CHAPTER 2

Active Microwave Remote Sensing of Earth/Land

Active Microwave Working Group

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INTRODUCTION

The objectives of the Earth/land panel were (1) to identify needed Earth resources survey and solid Earth applications in which active microwave techniques are potentially useful, (2) to divide these applications into those known to be feasible and those believed to be feasible, and (3) to outline the experiments and systems needed to implement presently feasible methods and to bring other methods to the feasible stage. A summary of the Earth/land panel tasks and recommendations is presented in chapter 1.

The Earth/land panel undertook its work in the following sequence: (1) to identify broad areas of Earth resources and solid Earth applications; for example, agriculture, (2) to define key applications within these broad areas; for example, crop condition, (3) to specify information of value to users responsible for resource management decisions; for example, plant moisture content for crop yield forecasts, (4) to identify physical phenomena that must be measured to gain this information of value; for example, permittivity, (5) to specify preliminary functional requirements concerning data acquisition, processing, analysis and distribution (including required ground truth); for example, wavelength, repetition rate, time of year, and timeliness of data delivery to ultimate user, and tradeoffs among functional requirements, (e.g., spatial resolution compared to swath width), (6) to indicate needed research, covering the complete range from theory and laboratory experimentation to field, aircraft, and spacecraft tests; for example, experiment plan flow diagram, and (7) to identify any issues raised by the foregoing analysis; for example, changes needed in the way responsible institutions currently use remote-sensing data to derive information for resource management.

The Earth/land panel report is divided by broad applications areas into (1) mineral resources and geologic applications (including earthquakes and crustal motions); (2) water resources; (3) agriculture, forestry, range, and soils (including soil moisture); and (4) land use, urban, environmental, and mapping applications. Appendix 1B of chapter 1 presents a review of the Earth observation program, the importance of active microwave sensing, and the program plans.

PART A

MINERAL RESOURCES AND GEOLOGIC APPLICATION

GENERAL OBJECTIVES

The objectives of part A are to describe the geoscience applications of active microwave systems. The unique contribution of imaging radars for mineral resource, petroleum and ground-water exploration, and geomorphic analysis in the cloud-shrouded tropics has been demonstrated. In the area of civil works, applications are found in the selection and evaluation of sites for major construction, such as nuclear powerplants, dams, pipelines, schools, and hospitals. In solid Earth studies (including geophysics), the possibility of utilizing active microwave sensors to detect small crustal movements before earthquakes appears to have some potential.

Active microwave systems should provide unique terrain data to facilitate geoscience interpretations. An obvious need for signal penetration exists where vegetation or a thin soil cover masks shallow outcrop patterns; thus, multifrequency microwave systems may provide this capability. In addition, the feasibility of obtaining multipolarization terrain parameters and an insight into dielectric properties may provide data for terrain analysis not otherwise available when using existing airborne systems.

The objectives of the various remote-sensing systems are quite similar. Ideally, remote sensing should provide quick, economic, and accurate data about the surface of the Earth. This requirement is particularly true for instances in which repetitive observations are required or in which traditional ground observations would be costly and impractical.

DEMONSTRATED REMOTE-SENSING OBSERVATIONS COMPARED TO OBJECTIVES

Earth Resources Technology Satellite 1

The major geologic objectives of Earth Resources Technology Satellite (ERTS) investigations are to delineate large structures, recognize new mineral and oil deposits (or at least promising areas for ground exploration), prepare maps of poorly known areas, and monitor geologic hazards. Most published analyses have been done by more-or-less conventional photogeologic interpretation, supplemented by additive color enhancement. Enhancement techniques, such as spectral band ratioing involving digital tape, have been done by only a few specialized facilities. These techniques will undoubtedly become more important in future lithologic identification.

The most important feature seen on the imagery is the linear, or the larger and more complex lineament. Therefore, much interpretation has been concerned with linear analysis. Linears have been found to correlate with known faults and with ground-measured fracture trends. The remaining features are mainly topographic or tonally expressed lithologic contacts or are indeterminate. In northern California, linear systems (patterns) have been recognized and dated relatively on the basis of truncations. Mine-hazard maps based on ERTS linear traces have been made and verified in Indiana.

Many previously mapped high-angle faults have been identified. Several of these faults have been extended beyond known limits and connections have been established between formerly separated faults. A major right-slip fault zone along the California-Nevada State line has been discovered. In Alaska, a comparison of seismicity with linears has shown that some of the linears have not been mapped as faults. On the other hand, in the Southwest United States, faults with evidence of recent movements but not related to present seismicity may be keys for potential seismic hazard. Low-angle faults are difficult or impossible to discern.

Some new folds have been discovered, but other apparent folds on ERTS imagery have been found not to exist when field checked. Several circular features have been noted, not all related to any known geologic feature. Alinements of volcanic or plutonic activity may lie along unmapped fault zones. Some loci of igneous activity may be related to intersections of linears.

Mapping of lithologies has been only partially successful with ERTS data. Distinctive iron formations and some other Precambrian lithologies have been outlined in Wyoming. Remote-sensing units usually do not correspond to stratigraphic units, but nevertheless are helpful in delineating structure in some areas. In many cases, units are mainly separable on physiographic criteria. Correlation of ERTS geomorphological units with geostructural units has been made in Bolivia. In the same area, some success has been achieved in determining regional boundaries and relative ages of volcanics. Volcanic formations (and, similarly, other lithologies) are not always distinguishable unless they exhibit a characteristic morphology.

No direct evidence of ore deposits has been found. Known mineralized areas have been plotted on ERTS images to determine if there are correlations with linears, intersections, color-tonal anomalies, large structural bends, and discontinuities. The ERTS analysis suggests general areas that must be subjected to detailed field and geophysical studies.

The ERTS resolution of spatial detail is poor in areas of flat-lying rocks and low relief. However, some enhancement of topography and linears is observed on winter scenes with low Sun angle and where snow cover is not too deep.

Regular and continuing repetition of coverage is not necessary for geologic problems other than for monitoring volcanic activity and possibly some hazards. However, multiple coverage (winter, later spring, and fall) is desirable because of seasonal changes in vegetation and soil moisture and variations in atmospheric haze and cloud cover.

There is general agreement that the synoptic coverage and the orthophotographic characteristic of the ERTS images are the most valuable features of the system. Synoptic coverage provides a regional view under nearly uniform illumination and thus avoids the need for mosaics made from conventional aerial photographs. Because of the lack of scale distortion, the orthophotographic characteristic allows the image to be directly compared or overlaid with base maps of scales as large as 1:250 000.

High-quality color composites have been the most useful form of data, but all images have their advantages. Multispectral scanner (MSS) band 5 (red) emphasizes vegetational and other tonal contrasts, whereas MSS band 7 (infrared (IR)) emphasizes topography. The southeast look direction has subdued the northwest trends. Stereographic viewing is helpful, but complete coverage will not be available because of orbital design constraints.

Skylab

Few results are available from Skylab at present. Most geological studies are using the S190–A multispectral camera (black and white, color IR, and color) and the S190–B Earth terrain camera (high-resolution black and white, color IR, or color). Objectives of these studies are much the same as those of ERTS–1.

The black-and-white film (red band) and color film from S190–A and S190–B provide excellent detail, considerably better than ERTS. Stereographic coverage along many of the flight lines is complete. Individual frames provide a good regional view, although not of as large an area as ERTS. Skylab does not provide complete coverage of a given project area. The lack of repetitive coverage means that any portion of a project area may have too much cloud cover.

