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CHAPTER 1

Summary of the Active Microwave Workshop

INTRODUCTION

NASA Applications Objectives

NASA is responsible for planning, directing, and conducting aeronautical and space activities. To help meet this responsibility, the NASA applications program has the following objectives:

1. To develop and test procedures, instruments, spacecraft, and interpretive techniques in the various disciplines in applications.
2. To accomplish long-range studies of potential benefits to be gained from, and the problems involved in, the utilization of space capabilities.
3. To conduct a comprehensive and meaningful space applications program to help maintain U.S. scientific, technological, and economic leadership.

These objectives can be met by the use of aircraft and spacecraft systems for obtaining information about the Earth, the oceans, and the atmosphere. Remote sensor systems for providing improved data in a variety of discipline areas are the core of the missions to be performed with these aircraft and satellites.

In the past, the major emphasis on remote sensor systems in the applications program has been on visible-region sensors for both aircraft and satellites. Camera, vidicon, and multispectral scanner systems have been used extensively in the space program aboard Earth resources aircraft and on spacecraft such as Apollo, Nimbus, Earth Resources Technology Satellite (ERTS), Skylab, and others. Similar systems are planned for future spacecraft, such as the Earth Observatory Satellite (EOS) series. As a result of these and associated activities, such as the development of large multispectral data-processing centers, there exists a significant amount of empirical data and data analysis results supporting the application potential of visible-region sensors.

In comparison, active microwave sensors have had limited application, and the amount of usable empirical data is inadequate. Thus, the application potential cannot be documented with similar confidence. The active microwave sensing field has the advantage of a far more extensive background in theoretical and analytical modeling studies, and many of the applications presented in this report are based on these fundamental studies of the physical phenomena measurable in the microwave region.

The Active Microwave Workshop (AMW) is the first concerted effort made 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 presented in this report convincingly show the desirability and feasibility of using active microwave sensors on future Earth observations missions.

Objectives of the AMW

The basic objective of the AMW was to review and define the anticipated advantages of active microwave systems in future aerospace and applications programs. Specific objectives included the following:

1. Definition of user/applications requirements in each of three areas of interest—namely, Earth/land, oceans, and atmosphere.

2. Description and specification of active microwave systems and signature data that can be obtained or are needed to meet user/applications requirements in each area of interest.

3. Identification of active microwave sensor technology capabilities and anticipated technological developments that might impact overall area objectives.

4. Formulation of guidelines and recommendations for applying active microwave systems technology to NASA programmatic goals and future mission planning.

The approach taken by the three discipline panels—Earth/land, oceans, and atmosphere—to meet the AMW objectives was

1. To identify needed Earth observations applications in which active microwave sensor techniques are potentially useful.

2. To divide these applications into those known to be feasible and those believed to be feasible.

3. To outline the experiments and systems needed to implement presently feasible methods and to bring others to the feasible stage.

Structure of the AMW

The active microwave working group, composed of approximately 70 scientists and engineers, was directed by a 12-man steering committee. The selection of the working group members was based on the applicants' experience in the Earth observations areas of interest and/or in active microwave systems. The membership of the working group is shown in appendix 1A. The multidisciplinary objectives of the AMW required the formation of three discipline panels (Earth/land, oceans, and atmosphere) and a technology support group.

A 2-day meeting of the participants was held April 24 and 25, 1974, in Houston, Tex., to acquaint the participants with the objectives and scope of the AMW program, to structure the AMW report, and to assign tasks to the participants for specific contributions to this report.

The AMW was held from July 22 to 26, 1974, in Houston, Tex. The participants submitted contributions to the AMW report in advance of the AMW meetings to facilitate compilation of a working draft for the 5-day session in July. These advance contributions were abstracted, evaluated, reproduced, and distributed to the participants 3 weeks in advance of the AMW meetings.

During the weeklong AMW working sessions, the advance contributions were rewritten, edited, reviewed, and summarized by the panels and the support group to form a draft of the full AMW report. The draft formed the basis for the final report.

PANEL RECOMMENDATIONS

Earth/Land Panel

The panel recommends the following activities to bring active microwave remote sensing to its full potential:

1. Program development: Initiate a coordinated interdisciplinary program for development of active microwave sensing of the Earth.

2. Measurements: Establish multifrequency, multipolarization, ground-based/aircraft experiments and develop modeling programs to study the characteristics of microwave energy interaction mechanisms associated with measurements of soil moisture, surficial materials, vegetation penetration, crop moisture effect, vegetation species, snow moisture content, frozen ground, and others.

3. Interpretation: Train a wide range of users in interpretation of radar images to take advantage of unique and full-time operational capability. Develop image interpretation methodology for use with active microwave images.

4. Operational tests: Conduct semioperational demonstrations for those imaging radar applications that are identified as feasible, that are potentially useful, and that capitalize on the unique characteristics of radar.

5. Satellite experiment: Conduct a satellite imaging radar experiment using a single- or dual-wavelength imaging radar system to

establish the effect of orbital operation on the system and the radar data.

6. Data analysis: Place high priority on the data analysis and interpretation techniques and their funding in all present and future active microwave programs.

Oceans Panel

Programmatic recommendations.—The programmatic recommendations are as follows:

1. Immediately develop a focused and coordinated program for the specific use of aerospace microwave systems for oceanographic applications.
2. Increase the emphasis on research and development in (1) the proper interpretation of microwave signals returned from the sea or ice surface, and (2) the mathematical modeling of ocean-surface phenomena as applicable to microwave observations.
3. Initiate a vigorous program in the development of end-to-end data processing for ocean phenomena as detectable by active microwave systems.
4. Initiate an active microwave test program using aircraft dedicated to the study of oceanographic phenomena.
5. Explore the complementary role of passive sensors used in conjunction with active microwave systems.
6. Explore coastal zone requirements that can be satisfied by using airborne remote active microwave systems together with other sensors.

Technical recommendations.—Particular priority should be given to the design and development of—

1. A high-resolution imaging radar (10-m resolution, 200-km swath width).
2. A high-precision radar altimeter (2- to 5-cm accuracy).
3. A high-precision scatterometer (0.2-dB accuracy, 30-km spatial resolution).
4. Digital techniques for ocean data handling for active microwave systems.

Further emphasis should be placed on acquiring—

1. A microwave remote-sensing device for measuring surface wind velocity (as high as 50 m/sec, $\pm 10°$ direction, ± 10 percent speed, 25-km resolution).
2. A real aperture aircraft radar potentially including Doppler capacity (10-m resolution).
3. A wave directional spectrometer (ocean wavelength of 30 to 50 m; angle resolution of $\pm 10°$, ± 10 percent).
4. A multifrequency, multipolarization radar.

Atmosphere Panel

The atmosphere panel recommendations are as follows:

1. A single cohesive research program should be established in NASA to develop active microwave techniques to be applied to requirements in the meteorological discipline as well as the oceanographic and Earth resources disciplines. The concepts discussed in this report, virtually for the first time, indicate that the applications may be feasible from space.
2. The scientific commonality of certain requirements between two or more disciplines should be recognized and emphasized. For example, both the oceanographic and atmospheric disciplines measure ice cover over polar regions.
3. The technological commonality of active microwave systems required by the meteorological, oceanographic, and Earth resources disciplines should be studied to achieve maximum cost effectiveness. It appears possible that one active microwave system (e.g., an imaging pulse radar), if suitably designed, may satisfy some of the requirements of more than one discipline. This possibility should be thoroughly investigated.
4. A major allocation of resources should be designated for the reduction, validation, analysis, and interpretation of data to be acquired in the flight program. Too often in the past, the analysis of data received little support in flight programs. The panel believes that the comprehensive and timely analysis of the data is of such importance

that, if necessary, it would be preferable to eliminate an entire flight experiment to provide for adequate data analysis rather than devote essentially all the available resources to flight systems and prevent the adequate exploitation of the data. In addition to the primary analysis, such exploitation should provide for the acquisition of "truth" data (e.g., from ships, instrumented aircraft, etc.) to be used in validating the satellite observations.

5. A downward-looking, scanning pulse radar technique should be developed for satellite use in a low-altitude orbit. The instrument resulting from this development would provide global measurements of rain intensities, heights of echo top, and the melting level in rain clouds. In addition, it may be possible to combine this instrument with the scatterometer proposed by the oceans panel for measuring ocean surface winds. These techniques are important in short- and long-term weather forecasting.

6. In-depth feasibility studies of the active microwave systems proposed in this report should now be undertaken. Initial evaluations have shown these systems to have promise. Calculations of required resolutions and sensitivities should be matched with expected technological capabilities. Furthermore, the panel thinks that fundamental research on active remote-sensing techniques should be broadened to include frequencies other than microwave. For example, the possible use of a carbon dioxide Doppler laser system operating at a wavelength of approximately 10 μm for measuring cloud boundary motion or clear air motion by means of scattering from aerosols, either from a geostationary or a low-altitude satellite, is discussed in the section entitled "Satellite-Borne Radar With Doppler Capability" in chapter 4. However, insufficient data exist now for the assessment of the utility of the method; hence, further theoretical and experimental work is needed to permit such an assessment.

Technology Support Group

The technology support group recognizes an urgent need for establishing a program to develop a spaceborne onboard digital data-handling system for processing imaging radar data. Fundamental areas to be considered include the requirements for multiple-look processing and the tradeoff criteria between data compaction and image interpretability.

The technology support group also recommends a program be established to develop lightweight, space-deployable antennas to satisfy swath width and resolution requirements to meet the measurement objectives set forth by the discipline panels. If such an ongoing program in the communication area exists, a medium should be established to allow radar technology to interact with the program.

In reviewing the overall technological goals in using active microwave sensors in Earth resources applications, it is recommended that NASA establish a unified radar sensor development and applications program. A pertinent aspect of this program should be to provide ways and means for various investigations to have a common source of information. A central repository for reports would be highly desirable. A centrally located area where investigators could work individually or in a group on various pertinent problems would allow NASA to focus on key application areas and thereby provide long-term cost savings.

A concerted experimental program should be established with the data acquisition and analysis objectives focused on answering the important questions related to near-future missions. Sensor calibration and application studies on a local-area basis are prerequisites to establishing system requirements for orbital spacecraft missions. Such a program will require the use of one or two dedicated aircraft. At least one high-altitude aircraft is needed.

Data acquisition and instrument development activities should be emphasized in future NASA programs, whereas study tasks resulting in no data acquisition and/or no hardware development should be deemphasized. The study programs have reached a state of maturity that must now be supported by system technology development.

PANEL SUMMARIES

Earth/Land Panel Summary

The Earth/land panel performed its tasks against the backdrop of the extensive ERTS applications studies, which have dominated the attention of the remote-sensing field for more than 2 yr. Consequently, the application areas addressed are familiar, and the value of acquiring remotely sensed data in support of these applications has been well established (app. 1B). The panel determined that active microwave sensors can significantly improve the acquisition of information needed to effectively exploit these application areas. The Earth/land panel report (ch. 2) is the most extensive document available on active microwave remote sensing of terrain features and will prove to be an invaluable reference for all future Earth observations programs.

Scope of study.—The Earth/land panel was composed of four subpanels, each of which considered a different class of discipline needs: mineral resources and geologic applications, water resources, vegetation and soils, and land use and urban environment.

