
   5.86     820.50      F   F   T   F   T   T
              -5747.95      0.74       0.73       0.75       0.70       0.79       0.67       0.72       0.81
   5.86     820.50      F   F   F   T   T   T
              -5747.95      0.74       0.73       0.75       0.70       0.79       0.67       0.72       0.81
```

```
BEFORE GOING TO A NEW M, DO YOU WANT TO CHANGE ITALLY? T:YES,F:NO
=f
score      cost          20  21  22  23  24  25

GOAL VALUES
M=   2 DO YOU WISH TO ENTER A STARTING Y VECTOR ? T:YES;F:NO
=f
BEFORE GOING TO A NEW M, DO YOU WANT TO CHANGE ITALLY? T:YES,F:NO
=f
score      cost          20  21  22  23  24  25

GOAL VALUES
M=   1 DO YOU WISH TO ENTER A STARTING Y VECTOR ? T:YES;F:NO
=f
BEFORE GOING TO A NEW M, DO YOU WANT TO CHANGE ITALLY? T:YES,F:NO
=f

THE BEST SCORE WAS   5.86 USING TECHNOLOGIES
    1
    4
    6
    9
   10
   11
   12
   13
   14
   15
   16
   17
   18
   19
   20
   22
   23
   24

*
```

.1 A.3.1. PRISM - BALLPARK MODEL LISTINGS

```
10 dimension a(25,12),b(25,12),ic(25,12),bensol(20),costec(30),
20&  IDGOL(20),IDPRG(20),IDTEC(30),PI(20),IX(30),IY(20),RHO(30),
30&  LOWEST(30),BENFIT(30),IPCRIT(20)
35        dimension sp(12)
40    COMMON B,IC
50     CHARACTER FILNME*12
60C
70C  ALLOCATION OF FUNDS AMONG INTERDEPENDENT TECHNOLOGIES--QD METHOD
80C
90C
100C  IDENTIFICATION OF SUBSCRIPTED VARIABLES
110C    ARRAYS :
120C      A       :  GOAL-PROGRAM MATRIX
130C      B       :  PROGRAM-TECHNOLOGY ENHANCEMENT MATRIX
140C      IC      :  PROGRAM TECHNOLOGY ENABLEMENT MATRIX
150C    VECTORS:
160C      BENGOL  :  RELATIVE BENEFITTS OF GOALS
170C      COSTEC  :  COSTS OF TECHNOLOGIES
180C      IDGOL   :  ID NUMBER OF GOALS
190C      IDPRG   :   "    "    " PROGRAMS
200C      IDTEC   :   "     "    " TECHNOLOGIES
210C      IPCRIT  :  SCORE VECTOR--TELLS # OF ENABLING TECHS PER PROG
220C      IX      :  TECHNOLOGY VECTOR* 1=FUNDED,0=NOT FUNDED
230C      IY      :  PROGRAM VECTOR* 1=COMPLETE, 0=NOT COMPLETE
240C      RHO     :  BENEFIT/COST RATIO FOR EACH TECH
250C      BENFIT  :  CURRENT BENEFIT MEASURE FOR EACH TECH
260C      PI      :  RELATIVE BENEFIT OF EACH PROGRAM
270C      LOWEST  :  MINIMUM RHO(S)*1=MINIMUM(S),0=NONMINIMA
280C
290  DATA RHODEL/3./
300C
310C  FIRST PRINT THE HEADERS
320   WRITE (6,10)
330 10  format(1h ,2x,
340&   49HALLOCATION OF FUNDS AMONG INTERDEPENDENT PROGRAMS   )
350  WRITE (6,20)
360#20 FORMAT (1H0)
370C
380C  READ IN THE NO. OF GOALS, PROGRAMS, & TECHNOLOGIES
400     PRINT,'ENTER NUMGOL,NUMPRG,NUMTEC'
410  READ, NUMGOL,NUMPRG,NUMTEC
420C
430C  INITIALIZE THE ID VECTORS
440    DO 30 I=1,20
450#30  IDGOL(I) = 0
460   DO 40 I=1,20
470#40  IDPRG(I) = 0
480   DO 50 I=1,30
490#50   IDTEC(I) =0
500C
510C  READ IN THE ID NUMBERS
530     PRINT,'ENTER THE GOAL IDENTIFICATION VECTOR = IDGOL;'
540     READ,FILNME
541     CALL ATTACH(10,FILNME,1,0,ISTAT,)
542     CALL DUMY5(IDGOL,NUMGOL)
560     PRINT,'ENTER THE PROGRAM ID VECTOR = IDPRG;'
570     READ,FILNME
571     CALL DETACH(10,ISTAT,)
572     CALL ATTACH(10,FILNME,1,0,ISTAT,)
573     CALL DUMY6(IDPRG,NUMPRG)
590     PRINT,'ENTER THE TECHNOLOGY ID VECTOR = IDTEC;'
600     READ,FILNME
601     CALL DETACH(10,ISTAT,)
602     CALL ATTACH(10,FILNME,1,0,ISTAT,)
603     CALL DUMY7(IDTEC,NUMTEC)
```

```
610C  READ IN THE ARRAYS A COLUMN AT A TIME
630    PRINT,'ENTER THE PROGRAM-GOAL MATRIX, INPUT=GMATRIX;'
640     READ,FILNME
641     CALL DETACH(10,ISTAT,)
660     CALL ATTACH(10,FILNME,1,0,ISTAT,)
670     CALL DUMY1(A,NUMPRG,NUMGOL)
690     PRINT,'ENTER THE B MATRIX,INPUT=BMATRIX;'
700     READ,FILNME
705     CALL DETACH(10,ISTAT,)
710     CALL ATTACH(10,FILNME,1,0,ISTAT,)
711     IF(ISTAT.NE.0) PRINT 101,ISTAT
712 101 FORMAT(O14)
720     CALL DUMY2(B,NUMTEC,NUMPRG)
740     PRINT,'ENTER THE C MATRIX,INPUT=CMATRIX;'
750     READ,FILNME
755     CALL DETACH(10,ISTAT,)
760     CALL ATTACH(10,FILNME,1,0,ISTAT,)
770     CALL DUMY3(IC,NUMTEC,NUMPRG)
780C
790C  READ THE FUDGE FACTOR THAT RELATES ENABLING TECHS TO ENHANCING
810    PRINT,'ENTER THE ENABLE-ENHANCE FUDGE FACTOR'
830   READ, FUDGE
840C
850C
860C  READ COSTS OF TECHS & RELATIVE VALUES OF GOALS
880     PRINT,'ENTER THE TECHNOLOGY COST VECTOR,INPUT=COSTEC;'
890     READ,FILNME
895     CALL DETACH(10,ISTAT,)
910     CALL ATTACH(10,FILNME,1,0,ISTAT,)
920     CALL DUMY4(COSTEC,NUMTEC)
950     PRINT,'ENTER THE GOAL BENEFIT VECTOR'
960   READ, (BENGOL(I), I=1,NUMGOL)
970C
980C  CALCULATE THE VALUE OF EACH PROGRAM
990   CALL HORTOT(A,BENGOL,NUMPRG,NUMGOL,PI)
1000C
1010C  PRINT OUT THE INPUT DATA WITH APPROPRIATE HEADERS
1015     go to 333
1020   WRITE (6,150)
1030#150  FORMAT (1H0,12HINPUT DATA:    )
1040   WRITE (6,160)
1050#160  FORMAT(1H0,6HGOAL #,2X,11HDESCRIPTION,9X,14HRELATIVE VALUE)
1060   DO 180 I=1,NUMGOL
1070      WRITE (6,170)IDGOL(I),BENGOL(I)
1080#170  FORMAT (1H ,1X,I4,24(1H_),F6.2)
1090#180 CONTINUE
1100   WRITE (6,190)
1110#190  FORMAT (1H0,6HPROG #,2X,11HDESCRIPTION,9X,14HRELATIVE VALUE)
1120   DO 210 I=1,NUMPRG
1130       WRITE (6,170)IDPRG(I),PI(I)
1140#210 CONTINUE
1150   WRITE (6,220)
1160#220 FORMAT (1H0,6HTECH #,2X,11HDESCRIPTION,9X,4HCOST)
1170   DO 240 I=1,NUMTEC
1180       WRITE (6,170)IDTEC(I),COSTEC(I)
1190#240 CONTINUE
1200C
1210C  WRITE OUT THE MATRICES
1220   WRITE (6,250)
1230#250  FORMAT(1H0,20HINTERACTION MATRICES )
1240  WRITE(6,260)
1250#260  FORMAT(1H0,18HGOALS AND PROGRAMS )
1260   WRITE (6,270)
1270#270 FORMAT(1H0,10X,5HGOALS)
1280   WRITE (6,280)
1290#280 FORMAT(1H0)
```

```
1300    CALL TOPLIN(NUMGOL,IDGOL)
1310    WRITE (6,290)
1320#290 FORMAT (1H ,5HPROG ,70(1H-))
1330    CALL ARRPRT(A,NUMPRG,NUMGOL,IDPRG)
1340    WRITE (6,280)
1350    WRITE (6,300)
1360#300 FORMAT(1H0, 34HPROGRAMS AND TECHNOLOGIES:B-MATRIX)
1370    WRITE (6,305)
1380#305  FORMAT (1H0,10X,8HPROGRAMS )
1390    CALL TOPLIN(NUMPRG,IDPRG)
1400    WRITE (6,310)
1410#310 FORMAT (1H ,5HTECH ,70(1H-))
1420    CALL ARRPRT(B,NUMTEC,NUMPRG,IDTEC)
1430    WRITE (6,280)
1440    WRITE (6,320)
1450#320 FORMAT(1H0,44HPROGRAMS AND ENABLING TECHNOLOGIES: C-MATRIX )
1460    WRITE (6,280)
1470    WRITE (6,305)
1480    CALL TOPLIN(NUMPRG,IDPRG)
1490    WRITE (6,310)
1500    CALL MAPRT(IC,NUMTEC,NUMPRG,IDTEC)
1510C
1520C
1525  333      continue
1529      call detach(41,istat,)
1530C  READ IN THE AMOUNT OF FUNDS AVAILABLE
1540#325 WRITE (6,323)
1550#323 FORMAT (1H0,'ENTER THE AMOUNT OF FUNDS AVAILABLE')
1560    READ, DOLLAR
1570    IF(DOLLAR.LE.1.0E-6)GOTO 999
1580    WRITE(6,324)
1590#324  FORMAT(1H0,'ENTER OPTION1: 1-NON-ALLOCATED COST;2-ALLOCATED')
1600    READ, IOPT1
1610    WRITE(6,328)
1620#328  FORMAT (1H0,'ENTER OPTION2; 1-BENEFIT/COST;2-BENEFIT')
1630    READ,IOPT2
1640    WRITE (6,330)DOLLAR
1650#330 FORMAT(1H0,31HTHE TOTAL FUNDING AVAILABLE IS  ,F7.2,1X,
1660&      8HDOLLARS )
1670C
1680C   CALCULATE #'S THAT TELL WHEN PROG IS COMPLETE
1690   CALL VERSUM(IC,NUMTEC,NUMPRG,IPCRIT)
1710C  INITIALIZE THE X VECTOR WITH 1'S,I.E. EVERYTHING FUNDED
1720    DO 500 I =1,NUMTEC
1730#500    IX(I)=1
1740C
1750C  CALCULATE WHICH PROGS ARE COMPLETE
1760#510  CALL COMPRG(IC,IX,NUMTEC,NUMPRG,IPCRIT,IY)
1770C
1780C
1790C   CALCULATE THE TOTAL COST
1800     TOTBUK = TOT(COSTEC,IX,NUMTEC)
1810     IF(TOTBUK.LE.DOLLAR)GOTO 700
1820C
1830C     IF YOU'RE HERE, THE CURRENT CONSTELLATON OF TECNOLOGIES IS
1840C     TOO EXPENSIVE.  YOU'RE GOING TO HAVE TO START ELIMINATING
1850C     THE TECHNOLOGIES WITH THE LEAST BENEFIT.
1860C
1870C     CALCULATE THE BENEFIT OF EACH TECH IN LIGHT OF CURRENTLY
1880C      COMPLETE PROGRAMS
1890C
1900    CALL BENTOT(PI,IY,FUDGE,NUMTEC,NUMPRG,IPCRIT,IOPT1,BENFIT)
1910C
1920    IF(IOPT2.NE.1)GOTO 540
1930C     CALCULATE THE BENEFIT/COST RATIOS
1940      DO 530 I=1,NUMTEC
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1950#530     RHO(I)=BENFIT(I)/COSTEC(I)
1960C
1970C    FIND THE SMALLEST RHOS
1980       CALL LEAST(RHO,IX,NUMTEC,LOWEST,RHODEL)
1990C
2000#540  IF(IOPT2.NE.2)GOTO 550
2010           CALL LEAST(BENFIT,IX,NUMTEC,LOWEST,RHODEL)
2020#550  CONTINUE
2030C
2040C    SELECT ONE OF THE SMALLEST RHOS
2050       K = ISEL2(LOWEST,NUMTEC,NUMPRG,IY ,IC)
2060       IX(K) = 0
2070         GOTO 510
2080C
2090C  PRINT OUT THE LIST OF TECHNOLOGIES USED
2100#700 WRITE (6,600)
2110#600  FORMAT(1H0,21HFUNDED TECHNOLOGIES:   )
2120       CALL PRLST(IDTEC,IX,NUMTEC)
2130C
2140C   PRINT OUT THE LIST OF COMPLETED PROGRAMS
2150      WRITE (6,610)
2160#610 FORMAT(1H0,20HPROGRAMS COMPLETED:   )
2170       CALL PRLST(IDPRG,IY,NUMPRG)
2180C
2190C    PRINT OUT THE TOTAL COST
2200       WRITE (6,620)TOTBUK
2210#620 FORMAT(1H0,22HTOTAL FUNDS EXPENDED:   ,F6.2,8H DOLLARS )
2220C
2230C    CALCULATE AND PRINT OUT THE TOTAL BENEFIT
2240       TOTBEN = TOT(PI,IY,NUMPRG)
2250       TOTBEN = FUDGE*TOTBEN
2260       ENHANC = 0.0
2270       DO 624  J=1,NUMPRG
2280          DO 622 I=1,NUMTEC
2290             ENHANC = ENHANC + IY(J)*IX(I)*B(I,J)
2300#622        CONTINUE
2310#624  CONTINUE
2320       TOTBEN = TOTBEN + ENHANC
2330       WRITE (6,630)TOTBEN
2340 630  format (1h0,30htotal benefit from programs:    ,f10.2)
2350       GOTO 325
2360#999 WRITE (6,635)
2370#635 FORMAT (1H0,'END OF RUN')
2380       STOP
2390       END
2400 FUNCTION TOT(COST,KEY,NUM)
2410C  THIS FUNCTION RETURNS THE TOTAL OF THOSE ELEMENTS IN THE VECTOR
2420C  'COST' THAT CORRESPOND TO THE 1 ELEMENTS OF THE 0-1 VECTOR 'KEY'
2430C
2440C   INPUTS:
2450C     COST: A REAL VECTOR OF RANK NUM
2460C     KEY : A 0-1 VECTOR OF RANK NUM
2470C     NUM : AN INTEGER
2480C
2490 DIMENSION COST(30),KEY(30)
2500  TOT = 0
2510  DO 10 I=1,N
2520      TOT=TOT+COST(I)*KEY(I)
2530#10  CONTINUE
2540 RETURN
2550  END
2560C
2570C
2580    SUBROUTINE DUMY1(A,I,J)
2590      DIMENSION A(I,J)
2600      READ(10,200) ((A(L,M),L=1,I),M=1,J)
```

