NASA Conference Publication 2030

Active Microwave Users Workshop Report

Proceedings of a Workshop held at
Lyndon B. Johnson Space Center
Houston, Texas
August 1976

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Edited by Richard E. Matthews

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FOREWORD

The Active Microwave Users Workshop was organized by the NASA Lyndon B. Johnson Space Center (JSC) in August 1976 for the purpose of preparing advanced plans for the microwave applications program. The scope of the workshop was expanded beyond this initial objective to address issues of particular concern at this stage in the effort. Included among these issues are potential land applications of Seasat data and imaging radar data processing system options.

The Active Microwave Workshop conducted by the JSC in July 1974 set the stage for a series of events that has significantly expanded the microwave remote-sensing effort within NASA. The Active Microwave Users Workshop continued this definition process and provided specific guidelines for future development.

The 1976 workshop was composed of 55 scientists and engineers having extensive experience in remote sensing. The participants were selected for their ability to contribute to one of the four panel topics.

Applications Panel: F. P. Weber, chairman

Seasat Land Experiments Panel: J. E. Estes, chairman

Program Planning Panel: F. T. Ulaby, chairman

Synthetic Aperture Radar (SAR) Data Processing Panel: F. L. Beckner, chairman

A Steering Committee, chaired by R. E. Matthews, coordinated the efforts of the various panels.

Many people contributed significantly to the activities of the workshop, and to list their contributions individually is not possible. However, special thanks are due the workshop participants and the members of the Steering Committee for their support and contributions.

It will be noted that individual author identity is missing from this report. To ensure better continuity and coverage, each chapter was written as a unified entity rather than as a series of individually authored papers.

The contents of this report represent the collective knowledge, views, and opinions of the Active Microwave Users Workshop participants. The recommendations and conclusions contained in the report are those of the workshop members and do not necessarily represent the policy and program direction of NASA.

As an aid to the reader, where necessary the original units of measure have been converted to the equivalent value in the Système International d'Unités (SI). The SI units are written first, and the original units are written parenthetically thereafter. Further, the definitions of all abbreviations, acronyms, and symbols used in the report are provided in the concluding appendix.

Lyndon B. Johnson Space Center

October 20, 1977

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CHAPTER I

SUMMARY OF THE ACTIVE MICROWAVE USERS WORKSHOP

INTRODUCTION

In 1974, the National Aeronautics and Space Administration (NASA) conducted the Active Microwave Workshop (AMW) as the first concerted effort to bring together the several elements of the active microwave remote-sensing field in such a way as to demonstrate the applications of this technology. The results of that effort firmly established the following conclusions.

1. An all-weather, day or night remote-sensing capability would significantly improve orbital monitoring of terrain and ocean surfaces.

2. The unique and/or supplementary information obtainable in the microwave region of the electromagnetic spectrum would substantially increase the value of remote-sensing measurements for Earth, ocean, and atmospheric applications.

As a result of these findings, the NASA Office of Applications has initiated a coordinated microwave applications development program. The goals of this microwave program are to improve the capability to (1) identify, monitor, and assess the Earth's resources and (2) monitor the Earth's environment and predict significant changes.

The program consists of the scientific, technical, and programmatic activities required to develop microwave remote sensing into an operational tool for systematic Earth observations. The approach adopted calls for NASA to perform the following tasks.

1. Develop microwave remote sensing for those applications for which this technology provides a unique or complementary source of information.

2. Develop the technology and facilities necessary to test and implement microwave remote-sensing techniques for Earth observations.

3. Develop the means to ensure direct involvement by potential users in the formulation, evaluation, and implementation of the microwave program.

4. Provide coordination among NASA centers, institutions, and agencies to minimize costs and duplication of effort.

5. Facilitate communication throughout the community of scientists, technologists, and microwave data users.

6. Prepare advanced mission plans and identify advanced components and systems development required to meet future needs.

The Active Microwave Users Workshop (AMUW) was an extension of the AMW designed to provide a sharper focus of the applications and to begin the process of converting the general approach described previously into an action plan. The results presented in this report provide the foundation for developing and implementing a plan to establish the measurement potential of active microwave imaging sensors.

The AMUW was conducted to accomplish the following four basic objectives.

1. Obtain an unbiased evaluation of the potential of imaging-radar data to provide unique and/or supplementary information of value to specific Earth resources applications.

2. Determine the potential of the Seasat sensors to provide useful data for land applications and design specific experiments to investigate the information content of Seasat data.

3. Develop preliminary technical and programmatic plans to guide the imaging-radar applications development effort.

4. Define the radar image and data-processing requirements associated with the applications and recommend approaches for the development of an electronic data-processing capability in NASA to support future orbital sensor systems.

The AMUW was composed of approximately 50 scientists and engineers. The group was directed by an eight-man Steering Committee. To fulfill the multifaceted objectives of the AMUW, formation of the following four panels was necessary.

1. Applications Panel

2. Seasat Land Experiments Panel

3. Program Planning Panel

4. Synthetic Aperture Radar (SAR) Data Processing Panel

The panel members were selected by Texas A. & M. University personnel, who organized and conducted the workshop, in consultation with the Steering Committee. Each participant was chosen on the basis of his experience in the topics to be addressed in each panel. The members of the Applications Panel were selected to represent the remote-sensing field in general, rather than the microwave area in particular. Most were discipline specialists with strong backgrounds in the use of visible-infrared data. (See appendix.)

The AMUW was held August 10-12, 1976, in Houston, Texas. All participants were supplied advance material, including a statement of the specific objectives of their panel, background literature, and appropriate bibliographies. During the 3 days of meetings, each panel prepared a draft report of its conclusions and recommendations. This draft formed the basis of the final report.

PANEL RECOMMENDATIONS

The recommendations of each of the four panels are presented in the following subsections.

Applications Panel

The Applications Panel believes that although important and unique applications of active microwave sensing can be identified now, significant research and development is needed in advance of committing large sums of money to sophisticated space systems. The panel strongly recommends that NASA immediately commit major funds for an imaging microwave applications development program supported by development and utilization of a sophisticated airborne multifrequency imaging radar system. The panel recommends that this microwave applications development program be structured around the following seven application areas, which show the most promise for early return on the research and development investment.

1. Natural vegetation
   a. Range improvement
   b. Range biomass productivity
   c. Range inventory
   d. Forest assessment
   e. Tropical forest inventory
2. Cultivated vegetation
   a. Crop productivity estimates
   b. Identification of stress
3. Water resources
   a. Streamflow forecast
   b. Watershed characteristics
   c. Frozen-lake mapping
4. Mineral-energy resources - mineral and petroleum exploration
5. Oceanography
   a. Ship navigation and routing
   b. Pollution monitoring
   c. Ocean engineering hazards

6. Hazard surveys

   a. Flood mapping

   b. Hurricane damage assessment

   c. Tornado damage assessment

   d. Forest and range fire damage assessment

   e. Landslide and Earth slippage assessment

   f. Earthquake prediction and damage assessment

7. Land use - existing land cover other than vegetation

Seasat Land Experiments Panel

The Seasat Land Experiments Panel concluded that the Seasat mission has significant implications in the area of land applications. The Seasat SAR's all-weather, day or night imaging capability; its possible compatibility with Landsat data; and its potential for providing unique data for a number of key application areas make this system important for exploitation in the Earth observations program. To obtain maximum benefit from this opportunity to conduct land experiments with the first orbital-imaging-radar data available to the public, the Seasat Land Experiments Panel recommends that NASA perform the following tasks.

1. Conduct a number of specific land-applications experiments in the areas of land-cover analysis, food and fiber production, water resources, and geology.

2. Establish a Seasat SAR Land Applications Team to assist in mission planning in the evaluation and management of the land-applications experiments.

3. Initiate a land-applications experiment program at the earliest possible date to facilitate its incorporation into the Seasat mission plan.

4. Employ the 24-day (Cambridge) orbit, which is more suitable for land observations, during at least 1 year of the first 2 years of the Seasat mission.

Program Planning Panel

The Program Planning Panel undertook to develop a detailed programmatic and technical plan for active microwave technology in each of four application areas: (1) vegetation resources, (2) water resources, (3) mineral resources and geologic applications, and (4) oceanographic applications. The following panel recommendations are grouped by activity.

1. User community involvement and cost/benefit analysis

a. Active involvement of the user community on all appropriate levels - Federal, State, and industrial - should be emphasized in the program planning and execution of active microwave research for Earth resources applications.

b. Cost/benefit studies should be conducted to evaluate the potential contributions of active microwave technology to each major application area.

2. System development

a. The development of additional multifrequency, multipolarization radar spectrometers to supplement the existing 1- to 8-GHz and 8- to 18-GHz microwave active spectrometer (MAS) systems at the University of Kansas should be pursued vigorously.

b. An airborne SAR should be developed for soil moisture monitoring. Ground-based measurement results indicate that the system should be a calibrated instrument capable of operating in the 4- to 5-GHz band in the incident angle range of 7° to 17°.

c. An airborne SAR should be developed for monitoring agricultural resources. Ground-based measurement results indicate that the system should be a dual-polarized, calibrated instrument capable of operating in the 14- to 15-GHz band in the incident angle range of 45° to 55°.

3. Measurement program

a. Aircraft-based radar studies over natural and cultivated vegetation should be expanded.

b. Analysis of repetitive aircraft measurements and observations of soil moisture variations over Kansas, Oklahoma, and southern California test sites should be emphasized.

c. Ground-based and aircraft measurement of snow properties with the use of test sites in the central Sierra Nevada Mountains of California and the Rocky Mountains of Colorado should be emphasized.

d. Correlation should be established between aircraft and spaceborne SAR observations and measured runoff coefficients with the use of Oklahoma, Texas, and Pennsylvania test sites.

e. NASA should place renewed emphasis on the definition of optimum system parameters for a wide range of geologic investigations and special emphasis on the development of the polarization capability of the radar measurement system.

Synthetic Aperture Radar (SAR) Data Processing Panel

The recommendations of the SAR Data Processing Panel are as follows.

1. An Imaging Radar Technology Group should be established by NASA to develop and maintain technical expertise applicable to current and proposed NASA imaging-radar systems. This group should meet at least once a year.

2. An imaging-radar-technology study program to conduct investigations related to the gathering, processing, and dissemination of imaging-radar data should be supported by NASA. The following study areas should be supported.

a. Requirements for antenna pointing and motion compensation for satellite-borne SAR systems

b. Requirements and processing implications for squint-mode SAR operation

c. Interpretability versus image parameter trade-offs for digital SAR imagery

d. Techniques for SAR calibration

e. The interface between a SAR image formation facility and the users

3. A central SAR image formation processing facility should be established by NASA to provide users with cataloged SAR data in standard formats.

4. The development of onboard processors for dedicated applications requiring timely dissemination of image data should be pursued.

5. Existing airborne SAR measurement facilities should be modified to include the recording of raw sensor data in digital form.

6. Raw aircraft and Seasat data should be made available to support the recommended imaging-radar-technology study program.

7. The development of high-density data storage devices such as the RCA 240-Mbps magnetic tape recorder should be continued.

PANEL SUMMARIES

The accomplishments of each of the four panels are summarized in the following subsections.

Applications Panel

The Applications Panel was composed of remote-sensing specialists with strong discipline-oriented backgrounds but with limited experience in microwave remote sensing. The composition of this panel was especially selected to eliminate any possible bias that may have existed in earlier studies of this kind.

The panel surveyed existing literature and documentation on potential microwave sensor applications. Over 200 potential applications were identified and rated relative to priority and feasibility on a scale of 1 to 6. Twenty-five applications were found to have a high priority-high feasibility rating (scale factor 1). These applications were grouped into seven application or discipline areas.

1. Natural vegetation

2. Cultivated vegetation

3. Water resources

4. Mineral and energy resources and geologic applications

5. Oceanography

6. Hazard surveys

7. Land use

The user requirements were identified, and an active microwave development program is suggested for each area. The program recommendations include ground-based, aircraft, and spacecraft measurements. Within each major discipline area, a number of specific tasks are identified.

The panel expressed the opinion that the greatest potential for microwave remote sensing in the near future is in the heretofore lightly explored areas of natural vegetation, hazard surveys, and land use. Each of these important areas is currently being addressed with other remote-sensing techniques; however, in each case, microwave sensing can contribute significantly with complementary data required to satisfy the information needs.

Seasat Land Experiments Panel

The following experiments involving the use of Seasat data were identified and defined.

1. Mapping and land-cover analysis

   a. Assessing the planimetric accuracy of Seasat-A SAR images

   b. Land-cover mapping in metropolitan regions

2. Food and fiber

a. Rangeland and forest biomass assessment

b. Soil moisture/crop yield monitoring

c. Monitoring aquatic vegetation

d. Crop discrimination and stress evaluation

e. Saline seep/soil salinity detection and monitoring

3. Water resources

a. Watershed runoff estimation

b. Surface-water and flood mapping

c. Snowfield mapping

d. Alaskan lakes mapping

4. Geology

a. Alaskan Placer Gold Belt mapping

b. Assessment of glacial ice dynamics

c. Evaluation of utility of SAR data for mineral and petroleum exploration in forested areas

d. Geomorphic mapping in coastal wetlands and marshes

e. Evaluation of utility of SAR data for potash exploration

f. Discrimination of hydrothermal alterations

g. Identification of construction materials

h. Evaluation of terrain roughness

i. Examination of Arctic coastal ice structure and dynamics

j. Evaluation of SAR data for high-relief, mineral rich areas

k. Evaluation of utility of SAR data for base metals exploration

l. Evaluation of utility of SAR data in sulphur deposit exploration

m. Interpretation of geologic structures in areas of low relief

Program Planning Panel

The Program Planning Panel concluded that orbital, multiparameter imaging-radar data are essential for development of the application of SAR technology. In this report (ch. 4), the following information is provided.

1. Identification of the primary information needs within each of four application areas: vegetation resources, water resources, mineral resources and geologic applications, and oceanographic applications

2. Evaluation in general terms of the impact of each application in terms of social and economic gains and specification of the technical requirements of the user community

3. Summarization of the present state of knowledge of the applicability of active microwave sensing to each application area and evaluation of its role relative to other remote-sensing techniques

4. Identification of the analysis and data acquisition techniques needed to resolve the effects of interference factors in order to establish an operational capability in each area

5. Flow charts of accomplished and required technical activities in each application area leading to operational capability

6. Programmatic guidelines to support the applications development tasks

Synthetic Aperture Radar (SAR) Data Processing Panel

The SAR Data Processing Panel undertook to identify the available and optimal methods for generating SAR imagery for NASA applications. The major conclusions of the panel were as follows.

1. The SAR data processing of interest to NASA falls into three categories: onboard processing for special applications requiring timely dissemination of data, ground image formation processing into standard formats for general applications, and postprocessing of image data to derive specific quantitative information.

2. The early radar (including the Seasat SAR and the spaceborne imaging radar) NASA ground image formation processing requirements are within the present state-of-the-art of both optical and digital technology.

3. Onboard processors are presently not within the state-of-the-art but probably will be when such processors are actually needed.

4. The output imagery from a large ground-based image formation processor should be provided in the same manner and format as Landsat imagery to facilitate SAR image acquisition and correlation with optical imagery.

5. There is no optimum SAR-data-processing architecture, because the processor architecture depends on the application (which determines the imaging geometry) and the technology utilized.

6. The selection of a technology for SAR data processing is presently driven by memory considerations, not arithmetic considerations. Other important considerations are power, weight, size, flexibility, and cost.

7. In a large ground-based SAR-data-processing facility, some form of real-time quick-look processing capability should be provided to allow prescreening of the data to be processed.

CONCLUDING REMARKS

The Active Microwave Users Workshop (AMUW) satisfied four specific needs of the NASA microwave program.

1. An objective evaluation of the relative worth of microwave-sensing capabilities for Earth observations applications

2. A definitive experiment plan for use of Seasat data in land-applications studies

3. An examination of the research, equipment, and resources required to develop the applications potential of microwave remote sensing and a preliminary plan to coordinate these elements over the next 5 years

4. An assessment of the technology and techniques available to solve the important synthetic aperture radar data processing problem and a recommended course of action in this area

The AMUW results provide an independent endorsement for the conclusions of the Active Microwave Workshop, which confirmed that orbital microwave remote sensing is both feasible and highly desirable and that there are several important applications for which the unique, supplementary or complementary capabilities of this approach are extremely valuable.

APPENDIX

ORGANIZATION AND ADDRESSES OF THE ACTIVE MICROWAVE USERS WORKSHOP GROUP

The AMUW group consisted of a Steering Committee and the following four panels: (1) the Applications of Active Microwave Imagery Panel, (2) the Seasat Land Experiments Panel, (3) the Microwave Program Planning Panel, and (4) the SAR Data Processing Panel.

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CHAPTER 2

APPLICATIONS OF ACTIVE MICROWAVE IMAGERY

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INTRODUCTION

The objectives of the Active Microwave Imagery Applications Panel were as follows.

1. To review and critique the applications potential of active microwave image data

2. To review the findings of the Microwave Applications Task Force

3. To prioritize potential active microwave applications that are considered "payoff applications" by users such as resource managers and planners

The Applications Panel members were selected from the academic community, Federal Government, and private industry. Although some members have had previous experience with active microwave, they consider themselves as nonexperts who are inclined to view the potential for active microwave applications in a different light and with significantly different priorities than their counterparts at the workshop who are radar technologists. However, each Applications Panel member is an expert in one or more of the Earth resources disciplines and has had considerable experience in applying other forms of remote-sensing data. Panel members do represent the users who will determine the eventual success or failure of the active microwave program in Earth resources application.

Early in the workshop, the Applications Panel received a detailed briefing on microwave technology from Professor R. K. Moore, University of Kansas. The panel chairman provided an extensive library of radar and microwave literature, much of it applications oriented. Members also received a formal briefing on Seasat and entered into numerous discussions with other workshop members who were available for technical discussions. Likewise, application experts from the panel were called upon to consult with other workshop panels regarding the relevancy and priority of active microwave applications in various Earth resources disciplines.

Among the many recent documents on microwave reviewed by the Applications Panel, two were of special interest: the "Active Microwave Workshop Report" and "Applications Review for a Space Program Imaging Radar (SPIR)" (refs. 2-1 and 2-2, respectively). Also reviewed were numerous documents related to the active microwave research program stimulated by the Jet Propulsion Laboratory Symposium, May 1976.

Concurrently with the discussions of active microwave applications, the panel worked in four subpanel groups to discuss the following subjects.

1. Use of imaging radar to improve the data collection/analysis process

2. Unique data collection tasks for radar that other systems will not perform

3. Data reduction concepts

4. System and vehicle parameters: aircraft and spacecraft

The first task for the Applications Panel was to survey the aforementioned literature and document all potential microwave applications and any special data requirements noted - i.e., microwave parameters. This information was accumulated on form AP-1, "Active Microwave Applications Survey" (sample copy included in appendix).

Each of the 200 potential applications recorded on the AP-1 forms was prioritized on a scale of 1 to 6 (see appendix), denoting priority and feasibility; e.g., scale factor 1 rated high priority and high feasibility. Panel members then transferred all of the 25 scale factor 1 application tasks to form AP-2, "Application Matrix Master," and grouped them into 7 major application or discipline areas (see appendix). The resulting focus on the "high payoff" application tasks was accomplished, according to instructions received by the panel from the workshop chairman.

The Applications Panel determined seven major areas for high-payoff applications with a well-coordinated active microwave program including field measurements, aircraft, and spacecraft. Within each major discipline area, a number of specific activities were indicated, many of which are common among major areas. Specific tasks such as inventory, monitoring, and assessment appear to be the most important application roles in the future.

Whereas it is not certain that all 25 application tasks will eventually be satisfied from space-derived data, some could currently be successfully accomplished in the near future from aircraft platforms, achievement being predicated on the availability of suitable active microwave aircraft systems.

NATURAL VEGETATION

Currently, 6.27 Mm^2 (1.55 billion acres), approximately 67 percent of the Nation's land area, are classified as natural vegetation, principally forest and rangeland (ref. 2-3). The remaining area is classified as inland water, cropland, improved pasture, and other lands - i.e., deserts, barrens, and land used as residential and industrial sites, roads, and airports and for miscellaneous other purposes.

Two-thirds of the natural vegetation area, approximately 4.5 Mm^2 (1.1 billion acres), are classified as rangeland and noncommercial forest (ref. 2-4). The rangeland includes natural grasslands, savannas, shrub lands, most deserts, tundra, coastal marshes, and wet meadows. The noncommercial forest includes ecosystems such as the pinyon-juniper forests of the Southwest that are incapable of producing crops of industrial wood because of poor site or other adverse conditions, and productive forested land withdrawn for parks, wildlife refuges, recreation areas, or other uses not compatible with timber production. Another 2.0 Mm^2 (0.5 billion acres) are classified as commercial forest land; i.e., land capable of producing more than 0.57 m^3 (20 ft^3) of industrial wood a year in natural stands and not withdrawn for other uses.

As a result of the large area and wide geographic distribution, the Nation's lands have a diversified natural vegetation cover ranging from moss, lichens, and short grasses through high shrubs and cacti, to the large trees of the Pacific coast such as redwood and Douglas fir. This diversified natural vegetation is classified into 34 ecosystems - 14 nonforested and 20 forested. The nonforested ecosystems are based on the natural plant communities of the United States as described by A. W. Kuchler (ref. 2-5). The forested ecosystems are based on the forest types used in the forest survey, conducted by the United States Forest Service (USFS).

Rangelands are highly variable. They occur from sea level to the highest mountains. Some are flat and smooth; others are steep, rough, and rocky. Rangelands may be dominated by short grasses only 7.6 to 10.2 cm (3 to 4 in.) tall, such as buffalo grass of the Great Plains, or by grasses 1.8 to 2.4 m (6 to 8 ft) tall, such as big bluestem in the tall-grass prairie. The vegetation includes such common and widespread shrubs as sagebrush and rabbit brush, literally thousands of species of flowering forbes and grasses, and even tall shrubs and some trees.

Rangeland resources are receiving increased levels of attention on regional, national, and international scales. Mounting pressures through legislative mandates and economic factors have resulted in a requirement for optimization of rangeland management and productivity. Legislated actions are required of agencies such as the USFS, Soil Conservation Service (SCS), and Bureau of Land Management (BLM) to inventory and monitor various aspects of rangeland resources. Economic factors such as the high cost of supplemental feeds on ranches and the feedlot finishing of cattle are pushing a heavier burden on rangeland production for cattle grazing.

Rangeland extents and jurisdictions are very large for Government and private landowners. Each manager in the BLM, for instance, is responsible for extensive areas averaging tens of hundreds of square kilometers (hundreds of thousands of acres) in size. For example, two adjoining district offices are located in Phoenix, Arizona, and Las Vegas, Nevada. Approximately 8093.7 km^2 (2 million acres) of Texas State-owned lands are managed under one man. Few managers and planners, however, have accurate knowledge relating to many of the aspects of rangeland that they are required to deal with. The competitive possible uses of rangelands and varying agency priorities complicate management objectives on all scales. Federal agencies must consider a number of resource system requirements in managing rangelands and providing livestock grazing permits. In addition to range, the areas requiring consideration are as follows.

1. Recreation and wilderness

2. Wildlife and fisheries

3. Timber

4. Land and water

5. Human and community development

Even ranchers must consider the interplay of wildlife and livestock because, in many cases, hunting leases bring more income than livestock sales.

Because of the huge areal extent and paucity of information, coupled with the management activities concerning rangelands, optimum utilization of information-gathering facilities is required. Three high-priority applications that require active microwave data as part of the data base collection activity have been singled out.

1. Rangeland inventory

2. Rangeland productivity

3. Rangeland improvement

Rangeland Inventory

The rangelands of the United States provide the renewable resource base for a multimillion dollar industry. Much of the rangeland area in the western United States is under Federal ownership and is the management responsibility of Federal agencies, particularly the BLM and the USFS. Grazing rights on thousands of square kilometers (millions of acres) of land are leased by these agencies to ranchers. However, adequate information concerning the condition of these rangelands is not widely available.

A key requirement for effective management is knowledge concerning the location, extent, and condition of the various rangeland areas throughout the United States. The Forest and Rangeland Renewable Resources Act of 1974 has mandated that such a rangeland inventory be conducted as a part of the 1979 assessment and updated at 10-year intervals thereafter. At present, the USFS does not have an established national rangeland inventory system as it does for timberland, with the forest survey. Because of the size of the area involved, space-acquired data appear to be one effective approach to meeting such a requirement and perhaps the only cost-effective method.

Before the condition of the rangeland areas can be effectively assessed, a basic rangeland inventory must be obtained. Because the SAR will provide data on moisture content and surface roughness characteristics of the target, it is anticipated that the SAR would provide a highly useful addition to the type of information that can be acquired from Landsat multispectral scanner (MSS) systems. Therefore, for a national rangeland inventory, the geometric correction and registration of MSS and SAR data will be necessary to provide the most effective data base for analysis.

Rangeland Productivity

As indicated in the discussion on rangeland inventory, there is a tremendous need for accurate, comprehensive information on the condition of the rangeland resources. The biomass available for grazing changes throughout the year, as a function of grazing intensity and weather conditions. Because of the sensitivity of radar systems to differences in total biomass and the moisture content of vegetation, such a system should have advantages for obtaining data useful in an assessment of rangeland productivity.

Because grazing permits are issued for varying numbers of cattle on the basis of the amount of vegetation available, ranchers often move their herds from one area to another throughout the year to prevent overgrazing of any one area; hence, there is a critical need for obtaining current data on a periodic basis. Such data should be obtained every 2 weeks during the summer and once per month during the remainder of the year. Also, a multistage sampling scheme should be established to monitor the condition and productivity of key areas; thereby, an effective and efficient subsampling system would be created for obtaining such information for compilation into a national statistical base.

Rangeland Improvement

Optimum management and utilization of rangeland resources requires improvement of those resources. Dollar investments in rangeland improvements, however, must be judicious because of the marginal return expectable. Improvements, consequently, must be limited to a few high-priority items - e.g., fertilization, rest rotation, and brush control.

In semiarid lands, brush control is the number one problem. Brush species (woody species) include mesquite and cedar, among others. Approximately 8093.7 km^2 (2 million acres) of State-owned lands in west Texas are now under a new flexible leasing program. The leaseholder is required to provide brush control on his leases when brush reaches a 30-percent canopy cover, to maintain good-quality range forage condition. The enforcement of the policy requires accurate determination of the brush cover percent on a semiannual basis. Other State and Federal agencies have, or will have, similar management information needs.

The unique capabilities of SAR systems in their high sensitivity to geomorphic properties of vegetation cover, land-cover texture, and plant moisture content will significantly improve the brush survey techniques being developed with visible/near-infrared sensors. Inclusion of SAR data with Landsat MSS data in a scene-registered, geometrically corrected format should provide a powerful multichannel, multisensor data set. Table 2-1 illustrates the user requirements for rangeland information as related to inventory, productivity, and improvement.

Forest Assessment

In contrast to the rangelands, which are nearly all in the West and Alaska, three-quarters of the area in the Nation's forest ecosystems classified as commercial timberlands are in the East.

The southern pine ecosystem, the source of more than one-fourth of the timber harvest in the United States, made up a little more than 14 percent of the Nation's commercial timberlands in 1970. Southern pines are concentrated on the Coastal Plain and Piedmont extending from New Jersey to Texas.

In the West, the bulk of the commercial timberland is softwood ecosystems. The Douglas fir and ponderosa pine systems make up approximately 6 percent of the total commercial timberland in the United States; and other western softwoods, 9 percent.

The ponderosa pine ecosystem occupies a large area in eastern Oregon and Washington and is the most extensive commercial forest type in California and the Rocky Mountains. In most ecosystems, and especially those in the West, there are substantial additional areas classified as noncommercial forest. For example, the total area in the ponderosa pine ecosystem is estimated to be 152 161.8 km^2 (37.6 million acres), or 38 849.8 km^2 (9.6 million acres) greater than the estimate of commercial area.

In examining the problem of measuring forest biomass productivity as a part of a forest assessment, the importance of at least one measurement requirement - losses from forest stress - should be considered in detail.

Stress detection in our Nation's wild lands and forests is a multiagency task, costing several millions of dollars each year in aerial and ground surveys. In the national forest system, the stress comes primarily from insects or disease; and its impact is evaluated by a count of killed or damaged trees.

TABLE 2-1.- USER REQUIREMENTS FOR RANGELAND INFORMATION AS RELATED TO INVENTORY, PRODUCTIVITY, AND IMPROVEMENT

User needs	Inventory	Productivity	Improvements
Justification	See text	See text	See text
User agencies	USFS, BLM, States	USFS, BLM, States	USFS, BLM, States
Importance	Very high priority	Very high priority	Very high priority
Time requirements	One every 10 years for entire United States; every 5 years for USFS and BLM lands (in early summer?)	Every 2 weeks in summer; monthly during rest of year	Semiannually
Area coverage	Entire western United States	Sample points within each strata defined in the inventory (sample data would come from locations throughout western United States)	Texas and other semiarid land areas
Measurement parameters	Location of rangeland type/ composition of species mixtures	Biomass of rangeland vegetation (density + height); moisture	Brush density (percent ground cover); 30-percent ground cover is maximum allowable in Texas lease situation
Data products	Maps of complete area coverage showing total rangeland area and individual types of range cover (species composition, mixtures); tables of areas of each rangeland type, by country or some TBD[a] designated geographic areas	Maps of sample sites and tabular display of biomass estimate for each site	Maps of entire area showing different brush density groupings
Cartographic products required	Yes	Yes	Yes

[a]To be determined.

Catastrophic outbreaks of forest insects, largely bark beetles and defoliators, continue to be the major cause of timber mortality, which annually equates to 23 597 372.2 m^3 (10 billion fbm). Forest management activities can play a major role in limiting these losses. Unfortunately, forest managers often do not have the information required to prevent serious losses and to utilize dead timber. The problem is not unique to the United States. The need for forest biomass productivity information is just as great in tropical forest ecosystems. To that end, microwave sensors are thought to be capable of contributing important and unique information to an all-source data base.

The overall aspects of the problem may be summarized as follows.

1. Problem definition - Measure forest biomass productivity. Investigate the use of SAR for identifying forest species and assessing stand composition, stand density, stand vigor, height/site quality, and soil moisture content.

a. Time requirements - Immediate need for global forest assessment.

b. Area coverage - 100-km^2 units and mapping to 0.1-km^2-minimum (10 ha minimum) land units.

c. Measurement parameters -

(1) Timber class boundaries.

(2) Timber stand height.

(3) Timber stand density.

(4) Dead and dying timber.

(5) Species identification.

(6) Soil moisture in plant root zone (2 m).

(7) Site quality.

d. Spatial resolution - 20 m except 100 m for soil moisture and site quality.

e. Revisit needs - 5- to 10-year intervals.

f. Priority - 1.

g. Justification - A rapid, global forest land inventory is needed to determine worldwide timber resources. The problem is global.

2. Present data collection methods - Aircraft photography and ground observations are currently being used. Manual methods are usually employed for photo interpretation and mensuration. Products are timber volume estimates and forest-type maps. Radar offers the potential of

digital data correlating to timber types, boundary delineations, biomass of standing vegetation, losses from stress, and site quality. Radar provides all-weather capability and an additional information source for inclusion with Landsat and thematic mapper data.

3. Energy-matter relationships - Microwave records geometric information, as well as scene reflectance of a radar signal. The signal is attenuated by the surface roughness and dielectric constant of scene components. Therefore, it is postulated that each timber/environmental unit will have a unique signature from reflected energy, providing information on timber stand characteristics and site quality.

4. Data needs -

a. Timing - Data are needed in 1 month or less from acquisition, and summer coverage is mandatory.

b. Products - Maps and area tables of vegetation types and site class boundaries, estimates of volume/biomass for each timber type mapped, species identification of timber classes, and cartographic map products.

c. Area - Estimate of each map class.

d. Collateral information - Ground and photo interpretation information for control and verification of radar data.

5. Candidate test sites - Nationwide forestry applications test sites representative of major forest ecosystems across the Nation are suggested.

a. St. Louis County, Minnesota.

b. Grand County, Colorado.

c. Jefferson County, Washington.

d. Kershaw County, South Carolina.

e. Clearwater-Coeur d'Alene National Forests.

f. Washington County, Missouri.

6. Ongoing research - Forestry applications program; University of California, Berkeley; Oregon State University; Texas A. & M. University; University of Idaho; and University of Minnesota.

7. Costs - Most timber volume and forest site information for selected areas is available from existing forest inventory. Correlation of radar data with existing data would be needed. Cost estimates to undertake the study are not available at this time. User interest would be very high for a rapid, automated system of global forest assessment, particularly if the method would require a minimum of ground data input because of the high field costs and the existence of denied-access areas such as the Union of Soviet Socialist Republics (U.S.S.R.).

8. Shuttle compatibility - A coordinated investigation plan could be prepared leading to experiments and application tasks on the initial Shuttle SAR flights. Test sites are established, and collateral ground-truth data are available.

Tropical Forest Inventory

In the same manner for which forest inventories are required in the temperate areas of the world, tropical forest inventory data are also required; thus, the forest inventory process is of global importance. The overall aspects of the problem may be summarized as follows.

1. Problem definition -

a. User needs - Many less-developed areas of the world contain large tracts of tropical forests. These areas provide the potential for vast quantities of forest products, as well as potential sites for other resource uses such as water supply, hydroelectric power generation, agricultural lands, and urban sites. Land and resource managers need information on tropical forest lands - timber species, volume, and areas involved - to develop these land areas and plan for management operations. Vast areas of tropical rain forests are totally obscured by clouds and haze for most of the year. As in the case of the recent Brazilian survey, the SAR can provide timely information on forest resources over vast remote regions where no cartographic control is available and only limited ground measurement is possible.

b. Time requirements - Data are needed as soon as agencies and responsibilities are assigned.

c. Area coverage - 1000 km^2, minimum area of interest.

d. Measurement parameters - Stand boundaries, location, tree stand height, density, species identification, and land-use information are needed.

e. Spatial resolution - 100 m.

f. Revisit needs - 10- to 15-year intervals.

2. Present data collection methods - Very few inventory data are being collected in tropical areas except for isolated areas in which conventional photo and ground techniques are being used where possible. Persistent cloud cover in tropical forest areas severely limits the use of conventional photographic systems for data collection.

3. Energy-matter relationships - Radar could provide a rapid data source in digital form for tropical forest inventory. Radar has unique properties of geometric and energy recording that could reveal information on location and biomass of tropical forests. Experience in the radar mapping of the Amazon project in the Brazilian Amazon Basin indicated the potential for gross-vegetation-type mapping in tropical forests and identification of certain high-interest vegetation communities for agricultural development.

4. Data needs -

a. Timing - Data are needed in 1 month or less from acquisition.

b. Products - Map of vegetation types showing boundaries and species identification, volume estimates, and associated land use.

c. Area - Minimum class sizes would be 1 km^2 (100 ha).

d. Collateral information - Ground-truth data for control and verification of radar data. Cartographic quality of maps is needed.

5. Candidate test sites - Eastern Bolivia, Taiwan, and northern Thailand.

6. Project support - Advisory personnel - Roger Hoffer, Robert N. Colwell, F. P. Weber, and Robert W. Brandt.

7. Costs - Not available.

8. User interest - Key interest to Food and Agriculture Organization, Rome, Italy.

9. Shuttle compatibility - Yes.

Present remote-sensing data used in the assessment of natural vegetation include those derived from aerial photography, the multispectral scanner, forward-looking infrared, and Landsat. Current analysis is based on algorithms such as the transformed-vegetation index (based on bands 7 and 5, Landsat MSS) and LARSYS[1] classification. Aerial photography interpreted by manual techniques is the mainstay of current remote-sensing application. Recently, advanced technology remote-sensing data have been demonstrated to be a useful base for resource managers and planners.

Imaging-radar data should be highly useful in a complementary - and in some cases, primary - role in conjunction with Landsat and photographic data. Unique properties of radar data include plant and soil moisture sensitivity, vegetation geomorphic property sensitivity, and surface roughness (texture) sensitivity.

The requirements for SAR data are completely compatible with the timing, resolution, areal coverage, and measurement parameter capabilities of the proposed spaceborne imaging radar (SIR) for the Shuttle.

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[1]Computer programs developed at the Laboratory for Applications of Remote Sensing (Purdue University).

CULTIVATED VEGETATION - CROP PRODUCTION ESTIMATES AND PLANT STRESS ASSESSMENT

The need for accurate crop production estimates is universally recognized as a fact of life on a global scale. Data concerning any stress factors that can alter production estimates during the growth and maturation of a given crop are likewise recognized as information of tremendous economic, social, and political importance. The present methods of collecting such data and disseminating information about crop production are reasonably accurate and inclusive for only a small portion of the world. The information is not, however, disseminated in anything like near real time. Active microwave sensors have the unique feature of all-weather capability and the ability to sense stress factors in crops. With present data-processing techniques, these data can be reduced to usable information that could be made available in a near-real-time system of the future.

There presently exists in the United States one method for estimating crop production. It is the Statistical Reporting Service's method of random sampling, with subsequent expansion of the data to produce a nationwide crop production estimate.

Another system is presently being developed and tested jointly by NASA, the National Oceanographic and Atmospheric Administration (NOAA), and the U.S. Department of Agriculture (USDA). This system is known as the Large Area Crop Inventory Experiment (LACIE). The LACIE system presently uses Landsat MSS data as the primary remote-sensing data input to identify wheat in the U.S. Great Plains area. In attempting to create a growth and productivity model for the LACIE, it was discovered that there is no reasonable method available today to estimate accurately the effect of stress during the growing season and the resulting adverse effect on crop production.

Active microwave sensors could be developed and deployed on orbital platforms such as the Shuttle to complement the Landsat MSS data as added channels of remotely sensed data. Microwave sensors also have the added capability to gather data in cloud-obscured areas that would be opaque to the MSS. These benefits of active microwave sensors would greatly enhance the prospect of monitoring worldwide agricultural crop production.

Active microwave systems not only possess the all-weather capability, but also are able to discern volumetric moisture content of plant biomass. This unique ability allows for the comparison of signatures of any given crop during the growing season and the determination of the degree of stress that has been introduced into the plant canopy. Stress may occur in the form of drought, disease, insect damage, or any one of many mechanically or physiologically induced vigor suppressors. By measuring (volumetrically) the above-ground moisture content of a crop, a direct relationship can be empirically determined between crop canopy moisture content and plant stress.

The data collection frequency required for this type of application would be on the order of once every 2 weeks. It is immediately evident that it would be impossible to monitor the entire area of any one crop every 2 weeks; so a well-defined and properly designed sampling system could be used to produce reliable data that would form the basis for accurate crop production estimates. Evidence is available to suggest that the combination of MSS and active microwave sensors may have a synergistic effect for the amount of information that may be extracted from a scene.

The output product could be in any format as needed by the user. Such products as maps, images, overlays for maps, tabular data, or any other similar product are possible for this system.

Candidate areas for research and development testing could be the LACIE test segments that are currently being used to develop the LACIE system techniques. Many data and experiences are being amassed as a result of this effort and would be invaluable in developing a viable test for the proposed system.

Project support should be forthcoming from organizations that have a direct interest in crop production. Farmers, ranchers, and their cooperative organizations, as well as State and Federal agricultural agencies, should be supportive of such an effort. Grain-marketing groups should have this information made available to them just as they now receive the monthly crop estimates.

The microwave sensors to be used in such a system should possess the following characteristics.

1. Resolution - 30 m

2. Frequency(ies) - X, C, L, and/or K band(s)

3. Polarization - like and cross

4. Look angle - 7° to 20° and 40° to 60° from vertical

This application of microwave sensing to crop production and plant stress assessment is well suited to the Shuttle operations of the 1980's. It is a practical and feasible proposal that has high user application in the time of diminishing food production and expanding world population.

WATER RESOURCES

The applications of active microwave imagery relevant to water resources are described in the following subsections.

Streamflow Forecast

Current studies show that hydroelectric power production can be increased in the Western States by 5 to 7 percent with a modest increase in the accuracy of streamflow forecasting for snowmelt-fed streams. This increased production can be accomplished by a reduction in the quantity of water "wasted" over the spillways of reservoirs as a result of poor streamflow forecasts.

The most significant increases in forecast accuracy can be obtained with the use of more accurate data or better information on all of the following six items.

1. Precipitation volume/unit area and extent

2. Areal extent of snow

3. Snow wetness (or relative ripeness and susceptibility to melt-producing factors)

4. Soil moisture index

5. Snow depth

6. Snow water content

The best estimates of streamflow will be obtained with a mix of ground-based and remote, noncontact methodology. Currently, the precipitation amount is only crudely estimated and is one of the most serious inadequacies in the current data-gathering systems applied in hydrology. This problem is global, and a solution to it is needed for all land-management activities; thus, it has a high priority. The present data collection method consists of catching precipitation in rain gages (cans) placed at very wide intervals in a watershed. From these few samples, inferences are drawn as to gross amounts distributed over entire mountain ranges. Active microwave sensors can provide an improvement on this method either by measurement of soil moisture content and distribution or by direct precipitation measurements. Data needs are for real-time data with constant, 100-percent coverage. This concept will require much research and could perhaps be tested with active microwave on board the Shuttle. The spaceborne meteorological radar concept being examined at the Goddard Space Flight Center (GSFC) is one possible approach.

Information on the areal extent of snow is needed by all agencies making forecasts on the basis of snowfields - the SCS, State water agencies, the U.S. Bureau of Reclamation (USBR), the U.S. Geological Survey (USGS), the U.S. Army Corps of Engineers (USACE), the National Weather Service, power companies, etc. The information is required to determine the snow/bare soil interface (freezing line) and the snow-covered area within each watershed. If this high-priority data need can be satisfied with the use of microwave sensors, the data can be used in the current information systems to enhance accuracy.

Currently, snowline information can be obtained by visual observation except during rainstorms, when data are urgently needed. The occurrence of such a storm is a critical phenomenon; and at that time, an imaging-microwave system becomes most needed, with the potential to penetrate cloud cover before and after rains and produce timely and accurate information. During storms, the rainfall pattern can be delineated by means of microwave images. Specifically, what is needed is the location of the snowline by map coordinates to within 20 m in the mountains and 100 m in the plains. Weekly coverage is needed, with a 24-hour delivery time to analysts.

The American River and San Joaquin River basins in the Sierra Nevada Mountain Range of California provide excellent test sites for this study. The American River basin is the location of the USBR weather modification tests, which are being conducted through 1983; and the San Joaquin River basin is the site of a snow project study by James L. Smith, Forest Service Experiment Station in Berkeley, California. The USFS studies encompass both watershed basins, and ground truth will be taken of some elements in both studies.

Snow wetness is a measure of the relative water-holding capacity of a snowpack. Currently, inferential data are obtained through measurement of a snowpack density. However, with a direct measure of wetness, the amount of new water from a melt or rain that a pack can hold before melting can be determined. No current remote-sensing method provides a capability for measuring snow wetness, but microwave sensors appear to offer a possible means. Research is now underway to confirm this potential. Weekly measurements are required during the snow season, with 24-hour data delivery. A stratified sampling scheme should be employed in a data collection system, and cartographic overlays would be required.

An excellent test site for studies of snow wetness with microwaves would be the USFS instrumented Central Sierra Snow Laboratory (CSSL), Soda Springs, California. There is an ongoing study to develop and test a profiling microwave wetness sensor at the CSSL, being conducted by Dr. W. I. Linlor of the NASA Ames Research Center (Moffett Field, California) and Dr. J. L. Smith of the USFS (P.O. Box 245, Berkeley, California). These two investigators are suggested as advisors. Current effort is coordinated with the State of California, the USACE, the USGS, and other interested agencies.

The soil under melting snow is a reservoir in which part of the snowmelt is stored, part is used by plants, and part is delivered to streams during the ensuing months. Lack of knowledge of this complex process is a global problem. There are no current quantitative data collected; only guesses are made. By measuring the water vapor in a cube of air including the surface of the area and vegetation on the slope, an estimate of evaporation/transportation can be made for different parts of a slope. This estimate can then be related to water movement within the soil and subsequent streamflow. Ultimately, an estimate of water left in the slope in the soil for subsequent addition to streamflow can be made.

Microwave technology is thought to offer a way to measure the aforementioned items, although little is known about the requirements for microwave parameters. Monthly, statistically stratified samples with identifiable sites on a cartographic base are needed to satisfy the user requirement. The Onion Creek experiment forest and the CSSL offer the best possibilities for research and development work on soil moisture index as related to active microwave remote sensing.

Snow depth varies widely with area even within a climatic region, although snow density varies only slightly with area. If the depth can be measured, it can be correlated with the density obtained by onsite measurement, and this correlation can then be extended to broader areas. With these two measurements, one can compute the water content of the snow, a most important variable in streamflow forecasts, which are a global problem of high priority.

The present data collection method is manual inspection, either by ground observation of a snow course or by flying over vertical graduated posts and reading snow depth; this method cannot be used during inclement weather. Present methods provide only a very restricted sample. Imaging, calibrated radar is a potentially promising means of making large-scale samples available in all types of weather.

Because of the relationship of the data (one element to another), it is desirable to obtain snow depth, snow wetness, areal extent of snow, and snow water content from the same remote-sensing effort. Weekly data are required during the snow season, with 24-hour delivery. Statistically stratified samples are desired, located at the same points for each survey. Point data on snow depth must be presented on maps or by a listing of coordinate location. Any of the snow survey sites in California or the USDA SCS-administered sites in other Western States would be suitable test sites for active microwave studies.

All other snow inventory data are taken to get an estimate of snow water content. The current system consists of a mix of manual and remote ground measurement of depth and density of snow; and from this information, water content is estimated. Only a few samples are taken in an entire river basin; and from these data (and by correlation to historical snow water content versus streamflow data), estimates of future streamflow are made. Errors of estimate range from 10 to 25 percent. If a large sample inventory of snow can be obtained periodically for the entire watershed, a more accurate streamflow can be predicted. With information on snow water content, snow wetness, precipitation input for rainfall, and soil water storage, an estimate of streamflow can be made to a precision never before attained. Microwave sensors are a possible means whereby these parameters can be remotely measured, but the application of microwave sensors requires much supporting research.

Watershed Characteristics

The physical characteristics of a watershed are described in terms of topography and physiography, including vegetation cover. Specific measurements - slope angle and aspect, soil depth, type and extent of vegetation cover, and stream characteristics such as length, gradient, and area - are used to classify watersheds.

The great importance of accurately determining watershed characteristics is derived from the need to determine the rate at which snowmelt and rainwater are delivered to streams and, thence, downstream to reservoirs for man's use. Physical measurements are frequently used to create a watershed model that is applied to streamflow forecasts for flood prediction and reservoir management. The ideal model, correctly applied, minimizes unnecessary "spills" from reservoirs and, when interfaced with hydrologic data, optimizes water resource management and utilization.

Few of the major watersheds in the United States are accurately quantified in terms of the five major characteristics.

1. Stream length

2. Stream gradient

3. Area of watershed

4. Stream ordering

5. Classification, location, and area of vegetation cover type

The greatest inaccuracies and, in many cases, a total lack of understanding are associated with the mountain watersheds. Because many mountain watersheds are perpetually cloud covered, especially in southeast Alaska and the Pacific Northwest, microwave sensors are thought to be very promising as a means of providing remote-sensing data that will accurately describe and quantify watershed characteristics. The combination of imaging-radar data with registered multispectral scanner data can provide an even better remote-sensing data base for measuring the physical characteristics of watersheds.

Frozen-Lake Mapping (Alaska)

Moderate to large quantities of water are required throughout the year for development of petroleum reserves. In Arctic regions, the availability of water, potable or otherwise, becomes a significant limiting factor in exploration and exploitation.

Ground water generally is not available because of extensive permanently frozen soil. Major streams and lakes are sometimes suitable water sources in summer months, but there are few sources of data on the availability of water in the wintertime. Potential sources of water during the Arctic winters are deep lakes and moving rivers that do not become solidly frozen. The extent of Arctic petroleum resources precludes the conventional core drilling of thousands of lakes and rivers, which are potential sources of water.

It has been proposed by radar technologists that imaging microwave has great potential as a remote-sensing tool to provide inventory data on the existence and availability of water in the Arctic during the winter. The significant microwave parameters for mapping Arctic water sources are as follows.

Wavelengths: Multifrequency L-band (for thicker-ice-covered water), X-band (for delineation of ice- and snow-covered water)

Resolution: 30 m

Polarization: horizontal-horizontal (HH) and horizontal-vertical (HV)

Incident angle: 40°

Coverage: Monthly, December through April

Output product: Either a 1:250 000-scale map showing water source location, stratified by probability of existence, or a coordinate location listing, similarly stratified

The Shuttle imaging radar affords an excellent opportunity for investigating this application; however, feasibility studies with aircraft and perhaps Seasat-A are appropriate.

MINERAL AND ENERGY RESOURCES AND GEOLOGIC APPLICATIONS

The search for new sources of mineral and energy resources is a prime goal for a large number of users of remote-sensing data. The continued depletion of the United State's and the world's supply of these nonrenewable resources necessitates utilization of the most advanced exploration tools available for this search. Active microwave imagery will provide unique geologic information, including terrain data not otherwise available from existing remote-sensing systems.

The search for new mineral and energy resources is global in nature and includes both polar and tropical areas. The capability of active microwave sensors to "see" through clouds and plant canopy is especially useful. Although geologic features do not change rapidly with time, seasonal coverage is recommended because of the potential for surface variation indicators to infer structural and/or subsurface changes. This application is considered a number one priority of national significance.

The mineral and petroleum industries currently use Landsat-1 and -2 data and aircraft data, as well as the conventional means, for exploration purposes. Landsat-1 and -2 data do not have the necessary spatial resolution or stereo coverage desired by these industries, and they were not obtained with the use of optimum spectral bands. Hence, the existing Landsat systems have not had a great impact on solving the problem of the growing worldwide need for energy and mineral resources.

The Landsat multispectral sensor technology was developed before 1970; and, basically, this same technology will be used with Landsat-C in 1978 and the subsequent Landsat follow-on program. An active microwave system would, however, provide a different mix of information with all-weather, day/night sensing possibilities; high-resolution, calibrated, multichannel, multipolarization images; Landsat-compatible image data; and measurements of unique parameters not possible with infrared (IR) and visible sensors.

The kinds of surface features that need to be identified and mapped include linear and curvilinear structures, rock types, the composition of superficial material, underlying rock types, vegetation changes and boundaries, faults, and fractures. Sensing these features with active microwaves requires use of the following parameters.

Incident angle: $\simeq 45^{\circ}$

Polarization: HH, HV, and vertical-vertical (VV)

Frequency: TBD

Resolution: $\simeq$ 20 m

The principal data products that will be used by geologists should be Landsat-compatible imagery registered to geologic maps. Both the mineral industry and petroleum industry users have expressed a great need for stereo data products.

Proof-of-concept experiments can be demonstrated on the Shuttle flights utilizing the SIR. The operational use of active microwave for full exploration of its potential for mineral and petroleum exploration will require global and repetitive (seasonal) coverage. Initial data may be obtained from the radar flight (Seasat-modified) being proposed for the Shuttle Orbital Flight Test 2 (OFT-2). It is suggested that existing NASA expertise be used to closely coordinate the program being developed by the Geosat committee.

OCEANOGRAPHIC APPLICATIONS

Six high-priority application tasks were identified in the category of oceanography.

1. Ship navigation and routing
2. Navigation hazards
3. Pollution monitoring
4. Ocean engineering hazards
5. Commercial fishing intensity
6. Sea ice

Each task has global implications in the sense of multinational benefits to be derived from cost savings in shorter and safer merchant ship routing, more efficient deployment of fishing vessels, protection of the quality of the environment, and lower costs of outer-continental-shelf explorations.

Information useful for ship routing and safety is needed on a daily basis, especially along the major shipping lanes of the world. Specialized data are needed in Arctic waters regarding ice flows and icebergs because of increased shipping for exploration and transfer of oil. At the same time, monitoring for oil spills in environmentally sensitive locations is needed for protection of marine life and habitat.

In many of the new areas, microwave sensors show promise for providing much of the critical data required; e.g., exploration in the design of structures and placement of drilling platforms, and the location of new facilities for deep seaports and for building shore power plants. Information on wave forces - their duration, intensity, and frequency - is not sufficiently known.

Earlier experiments with aircraft and satellite sensors (Skylab, S193 and S194) have shown the feasibility and promise of achievement from future operational satellites with both passive and active microwave sensors. The penetration of cloud cover and the response of a microwave signal to sea state - the correlation between microwave signal response and wind profiles, capillary waves, and the detection of surface waves - have both been successfully demonstrated with microwave sensors. The suppression of backscattered signal due to oil films has also been successfully detected. Imaging radar of proper frequency and polarization on a satellite platform would provide a synoptic view, day or night, irrespective of cloud conditions, and at times during storms when the most severe wave forces are generated but for which few reliable data are available. These data would also be complementary to Landsat data in the mapping of currents, the tracking of pollution, and the detection and measurement of shipping hazards.

For data needs for each of the priority applications, resolutions in the 25- to 100-m range are required. A well-organized approach to determining frequencies, polarizations, and bandwidths is being determined by cooperative radar sensor working groups in aircraft and Seasat programs. (See ref. 2-1, ch. 3.) Imaging-radar sensors, in conjunction with radar altimeters, scatterometers, and passive microwave radiometers, are expected to provide most of the measurements required for successfully meeting the objectives of oceanographic applications.

In certain cases, data are needed daily. For the ocean engineering hazards, application users have defined data requirements as being needed on a 3-hour, 3-day basis (ref. 2-2, ch. 5). Candidate test sites for early experimentation would be the North Atlantic and North Pacific, the Atlantic coast, and the Gulf of Alaska. Project support and instrumentation are available from several research organizations and groups in various Government installations within the NOAA, the USGS, the Naval Research Laboratory (NRL), and NASA, as well as in several universities and private industries.

Continued research with aircraft sensors in support of the Seasat program will prove to be a decisive factor in the future definition of radar requirements. The Space Shuttle, with 3- to 5-day experimentation potential, could be used for proving satellite capability with a variety of sensor parameters in a sophisticated operational test. Coastal test sites could be defined, with ship and aircraft support organized to coincide with Space Shuttle overpasses.

The new 370.4-km (200 n. mi.) limit defined as national waters along U.S. coastlines brings new emphasis for improved capability in monitoring this resource area. Satellite sensors afford the best chance for a complete system capable of managing resources found in that continental shelf zone.

HAZARD SURVEYS

The monitoring of major disaster situations has been traditionally posed as a potential application for a Shuttle (or standby Shuttle) imaging-radar system. The analysis and prioritization of application areas have resulted in determining that events such as floods, hurricanes, etc., are of a very high national and worldwide priority for monitoring, and that the SAR has an extremely good potential for utility in these situations because of its nighttime and all-weather capability. Furthermore, the timely acquisition and display of such data can be of significant benefit. For the most part, however, an airborne SAR system with possibly a digital readout to a communications relay satellite system for timely processing at a central ground station can fulfill a majority of disaster-monitoring requirements. Even an onboard recording scheme with subsequent processing can meet a surprising number of crisis-oriented delivery schedules. For this reason, it is recommended that such application areas be given a low priority for Shuttle implementation in favor of the more Shuttle-unique applications discussed previously. Within the realm of understanding that all active microwave user applications will not be solved from space platforms, and for report completeness, a discussion of these disaster-situation radar requirements and conclusions is provided.

Flood Mapping

The effective monitoring of flood conditions can have a significant impact on evacuation strategies, watershed runoff model updates, flood models, relief and insurance grants, levee/dam design and implementation, and rehabilitation plans. The SAR imagery, with its all-weather, nighttime, and high-resolution capabilities, can provide the necessary input for monitoring this type of disaster.

Essential inputs to a comprehensive flood-monitoring program would include flood extent, flow patterns, erosion/accretion mapping, and debris tracking. All measurements could be obtained with X- and L-band radar imagery of 30-m resolution, although for small-debris tracking, a resolution of 10 to 15 m or better might be required. A generally low depression angle and 50-km swath are sufficient. The output imagery is desired in near real time (hourly) and would perhaps be displayed in both film and cathode ray tube (CRT) formats. Eventual output products would include thematic flood maps, forecasts as to flooding depths, and map overlays.

The basic requirements for flood mapping can be met with a high-flying-aircraft SAR system with digital readout. Timing considerations, especially for a Shuttle application, seem to preclude the use of a space platform. For additional flexibility of such a scheme, the possibility for timely multiple looks and multiple resolutions (low resolution over the flood extent, high resolution over selected sample areas) is included. Interactive image-processing techniques may be appropriate.

Hurricane Damage Assessment

Hurricane monitoring and damage assessment can be valuable for possible warning/evacuation schemes, seawall and levee system design and evaluation, Federal aid determination, insurance claims, and the update of hurricane models. Again, the SAR is particularly appropriate because of its all-weather and nighttime operating characteristics.

There are four primary measurements desired for this application: flood extent, vegetation wind damage, vegetation flood damage, and urban damage in general. Vegetation wind/flood damage assessments, as well as urban damage assessments for larger features, can be achieved with resolutions of 10 to 20 m, whereas flood extent can be determined with a 50-m resolution in most cases. For a flood extent determination, data over a 100-km swath will probably be required; whereas damage assessments will be determined over smaller regions, say 20-km swaths. A daily output of film, thematic maps, and map overlays rectified to ground coordinates is required.

A high-flying aircraft with SAR capability can meet the aforementioned measurement requirements. Such a platform, with the side-looking aspects of the radar system, would not necessarily be required to be flown in storms but, rather, could be flown alongside. Furthermore, variable resolution desired (low during storm, high afterwards) can easily be obtained.

Tornado Damage Assessment

Justification is similar to that for hurricane monitoring. However, an additional unique SAR characteristic is applicable in this case - the capability to detect the shallow trough of displaced soil that accompanies most tornado situations. The required measurements and output products are identical to those for hurricane monitoring with the exception of flood extent and flood damage.

Because of the generally localized nature of tornado activity, as well as the rapidity with which funnel clouds form and strike, an aircraft platform SAR is more appropriate to use than a satellite platform SAR. This method would enable high-resolution and limited-area coverage of affected areas in a timely manner consistent with relief and/or evaluation requirements.

Earthquake Prediction and Damage Assessment

The monitoring of earthquake activity and regions will facilitate appropriate land-use planning, aid, prediction, potential strain relief by water injection, and a significant saving of lives and property. The SAR is properly suited to many geologic applications such as fault detection and terrain analysis. It can, therefore, provide useful input to crustal-motion-monitoring schemes.

Crustal motion detection, fault location, and terrain analysis are all required for earthquake monitoring/prediction schemes, whereas resource and urban damage assessments are required for actual disaster scope determination. For all five measurements, a resolution in the 10- to 20-m range and a maximum swath of 50 km are required. Repetitive and stereo data are a distinct requirement, and thematic displacement maps on a map overlay would be useful outputs. Measuring Earth crustal motion may be best accomplished by using corner reflectors placed at strategic points. To produce artifacts such as shadowing and overlay, multiple looks and perspectives best done by aircraft are required.

Forest and Range Fire Damage Assessment

Whereas some types of active microwave measurements - hourly burn determination, burn intensity, soil-type classification, and terrain-type classification - are primarily intended for subsequent damage assessment and planning, microwave sensors may make the greatest contribution in a related task. If microwave sensors can, as some radar technologists suggest, monitor vegetation moisture and fuel loading, these data will contribute to a very great need for this type of information over extensive areas of the West for fuels inventory and suppression preplanning.

LAND USE

For land-use applications in natural settings, remotely sensed data of all types are primarily needed to provide information on the existing types of ground cover that prevail throughout a management region. Such information is most useful in the form of maps and tabular data that characterize the extent, location, and boundaries of each recognizable category. Indeed, classification maps that address existing types of ground cover are the basic tools for a number of applications other than land use that also have important priorities. Knowledge of existing patterns of natural vegetation, water, barren ground categories (sand, rocks, snow, or ice), or human activities is a prerequisite to any decisionmaking process.

The land-use-planning aspect of environmental management joins many other applications in being based upon the recognition and classification of types of surface cover. Typically, agencies at all levels of Government conduct land-use-planning activities and are subject, in this respect, to varying degrees of pressure to develop plans for accommodating expanding population or resource exploitation or for quality-of-life factors. All planning activities involve making long-term commitments of allocating resources that have deep impacts on today's citizens, as well as on succeeding generations. Thus, the best possible information is needed to assist the planning process.

The quality of global information currently available to regional land-use planners typically supports category classification to only levels I and II. These classes are too broad for many land-use decisions, and planners constantly desire the capability of classifying cover to levels III and IV, levels which heretofore have been achieved only with the use of medium-scale aerial photography. The SAR capabilities, both from aircraft and spacecraft platforms, together with that of the thematic mapper, show strong evidence that level III and, in some cases, level IV classification will become possible on a regional basis in a cost-effective manner. The SAR data provided for all land-use applications must be corrected to a standard map base so that they can be effectively overlaid with Landsat MSS data.

In undeveloped or partially developed areas, the type of natural ground cover that typically predominates is vegetation. Not only are accurate, detailed vegetation maps of prime concern for agricultural and forestry applications (as aforementioned), but these maps are equally valuable for the determination of the many aspects that make up other development-related decisions. Barring the ability to sense beneath the soil surface or the canopy of vegetation, the density and mixture of naturally occurring vegetation are leading indicators of certain critical soil factors that influence certain kinds of cultural features. Potential limestone sink holes in Florida frequently produce clues in the surface vegetation, whereas the extent of grass, indicating shallow permafrost, in interior Alaska is related to the extent of dwarf black spruce stands. Conventional classification maps of natural vegetation prepared from the enhanced-resolution (10 to 30 m) data of the SAR coupled with MSS data from the thematic mapper would be a valuable, cost-beneficial tool for land-use planning.

Although international organizations such as the Food Agriculture Organization desire global information on land use on a more or less regular basis - e.g., a 5-year update - some areas are changing so rapidly that an update on new data is required on a yearly basis. This task clearly is a mission designed for spacecraft platforms, especially when the coverage per pass is decreased to compensate for achieving high spatial resolution. Together with the six or seven bands in the visible and IR wavelengths, the spaceborne SAR system, deployed for collecting land-use data, should employ cross-polarization data from two wavelengths.

Although obtaining total land-cover data is important globally, land-use planning and mapping of urban areas is critical. The core areas of cities, which include commercial and industrial areas, form integral components in the deployment of the limited resources for firefighting and police protection, for transportation and refuse services, and for tax-base projections for the frequently hard pressed administration of city governments. Presently, the extent and change in characteristics of urban areas are determined with aerial photography because of the limited spatial resolution capabilities of Landsat scanners. Analysis of data from two polarizations of X-band radar will make possible the differentiation of commercial centers from industrial areas. The radar data, with high contrast from corner-reflector effects of buildings and paved surfaces, should be an effective supplement to the data produced by shorter wavelength sensors. Coverage of metropolitan areas should be on a semiannual basis, with routine information extraction and delivery schedules.

The SAR data provide excellent information for mapping transportation networks, which are another important variable in land-use planning. Transportation services must be provided for commuters and for moving materials and products, without causing undue interference in the achievement of environmental values. The SAR data have proven to be a valuable form of remote-sensing data for gathering information on existing transportation capabilities, as well as for providing insight for developing transportation potential.

CONCLUDING REMARKS

The Applications Panel of the Active Microwave Users Workshop considered seven major areas in which a coordinated aircraft, spacecraft, and field measurements program should be directed in the future. Within each area a number of specific activities are indicated, many of which are common among major areas.

1. Natural vegetation
   a. Range improvement
   b. Range biomass productivity
   c. Range inventory
   d. Forest assessment
   e. Tropical forest inventory
2. Cultivated vegetation
   a. Crop productivity estimates
   b. Stress identification
3. Water resources
   a. Streamflow forecast
   b. Watershed chracteristics
   c. Frozen-lake mapping
4. Mineral-energy resources - mineral and petroleum exploration

5. Oceanography

a. Ship navigation and routing

b. Pollution monitoring

c. Ocean engineering hazards

6. Hazard surveys

a. Flood mapping

b. Hurricane damage assessment

c. Tornado damage assessment

d. Forest and range fire damage assessment

e. Landslide and Earth slippage assessment

f. Earthquake prediction and damage assessment

7. Land use - determination of existing land cover other than vegetation

Specific tasks such as inventory, monitoring, and assessment seem to be the most important applications roles in the future. Owing to the focus of past microwave remote-sensing research and development, more specific knowledge exists for applications of geology, oceanography, and cultivated-crop assessments. However, the panel expressed a strong opinion that the greatest potential for microwave applications in the future is in the heretofore lightly explored areas of natural vegetation, hazard surveys, and land use. Each of these important areas is currently covered by other forms of remote-sensing activity, but in most cases microwave sensing can offer a considerable boost in contributing complementary data to help satisfy information needs.

Although the water resources area of investigation has received a moderate amount of attention in the past with respect to microwave investigation, the possibilities for using this technique for such applications as streamflow forecast and watershed modeling are essentially unexplored.

The Applications Panel was composed entirely of nonmicrowave experts who were inclined to view the potential for active microwave applications in a different light and with significantly different priorities than the radar technologists. However, each member is an expert in one or more Earth resources discipline fields and has had considerable experience in applying other forms of remote-sensing data. Panel members do represent the users who will determine the eventual success or failure of the active microwave program in Earth resources applications.

The Active Microwave Applications Panel believes that although it is not difficult to identify important and unique applications for active microwave, a significant commitment to a research and development program is needed now, far in advance of committing large sums of money to sophisticated space systems. Therefore, the strongest recommendation is for an immediate commitment by NASA of major funds for an imaging-microwave program supported by the development and utilization of a sophisticated airborne multifrequency active microwave imaging radar system for use in the Earth resources program.

It is recommended that an active microwave program be built around the aforementioned seven application areas, which show the most promise for early return on the research and development investment. Special attention must be given in structuring the microwave applications program to focus on the high-priority activities within each application area.

To one extent or another, it will be necessary within each application area to develop a coordinated program plan, including field measurements and a supporting aircraft data collection effort, leading to the definition of space experiments and, more importantly, characteristics of space hardware. It is recommended that a detailed investigation plan for active microwave activities be written to include the priority applications identified by this panel of users.

APPENDIX

APPLICATION SURVEY FORM AND MATRIX MASTER

The application survey form, form AP-1, is illustrated in figure 2-1. The application matrix master terms are defined as follows.

1. Application - Refers to the seven major application areas identified by the panel as potential areas for imaging-radar investigations

2. Measurement required - Refers to the specific active microwave measurement; e.g., moisture in the plant root zone to a depth of 3 m

3. Resolution - A spatial requirement of an active system related to a photographic interpretation requirement

4. Comments - Ancillary considerations; i.e., season or biowindow in which to observe a phenomenon

5. Radar priority versus technological feasibility - Scale of 1 to 6.

 1 = high priority - high feasibility

 2 = high priority - low feasibility

 3 = medium priority - high feasibility

 4 = medium priority - low feasibility

 5 = low priority - high feasibility

Form AP-1

Active microwave applications survey

Application:

Objective:

Advantages of microwave:

User interest:

Radar data required:

Coverage:

Resolution:

Frequency:

Polarization:

Look angle:

Other collateral data:

Output product:

Figure 2-1.- Sample copy of form AP-1.

6 = low priority - low feasibility

This scheme was used to arrive at the high-priority and high-potential-payoff applications. Because only applications that received a scale factor 1 rating were developed in detail by the panel, a column is not used in the application matrix master (form AP-2 (table 2-2)) to denote scale factor.

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2-1. Matthews, Richard E., ed.: Active Microwave Workshop Report. NASA SP-376, 1975.

2-2. Simonett, D. S., ed.: Applications Review for a Space Program Imaging Radar (SPIR). NASA CR-151182, 1976.

2-3. U.S. Department of Agriculture, Forest Service: The Outlook for Timber in the United States. Forest Resources Rep. No. 20, 1973.

2-4. U.S. Department of Agriculture, Forest Service: The Nation's Renewable Resources - an Assessment. 1975.

2-5. Kuchler, A. W.: Potential Natural Vegetation of the Conterminous United States. American Geographical Society, Special Publ. No. 36, 1964.

