be studied further and that existing aircraft radars be modified to provide digital data so that these compaction techniques can be tested.

Data management for SEASAT–A imaging radar provided an example of a possible end-to-end data system for a future spacecraft imaging radar. This example indicated that—

1. A radar image is similar to the photographic products from other spacecraft such as ERTS, Mariner, and Pioneer.
2. The user products and the radar parameters enter the processing at several different points in the system (i.e., the ends of an end-to-end system are not singular points).
3. Two basic data products must be considered: computer digital tapes and analog photographs.
4. Ground processing must be flexible and adaptive.
5. A library for radar data is needed.

Automatic computer-processing and pattern-recognition techniques must be implemented near the user end of an end-to-end data system. The applications of these processes to imaging radar data will expand, based on previous work with multispectral data.

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PART D

PROGRAM PLANNING

This section presents a discussion and recommendations for future activities necessary to support satellite microwave sensing. The need exists for a program that will provide information in the following areas:

1. Experimental test program to establish the interaction of electromagnetic waves and sensed parameters.
2. Component development.
3. Data processing.
4. Calibration.
5. Design and fabrication of a multifrequency system.

Each area will be discussed in greater detail in the following paragraphs.

Inputs to this section were obtained from joint discussions between the TSG and the three panels of the Active Microwave Workshop.

EXPERIMENTAL TEST PROGRAMS

A requirement exists to determine experimentally the characteristics of surface features when these features are sensed by electromagnetic waves in the microwave portion of the spectrum. The stated desires and requirements of the Earth/land panel for experimental data from controlled tests were adequate to keep several aircraft systems busy on a continuous basis.

Earth/Land

The Earth/land panel has suggested an aircraft research program the objective of which would be to provide the information that has been lacking or fragmentary in this important field of remote sensing. Two additional items are highlighted for future effort: small-scale surface-texture measurements and polarization signatures.

Small-scale surface texture.—The unique capability of active microwave systems to detect variations in surface texture of geologic materials is potentially one of the most useful applications of microwave remote sensing.

A recent example of the type of detailed feasibility study necessary for a thorough examination of SLAR surface texture analysis is included in the section entitled “Combined RAR and SAR Imaging." This investigation, using radar images of Death Valley, clearly indicates the importance of multifrequency radar systems to delineate small-scale surface texture, and, thus, distinct lithologies.

Sufficient SLAR images are not yet available at diverse wavelengths, polarizations, and look directions over any particular study area for a comprehensive evaluation of optimum system design for surface-texture analysis.

As part of the NASA aircraft programs plan, it is proposed that an optimum SLAR system be designed for surface lithologic identification. The system would have the following characteristics:

1. A wide spread in wavelengths (i.e., 3 cm, 25 cm, 10 m).
2. Dual polarization (HH and cross) for at least the 3- and 25-cm wavelengths.
3. Incident-angle capability from 0° to 70° (0° to 45° nominal use).
4. Maximum attainable power.

The system would have surface-texture sensitivity ranging from 0.2 to 1.8 cm and should provide geoscience users with much greater success in mapping lithologic materials than previously encountered. The NASA Jet Propulsion Laboratory X-, L-, and P-band systems and the ERIM X- and L-band systems would have immediate application to this area of investigation.

Polarization signatures.—A unique polarization technique has been demonstrated by Martin (ref. 5–39) that appears almost unknown in the microwave-sensing community. The technique is the ability to change polarization at the PRF rate (e.g., 5000 times/sec). Thus, polarization changes can be obtained in small steps (e.g., 11.25° increments). This system can obtain polarization signatures (figs. 5–108 and 5–109) on a single pass over small areas.

Use of existing data and systems.—The initiation of several interim steps is proposed to reduce the time required to provide at least part of the needed experimental information.