The active microwave sensor applications identified by each subpanel are as follows:

1. Mineral resources and geologic applications:
   - *a.* Landform identification and terrain analysis
   - *b.* Mineral deposit location
   - *c.* Petroleum exploration
   - *d.* Ground water exploration
   - *e.* Crustal motion
   - *f.* Civil works
     - (1) Major construction site monitoring
     - (2) Construction material location
2. Water resources applications:
   - *a.* Lake ice monitoring
   - *b.* Flood forecasting and monitoring
   - *c.* Lake level determination and eutrophication
   - *d.* Coastal wetlands mapping
   - *e.* Water pollution monitoring
   - *f.* Frozen water hydrologic observations
     - (1) Snowfields
     - (2) Glaciers
     - (3) Permafrost
3. Agriculture, forestry, range, and soil applications
   - *a.* Crop identification
   - *b.* Crop cover and condition
   - *c.* Range inventory and biomass assessment
   - *d.* Soil types and properties mapping
   - *e.* Soil moisture determination
     - (1) Watershed management
     - (2) Crop yield prediction
4. Land use, urban, regulatory, and cartographic applications
   - *a.* Disaster monitoring
     - (1) Floodwater and coastal inundation
     - (2) Fire
     - (3) Wind damage
     - (4) Snowfall damage
     - (5) Earthquake damage
     - (6) Landslides
   - *b.* Land use monitoring
     - (1) Existing land use
     - (2) Transportation networks
     - (3) Location of engineering materials
   - *c.* Regulatory monitoring—oil spills
   - *d.* Cartography

Status.—Perhaps the most significant results of the AMW effort were, first, the recognition of the current lack of adequate experimental results to verify the feasibility of active microwave sensors for select applications and, second, the subsequent identification of immediate research needs. In many cases, there exist theoretical studies of basic electromagnetic interaction mechanisms that suggest the potential application, but many of these models are inadequately supported by experimental results.

In summarizing the status of active microwave sensor applications, the following applications were found to have proven feasibility:

1. Lake ice monitoring

2. Flood mapping
3. Oil-spill detection
4. Landform identification and terrain analysis
5. Grain crop identification
6. Broad-class land-use mapping

Those applications for which the basic phenomena of interest are believed to be measurable by active microwave sensing techniques are as follows:

1. Soil moisture determination
2. Soil-type mapping
3. Petroleum exploration
4. Rangeland inventories
5. Crop condition and biomass estimates
6. Mineral deposit mapping
7. Coastal wetlands mapping
8. Snowfield mapping

Each of these areas requires additional experimental investigation to confirm the feasibility of microwave remote-sensing methods. These areas represent the principal applications for which immediate research is needed. For example, petroleum exploration and mineral deposit mapping are two geological applications in which the unique capability of active microwave sensors to penetrate surface vegetation could be extremely valuable. Operation at 50-cm wavelengths is feasible from satellite altitudes, and aircraft systems operating at 100-cm wavelengths are practical. These long-wavelength signals penetrate most natural vegetation and should suit the geologist's needs. However, the experimental data to confirm this potential are inadequate.

Comparison with visible-region sensors.—Because the visible-region sensors have such a commanding lead over microwave sensors in documented applicability to Earth observations, the panel accepted the need to show the relative merits of microwave sensors in the applications areas addressed. The examples in table 1–I illustrate how such a comparison confirms the desirability of microwave systems in future Earth observations efforts.

Unique applications. — Imaging radar, among the fine-resolution sensors, is uniquely suited to monitoring soil moisture. As previously stated, this is partly because of its ability to penetrate the soil, whereas the color seen by visible-region sensors changes as soon as the very top millimeter becomes wetter or drier. Active microwave sensors can detect soil moisture because the dielectric properties of the soil are affected by the amount of moisture present due to the large differences between the permittivity of dry soil and that of water. Such measurements have numerous applications to flood forecasting, agricultural production estimates, and watershed management.

The moisture content of snow strongly influences the scattered microwave signal because the amount of compaction and the amount of liquid-free water in the snow have a major influence on its permittivity and therefore on the volume scatter from within the snow. Although this application has not yet been turned into a proven quantitative measure, the phenomenon has been observed qualitatively and can be fully justified on physical grounds.

Frozen ground can often be readily distinguished from unfrozen ground by active microwave sensors because of the change in dielectric properties as the moisture in the soil changes from liquid to solid form. This application has important consequences in forecasting flood runoff.

The strong microwave effects associated with edges in lake and river ice make the structure of the ice much more visible on radar images than on visible images; consequently, active microwave sensors have special application to monitoring ice structure in the Great Lakes and major rivers.

The ability to control the angle of incident radiation with active microwave sensors has led to unique applications in geology and geomorphology. When illumination and observation are at relatively shallow grazing angles, the shadowing that can be observed in areas of small relief permits discrimination of structural features much better than the comparable features that can be observed

TABLE 1-I.—*A Comparison of Active Microwave Sensors and Visible-Region Sensors*

Application	Unique capabilities of active microwave sensors	Unique capabilities of visible-region sensors	Capabilities shared by both sensors
Crop identification and assessment.	Plant moisture condition may be recordable. Soil moisture condition may be recordable. Temporal behavior can be recorded on timely basis.	Spectral reflectance data.	Plant structure. Canopy cover. Areal extent. Computer-compatible data.
Soil moisture determination.	Vegetation and surface can be penetrated. Moisture changes on diurnal cycle may be recordable. Temporal behavior can be recorded on timely basis.	No quantitative capability.	Vegetation response to soil moisture change. Computer-compatible data.
Soil type and property mapping.	Vegetation and surface can be penetrated. Dielectric characteristics may be recordable. Soil moisture retention characteristics may be recordable. Temporal behavior on indicator vegetation can be recorded on timely basis.	Soil color.	Vegetation identification for soil-type mapping. Computer-compatible data.
Range inventory and biomass assessment.	Plant moisture condition may be recordable. Soil moisture condition may be recordable. Temporal behavior can be recorded on timely basis.	Spectral reflectance data.	Plant structure. Canopy cover. Areal extent and distribution. Computer-compatible data.
Disaster monitoring......	Floodwater boundaries in vegetated areas can be detected. Earthquake-caused surface structure changes can be enhanced. Storm and fire damage can be assessed through clouds and smoke, day or night. Disaster events can be recorded on timely basis.	High-resolution color information.	Two-dimensional broad-area images. Land-use patterns and cultural features. Computer-compatible data.
Mineral deposits location.	Vegetation can be penetrated. Location is dependent on surface texture. Illumination angle can be controlled for feature enhancement. Polarization-dependent	Surface material color (where exposed).	Two-dimensional broad-area data. Vegetation indicator. Computer-compatible data.

TABLE 1–I—*Continued*

Application	Unique capabilities of active microwave sensors	Unique capabilities of visible-region sensors	Capabilities shared by both sensors
Mineral deposits location —Con.	surface information can be provided. Maps in regions of extensive cloud cover can be provided.		
Lake ice monitoring	Sensor is sensitive to ice type/thickness. Ridges, open water, and shoreline under snow cover can be delineated. Temporal behavior can be recorded on timely basis through clouds.	None.	Two-dimensional broad-area images. Computer-compatible data.
Flood forecasting and monitoring.	State of soil (i.e., frozen) may be recordable. Floodwaters under vegetation may be recordable. Soil water retention characteristics may be recordable. Soil moisture may be recordable. Temporal behavior can be recorded on timely basis through clouds.	More sensitive to flood-induced vegetation stress.	Two-dimensional images. Areal extent of floods. Computer-compatible data.
Coastal wetlands mapping.	Soil moisture may be recordable. Plant moisture may be recordable. Vegetation can be penetrated. Polarization-dependent soil conditions can be recorded. Temporal behavior can be recorded on timely basis.	Spectral reflectance data.	Plant structure. Canopy cover. Areal extent. Computer-compatible data.
Frozen water hydrologic observations.	Soil below surface can be penetrated. Snow cover can be penetrated. Sensor is sensitive to snow moisture content. Sensor is sensitive to subsurface dielectric properties. Temporal behavior can be recorded on timely basis through clouds.	Albedo of snow cover recordable.	Image format data. Computer-compatible data.

with passive sensors at any wavelength. This effect has been widely used in the commercial application of radar imagery by mineral companies and the application by governmental agencies that map geological phenomena.

Ocean Panel Summary

Oceans have an effect on everyone in some manner, whether by the food they produce or their effect on the weather and climate. However, because of their vastness, conventional studies of oceans have been, and can only be, economically attempted on a local scale. Trying to instrument the oceans on a global basis would be prohibitive in cost. The advent of remote sensing from aircraft, and especially from satellites, permits complete synoptic, sequential coverage. Using such techniques, the cost per data point will be several orders of magnitude less than when using conventional techniques. Remote-sensing techniques provide the means of achieving an unparalleled increase in the knowledge and thus the use of all the oceans of the world.

Practical applications and considerable economic benefits may be derived from remote sensing of the oceans by active microwave systems. These applications include improved warning systems for protection of life and property, more accurate weather forecasting, better monitoring of environmental quality, more efficient management of marine resources, improved commercial fishing, greater safety of shipping and navigation, better information for ship and coastal structure design, and enhanced knowledge of deviations from the geoid.

The benefits will be many faceted; they fall, in general, into the eight categories mentioned. Safety of life and property in the coastal areas has heavily depended in the past (and will heavily depend in the future) on the behavior of the ocean waters nearby. Tides, storm surges, pileups, and currents all have a large impact. Because these phenomena are all detectable by using active microwave techniques, such systems can give the proper information for forecasts and warnings. Data on wave direction, wave spectra, and wave diffraction, in particular, are economically detectable only if such systems are used.

The benefits of better weather forecasting are closely related to the previously mentioned coastal phenomena. In addition, the anticipated international agreement on increasing the "economic coastal region" to 360 km will require monitoring an area approximately 20 times larger than has been historically required. Furthermore, with the increased number of people living in the coastal States (where approximately 80 percent of the U.S. population resides), the cultural stress placed on U.S. coastal waters is ever increasing.

Spaceborne active microwave systems with a 10- to 50-m spatial resolution and a swath width of approximately 200 km could, for instance, be immediately applied to monitoring the aerial extent of this economic coastal region for detection of oil spills, management of marine resources, enhancement of commercial fishing, observation of ship activities in support of international agreements, warning of storm surges, indication of shoaling, and monitoring of ice conditions on the Great Lakes, North Slope, and polar regions.

The importance of observing and subsequently forecasting the ocean environment is illustrated by three examples. First, the determination of the wave climate near shore areas will offer invaluable support to ongoing coastal activities—for example, ongoing construction and planning for future projects. Second, a better understanding of the influence of the heat exchange phenomena is essential to long-term weather modeling. Third, monitoring the open water areas in the northern regions is very important for the shipping industry. The oceans panel determined that airborne, and particularly spaceborne, active microwave systems are essential for synoptic remote sensing of both local and large-scale phenomena.

Local phenomena are those oceanic and coastal phenomena with dimensions up to

100 km. These phenomena include surface waves and wind, internal waves, land/sea interaction, and the properties of inland and estuarine waters. Man's activities at sea are very much influenced by gravity waves. These are, in general, classified as waves with lengths of 2 cm to 500 m and heights to 30 m; they change shorelines, damage structures and cargo, and slow the progress of ships. A better understanding of such waves, their structure, diffraction, energy-exchange mechanism, and prediction will benefit marine activities.

Wave forecasting, an important factor in coastal management, can greatly benefit by the measurement or determination of surface wind fields. For centuries, seafarers have known that ocean waves increase in size with increasing windspeed. To determine the proper relationship between wind and waves is important not only for the coastal areas but also for the open ocean. The degree of vessel rolling, and hence the potential for cargo damage, is a function of wave height, wave direction with respect to the heading of the ship, and wave period with respect to the speed of the ship.

Land/sea interactions are most pronounced on the continental shelf and in the vicinity of islands. It is estimated that approximately 90 percent of man's ocean activities are in water depths less than 30 m, in which wave-effect forecasting is important but, unfortunately, is in a rather embryonic stage because of problems connected with shoaling, refraction, bottom friction, and breaking. Studies of these phenomena are far more than academic, considering man's heavy activities in the continental shelf areas.