TABLE 2-2.- APPLICATION MATRIX MASTER

APPLICATION: Natural vegetation

APPLICATION TASK	MEASUREMENT REQUIRED	RESOLUTION (METERS)	COMMENTS
Range improvement	Brush density, location, and area Erosion patterns Bare soil vs. vegetation	30	Yearly
Range biomass productivity	Soil moisture index Biomass/density	100	Summer, biweekly Winter, monthly
Range inventory	Vegetation complex Vegetation quality Area of cover	100	Yearly
Forest assessment	Forest stand complex Canopy density Losses from stress (dead timber) Soil moisture in root zone	20 100	Annual Biannual
Tropical forest inventory	Location and extent of vegetation cover Potential agricultural production areas	100 30	10-yr intervals

APPLICATION: Cultivated vegetation

APPLICATION TASK	MEASUREMENT REQUIRED	RESOLUTION (METERS)	COMMENTS
Crop production estimates	Crop identification Growth stage Area determination Soil moistures Precipitation amount and extent	30	Biweekly data required during growing season
Stress reducing crop yield	Effect and extent of: Hail Drought Flood Freezing Insect/disease	20	Weekly data required during growing season

TABLE 2-2.- Continued

APPLICATION: Water resources

APPLICATION TASK	MEASUREMENT REQUIRED	RESOLUTION (METERS)	COMMENTS
Streamflow forecast	Precipitation volume/unit area times extent Areal extent of snow Snow wetness Soil moisture index Snow depth Snow water content	20, mountains 100, plains	Weekly measurements required
Watershed characteristics	Stream length and gradient Area of watershed	30	5-yr data interval acceptable
	Vegetation cover type by area Erosion: gully or stream bank	10	Yearly measurement required
Frozen-lake mapping	Ice depth Availability of water under ice	70	Monthly during lake ice season

APPLICATION: *Mineral and energy resources and geologic features*

APPLICATION TASK	MEASUREMENT REQUIRED	RESOLUTION (METERS)	COMMENTS
Mineral exploration	Faults and fractures Rock-type boundaries Vegetation alteration Erosion features	30	Data required once annually depending on data quality
Energy resources exploration	Surface alteration Structural folds in faults Sedimentary basins	30	One-time data requirement

TABLE 2-2.- Continued

APPLICATION: Oceanography

APPLICATION TASK	MEASUREMENT REQUIRED	RESOLUTION (METERS)	COMMENTS
Ship navigation and routing	Sea state Wind velocity	95 to 100	Daily measurement
Navigation hazards	Location and tracking of icebergs and ice flows	50 to 100	Weekly tracking
Pollution monitoring	Oil spills and waste dumpings - detection, identification, direction/extent	50	Quick response to disasters and weekly monitoring
Ocean engineering hazard	Wave forces Current boundaries	10 to 30	3-day measurements with 3-hr forecasts for continental shelf explorations
Fishing intensity (commerical)	Numbered location of fishing vessels within legal zone	10	Weekly sampling
Sea ice	Map ice type Map land/ice boundary Map open water Map pressure ridges/leads	100	Weekly coverage required

TABLE 2-2.- Continued

APPLICATION: Hazard surveys

APPLICATION TASK	MEASUREMENT REQUIRED	RESOLUTION (METERS)	COMMENTS
Flood mapping	Flood extent Flow patterns Debris monitoring Erosion/accretion	30	Quick response to phenomenon
Hurricane damage assessment	Flood extent Crop wind damage Crop flood damage Wind pattern measurement Urban damage	30	Quick response to phenomenon
Tornado damage assessment	Crop wind damage Urban wind damage Mapping and evaluation of extent of damage	20 to 30	Quick response to phenomenon
Forest and range fire damage assessment	Burn boundary determination Burn intensity Soil-type classification Terrain-type classification	30 to 50	Quick response to phenomenon
Landslide/Earth slippage	Terrain classification Fault location Slip/slide delineation	20 to 30	Quick response to phenomenon
Earthquake prediction/ damage assessment	Crustal movement Fault location Terrain analysis Resource damage assessment Urban damage assessment	10 to 30	Yearly monitoring with quick response to phenomenon May require corner reflections at critical points

TABLE 2-2.- Concluded

APPLICATION: Land use

APPLICATION TASK	MEASUREMENT REQUIRED	RESOLUTION (METERS)	COMMENTS
Land use (nonvegetation)	Existing land-cover map Urban change Residential Rural Extractive Transportation	30 to 50	Biannual; data also used for site selection studies and environmental input monitoring/ prediction

CHAPTER 3

SEASAT LAND EXPERIMENTS

Active Microwave Users Working Group

Seasat Land Experiments Panel:

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INTRODUCTION

The basic objectives of the Seasat Land Experiments Panel were as follows.

1. To review documents concerning the potential roles for active microwave imaging systems on board satellites, with particular emphasis on the Seasat SAR

2. To make recommendations concerning the types of experiments that could most profitably be conducted over land with the Seasat SAR system capabilities available

Primary emphasis during the 3-day Houston workshop was on the second of these tasks.

The Seasat Land Experiments Panel was composed of representatives from private industry, the academic community, and the Federal Government. A basic criterion for member selection was land-applications expertise. In advance of the workshop initiation, the selected participants were provided background material on the Seasat program in general, the Seasat SAR system in particular, the basic panel objectives, a suggested list of types and/or classes of questions to be addressed, and a tentative schedule of activities for the 3-day meeting in Houston. In addition to the aforementioned background material, during the first morning session of the workshop on August 10, 1976, panel members were provided with additional written background material and briefed on potential applications of a space program imaging radar by members of the Active Microwave Task Force.

OVERVIEW

An overview of the Seasat land experiments program is presented in the following subsections.

Seasat Mission

On the afternoon of August 10, 1976, Seasat representatives discussed the project - its organizational structure, sensor complement, satellite system, mission design, data acquisition and distribution plans, and experiment team activities. J. A. Dunne, Seasat-A Ocean Experiments Manager, provided an overview of the Seasat-A program with particular emphasis on the proof-of-concept nature of the experiment and the science/user advisory apparatus that has been operating since the initiation of the project (see the organization chart, fig. 3-1). The subsystems, together with the associated responsible agencies, were itemized as follows.

Satellite: Jet Propulsion Laboratory (JPL)/Lockheed Missiles and Space Corporation

Tracking and data acquisition: GSFC/Spaceflight Tracking and Data Network (STDN)

Mission operations and control: GSFC

Project data processing: JPL

SAR data processing: JPL

Operational data processing: Fleet Numerical Weather Central (FNWC)

Experiment teams: Various

User data distribution: NOAA, FNWC, USGS/EROS[2] Data Center

Mission planning: JPL

He pointed out that, because they represent user interest in the formulation of plans for aircraft test experiments and surface-truth-activities experiments to be conducted with the use of satellite data, the Science Steering Group (SSG) and the experiment teams are important elements in achievement of the project objectives, which include the demonstration of techniques for global monitoring of oceanographic phenomena and features, the provision of oceanographic data for both application and scientific users, and the determination of key features of an operational ocean dynamics monitoring system. Further, they will provide an objective assessment of the geophysical performance of the microwave instrument complement. (Table 3-1 lists the sensors, and the organizations represented on the respective experiment teams.) With regard to interactions between the broad user communities, as

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[2]Earth resources observation system.

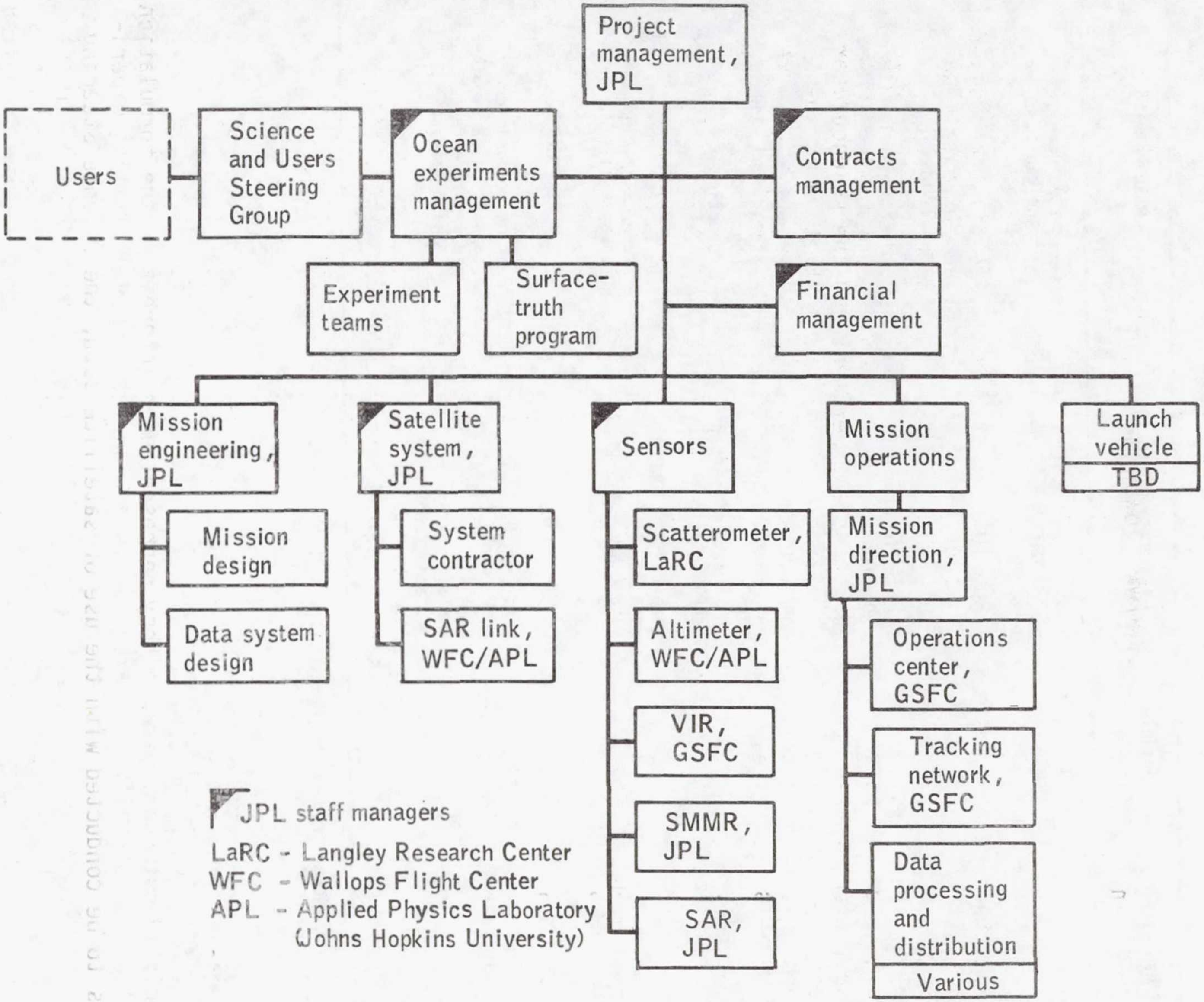


Figure 3-1.- Seasat-A functional organization.

TABLE 3-1.- SEASAT-A SENSORS

Sensor	Responsible organization	Team representation	Measurements
Altimeter	WFC	NOAA (AOML,[a] NOS,[b] HQ[c]) DOD[d] (NSWC,[e] NRL, NOO[f]) NASA (WFC, JPL) Smithsonian Astrophysical Observatory	Ocean topography, marine geoid, sea state
Synthetic aperture radar (SAR)	JPL	NOAA (NESS,[g] AOML[a]) USGS Scripps Institute of Oceanography ERIM[h] NASA (JPL)	Coastal interactions, wave directional spectra, ice studies
Windfield scatterometer	LaRC	NOAA (NOS,[b] HQ[c]) NASA (LaRC, JPL) CUNY[i] University of Kansas Penn State University	Windspeed (surface stress) and wind magnitude and direction
Scanning multichannel microwave radiometer (SMMR)	JPL	NOAA (NESS,[g] AOML[a]) USGS NASA (LaRC, JPL, WFC, GSFC) DOD[d] (NRL) CUNY[i]	Sea surface temperature, high-windspeed measurements
Visible and infrared radiometer (VIR)	GSFC	NOAA (NESS[g]) DOD[d] (NOO[f]) NASA (GSFC) Scripps Institute of Oceanography Research Triangle Institute	Feature recognition support, clear-weather sea surface temperature, cloud temperature

[a]Atlantic Oceanographic and Meteorological Laboratory.
[b]National Ocean Survey.
[c]Headquarters.
[d]Department of Defense.
[e]Naval Surface Weapons Center.
[f]Naval Oceanographic Office.
[g]National Environmental Satellite Service.
[h]Environmental Research Institute of Michigan.
[i]City University of New York.

represented by this panel, for example, Dunne stated that access to the project is provided through the SSG and the experiment teams. Figures 3-2 through 3-4 provide information on the Seasat-A orbit, data system, and SAR station coverage. The telemetry system has two radiofrequency (rf) data links, as follows.

1. Unified S-band: 2287.5-MHz downlink, 2106.4-MHz uplink

a. Real-time low-rate telemetry (T/M) from altimeter, scatterometer, SMMR, VIR, and satellite engineering/attitude data; data rate = 25 to 32 kbps

b. Playback T/M, consisting of recorded real-time low-rate T/M; data rate = 640 to 800 kbps

c. Command; 1 to 2 kbps

d. Tone ranging, transponded Doppler range-rate

2. S-band real-time SAR link: 2265.5-MHz downlink, 18-MHz analog modulation, raw data from the SAR sensor

The data acquisition capability may be summarized as follows.

1. The STDN sites at Alaska, Goldstone, Rosman, Madrid, and Orroral will be utilized for low-rate data acquisition. Playback data will be source of data records. Real-time data will be used for monitoring and control.

2. Alaska, Goldstone, and Rosman probably will be equipped to receive/record SAR data. Signal film/tape will be shipped to JPL for processing.

3. Low-rate data (real-time and playback) will be returned to GSFC by means of 56-kbps wide-band lines (NASA ground communications system).

4. Near-real-time data link from Alaska only to FNWC/Monterey will relay playback data.

This capability is important to those interested in SAR data, which can be acquired only through a suitably equipped tracking station.

Charles Elachi, leader of the JPL Radar Applications Group, provided a detailed discussion of the Seasat SAR (figs. 3-5 and 3-6). The system characteristics were summarized as follows.

Frequency - 1275 MHz

Look angle - 20° from nadir (not variable)

Altitude - 794 km

Resolution - 25 m in range and azimuth

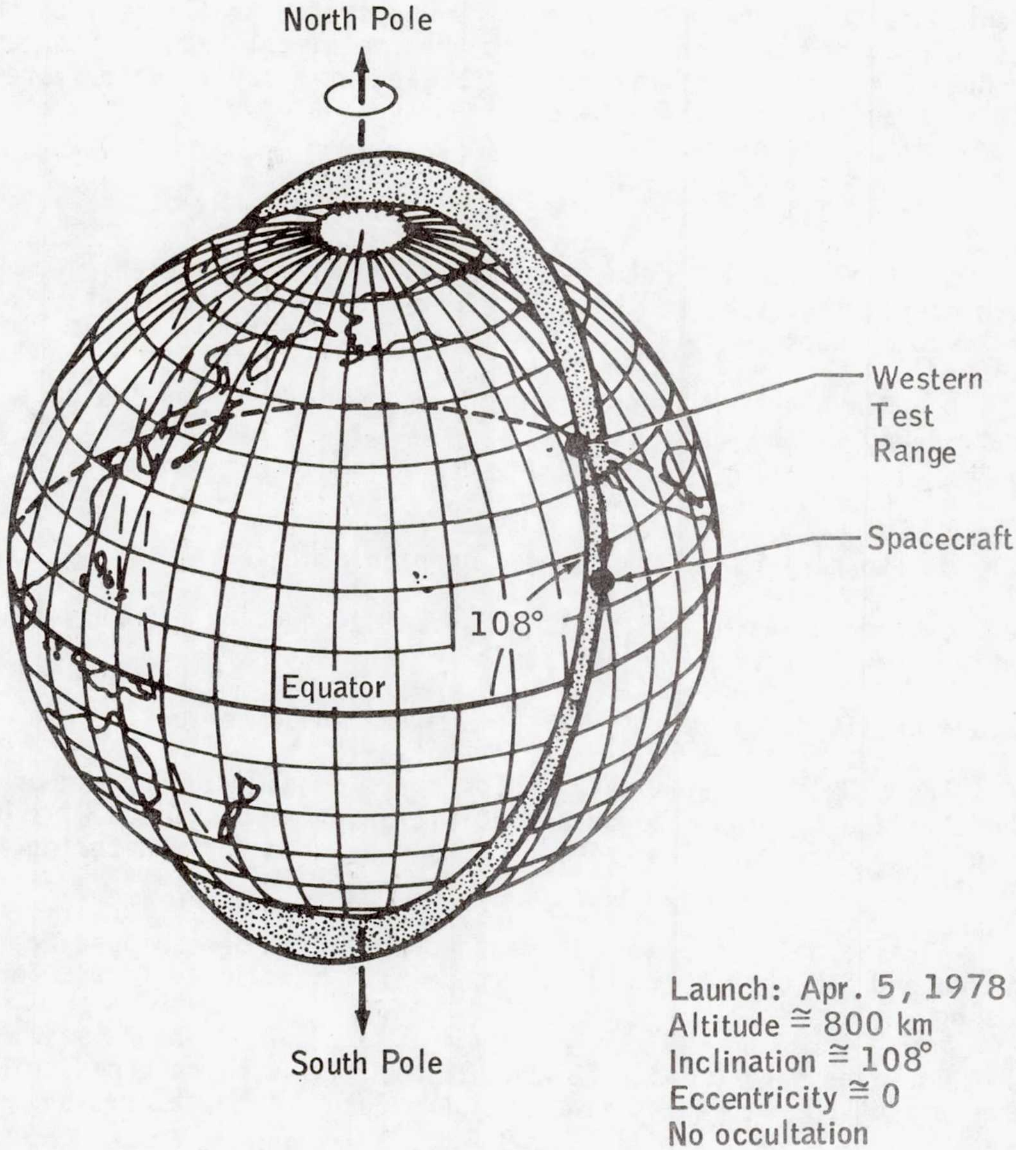


Figure 3-2.- Seasat-A orbit geometry.

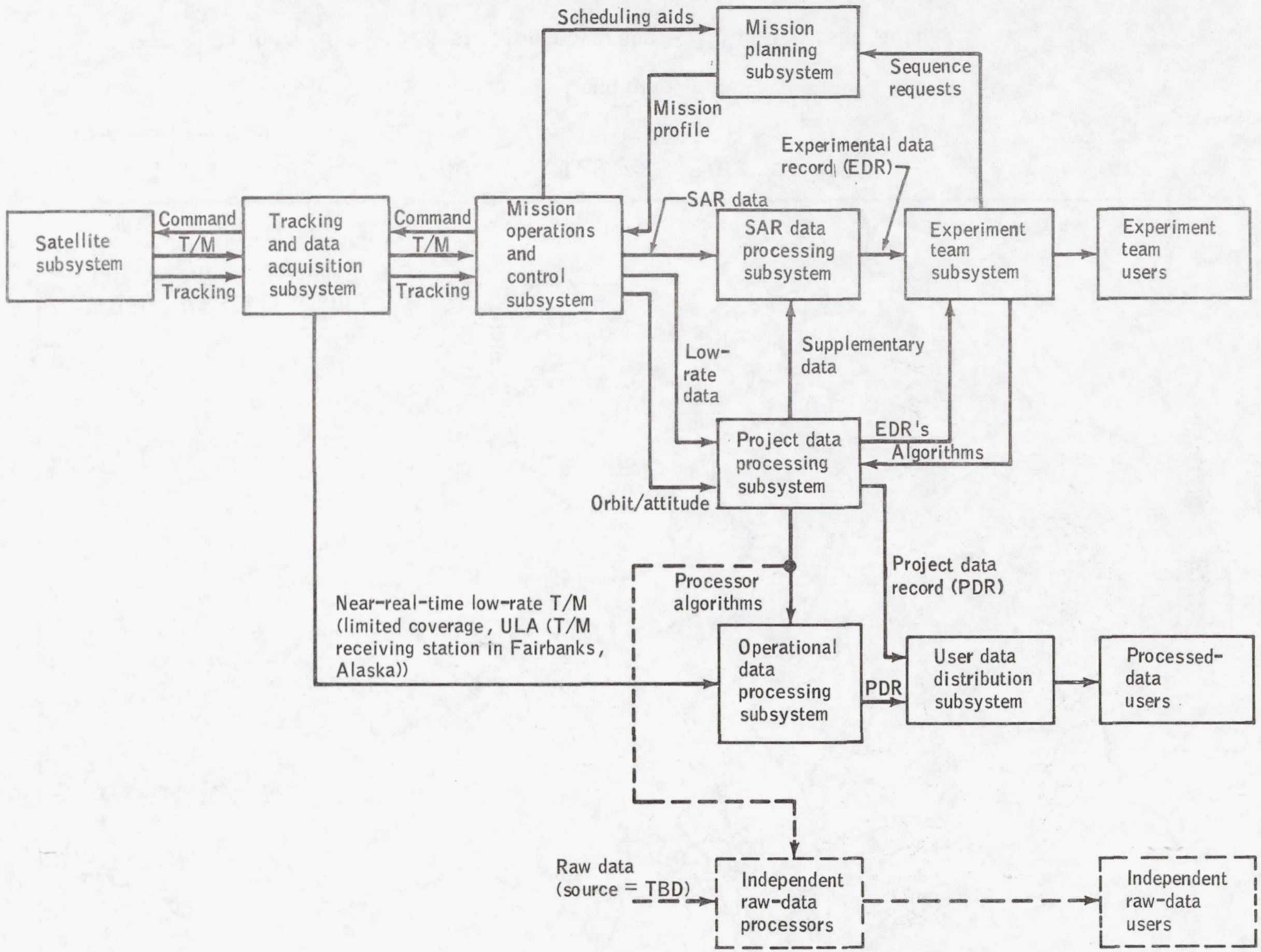


Figure 3-3.- Elements of the Seasat-A end-to-end data system.

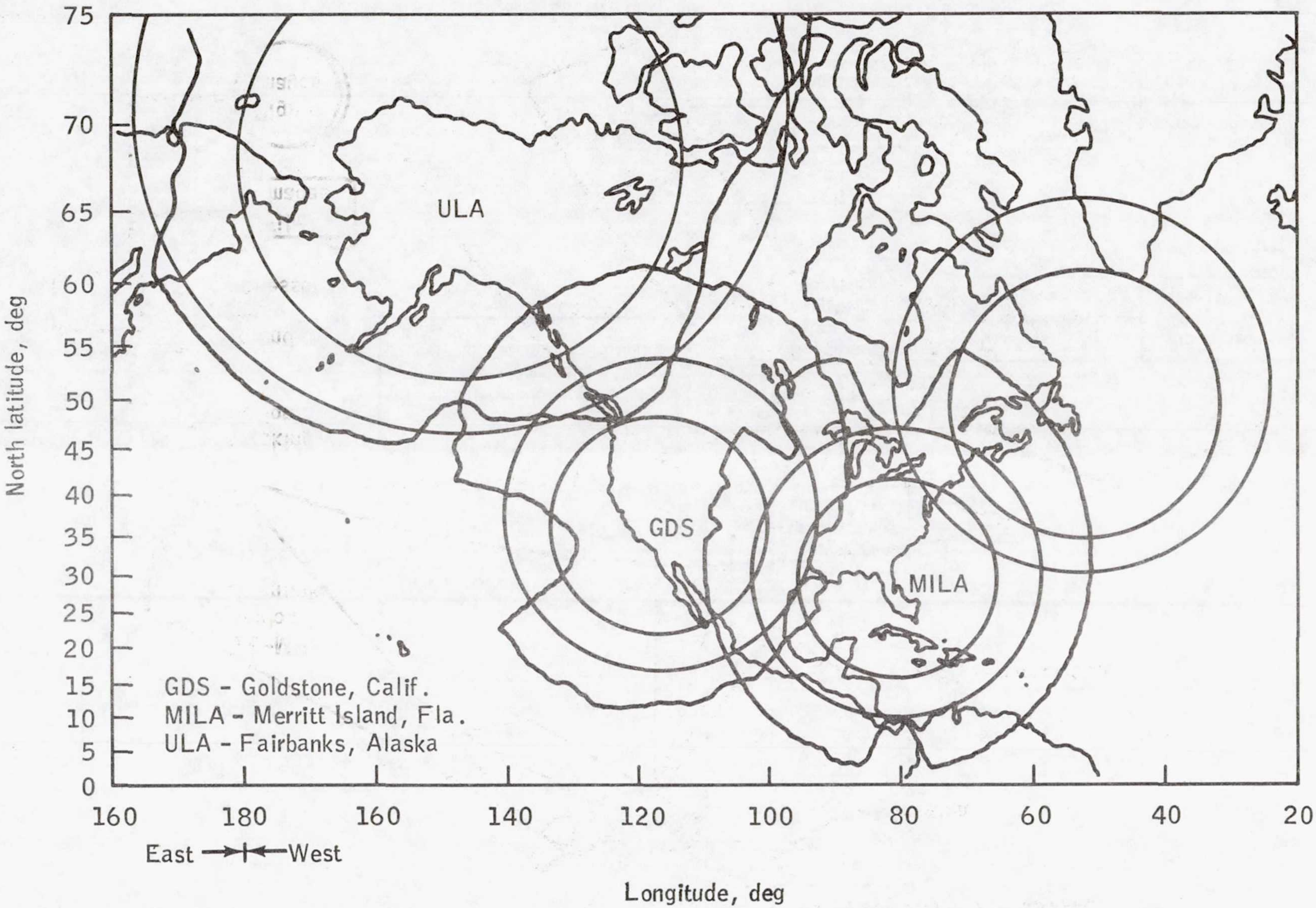


Figure 3-4.- SAR station coverage - 10°, 20°, and actual.

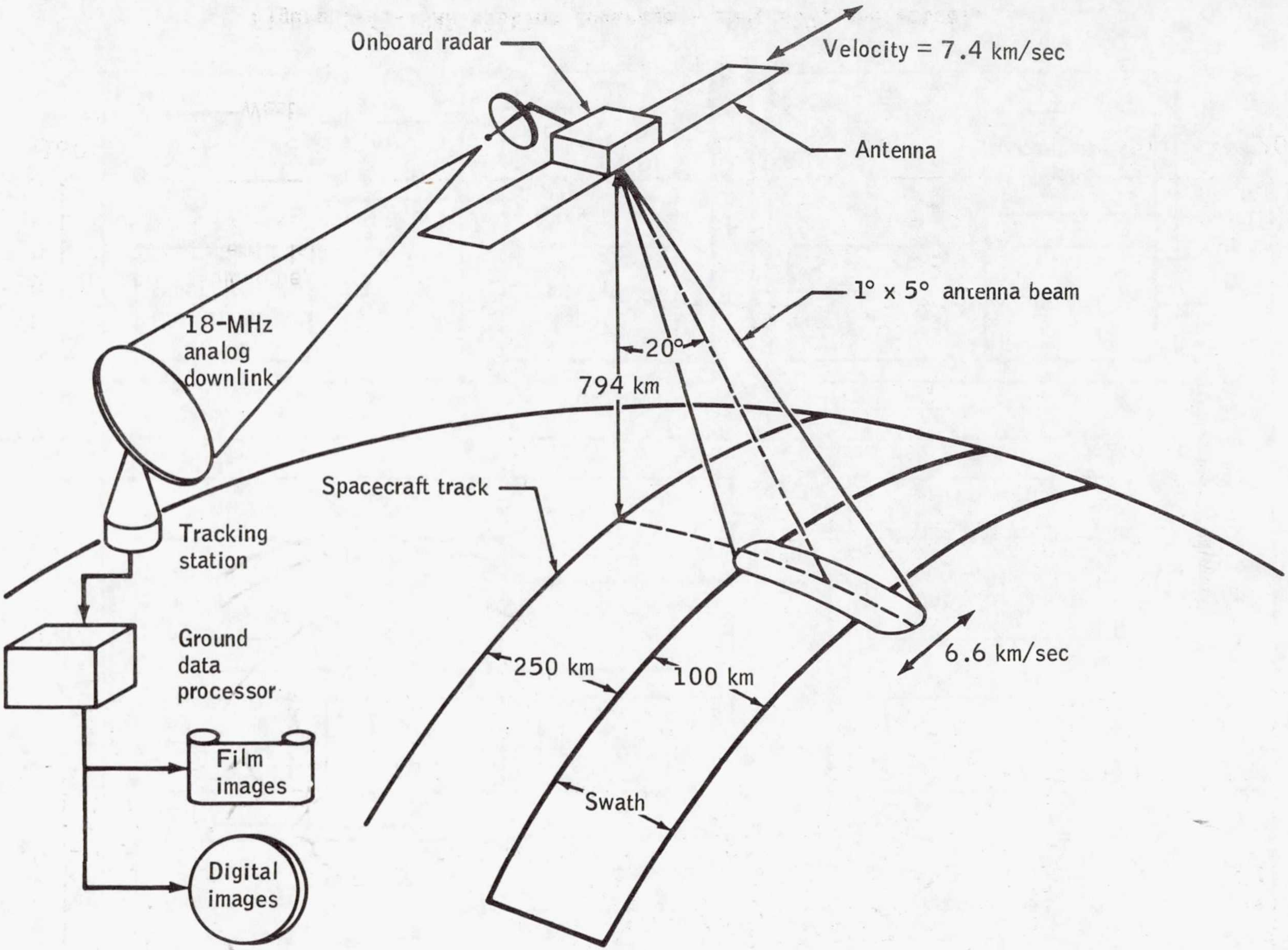


Figure 3-5.- Seasat-A SAR.

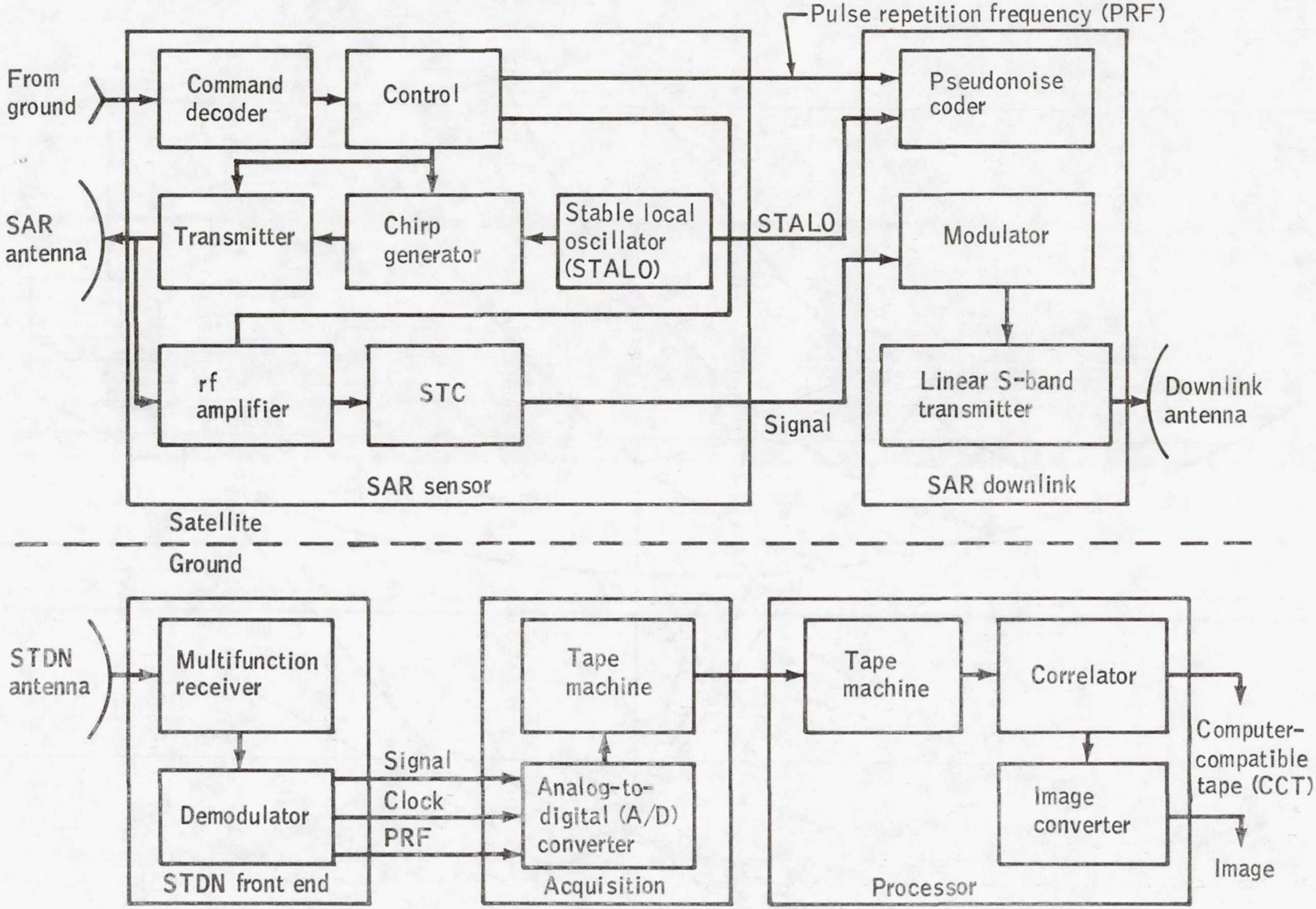


Figure 3-6.- Functional diagram: Seasat-A SAR system.

Swath width - 90 to 105 km as defined in the experiment plan

Number of looks - 4.0

Recording-pass length - 4600 km

Number of passes recorded - 400

Number of passes processed - 260

Dynamic range - up to 20 dB for uniform-scattering regions

Sensor flexibility - automatic or commandable gain control and commandable sensitivity time control (STC)

Paul Teleki, USGS, Seasat SAR Experiment Team Leader, discussed the elements of the experiment plan under development by that group, with particular emphasis on land applications (table 3-2). Teleki pointed out that satellite system constraints will limit total SAR data collection time to approximately 15 000 min/yr. The data that will be processed into final form will correspond to a collection time of approximately 3000 minutes, a limitation imposed primarily because of processing costs. Of the processed data, approximately 30 percent has been identified by the SAR Team as being required for land-application studies, corresponding to an areal coverage of approximately 40 Mm^2. Teleki emphasized that plans for utilization of the SAR are still in the formative stages and that the team would welcome suggestions for well-coordinated experiments.

Panel Structure

Following the briefing by members of the Seasat program, four land-applications subpanels were formed to address the following topics.

1. Mapping and land-cover analysis

2. Food and fiber

3. Water resources

4. Geology

Although individual panel members were assigned to specific subpanels, members contributed to more than one applications area.

The following criteria were used by panel members during the proposal and evaluation of land-applications experiments.

1. Scientific merit

2. Potential for successful achievement of proposed goals

3. Established need for the data that the experiment is designed to produce within the user community

TABLE 3-2.- PROJECTED USES OF SEASAT-A SAR TO EARTH RESOURCES AND ENVIRONMENTAL ASSESSMENTS

Application area	Assumed uses and benefits	Evaluation[a]/ priority[b]	Frequency of coverage, days	Resolution exceeding 25 by 25 m	Comments
		Mineral resources and geologic features			
Land-form identification and terrain analysis	Mapping of uncharted land surfaces		Multiple passes (more than two) required within a month; two different seasons	No	For best resolvability, at minimum, one ascending and one descending orbit are needed to rectify relief (inaccuracy of point on ground not to exceed 50 m); coverage from overlapping orbits is also desirable
In regions of perennial cloud cover		A1			
With foliage penetration		B1			
Detection of geologic features related to mineral location and exploration	Regional geological mapping for resource identification		At least two passes; time of year not specified	No	Same as above
Stratigraphic and structural traps	Hydrocarbons	B1			
Linears, dikes, and intrusive bodies	Metallic minerals	C1			
	Nonmetallic minerals	B1			
Seismicity/tectonics					
Lineaments related to earthquake epicenters	Seismic zonation	B1	At least two passes within 6 mo	No	

[a]Application evaluation key:
- A - demonstrated
- B - highly probable, partially demonstrated
- C - speculative, further research needed
- D - inapplicable
- E - untested concept

[b]Application priority key:
- 1 - high
- 2 - moderate
- 3 - low

TABLE 3-2.- Continued

Application area	Assumed uses and benefits	Evaluation[a]/ priority[b]	Frequency of coverage, days	Resolution exceeding 25 by 25 m	Comments
		Mineral resources and geologic features (cont'd.)			
Seismicity/tectonics (cont'd.)					
Illuminated targets on faults for dilatancy measurements	Crustal motion detection	E2			Special application requiring aircraft underflight
Engineering geology					
Site evaluation and selection	Construction sites	A1	At least two passes within 6 mo under identical environmental conditions	No	
Material differentiation	Construction material location	C1		No	Differentiating for gravels is demonstrated
Fracture tones, faults, and volcanic activity		A1		No	Carbonates and igneous rocks not tested with L-band (only X-band)
		Water resources			
Surface water					
Watershed delineation	Water runoff prediction	A1	At least two passes, preferably in summer	No	Catchment basin/drainage pattern analysis (proven by Landsat)
Wetlands delineation	Wetlands inventories	B1	Two passes per season	No	
Flood detection, mapping, and monitoring	For forecasting purposes	B1	Bracketing occurrence of event	Preferred: 10 by 10 m	Need for imagery before, during, and after event

[a]Application evaluation key:
- A - demonstrated
- B - highly probable, partially demonstrated
- C - speculative, further research needed
- D - inapplicable
- E - untested concept

[b]Application priority key:
- 1 - high
- 2 - moderate
- 3 - low

TABLE 3-2.- Continued

Application area	Assumed uses and benefits	Evaluation[a]/ priority[b]	Frequency of coverage, days	Resolution exceeding 25 by 25 m	Comments
Water resources (cont'd.)					
Ground water		D			
Snow and ice					
Permafrost	Inventory and engineering purposes	E2	Two passes within 6-mo interval	No	
Frostline detection	Agricultural use; freeze/thaw line	E2 C2	As often as possible in the spring season	No	Differences between dielectric constants of frozen and unfrozen soils should be measurable
Snow cover	Runoff estimation	C1	As often as possible in the winter season	No	Data base is lacking
Mapping glaciers and glacier surges	Information for iceberg season (calving rate)	A1	Once at beginning and once at end of Seasat period	No	
Glacial sounding	Measuring rate of migration	A2	At every opportunity for selected glacier	No	Detection of ice structures below surface of glacier
Extent of freshwater ice (lakes and rivers)	Mapping to aid navigation	A1	Every pass	No	
Thickness and type of freshwater ice		C1	Every pass	No	
Water quality	Detecting pollutants	D			

[a]Application evaluation key:
- A - demonstrated
- B - highly probable, partially demonstrated
- C - speculative, further research needed
- D - inapplicable
- E - untested concept

[b]Application priority key:
- 1 - high
- 2 - moderate
- 3 - low

TABLE 3-2.- Continued

Application area	Assumed uses and benefits	Evaluation[a]/ priority[b]	Frequency of coverage, days	Resolution exceeding 25 by 25 m	Comments
		Agriculture and forestry			
Crops, forest and range			At least once each season; one pass per month in growing season at selected test sites		If L-band does not penetrate
Imaging cultivated areas	Crop identification, extent of cover, and yield prediction	C1		No	
Imaging rangelands	Range identification	B2		No	
Differentiating rangeland conditions	Differences in grazing conditions	D		No	
Soil mapping					
Types of soils		D			
Soil properties		D			
Soil moisture	Watershed management and crop yields	B1	Every pass at selected test sites	No	Data have been collected, have not been analyzed

[a]Application evaluation key:
A - demonstrated
B - highly probable, partially demonstrated
C - speculative, further research needed
D - inapplicable
E - untested concept

[b]Application priority key:
1 - high
2 - moderate
3 - low

TABLE 3-2.- Continued

Application area	Assumed uses and benefits	Evaluation[a]/priority[b]	Frequency of coverage, days	Resolution exceeding 25 by 25 m	Comments
		Land use and hazards			
Disaster monitoring	Cooling and peatbog fire detection	B2	Event related	No	Change in backscatter
Fire	Rangeland and timber management	A2	Event related	No	Change in backscatter
Earthquake, landslide, avalanche, and wind damage	Delineation of disaster areas	C2	Event related	No	Proven in concept only
Land-use monitoring					
Marshlands, wetlands, and swamps	Coastal zone resource management	B2	One pass each season	No	Data available for St. Johns River, Fla.
Irrigation networks and reservoirs	Agriculture	A1	Every opportunity	No	
Transportation networks	Delineation of new pipelines, powerlines, highways, and railroads	A2	Two passes per year	No	
Regulatory monitoring					
Oil spills on land	Environmental assessment	C1	Every target of opportunity	No	Detection of pipe break; effect of heated oil on Arctic environment

[a]Application evaluation key:
A - demonstrated
B - highly probable, partially demonstrated
C - speculative, further research needed
D - inapplicable
E - untested concept

[b]Application priority key:
1 - high
2 - moderate
3 - low

TABLE 3-2.- Concluded

Application area	Assumed uses and benefits	Evaluation[a]/ priority[b]	Frequency of coverage, days	Resolution exceeding 25 by 25 m	Comments
Land use and hazards (cont'd.)					
Regulatory monitoring (cont'd.)					
Strip mining	Change detection	B1	Monthly	No	
Disposal of subsurface mine wastes		C2	Twice yearly, two passes each	No	Radar imagery superimposed on Landsat MSS imagery
Forest logging		A1	Monthly	No	
Cartography	Planimetric mapping	A1	Temporal coverage	No	Required accuracy
Radar imagery mosaics	Topographic mapping	E1	Multiple passes	No	Vertical, 100 m; horizontal, 50 m

[a]Application evaluation key:
A - demonstrated
B - highly probable, partially demonstrated
C - speculative, further research needed
D - inapplicable
E - untested concept

[b]Application priority key:
1 - high
2 - moderate
3 - low

4. Potential economic benefit to the user community should such data become available

5. Impact of the experiment on the design and development of future microwave space systems and missions

The aforementioned criteria are not listed in rank order, and panel members tended to consider each of them equally during the evaluation of individual experiments.

In the following subsection, the experiments proposed by the subpanels have been ranked as high-, medium-, and low-priority experiments. All experiments discussed herein are considered important. Indeed, because of the difficulty in assigning relative priorities to individual application areas, the uncertainties in the dates of specific test site overflights, and the consensus of the panel that a wide range of applications should be demonstrated, no attempt has been made to rank experiments other than within each of the four topic areas. The priority ranking was performed at the request of the workshop sponsors.

As panel members proposed and assessed potential experiments, they were careful to examine each from the following standpoints.

1. What is the basic objective of the experiment?

2. What sensors on board Seasat-A would be employed?

3. What potential test sites could be employed?

4. What volume of data would be required to successfully complete the experiment?

5. What supporting remote sensor or in situ data would be required?

6. Who would be the potential users of the data?

7. What is the overall significance of the proposed experiment?

Experiments

The proposed experiments are understood to be in a preliminary outline form. In addition, it is recognized that the orbital parameters and system capabilities specific to the Seasat SAR may not be optimum for all experiments. However, because of the level of significance attached to such experiments by panel members, they have been included because they deserve thorough evaluation. The need for more specific documentation is fully recognized, but the material presented is adequate for initial evaluation.

A specific assignment of considerable importance in the conduct of this panel was to aid NASA in assessing both the data type and volume requirements for a Seasat land experiments program. These data requirements have been included for each experiment. Figure 3-7 is a map illustrating the test sites for the proposed experiments. Table 3-3 provides an overview of

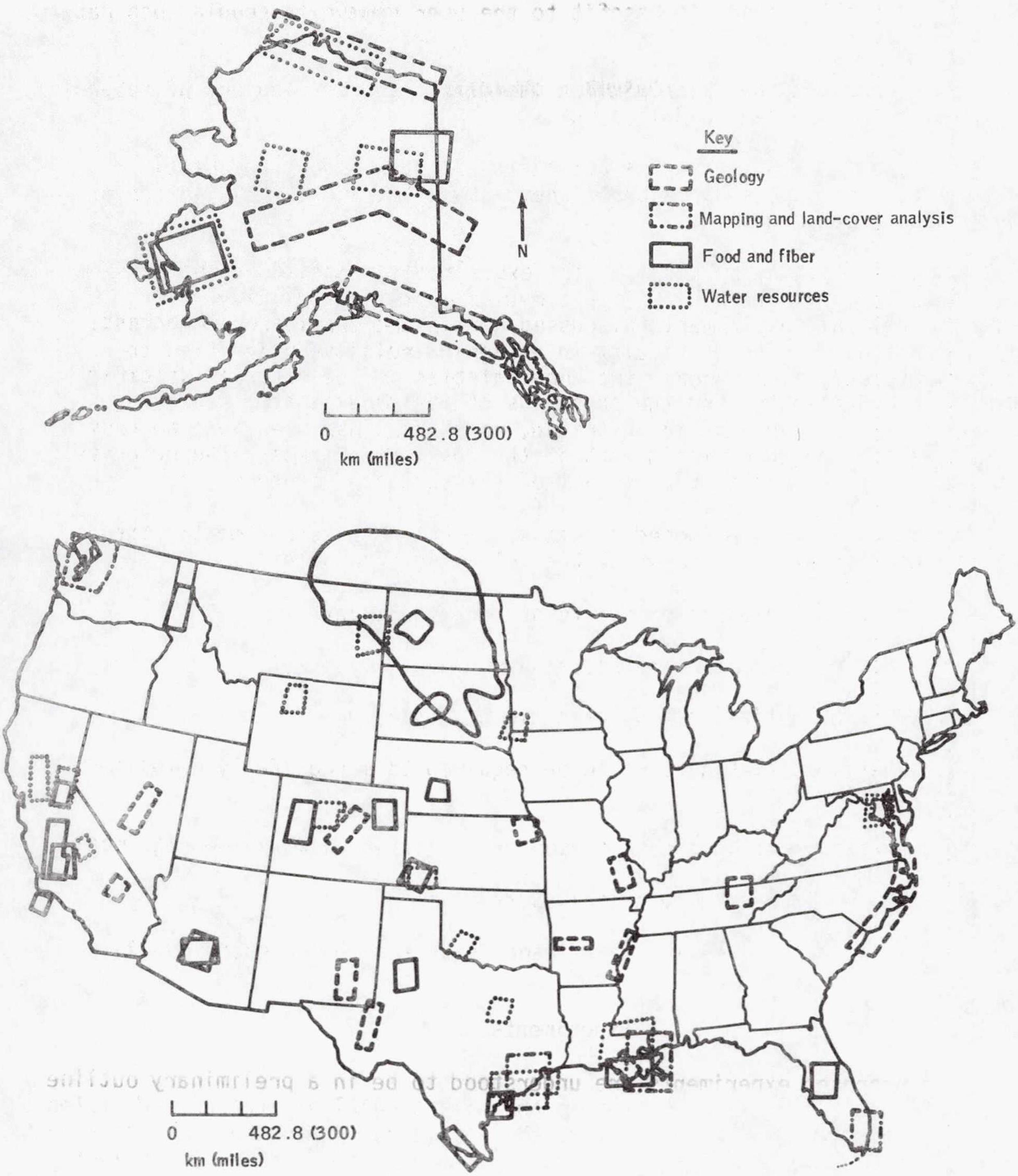


Figure 3-7.- Seasat land experiment potential test site locations.

TABLE 3-3.- OVERVIEW OF EXPERIMENTS PROPOSED BY THE SEASAT LAND EXPERIMENTS PANEL

Experiment title	Priority[a]	Potential test site locations	No. of Seasat passes required	Flightline length required, km	Time spent to accumulate Seasat SAR data, sec/yr[b]
		Mapping and land-cover analysis			
Planimetric Mapping	H	Washington, D.C.; Garden City, Kans.; and vicinity of Whittier, Alaska	2/site	100/site	78
Metropolitan Land Cover Mapping	H	Puget Sound, Wash.; New Orleans, La.; Houston-Galveston, Tex.; and Miami-Dade County, Fla.	2/site	200/site	208
		Subtotals:	14	1100	286
		Food and fiber			
Forest Fuels Assessment	H	Idaho Panhandle	2/yr	100	26
Forest and Range Biomass	H	Colo.	2/yr	100	26
Wild-Land Renewable Resource Evaluation	H	Salmon, Alaska	2/yr	100	26
Soil Moisture/Crop Yield	H	N. Dak., S. Dak., Kans., Calif., Ariz., Colo., Nebr., and Tex.	3/season/site	100/site	312
Saline Seep/Soil Salinity Detection and Mapping	H	Mont., N. Dak., and S. Dak. (four sites)	2/yr/site	150 (av)/site	156
Crop Discrimination and Stress Evaluation	M	Maricopa City, Ariz.; the lower Rio Grande Valley, Tex.; central Fla.; Bakersfield, Calif.; and the Tex. High Plains	1/growing season/site	100/site	65
Vegetative Cover Mapping for Wildlife Habitat	M	Yukon-Kuskokwim Delta, Alaska	Every June pass (5 assumed)	200/pass	130
Aquatic Vegetation	M	Calif., Tex., La., Fla., Wash., and the Sargasso Sea	2/3 mo/site	100/site	624
		Subtotals:	168	3800	1365

[a]Priorities listed here are relative. All experiments listed are considered significant and have been listed as high (H), medium (M), and low (L) upon request. The judgements were made on the basis of members' experience and took into account the scientific merit, the potential for successful achievement of proposed goals, the established need for data, and the potential economic benefit.
[b]Potential maximum.

TABLE 3-3.- Continued

Experiment title	Priority[a]	Potential test site locations	No. of Seasat passes required	Flightline length required, km	Time spent to accumulate Seasat SAR data, sec/yr[b]
		Water resources			
Watershed Runoff	H	The Kern River, Calif.; Chickasha, Okla.; Waco-Refugio, Tex.; and the Patuxent River, Md.	3 to 4/yr/site	100/site	416
Surface Water/Flood Mapping	H	Targets of opportunity and the rice-growing areas in south-central La., the vicinity of Houston, Tex., and the Sacramento Valley, Calif.	3/yr/nationwide; 2 to 3/growing season/site	100/site	39 117
Snow Mapping	M	The central Sierra Nevada Mts., Calif.; Steamboat Springs, Colo.; the Wind River Mts., Wyo.; Luverne, Minn.; the upper Missouri River; and the Sangre de Cristo Mts., Colo.-N. Mex.	4/site/yr	100/site	260
Alaskan Lakes Mapping	M	The Arctic coast; the Bethel, Alaska, region; the Koyukuk, Alaska, region; and the Mackenzie River Delta, N.W.T., Canada	2/site/yr	100/site	78
		Subtotals:	57	1700	910
		Geology			
Placer Gold Belt Mapping	H	The central Yukon River area, Yukon Terr., Canada	2 to 4/yr	1150	600
Assessment of Glacial Ice Dynamics	H	Skagway to Palmer, Alaska	1 to 2/yr	850	222
Mineral and Petroleum Exploration	H	Central Ark.	4/yr	200	104

[a]Priorities listed here are relative. All experiments listed are considered significant and have been listed as high (H), medium (M), and low (L) upon request. The judgements were made on the basis of members' experience and took into account the scientific merit, the potential for successful achievement of proposed goals, the established need for data, and the potential economic benefit.

[b]Potential maximum.

TABLE 3-3.- Concluded

Experiment title	Priority[a]	Potential test site locations	No. of Seasat passes required	Flightline length required, km	Time spent to accumulate Seasat SAR data, sec/yr[b]
		Geology (cont'd.)			
Geomorphic Mapping in Coastal Wetlands and Marshes	H	La.	4/yr	100	52
Land Subsidence	H	Carlsbad, N. Mex., area	2/yr	100	26
Discrimination of Construction Materials	H	Goldfield, Nev.	2	100	26
Discrimination of Terrain	H	Memphis, Tenn., vicinity	2	100	26
Roughness and Texture	H	Death Valley, Calif.	4	100	52
Discrimination of Geologic Structure in Areas of Low Relief	M	Northern S.C. to Va.	2/yr	400	104
Evaluation of Arctic Coastal Ice Structure and Dynamics	M	Arctic coastline of Alaska	2 to 4/yr	800	416
Evaluation of High-Relief Terrain	M	Colo. mineral belt	1	200	26
Linear Assessment	L	Northeast Kans.	1	100	13
Midcontinent Base Metals Exploration	L	North-central Tenn. to south-central Ky., southeast Mo.	2/yr/site	150/site	78
Sulphur Deposit Exploration	L	Orla-Van Horn, Tex.	2	100	26
		Subtotals:	38	4600	1771

[a]Priorities listed here are relative. All experiments listed are considered significant and have been listed as high (H), medium (M), and low (L) upon request. The judgements were made on the basis of members' experience and took into account the scientific merit, the potential for successful achievement of proposed goals, the established need for data, and the potential economic benefit.

[b]Potential maximum.

the range of experiments proposed by the panel. Table 3-4 presents a summary of the total aerial coverage and volume of data required for the experiments listed in the four land-applications subareas.

Data Requirements

The land applications found in table 3-3 tend to indicate that implementation of all suggested experiments would not result in a particularly heavy data-processing load, even if the maximum amount of data were acquired for each experiment. The table summarizes the experiments proposed for each application area, specific site locations, the number of Seasat passes, and the flightline lengths required. The final column translates number of passes per year per site length into real-time seconds of accumulated Seasat SAR data per year per experiment.

A number of experiments proposed require seasonal data, some annual data; a few require data only once, whereas several are event dependent. The right-hand column (table 3-4), therefore, represents a maximum data requirement that may be expected in a single year from the Seasat land experiments; however, it is highly probable that the total would actually be less than the cumulative amounts shown. In addition, no attempt has been made to reduce the total requirement that would result from concurrent data acquisition for two or more sites - i.e., overlap of sites between experiments.

The total precision-processed-SAR-data requirement for all experiments, if potential savings resulting from concurrent acquisition are disregarded, is estimated to be approximately 4400 sec/yr, or approximately 73.5 minutes. This figure equals one-half of 1 percent of the total annual unprocessed data acquisition capability of the Seasat SAR sensor system. In terms of processed data, this figure represents only a modest portion of both the total projected processed data and the total processed data projected for allocation to land experiment programs.

EXPERIMENT DESCRIPTION

The proposed Seasat land experiments are described in the following subsections.

Mapping and Land-Cover-Analysis Experiments

For all anticipated land applications, the comparison of SAR imagery with existing maps and ground-truth data will be required. For many applications, the digital interfacing of Seasat SAR and Landsat digital imagery for a variety of computer analysis procedures (i.e., supervised and unsupervised classification, modeling, and geographic information systems) is anticipated. Both types of applications require the geometric rectification of raw data to ground coordinate systems. The experiments proposed under this subsection will result in the following accomplishments.

TABLE 3-4.- SUMMARY: SEASAT SAR LAND APPLICATIONS DATA REQUIREMENTS

Category	No. of Seasat passes required	Flightline length required, km	Time spent to accumulate Seasat SAR data, sec/yr
Mapping and land-cover analysis	14	1 100	286
Food and fiber	168	3 800	1365
Water resources	57	1 700	910
Geology	38	4 600	1771
Maximum annual totals:	277	11 200	4332

1. Determination of the sensor map accuracy standard

2. Investigation of the potential for integrating Seasat SAR imagery into automated data base management systems capable of assessing and predicting the impact of changing natural phenomena on the land in a manner similar to that being undertaken in weather and oceanographic experiments on Seasat

Assessing the planimetric accuracy of Seasat-A synthetic aperture radar (SAR) image data.- A need common to all land applications of SAR data is the geometric rectification of raw data to ground coordinate systems, for ultimately most information obtained from SAR data will be related to surface data - or displayed in a map format. In addition, geometric rectification is a necessary step if the SAR data are to be merged with complementary data (e.g., Landsat data). An experiment to examine this problem is outlined in table 3-5.

At a minimum, an experiment should be performed to establish the equivalent national map accuracy standards obtainable with SAR data acquired by Seasat. Procedures for merging digital data from SAR with complementary data (e.g., Landsat data) would be an important part of this experiment.

The Active Microwave Task Force (ref. 3-1) strongly recommended that "NASA....provide digital radar data computer compatible with Landsat D." The study group recognized that raw Seasat SAR data would have limited utility to the user community because of the complex and costly processing required to relate the data to existing surface information and ancillary data.

The three areas chosen for the test represent three types of topography - flat (Garden City, Finney County, Kansas), undulating (Washington, D.C., region), and mountainous (Whittier-Portage region of Alaska). All three areas have highly accurate geodetic control points and represent sites of interest to several experimenters. The data for each site are to be checked for root mean square (rms) error over 15' by 15' quadrangles for the Kansas and Washington, D.C., sites and over a 15' by 30' quadrangle for the Alaskan case.

Land-cover mapping in metropolitan regions.- It is proposed that Seasat SAR digital imagery be utilized for selected metropolitan regions to (1) determine the feasibility of delineating the rural/urban fringe directly and (2) determine the improvement, if any, to be derived from the merging of SAR data with Landsat MSS digital imagery in urban-land-cover classification/mapping. An experiment to test this capability is outlined in table 3-6.

The metropolitan regions chosen for the experiment (Puget Sound, New Orleans, Houston-Galveston, and Miami) are characterized as being coastal, having rapid urban growth, and having a high incidence of cloud cover. All the potential sites are major (and growing) sources of coastal water pollution. The delineation of land cover and statistical summaries of areas could be used in conjunction with coastal zone experiments to assess the impact of nonpoint water runoff pollution.

TABLE 3-5.- ASSESSING THE PLANIMETRIC ACCURACY OF SEASAT-A IMAGE DATA

Item	Discourse
Objective	Determine the planimetric accuracy of Seasat SAR in terms of national map standards. Also, investigate the value of Seasat CCT data that have been geometrically rectified as they relate to interacting with other data sources. In particular, utilize SAR and Landsat data as input into digital classification algorithms.
Seasat-A sensor requirement	SAR.
Potential test sites	Flat terrain - Garden City, Kans. Undulating terrain - Washington, D.C. Mountainous terrain - Whittier-Portage, Alaska.
Data volume requirements	Two passes per site - one ascending, one descending.
Supporting remote sensor data	Multispectral scanner data available from Landsat.
Ground data	U.S. Coast and Geodetic Survey and USGS control points.
Potential users of data output	Common requirements for all land applications of SAR.
Recommendations	
Minimum	Experiment should be performed to define earthographic accuracy of space SAR data and procedures for digital merge with complimentary data (e.g., Landsat data).
Optimum	NASA should provide SAR computer-compatible tapes to users, geometrically rectified to be compatible with Landsat data.

TABLE 3-6.- LAND-COVER MAPPING IN METROPOLITAN REGIONS

Item	Discourse
Objective	Delineate the rural/urban boundary directly from Seasat SAR and interface Seasat SAR digital imagery with Landsat MSS digital imagery to improve multispectral classification in urban regions and assess flooding damage and nonpoint source coastal water pollution.
Seasat-A sensor requirement	SAR.
Potential test sites	Puget Sound, New Orleans, Houston-Galveston, Miami-Dade County (in order of priority).
Data volume requirements	Passes per site: one ascending, one descending. Flooding data: one pass. Area: 200 km long, 100 km wide.
Supporting remote sensor data	High-altitude color-IR and fine-grain black-and-white aerial photography.
Ground data	Field surveys.
Potential users of data output	U.S. Census, Geographic Areas Branch. U.S. Dept. of Housing and Urban Development (HUD) Federal Insurance Agency. Environmental Protection Agency and other coastal-water-pollution monitoring agencies.
Significance	Assist Census in annual delineation of urban fringe in high-cloud-cover regions, provide for automated assessment of flood damage in metropolitan regions, and assist in coastal water and tidelands water pollution modeling.

The high incidence of cloud cover over the selected sites has made it difficult to obtain timely Landsat coverage for the monitoring of urban development. As a proof-of-concept test, it would be useful to test whether Seasat SAR imagery can be advantageous to the U.S. Census in the execution of its recently imposed mandate to delineate urban/rural boundaries. Urbanized areas, defined as those areas with more than 386.1 persons per square kilometer (1000 persons per square mile), are to be delineated annually for the 275 standard metropolitan statistical areas after 1980. Comparative images such as those seen in figure 3-8, and research reports (ref. 3-1), suggest that resolution requirements for urban limits delineation from SAR imagery by using standard photo interpretation techniques should be met by the Seasat SAR sensor.

All the metropolitan areas mentioned are subject to flooding, either from storm water runoff or tidal surges associated with hurricanes or both. Disaster relief agencies not only need to know the regions inundated but also need to arrive at dollar estimates of the damage. As a proof-of-concept test, it would be useful to have land-cover digital images that conform to the scale and flightpath characteristics of Seasat SAR digital images in addition to the SAR imagery taken during flooding. The interfacing of land-use image and flooding-period image would permit an automated tabulation of area for each land-cover type flooded.

Panel members are aware that Seasat SAR data acquisition need not be confined to the cities mentioned in cases of specific significant environmental disruption. In such instances, it would still be possible, within the proof-of-concept nature of the Seasat mission, to conduct viable experiments. This task could be accomplished by going back through past Landsat data for the area under study and constructing the data base needed for the experiment. One problem that would arise, however, would be in connection with the amount and quality of the ground-truth data available for the study site. Ground data collection would be access dependent; and the cost associated with in situ data acquisition, which would depend on a variety of factors, could range from minimal to excessive.

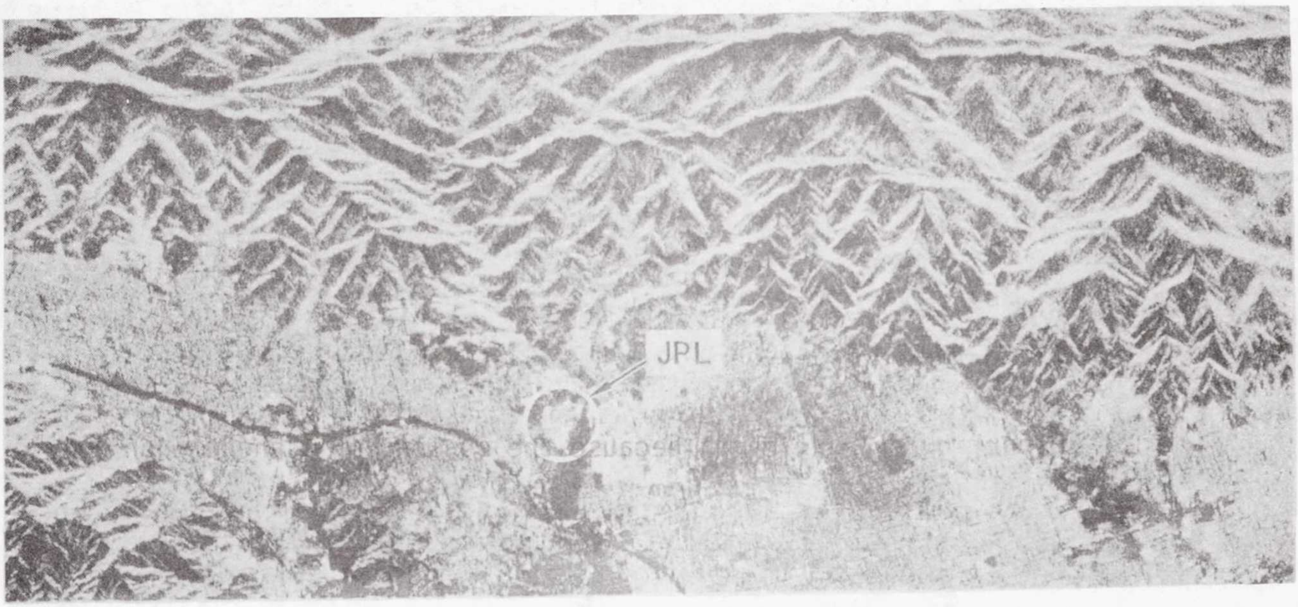
Food and Fiber Experiments

A sizeable portion of the highly productive rangeland and commercial forest land in the western United States and Alaska is located in areas that are difficult to assess by using conventional remote-sensing methods. This fact is particularly relevant because the sensing of a phenomenon such as vegetation stress is highly time dependent. Managers of large tracts of forest and rangeland are in need of alternatives to conventional remote-sensing methods, which include the use of high-altitude-aircraft photography and Landsat MSS imagery.

The SAR, although virtually unexplored as a renewable resource assessment tool for wild-land areas, has the potential of being a highly beneficial complementary data source for performing time-dependent renewable resource evaluations.

Foresters, rangeland inventory specialists, and wildlife experts have suggested a number of specific experiments - "Forest and Range Biomass,"

(a) Landsat image.



(b) JPL imaging-radar image (simulates Seasat resolution).

Figure 3-8.- Landsat and radar image of La Canada/JPL/Pasadena area.

"Wild-Land Renewable Resource Evaluation," "Forest Fuels Assessment," and "Vegetative Cover/Wildlife Habitat Mapping" - for testing microwave capabilities. In addition to these experiments, the panel strongly supports the snow-mapping experiment proposed in the "Water Resources Experiments" subsection of this chapter. Whereas it is highly desirable to correlate satellite experiments with the collection of calibrated aircraft and field measurement data, such ancillary data are not mandatory to significantly advance the state of knowledge from the current base of understanding.

Forest and range biomass.- The Nation's forest and range resources managed by the USFS are an important source of food, fiber, and fodder. The yearly production of timber from our forest lands and cattle and sheep from our rangeland is evidence of the importance of this resource. Managers charged with the responsibility for the wise use of this resource require a wide range of timely, accurate information. Specifically, with respect to the range, resource managers require data on the readiness of a given range, as well as information concerning its carrying capacity and early indications of overuse. Such information, which is associated with biomass estimation, is important because managers try to plan the long-range use of both forest and range resources.

This experiment would test the capability of Seasat SAR data to provide management with information that would aid in the estimation of biomass for a given area (see table 3-7). Such biomass estimates could be used in forest fuels fire predictive models (see table in "Forest Fuels Assessment" subsection) in the case of forest biomass or to calculate range productivity and carrying capacity for livestock and wildlife (see table in "Soil Moisture/Crop Yield System" subsection).

Wild-land renewable resource evaluation.- To promote the wise use of this Nation's renewable resources, information concerning their state and extent must be gathered on a timely basis. In many areas, however, the acquisition of information concerning those renewable resources presents difficult problems. Such is the case in the State of Alaska. Much of the interior of Alaska has not been intensively inventoried with respect to natural resources because of environmental and technological obstacles. In this harsh environment, conventional survey techniques are hazardous and it is difficult and expensive to obtain the required data by using conventional remote-sensing techniques. The Seasat SAR system has the potential to provide an alternative source of resource information. This experiment is designed to test the feasibility of using the Seasat SAR system to provide information for the periodic assessment of the renewable resources in the interior of Alaska (see table 3-8).

The suggested experimental objectives are keyed to a specific geographic site that offers different challenges for a Seasat land-applications test. The test sites also provide opportunities for using collateral data in that they are established centers of research and development activity by resource management agencies such as the USFS.

The agricultural industry is the largest U.S. industry. Exports from its remarkably efficient system both account for the periods of favorable balance of payments and pay for vast amounts of imported petroleum.

TABLE 3-7.- FOREST AND RANGE BIOMASS

Item	Discourse
Objective	To estimate total biomass of vegetation in designated management areas. It is desirable to distinguish forest biomass from range biomass because the data are used in different management models.
Seasat-A sensor requirements	SAR, VIR, and scatterometer.
Potential test site	Grand County, Colo.
Data volume requirements	One pass in June and one pass in Aug., per year. Area: 64.8 by 88.9 km (35 by 48 n. mi.).
Supporting remote sensor data	High-altitude color-IR photography. Metric camera, 30.5-cm (12 in.) focal length, from 198.1 Mm (65 000 ft). Low-altitude color-IR photography. 70-mm strips at 1:1200 scale.
Ground data	Forest and range biomass inventory ground sites and collateral field measurement data.
Potential users of data output	USFS, BLM, Colo. Bureau of Fish and Game, and U.S. Fish and Wildlife Service.
Significance	Forest biomass estimates are used in forest fuels fire prediction models, and similar range biomass estimates are used to calculate range productivity and carrying capacity for livestock and wildlife.

TABLE 3-8.- WILD-LAND RENEWABLE RESOURCE EVALUATION

Item	Discourse
Objective	To determine the feasibility of using SAR data in remote areas of interior Alaska for periodic assessments of the renewable resources.
Seasat-A sensor requirements	SAR, SMMR, VIR, scatterometer, and radar altimeter.
Potential test site	Salmon, Alaska.
Data volume requirements	Passes per site: one ascending, one descending, July and August. Area: 175.9 by 203.7 km (95 by 110 n. mi.), centered on Salmon.
Supporting remote sensor data	High-altitude color-IR photography from 198.1 Mm (65 000 ft). Metric camera, 15.2-cm (6 in.) focal length. Low-altitude color-IR photography. 70-mm strips at 1:4000 scale.
Ground data	Ground inventory data.
Potential users of data output	USFS, BLM, USACE, SCS, and Alaskan Land Use Planning Team.
Significance	Much of interior Alaska has not been surveyed for an extensive inventory of renewable resources, and there are major obstacles in performing such an inventory because of the difficulty of obtaining conventional remote-sensing data. SAR data obtained from a special platform provide a potential alternative source of collateral extensive-type resource information.