```
2605 200 FORMAT(V)
2610     RETURN
2620     END
2621C
2622C
2630      SUBROUTINE DUMY3(IC,I,J)
2640     DIMENSION IC(I,J)
2650     READ(10,200) ((IC(L,M),L=1,I),M=1,J)
2655 200 FORMAT(V)
2660     RETURN
2670     END
2680C
2690C
2700      SUBROUTINE DUMY4(COSTEC,I)
2710       DIMENSION COSTEC(I)
2720     READ(10,200) (COSTEC(L),L=1,I)
2722 200 FORMAT(V)
2730     RETURN
2740     END
2741C
2742C
2750 SUBROUTINE PRLST(IDVEC,KEY,NU
2760C  THIS SUBROUTINE PRINTS OUT THE VALUES OF EACH OF THE ELEMENTS
2770C  OF 'IDVEC' CORRESPONDING TO 1 ELEMENTS IN THE KEY VECTOR
2780C
2790C  INPUTS:
2800C     IDVEC:  AN INTEGER VECTOR OF RANK NUM
2810C     KEY  :  A 0-1 VECTOR OF RANK NUM
2820C     NUM  :  AN INTEGER
2830  DIMENSION IDVEC(30),KEY(30)
2840  DO 20 I=1,NUM
2850     IF(KEY(I).EQ.0)GOTO 20
2860     WRITE(6,10)IDVEC(I)
2870#10  FORMAT(1H ,2X,I4)
2880#20 CONTINUE
2890  RETURN
2900  END
2910C
2920C
2930      SUBROUTINE DUMY2(B,I,J)
2940     DIMENSION B(I,J)
2950     READ(10,200)((B(L,M),L=1,I),M=1,J)
2955 200 FORMAT(V)
2960     RETURN
2970     END
2971C
2972C
2973      SUBROUTINE DUMY5(IDGOL,I)
2974     DIMENSION IDGOL(I)
2975     READ(10,200) (IDGOL(L),L=1,I)
2976 200 FORMAT(V)
2977     RETURN
2978     END
2980C
2981C
2982      SUBROUTINE DUMY6(IDPRG,I)
2983     DIMENSION IDPRG(I)
2984     READ(10,200) (IDPRG(L),L=1,I)
2985 200 FORMAT(V)
2986     RETURN
2987     END
2990C
2991C
2992      SUBROUTINE DUMY7(IDTEC,I)
2993     DIMENSION IDTEC(I)
2994     READ(10,200) (IDTEC(L),L=1,I)
```

C-5

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2995 200 FORMAT(V)
2996      RETURN
2997      END
3000C
3010C
3020  FUNCTION ISEL1(IVEC,IRANK)
3030C  THIS FUNCTION RETURNS THE INDEX OF THE FIRST 1 ELEMENT IN THE
3040C  VECTOR 'IVEC'
3050C
3060C  INPUTS:
3070C    IVEC :  A 0-1 VECTOR OF RANK IRANK
3080C    IRANK:  AN INTEGER
3090  DIMENSION IVEC(30)
3100  DO 10 I=1,IRANK
3110      IF(IVEC(I).EQ.1)GOTO 20
3120C      JUMP OUT OF THE LOOP AS SOON AS YOU HIT A 1
3130#10 CONTINUE
3140C  IF YOU GO ALL THE WAY THROUGH AND DON'T HIT A 1, OUTPUT 0
3150   ISEL1 = 0
3160   GOTO 30
3170#20 ISEL1=I
3180#30 CONTINUE
3190  RETURN
3200  END
3210C
3220C
3230      SUBROUTINE COMPRG(MATRIX,IVEC,IROW,ICOL,ISTNDD,ISCOR)
3240  DIMENSION MATRIX(IROW,ICOL),IVEC(30),ISTNDD(20),ISCOR(20)
3250C  THIS SUBROUTINE LOOKS AT THE INTERACTION MATRIX 'MATRIX' AND
3260C  THE TECHNOLOGY VECTOR 'IVEC'.  IF A PROGRAM J GETS AS MANY
3270C  ENABLING TECHS AS THE VECTOR ISTNND SAYS IT SHOULD HAVE,
3280C  THAT PROGRAM IS COMPLETE AND ISCOR(J) IS 1.  OTHERWISE ISCOR
3290C  (J) IS ZERO
3300C
3310C  INPUTS:
3320C    MATRIX:  AN IROW X ICOL 0-1 INTERACTION MATRIX
3330C    IVEC  :  A 0-1 VECTOR OF RANK IROW (THE TECH VECTOR)
3340C    ISTNDD:  AN INTEGER VECTOR OF RANK ICOL SPECIFYING THE
3350C                NUMBER OF ENABLING TECHS FOR EACH PROG
3360C    IROW  :  AN INTEGER
3370C    ICOL  :  '     '
3380C  OUTPUTS:
3390C    ISCOR :  A 0-1 VECTOR OF RANK C (THE PROG. VECTOR)
3400C
3410C
3420  DO 30 J=1,ICOL
3430    ISCOR(J) = 0
3440C    INITIALIZE THE SCORE
3450    DO 10 I=1,IROW
3460       ISCOR(J) = ISCOR(J)+MATRIX(I,J)*IVEC(I)
3470#10  CONTINUE
3480    IF(ISCOR(J).LT.ISTNDD(J))GOTO 20
3490C       IF SUM OF INPUTSPRODUCTS EQUAL STD...
3500       ISCOR(J)=1
3510       GOTO 30
3520C       IF SUM OF INPUT PRODUCTS LESS THAN STD...
3530#20    ISCOR(J) = 0
3540#30 CONTINUE
3550  RETURN
3560  END
3570C
3580C
3590  SUBROUTINE HORTOT(ARRAY,VECTOR,IROW,ICOL,OUT)
3600  DIMENSION ARRAY(IROW,ICOL),VECTOR(20),OUT(30)
3610C  THIS SUBROUTINE MULTIPLIES THE REAL MATRIX 'ARRAY' BY THE
3620C  REAL VECTOR 'VECTOR' AND RETURNS THE RESULTANT REAL VECTOR 'OUT'
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3630C
3640C  INPUTS:
3650C     ARRAY :  A REAL IROW X ICOL MATRIX
3660C     VECTOR:  A REAL VECTOR OF RANK IROW
3670C     IROW  :  AN INTEGER
3680C     ICOL        "      "
3690C  OUTPUTS:
3700C     OUT   :  A REAL VECTOR OF RANK ICOL
3710  DO 20 I =1,IROW
3720     OUT(I) =0
3730     DO 10 J=1,ICOL
3740        OUT(I) = OUT(I) + ARRAY(I,J)*VECTOR(J)
3750*10  CONTINUE
3760*20 CONTINUE
3770  RETURN
3780  END
3790C
3800C
3810  SUBROUTINE VERSUM(M,IROW,ICOL,ISUM)
3820  DIMENSION M(IROW,ICOL),ISUM(20)
3830C
3840C THIS SUBROUTINE SUMS THE COLUMNS IN AN INTEGER MATRIX
3850C
3860C  INPUTS:
3870C     M      :  AN IROW X ICOL INTEGER ARRAY
3880C     IROW   :  AN INTEGER
3890C     ICOL         "     "
3900C  OUTPUTS:
3910C     ISUM   :   AN INTEGER VECTOR OF RANK ICOL
3920C
3930  DO 20 J =1,ICOL
3940     ISUM(J) = 0
3950     DO 10  I=1,IROW
3960        ISUM(J)   = ISUM(J) + M(I,J)
3970*10   CONTINUE
3980*20 CONTINUE
3990  RETURN
4000  END
4010C
4020C
4030  SUBROUTINE LEAST(VECTOR,KEY,NUM,LOWEST,PERCNT)
4040  DIMENSION VECTOR(30),KEY(30),LOWEST(30)
4050C
4060C
4070C  THIS SUBROUTINE EXAMINES THE SUBSET OF 'VECTOR' IDENTIFIED BY
4080C   1'S IN THE KEY VECTOR 'KEY' AND LOOKS FOR THE MINIMUM.  IT RETURNS
4090C  A 0-1 VECTOR 'LOWEST' WHERE ONES INDICATE ALL ELEMENTS OF THE
4100C  SUBSET THAT ARE EQUAL TO THE MINIMUM OR WITHIN 'PERCNT' PERCENT
4110C  OF IT.
4120C
4130C  INPUT:
4140C     VECTOR:  A REAL VECTOR OF RANK NUM
4150C     KEY   :  A ZERO-ONE VECTOR OF RANK NUM
4160C     NUM   :  AN INTEGER
4170C     PERCNT:  A REAL NUMBER DICTATING PERCENT TOLERANCE
4180C  OUTPUTS:
4190C     LOWEST:  A 0-1 VECTOR OF RANK NUM
4200C
4210C
4220  AMIN = 1.0E30
4230C
4240C  THIS LOOP FINDS THE VALUE OF THE MINIMUM
4250C
4260  DO  10 I=1,NUM
4270      IF(KEY(I).NE.1)GOTO 10
4280C        IF YOU HAVE A 1 IN THE KEY...
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4290          IF(VECTOR(I).GE.AMIN)GOTO 10
4300C             IF THIS ELT IS SMALLER THAN THE OLD MIN...
4310              AMIN=VECTOR(I)
4320#10  CONTINUE
4330  AMIN = AMIN*(1.00 + (PERCNT/100.) )
4340C
4350C  THIS LOOP MARKS ALL ELEMENTS EQUAL TO THE MINIMUM
4360C
4370  DO 30  I=1,NUM
4380     IF(KEY(I).NE.1)GOTO 20
4390    IF(VECTOR(I).GT.AMIN)GOTO 20
4400        LOWEST(I)=1
4410        GOTO 30
4420#20     LOWEST(I)=0
4430#30 CONTINUE
4440  RETURN
4450  END
4460C
4470C
4480  SUBROUTINE TOPLIN(ICOL,ICOLAB)
4490  DIMENSION ICOLAB(20),FORM(22),ICARRY(20)
4500  REAL LEFT1
4510 DATA LEFT1,RIGHT,ALPHA,DIGITI,BLANK/4H(10X,1H),3H,A6,3H,I6,4H    /
4520C
4530C
4540C  THIS SUBROUTINE PRINTS THE LABELS FOR THE COLUMNS OF A MATRIX.
4550C  IT IS NORMALLY FOLLOWED BY EITHER MAPRRT OR ARRPRT.
4560C
4570C  INPUTS:
4580C    ICOLAB: AN INTEGER VECTOR OF RANK ICOL CONTAINING COLUMN LABELS
4590C    ICOL  : AN INTEGER
4600C
4610C
4620C  FIRST INITIALIZE THE FORMAT STATEMENT
4630  FORM(1)= LEFT1
4640  FORM(22)= RIGHT
4650C
4660C  INSURE THAT NO GARBAGE IS INCLUDED IN THE FORMAT STATEMENT
4670  DO 10 I=2,21
4680     FORM(I) = BLANK
4690#10 CONTINUE
4700C
4710C   SET THE FORMAT STATEMENT TO PRINT THE COLUMN LABELS
4720  DO 20 I=1,ICOL
4730     I1=I+1
4740     FORM(I1) = DIGITT
4750     ICARRY(I)= ICOLAB(I)
4760#20 CONTINUE
4770C
4780C   PUT BLANKS ON THE RIGHT HAND SIDE AND ADJUST THE FORMAT STATEMENT
4790  ICOL1=ICOL + 1
4800  DO 30 I =ICOL1,20
4810     I1 = I+1
4820     FORM(I1) = ALPHA
4830     ICARRY(1) = BLANK
4840#30  CONTINUE
4850 WRITE (6,FORM)ICARRY
4860  RETURN
4870  END
4880C
4890C
4900  SUBROUTINE MAPRT(MATRIX,IROW,ICOL,IDROW)
4910  DIMENSION MATRIX(IROW,ICOL),IDROW(30),FORM(24),IVAL(20)
4920  REAL LEFT2,LEFT3,LEFT4
4930C
4940C THIS SUBROUTINE PRINTS AN INTEGER MATRIX WHOSE DIMENSIONS ARE NOT
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4950C  KNOWN UNTIL RUN TIME. IT INSERTS BLANKS FOR ZERO ELEMENNTS IN THE
4960C  MATRIX AND PRINTS ONLY THE NUMBER OF COLUMNS NECESSARY
4970C
4980C  INPUTS:
4990C    MATRIX:  AN IROW X ICOL INTEGER MATRIX
5000C    IDROW :  AN INTEGER VECTOR OF RANK IROW CONTAINING IDENTIFYING
5010C                 NUMBERS FOR THE ROWS OF THE MATRIX
5020C    IROW  :  AN INTEGER
5030C    ICOL  :   "    "
5040C
5050  INTEGER BLANK
5060  DATA LEFT2,LEFT3,LEFT4,RIGHT,ALPHA,DIGITI,BLANK/4H( I4,
5070&  4H,5X,,3H1H!,1H),3H,A6,3H,I6,4H    /
5080C
5090C  INITIALIZE THE FORMAT STATEMENT
5100   FORM(1) = LEFT2
5110   FORM(2) = LEFT3
5120   FORM(3) = LEFT4
5130   FORM(24)= RIGHT
5140C
5150C  INSURE AGAINST GARBAGE IN THE FORMAT STATEMENT
5160   DO 10 I=4,23
5170      FORM(I) = BLANK
5180*10 CONTINUE
5190C
5200C  PUT ALPHAS AND BLANKS IN TO FILL OUT THE RIGHT-HAND SIDE
5210C    (YOU ONLY HAVE TO DO IT ONCE)
5220   ICOL1 = ICOL+1
5230   DO 20 I=ICOL1,20
5240       I3 =I+3
5250      FORM(I3) = ALPHA
5260      IVAL(I) = BLANK
5270*20  CONTINUE
5280C
5290C   SET UP THE FORMAT STATEMENT FOR EACH ROW A ROW AT A TIME
5300   DO 50 I =1,IROW
5310      DO 40 J=1,ICOL
5320          J3=J+3
5330          IF(MATRIX(I,J).NE.0)GOTO 30
5340C             INSERT A BLANK FOR EMBEDDED ZEROS..
5350              IVAL(J)   = BLANK
5360
5370              FOR M(J3) = ALPHA
5380              GOTO 40
5390*30          IVAL(J) = MATRIX(I,J)
5400             FORM(J3)= DIGITI
5410*40   CONTINUE
5420   WRITE (6,FORM)IDROW(I),IVAL
5430*50  CONTINUE
5440  RETURN
5450  END
5460C
5470C
5480   SUBROUTINE ARRPRT(ARRAY,IROW,ICOL,IDROW)
5490  REAL LEFT2,LEFT3,LEFT4
5500   DIMENSION  ARRAY(IROW,ICOL),IDROW(30),FORM(44),VAL(20)
5510C  THIS SUBROUTINE PRINTS A REAL MATRIX WHOSE DIMENSIONS ARE NOT
5520C  KNOWN UNTIL RUN TIME.  IT INSERTS BLANKS FOR SERO ELEMENTS IN THE
5530C  MATRIX AND PRINTS ONLY THE NUMBER OF COLUMNS NECESSARY
5540C
5550C  INPUTS:
5560C    ARRAY :  AN IROW X ICOL REAL MATRIX
5570C    IDROW :  AN INTEGER VECTOR OF RANK IROW CONTAINING IDENTIFYING
5580C                 NUMBERS FOR THE ROWS OF THE MATRIX
5590C    IROW  :  AN INTEGER
5600C    ICOL  :   "    "
```

```
C
      DATA LEFT2,LEFT3,LEFT4,RIGHT,ALPHA,DIGITR,COMMA,BLANK/4H( I4,
&       4H,5X,,3H1H!,1H),2HA6,4HF6.2,1H,,4H    /
C
C      INITIALIZE THE FORMAT STATEMENT
      FORM(1) = LEFT2
      FORM(2) = LEFT3
      FORM(3) = LEFT4
      FORM(44) = RIGHT
C
C         INSURE AGAINST GARBAGE IN THE FORMAT STATEMENT
      DO 10 I =4,43
          FORM(I) = BLANK
   10 CONTINUE
C
C      PUT ALPHAS AND BLANKS TO FILL OUT THE RIGHT HAND SIDE.
C           (YOU ONLY HAVE TO DO IT ONCE)
      ICOL1 = ICOL + 1
      DO 20  I=ICOL1,20
          VAL(I) = BLANK
          IZ = I+I+2
          FORM(IZ) = COMMA
          FORM(IZ+1) = ALPHA
   20 CONTINUE
C
C      SET THE FORMAT FOR EACH NEW ROW, A ROW AT A TIME
      DO 50  I=1,IROW
          DO 40 J=1,ICOL
              JX = J+J+2
              JY = JX +1
             IF(ABS(ARRAY(I,J)).GE.1.0E-7)GOTO 30
C                 INSERT A BLANK FOR EMBEDDED ZEROS
                   VAL(J) = BLANK
                   FORM(JX)=COMMA
                   FORM(JY)=ALPHA
                    GOTO 40
   30              VAL(J)= ARRAY(I,J)
                   FORM(JX) = COMMA
                   FORM(JY) = DIGITR
   40   CONTINUE
      WRITE (6,FORM)IDROW(I),VAL
   50 CONTINUE
      RETURN
      END
C
C
      FUNCTION ISEL2(LOWEST,NUMTEC,NUMPRG,IY,IC)
         dimension lowest(30),iy(20),ic(25,12)
C
C      THIS FUNCTION RETURNS THE INDEX OF THAT '1' ELEMENT IN THE
C      VECTOR 'LOWEST' WHICH CONTRIBUTES TO FEWEST COMPLETED PROGRAMS.
C
       ISCMIN = 10000
       DO 20 I=1,NUMTEC
          IF(LOWEST(I).NE.1)GOTO 20
    5     CONTINUE
          ISCORE = 0
          DO 10 J= 1,NUMPRG
   10      ISCORE = ISCORE + IY(J)*IC(I,J)
          IF(ISCORE.GE.ISCMIN)GOTO 20
             ISEL2=I
             ISCMIN= ISCORE
   20 CONTINUE
       RETURN
       END
C
```

```
6270C
6280  SUBROUTINE BENTOT(PI,IY,FUDGE,NUMTEC,NUMPRG,IPCRIT,IOPT1,BENFIT)
6290     dimension b(25,12),ic(25,12),pi(20),iy(20),ipcrit(20),benfit(30)
6310  COMMON B,IC
6330C
6340C
6350    DO 40 I=1,NUMTEC
6360       IF(IOPT1.NE.1)GOTO 20
6370          DO 10 J=1,NUMPRG
6380#10          BENFIT(I)=FLOAT(IY(J))*(FUDGE*FLOAT(IC(I,J))*PI(J)
6390&                      +B(I,J))+BENFIT(I)
6400#20    IF(IOPT1.NE.2)GOTO 40
6410          DO 30 K=1,NUMPRG
6420             IF(IPCRIT(K).EQ.0)GOTO  25
6430                BENFIT(I)=FLOAT(IY(K))*(FUDGE*FLOAT(IC(I,K))
6440&                         *PI(K)/IPCRIT(K) +B(I,K))+BENFIT(I)
6450#25          IF(IPCRIT(K).NE.0)GOTO 30
6460                BENFIT(I)= BENFIT(I)+FLOAT(IY(K)*B(I,K))
6470#30       CONTINUE
6480#40   CONTINUE
6490     RETURN
6500    END
```