Large-scale phenomena include the topography of the ocean surface—a complicated compound of geoidal variations and quasi-static spatial variations caused by tidal and meterological forces. Geostrophic currents and the polar ice coverage are also large-scale phenomena. The physical surface of the oceans is ever changing and is influenced by tides, air pressure, winds, salinity, temperature, density or pressure gradients, and geologic changes associated with the melting of glaciers. The determination of the deviation of this surface from the geoid (5 to 20 cm) is of importance for the computation of large-scale geostrophic currents. Because these currents transport large amounts of heat energy on a global scale, their improved measurement is important for improved methodology for forecasting weather and climate. The same is true for monitoring oceanic tides for possible applications of tidal-power harnessing and for better estimation of the Earth tides—that is, ocean loading of coastal areas as it relates to Earth dynamics (earthquake studies). Storm surges and wind setups are further dynamic manifestations of the same effect; both contribute to the danger of flooding of low coastal areas.

Global wave statistics, another large-scale consideration, are needed to establish a reference condition for planning ship routes and for designing ships and offshore structures. The same is true for the polar ice regions. Knowledge of the heat exchanged between the atmosphere and open water areas in these regions is essential for long-range weather forecasting and ship routing.

The oceans panel conclusions are as follows:

1. Certain all-weather, synoptic, high-resolution observations can best be provided by spaceborne active microwave systems. These observations include wave height, wave spectra, wave diffraction, distribution of sea and lake ice and open water areas within them, subsurface structure of glacier ice, the ocean geoid, and the static and dynamic topography of sea surfaces.

2. To date, the only Earth-oriented spaceborne active microwave systems in orbit were on Skylab. The information obtained from the S193 altimeter experiment has considerably exceeded all expectations and has provided unique oceanographic data. Surface variations with an accuracy of 1 to 2 m on a local scale and 5 to 20 m on a global scale have been detected. Preliminary indications from the S193 radiometer/scatter-

ometer (RADSCAT) system suggest that windspeeds as high as 20 m/sec are measurable from spacecraft.

3. Because many important ocean events are time dependent and short lived, it has been difficult to acquire the proper data because of the lack of dedicated oceanic research aircraft. The problem is further compounded by the lack of integrated planning and timely assignments of aircraft to ongoing in situ observations.

4. Quantitative relationships between radar signatures and oceanographic geophysical parameters have not been firmly established in many cases, primarily because of insufficient observations.

5. Development programs for active microwave sensors for ocean observation appear to be dispersed and have only limited coordination.

Atmosphere Panel Summary

The atmosphere panel considered the possible applications of active microwave systems in terms of more than three decades of operating experience with ground-based weather radar systems and in terms of a well-established meteorological satellite program extending back more than 14 yr, during which more than 30 experimental and operational satellites have been launched into both near-Earth and geostationary orbits. The satellites have carried a large variety of instruments that passively sensed radiation in the ultraviolet, visible, infrared, and microwave regions of the spectrum. An iterative exchange between discipline scientists and radar technologists led to the development of a list of applications using the following criteria:

1. The application must be of value to the discipline and in support of one or more of the following six NASA meteorology program objectives.

a. Operational support: Support the development of the operational meteorological satellite system.

b. Weather prediction: Develop space technology for determining the vertical structure of the atmosphere globally, which, when supplemented by simulation techniques, models, and conventional observations, will provide required data with emphasis on large-scale long-term weather forecasts.

c. Atmospheric pollution: Develop a space-sensing capability to identify and quantitatively monitor the distribution of natural and manmade pollution in the lower and upper atmosphere on global and regional scales.

d. Climate and weather modification: Apply space-acquired data from remote sensors, data collection systems, and/or inflight experiments requiring unique orbital conditions (such as a gravity-free environment) to the development of models and the establishment of mechanisms for the rational examination of deliberate and inadvertent means for modifying weather and climate.

e. Weather danger and disaster warning: Develop and establish a system for continuous observation of atmospheric features to permit early identification and quantitative measurement of atmospheric conditions conducive to the formation of severe atmospheric phenomena (e.g., thunderstorms, tornadoes, hurricanes, etc.) to serve as a basis for timely warning to the public.

f. Processes and interactions: Investigate fundamental atmospheric processes and interactions on various temporal and spatial scales within the atmosphere, in response to solar inputs, and at the air/surface interface through the observation of the structure, composition, and energetics of the atmosphere for the purpose of effectively applying space capabilities in pursuance of the previously mentioned objectives.

2. The application must be reasonably achievable by active microwave means or by a combined active/passive system.

3. The application must be unique to active microwave systems or must be accomplished more effectively by active microwave techniques than by other means (e.g., passive radiometry in the visible, infrared, or microwave region).

The resulting applications are as follows:

1. Mapping maximum echo heights in rain clouds to provide an indication of storm intensity and rainfall production.

2. Measuring the height of the 273-K level in rain clouds as input to numerical weather prediction models and for assessing the intensity of tropical storms.

3. Mapping rain intensities over the globe as an input for future numerical models for long-range forecasting.

4. Quantitatively measuring liquid water content, drop-size spectra, and rainfall rates on a global scale: Condensed water is a critical component in the heat and water budgets of dynamic processes in the atmosphere; it is also important in short-range forecasting of local weather and in flood prediction.

5. Mapping horizontal motion within cloud systems: The measurement of horizontal winds is useful in weather forecasting. At present, radiosonde wind measurements are made manually and are essentially point measurements. A satellite Doppler radar wind measurement would map wind motion in a continuous manner throughout the storm. Wind field convergence properties of large systems may also be obtained efficiently.

6. Measuring surface pressure globally along the subsatellite track: These measurements would provide a major breakthrough for meteorological surface analysis and weather forecasting. If successful, such measurements would obviate the need for the myriad surface pressure measurements made daily over the globe. Even more importantly, these measurements would increase the accuracy of forecasts by extending the ground-based observations to oceans and other inadequately covered regions. A primary use would be to serve as a reference level for the temperature profiles now obtained routinely from atmospheric sounders on operational satellites, thus markedly increasing the accuracy of the profiles for updating forecast models.

7. Measuring surface winds over the oceans: These measurements would provide a new set of initial-state parameters for improving synoptic-scale weather forecasting; they would provide valuable information for weather danger warnings—for example, hurricane winds and storm surges. These measurements would assist in improving the understanding of the tropical atmosphere.

8. Mapping polar sea ice cover to measure the atmospheric heat balance in polar regions: This mapping would serve also as an input to numerical models of the general circulation for weather prediction purposes.

9. Applying bistatic measurements to communications needs such as attenuation and fading statistics for radio links: If coupled with depolarization measurements, bistatic measurements can provide information on raindrop and ice crystal sizes, shapes, and number density. Forward scatter geometries are also especially suited for detection of clear air turbulence. Because data from geostationary communications satellites contain meteorological information (generally considered to be "noise" in the communications system) and are available at little or no cost to the meteorologist, they should be used for atmospheric research.

10. Continuously monitoring maximum echo heights of storms from a geostationary satellite: If this monitoring could be done, it would be of extreme importance for monitoring the development and motion of severe storms and would lead to improved short-term forecasts and improved disaster warnings.

These 10 applications together with the 8 types of active microwave systems required to obtain the necessary measurements are summarized in table 1–II. A preliminary compilation of systems design criteria is shown in table 1–III.

Technology Support Group Summary

Many of the scientific objectives of the discipline panels, when translated into sensor requirements, indicate the need for imaging radar systems. Furthermore, the imaging radar performance specifications that can be inferred from the various application re-

TABLE 1–II.—*Application Requirements and Corresponding Active Microwave Systems*

Application requirements	Applicable active microwave systems [a]
Global coverage from low-altitude satellites	
1. Map maximum echo heights in rain clouds.	A. Downward-looking scanning pulse radar (design study).
2. Map height of melting layer in rain clouds.	A. Downward-looking scanning pulse radar (design study).
3. Map precipitation intensity.	A. Downward-looking scanning pulse radar (design study).
4. Map liquid water content and drop-size spectra (plus all above).	B. Multiwavelength radar (design study).
5. Map horizontal motion within cloud systems (e.g., tropical storms).	C. Doppler radar (feasibility study).
6. Determine surface pressure.	D. Active microwave transmissivity measurement in 5-mm oxygen (O_2) band (feasibility study).
7. Map surface winds over ocean areas.	E. Radiometer/scatterometer (RADSCAT) (ocean panel).
8. Map polar sea ice cover.	F. Synthetic aperture radar (SAR) (ocean panel).
Regional coverage at high temporal resolution from geostationary satellites	
9. Investigate fundamental atmospheric parameters (e.g., absorption, scattering, polarization, turbulence, etc.).	G. Data from existing and planned communications satellite systems (e.g., Applications Technology Satellite 6 (ATS–6)).
10. Continuously monitor maximum echo heights (development and intensity) of storms.	H. Short-wavelength radar with large antenna (feasibility study).

[a] Letters reference these systems to those in table 1–III.

quirements can, for the most part, be met by the current radar technology. Certain areas, such as data-handling capacity and deployment of large antennas in space, require further development to establish the technology to meet necessary performance requirements. Such development will likely be accomplished within 5 yr.

A significant portion of the sensor requirements necessary to meet the Earth/land and the oceans panels objectives could be satisfied by a single spaceborne imaging radar system. The multifrequency (Ka-, X-, and L-bands), multipolarization imaging radar configuration being considered for Space Shuttle flights should satisfy a high percentage of the user needs outlined by these panels. The nature of radar systems dictates that initial mission efforts include engineering and calibration objectives. Unlike the performance of some sensors (e.g., cameras), which can be measured either on the ground or in aircraft, the performance of active microwave sensors can be accurately assessed only under actual in-flight conditions. The first real test of the system comes when the radar is in orbit.

The need for other types of active microwave systems (i.e., scatterometers, altimeters, and sounders) is limited to a few special applications. Scatterometers are useful primarily in measuring surface windspeed over the ocean, and altimeters are required for measuring the shape of the geoid.

Advancement in radar technology is hampered in many areas by a lack of knowledge of the interaction of surface properties and the echo characteristics. Oceanographic and some agricultural application studies are maturing, but the success of these programs depends on an adequate data base. Additional

TABLE 1-III.—*Systems Design Criteria*

Applicable systems	Coverage	Circular orbit: Height, km	Circular orbit: Inclination, deg	Number of spectral bands	Wave-length cm	Frequency, GHz	Polarization	IFOV,[a] deg	Type of scan	Scan angle from nadir, deg	Swath width, km	Average power, W	Diameter of antenna, m	Vertical resolution, km	Frequency of coverage, hr
A. Pulse radar	Global	~400	Not critical	1	0.8 or longer	Up to 37	No	0.3 beam	Transverse	±45	750	10	2.6 or more	1 to 2	12
B. Multiwavelength radar	Global	~400	Not critical	2, 3, or 4	0.5, 1, 3, or 10	3, 10, 30, or 60	Circular (both components	0.3 beam	Transverse	±45	750	—	2.6 or more	1 to 2	12
C. Doppler radar	Global	500	58 or Sun-synchronous	1	5 to 6	6 to 5	No	0.3 multibeam	Conical (360°)	60	2200	100 (per beam)	11	3 (3 to 5 layers)	12 12
D. Active microwave transmissivity instrument for surface pressure	Global	Not critical	Not critical	4	~.6	~50	No	10 to 20	Nadir-looking	NA[b]	NA	10	0.3	NA	12
E. RADSCAT	Global	800	108	1	2.2	13.9	No	25 to 50	Transverse	45	2 swaths × 500 = 1000	50	0.4	NA	12
F. SAR	Selected polar regions	800	85 to 95	1	3.0	10	No	3 to 30	NA	NA	100	200	8 by 5	NA	12
G. Communications satellite for meteorological use	Earth disk	36 000 (geo-stationary)	0	1 or 2	≤3	≤10	Orthogonal, linear, or circular	[c]	[c]	[c]	NA	2	≤10	NA	Continuous
H. Short-wavelength radar for geostationary satellites	Earth disk	36 000 (geo-stationary)	0	1	≤.3	≥94	—	15	Transverse	±10 (Earth disk)	Earth disk (to great circle angle ~50°)	100 to 200	≥10	NA	0.25

[a] Instantaneous field of view.
[b] Not applicable.
[c] Depends on number and location of ground stations.

research results in this critical area would help to determine the need for advanced technology and to define the performance requirements for future active microwave systems.