In northern Wyoming, southern Montana, and western South Dakota, Skylab imagery, where cloud free, allows for much more detailed structural and lithologic mapping than ERTS. Many more folds can be recognized and certain linears (faults) can be traced with more confidence. In the Coachella Valley of southern California, major faults can be traced under alluvium because they act as ground-water barriers, which support lines of vegetation at the surface. In Nevada, exposures of limestone were located in areas thought to be covered by volcanics. Therefore, aeromagnetic anomalies in these areas are related to features at depth (plutons which might be sources of metals), not to volcanics.

Apollo Lunar Sounder Experiment

The Apollo lunar sounder experiment (ALSE) flown on the Apollo 17 mission is providing a first good test of advanced orbital planetary radar concepts. It is an active microwave system designed to compromise between sounding and imaging. The ALSE is not optimum for Earth applications; however, it offers the following features, which can be readily incorporated into resources-oriented radar:

1. Multispectral (3 bands at 5.0 to 5.5 MHz, 15 to 16.5 MHz, and 150 to 164 MHz).
2. Coherent synthetic aperture.
3. Large dynamic range.
4. Amplitude calibration.
5. Coherent optical data processing.
6. Image dissection to produce digital data.
7. Digital data processing.
8. Holographic data display.
9. Stereographic data display.

Data products from the ALSE experiment are the surface radar imagery, the surface topographic profile, and the subsurface sounding. The surface radar imagery has several important uses, among which is the study of volcanic and tectonic features of radar backscatter and radar albedo. The data can also be used in conjunction with other lunar data to study various evolutionary processes that have shaped the lunar surface.

The continuous radar profile of the Moon can be used in conjunction with the laser altimeter data and stereophotography to study both the features of the Moon and local and regional lunar topography. For example, local topographic information from the surface profile can be used to study the mare basin structure in relationship to the mascon structure. Some interesting examples of crater rebound phenomena are also apparent in the local topographic profile.

The ALSE subsurface sounding will provide information on the subsurface stratigraphy and hence may be used to study volcanic flows, ejecta blankets, and regolith thickness. Relative changes in the surface profile and subsurface stratigraphy can provide information on the processes of tectonic activity such as intrusion and faulting.

Present Aircraft Systems With Imaging Microwave Systems

Two side-looking radar imaging systems are available for contract survey work at present. The Aerospace Division of Westinghouse was first to offer services using an APQ–97 installed in a DC–6B aircraft with complete onboard processing facilities. This conventional real aperture system has moderate resolution and operates at 0.86 cm (Ka-band). Imagery can be acquired of a swath 20 km wide from either side of the aircraft at a nominal altitude of 6 km. The imagery scale is approximately 1:200 000. Early in 1971, the Goodyear Electronic Mapping System 1000 was installed in a Caravelle jet operated by Aero Service Corp. This radar system, a modification of the APS–102, is an X-band synthetic aperture system. The data film is processed in an optical correlator to produce ground-range imagery of good resolution. Two adjacent swaths are imaged simultaneously in both look directions, totaling 37 km. Missions have been flown with a 26-percent overlap, which provides approximately a 50-percent stereographic coverage. Nominal flight altitude is 12 km. Imagery is produced at a 1:400 000 scale but usually is delivered at a 1:250 000 scale.

Several organizations have side-looking radar systems for research projects related to civil remote-sensing activities; they include the NASA Lyndon B. Johnson Space Center (JSC), the University of Michigan, the U.S. Geological Survey, the U.S. Coast Guard, and the Jet Propulsion Laboratory (JPL).

MAJOR MINERAL RESOURCES AND GEOLOGICAL APPLICATIONS OF ACTIVE MICROWAVE SENSING

This section reviews the following areas in which radar imagery can provide useful information:

1. Mineral exploration.
2. Petroleum exploration.
3. Ground-water exploration.
4. Civil works.
5. Geologic mapping.
6. Landform identification and terrain analysis.

A state-of-the-art summary for each area is given in table 2–I. A concluding subsection briefly outlines the research needs for earthquake mechanisms and crustal motion.

Mineral Exploration

Radar imagery provides a useful information base on which to plan specific ground exploration programs. In the past, apart from problems of access and movement, a major hindrance has been the absence of a regional geologic map to which mineral occurrences could be related with an imaging radar. Areas having indicators of potential mineralization may now be more confidently defined. An example of a radar image is given in figure 2–1.

The common surface indicators signaling mineralization to the radar interpreter include fracture zones, veins, and rock-type association. The sites of igneous plugs, or volcanic centers in general, are highly prospective for metal mineralization (e.g., sulfide veins), especially if they are associated with fractures having obvious tensional orientations. The margins of discrete igneous intrusive bodies such as stocks are similarly prospective, especially where fault swarms, radial faults, or other tensional fractures coincide. A detailed geologic study using radar imagery of eastern Panama has highlighted potential mineralized areas based on most of the previously stated criteria (ref. 2–2). Wing also documented the utility of radar imagery for inferring the location of placer deposits. Based on the work of MacDonald and Waite (ref. 2–3), it seems feasible to identify and map sand and gravel deposits, which are critical to the construction industry.

Several other radar exploration programs concerning minerals have been completed in the tropics. For example, in November 1971, a side-looking airborne radar (SLAR) survey of the entire country of Nicaragua was undertaken for the Nicaraguan Government. The 1:250 000-scale imagery obtained was compiled into a 1:100 000- and 1:500 000-scale mosaic series by a commercial firm. The interpretations were directed at topography, geomorphology, land use, vegetation, and geology overlays for the 1:100 000-scale radar mosaics. It was concluded from this Nicaraguan study that the potential exists

TABLE 2–I.—*State-of-the-Art Summary of*

Discipline	Special functional requirements	Application	Parameters to be measured or identified
Mineral exploration [a]	Steerable antenna; multiple look directions; multiple polarizations; multiple frequencies; measurement of dielectric properties.	Worldwide location of economic mineral deposits (metals, nonmetals, coal, clay, including bentonite, aggregate/sand, and gravel).	Surface texture and roughness; porosity and dielectric properties of rocks; plant types/stress possibly indicating geochemical anomalies; drainage patterns and topography indicating underlying rock type and structural control (possible indicators of mineralization/alteration "halos").
Petroleum exploration [a].	Pointable antenna; multiple look directions; multiple polarizations; multiple frequencies; measurement of dielectric properties.	Petroleum exploration (oil, gas, and surficial petroleum deposits such as tar, asphalt, oil, and shale); delineation of structure, rock type, and surficial material; composition for location of favorable oil and gas structures or surficial petroleum deposits.	Structure and rock type; morphology of the land surface beneath the vegetation canopy; vegetation types and boundaries; texture and composition of surficial materials; soil and moisture linears. (These parameters lead to direct mapping of rock type and structure and permit the location of favorable drill sites.)
Ground-water exploration	Simultaneous short- and long-wavelength data.	Location and determination of ground-water resources.	Same as for mineral exploration; determination of stream drainage parameters and ground-water seepage.
Civil works	Multiple frequencies advantageous for determining terrain texture parameters; requirement for subsurface penetration to determine soil thickness and soil properties.	Selection, evaluation, and monitoring of major construction sites/routes; location of construction materials.	Physical properties of soils (porosity, permeability, grain size, and shear strength); subsurface structure (primarily planes of weakness); rock type.
Geologic mapping [b]	Long wavelength; low depression angle; synoptic	Mapping for minerals, petroleum, and	Surface texture and roughness; dielectric properties