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A.3.2. PRISM - GOODNESS MEASURE MODE LISTINGS

```
10 logical x,y,itally,go,besty,flag,ifix,ans1,ans2,ans3
20      dimension g(12,9),iq(25,12),b(25,12),alpha(12),
30&  COSTEC(30),COSPRG(20),IDGOL(20),IDPRG(30),IDTEC(30),ITALLY(30),
40&   X(30).Y(30).BESTY(30),IADD(30),GOOD(20)
50      CHARACTER FILNME*12
60C  ALLOCATION OF FUNDS AMONG INTERDEPENDENT TECHNOLOGIES--SC METHOD
70C
80C
90C  IDENTIFICATION OF SUBSCRIPTED VARIABLES
100C    ARRAYS:
110C       G       :  GOAL-PROGRAM MATRIX
120C       IQ      :  PROGRAM-TECHNOLOGY ENABLEMENT MATRIX. 0:ROW ENABLES COL
130C       B       :  PROGRAM-TECHNOLOGY ENHANCEMENT MATRIX. NEGATIVE ENTRIES
140C                       INDICATE ENABLING TECHS
150C    VECTORS:
160C       ALPHA   :  RELATIVE WEIGHTS OF GOALS
170C       BESTY   :  Y-VECTOR GIVING BEST SCORE SO FAR
180C       COSPRG  :  COST OF ENABLED PROGRAM
190C       COSTEC  :  COST OF TECHNOLOGIES
200C       IADD    :  ADDRESSES OF T'S IN Y-VECTOR
210C       IDGOL   :  ID NUMBERS OF GOALS
220C       IDPRG   :   "     "       " PROGRAMS
230C       IDTEC   :   "     "       " TECHNOLOGIES
240C       ITALLY  :  M-VALUES NOT WORTH CHECKING. T: DON'T CHECK THIS VALUE
250C       X       :  PROGRAM VECTOR. T: ENABLED
260C       Y       :  TECHNOLOGY VECTOR. T: FUNDED
261C       GOOD    :  VALUES OF A SET OF TECHS TO EACH GOAL
270C
280C     READ THE INPUTS
300       print,'enter the number of goals,programs,technologies and the numbe
310   READ, NUMGOL,NUMPRG,NUMTEC,NUMFIX
320   NUMVAR=NUMTEC - NUMFIX
330   NUMF1 = NUMFIX + 1
340   NUMGL1 = NUMGOL + 1
350       thresh= 10.e10
360    ICOUNT = 0
370C
380C  INITIALIZE THE ID VECTORS
390    DO 20 I=1,20
400#20       IDGOL(I) = 0
410    DO 30 I=1,30
420        IDPRG(I)=0
430#30     IDTEC(I) = 0
440C
450C    READ  IN THE IDVECTORS
470       print,'enter the goal identification vector'
480       read,filnme
481       call attach(10,filnme,1,0,istat,)
482       call dumy6(idgol,numgol)
500       print,'enter the program id vector = idprg;'
510       read,filnme
511       call detach(10,istat,)
512       call attach(10,filnme,1,0,istat,)
513       call dumy7(idprg,numprg)
520    WRITE (6,80)NUMFIX
530#80 FORMAT (1H ,'ENTER TECH ID S. REMEMBER THE FIRST ',I3,' ARE
540&      FIXED' )
550       read,filnme
551       call detach(10,istat,)
552       call attach(10,filnme,1,0,istat,)
553       call dumy8(idtec,numtec)
560C
570C  READ IN THE MATRICES
580C
```

```
600      print,'enter the goal-program matrix , input=gmatrix;'
602      READ,FILNME
603      call detach(10,istat,)
604      CALL ATTACH(10,FILNME,1,0,ISTAT,)
606      CALL DUMY1(G,NUMPRG,NUMGL1)
630      print,'enter the qmatrix, input=qmatrix;'
642      READ,FILNME
644      CALL DETACH(10,ISTAT,)
646      CALL ATTACH(10,FILNME,1,0,ISTAT,)
648      call dumy2(iq,numtec,numprg)
670      print,'enter the b matrix, input=matrixb;'
680      READ,FILNME
682      CALL DETACH(10,ISTAT,)
684      CALL ATTACH(10,FILNME,1,0,ISTAT,)
688      CALL DUMY3(B,NUMTEC,NUMPRG)
690C
700C   READ IN THE ALPHA VECTOR AND COST VECTORS
710C
730      print,'enter the alpha vector'
740     READ, (ALPHA(I), I=1,NUMGL1)
770      print,'enter the technology cost vector = costec;'
771      read, filnme
772      call detach(10,istat,)
773      call attach(10,filnme,1,0,istat,)
774      call dumy4(costec,numtec)
780      print,'enter the program cost vector = cosprg;'
790      read,filnme
800      call detach(10,istat,)
801      call attach(10,filnme,1,0,istat,)
802      call dumy5(cosprg,numprg)
810   IF(NUMFIX.EQ.0) GOTO 165
820C       READ THE FIXED TECHNOLOGY VECTOR
830        WRITE (6,160)
840#160     FORMAT (1H ,'ENTER FIXED PORTION OF TECH VECTOR. T = FUNDED,
850&        F = NOT FUNDED')
860         READ, (Y(I), I=1,NUMFIX)
870C
880C
890C      PRINT OUT THE INPUT DATA
910#165 WRITE (6,170)
920#170  FORMAT (1HO,'INPUT DATA:')
930      WRITE (6,180)
940#180 FORMAT (1HO,6HGOAL #,2X,11HDESCRIPTION,13X,5HALPHA)
950      DO 200 I=1,NUMGOL
960         WRITE (6,190)IDGOL(I),ALPHA(I)
970#190       FORMAT (1H ,1X,I4,24(1H_),F9.2)
980#200 CONTINUE
990      WRITE (6,210)
1000#210  FORMAT (1HO,6HPROG #,2X,11HDESCRIPTION,13X,9HPROG COST)
1010     DO 230 I=1,NUMPRG
1020           WRITE (6,190)IDPRG(I),COSPRG(I)
1030#230  CONTINUE
1040      WRITE (6,240)
1050#240  FORMAT (1HO,6HTECH #,2X,11HDESCRIPTION,13X,4HCOST)
1060      DO 260 I=1,NUMTEC
1070          WRITE (6,190)IDTEC(I),COSTEC(I)
1080#260 CONTINUE
1090C
1100C    PRINT OUT THE MATRICES
1120     WRITE (6,270)
1130#270 FORMAT (1HO,'INTERACTION MATRICES')
1140     WRITE (6,280)
1150#280 FORMAT (1HO,'G-MATRIX: GOALS AND PROGRAMS')
1160     WRITE (6,290)
1170#290 FORMAT (1HO,10X,5HGOALS)
1180C
```

```
1190   CALL TOPLIN(NUMGOL,IDGOL)
1200C
1210    WRITE (6,300)
1220#300 FORMAT (1H ,5HPROG ,70(1H-))
1230C
1240    CALL GPRT(G,NUMPRG,NUMGOL,IDPRG)
1250    WRITE (6,310)
1260#310 FORMAT(1H0)
1270    WRITE (6,320)
1280#320 FORMAT (1H0,'PROGRAMS AND TECHNOLOGIES: Q-MATRIX')
1290    WRITE (6,330)
1300#330 FORMAT (1H0,10X,8HPROGRAMS)
1310C
1320    CALL TOPLIN(NUMPRG,IDPRG)
1330C
1340    WRITE (6,340)
1350#340 FORMAT (1H ,5HTECH ,100(1H-))
1360C
1370    CALL QPRT(IQ,NUMTEC,NUMPRG,IDTEC)
1380C
1390    WRITE (6,310)
1400    WRITE (6,350)
1410#350 FORMAT (1H0,'PROGRAMS AND TECHNOLOGIES: B-MATRIX')
1420    WRITE (6,330)
1430C
1440    CALL TOPLIN(NUMPRG,IDPRG)
1450C
1460    WRITE (6,340)
1480    CALL BPRT(B,NUMTEC,NUMPRG,IDTEC)
1490C
1500C   READ IN THE AMOUNT OF FUNDS AVAILABLE
1520    WRITE (6,360)
1530#360 FORMAT(1H0,'ENTER THE AMOUNT OF FUNDS AVAILABLE')
1535     call detach(41,istat,)
1540    READ, BUDGET
1550    WRITE (6,310)
1560    WRITE (6,380)BUDGET
1570#380 FORMAT (1h ,'THE TOTAL FUNDING AVAILABLE IS ',F6.2,' DOLLARS')
1610     print,"Enter an estimate of the no of techs that will be needed in
1620& to the fixed techs. If you dont wish to guess enter 0."
1640C
1650    READ, IGUESS
1660     BASBUX = 0.0
1670C
1680C  PRINT OUT THE LIST OF FIXED TECHS. IF THERE ARE NONE,JUMP TO
1690C  LINE 405
1700C
1710    IF(NUMFIX.EQ.0)GOTO 405
1720        WRITE (6,310)
1730        WRITE (6,392)
1740#392    FORMAT (1H0,'THE FOLLOWING TECHNOLOGIES ARE ALWAYS FUNDED:')
1750        DO 397 I=1,NUMFIX
1760           IF(.NOT.Y(I))GOTO 397
1770              WRITE (6,395) IDTEC(I)
1780#395           FORMAT (1H ,2X,I4)
1790#397     CONTINUE
1800C
1810C       CALCULATE THE AMOUNT OF MONEY LEFT TO PLAY WITH
1820C
1830        DO 400 I=1,NUMFIX
1840           IF(.NOT.Y(I))GOTO 400
1850              BASBUX = BASBUX + COSTEC(I)
1860#400    CONTINUE
1870C
```

```
1880C  SUBTRACT THE COST OF THE FIXED TECHNOLOGIES FROM THE INITIAL
1890C   BUDGET TO GET THE AMOUNT LEFT FOR THE VARIABLE TECHS
1900C
1910#405  BUDG1=BUDGET - BASBUX
1920C
1930C  IF YOU DON'T HAVE ANY MONEY TO PLAY WITH, QUIT.
1940       IF(BUDG1.GT.0.0)GOTO 420
1950C        YOU'RE HERE IF YOU DON'T HAVE ANY MONEY LEFT
1960         WRITE (6,410) BASBUX
1970#410      FORMAT (1H0,'FIXED TECHNOLOGIES COST ',F6.2,
1980&         'DOLLARS. NONE LEFT FOR OPTIONAL TECHS.')
1990          GOTO 999
2000C
2010C  CHECK THE ESTIMATE OF THE NUMBER OF OPTIONAL TECHS YOU CAN FUND
2020C
2030#420 IF((IGUESS+NUMFIX).GT.NUMTEC)IGUESS=0
2040       IF(IGUESS.GT.0)GOTO 440
2050C        YOU'RE HERE IF YOU HAVE TO SUPPLY YOUR OWN GUESS
2060         SUM = 0.0
2070       IF(NUMF1.LT.NUMTEC)GOTO 425
2080          IGUESS= 0
2090          GOTO 440
2100#425    DO 430 I=NUMF1,NUMTEC
2110#430      SUM = SUM + COSTEC(I)
2120        AVGCST  = SUM/(NUMTEC-NUMF1)
2130       RGUESS = BUDG1/AVGCST
2140       IGUESS = INT(RGUESS)
2150#440 M=IGUESS
2160C
2170C  PREPARE TO FIND THE BEST OF ALL THE COMBINATIONS TO COME
2180     BEST = 0.0
2190C
2200C   FIND THE CHEAPEST AND MOST EXPENSIVE TECHNOLOGIES.
2210     CTMIN = 1.0E36
2220     CTMAX = -1.0E36
2230     DO 450 I=NUMF1,NUMTEC
2240        CTMIN = AMIN1(CTMIN,COSTEC(I))
2250        CTMAX=  AMAX1(CTMAX,COSTEC(I))
2260#450 CONTINUE
2265    BUDGMN = BUDGET - CTMAX
2270C
2310C
2320C   THE VECTOR 'ITALLY' KEEPS TRACK OF THE M VALUES ALREADY
2330C   CHECKED. ITALLY(I)=FALSE MEANS THAT M=I MUST STILL BE CHECKED
2340C  NOTE: WE ARE ONLY WORKING WITH THE VARIABLE PORTION OF THE
2350C        Y-VECTOR.
2360C
2370    DO 470 I = 1,NUMVAR
2380#470   ITALLY(I)=.FALSE.
2390    WRITE(6,471)
2400#471  FORMAT(1H ,'DO YOU WISH TO ENTER AN ITALLY VECTOR? T:YES;F:NO
2410&  ')
2420    READ, ANS1
2430    IF(.NOT.ANS1)GOTO 480
2440       WRITE (6,472)
2450#472    FORMAT(1H ,'ENTER NEW ITALLY. T=DONT CHECK THIS M,F:ELSE')
2460       READ, (ITALLY(I),I=1,NUMVAR)
2470C
2480C   SET UP SOME PARAMETERS THAT MUST BE RESET FOR EACH NEW VALUE
2490C    OF M
2500C
2510#480 MRIGHT = NUMVAR - M + 1
2520     GO = .TRUE.
2530     ITALLY(M) = .TRUE.
2540      CXMIN = 1.0E36
2550     CXMAX = 0.0
```