Recent bans on important agricultural chemicals by the Federal Government have seriously damaged the efficiency of the American agricultural industry and significantly increased the cost of food. If the United States is to continue to pay for imported petroleum with exported agricultural crops, it is imperative that the agricultural community utilize every available and economically viable scientific and technological breakthrough.

Imagery obtained from Landsat, Skylab, and NASA high-altitude aircraft can contribute to the efficiency of modern agriculture. Imagery from these space platforms and from both visible and IR portions of the electromagnetic spectrum has value for identifying crops, detecting and monitoring stress, and evaluating crop yield potential. Unfortunately, clouds and related weather phenomena, as well as insufficient solar illumination, prevent collection of imagery during critical phases of the crop cycle. The experiments listed in the following subsections are designed to test the capabilities of the Seasat SAR system to impact the agricultural communities' information requirements, particularly in the critical area of crop stress evaluation (see tables in subsections "Soil Moisture/Crop Yield System," "Saline Seep/Soil Salinity Detection and Monitoring," and "Crop Discrimination and Stress Evaluation"). Improved information on crop stress can be of major importance with respect to both management decisions and economic considerations in U.S. agriculture.

<u>Forest fuels assessment</u>.- Each year, fires consume hundreds to thousands of square kilometers (hundreds of thousands of acres) of valuable timber and rangeland. The USFS, through its Firescan project, is currently employing remotely sensed data to combat this problem. Project Firescan is designed to detect areas of latent fire hazards and thereby contribute to minimizing the potential for environmental disruption. The experiment proposed herein is an attempt to determine whether this early warning capability can be augmented with a system that, hopefully, has the potential of providing data relative to the severity of the fire hazard that exists in a given area (see table 3-9). This determination would be accomplished by assessing the capabilities of the Seasat SAR for providing data relative to the moisture status of forest fuels - e.g., the total complex of dead materials that accumulate in forest and wild-land areas.

This information is currently gathered by using conventional ground survey techniques, which are often augmented in a number of areas by aerial surveys. A successful proof-of-concept demonstration would provide important information to foresters and wild-land managers as they attempt to minimize the impact of fires on our forest resource.

<u>Soil moisture/crop yield system</u>.- Recent experimental results and reference data indicate that soil moisture content may be measurable by using an L-band SAR imagery system. These data could have a significant impact on crop yield prediction models. Soil moisture is an important variable affecting the prediction of yield of agricultural crops. Yet, soil moisture is essentially an unmeasurable quantity as pertains to crop yield prediction models. Conducting a program of data acquisition by using conventional point-sampling techniques on a scale necessary to impact these models would be both costly and to a large extent unproductive. As a result, for crop yield prediction models, such as the wheat yield modeling system, a variety of surrogate data is used to supply information

TABLE 3-9.- FOREST FUELS ASSESSMENT

Item	Discourse
Objective	To monitor the moisture status of forest fuels that resulted from logging residue, the forest mortality from insect and disease infestation, and the total complex of dead material that accumulates in the forest and wild-land areas.
Seasat-A sensor requirements	SAR, SMMR, VIR, scatterometer, and radar altimeter.
Potential test sites	Idaho Panhandle, Salmon River north to the Canadian border.
Data volume requirements	Passes per site: one ascending, one descending. Area: 138.9 by 342.6 km (75 by 185 n. mi.).
Supporting remote sensor data	Two-stage high-altitude aerial photography from 198.1 Mm (65 000 ft). Metric camera, 15.2-cm (6 in.) focal length, with color-IR film. Reconnaissance camera, 61.0-cm (24 in.) focal length, with color-IR film.
Ground data	Fuel inventory ground plots and supporting field measurement data.
Potential users of data output	USFS, BLM, and State and private forest groups.
Significance	Fuel moisture data are a major input to a national fire model for predicting the rate of spread and fire hazard.

on soil moisture. The Earth Satellite Corporation (Earth Sat) Agmet system employs manual image analysis of Synchronous Meteorological Satellite (SMS) visible and IR images to produce data on cloud types, patterns, and amounts. These data are typically incorporated, together with data from other satellite systems and ground meteorological networks, to derive information on parameters affecting yields, such as precipitation, incoming solar radiation, net radiation, and potential evapotranspiration.

Data on the duration, type, and amount of precipitation are used in these prediction models as a surrogate for soil moisture. Soil moisture may be measurable by combining data obtained by the L-band imager and microwave radiometer during passage over rain-free areas. In regions undergoing precipitation, similar measurements may determine the areal extent of precipitation and perhaps its intensity. The IR radiometer data currently used to estimate precipitation probabilities from cloudtop temperatures could be improved with the microwave data. Although Seasat-A will not provide the frequency of measurements supplied by the SMS, this experiment would be useful in demonstrating the concept of remotely measuring soil moisture with microwave sensors (see table 3-10).

For this experiment, test sites should be carefully selected, be sufficiently large, be well instrumented or have adequate control, and exhibit a diversity of soil moisture conditions. In this respect, attempts should be made to include data from large-field commercial farms. In addition, the panel believes that it is important to include areas where a variety of irrigated commercial field crops are grown. Because of the intensified interest in predictive yield modeling efforts within the LACIE program, the panel believes that a determination of the interest of scientists associated with the LACIE to participate in this experiment should be made.

The Seasat passive microwave radiometer (the SMMR) may be used to reduce bias errors in the estimation of soil moisture content obtained by use of the SAR. This task can be accomplished by comparing the moisture estimate based on the radiometer temperature of its large footprint with the integrated moisture estimate based on the SAR data for the same footprint, and then using the ratio of the two estimates to generate a new high-resolution soil moisture contour map.

In addition to ground-truth data collection, it is proposed that airborne sensors with proven soil moisture sensitivity be used in support of this experiment. These sensors include C-band radar (preferably imager) and the NASA Lyndon B. Johnson Space Center (JSC) multifrequency microwave radiometer (MFMR) (see table 3-10).

Saline seep/soil salinity detection and monitoring.- Salt-affected soils are found in many agricultural areas of the United States and cause untold loss of income to the national economy. Saline seeps represent one form of salt-affected soils. In these areas, extremely high salt concentrations at the soil surface can cause significant crop losses; e.g., in Montana, biennial wheat loss has been estimated to be approximately $50 million. If saline seep areas can be identified early, alfalfa or similar crops can be planted to increase evapotranspiration and prevent the buildup of salts at the soil surface. Theoretical computations by Keith Carver,

TABLE 3-10.- SOIL MOISTURE/CROP YIELD SYSTEM

Item	Discourse
Objective	To determine the potential of the L-band SAR system to provide soil moisture data for input into agricultural crop yield predictive models.
Seasat-A sensor requirements	SAR, VIR, scatterometer, and SMMR.
Potential test sites	LACIE intensive sites: Williams County, N. Dak Hand County, S. Dak. Finney County, Kans. Southern San Joaquin Valley, Calif. Maricopa County, Ariz. Center pivot irrigation areas in Nebr., Colo., and Tex.
Data volume requirements	Passes per site: three to four passes during critical period in growth cycle (field prepared through fruiting). Length per site: 24.1 to 80.5 km (15 to 50 miles). Area: LACIE sample sites, 8.0 by 9.7 km (5 by 6 miles).
Supporting remote sensor data	Landsat data, including thermal-channel data. S-191 and large-scale high-altitude aerial photography, 1:32 000. Aircraft scatterometers: 1.6 GHz, C-band. Imaging radar: L-band, C-band.
Ground data	Field spectroradiometer. Precision radiation thermometer (PRT-5). Capability for systematic field soil moisture sampling and rainfall monitoring. Truck-based systems: MAS and microwave signature acquisition system (MSAS).
Potential users of data output	USDA, private industry, and food producers.
Significance	The data are important to upgrade the overflight quality of our agricultural yield forecasting capabilities.

New Mexico State University, indicate that saline soils can be differentiated from normal soils by using L-band radar data. Preliminary measurements at Texas A. & M. University also indicate that dielectric properties of saline-seep-affected soils can be detected. The L-band Seasat-A imager is therefore considered satisfactory for proof-of-concept verification (see table 3-11).

Several State leaders have recognized the problem of saline seeps. The Governors of Minnesota, North Dakota, South Dakota, and Montana, meeting in 1975, agreed on the need to obtain information on the location and degree of development of saline seeps. Areas of salt-affected soils are also found in areas of extensive irrigated agriculture in the arid southwestern United States. The Imperial Valley and southern San Joaquin Valley of California; Maricopa County, Arizona; and the lower Rio Grande Valley of southwest Texas are all potential sites for testing the capabilities of the Seasat sensors to complement existing systems and provide data relative to this important problem.

Crop discrimination and stress evaluation.- Cloud-related weather phenomena and insufficient solar illumination usually cause difficulties in the identification of crops and the detection of stress by conventional remote-sensing techniques. Visible and IR wavelengths will not adequately penetrate cloud cover during periods of adverse weather. Consequently, it is now virtually impossible to gather necessary crop identity and stress data over large portions of important agricultural areas during critical phases of the crop cycle.

The Seasat-A program can overcome some of these shortcomings. It can provide needed data and greatly enhance the value of Landsat and high-altitude-aircraft imagery. The wavelengths employed by Seasat's microwave sensors will penetrate clouds and thus may enable acquisition of crop stress and soil cover data during both nighttime and periods of adverse weather. Furthermore, the microwave sensors can penetrate leaf canopies and thus detect both surface and shallow root zone soil moisture. Such information can thus supplement the imagery obtained simultaneously by other means and greatly enhance the value of all remote-sensing systems employed (see table 3-12). It is recognized that the L-band SAR is not optimum for crop detection; however, recent test results suggest that some vegetation discrimination is possible even at these long wavelengths. This indication can be verified in the proposed experiment.

Although many investigators prefer and expect multidate imagery, ecomomic constraints sometimes necessitate that agribusiness interest groups limit their investigations to a single pass over a specified area during a critical phase of the crop cycle. Thus, if, during the single pass, imagery can be simultaneously obtained from the visible, near-IR, thermal-IR, and microwave portions of the electromagnetic spectrum, the optimum benefit to agriculture should be realized.

Vegetative cover mapping for wildlife habitat.- Wildlife habitat mapping is a difficult endeavor, complicated by the absence of an adequate definition of habitat. Simplistically, habitat and vegetative association can be used interchangeably. One virtue of this simplification is that it

TABLE 3-11.- SALINE SEEP/SOIL SALINITY DETECTION AND MONITORING

Item	Discourse
Objective	Detection of saline seeps by using Seasat-A SAR
Seasat-A sensor requirements	SAR and SMMR
Potential test sites	N. Dak.; NE. Ariz., Maricopa County; S. Dak.; central or west Calif., Imperial Valley or southern San Joaquin Valley; Tex., Rio Grande Valley; Mont., NE.
Data volume requirements	Passes per site: two per year Length per site: 241.4 to 482.8 km (150 to 300 miles)
Supporting remote sensor data	S-191 and photography Scatterometer (JSC), 1.6 GHz Imaging radar (JPL), L-band MFMR (JSC)
Ground data	Map of the saline seep
Potential users of data output	Farmers and ranchers USDA USACE Food processors
Significance	590 517.3-km^2 (228 000 mi^2) potential saline seep area

TABLE 3-12.- CROP DISCRIMINATION AND STRESS EVALUATION

Item	Discourse
Objectives	To aid crop identification and stress detection by combining reflective data from Seasat-A with spectral data from Landsat systems. To prove the concept that wide-band, multichannel, visible-to-microwave-frequency sensor data provide more timely and economically useful information than MSS data alone. To ascertain the value of Seasat-A sensors for measuring soil moisture. Degree of vegetation penetration and sensitivity of sensors to soil moisture changes should also be recorded.
Seasat-A sensor requirements	SAR and scatterometer.
Potential test sites	Maricopa County, Ariz.; lower Rio Grande Valley, Tex.; central Fla.; southern San Joaquin Valley, Calif.; Tex. High Plains. Test sites selected should be governed by availability of current ground truth, coincidence of Seasat/Landsat coverage, and presence of several types of economically significant field crops during most of the crop year.
Data volume requirements	Passes per site: one per peak growing season/coincident with Landsat overpass. Length: standard 100- by 100-km scene. Landsat coincident data.
Supporting remote sensor data	Underflight L-band imagery. Color-IR photography.
Ground data	See above.
Potential users of data output	Producers and processors of food.
Significance	If the proof of concept is achieved, future agricultural monitoring systems would be cost/benefit attractive to elements of the agribusiness community.

allows use of remote-sensing techniques to arrive at a first approximation of habitat. Conventional - i.e., visible/near-IR - instrumentation is perhaps the most versatile and most widely used in this respect. However, for areas in which cloud cover is a severe constraint in these wavelengths, other sources such as imaging microwave systems (SAR) must be considered.

Habitat is, of course, a function of the wildlife species under consideration; but, in general, loss of habitat is the major threat, especially when considered on the national level, to wildlife survival. Hence, the need exists to inventory and monitor wildlife habitat, especially for threatened and endangered species. Nearly all developmental activities (urbanization, agriculture, energy extraction, and water resources development) destroy or modify habitat. Thus, their effect is on population and not so much on individuals. Budget constraints of Federal and State agencies concerned with wildlife (habitat) preservation make it mandatory to use cost-effective methods for assessing available and impacted habitat. The use of SAR (in special cases) and other remote-sensing methodologies has become central to wildlife management. To test the applicability of Seasat SAR data for studying wildlife habitat, an experiment to assess the importance of these data for providing information relative to Arctic goose nesting success is proposed.

Each year, the Fish and Wildlife Service sets migratory-bird-hunting regulations, which form the basis for season lengths and bag limits established for each flyway and State. This task represents a multimillion dollar effort involving numerous data sources and resource inputs. A major component of the migrating waterfowl is Arctic nesting geese (snow geese, brant, Canada geese, etc.). Of the 1.8 million geese taken in the 1975 hunting season, fully 1.6 million nested in the Arctic. A critical datum needed in setting hunting limits is productivity (nesting success) each year. Because of the remoteness and vastness of the areas involved, these data are difficult, if not impossible, to obtain. The most critical information is whether or not the potential nesting sites are clear of ice at the time the goose-pairs are ready to build nests. If no ice-free nesting sites are available, the females resorb the eggs and no young are produced. The period involved is at most a month, generally less. Within 6 weeks of this period, preliminary hunting regulations incorporating that year's nesting success must be determined. Thus, for a short, crucial period, ice conditions determine nesting success or failure. The recent use of satellite data (NOAA-3 very high resolution radiometer (VHRR), Landsat MSS) has resulted in a significant increase in the ability to forecast ice conditions - hence, the probability of nesting success - on the Arctic breeding grounds. However, frequent cloud cover at the critical period limits the certainty of these data sources. The ability of the Seasat SAR to penetrate clouds and map ice versus ice-free regions (the freeze-thaw line) at 25-m resolution should finally provide a means to close this management information gap (see table 3-13).

Monitoring of aquatic vegetation.- Aquatic vegetation is of considerable importance. Kelp, for example, is a basic element in the aquatic food chain. In some cultures, it is a recognized food product in its own right; and it is an important harvestable commercial crop in such areas as California and the northeast coast. Similarly, the estuarine marshes of the gulf coast and eastern seaboard are central to marine food productivity. The wetlands,

TABLE 3-13.- VEGETATIVE COVER MAPPING FOR WILDLIFE HABITAT

Item	Discourse
Objective	To detect the freeze/thaw line and relate this information to lake ice conditions in the Arctic as a prediction of goose nesting success.
Seasat-A sensor requirements	SAR, SMMR, and scatterometer.
Potential test site	Yukon-Kuskokwim Delta, Alaska.
Data volume requirements	All passes over the study area from May 15 to July 15.
Supporting remote sensor data	High-altitude color and color-IR photography, L-band imaging radar data from aircraft.
Potential users of data output	U.S. Fish and Wildlife Service, Canadian Wildlife Service.
Significance	Demonstration of proof of concept would not only lead to improved management of Arctic waterfowl but would have important implications in many areas of wildlife management.

which are susceptible to man-imposed stress, have a significant direct impact on man, the ultimate food consumer. Conversely, noxious aquatic plants cause great damage worldwide in the freshwater environment by clogging waterways, by increasing losses of water from reservoirs, and by diminishing recreational potential. This seemingly disparate vegetation has a common denominator, that of necessitating management by man. A key element in aquatic vegetation management is the monitoring of its spread and condition, a task somewhat synonymous with the tracking of its areal extent and relative biomass.

Provision of timely information by remote sensing enables valid decisions to be made concerning how these vegetative classes are to be handled for optimum benefit to man. Imaging radar can provide the sort of broad, all-weather, detailed monitoring coverage that would not be possible to economically obtain with other sensor types.

Kelp is quite common in the west coast environment. A prodigious grower, healthy kelp can be cut several times per year by commercial harvesters in California, where it is the basis for a $46 000 000-per-year industry. Kelp is also susceptible to environmental damage from storms, marine organisms, and sewage outfalls. Consequently, a monitoring program designed to measure areal extent, plant rigor, and biomass is an important element in the optimal use of this increasingly economic resource.

As a result of research conducted by John Estes, University of California, Santa Barbara, the ability of Landsat and high-altitude visible-sensing systems to monitor kelp has been documented; however, as is common along the west coasts of continents, the extensive and persistent occurrence of stratus clouds severely inhibits the use of such procedures. The Seasat SAR system, with 25-m resolution and all-weather capability, should significantly improve the ability to monitor this resource. The X-band imagery of the Santa Barbara coastline obtained during a flight by the U.S. Coast Guard has already demonstrated the effectiveness of microwave sensing systems for this application. Seasat will provide an optimum test bed for determining the feasibility of a worldwide kelp-monitoring system.

A somewhat related phenomenon is the vast coverage of parts of the tropical North Atlantic Ocean by Sargassum weed; the chief component of this coverage is normally referred to as the Sargasso Sea. The potential for gaining information on the structure dynamics and morphology of this little-understood area could be assessed by using SAR data.

The natural estuarine habitat is many times more food productive than farmland of equal area. Most food from the sea is directly or indirectly dependent on estuarine basic productivity, which in turn is a function of the amount of available marsh vegetation. The wetlands environment is easily stressed by coastal construction, by estuarine pollution, and even by improper operation of reservoirs upstream, all of which are controllable management activities. The entire coastal fisheries industry, both finfish and shellfish, is directly dependent on the proper maintenance of the estuarine ecology.

The periods of greatest plant production in the gulf coast wetlands occur at a time when clear weather periods are at an annual minimum; thus, radar imagery has relevance as a monitoring sensor.

A relatively unknown but extremely damaging natural phenomenon is the fairly recent proliferation of noxious aquatic plants in the reservoirs and waterways of much of the United States. Their effect is to increase evapotranspiration of water from reservoirs, block navigable channels, destroy waterfront property values, reduce or eliminate recreational potential, block the flow in irrigation canals, and provide an ideal habitat for insect vectors of such diseases as malaria, encephalitis, and filariasis. Florida, which now expends over $15 000 000 per year on aquatic plant control measures, experiences damages on the order of $100 000 000 per year from their continuing presence. Florida agencies find themselves unable to cope with the problem of monitoring the extent of infestation in the State's 10 000 km^2 (10^6 ha) of freshwater lakes.

Texas, now embarked on a mammoth reservoir construction program that will eventually produce a greater freshwater area than that of Florida, has recently experienced major outbreaks of noxious aquatic plant infestations. If unchecked, the waterhyacinth infestation alone could account for 100 million dollars' worth of unanticipated water losses per year through evapotranspiration.

Louisiana is estimated to have a greater infestation of aquatic weeds than either Florida or Texas, comprising an area on the order of 5000 km^2 (500 x 10^3 ha). Many of these infestations occur in relatively inaccessible areas and are therefore difficult to monitor.

In all three States, agencies responsible for aquatic plant control are not able to track the location and extent of the infested areas. Ground monitoring is not feasible. Seasonal aerial photographic monitoring is considered to be too expensive. Landsat monitoring is inhibited by clouds and by the relatively poor resolution of the available sensor. With Landsat MSS imagery, by the time the infestation is large enough to be discernable, the situation has already gotten out of control.

The application is ideal for the SAR. Imagery from SAR experiments over Central America shows the presence of aquatic plants with great clarity, as would be expected from the sensor's high resolution and excellent capability for detecting vegetation. The SAR could provide all-weather monitoring of aquatic plants with a resolution significantly better than that currently available from Landsat.

With SAR data on hand, the aquatic plant control program managers would, for once, have timely and accurate information on the location and extent of noxious aquatic plant outbreaks. They could thus direct their herbicide application efforts far more effectively than is now the case and reverse the established trend of steadily increasing total infestation (see table 3-14).

TABLE 3-14.- MONITORING OF AQUATIC VEGETATION

Item	Discourse
Objective	Use Seasat for monitoring large-scale occurrences of aquatic vegetation.
Seasat-A sensor requirement	SAR.
Potential test sites	Kelp: Calif., Santa Barbara Channel, where there are ongoing kelp studies; Wash., Rosario Strait, where there may be a critical interaction between tanker navigation and kelp bed presence; and the Sargasso Sea, where vast areas of Sargassum drift in the tropical Atlantic. Coastal marshes: Tex. - Aransas Pass area, Pass Cavallo area, and Colorado River Delta area, where seasonal aerial photography and intensive ground truth are used in ongoing studies. Noxious aquatic plants: Fla., Rodman Reservoir, where extensive tests of aquatic plant control methods are being made; La., lowlands bayous, where upwards of 5000 km^2 (500 x 10^3 ha) of waterhyacinth are proliferating; and Tex., Lake Livingston, where aerial photographic monitoring tests are being undertaken and where the Texas Parks and Wildlife Department is undertaking a major test of chemical control of <u>Hydrilla verticillata</u>.
Data volume requirements	Passes per site: two per season - all. Length: 100 km - all.
Supporting remote sensor data	Landsat data. Color-IR underflights - all except Sargasso. L-band imaging radar (concurrent) - all except Sargasso.
Ground data	Taxonomic and phycological field surveys.
Potential users of data output	Kelp: U.S. National Maritime and Fisheries Service (NMFS), Fleet Weather Service (FWS), Calif. Dept. of Fish and Game, Wash. Dept. of Commercial Harvesters. Coastal wetlands: NMFS, FWS, commercial fisheries, Tex. Water Development Board, USACE, Tex. General Land Office (Coastal Zone Management), NOAA (Office of Coastal Zone Management). Noxious plants: Fla. Dept. of Natural Resources, La. Wildlife and Fisheries Commission, Tex. Parks and Wildlife Dept., Tex. Water Development Board, USACE.

Water Resources Experiments

By 1978, there will have been several results involving active microwave ground-based and aircraft measurements that will need to be evaluated and compared to spaceborne SAR observations available from Seasat-A. These results will have demonstrated the potential capability of observing variations in soil moisture, surface-water extent (particularly during stormy or cloudy periods), and spatial variations in runoff potential from small watersheds. This opportunity for evaluating the utility of active microwave data by using Seasat-A must be seized for the following reasons.

1. Microwave has an apparently strong potential for providing the capability to observe the fundamental parameters noted previously.

2. The Seasat-A SAR data evaluation opportunity is the first such opportunity, and it may be the only one until 1980, when the first Shuttle engineering flights occur. It may be, perhaps, the only opportunity until 1982 or 1983, when the flight of the SIR system is planned to occur.

The following subsections describe experiments, test sites, and the significance of these activities. The plans were configured to coincide with as many other ongoing activities and research programs as possible to minimize duplication of effort. Overall, it is with great anticipation that these plans have been drafted because the potential is great for providing substantial evidences of the beneficial observations for water resources by using active microwave and passive microwave observations from Seasat-A.

Watershed runoff.- Watershed runoff information is important to water resource managers. Decisionmaking in the development and management of water resources is based, to a large extent, on mathematical models of varying complexity - e.g., the Generalized Stream Flow Simulation System, Stanford IV, Watershed Model and the SCS urban hydrology procedures. Few of the Nation's watersheds smaller than 500 km^2 have acceptable and reliable model input data owing largely to the time and costs associated with the acquisition of these data. A representative model that is used by the USDA, SCS, uses a single number or coefficient to represent the combined effects of soil type, land use, and antecedent moisture conditions. Although objectively specifying this coefficient is difficult, results from studies of passive microwave data indicate that it is possible by using passive microwave observations averaged over the total small-watershed area. These results are illustrated in figure 3-9. Because active microwave observations are sensitive to roughness, moisture, and soil properties, they will also be quite useful in this regard.

The panel believes that it is important to test the ability of the L-band SAR imaging system Seasat to provide this type of data.

To assess the ability of the Seasat SAR to provide data to indicate the runoff potential of watersheds, three major sites are suggested. In these cases, runoff potential determination will involve interpreting the microwave observations for variability in hydrologically related land use

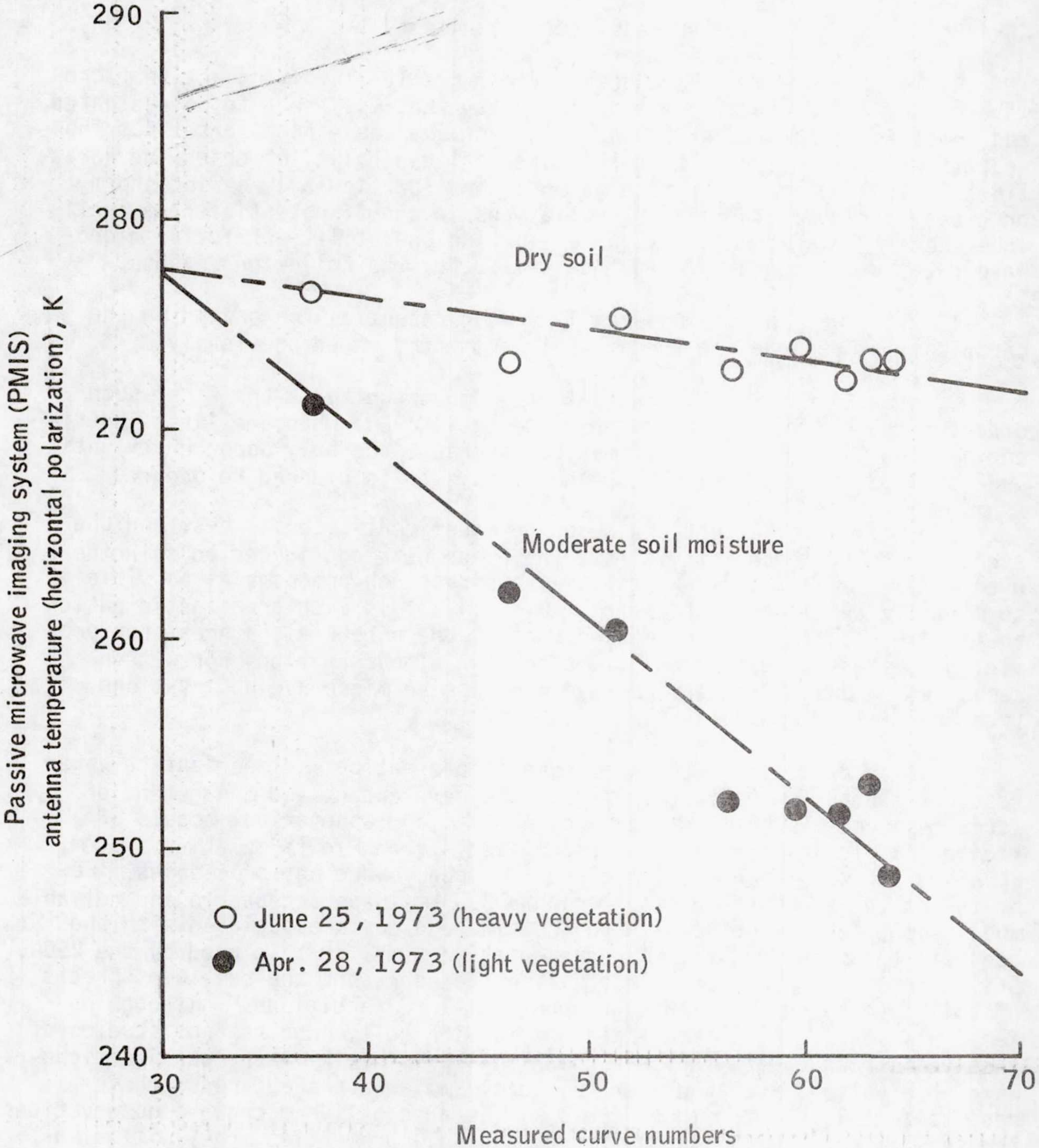


Figure 3-9.- Relationship between storm runoff (curve numbers) and microwave temperature.

(particularly related to imperviousness), soil type and permeability, vegetative cover, and soil moisture dynamics. The three areas suggested are as follows.

1. The Kern River watershed in southern California. This watershed is an analog test site to the Tashkent/Fergana Valley area of Soviet central Asia and affords a wide variety of surface cover, some snow cover, and moderate relief. These efforts would support one of the tasks of the Joint U.S./U.S.S.R. Working Group on the National Environment.

2. The southern Oklahoma-northern Texas area, including subareas near Chickasha, Oklahoma, and Waco and Refugio, Texas. The principal emphasis will be on objectively specifying runoff coefficients for small agricultural watersheds; but also, and in complementary fashion, the ability to monitor soil moisture in the watershed runoff prediction context will be assessed.

3. The Patuxent River watershed in Maryland. This watershed offers a wide variety of land use, heavy vegetative cover, and a substantial percentage of urban area.

In each of the test areas, considerable research has been or is being conducted as to the capabilities and limitations of remote sensor data in providing information related to watershed runoff potential. Should such analysis prove successful, in that pertinent information related to runoff potential is provided, these data should enable the SCS of the USDA, for example, to more accurately and quickly acquire runoff coefficients and help perform the approximately 1000 design studies that are in progress each year for the construction of flood control structures on small watersheds.

In addition to experiments conducted at the sites previously discussed, members of the Water Resources Subpanel believe that an assessment should be made of the feasibility of monitoring soil moisture variability over large regions by using the SMMR on Seasat. As previously stated, a considerable body of evidence exists detailing the capability of passive microwave systems to provide data relative to soil moisture conditions. To assess the Seasat SMMR capabilities in this area, it is suggested that the experiments be conducted in areas such as the southern High Plains of Texas, the Great Basin area west of Salt Lake City, and the lower Mississippi Valley. Successful and useful observations have been acquired for these areas with the Nimbus-5 electronically scanning microwave radiometer (ESMR) and the S193 and experiments on Skylab. Data from such experiments would be of interest to a wide variety of users (see table 3-15).

Concurrently with the SMMR experiment over the Salt Lake Desert, the SAR data would be used to determine the capability of the L-band radar to detect and map saline and moisture content in a desert playa. The water table in the Salt Lake Desert is about 1 m below the surface. Previous radar scatterometry experiments on Skylab succeeded in detecting high-moisture areas.

TABLE 3-15.- WATERSHED RUNOFF

Item	Discourse
Objective	To determine the capability of the Seasat-A sensor complement to provide data inputs to hydrologic models of use in assessing the runoff potential of watershed.
Seasat-A sensor requirements	SAR, SMMR, and VIR.
Potential test sites	SAR experiment: Kern River watershed, Kern County, Calif. Washita River Basin near Chickasha, Okla., and small watershed areas near Waco and Refugio, Tex. Patuxent River watershed, Md. SMMR experiment: Southern High Plains, Tex. Great Basin area west over Salt Lake City. Lower Mississippi Valley.
Data volume requirements	Passes per site: three to four per year. Pass length: average, 241.4 to 321.9 km (150 to 200 miles) per site. For the SAR, a 300-km path twice a year over the Salt Lake Desert is required; one path in Aug. and one in Dec.
Supporting remote sensor data	Landsat data. High-altitude aerial photography, 1:60 000 or 1:120 000. Aircraft radiometers: MFMR, PMIS. Imaging radar: L-band, C-band. Aircraft scatterometers: 0.4, 1.6, and 13.3 GHz.
Ground data	Field data: soil moisture, rainfall, etc. Truck-based systems: MAS, MSAS. PRT-5.
Potential users of data output	USDA SCS/USFS, public and private utility companies, commercial companies, regional and local water districts, NOAA, USACE, USGS, USBR, Bonneville Power Admin., Tenn. Valley Authority, etc.
Significance	These data are of value in determining the need for the construction of flood control structures and could be used in watershed and reservoir management. These data are useful for monitoring the saline content of a playa desert.

Surface-water/flood mapping.- Floods are major environmental hazards. Each year, lives are lost and property is damaged or destroyed. Individuals involved in disaster assessment and relief operations need timely, accurate information concerning the extent and severity of flood conditions. Often, these data are difficult to obtain owing to the presence of cloud cover. It has been estimated that flooding takes place almost weekly somewhere in the world. The nature of such events, however, precludes the selection of specific test sites and instead requires the adoption of the potential for including targets of opportunity within the Seasat mission-planning profile. The panel understands that this capability has been identified as significant by the Seasat SAR Team and that the Seasat Mission Design Team is currently working on this problem. This effort is strongly encouraged.

The ability to monitor flooding could be accomplished through the monitoring of U.S. rice-growing areas in the springtime, before vegetation covers the water (e.g., central Louisiana, the Texas gulf coast, and central Sacramento Valley, California). Monitoring of rice areas has the added advantage of providing data relative to an agricultural crop that is the basic staple in the diet of 90 percent of the world's population. In addition, the signature variation that will occur in these areas with vegetation growth and drainage will occur within a time frame and over a range of longitudes that appears appropriate to ensure coverage, on the basis of Seasat's projected orbital characteristics (see table 3-16).

Snow mapping.- The melting of snow in a majority of the watersheds in the western United States provides the most important portion of the total runoff. This runoff occurs over a relatively short period of time in the spring. Analyses and applications of satellite snow-cover observations from Landsat and NOAA satellites have demonstrated their contribution for improved management of snowpack runoff. However, the more fundamental observation of snowpack moisture equivalent and wetness would obviously contribute to better snowpack runoff forecasts by providing a more complete measure of the volume of water stored in the snowpack rather than an index of this quantity gathered from a few point measurements or measurements of snow-cover area. The microwave system would allow observations to be made through the cloud cover that persists most notably in the Pacific Northwest, where hydroelectric power generation is prevalent, and in Alaska.

Radar images have been acquired that show that there is potential for snowpack monitoring, and theoretical studies show the sensitivity of backscatter observations to variations in snowpack wetness. However, much more analysis of active and passive microwave observations needs to be accomplished to establish the potential in this area (Salomonson, in ref. 3-2; ref. 3-1). It would appear that the level of utility of successful observations would certainly justify such an effort (see table 3-17). It is recognized that the long wavelength of the Seasat SAR may be inappropriate for this application; however, an evaluation of these data is warranted because of the importance of the topic.

Alaskan lakes mapping.- During the winter season, the shallow lakes on the northern and western coasts of Alaska freeze at the top. The top ice layer is approximately 1 to 2 m thick. Because of the shallow depth,

TABLE 3-16.- SURFACE-WATER/FLOOD MAPPING

Item	Discourse
Objective	To assess the potential of the Seasat sensor compliment to provide data/ information to resource managers concerned with relief operations and disaster assessment.
Seasat-A sensor requirements	SAR, SMMR, and VIR.
Potential test sites	Target of opportunity. Rice areas: Central La. Tex. gulf coast near Houston. Central Sacramento Valley, Calif.
Data volume requirements	Passes per site: two to three per event. Pass length per site: 40.2 to 80.5 km (25 to 50 miles).
Supporting remote sensor data	High-altitude aerial photography, 1:60 000/1:120 000.
Ground data	Field verification of ground scene features. Water depth information. Land-water boundaries.
Potential users of data output	USACE, USGS, HUD, local water and flood control districts.
Significance	Rapid assessment of areas of environmental disruption and the potential for speeding information - discriminate and status briefings - for rescue relief and rehabilitation make this an important application area.

TABLE 3-17.- SNOW MAPPING

Item	Discourse
Objective	This experiment is designed to assess the information content of the L-band SAR and SMMR instrumentation for monitoring snow cover and snowpack moisture content and liquid-water content. The purpose of this effort is to provide improved input for watershed runoff estimates, which will lend toward improved reservoir management for hydroelectric power generation, irrigation, flood control, recreation, etc.
Seasat-A sensor requirements	SAR, SMMR, and radar altimeter.
Potential test sites	Mountainous areas (prioritized): The central Sierra Nevada Mts. near the CSSL. Steamboat Springs, Colo. Wind River Mts., Wyo. Great Plains areas (prioritized): Luverne, Minn., site. Upper Missouri River Basin.
Data volume requirements	Four passes per site during the winter/spring snowmelt season would be desirable. At least two passes are necessary (Mar.-May period). Passes over the sites with each instrument on the following basis: 100 km long, with SAR. 200 to 500 km, with SMMR. 200 to 500 km, with radar altimeter.
Supporting remote sensor data	Concurrent flights with the L-band imager, the SMMR simulator, and the L-band radiometer on the Convair 990, plus documentation photography. Concurrent flights with C-130 or P-3 microwave instrumentation would be desirable as resources permit.
Ground data	Concurrent measurements of depth, moisture content, wetness, etc. Use should be made wherever possible of snow-profiling gages and the snow wetness/microwave, ground-based instrumentation.
Potential users of data output	USDA/USFS; USDA/SCS; USACE; NOAA/U.S. National Weather Service/River Forecast Service; Snow Surveys Branch, State of Calif.; State of Calif. Water Resources Control Board; Bonneville Power Administration.
Significance	If a capability to measure wetness and water equivalent can be developed that is accurate to $\pm$ 10 to 15 percent at a given point, the high observational density afforded by satellite sensors will combine to provide a capability that is a significant (in terms of cost effectiveness and benefit) improvement over existing conventional systems.

some of these lakes freeze to the bottom. The L-band imaging radar, because of its capability to penetrate through fresh ice, can detect the presence of liquid water below the frozen layer. This capability is a result of the fact that the ice-water interface will reflect the electromagnetic wave much more than the ice-sediment interface, which corresponds to the areas where frozen ice reaches the bottom. This concept has been verified with the JPL L-band imaging radar.

There are two major applications: (1) These lakes are used as a source of freshwater in the winter season and (2) these lakes will be used as landing strips for large cargo aircraft, especially in the northwest region, where large oil deposits are located. It is critical to know which lakes are frozen to the bottom and thus can be used as landing strips. The Seasat radar can be used on an operational basis to map these lakes (see table 3-18).

Geology Experiments

Short wavelength (Ka- and X-band) side-looking aperture radar (SLAR) systems are established reconnaissance tools for the geologic mapping of areas where clouds or daylight conditions limit the operation of cameras and other visible-spectrum remote-sensing techniques. However, the geological utility of longer wavelength systems has been essentially ignored. Most of the demonstrated geologic applications of radar imagery have, in fact, publicized operational advantages rather than any unique information contained in the microwave spectrum. More importantly, very little research effort has been devoted to assessing the geological value of multispectral radar images, a technique that has received wide acceptance in the analysis of data from visible-spectrum sensors. Seasat SAR land-geology experiments can provide an important initial step in the ultimate design and experimental development of a multifrequency, multipolarization, free-flyer radar system that would satisfy a wide variety of geological requirements.

Seasat SAR imagery can be expected to provide minimal shadowing of subtle terrain features because of the relatively steep depression angles; and consequently, the detection of many geologic phenomena will be dependent on surface configuration and dielectric properties. Surface roughness (in both vegetated and nonvegetated areas) is expected to provide a significant contribution to the radar return signal. This roughness or texture sensitivity of the return signal adds another dimension to discrimination in cases wherein another sensor can provide information regarding homogeneity of material.

The proposed experiments have been assigned priorities based on (1) the liklihood of microwave applicability not previously possible through other systems, (2) the most immediate economic and/or scientific benefit, and (3) the contribution to the verification of design parameters for a Shuttle imaging radar and/or free flyer.

Because the proposed four-station reception of data corresponds to coverage of North America only, Alaska has emerged as a geologically unique area where the likelihood of immediate applicability may be greatest. The choice of the other experimental sites is based on a proof-of-concept testing

TABLE 3-18.- ALASKAN LAKES MAPPING

Item	Discourse
Objective	Map Alaskan lakes during the winter and determine which ones are frozen to the bottom and which ones are not.
Seasat-A sensor requirement	SAR.
Potential test sites	North Alaskan slope (Arctic coast). Bethel region, Alaska. Koyukuk region, Alaska. Mackenzie River Delta (Canada).
Data volume requirements	One path in Jan., one path in Mar. or early Apr.
Supporting remote sensor data	One underflight is desirable.
Ground data	Ground truth in a sample of 10 to 12 lakes of different sizes, simultaneously with overflight.
Potential users of data output	Department of Interior - for freshwater sources in winter. Oil companies, Navy - for use of frozen lakes as landing strips.
Significance	The classification of lakes in two categories, frozen to the bottom and not frozen to the bottom, would determine the lakes that can be used as landing strips for cargo aircraft and as sources of freshwater in the winter season.

to coincide with ongoing research activities in the greatest variety of terrain/geological environments.

Test site priorities (H, M, and L) are based on geological uniqueness in relation to Seasat SAR potential and usefulness of data. High-priority experiments are described in tables contained in the next eight subsections, medium-priority experiments in tables contained in the two subsequent subsections, and low-priority experiments in tables contained in the last four subsections. The objective of the Seasat SAR geology experiments is definition of the microwave parameters that are appropriate to particular geological problems; success therein may ultimately lead to the development of radar image products that more directly lend themselves to geological analysis.

Placer Gold Belt mapping.- This experiment is designed to test the capability of Seasat SAR imagery to provide data on the location of gold-bearing gravel deposits in the interior of Alaska. Mapping of these extensive gravel deposits has not been accomplished. Seasat SAR should be an ideal data source for gravel mapping because of its ability to provide high-quality, high-resolution image data under conditions of poor illumination or during periods of inclement weather. Gold reserve known to be associated with the gravels and the great need for gravel in an area where large construction projects are underway and planned are evidence of the economic importance in estimating these gravel reserves. The goal of this experiment is to provide a map of these deposits with the location of bedrock areas and potential placer deposits indicated (see table 3-19).

Assessment of glacial ice dynamics.- Glaciers contain a large amount of the world's freshwater supply. In addition, glaciers provide sensitive indicators of variations in global climatic conditions. Because of severe weather, low angles of solar illumination limiting the practicability of most remote sensor systems, and light snow cover on rocks, active microwave sensors are needed for the study of the massive glacial ice deposits in southeastern Alaska. The Seasat L-band SAR system should be capable of delineating these ice masses.

Mapping of the extent and structure of the large glaciers and icefields in the Chugach and St. Elias Mountain Ranges, Alaska, is important for estimating freshwater storage of the region. Also, it is important for determining possible hazards that glacial surges would pose to the proposed oil and gas development of the Yakataga and Yakutat oilfields, and for determining ice hazards to the tanker traffic of Prince William Sound and Yakutat Bay (see table 3-20).

Mineral and petroleum exploration.- Exploration methods used during the past two decades are inadequate for providing new reserves that will exceed the present consumption rate of mineral and petroleum products. Although an integrated exploration concept would take advantage of a host of exploration techniques, radar remote sensing such as that provided by Seasat SAR holds promise for revealing new areas of exploration potential (see table 3-21).

TABLE 3-19.- PLACER GOLD BELT MAPPING

Item	Discourse
Objective	Delineate and map the gold-bearing gravel deposits of interior Alaska. Present knowledge of these economically significant deposits is limited because of poor lighting, weather conditions, and snow cover.
Seasat-A sensor requirement	SAR imagery.
Potential test site	Placer Gold Belt of interior Alaska.
Data volume requirements	Passes per site: two to four per year. Length of site: 1150 km. Area of site: 115 000 km^2.
Supporting remote sensor data	Landsat data and possible low-altitude-aircraft data.
Ground data	Limited field information; extent of deposits unknown.
Potential users of data output	Pipeline companies, mineral industries, Alaska State Geological Survey, USGS, BLM, Alaska State Highway Dept.
Significance	Mapping of the extensive gravel deposits of interior Alaska has not been done. Yet, it is of great economic importance that the gravel reserves be estimated because of the gold reserve associated with the gravels and the great need for gravel in an area where large construction projects are underway and planned. The Seasat SAR should be an ideal data source for gravel mapping. Assist in mapping extent of relatively unknown deposits.

TABLE 3-20.- ASSESSMENT OF GLACIAL ICE DYNAMICS

Item	Discourse
Objective	To study the massive glacial ice deposits of the icefields and the mountain ranges in areas that have persistent cloud cover, low Sun, and snow cover.
Seasat-A sensor requirement	SAR imagery.
Potential test site	Glaciers of southeastern Alaska.
Data volume requirements	Passes per site: one to two per year. Length of site: 850 km. Area of site: 85 000 km^2.
Supporting remote sensor data	Landsat data.
Ground data	Published fieldwork.
Potential users of data output	Oil and gas companies, USFS, USGS, BLM, Coast Guard/NOAA.
Significance	Mapping of the extent and structure of the large glaciers and icefields in the Chugach and St. Elias Mountain Ranges to estimate freshwater storage of the region and to determine possible hazards that glacial surges would pose to the proposed oil and gas development of the Yakataga and Yakutat oilfields. Determining ice hazards to the tanker traffic in Prince William Sound and Yakutat Bay.

TABLE 3-21.- MINERAL AND PETROLEUM EXPLORATION

Item	Discourse
Objective	Evaluate the utility of Seasat SAR imagery interfaced with MSS imagery for mineral and petroleum exploration in heavily forested terrain having relatively complex geology with surface structure related to subsurface structure. Radar applicability to be evaluated includes viewing angle, vegetation penetration, temporal aspect, effect of snow cover, and compatibility with Landsat data.
Seasat-A sensor requirement	SAR imagery.
Potential test site	Arkoma Basin, central Ark.
Data volume requirements	SAR, near-coincident with Landsat, seasonal coverage. Ascending and descending passes.
Supporting remote sensor data	Underflight coverage with shorter wavelength systems would be helpful but not necessary. Underflight with JPL L-band and NASA 102 systems requested.
Ground data	Reconnaissance of terrain and vegetation conditions at time of overflight.
Potential users of data output	Mineral and petroleum exploration companies, U.S. Bureau of Mines, USGS, State geological agencies, Ark. Geological Commission.
Significance	Long-wavelength radar data to be evaluated as a unique or supplemental tool for petroleum and mineral exploration. Provide geologists with an additional exploration tool for structural mapping. Assist geological mapping in relatively unmapped regions. The study area has relatively complex geology, with surface structures related to subsurface petroleum production. Long-wavelength radar data to be evaluated as a unique or supplemental tool for petroleum and mineral exploration. Central Ark. is ideally suited for evaluating the "penetration" capability of longer wavelength SAR systems.

The Landsat and Skylab programs have demonstrated conclusively the utility of spacecraft data for mineral and petroleum exploration. The exploration utility of a long-wavelength SAR system has not been proven, and the central Arkansas test site is ideal for an evaluation of SAR data in heavily forested terrain. The test site is masked with a cover of deciduous, conifer, and mixed forest areas. Beneath this canopy are complex surface structures that, in many cases, are related to petroleum production. A new technique for mapping previously unrecognized surface structures would provide the petroleum geologist with an important exploration technique.

Seasat SAR, being an active system, provides its own source of illumination and does not measure diurnal changes in the radiation emitted or reflected from the Earth's surface. This relative independence from time of day and weather may be a particularly important advantage for geological interpretation, especially for the detection of lineaments that are highly dependent on such parameters as viewing angle, look direction, radar frequency, vegetation penetration, temporal aspect, terrain roughness, soil moisture, snow cover, etc. The use of Seasat SAR data in conjunction with Landsat data holds a potential for improving terrain landform discrimination, an accomplishment that would be an important contribution to the mineral and petroleum phase of geological exploration.

Geomorphic mapping in coastal wetlands and marshes.- Coastal wetlands and marshes provide the locations for many highly productive oilfields and gasfields, especially salt domes. The expression of geological structure at the surface is so slight that the traditional use of a low incident angle of illumination for relief enhancement is not practical. Coastal geomorphic analysis to define petroleum prospects in coastal marsh and swamp terrains involves detailed examination of drainage patterns and texture and gross determination of plant community spatial relationships. The interpretation of physiographic features, coupled with the creation of vegetation maps and the measurement of primary food-chain production over large areas of the tidal marsh, would be especially useful to ecologists and other scientists. Seasat SAR provides a unique opportunity for examining the regional fabric of coastal marsh and wetlands. Local departures from the regional pattern would be considered anomalies, warranting further investigation. Because of the relatively steep depression angle used, the L-band imagery may provide a data format that will be a valuable supplement to imagery sources such as Landsat.

The Atchafalaya Basin in Louisiana provides a test site where oilfields and gasfields are sometimes defined by subtle changes in drainage, contrasting plant communities, and subtle terrain texture changes. This experiment test site provides for an abundance of ground-truth data where considerable remote-sensing data have already been acquired. The experiment design calls for using Seasat SAR imagery as both a unique and supplemental data source for terrain interpretation. As such, it will ultimately contribute to petroleum exploration in these low-relief environments.

Seasat SAR parameters such as viewing angle, look direction, vegetation penetration, and temporal changes in terrain conditions will be evaluated according to the detectability of geomorphic features (see table 3-22).

TABLE 3-22.- GEOMORPHIC MAPPING IN COASTAL WETLANDS AND MARSHES

Item	Discourse
Objective	Demonstrate the applicability of Seasat SAR imagery for geomorphic analysis (mineral and petroleum exploration) in coastal marsh and swamp environments, where the expression of relief is defined by drainage patterns, contrasting plant community associations, and subtle terrain texture changes.
Seasat-A sensor requirement	SAR imagery.
Potential test site	Atchafalaya Basin, La.
Data volume requirements	SAR, near-coincident Landsat, seasonal coverage.
Supporting remote sensor data	Short-wavelength (Ka- and X-band) coverage would be necessary.
Ground data	Existing terrain and vegetation conditions at time of overflight.
Potential users of data output	Industry exploration geologists, wetland ecologists, hydrologists, USACE, USGS, coastal geomorphologists.
Significance	Assist in coastal mapping of high-cloud-cover regions. Aid in the detection of salt domes in low-relief areas. Provide an indication as to the utility of Landsat and Seasat SAR for coastal geomorphic definition. The expression of relief in the coastal marsh and swamp is so slight and the SAR depression angle so steep that the use of subtle shadowing for relief enhancement is not practical. Analysis of drainage patterns can sometimes offer a very sensitive indicator of small relief changes and thus the underlying structure. The steep SAR depression angle may provide an effective technique for rereading the surface expression of salt domes.

Land subsidence detection.- This experiment is designed to detect areas of subsidence caused by potash mining, natural saline seeps, and subcrop position of the potash-hosting Salado Formation.

The test site for this study is well documented and sparsely vegetated and provides a number of other geologic/mineral occurrences. It is underlain by producing oilfields and is currently under investigation as a site for radioactive waste disposal in the Permian salt deposits found in the area.

Domestic exploration for potash is a necessity because of the political and logistical sensitivity associated with this high-volume/low-value essential commodity. Recognition of distinctive subcropping occurrences of the soluble minerals mentioned could provide a valuable tool for exploration. It is anticipated that Seasat SAR imagery will provide data that can aid in the identification and mapping of the subcrop positions (see table 3-23).

Discrimination of hydrothermal alteration.- The experiment will test the capability of L-band systems to discriminate among types of hydrothermal alteration on the basis of surface morphological characteristics. More importantly, a test will be made of the separability of altered units and alluvium.

Landsat data are being used to separate out areas of hydrothermal alteration as potential exploration sites. However, many alluvial areas falsely register as areas of hydrothermally altered rocks. A separation should be possible based on surface scattering characteristics. This experiment has a reasonably high probability of success (see table 3-24).

Discrimination of construction materials.- Gravel and sand deposits and similar construction materials are in extremely short supply in many parts of the United States. Especially in heavily vegetated flood plains, the delineation of construction materials is difficult because of a vegetation canopy, masking by soils, or man's activities related to agricultural land use. Seasat SAR imagery interpretation may provide a new technique for finding these deposits, whose hard-mineral dollar value in the United States is only exceeded by that of coal.

The overall design of the experiment is to evaluate Seasat SAR as a unique or supplemental remote sensor data source for discriminating subtle terrain texture change. The northern Boeuf-Tensas Basin in the lower Mississippi Valley provides a test site ideally suited for Seasat SAR evaluation. The USACE has done considerable geologic and soils mapping in the area; and, as a consequence, the need for extensive ground truth is minimized.

Seasat SAR parameters such as viewing angle, look direction, vegetation penetration, and temporal changes in terrain conditions will be evaluated according to the detectability of sand and gravel deposits (see table 3-25).

Discrimination of terrain roughness and texture.- It is known that radar shadowing enhances such geologic features as joint systems, faults, and folded strata. However, terrain roughness-texture properties as seen

TABLE 3-23.- LAND SUBSIDENCE DETECTION

Item	Discourse
Objective	Detection of areas of subsidence caused by potash mining, natural saline seeps, and subcrop position of the potash-hosting Salado Formation in a district that is underlain by producing oilfields and is currently under investigation as a site for radioactive waste disposal in the Permian salt deposits found in the area.
Seasat-A sensor requirement	SAR imagery.
Potential test site	Carlsbad Mining District, 16.1 to 48.3 km (10 to 30 miles) east of Carlsbad, N. Mex.
Data volume requirements	Site passes: two per year.
Supporting remote sensor data	Imaging radar (X-band) and Landsat.
Ground data	Environmental Analysis Report completed 1976. Terrain conditions at time of overflight.
Potential users of data output	Industry, Governmental agencies.
Significance	Domestic exploration for potash is a necessity because of the political and logistical sensitivity associated with this high-volume/low-value essential commodity. The experiment site is well documented and sparsely vegetated and provides the other geologic/mineral occurrences cited above. Recognition of distinctive subcropping occurrences of these soluble minerals could provide a valuable tool for exploration.

TABLE 3-24.- DISCRIMINATION OF HYDROTHERMAL ALTERATION

Item	Discourse
Objective	Separation of alluvium and outcrop in areas of hydrothermal alteration and separation of alteration types as a means of targeting likely areas for detailed mineral exploration.
Seasat-A sensor requirement	SAR imagery.
Potential test sites	Virginia Range (Reno, Nev.); Goldfield, Nev.
Data volume requirements	Passes per site: two. Length: 50 km each.
Supporting remote sensor data	Preflight aircraft coverage, Landsat, color airphotos in stereo.
Ground data	Particle size measurements, soil moisture.
Potential users of data output	Mineral exploration industry.
Significance	With present Landsat data, alluvial areas cannot be separated from outcrops of hydrothermally altered rocks; however, SAR imagery textural discrimination may provide the necessary signature. Alteration is used in mineral exploration as a means of targeting likely areas for undertaking ground geological and geophysical work. Because present Landsat data do not enable separation of alluvial areas from outcrops of hydrothermally altered rocks, many false alarms are generated. Separation of the types of alteration - for instance, silicon versus argillic or chloritic - has bearing on the exploration process. These types may be separable by their weathering patterns.

TABLE 3-25.- DISCRIMINATION OF CONSTRUCTION MATERIALS

Item	Discourse
Objective	Determine applicability of using SAR radar imagery to detect construction materials (sand/gravel) in typical alluvial environments (textural discrimination of actual deposits or their geomorphic expression).
Seasat-A sensor requirement	SAR imagery.
Potential test site	Alluvial flood plain of Mississippi River near Memphis, Tenn., where Seasat orbit nearly matches Landsat orbit.
Data volume requirements	SAR two-season coverage; near-coincident Landsat coverage.
Supporting remote sensor data	Short-wavelength (Ka- or X-band) underflight would be helpful.
Ground data	Terrain and vegetation conditions at time of underflight.
Potential users of data output	USGS; USACE; Federal, State, and local construction companies.
Significance	Gravel and sand deposits and other construction materials are in extremely short supply in many parts of the United States. SAR imagery interpretation may provide a new technique for finding new supplies of these hard-mineral deposits, whose dollar value in the United States is only exceeded by that of coal. In addition, the test site selected for this analysis is located in an area of high agricultural productivity that is subjected to seasonal flooding. By following the site through time, it may be possible to gain important insights into the capabilities of space imaging radar for several types of investigations.

on SAR images also need to be evaluated. This experiment will provide for this evaluation, as well as for derivation and comparison scattering models.

The Death Valley, California, test site is perhaps the best documented natural test site yet investigated for roughness backscatter modeling of radar return. Extensive studies have been done in this area, especially in detailed roughness mapping (see table 3-26).

Discrimination of geologic structure in areas of low relief.- This experiment is designed to determine the utility of SAR for revealing subtle geologic structure in low-relief, forested areas such as the Eastern Coastal Plain. Nuclear reactor powerplants have been built, and many more may be constructed along the Eastern Coastal Plain. Although this area is not considered to be an active earthquake zone, major historical earthquakes have occurred along a band stretching from Cape Ann, Massachusetts, to Charleston, South Carolina. Radar shadowing emphasizes geologic features and irregularities on the Earth's surface; terrain morphology, from which structural or geologic inferences can be made, is depicted more starkly than on photography. As a result, SAR image analysis is a potential means for providing a better understanding of the tectonic character of a region. In this experiment, various cosmetic, filtering, and band-stretching image enhancement techniques will also be evaluated. It is hoped that the results of this experiment will provide the proof of concept for the use of SAR data to provide information on the morphology of the terrain in areas of low relief, information that may lead to improved assessments of the geologic hazards in such areas (see table 3-27).

Evaluation of Arctic coastal ice structure and dynamics.- Alaska has approximately 53 000 km of coastline, over half of which is affected by ice most of the year. Surrounding this lengthy coastline are approximately 1.5 Mm^2 (150 x 10^6 ha) of continental shelf potentially exploitable through construction of offshore facilities. Climatically, Alaska is a prima facie case for radar monitoring, with severe weather and low angles of solar illumination limiting the practicability of most remote sensor systems. Fieldwork is typically difficult and hazardous. The discoveries of oil on Alaska's north slope have increased our Nation's potential for greater energy independence. However, because of heightened environmental awareness, these discoveries have generated controversy about the potential environmental disruption associated with exploiting these resources. Timely, accurate information is required to inventory critical resources and monitor this development to minimize or eliminate potential adverse environmental impacts. This experiment will focus on only one critical parameter affecting the ability to maximize the potential benefits to be derived from this important resource - i.e., the monitoring of Alaskan coastal ice structure and dynamics (see table 3-28).

Evaluation of high-relief terrain.- This experiment will test the advantages in using high-angle L-band radar to map surface geologic units in mountainous terrain.

Seasat will provide high-angle L-band radar images of land areas. These data will be of little value in enhancing subtle topographic features. However, in mountainous terrain, high-angle illumination is required to

TABLE 3-26.- DISCRIMINATION OF TERRAIN ROUGHNESS AND TEXTURE

Item	Discourse
Objectives	Evaluation of terrain roughness-texture properties as defined by SAR. Derivation and comparison scattering models from SLAR image data.
Seasat-A sensor requirements	SAR imagery, scatterometer, radar altimeter, and microwave radiometer.
Potential test site	Death Valley, Calif.
Data volume requirements	Four passes total, which would cover all of Death Valley: two ascending passes, one in June/July period and one in Feb./Mar. period; two descending passes, one in June/July period and one in Feb./Mar. period.
Supporting remote sensor data	Aircraft underflights with the JPL L-band radar are required.
Ground data	Complete ongoing effort by G. Schaber (USGS, Flagstaff) for detailed roughness mapping of the Valley, in situ field measurements at time of overflight.
Potential users of data output	Researchers in roughness modeling.
Significance	Proof of concept for terrain texture discrimination. Because of extensive studies in the area, the Death Valley test site is perhaps the best documented natural test site yet investigated for roughness backscatter modeling of radar return.

TABLE 3-27.- DISCRIMINATION OF GEOLOGIC STRUCTURE IN AREAS OF LOW RELIEF

Item	Discourse
Objective	Determine utility of SAR for revealing subtle geologic structure in low-relief, forested areas such as the Eastern Coastal Plain. Various cosmetic, filtering, and band-stretching image enhancement techniques will be evaluated.
Seasat-A sensor requirement	SAR imagery.
Potential test sites	Sites under extensive study by the USGS and others in the reactor hazards program.
Data volume requirements	Two-season coverage, near-coincident Landsat coverage.
Supporting remote sensor data	Short-wavelength (Ka- and X-band) data would be helpful but are not necessary. JPL L-band coverage is requested.
Ground data	Extensive mapping provided by USGS.
Potential users of data output	USGS, State surveys, exploration geologists.
Significance	Nuclear reactor powerplants have been built, and many more may be constructed along the Eastern Coastal Plain. Although this area is not considered to be an active earthquake zone, major historical earthquakes have occurred along a band stretching from Cape Ann, Mass., to Charleston, S.C. SAR image analysis may yield a better understanding of the tectonic character of the region.

TABLE 3-28.- EVALUATION OF ARCTIC COASTAL ICE STRUCTURE AND DYNAMICS

Item	Discourse
Objective	To study ice structure near the coast during the Arctic night.
Seasat-A sensor requirement	SAR imagery.
Potential test site	Arctic Ocean coastal ice.
Data volume requirements	Passes per site: two to four per year, winter and summer. Length of site: 800 km. Area of site: 80 000 km^2.
Supporting remote sensor data	Aircraft-borne radar; suggest aircraft underflights.
Potential users of data output	Oil and gas companies, Navy, Coast Guard/NOAA.
Significance	Coastal ice cannot be studied because of darkness and/or cloudy conditions throughout much of the year. Oil and gas development has begun here and will continue for the next 15 to 20 yr. The unique ability of the Seasat SAR to obtain data during the Arctic night will be a great help in studying ice conditions.

image the surface. Low-angle illumination, common to existing radars, creates shadows in these areas.

Seasat will provide the first high-angle radar data available for geologic mapping. These data may help in discriminating geologic units in rough terrain because of the effect of surface characteristics on the L-band return signal (see table 3-29).

Linear assessment.- State and Federal agencies charged with the responsibility for siting nuclear power generating facilities are extremely interested in techniques that can improve the assessment of the geologic hazard that may exist in a given area. These agencies, together with other user groups with responsibilities for site evaluation for construction projects, are particularly concerned with faulting - especially that which has occurred in Holocene times - in regions where construction of nuclear powerplants is proposed. This experiment is designed to evaluate Seasat SAR imagery for the detection, identification, and mapping of linear - and to a lesser degree, circular - trends previously mapped in field studies. SAR imagery interpretation may provide a signficant data input by means of textural discrimination of geomorphically expressed structural units (see table 3-30). Demonstration of potential in this important area would be of significant benefit to a wide variety of users. It should be emphasized that the mapping of linears can provide clues to the location of mineral deposits.

Midcontinent base metals exploration.- An opportunity exists to provide a tool to aid base metal exploration - particularly, domestic - in the continuing search for nonoutcropping ore deposits. In the experiment, an evaluation of "blind" mining districts will be performed on Seasat SAR imagery. The capability of SAR systems to provide data on these districts could have considerable economic impact.

The U.S. production from Mississippi Valley-type deposits such as those in Tennessee and Missouri was valued at $243 million in 1973. In central Tennessee, deposits are largely undeveloped and occur at depths ranging from 300 to 1000 m. Solution-collapse breccias are hosts to mineralization and can possibly be detected as curvilinears at the surface. Stressed vegetation (retarded by metal ion content in soil or enhanced by moisture increase) may be detectable over such areas. In southeast Missouri, a discontinuous mineral trend approximately 100 km in length and 1.6 km in width has been under development and mined since 1958. This completely blind occurrence on the west side of the Ozarks Precambrian high is a more deeply buried extension of the nearer surface occurrences mined approximately 100 km to the east for more than 100 years. No direct, surface geophysical expression of the west side Viburnum trend has ever been recorded. The ore in Missouri has a greater variety of occurrences than that in Tennessee. However, the two areas provide an almost complete range that is representative of Mississippi Valley-type deposits (see table 3-31).

Sulphur deposit exploration.- Geologic structures and irregularities can be detected on radar imagery. In this experiment, the ability of Seasat SAR to define large petroliferous or paleopetroliferous environments by detecting structural changes associated with low-porosity capping rock that typifies the centers of such areas from the surrounding less-porous rock will be tested.

TABLE 3-29.- EVALUATION OF HIGH-RELIEF TERRAIN

Item	Discourse
Objective	Evaluation of steep depression angle SAR imagery in rough terrain, high-relief areas of mineral exploration, where conventional photography is often useless because of cloud cover or poor illumination.
Seasat-A sensor requirement	SAR imagery.
Potential test site	Colorado Mineral Belt, Eastern Front Range, Colo.
Data volume requirements	One pass, 300 km.
Supporting remote sensor data	Aircraft photography. Aircraft SLAR 16.1-km (10 mile) strip, near-coincident Landsat coverage.
Ground data	Mineral and mine maps, provided by the USGS and exploration companies.
Potential users of data output	Mineral explorationists.
Significance	The unique high-angle illumination from Seasat SAR will provide a different view, potentially with which to map morphological and texture features on the slopes. Assist in defining optimum SAR depression angles for optimum geological data analysis. Provide an improved method for mineral exploration programing. In rugged terrain, aircraft photography and airborne radar become difficult to interpret because of the steep and often-shaded slopes. The unique high-angle illumination from Seasat will provide a different view, potentially with which to map morphological and texture features on the slopes.

TABLE 3-30.- LINEAR ASSESSMENT

Item	Discourse
Objective	Evaluate Seasat imaging-radar data for presentation of linear - and to a lesser degree, circular - trends previously mapped in field studies for the Nuclear Regulatory Commission.
Seasat-A sensor requirement	SAR imagery.
Potential test sites	Area in northeastern Kans. with a high clarity of lineaments and an area in which documentation of origin has been reasonably successful.
Data volume requirements	SAR - near coincident with Landsat.
Supporting remote sensor data	Multifrequency-imaging-radar underflights (at least shorter Ka- or X-band).
Ground data	Pertinent data (vegetation conditions, soil moisture, etc.) will be collected during the overflight.
Potential users of data output	Environmental and exploration geologists; Federal, State, and local geologic groups.
Significance	The Nuclear Regulatory Commission is concerned with faulting - particularly, recent - in regions where construction of nuclear powerplants is proposed. Seasat SAR imagery interpretation may provide a significant data input by means of textural discrimination of geomorphically expressed structural units. Provide an improved method for geologic mapping.

TABLE 3-31.- MIDCONTINENT BASE METALS EXPLORATION

Item	Discourse
Objective	Seasat SAR may provide a tool to aid base metal exploration (particularly, domestic) in the continuing search for what is increasingly becoming a search for nonoutcropping ore deposits. Solution-collapse breccias are hosts to mineralization and might be detected as curvilinears at the surface by examination of SAR imagery.
Seasat-A sensor requirement	SAR imagery.
Potential test sites	North-central Tenn. to south-central Ky. Southeast Mo. Viburnum trend.
Data volume requirements	Site passes: two per year (4). Pass length: 160.9 km (100 miles) each (4).
Supporting remote sensor data	Imaging radar, X-band, Landsat.
Ground data	State/Federal geologic mapping. Industry drilling results.
Potential users of data output	Industry, State, and Federal agencies.
Significance	Assist in mapping surface trends that may be indicative of subsurface mineralization. Provide a technique for detecting areas of vegetation stress or terrain textural changes over areas where soil geochemistry is related to mineralization. Provide the potential of correlating surface producing trends into nearby regions that appear geologically favorable.

Detection of criteria pertinent to the occurrences of sulphur deposits could aid continuing searches in the west Texas region and elsewhere. Chemical fertilizer industry requirements for native sulphur continue to grow. Gulf coast production from salt domes continues to decline as production costs increase and new discoveries become rare. The existence of an approximately 54.4-Tg (60 million ton) sulphur-producing property and at least five smaller, nonproducing sulphur occurrences in the potential test site area will provide ground truth for an orientation survey over these non-salt-dome-associated occurrences (see table 3-32).

CONCLUDING REMARKS

It is apparent from the variety of experiments suggested by the Seasat Land Experiments Panel that the Seasat mission has important implications in the area of land applications. Although the Seasat system is intended to serve users within the oceanographic community, the panel believes that Seasat synthetic aperture radar (SAR) can be used to carry out a variety of proof-of-concept experiments over land.