Radar Imagery for Exploration

Information objectives	Feasibility	Research needed
Delineation of surface occurrences of economic materials (direct evidence); distribution and structure of bedrock at surface from which interpretations of structure, rock type, and possible occurrences at depth can be made.	Present active microwave systems give excellent topographic information—for example, an intrusive discovery in Venezuela shows differences exist in laboratory dielectric measurement of rocks and surficial materials.	Penetration of vegetation and soils to yield direct information on bedrock and structure; if feasible, spectral signatures of different rocks and metallic mineral alteration; image enhancement by multifrequency polarization; image ratioing; pattern recognition emphasizing texture; spectral classification; edge enhancement of structures; coordinated aircraft and ground data; coordinated data on temporal aspect of geologic information, especially snow cover and extreme moisture conditions; data on value of long-wavelength active microwave sensors (imager and profiler/sounder) in vegetated area for determining surface morphology.
"Hazy" anomalies, if real; structural traps (fault dome, etc.); stratigraphic (pinch-out and porosity) traps.	Feasibility has been established for petroleum exploration with single-frequency radar imagery—for example, location of drill sites in Colombia using commercial imagery. Offshore oil seep detection with microwave systems is underway.	Same as for mineral exploration.
Mapping aquifer and recharge areas; location of ground-water effluents; position of water table, if feasible; water quality, if feasible; surface seepage and areas of surface water/ground water; sources of ground-water contamination relative to changing land usage.	Inference can be made on most of the parameters except soil moisture detection, ground-water effluents, and water quality.	Same as for minerals and civil work; also soil moisture detection and ground-water effluents and water.
Slope stability; ease of excavation of Earth; bearing capacity; suitability of Earth materials; geologic hazards (subsidence, avalanches, landslides, and active faults); grain size and column depth of sand, gravel, and fill materials.	Feasibility has been established for grain size of soils; faults, joints, and bedding planes; and inferences concerning subsurface structure and rock type.	Low-frequency systems capable of penetrating surface to determine physical properties of Earth materials and saturated/unsaturated condition.
Distribution and structure of rocks at the surface.	Present active microwave systems provide textural and topo-	Delineation of major lithologic boundaries in areas of uniform, heavy

TABLE 2–I.—*State-of-the-Art Summary of*

Discipline	Special functional requirements	Application	Parameters to be measured or identified
	coverage; and subsatellite point profiling.	ground water; civil works; geologic hazards.	of rocks; drainage patterns, topography, and lineaments as an indicator of rock type and structure.
Landform identification and terrain analysis	Addition of a radar interferometer and perhaps a scatterometer for terrain slope data; accurate recording of depression angles across the range and, if required by a specific need, the presentation of such data directly on the image; extension of depression angle in the far range to 5° or less, if feasible; processing techniques to enable the enhancement of subtle tonal changes usually lost in radar signals in both excessively dark or light tones.	Landform identification and terrain analysis for oil and mineral exploration, civil engineering, land use mapping, land capability, soil mapping, flood prediction, and so forth.	Terrain slope; slope length; elevation; relative relief; drainage anomalies; landform distribution; surface configuration; other parameters directly interpretable by standard geophotographic techniques.

[a] Dynatrend (ref. 2–1) estimates that, at 1972 values, U.S. oil companies could save $62.5 million on the cost of reconnaissance surveys. For other minerals, industry might save as much as $12 million.

[b] The Dynatrend survey (ref. 2–1) estimates that the cumulative savings in military geology mapping, topographic mapping, and in U.S. Geological Survey regional and small-scale geologic mapping could approach $1.4 million annually.

for application to forestry, livestock, and general agriculture and that selected areas urgently deserve systematic search for mineralization.

During the fall of 1972, President Rafael Caldera of Venezuela announced a new mineral find "of great importance," including iron and possibly uranium, as a result of radar mapping in south Venezuela. The SLAR used was the Goodyear 102 system, and the imagery was contracted by a company created to promote development of southern Venezuela. Two contractor geologists were credited with the actual discovery. The imagery does not show mineral deposits but indicates to geologists where ground surveys should be made. Caldera said that the find, named "Cerro Impacto," contains a complex combination of minerals of great commercial and strategic value including a high content of iron, manganese, thorium, niobium, and radioactive materials.

Petroleum Exploration

Imaging microwave sensing for oil involves interpretation of surface geology. The interpreter relies strongly on trends that are apparent at the surface and meaningful to the particular investigation. A few of the phenomena noted and placed on the base map are the type, thickness, and attitude of formations and the fault traces and disposition. The interpreter also uses associative clues indicating structure and lithology as well as stream patterns and vegetation. Interpreta-

Radar Imagery for Exploration—Concluded

Information objectives	Feasibility	Research needed
	graphic data from which geologic maps showing rock formations and structure can be prepared.	forest cover; enhanced drainage and topographic detail areas of very low relief and flat-lying nonresistant rocks; detection of growth faults.
Radar shadow (both length and frequency); standard photointerpretation keys such as tone, texture, stereograph, site, and situation.	Research feasibility of collecting valid morphometric data has been established in mountainous terrain; operational feasibility has also been demonstrated under select situations in which standard photographic coverage and field mapping are prohibitive.	The utility of morphometric data from radar imagery in lowland areas cannot be evaluated until radar imaging systems with depression angles less than 5° are developed. Further refinements of slope-measuring techniques are needed. A complete documentation of the importance of radar image interpretation in other environments outside the tropics and the introduction of automatic interpretation are also necessary. Morphometric information from interferometer data should also be investigated (i.e., automatic slope-measurement capability). Automatic data processing techniques must be established.

tion of radar imagery is similar in these respects to that used in photogeology.

Depending on the terrain configuration, radar imagery is often superior to vertical aerial photographs for display and detection of surface features such as faults, fold patterns, and lineaments (refs. 2–4 to 2–6). Although vertical aerial photographs may more clearly reveal the smaller details of structural elements and patterns, radar imagery can often show, as well or better, the true nature and extent of structural patterns. Figure 2–2 is a striking example of the detail available on radar imagery.

Many radar mapping programs have been conducted by petroleum companies; however, because of the proprietary nature of this information, published reports are not available. Areas of extensive recent radar mapping include Brazil, Venezuela, Colombia, Panama, Nicaragua, Indonesia, New Guinea, and Australia. The only published report concerned specifically with radar mapping and petroleum exploration was completed in eastern Panama and northwestern Colombia by Wing and MacDonald (ref. 2–7). These authors concluded that "with the exception of those data provided by field investigation, the geologic information interpretable from the radar imagery of eastern Panama far exceeds those data previously available through conventional airborne reconnaissance methods." Certainly, radar remote sensing offers the only practical technique for reconnaissance mapping in the wet tropics; however, even where conventional