The first approach recommended is to begin analysis of existing imagery. Considerable radar-image coverage of the United States exists at several locations. This imagery has had only limited analysis for resource applications. Several application areas could benefit from a well-planned pro-

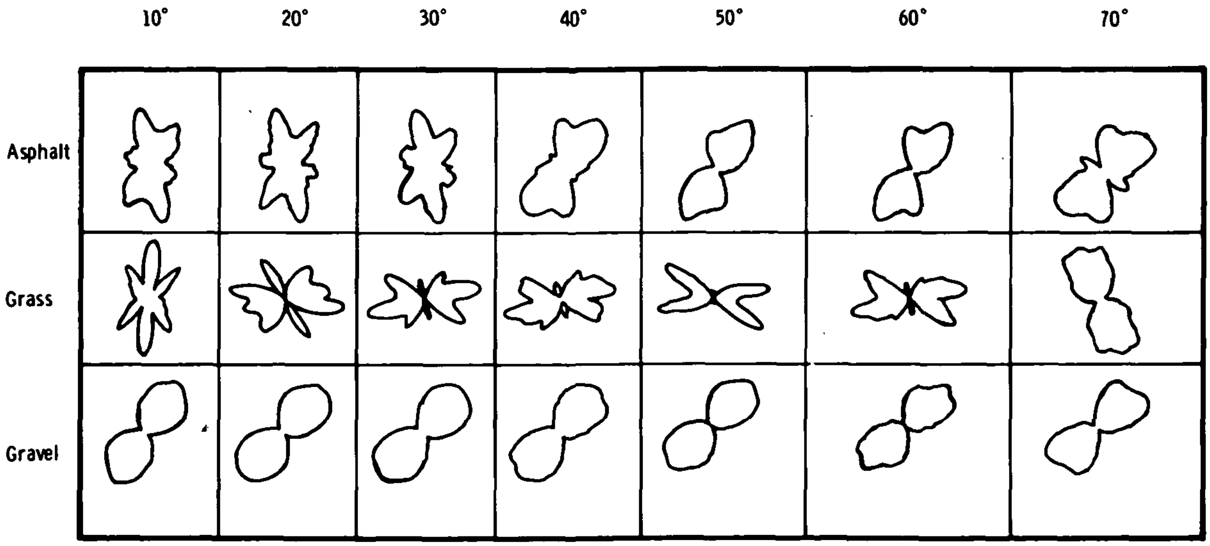

FIGURE 5–108.—Direct polarization profiles for asphalt, grass, and gravel at 8.505 GHz for various incident angles.

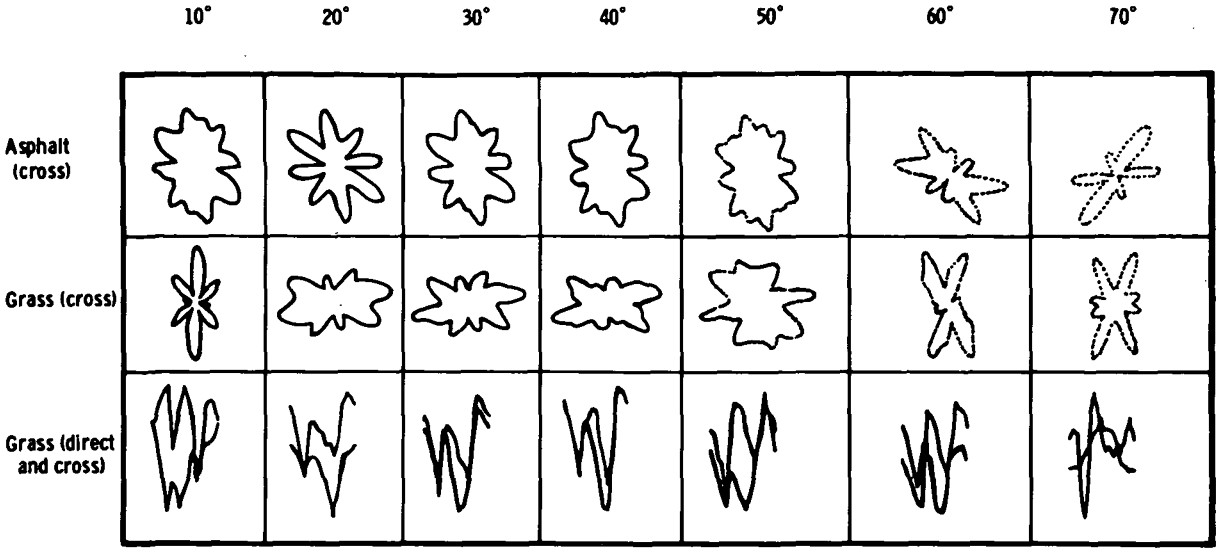

FIGURE 5–109.—Cross-polarization profiles for asphalt and grass at 8.505 GHz for various incident angles.

gram using these data. A fruitful area would be the comparison of ERTS multispectral scanner data with radar data in the area of geology and vegetation.