Seasat represents the first space program imaging radar available to the Earth resources community. This potential should be exploited to the fullest possible extent within Seasat mission constraints. The Seasat SAR will enable researchers to examine the potential of active microwave systems in a number of areas where the opportunity exists for gaining unique and significant information - areas such as soil moisture and snowpack wetness determination, range management, geological exploration, and flood monitoring. In addition, because the projected resolution of Seasat SAR approximates that projected for Landsat-C, there is significant potential for upgrading the capability of both systems for a variety of land applications. Finally, the all-weather, day/night capability of the Seasat SAR affords the potentiality that coverage can be guaranteed (within orbital constraints) to applications that require data within a narrow temporal window.

The experimental programs proposed are in a preliminary form. More work and detailed preparations would have to be accomplished before any of these experiments could be carried out. The ideas, however, are sound. The panel believes that these data should be particularly useful to NASA in general and to the Seasat program in particular, as the volume of experimental data required to conduct a successful land experiments program with use of the Seasat SAR is very reasonable.

Again, it is important that NASA take advantage of this opportunity. The planning of a Seasat land experiments program, already begun in several forms, should be continued and accelerated. A program should be identified and work begun on the gathering of background data to work out data flows and test experiment designs at the earliest possible date. Seasat SAR capabilities are important to the land applications area of the Earth observations program. Maximum use should be made of them.

TABLE 3-32.- SULPHUR DEPOSIT EXPLORATION

Item	Discourse
Objective	Test ability of SAR to define large petroliferous or paleopetroliferous environments by detecting textural changes associated with low-porosity capping rock that typifies the centers of such areas from the surrounding less-porous rock.
Seasat-A sensor requirement	SAR imagery.
Potential test site	Sixty-mile-wide zone centered on a north-south line from Orla to Van Horn, Tex.
Data volume requirements	Site passes: two per year. Pass length: 100 to 125 km.
Supporting remote sensor data	Imaging radar - X-band Landsat; aircraft photography.
Ground data	Geologic mapping to be provided by exploration companies.
Potential users of data output	Exploration companies, industry.
Significance	Chemical fertilizer industry requirements for native sulphur continue to grow. Gulf coast production from salt domes continues to decline as production costs increase and new discoveries become rare. The existence of an approximately 54.4-Tg (60 million ton) sulphur-producing property and at least five smaller, nonproducing sulphur occurrences in the potential test site area will provide ground truth for an orientation survey over these non-salt-dome-associated occurrences. Detection of criteria pertinent to the occurrences could aid continuing searches in this region and elsewhere.

On the basis of the discussions of the capabilities of the Seasat SAR, the Seasat Land Experiments Panel makes the following recommendations.

1. Land experiments, such as those contained in the body of this report, should be undertaken. The panel believes that the SAR systems on board Seasat have a wide range of applications to land experiments and a significant potential for improving both quantitatively and qualitatively the information base in a number of key areas.

2. Steps should be taken to begin to integrate specific land experiments into the Seasat mission plan. This task should include the initiation of experiments and the acquisition of data for a variety of test sites. Those data should include imagery from existing airborne L-band imaging systems, as well as such field verification and collateral material as is appropriate to ensure a high probability of conducting successful experiments with Seasat data as they become available.

3. For most land applications, the Cambridge (24 day) orbit is preferable. This orbit should be used for one of the first 2 years of the Seasat mission.

4. Finally, a Seasat Land Applications Team should be formed. This team may be incorporated into the existing Seasat SAR Team structure but could, if necessary, be an entity with appropriate channels of communication. However structured, the panel believes that such a body is necessary to ensure the successful completion of meaningful land experiments in which the Seasat SAR system is used.

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[3]This material was provided to panel members at or before the meeting for background.

CHAPTER 4

PROGRAM PLANNING

Active Microwave Users Working Group

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INTRODUCTION

The basic objective of the Microwave Program Planning Panel is to develop a detailed programmatic and technical development plan for active microwave technology in each of four user activities: (1) vegetation resources, (2) water resources, (3) mineral resources and geologic applications, and (4) oceanographic applications. This general objective is further defined in terms of the following specific objectives.

1. Identify major application areas.

2. Evaluate the impact of each application area in terms of social and economic gains and specify the technical requirements of the user community, including State and Federal agencies and the private sector.

3. Summarize the present state of knowledge of the applicability of active microwave remote sensing to each application area and evaluate its role relative to other remote-sensing devices.

4. Identify the analysis and data acquisition techniques needed to resolve the effects of interference factors in order to establish an operational capability in each application area.

5. Structure flow charts of accomplished and required activities in each application area that lead to operational capability.

6. Develop programmatic guidelines to support the applications development tasks.

In 1974, the NASA-sponsored AMW was held in Houston, Texas, "to review and define the anticipated advantages of active microwave systems in future Aerospace Applications Programs" (ref. 4-1). The final product of the workshop was a well-documented report that presented a comprehensive state-of-the-art review of the capabilities and limitations of active microwave sensors for providing the required information to user applications in each of three areas: (1) Earth/land, (2) ocean, and (3) atmosphere. The findings of the 1974 AMW were recently (July 1976) updated by an Active Microwave Task Team study in the form of a report that "reviews needs, applications, user support, and empirical research and theoretical studies with imaging radar" (ref. 4-2).

In preparing the program plan contained in this report, the Program Planning Panel relied heavily on the contents of the AMW and the Active Microwave Task Team reports (refs. 4-1 and 4-2, respectively), as well as on the microwave program plan charts prepared by Dr. John Rouse for NASA Headquarters.

Incorporated in the approach taken by the Program Planning Panel to meet its objectives were the following considerations.

1. The 16 panel members, experienced engineers and scientists in active microwave remote sensing, were selected such that all four application areas of interest (vegetation resources, water resources, mineral resources and geologic applications, and oceanographic applications) were well represented.

2. The program plan developed for each application area - which included laboratory, ground-based, airborne, and spaceborne experiments, as well as models and analysis techniques development - was structured in such a way as to make maximum use of Seasat to test parameters of interest and to lead to operational capability on the Space Shuttle, if feasible.

3. Emphasis was placed on sensing parameters with a wide range of applications (e.g., soil moisture for crop yield prediction, runoff prediction, detection of locust breeding grounds in arid environments, etc.) and on developing techniques applicable over large parts of the world.

4. Test sites were carefully selected to serve (where feasible) more than one application so that maximum use could be made of time, funds, equipment, and personnel. Moreover, test site selection was coordinated with that of the Seasat Land Experiments Panel.

5. Evaluation was made of the total sensor package required for each application; the relative role of each sensor was indicated.

VEGETATION RESOURCES PROGRAM PLAN

Introduction

Cultivated and natural vegetation plays a vital role in man's everyday activities and in the economic health of a nation. The wise management and conservation of these resources is of concern to the farmer, rancher, forester, and consumer; to several State and Federal agencies having regulatory functions; and to nations determining international policy in this respect. The need to inventory and monitor large areas over relatively short periods of time can be met feasibly only by the use of spaceborne remote sensors, although the need for supplementary field data from selected sample sites will probably always exist. Despite the great potential of Landsat photographic imagery, there is, in the area of vegetation resources, need for incorporation of active microwave sensors into an Earth resources observation program.

The primary vegetation-related applications of active microwave sensors as identified by this panel are as follows.

1. Monitoring soil moisture for purposes of estimating crop yield and predicting outbreaks of locusts and other insects whose life cycles are related to soil moisture

2. Identifying, mapping, and inventorying areas of vegetation, both natural and cultivated, for estimating productivity and for managerial purposes

3. Monitoring vegetation moisture content for detecting insect infestations or diseased plants, for estimating crop vigor and yield, and for detecting potential fire hazards

4. Detecting, mapping, and monitoring saline seeps in agricultural areas

5. Mapping general soil types and detecting deleterious soil conditions such as mineralized soils, claypans, blowouts, etc.

In view of the aforementioned applications, it is important to delineate the primary goals of a comprehensive investigation of an active microwave sensor as applied to vegetation resource management. These goals are as follows.

1. Information needs and availability: To make maximum use of time and resources, determining the observational requirements of the ultimate users of an active microwave sensor is necessary. Subsequent to such a determination, ascertaining the ability or inability to extract such information from data generated by an active microwave sensor will be necessary.

2. Information model compatibility: Although active microwave data may directly supply the user with immediate information, such data will probably be used in conjunction with data supplied by other sources. It is important to determine that microwave observations are indeed complementary to nonmicrowave observations and that such data can be successfully incorporated into existing biological/agricultural models. Moreover, it should be shown that, as a result of this incorporation, data quality is substantially improved and/or data are generated at a substantially faster rate because of the availability of radar observations.

3. Applications systems verification test (ASVT): Before the final development of an operational active microwave observational program, the

sensor-model-user system should be evaluated in a semioperational environment. As specified by NASA, this directive implies system evaluation in an ASVT.

Critical to the development of an operational active microwave Earth observation program as applied to vegetation resources is the generation of a data base acquired from a broad range of vegetation classes during a variety of plant development stages. Being governed by the rate of plant development, this data collection process is time consuming. Whereas it may seem that 4 months of data collection are adequate to determine the scattering properties of a cornfield, for example, it must be realized that factors such as climate, planting practices, and differing plant varieties will introduce considerable variance into such scattering data Thus, a single cornfield should be observed for a number of years before its scattering properties are absolutely determined.

Although statements such as these may seem to present a pessimistic view of the status of the generation of a data base on the radar response to vegetation, it must be remembered that programs to gather the needed data have been ongoing for more than a decade. The inherent dynamics of vegetation necessitate, however, that more investigative work be conducted. In table 4-1, the status of the present knowledge on the radar response to vegetation is placed in perspective; and in table 4-2, a detailed breakdown of the major variables affecting the active microwave response in each of the application areas is presented.

Approach

Soil moisture monitoring through vegetation.- Many crop yield models now utilize soil moisture data rather than rainfall data (ref. 4-3). Because radar, unlike the photographic sensors, is highly sensitive to soil moisture conditions, it may become the prime source of information on this important parameter. Landsat imagery, however, could still provide supportive data. Because soil/water physics is essentially the same worldwide, with allowance for local variations in soil type, topography, etc., basic techniques worked out for localized test sites can be expanded and improved for use from spaceborne platforms.

The influence of complicating effects such as frozen and thawed soil states, snow cover, and vegetation cover has yet to be clearly understood. Through the development of such an understanding, it seems reasonable to expect to be able to employ radar data to monitor soil moisture conditions for input into yield models for cropland and rangeland. (Because microwaves will not penetrate to the soil through dense forest canopies, sensing vegetation moisture will be limited to mapping cover types.) Such data are also of value to hydrologists for flood prediction and water resource management. Moreover, the same data would aid in the prediction of conditions conducive to an outbreak of insect pests or plant pathogens whose life cycles and relative abundance are closely tied to the soil moisture regime. Many sensors necessary for air- and ground-based experiments have been developed and are available. Enough ground-based radar experiments have been completed to indicate that fallow fields for the following radar parameters appear optimal for an operational soil moisture mapping

TABLE 4-1.- VEGETATION RESOURCES APPLICATIONS SYSTEMS REQUIREMENTS

Application	Role[a]			Wavelength, cm	Interpretation resolution, m		Nadir angle, deg	Polarization type	Revisit interval	Status[b]	Priority[c]	Comments
	Active microwave	Passive microwave	Visible/IR		Desire	Accept						
Soil moisture for yield estimate												Extremely significant, unique capability
Cultivated	P	P	S	6 to 8 and 1.7 to 2.2	90	200	7 to 17	HH and cross	1 to 7 days DGS[d]	SE	VH	
Natural/range	P	P	S	6 to 8	90	200	7 to 17	HH and cross	1 to 7 days	PS	VH	
Natural/forest	S	S	S	5 to 30 MF[e]	90	200	7 to 17	HH and cross		UT	L	
Vegetation identification and mapping												All-weather complement to visible data
Cultivated	P	N	P	.8 to 3 MF[e]	30	90	40 to 60	HH/VV/cross	10 days DGS[d]	SE	VH	Limited experimentation to date
Natural/range	P	N	P	.8 to 3 MF[e]	30	90	40 to 60	HH/VV/cross		PT	M	
Natural/forest	S	N	P	.8 to 3 MF[e]	30	90	40 to 60	HH/VV/cross	Seasonally	PS	H	
Vegetation moisture monitoring												Unique capability
Cultivated	P	N	S	.8 to 5 MF[e]	30	90	40 to 60	HH/VV/cross	10 days DGS[d]	SE	VH	
Natural/range	P	N	S	.8 to 5 MF[e]	30	90	40 to 60	HH/VV/cross		PT	M	
Natural/forest	P	N	S	.8 to 5 MF[e]	30	90	40 to 60	HH/VV/cross	Seasonally	PT	H	
Saline seep monitoring	P	S	S	3 to 30 MF[e]	30	200	7 to 17	HH/VV/cross	Seasonally	PT	VH	New application
Soil mapping	S	S	P	.8 to 30 MF[e]	90	200	CS[f]	CS[f]	Event determined		M	Limited experimentation to date

[a]The role symbols are defined as follows.
P - prime sensor
C - complementary sensor
S - supportive sensor
N - not needed

[b]The status symbols are defined as follows.
PC - proven capability
SE - strong evidence of capability
PS - potential suggested by experimentation
PT - potential suggested by theory or analogy
UT - under test

[c]The priority symbols are defined as follows.
VH - very high priority and feasibility
H - high priority and feasibility
M - medium priority and feasibility
L - low priority and feasibility

[d]DGS - during growing season.

[e]MF - multifrequency.

[f]CS - cannot be specified at this time.

TABLE 4-2.- STATUS OF ACTIVE MICROWAVE PROGRAM IN VEGETATION RESOURCES APPLICATIONS

(a) Soil moisture monitoring,[a] vegetation identification and mapping, and vegetaion moisture monitoring[b]

Variable	Theoretical modeling and laboratory experiments			Ground-based experiments			Aircraft experiments			Spacecraft experiments		
	Cover			Cover			Cover			Cover		
	Cultivated	Range	Forest	Cultivated	Range	Forest	Cultivated	Range	Forest	Cultivated	Range	Forest
Vegetation dielectric properties	1	1	--	N	N	N	N	N	N	N	N	N
Vegetation attenuation	1	--	--	1	--	--	N	N	N	N	N	N
Soil moisture	2	1	--	2	1	--	1	--	--	--	--	--
Soil type	1	1	--	1	1	--	1	--	--	--	--	--
Soil roughness	1	1	--	2	1	--	1	--	--	--	--	--
Plant moisture	1	1	1	2	--	--	--	--	--	--	--	--
Vegetation density	1	1	1	2	--	--	--	--	--	--	--	--
Row direction	1	N	N	2	N	N	1	N	N	N	N	N
Diurnal cycle	--	--	--	1	--	--	--	--	--	--	--	--
Crop or forest type	1	--	1	2	--	1	1	--	1	--	--	1
Stress (disease)	--	--	--	1	--	--	--	--	--	--	--	--
Mechanical damage	--	--	--	--	--	--	--	--	--	--	--	--
Wind	1	--	1	1	--	1	1	--	1	--	--	--
Freeze/thaw state	--	--	--	--	1	--	--	--	--	--	--	--
Snow cover	--	--	--	--	1	--	--	--	--	--	--	--
Temporal variation	--	--	--	3	--	1	1	--	--	--	--	--

(b) Saline seep monitoring

No active microwave data have been acquired of saline seeps. Preliminary laboratory tests have been conducted to measure the effects of salt content on the soil dielectric properties.

(c) Soil mapping[b]

Variable	Theoretical modeling and laboratory experiments	Ground-based experiments	Aircraft experiments	Spacecraft experiments
Soil dielectric properties	3	N	N	N
Soil type	N	--	1	--
Soil roughness	3	3	1	--
Soil moisture	3	3	1	--
Freeze/thaw state	1	1	--	--
Mineralization	1	--	--	--
Vegetation cover	1	--	1	--

[a]See table 4-5 (water resources).
[b]The table symbols are defined as follows.
N = not applicable
-- = no data acquired to date
1 = <35 percent of needed data acquired to date
2 = 35 to 65 percent of needed data acquired to date
3 = >65 percent but <100 percent of needed data acquired to date
+ = data collection complete

system: frequency = 4 GHz, angle-of-incidence range = 7^0 to 17^0, and polarization = HH. Adequate interpretation techniques and data-processing methods also exist except for the case of irrigated terrain. However, a considerable amount of laboratory and theoretical investigation plus followup fieldwork remains to be done. The proposed program plan for this application is covered in detail in the "Water Resources Program Plan" section.

Vegetation identification and mapping, and vegetation moisture monitoring.- Applications relating to direct observation of the Earth's vegetation cover may be divided into two broad categories. One category involves the identification of the crop species, range type, or forest type, and the mapping and measuring of the area involved. The second category is concerned with a more precise determination of the moisture content of the plant and the manner in which this parameter reflects crop maturity or stresses due to moisture deficit, insect infestations, plant pathogens, or other sources. Both types of applications, however, can be investigated in the same set of experiments, and the comments in this section apply to both.

Improvement in the ability to recognize and inventory specific crop or natural vegetation types and also to detect vegetation cover conditions from a spaceborne platform can be translated into economic benefits along several routes, as follows.

1. The cost of producing crop forecasts can be reduced. At present, the U.S. Government spends $40 million per year on such forecasts.

2. Crop forecast accuracy can be improved. According to Hayami and Peterson (ref. 4-4), each 1-percent error in such forecasts costs $300 million, partially because of incorrect decisions regarding grain exports and other factors that affect grain prices.

3. Detection of stresses due to various causes provides further input into yield calculations. It also warns that remedial action (application of herbicides, fire hazard warnings, etc.) should be taken if possible; thus, further savings are achieved by reducing losses due to insect infestation, forest fires, etc.

4. A more accurate inventory of natural resources is also of considerable value in making long-term decisions or defining long-term goals with regard to management of Federal lands such as national forests.

Most microwave research to date has focused on a few major U.S. crops - wheat, corn, grain sorghum, soybeans, and alfalfa - and most of this work has been ground based. Results of these studies have been significant and indicate strongly the direction that future research should take with regard to sensor parameters. Briefly, the following facts have been determined (refs. 4-5 to 4-7).

1. Plant geometry, density, and water content affect radar backscatter.

2. Radar backscatter varies significantly with the biophase of crops.

3. Maximum correlation between radar backscatter and vegetation characteristics occurs for wavelengths less than 3 cm and incident angles greater than 45°.

4. With multidate data obtained with a frequency of coverage of approximately once every 10 days, corn, wheat, milo, soybeans, alfalfa, and bare ground can be separated with better-than-90-percent-correct classification. Specifically, after 30 days of sampling (at 10-day intervals), with 14-GHz dual-polarized (VV and HH) data, the aforementioned crops can be classified with better-than-95-percent accuracy (ref. 4-7).

5. Leaf area index and row direction affect radar backscatter, especially early in the growth cycle. The effect of row direction is minimal above 8 GHz.

6. Radar response to vegetation varies over the diurnal cycle; however, the effects are minimal above 8 GHz.

To acquire an operational capability in this application area, the following tasks are recommended.

1. Task A - Theoretical modeling and laboratory experiments.

a. Measurements of the dielectric constant effects on plant matter with respect to vegetation type, stage of growth, and moisture content should be performed. These data should subsequently be used to determine an effective dielectric constant for a cultivated field.

b. Backscatter models of vegetation canopies should be developed, not only to aid in relating radar data to vegetation characteristics of interest to users but also to aid in developing a basic understanding of electromagnetic scatter from plant communities.

2. Task B - Ground-based experiments.

a. Cultivated crops - Microwave observations of cultivated crops should be continued with the following objectives in mind: (1) development of data base of detailed phenological observations of specific vegetation types, (2) development of crop identification schemes in which microwave data inputs are used, and (3) collection of detailed observations of crop types, with emphasis placed on crop stress detection. Such objectives could be met by continuing controlled, ground-based MAS studies for integration with data from other active and passive sensors on aircraft.

(1) Sensors - The 8- to 18-GHz MAS (Kansas University), C- and K-band scatterometers (JSC), and an X-band imager (JSC's RB-57F or the JPL Convair 990).

(2) Availability of needed sensors - All are presently available. Additional 8- to 18-GHz truck-mounted systems are desired in Texas and/or California to increase efficiency and speed of ground-based studies.

(3) Test sites -

(a) Fiscal year (FY) 1977 to 1978 - Garden City area, Finney County, Kansas - LACIE super site, cropland and range.

(b) FY 1978 to 1980 - Grand County, Colorado - LACIE super site, range and forest.

(c) FY 1978 to 1981 - Eventually expand to other sites in United States - California, Idaho, Montana, Pennsylvania, etc. (see fig. 4-1) - and other countries.

(4) Ground-truth support - Soil moisture profiles, bulk density profiles, soil roughness, plant type, row spacing, row direction, crop height, moisture, etc.

(5) Frequency of data collection - Every 9 days, coincident with overflights by Landsat-1 and -2; total of 18 missions each season.

b. Forest lands - Microwave observations of forest land should be initiated to determine relationships between radar return and forest type, canopy structure, vegetation moisture content, and site parameters. It is suggested that such investigations begin with ground-based experiments in which the University of Kansas 8- to 18-GHz MAS is used in the Missouri Ozarks, with initial emphasis on empirical observations of differences in backscatter from coniferous versus broadleaf tree types and of temporal variations in vegetation moisture content. If possible, data will also be collected for trees damaged by sulfur dioxide gas from lead smelters in the vicinity.

(1) Sensors - An 8- to 18-GHz ground-based radar.

(2) Sensor availability - Available.

(3) Test site - Pine-oak-hickory forests in the St. Francois Mountains of eastern Missouri, on land belonging to Clark National Forest and also in the general vicinity of a new lead-mining region (the Viburnum trend).

(4) Frequency of data collection - Seasonally.

3. Task C - Aircraft experiments. An extensive airborne microwave response data acquisition program should be initiated as soon as feasible. The main advantage of such a program would be that of data collection over widely varying vegetation conditions. Such data are badly needed to confirm or refute conclusions reached after analyses of the data gathered on a local basis by ground-based systems.

a. Sensors -

(1) Ground - An 8- to 18-GHz ground-based radar.

(2) Airborne - L-band, C-band, and Ku-band JSC scatterometers.

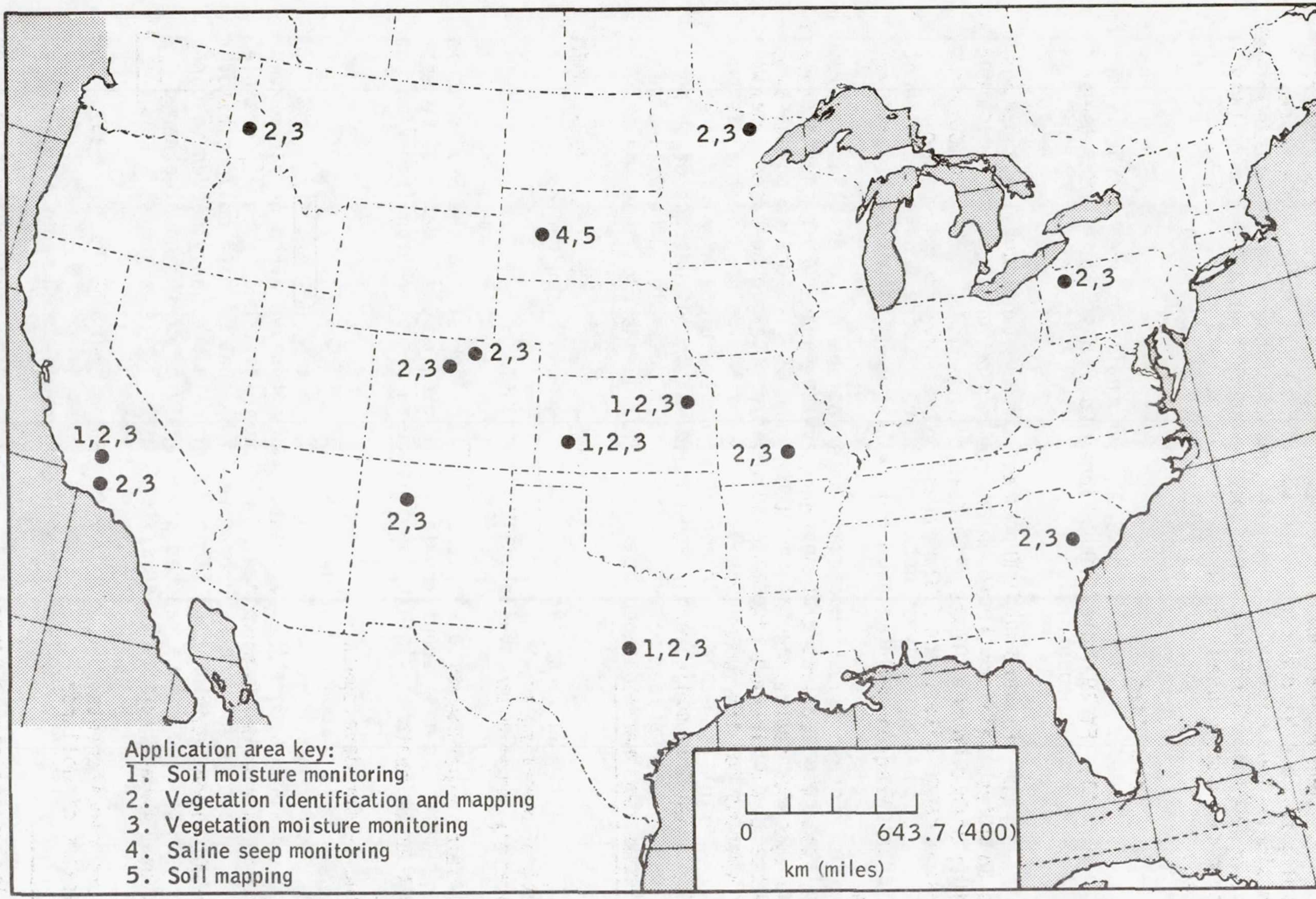


Figure 4-1.- Vegetation resources applications test sites.

b. Sensor availability - L-band and K-band scatterometers are available; but a C-band radar system with 5° to 20° nadir angle range, 12.5-m single-look resolution, and HH- and cross-polarization capabilities must be developed. Although, for experimental purposes, the JSC K-band scatterometer can be used, an imager should be developed for ASVT purposes.

c. Test sites -

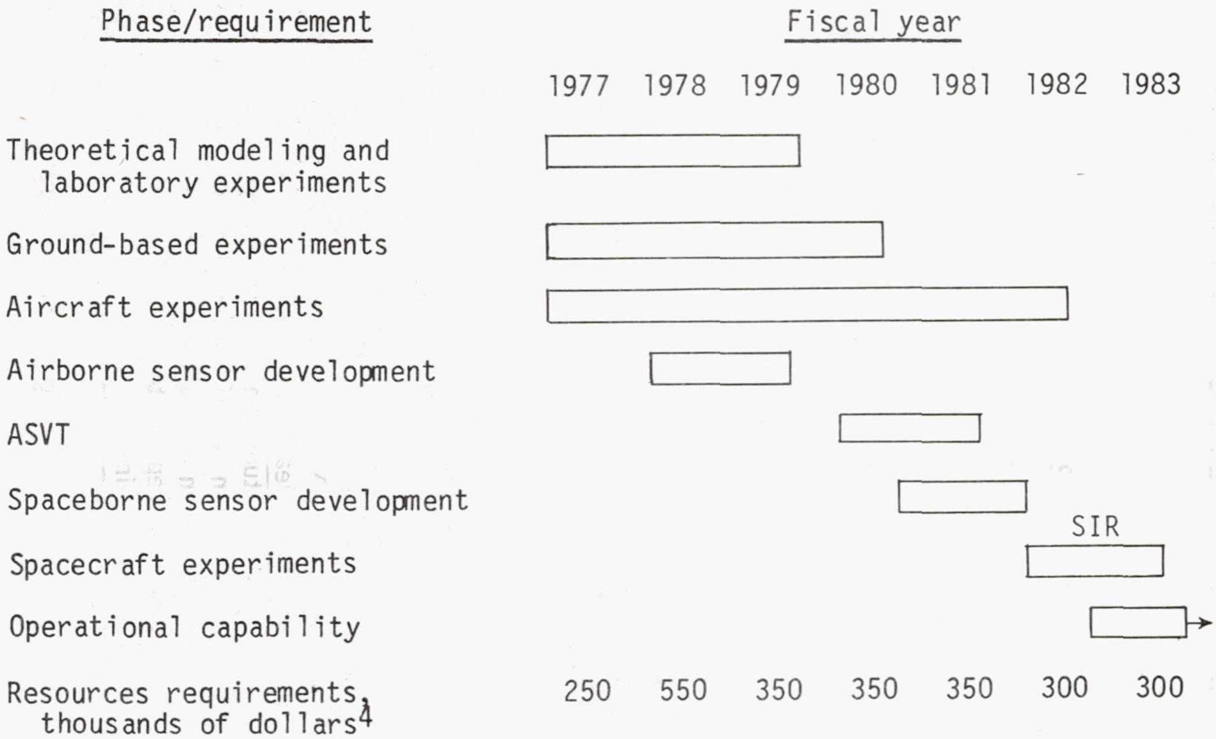
(1) FY 1977 to 1979 - Finney County, Kansas - LACIE super site.

(2) FY 1978 to 1980 - Grand County, Colorado, and Kern and Plumas Counties, California, are being considered. Sites in other States - including Brazos County, Texas, the Pawnee grasslands in eastern Colorado, New Mexico range sites, and Idaho forest sites - may be added also.

d. Frequency of data collection - Nine days during the growing season.

4. Task D - Spacecraft experiments. It is premature to detail experiment designs for spacecraft at this time. However, knowledge gained from ground-based and aircraft studies will enable the development of optimal sensor systems for the Space Shuttle.

The scheduling relevant to these tasks is as follows.



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[4]Includes airborne sensor development but not spaceborne sensor development.

Saline seep monitoring.- A saline seep is a terrain area with extremely high salt concentration at the soil surface, caused by the transport of excess water through salty upper strata underlain by impermeable layers, usually salt-laden shales. In the north-central plains, seep formation is aggravated by the every-other-summer dryland fallowing practice used to conserve water.

Approximately 590 517 km^2 (228 000 mi^2) in the Wheat Belt zones in the Dakotas, Montana, Alberta, Saskatchewan, and Manitoba are potential saline seep areas. Similar areas have also become evident in various parts of the world. From 1969 to 1974, there has been a 300-percent increase in the saline seep area in Montana, where the biennial wheat losses are valued at approximately $50 million.

Saline seep areas can sometimes be improved by deep plowing. If potential seep areas can be identified early, alfalfa or similar vegetation can be planted, with the result that evapotranspiration will be increased and the buildup of salts at the surface prevented. The objective of this application is to develop the technique for early identification and mapping of saline seep areas so that early preventive measures may be taken.

For this particular application, active microwave is considered the prime sensor, although passive microwave and visible/IR sensors will provide complementary data.

Direct methods of identifying potential seeps and the location of active seeps include (1) a four-probe soil conductivity technique and (2) the refraction seismographic method. These methods are useful tools but require enormous expenditures of time and labor.

High-water tables in the seeped areas have an influence on the surface thermal properties, as well as on the growth patterns of indicator plants that can provide detectable thermal IR and visible signatures. Experiments are in progress that use change detection procedures to give an estimate of the rate of increase or decrease of seeped areas; in addition, specialized imagery enhancement techniques - e.g., density slicing - are being used to attempt a separation of seep areas from nonseep areas.

Ongoing research indicates that thermal IR is useful in defining the spatial extent of surfaces of high evaporation in a normally dry region and thereby in predicting areas of potential seeps. However, this interpretive technique is necessarily complex because it depends on the dynamics of soil evaporation; and whereas some spatial information is provided, seep severity cannot be quantified because the visible/IR reflectivity is not uniquely dependent on soil salinity.

The identification of potential seeps by using complementary microwave and visible/IR imagery should be possible because the microwave response (either scattering cross section or emissivity) is much less sensitive to soil thermal profiles and much more sensitive to dielectric constant as compared to thermal IR.

Preliminary laboratory measurements of saline-seeped-soil dielectric constants have been made, and a relationship has been established between soil salinity levels and their effects on the growth of crops such as wheat and barley. In addition, calculations have been made for expected passive and active signatures. Laboratory work and fieldwork are required on scattering cross sections and the modeling of surface roughness and to establish optimum frequency, polarization, look angle, etc. Necessary sensors - i.e., the Kansas University MAS and possibly the Texas A. & M. University passive radiometer - are available, together with airborne scatterometers, radiometers, and imaging radars. Algorithms permitting the separation of moisture effects from salinity effects on radar backscatter have not yet been developed.

Aircraft experiments in which scatterometers and radiometers are used will be required as an extension of the ground measurements program. Aircraft SAR flights would be a follow-on activity to establish the techniques for large-area detection and mapping of the saline seep areas. Sensor development requirements for the aircraft program will be dependent on the results of the ground-based experiments with regard to the optimum frequency, polarization, etc. Early results indicate that a multiple polarization system operating at L- or C-band may be the optimum. Existing and/or proposed scatterometers and SAR's will satisfy this requirement.

Global identification, mapping, and monitoring of saline seep areas is the ultimate objective, which can only reasonably be achieved with spacecraft systems. Spacecraft experiments to establish the specific instrument parameters and techniques are essential precursors to an operational capability.

On the basis of the preliminary ground measurements that indicate L-band as being a suitable frequency, data from the Seasat SAR will provide an early opportunity to evaluate the utility of a spacecraft system for saline seep mapping. The look angle and spatial resolution of that system are also supportive of this requirement.

A spacecraft system such as the proposed SIR will be required in order to fully evaluate the technique from space. The dual frequency, dual polarization, wide-swath coverage and variable-look-angle capability, as proposed for the SIR, will be essential to establish the parameters for an operational system. Because the frequency-of-coverage requirement for saline seep monitoring is low, it is possible that periodic flights with the SIR or similar Shuttle system could satisfy the operational needs.

To acquire an operational capability in this application area, the following tasks are recommended.

1. Task A - Theoretical modeling and laboratory experiments. A program for measuring the dielectric properties of salt-laden soil should be vigorously pursued. Dielectric content should be measured as a function of salt content, moisture content, and frequency.

2. Task B - Ground-based experiments. Ground-based studies to determine microwave signatures characteristic of particular soil types and terrain conditions should be initiated. Results of studies by Ulaby and associates at the University of Kansas on soil moisture and roughness

effects on backscatter and of studies by de Loor (ref. 4-8) in the Netherlands will be applicable to these studies. Of major interest in such investigations should be the effect of salt content on the radar response. Ground-based studies should be followed by aircraft studies, and microwave imagery eventually should be combined with photographic imagery. A wide variety of radar frequencies will be needed to test the theoretical relationships between soil and sensor parameters.

a. Sensors - The 1- to 8-GHz and 8- to 18-GHz ground-based radar systems and a JSC L-band truck-mounted radiometer.

b. Sensor availability - All sensors are available.

c. Test sites -

(1) FY 1978 to 1979 - Harding County, South Dakota, and Dickinson, North Dakota.

(2) FY 1979 to 1981 - The Highwood Bench and Rapelje, Montana.

3. Task C - Aircraft experiments. With the use of L-band, C-band, and ultrahigh frequency (uhf) scatterometers on the JSC C-130 aircraft and the MFMR on the JSC NP-3A aircraft, the objective of the airborne experiments is to determine the active and passive microwave response to (1) average seep salinity, (2) soil moisture, (3) frequency, (4) polarization, and (5) look angle; also, with use of the JPL L-band SAR imager, to determine image characteristics of seeped areas.

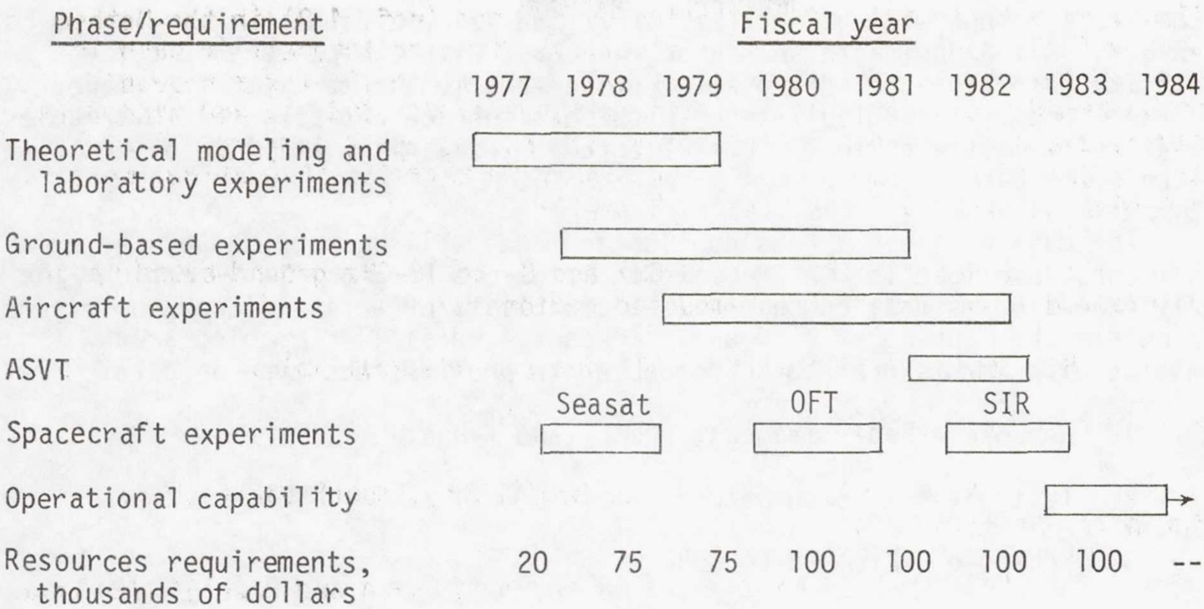
a. Sensors - NASA JSC L-band, C-band, and uhf (0.4 GHz) scatterometers; JPL L-band SAR imager.

b. Availability of sensors - JSC L-band and uhf scatterometers and JPL SAR are presently available; NASA JSC C-band scatterometer is expected by October 1977.

c. Test sites - (See task B, ground-based experiments.)

d. Data collection frequency - Once in April-May period and once in September-October period.

The scheduling relevant to these tasks is as follows.



Soil mapping.- Limited investigations (refs. 4-9 and 4-10) conducted in a range of environments indicate that active microwave has the capability for generalized soil discrimination. Radar imagery could provide the soil scientist with preliminary information for selected geographic regions to determine whether conventional detailed mapping is desired. Detection of localized problem areas such as claypans, plowpans, blowouts, etc., would provide supplementary data for the Federal LACIE, the U.S. SCS, and similar State and Federal agencies and programs. Detection of unused land suitable for cultivation or grazing and the determination of the engineering characteristics of soil (i.e., suitability for construction sites, etc.) could be especially advantageous in remote or undeveloped regions where extensive ground observations would be prohibitively expensive and time consuming. Because differences in soil makeup are frequently accompanied by parallel differences in water-holding capacity, multidate radar observations can be used to detect regions of differential drying rates. This difference may also be reflected in the vegetation cover, because plant community composition differs between mesic and xeric sites. The interpretation resolution required will, of course, depend on the end product desired - small-scale regional soil maps or large-scale, more localized maps. Although radar imagery can provide some soil information not extractable from photography, the converse is also true (ref. 4-11). Useful information is also obtainable from passive measurements, and it is likely that all three sensors - especially active microwave and photography - will continue to be desirable for soil mapping.

Only limited experimentation with this application has been performed to date. Additional research is required to develop quantitative interpretation techniques correlating microwave signatures and various environmental parameters such as surface roughness, soil moisture, and vegetation cover. Preliminary ground-based experiments with the University of Kansas truck-mounted MAS systems or similar systems for determining optimal frequency and incident angle will be necessary, together with laboratory measurements of the dielectric properties of various soil types. Followup aircraft flights for field checking ground-based studies and associated model development will be necessary for finalizing designs for spaceborne sensors. All experiments should be conducted with the primary objective being to determine the interplay among various sensor parameters (frequency, incident angle, and polarization) with soil surface and subsurface variables (texture, moisture content, vegetation cover, salinity, etc.) in determining radar backscatter.

The data needed for this application area will be provided by the experiments described in the "Vegetation Resources Program Plan" section. The only exception is data concerning the capability of active microwave sensors to enable the mapping of claypans, plowpans, and similar problem areas; imaging experiments need to be conducted to provide this type of data.

1. Sensors - Radar imagers, JPL L- and X-band

2. Test sites - South Dakota

3. Schedule - FY 1978 to 1980

4. Resources requirements - $25 000 per year

Development Plan

Figure 4-2 is a vegetation resources applications development plan, in a flow chart format, summarizing the major steps between the present status of each application area and the ultimate goal - i.e., operational capability. The associated schedules of ground-based, aircraft, and spacecraft experiments for each of the major application areas are summarized in figure 4-3, the corresponding resource requirements are summarized in table 4-3, and the test site locations are indicated in figure 4-1, presented earlier in this section.

Summary and Recommendations

The major application areas were rated with respect to priority and feasibility as follows.

<u>Very high</u>:

1. Soil moisture monitoring for crops and rangeland

2. Crop identification and inventorying

3. Crop moisture and health monitoring

4. Saline seep detecting and monitoring

<u>High</u>:

1. Forest community identification and inventorying

2. Forest moisture and health monitoring

- **SOIL MOISTURE AND YIELD ESTIMATES**
- **VEGETATION IDENTIFICATION AND MAPPING**
- **VEGETATION MOISTURE MONITORING**

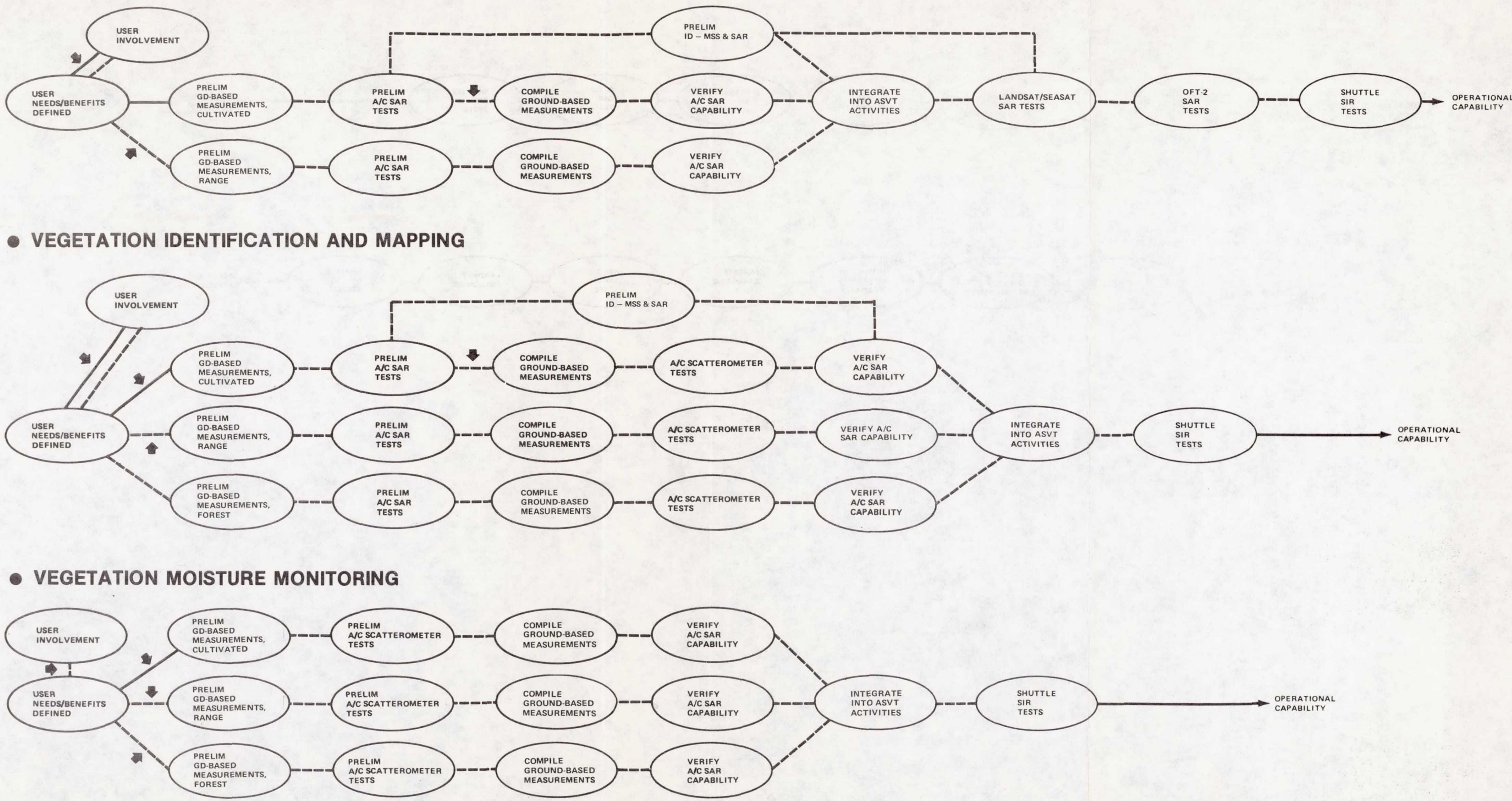
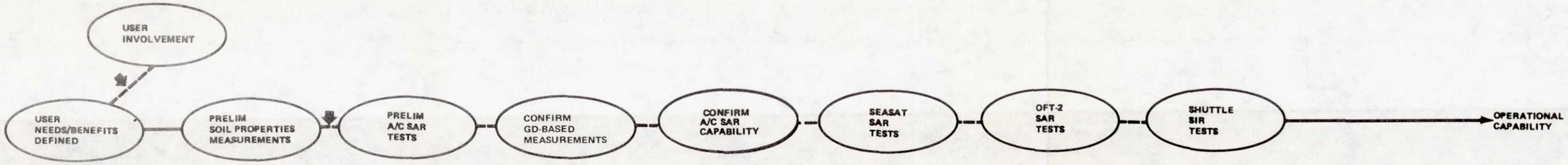


Figure 4-2.- Vegetation resources development plan.

- SALINE SEEP DETECTION AND MONITORING



- SOILS MAPPING

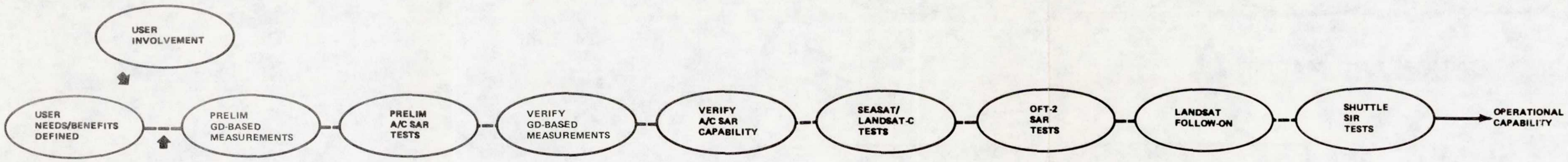


Figure 4-2.- Concluded.

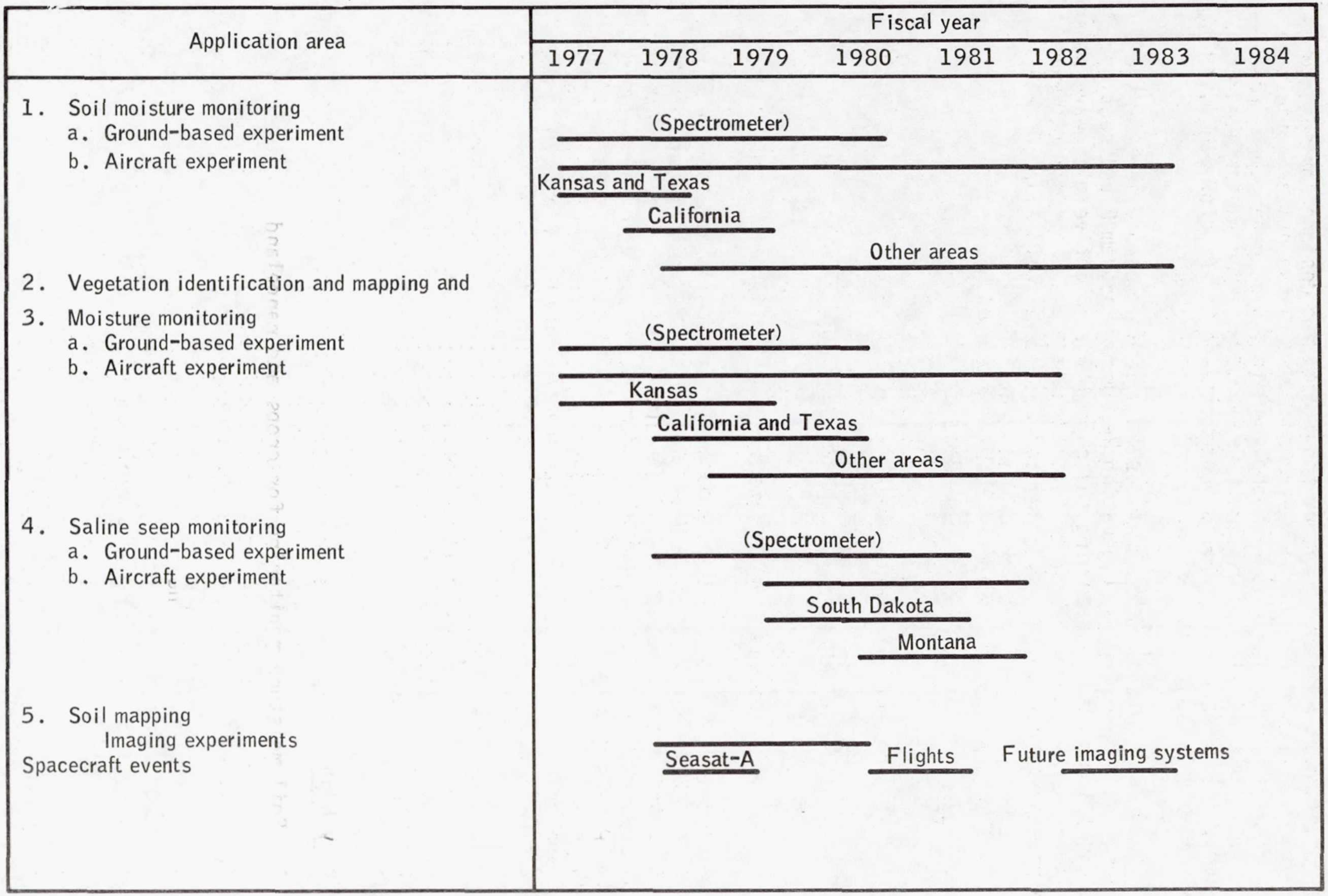


Figure 4-3.- Vegetation resources/active microwave activities.

TABLE 4-3.- VEGETATION RESOURCES FUNDING REQUIREMENTS

Application area	Fiscal year						
	1977	1978	1979	1980	1981	1982	1983
Soil moisture monitoring, vegetation observations	$300 000	$550 000	$350 000	$350 000	$300 000	$300 000	--
Identification and mapping Moisture monitoring	250 000	550 000	350 000	350 000	350 000	300 000	$300 000
Saline seep monitoring	20 000	75 000	75 000	100 000	100 000	100 000	100 000
Soil mapping	--	25 000	25 000	25 000	--	--	--
Total resources[a]	$270 000	$650 000	$450 000	$475 000	$450 000	$400 000	$400 000

[a]Resources for the soil-moisture-monitoring task are already included under the water resources; hence, they will not be included here.

Medium: Monitoring of erosion, hardpans, plowpans, and other deleterious properties in agricultural areas

Low:

1. Soil reconnaissance mapping

2. Soil moisture monitoring in forested areas

The recommendations are as follows.

1. The development of additional multifrequency, multipolarization radar spectrometers to supplement the existing 1- to 8-GHz and 8- to 18-GHz MAS systems at the University of Kansas should be pursued vigorously.

2. Airborne radar studies over natural and cultivated vegetation should be expanded.

3. Additional data must be gathered immediately to further define suitable specifications for a Shuttle radar optimized, at least in part, for vegetation and soil moisture studies. At this time, a dual frequency (approximately 4 and 14 GHz), dual polarization (HH and VV) radar seems optimal for soil moisture and vegetation data.

WATER RESOURCES PROGRAM PLAN

Introduction

Many agencies on all levels (Federal, State, and local) have responsibilities for water resources management. It is estimated that $12 to $15 billion per year are expended for water resources management, of which $3 billion per year are spent by the Federal Government and $9 to $12 billion by State, local, and regional agencies. Twenty percent of all the expenditures associated with municipalities in the United States is devoted to water resources problems. The responsibilities and areas of need on the part of Federal agencies are provided in ref. 4-2.

There has been substantial progress in demonstrating and applying remote-sensing observations for water resources management with use of the Landsat-1, Landsat-2, and NOAA VHRR systems, wherein the visible, near-IR, and thermal regions of the electromagnetic spectrum have been employed. The results show, for example, that the dynamics of snow cover, surface-water area (including postflood, inundated areas), and land-use or surface-cover themes relevant to hydrology can be delineated and used for water management and prediction purposes.

There are some important and fundamental parameters that are not amenable to direct sampling by visible, near-IR, and thermal-IR systems. They do appear amenable to microwave sampling in that microwave radiation will penetrate the materials involved (soil or snow) and is quite sensitive to changes in the dielectric properties caused primarily by variations in water content. In addition, it is known that microwave radiation, under properly chosen conditions, can penetrate clouds and modest amounts of vegetation. Furthermore, it is quite clear that active microwave approaches provide a mechanism by which to obtain high spatial resolutions compatible with requirements for monitoring flooded areas, drainage basin characteristics, and soil moisture variations over small watersheds or fields.

Within the water resources area, there are several application areas that must be given priority, as follows.

1. Soil moisture monitoring to help specify water balance and runoff potential on watersheds.

2. Snowpack moisture equivalent and liquid-water monitoring to specify water available for runoff. This application is particularly important in the western United States, where snowpack yield provides the water for most hydroelectric power generation, irrigation, some flooding, and recreation.

3. Quantitative specification of runoff coefficients on small watersheds; the integrated effects of land use/surface cover, soil permeability and type, and surface cover must be specified - together with other efforts to delineate stream pattern, stream density, stream lengths and widths, and basin area - to make estimates of watershed yield.

4. Delineation of freeze/thaw lines in many areas, particularly in the spring months on the northern Great Plains, where this condition markedly affects the magnitude and character of runoff.

For the aforementioned application areas, the major investigation objectives and activities that must be considered in developing a microwave observational capability are as follows.

1. Information content - The first step in deducing the applicability of remote-sensing observations is to ascertain what information resides within these observations, to what accuracy the information can be specified, and the observational needs of the hydrologic community in order to exceed the capability provided by conventional observational systems.

2. Watershed runoff/water balance/water resources systems models - For the great majority of water resources management agencies, models represent the major management, decisionmaking tool. Therefore, to demonstrate applicability, it must be shown that remote-sensing data can be used in models of the aforementioned type. These models may range from the empirical, simple watershed runoff models of the "rational formula" type, where a coefficient is involved, to the numerical, continuous simulation parametric models of the type represented by the Stanford IV or USACE SSARR[5] models. In any case, it should be demonstrated that these models can utilize the remote-sensing data to produce comparable or more accurate results than can be presently derived and that the input data can be acquired faster and at less cost.

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[5]Streamflow synthesis and reservoir regulations.

3. ASVT - The final step before operational utilization of remotely sensed data is its evaluation in a quasi-operational framework. Within the NASA framework, the data would be evaluated in an ASVT environment. The same procedure needs to be followed in developing and demonstrating a microwave observational capability. In the following subsections, the time periods in which these tests should occur are specified.

Considerable effort has already been devoted to assessing the applicability of active microwave systems for application areas in water resources (refs. 4-1 and 4-5). Some of this work is summarized in table 4-4; indications of progress are provided, as well as observational requirements and the relationship to other systems such as passive microwave systems and visible/IR sensors. Table 4-5 contains a quantification of the current status of knowledge of the active microwave response to specific parameters pertaining to each of five water resources applications. The approach utilizes the progressive steps toward spaceborne system implementation by starting with theory and laboratory work and progressing toward that ultimate goal with the use of ground-based and aircraft systems.

These tables generally indicate that, in all areas, substantial work is still needed; but the most progress and usable/referenceable knowledge exist in the case of surface-water mapping, followed by soil moisture and, then, freeze/thaw lines and snowpack monitoring. For all areas, the flight of an active microwave SAR in space is being awaited. The first opportunity to see such data will come with the launch of Seasat-A in 1978.

Approach

Soil moisture monitoring.- The purpose of this activity is to monitor soil moisture variations under bare and vegetated conditions. Soil moisture content is a fundamental parameter in water resources applications, including crop yield prediction, flood forecasting, runoff prediction for assessing watershed yield and planning, reservoir management, and a variety of other agricultural, hydrological, and meteorological applications. Although it has been experimentally demonstrated that the radar response is very sensitive to soil moisture content, a quantitative determination of moisture content requires a thorough understanding of the dependence of the radar response on interference factors such as surface roughness and vegetation cover. Research to date indicates that the effect of surface roughness can be minimized by operating in the 4- to 5-GHz frequency range at nadir angles in the 7° to 17° range (ref. 4-12). The sensitivity of radar to moisture in the soil underlying a vegetation canopy has also been investigated for a few economically important crops such as wheat, corn, milo, soybeans, and others. Preliminary results of this ongoing research effort at the University of Kansas indicate that algorithms for predicting soil moisture content of vegetated terrain will probably require the use of a two-frequency radar system.

TABLE 4-4.- WATER RESOURCES APPLICATIONS SYSTEMS REQUIREMENTS

Application	Role[a]			Wave-length, cm	Interpretation resolution, m		Nadir angle, deg	Polar-ization type	Revisit interval	Status[b]	Priority and feasibility[c]	Comments
	Active microwave	Passive microwave	Visible/IR		Desire	Accept						
Soil moisture monitoring												Unique capability
Cultivated areas	P	P	S	6 to 8 and 1.7 to 2.2	30	90	7 to 17	HH and cross	1 to 7 days	SE	VH	
Uncultivated areas	P	P	S	2 to 30 MF[d]	30	90	7 to 17	HH and cross	1 to 7 days	SE	VH	
Snowfield (equivalent moisture and liquid water) mapping	P	C	C	1 to 30 MF[d]	30	90	CS[e]	CS[e]	3 to 15 days	UT	VH	Limited experimentation to date
Watershed												Unique capability Proven capability
Runoff coefficient estimate	F	P	S	3 to 30 MF[d]	30	90	CS[e]	CS[e]	Seasonal	SE	H	
Drainage pattern	P	N	C	3 to 30 MF[d]	30	90	CS[e]	CS[e]	Annual	PS	L	
Land-use mapping	P	N	C	3 to 30 MF[d]	30	90	CS[e]	CS[e]	Annual	SE	L	
Surface-water, flood, and wetland mapping	P	N	C	Any	10	30	Any	Any	Event determined	PC/SE	M	Operational capability
Freeze/thaw line monitoring	P	C	S	3 to 30 MF[d]	90	200	CS[e]	CS[e]	3 to 15 days	UT	M	Limited experimentation to date

[a]The role symbols are defined as follows.
- P - prime sensor
- C - complementary sensor
- S - supportive sensor
- N - not needed

[b]The status symbols are defined as follows.
- PC - proven capability
- SE - strong evidence of capability
- PS - potential suggested by experimentation
- UT - under test

[c]The priority and feasibility symbols are defined as follows.
- VH - very high priority and feasibility
- H - high priority and feasibility
- M - medium priority and feasibility
- L - low priority and feasibility

[d]MF - multifrequency.

[e]CS - cannot be specified at this time.

TABLE 4-5.- STATUS OF ACTIVE MICROWAVE PROGRAM IN WATER RESOURCES APPLICATIONS[a]

(a) Soil moisture monitoring

Variable	Theoretical modeling and laboratory experiments			Ground-based experiments			Aircraft experiments			Spacecraft experiments		
	Cover			Cover			Cover			Cover		
	Bare	Vegetation	Snow	Bare	Vegetation	Snow	Bare	Vegetation	Snow	Bare	Vegetation	Snow
Surface moisture content	2	2	1	3	2	1	1	1	1	1	1	--
Moisture profile	2	2	1	3	2	1	--	--	--	--	--	--
Surface roughness	3	2	--	3	2	--	1	1	--	--	--	--
Salinity	2	2	--	--	--	--	--	--	--	--	--	--
Surface slope	2	2	--	3	2	--	2	2	--	--	--	--
Soil type	3	3	2	1	1	--	--	--	--	--	--	--
Freeze/thaw state	2	2	1	1	1	1	1	--	--	--	--	--
Vegetation type	N	2	--	N	2	--	N	2	--	--	--	--
Vegetation density	N	2	--	N	2	--	N	1	--	--	--	--
Vegetation moisture	N	2	--	N	2	--	N	1	--	--	--	--
Vegetation row effect	N	2	--	N	2	--	N	2	--	--	--	--
Diurnal cycle	N	1	--	N	2	1	N	--	--	--	--	--
Snow cover	1	--	1	N	--	1	--	--	1	--	--	--
Soil dielectric properties	3	N	N	N	N	N	N	N	N	N	N	N
Vegetation dielectric properties	N	1	N	N	N	N	N	N	N	N	N	N
Snow dielectric properties	N	N	2	N	N	N	N	N	N	N	N	N

(b) Snowfield (equivalent moisture) mapping

Variable	Theoretical modeling and laboratory experiments	Ground-based experiments	Aircraft experiments	Spacecraft experiments
Snow depth	3	1	--	--
Snow density	3	1	--	--
Snow temperature	1	1	--	--
Snow layering	1	--	--	--
Surface roughness	1	--	--	--
Snow wetness	1	1	--	--
Crystal structure (age parameter)	--	--	--	--
Diurnal cycle	--	1	--	--
Snow dielectric properties	3	1	N	N

[a]Table symbols are defined as follows.
N = not applicable
-- = no data acquired to date
1 = <35 percent of needed data acquired to date
2 = 35 to 65 percent of needed data acquired to date
3 = >65 percent but <100 percent of needed data acquired to date
+ = data collection complete

TABLE 4-5.- Concluded[b]

(c) Watershed runoff coefficient estimation and mapping of drainage basin characteristics

Variable	Theoretical modeling and laboratory experiments	Ground-based experiments	Aircraft experiments	Spacecraft experiments
Watershed size	N	N	1	--
Drainage density	N	N	+	--
Stream length	N	N	+	--
Stream width	N	N	+	--
Slope	N	N	1	--
Land use	N	N	2	--
Sinuosity	N	N	3	--
Permeability	N	N	--	--

(d) Surface-water and flood mapping

Variable	Theoretical modeling and laboratory experiments	Ground-based experiments	Aircraft experiments	Spacecraft experiments
Area	+	3	3	--
Area extent of vegetation cover	+	3	3	--
Vegetation density	N	--	1	--

(e) Freeze/thaw line monitoring

Variable	Theoretical modeling and laboratory experiments	Ground-based experiments	Aircraft experiments	Spacecraft experiments
Bare	+	1	--	--
Vegetated cover	1	1	--	--
Snow cover	1	1	--	--

[b]Table symbols are defined as follows.

N = not applicable
-- = no data acquired to date
1 = <35 percent of needed data acquired to date
2 = 35 to 65 percent of needed data acquired to date
3 = >65 percent but <100 percent of needed data acquired to date
+ = data collection complete

To acquire an operational capability in this application area, the following tasks are recommended.

1. Task A - Theoretical modeling and laboratory experiments.

a. Dielectric properties of soils should be measured as a function of moisture content, salinity, and temperature over the 1- to 8-GHz region. The data should be used to develop appropriate dielectric-mixing formulas.

b. Backscatter and emission models (based on experimental data) should be developed that incorporate the effects of soil moisture content and vegetation cover parameters.

c. Backscatter and emission models (based on experimental data) should be developed that incorporate the effects of soil moisture content for unfrozen ground with snow cover and frozen ground with and without snow cover.

2. Task B - Ground-based experiments.

a. Vegetation attenuation - If data on the attenuation by vegetation canopies are available, algorithms can be constructed to improve the accuracy of the soil moisture estimate provided by microwave sensors. To date, very few experiments have been conducted to acquire such data. Hence, it is recommended that a transmission system approach be used to measure the attenuation of each of several types of vegetation canopies as a function of frequency (1 to 8 GHz), nadir angle (0° to 30°), vegetation parameters (crop type, height, plant moisture content, density, row direction, etc.), and time of day.

(1) Sensor - A 1- to 8-GHz ground-based radar.

(2) Test site - Any agricultural test site.

(3) Frequency of data acquisition - Once every 7 to 10 days during the growing cycle.

(4) Interpretation technique development - Attenuation data should be integrated into radar soil moisture estimation models to improve accuracy of the estimate.

b. Simultaneous active/passive microwave measurements - Although a passive microwave radiometer is not yet capable of producing high-resolution imagery from space platforms, its demonstrated sensitivity to soil moisture content may potentially be used to "calibrate" the high-spatial-resolution soil moisture estimate provided by radar. A ground-based experiment with a combination of passive and active microwave sensors should be conducted to determine the improvement in the soil moisture estimate provided by the combined sensors over that provided by radar alone. The experiment should include both bare and vegetation-covered conditions.

(1) Sensors - C-band ground-based scatterometer and L-band or C-band radiometer.

(2) Needed sensor development - None, if the University of Kansas active system is used and the JSC or GSFC L-band radiometer system is used to acquire data simultaneously with the active microwave sensor.

(3) Test site - Any agricultural test site.

(4) Interpretive technique development - Algorithms should be developed for utilizing the combination of active and passive microwave data for predicting soil moisture content.

3. Task C - Aircraft experiments. The soil-moisture-mapping capability attributable to active microwave remote sensing should be evaluated for a variety of cultivated and uncultivated test sites through repetitive coverage simulating periodic coverage by a satellite system. Because the microwave sensors respond only to the moisture content in the top few centimeters of the soil, a water-balance model should be developed to incorporate the multidate data provided by the microwave sensors to predict the moisture content at the deeper layers. In addition to airborne sensors, ground-based sensors should also be used to calibrate the airborne sensors and to monitor the moisture content of selected fields on a daily basis so that an accurate evaluation of the needed frequency of coverage of a satellite system can be made.

a. Sensors -

(1) Airborne sensors - L-band, C-band, and Ku-band NASA/JSC scatterometers and imagers as availability and resources permit, plus the NASA/JSC MFMR.

(2) Ground sensors - Ground-based radar spectrometer.

b. Coverage requirements - Every 9 days during the growing season.

c. Test sites -

(1) FY 1977 to 1979 - Finney County, Kansas, LACIE test site.

(2) FY 1978 to 1980 - To be determined; possible candidates include the Washita River test site near Chickasha, Oklahoma, and the Kern River test site in southern California.

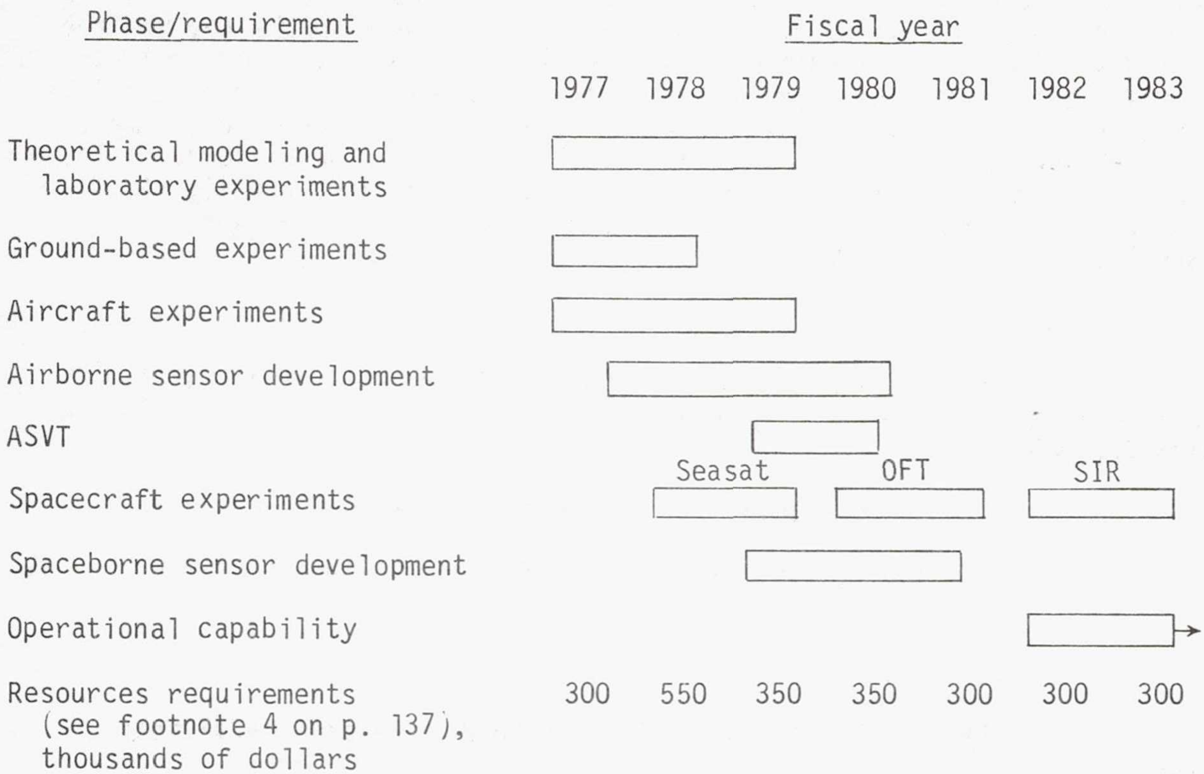
d. Needed sensor development - C-band imager, 5^{o} to 20^{o} nadir angle range, 12.5-m single-look resolution, and HH- and cross-polarization capability.

e. Interpretation techniques development - An appropriate water-balance model for bare and vegetated terrain should be developed that uses radar data and weather station information as inputs and yields an estimate-of-soil-moisture profile down to 50 cm as output.

f. Ground-truth support - Soil moisture content profile and vegetation cover parameters (crop type, density, row direction and spacing, plant moisture, etc.).