General status of sensor technology.—The technology for transmitting and receiving microwave energy in a manner that provides high-resolution range and azimuth spatial information is well developed. The power and weight demands of such systems no longer prohibit their use on spacecraft. For example, an L-band synthetic aperture imaging radar (providing a 100-km swath of approximately 30-m spatial resolution imagery from a 186-km altitude) requires less than 350 W of average power and would weigh less than 159 kg. Such a system would require an 8-m-long antenna.

Few active microwave systems and no imaging radar systems have been operated on spacecraft; therefore, there exists very limited experience in spacecraft antenna design. This problem is significant because the large engineering development cost for these antennas must be borne by the first few such systems used. In addition, the necessary design criteria are yet to be established. For rigid antenna structures, such as the antenna being considered for a Space Shuttle imaging radar, the aircraft antenna technology should be adequate to support the development. However, for the larger structures necessary for wide-swath-width imaging or narrow-beamwidth operation, considerably more development will be required.

The problem of handling the volume of data acquired by active microwave sensors is no more or no less severe than with any remote-sensor system. The required processing equipment to handle radar image data having a scale and resolution comparable to those of ERTS is approximately the same as that now used on ERTS–1. However, as with visible-region sensor data, the data-handling problem is a major obstacle to satellite remote sensing with fine-resolution active microwave sensors. Improved digital data-handling techniques are needed in the near future if the full potential of orbiting sensor systems is to be realized.

Projection of present technology.—The present trend in solid-state electronics indicates that future active microwave systems will continue to decrease in power, size, and weight requirements. Antenna design is also improving, but at a less dynamic rate. The most promising area of rapid technological development, relative to active microwave remote sensing, is in the field of data-handling techniques and hardware. The continual advancement in the state of the art of digital data handling and storage should soon remove the most serious obstacle to effective satellite remote sensing with high-resolution synoptic sensors.

It is expected that, within 10 yr, a multispectral imaging microwave system will be competitive in power, size, weight, and cost to the present ERTS multispectral scanner (MSS) system. Furthermore, it is expected that the data-handling capabilities will have an improved 10- to 30-m spatial resolution, without overloading the data-handling system.

CONCLUSIONS

This report provides an overview of the utility, feasibility, and advantages of active microwave sensors for a broad range of applications. In many instances, the material provides an in-depth examination of the applicability and/or the technology of microwave remote sensing, and considerable documentation is presented in support of these techniques.

Active microwave sensors can contribute significantly to Earth observations because of their capability to perform one or more of the following functions:

1. As unique sensors providing information on the phenomena under study that is unobtainable by any known practical means.
2. As complementary sensors providing an extension of the spectral description of the phenomena under study.
3. As supplementary sensors providing an

extension of the observation coverage of the phenomena under study.

The unique capability of microwave sensors to provide data night or day during nearly all weather conditions is only significant if the data have a quality and information content level adequate to supply the needs of the application. An assessment of the relative strengths and weaknesses of active microwave sensor data indicates that satisfactory data are obtainable for several significant applications.

Briefly summarized, the strengths and weaknesses of active microwave sensors are as follows:

1. Strengths:
   a. Records otherwise unobservable phenomena
      (1) Penetrates vegetation and near-surface material
      (2) Dependent on surface composition and roughness
      (3) Sensitive to vegetation, soil, and snow moisture
      (4) Has controlled viewing angle for feature enhancement
      (5) Provides broad spectral range information
   b. Has coincident capability with visible sensors for many applications
      (1) Provides two-dimensional image data
      (2) Has broad areal coverage with moderate-to-high spatial resolution
      (3) Records land-use patterns and changes
      (4) Has computer-compatible information
      (5) Sensitive to vegetation type and condition
   c. Provides day/night, near-all-weather operation
2. Weaknesses:
   a. Cannot record color-dependent phenomena
   b. Data not spatially coincident with other sensors
   c. Geostationary imaging operation not practical

The complementary and supplementary capabilities of active microwave sensors are significant, and it is probably in these capacities that active microwave systems will be introduced into satellite remote-sensing programs. However, a major effort of the active microwave working group was devoted to identifying the unique capabilities of active microwave sensors to establish clearly the advantages offered by these sensing techniques. The following list delineates the applications, by discipline area, for which active microwave sensors provide the most practical, the most advantageous, or the exclusive means of obtaining the needed information.

1. Earth/land:
   a. Determine soil moisture for crop yield prediction
   b. Map snowfields and glaciers
   c. Monitor lake ice
   d. Assess disasters for assistance and recovery
   e. Perform landform identification and terrain analysis
   f. Perform flood forecasting and watershed management
2. Oceans:
   a. Determine sea state and surface winds
   b. Map sea ice and iceberg locations
   c. Monitor coastal processes
   d. Monitor wave buildup in storm areas
   e. Measure undulations of the geoid
3. Atmosphere:
   a. Map freeze level height in rain clouds
   b. Map rain intensity
   c. Measure liquid water content
   d. Map horizontal motion within cloud systems
   e. Measure surface winds over the oceans
   f. Map polar sea ice cover
   g. Monitor maximum echo heights of storms

Each panel assessed the potential of active microwave systems from the distinctive perspectives associated with the disciplines involved. The applications identified and the techniques selected to address these applications evolved from the individual backgrounds of the Earth scientists, oceanographers, and meteorologists who guided the development of the material presented in this report. The common viewpoint shared by each panel was the awareness that active microwave sensors have unique capabilities that are not being adequately used.

The principal conclusions of the report are as follows:

1. Studies of microwave energy interaction with Earth surfaces, oceans, and the atmosphere (many supported by experimental evidence) clearly indicate the potential of active microwave sensors for numerous applications in these areas; these are applications for which the needed information can be obtained by no other more practical means than by active microwave sensors.

2. Active microwave sensors have unique capabilities for acquisition of descriptive data on many physical phenomena that may be otherwise obscured because of lighting or cloud conditions or that are unobservable by any other sensing method. These data are comparable in information content to visible-region sensor data.

3. Many applications for which the unique, supplementary, or complementary capabilities of active microwave sensors are invaluable have been identified in this report. Many of these applications can be addressed immediately by using available technology and analysis capabilities. For other applications, the research needed to establish firmly the operational feasibility of these sensors is indicated; many of the needed research results are close at hand. The difficulty in acquiring the necessary information is caused partly by the lack of ground-based and aircraft microwave sensors available to support experimental research. These systems and the funds to analyze the resultant data must be made available if the potential of microwave remote sensing is to be realized.

4. The active microwave sensor technology now available is completely adequate to support a majority of the applications identified in this report. The rapid development of solid-state electronics is continuing to enhance the hardware capabilities for sensor systems and data processing. The power, weight, and size parameters, long thought to be deterrents to spaceborne microwave systems, are compatible with modern spacecraft specifications. However, the current lack of experience with actual satellite imaging radar configurations, particularly the antenna assemblies, can only be overcome by conducting orbital tests on such systems. These tests are a necessary first step in the development of future satellite microwave remote-sensing systems for operational Earth observations.

5. The concentration of attention and resources on the ERTS and Skylab Programs, especially with regard to aircraft facilities and research funds, has had the effect of slowing the development of microwave remote sensing after 1970. As a result, an adequate base of information to firmly establish the feasibility of these techniques does not exist for many of the most important applications.

6. The coordinated multidisciplinary "team" concept, which stimulated remote-sensing activities during the 1960's and provided guidance for the rapid development of the field, should be reestablished to encourage the orderly introduction of microwave sensors in future Earth observations missions.

APPENDIX 1A

ORGANIZATION AND ADDRESSES OF THE AMW GROUP

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APPENDIX 1B

EARTH RESOURCES SURVEY PROGRAM USING ACTIVE MICROWAVE SENSING: RECOMMENDATIONS FOR THE FUTURE

This appendix outlines the following areas of the Earth resources program:

1. The general accomplishments of the Earth resources survey program and future mission plans.
2. The importance of active microwave sensing, especially in terms of unique features and operational potential; the state of the art, including European activity; and the need for research and development, stressing the need to conduct measurements aimed at increased understanding of interactions between microwave energy and natural/manmade materials.
3. The potential applications and benefits of active microwave sensing, both near term (within 5 yr) and longer term (within 10 yr).
4. The outline of a program plan, identifying operational goals, experimental program, and overall schedule.

REVIEW OF EARTH OBSERVATION PROGRAM

Applications Research

The NASA Applications Aircraft Research Program has led to the emergence of remote sensing as an important scientific discipline and tool for many uses. The ERTS and Skylab Earth resources experiment package (EREP) sensors evolved from this program, and commercial radar mapping services began partly because of the interest created by results of the program.

This program was started in 1964 by the Manned Space Science Division. The original program was conceived as an adjunct to the development of sensors for mapping the lunar surface from orbit. The sensors were to be developed for use during the Apollo Program and tested in Earth orbit by observing designated terrain features alongside those features being observed as lunar analog test sites.

Initially, the program developed around a series of "instrumentation teams," each of which combined individuals and agencies having instrument expertise with those having expertise in uses of the data and in automatic data processing and analysis. This effort appears to have been the first major attempt in the United States to bring together groups of civilian users and instrumentation specialists. The major teams were as follows: photography, chaired by John Cronin of the Air Force Cambridge Research Laboratories; infrared, chaired by R. J. P. Lyon of Stanford University; radar, chaired by R. K. Moore of the University of Kansas; and passive microwave, chaired by Frank Barath of the Jet Propulsion Laboratory (JPL). Aircraft support was provided by the cooperation of military agencies and by the NASA Lyndon B. Johnson Space Center (JSC).

Radar was included among the sensors considered for the lunar landing program because of the potential for obtaining information about subsurface features due to the postulated low absorption of microwave energy by the lunar-surface materials; this assumption was later verified by the lunar sounder experiment conducted during the Apollo 17 mission. The Earth-oriented users in the early stages were especially interested in active microwave sensors and the ability of radio waves to penetrate farther than waves in the visible and infrared regions, regardless of whether this penetration was through clouds, vegetation, or upper soil layers. Many scientists recognized that timely remote-sensing measurements would be required for many applications and that most of the Earth is covered by clouds often enough so that only microwave sensors could provide the information at the time it was needed. Other scientists were interested in information about surfaces covered by vegetation that might be penetrated by microwave sensors but not by the shorter wavelength sensors. Still other scientists hoped to obtain geological information by penetrating the topsoil to reveal underlying structure. The ability of active microwave sensors to detect phenomena in which shape and context were the prime discriminants was recognized, but little knowledge was available to indicate whether these sensors could also provide unique information about materials that had to be distinguished by tone or spectral/polarization signatures. A major contribution of this program has been the demonstration that many of these desirable features could be identified from radar image tone and texture; therefore, the advantages of cloud and vegetation penetration were realized in practice. Other unique applications of active microwave data for distinguishing geologic structure and so forth have been discovered serendipitously. However, some of the hopes for deep soil penetration have been impossible to fulfill.

Activities of the Radar Team

The radar team was formed in May 1964 and was active for approximately 2 yr. The University of Kansas undertook leadership of the team, which included members from many institutions (notably, the U.S. Geological Survey (USGS), the Naval Oceanographic Office, the University of Michigan, the University of California, and several Department of Defense (DOD) agencies).