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```
2551C
2552C PRITN THE HEADERS FOR THE COMBINATIONS TO COME
2553       write(6,481)(idtec(i),i=numf1,numtec)
2534 481 format(1h ,8hscore   ,3x,8hcost    ,3x,30i4)
2555     WRITE(6,482)(IDGOL(I),I=1,NUMGOL)
2556#482  FORMAT(1H0,'GOAL VALUES',' GO ',10I12)
2557C
2560C
2570C  SET UP THE INITIAL Y-VECTOR.  'IADD' IS A VECTOR THAT RECORDS THE
2580C  POSITION OF THE 1'S.IADD(1) IS THE POSITION OF THE
2590C  RIGHTMOST 1, IADD(2) THE NEXT RIGHTMOST 1, ETC.
2600C
2610C     FIRST FILL THIS ADDRESS POINTER WITH ZEROS
2620       DO  483 I=1,NUMVAR
2630#483    IADD(I) = 0
2640C
2650C     NOW PUT 1'S IN THE FIRST M PLACES.
2660        DO 485 I=1,M
2670#485      IADD(I) = M - I + 1
2680  WRITE (6,486) M
2690#486 FORMAT(1H ,'M= ',I3,' DO YOU WISH TO ENTER A STARTING Y VECTOR
2700& ? T:YES;F:NO')
2710  READ,ANS2
2720   IF(.NOT.ANS2)GOTO 490
2730       WRITE (6,487)M
2740#487  FORMAT(1H  'ENTER THE POSITION OF THE',I3,'FUNDED TECHS, RIGHT
2750& MOST FIRST')
2760       WRITE (6,488)
2770#488  FORMAT(1H ,'E.G. 4,2,1 MEANS: THERE ARE 1S IN THE LEFTMOST,
2780& 2ND,&4TH PLACES')
2790       READ, (IADD(I),I=1,M)
2800C
2810C
2820C  CHECK TO SEE IF YOU STILL HAVE UNTRIED PERMUTATIONS USING THIS M
2830C
2840C
2850#490 IF(GO)GOTO 492
2860C        ...IF YOU DON'T, CALL THE ROUTINE THAT WILL GIVE YOU A NEW M
2870        WRITE (6,491)
2880#491  FORMAT(1H ,'BEFORE GOING TO A NEW M, DO YOU WANT TO CHANGE
2890& ITALLY? T:YES,F:NO')
2900        READ, ANS3
2910        IF(.NOT.ANS3)GOTO 4919
2920          WRITE (6,4912)
2930#4912 FORMAT(1H ,'ENTER NEW ITALLY. T:DONT CHECK THIS M;F:ELSE')
2940          READ, (ITALLY(I),I=1,NUMVAR)
2950#4919 CONTINUE
2955C
2960         CALL MSEL(BUDG1,M,CTMIN,CTMAX,CXMIN,CXMAX,JUMP,NUMVAR,
2970&          NUMTEC,ITALLY)
2980         GOTO(900,480),JUMP
2990C
3000C  TRANSLATE IADD INTO A USEABLE Y-VECTOR
3010#492 DO 493 L=NUMF1,NUMTEC
3020#493       Y(L) = .FALSE.
3030C        ...NOW PUT 1'S IN THE PROPER POSITION
3040       IF(M.EQ.0)GOTO 500
3050       DO 495 L=1,M
3060          K = IADD(L)+NUMFIX
3070#495      Y(K) = .TRUE.
3080#500  CONTINUE
3090C
3100C  DETERMINE THE COST OF THE Y-VECTOR JUST SELECTED
3110C
3120   COST = BASBUD
```