4. Task D - Spacecraft experiments. The first opportunity to evaluate the potential of active microwave remote sensing in soil moisture determination will be provided by the Seasat L-band SAR. Although experimental evidence to date indicates that C-band is superior to L-band for mapping soil moisture content, the Seasat L-band SAR should certainly provide results superior to what can be obtained with optical and thermal-IR sensors. Other opportunities include the Shuttle OFT flights and the projected 1982 or 1983 flight of the SIR. Detailed experiment specifications (test sites, exact sensor parameters, ground truth, etc.) will have to be deferred until extensive testing from airborne platforms has been conducted.

The scheduling relevant to these tasks is as follows.



Snowfield mapping.- Snowpacks provide most of the water supply in the western United States. The water runoff from high elevations also provides a major portion of the electrical energy. Knowledge of the depth, density, extent, and wetness of snowpacks on a timely basis permits optimum management of water reservoirs, allocation of water resources, scheduling of hydroelectric power, and irrigation planning. Sudden thaws of the snow can cause extensive flooding resulting in loss of lives and property. Such hazards can be reduced or eliminated if snowpack conditions are known with an adequate lead time.

Snow course measurements presently provide information regarding how much water equivalent exists at the time on the basis of statistical inference. Automated measurements by "snow pillows" or by the Smith density profile technique can furnish significant additional information. The SCS is installing a network of approximately 400 pressure pillows for remote, automatic acquisition of snow mass data (termed "water equivalent") in its "Sno-Tel" system.

At the present time, little information is available regarding the time and rate of release of melt water from the snowpack. Also, the water storage capacity of snowpacks for rainfall is not known.

Information about the snowpack evidently can be improved and would be valuable if it were available on a timely basis. Satellite-borne active microwave sensors have the potential to provide synoptic, repetitive information regarding snowpack extent, depth, density, and wetness.

To acquire an operational capability in this application area, the following tasks are recommended.

1. Task A - Theoretical modeling and laboratory experiments.

a. Extensive measurements should be conducted to determine the dependence of the dielectric properties of snow on wetness, density, average grain size, crystal structure, and microwave frequency (1 to 18 GHz and 35 GHz).

b. Backscatter and emission models (based on experimental data) should be developed that incorporate the effects of snow parameters (wetness, temperature and density profiles, depth, grain size, and crystal structure) as a function of the sensor parameters (frequency, polarization, and nadir angle).

2. Task B - Ground-based experiments. Knowledge of microwave response to snow moisture and wetness is limited, although significant and important knowledge indicating a potential for water resources management has been gained. It is recommended that an extensive measurement program be conducted to determine the backscatter and radiative emission response to snow as a function of the snow parameters (wetness, density and temperature profiles, depth, density, grain size, and crystalline structure) and the sensor parameters (frequency, polarization, and nadir angle). Although radar is the primary sensor of interest in ongoing experiments, passive microwave radiometers should also be included whenever it is feasible.

a. Sensors - A truck-mounted radar spectrometer plus available passive microwave radiometers.

b. Test sites -

(1) FY 1977 to 1978 - The CSSL's test site.

(2) FY 1978 to 1979 - Test site to be chosen in Colorado. Steamboat Springs test site is a likely candidate. Experiment can be

conducted in cooperation with NOAA (Boulder, Colorado), USFS, SCS, Institute for Alpine Research, and USGS.

c. Ground-truth support - Snow wetness, density and temperature profiles, snow depth, grain size, and crystalline structure. Two approaches are recommended for measuring snow wetness: (1) freezing calorimeter technique and (2) the microwave transmission technique developed by Linlor (NASA/Ames Research Center).

3. Task C - Aircraft experiments. An aircraft program should be instituted to acquire microwave data supported by ground-truth data over selected sites. Starting with the Steamboat Springs, Colorado, test site in 1978, the program can be gradually broadened to include other sites involving other types of snow as success and insight are gained from the results of the ground-based experiments.

a. Sensors - L-band, C-band, and Ku-band NASA/JSC scatterometers and the MFMR system.

b. Coverage requirements - Four flights during the winter season.

c. Test sites -

(1) FY 1978 to 1980 - Steamboat Springs, Colorado.

(2) FY 1979 to 1982 - Test sites with different snow types (Minnesota, Sierra Nevada Range, Cascade Range, Alaska, etc.).

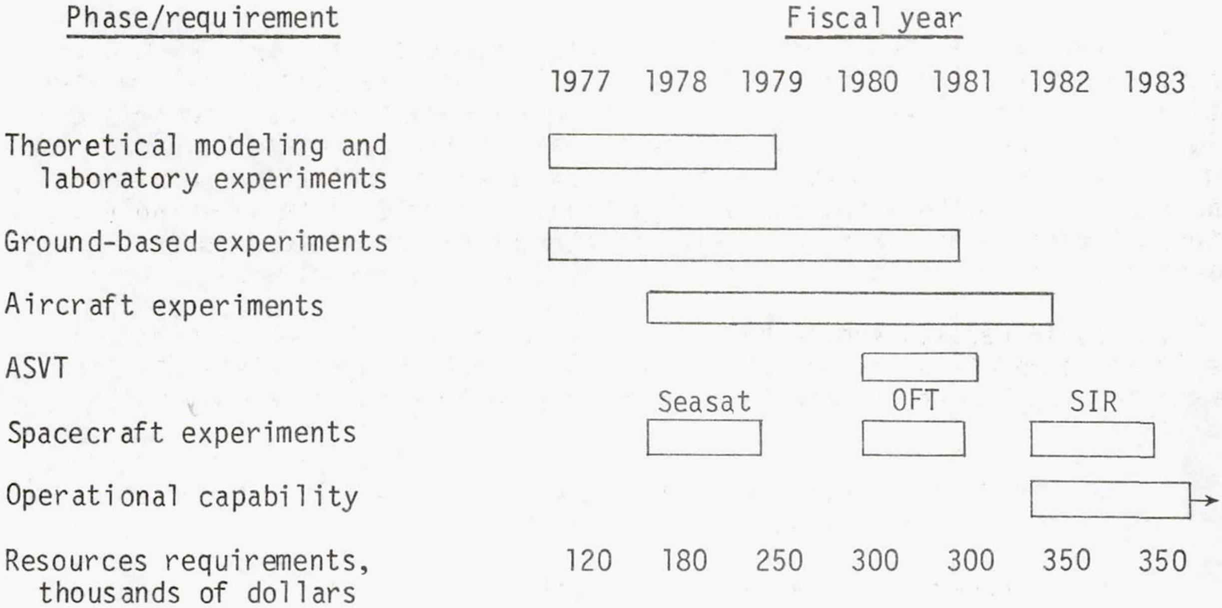
d. Needed sensor development - Unknown at this time; specification of optimum sensor parameters for snow mapping will depend on the results of ground-based experiments.

e. Interpretation techniques development - Algorithms should be developed that utilize active (and passive) microwave data to estimate snowpack/runoff.

f. Ground-truth support - Similar to that for ground-based experiments.

4. Task D - Spacecraft experiments. Seasat, with its L-band SAR, will provide the first opportunity for evaluating the potential of active microwave sensing of snow. An operational system will probably require a two-frequency SAR - e.g., one frequency around the L-band and a higher frequency in the Ku- or Ka-band. Such an opportunity will come with the projected 1982 to 1983 flight of the SIR.

The scheduling relevant to these tasks is as follows.



Watershed runoff coefficient estimation and mapping of drainage basin characteristics.- The general purpose for this area of endeavor is to predict runoff potential for ungaged, medium-sized watersheds ranging in size from 2 to 1000 km^2 in projected surface area. Storm runoff is related to the amount of storage available in or near the surface, occurring in the form of interception, storage, and infiltration. The yield of watershed is related to basin site, stream length and density, and other factors because the drainage basin evolves in such a way as to achieve a balanced throughput capability as a function of the climate and the magnitude of the input variables (precipitation).

Runoff coefficient quantification: Active microwave systems of appropriate wavelengths are thought to be sensitive to soil particle size, vegetation, roughness, and scene moisture. At this time, these factors are reflected in the choice of runoff coefficient determined subjectively by an experienced hydrologist working on a given watershed. This coefficient is provided in an equation of the type utilized by the SCS (see ref. 4-1).

To acquire an operational capability in this application area, the following tasks are recommended.

1. Task A - Theoretical modeling and ground-based experiments. This task is, at the outset, an empirically oriented one. Therefore, theory and ground-based measurements are not suggested initially. After the feasibility and correlation of aircraft and spacecraft SAR observations with measured runoff coefficients are established, careful ground-based measurements should be made to establish the responsiveness of active microwave measurements to soil porosity or infiltration capacity and vegetation density to develop the capability to provide these parameters to more complex

models. Some or all of these tasks may be accomplished in agriculturally related tasks.

2. Task B - Aircraft experiments. The first phase in applying active microwave systems for specifying runoff coefficients was started with observations over small watersheds in Oklahoma, where data have been acquired by using the JPL L-band imaging system on the NASA Convair 990 and the ERIM SAR system. The preliminary results of this research indicate that high-runoff-potential watersheds can be objectively separated from low-runoff-potential watersheds. More work with scatterometer data is needed to understand and specify more clearly the validity of these results.

The early results should be tested over a variety of areas - first in the Oklahoma and Texas areas, with gradual movement to other distinctly different areas. Suggested other areas are small watersheds in Pennsylvania and Idaho.

a. Sensors - L-band, C-band, and Ku-band NASA/JSC scatterometers and imagers as availability and resources permit.

b. Frequency of coverage - Once per season.

c. Test sites -

(1) FY 1976 to 1978 - Selected watersheds in Texas and Oklahoma.

(2) FY 1977 to 1979 - Selected watersheds in Pennsylvania.

(3) FY 1978 to 1979 - Selected watersheds in Idaho.

d. Ground-truth support - The basic ground-based data that are needed for this effort consist of detailed rainfall and runoff data covering a long period of time so that correlations between measured runoff coefficients and microwave observations can be established. In addition, good information on land use, surface cover, and soil characteristics is needed. In the last instance, information on soil permeability and/or hydrologic conductivity is necessary. The total information set needed here is, in general, only available at experimental watershed sites such as those operated by USDA agency research centers. Whenever possible, these watersheds should be utilized in microwave runoff coefficient studies.

3. Task C - Spacecraft experiments. Every opportunity should be used to develop correlations between measured runoff coefficients and data from active microwave observations from space having appropriate spatial resolutions (<100 m). The first opportunity will come with Seasat, L-band SAR, which should be providing data in the 1978 to 1979 time frame. Other opportunities should follow with the Shuttle OFT flights and the projected 1982 to 1983 flight of the SIR.

a. FY 1978 to 1979 - Seasat SAR - observations and analysis.

b. FY 1980 to 1981 - Shuttle geology SAR (OFT-2) flights and possibly Technology Development Satellite/SAR (OFT-5) flights over Texas, Oklahoma, Maryland, and California.

c. FY 1982 to 1983 - Shuttle sortie SIR flights over areas noted previously.

The scheduling relevant to these tasks is as follows.

Phase/requirement — Fiscal year: 1977 1978 1979 1980 1981 1982 1983

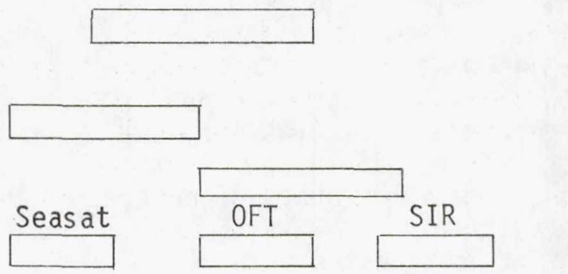
Theoretical modeling and ground-based experiments

Aircraft experiments

ASVT

Spacecraft experiments

Operational capability



Resources requirements, thousands of dollars	1977	1978	1979	1980	1981	1982	1983
Aircraft experiments		50	50	50	50	50	50
Spacecraft experiments		25	75	50	50	25	75
Total		75	125	100	100	75	125

Drainage basin characteristics: The variation in drainage basin characteristics and land-use features can be used to provide indices of peak flows, minimum flows, and annual yields (measurements of stream length, drainage density, basin area, etc.) or to estimate the degree of imperviousness, information leading toward better estimates of flow rates and storm runoff volume in response to various storm inputs.

The feasibility of observing stream networks has already been established by McCoy (ref. 4-13) with the use of aircraft data. The role of active microwave data for land-use identification and basin feature mapping will largely be supportive of high-resolution spacecraft and aircraft observations in the visible/IR regions. The advantages of all-weather coverage are counterbalanced by the low frequency-of-coverage requirements. High spatial resolution can also be provided by these competitive systems. An evaluation of radar/microwave data, when combined with visible, near-IR, and thermal-IR observations, should be made to determine how much improvement in classification accuracy can be attained. The ability to penetrate modest amounts of vegetation and snow cover will be an advantage that should result in improved delineation of drainage basin features and land-use features.

At every opportunity, spacecraft observations should be evaluated to quantify the contribution to delineating the aforementioned features. As already noted, Seasat, Shuttle OFT flights, and Shuttle sortie flights are expected to carry sensors that will afford this opportunity.

Cost-benefit studies and user agency interaction: The contribution of microwave data to improving specification of runoff coefficients and drainage basin characteristics needs to be quantified in terms of cost effectiveness (savings in speed and costs for labor) and benefits (reduction in design costs). These factors must be specified in terms of their gain in contribution over and above contributions made by visible/IR systems.

Space systems and sensor requirements studies: Because aircraft measurements are performed with relatively high resolutions (10 to 25 m), care should be taken to allow the eventual degradation of the data to evaluate the results associated with various resolution factors and signal-to-noise ratios. This task should be performed in terms of specifying differences in runoff coefficients between watersheds, mapping drainage networks, and classifying land use. Furthermore, care should be taken to define requirements for frequency of coverage. In this case, the task should not be difficult because the requirements are apparently not very stringent.

Surface-water and flood mapping.- The capability of mapping surface-water bodies (ponds, lakes, etc.) is useful under the general framework of water resources management. Of particular interest is the ability to map flood-inundated areas under cloud cover conditions. Such a capability can be used for conducting relief efforts, assessing loss of life and property, and delineating the extent of the flood plain.

To acquire an operational capability in this application area, the following tasks are recommended.

1. Task A - Theoretical modeling and laboratory experiments. In the absence of vegetation, the discrimination of water and land surfaces is made on the basis of backscatter return differences due to the difference in surface roughness. In virtually all cases, water is a smoother, more homogeneous target giving a much lower return intensity. Theoretical models for rough-surface scattering are in good agreement with experimental evidence and indicate that discrimination may be easily performed over a wide range of frequencies, incident angles, and polarizations. No additional theoretical or laboratory work is required to support this application.

The presence of vegetation standing above a water surface develops into a distinctly different scattering problem. A volume scattering model that takes into account features standing above a perfectly conducting plane must now be considered. Some theoretical models exist that give some insight into this problem; however, additional work is needed. The complexity and size of the target make this problem unsuitable for detailed laboratory investigation other than definition of vegetation dielectric constant as a function of moisture content. Theoretical models should be developed on the basis of data generated by ground-based experiments.

2. Task B - Ground-based experiments. For flood and wetland mapping, it is desirable to detect surface standing water beneath vegetation cover that may range from a few centimeters of grass to approximately a 30-m height of trees.

Ground-based experiments are extremely desirable for vegetation height and sizes compatible with the elevation and resolution cell size of practical ground-based systems. A ground-based program for the measurement of grass and sedges in a coastal marsh is needed. The extension to greater vegetation heights and a wider variety of environment must be performed initially with an airborne sensor.

The data needed for the vegetated test sites are those of backscattering cross section over a frequency range of 1 to 35 GHz, an incident angle range of 0^{o} to 60^{o}, and a full polarization complement.

a. Sensor - Truck-mounted radar spectrometer.

b. Test sites - Two basic test sites are required, one in a coastal wetland environment and another is an inland freshwater environment. In both cases, the vegetation cover should span as many types and species as possible in a restricted region and under a height limitation on the order of 1 m (a few feet). The following sites are suggested.

(1) Atchafalaya Floodway in Louisiana - This region has served as a coastal marsh test site, and extensive prior data are available for the region.

(2) Freshwater test site - The location of this site is not critical and is not specified. The primary criterion for selection of this site should be proximity to the site location of the measurement facility.

3. Task C - Aircraft experiments. The test sites established for the ground-based measurement program should be used here as well. An additional freshwater wetland area should be included. This additional coverage could best be achieved by moving inland in the Atchafalaya region. Another possible alternative is establishment of a separate freshwater wetland site along the Mississippi River.

To test the capabilities of radar to provide data for mapping flooded areas, missions should be flown over targets of opportunity in storm situations, above the cloud cover.

a. Sensors - Available imaging systems such as JPL's X-band and L-band SAR's or JSC's X-band imager.

b. Coverage requirements -

(1) Wetland mapping - No specific requirements.

(2) Flood situations - As soon as the flooding occurs.

c. Test sites -

(1) Wetland mapping - Same as noted previously.

(2) Flood situations - Flooded areas.

(3) Rice croplands - Early season bare-water scenes.

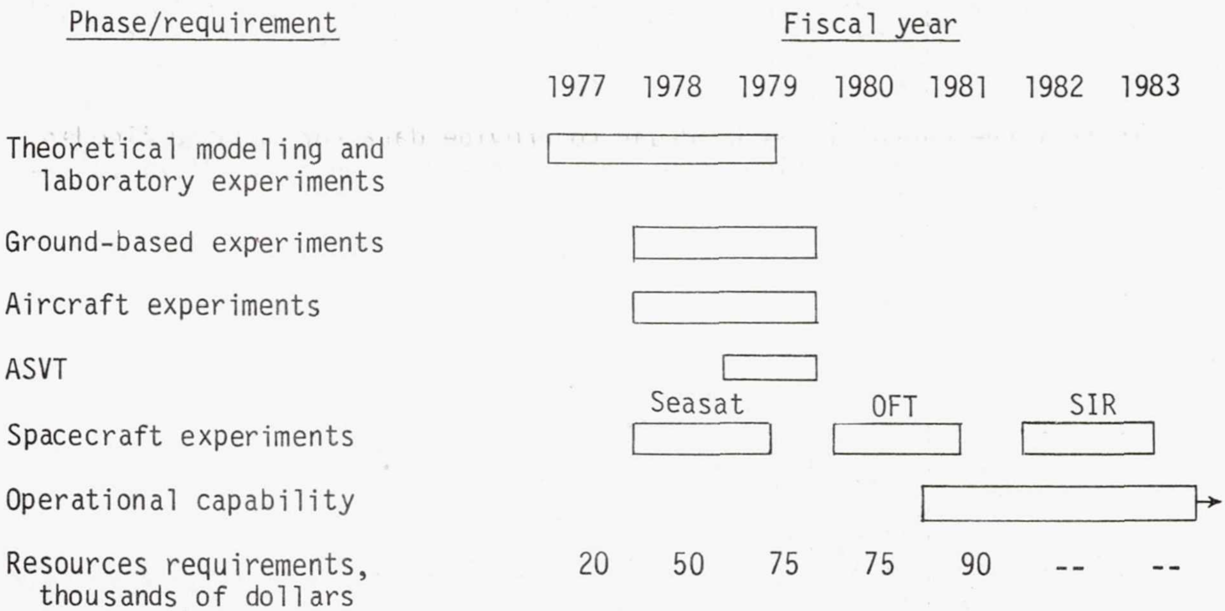
d. Interpretation techniques development - Resolution requirements should be established for conducting wet lake/playa census, dam inventory, and reservoir status monitoring.

e. Ground-truth support - Simultaneous ground-truth support must be provided in conjunction with each aircraft mission. For the water, only two basic measurements are required. First, the areal extent of water that may be masked by vegetation cover must be defined. Second, in the coastal environment, the salinity of the water must be measured. The bulk of ground truth will involve sampling of the vegetation to include type, height, density, and moisture content. The delineation of vegetation type will not normally change over the test interval and will require only periodic updating. However, the height, density, and moisture content measurements must be concurrent with the aircraft overflights.

4. Task D - Spacecraft experiments. The test sites established for the aircraft program should be maintained for initial spacecraft verification experiments with Seasat. With the additional coverage available with the Shuttle system, at least one additional wetland test site should be established in a tropical environment.

Active microwave imagery acquired by satellite systems over flooded areas should be interpreted by using data-processing algorithms to determine the operational utility of radar in flood relief operations.

The scheduling relevant to these tasks is as follows.



Freeze/thaw line monitoring.- There is considerable interest in defining areas on the ground that are frozen (either temporarily or permanently) so that special precautions can be taken to accommodate rapid change of environmental conditions. These changes could be in the form of rapid runoff of melted snow into reservoir areas, extreme ground motion caused by freeze/thaw cycles, changes in trafficability conditions for cross-country mobility, etc. If environmental changes are slow, there are generally precautions that have been established to control the large forces involved. Even when these environmental changes caused by freeze/thaw cycles take place over short time intervals, procedures can be followed to minimize damage or loss of resources if a warning or monitoring system can be devised.

One such monitoring system that appears to have a high potential for success is an active microwave sensor system. These systems are well qualified for freeze/thaw monitoring because (1) they can be used to produce images of large areas quickly and accurately, (2) microwaves are sensitive to the large change in electrical properties of the ground when the ground changes state in the freeze/thaw cycle, and (3) microwaves (at certain frequencies) can penetrate surface materials (i.e., snow, vegetation, and - to a certain extent - unfrozen surface soil) to detect a frozen material interface.

The basic application areas for monitoring freeze/thaw lines are in mapping the permanently frozen areas (permafrost zones), mapping frozen surface materials for runoff calculation in hydrologic studies, and mapping frozen surface materials for agricultural use.

For the aforementioned application areas to be effectively addressed, two scientific objectives must be achieved through microwave measurements: (1) definition of the bounded area defined by surface and/or subsurface frozen material and (2) determination of the depth to the frozen boundaries. These scientific objectives are by no means trivial, because the definitions of areal extent and depth of frozen material are not clear even when ground measurements are taken. A predominantly frozen area can include smaller packets of unfrozen materials at various times during a diurnal cycle. Similarly, repeated freeze/thaw cycles can produce multiple layers of frozen and thawed material as a function of depth.

Fortunately, extremely accurate results are not required for most of the freeze/thaw applications. A microwave sensor with 90- to 200-m spatial resolution would generally give acceptable results. Even depth resolution is not extremely critical. Knowledge of the presence of frozen material, coupled with information relating short-time thermal history of the area, may provide enough information in many cases. Under extremely critical user requirements, crude estimates of the frozen layer thickness are adequate.

Once the state of the ground is known, as well as an estimate of freeze depth, the freeze/thaw line can be updated by using thermal-balance models and weather records. Corrections to model predictions can be made as measurement updates are obtained (every 3 to 15 days).

To acquire an operational capability in this application area, the following tasks are recommended.

1. Task A - Theoretical modeling and laboratory experiments.

a. Laboratory measurements of the dielectric properties of soils as a function of temperature, soil type, and moisture content have been conducted by Hoekstra and Delaney (ref. 4-14). Additional experiments should be conducted to determine the effect of layering.

b. Theoretical backscatter models should be developed (on the basis of ground-based and aircraft data) to improve the choice of sensor parameters for delineating freeze/thaw boundaries under bare and vegetated conditions.

2. Task B - Ground-based experiments. The theoretical relationships used in the identification of the freeze/thaw line are concerned with a decrease in reflectivity for the ground as the ground material changes from the thawed state to the frozen state. The change in reflectivity is due to the change in electrical properties at freezing temperatures. Recent measurements of the radar backscattering coefficient across the 1- to 8-GHz band (ref. 4-15) indicate a strong sensitivity to frozen/unfrozen soil conditions. It is planned to continue this investigation over the 1- to 18-GHz spectral range in conjunction with passive microwave measurements. Because of the nature of this application, the ground-based measurement portion can be conducted jointly with the snowfield-mapping application (see "Snowfield Mapping" subsection).

3. Task C - Aircraft experiments. Airborne experiments should be conducted for a variety of surface conditions on temporarily frozen ground and permafrost. Tests should be conducted during a freeze/thaw cycle so that the change in properties can be monitored. Because the freeze/thaw line detection depends on the identification of reflectance change, standard interpretation and data-processing techniques can be used. All such experiments should be supported with ground-truth surveys to document freeze/thaw conditions during airborne tests.

a. Sensors - L-band, C-band, and Ku-band NASA/JSC scatterometers and the MFMR system.

b. Coverage requirements - Several flights during the spring freeze/thaw cycles. Also, some of the experiments should include several flights during the 24-hour diurnal cycle.

c. Test sites -

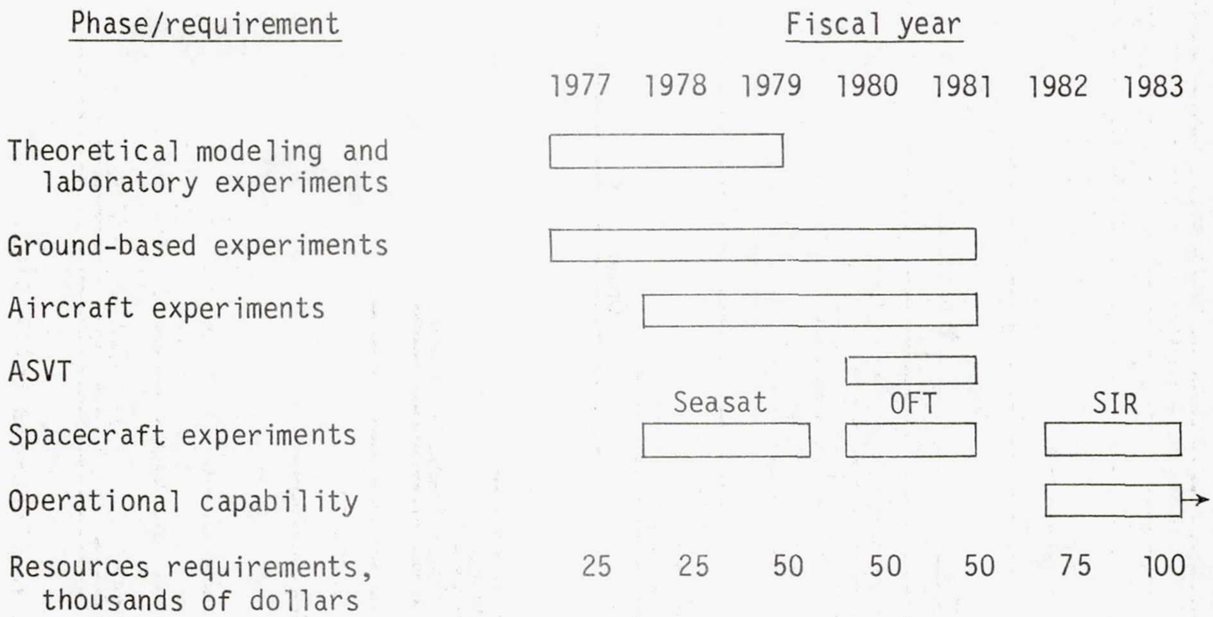
(1) FY 1978 to 1980 - Steamboat Springs, Colorado, test site.

(2) FY 1979 to 1982 - To be selected.

4. Task D - Spacecraft experiments. The first opportunity to evaluate the capabilities of active microwave sensors in delineating freeze/thaw boundaries will be provided by the Seasat SAR system. Other opportunities will follow with the Shuttle OFT flight and the projected flight of the SIR

scheduled for 1982 to 1983. Studies should be conducted with Seasat imagery to evaluate resolution requirements for mapping freeze/thaw boundaries.

The scheduling relevant to these tasks is as follows.



Development Plan

Figure 4-4 is a water resources applications development plan, in flow chart format, summarizing the major steps between the present status of each application area and the ultimate goal - operational capability. The associated schedules of ground-based, aircraft, and spacecraft experiments for each of the major application areas are summarized in figure 4-5, the corresponding resource requirements are summarized in table 4-6, and the test site locations are indicated in figure 4-6.

Summary and Recommendations

The major application areas were rated with respect to priority and feasibility as follows.

Very high:

1. Soil moisture monitoring (including cultivated and uncultivated areas)

2. Snowpack moisture equivalent and wetness monitoring

High: Watershed runoff coefficient estimation

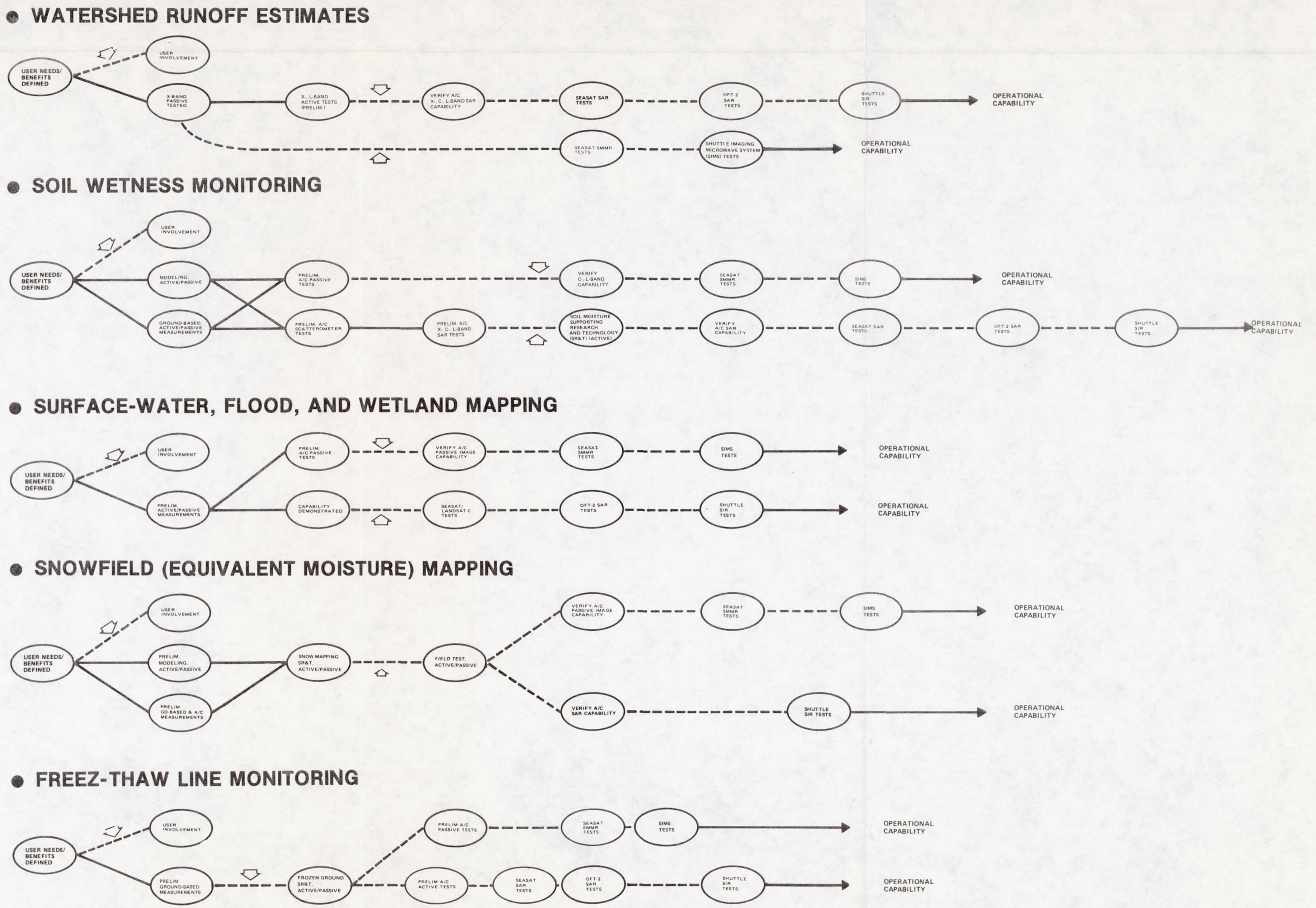


Figure 4-4.- Water resources development plan.

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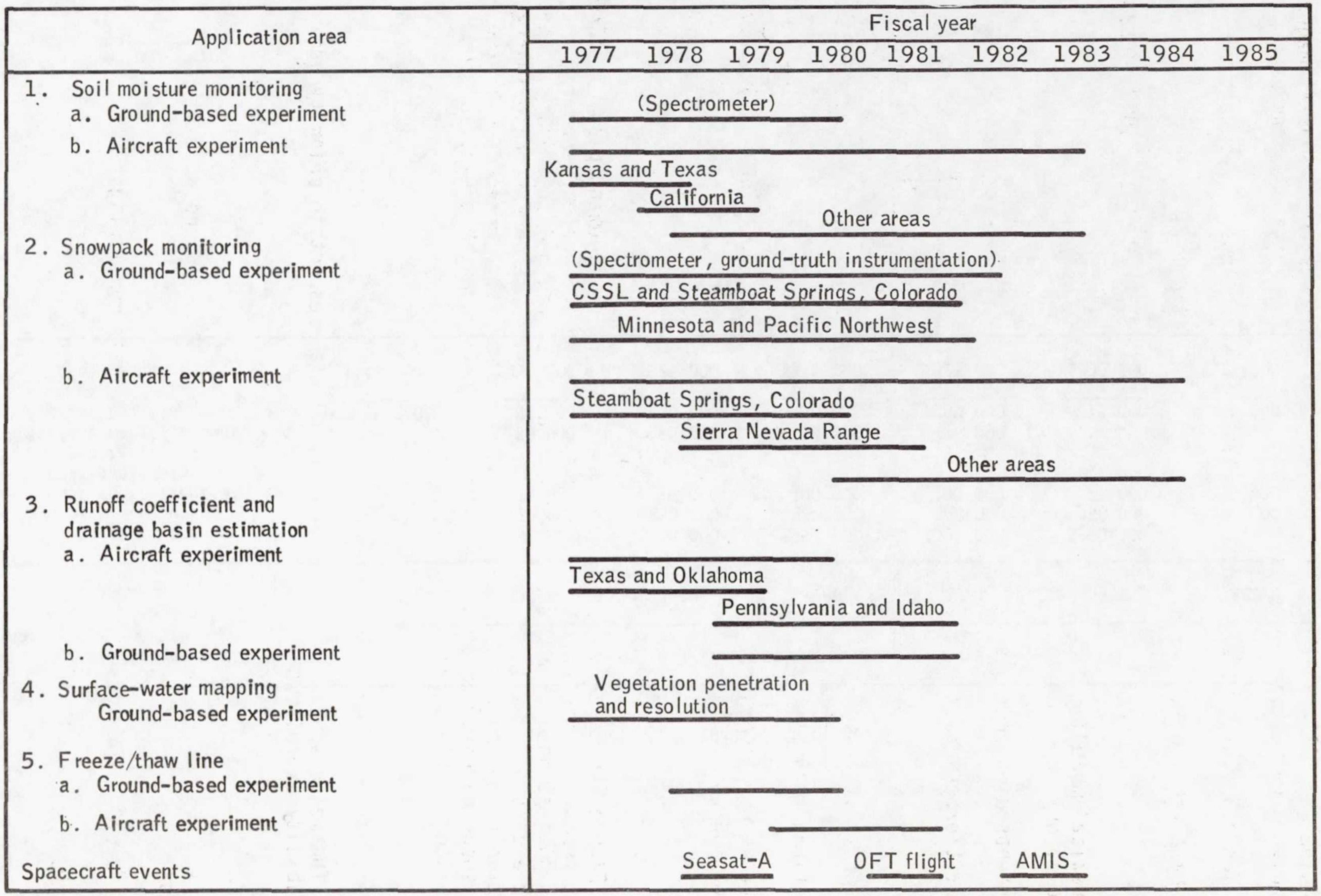

Figure 4-5.- Water resources/active microwave activities.

TABLE 4-6.- WATER RESOURCES FUNDING REQUIREMENTS

Application area	Fiscal year						
	1977	1978	1979	1980	1981	1982	1983
Soil moisture monitoring	$300 000	$550 000	$350 000	$350 000	$300 000	$300 000	--
Snowpack monitoring	120 000	180 000	250 000	300 000	300 000	350 000	$350 000
Runoff coefficient and drainage basin characteristics		75 000	125 000	100 000	100 000	75 000	125 000
Surface water, floods, etc.		20 000	50 000	75 000	75 000	--	--
Freeze/thaw line	25 000	25 000	50 000	50 000	50 000	75 000	100 000
Total resources	$445 000	$850 000	$825 000	$875 000	$825 000	$800 000	$575 000

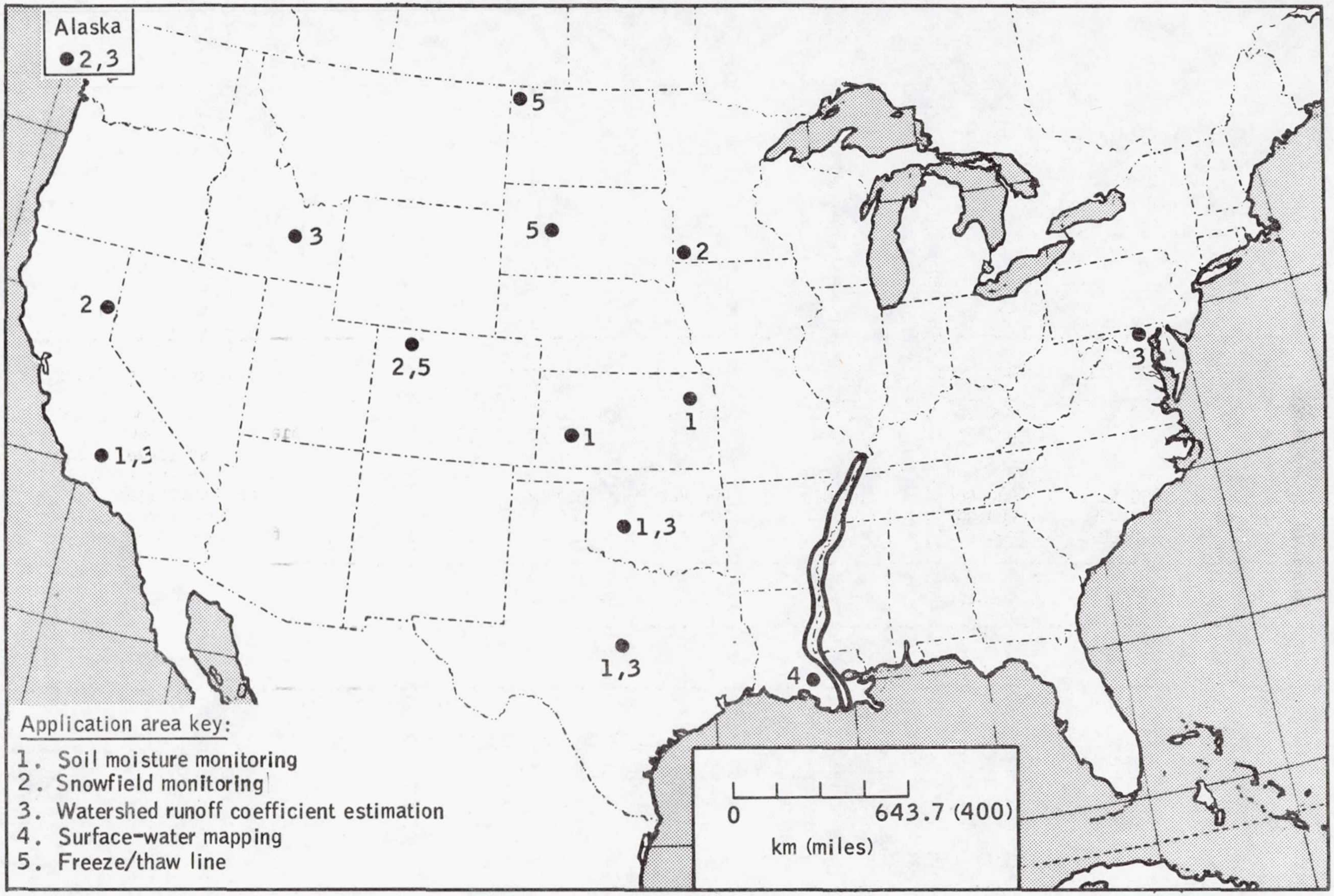

Figure 4-6.- Water resources applications test sites.

Medium:

1. Surface-water, flood, and wetland mapping

2. Freeze/thaw line monitoring

Low:

1. Drainage pattern mapping

2. Land-use mapping

The recommendations are as follows.

1. Develop an airborne SAR for soil moisture monitoring. On the basis of ground-based-measurement results, the system should be a calibrated instrument capable of operating in the 4- to 5-GHz band with a 7° to 17° nadir angle range (minimum).

2. Emphasize analysis of repetitive aircraft measurements and Seasat-A observations of soil moisture variations over Kansas, Oklahoma, and southern California test sites.

3. Emphasize ground-based and aircraft measurement of snow properties with the use of test sites in the central Sierra Nevada Mountains of California and the Rocky Mountains of Colorado.

4. Establish correlation between aircraft and spaceborne SAR observations and measured runoff coefficients with the use of Oklahoma, Texas, and Pennsylvania test sites.

5. Demonstrate, by using spacecraft SAR, the near all-weather capability of spaceborne SAR (e.g., Seasat SAR) to provide data for mapping surface-water variations, including flooding situations.

MINERAL RESOURCES AND GEOLOGIC APPLICATIONS PROGRAM PLAN

Introduction

In geological exploration, more so than in any other geoscience endeavor, radar imagery has been documented as a major source of information. Imaging radars utilized as reconnaissance exploration tools over a wide spectrum of terrains have contributed important data leading to exploration and discovery of a wide diversity of mineral products. As a reconnaissance tool, radar imagery, through the presentation of a synoptic view, enables the geologist to rapidly delimit areas of potential interest that warrant low-altitude aerial coverage and surface examination in order to determine the desirability of subsurface exploration. One major reason radar provides unique data is that the angle and direction of illumination can be controlled regardless of lighting or weather conditions, a capability thus facilitating maximum enhancement of the geological structures most commonly topographically expressed. Equally significant is the capability of SAR to "sense" in a portion of the electromagnetic spectrum to which the human eye is denied access.

Although the geologist has already used imaging radars in varying degrees for (1) mineral and petroleum exploration, (2) regional geologic mapping, (3) detailed geologic mapping, (4) nuclear plant, dam, and other construction site selection, and (5) ground-water exploration through identification of porosity- and permeability-controlling fracture patterns, the full potential of such systems is yet to be realized. In fact, there is not yet a full understanding of terrain-energy interaction with changes in system and target parameters. Without such an understanding, optimum utilization of SAR's will not be achieved. Thus, efforts must be directed toward the following tasks.

1. The development of a better understanding of the effect of variations in terrain and system parameter interactions as reflected in the return signal

2. A better definition of the role of radar in a total-remote-sensing program

3. A further demonstration of the suitability of radar for a wide range of geologic investigations

To achieve such an end, experiments have been defined and categorized both to demonstrate utilization (application) and to better define energy-target interaction (developmental). The highest priority in the developmental area was assigned to the use of polarization properties for definition of surface parameters. The highest priority in the application area has been given to problems associated with mineral and petroleum exploration. Required conditions for the proposed experiments are as follows.

1. High incident angles for topographic information

2. Multifrequency, multipolarization transmission and reception

3. Observations at two or more aspect angles

4. Observations during different seasons

Any study of system parameters and the effect of variations in system parameters with variation in terrain parameters, if accomplished through imaging from a satellite or aircraft platform, necessarily will depend on the analysis of imagery. As a result, although the objectives of this program are twofold, they are isolated only by definition.

The geologist is in a somewhat unique position, for unlike his counterpart in the natural sciences, his demand for data is generally on a one-time basis and the areal extent of his investigation, once defined, is relatively small. The problems of the geologist, in many instances, have been solved without regard to frequency and polarization for numerous areas throughout the world in need of a "first look" reconnaissance survey. Because of this well-established capability, radar rapidly evolved from a Government-financed research and developmental sensor to an industrially utilized operational sensor. This change unfortunately resulted in a de-emphasis of evaluation of system-terrain parameter interaction and a failure to fully exploit radar's capabilities. Thus, radars must continue to be used as operational systems, with their capabilities demonstrated for providing geologic data other than that of a reconnaissance nature. At the same time, system and terrain parameter interactions must continue to be researched. Although ultimately the majority of geologically oriented problems may be solved with single or low-multiple coverage, repeated coverage will be necessary in the experimental stage to define optimum terrain, seasonal, and system parameters for any specific task in a wide variety of environments. Table 4-7 is a summary of systems requirements for five utilization areas in mineral resources and geologic applications.

The present status (table 4-8) of the five broad areas of utilization indicates the degree to which operational radars are being used today. The majority of radar surveys in recent years have been wholly or partially oriented toward the acquisition of geologic data. Well understood is the effect of depression angle (ref. 4-16) on the return signal. The lack of full understanding of the effect of frequency variations (refs. 4-17 to 4-19) and polarization effects (ref. 4-20), together with the utilization of only X-band single-polarization systems commercially, has limited the utilization of radars in some areas of geologic investigation and provided the user with a less-than-optimum product.

Approach

Mapping structural features.- To define lineament or other structural or terrain features not subject to short-term change, in several of the test sites, it is proposed to detect and map lineaments as well as other terrain features, particularly those that are not detected through sensing in the visible region of the spectrum. However, the objectives are not confined to mapping per se but are also designed to demonstrate the role of radar in a total-remote-sensing program. Although radar may stand alone as an all-weather, day or night sensor (refs. 4-21 and 4-22), its role in geologic investigations becomes further enhanced with the demonstration that unique data - data provided neither by the Landsat MSS nor by aerial camera - can be generated. Through controlled experiments with simultaneous acquisition of ground data, an explanation for the revelation of unique terrain information would also be developed; thus, the geoscientist would be presented with necessary information for mission planning to obtain optimum results in other terrains. Because of the identification of numerous terrain elements and, to a large degree, the lack of understanding of the cause of their revelation, it is most important that the cause of revelation - not just revelation alone - be documented. Although extensive research in the past has suggested the reason for the detection of such features in numerous and diverse areas (refs. 4-11 and 4-23), for the most part this documentation has been without the benefit of simultaneous ground-truth acquisition and comparison with simultaneously generated aerial photography or Landsat MSS imagery.

TABLE 4-7.- MINERAL RESOURCES AND GEOLOGIC APPLICATIONS SYSTEMS REQUIREMENTS

Application	Role[a]			Wave-length, cm	Interpretation resolution, m		Nadir angle, deg	Polar-ization type	Revisit interval	Status[b]	Priority[c]	Comments
	Active microwave	Passive microwave	Visible/ IR		Desire	Accept						
Mineral and petroleum exploration	P	N	P	0.8 to 25 MF[d]	15	30	Stereo (aspect angle and incident angle dependent)	HH or VV, cross	Seasonal (4 times/yr)	SE	H	Excellent experimental evidence
Regional geologic mapping	P	N	S	.8 to 25 MF[d]	25	50	40 to 70	HH or VV, cross	Seasonal	PC	H	Operational capability
Detailed geologic mapping	S	N	P	.8 to 25 MF[d]	3	15	40 to 70 (stereo)	HH or VV, cross	Seasonal	SE	M	Limited evidence
Civil works applications	P	N	P	.8 to 25 MF[d]	15	30	40 to 70 (stereo)	HH or VV, cross	Seasonal	PC	H	Excellent experimental evidence
Ground-water exploration	P	S	P	.8 to 25	25	30	40 to 70 (aspect angle dependent)	HH or VV, cross	Seasonal	PS	M	Limited experimentation to date - fracture pattern detection

[a]The role symbols are defined as follows.
P - prime sensor
C - complementary sensor
S - supportive sensor
N - not needed

[b]The status symbols are defined as follows.
PC - proven capability
SE - strong evidence of capability
PS - potential suggested by experimentation

[c]The priority symbols are defined as follows.
H - high priority and feasibility application
M - medium priority and feasibility application

[d]MF - multifrequency.

TABLE 4-8.- STATUS OF ACTIVE MICROWAVE PROGRAM IN MINERAL RESOURCES AND GEOLOGIC APPLICATIONS

Variable	No. of theoretical modeling and laboratory experiments	No. of ground-based experiments	No. of aircraft experiments	No. of spacecraft experiments
Mineral and petroleum exploration and regional geologic mapping				
Drainage pattern	(a)	(a)	2	--
Topography	(a)	(a)	2	--
Fracture pattern	(a)	--	2	--
Rock type	1	--	--	--
Soil/rock cover (size)	1	--	2	--
Soil/rock cover (composition)	1	--	--	--
Vegetation	(a)	2	2	--
Moisture content	1	2	1	--
Detailed geologic mapping				
Drainage pattern	(a)	(a)	2	--
Topography	(a)	(a)	2	--
Fracture pattern	(a)	--	2	--
Rock type	1	--	--	--
Soil/rock cover (size)	1	--	2	--
Soil/rock cover (composition)	1	--	--	--
Vegetation	(a)	2	2	--
Moisture content	1	2	1	--
Civil works applications				
Drainage pattern	(a)	(a)	2	--
Topography	(a)	(a)	2	--
Fracture pattern	(a)	--	2	--
Rock type	1	--	--	--
Soil/rock cover (size)	1	--	2	--
Soil/rock cover (composition)	1	--	--	--
Vegetation	(a)	2	2	--
Moisture content	1	2	1	--
Ground-water exploration				
Drainage pattern	(a)	--	2	--
Topography	(a)	(a)	2	--
Fracture pattern	(a)	--	2	--
Rock type	(a)	(a)	--	--
Soil/rock cover (size)	1	--	2	--
Soil/rock cover (composition)	(a)	(a)	(a)	--
Vegetation	(a)	2	2	--
Moisture content	1	2	1	--

[a]Not applicable.

To acquire an operational capability in this application area, the following tasks are recommended.

1. Task A - Aircraft and spacecraft experiments. The capability of the SLAR to provide mapping data has already been well documented; hence, the following experiments are designed to further demonstrate that capability (in areas of renewed interest - for petroleum exploration and for critical fault data for nuclear reactor site selection), as well as utilize the all-weather, day or night capability (in an area of high-percentage cloud cover for which few geologic data are available).

a. Mineral and petroleum exploration - central Arkansas.

(1) Objective - To demonstrate the utility of temporal multifrequency-polarization radar data for mineral and petroleum exploration in a heavily forested terrain.

(2) Approach -

(a) Initially, aircraft radar imagery will be acquired and analyzed. Definition of best available frequency and polarization or combinations will be achieved.

(b) Comparisons will be made with published and field-acquired data.

(c) Spacecraft data covering the same area will be analyzed and correlated with aircraft-acquired data to establish the feasibility of spacecraft imaging. Once this feasibility is defined, additional sites of similar terrain environment will be evaluated.

(3) Sensors - Multifrequency, multipolarized radar imagery is required; however, optimum parameters of the system are not defined (but will be determined) because only single-frequency systems have been used to any extent in geologic mapping.

(4) Test site - Central Arkansas (center geographic coordinates: $35^{o}30'$ N., $93^{o}30'$ W.).

(5) Frequency of coverage - Seasonal coverage is required initially but probably is not required following the determination of the "best" time for coverage.

(6) Season and time constraints - Probably one after initial acquisition and analysis of data.

b. Geologic analysis - Eastern Coastal Plain.

(1) Objective - To determine utility of radar for the interpretation of subtle geological structure in a relatively low relief environment as related to site selection of nuclear reactors.

(2) Approach -

(a) Use photo-geologic techniques with aircraft-acquired radar to detect subtle structural features from variations in forest canopy and soil moisture.

(b) Radar imagery will be compared to processed NASA photography, and image products will be analyzed by various geologists and Earth scientists.

(3) Sensors - Dual wavelength (2 cm and 25 cm) radar, low and high incident angle, and two-aspect-angle imagery analysis.

(4) Test sites - Two areas will be studied: (1) near Fredericksburg, Virginia, (center geographic coordinates are approximately 38° N., 78° W.) and (2) near Charleston, South Carolina (center geographic coordinates are approximately 33° N., 81° W.).

(5) Frequency of coverage - Not applicable following the determination of "best" season coverage.

(6) Season and time constraints - Data should be collected twice during the year, once in January or February and once during the summer.

c. Geomorphic expression of geologic structure - Tertiary basins of Alaska.

(1) Objective - To demonstrate in relatively inaccessible terrain the utility of radar geomorphic studies and to relate geomorphic features to underlying geologic structure. Ultimate aim will be the definition of targets for petroleum exploration.

(2) Approach -

(a) Acquire aircraft radar data and prepare a geomorphic map from imagery. The geomorphic map will be based on and include lineation, slope distribution, drainage patterns, terrain texture, and topographic profiles. Correlate geomorphic and geologic data whenever it is possible to do so.

(b) Compare radar-derived geomorphic maps with the published maps.

(c) Field check the geomorphic maps and determine their reliability.

(3) Sensors - Multipolarized, multifrequency radar imagery is required; however, specific parameters of the system are not defined because of lack of data.

(4) Test sites - Tertiary basins in Alaska. Major basin is centered at approximately 65° N. latitude and 140° W. longitude.

(5) Frequency of coverage - Basically, one-time coverage with initial consideration given to seasonal and time constraints. For the first time, spring, summer, and fall coverage is desired.

d. Geomorphic and geologic analysis - Coastal marsh and swamp environments.

(1) Objective - To demonstrate applicability of dual-/cross-polarized, multifrequency radar for geomorphic/geologic analysis of wetland environments.

(2) Approach -

(a) Obtain multipolarized, multifrequency radar imagery at the time of field data collection.

(b) Make quick-look analysis of data and take into field (helicopter support preferred) to check possible problem interpretive areas.

(c) Do more detailed interpretation based on published data and on "before and after" field data.

(3) Sensors - A dual-/cross-polarization, multifrequency aircraft-mounted radar. Specific bands are not suggested because the data needed to draw conclusions are not available. However, the broad band between the K- and L-band will probably provide the most information. Spacecraft-mounted radar to be used for followup.

(4) Test site - Lower Atchafalaya River Basin and Atchafalaya Bay coastal region. Center geographic coordinates are 30°00' N., 91°30' W.

(5) Frequency of coverage - Initially, seasonal but not required continually.

(6) Season and time constraints - Signal dependence on vegetation relationship to seasonal temperature and hydrologic changes necessitates coverage from at least two, and probably four, times of the year.

Monitoring terrain alterations.- Radar utilized as a change-monitoring device has obvious value in its capability for all-weather, day or night surveillance. Early detection of erosion problems, either on land or at the land-sea interface, facilitates immediate corrective action, with the result that the destruction of valuable land is prevented and the probability of financial losses is reduced. Only one sensor, radar, has such a monitoring capability - a capability postulated but not proven. Only a satellite-borne system is financially feasible, and a demonstration of such a capability would suggest to the scientific community numerous possibilities for utilization of the system in monitoring ongoing geologic processes.

The proposed missions (aircraft and spacecraft experiments) are basically for mapping purposes and emphasize the all-weather, day or night capability of the SLAR. Additionally, a study of resolution requirements for these applications should be conducted. The following experiments are proposed.

1. Soil erosion, lumbering effects.

a. Objective - Determine and monitor the soil erosion effects caused by various lumbering practices, with the ultimate objective of determining the method least likely to produce detrimental terrain modification.

b. Approach -

(1) Image the test site area with radars of various frequencies. Use various incident angles and observe the area during the four seasons. Use image enhancement techniques to extract information.

(2) Develop a program for continuous monitoring of lumbering operations and early detection of soil erosion problems.

(3) Determine the feasibility of such monitoring of small-scale effects by spacecraft radars.

c. Sensors - Very high frequency (vhf), JPL L- and X-band multi-polarization SAR.

d. Test site - Redwood National Park, California. Corner coordinates are as follows.

34°00' N., 81°00' W.

33°15' N., 79°15' W.

32°00' N., 81°00' W.

32°45' N., 82°00' W.

e. Frequency of coverage - Once in January or February, once during summer months.

2. Monitoring coastal processes and change - U.S. west coast.

a. Objective - To monitor coastal processes during and immediately following major storms, when the greatest change occurs and the regions are masked by cloud cover.

b. Approach -

(1) Establish five test sites along the coast encompassing different conditions (dunes, cliff, estuarine/river mouth, marsh, and culturally influenced).

(2) Establish a time-line data base using available published data, aerial photography, and K-band radar (1965) for determining long-range changes.

(3) Acquire aircraft radar data from two opposite aspect angles (both parallel to coastline) during several winter storms, when the major coastal changes take place. Collect field data at same time.

(4) Overlay data in two time sequences for change detection on long- and short-term basis.

(5) Use image-processing techniques to "stretch" the low-return areas from water and open sand and thus increase image information.

(6) Use image enhancement techniques to combine data gathered in a different time, polarization, and frequency format.

c. Sensors - Multifrequency, multipolarized, multilook imaging radar must be flown as an attempt to determine the best combination of these image parameters required for coastal investigations.

d. Test sites - Specific test sites have not been selected. Five sites would embrace different natural and cultural environments.

e. Frequency of coverage - Both remote-sensing and field data need to be acquired before, during, and following several major storms (hopefully of different magnitudes and coming from different directions). This acquisition would be followed by a continuing program in which data would be acquired at a preset interval, with greater frequency of coverage coming during the period of major storms (winter).

f. Season and time constraint - The initial coverage is strongly seasonal and time dependent. Time of data acquisition will be storm dependent.

Terrain-sensor interaction studies.- The second objective is to improve definition of terrain-sensor interaction with variation in system and terrain parameters. Of specific interest are frequency-roughness and polarization-microrelief relationships and the isolation of the effect of dielectric constant variations on the return signal. Regardless of environment, but particularly in arid and semiarid regions, the configuration of fragments of a residual cover is indicative of the nature of the underlying rock material and, thus, may aid considerably in the delineation of geologic units. Where bare rocks are exposed at the surface, their weathering characteristics are diverse; and the surface configuration, as well as the degree of weathering and resulting contrast in topography, aids in identification and mapping. Of importance in such discrimination is an understanding of the effect of variations, polarization, and wavelength on the separation of units as expressed in the resulting image. A singular study (ref. 4-20) on the value of polarization in a single frequency has provided positive evidence that polarization orientation is important. Several studies (refs. 4-24, 4-16, and 4-19) concerned with rock discrimination relative to radar frequency have pointed to the value of multifrequency systems. Further studies in diverse terrains with multipolarization, multifrequency systems are needed to determine the optimum parameters for a wide range of terrain studies.

Although a great deal has been done to define the effect on the return signal of soil moisture content at a range of frequencies, only preliminary studies have been made to isolate the effect of saline content on the dielectric properties of surficial materials and determine the effect on the return signal.

Well recognized in several areas in the United States today is the problem of saline pollution through circulation of salt water to the surface. Any attempt to correct such conditions initially requires the identification of areas of pollution, as well as continued monitoring of the shape or size of the polluted area. Preliminary laboratory and Skylab microwave data acquired over the Great Salt Lake Desert indicate that saline content can strongly influence the radar return signal. Particularly in areas where climatic conditions pose problems for aerial monitoring, radar, with a capability to detect subtle contrasts in saline content of surface and ground water, should prove invaluable. If pollution has affected the vegetation pattern, near-IR photography should detect the contrast between contaminated and uncontaminated areas. However, for repetitive monitoring in order to detect change and for all-season monitoring when vegetation contrasts are largely eliminated, radar shows potential for being the prime sensor in such a study.

Theoretical modeling and laboratory, ground-based, and aircraft experiments to determine the effects of saline seeps on the radar backscatter have been covered in the "Vegetation Resources Program Plan" section and, hence, will not be repeated here.

To acquire an operational capability in this application area, the following tasks are recommended.

1. Task A - Ground-based experiments. With the exception of acquisition of ground data simultaneously with overflights, ground-based experiments are required only for the polarization signature study, for which the X-band polarization modulation system mounted on a mobile ground platform will be utilized. A description of this study may be summarized as follows.

a. Objective - Determine backscatter polarization signatures for the purpose of identifying surface-roughness types and vegetation.

b. Approach - Reassemble the X-band polarization modulation systems, mount the radar on the cherry picker and truck, and deploy the sensor at selected sites.

c. Sensors - X-band short-pulse radar, polarization modulation antenna, cherry picker, and truck.

d. Availability - The radar system was completed in 1972, some data were obtained, and the system was disassembled, with some components going to the X-band imaging radar. The antenna, which is a major component, is in storage; the status of the logic and modulator is uncertain. However, the system could probably be reassembled at a relatively low cost.

e. Test sites - The truck would go to various sites - such as Death Valley, California, crop identification sites (Kansas), snow cover sites, etc. - to obtain polarization signatures.

f. Frequency of coverage - In areas where the scatter changes with season, the truck would revisit the sites at appropriate times.

g. Schedule - One year is needed to assemble the sensor; included will be the radar, the cherry picker, the truck data-storage device, and the system for processing data. One year is assigned to accumulating the signature data.

h. Cost estimate -

(1) Antenna - Available, no cost.

(2) Cherry picker - Available, no cost.

(3) Truck - Available, no cost.

(4) Radar - Reassemble some components,	$150 000
(5) Data storage -	40 000
(6) Data-processing software -	30 000
(7) Operations (1 year) -	60 000
	$280 000

2. Task B - Aircraft and spacecraft experiments.

a. Death Valley, California, backscatter modeling -

(1) Objective - Determine the effect of surface roughness on radar backscatter at various wavelengths. Establish a calibration site for all radar systems.

(2) Approach - Measure surface roughness with surface devices such as stereophotographs and profile gages; measure dielectric properties, water content, and gravel sizes. Conduct aircraft flights in which scatterometers and imaging radars are used. Conduct spacecraft radar observations on the site.

(3) Sensors -

(a) Three-frequency (0.4, 1.6, and 13.3 GHz) scatterometer (JSC).

(b) Passive microwave (1.4 GHz) radiometer (JSC).

(c) IR spot radiometer (JSC).

(d) L- and X-band imaging radars, vhf (JPL).

(e) Seasat SAR, L-band (JPL).

(4) Test site - Death Valley, California.

(5) Frequency of coverage - Not applicable.

(6) Season and time constraints - Not applicable.

b. Polarization studies - Pisgah Crater, California, and central Utah.

(1) Objective - To determine the polarization-frequency interrelationships of the radar return from natural geologic terrains.

(2) Approach - Review previous data and obtain X- and L-band imagery (and any other available) with HH-, VV-, and cross-polarization. Surface configuration, composition, and moisture data will be acquired during overflights; imagery will be evaluated annually and in various combined formats; and the correlation of radar signature and terrain characteristics will be investigated.

(3) Sensors - L-band and X-band SAR, aerial cameras.

(4) Test sites - Pisgah Crater, California, and San Rafael Swell, Utah.

(5) Frequency of coverage - Dual coverage.

(6) Season and time constraints - Not applicable.

c. The role of salt content in control of SAR return signature from a playa or desert area, Great Salt Lake Desert, Utah -

(1) Objective - Develop a mechanism for determining the salt content of desert and playa soils with the use of SAR imagery.

(2) Approach - Identify, from ongoing studies, areas of contrasting salt content, lithologies and roughness, and vegetative cover for coverage with JPL X- and L-band radar. Identify, insofar as possible, the contribution of roughness, soil composition, vegetation, soil moisture, and salt content to the return signal.

(3) Sensors - JPL X- and L-band radar with multipolarization capability. Aerial camera for control, feature identification, and sample-site location.

(4) Test site - Great Salt Lake Desert, Utah; 100- by 200-km flight lines as defined on accompanying map.

(5) Frequency of coverage - Two flights.

(6) Season and time constraints - August and December during periods of relative surface dryness.

d. Comparative study of Landsat and SAR imagery -

(1) Objective - A comparison between Landsat MSS imagery and two-polarization JPL X- and L-band SAR imagery to document any unique (other than cloud penetration) capability of the SAR and, at the same time, compare the relative data content of X- and L-band imagery for two polarizations.

(2) Approach - Selection of the site will be based on the intensity and diversity of origin of structural (primarily linear or curvilinear) features identified within the area in eastern Kansas now subject to intense scrutiny for evidence of recent faulting and/or earthquake activity. SAR imagery and near simultaneously acquired Landsat imagery would be independently evaluated for structural content, and the cause for correlation or lack of correlation with terrain features would be determined. Unique capabilities of SAR and the reason for such should be expected to be established.

(3) Sensors - JPL X- and L-band multipolarization SAR, Landsat imagery.

(4) Test sites - Kansas, east of Nemaha Uplift (precise definition on basis of results of current investigation).

(5) Frequency of coverage - Seasonal (four times). If feasible, winter coverage during period of snow cover for maximum enhancement of features on Landsat (MSS) imagery.

(6) Season and time constraints - Near simultaneous acquisition of SAR and Landsat imagery. Winter scene with snow cover preferable.

Development Plan

Figure 4-7 is a mineral resources and geologic applications development plan, in a flow chart format, summarizing the major steps between the present status of each application area and the ultimate goal - i.e., operational capability. The associated schedules of aircraft and spacecraft experiments for each of the major application areas are summarized in figure 4-8, the corresponding resource requirements are summarized in table 4-9, and the test site locations are indicated in figure 4-9.

Summary and Recommendations

The proposed experiments, although somewhat diverse in immediate objectives, are basically designed to achieve the following two long-range objectives.

1. To demonstrate utilization of active microwave technology in a wide range of geologic investigations in a wide range of environments

a. To define lineament or other structural or terrain features not subject to short-term change

b. To monitor natural or man-induced physical or chemical terrain alteration

2. To better define target-terrain interaction with system-terrain parameter variation

Specifically, it is recommended that NASA place renewed emphasis on the definition of optimum system parameters for a wide range of geologic investigations, and special emphasis on the development of the polarization capability of the radar measurement system. At the same time, applications research and demonstration should continue in order to further industrial as well as governmental understanding and acceptance of radar as a significant exploration tool.

OCEANOGRAPHIC APPLICATIONS PROGRAM PLAN

Introduction

The subpanel on oceanographic applications recognizes the potential value of imaging-radar experiments from the Shuttle in the development and demonstration of techniques for ocean applications. Certainly, those people involved in oceanographic work look forward to opportunities to make use of these data. It is the present consensus of the oceanographic community that the Shuttle represents a desirable, but not indispensable, link between present technology and that required to implement an operational system of oceanographic satellites deploying imaging radar. It now appears that SAR data processing, rather than SAR sensor development, is the key problem to be solved. Table 4-10 is a summary of progress, observational requirements, and relationships to other sensors pertaining to each major oceanographic application area.