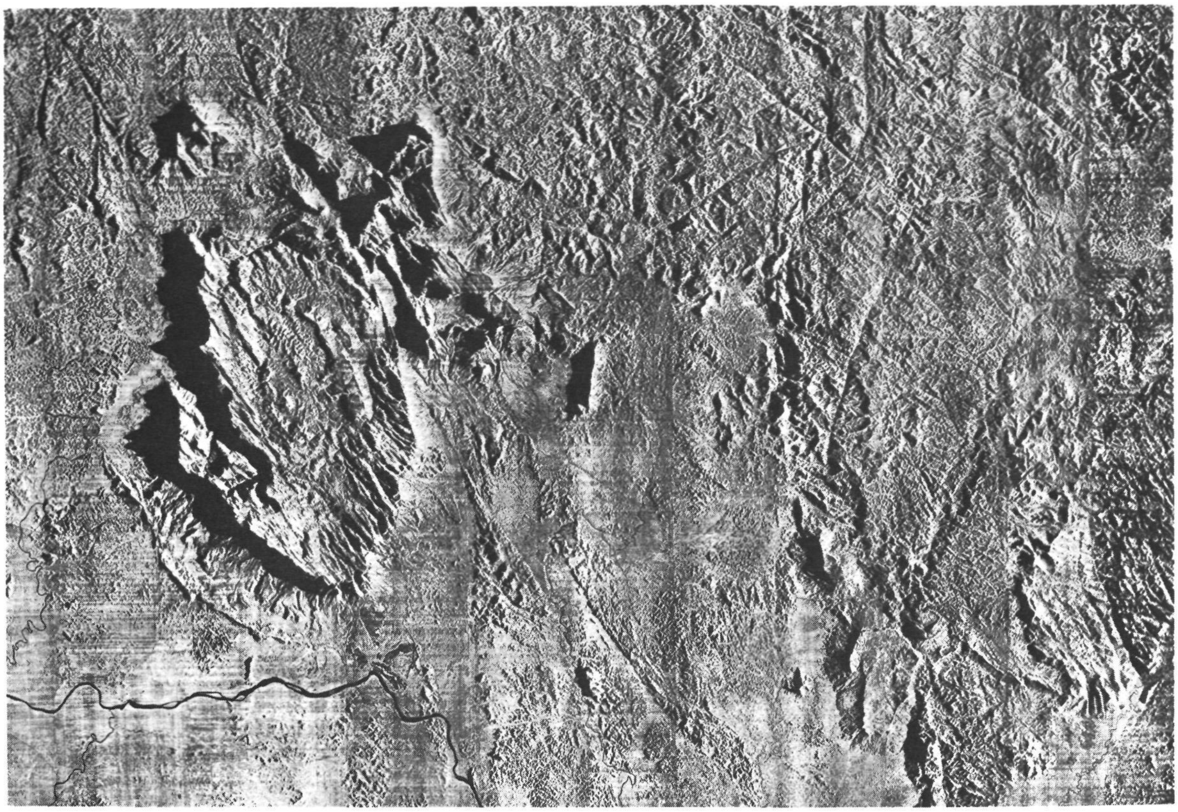

FIGURE 2–1.—Mosaic of an area in Venezuela using a synthetic aperture AN/APQ–102 radar system (31-mm wavelength).

aerial photographic coverage can be obtained, radar imagery can be a valuable supplement because of its unique data content.

Ground-Water Exploration

The overall objective of ground-water exploration is to define the geologic and hydrologic conditions relating to occurrence, quantity, and quality of ground water. The surface phenomena of interest include topography and drainage (structure and lithology), vegetation differences, soil moisture, springs, and possibly permafrost indicators (ref. 2–8). Surface hydrologic features relate mostly to those terrain parameters previously outlined. Soil moisture information would be especially helpful for locating springs or areas of seepage associated with perched water tables or faulted aquifers. Because springs and seepage areas have variations in discharges depending on the time of year, the temporal aspect of microwave coverage must be considered.

Vegetation can sometimes be a good surface indicator of ground water, especially in arid and semiarid regions. Fracture trend analysis has special application to ground-water exploration in certain terrain configurations. In the Apollo 9 photographs, the apparent coincidence of gross linears with areas of known anomalies of stream flow and of large capacity wells and springs, suggests a method for ground-water exploration (ref. 2–9).

In carbonate terrains, techniques of radar mapping in conjunction with techniques of fracture analysis for locating high-yield water wells could be substantially more effective than the usual random approach. In addition to satisfying the requirement for a

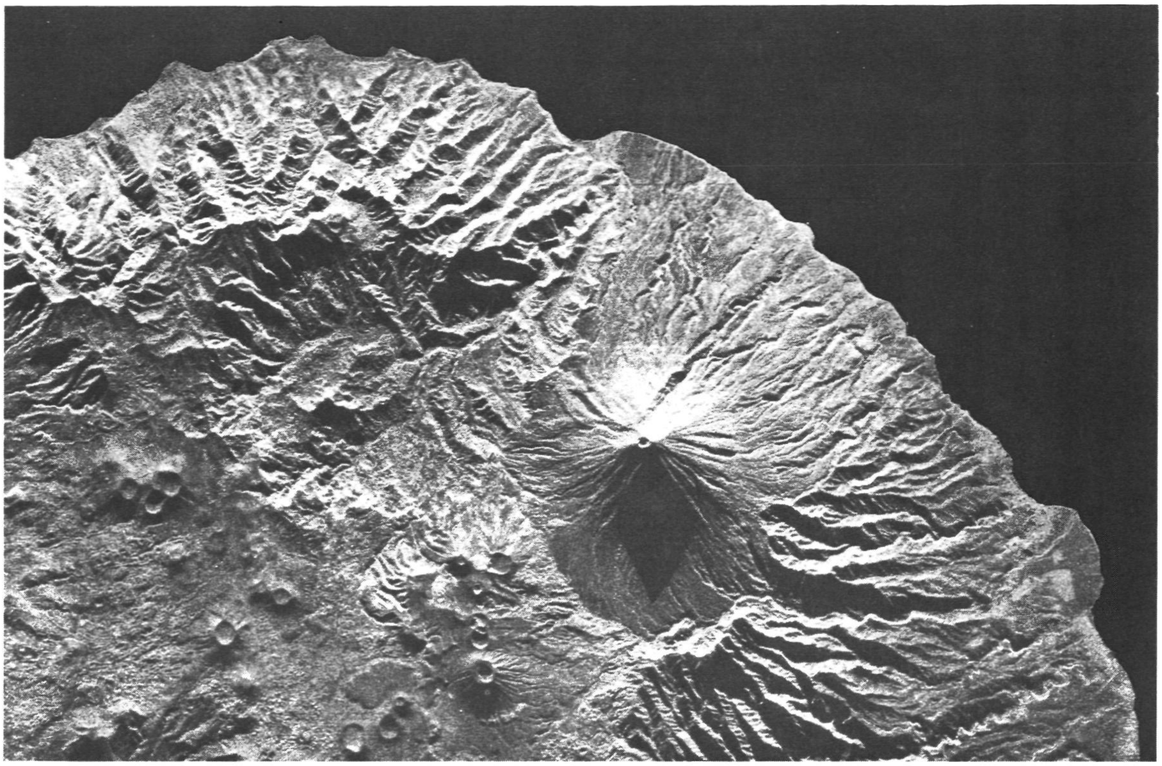

FIGURE 2-2.—Radar image of volcanic terrain on the Island of Bali, Indonesia, using the AN/APQ-102 radar system (31-mm wavelength).

rapid and synoptic terrain data-gathering technique, broad-spectrum microwave measurements of soil reflectivity provide evidence that variations in soil moisture may also be available with imaging radars. Microwave measurements are sensitive to the moisture content of the soil surface, and the potential for aiding in the detection of fracture trends is particularly appealing for ground-water exploration (ref. 2-10).