```
3130     DO 505  I=1,M
3140c*505      COST = COST + COSTEC(IADD(I))
3141        jfix=numfix+iadd(i)
3144 505 cost=cost+costec(jfix)
3160C COMPARE THIS COST WITH OTHER VECTORS HAVING THE SAME M
3170C
3180     CXMIN = AMIN1(COST,CXMIN)
3190     CXMAX = AMAX1(COST,CXMAX)
3200C
3210C   IF THIS Y-VECTOR COSTS TOO MUCH OR TOO LITTLE, DON'T BOTHER TO
3220C   DO ANYTHING MORE WITH IT. JUST PICK A NEW Y.
3230C
3240      IF(COST.LE.BUDGET.AND.COST.GE.BUDGMN)GOTO 509
3270        GOTO 625
3280C
3290C   IF YOU ARE HERE, THE Y-VECTOR MEETS THE BUDGET CONSTRAINTS
3300C   NOW DETERMINE THE X VECTOR ENABLED BY THIS Y-VECTOR.
3310C
3320*509 DO 540 J=1,NUMPRG
3330          ICHECK = 0
3340          DO 520 I =1,NUMTEC
3350             IF(IQ(I,J).EQ.0)GOTO 510
3360                ICHECK = ICHECK+1
3370                GOTO 520
3380*510           IF(.NOT.Y(I))GOTO 520
3390                 ICHECK = ICHECK + 1
3400*520       CONTINUE
3410           IF(ICHECK.EQ.NUMTEC)GOTO 530
3420             X(J)=.FALSE.
3430             GOTO 540
3440*530        X(J) =.TRUE.
3445
3450*540 CONTINUE
3460C
3470C    CALCULATE THE VALUES FOR THE FIRST COLUMN OF TH  G-MATRIX.
3480C
3490*550 DO 580 J=1,NUMPRG
3500           G(J,1) = 0
3510C          FLAG WILL GO TRUE IF YOU SEE A STAR IN THIS COLUMN
3520           FLAG = .FALSE.
3530           DO 570 I=1,NUMTEC
3540C             WATCH FOR STARS
3550              IF(B(I,J).GE.0.0)GOTO 560
3560C                IF YOU GET A STAR, SET THE FLAG
3570                 FLAG = .TRUE.
3580                 GOTO 570
3590C             SUM THE B'S FOR PROGRAMS THAT ARRE COMPLETE
3600*560          IF(.NOT.X(I))GOTO 570
3610C                 ADD THE NON-STARRED B'S
3620                  G(J,1) = G(J,1) + B(I,J)
3625
3630*570       CONTINUE
3640C
3650C          IF YOU HAVE ENCOUNTERED A STAR, SUBTRACT COSPRG FORM THE RESULT
3660           IF(.NOT.FLAG)GOTO 580
3670              G(J,1) = G(J,1) - COSPRG(J)
3680*580 CONTINUE
3690C
3700C   CALCULATE THE TOTAL BENEFIT DERIVED FROM THIS Y VECTOR
3710C
3720      SCORE = 0.0
3730      DO 600 J=1,NUMGL1
3740           GOOD(J)=0.0
3750           DO 590 I = 1,NUMPRG
3760C             SUM THE BENEFITS OF COMPLETE PROGRAMS
3770              IF(.NOT.X(I))GOTO 590
```

```
3780                 GOOD(J) = GOOD(J) + G(I,J)
3790#590      CONTINUE
3800          SCORE = SCORE + ALPHA(J)*GOOD(J)
3810#600 CONTINUE
3820C
3830C PRINT THE RESULTS OF THIS Y-VECTOR
3840  IF(SCORE.LT.THRESH)GOTO 615
3850    ICOUNT = ICOUNT + 1
3860  WRITE(6,610)SCORE,COST,(Y(I), I=NUMF1,NUMTEC)
3870 610 format(1h ,f7.2,3x,f7.2,3x,30l4)
3872  WRITE(6,612) (GOOD(J),J=1,NUMGL1)
3873 612 format(1h ,11x,11f10.2)
3880#615  IF(ICOUNT.LT.25)GOTO 619
3890          WRITE (6,618)
3900#618      FORMAT(1H  ,'ENTER NEW THRESHOLD')
3910          READ, THRESH
3920          ICOUNT = 0
3930#619 CONTINUE
3940C  SEE IF IT'S BETTER THAN PRECEDING COMBINATIONS
3950C
3960     IF(SCORE.LE.BEST)GOTO 625
3970C       IF THIS IS THE BEST SCORE SO FAR, SAVE Y
3980           BEST = SCORE
3990           DO 620 I=1,NUMTEC
4000#620          BESTY(I) = Y(I)
4010C
4020C  NOW PICK THE NEXT Y VECTOR
4030C
4040C  IF THE LEFTMOST 1 IS AS FAR RIGHT AS IT CAN GO,QUIT (I.E. RETURN
4050C  A GO = .FALSE.)
4060C
4070#625  IF(IADD(M).LT.MRIGHT)GOTO 630
4080          GO = .FALSE.
4090          GOTO 490
4100C
4110C    IF THE RIGHTMOST 1 IS NOT IN THE RIGHTMOST SPACE, LMOVE IT ONE SPACE
4120C     TO THE RIGHT AND QUIT
4130#630 IF(IADD(1).GE.NUMVAR)GOTO 640
4140        IADD(1) = IADD(1) + 1
4150        GOTO 490
4160C
4170C     ...IF IT IS, LOOK AT THE NEXT 1
4180#640  JPLACE = 2
4190#650  IF(IADD(JPLACE).LT.(NUMVAR-JPLACE+1))GOTO 660
4200C
4210C          IF THIS 1 IS AS FAR RIGHT AS IT CAN GO, LOOK ATH THE NEXT 1
4220           JPLACE = JPLACE + 1
4230           GOTO 650
4240C
4250C      MOVE THE FIRST 1 YOU FIND THAT HAS A ZERO TO THE RIGHT OF IT .
4260C      PUT ALL 1'S THAT LIE TO THE RIGHT OF IT IN ADJACENT SPACES
4270#660   IDUMMY = IADD(JPLACE)
4280       DO 670 K=1,JPLACE
4290#670      IADD(JPLACE-K+1) = IDUMMY +K
4300       GOTO 490
4310C
4320C
4330C     SELECT THE BEST OF ALL THE Y-VECTORS EXAMINED
4340C
4350C
4360#900  WRITE (6,910)BEST
4370#910   FORMAT (1H0,'THE BEST SCORE WAS ',F6.2,' USING TECHNOLOGIES')
4380       DO 930 I=1,NUMTEC
4390          IF(.NOT.BESTY(I))GOTO 930
4400            WRITE (6,920) IDTEC(I)
```

```
4410#920          FORMAT (1H ,2X,I3)
4420#930   CONTINUE
4430#999   STOP
4440       END
4441C
4442      SUBROUTINE DUMY1(G,I,J)
4443      DIMENSION G(I,J)
4444     READ(10,201)((G(L,M),L=1,I),M=2,J)
4445 201 FORMAT(V)
4446      RETURN
4447      END
4448C
4449C
4450      SUBROUTINE DUMY2(IQ,I,J)
4451      DIMENSION IQ(I,J)
4452      READ(10,201) ((IQ(L,M),L=1,I),M=1,J)
4453 201 FORMAT(V)
4454      RETURN
4455      END
4456C
4457C
4458      SUBROUTINE DUMY3(B,I,J)
4459      DIMENSION B(I,J)
4460      READ(10,201) ((B(L,M),L=1,I),M=1,J)
4461 201 FORMAT(V)
4462      RETURN
4463      END
4464      subroutine dumy4(costec,i)
4465      dimension costec(i)
4466      read(10,201)(costec(l),l=1,i)
4467 201 format(v)
4468      return
4469      end
4470    SUBROUTINE MSEL(BUDGET,M,COSMIN,COSMAX,CMIN,CMAX,JUMP,
4480&    NUMVAR,NUMTEC,ITALLY)
4490C
4500    LOGICAL ITALLY
4510    DIMENSION ITALLY(30)
4511C
4512C  THIS SUBROUTINE SELECTS A NEW M VALUE WHEN THE MAIN PROGRAM SIGNALS
4513C  THAT IT HAS LOOKED AT ALL PERMUTATIONS OF M COMPLETE TECHS. THE
4514C  SUBROUTINE LOOKS AT THE ITALLY VECTOR AND CHOOSES AN M FROM AMONG
4515C  THOSE I FOR WHICH ITALLY(I) IS FALSE. IT KILLS ALL HIGHER M'S IF
4516C  THE CURRENT M COSTS TOO MUCH, AND IT KILLS ALL LOWER M'S IF THE
4517C  CURRENT M COSTS TOO LITTLE.
4518C
4519C  INPUTS:
4520C      BUDGET :  THE TOTAL AMOUNT OF FUNDS AVAILABLE
4521C      M      :  THE CURRENT (I.E. OLD) M VALUE
4522C      COSMIN :  THE MINIMUM COST ACHIEVED WITH THE CURRENT M
4523C      COSMAX :   "  MAXIMUM   "      "       "    "     "    "
4524C      CMIN   :  COST OF THE CHEAPEST TECHNOLOGY
4525C      CMAX   :    "   "  "  MOST EXPENSIVE TECHNOLOGY
4526C      NUMVAR :  NUMBER OF VARIABLE TECHNOLOGIES
4527C      NUMTEC :  TOTAL NUMBER OF TECHNOLOGIES
4528C      ITALLY :  VECTOR INDICATING STATUS OF M'S. T: DON'T CHECK IT
4529C   OUTPUTS:
4530C      M      :  THE NEW M VALUE
4531C      ITALLY :  THE NEW ITALLY VECTOR
4532C      JUMP   :  CONTROL POINTER: 1=END OF RUN;2=CONTINUE W/NEW M
4540    IF(M.LE.0)GOTO 65
4543    M2 = M
4546    M1 = M+1
4550C
```

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```
4560C  CHECK TO SEE IF M IS TOO HIGH
4570C
4580       IF((BUDGET-COSMIN).GE.CMIN)GOTO20
4590C    IF YOU'RE HERE,M IS TOO HIGH; ELIM. ALL LARGER M'S
4600       DO 10 L = M,NUMVAR
4610#10        ITALLY(1) = .TRUE.
4620C
4630C    CHECK TO SEE IF M IS TOO LOW
4640#20 IF((BUDGET-COSMAX).LE.CMAX)GOTO 40
4650C     HERE M IS TOO LOW; ELIM. ALL SMALLER M'S
4660      DO 30 I=1,M
4670#30        ITALLY(I) = .TRUE.
4680C
4690C  HERE M IS IN THE RIGHT RANGE. UNFORTUNATELY, THIS IS THE OLD
4700C   M AND WE WANT A NEW ONE...
4710C    ...FIRST LOOK FOR ONE A LITTLE LARGER.
4720#40  IF(M.GE.NUMVAR)GOTO 55
4730      DO 50 M =M1,NUMVAR
4740C       LOOK FOR A FEASIBLE M LARGER THAN THE CURRENT ONE
4750        IF(.NOT.ITALLY(M))GOTO 70
4760#50   CONTINUE
4770C
4780C    ...IF YOU DON'T FIND A LARGER M, LOOK FOR A SMALLER ONE
4790#55   DO 60 MINV = 1,M2
4800         M=M2 - MINV + 1
4810         IF(.NOT.ITALLY(M))GOTO 70
4820#60   CONTINUE
4830C
4840C IF YOU ARE HERE, NO FEASIBLE M'S ARE LEFT. TELL THE MAIN PROGRAM
4850C  TO PRINT THE BEST RESULT AND STOP.
4860C
4870#65    JUMP = 1
4880     GOTO 100
4890#70  JUMP = 2
4900#100 CONTINUE
4910     RETURN
4920     END
4930c
4931      subroutine dumy5(cosprs,i)
4932      dimension cosprs(i)
4933      read(10,201)(cosprs(l),l=1,i)
4934 201  format(v)
4935      return
4936      end
4937c
4938      subroutine dumy6(idsol,i)
4939      dimension idsol(i)
4940      read(10,201)(idsol(l),l=1,i)
4941 201  format(v)
4942      return
4943      end
4944c
4945      subroutine dumy7(idprs,i)
4946      dimension idprs(i)
4947      read(10,201)(idprs(l),l=1,i)
4948 201  format(v)
4950      return
4951      end
4952      subroutine  dumy8(idtec,i)
4953      dimension idtec(i)
4954      read(10,201)(idtec(l),l=1,i)
4955 201  format(v)
4956      return
4957      end
4958c
```

```
4959     subroutine toplin(icol,icolab)
4960  DIMENSION ICOLAB(20),FORM(22),ICARRY(20)
4970  REAL LEFT1
4980  DATA LEFT1,RIGHT,ALPHA,DIGITI,BLANK/4H(10X,1H),3H,A6,3H,I6,4H    /
4990C
5000C  THIS SUBROUTINE PRINTS THE LABELS FOR THE COLUMNS OF A MATRIX.
5010C  IT IS NORMALLY FOLLOWED BY A MATRIX PRINTING SUBROUTINE.
5020C
5030C  INPUTS:
5040C    ICOLAB: AN INTEGER VECTOR OF RANK ICOL CONTAINING COLUMN LABELS
5050C    ICOL  : AN INTEGER ( THE NUMBER OF COLUMNS)
5060C
5070C  FIRST INITIALIZE THE FORMAT STATEMENT
5080   FORM(1) = LEFT1
5090   FORM(22)= RIGHT
5100C
5110C  INSURE THAT NO GARBAGE IS INCLUDED IN THE FORMAT STATEMNT
5120   DO 10 I=2,21
5130      FORM(I) = BLANK
5140#10 CONTINUE
5150C
5160C  SET THE FORMAT STATEMNT TO PRINT THE COLUMN LABELS
5170   DO 20 I=1,ICOL
5180      I1 = I + 1
5190      FORM(I1) = DIGITI
5200      ICARRY(I) = ICOLAB(I)
5210#20 CONTINUE
5220C
5230C  PUT BLANKS ON THE RIGHT-HAND SIDE AND ADJUST THE FORMAT STATEMENT
5240   ICOL1 = ICOL+1
5250   DO 30 I =ICOL1,20
5260      I1 = I+1
5270      FORM(I1) = ALPHA
5280      ICARRY(I) = BLANK
5290#30  CONTINUE
5300 WRITE (6,FORM) (ICARRY(J),J=1,ICOL)
5310   RETURN
5320   END
5330C
5340C
5350  SUBROUTINE GPRT(ARRAY,IROW,ICOL,IDROW)
5360  REAL LEFT1,LEFT2,LEFT3
5370  DIMENSION ARRAY(12,9),IDROW(30),FORM(30),VAL(20)
5380C
5390C  THIS SUBROUTINE PRINTS ALL EXCEPT THE FIRST COLUMN OF THE G-MATRIX.
5400C  IT INSERTS BLANKS FOR ZERO ELEMENTS IN THE MATRIX AND PRINTS
5410C   ONLY THE NUMBER OF COLUMNS NECESSARY.
5420C
5430C  INPUTS:
5440C    ARRAY:  AN IROW X (ICOL+1) REAL MATRIX
5450C    IDROW:  AN INTEGER VECTOR OF RANK IROW CONTAINING NUMBERS THAT
5460C                IDENTIFY THE ROWS OF THE MATRIX
5470C    IROW :  AN INTEGER
5480C    ICOL :  "     "
5490C
5500   DATA LEFT1,LEFT2,LEFT3,RIGHT,ALPHA,DIGITR,COMMA,BLANK/4H( I8,
5510&    4H,5X,,3H1H!,1H),2HA6,4HF8.3,1H,,4H     /
5520C
5530C  INITIALIZE THE FORMAT STATEMENT
5540  FORM(1) = LEFT1
5550  FORM(2) = LEFT2
5560  FORM(3) = LEFT3
5570  FORM(24)= RIGHT
5580  ICOL1   = ICOL +1
5590C
```