Approach

For several years, a representative cross section of the oceanographic community has been meeting on a regular basis to plan experiments in connection with Seasat. The members of this subpanel, many of whom participated in these meetings, do not believe that it is desirable to attempt to summarize these plans here. These plans have been through several iterations, such as those found in the following internal NASA reports.[6]

Seasat-A Science Contributions

Seasat-A Phase B Study Report

EODAP[7] Program Plan (in revision)

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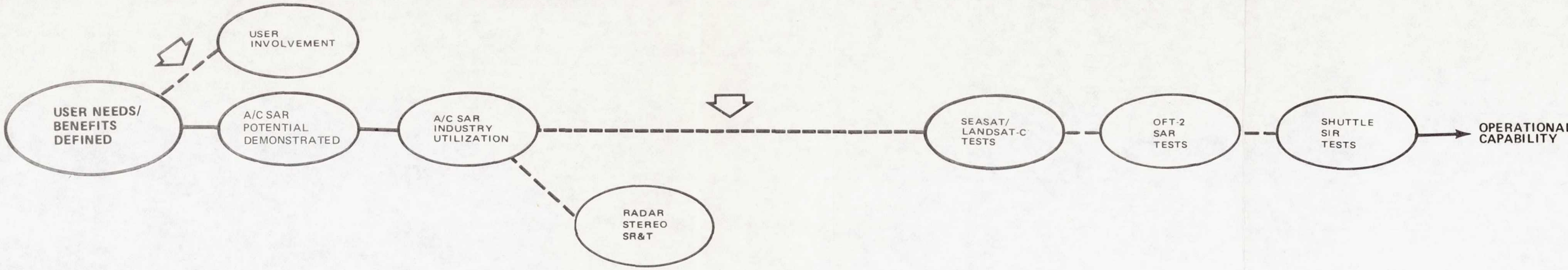
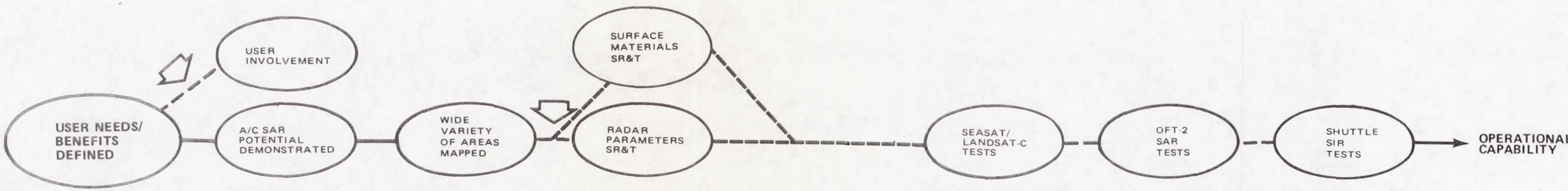
[6]Not available to public.
[7]Earth and Ocean Dynamics Applications Program.

● MINERAL, PETROLEUM, AND GROUND-WATER EXPLORATION



● GEOLOGIC MAPPING



● CIVIL WORKS APPLICATIONS

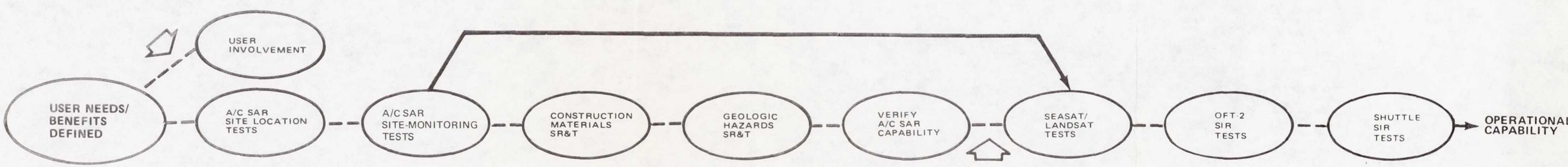


Figure 4-7.- Mineral resources and geologic applications development plan.

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Application area	Fiscal year 1976–1978: Aircraft experiments	Fiscal year 1979–1980: Spacecraft experiments
1. Mapping structural features		
a. Mineral and petroleum exploration - central Arkansas	▽ A D △	Seasat △ OFT-2 △
b. Geologic analysis - Eastern Coastal Plain	OG A D △	Seasat △ OFT-2 △
c. Geomorphic study - Alaska	▽ A D △	Seasat △ OFT-2 △
d. Geomorphic analysis - coastal and swamp	▽ A D △	Seasat △ OFT-2 △
2. Monitoring terrain alterations		
a. Soil erosion-lumbering effects	▽ A D △	Seasat △ OFT-2 △
b. Monitoring coastal processes	▽ A △	Seasat △ OFT-2 △
3. Terrain-sensor interaction studies		
a. Death Valley, California, backscatter modeling	OG A D A D △	Seasat △ OFT-2 △
b. Polarization study - Pisgah Crater, California	▽ A D △	
c. Salt content effects - Salt Lake Desert, Utah	OG A D A D △	
d. SAR/Landsat comparative study	OG A D △	

Key:

A - Aircraft flights complete
D - Data read/analysis complete
OG - Ongoing
▽ - Initiate
△ - Reports, project complete

Figure 4-8.- Mineral resources and geologic applications/active microwave activities.

TABLE 4-9.- MINERAL RESOURCES AND GEOLOGIC APPLICATIONS FUNDING REQUIREMENTS

Application area	Fiscal year				
	1976	1977	1978	1979	1980
Ground-based experiments					
Polarization signature study	$150 000	$140 000	$ 90 000	$ 60 000	--
Aircraft experiments					
Mapping structural features					
Mineral and petroleum exploration - central Ark.	20 000	60 000	50 000	60 000	$ 60 000
Geologic analysis - eastern Central Plain	Ongoing	80 000	50 000	60 000	60 000
Geomorphic study - Alaska	--	80 000	120 000	60 000	60 000
Geomorphic analysis - coastal and swamp	--	80 000	60 000	60 000	60 000
Monitoring terrain alterations					
Soil erosion - lumbering effects	20 000	60 000	50 000	50 000	40 000
Monitoring coastal processes	--	80 000	100 000	60 000	60 000
Terrain-sensor interaction studies					
Death Valley, Calif., backscatter modeling	Ongoing	80 000	40 000	60 000	60 000
Polarization study - Pisgah Crater, Calif.	--	80 000	60 000	--	--
Salt content effects - Great Salt Lake Desert, Utah	Ongoing	80 000	60 000	--	--
SAR/Landsat comparative study	Ongoing	50 000	60 000	--	--
Total resources	$190 000	$870 000	$740 000	$470 000	$400 000

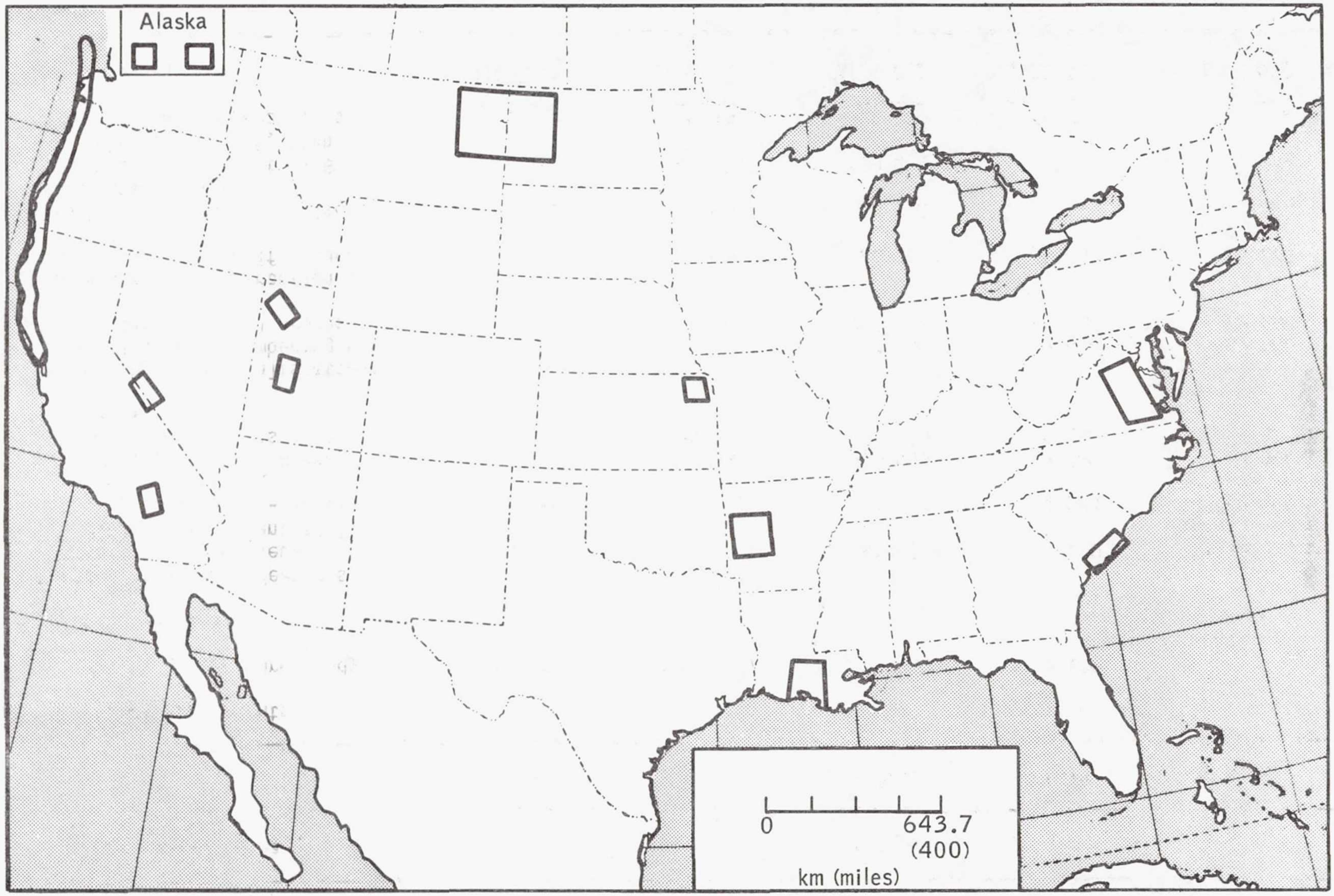

Figure 4-9.- Mineral resources and geologic applications test sites.

TABLE 4-10.- OCEANOGRAPHIC APPLICATIONS SYSTEMS REQUIREMENTS

Application	Role[a]			Wave-length,[b] cm	Interpretation resolution, m		Nadir angle, deg	Polar-ization type	Revisit interval, hr	Status[c]	Priority[d]	Comments
	Active microwave	Passive microwave	Visible/ IR		Desire	Accept						
Ocean waves and sea state monitoring	P	C	N	1 to 30 MF	3	25	0 to 25	HH, VV	6 to 12	PS	H	Extensive experiments in progress
Sea ice monitoring	P	P	N	1 to 30 MF	25	25	0 to 25	HH/VV/cross	6 to 12	PC	H	Proven sea ice capability
Icebergs and ship monitoring	P	S	N	1 to 30 MF	10	25	25 to 60	HH/VV/cross	6 to 12	SE	M	Experiments in progress
Oil pollution monitoring[e]	P	S	S	1 to 30 MF	25	25	0 to 25	VV, cross	6 to 12	PC	M	Proven oil spill detection

[a]The role symbols are defined as follows.
- P - prime sensor
- C - complementary sensor
- S - supportive sensor
- N - not needed

[b]MF = multifrequency.

[c]The status symbols are defined as follows.
- PC - proven capability
- SE - strong evidence of capability
- PS - potential suggested by experimentation

[d]The priority symbols are defined as follows.
- H - high priority
- M - medium priority

[e]Extensive testing underway by Coast Guard.

Seasat-A Project Plan

SAR Experiment Plan (in preparation)

NOAA Seasat-A Program Development Plan

Development Plan

Figure 4-10 is an oceanographic applications development plan, and figure 4-11 presents summary schedules.

Summary and Recommendations

The major application areas were rated with respect to priority and feasibility as follows.

High:

1. Ocean waves and sea state monitoring and forecasting

2. Sea ice monitoring

Medium:

1. Iceberg monitoring and ship navigation routing

2. Oil pollution monitoring

3. Coastal structure placement

Because most of the parameters of interest in oceanography and ship monitoring change significantly from hour to hour, the data from a short-lived-satellite imaging radar system have no operational value in themselves. For the oceanographer, the usefulness of the SIR program is with respect to advancing the instrument's development and conducting space engineering/environmental tests. Hence, it is recommended that NASA place special emphasis on these aspects.

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• OCEAN WAVE AND SEA STATE MONITORING

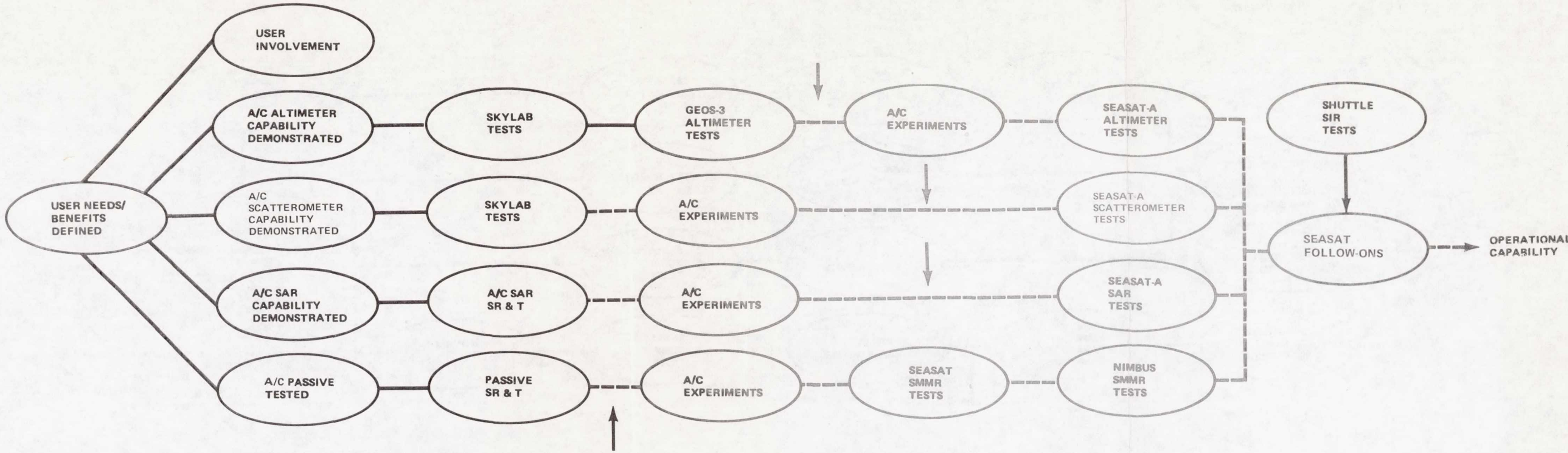

Figure 4-10.- Oceanographic applications development plan.

● SEA ICE MONITORING

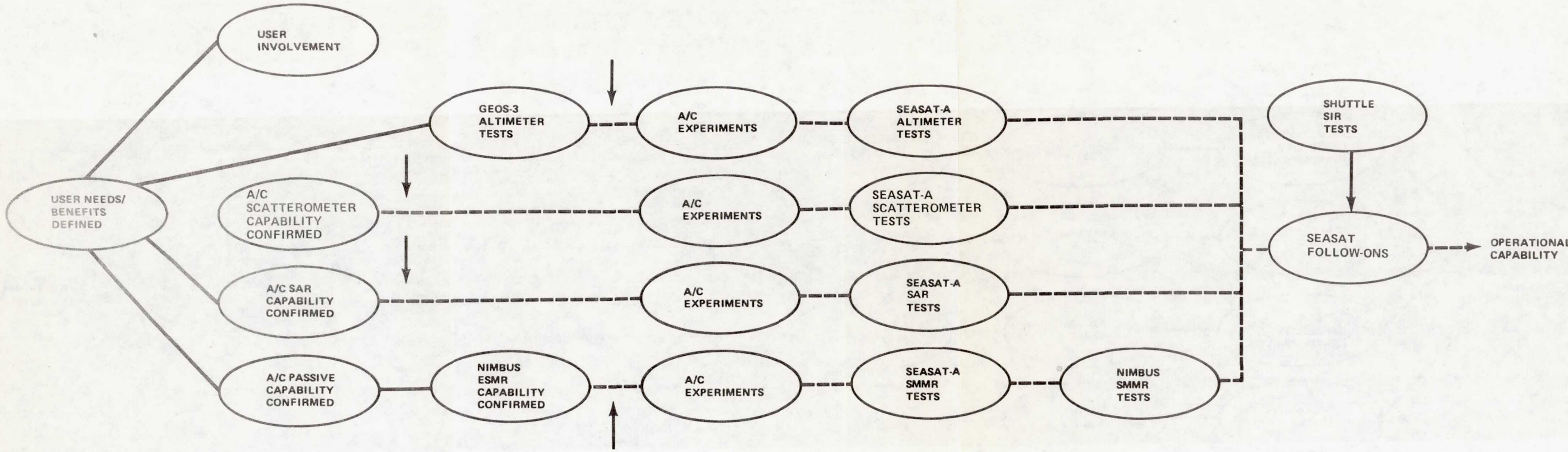

Figure 4-10.- Continued.

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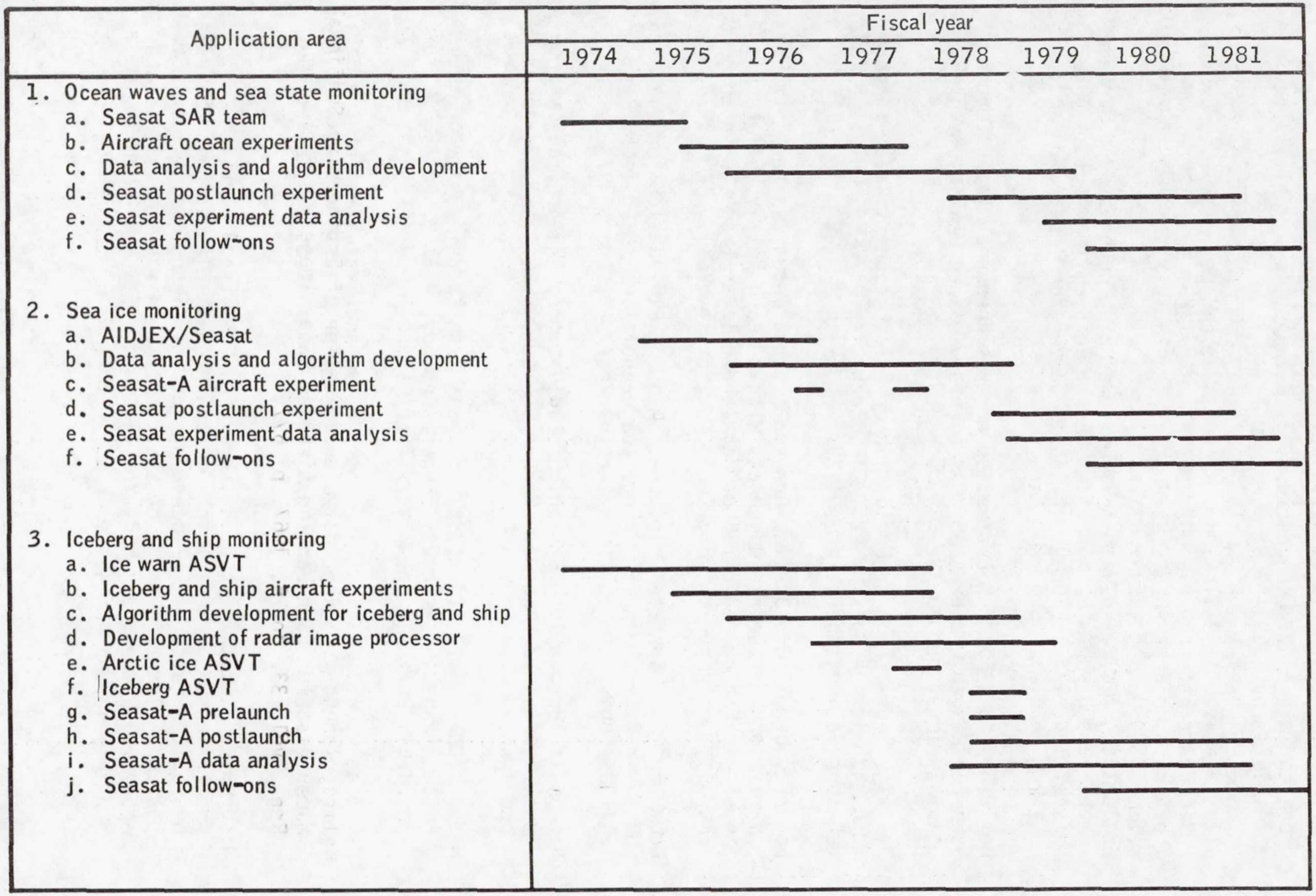

Figure 4-11.- Oceanographic applications/active microwave activities.

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CHAPTER 5

SYNTHETIC APERTURE RADAR (SAR) DATA PROCESSING

Active Microwave Users Working Group

SAR Data Processing Panel:

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INTRODUCTION

The SAR Data Processing Panel met to "identify the available and optimal methods for generating SAR imagery for NASA applications." Because this panel was the first NASA-sponsored workshop panel to address the SAR-data-processing problem specifically, it was decided that the panel should cover this subject in a broad manner, by (1) starting with the known applications for SAR imagery, (2) identifying the SAR image quality and data-processing requirements associated with these applications, (3) defining the mathematical operations and algorithms required to process sensor data into SAR imagery, (4) discussing the architecture of dedicated SAR image formation processors, and (5) addressing the technology necessary to implement the SAR data processors used in both general purpose and dedicated imaging systems.

To focus the panel's work, a list of 21 questions divided into the categories of (1) Applications and Requirements, (2) Algorithms and Architecture, and (3) Implementation Technology was provided the participants. Each panel member was provided with copies of pertinent documents (refs. 5-1 to 5-4). Additional reference documentation was available as described in the bibliography at the end of this chapter. Presentations were made to the panel as a whole by Mr. R. Jordan of the JPL, who discussed the Seasat SAR and its associated data processing; by Mr. B. Manning of the Goodyear Aerospace Corporation, who described the digital SAR data processors built by Goodyear for military applications; by Dr. R. Thoene of the Hughes Aircraft Company, who discussed the Hughes programmable signal processor (PSP) approach to SAR data processing; and by Dr. R. K. Moore of the University of Kansas, who discussed the scanning synthetic aperture radar (scansar) concept and a number of different techniques for SAR data processing.

After these general presentations, the panel was divided into three subpanels to address the three major categories of questions. These subpanels were constituted as follows.

Subpanel A, Applications and Requirements

R. K. Moore, chairman
H. A. Ahr
R. E. Harrison
R. C. Webber

Subpanel B, Algorithms and Architecture

S. Francisco, chairman
D. A. Ausherman
R. L. Jordan
R. Thoene

Subpanel C, Implementation Technology

B. Manning, chairman
L. J. Cutrona
J. S. Heuser
J. Justus

These subpanels discussed and wrote responses to their assigned questions. These written responses were supplied to all the panel members for comment and review.

After the written responses to the questions were reviewed, the panel was assembled as a whole and a list of recommendations was drawn up. Finally, the individual panel members were polled to compile a list of the important conclusions drawn from the workshop.

ORBITAL SYNTHETIC APERTURE RADAR (SAR) SENSING

An important objective of the NASA microwave-remote-sensing program is to provide a readily accessible source of remotely sensed data for Federal, State, and private agencies in a form that will provide accurate and timely information on which to base policy and planning decisions. A major component of the microwave-remote-sensing program is, and will continue to be, synthetic aperture imaging radar systems.

The economic benefits from the uses of optical imagery obtained from Earth-orbiting satellites are well known. Active microwave imagery with resolution better than that of optical imagery and with coverage matching that of optical imagery can be obtained by using the SAR on orbiting platforms. It is reasonable to expect substantial additional economic benefits from the use of active microwave imagery to supplement and complement optical imagery. For these benefits to be fully realized, it will be necessary for NASA to provide users with active microwave imagery in the same way that optical imagery is presently provided.

Because of the complexity of the SAR-data-processing problem, users cannot be expected to perform the processing required to form SAR images from raw sensor data. Thus, NASA must pursue the development of appropriate SAR-data-processing capabilities.

It is recognized that two distinct types of processing requirements must be addressed: those requirements that apply to systems designed to support a broad range of applications - in a manner not unlike that of the present Landsat program - and those requirements that apply to dedicated systems such as might be implemented to monitor soil moisture or sea ice conditions. For the case of satellites that support a number of different user applications, the scope of the data-processing problem (i.e., the diverse applications requirements, the wide range of engineering trade-offs and system implementation options, and the sheer volume of data that could be accumulated) is such that the required processing capability can best be addressed by a highly flexible and complex centralized-data-processing facility. For dedicated systems, onboard processing appears to be an attractive alternative. This alternative will become an increasingly viable option as the technologies of small, low-power processing modules (e.g., charge-coupled devices (CCD's)) mature.

A program for development of (1) imaging radar systems for space use and (2) the associated processors must be viewed as part of a long-term development to a full operational capability at some date rather far in the future. If this view is taken, the various components of the program can follow logically and the required capabilities will be ready for use when the uses are authorized.

One can envision an ultimate system in which the constituents of a family of Earth observation spacecraft are simultaneously in orbit, providing different services. Such a family will include special-purpose spacecraft for particular applications (such as water resources or geology), special-purpose spacecraft for performing particular measurements of value in many applications (such as soil moisture), and large, general-purpose spacecraft systems capable of providing high-quality image information for a wide variety of users. Although the spacecraft considered here will all carry radar systems, many of them (if not all) will also carry other sensors so that the complementary nature of microwave and visible-IR sensors can be exploited for maximum user benefit.

Some of these radars will provide large quantities of data for which sophisticated processing in a central data facility will be required. Other radars will provide smaller quantities of data for specialized purposes, with immediate use thereof required; these sensors will undoubtedly process the data to image form on board and be capable of being interrogated by telemetry readout stations under the control of widely dispersed users, in the mode of the automatic picture transmission (APT) system with meteorological satellites. The central facility will produce several kinds of products tailored to the needs of different classes of user; some of these products may be planimetric images, but others will almost certainly be feature maps at scales commensurate with other types of maps in the hands of the users. The central facility products will also be available to users throughout the world by means of telecommunications facilities enabling readout of images or maps direct from the central computer to displays or computers at the user facilities.

Before such a status of operational capability is reached, various intermediate stages will be involved. The first of these stages is about to start with the advent of the imaging radar on Seasat, which will undoubtedly be representative of a class of modest-capability imaging radar systems on satellites, most of which will also carry other sensors and all of which will be dedicated primarily to easily identifiable special uses.

Simultaneous with the development of these systems will be the development and testing of radar systems with use of the Shuttle platform. The Shuttle can be used for radars that will enable the testing of user applications but that also will enable the testing of numerous alternative processing systems and radar configurations, both for future use on large spacecraft and for use on smaller, dedicated free-flying spacecraft.

The early dedicated small spacecraft will probably employ ground processing. Somewhat later, the alternative of onboard processing will be used, but with telemetry to central processing facilities. This system will no doubt be followed soon by an APT capability. The Shuttle test bed will enable the checking out of onboard processing systems; but more than that, it will enable the production of more complex (finer resolution, more frequencies, more polarizations) data, which will facilitate development of the ground-based central processing facility capability to that needed for operational systems. Also, the availability of these more complex processed images will enable use of the central facility for experiments in developing the various kinds of user-desired products.

Before spacecraft systems can become operational, research and development is needed in several areas - not so much to provide inputs to the design of the first radars, because the capability exists now to build them, but rather to prepare for the future experiments to be conducted on the Shuttle and for the future specialized free-flyer radars.

Such research is urgently needed to establish the true needs of the user community. Actual needs for resolution, for example, have a major impact on the complexity of processors; if a special application is to be addressed either with a Shuttle test or with a dedicated free-flyer, the true needs in resolution, gray-level rendition, swath width, frequency of or timeliness of coverage, and radar system parameters must be known to enable design of the simplest system that will meet the user needs. Studies and preliminary development need to be conducted on a wide variety of processing techniques, especially for onboard processor systems.

The number of ways in which SAR signals can be processed into images is large, and several of the possible techniques have not been tested. The trade-offs between these new techniques and the traditional ones must be evaluated. As the electronic art progresses, the optimum solutions to the processor design problem will change; and an ongoing effort in designing alternative processors is needed if decisions to use workable but obsolete techniques are to be avoided at the time hardware decisions are made for the space systems.

Although radar systems themselves are not part of the work of this panel, it is noted that similar studies should be ongoing with regard to the radars that feed into the processor. Not only will this effort enable appropriate components to be available so that the optimum, rather than available, systems can be built, but many radar system decisions also affect processor decisions and the radar studies are an important component of the inputs to the processor studies.

For numerous applications of radar, the combining of images from multiple passes of the radar will be required, as well as the combining of radar images with MSS images, maps, and photographs. Research into the kinds of processing that will be needed to convert the raw radar images into products suitable for such combinations is essential and needed soon. If possible, the results should be tested by using both aircraft-radar and early-space-radar images. In turn, as the space radars become more sophisticated and the number of proven uses increases, such research should continue.

APPLICATIONS AND REQUIREMENTS

The Applications and Requirements Subpanel was supplied with the following questions/instructions to guide its work.

1. What are the applications for SAR imagery? Identify the expected users.

2. What are the SAR image requirements for these applications? Define the requirements in terms of image quality, coverage, and timeliness.

3. How is SAR image quality best defined?

4. What data formats are preferred by the users?

5. What auxiliary information is required by the users?

6. What aircraft experiments should be considered to enable optimization of processing options such as number of looks, quantization level, etc., as a function of application?

7. What data indexing and editing capabilities should the ground data-processing station have?

8. What image registration accuracy should be specified to enable matching radar imagery to that of other image sources?

Radar, Image, and Mission Parameter Requirements

The applications for SAR imagery are described in detail in chapter 2 of this report and in the Active Microwave Workshop Report (ref. 5-1). Of most importance in SAR data processing are the sensor, image, and mission parameters required for the different applications. Different applications call for different radar, image, and mission parameters. These requirements have been summarized in tables 5-1 to 5-3; the particular requirements for each application are given. Many of the requirements cannot be fully specified at this time because of lack of information on either the character of the radar return or the needs for specific applications, and this deficiency has been indicated in the tables.

The tables have been subdivided into three categories: radar, image quality, and data repetition and timing requirements. Resolution is often considered to be a radar parameter, but in the synthetic aperture system, processing in different ways can give different resolutions; hence, it has been listed in the image quality category.

The incidence angle is defined as the angle between the ray from the radar to the target and the local vertical at the target. For some applications, measurements at specific incidence angles are needed; but most applications can be accommodated with measurements made within rather wide ranges of incidence angle. When the table specifies a wide range, the implication is that any angle within this range will suffice.

In a few cases, the best single frequency for performing a particular task is known; but in most cases, insufficient information is available to enable specifying such a frequency. The frequencies are known for cases wherein microwave spectrometer measurements have been made (primarily those associated with soil moisture and vegetation). In other cases, the primary quantity required is shape and contrast information and the frequency is essentially immaterial. The tables contain examples of all three cases.

For some applications (but not for most), the use of multiple frequencies is required for performing classification tasks or profiling. The column on needed multiple frequencies has examples both of cases wherein the multiple frequencies are actually required and those wherein they are desirable. Only in a few cases is it possible to specify exactly what frequencies are needed, even when it is known that multiple frequencies are either needed or desirable.

Polarization is an important discrimination factor available to the radar interpreter; yet for many applications, only a single polarization is needed and often the particular one used is unimportant. Only in a few cases has it been possible or necessary to identify a particular required like polarization; and for most of the applications wherein multiple polarizations are required, either vertical or horizontal polarization and one of the cross-polarized components are needed.

Image quality depends on a variety of factors, but probably the most important ones are the resolution and the amount of coherent speckle in the image caused by fading of the received signal. Coherent speckle is a fundamental characteristic of monochromatic radar images. It may be significantly reduced by incoherently averaging several independent "looks" at a given scene or by other methods that are equivalent to such averaging.

A recent study has shown how the combined effects of pixel size, shape, and speckle can be treated together and trade-offs made between

TABLE 5-1.- RADAR PARAMETER REQUIREMENTS

Application	Incidence angle, deg	Best single frequency	Needed multifrequency	Polarization
Geology and mineral resources applications				
Structure	≈45 in mountains; near grazing in flat areas	Not important; lower better for vegetation penetration	Ku-band to show structural evidence in vegetation and L-band to penetrate vegetation	Like and cross, VV or HH
Lithology	10 to 20, and anywhere in the 20 to 70 range	Unknown; lower better for vegetation penetration	Unknown, but multiple frequencies are desirable	Like and cross, VV or HH
Construction materials	10 to 20, and anywhere in the 20 to 70 range	Unknown; lower better for vegetation penetration	Unknown, but multiple frequencies are desirable	Like and cross, VV or HH
Route and dam location	≈45 in mountains; near grazing in flat areas	Unknown; lower better for vegetation penetration	A high frequency and a low frequency are desirable	Like and cross, VV or HH
Oceanic applications				
Waves	>20	TBD	TBD	TBD
Sea ice				
Navigation	>20	X- to Ku-band	TBD	Cross
Mapping	>20	X- to Ku-band	TBD	Cross
Icebergs	>50	TBD	TBD	Multiple
Ships and fishing boats	>50	None	None	Single
Pollution	25 to 70	>5 GHz	TBD	Multiple
Coastal changes	>5	None	TBD	Multiple, linear and circular
Kelp monitoring	>30	>12 GHz	None	Multiple
Hurricanes	>10	<3 GHz	TBD	Multiple
Currents	>20	TBD	TBD	Multiple

TABLE 5-1.- Continued

Application	Incidence angle, deg	Best single frequency	Needed multifrequency	Polarization
Cartography and land-use applications				
Urban changes	20 to 70	Probably none - TBD	Not likely	Like and cross
Transportation				
Routes	20 to 70	Probably none - TBD	No	Like and cross
Traffic	50 to 80	Probably none - TBD	No	Like and cross
Remote area topography	30 to 80	Probably none - TBD	No	Like
Land use				
Suburban	20 to 80	> 8 GHz	Yes - TBD	Like and cross
Rural	20 to 80	> 8 GHz	Yes - TBD	Like and cross
Agriculture and natural vegetation applications				
Crop identification	30 to 70	14 GHz	Yes - 9, 14, and 17 GHz	Like and cross
Crop and pasture condition				
State of growth	30 to 70	> 8 GHz	Yes - TBD	Single
Stress, disease	30 to 70	> 8 GHz	Yes - TBD	Single
Soil moisture	5 to 20	4 to 5 GHz	Probably not - TBD	Single
Field boundaries	30 to 70	> 8 GHz	Probably not - TBD	Like and cross
Farming practices	30 to 80	Probably none - TBD	Probably not - TBD	Like and cross
Natural vegetation	30 to 70	> 8 GHz	Yes - TBD	Like and cross
Forest community				
Identification	20 to 70	TBD	Yes - TBD	Like and cross
Status	20 to 70	TBD	Yes - TBD	Like and cross
Forest burn and harvest	10 to 40	TBD	No	Single
Erosion	30 to 80	Probably none - TBD	No	Single
Irrigation	5 to 20	4 to 5 GHz	Probably not - TBD	Single

TABLE 5-1.- *Concluded*

Application	Incidence angle, deg	Best single frequency	Needed multifrequency	Polarization
Water resources applications				
Soil moisture condition	7 to 22	4 to 5 GHz	Probably not - TBD	Single (VV or HH)
Rainfall assessment	7 to 22	4 to 5 GHz	Probably not - TBD	Single
Watershed runoff coefficient	30 to 70	TBD	Probably yes - TBD	Like and cross
Standing water, ponds and lakes	> 30	High better	No	HH and cross
Lake ice	30 to 80	TBD	Possibly desirable - TBD	TBD
Snow cover	25 to 75 (TBD)	TBD	TBD	TBD
Thaw line	22 to 50 (TBD)	TBD	TBD	TBD
Glaciers	TBD	TBD	TBD	TBD
Water pollution	25 to 70	TBD	TBD	VV and cross

TABLE 5-2.- IMAGE PARAMETER REQUIREMENTS

Application	Equivalent resolution, m	Gray-level precision, dB	Geometric precision, m	Single-product dynamic range, dB	Multiple products
Geology and mineral resources applications					
Structure	30 to 200	Not important	TBD	15 to 20	No
Lithology	30 to 100	Unknown (1?)	TBD	15 to 20	Probably none
Construction materials	30 to 100	Unknown (1?)	TBD	15 to 20	Probably none
Route and dam location	20 to 50	Unknown; probably none	TBD	15 to 20	Probably none
Oceanic applications					
Waves	< 20 to 30	1	TBD	20	Probably image and spectrum
Sea ice					
Navigation	25 to 75	1	TBD	15 to 20	No
Mapping	100	1	TBD	15 to 20	No
Icebergs	1 to 25 - TBD	TBD	TBD	15 to 20	Possibly - TBD
Ships and fishing boats	100 to 400	No requirement	TBD	15 to 20	Possibly - TBD
Pollution	100	2?	TBD	15 to 20	Possibly - TBD
Coastal changes	10 to 50	TBD	TBD	15 to 20	Possibly - TBD
Kelp monitoring	30 to 100	TBD	TBD	15 to 20?	No
Hurricanes	100 to 500	TBD	TBD	20 to 30	Possibly - TBD
Currents	50 to 500	TBD	TBD	15 to 20	Possibly - TBD

TABLE 5-2.- Continued

Application	Equivalent resolution, m	Gray-level precision, dB	Geometric precision, m	Single-product dynamic range, dB	Multiple products
Cartography and land-use applications					
Urban changes	5 to 50	3	< 10	30	Yes
Transportation					
Routes	10 to 50	2	< 10	30	Yes
Traffic	5 to 15	3	< 10	20	Yes
Remote area topography	25 to 100	3 - TBD	100	20	No
Land use					
Suburban	25 to 100	2	25	20	Possibly - TBD
Rural	25 to 100	2	25	20	Possibly - TBD
Agriculture and natural vegetation applications					
Crop identification	20 to 100	1	50	20	Probably - TBD
Crop and pasture condition					
State of growth	20 to 100	1	50	20	Possibly - TBD
Stress, disease	10 to 100				
Soil moisture	20 to 200	1	50	20	Possibly - TBD
Field boundaries	20 to 100	2	50	20	Possibly - TBD
Farming practices	20 to 100	2 to 3	50	20	Possibly - TBD
Natural vegetation	50 to 200	1	50	20	Possibly - TBD
Forest community					
Identification	3, or 50 to 200	1	100	20	Possibly - TBD
Status	3, or 20 to 50	1	50	20	Possibly - TBD
Forest burn and harvest	20 to 100	3	100	20	Possibly - TBD
Erosion	10 to 50	1 to 2	100	20	No
Irrigation	20 to 100	1	100	20	Possibly - TBD

TABLE 5-2.- Concluded

Application	Equivalent resolution, m	Gray-level precision, dB	Geometric precision, m	Single-product dynamic range, dB	Multiple products
Water resources applications					
Soil moisture condition	20 to 200	1	TBD	20	Possibly - TBD
Rainfall assessment	20 to 200	1	TBD	20	Possibly - TBD
Watershed runoff coefficient	20 to 200	1 - TBD	TBD	20	No
Standing water, ponds and lakes	50	Coarse - TBD	TBD	20	Possibly - TBD
Lake ice	50	1	TBD	20	Yes - map and image
Snow cover	100 to 200	TBD	TBD	20	Possibly - TBD
Thaw line	200	TBD	TBD	20	Possibly - TBD
Glaciers	3 to 100	TBD	TBD	20	TBD
Water pollution	10 to 50	TBD	TBD	30	Probably - TBD

TABLE 5-3.- MISSION PARAMETER REQUIREMENTS

Application	Need for multiple-aspect looks	Frequency of coverage	Timeliness required	Data lag allowed	Time-of-day requirement	Area of coverage, km^2	Extent of coverage, percent
Geology and mineral resources applications							
Structure	At least two at 90°; prefer three at 0°, 90°, and 180°	Winter and summer	None	Months	None	>5 000	100
Lithology	At least two at 90°	Once	In winter	Months	None	>625	100
Construction materials	At least two at 90°	Winter and summer	At least in winter	2 mo	None	>625	100
Route and dam location	At least two at 90°	Winter and summer	Depends on project	2 to 3 mo	All	>625	100
Oceanic applications							
Waves	None	6 to 12 hr	TBD	6 hr	All	400	<100
Sea ice							
Navigation	None	12 to 48 hr	TBD	6 hr	All	Wide area	100
Mapping	None	Weekly	TBD	5 d	All	Wide area	<100
Icebergs	None	1 to 3 d	Yes	6 hr	TBD	Wide area	100
Ships and fishing boats	None	Daily	Yes	1 d	TBD	Wide area	100 (of selected areas)
Pollution	None	Daily	Yes	2 to 24 hr	TBD	400	100
Coastal changes	None	6 mo	Yes	1 mo	None	1 000	100
Kelp monitoring	None	6 mo	TBD	10 d	TBD	TBD	TBD
Hurricanes	TBD	TBD	Yes	2 hr	All	40 000	100
Currents	TBD	TBD	TBD	5 to 15 d	None	TBD	TBD

TABLE 5-3.- Continued

Application	Need for multiple-aspect looks	Frequency of coverage	Timeliness required	Data lag allowed	Time-of-day requirement	Area of coverage, km^2	Extent of coverage, percent
Cartography and land-use applications							
Urban changes	Yes	30 d	(a)	15 d	Indefinite	10^7	10
Transportation							
Routes	Yes	30 d	(a)	7 d	None	10^7	10
Traffic	Yes	30 d	TBD	7 d	Rush hours	10^7	10
Remote area topography	Yes	Indefinite	(a)	90 d	None	10^7	TBD
Land use							
Suburban	No	6 mo	(a)	30 d	None	10^7	TBD
Rural	Yes	3 mo	(a)	15 d	None	10^7	TBD
Agriculture and natural vegetation applications							
Crop identification	Probably - TBD	7 d	Yes	2 d	Probably none - TBD	10^7	TBD
Crop and pasture condition							
State of growth	Probably - TBD	7 d	Yes	2 d	Probably none - TBD	10^7	TBD
Stress, disease	Probably not - TBD	7 d	TBD	TBD	Probably none - TBD	10^7	TBD
Soil moisture	Probably - TBD	2 d	Yes - TBD	TBD	Yes - TBD	10^7	TBD
Field boundaries	No	1 yr	Yes	30 d	None	10^7	TBD
Farming practices	Yes	30 d	(a)	2 d	None	10^7	TBD
Natural vegetation	In some areas	7 d	Yes	2 d	Probably none - TBD	10^7	TBD
Forest community							
Identification	In some areas	1 yr	TBD	30 d	Probably none - TBD	10^7	TBD
Status	In some areas	1 yr	TBD	30 d	Probably none - TBD	10^7	TBD
Forest burn and harvest	In some areas	7 d	Yes	TBD	None	10^7	TBD

[a]Not applicable.

TABLE 5-3.- Concluded

Application	Need for multiple-aspect looks	Frequency of coverage	Timeliness required	Data lag allowed	Time-of-day requirement	Area of coverage, km^2	Extent of coverage, percent
Agriculture and natural vegetation applications (Cont'd.)							
Erosion	In some areas	7 mo	(b)	30 d	None	10^7	TBD
Irrigation	TBD	2 to 10 d	Yes	TBD	None	10^7	TBD
Water resources applications							
Soil moisture condition	No	2 to 10 d	Yes	2 d	Yes - TBD	10^7	25
Rainfall assessment	No	(b)	1 to 3 d after rainfall	2 d	(b)	10^5	100
Watershed runoff coefficient	Two orthogonal	3 mo	(b)	1 mo	(b)	250 000	20
Standing water, ponds and lakes	None	Weekly	Yes	2 d	(b)	10^7	1
Lake ice (not for navigation)	None	Weekly	Yes	2 d	TBD	10^5	20
Snow cover	Two orthogonal	2 to 6 d	Yes	2 d	Yes	10^6	50
Thaw line	None	6 d	Yes	2 d	Yes	10^5	<50
Glaciers	Two orthogonal	6 mo	Yes	1 mo	TBD	10^5	20
Water pollution	None	Weekly	Yes	2 d	None	10^6	10

[b]Not applicable.

them (ref. 5-5). In that study, the effect of the speckle is described quantitatively by a "gray-level resolution." The equivalent number of independent looks for a photograph is essentially infinite (because the illumination is not monochromatic), and the equivalent pixel dimensions for radar images with specific numbers of looks averaged can be obtained from that for a photograph by calculation. The best way to describe the required resolution is in terms of that required for a photographic image, and the radar designer can then modify the required pixel dimensions and number of looks to match the requirements of the user in the best way from a technological standpoint. Thus, the resolution listed in this column is that for an equivalent square photographic pixel.

For a few applications, specific measurements of the relative intensity of the backscattered radar signal are called for. An example is the measurement of soil moisture, for which a numerical value, rather than an interpretation, is required. In these cases, the required gray-level measurement precision has been indicated.

The requirement for geometric precision has been one of the most difficult to specify. Included are the requirements for transformation of the image to a format suitable for combining with other radar images and with images in the visible and IR regions of the spectrum. Also included is the precision needed in location so that the radar image may be used in connection with maps and other data to give specific geographic coordinates to a particular element observed.

The dynamic range required for an image is usually less than the total dynamic range required for a system. Most land and ocean surfaces exhibit relatively modest ranges of variation of the mean scattering coefficient at a particular incidence angle, but the center of this range may vary considerably from one class of area to another. For instance, the return signal from sea is usually much lower than that from land, but the user may need to expand this low-mean-value part of the possible signal range to detect fine gradations in the signal returned from the sea. Two columns in the table relate to this aspect: One column gives the dynamic range required (if properly centered) for a single data product, and the other column indicates the need for tailoring the dynamic range to cover different mean levels. The latter requirement can be met by expanding two parts of the range so that, for example, fine gradations in the water surface and fine gradations in the land surface can be seen on the same image. In many cases, however, a better way to meet this requirement is to provide multiple image products to the users of water data and the users of land data - or to the users of agricultural data and the users of urban data. The information for all the applications will be contained in the dynamic range of the radar itself; but because of the limited dynamic range of film, the radar range must be split to provide adequate images for the different applications.

The need for observation of the ground from multiple viewing aspects (azimuthal angles) is well established for geology. The reason is because shadowing and other effects of slopes in the mountains cause mountainous terrain to appear quite different from different viewing directions; much additional information is obtained by use of the views from the different directions. Because this effect is well known for geology, it can be inferred that multiple viewing angles will be required for most applications in mountainous regions and for some others, such as the viewing of buildings in cities.

For some applications, frequent repeated coverage of the same terrain is required; whereas for others, although infrequent viewing is required, it must be timed well to coincide with certain natural events such as floods or snowmelts. For the applications requiring regular repetition, the column "Frequency of coverage" has been used to indicate the necessary repetition interval. For those applications wherein repetition is not important but timeliness is required, the need is indicated - sometimes with a period within which the imaging must be accomplished - in the column "Timeliness needs."

When frequent repetition or timely coverage is needed, the results must usually be provided to users quickly; for other applications, longer delays are possible. No matter how effective the spacecraft system and the image processing system are, the system for delivery of images to users could make the results of little value if it imposes too much time lag. Consequently, a column has been incorporated to specify the allowable lag time between the collection of the radar data and the delivery of the product to the user.

A few applications are critical as to time of day, primarily because of differences in the radar signal caused by diurnal effects. For instance, in monitoring snow, the results obtained in the middle of a cold night are quite different from those obtained at the high point of the solar heating during the day, when the snow may contain considerable water in unfrozen form. At lower microwave frequencies, vegetation exhibits diurnal variations in radar return. A column has been provided to indicate those applications for which such time-of-day effects are important.

Attempts have been made to identify the area of coverage required for the different applications. In some general application categories, this quantity is stated in terms of the total area within the 48 contiguous States that must be covered; and in other major categories, it has been stated in terms of the minimum size of coverage area required in a particular image to achieve the goals of the user. The area of the continental United States is taken as 10^7 km^2.

For some applications, continuous coverage of the area of interest is required; for others, success can be attained with the use of sampling techniques. This point has been considered and incorporated in the column "Extent of coverage."

In summary, one can say that a capability of processing multifrequency and multiple-polarization SAR data obtained at incidence angles ranging from 5^o to 80^o, obtaining imagery with a 25-m spatial resolution, a 1-dB gray-level resolution, a 20-dB dynamic range, and a 10-m geometric precision, will satisfy the requirements for most applications if the processed image data can be made available within a week of the SAR measurement.

Synthetic Aperture Radar (SAR) Image Quality

The SAR image quality can be determined by the measurement of a number of image quality parameters. To be most useful, an image quality parameter should be measurable from imagery alone. In most cases, a special scene must be imaged in order to make a measurement of an image quality parameter.

A number of image quality parameters are determined from measurements of the SAR system impulse amplitude response ($I(x)$). For optically processed imagery (which is, by implication, infinitely oversampled), the system impulse response can be obtained from a single image of a strong point scatterer in a low-reflectance background. A number of images, each having the point scatterer echo falling at different positions relative to the sampling grid, are necessary to evaluate the impulse response of a digitally processed SAR. The following image quality parameters are derivable from impulse response measurements.

1. Mainlobe width (MLW)

2. Clutter width (CW)

3. Flare ratio (f)

4. Integrated sidelobe ratio (ISR)

5. Peak range and azimuth sidelobe levels

Figure 5-1 illustrates the definition of some of these image quality parameters for the case wherein $I(x) = (\sin x)/x$.

The MLW is the width of the impulse power response, $S(x)$, at the 3-dB points relative to the peak response, where $S(x) = I(x) \cdot I(x)$. The MLW is related to the resolution of the SAR image but should not be mistaken for the resolvable distance, which is a better indicator of SAR resolution. The MLW should be determined in both the range and azimuth directions.

The CW is the width of a rectangle of unit height having the same area as that under the normalized impulse power response function. The CW is meaningful only if the impulse power response falls off faster than the reciprocal of the distance from the peak response. The CW cannot be estimated with perfect accuracy from imagery with a finite swath width, because the contributions to the CW from regions outside the imaged swath cannot be measured. The CW should also be measured in both the range and azimuth directions.

The flare ratio, f, is a parameter derived from the MLW and the CW.

$$f = (CW - MLW)/CW \qquad (5\text{-}1)$$

The flare ratio has a maximum value of 1.0 and approaches zero as the impulse response outside the mainlobe approaches zero.

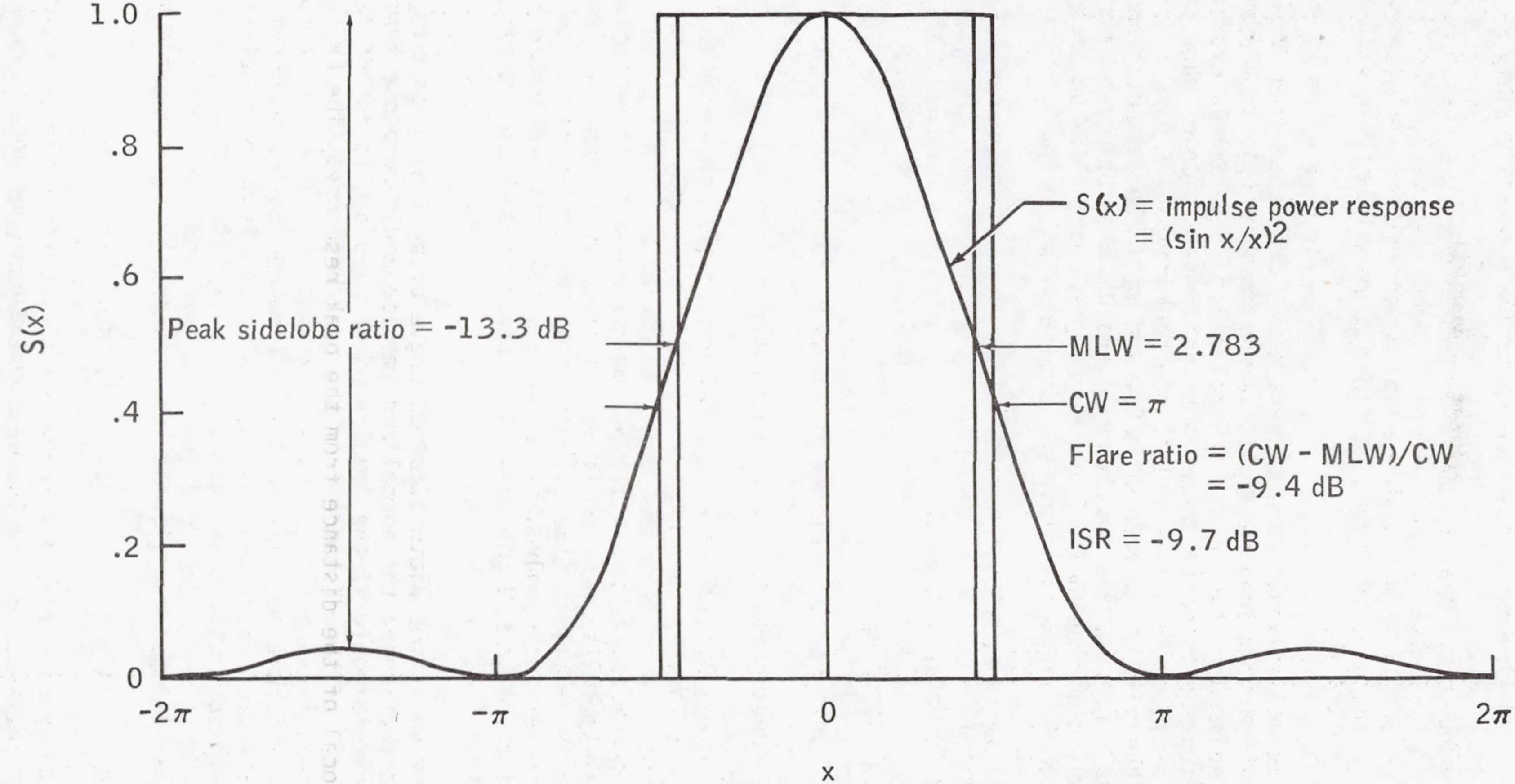


Figure 5-1.- An example of some image quality parameters obtained from measurements of the system impulse response.

The flare ratio is similar but not identical to the ISR, which is the ratio of the integrated impulse response in the sidelobe region to that in the mainlobe.

$$ISR = \int_{sidelobes} S(x)\,dx / \int_{mainlobe} S(x)\,dx \qquad (5\text{-}2)$$

If the impulse response has no null separating the mainlobe from the first sidelobe or if the response monotonically decreases from the peak value, it is impossible to precisely define a boundary between the mainlobe and sidelobe regions. Thus, the flare ratio is preferred over the integrated sidelobe ratio as an image quality parameter.

The peak sidelobe ratio is the ratio of the largest peak in the sidelobe region of the impulse response to the maximum mainlobe response. Measurement of the peak sidelobe ratio is complicated by uncertainties in defining the mainlobe and sidelobe regions in the same way as for the measurement of the integrated sidelobe ratio.

The spatial resolution of a SAR system is best specified by the image quality parameter "X-dB resolvable distance." To measure this image quality parameter requires the imaging of pairs of equal point scatterers with different separations; and in the case of digitally processed imagery, a number of images are required to measure this parameter. The X-dB resolvable distance is defined as the separation between two equal-strength point scatterers that produces an X-dB minimum dip in the level of the image between the maxima associated with the source pair. For a finitely sampled image, the X-dB resolvable distance is a statistical quantity. This parameter should be measured in both range and azimuth.

Another important image quality parameter is background roughness, which is defined as the ratio of the standard deviation to the mean level of linear power noise-free image data from an extended uniform scene. The background roughness parameter is a measure of the amount of coherent speckle or fading in the image and is important in determining the precision with which a single-pixel echo power measurement represents the true mean image echo power.

The maximum contrast is the ratio of the maximum image level to the minimum nonzero level of linear power image data. The maximum contrast can be measured for any image and is limited by the sidelobes of the system impulse response and by the signal-to-noise ratio.

Dark-target contrast is defined as the ratio of the mean image level in an area of zero reflectivity to the mean level of a large surrounding uniform-reflectance background. The dark-target contrast is affected primarily by the sidelobe level of the system impulse response and by the signal-to-thermal-noise ratio.

Adjacent-sample contrast is an image quality parameter strictly applicable only to sampled imagery. Optically processed (infinitely oversampled) imagery has an adjacent-sample contrast of 1. Adjacent-sample contrast is defined as the ratio of the maximum image response to a point scatter to the average of the response in the adjacent pixels. This parameter is strongly affected by the size of the minimum pixel spacing relative to the MLW.

Mean level is the average level of linear power image data. The mean level is an indicator of the average signal-plus-noise power in the image.

Noise level is the average level of the image in response to a system noise-only input. The system mean signal-to-noise ratio is the mean level minus the noise level, divided by the noise level.

Geometric fidelity is the rms positional error averaged over an image between the displayed locations of the echo from a point scatterer and the true locations of this scatterer. The center of the image is assumed to be located precisely, and the true positions of the scatterer must be known relative to this point.

Table 5-4 lists the image quality parameters measurable from imagery, the type of scene required for the measurement, the subjective image quality most directly measured by the parameter, and approximate values for the parameters that will produce acceptable quality imagery for most applications.

Preferred Data Formats

The user community requires two basic output products.

1. Image film or image prints ("pictures")

2. CCT's containing digital imagery and/or raw data

These products can be for one of two purposes.

1. Browsing over a large area of coverage to locate specific areas of interest

2. Intermediate/final analysis and information extraction from specifically selected and processed frames of data (e.g., a 100- by 100-km image at 25-m resolution)

The output products required for browsing will tend to be large in volume (that is, many frames), at a coarse resolution, and for a single polarization and frequency. On the other hand, final products will tend to be one frame or a few frames for the desired resolution and for specific polarizations, frequencies, and looks.

The most acceptable format for either the film or the CCT products is one compatible with those produced for Landsat data today. It is clear that user utilization of SAR data will be greatly helped by making the data presentation and products like those that the users are familiar with and equipped to handle.

TABLE 5-4.- SUMMARY OF IMAGE QUALITY PARAMETER REQUIREMENTS

Image quality parameter	Required scene	Quality measured	Range of acceptable values
Mainlobe width	Single-point target	Resolution	Less than one-eighth of the size of the smallest object to be identified
Clutter width	Single-point target	None	Not applicable
Flare ratio	Single-point target	Contrast	<-10 dB
Integrated sidelobe ratio	Single-point target	Contrast	<-10 dB
Peak sidelobe ratio	Single-point target	Spurious responses	<-15 dB
X-dB resolvable distance	Pairs of equal reflectors at different spacings	Resolution	Less than one-sixth of the size of the smallest object to be identified
Background roughness	Extended area of uniform reflectance	Speckle	<-6 dB
Maximum contrast	Any scene	Dynamic range	>25 dB
Dark-target contrast	Extended uniform scene surrounding an area of zero reflectivity	Shadow contrast	<-10 dB
Adjacent sample contrast	Single-point target	Crispness	Approximately one gray shade
Mean level	Any scene	Brightness	As required
Noise level	System noise only	Snow	<-8 dB relative to mean level
Geometric fidelity	An array of surveyed point targets	Distortion	Approximately one-half of the pixel spacing

Aircraft Experiment Requirements

In the development of a multimission digital SAR processor, radar data need to be gathered in digital form to be used in the verification of the particular processor implementation. Currently, implementation ideas exist for digital processors to meet spacecraft SAR-data-processing requirements; but when these processors are developed, their design must be verified as producing imagery of the required quality.

Users of SAR data have used optically processed data almost exclusively to date, and answers to some obvious questions concerning digitally processed SAR imagery do not exist or are not well known. Some of these questions are as follows.

1. What resolutions, peak sidelobe levels, and signal-to-noise ratios are required for specific applications?

2. How much should the output image spatial oversampling be?

3. How many looks are required to meet the needs of individual users?

4. What are the instantaneous (specular) and distributed target (diffuse) dynamic range requirements for users?

5. For digital processing of data with significant range migration, what are the spatial and quantization requirements for range migration correction?

6. What are the sources of error limiting the achievable calibration accuracy for SAR imagery?

7. For purposes of display of multilook data, should the looks be added linearly, by the square of the amplitude (power), or how? What is the impact of multilook on interpretability?

As time goes on, theoretical answers to all these questions may be available, but they will need to be verified. In the meantime, radar data will be acquired optically by the ongoing aircraft programs. A digital recording system should be installed in at least one of these programs and a library of raw data obtained so that digital data will be available when the digital processor is available. This accomplishment could significantly reduce the time lapse preceding NASA acquisition of an operational digital processor for SAR data.

Image Registration Accuracy

The basic requirement with respect to image registration accuracy is that "it be as good as possible and at least as good as for current optical imagery." This description means registration to the nearest pixel, as will be provided by the master data processor system being developed for the GSFC. Further, it is imperative that registration of SAR data to Landsat/thematic mapper data be provided.

ALGORITHMS AND ARCHITECTURE

The Algorithms and Architecture Subpanel was supplied with the following questions/instructions to guide its work.

1. What are the steps or operations required to process SAR imagery? Define the SAR-data-processing problem, starting with sensor in-phase/ quadrature (I/Q) video signals and ending with finished output imagery and data.

2. Estimate the type and quantity of arithmetic operations required to perform the basic SAR-data-processing functions.

3. What are the most efficient algorithms that can be used to perform the SAR-data-processing functions?

4. What is the best processor architecture for a large ground-based SAR-data-processing system?

5. What is the minimum I/Q video quantization precision that will provide imagery satisfying the user requirements?

6. What are the input data requirements needed to produce imagery of the required quality?

Basic Principles of Synthetic Aperture Radar (SAR) Data Processing

Coherent integration is the basic principle underlying SAR data processing. To produce a SAR image of a given point in space from a sequence of coherent (vector) radar echo measurements made along an arbitrary trajectory, it is first necessary to calculate how the phase of an echo from a fictitious point scatterer at the given point would change from measurement point to measurement point along the trajectory. The radar echo vectors measured at each point are then rotated by the appropriate phase angles so that the echoes from a point scatterer located at the given image point would all be in phase; that is, would all have the same phase angle. The phase-adjusted received echoes are then summed, with the result that the echoes from the given point add coherently whereas echoes from other points sufficiently removed from the given point add incoherently and are thus suppressed by a factor equal to the number of samples coherently processed. The basic operations in SAR data processing are complex multiplication (required to perform the phase rotation) and summation. Although the fundamental principle of SAR data processing is a relatively simple concept, coherent integration, the implementation of this concept to yield useful imagery in a practical and economic manner is a decidedly nontrivial matter involving a number of complicated considerations.

Typical Steps Required in Processing Synthetic Aperture Radar (SAR) Imagery

In figure 5-2, the steps typically required to digitally process raw SAR sensor data into imagery are diagramed. These steps may be summarized as follows.

1. A/D conversion - Subsequent to the generation of a bandpass-limited analog video by the radar sensor, the information must be converted to digital form. This operation must be performed in synchronism with the sensor clock subsystem in order to retain system coherence and with a high timing accuracy in order to retain a low ISR.

2. PRF buffering - The radar system generates data at a less-than-unity duty cycle. To lower the data generation rate and utilize the interval between subsequent pulses more efficiently, a buffering operation should be performed.

3. Range compression - Spaceborne SAR systems will invariably use some method of transmitted pulse coding or dispersion to make use of available transmitter average power. Consequently, during the generation of the SAR image, a pulse compression operation must be performed. A number of techniques exist for performing this operation, two of which are as follows: (1) convolution or correlation compression and (2) fast Fourier transform (FFT), complex filter multiply, and inverse FFT. Variations in system gain can be compensated for at this time, and the appropriate array weighting for sidelobe control can be applied.

4. Azimuth prefiltering - This function is peculiar to the implementation in which separate processors are used for each look. For each of these processors, the azimuth time-bandwidth product required to attain the required resolution is much lower than the available azimuth time-bandwidth product. Consequently, to utilize the azimuth memory, it is advantageous to use bandpass filtering of the azimuth spectrum and thereby limit the data to the portion of that spectrum required by each look. Because the sampling rate after bandpass filtering generally exceeds the Nyguist rate, it is then also advantageous to resample the data. For the spacecraft applications for which this function is required, the Doppler spectrum centroid determination must be performed before the prefiltering function.

5. Data reformatting (or corner turning) - In processing steps 1 through 3, the SAR data are naturally required to be in a range-ordered format; in subsequent processing steps, the data are ordered according to the radar pulse repetition interval. Thus, it is necessary that the SAR data measured during an array be stored and read out orthogonally. This data reordering is sometimes called corner turning.

6. Doppler spectrum centroid determination - Because of the range migration compensations that must be performed because of the Earth's rotation, the spacecraft attitude control errors, and the orbital characteristics of the spacecraft, the center of the incoming Doppler spectra at different portions of the range swath must be adequately determined. This function must be performed before the range migration characteristics are

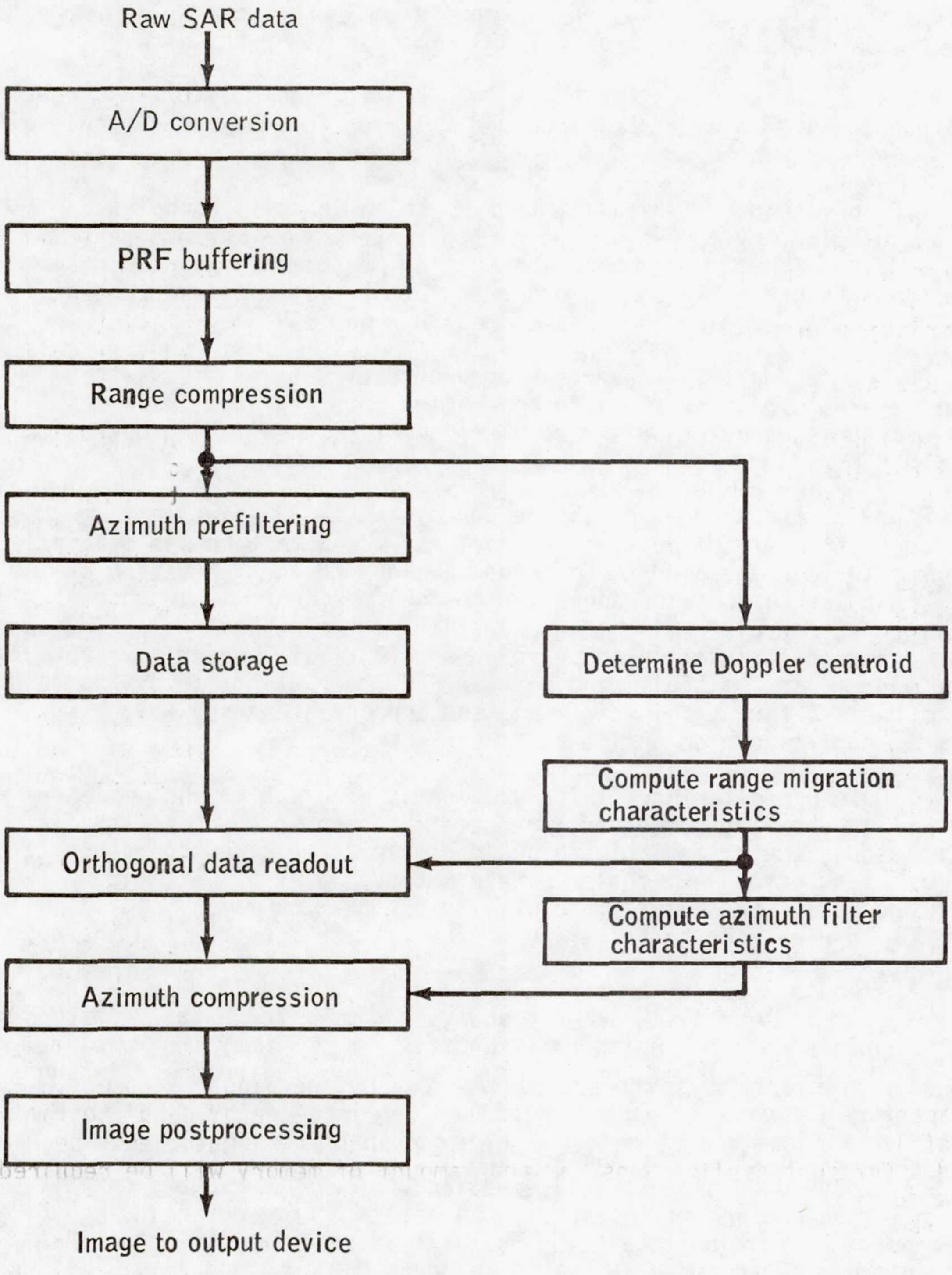


Figure 5-2.- Steps required in SAR data processing.

computed and, in the case of the separate-look processor, before the azimuth prefiltering and resampling.

7. Range migration compensation computation - The path that the echo from one point will take to pass through memory must be computed. The range migration characteristics are derived from the azimuth spectra centroid and target range.

8. Azimuth matched-filter computation - The azimuth matched-filter or reference function characteristics must be computed for different portions of the range swath. It is usually advantageous to store these characteristics in memory. For fully focused SAR, this matched-filter computation is range dependent and thus each range interval has a different matched filter.