The regional applicability of using SLAR data for ground-water studies was provided by Feder and Barks (ref. 2-11). Using SLAR imagery, these investigators identified a losing drainage basin in the Missouri Ozarks by examining distinctive tonal and textural contrasts. More recently, a study by MacDonald and Waite (ref. 2-3) has shown that certain hydrologically significant characteristics of desert valleys and playas can be defined using imaging radars. For example, alluvial fans are avenues for the recharge of many valley aquifers, and localities near the toes of fan deposits generally contain important areas of water-well development. Water wells yielding moderate quantities can sometimes be drilled near the fringes of playas where coarser alluvial deposits interfinger with playa sediments. These zones of contrasting surface roughness are easily defined by shorter wavelength imaging systems.

Civil Works

In civil works, the primary goal is to improve the process for selecting and evaluating sites for major engineering projects, such as powerplants, dams, aqueducts, pipelines, and tunnels. Postconstruction monitoring is considered a necessary part of the site evaluation process.

The site selection and evaluation process involves (1) the determination of land capability for the proposed foundations and excavations; (2) the identification and assessment of risk from such geologic hazards as earthquakes, landslides, and subsidence; and (3) the nature and location of natural construction materials.

Regional analysis for site selection is often conducted by using image interpretation to rapidly identify and characterize landforms and materials. Conventional photointerpretation of imagery relies heavily on recognition of drainage patterns and associated landforms. These patterns and landforms indicate active land-forming processes, composition of unconsolidated materials, and bedrock characteristics. This type of analysis uses identification of tonal differences associated with differential Sun illumination reflectance differences of materials.

The radar shadow effect enables the effective determination of drainage patterns (ref. 2–12), which are indicative of the character of Earth materials (including grain size, weathering, and erosion characteristics) and planes of weakness. Long-wavelength active microwave sensors are especially applicable in forested areas where the signal must penetrate cover to detect patterns.

The ability of radar to effectively delineate fractures in Earth materials is well documented (refs. 2–2 and 2–13 to 2–16). In engineering geology, investigations of this capability pertain to earthquake risk assessment (ref. 2–17) and to identification of surface fracturing, which is incipient to subsidence and landsliding. In addition, information on terrain slopes and individual geomorphic features has been demonstrated by Lewis (ref. 2–18). Other possible applications include the use of low-frequency radar to determine the depth to the water table or the overburden depth; however, these applications have not been demonstrated.

Radar reflectance differences permit the identification of surficial Earth materials (refs. 2–3, 2–19, and 2–20). In civil works projects, this property applies to soil mapping, the location of construction materials (sand, gravel, fill), and identification of recently deposited stream alluvium as a means of assessing flood hazards. The usefulness of active microwave sensors for engineering soils interpretation has been summarized by Barr (ref. 2–20).

1. It is possible to interpret regional engineering soil types from SLAR imagery by means of an inference technique based on recognition and evaluation of repetitive characteristic patterns. The SLAR imagery shows pattern elements, average areal tones, and image texture, which, in various combinations, form SLAR image patterns indicative of specific terrain surface conditions.

2. The extent to which inferences can be made concerning local land-surface conditions such as surface roughness or vegetative cover is governed by the dynamic range of tone values expressed on the imagery.

3. The systematic SLAR image interpretation technique provides a logical basis for interpretation of engineering soil types and insures results consistent in derivation. The confidence with which an interpretation can be made is greatly increased if adequate field data are available. The technique attains a maximum usefulness if used to extend knowledge from areas with known conditions.

4. The relatively small scale at which SLAR imagery is obtained and the resolution of typical imagery are considered advantageous for regional engineering soils interpretation. A synoptic view of terrain, unconfused by minor tonal contrasts, is afforded by SLAR imagery.

The use of radar imagery in conjunction with photographic systems for civil works site selection and evaluation is desirable because it can provide more information on materials and landforms than conventional aerial cameras. More information is provided for these reasons:

1. Microwave signals are strongly dependent on composition of the illuminated area, moisture content of materials, and surface roughness of materials.

2. Vegetation associated with materials

can be eliminated or enhanced by selection of appropriate microwave wavelengths.

3. Terrain can be differentially illuminated by side-looking radars, thus enhancing landform and drainage patterns.

4. Active microwave sensing is time and weather independent.

Geologic Mapping

The geologic map is the basic foundation from which interpretations and recommendations can be made that concern the discovery of mineral and oil accumulations, delineation of geologic hazards, planning of civil works, reclamation, and many other applications.

The geologic map is a compilation of rock-type distributions (mostly represented by "formation," the mapping unit of the geologist) and of geologic structure. Rock types are generally separated on the basis of composition (lithologies) and orientation at the surface (many are tabular and it is important to determine their degree of inclination from the horizontal). From this map of the attitudes and distributions of various rock bodies, particularly as they indicate folding and faulting, the geologist makes interpretations of the geology beneath the surface. These interpretations at depth lead to recommendations for drilling and geophysical surveys to gain more detailed subsurface information that can lead to discovery and later exploitation of buried mineral and oil deposits.

Geological maps are compiled from mapping on the ground, from photogeologic analyses of aerial and satellite photography, and from radar imagery. When possible, the geologist uses all these techniques. Though mapping on the ground ultimately provides the greatest amount of detail and is the most accurate, it is also the most time consuming and not the most efficient method for reconnaissance. Satellite imagery has its greatest value at the reconnaissance level.

The ERTS and Skylab results indicate that much of the geologic information obtained is through geomorphic analysis, primarily of topography and drainage patterns. Though this satellite imagery provides an excellent map basis because of lack of distortion, adequate mapping can be restricted because of low resolution, poor weather, single look direction, heavy vegetation, low relief, and so forth. Radar has demonstrated its capability for providing detailed physiographic information that is free of most of these adversities and that has a choice of look direction and angle.

Utilization of satellite altimetry over land regions permits profiling the subsatellite point. This was attempted with the S193 altimeter aboard Skylab. Figure 2–3 shows a pass over the Midwest States. The altimeter profile is compared with topographic maps over the same groundtrack, and the correlation is extremely good.

Future uses of this concept will enable topographic mapping of remote regions. In addition, with accurate tracking of satellites, the topographic features can be positioned with accuracies equal to or better than conventional means.