A second proposed approach is to use existing multiparameter systems in a coordinated measurement program. At least two existing systems have simultaneous frequencies on two or more wavelengths and two polarization channels. The use of these systems would provide much imaging information needed for both Earth/land and ocean applications.

Many of the reports and articles concerned with imaging radar classify the carrier wavelength or frequency into bands identified by letters, such as X-band. Presently, there are three recognized systems of band identification. To avoid confusion, in this section the carrier is specified by the wavelength expressed in millimeters, because wavelength is more meaningful to Earth scientists.

Oceans

In the area of ocean sensing, an effort is needed to determine which part or parts of the ocean wave reflect the radar energy, and further study is needed to develop methods to obtain two-dimensional wave spectra from imaging radar data. Most existing ice-measurement data provide information on physical parameters such as size and patterns. A need exists to use multiparameter radar systems to improve ice-type identification.

There is an established user requirement for the previously mentioned items. Consequently, high priority should be given to instituting programs that will supply the required information.

Atmosphere

The atmosphere panel has generated a requirement for radar observations of tropical storms. The requirements for such observations are presented as an item for a feasibility study. Tropical storms (including hurricanes and typhoons) appear to be promising targets for meteorological radar observations from orbiting satellites. Some characteristics of the storm systems are summarized in the following paragraphs, and minimum and desirable radar-observing capabilities are given.

Some significant characteristics of the storm systems are given in table 5–XIII.

TABLE 5-XIII.—*Significant Characteristics of Storm Systems*

Typical overall dimensions of the precipitation region:	
Diameter, km	560
Height, km	18
Lifetime, weeks	1 to 3
Reflectivity factor range of interest, dBZ	20 to 70
Windspeed range of interest, m/sec	0 to 75

Radar observations of the precipitation distribution in tropical storms throughout their life cycles are not now available. However, the Global Atmosphere Research Program Atlantic Tropical Experiment (GATE) radar program may provide a few sets of such observations.

Estimates of the minimum and the desired radar observational capabilities to provide useful information for hurricane studies are as follows:

1. Minimum capability: Determine the horizontal (i.e., two dimensional) distribution of precipitation echoes, with resolution as follows:
   a. Horizontal: 20 km
   b. Time: 24 hr
   c. Reflectivity factor: semiquantitative
2. Desired capability: Determine the three-dimensional distribution of precipitation echoes, with resolution as follows:
   a. Horizontal: 2 km
   b. Vertical: 1 km
   c. Reflectivity factor: 3 dB
   d. Time: 12 hr
3. Determine wind velocities, with resolution as follows:
   a. Horizontal: 2 km [3]
   b. Vertical: 1 km
   c. Wind velocity: 2.5 m/sec, 20°
4. Determine storm movement, with resolution of 1 m/sec, 10°.

The minimum requirements are based mainly on the characteristics of present-day numerical models. In general, those models deal with only two-dimensional distributions of precipitation or with a vertical structure represented by a few levels.

COMPONENT DEVELOPMENT

The equipment requirements of the applications panels are within the current state of the art, with the exception of possible deployment techniques for large space antennas. There is a need for deployable antennas for some imaging radar applications in the frequency range from 100 to approximately 40 000 MHz, having along-track dimensions of 5 to 20 m and crosstrack beamwidths of 6° to 15°. Side lobes in both dimensions must be kept below approximately −20 dB. A program should be initiated to develop a space-qualified antenna to meet these requirements.

DATA PROCESSING

Any plan designed to gather data from an aircraft for investigative purposes must include an adequate data-reduction facility to give the user/investigator the required data in a timely manner. If the same instrumentation is to serve a large number of user/investigators, at different wavelengths and polarizations, the data should take the form of a universally usable data-distribution method such as a computer-compatible tape. In the development of the instrumentation required, the merging of operational parameters (such as altitude, latitude, longitude, velocity, windspeed, wavelength, polarization, and swath width) with the data must be considered.