9. Azimuth line readout and data point interpolation - Subsequent to the data-reformatting operation, the radar data must be read out according to the computed paths that a point target will take through memory. This data readout and transfer is routed to the azimuth compression device. This function will require either an interpolation between points - as the path that a point target takes through memory does not always pass through the discrete points - or a resampling of the data in range to account for this slippage.

10. Azimuth compression - Subsequent to the azimuth data readout, a one-dimensional compression must be performed. This operation, like the range compression operation, may be a correlation process in the spatial domain or a conversion to the transform domain, a complex multiplication against the matched filter and an inverse transform.

11. Image detection - Up to this point, all operations were of a complex form; i.e., two separate channels were employed - one in-phase (I) channel and one quadrature (Q) channel. The magnitude of the vector processor output at each data point is computed by squaring the two corresponding data points in the I and Q channels, adding them, and obtaining the square root. At this point, a single-look image is obtained.

12. Separate-image delay - For the separate-look processor, each look is separated spatially from the subsequent look by the length of the synthetic aperture required by each look. Thus, an image delay equal to the number of looks minus one, times the synthetic aperture length, must be provided. For most applications, a large amount of memory will be required for this delay. At the end of each of these delays, an image line addition must be made.

13. Image formatting and readout - The output image display will take a form that is proportional to either the amplitude of the signal, the power of the signal, the logarithm of the signal power, or some alternate encoding scheme. Thus, a reformatting operation must be performed. In general, many of these functions may be performed in different orders because the operations are primarily linear. The driving functions to the architecture may be technological in nature, but - in any case - they must be performed.

These steps must be performed regardless of the implementation method employed. However, steps 4 and 12 (azimuth prefiltering/resampling and separate-image delay) are peculiar to the technique in which separate processors are employed for each of the multiple looks generated.

The steps required to process SAR data depend somewhat on how the multiple-look postprocessing is implemented. The two basic methods of implementing a multiple-look processor are as follows: (1) Process the radar data to the ultimate resolution and subsequently degrade the final image by a noncoherent process or (2) process the data to the required resolution for each look separately and then noncoherently add the separate images together.

Each method offers some advantage over the other, and which method is optimum is highly technology dependent. However, the following statements can be made regarding each of these two classes of processors.

Fully focused processor.- The architecture of the fully focused processor is simpler than that of the partially focused separate-look processor in that some functions are not required. However, the number of azimuth cells in each range bin is much larger than that required by the separate-look processor. The result is that a larger azimuth memory is required, as well as a larger azimuth compression device. The effect of multiple looks is obtained by degrading the output product by averaging adjoining cells. Furthermore, the problems of range migration and depth of focus both increase as the square of the length of the processed aperture; so the relative architectural simplicity of the fully focused processor is more apparent than real.

Separate-look processor.- The operation of the separate-look processor is basically to process the radar data separately for each look and then subsequently add the images together. This implementation requires that the processor incorporate an azimuth prefilter and resampler or a separate local oscillator (LO) for each look. The number of picture elements (pixels) output by each look processed is much lower than that of the fully focused processor. This factor is, in its optimum sense, equal to the square of the number of multiple looks (N) required. However, N such processors must be used. After each look is processed, the separate images must be added together. Because each look is processed with a spatial separation from each other look, a reasonably large but slow buffer must be employed to provide this spatial image delay. This buffer is not required by the fully focused processor, and neither is the azimuth prefilter and resampler. Another disadvantage of the separate-look processor is that the exact characteristics for each look processed will be dependent on the system antenna attitude with respect to the Doppler coordinates, and the range migration compensation must take this effect into account. This problem is not severe for frequencies greater than 3 to 4 GHz because of the shorter required aperture; but the range migration problem is still present in the addition of the multiple looks, although it is simpler to accomplish at this point in the processing.

Arithmetic Operations in Synthetic Aperture Radar (SAR) Data Processing

Extensive processing of the radar return signals is required to produce a SAR image. The SAR data processing may be performed by using either digital or analog methods. The former method will be considered in detail here because the technology exists in this area to provide real-time or near-real-time processing.

For an all-digital approach to the SAR-data-processing problem, the radar return signals are sampled after a conversion to video frequencies. These samples must be processed as they are received or stored for future processing. In either case, the processing load is comparable and the types of arithmetic operations are similar. These operations are identified subsequently, and the quantity of each required to perform conventional SAR algorithms is estimated.

In general, computation involves the basic arithmetic operations - addition, subtraction, multiplication, and division. These operations (or their equivalent) are required in SAR data processing, but addition, subtraction, and multiplication are used much more frequently in the algorithms than division. This fact is fortuitous because digital processors inherently can perform addition, subtraction, and multiplication more rapidly than division, with less hardware.

In the SAR algorithms described in the previous section, the summation of amplitude-weighted and possibly phase-rotated received signal samples is required. For the general case of complex (in-phase and quadrature) samples, amplitude weighting requires multiplication of a real number by a complex number (or equivalently, two real multiplications), phase rotation requires multiplication of two complex numbers (or equivalently, four real multiplications and two real additions), and summation requires an addition of two complex numbers (or two real additions). Other frequent computations, such as an FFT, represent combinations of the functions previously described. The basic element of the FFT, the butterfly, consists of one complex multiplication followed by two complex additions (ref. 5-6).

The processor should be designed with adequate word length so that the great majority of computations can be performed with single-precision arithmetic. Double-precision arithmetic has a time penalty associated with it. However, there is generally some double-precision arithmetic required in a processor that is designed for cost economy. This type of computation is usually not performed on data samples. Rather, it is performed for control functions, where the error in the least significant bit of some quantity can propagate - because of iterative operations - to more significant bits and thus possibly result in unacceptable image quality. An example is the interpolation and resampling of data in which the integral portion of a computed control word represents the location of the resampled data and the fractional part of that word represents the location of an original sample relative to the desired location of the resampled data.

Division by individual radar samples is never required. There are occasions when division by a date-derived number is required, such as for automatic gain control (AGC) operations; but when this instance occurs, the same divisor is used repetitively. In this case, the proper computational procedure would be to invert the divisor by dividing unity by it and use this result as a multiplier in subsequent calculations.

A time-saving technique for generating functions required frequently is to store in a table samples of the function corresponding to values of the independent variable. Obtaining a value from a table is much more rapid than computation of the value. Examples of where this arrangement is useful are applications in which amplitude weighting is required or the logarithms of samples are required.

Because of the large amount of data that must be stored to produce large images and the usual requirement that they be accessible in sequence in either of two orthogonal dimensions, data or memory management places demands on the processor regardless of the storage medium. The amount of computation required for this function is greatly dependent on the memory architecture. However, if the memory is dedicated to a particular task, supervision of it is not a large or difficult task.

Data-dependent branching is not required in a SAR processor, although branching may occur on the basis of the locations of the data samples. There are ways to handle almost any SAR-data-processing function, however, without branching. This fact has important architecture implications for both the arithmetic unit of the processor and the memory.

Various techniques have been developed that reduce the number of multiplications required for processing, primarily by trading multiplications for additions because multiplication is inherently more complex than addition. In any arithmetic unit, more time and/or hardware is required to perform multiplication than addition. One technique of achieving the trade is to convert all data samples into polar coordinates and take the logarithm of the magnitude and likewise of the amplitude-weighting coefficients. Then, for phase rotation, one real addition (on the angle) is required rather than a complex multiplication. For amplitude weighting, one real addition (on the magnitude of the datum) is required. Accumulation summation could be performed by means of a table lookup or by converting back to linear Cartesian coordinates and performing a complex addition.

A second efficient processing scheme that has been used is to substitute fast Walsh-Hadamand transforms for FFT's. Both the in-phase and quadrature parts of these transforms have unit amplitude; so multiplication is avoided in filter formation by this technique. The resulting filters have poor sidelobes, however, and extensive processing on the filter outputs is required to improve the shape of their passband. A performance equivalent to that obtained with FFT's is possible, but - in that case - subsequent filter-formation processing is expensive. The applicability of Walsh-Hadamand transforms is therefore confined to uses for which performance level requirements are not too stringent.

Quantity of Arithmetic Operations Required

An estimate of the number of each basic type of arithmetic operations required can be made for the most frequently used processing algorithms. Among the common ones, presum filtering, interpolation, the FFT, and convolution are estimated here.

In some SAR applications, only a portion of the real antenna beam is processed. (This is common in airborne strip map applications in which the azimuth resolution, wavelength, and antenna beamwidth are such that the rotation of the line of sight required for SAR processing is much less than the antenna beamwidth.) For space applications, however, the entire beam is generally processed. Presumming still has application here because usually only a portion of the beam can be processed with the same corrections for platform motion, Doppler curvature, and range walk. Presum filtering is then often performed to reduce the Doppler bandwidth of the received data so that it corresponds to the extent in azimuth of the desired image patch. The amount of data that must be stored in memory is reduced by presumming. For presum filtering, the requirement is merely amplitude weighting for shaping and summation if the filter is to be centered at zero frequency. At any other center frequency, a phase rotation would be required as well. On the assumption that the amplitude weighting would be imposed on the phasors before the data samples are presummed and that the data samples from a pulse are spread uniformly in time over the interpulse period through buffering, the computation rate required for presumming in real time is $\kappa f_r N_r$ complex multiplications and additions per second for each presum Doppler band. In this case, f_r is the PRF, N_r is the number of range samples, and $1/\kappa$ is the portion of azimuth samples in the presum input array that are not common to those in the subsequent presum input array. For space applications, a typical value for f_r is 1500 Hz and N_r might be 4096. The array overlap factor, κ, is typically between 2 and 4. For $\kappa = 2$, the computation rate for presumming in this example is 12.3×10^6 multiplications and additions per second. If the data are recorded before processing, the computation rate could be reduced considerably provided the data collection duty factor is small.

Interpolation and resampling can generally be combined with presumming. In cases wherein the PRF is not sufficiently greater than the desired presum filter bandwidth, interpolation may require a larger κ factor (more input array overlap) to obtain adequate image quality. For one-dimensional cubic convolution interpolation, which is a commonly used compromise to the optimum $(\sin x)/x$ interpolation scheme, κ cannot exceed 4.

An FFT on N points requires $(N/2)\log_2 N$ butterflies or, equivalently, that many multiplications and twice that many additions. For a two-dimensional $M \times N$ array of data on which an FFT is to be performed in two orthogonal dimensions, $MN(\log_2 N + \log_2 M)$ butterflies are required (on the assumption that M and N are powers of 2). (Some slight additional penalty results if M or N is not a power of 2.) An array of $N_r = 4096$ (samples in range), for example, and $M = 512$ (samples in azimuth) requires 44×10^6 butterflies.

Convolution can be performed in the time domain or in the frequency domain. If it is performed in the time domain by brute force, the number of multiplications and additions per pulse is $N_r P$, where P is the pulse compression ratio. For typical numbers of $N_r = 4096$ and $P = 512$, 2.1×10^6 multiplications and additions are required per pulse. A more efficient method of performing pulse compression exists when the compression ratio is large. It requires transforming the data samples, multiplying the result - term by term - by the transform of the pulse compression waveform, and taking the inverse transform of the product sequence. The number of multiplications required to perform pulse compression by this method is $N_m = (N_r + P)\log_2(N_r + P) + N_r + P$, on the assumption that $N_r + P$ is a power of 2. The number of additions is $N_a = 2(N_r + P)\log_2(N_r + P)$. For the parameter values previously supposed, $N_m = 65 \times 10^3$ (number of multiplications) and $N_a = 120 \times 10^3$ (number of additions), where $\log_2(N_r + P)$ is rounded off to an integral value. A 32:1 savings on multiplications and a 17:1 savings on additions are achieved relative to time-domain compression.

Synthetic Aperture Radar (SAR) Data Processing Techniques

In the previous subsections, the essential processing procedures required to convert SAR signal histories into imagery were established. The required operations are sufficiently general such that many implementation schemes exist. In this subsection, several techniques commonly proposed for SAR image formation processing are documented.

The discussion here will focus on purely digital processing technology. It is evident, however, that many applications could successfully rely upon the more conventional optical processing media (refs. 5-7 to 5-10). In addition, several hybrid approaches appear feasible that make use of analog-signal-processing elements as major links in the SAR-data-processing chain. The latter includes configurations that employ CCD's for both memory and signal processing (ref. 5-11), as well as systems utilizing surface acoustic wave (SAW) devices for signal compression (ref. 5-12).

Rather than seriously diluting this rather brief presentation of SAR data processing with a discussion of alternate processing media, a purely digital approach to the problem will be concentrated on in this report. However, where possible, references will be made to those processing steps that are amenable to economic application of alternate processing media.

Decomposition into Range and Azimuth Processing

As indicated earlier, conventional SAR systems obtain range resolution by transmitting dispersed pulses and applying pulse compression techniques to the returned signals. Azimuth resolution is obtained by recording the Doppler frequency shifts associated with returns from point scatterers as they migrate through the antenna beam. Knowledge of the Doppler-frequency-versus-time relationship for a point scatterer at a given range enables one to precisely locate the scatterer in azimuth in a manner analogous to application of the pulse compression in the range dimension. In this manner, the SAR processor functions essentially as a two-dimensional filter matched to the signal generated by a point scatterer during the period that the scatterer is illuminated by the antenna beam.

To a first order, the two-dimensional processing function can be separated into two orthogonal, one-dimensional, pulse-compression steps (ref. 5-9). This apparent simplicity must be tempered by the fact that the azimuth compression filter varies as a function of the range distance associated with the data being compressed in the azimuth dimension. Thus, on the basis of the resolution requirement for a given system, a specific azimuth filter may be adequate for only a small portion of the desired range coverage. For shorter SAR wavelengths and gross resolutions, this problem is minimal. The usual digital solution to this problem is to implement a sufficient number of azimuth filters to obtain the required resolution over the desired range interval.

An additional complication is associated with the separable and orthogonal notion of range and azimuth processing. Many SAR imaging geometries imply that a point target does not remain within a single range-resolution interval during the synthetic aperture period. In reality, the scatterer can migrate through many range cells, either because a constant range from the antenna is represented by a sphere (range curvature) or because a need exists to image with the radar antenna squinted either fore or aft of broadside. These two effects are illustrated in figure 5-3. For a spaceborne SAR with long synthetic aperture intervals, the Earth's rotation can also cause a range-walk effect.

Uncompensated, these effects cause both range and azimuth target smearing to occur. If the resolution requirements are sufficiently stringent, the range migration must be compensated for. By using a stationary, flat Earth assumption, it can be shown (ref. 5-3) that range curvature will exceed one-half of the range resolution for slant range R such that

$$R > \frac{16\rho_a{}^2\rho_r}{\lambda^2 K_a{}^2} \qquad (5\text{-}3)$$

where

ρ_a = required azimuth resolution

ρ_r = required range resolution

λ = radar wavelength

K_a = array factor

Similarly, range walk must be accounted for in operating ranges such that

$$R > \frac{\rho_r \rho_a}{K_a \lambda \tan \alpha} \qquad (5\text{-}4)$$

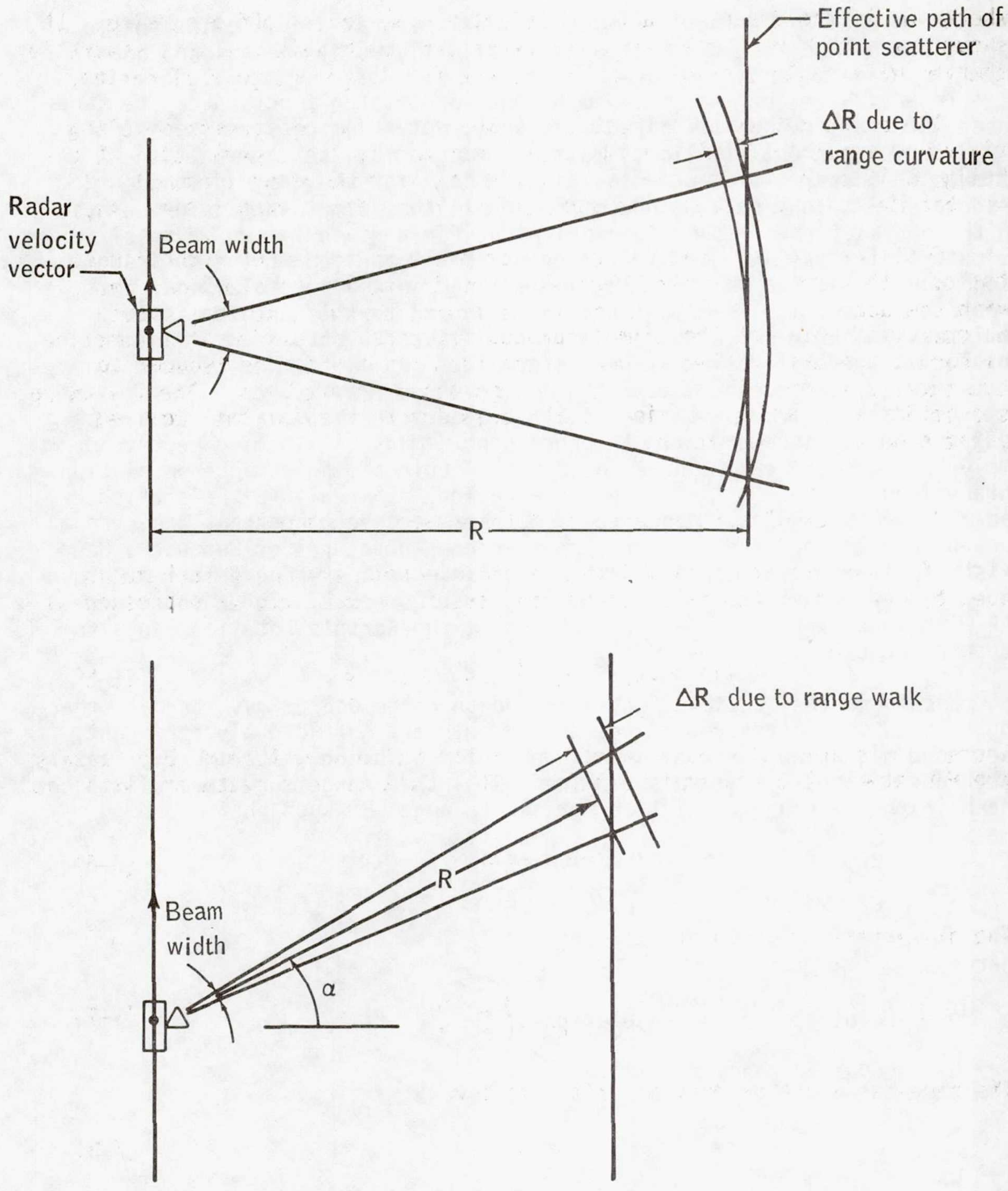


Figure 5-3.- Range migration of point scatterer due to SAR imaging geometry.

where α is the amount of angular (slant range) squint off broadside. It should be noted that both range curvature and range walk are less severe for shorter wavelength systems and more severe for longer range applications.

The range migration effects are compensated for by processing along tilted or curved azimuth apertures or lines within the signal data. Digitally, this compensation can be performed by interpolating (resampling) the SAR data in the range dimension before the azimuth compression step.

Once the range-migration correction procedure has been accomplished, the azimuth compression step becomes a one-dimensional operation. Thus, with the acknowledgement that the range migration must, in many cases, be corrected and that the azimuth processing function varies as a function of range, the basic SAR-data-processing requirements can be reduced to two successive one-dimensional pulse compression procedures. The following subsection will address various techniques for performing the required pulse-compression operation.

One-Dimensional Pulse Compression Techniques

If it is assumed that a linear frequency modulation (FM) scheme is used by the radar, the pulse to be compressed in range can be expressed as

$$s(t) = \exp\left(-\pi i \frac{B}{\tau} t^2\right), \quad -\frac{\tau}{2} \leq t \leq \frac{\tau}{2} \tag{5-5}$$

where B is the pulse bandwidth, τ is the pulse length, and B/τ equals the FM rate of the transmitted pulse. The instantaneous phase of $s(t)$ is

$$\phi(t) = -\frac{B}{\pi\tau} t^2 \tag{5-6}$$

The instantaneous frequency is

$$\nu(t) = \frac{1}{2\pi} \frac{d\phi}{dt} = -\frac{B}{\tau} t \tag{5-7}$$

The time-bandwidth product of $s(t)$ is simply

$$K = \tau B \tag{5-8}$$

K also represents the compression ratio attainable when $s(t)$ is passed through the matched filter.

$$h(t) = s(-t)$$

$$= \exp\left(\pi i \frac{B}{\tau} t^2\right), \quad -\frac{\tau}{2} < t < \frac{\tau}{2} \qquad (5\text{-}9)$$

The signal $s(t)$ represents the complex modulation of the transmitted signal. However, if $t = x$ (along track position) and $B/\tau = 2/R\lambda$, then equation (5-5) represents the azimuth signal from a broadside point target at slant range R.

Convolution Pulse Compression

Pulse compression consists of forming the convolution

$$a(t) = h(t) \cdot s(t)$$

$$= \int_{-\tau/2}^{\tau/2} h(t - u) \cdot s(u)\, du \qquad (5\text{-}10)$$

where $s(t)$ is the range or azimuth signal, τ is the signal duration, and a is the filter output.

In a digital processing system, $h(t)$ is replaced by its sampled equivalent.

$$h_k = (k\, \Delta t) = \exp\left(\pi i k^2/K\right) \qquad (5\text{-}11)$$

where

$$k = -\frac{K}{2}, \ldots, 0, 1, \ldots, \frac{K}{2} - 1$$

$\Delta t = 1/B$ is the maximum sampling interval, and $K = \tau/\Delta t$ is the minimum number of samples.

Then if s_n is the sampled signal, the filter output is given by the discrete convolution

$$a_n = h_n \cdot s_n$$

$$= \sum_{k=-K/2}^{k=(K/2)-1} h_k s_{n-k} \qquad (5\text{-}12)$$

Direct implementation of the convolution (as shown in fig. 5-4) requires K memory cells and K operations for each output point, where K is equal to both the filter length and the compression ratio and an operation is defined as a complex multiplication plus a complex addition.

Often, these "brute force" requirements for arithmetic operations and memory cells are unacceptably high. Various alternative schemes exist whereby one may, under certain conditions, gain in both computational and memory efficiency.

Fast Convolution by Using the Fast Fourier Transform (FFT) Algorithm

One method of improving computational efficiency in some cases is to use the fast Fourier transform (FFT). To illustrate its application, consider the convolution of the sequences h_n $(n = 0, 1, \ldots, N_1 - 1)$ and x_n $(n = 0, 1, \ldots, N_2 - 1)$. Let $N_2 > N_1$ and let

$$a_n = h_n \cdot s_n \tag{5-13}$$

be filtered sequence. Then, the sequence a_n has length

$$N_3 = N_1 + N_2 - 1 \tag{5-14}$$

However, the interval over which the output a_n is weighted by the entire filter sequence h_n is equal to

$$N_F = N_2 - N_1 + 1 \tag{5-15}$$

This point is illustrated in figure 5-5. To perform the convolution of equation (5-10) by using the FFT, append enough zeros to the sequences x_n and h_n to increase their lengths to N_3. Then take the discrete Fourier transform (DFT) of the extended sequences, using the FFT algorithm; i.e., let

$$S_m = F(s_n) \tag{5-16}$$

$$H_m = F(h_n) \tag{5-17}$$

where F is the FFT operator. Then, by the convolution theorem, the DFT of a_n is given by

$$A_m = S_m H_m \tag{5-18}$$

Then a_n is given by the inverse DFT of A_m,

$$a_n = F^{-1}(A_m) \tag{5-19}$$

which forms the desired compressed-pulse output.

The efficiency of this approach results from the inherent efficiency of the FFT for large sequences (large N_3). However, the penalty in terms of additional memory requirements for zero padding and reference spectrum

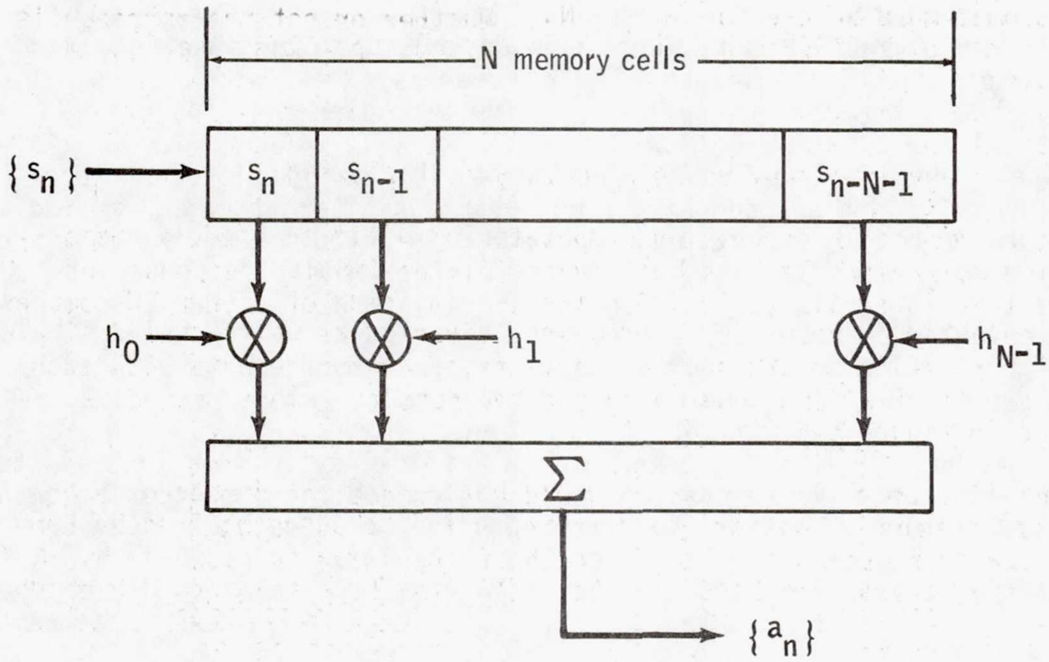
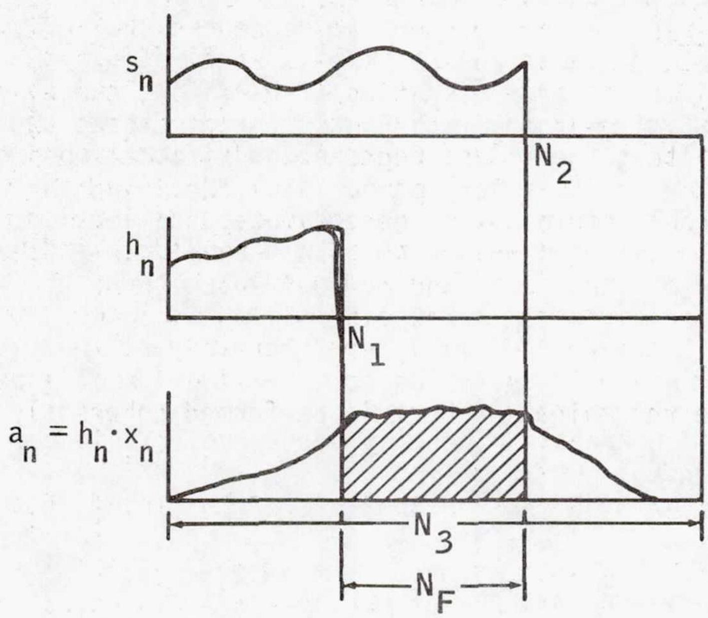


Figure 5-4.- Direct convolution pulse compression.



$$N_F = N_2 - N_1 + 1$$

$$N_3 = N_1 + N_2 - 1$$

Figure 5-5.- Convolution of finite-length sequences.

storage becomes more severe for large N_3. Whether or not the approach is warranted for a given system configuration depends upon the radar parameters involved.

Convolution by Using Frequency Multiplexing

A second method of increasing computational efficiency while decreasing memory requirements is to subdivide the filter impulse response into N contiguous time intervals (which, for the special case of linear FM compression, conveniently corresponds to frequency division as well), build simpler filters corresponding to the shorter sections, process the data with each filter, and then delay and coherently add the results. This method is illustrated in figure 5-6 for $N = 4$.

Ordinarily, this implementation would not reduce the number of operations or save memory. However, for a chirp pulse, the savings can be substantial because reducing the length of the filter impulse response by N simultaneously reduces the bandwidth to B/N and the time-bandwidth product to K/N^2.

The passbands of the individual filters are ideally nonoverlapping. If the filters are used for azimuth focusing, the first filter, $h_1(t)$, processes the leading edge of the antenna beam or highest Doppler frequencies, and the last filter processes the trailing edge or lowest Doppler frequencies. Hence, the individual filter inputs can be preceded by bandpass filters and resampled at the lower rate, B/N, to reduce the individual filter computation rates. This procedure also reduces the individual filter memory sizes and required operations to K/N^2. At first glance, in considering that there are N channels operating in parallel, there is an apparent savings in both number of operations and memory proportional to K/N. However, the bandpass filters themselves represent additional computational operations, and the requirements for appropriately delaying the multichannel data before the coherent recombination necessitate additional memory. In addition, it is impossible in practice to obtain the idealized bandpass filters; this constraint implies a required overlap between the channels and a resulting erosion of the apparent algorithm efficiency. Once again, the applicability of the technique will depend heavily on the radar system parameters. This technique is analogous to the azimuth multilook technique except that the recombination here is performed coherently.

Pulse Compression by Frequency Analysis of Dechirped Pulse

Another method of pulse compression is to dechirp the input data by multiplying it by a chirp reference and then perform a spectral analysis on the residual data as shown in figure 5-7. For efficiency, the spectral analysis is performed with use of the FFT algorithm.

A more efficient method of doing the spectral analysis after dechirping is to use a two-stage FFT algorithm in a manner analogous to use of the two-stage correlation algorithm discussed previously. In the first stage, the input sequence is dechirped over an interval of length N, which is less than the total pulse length. This sequence is filtered by using

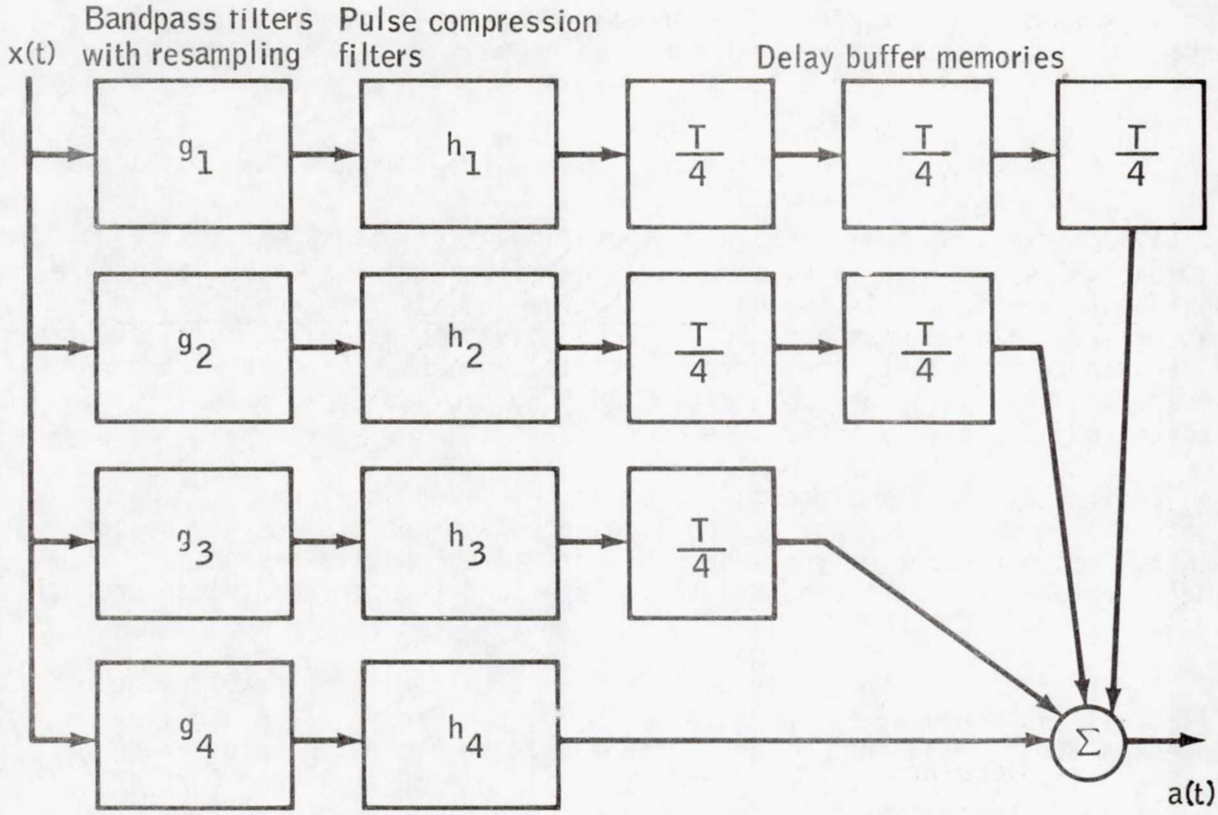


Figure 5-6.- Frequency-multiplexed pulse compression system.

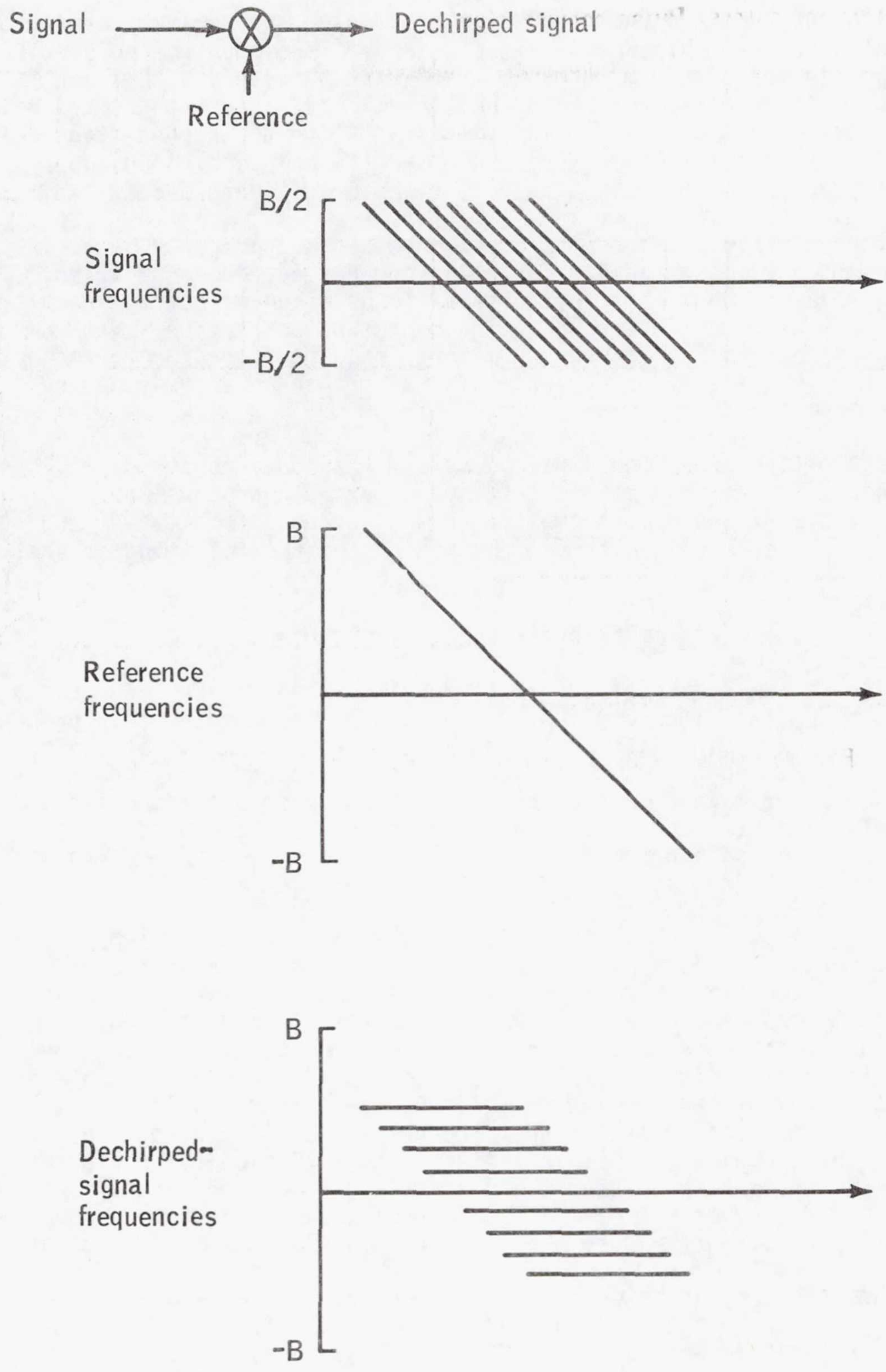


Figure 5-7.- Frequency-time diagrams of Fourier transform pulse compression processor.

the FFT algorithm, and the results are resampled and delayed for the second-stage FFT. If the chirp pulse has a negative FM slope, the pulse energy successively travels from the highest frequency filter to the lowest. By introducing more delay for the highest frequency filter, the total history of a single target can be a simultaneous input to the second-stage FFT filter. The target is then resolved by additional dechirping and filtering. A block diagram of the two-stage FFT is shown in figure 5-8.

After the first stage of processing, the data produced by a single FFT element are, essentially, partially compressed, low-resolution, complex-valued data. This fact often affords a convenient opportunity to provide motion compensation and range migration corrections with computation rates potentially reduced from those required for a brute-force approach. The relative efficiency of the approach obviously depends upon system parameters.

Each of the one-dimensional pulse compression algorithms previously described is applicable to either range or azimuth processing. The configuration of one-dimensional processing steps into a two-dimensional SAR-data-processing algorithm is the subject of the following subsection.

Two-Dimensional-Processor Organization

With the existence of suitable one-dimensional pulse compression technology, a SAR two-dimensional processor can be implemented in a number of configurations. The basic decision involves the selection of the order in which the "orthogonal" range and azimuth compressions are performed. Either the range or azimuth dimension may theoretically be processed first, although the impact of process sequence on processor memory requirements and on motion compensation techniques usually dictates the order of processing for a given application.

The processor configuration illustrated in figure 5-9 depicts the range compression being performed before the processing in the azimuth dimension. The first step in processing is usually a PRF buffering operation that provides for a real-time peak-data-rate reduction by spreading the data contained in a signal radar return over the entire interpulse period associated with the PRF. The second stage consists of an azimuth prefilter, which - for a single-look system - is essentially an azimuth low-pass filter and resampler that reduces the Doppler bandwidth and data rate to that required to obtain the desired resolution for the number of azimuth looks to be processed. For multilook operation, the azimuth prefilter could provide several independent channels of data for subsequent parallel processing. Figure 5-9 depicts a single-look system configuration.

The image formation processing of SAR data must, of course, compensate for the non-straight-line motion of the antenna phase center during the synthetic aperture interval (ref. 5-13). This compensation usually involves some adjustment of the range-sampling intervals (range gating) and adjustment of the signal phases as a function of instantaneous range to the various range intervals. If these operations are not performed as part of the receiver and digitizing operations themselves, they must be incorporated as part of the processing operations. Auxiliary motion and

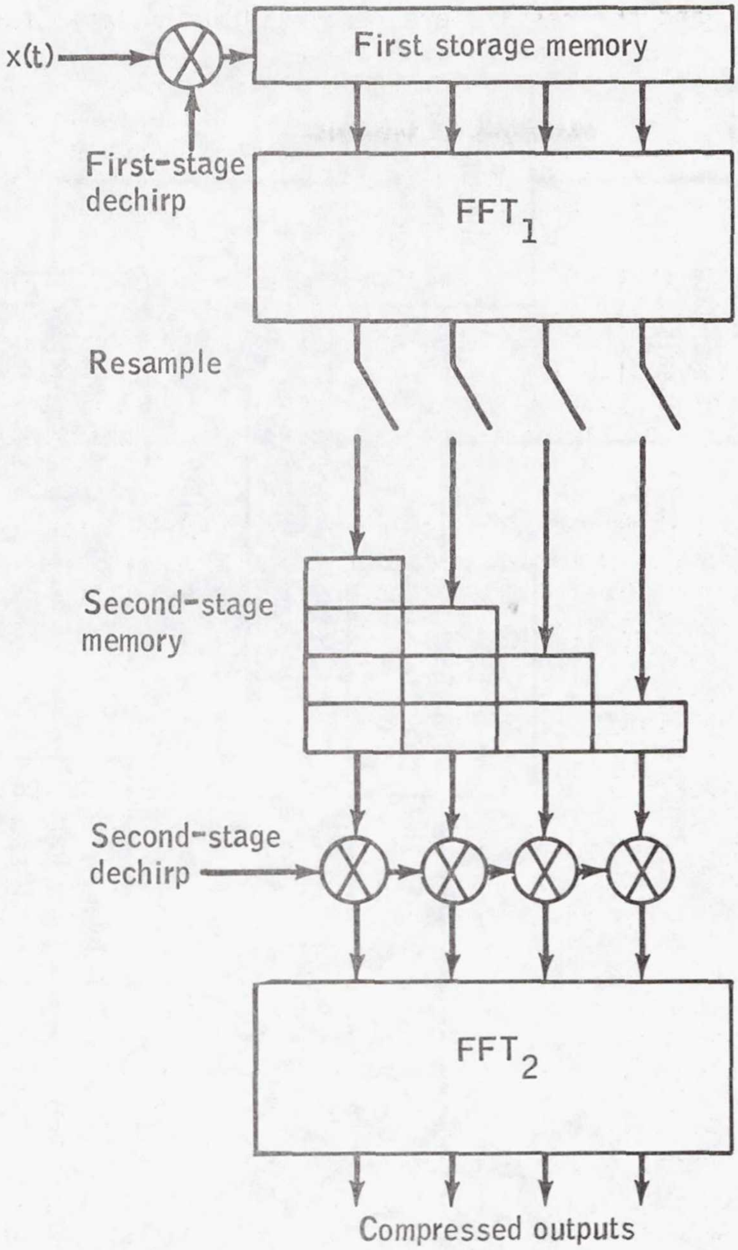


Figure 5-8.- Two-stage FFT pulse compression processor.

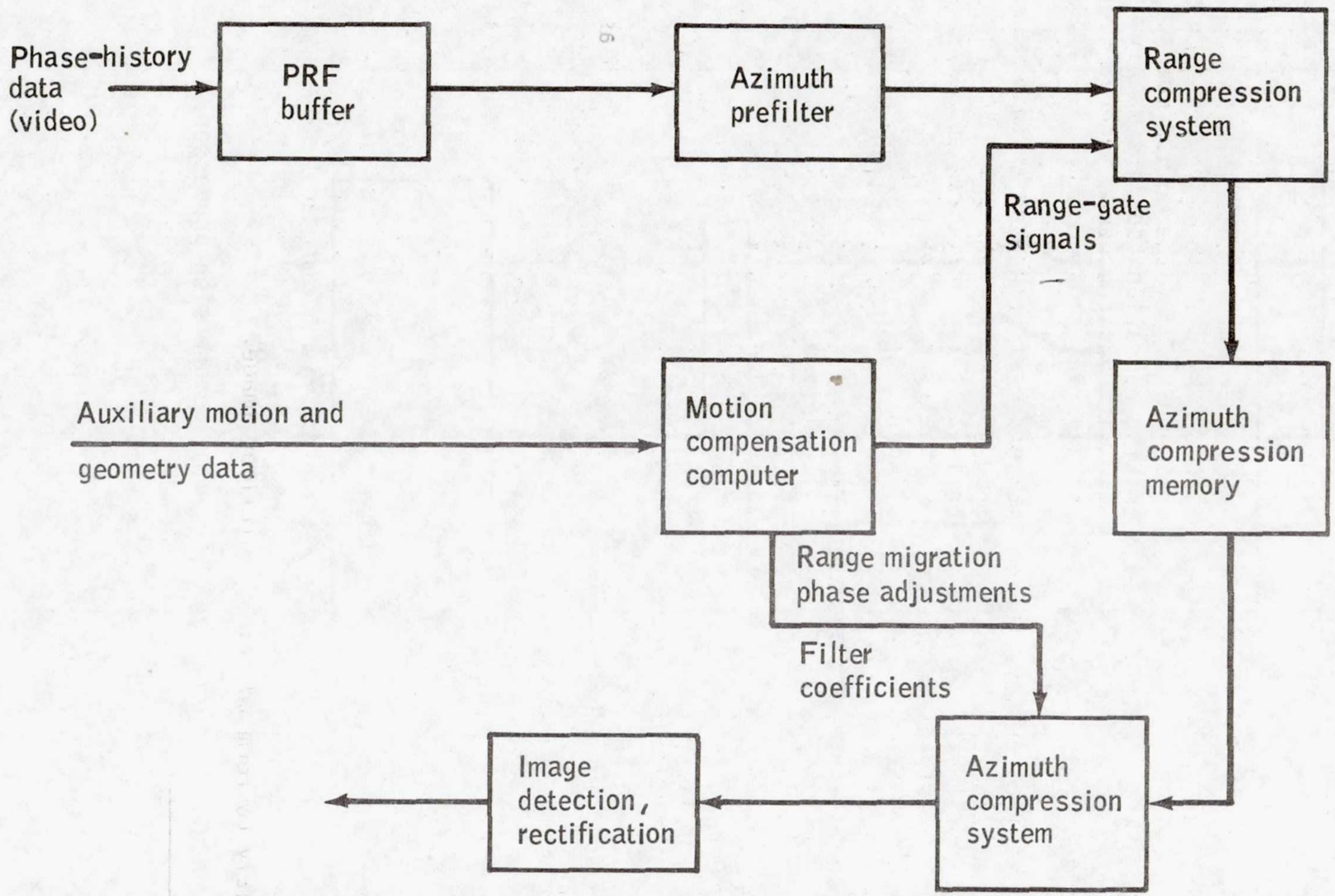


Figure 5-9.- Single-look SAR processor configuration.

imaging-geometry data must therefore be provided to permit computation of the required sampling and phase perturbations. A separate computing module is often incorporated for this purpose.

As illustrated in figure 5-9, a buffer memory must be provided before azimuth compression to permit accumulation of all the data corresponding to a synthetic aperture. Once accumulated, the azimuth data can be pulse-compressed by using filter coefficients generated by the motion compensation computer. (The coefficient-generating operation consists mainly of computing the Doppler FM rate associated with various range intervals traversing the scene, as perturbed by extraneous platform and Earth movement.)

As was stated earlier, the optimum order of range and azimuth processing is based on a trade-off between required memory size and processor complexity. A consequence of the pulse compression is that the instantaneous amplitude of point target returns is increased by the square root of the compression ratio. Thus, the dynamic range (i.e., word length) of the memory following the first stage of processing must be increased proportionally. The length of the memory associated with range compression is essentially equal to the number of range elements multiplied by the azimuth compression ratio.[8] Thus, from a memory perspective, it is desirable to do azimuth compression first. However, because the azimuth compression (and often motion compensation and range migration correction) is performed as a function of range, it is sometimes desirable to perform range compression first. The final choice depends on the actual processing parameters associated with a given application.

Utilization of the more exotic pulse compression schemes (such as the two-stage FFT technique described in the previous subsection) affords more flexibility in processor operations sequencing. The multistage processing approach permits an interlacing of partial range and azimuth compression with use of the basic two-stage dechirp and spectral analysis approach. Such a scheme may be somewhat advantageous in terms of computation rates, memory requirements, and convenience of compensating for motion perturbations. In addition, some convenience with respect to multimode processing of multilook data may be possible. If single-look, full-resolution data are required, the final range and azimuth compressions can be performed as depicted. However, if multiple range and/or azimuth looks are desired, the partially compressed data could potentially be detected and combined noncoherently to form the final multilook image.

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[8] If the range and azimuth resolution cell sizes are given in feet, the bulk memory size of the processor is

$$M = \eta N_\ell R \lambda W (K_a/\rho)^3 N_b \text{ bits}$$

where η is the memory utilization factor ($0 < \eta \leq 1.0$), which is a function of the efficiency of the azimuth processing algorithm, N_ℓ is the number of noncoherent integrations, R is the range to midswath, λ is the wavelength, W is the swath width, K_a is the pulse-broadening factor, which is a function of aperture weighting, and N_b is the memory word size for the in-phase or quadrature component.

The actual choice of processor architecture will depend heavily on the radar system parameters and on the availability of new-technology hardware components. For example, if memory costs continue to decrease to the point of no longer dominating the processor costs, then less emphasis would be placed on memory reduction schemes and perhaps more on overall processor complexity reduction. In addition, for many applications, the range and/or azimuth compression subsystems might justifiably be replaced with analog or hybrid analog-digital pulse compression networks, with a resultant decrease in overall system weight and power requirements.

Additional Processing Considerations

Additional SAR system considerations can greatly impact the aforementioned processor implementations. In particular, the following subjects have yet to be examined in the context of this document: (1) alternate modulation schemes, (2) autofocus requirements, (3) image rectification, and (4) multimode considerations. This subsection will provide some brief commentary concerning these key design issues.

Alternate modulation schemes.- The choice of radar pulse modulation as a linear FM may not, in some circumstances, be the best available. Other pulse modulation schemes may possess features that make them attractive from either a generation, recording, or processing point of view. In particular, certain approximations to the linear FM approach have been shown to result in computational savings in terms of compression (and generation).

Alternate modulation schemes should be considered and studied for Earth resources applications. A key component in these investigations would be an assessment of the impact on processor-architecture resulting from an alternative approach. For example, the use of binary phase-coded modulation may be a good approach for certain processor configurations.

Autofocus requirements.- As previously discussed, the compression of SAR phase histories into imagery requires knowledge of the relative motion between the antenna phase center and the terrain strip being imaged. The constraints on the accuracy of these motion measurements are quite severe. Over a synthetic aperture interval, the short-term antenna movements (introducing so-called high-frequency phase errors) must be known and corrected to a fraction of a wavelength. The long-term motion (principally the platform velocity) must be known to within a fraction of a percent to enable adequate focusing of the data. Errors in the velocity estimates cause azimuth defocusing (blurring) of the image data. Current and projected airborne systems do not have adequate inertial navigation capabilities to obtain the necessary long-term velocity accuracies. For a spaceborne system, this limitation may be considerably eased because of the smoother flight environment.

If velocity errors are present in the system, then either manual or automatic focus corrections must be made to correct for the erroneous estimate of Doppler FM rate. Optically, such a correction is easily made by simply moving lenses. Digitally, the correction involves changing the filter coefficients. The most difficult aspect of the digital problem is sensing the amount of focus correction required. Many techniques have been proposed, and some successfully demonstrated.

A requirement for an autofocus capability as part of a spaceborne SAR imaging system would have a nonnegligible impact on the processor architecture and algorithm selection. The requirement depends on the resolution required for a given application and on the quality of the auxiliary motion information accompanying the signal data. An autofocus capability would probably be required to produce focused imagery of ships at sea.

Image rectification.- It appears highly desirable to have the final image data geometrically registered to a common projection format - perhaps compatible with the Landsat-D proposed image format. Range layover conditions must be ignored in this context because they will result in unavoidable registration errors. The image rectification can be performed as a two-dimensional interpolation of the final digital image. This approach is best if many diverse image mappings are eventually required.

However, if a standard projection can be accepted, it is possible to engrain the image rectification feature into the processor itself. This task is achieved by appropriately adjusting linear phase corrections and resamplings within the processor. Because some of the required operations are already performed in the processor, some hardware savings might be possible by incorporating the rectification into the image formation process itself.

Multimode considerations.- A SAR image formation processor can readily be optimized (in terms of hardware complexity) for a given imaging geometry and radar wavelength. However, if a single processing facility is expected to provide image data for a variety of imaging geometries and over a number of wavelengths, the design task is obviously more difficult. These multimode considerations must be examined.

As an example of a key processor component that is impacted by both wavelength and geometry, consider the brute-force-processor bulk memory requirements. As was given in footnote 8 (p. 242), the bulk memory requirement is proportional to both range and wavelength. Thus, a general-purpose-SAR-processor's memory must be flexible both in terms of size and organization. The impact of memory organization flexibility on certain block-oriented memory technologies (such as CCD's or block-oriented random access memories) may significantly decrease the suitability of such technologies to the general-purpose-processor problem; however, the use of suitably sized memory blocks may make these technologies acceptable even for flexible processors.

If the problems encountered in producing a multimode processor become severe enough, it may become necessary to build several simpler processors to perform the various roles. The multimode question should therefore be thoroughly examined with respect to the projected system applications.

Possible processor configurations.- The nature of the synthetic aperture process lends itself well to the use of any one of a large variety of processing techniques to produce images from the original data. Some of these techniques are more suited to ground processing of the data, whereas others may not be as suitable for the ground station but because of low power consumption and small size are especially suitable for onboard processing. Some methods are particularly advantageous for relatively modest resolution processing but are not significantly advantageous for fine-resolution processing, whereas others seem to be more general-purpose methods but may be cumbersome for the modest-resolution case.

In all cases of synthetic aperture imaging, the use of averaging of multiple independent samples is called for (multilook). Interpretability of images is better if the spatial resolution is sacrificed somewhat to the multilook capability, as indeed it must be for low-resolution imagery. Thus, all processors considered have a multilook capability.

Optical processing has been the traditional method used, but it will not be considered in this discussion because of the limitations associated with the use of silver halide film as the data storage medium. If some hybrid storage medium with electronic input and optical readout can be found to replace film, optical processing may become the method of choice.

Useful processors using all-digital, all-analog (continuous or sampled data), or hybrid digital-analog techniques can be developed. The latter type appears to offer the most promise for small onboard systems, but all of the techniques should be evaluated in terms of the ability to meet the needs for radars aimed at the different users. Questions arise in processor design, particularly for hybrid systems, regarding where and how to do motion compensation, where and how to do range "dechirping," and where and how to do "azimuth dechirping." To obtain the answers to these questions, a detailed study of the techniques available at any particular time in the development of component technology will be required.

Processors tend to be subdivided into range-gated processors, which treat each range element separately for generating the azimuth resolution, and range sequential (usually range offset) processors, which process range elements one at a time but do not separate them until after the azimuth processing has been done. Both systems have advantages and disadvantages. Some of the earliest processors were range sequential, but development of digital techniques caused a trend toward range-gated processors and most of the current electronic processors are range gated. Recent developments in analog storage techniques (CCD and serial analog memory (SAM)) have again focused interest on range sequential processing; and in the process of reexamining this old technique, it has become apparent that digital implementations of range sequential processing may also be desirable. The processor types outlined in the following two subsections have been grouped into these two classes.

The types of processor that might be considered include those listed; but, no doubt, both new techniques and variations of the listed ones will be forthcoming in the next few years.

Range-gated processors: The range-gated processors under consideration are as follows.

1. Unfocused integration processor - For most applications, the use of focused processing is required to achieve adequate resolution; but for

some, unfocused processing - which is inherently simpler to accomplish - is sufficient. A single-look unfocused processor using this technique is shown in figure 5-10. Implementation for multiple looks requires using a separate LO for each look and duplicating the structure shown. The outputs must then be combined before they are made into an image.

2. FFT processor - The FFT algorithms enable filtering with minimum hardware for applications of the kind in space imaging radar. Special-purpose FFT processors for filtering are becoming part of various instruments used in the laboratory, and the same techniques can be and have been applied to SAR data processing. The FFT processor can be used for both range and azimuth dechirping, but here it will be assumed that the range dechirping has been accomplished elsewhere, probably with an analog, SAW device. The next step in the FFT processor is converting the chirped-signal returns into constant-frequency returns; this conversion may be accomplished in an analog fashion by mixing with a chirped LO (as shown), and in a digital fashion by performing the same operation digitally. An FFT processor is shown in figure 5-11. Note that the signal is first heterodyned down to a zero-frequency i.f. and that this transition requires I (in-phase) and Q (quadrature) channels. This technique seems to be preferred at present, but heterodyning to an "azimuth-offset" i.f. at PRF/4 is also possible, in which case the FFT operates at a higher rate but requires only one channel.

3. Correlation processor - A technique that has been used successfully in several organizations for processing images involves the correlation of the returned signal with a reference signal that is a replica of the signal from a point scatterer at the desired image point. This technique is diagrammed in figure 5-12. It, too, is usually used with I and Q channels but could be done with an azimuth offset and a single longer channel.

4. CCD-SAW analog azimuth processor - A processor using a CCD special chip for "corner-turning" memory and a SAW frequency-sensitive delay line for azimuth dechirping has been built for other purposes at the Royal Signals and Radar Establishment in England, and the SAW line has been used for these purposes at Rockwell International. This processor has great promise for modest-resolution SAR data onboard processing because of its small size and low power consumption. Such a processor is diagrammed in figure 5-13.

Serial synthetic aperture radar (SAR) processors: The serial SAR processors under consideration are as follows.

1. Unfocused recirculating processor - The early unfocused radars used a recirculating bulk-acoustic-wave delay line for processing. Today, this technique still appears applicable, but sampled-data devices such as CCD's and SAM's appear more suitable because of instabilities in the delay of the analog delay line caused by temperature. This technique could also be implemented by using digital shift registers. The method is very simple. A sketch of its architecture is shown in figure 5-14.

2. Comb-filter focused processor - The frequency response of a filter consisting of a recirculating delay line is a comb of responses,

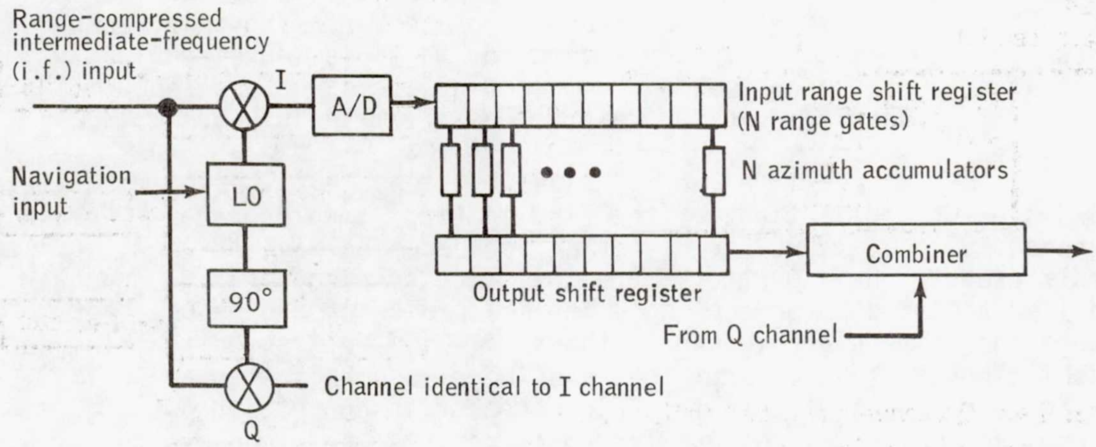

Figure 5-10.- Basic unfocused integration processor.

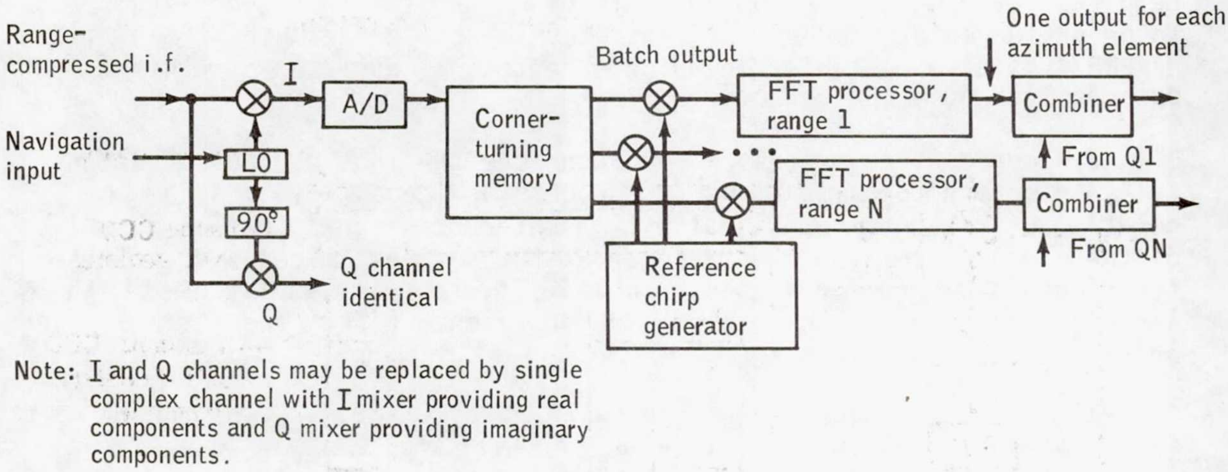

Figure 5-11.- Basic FFT processor.

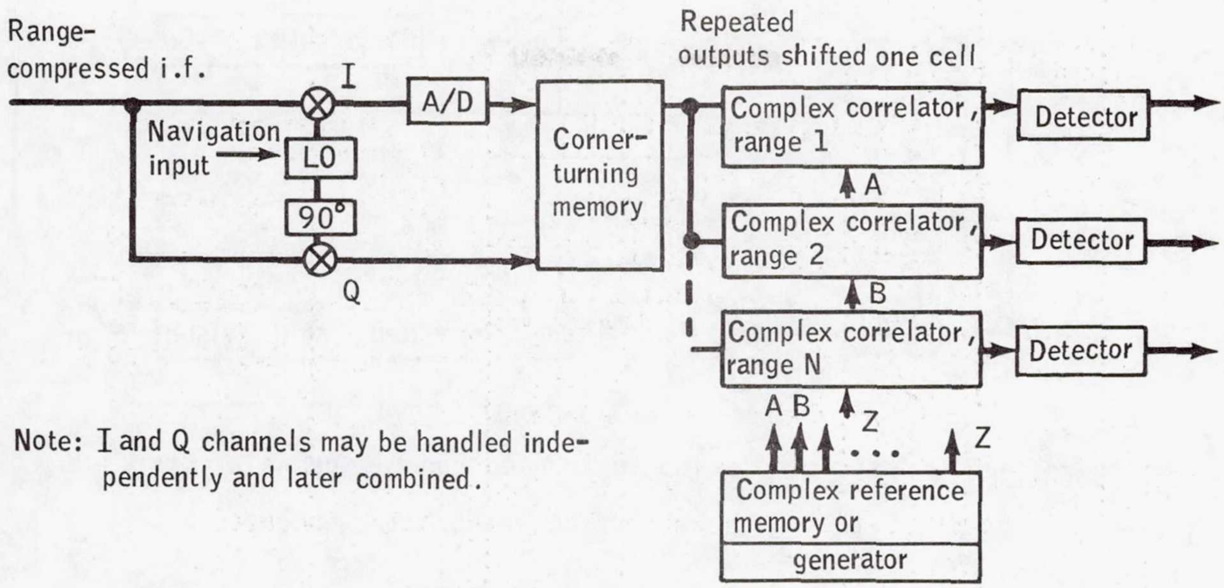

Figure 5-12.- Basic correlation processor.

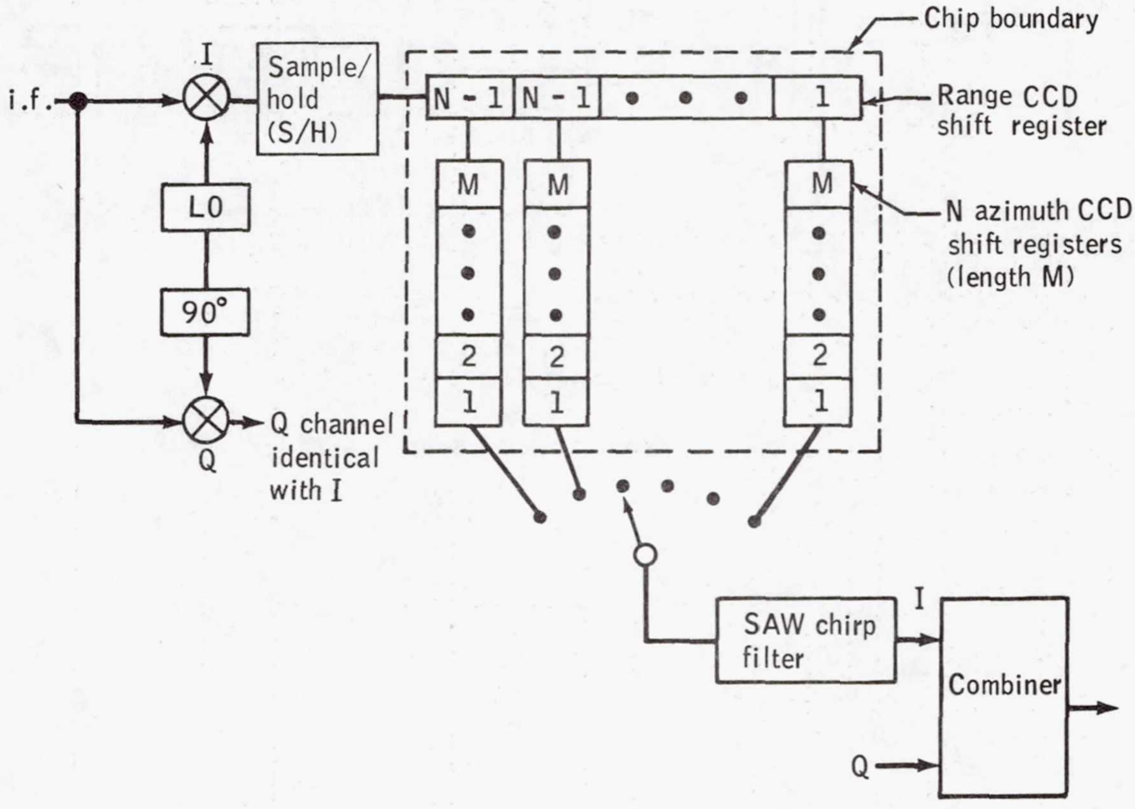

Figure 5-13.- CCD-SAW processor basic configuration - one look.

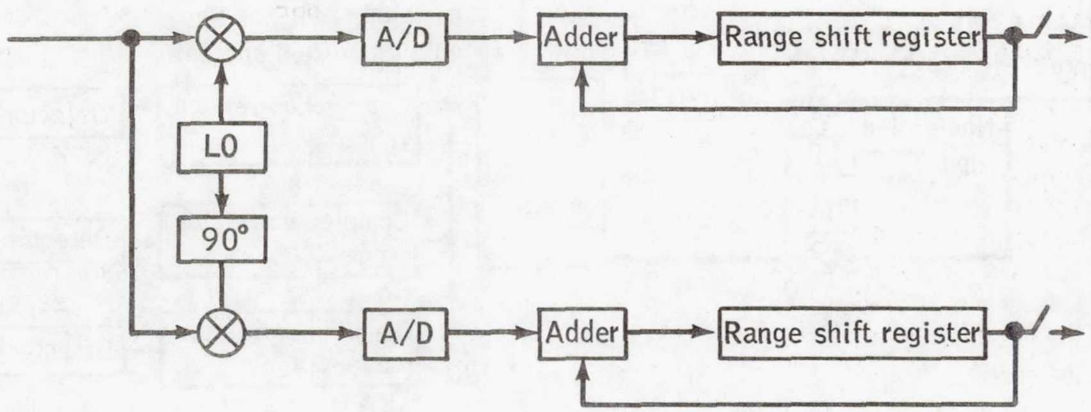

Figure 5-14.- Basic single-look unfocused range-sequential processor.