The task of the interpreter using microwave remote sensing for geological analysis is to identify features (such as faults, folds, and lateral changes in rock units) exhibited or reflected by the Earth surface and faithfully reproduced in the imagery. Like photogeology, microwave terrain data interpretation is an attempt to understand geologic conditions, the existence of which can be inferred from radar image analysis of stream patterns, soil textures and patterns, lineations, shapes of hills and valleys, and the presence or absence of specific vegetation types. Some geologic features are so clearly expressed in their landform configuration that they can be identified directly; the nature of other geologic features can be determined only by ground examination. The extent to which geology can be mapped from microwave remote-sensing terrain data varies considerably, depending on the geologic and geomorphic characteristics of a region, the climate and density of vegetation, and the amount of surficial debris. Regardless of the sensor used, the principal kinds of geo-

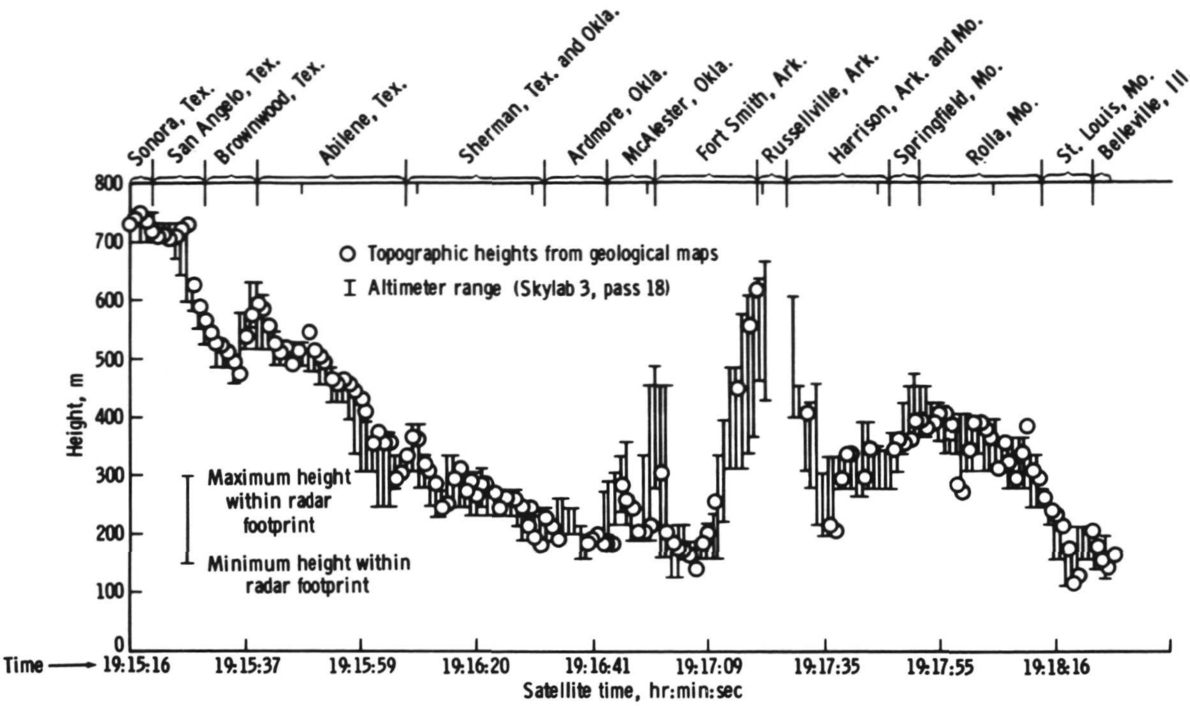

FIGURE 2–3.—Topographic heights from Skylab altimeter (Skylab 3, pass 18) compared with topographic heights from geological maps.

logic mapping information may be broadly grouped into two categories: lithologic and structural.

A few of the more important surface parameters of prime concern for making lithologic inference are—

1. Topography and microrelief.
2. Material type and texture.
3. Vegetation cover, type, and extent.
4. Moisture content, permeability, and porosity.
5. Unit thickness and stratification.

Published regional and localized lithologic studies using imaging radars have been conducted in California (ref. 2–21), Arizona (ref. 2–22), and Panama (refs. 2–3, 2–23, and 2–24). The practicality of using an imaging radar for regional lithologic mapping has also been demonstrated in many unpublished mapping programs in countries such as Nicaragua, Brazil, Colombia, New Guinea, and Venezuela.

Identification of rock types with airborne or spaceborne sensors has long been a goal that consistently remains elusive. The accuracy of a geologic map is generally dependent on selecting rock units that have sufficient areal extent to be significant and that are distinctive enough on the radar format to be easily mapped. In those regions where broad expanses of rock are exposed and/or are closely reflected in the terrain configuration, generalized rock types and regional facies changes in major sedimentary units might be mapped from evidence presented on a radar data format. However, in those areas having the combination of low relief and heavy vegetation or mantle cover, or in areas having poorly exposed rock units, diagnostic or suggestive lithic criteria may be completely absent. Previous lithologic data interpreted from radar imagery have been derived from surrogates rather than through direct identification.

Geologic structures frequently exert a strong influence on surface topography. As with photointerpretation, structural analysis with radar is an attempt (1) to mark attitudes, distribution, continuity, and discontinuity of key horizons, and (2) to deduce the structural relationship from this information. Resistant relief-forming strata usually provide good key beds; however, any horizon that can be traced over a sufficiently large area will generally provide a satisfactory marker bed. Structural discontinuities, such as fractures, joints, and faults, are generally more easily eroded than surrounding rock, which results in linear segments (usually depressions) in the landscape. Consequently, the analyses of drainage, lineament, *soil texture, and vegetation patterns* help corroborate any structural interpretation. Recording of slopes and slope changes on various landforms is important in deducing a coherent structural picture.

Where topographic relief is great, the oblique angle of illumination of an imaging SLAR system can cause extensive shadowing, which may be a detriment to structural interpretation. However, there is no doubt that, in low-relief areas, the highlight and shadow effect tends to enhance subtle terrain features such as fault and joint patterns.

The most significant radar study of structural features was provided by Wing (ref. 2–25). This comprehensive investigation shows the usefulness of SLAR imagery when other terrain data were limited or not available.

An airborne radar image strip may be several hundred kilometers land and tens of kilometers in swath width. This strip gives the interpreter a synoptic view of the terrain and aids him in making regional geologic generalizations, which are a necessary preliminary for selecting areas for more detailed study.

All geologic data, from whatever source, are plotted on planimetrically accurate base maps. When good topographic base maps are available, radar imagery can usually be correlated with the topographic map. Hence, any geologic data and interpretations can be transferred to the base map by inspection. However, in areas in which base maps are poor or nonexistent, a rectified radar image is needed to provide the necessary planimetric base maps. In conducting mineral exploration, for example, it was found that there were no reliable maps of interior New Guinea and that aerial photography could not be obtained because of perpetual cloud cover. The SLAR imagery was obtained, which provided a drainage base map that finally enabled the pursuit of ground reconnaissance.

Three research areas are suggested to aid in the preparation of improved geologic maps using active microwave sensors.

1. The *delineation of major lithologic* boundaries is needed in areas of uniform, heavy forest cover. For example, in the Black Hills region, it is impossible to separate the Precambrian rocks from the Paleozoic rocks with any confidence when using any of the available photographic imagery. Analysis of ERTS imagery has shown that perhaps there are textural differences in the topography on the two major rock types, but the low spatial resolution is a hindrance to a satisfactory study. The higher resolution of Skylab may help, and analysis is currently being conducted. Unfortunately, Skylab coverage of the Black Hills is incomplete. Radar imagery might provide a better textural distinction between the Precambrian crystalline rocks and the younger sedimentary rocks and between the granitic and schist terrains within the Precambrian core. The economically valuable pegmatites, iron formations, and gold deposits are found in the Precambrian rocks. The ability to outline such areas of potentially valuable crystalline rocks in other regions would greatly assist mineral exploration. The ability of radar imagery to provide lithologic information in much greater detail than that obtainable from ERTS imagery has been shown in the heavily forested Amazon region.