Future effort should be concerned with geometric fidelity of radar imagery and with the problem of producing images that are compatible with maps and other systems outputs such as ERTS. Consideration should be given to rectifying radar imagery and removing geometric distortion in the processing state of the data chain.

The recommendation concerning data processing and management is clear. Efforts must be initiated that will specify all phases of data processing and management from

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[3] For some purposes, the horizontal resolution requirements of the wind measurements can be relaxed to 10 to 20 km.

the collection of the data to the data analysis and, where possible, the dissemination of the final product. More efficient data reduction algorithms are necessary for this effort.

The desired observing capabilities are based on anticipated future development of the hurricane models and extrapolation from the capabilities of presently available ground-based weather radar systems. Much finer resolution is needed in both the horizontal and vertical directions, and somewhat finer resolution is generally desirable in the vertical dimension. Moreover, nonattenuating wavelengths would be required to obtain quantitative echo intensity measurements.

The observing capability required for any specific investigation must be determined by reference to the detailed scientific objectives. Thus, the present estimate indicates design goals that may serve as a basis for deciding whether the needed capabilities can even be approached by satellite-borne weather radar systems.

CALIBRATION

Stated requirements for system calibration range from 2 to 5 dB, absolute, and from 0.1 to 3 dB, relative. The attainment of these requirements for some systems has not yet been demonstrated. Furthermore, the calibration must be maintained during extended periods of operation. A program is needed to establish the methods of calibration for each system, determine the level of calibration that can be achieved, and predict the degradation of calibration with time and environment during operation.

MULTIPARAMETER SYSTEM

The Active Microwave Workshop panels expressed the desire for multifrequency and multipolarization data. Of the three panels, the Earth/land panel specified imagery for two or more frequencies and at least two polarizations. This need, together with the shortage of existing data on simultaneous coverage with multiparameter systems, provides a strong justification to implement a program in the design and procurement of such a system and to institute an experimental measurements program.

SUMMARY OF RECOMMENDATIONS

The TSG has determined that a need exists for each of the following recommendations:

1. An experimental aircraft program for ocean wave and ice investigations.
2. An experimental aircraft program for Earth/land investigations.
3. A polarization signature study.
4. A coordinated program to analyze existing imagery.
5. A program to use existing multiparameter systems in the collection of needed data.
6. A feasibility study on the subject of equipment for the observation of tropical storms.
7. A program to develop large deployable space antennas.
8. A program to address the subject of data processing, data analysis, and data management.
9. A program to determine system calibration capabilities and methods of calibration.
10. The development of a multiparameter imaging system.

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APPENDIX 5A

PATTERN RECOGNITION CONSIDERATIONS

ESSENTIAL PROCESSING OF RADAR IMAGES

To extract the maximum useful information in data processing and pattern recognition, Nagy (ref. 5A-1) has identified the following necessary procedures.

1. Image enhancement by digital and/or analog means is needed as an aid for human interpretation of the data. Specific approaches in digital image enhancement include orthogonal transformations, linear transformation, two-dimensional filtering, and so forth. Difficulties may arise because the transformations required to reveal or emphasize one set of features may, in fact, degrade features desirable for another purpose. In this case, several transformations may be needed at the same time.

2. The need for exact (element by element) superimposition of two images of the same scene upon one another arises in preparing a composite image, chronological observations, and so forth. It is also desirable in many application areas to bring together radar images and multispectral sensor images of the same scene. In this instance, the geometric and radiometric correction techniques may be different, but the problems are identical. It is necessary to correct, although it may not be possible to completely eliminate, the differences that may occur between two images of the same scene.

3. Geometric distortions caused by changes in the attitude and altitude of the sensor can be corrected by digital techniques while preserving the resolution requirement.

4. Radiometric corrections are data corrections arising from a variety of sources, the most common of which are calibration corrections, empirical corrections for data recording and processing errors, and atmospheric corrections.