The first extensive radar flight program under these auspices was conducted during the period 1965 to 1966 with the Westinghouse APQ–97 real aperture multipolarization radar under contract to NASA. More than 500 000 km^2 were imaged in different parts of the United States. Application of these images was made to numerous research efforts, which included geology, natural vegetation, agriculture, land use, hydrology, and coastal studies. Data from these flights are still being studied, and important results are still forthcoming. The use of these data by many groups led to the decision to use the APQ–97 radar to provide the first commercial imaging radar service in 1969. This service and subsequent commercial imaging radar services by Aero Services/Goodyear and by Grumman/Motorola have provided millions of square kilometers of worldwide images for both governments and private mineral firms.

Initially, efforts were made to obtain various military radar systems for NASA aircraft. Finally, in 1967 an experimental unfocused synthetic aperture system, the Philco-Ford DPD–2, was acquired and placed in operation on the NP–3A. This system was flown over numerous sites in the United States and also provided images through cooperative ventures with Mexico and Brazil. Although the Brazilian images were not of especially high quality, they demonstrated the potential to the extent that Brazilians, introduced to remote sensing by the NASA program, arranged for commercial imaging of the entire Amazon Basin. This offshoot of the NASA Applications Aircraft Research Program is the largest single active microwave remote-sensing effort to date.

The University of Michigan Willow Run Laboratory (now the Environmental Research Institute of Michigan (ERIM)) high-resolution, X-band, synthetic aperture radar system developed for DOD was flown for the Earth Resources Aircraft Program (ERAP), and useful information was obtained for agriculture and geology. The system was modified to add an L-band capability under this program, and the two-frequency system has been especially valuable in demonstrating potential for multispectral radar. This system has also been used in studies of ice in the Great Lakes. A real aperture X-band radar was also flown for this purpose under NASA Lewis Research Center support during the 1973–74 ice season. Excellent practical results were obtained relative to extension of the ice navigation season.

Near the beginning of the program, the Naval Research Laboratory (NRL) four-frequency radar was used for scatterometry; however, it soon became apparent that this system could be modified to produce synthetic aperture images. The images from this system were the first to clearly demonstrate uses of multispectral radar.

Another two-frequency radar, developed at JPL, was an outgrowth of systems developed at L-band frequency for Venus studies and at lower frequencies for lunar sounding. This system, which has been used especially for oceanographic and geologic imaging, has the unique characteristic of providing altimetry directly on the image.

The radar scatterometers flown during this program have been instrumental in the development of oceanic wind measurement techniques tested on Skylab and planned for SEASAT. The 13.3-GHz NASA scatterometer was used in six flights over the North Atlantic at yearly intervals to test the wind measurement capability. The results obtained in these flights have been verified by the Skylab S193 microwave device.

The emphasis of ERAP necessarily shifted from the active microwave sensors as preparations for ERTS became more important. One of the earlier major programs that took much aircraft time was the corn blight watch in 1971 and 1972. With the Skylab launch, these facilities were even more in demand for spacecraft underflights, and ERAP provided a very large quantity of useful collateral data to many ERTS and EREP investigators. However, during this period, the ERIM two-frequency side-looking airborne radar (SLAR) was improved. An X-band frequency was added to the JPL SLAR, and the advanced application flight experiments (AAFE) RADSCAT was constructed. Much research in the microwave area during this period concentrated on oceanic wind and wave measurements, partly in support of the Skylab S193 experiment. The AAFE RADSCAT was flown over the ocean numerous times and also provided some underflight data over the land.

The first opportunity to fly an active microwave system to look at the Earth from space was on Skylab in the S193 experiment of EREP. The altimeter experiments and the oceanic RADSCAT results are discussed in chapter 3. An example of the Skylab altimetry data is shown in figure 2–3 of chapter 2.

One of the major purposes of the scatterometer terrain measurements was to ascertain the likely range of scattering coefficients. Histograms illustrating this have been prepared and are now being analyzed. An example is shown in figure 1B–1. The design information provided in this experiment should aid greatly in answering the question concerning the power required for a spaceborne imaging radar.

The ERAP has led to major advancements in the ability to monitor the Earth. Part of this advancement has been due to the direct measurements acquired within the program, and part has been due to the development of a community of users and interpreters of remotely sensed data, which was large enough to become self-supporting and self-expanding.

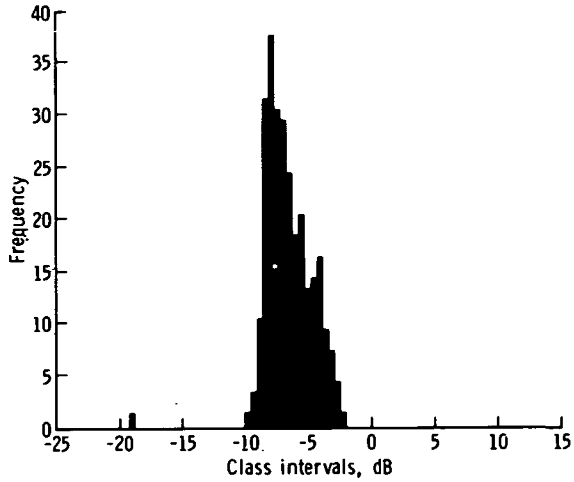

FIGURE 1B-1.—Histogram of a distribution of differential backscattering coefficient.

Future Elements

The success of ERTS-1 has clearly demonstrated, both in the United States and throughout the world, the practical value of orbital remote-sensing methods and their relevance to many of the critical problems of today. As a result of the success of ERTS-1, a second satellite, ERTS-B, has been approved for launch in 1975. In addition, the possibility of launching an ERTS-C, which would include a five-channel MSS, is being discussed.

A range of satellite systems (fig. 1B-2) is being studied that has a direct interest to applications in the Earth/land area. Perhaps the most important system is the EOS series. The first of these satellites, EOS-A, is currently scheduled for launch into a near-polar orbit in the late 1970's. A major systems objective for EOS is to provide a low-cost design based on a modular "building block" concept. This approach enables simple reconfigurations of the basic satellite to be made for different combinations of sensor types and also introduces the possibility of in-orbit repair or retrieval by using the Space Shuttle. The main sensors presently planned for the EOS-A mission are the thematic mapper and the high-resolution pointable imager. Later satellites in the EOS series are expected to include synthetic aperture radar systems for applications related to geological surveys, land-use monitoring, and water/ice monitoring.

The requirements for continuous or near-continuous observations of dynamic phenomena and the need to make measurements through gaps in cloud cover or at specific times of day have led to the study of high-resolution imagery obtained from synchronous altitudes. The Synchronous Earth Observatory Satellite (SEOS) is currently scheduled for launch in the early 1980's to monitor the continental and coastal regions of the United States in the following application areas: Earth resources, mesoscale weather phenomena, and timely warnings and alerts (e.g., floods and storms). The prime sensor for SEOS will be the multispectral large Earth survey telescope (LEST), which is capable of imaging in the visible and infrared (IR) bands. The predicted subsatellite ground resolutions for image data are 100 m in the visible bands and 800 m in the thermal IR bands. In addition to the LEST instrument, other candidate sensors for SEOS include atmospheric sounders, imaging microwave radiometers, microwave sounders, and a framing camera.

In addition to major facilities such as the proposed EOS and SEOS systems, low-cost applications Explorer spacecraft have been studied. These spacecraft could be launched by a Scout vehicle into a wide range of orbits from equatorial to polar inclinations. The system flexibility is such that a variety of instrument requirements could be accommodated without significant subsystem modifications. The first mission to be examined in detail is a heat capacity mapping mission to be flown in the late 1970's. The main sensor will be a cooled two-channel imaging radiometer providing data in the 0.8- to 1.1-μm and the 10.5- to 12.5-μm bands. Measurements will be made of thermal emission and surface albedo to develop models that use remotely sensed data to determine surface composition

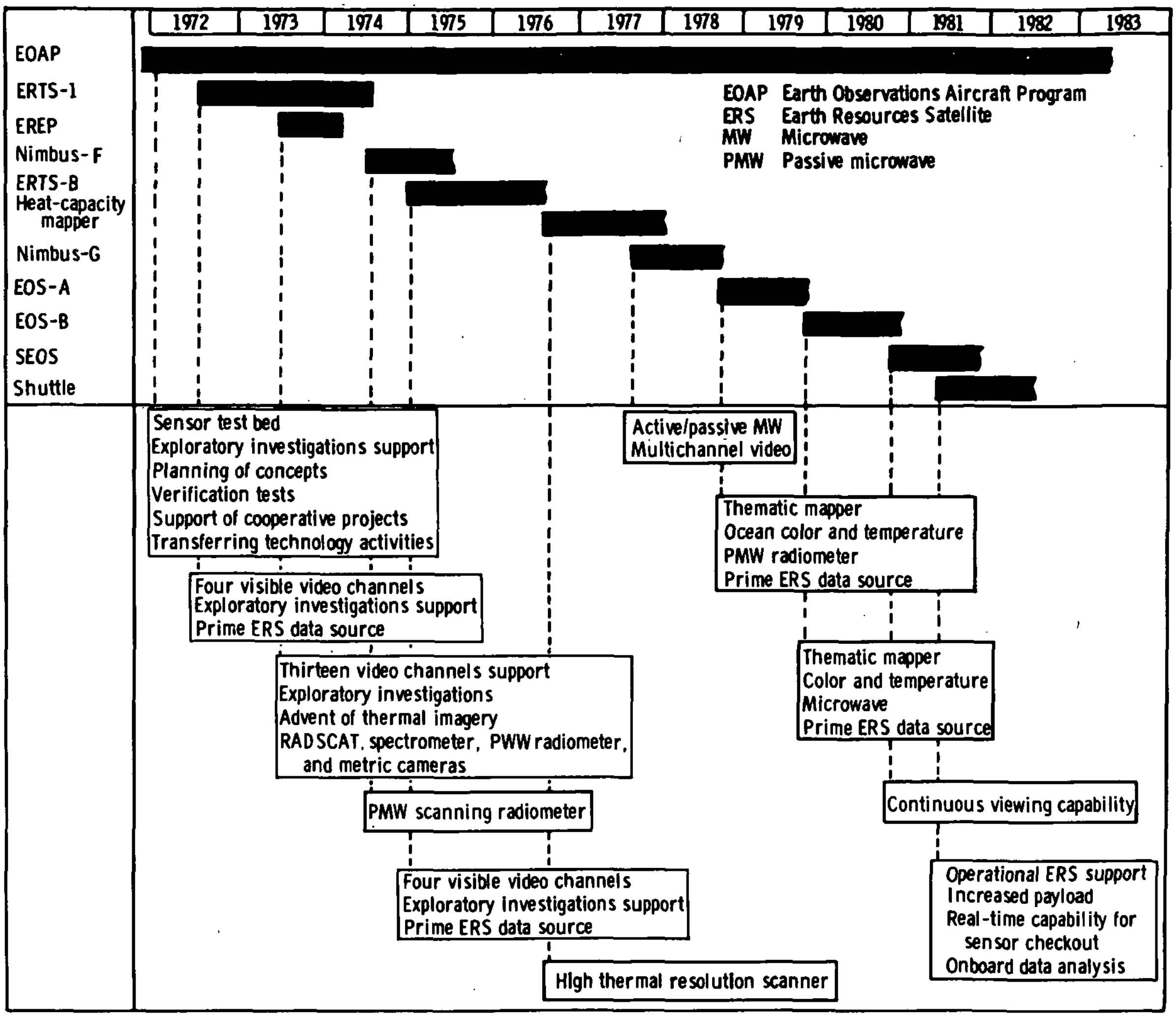

FIGURE 1B-2.—Diagram showing a range of satellite systems being studied and having applications in the Earth/land area.

from thermal measurements. Expected applications include surface geology, soil moisture, and investigations into transient thermal effects.