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5600C  INSURE AGAINST GARBAGE IN THE FORMAT STATEMENT
5610   DO 10 I=4,23
5620#10   FORM(I) = BLANK
5630C
5640C  SET THE FORMAT FOR EACH NEW ROW, A ROW AT A TIME
5650   DO 50 I=1,IROW
5660      DO 40  J=2,ICOL1
5670              JX=J+J
5680              JY=JX+1
5690              IF(ABS(ARRAY(I,J)).GE.1.0E-7)GOTO 30
5700C               INSERT A BLANK FOR EMBEDDED ZEROS
5710                VAL(J-1) = BLANK
5720                FORM(JX) = COMMA
5730                FORM(JY) = ALPHA
5740                GOTO 40
5750#30           VAL(J-1)  = ARRAY(I,J)
5760               FORM(JX) = COMMA
5770               FORM(JY) = DIGITR
5780#40     CONTINUE
5790       WRITE (6,FORM) IDROW(I),(VAL(J), J=1,ICOL)
5800#50 CONTINUE
5810    RETURN
5820    END
5830C
5840C
5850   SUBROUTINE QPRT(MATRIX,IROW,ICOL,IDROW)
5860   DIMENSION MATRIX(25,12),IDROW(25),VAL(30),WYE(30)
5870C
5880C   THIS SUBROUTINE PRINTS THE Q-MATRIX. IT WILL PRINT THE APPRO
5890C   PRIATE Y VARIABLE WHERE THE INPUT DATA HAS A ZERO
5900C
5910C   INPUTS:  SIMILAR TO GPRT
5920C
5930#10 FORMAT (1H ,I8,5X,1H!,20A6)
5940    DATA ONE,BLANK/4H   1,4H    /
5950    DATA (WYE(I),I=1,30)/4H  Y1,4H  Y2,4H  Y3,4H  Y4,4H  Y5,4H  Y6,
5960&     4H  Y7,4H  Y8,4H  Y9,4H Y10,4H Y11,4H Y12,4H Y13,4H Y14,
5970&     4H Y15,4H Y16,4H Y17,4H Y18,4H Y19,4H Y20,4H Y21,4H Y22,
5980&     4H Y23,4H Y24,4H Y25,4H Y26,4H Y27,4H Y28,4H Y29,4H Y30/
5990C
6000C  FILL OUT THE VALUE STATEMENT WITH BLANKS
6010   ICOL1 = ICOL+1
6020   DO 20 I=ICOL1,20
6030#20   VAL(I)=BLANK
6040C
6050C  ESTABLISH THE OUTPUT STRING FOR EACH ROW OF THE MATRIX
6060   DO 50 I=1,IROW
6070      DO 40  J=1,ICOL
6080         IF(MATRIX(I,J).EQ.1)VAL(J)=ONE
6090         IF(MATRIX(I,J).NE.1)VAL(J)=WYE(I)
6100#40     CONTINUE
6110      WRITE (6,10)IDROW(I),(VAL(J),J=1,ICOL)
6120#50 CONTINUE
6130   RETURN
6140   END
6150C
6160C
6170   SUBROUTINE BPRT(ARRAY,IROW,ICOL,IDROW)
6180   REAL LEFT1,LEFT2,LEFT3
6190   DIMENSION ARRAY(25,12),IDROW(30),FORM(44),VAL(20)
6200C
6210C  THIS SUBROUTINE PRINTS OUT THE B-MATRIX. IT PRINTS A STAR WHERE
6220C   IT ENCOUNTERS A NEGATIVE VALUE IN THE INPUT DATA
6230C
6240C  INPUTS:  SIMILAR TO GPRT
6250C
```