5. In the case of data dropouts, interpolation techniques must be used to compensate for data loss. In multifrequency and multipolarization operation, the amplitudes of the data from all channels must be scaled and calibrated to remove the variations among different channels.

6. The atmospheric effects of scattering and diffraction also degrade the images. It is necessary to assess and remove such effects, especially in the determination of surface reflectance. The removal of these effects

is also needed in the pattern recognition process in which ground-truth sites are used as training samples and the signatures are extended over other areas in the recognition process. If variations in the atmosphere are large enough to introduce significant variations in the signature, then the recognition performance will suffer. Atmospheric effects can be corrected by using the theoretical atmospheric model and the actual observations. The effects are highly dependent on the operating frequency and the turbidity and humidity of the atmosphere.

7. Once the images to be matched have been corrected for the previously mentioned sources of error, the relative location of the images must still be determined before an objective point-by-point comparison can be performed. Tracking and ephemeris data usually provide a first approximation to the position of the sensor at the time the data are acquired; but, for exact registration, more accurate localization is required.

AUTOMATIC PATTERN RECOGNITION CONSIDERATIONS

As with other sensors, the large amounts of data generated on an active microwave system make it desirable to use machine interpretation of the data whenever feasible. Machine interpretation requires the use of automatic pattern-recognition techniques. Although particular emphasis is placed on the automatic recognition of radar images, the techniques should be useful to other radar data, such as data from the scatterometer, altimeter, and so forth. Experience gained from the machine processing of other remotely sensed data, such as from ERTS–1, should be very useful for the automatic processing of the active microwave sensor data. The data acquisition and formatting may be different, but the basic recognition process entails the following three operations performed in sequence.

1. Preprocessing is performed to enhance the pattern characteristics that are important for recognition and to remove the irrelevant details. Preprocessing techniques are application dependent. Typical examples are Laplacian filtering for edge enhancement, regulation of input field size, and so forth. In most image-recognition experiments, the first step in the preprocessing phase entails reducing the radar image to digital form by means of a flying spot scanner and an A/D converter. The digitized image consists of an array of numbers, with each number representing the gray level at a particular point.

2. Feature extraction and selection is performed to obtain a pattern representation of lower dimensionality compared to the original input field. These features (properties) must also admit an effective decision function of a simple form. Features should be derived from spatial, tonal, and textual-contextual information of the images. The knowledge of which set of features to extract will guide the designing of the preprocessing operations, and the appropriate preprocessing of the image data will facilitate the extraction of significant features. These two closely related operations are the keys to the success of automatic recognition of radar images.

3. Classification, accomplished by applying a decision function to the feature set, is performed to assign the pattern to one of several preselected classes. The classes are defined according to a priori knowledge. The definition of pattern class may be modified at different levels of classification. For example, in radar discrimination of sea ice (ref. 5A–2), seven categories of sea ice can be identified with the scatterometer experiment. However, in an SLAR experiment, only four categories could be distinguished. Similar examples can be given in land-use classification. The training samples are usually required to obtain any reasonable recognition result. Typical classification or decision procedures are the maximum-likelihood decision rule, the nearest-neighbor decision rule, and the linear decision functions.

DATA FORMAT

Quantization introduces a nonrecoverable error in the specification of the amplitude of each image sample. The number of quantization levels required to maintain the quantization error below the subjective threshold of noticeability is strongly dependent on the characteristics of the image sensor and display. As many as 256 quantization levels may be required for flying a spot scanner display. For classification purposes, the data-format requirement is different. Suppose an image is divided into several subimages and each subimage is represented by a vector sample. If the number of samples (i.e., the sample size) is finite, which is typical in most remote-sensing problems, the mean recognition accuracy improves as the number of discrete values of the sample increases, until the number reaches a certain optimum number beyond which the recognition accuracy worsens. This result is due to the discrete nature of the feature measurement and the finiteness of sample size. The optimum number does not depend on the resolution and signal-to-noise ratio. Let the dimensionality of a vector sample be $n=q^N$ discrete levels, where N is the number of components of the vector. Thus, it has been shown that for two classes which are equally likely and have a finite number of samples, there exist optimum N and q, depending on the sample size, at which the mean recognition accuracy is the highest. For small sample size, the optimum q is 3 for $n \leq 5$. If the sample size is 40 and $N=2$, the optimum q is 6. If $q=2$ (i.e., binary measurements are used) and 500 samples are used, the optimum dimension is 23, which requires $N \leq 5$.