The introduction of the Space Transportation System (Space Shuttle, Spacelab, and Space Tug) at the end of this decade is expected to have a major effect on future experimental and operational Earth observation satellites. Automatic spacecraft such as EOS can be placed into orbit by the Space Shuttle and, if necessary, recovered for in situ repair or returned to Earth for refurbishment and eventual relaunch. Many missions for the post-1980's are being planned for Spacelab in the areas of science, applications, and technology. Spacelab is a modular system comprising a manned pressurized module and an unpressurized instrument-carrying pallet that fits into the cargo bay of the Space Shuttle and is carried into orbit for sortie missions of 7 days, which can be extended up to 30 days. The modular concept enables various module and pallet lengths to be used between the extremes of flying a long module with no pallet to pallet-only missions. Preliminary studies on the role of Spacelab for Earth resources surveys have highlighted its value as a flexible orbital laboratory that could be used to link the present experimental aircraft programs to the future automatic operational satellite programs. Secondary Spacelab roles have also been identified, such as in-orbit testing and qualifications of sensors before their integration into automatic satellites and certain operational applications in which synoptic high-resolution data are required at infrequent intervals.

ACTIVE MICROWAVE SENSING

Importance to Earth/Land Area

The reasons for using active microwave sensors in place of or in addition to sensors in the visible IR range of the spectrum are as follows:

1. To provide timely information despite clouds or darkness (operational potential).
2. To penetrate vegetation and thin soil.
3. To complement (or replace) photography.
4. To provide special applications.

Probably the most important use is the capability to observe the terrain when clouds or darkness obscure the ground. This capability was the primary reason for developing the early airborne bombing radars, which were the predecessors of all airborne imaging radars.

A unique reason for using active microwave sensors is the ability of radio waves to penetrate vegetation and soil. The shorter wavelength signals in the microwave region cannot penetrate extremely dense vegetation all the way to the ground, and no microwave wavelength usable from space penetrates more than a few decimeters or meters into the soil. However, this amount of penetration makes visible many phenomena not observable at the shorter wavelengths.

The use of color in photography and its MSS extension into the thermal-IR region is well established for aiding interpretation of aerial imagery; the addition of almost two decades of spectrum in the microwave region enables extending the concept of color much further. This means that multispectral (or even single wavelength) active microwave sensors can add to the information available with multispectral scanning in the visible-IR region, thus making identification of ground objects easier. When clouds are present, microwave "color" may replace visible-IR color as a discriminant for differences in ground properties.

Active microwave sensors also have certain unique applications dependent particularly on the physics of microwave sensing—that is, applications in which visible-IR sensing will not work even if cloud and vegetation penetration is of no significance. Surface scatter from the ocean for wind sensing, volume scatter from snow and soil for moisture sensing, and detection of frozen ground are examples of this fact.

Details of the need for active microwave sensing are presented for introductory purposes. No examples are presented for the complementary role of active microwave sensing in adding to the available spectrum.

Cloud penetration.—Cloud penetration is particularly important when operational information must be gathered on a timely basis —that is, when there is no time to wait for the clouds to clear. Immediate monitoring of the extent of flooding is often important for warning those downstream and for dispatching help to the inundated areas. Monitoring flood damage as soon as possible after it occurs can aid in effective allocation of resources for repair and for aiding victims. Monitoring the full extent of a flood can also be important in forecasting its effect (positive and negative) on agriculture in the flooded area. Examples of the operational need for cloud penetration are as follows:

1. To monitor floods and flood damage.
2. To map lake ice.
3. To measure soil moisture.
4. To monitor harvest progress.

Great Lakes ice distribution must be observed on a timely basis if ship-route forecasting is to be effective. This monitoring is already being done in the U.S.S.R. Furthermore, because of the changing nature of the icepack, this monitoring must be repeated frequently.

Soil moisture measurements are important for many hydrologic and agricultural applications. Because the moisture conditions change rapidly, timely observations are important.

The progress of harvesting a particular crop is important not only to agricultural agencies but also to transportation agencies. Facilities for transporting the crop to its destination must be dispatched efficiently, and (at least in the U.S. Great Plains) harvest machinery and itinerant labor must be in the right place at the right time to take full advantage of the crop calendar. Because of the synoptic view provided by remote sensing, automatically processed sensor output can be more effective for this purpose than land communication networks that depend on gathering information from thousands of individual points. However, such a remote-sensing system cannot work if it must await good weather for photography.

Vegetation penetration.—Numerous applications of remote sensing require knowledge of conditions beneath the top of a plant canopy or a thin soil layer. Boundaries between different soil types and surface lithologies may be observed directly if the vegetation canopy can be penetrated, and a suitable choice of microwave sensor wavelength and incidence angle enables the penetration of most vegetation except dense forests. Some boundaries are also identifiable from the vegetation differences, which may be observed on either visible-IR or radar images, particularly if the observation is made at exactly the right time in the phenologic cycle. Examples of the operational need for vegetation penetration are as follows:

1. To map surface soil and rock boundaries.
2. To monitor floods in forested areas.
3. To measure soil moisture.
4. To inventory forests.
5. To map surficial materials.
6. To improve geologic mapping.

Floods often occur in forested areas where the extent of floodwaters is very difficult to measure with photography because of the leaf canopy. One leaf between the camera and surface can prevent observation; however, radar can normally penetrate significant amounts of canopy, depending on incident angle and wavelength.

The moisture content at the surface of bare soil can be inferred from visible-IR sensor data. However, if the soil is covered with dense vegetation, monitoring changes in moisture content is impossible without using the penetrating capability of microwave signals. Furthermore, even with bare soil, the capability of the microwave signal to obtain responses from some distances (centimeters to meters) within the soil means that moist subsurface layers can be observed even if the top centimeter has dried. The effect of a recent small rainfall or heavy dew in barely wetting the surface can be discounted when microwave sensors observe the integrated effect of the surface and near-subsurface. The wavelength of the microwave sensors is particularly important for this application because longer wavelengths can penetrate more vegetation and soil.

Forest inventory by photographic remote sensing involves very fine resolution so that individual tree-crown sizes can be measured and counted. The penetration capability of longer wavelength radar should enable estimating the volume of timber (rather than only of leaves) without using the fine resolution required for photography. Although this has not been proved, it will probably be an important use of active microwave sensors, at least in monospecific stands of timber.

Unique applications.—Moisture content of snow strongly influences the scattered microwave signal, whereas it has little effect on the visible response of the snow. The amount of compaction and liquid-free water in the snow has a major influence on its permittivity and therefore on the volume scatter from within the snow. Although this application has not yet become a proven quantitative measure, the phenomenon has been observed qualitatively and can be fully justified on a physical basis.

Frozen ground can often be readily distinguished from unfrozen ground by active microwave sensors because of the change in dielectric properties as the moisture in the soil changes from liquid to solid. This application has important consequences in forecasting flood runoff.

The strong microwave effects associated with edges in lake and river ice make the structure of the ice much more visible on radar images than on visible images; consequently, active microwave sensors have special application to monitoring ice structure in the Great Lakes and major rivers.

Among the fine-resolution sensors, imaging radar is uniquely suited to monitoring soil moisture because of its ability to penetrate the soil, whereas the color seen by other sensors changes as soon as the very top millimeter becomes wetter or drier. Active microwave sensors can detect soil moisture because the dielectric properties of the soil are affected by the amount of moisture present due to the large difference between the permittivity of dry soil and that of water. Such measurements have numerous applications to flood forecasting, agricultural production estimates, and watershed management.

The ability to control the angle of incident radiation with active microwave sensors led to unique applications in geology and geomorphology. The shadowing that can be observed in areas of small relief, when illumination and observation are at relatively shallow grazing angles, enables discrimination of structural features that cannot be observed with passive microwave sensors. This effect has been widely used in the commercial application of radar imagery by mineral companies and in the application by governmental agencies responsible for mapping geological phenomena. Some of the unique applications of active microwave systems are as follows:

1. Monitoring moisture content of snow.
2. Monitoring frozen ground.
3. Mapping lake and river ice.
4. Mapping structures in areas of low relief.
5. Monitoring soil moisture.

Summary of the importance of different factors to Earth/land applications.—Table 1B–I summarizes the unique features of active microwave sensing and their relative value to Earth/land applications. Clearly, some element from each of the application classes has proved feasible and important, and, in every instance, some part of the application requires the all-weather capability of active microwave sensors. The need for nighttime sensing is not so critical in many instances, and, in other instances, the need has yet to be demonstrated. In every situation, however, the ability to sense at night aids in more rapid acquisition of data because the number of useful passes over a given area is more than doubled relative to sunlight-dependent sensors.

Status of Active Microwave Sensing of Earth/Land

Microwave sensing of the land for civilian purposes was conducted to a limited degree before 1962 with plan position indicator (PPI) radar systems in aircraft and some specialized ground-based systems. However, the first significant studies of this topic began in 1963. Imaging radars used for such research have all been developed originally for military purposes. The L-band modification of the ERIM synthetic aperture radar and the recently completed S-band real aperture radar at the University of Kansas were the first systems constructed with civil use in mind. This means that parameters of the radars used were those considered appropriate for military reconnaissance, and the selection of frequencies, polarizations, and other parameters specifically for Earth/land sensing has been very limited.

Airborne sensing in which the goal is the development of civil applications of imaging radar has also been conducted using scatterometers. These instruments were developed primarily for collecting design and applica-

TABLE 1B–I.—*Unique Features of Active Microwave Sensing and Their Relative Value* [a] *to Earth/Land Applications*

Application	All weather	Day/ night	Penetra- tion	Dielectric constant	Surface roughness	Structural sensi- tivity [b]	Incident angle effects	Polariza- tion effects	Wave- length effects	Azimuth angle effects	Ground texture	Shadow- ing slopes
Land (solid earth), geology, minerals, civil works, and so forth	1	3	1	1	1	1	1	1	2	1	2	1
Soils and soil moisture	1	1	1	1	2	2	1	2	2	3	2	1
Vegetation (natural and cultivated)	1	1	1	1	2	1	1	1	1	2	1	4
Land use (urban and rural)	1	4	1	2	1	1	2	1	2	2	1	2
Water (inland water surfaces)	1	1	3	3	1	3	2	1	2	3	3	3
Snow and ice	1	1	1	1	2	1	2	2	2	2	2	2

[a] No. 1 is a proven or strong indication of value (research may still be needed for optimization and for unproven subareas); No. 2 is a potentially important value (needs research and development); No. 3 is no major value; and No. 4 is an unknown value.

[b] Sensitivity to shape of objects above or within a surface (e.g., vegetation, buildings, and volume scatter in ice). To be distinguished from roughness of soil, water, or ice and from the air-surface interface.

tion data for NASA; they have also been limited in their characteristics and terrain uses.

Ground-based (or truck-mounted) systems have been used by various experimenters for fundamental studies, and measurements have been made over a wider range of frequencies than with the airborne systems. The first significant study of this kind was conducted by Ohio State University. Since 1970, truck-mounted scatterometers covering an octave or more in bandwidth have been used at the University of Kansas, but no other broad-band systems of this kind are known. By the summer of 1973, measurements over the 1- to 18-GHz range had been made with this system, but the objects sensed were restricted primarily to soils and crops.

This background clearly shows that the determination of the optimum frequency and polarization combination for most applications of active microwave sensors has not been accomplished. Nevertheless, many useful applications have been identified and proved. For example, imaging radars are widely used today in mineral exploration.

State of the art in mineral resources and geologic applications.—In many respects, this class of active microwave sensor applications is further developed than any other, because most of the interpretation techniques used in photogeology are readily extended to radar geology. This fact is partially due to the extensive demonstration project conducted in Panama by the U.S. Army Corps of Engineers and partially due to the use of imagery collected for NASA from 1964 to 1966.

The ability to map geologic structure and to map or infer lithology has been demonstrated in numerous environments. This activity is conducted extensively by both Government agencies and mineral/petroleum exploration companies in many countries. Perhaps the largest project is radar of the Amazon (RADAM) in Brazil, but the U.S.S.R. has used this kind of mapping since approximately 1968.