```
6260    DATA LEFT1,LEFT2,LEFT3,RIGHT,ALPHA,DIGITR,COMMA,STAR,BLANK/
6270&    4H( I8,4H,5X,,3H1H!,1H),2HA8,4HF8.2,1H,,1H*,4H     /
6280C
6290C   INITIALIZE THE FORMAT STATEMENT
6300    FORM(1) = LEFT1
6310    FORM(2) = LEFT2
6320    FORM(3) = LEFT3
6330    FORM(44)= RIGHT
6340C
6350C   INSURE AGAINST GARBAGE
6360     DO 10  I=4,43
6370#10     FORM(I) = BLANK
6380C
6390C   SET THE FORMAT FOR EACH ROW, A ROW AT A TIME
6400    DO 60 I =1,IROW
6410       DO 50 J =1,ICOL
6420          JX=J+J+2
6430          JY=JX+1
6440          IF(ABS(ARRAY(I,J)).GT.1.0E-7)GOTO 30
6450C           INSERT A BLANK FOR EMBEDDED ZEROS
6460            VAL(J)=BLANK
6470            FORM(JX)=COMMA
6480            FORM(JY)=ALPHA
6490            GOTO 50
6500#30        IF(ARRAY(I,J).GT.0.0)GOTO 40
6510C           INSERT A STAR FOR NEGATIVE NUMBERS
6520            VAL(J)   = STAR
6530            FORM(JX)= COMMA
6540            FORM(JY)= ALPHA
6550            GOTO 50
6560#40        VAL(J) = ARRAY(I,J)
6570            FORM(JX) = COMMA
6580            FORM(JY) = DIGITR
6590#50     CONTINUE
6600       WRITE(6,FORM)IDROW(I),(VAL(J), J=1,ICOL)
6610#60 CONTINUE
6620     RETURN
6630     END
```

Appendix A.4.1 Detailed Flowchart, Ballpark Mode

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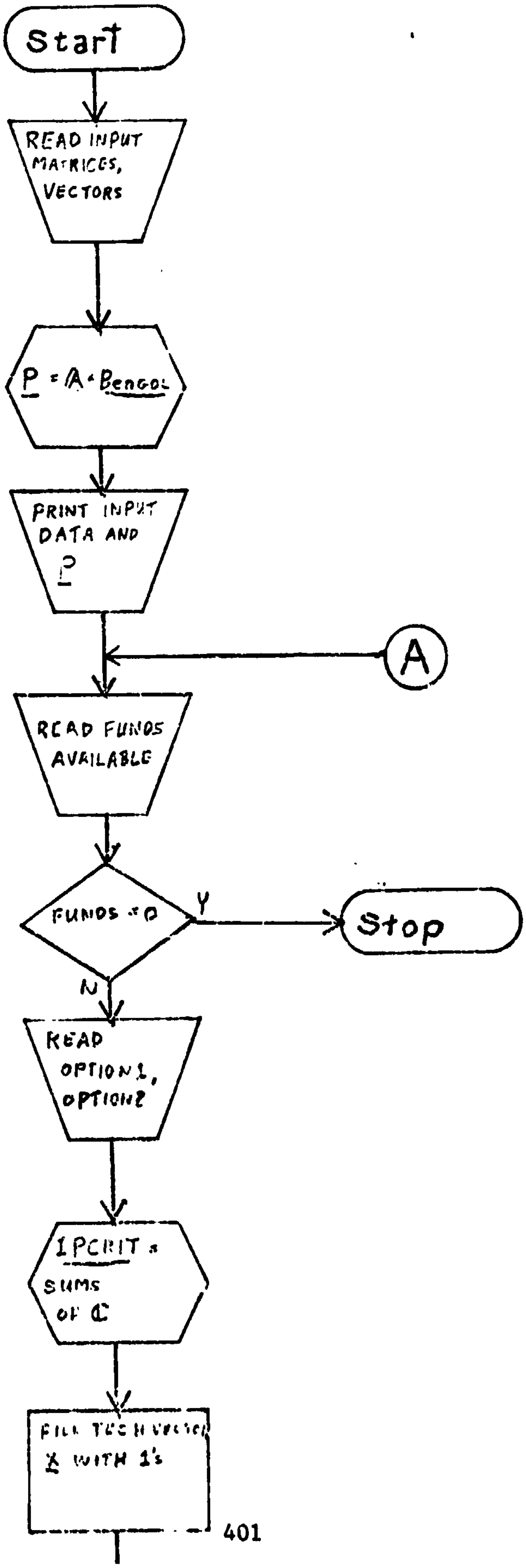
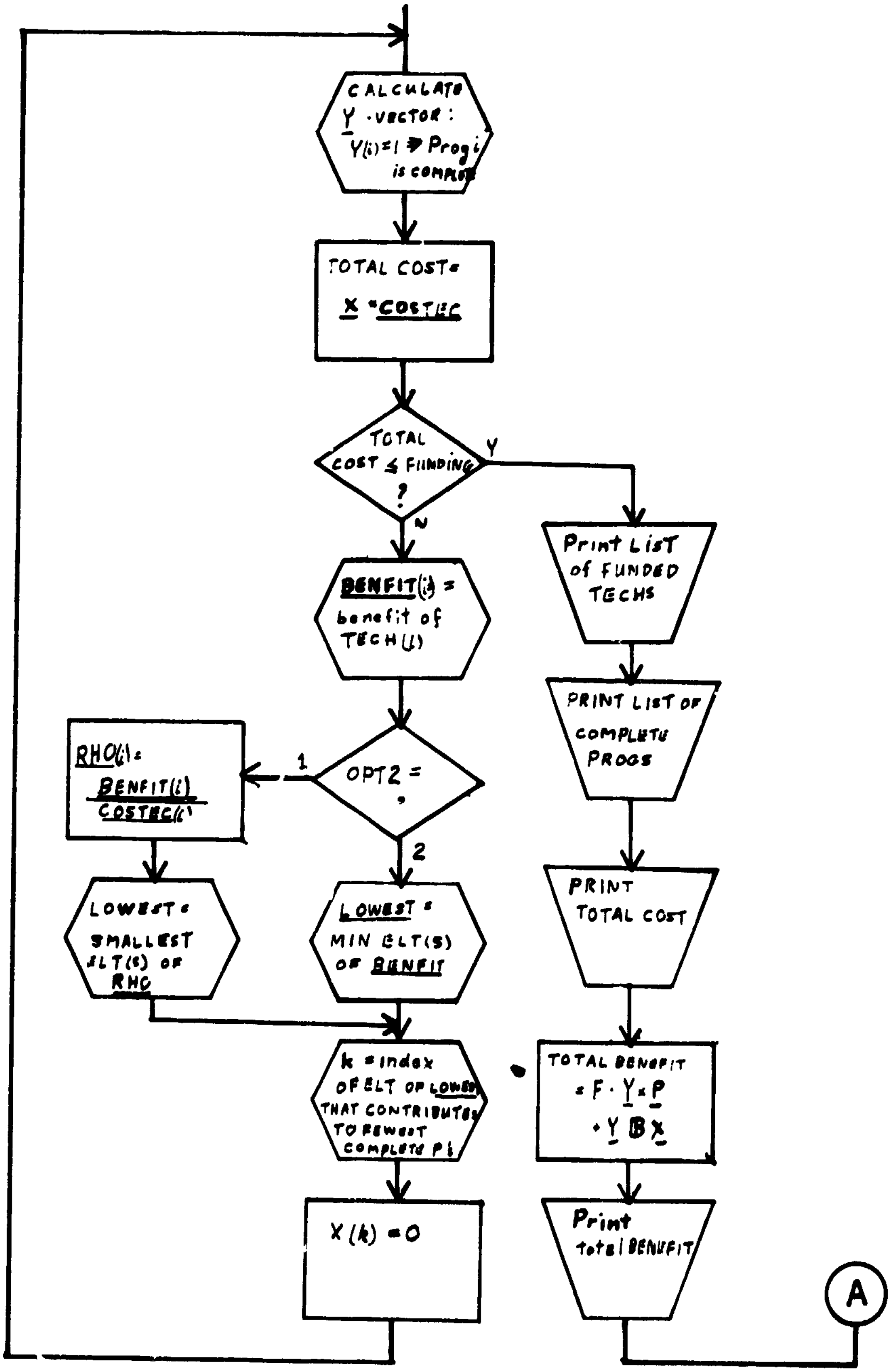
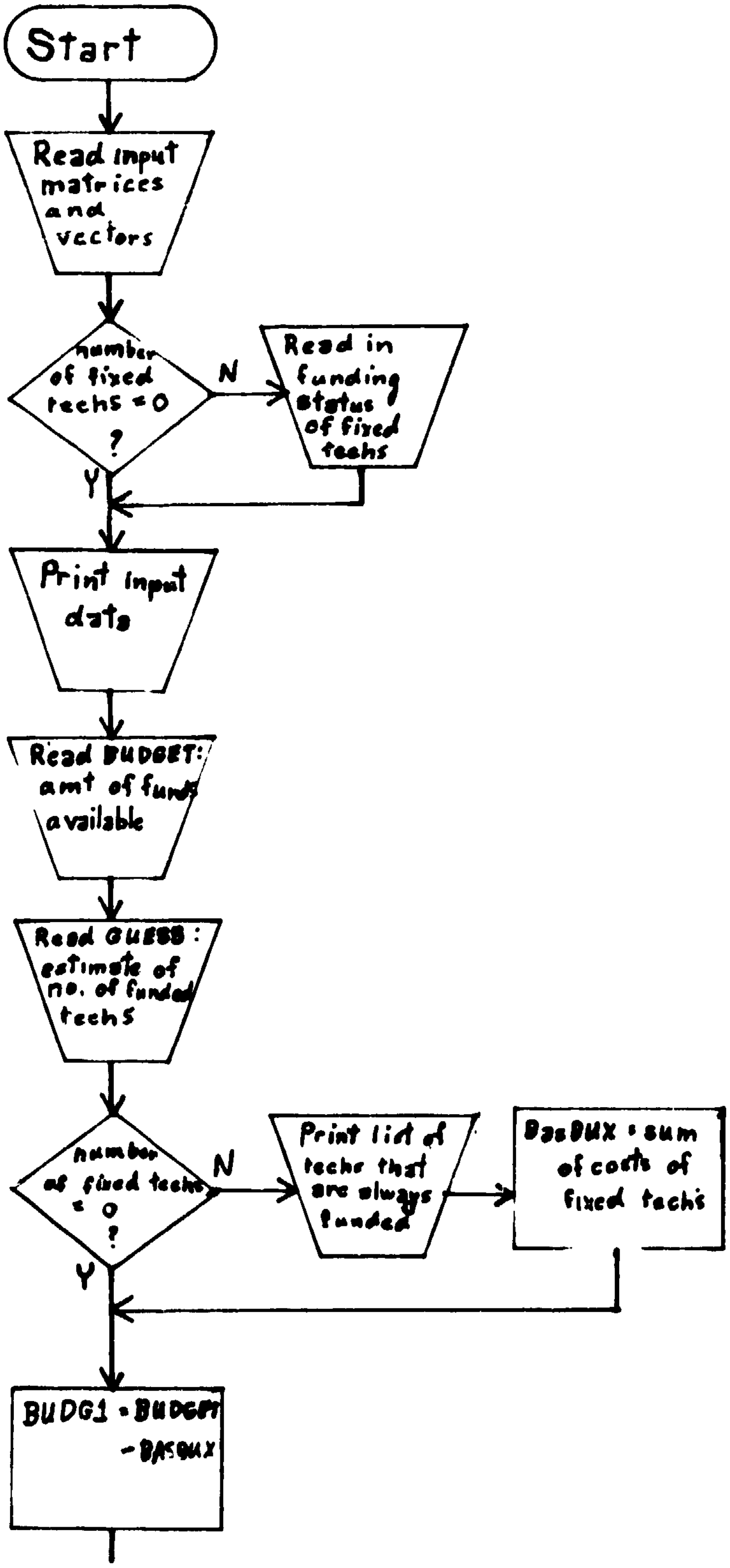
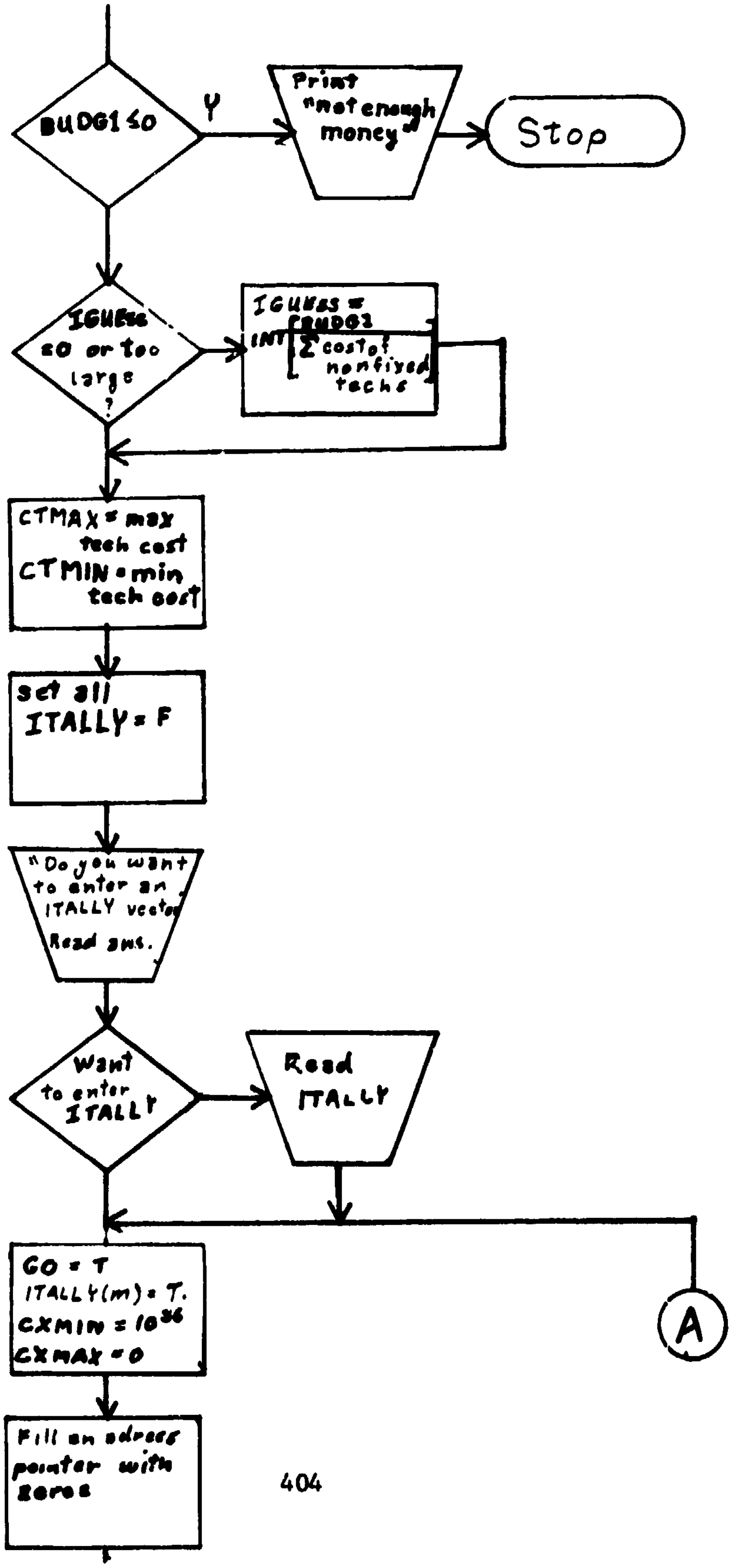



CALCULATE Y-VECTOR: Y(i)=1 ⇒ Prog i is COMPLETE
TOTAL COST = X · COSTEC
TOTAL COST ≤ FUNDING ?
Y
N
Print List of FUNDED TECHS
BENFIT(i) = benefit of TECH(i)
PRINT LIST OF COMPLETE PROGS
OPT2 = ?
1
2
RHO(i) = BENFIT(i) / COSTEC(i)