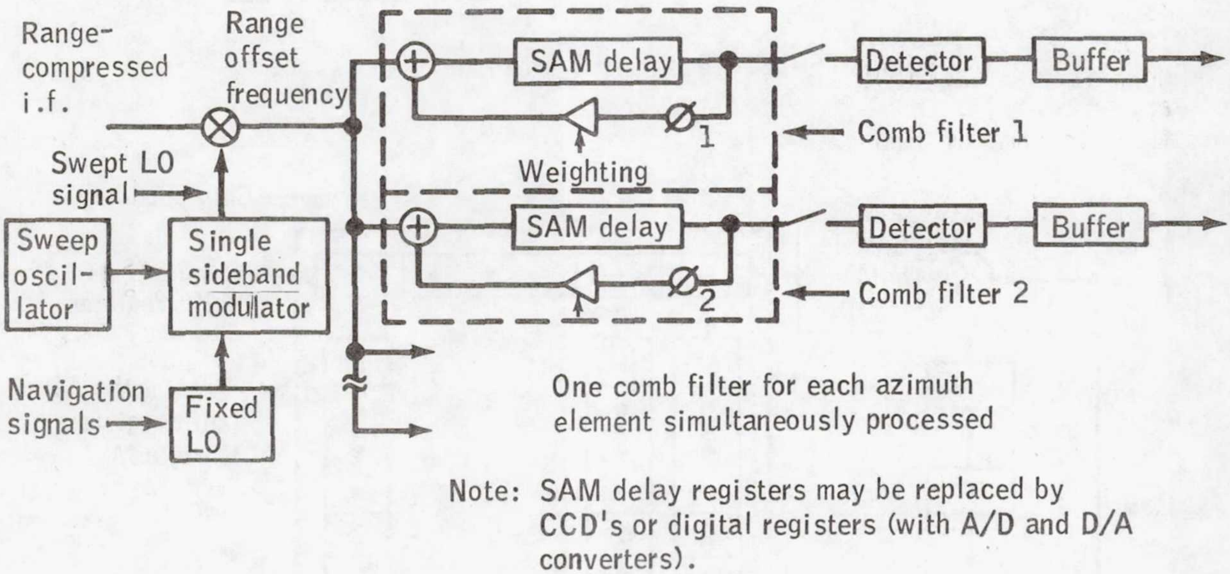

Figure 5-15.- Basic comb-filter range-sequential processor.

with each tooth centered about a multiple of the PRF. When a frequency-independent phase shift is introduced into the feedback loop of the delay line (or delay shift register), the teeth of the comb shift somewhat in frequency. Thus, a series of comb filters can select out of a return pulse a series of returns corresponding to different Doppler offset frequencies and therefore to different azimuth elements. Such a comb filter can be used in two ways in SAR data processing: (1) with fixed phase shift and a sweep LO preceding the comb filter to convert all received azimuth signals to fixed offsets as in the FFT processor or (2) with a variable phase shift permitting sweeping the comb filter response to follow the changing Doppler shift from a given azimuth position. A processor of the first type is shown in figure 5-15.

3. True synthetic aperture processor - A recent proposal by Texas Instruments, Inc., and the JPL is for a "true SAR" processor using analog implementations with CCD memories. This system, like the CCD-SAW processor, seems to offer a great deal of promise in terms of minimizing the power and space requirements of an onboard processor. The configuration is diagrammed in figure 5-16. When the number of pulses required to be processed has arrived, all the CCD's are full. At that time, the outputs go through the range-walk correctors to the multipliers that apply the appropriate phase corrections for each point in the aperture. The output then is summed and appears range sequentially for each azimuth position.

This group of processor options offers considerable promise that optimum processors can be developed for both onboard and ground applications. Some are already available for aircraft radars, and others need preliminary testing. The entire group needs to be considered to examine the optimum configurations for the different applications, and development on the untested versions needs to be conducted to verify the predicted performance. Such a program should be ongoing, because the right choice with today's component state-of-the-art may not be right tomorrow. On the other hand, this very fact indicates that full-scale development of prototype space systems should be delayed until a mission is identified so that the best trade-off can be made as to the hardware availability at that time.

Large Ground-Based Synthetic Aperture Radar (SAR) Data Processing Architecture

Formulative studies for application of the SAR have illuminated the need to deploy radar sensors operating from L-band through X-band on platforms ranging from aircraft through various types of satellites. Application requirements such as wavelength, image resolution, viewing geometry, and surveillance area differ significantly as a function of the application objectives and physics; and during the initial radar programs, optimum selection of these requirements will not be conclusively established. Many of the experimental programs will be intensive but short-duration efforts, with requirements to reduce acquired data through signal processes with variable parameter sets so as to develop relative sensor performance data comparisons.

The processing load for SAR data is of such magnitude as to preclude the application of conventional computation centers. It would be economically unrealistic to plan on handling sufficient data quantity to be statistically significant even during the experimental phases of radar application programs. If the optimum processing parameters were known and accepted within the community, practical special processors could be implemented with technology available today. However, this assumption is not valid, and such an approach would not be supportive of the experimental nature characteristic of early sensor application development.

These factors lead to the conclusion that flexibility rather than efficiency is the consideration that drives the architecture of a dedicated large ground-based SAR-data-processing facility. The architecture should initially support the experimental type of sensor programs, with the potential to be subsequently expanded to production processing of SAR image products to a format directly useful to the user community. A desirable but secondary consideration is the possibility of supporting advanced-technology processor development programs by providing simulation capabilities to emulate candidate specialized processor designs and to support input data generation and output data analysis during specialized hardware test activities.

Fortunately, there is a thread of commonality in SAR data processing across the many facility applications. The previous section on the operations required to produce SAR imagery illustrates this continuity. Algorithm options were found to be influenced by processor implementation technology selection more than by image application considerations. Existing processors for SAR or other intensive signal-processing applications illustrate the practicality of implementing the arithmetic functions as special dedicated processor modules or as programmable processor modules (e.g., the Hughes Aircraft Company's programmable signal processor built for the Air Force's forward-looking advanced multimode radar (FLAMR) program). The cost, size, power, and architectural selection of these processors have been controlled by memory technology considerations, and this trend is expected to continue.

A rational approach to the architecture of a large ground-based SAR-data-processing facility is to concentrate on the efficient but flexible utilization of memory available at the time of facility implementation. The SAR data are block oriented, and thus mechanical storage devices such as disks and drums would only be applicable if considerable process slowdown can be tolerated. This selection may be suitable as an interim facility step during the development of radar image applications, but the ultimate facility must have massive block-oriented solid-state data memory devices to support in a practical manner routine application image production. Because the relative size of internal SAR data buffers is dependent on the parameters for the specific application, this memory should be programmably allocatable to the different buffers through the use of a programmable storage controller. Provisions for efficient and convenient "corner turning" should be included as a hardware capability in this storage controller. Such a memory complex would provide the nucleus of a flexible processing facility, around which input/output (I/O) devices and programmable arithmetic processors could be coupled.

A system for ground-based SAR data processing extends beyond the hardware. Function, operational procedures, and (if programmable) software management must also be considered during the large ground-based SAR-data-processing architecture concept formulation. In the following paragraphs, key factors in these areas are tabulated. Principal issues that must be resolved before specifications are generated for the facility are also included.

Figure 5-17 shows a typical configuration for a large ground-based SAR-data-processing facility. The inputs required to operate such a facility are as follows.

1. Recorded sensor data

2. Platform motion data

3. Input data management parameters

4. Desired process parameters

The processing functions that such a facility must perform are as follows.

1. Data reading

2. Data editing and AGC correction

3. Pulse compression

4. Range-walk correction

5. Azimuth prefiltering

6. Clutter centroid estimation

7. Range-curvature correction

8. Azimuth compression

9. Pixel registration correction

10. Detection

11. Look averaging

12. Standard map projection

13. Image writing

14. Film copy preparation

15. CCT preparation

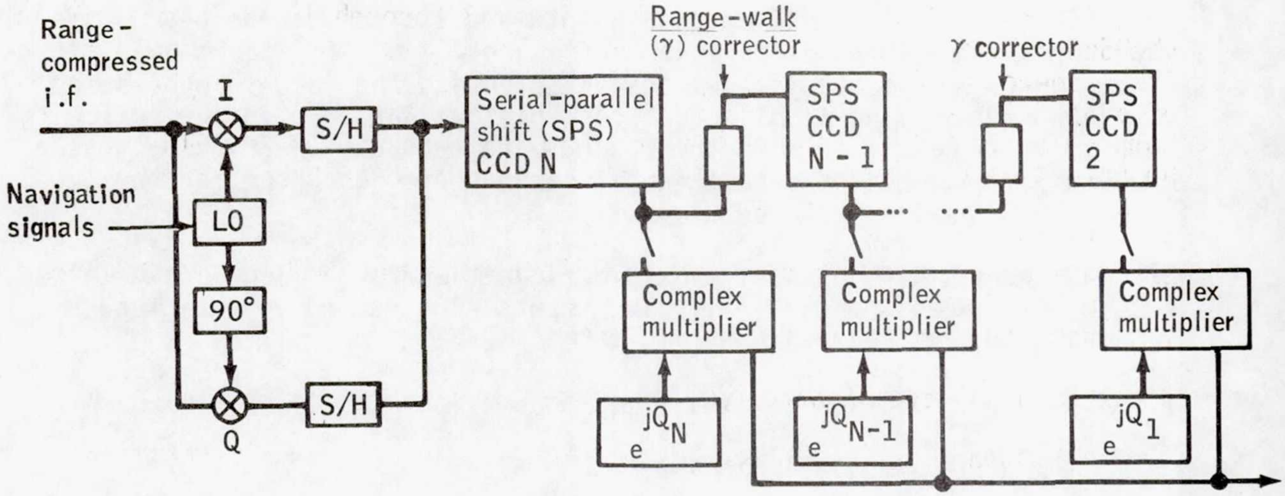

Figure 5-16.- Basic CCD true-synthetic-aperture processor.

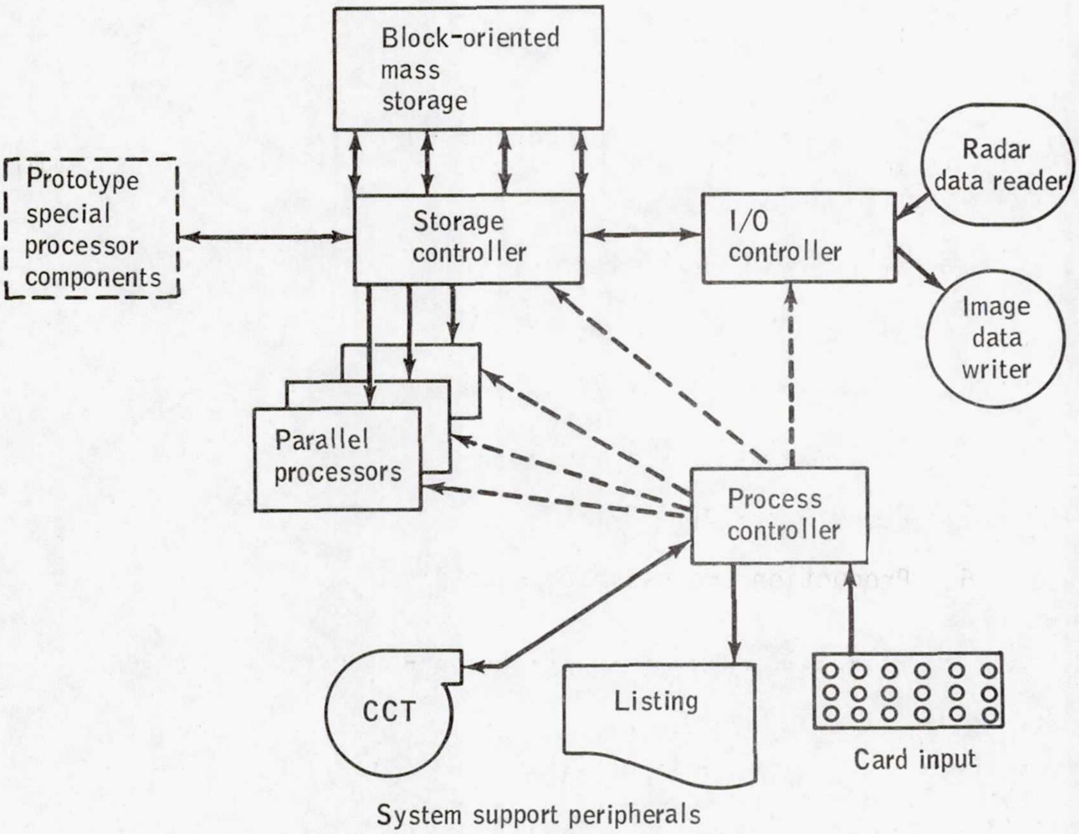

Figure 5-17.- SAR processor configuration.

Figure 5-18 illustrates how functions 13 through 15 are organized in the Seasat image formation processor currently under procurement by the JPL. There, the primary output is imagery on film, with secondary outputs of quantitative data for specific requirements available in CCT form. A comprehensive data-editing capability is necessary to select the data to be output in CCT form.

Extensive software will be required to implement a large ground-based SAR data processor. This software will include the following components.

1. SAR signal processing function library
2. High level control process assembler
3. Data library management programs
4. Control processor supervisor
5. Tape I/O support modules
6. CCT formatters
7. Diagnostic routines
8. Process configuration test data generator

Operation of a large SAR-data-processing facility will require the following elements.

1. Data library retention strategy
2. Machine readable tape identification and multitape linkage
3. Process configuration management and documentation
4. Standardized I/O formats
5. Process validation standards
6. Production process work sheets

Analog-to-Digital Quantization Precision Requirements

An A/D converter may be modeled as shown in figure 5-19. This figure consists of a box of unity transfer function plus a noise generator. The block diagram and the noise power level are given by W. Bennett (ref. 5-14). The noise power, N_q, added by the quantizer is shown by Bennett to be

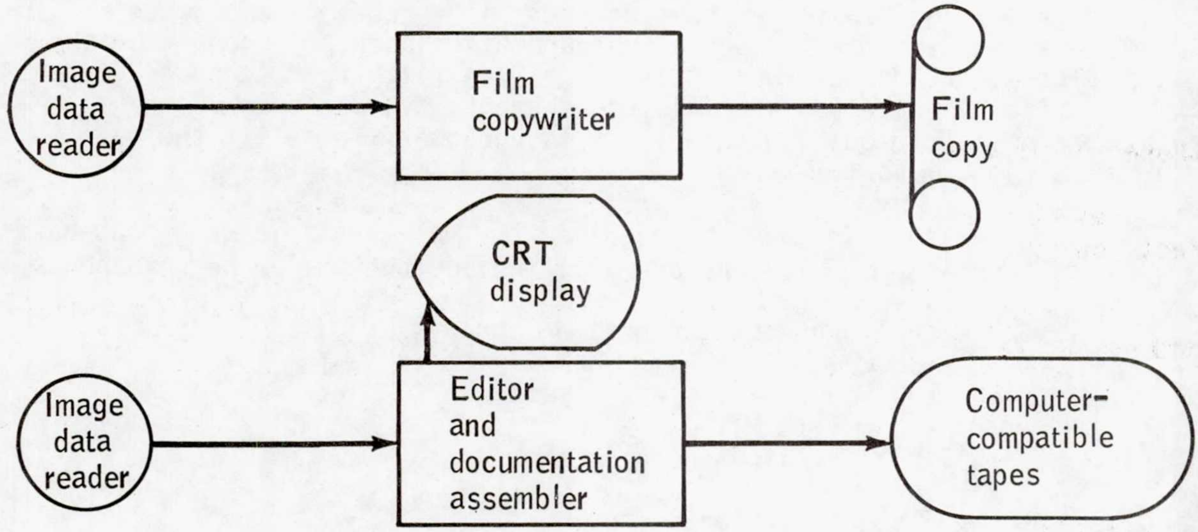

Figure 5-18.- Seasat product generation.

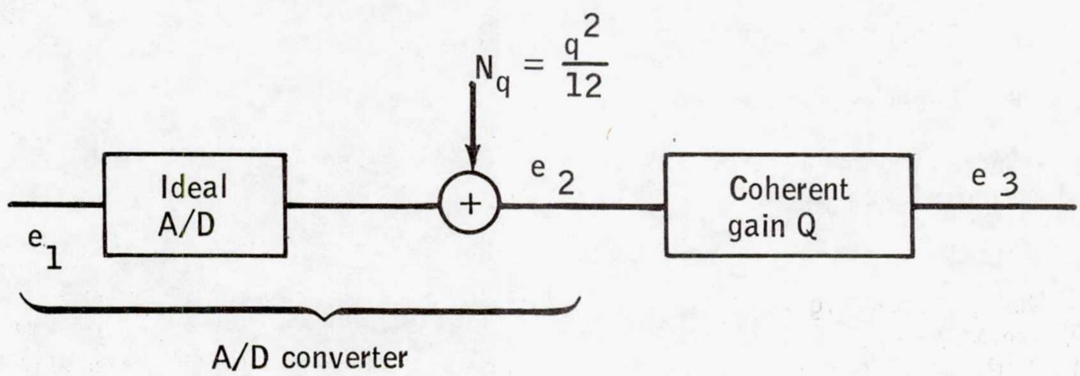

Figure 5-19.- Model of A/D converter.

$$N_q = \frac{q^2}{12} \tag{5-20}$$

where q is the least count of the A/D converter.

Let Q be the coherent gain between the A/D converter and the final radar output.

The power level at point 1 in figure 5-19 is S_1 and N_1 for signal and noise, respectively. These levels become

$$\left.\begin{aligned} S_2 &= S_1 \\ N_2 &= N_1 + N_q \end{aligned}\right\} \tag{5-21}$$

at point 2.

At the radar output, one has

$$\left.\begin{aligned} S_3 &= Q^2 S_1 \\ N_3 &= Q(N_1 + N_q) \end{aligned}\right\} \tag{5-22}$$

Hence,

$$\frac{S_3}{N_3} = \frac{QS_1}{N_1 + N_q} \tag{5-23}$$

Next, the assignment of the number of bits in the A/D converter needs to be considered. Following Bennett, proceed as follows: Let n_b be the number of bits in the A/D converter. Because bipolar signals are to be converted, assign $n_b - 1$ bits to the maximum amplitude of each polarity. Let $n_b - 3$ bits be assigned to the signal-plus-noise standard deviation (σ) at point 1, the converter input. Thus, full amplitude of the A/D converter corresponds to the 4-σ value, and the probability that signal plus noise at point 1 will exceed the A/D converter dynamic range is very small. The assignment of $n_b - 3$ bits to the standard deviation is written as

$$2^{n_b - 3} q = \sqrt{S_1 + N_1} \tag{5-24}$$

Combining equations (5-20) and (5-24) gives, on elimination of q,

$$N_q = \frac{S_1 + N_1}{12(4^{n_b - 3})} = \epsilon N_1 \tag{5-25}$$

The value for ε makes N_q equal to some acceptable multiple of N_1.

Use of equation (5-25) in (5-23) gives

$$\frac{S_3}{N_3} = \frac{Q}{1 + \varepsilon} \frac{S_1}{N_1} \tag{5-26}$$

Some minimum value for S_3/N_3 at the output is usually required. Hence, S_3/N_3 has a given value. Some value exists for S_1/N_1 at point 1. The system coherent gain Q can be computed with knowledge of the pulse compression and azimuth compression ratios. Hence, ε can be computed. From equation (5-25), the number of bits, n_b, in the A/D converter can be found from

$$2^{2(n_b-3)} = \frac{S_1 + N_1}{12\varepsilon N_1} \tag{5-27}$$

Hence,

$$2(n_b - 3) = \log_2 \left(\frac{S_1 + N_1}{12\varepsilon N_1} \right) \tag{5-28}$$

or

$$n_b = 2 - \log_2 \sqrt{3} + \log_2 \sqrt{1 + \frac{S_1}{N_1}} - \log_2 \sqrt{\varepsilon} \tag{5-29}$$

If ε is chosen so that the extra noise due to the A/D converter is small - e.g.,

$$\varepsilon = \frac{1}{12}$$

then

$$n_b = 3 + \log_2 \sqrt{1 + \frac{S_1}{N_1}} \tag{5-30}$$

If the noise due to the A/D converter is allowed to equal the input noise (e.g., $\varepsilon = 1$), then

$$n_b = 2 - \log_2 \sqrt{3} + \log_2 \sqrt{1 + \frac{S_1}{N_1}} \tag{5-31}$$

Thus, the number of bits required to place the quantization noise between the units of 1/12 and 1 times the input noise is between the values given by equations (5-30) and (5-31).

In addition to controlling quantization (and saturation) noise, another important consideration in the specification of A/D converter precision is A/D gain variation as a function of input signal level (small signal suppression).

Input Data Requirements

The SAR sensor differs considerably from the visual and IR sensors in both the form of input data and the processing required to obtain a usable image product. The principal differences will be described, and the essential input data components required to produce quality imagery will be identified.

Transmitted signal.- The SAR is an active imaging system in which the ground is illuminated by energy transmitted from the vehicle. The short pulses required to provide high range resolution are difficult to achieve because of technological difficulties of implementing the high peak power necessary to provide sufficient illumination energy in a short time. Today's radars overcome this limitation by transmitting a lengthened pulse of lower peak power that is frequency coded to permit subsequent pulse compression after return reception. For the radar to function properly, the following information must be known about the transmitted signal.

1. Transmitted waveform to establish effective carrier frequency and to permit pulse compression

2. Average pulse power for calibration

3. Pulse transmission time to reference range measurement (clock reference, PRF, and pulse count)

The transmitted waveform is extremely stable and needs only to be checked or updated every month. The pulse power is less stable and should be updated approximately once per hour. The pulse transmission time must be current; however, the PRF is traditionally derived from extremely stable clocks, and thus the transmission time is inherent in the pulse count. When range gating and sampling are derived from this same clock, time synchronization needs to be accomplished only upon system initialization and about once a day. Pulse count must be available for any block of input data.

Received radar data - The received radar data are characterized by amplitude and phase as a function of time relative to the epoch of the transmitted signal. The received-data bandwidth is limited by the response characteristics of the receiver so as to reject interference and noise outside the spectral window of the radar. Because the nominal signal strength can vary considerably as a function of range because of the $1/R^4$ term in the radar equation, a gain function (sensitivity versus time control or STC) is applied as a function of time to equalize the power level that must be accommodated by the data acquisition system components. The gain function is usually a prestored function modified by a slowly varying multiplier that adapts to the observed received-data power history. This gain function must be accounted for to retain an image calibration. Amplitude and phase data can be represented either as real and complex components at baseband (zero frequency for the i.f.) or as only the real component of data that has been offset in frequency so as to preclude interpretation ambiguity. If these data are sampled, they must be observed at a rate greater than two observations (one complex observation) per hertz of significant power bandwidth. These samples are usually acquired over only the fraction of received time that corresponds to surveillance ranges of interest.

In summary, the following information must be known about the received signal.

1. Video data (complex or real with offset value)

2. Video data time relative to pulse transmission (range gate reference, sample rate, and sample count)

3. STC function

4. AGC parameter

Video is the bulk of SAR data and must be collected with the dynamic range identified in the preceding sections. The range window reference and gain control parameter should be known for each pulse. The sample rate and STC functions are usually a constant for a particular system.

Precision vehicle navigation.- To form a synthetic radar aperture, the motion of some vehicle is used to translate the real antenna through space during an interval of time. During this interval of time, the antenna position must be known to a small fraction of a wavelength. The vehicle acceleration vector must be measured or otherwise known to achieve this result (acceleration can be calculated for satellite platforms). When the acceleration reference point (vehicle center-of-mass) is not at the antenna focal point, vehicle attitude histories and the antenna/acceleration reference point geometry must be known. In summary, the information needed is as follows.

1. Antenna/vehicle geometry

2. Vehicle attitude

3. Precision vehicle position (reference velocity and acceleration)

The quality of these data must be sufficient to allow one to estimate the relative vehicle position during the aperture time to within a small fraction (less than one-eighth) of a wavelength. For the L-band, this length is on the order of a centimeter. Higher radar frequencies require even more precision.

Vehicle/terrain geometry.- An SAR basically creates images in range and subtended angle relative to the average velocity vector during the synthetic aperture time period. These coordinates are derived from round-trip travel time and the observed Doppler history, and not from the real-antenna orientation. This distinction is a significant and often misunderstood difference between SAR and optical imagery. Knowledge of the terrain geometry relative to the vehicle is necessary to resolve the third coordinate variable. Thus, vehicle position affects more than just the registration of image data on a reference grid system. In summary, the information needed is as follows.

1. Vehicle position (to accuracy of uncorrected registration requirement)

2. Vehicle velocity vector (to accuracy of uncorrected image registration requirement at end of range arm)

3. Terrain relief (to accuracy necessary to register the map in range)

Antenna pattern projection.- Knowledge of the terrain projection of the antenna pattern is required to interpret the Doppler spectrum properly during the image processing and to correct shading caused by the real antenna for purposes of retaining image calibration. Note that the radar image registration is not affected by the antenna attitude. Thus, the attitude control of the sensor platform is significantly relaxed from that of the optical sensors. In summary, the parameters of importance are as follows.

1. Antenna pattern (antenna size and shading)

2. Antenna attitude (one-fiftieth of beamwidth)

Data management.- Because of the mass of SAR data, special considerations should be given to data management. The following conclusions are based on experience with other mass data systems.

1. The parameters and histories necessary for processing should be contained within the input data record format.

2. Contiguous data tapes should be unambiguously linked by header and trailer information.

3. Data library maintenance should be automated.

IMPLEMENTATION TECHNOLOGY

The Implementation Technology Subpanel was supplied with the following questions/instruction to guide its work.

1. What are the comparative merits of digital versus analog processing?

2. How should the radar data be recorded in the Shuttle? Contrast optical versus magnetic tape recording.

3. What hardware and technology developments are needed in the immediate future to allow realization of a fully digital SAR-data-processing system?

4. What memory technology is best suited for implementing an all-digital SAR data ground-processing facility?

5. How should processing be partitioned between in-flight and ground processing?

6. How should the processor output image be recorded?

7. What are the capabilities of existing SAR-data-processing systems?

A Comparison of Various Analog and Digital Techniques for Synthetic Aperture Radar (SAR) Data Processing

There are a number of analog and digital techniques that can be and have been used in SAR systems. There also are a number of hybrid systems in which a combination of analog and digital techniques is used. It is the purpose of this subsection to compare some of these systems with respect to complexity, speed of operation, cost, power requirements, etc.

The major analog system (and one of the earliest) is optical processing. In this type of system, use is made of the fact that linearly frequency modulated signals have self-focusing properties and that both chirp and synthetic aperture signals are of this form. In general, the focal lengths of the signals have inconvenient values, and telescopic, anamorphic lens systems are used to process these signals.

With such optical systems, the pulse compression and azimuth compression can be performed simultaneously. Moreover, storage on a film as dense as 40 to 100 lines/mm can be achieved, with a maximum dynamic range of approximately 25 dB at each such point. This accommodation is equivalent to a storage capability of approximately 1.6 megabits/cm^2 (10^7 bits/in^2).

The disadvantages of optical processing are mainly due to the necessity to use silver halide film as a storage medium. The use of chemicals is required to develop the film; and unless extreme care is used, a variation in the density achieved on the film is obtained.

Because the optical processing system is an analog device, one can expect an accuracy or repeatability of not over 0.1 percent.

Another problem is that of time delay. Two films, the signal history film and the output image film, must be developed. This process is, at the minimum, several minutes in duration.

Another problem with using film as the data storage medium in optical processing is that of film length in the developing stations. The finer the resolution on the film, the longer the distance along the flightpath that corresponds to that length of film. Thus, the vehicle may have gone a long distance before the film is available for exploitation of the image.

Although alternatives to silver halide film recording exist, they have not to date been too successful, largely because of the high level of energy required to expose them compared to that required for silver halide film.

Digital techniques can be used to perform both the pulse compression and azimuth compression in SAR's. Convolutional processing and its equivalent in FFT processing are appropriately implemented with the use of digital techniques.

In some cases, however, the data rate required becomes extreme. For example, Seasat has a swath width, W, of 100 km, with a range resolution, ρ_r, of 25 m; this combination corresponds to 4000 range elements.

At a speed V of approximately 8000 m/sec, in 10 minutes the number of azimuth elements passed over is

$$\frac{Vt}{\rho_a} \simeq 2 \times 10^5$$

where ρ_a is the azimuth resolution. Thus, approximately 8×10^8 points are viewed for each 10-minute pass.

After presumming, a minimum of V/ρ_a complex data points must be stored per range bin per second. For a dual-frequency dual-polarized system with a quantization precision of five bits, the total data storage required to record a 10-minute pass can be calculated from

$$N_b = \frac{2Vn_b n_f n_p Wt}{\rho_a \rho_r} = 30.7 \times 10^9 \text{ bits} \qquad (5\text{-}32)$$

where n_f is the number of system frequencies on which maps are to be formed, n_p is the number of polarizations, V is the platform velocity, n_b is the number of A/D bits used, W is the swath width, and t is the time.

Digital tape recorders can achieve approximately 7.9×10^3 spots/cm (20×10^3 spots/in) along the track, and 100 tracks across a 5.1-cm-wide (2 in. wide) tape. The density of spots on the tape is thus approximately 155.0×10^3 spots/cm^2 (10^6 spots/in^2). The area of digital magnetic tape required to store a 10-minute Seasat pass is thus $[N_b/(1550 \times 10^6)]$ m^2 = 19.8 m^2 (($N_b/10^6$) in^2 = 30.7×10^3 in^2). For 5.1-cm-wide (2 in. wide) tape, this area requires a tape length of 390.1 m (1280 ft). Approximately 1828.8 m (6000 ft) of 5.1-cm-wide (2 in. wide) tape are required to record the data prior to presumming. The minimum tape speed required to keep up with the Seasat data rate in real time is thus 1828.8 m/600 sec or 3.0 m/sec (6000 ft/600 sec or 10 ft/sec (120 in/sec)).

The spot density of 155.0×10^3 spots/cm^2 (10^6 spots/in^2) for magnetic tape is approximately equal to the spot density for silver halide film. If used digitally, the tape stores one bit on such a spot; if used in analog fashion, perhaps five or six bits per spot can be shared. Thus, the area of magnetic film is about equal to that of silver halide film if the magnetic tape is used to store an analog signal. If the tape is used to record a digital signal, then magnetic tape requires five or six times more area than does film (with analog storage). Of course, if digital data are stored on film, the film area required will be about the same as that used by magnetic tape in recording digital signals.

Alternatives (hybrid analog-digital techniques) exist in newer technologies such as the use of CCD's and bubble memory techniques. In these cases, it is possible to arrange architectures that greatly reduce the equipment and time required to perform the computations. The equipment can be configured to do both pulse compression and azimuth compression efficiently. Its state of development is not as far along as that of either the pure optical or pure digital equipment. Its potential for the future, however, is very great.

There are other variants to both the optical and the digital processors. For the optical case, a technique known as polar format makes it possible to process the signal history film by using a two-dimensional Fourier transform. There is, of course, a digital equivalent.

In the digital case, there is an alternate generally known as batch processing. This alternate and the aforementioned polar format are pertinent to the case of mapping an area about some selected point. The processing is an approximation; but for batch processing, an FFT gives N image points, with N equal to the number of samples used in a synthetic aperture computation. Thus, the computation rate is reduced. However, the batch processing approximation is valid only over a limited region about the selected focus point. A sequence can be taken of selected focus points properly arranged in range and along track to fill in an extended region such as in the scansar concept proposed by the University of Kansas (ref. 5-15).

Various combinations not previously discussed exist. Optical recording does not necessarily imply optical processing. One can record either analog or digital signals on film. The subsequent processing can either be optical or digital.

Similarly, the pulse compression can be done either by analog or digital means. The SAW devices are an excellent means for pulse compression. These devices do not limit the choice of how the azimuth compression is performed.

Time-Domain Filters

In the time-domain filtering technique, small SAW delay lines are used to perform chirp transforms for rapid, narrow-band signal processing. The time-domain filter (TDF) is so called because it forms dispersed and resolvable time waveforms in response to monochromatic signal tones having different frequencies. This dispersal in time results from the Fourier transform properties of pulse compression/expansion delay lines. The TDF is suitable for any processing system that requires narrow-band filtering, particularly if the processing-speed requirements are high. These devices have been used successfully in medium- and low-PRF-pulse Doppler and SAR systems. Because of its small size and weight and low power consumption, the TDF is well suited for missile and spaceborne radar applications and provides an attractive alternative to digital DFT mechanizations.

The key element of the TDF is the passive SAW delay line. These devices are constructed by deposition of metallic interdigital fingers (transducers) on a piezoelectric substrate. Lithium niobate and ST-quartz are common substrate materials. Well-controlled amplitude and phase responses are achieved by using highly accurate masks prepared by automated plotting equipment. Because of its simplicity and the fact that it contains no active elements, the SAW line offers a low-cost and highly reliable means of implementing high-speed, real-time filters.

Rockwell International has built and tested a number of TDF's for various radar applications. As an example, one of these devices performs the equivalent of a 64-point DFT in 8.5 seconds. This particular unit is contained on a 16.5- by 19.1-cm (6.5 by 7.5 in.) circuit board, weighs 0.54 kg (19 oz), and dissipates 5.5 W.

When the TDF is used in a sampled-data application such as azimuth correlation in an SAR, the required time-bandwidth product of the SAW lines is equal to the number of radar pulses to be correlated. Time-bandwidth products of several hundred can be achieved with SAW lines by using simple, conventional surface-wave structures. The conventional SAW devices are limited to bandwidths of less than 100 MHz and time delays (processing intervals) of less than 60 microseconds.

To illustrate the use of a TDF for SAR imaging, consider an application wherein the data rate is 25 MHz and the azimuth resolution improvement or number of azimuth samples to be correlated is 150. The bandwidth of the SAW lines is established by the input signal bandwidth, which is 25 MHz in this example, and the length of the lines would be 150/(25 MHz) or 6 microseconds. These parameters are well within the capability of conventional SAW lines.

A total of $2(150)\log_2 150$ or approximately 2000 multiplications would be required to perform this same function with an FFT processor. To accomplish the FFT in 6 microseconds, multiplications would have to be performed at an average rate of one per 3 nanoseconds. With present hardware technology, the digital multipliers required to implement the FFT can perform a multiplication in no less than approximately 50 nanoseconds. The TDF for this application can be contained on approximately 322.6 cm^2 (50 in^2) of circuit board.

Unlike DFT's, the TDF has a continuous output as a function of frequency. This characteristic enables sampling of the signal spectrum at frequency intervals less than the reciprocal of the observation time. Oversampling in the frequency domain reduces the effects of filter or range straddle such as reduced signal-to-noise ratio and distortions that degrade image quality.

Azimuth or range sidelobes may be reduced in the TDF by conventional amplitude weighting. Sidelobes of better than -40 dB have been achieved except at very low delay line time-bandwidth products.

Practical TDF's generally have dynamic ranges of from 40 to 50 dB. The SAW lines themselves have dynamic ranges in excess of 60 dB; however, the overall filter performance is degraded by noise generated in and picked up by peripheral electronic circuits.

Rationale for Data Recording in the Shuttle Imaging Radar

Whether Shuttle SAR data will be recorded or transmitted in real time will depend largely on the Shuttle mission purpose and the capability of the NASA tracking and data relay satellite system (TDRSS).

The purpose of the SIR is to support user requirements for radar imagery. It will, however, be a research and development tool that should be very flexible, with a capability for configuration changes as radar parameters become better defined and as mission requirements change. It will be used to define later free-flyer SAR instruments. It also may eventually be used as a quasi-operational Shuttle instrument, responding to emergency requests for radar data, and could eventually become a part of a space station. Near term, it will, however, be a development tool.

This means that, initially, the SAR data are not time critical; the 1-week delay (which corresponds to the Shuttle mission length) should provide no real problems. It also means that, initially, data volume and rates will be at a maximum; i.e., 280 to 350 Mbps. (Until parameters are better defined, there is a reluctance to do too much processing on board.)

In the time frame of Shuttle SAR's, the TDRSS will be the principal means of communication between Earth-orbiting satellites and the ground. The maximum rate of data relay by the TDRSS is 300 Mbps, less than the 350 Mbps desired for the SIR. Furthermore, if the SIR data rate exceeds 30 Mbps, it must provide its own link with the TDRSS. (The Shuttle relay link data rate is only 30 Mbps.) This specification implies (1) implementation of a relay link, (2) more onboard processing, or (3) provision of recorders.

Because time will not initially be critical and it is desirable to maximize flexibility, recorders are initially the best alternative. As development progresses and parameters become better defined, more onboard processing (such as presumming) could be incorporated to reduce the 350 Mbps of data to a more reasonable quantity of information. Later configurations should include the capability to transmit real-time data for at least one channel (for emergency support).

The previous paragraph implies that, at least for early flights, a recording capability is needed. The type of capability is dependent on the ground system and the purpose of the flight. The real technical trade-offs have been previously discussed. In the following paragraphs, however, some operational considerations are presented.

Either optical or digital recording would be workable in the Shuttle mode of operation. More experience has been obtained in the optical area, and hence this technique might be more readily implementable. It also may be more apropos for establishing an onboard quick-look display capability.

However, some accuracy and flexibility are sacrificed. Also, as the SIR is presently configured, new recorder capability, even in the optical area, must be developed. (The technology is there but must be reconfigured.) In an ERIM study done for the JSC, this required development was a significant cost item in the data system.

Furthermore, film would not be acceptable for free-flyer or space station designs growing out of the SIR flights because it would not be retrievable. Also, it would not be apropos for the "record → slow down → transmit" mode of using direct transmission to the ground for "emergency support." Therefore, because (1) development will be required either way, (2) future operational modes are more compatible with digital recording, and (3) maximum accuracy and flexibility are obtained with digital recording, the recommendation is to plan to use digital recording at this time.

Required Hardware and Technology Development

The technology exists today for a fully digital SAR-data-processing system - on the assumption of four-bit encoding of radar video. For five-bit or more encoding, advances in digital-tape-recording technology are required.

When CCD's and/or bubble memories mature, reliability and maintainability will be enhanced; and in addition, size and power requirements will be reduced.

A 100-megabit digital recorder using bubble domain memory elements is being developed by Rockwell International under contract to the NASA LaRC. The program monitor is Dr. Stermer. The recorder is space qualifiable and is scheduled for completion in early 1978. Characteristics of the recorder are listed in the following table.

Parameter	Characteristics
Memory organization	One 100-megabit memory or two 50-megabit memories or four 25-megabit memories
Input formats	Serial or parallel in eight-bit bytes
I/O rate	2.4 MHz or 1.2 MHz
Mean time between failures	40 000 hr
Volume	9832.2 cm^3 (600 in^3)
Power	100 W at 28 V (during write or read only)
Type of memory element	Nonvolatile bubble domain (memory held by permanent magnet)

NASA should continue support in developing the technology of magnetic tape recording and signal-processing elements with the use of CCD, SAW, and magnetic bubble techniques.

Preferred Memory Technologies

The preferred memory technologies for implementing an all-digital SAR data ground-processing facility are as follows: For recording the source data signal, high-density magnetic tape is the preferred technique. The corner-turning memory required is presently best implemented by using metallic oxide semiconductor (MOS) shift registers and random-access memories; but in the near future, CCD shift registers and bubble memories will be preferred. For non-real-time processing, large disk memories are preferred. The processed image data should be recorded on high-density, instrumentation-type color film.

Stages in the Development of Onboard Processors

At least three steps should be taken in the move toward onboard processing. Initially, such processing should be minimized. With data in their rawest form, there is maximum flexibility in defining engineering parameters. However, when SAR instrument calibration parameters have become more firm and the state-of-the-art in onboard processing has advanced, step 2 should be taken. This phase involves the implementation of onboard preprocessing of the Shuttle SAR data. This development should increase that facility's usefulness by decreasing data quantity. The TDRSS can be used or the recorders can be more appropriately used to store processed information rather than raw data.

The next step is the big one. As scientists begin to perfect SAR data analysis techniques, phase 3 should begin. This phase should correspond somewhat to the definition of special-purpose radar free-flyers whose characteristics have been determined by using the Shuttle SAR data. In these free-flyers, onboard processing should be expanded to include processing to an actual user-product form, data that have been corrected and possibly formed into a particular map projection, etc.

Ideally, there might be another step between steps 2 and 3 involving the implementation of a very flexible onboard processor in the Shuttle SAR system that could be programed to produce a variety of the aforementioned user products.

Capabilities of Existing Synthetic Aperture Radar (SAR) Data Processing Systems

Optical correlators.- Laboratory optical correlators at the Goodyear Aerospace Corporation, the ERIM, and the JPL all have similar capabilities; i.e., approximately a 5.1- by 5.1-cm (2 by 2 in.) aperture at the data plane. This size is sufficient to process a quarter swath of the proposed spaceborne SAR systems (Seasat/Shuttle X-band and L-band). Minor modifications to these processors are required to implement the range-curvature and range-walk corrections required in the orbital case. In addition, if data have not been compensated for the Earth's rotation and antenna pointing, additional minor modifications are required to implement an optical clutter lock.

Digital processors.- Candidate digital processors for proposed spaceborne SAR systems are the SAPPHIRE and the Hughes Aircraft Company PSP. The SAPPHIRE equipment (built by the Goodyear Aerospace Corporation) has adequate storage (30 megabits) for processing one azimuth look of the L-band system and all four azimuth looks of the X-band system. Techniques and additional equipment are required to combine the azimuth looks (of the L-band system) on subsequent processing passes. Modifications to the range compression filter would be required to accommodate the larger range compression ratio (approximately a factor of 4) of the spaceborne systems. Processing could be provided at a real-time rate.

A data-processing system consisting of a Hughes Aircraft Company PSP as its central element could be constructed that would have the capability of processing Seasat-A data. At an approximate vehicle speed of 7500 m/sec and for 25-m azimuth resolution, data are collected at a rate that can produce 300 (7500/25) lines of imagery per second. Because the number of range cells across the swath is approximately 4000, approximately 1.2×10^6 pixels must be formed per second to keep up in real time. On the order of 100 arithmetic operations per pixel are required to produce imagery; therefore, 120×10^6 operations per second are required to keep up in real time. The types of arithmetic operations that are required in quantity (multiplication and addition/subtraction) are performed at a rate of 20×10^6 per second on the PSP. Therefore, as far as its arithmetic capability is concerned, the PSP could perform Seasat-A processing with a 6:1 slowdown. It is projected that approximately 10 minutes of data per day will be collected. Therefore, as much as a 144:1 slowdown in processing could be tolerated to keep abreast with data collection on a daily basis. The PSP thus has a considerable margin, in terms of arithmetic capability, with which to account for overhead, maintenance, and downtime, as well as allow for far more computations per pixel than estimated.

Another aspect of the throughput problem, however, is mass storage and the bandwidth of data transfer between the mass storage device and the processor. For Seasat-A, on the order of 4 million words or 50 million bits of storage are required to process 4 azimuth looks. A random-access memory of this size does not presently exist at the Hughes Aircraft Company. Because a significant slowdown in processing Seasat-A data does not prevent keeping abreast with data collection on a daily basis, a completely random access memory is not required. However, disk memory does not serve well because only a few reads and writes of each data point can slow processing so drastically that the amount collected daily could not be processed in a day. Some disk memory is probably needed; but in addition, a large amount of block-oriented random-access buffer memory would be needed to feed, in a timely manner from disk, the random-access memory from which arithmetic operations are performed. The structure of this memory needs to be studied. The memory architecture that turns out to be optimum for Seasat-A on a cost/image production basis will probably be suitable for future satellite applications as well.

The existing PSP processing facility at the Hughes Aircraft Company has presently approximately 1.2 million bits of memory. Seasat-A processing could be performed with this system at approximately a 1000:1 slowdown. The memory is expandable, and that feature would be a firm requirement for timely Seasat-A processing.

The ERIM has established a digital processing facility that is dedicated to the processing of SAR digital data. The facility is useful for two purposes: (1) the development of two-dimensional digital signal-processing techniques applied to SAR image formation and (2) the development of manual and automatic exploitation techniques that will improve the practicability of imaging radars in various applications. The facility comprises a minicomputer-based system of specialized hardware in a multi-user operating environment. The system has been specifically tailored for efficient SAR data processing and image exploitation.

A block diagram of the digital facility appears in figure 5-20. The basic component of the system is a Digital Equipment Corporation (DEC) PDP-11/45 central processing unit that utilizes 262 144 bytes of online memory through the use of memory management hardware. An advanced operating system (RSC-11D) allows multiple real-time tasks to run concurrently on the machine, with a single task addressing as many as 65 536 bytes of memory. Intertask communication is permitted, a capability implying that several tasks could potentially be working on a single processing problem. Several computer terminals are provided so that several users can use the facility simultaneously.

Special provisions have been made for offline storage. Because of the vast amounts of data associated with SAR phase histories or images, a 116-million-byte random-access disk unit has been included in addition to a DEC RK05 disk unit (2.4 million bytes) used for operating-system and user program storage. The magnetic tape system consists of two nine-track and one seven-track dual-density-type drives and allows tape-to-tape processing in formats compatible with virtually all industry standards except the newer 2460.6-bit/cm (6250 bit/in) format.

To aid in implementing SAR digital-processing algorithms, a hard-wired FFT processor has been included in the system. The FFT processor (Time Data, Inc. FPE4) can perform a 1024-point complex FFT in 200 milliseconds. The data frame size for the FFT is controllable from 4 complex points up to 4096 complex points in powers of 2. In addition to real and complex, direct and inverse transforms, the processor can perform frequency domain Hanning filtering, as well as automatic and cross-spectrum averaging. Software has been generated that enables use of the FFT processor to perform a large-array two-dimensional FFT (as many as 1024 by 1024 complex points).

An interactive digital image display has been integrated into the digital facility. The RAMTEK display, which has a solid-state shift register refresh memory, is capable of displaying digital imagery in two modes: (1) 512 by 512 by 6 bits on a black and white TV monitor and (2) 256 by 256 bits on a color TV monitor, with 6 bits each controlling the red, green, and blue intensities for each picture element. Overlay channels are provided so that graphical information such as object

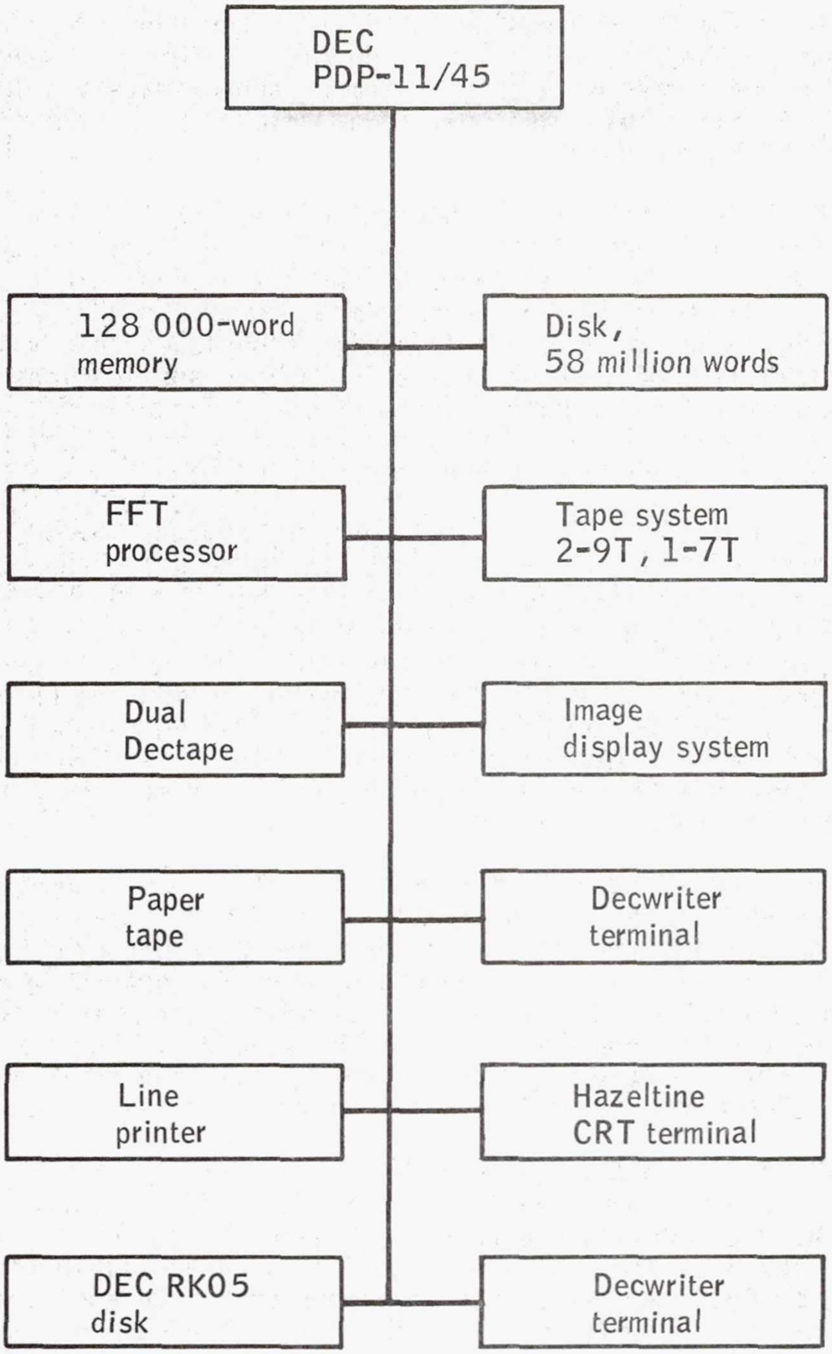

Figure 5-20.- Facility for digital radar data processing and exploitation.

outlines or annotation data can be superimposed on the displayed images without destroying the contents of the display memory. In addition, a trackball-controlled cursor allows the user to extract positional information from the displayed images. A diagram of the interactive display system is shown in figure 5-21.

Additional features of the display are the programmable table-lookup memories installed between the display memory and digital-to-analog (D/A) converters that provide the video intensities. Under program control, these memories can be loaded with intensity transfer functions that are then applied to the images on a point-by-point basis in real time as they are displayed. The transfer function can be constructed to provide contrast enhancement, thresholding, image intensity inversion, pseudocolor encoding, or any of a number of single-point image manipulations, the results of which are nearly instantaneously visible to the operator. The display is used to view digitally processed SAR imagery and to examine image exploitation techniques.

SAR digital processing consists primarily of the application of two-dimensional pulse compression techniques to digital signal histories. The digital facility serves as a general-purpose tool for examining such techniques. The two-dimensional pulse compression is generally implemented as two one-dimensional digital matched-filtering operations in conjunction with range and azimuth prefiltering operations analogous to the frequency plane filtering used in the optical processing technique previously described. The FFT hardware is useful for performing the various types of digital filtering operations. The digital facility has been structured for highly controlled experimental processing rather than for emphasizing real-time applications.

The facility has proven extremely valuable in SAR digital processing and simulation efforts. Data inputs that have been used to date include digitized versions of optically recorded phase histories, as well as purely digital phase histories obtained from both a ground-based SAR simulation system and from digitally recorded airborne phase histories. Several types of SAR data have been processed into imagery and subjected to digital image exploitation efforts.

The Westinghouse Corporation has the capability to process SAR data in its Interactive Processing Facility. This capability was designed to be very flexible to prove the application of various processing algorithms and the interaction of a human operator with the processing of the radar data. The facility is built around three Data General general-purpose computers: a Nova 800, a Nova 840, and an Eclipse S-200. The FFT operations involved in the data processing are accomplished with a hard-wired ELSYTEC FFT board in the Nova 840 to improve the processing rate. The bulk memory is in the form of four disk units. The peripheral equipment includes 315.0- and 629.9-bit/cm (800 and 1600 bit/in) tape units, CRT and teletype terminals, line printers, a film hard-copy unit, and a color CRT display for interactive processing.

The Applied Research Laboratory (ARL) of the University of Texas at Austin (UT) has an extensive background in SAR data processing, dating from 1968 and its involvement in the Air Force's FLAMR program as the

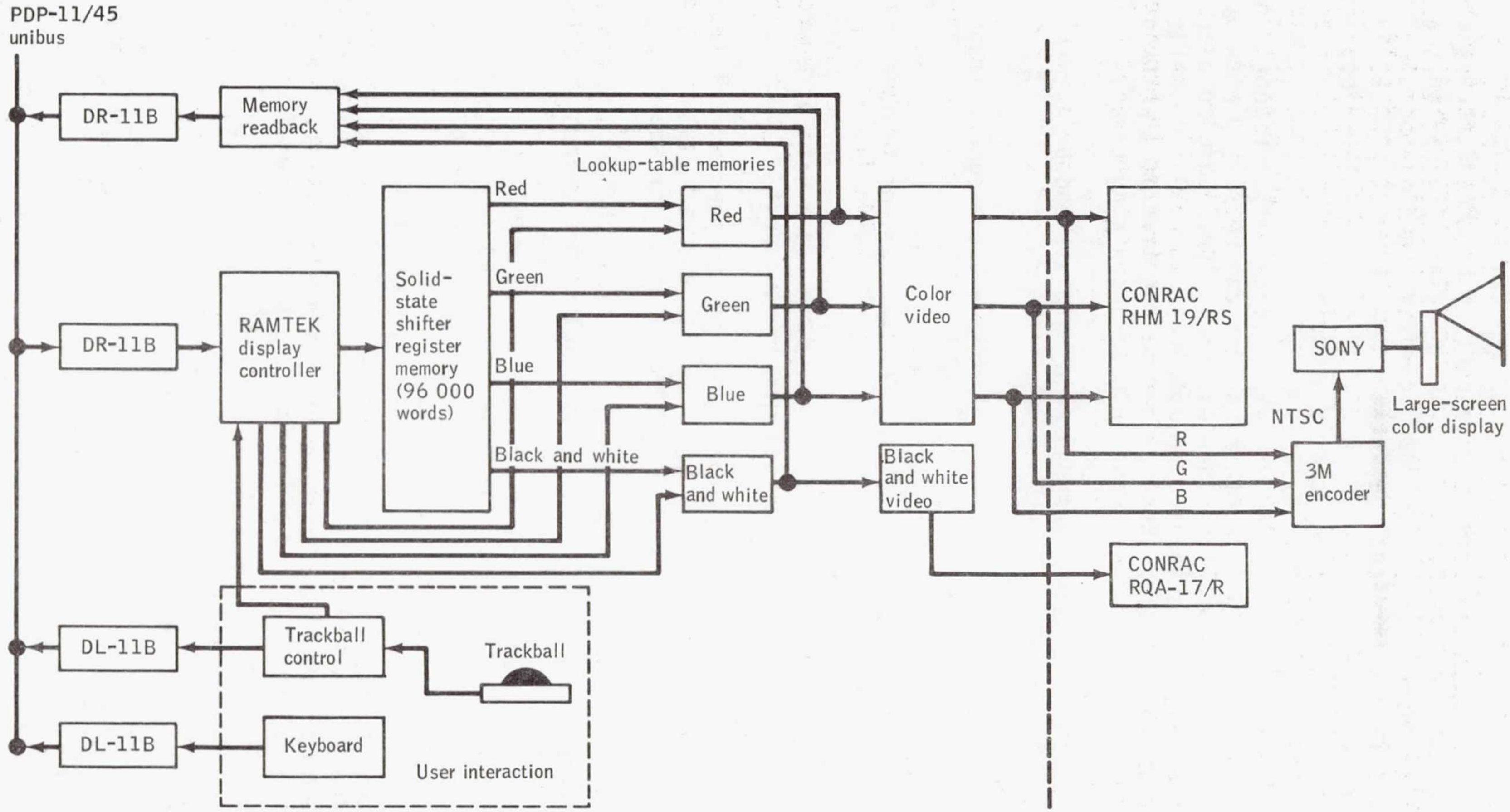

Figure 5-21.- RAMTEK digital image display block diagram.

data analysis contractor. The FLAMR system was the first real-time digitally processed SAR system flown. In support of the FLAMR, the ARL developed a large number of SAR-data-processing programs for use on the ARL twin Control Data Corporation (CDC) 3200 computers and on the UT CDC 6600 computer. The ARL presently maintains the FLAMR data bank, containing over 400 wide-band magnetic tapes of digital SAR I/Q video and auxiliary data from which SAR imagery can be produced.

Figure 5-22 shows the ARL SAR data analysis capability. Either FLAMR data or properly formatted data from other sources can be played back by using the FLAMR digital recorder interface equipment (DRIE) ground playback system. The DRIE allows the conversion of data from wide-band magnetic tape to CCT form for subsequent processing. Programs have been written to perform the following SAR image formation data-processing tasks.

1. Validating the raw SAR data and providing plots and printouts as required

2. Reformatting the data to allow more efficient subsequent image-formation processing

3. Performing range compression of the FLAMR binary phase coded waveform

4. Applying motion compensation to the raw I/Q video data with the use of information from the FLAMR inertial measurement unit

5. Performing azimuth compression of the range-compressed SAR video

6. Postprocessing the raw filter magnitude data by thresholding and assigning gray shades

7. Determining the statistics and image quality for processed SAR data

Other special software has been written to fulfill the following functions.

1. Degrading the imagery signal-to-noise ratio by the addition of band-limited noise to unprocessed SAR I/Q video data

2. Degrading the SAR I/Q video data precision to simulate data quantized with lesser precision to allow the investigation of the effects of data precision on image quality

3. Performing trade-off studies by varying the resolution, sampling interval, and overlay of processed imagery

4. Producing high-quality composite images on the ARL precision display for use in image interpretability studies

The ARL is also developing for NASA a general mathematical model of the SAR processes that will enable the generation of simulated I/Q video from complex scenes that can be processed to form SAR images of such scenes.

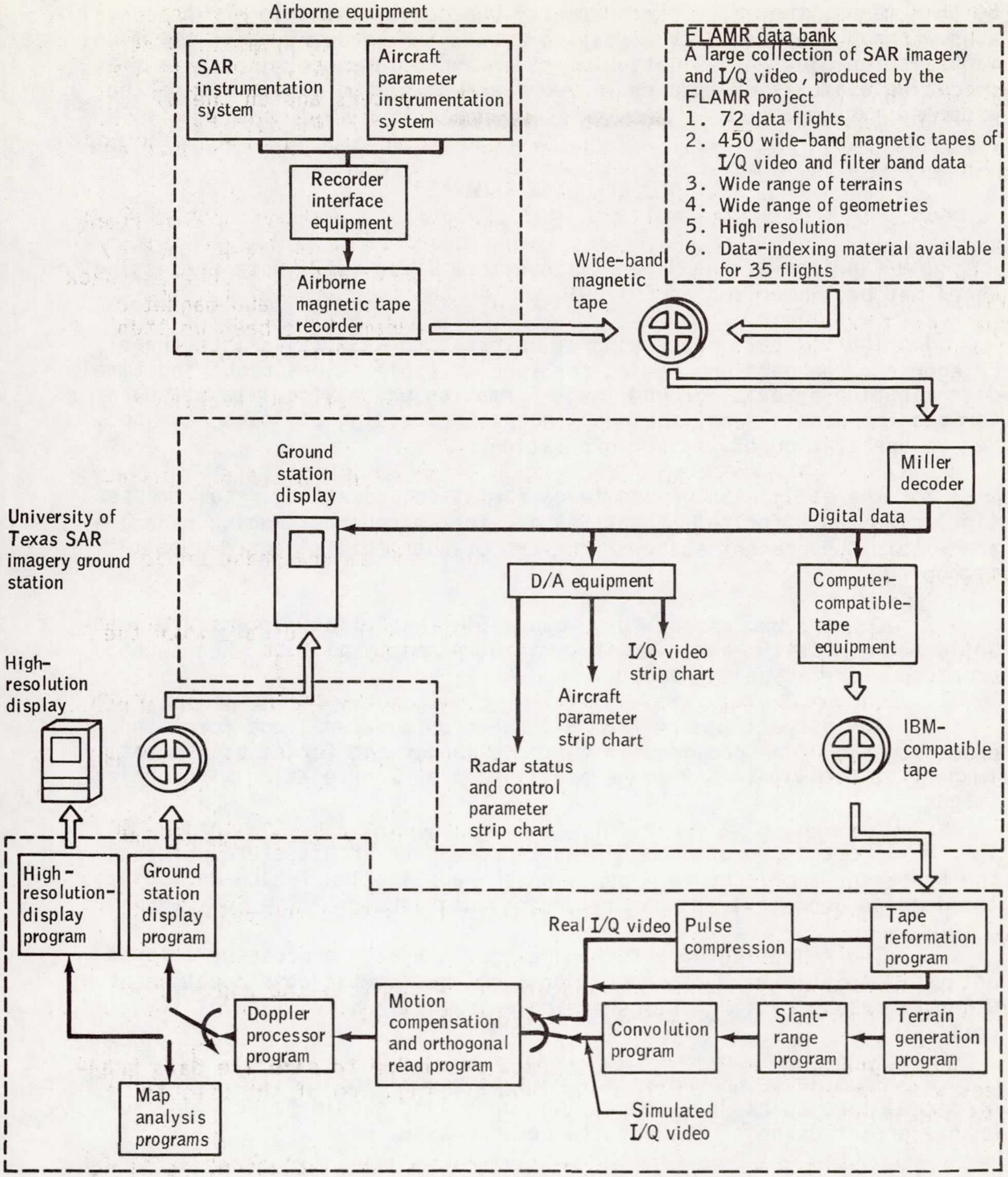

Figure 5-22.- The University of Texas (ARL) digital SAR processing capability.

By this means, the effects of geometry-dependent distortions can be evaluated without the necessity of flying actual SAR hardware. The ARL model will also enable the evaluation of radar and data-processing systems by producing examples of imagery formed with use of the parameters of the proposed systems.

CONCLUDING REMARKS

The findings of the Synthetic Aperture Radar (SAR) Data Processing Panel may be summarized as follows.

1. The SAR data processing of interest to NASA falls into three categories: onboard processing for special applications requiring timely dissemination of data, ground image formation processing into standard formats for general applications, and postprocessing of image data to derive specific quantitative information.

2. The early NASA ground image formation processing requirements (including those for the Seasat SAR and the spaceborne imaging radar) are within the present state-of-the-art of both optical and digital technology.

3. Onboard processors for L-band 25-m-resolution systems are presently not within the state-of-the-art but probably will be when such processors are actually needed.

4. The output imagery from a large ground-based image formation processor should be provided in the same manner and format as Landsat imagery to facilitate SAR image acquisition and correlation with optical imagery.

5. There is no optimum SAR-data-processing architecture, because the processor architecture depends on the application (which determines the imaging geometry) and the technology utilized.

6. The selection of a technology for SAR data processing is presently driven by memory considerations, not arithmetic considerations. Other important considerations are power, weight, size, flexibility, and cost.

7. In a large ground-based SAR-data-processing facility, some form of a real-time quick-look processing capability should be provided to enable prescreening of the data to be processed.

The panel recommendations are as follows.

1. An Imaging Radar Technology Group should be established by NASA to develop and maintain technical expertise applicable to current and proposed NASA imaging radar systems. This group should meet at least once a year.

2. NASA should support an imaging-radar-technology study program to conduct investigations related to gathering, processing, and disseminating imaging radar data. Study areas that should be suported are as follows.

a. Requirements for antenna pointing and motion compensation for satellite-borne SAR systems

b. Requirements and processing implications for squint-mode SAR operation

c. Interpretability-versus-image-parameter trade-offs for digital SAR imagery

d. SAR calibration techniques

e. The interface between a SAR image formation facility and the users

3. A central SAR image formation processing facility should be established by NASA to provide users with cataloged SAR data in standard formats.

4. The development of onboard processors for dedicated applications requiring timely dissemination of image data should be pursued.

5. Existing airborne SAR measurement facilities should be modified to include the recording of raw sensor data in digital form.

6. Raw aircraft and Seasat data should be made available to support the recommended imaging-radar-technology study program.

7. The development of high-density data storage devices such as the RCA 240-megabit/sec magnetic tape recorder should be continued.

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APPENDIX

ABBREVIATIONS, ACRONYMS, AND SYMBOLS

a	filter output signal
A	Fourier transform of filter output signal
A/C	aircraft
A/D	analog to digital
AGC	automatic gain control
AMUW	Active Microwave Users Workshop
AMW	Active Microwave Workshop
AOML	Atlantic Oceanographic and Meteorological Laboratory
APT	automatic picture transmission
ARL	Applied Research Laboratory
ASVT	applications systems verification test
B	bandwidth
BLM	Bureau of Land Management
CCD	charge-coupled device
CCT	computer-compatible tape
CDC	Control Data Corporation
cm	centimeter(s)
CRT	cathode ray tube
CSSL	Central Sierra Snow Laboratory
CUNY	City University of New York
CW	clutter width
d	day(s)
D/A	digital to analog
dB	decibel(s)

DEC	Digital Equipment Corporation
DFT	discrete Fourier transform
DOD	U.S. Department of Defense
DRIE	digital recorder interface equipment
EDR	experimental data record
ERIM	Environmental Research Institute of Michigan
ESMR	electronically scanning microwave radiometer
f	flare ratio
F	Fourier transform operator
FFT	fast Fourier transform
FLAMR	forward-looking advanced multimode radar
FM	frequency modulation
FNWC	Fleet Numerical Weather Central
f_r	pulse repetition frequency
ft	foot (feet)
FWS	Fleet Weather Service
FY	fiscal year
GHz	gigahertz
GSFC	Goddard Space Flight Center
h	filter impulse response
H	Fourier transform of filter impulse response
H	high
ha	hectare(s)
HH	horizontal-horizontal
HQ	headquarters
HUD	U.S. Department of Housing and Urban Development
HV	horizontal-vertical

Hz	hertz
I	system impulse response
ID	identification
i.f.	intermediate frequency
in.	inch(es)
I/O	input/output
I/Q	in-phase/quadrature
IR	infrared
ISR	integrated sidelobe ratio
JPL	Jet Propulsion Laboratory
JSC	NASA Lyndon B. Johnson Space Center
k	integer index
K	time-bandwidth product
K_a	array weighting factor
kbps	kilobits per second
km	kilometer(s)
L	low
LACIE	Large Area Crop Inventory Experiment
LaRC	Langley Research Center
LO	local oscillator
m	meter(s)
M	number of azimuth samples
M	medium
MAS	microwave active spectrometer
Mbps	megabits per second
MFMR	multifrequency microwave radiometer
MHz	megahertz

min	minute(s)
MLW	mainlobe width
mm	millimeter(s)
Mm	megameter(s)
mo	month(s)
MSAS	microwave signature acquisition system
MSS	multispectral scanner
n	integer index
N	number of frequency bands
N_a	number of additions
NASA	National Aeronautics and Space Administration
n_b	number of A/D bits
N_b	number of bits of data storage
NESS	National Environmental Satellite Service
N_ℓ	number of looks noncoherently averaged
N_m	number of multiplications
NMFS	National Maritime and Fisheries Service
n. mi.	nautical mile(s)
NOAA	National Oceanographic and Atmospheric Administration
NOO	Naval Oceanographic Office
NOS	National Ocean Survey
N_q	quantization noise power
N_r	number of range samples
NRL	Naval Research Laboratory
N_1	length of input data sequence
N_2	length of impulse response sequence
N_3	length of filtered data sequence

OFT	Orbital Flight Test
P	pulse compression ratio
PDR	project data record
PMIS	passive microwave imaging system
PRF	pulse repetition frequency
PRT	precision radiation thermometer
PSP	programmable signal processor
q	A/D converter LSB interval
Q	system coherent gain
R	radar range
rf	radiofrequency
rms	root mean square
s	complex signal
S	system impulse power response
SAM	serial analog memory
SAR	synthetic aperture radar
SAW	surface acoustic wave
scansar	scanning synthetic aperture radar
SCS	Soil Conservation Service
sec	second(s)
S/H	sample/hold
SIMS	shuttle imaging microwave system
SIR	spaceborne imaging radar
SLAR	side-looking aperture radar
SMMR	scanning multichannel microwave radiometer
SMS	Synchronous Meteorological Satellite
SPS	serial-parallel shift

SR&T	supporting research and technology
SSG	Science Steering Group
STALO	stable local oscillator
STC	sensitivity time control
STDN	Spaceflight Tracking and Data Network
t	time
TBD	to be determined
TDF	time-domain filter
TDRSS	tracking and data relay satellite system
T/M	telemetry
uhf	ultrahigh frequency
U.S.	United States
USACE	U.S. Army Corps of Engineers
USBR	U.S. Bureau of Reclamation
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
U.S.S.R.	Union of Soviet Socialist Republics
UT	University of Texas at Austin
V	magnitude of platform velocity
vhf	very high frequency
VHRR	very high resolution radiometer
VIR	visible and infrared radiometer
VV	vertical-vertical
W	swath width
WFC	Wallops Flight Center
yr	year(s)

α	squint angle from broadside
Δt	sample interval
ε	quantization-to-signal power ratio
η	memory utilization efficiency
γ corrector	range-walk corrector
κ	array overlap factor
λ	wavelength
ν	frequency
ϕ	phase angle
ρ	resolution
ρ_a	azimuth resolution
ρ_r	range resolution
σ	standard deviation
τ	transmitted pulse length

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16. Abstract

The Active Microwave Users Workshop was organized and conducted in August 1976. The purpose of the workshop was to serve as a followup to the Active Microwave Workshop, held in July 1974. The 1974 workshop addressed, in a very general way, radar remote-sensing activities in three areas: Earth/land, ocean, and atmosphere. A fourth topic of coverage was concerned with active microwave technology. The 1976 workshop coverage was much more focused. This workshop was organized into four panels: Applications, Seasat Land Experiments, Program Planning, and Synthetic Aperture Radar (SAR) Data Processing. The Applications Panel addressed the job of updating the 1974 workshop results. The remaining panels addressed topics as their names suggest. The findings of those four panels are documented in this report.

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