In the Panama project and elsewhere, identification of landforms was demonstrated and terrain analysis was conducted. This identification and analysis has been extended to some of the other countries imaged by the commercial systems.

The ability to identify possible construction material on radar images has been demonstrated. The U.S. Army Corps of Engineers conducted Project Sand, which demonstrated this capability first in Vietnam and later in Mississippi. Much research needs to be done in this area, but the application has definitely been successful.

State of the art in water resources applications.—Monitoring of ice and ice movements on the Great Lakes was demonstrated during the 1973–74 season with a low-resolution X-band system flown by Lewis Research Center. The effect of finer resolution has been demonstrated by the ERIM X-band system, and the utility of a combined X- and L-band system with modest resolution was demonstrated in 1973–74 by the same group.

Monitoring soil moisture is important in forecasting floods and in agricultural applications. Important fundamental work in this area, with application to bearing strength of soil, has been conducted for many years at the U.S. Army Corps of Engineers Waterways Experiment Station. The relationship between soil moisture and dielectric properties of soil has been well established in that program, particularly in the L-band region. Airborne scatterometer measurements by NASA show that recently irrigated agricultural fields can be clearly distinguished from drier fields, with and without vegetation cover, at angles of incidence within 40° of the vertical. Studies with a microwave spectrometer have demonstrated that a direct relationship exists between appropriate soil-moisture indicators for the surface layer and the observed radar signal. However, these studies also have shown some of the complications resulting because of different responses for soils prepared in different ways by plowing.

Studies of the coastal wetlands have been conducted by several investigators. The utility of imaging radar at the Ka-band was demonstrated in these studies, and cross-polarized returns proved especially helpful in making distinctions. Multifrequency measurements in the coastal wetlands have proved the value of the combination of X- and L-band frequencies.

Oil pollution has been studied at the NRL, and elsewhere, in saltwater environment; the results were so successful that the U.S. Coast Guard is in the process of obtaining a microwave system for semioperational use in harbors and along the coast. No work has been done to determine whether this technique applies to inland waters, but the physical principle indicates that it should work in those cases in which the water is disturbed by wind or turbulent currents.

The ability to determine the moisture content of snow would be of great economic benefit. No quantitative measurements have yet been made to support the ability of radar to make such measurements, but qualitative work by Waite and MacDonald (ref. 1B–1) indicates that old, probably wet, snow shows up clearly on Ka-band images, with the nature of the return indicating a volume-scatter phenomenon.

Minor work on glaciers was conducted in the United States in the late 1960's, and the indication was that dry snow covering the glacier and its environs could be penetrated by the radar signal. Thus, the desired location of the glacial boundary could be determined even in the winter. Interesting work conducted by the U.S.S.R. on glacier studies with active microwave sensors is reported in chapter 2.

State of the art in agriculture, forestry, range, and soils applications.—Some crop identification was conducted at Ohio State University with a truck-mounted scatterometer, but the area observed was limited. Studies using imaging radars and scatterometers have been conducted since 1965. In addition, microwave spectrometer measurements of crops have been made extensively during the last 3 yr. The ability of cross-polarized returns to help distinguish crops was demonstrated for the months of August and September by using Ka-band imagery. July crop identification using this single-frequency system was not as satisfactory. However, the single-frequency Ku-band DPD–2 flown by JSC demonstrated that wheat could be identified clearly and that a yield model giving 95 percent accuracy could be applied to a countywide area in Kansas.

The use of multiple frequencies for crop identification has been tested with a microwave spectrometer. Although data analysis is not complete, initial indications are that a proper choice of frequencies can enable accurate identification of several commercial crops. The optimum frequencies have not yet been ascertained, but one frequency should be relatively high, probably well above the X-band. Best results were obtained using a 14-GHz frequency in combination with either a 7- or 4-GHz frequency. No attempt has been made to show the value of a third frequency or to try other high frequencies, but cursory examination of the available data indicates that any possible ambiguities in the two-frequency data (and some do exist at certain incident angles) could be easily resolved by using three frequencies.

Another two-frequency experiment was conducted using the ERIM X- and L-band system at Garden City, Kans. Analysis of these data by photointerpretation techniques showed that moderately good separation was achieved but that the L-band did not add as much to the separation ability as the 4-GHz frequency used with the spectrometer in eastern Kansas. This difference was probably because the L-band penetrates to the soil for some of the crops, whereas the higher frequencies do not do so for well-developed crops at suitable incident angles.

No quantitative work of consequence has been conducted to determine crop condition with active microwave sensors. During the 1972 summer, a small patch of corn blight was observed with the University of Kansas spectrometer, and a distinctive signature was observed that enabled clear separation of this diseased patch from healthy corn. This single example is not statistically significant; it is reported only as a suggestion of what research may show. Furthermore, examination of radar images consistently shows patterns within fields that can only be caused by differences in the vigor of the plants, but no such images have been available soon enough after a flight in past experiments to enable ground checking.

Similarly, only qualitative indications of the ability to discriminate range conditions have been observed. On several occasions, interpreters have observed that rangeland on opposite sides of a fence in the sandhills near Garden City, Kans., showed significant differences in tone on X- and Ka-band radar, which could have been caused only by differences in range conditions (almost certainly due to differences in grazing pressure).

The ability to forecast runoff from watersheds is a significant factor in managing agricultural water resources, both for retaining water for future use and for preventing floods. McCoy (ref. 1B–2) demonstrated conclusively in a study of more than 30 basins in different environments that the appropriate stream-length and slope parameters could be derived from radar imagery by human interpretation; he also showed there may be promise in automated analysis of such basins.

The mapping of natural vegetation has been demonstrated successfully but not often used. Morain and Simonett (ref. 1B–3) showed that certain vegetation classes could be mapped quite well with the combination of like- and cross-polarized Ka-band imagery in a relatively arid mountainous region in Oregon. The same technique was used to map the gross vegetation types in Yellowstone National Park and was also successful in Utah. Extensive vegetation maps have been prepared in conjunction with various parts of the South and Central America radar mapping projects. An attempt to use Ka-band imagery for forest mapping in the Sierra Mountains of California was less successful.

State of the art of active microwave applications to land-use problems.—Various land-use maps have been prepared on a regional basis by different investigators using radar imagery. One of the first successful regional land-use maps was made by Nunnally (ref. 1B–4). In addition, several land-use maps of urban areas have been prepared with radar imagery. Although these maps have been moderately successful, the radar imagery used did not have sufficient resolution to enable detailed mapping; thus, the maps are of rather general categories and nowhere near as detailed as one can compile from aerial photography.

The potential use of moving target indicators to determine traffic flow in cities has been demonstrated in principle, but apparently no research has been conducted to apply this technique to the traffic-monitoring problem.

Identifying parked cars in industrial parking lots, in parking lots associated with recreational or residential complexes, or even identifying cars on major thoroughfares, without ascertaining whether they are moving, could lead to improved knowledge of human and industrial activity. Cars provide relatively strong returns on like-polarized imagery but weak returns on cross-polarized imagery. A pair of images of JSC showed strong returns from the buildings on both polarizations, but only the like-polarized image had strong returns from parking lots full of cars. Thus, the potential exists for use of this phenomenon.

Flood monitoring with radar is clearly feasible under some conditions. Images produced during the 1973 flooding of the Mississippi River appear to delineate the boundaries of flooded areas. These images were made in rural areas, and their application has not been tested in cities and suburbs where trees and buildings are present.

In addition to the previously discussed activities of the United States, a growing interest in active microwave sensing methods exists in many foreign remote-sensing programs. For example, the European Space Research Organization (ESRO) has recently completed a feasibility study on a synthetic aperture radar satellite system (ref. 1B–5).

One of the principal objectives of this study was to demonstrate that active microwave sensors are potentially capable of satisfying the operational requirements of the user community. Additional objectives were to identify critical technological areas and to indicate the research and development steps required to achieve the operational system. The main results of the study indicated the need for a 10-GHz focused synthetic aperture imaging radar capable of providing spatial resolutions of 50 m for a swath width of 80 km. Based on the results of the ESRO study, more detailed investigations are presently underway on radar systems for use on Spacelab missions as a preparatory step before the definition of the eventual operational system. The European scientists clearly recognize that a considerable amount of progress is possible by using ground-based instrumentation and airborne measurements. Accordingly, efforts are now underway to increase the number of fundamental measurements like those currently being conducted by DeLoor and Jurrieens (ref. 1B–6) in the Netherlands.

Need for Research, Development, and Training

Research, development, and training of interpreters are essential parts of a program to apply active microwave sensors to those operational functions for which their unique abilities provide an advantage over visible-IR sensors. Because many of the applications depend on the use of relatively conventional interpretation techniques, one of the most pressing needs is to train interpreters already familiar with aerial photography to work with radar images. Many applications appear sound from a physics viewpoint, but they have not been tried; consequently, applications research is needed to demonstrate that these potential uses of active microwave sensors can be made operational. Much additional research is needed to determine the optimum parameters for active microwave systems and to determine radar signatures so that multifrequency, multipolarization systems can use their "color" capability to discriminate among the various terrain phenomena of interest.

Need to develop expertise in conventional interpretation of radar images.—Many applications exist for which context, shape, timing, and texture are the most important interpretation tools. These same parameters are used in analysis of aerial photography and scanner images, and a large number of interpreters are familiar with their use. Professional photointerpreters normally use these techniques, but geologists, urban and regional planners, foresters, soil conservationists, and other researchers also use them regularly. Hence, a most important need is to insure that such users of photography are able to use radar images.

One of the most important needs is to overcome the natural hesitancy of these users to work with an unfamiliar medium. Breaking this resistance is most important because many applications can be handled better with radar images using exactly the same methods as photography.

Another problem that can be overcome with such a training program is the natural tendency of interpreters to want more resolution than they really need. This tendency has inhibited many researchers from using ERTS images; however, users of ERTS have demonstrated that even its relatively poor resolution can be applied to many problems for which "need matrices" have, in the past, specified much finer resolution. For many uses, fine resolution actually inhibits proper interpretation; yet interpreters often judge the quality of an image by looking at it to see what kinds of objects can be resolved. Thus, the problem really is one of overcoming prejudice.

Geometric effects on radar images are different from those on photographs and scanner images. For some applications, an understanding of these differences is important, particularly in mountainous terrain. This understanding can be gained quickly, and the interpreter who understands these differences can then proceed to use his normal technique.

Needs for active microwave sensor application and signature research.—The application discussed in chapter 2 require different kinds of research and development. Applications depending primarily on conventional photointerpretation methods require research into the ability of these methods to satisfy the application needs with radar images and requires development of operational techniques for using active microwave sensors. Some such applications are nearly frequency independent in the sense that the radar images currently available (almost all in the few-centimeter-wavelength regime) seem capable of being used without regard to the exact frequency chosen. Other applications depend on geometric, texture, context, and timing factors, but use of a relatively low frequency for the radar is indicated. For such applications, similar research on use of conventional methods is required, but a low-frequency synthetic aperture radar is required to produce images. These needs are outlined in table 1B–II, in which the applications presented in chapter 2 are compared with the type of research and development needed.

Although many applications appear somewhat wavelength dependent, an optimum frequency probably exists for distinguishing the boundaries and textures that are important for each application. One reason no optimum frequency can be specified at this time is that multifrequency imagery is exceedingly scarce, and experiments conducted in such a way that the relative value of different frequencies can be compared are totally nonexistent for most of the listed applications. Choice of polarization has been the subject of more research than choice of wavelength, and a significant amount of imagery with multiple polarizations has been produced in the United States. Nevertheless, definitive research to establish the best single polarization is also almost totally lacking, because most multipolarization research has been aimed at determining the value of polarization combinations. Consequently, research is needed for determining the best wavelength-polarization combination for most applications as indicated in table 1B–II.