2. Enhanced drainage and topographic detail is needed in areas of very low relief and flat-lying nonresistant rocks. Examples are the Powder River Basin and the Big Horn Basin. Satellite imagery is unsatisfactory

for revealing structures buried beneath the Eocene and younger rocks. Attempts have been unsuccessful in locating deeper domes and anticlines by using aerial photography to find drainage anomalies at the surface. Radar imagery using a low look angle and multiple look directions could provide much greater detail. A more important aspect, particularly in the Powder River Basin, is that many of the known buried oil traps are stratigraphic, which, in turn, may be related to major buried faults. These faults are not always expressed at the surface (or at least have not been identified), but their presence may possibly be detected by subtle features at the surface. Economic accumulations of oil are associated on the side of the fault where porosity has developed in dolomitized limestones. Many of these deep faults have been active several times in the geologic past and have affected the thickness and distribution of sedimentary facies, which are factors influencing the occurrence of oil. Therefore, any means of detecting these deep faults at the present surface has great economic value.

3. Detection of growth faults is needed. These faults are well-known features in the Gulf Coast and similar geologic environments, but active ones are not always easily recognizable on the ground or are not readily apparent in photographs. Growth faults are important in the localization of oil traps and have important implications in urban areas where they are breaking through roads, pipelines, and other types of construction. Again, radar imagery might reveal these features better than any other means.

Landform Identification and Terrain Analysis

Landform identification and terrain analysis (geomorphology) is a discipline that has applications in geologic exploration, civil engineering, soil mapping, land-use planning, and water resources management.

Most geomorphologists are interested in describing or identifying landform features or regions and understanding the processes responsible for shaping the landscape. This study can be qualitative or quantitative. Radar imagery is extremely helpful in either approach. Qualitatively, radar imagery can be used for regionalization of landform units as well as for identifying individual landform features. Quantitative landform data, relative relief and slope, can also be determined by using inherent radar distortions, radar foreshortening, shadowing, and, to a lesser degree, layover and parallax.

Regional geomorphology.—The texture, pattern, and shapes of the radar shadows resemble a typical Raisz diagram of the region and allow accurate and easy delineation of discrete landform units. Landform units mapped on radar have been found to agree well with units derived from topographic maps (refs. 2–18 and 2–26). In fact, along a proposed sea-level canal route in Panama, the agreement between map-derived and radar-derived units was remarkable. When only three landform units (plains, hills, and mountains) were compared, more than a 90-percent agreement was found in all cases (fig. 2–4). Exploration geologists have used the same surface expression, so evident on radar imagery, for the location of possible mining sites. Bauxite deposits have been discovered in Brazil by correlating terrace units having known bauxite deposits with previously unmapped terraces delineated on radar images. Other lithologic units have considerable surface expression characteristics and can therefore be mapped as geomorphic units.

Individual features.—Many geomorphic features are detectable on radar imagery. Some features are of interest to exploration geologists; for example, ring dikes, plugs, faults, fractures, calderas, shell bars, estuarine meanders, and drainage patterns. Evidence of glaciation (ref. 2–27), stream piracy (ref. 2–28), coastal erosion and deposition (ref. 2–18), and karst topography (ref. 2–24) have also been reported.

Quantitative geomorphology.—The accurate description of landforms is the first step in any geomorphic study. The three most

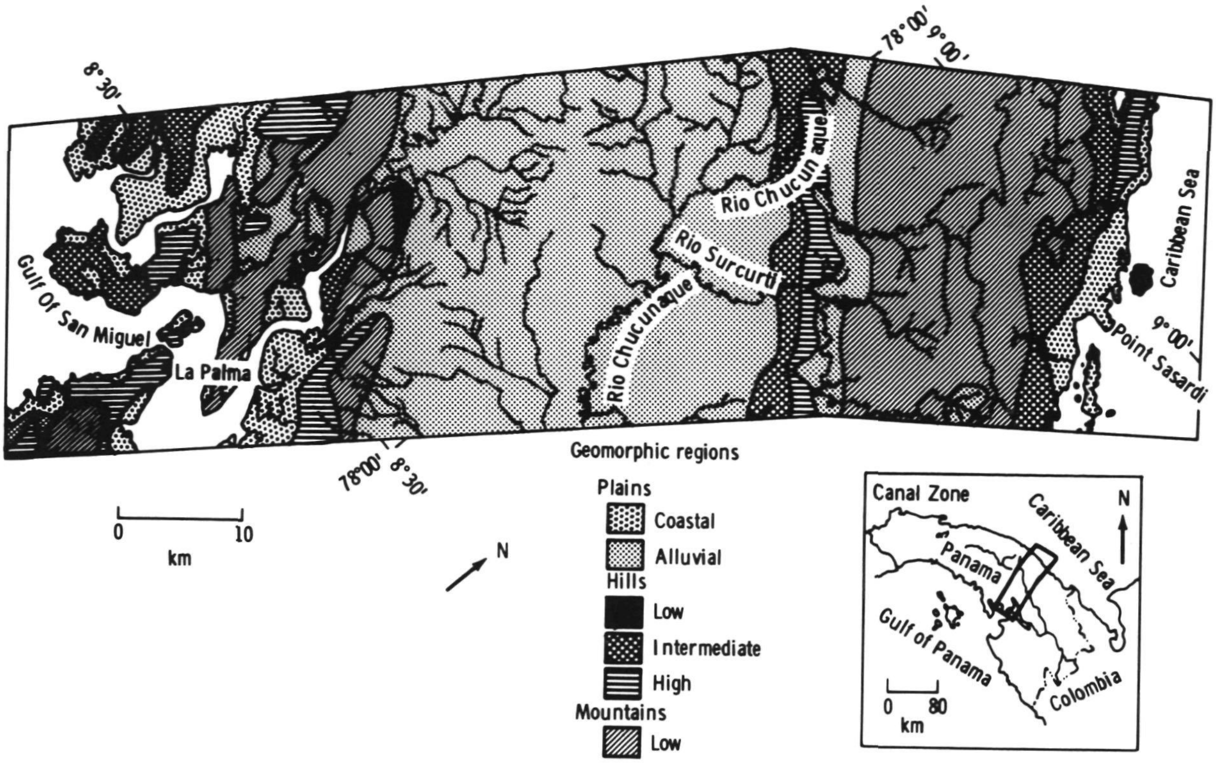

FIGURE 2-4.—Radar-derived geomorphic regions in area of possible route for sea-level canal in Panama.

important vertical dimensions used in landform analysis are elevation, relative relief, and slope. Of the three dimensions, slope is most widely used. By using inherent distortions of radar imagery (such as radar foreshortening, parallax, layover, and radar shadowing), relative relief and slope data can be collected (fig. 2-5).

Although active microwave sensing can, in some cases, be used to determine individual slope values, its real value concerns the determination of slope-angle distribution on a regional scale. Radar foreshortening (ref. 2-29), radar shadows (ref. 2-30), and radar power return (ref. 2-18) have all been evaluated as a source of slope data by comparing the radar-derived data with map-derived data. The studies referenced met with varying success, although radar layover and parallax are, in part, slope dependent and therefore are a potential source of

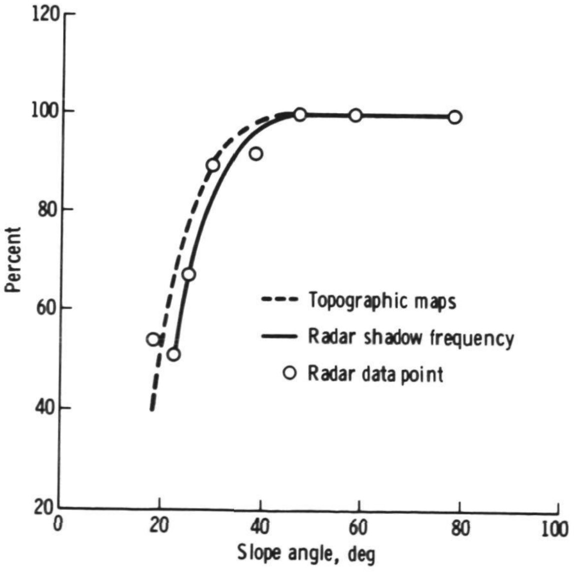

FIGURE 2-5.—Cumulative frequency curves of map-derived and radar-derived terrain slope α data (Annamoriah, West Virginia).

morphometric data. The difficulty of accurately measurable layover and parallax on radar imagery is a severe limitation.