LOWEST = SMALLEST ELT(S) OF RHO
LOWEST = MIN ELT(S) OF BENFIT
PRINT TOTAL COST
k = index OF ELT OF LOWEST THAT CONTRIBUTES TO FEWEST COMPLETE Pi
TOTAL BENEFIT = F · Y × P + Y B X
X(k) = 0
Print total BENEFIT
A

Appendix A.4.2 Detailed Flowchart, Goodness Measure Mode




BUDG1 ≤ 0
Y
Print "not enough money"
Stop
IGUESS ≤ 0 or too large ?
IGUESS = INT [FBUDG1 / Σ cost of nonfixed techs]
CTMAX = max tech cost
CTMIN = min tech cost
set all ITALLY = F
"Do you want to enter an ITALLY vector
Read ans.
Want to enter ITALLY
Read ITALLY
GO = T
ITALLY(m) = T.
CXMIN = 10^36
CXMAX = 0
Fill an adress pointer with zeros
A

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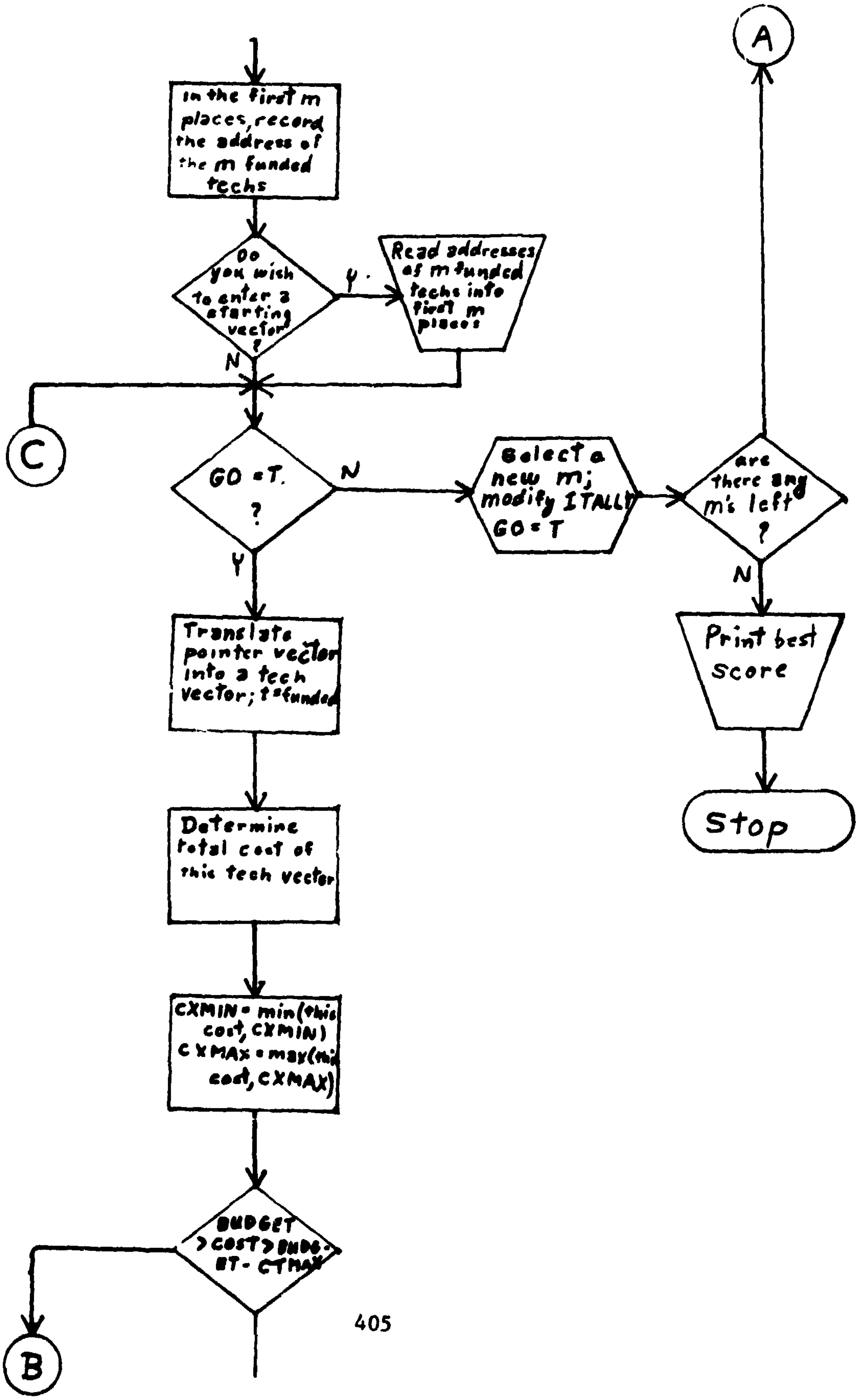
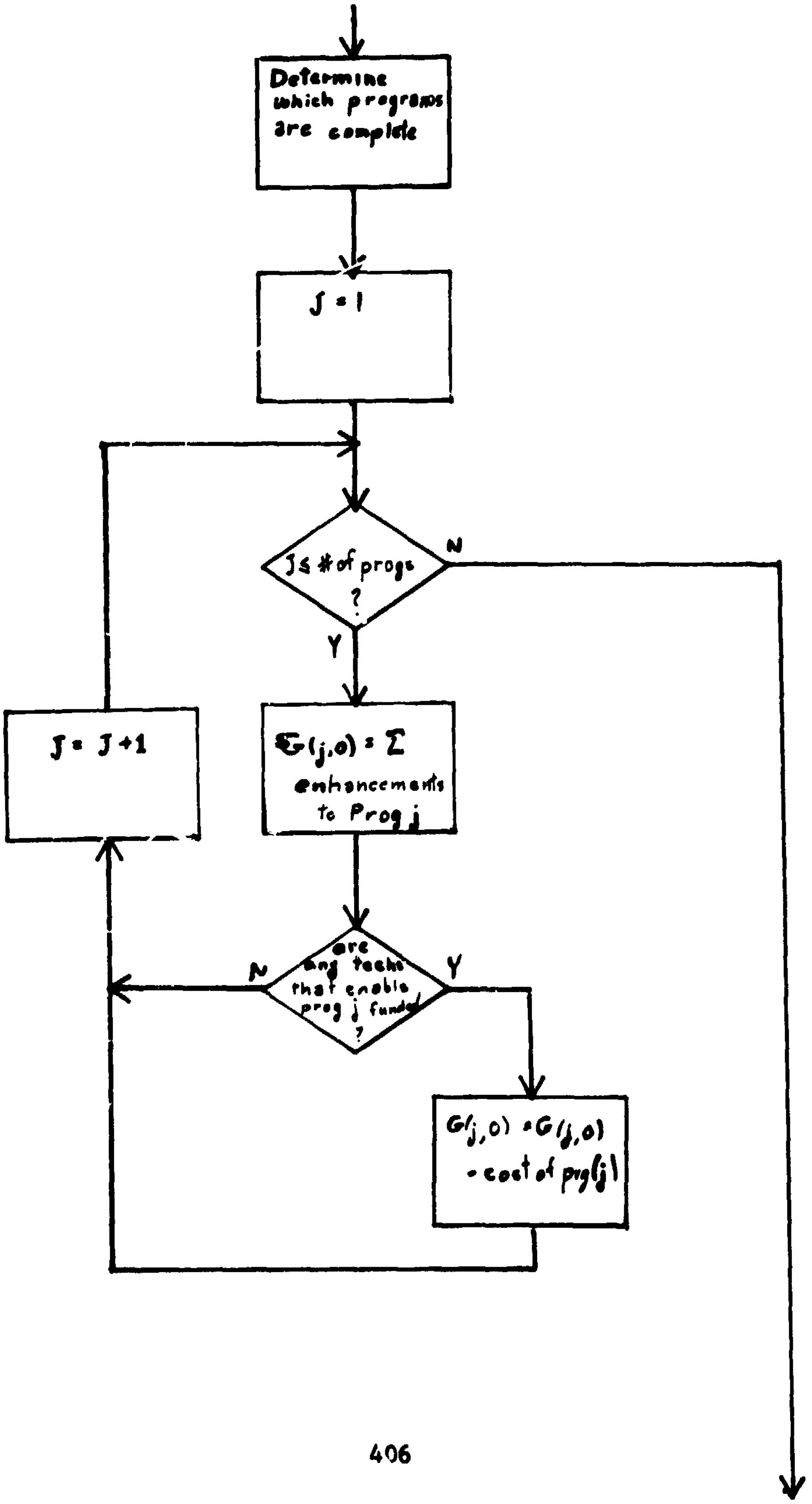
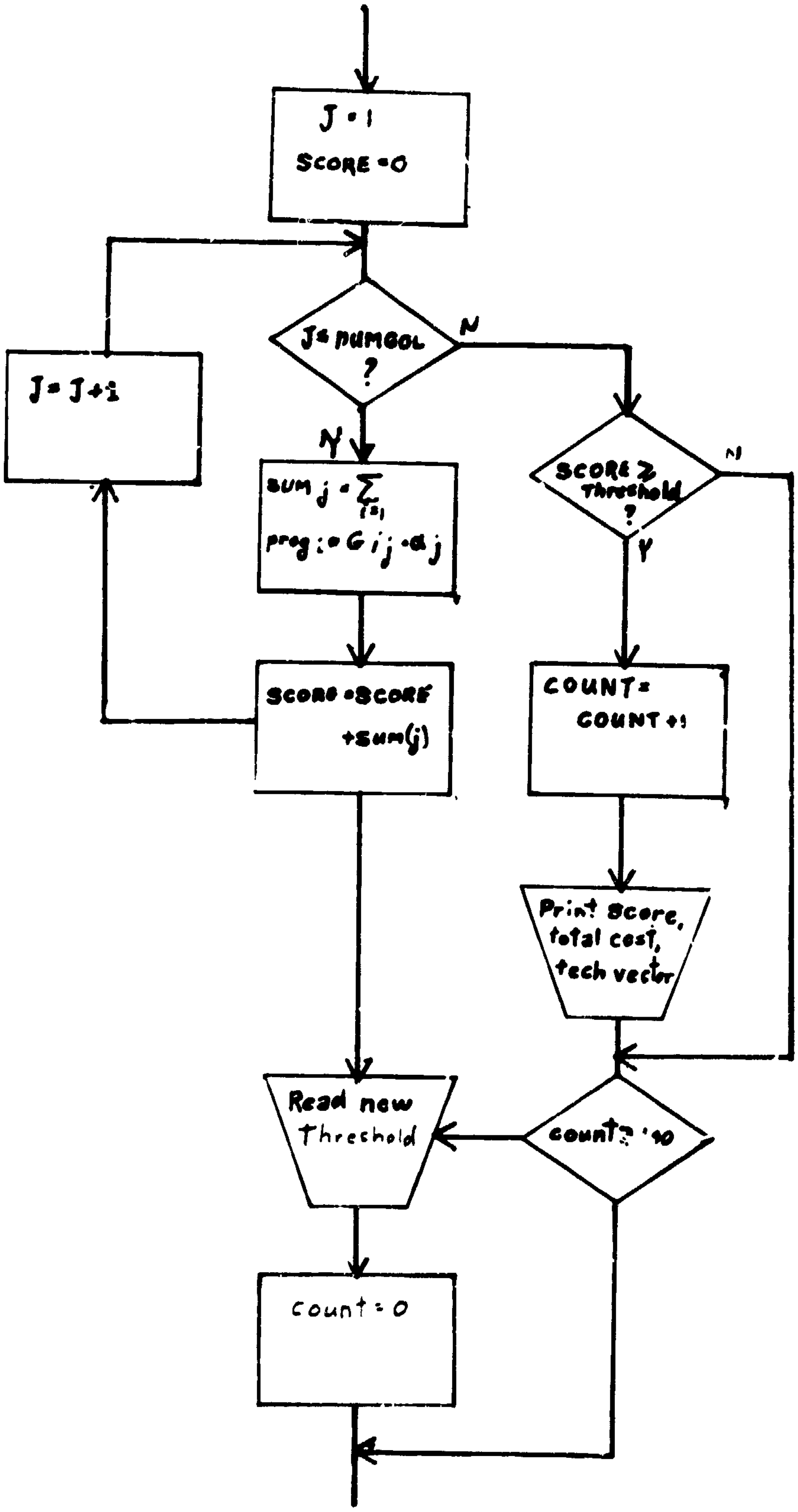
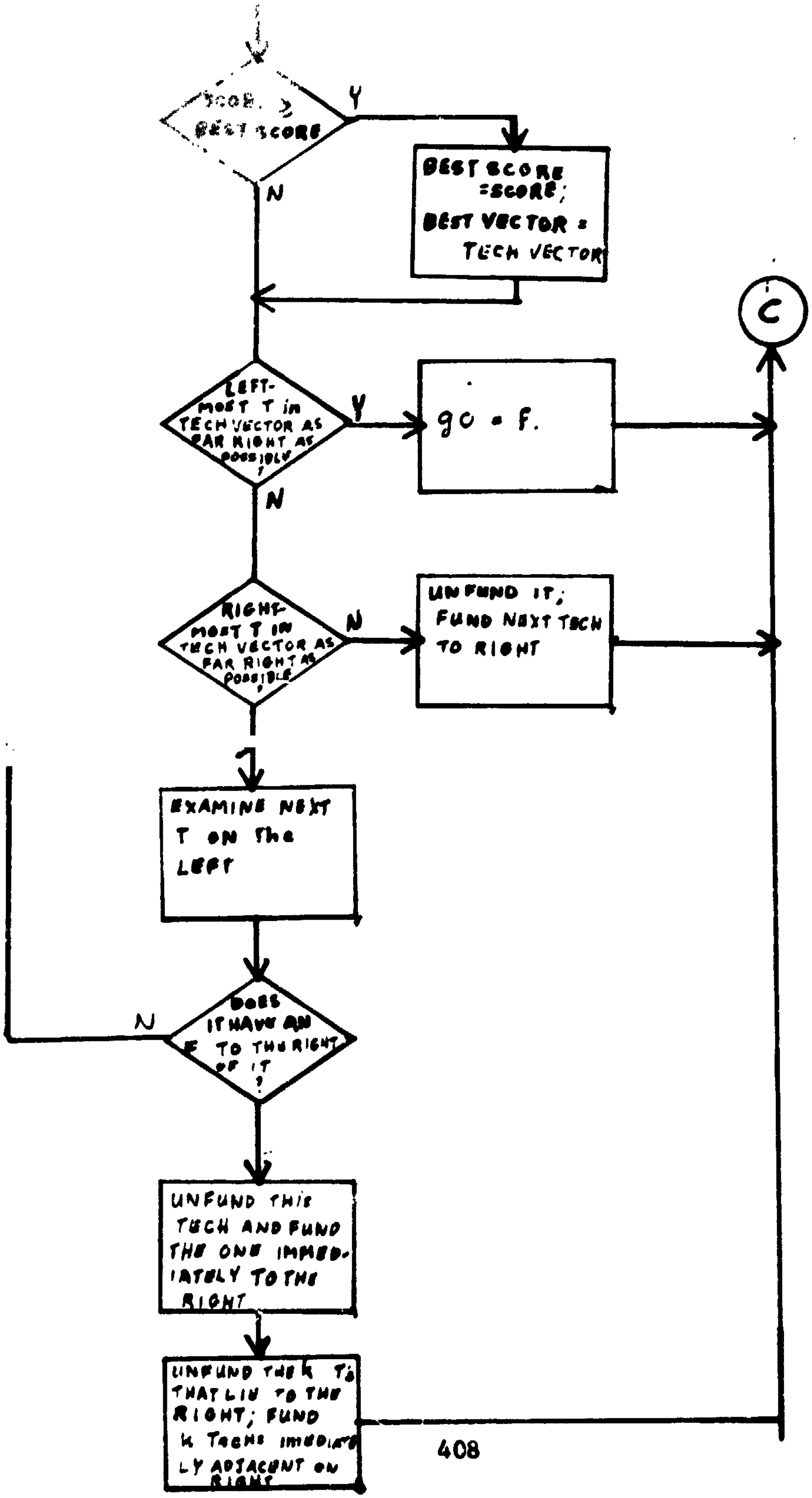



Determine which programs are complete
J = 1
J ≤ # of progs ?
N
Y
$G(j,0) = \Sigma$ enhancements to Prog j
J = J + 1
are any techs that enable prog j funded ?
N
Y
G(j,0) = G(j,0) - cost of prg(j)


J = 1
SCORE = 0
J ≤ NUMGOL ?
N
Y
J = J + 1
SUM j = Σ i=1 prog i · G ij · a j
SCORE = SCORE + SUM(j)
SCORE ≥ Threshold ?
N
Y
COUNT = COUNT + 1
Print Score, total cost, tech vector
count ≥ 10
Read new Threshold
count = 0


SCORE ≥ BEST SCORE
Y
N
BEST SCORE = SCORE;
BEST VECTOR = TECH VECTOR
C
LEFT-MOST T in TECH VECTOR AS FAR RIGHT AS POSSIBLE ?
Y
go = f.
N
RIGHT-MOST T IN TECH VECTOR AS FAR RIGHT AS POSSIBLE ?
N
UNFUND IT; FUND NEXT TECH TO RIGHT
EXAMINE NEXT T ON The LEFT
DOES IT HAVE AN F TO THE RIGHT OF IT ?
N
UNFUND THIS TECH AND FUND THE ONE IMMEDIATELY TO THE RIGHT
UNFUND THE k T's THAT LIE TO THE RIGHT; FUND k TECHS IMMEDIATELY ADJACENT ON RIGHT