DATA ACQUISITION AND RECOGNITION ACCURACY

The recognition result depends strongly on how the data are gathered. Properly acquired radar images will greatly simplify the subsequent recognition operation. The recognition accuracy will definitely improve with multifrequency and multipolarization operations. The effect of taking measurements from several angles has been examined by Parashar et al. (ref. 5A–2). The percentage of correct recognitions of sea-ice types that they reported for the radar scatterometer is listed in table 5A–I.

The exact relationship between signal-to-noise ratio, spatial resolution, and recognition accuracy is not available. However, as the signal-to-noise ratio and the spatial resolution are improved to certain levels, the recognition accuracy reaches a saturation point at which further improvement is negligible.

PREPROCESSING AND FEATURE EXTRACTION TECHNIQUES

A general approach to preprocessing and feature extraction is the use of orthogonal transformation techniques. This approach emphasizes image enhancement. The Karhunen-Loeve transform may be applied to the digital imagery to provide a set of uncorrelated principal component images useful in automatic recognition, signal-to-noise ratio improvement, and data compression. Fast algorithms should be used to reduce the computational complexity in orthogonal transforms.

A more efficient computational approach is to sequentially select fewer (but good) features to achieve an acceptable recognition accuracy. The spatial and textural properties and the distance measures can be used to construct such features. Each feature can then be evaluated sequentially. The best features are used for classification. In most

TABLE 5A–I.—*Recognition Accuracies for Scatterometer Data*

Frequency	Number of classes	Number of angles	Percentage correct
13.3 GHz	7	12	66
13.3 GHz	7	6	64
13.3 GHz	4	12	87
13.3 GHz	4	6	85
400 MHz	4	12	75
400 MHz	4	6	62

instances, the underlying distribution of the features cannot be assumed, and nonparametric methods are needed. For preprocessing, one important problem is the boundary detection, which may be performed by a thresholding method using both local (gray-level association) and global (second-order gray-level distribution) information.

Another useful approach that significantly speeds up (by a factor of 2 or more) the classification and feature selection is to incorporate the Cholesky decomposition in the LARSYS program (a computer program developed by Purdue University).

NONSUPERVISED CLASSIFICATION AND CLUSTERING

"Nonsupervised learning" or "cluster seeking" are terms applied to methods of data analysis in which only the observed values are used explicitly to group samples according to some intrinsic measure of similarity. In remote-sensing experiments, this approach has been used (1) to alleviate the problem of multimodel probability distributions in supervised classification methods, (2) to circumvent the need for a priori selection of training samples, and (3) to condense the amount of information stored or transmitted.

This approach is suboptimal compared with the supervised classification. It is still necessary to collect the ground truth to reduce the errors that may arise in this approach. Clustering techniques can be used to effectively determine the homogeneity and inhomogeneity in Earth scenes as an initial step toward automatic scene identification.

ONBOARD CLASSIFICATION

Performing pattern recognition processing onboard the satellite (ref. 5A–3) may considerably reduce the amount of data to be sent back to the ground. For example, in terrain classification, it is envisioned that the data to be transmitted would be a set of coordinates delineating the boundaries separating large homogeneous areas (e.g., mountains and plains) together with a code for designating the pattern class on each side of the boundary. The original scene could then be reconstructed on the ground from idealized models of the pattern classes. The complexity of these models would be a function of the discrimination capability of the pattern recognition process. The main advantage of the onboard classification would be the reduction of the transmission bandwidth and the overall computational and storage requirements. A possible disadvantage would be the inadequate recognition accuracy available from the onboard processor.

In summary, the important points concerning radar image processing and recognition are as follows:

1. Both geometric and radiometric corrections for radar images can be performed in generally the same manner as for photographic products from other Earth resource programs.
2. Basically, the same image processing and pattern recognition techniques used for multispectral sensor data can be used for radar images.
3. More efficient preprocessing and feature extraction algorithms for radar images are needed.

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