Many applications require the use of multiple frequencies and polarizations to produce "signatures" that permit fine distinctions to be made between classes of objects. These needs are particularly important in vegetation imaging, just as they are in the visible-IR part of the spectrum. Other such needs exist because varying depths of penetration with the different frequencies can be used jointly to learn more about a surface than could be learned with a signal that penetrates only to a single depth (under given conditions). Spectral signature studies have been conducted only for a very small number of materials under very specialized conditions; thus, this research area needs great expansion. The applications for which this kind of research is needed are listed in table 1B–II.

When signatures and temporal variations in response are important, fundamental understanding of the scattering process can contribute significantly to improved system design and to recognition of those areas in which microwaves may have great promise or in which applications may be more limited than indicated by present speculation. However, some applications, such as those depending on identification of land-water boundaries, are well understood from the standpoint of the physics of scattering, and such research is not likely to contribute to them. Some of the areas in which fundamental research shows most promise are itemized in table 1B–II.

PROGRAM PLANS

Active Microwave Sensing Experimental Program

Previous research and demonstrations have shown that active microwave systems are ready for many practical applications appropriate for both aircraft and spacecraft platforms. Systems that would be quite

TABLE 1B-II.—*Applications and Needed Research*

Application	Need for research on conventional techniques: Any frequency	Need for research on conventional techniques: High frequency	Need for research on conventional techniques: Low frequency	Need to establish best single frequency/ polarization	Need for signature research	Need for fundamental research
Mineral resources and geologic applications						
Landform identification and terrain analysis	X	....	X	X	....	....
Mineral deposit location	X	....	X	X	X	....
Petroleum exploration	X	....	X	X	....	....
Ground water exploration	X	....	X	X	....	....
Crustal motion	....	....	....	....	....	X
Major construction sites	X	....	X	X	X	....
Construction materials	X	....	X	X	X	....
Water resources applications						
Lake ice monitoring	....	....	....	X	X	X
Flood forecasting (soil moisture)	X	....	X	X	X	X
Flood mapping	X	....	X	X	....	....
Lake-level determination	X	....	....	X	....	....
Lake eutrophication	X	....	....	X	X	X
Coastal wetlands mapping	X	....	X	X	X	....
Water pollution monitoring	X	....	....	X	X	X
Snowfields	....	X	....	X	X	X
Glaciers	X	....	....	X	....	....
Permafrost	....	....	X	....	....	X
Agricultural, forestry, range, and soils applications						
Crop identification	....	....	....	X	X	X
Crop cover and condition	X	....	....	X	X	X
Range inventory	....	X	....	X	X	....
Soils mapping	X	....	X	X	X	....
Soil moisture:						
Watershed management	X	....	X	X	X	....
Crop yield	....	....	....	X	X	X
Forestry	X	....	X	X	X	X
Land use mapping						
Basic image analysis	X	....	....	X	X	....
Traffic	X	....	....	X	X	X
Parked cars	X	....	....	X	....	....
Disaster assessment						
Flooding (urban/suburban)	X	....	X	X	....	....
Previously flooded areas	X	....	....	X	X	....
Wind damage	X	X	....	X	X	....
Fire damage	X	....	....	X	....	....
Earthquake damage	X	....	....	X	....	....
Volcano activity	X	....	X	X	X	....

useful could be implemented without further research. Nevertheless, many of the most promising applications, in which active microwave sensors are strongly needed, require considerable research to show whether or not the promise of the present can be fulfilled. For applications in which active microwave systems are clearly ready to contribute, there is still little evidence whether such a choice would be optimum or whether (for many applications) the wavelength chosen makes much difference. Hence, a coherent research program is needed that places priorities both on developing the most important and promising applications and on investigating those that cannot be described as promising because of lack of knowledge.

Because many applications use conventional image interpretation techniques, a major effort should be made to provide these images to potential users and user-oriented researchers as soon as possible. In some instances, little ground truth is needed and existing images may be used; in other instances, new flights to provide imagery must be accompanied by extensive ground truth provided by investigators. Many applications require repeated coverage at frequent intervals or require very timely single coverage. An efficient mechanism is needed to make such coverage possible.

Many other applications depend on determining an optimum frequency that is critical enough to require experimental radars with several frequencies. When signature analysis is likely to be significant or when a considerable search must be made for the right wavelength, ground-based scatterometer/spectrometers will often be the most economical research instruments.

Fundamental studies, both theoretical and and experimental, can lead to understanding the phenomena associated with some applications well enough so that the costs of field and aircraft experiments can be significantly reduced. Such studies should be supported in which this kind of potential payoff can be identified and qualified researchers are available.

Sensors.—Sensors to be used in such research are available in several forms. The recommended active microwave research sensors are as follows:

1. Aircraft imaging systems:
   a. One multifrequency (four or five), multipolarization, fine-resolution synthetic aperture radar on NASA aircraft
   b. One single-frequency (probably X-band), multipolarization, fine-resolution synthetic aperture radar on NASA aircraft
   c. One or two existing multifrequency synthetic aperture radars on appropriate aircraft
   d. Two to six simple real aperture SLAR's on investigator aircraft
2. Airborne scatterometers:
   a. One AAFE RADSCAT
   b. One or two simple fan-beam systems (possible frequencies in the Ku-, X-, C-, and L-band) on small aircraft
3. Ground scatterometers and spectrometers:
   a. Four broadband spectrometers (multioctave) under control of actual researchers
   b. Four simple panchromatic but relatively narrowband scatterometers under control of actual researchers

The major national facilities suggested for NASA aircraft are complicated systems intended to answer the questions requiring fine resolution, requiring a full complement of polarizations, or requiring images at several frequencies. Such facilities must be scheduled relatively tightly because of the demand from many users both for these systems and for nonradar sensors on the aircraft. Because of the cost of such sensors, they are not appropriate for individual investigator groups. Existing systems, such as those at ERIM and JPL, might be used together with these central systems.

Although major systems are recommended for NASA aircraft, several (two to six) simple, inexpensive systems are recommended for use on aircraft under the control of investigators. Therefore, these systems need not be subject to the scheduling constraints, nor to the costs of flying on a large high-performance aircraft. These systems should be particularly valuable for experiments requiring frequent repetition of flights to observe time-dependent phenomena or requiring fewer flights in which timing is dependent on some unpredictable event. The kind of system used might be the APS–94 (used by Lewis Research Center and by USGS for ice studies) of the University of Kansas system, which could be duplicated for under $50 000 per unit. These systems have modest resolution and are not multifrequency, nor are they dual polarization, although this might be added relatively easily.

Much research can be accomplished by using available imagery. The 500 000 km^2 of Ka-band imagery obtained in 1965–66 are still useful for much research. Goodyear Aerospace has a computer-accessed library of U.S. Air Force images that cover many parts of the United States. Other image sources may also exist that could be used for some studies not requiring ground truth obtained at flight time.

The airborne scatterometer is a specialized instrument that can provide quantitative data from a wider range of areas than a ground-based system, but it does not provide an image. Its principal advantages are that it is inexpensive to add an additional frequency and that it provides multiangle data. Such systems can be flown on small aircraft that are inexpensive to operate.

One way to answer questions about optimum frequencies, polarizations, and their combinations in which images are not required is with swept-frequency scatterometer/spectrometers. At present, the 1- to 18-GHz system operated by the University of Kansas is the only system like this, but the development of three additional systems by qualified investigator groups is recommended. Such systems are much less costly to operate than multifrequency, multipolarization airborne systems, but they can only be used in relatively restricted areas at any particular time. Several of these systems need to be operating simultaneously in different areas if all the unanswered questions are to be addressed in a reasonable time period.

The number of groups capable of supporting such a sophisticated system and at the same time providing it with meaningful applications research is limited; hence, the development of approximately four additional simpler single-frequency systems is recommended so that these systems can be used by groups primarily oriented toward applications and without extensive engineering support. Such systems should be panchromatic (broadband) to guarantee that fading will not make data collection too difficult.

With this complement of sensors (distributed between operation by a national facility, such as the JSC, and by experimenters themselves), a program can be developed that should lead to the best use of limited resources in achieving the goals outlined in this report.

User-engineer-physicist coordination.—Every effort should be made to "team up" the user and application scientists with engineers or physicists interested in the relationship between the microwave signal and the terrain sensed. Experience from past programs has shown that many errors have been made by user scientists attempting to understand the electromagnetic fundamentals without adequate training. However, much of the research into applications of radar by engineers not teamed with users has produced meaningless data because the appropriate collateral data were not collected.

This "teaming up" of users and electromagnetic specialists can be achieved either by having both at the same institution or by assuring an institutional arrangement that encourages cooperation between persons located at different organizations. In the programs conducted to date, models exist for both of these arrangements.

Further coordination is necessary between these groups at a national and probably at an international level. A steering group should be established to advise NASA on the conduct and progress of the program. Such a group should meet at least semiannually. Its members should come from NASA and ESRO personnel, from appropriate user/agency personnel, and from researchers representing both the users and the electromagnetic interaction community. At least one representative should be selected from the radar hardware development community, and at least one should be selected from the data-processing community.

Meetings of this group should include occasional formal presentation of research or applications, but a major part of each meeting should be devoted to informal, but structured, discussion of the work in progress at various major and minor research groups in areas of interest. The meeting should also include reviews of the direction of the program and recommendations of priorities for future work.

If a set of instruments such as that described can be combined with an inspired research program conducted by multidisciplinary groups of the type outlined here, numerous active microwave space applications should emerge that will be of great economic and social benefit both to the United States and the world.

Balance Between Allocations for Data Acquisition and Data Analysis

Optimum allocation of resources requires a balance be maintained between the cost of acquiring remote-sensing data and the cost of data analysis. Acquisition involves tangible costs such as the price of an instrument, the cost of a carrier vehicle and its operation, and the cost of communication and computer time in data processing. However, data analysis requires large amounts of scientific and paraprofessional manpower over a long period. Because the acquisition costs are so readily quantified and because of a desire for relatively quick "proof" that these investments are worthwhile, allocations of funds often are for too small an amount and for too short a time. Consequently, vast amounts have been spent on collecting data that were never used because the funds were not allocated for their analysis.

Nearly all scientists agree that the cost of worthwhile data analysis is as high or higher than the usual cost of instruments and acquisition of data. A cursory review of the history of remote sensing and similar programs shows that this point is often overlooked in funding allocations. Furthermore, the length of time required to reach the analysis stage can result in fund withdrawal because of mission changes. This situation has resulted in the reacquisition of data at a later time, which could have been avoided had the earlier programs been carried to the proper conclusion. The future NASA active microwave program should give appropriate consideration to both the analysis and the acquisition phases.

REFERENCES

1B–1. WAITE, WILLIAM P., AND MACDONALD, HAROLD C.: Snowfield Mapping with K-band Radar. Remote Sensing of Environment, vol. 1, no. 2, Mar. 1970, pp. 143–150.

1B–2. MCCOY, ROGER MICHAEL: An Evaluation of Radar Imagery as a Tool for Drainage Basin Analysis. Ph.D. Dissertation, Univ. of Kansas, 1967.

1B–3. MORAIN, S. A., AND SIMONETT, D. S.: Vegetation Analysis With Radar Imagery. Proceedings of the Fourth Symposium on Remote Sensing of Environment, Univ. of Michigan, 1966, pp. 605–622.

1B–4. NUNNALLY, NELSON R.: Integrated Landscape Analysis With Radar Imagery. Remote Sensing of Environment, vol. 1, no. 1, Mar. 1969, pp. 1–6.

1B-5. EUROPEAN SPACE RESEARCH ORGANIZATION: Side-Looking Radar Systems and Their Potential Application to Earth-Resources Surveys. ESTEC Contract No. 1537/71, 1973.

1B–6. DELOOR, G. P., AND JURRIEENS, A. A.: The Radar Backscatter of Vegetation. AGARD Propagation Limitations in Remote Sensing, Oct. 1971.