The most practical source of morphometric data is radar shadowing. Although radar-derived slope data can be obtained for all types of terrain, shadowing is prominent. Radar foreshortening is most practical in moderate- and low-slope regions. However, foreshortening is limited by the extremely fine accuracy required by the foreshortening equation (ref. 2–18).

The use of radar power return as measured from radar image tone was tested as a source of slope data and met with little success. Although there is a linear correlation between radar tone and power return (ref. 2–31), the assumption that vegetation remains constant is impractical. However, using radar scatterometry and/or interferometry data would eliminate the problem and presumably make the measuring of terrain slope from interferometry power return a viable application.

The determination of relative relief is a logical extension of any slope-measuring method that requires the slope length as a known parameter; namely, radar foreshortening and radar layover. However, radar shadows can be used to measure relative relief by measuring shadow length instead of frequency. Of all the methods evaluated, shadow length was the most accurate, having a correlation coefficient value of 0.86, when compared with map-derived regional values.

Geomorphic summary.—The qualitative regionalization of landform regions and subsequent measuring of regional and individual morphometric parameters is of special value to the environmental geologist/physical geographer because it provides insight into landscape dissection, terrain surface roughness, and terrain mobility. The exploration geologist should be able to relate landform morphometric data to stratigraphic and lithologic units and to regional anomalies.

Earthquake Mechanisms and Crustal Motion

General objectives.—Measurement of solid Earth strain patterns may lead to a further understanding of earthquake mechanisms. It is of special interest to measure strains on a repetitive basis because the repetitions and accuracies are capable of discerning horizontal and vertical displacements of the surface that precede earthquake activity. Such premonitory strains are well known when on a large enough scale and near a natural or manmade gaging system—for example, the shoreline tilts recorded in Japan. Smaller scale motions (or those motions occurring in areas with no benchmarks for comparison) may occur often but remain undetected.

In particular, the phenomenon called dilatancy, a volumetric dilation of rocks ready to fail and generate an earthquake, has been described from observations in the Kuril Island chain by the U.S.S.R. Such a dilation should be accompanied by a vertical rise of the land surface above the volume affected. The extent of the rise is variously estimated to be between approximately 1 mm and 1 m, and undoubtedly varies from case to case, if, in fact, it occurs in a significant percentage of cases.

Vertical motions over large areas would tend to remain undetected if the strain is distributed broadly and neither local cracking nor tilting is involved. If an inland area were to rise a meter or more and the strain were distributed fairly uniformly over regions with dimensions of approximately 1000 km, the only effects would be similar to Earth tides and would rarely be detected. Although several programs are now in operation or are being planned to monitor horizontal strains, very few projects have been undertaken to monitor tilts or vertical changes, and no projects have been initiated to monitor the vertical positions of dozens of points in an area of earthquake interest. A system that could measure the relative elevations of numerous points on the Earth surface to an accuracy of a few centimeters would complement the existing horizontal ranging systems and could provide data necessary for a test of the hypothesis of dilatancy. One possible system would involve the principle of multilateration to numerous targets from aircraft or perhaps spacecraft.

Users of such data would be consulting engineering geologists and municipal, State, and Federal agencies. The end users are municipal, county, and State planning boards, the engineering and architectural professions, insurance underwriters, disaster-fighting operations, and others.

Functional requirements and discussion.—To secure measurements of dilatant uplift and the effects of strain, a system is required that enables relatively inexpensive portable devices to be moved from benchmark to benchmark over wide expanses of mountain and desert. These devices could facilitate establishing positions with true accuracies of 1 to 4 cm in three-dimensional space. Operators could know immediately when they have obtained useful results, without waiting for elaborate and costly computer reduction.

In analytical efforts to date, various methods of determining relative movement of non-line-of-sight points on the Earth surface were investigated: radar, distance-measuring equipment (DME), multilateration, and interferometry. Tradeoff analyses of each method support a final system choice of a unique multilateration scheme using active two-way microwave distance measurement. The system could use an aircraft platform that collects distance-measurement information of earthbound markers. Radar and electronic hardware either presently existing or currently under commercial development almost certainly will enable a suitable system to be built that is capable of 1- to 4-cm accuracy in three dimensions to relate benchmarks in local networks of precision survey points to a larger scale regional grid in which the grid points are established by another technique, such as satellite tracking. Such a system is described in appendix 2A.

GENERAL FUNCTIONAL REQUIREMENTS

Frequencies

The use of simultaneous multiple wavelengths appears to have great potential in the microwave remote-sensing field; however, examples of terrain applications are few because only a limited amount of multifrequency radar imagery has been available to the geoscientist. The obvious need for information on signal penetration exists where vegetation or a thin soil cover masks shallow outcrop patterns. In semiarid and arid terrain environments, the applicability of longer wavelength radars has been noted. For example, two multifrequency studies were conducted at the Pisgah Crater area in California (refs. 2–32 and 2–33). Both authors have recognized the surficial-cover-penetration potential of relatively long-wavelength imaging systems and note the necessity of obtaining simultaneous multiband coverage.

Many investigators have proposed using multiple frequencies to take advantage of the varying amounts of penetration or the change in roughness relative to wavelength. Most investigators have proposed as broad a coverage as is practical and consistent with orbital operation. On the high-frequency end, 35 GHz seems a reasonable choice in view of the difficulties encountered with atmospheric absorption and scattering at higher frequencies. This choice is consistent with equipment availability because considerable microwave work has been performed at this frequency.

A variety of low frequencies has been proposed ranging from 400 MHz to approximately 2 GHz. In general, proposals have been made to extend to the lowest practical frequency for orbital synthetic aperture operation. Limitations will depend on the phase resolution required and will probably be a tradeoff between the effect of Faraday rotation and the length of the synthetic aperture required for the desired ground resolution. The range of 30 cm is probably a reasonable choice. The utility of low-frequency data cannot be assessed at this time because few data analyses in this frequency range have been performed. Data required by the Environmental Research Institute of Michigan (ERIM) L-band system should, if widely disseminated, remedy this situation. The major reason for requesting low-frequency data has been the desire to increase penetration, particularly through vegetation, and to decrease the effects of roughness.

The upper and lower frequencies are principally chosen from considerations of operational constraints. Virtually every investigator has recommended at least one intermediate frequency, and this choice seems to consistently fall in the X-band region because of a combination of data and equipment availability. This choice is questionable. If use is to be made not only of the differing information at each frequency but also of the variation in scattering due to frequency change, the data must be compared with some type of predictive model. The bulk of the models that may be used for this purpose predict a variation in return at different frequencies proportional to some function of the wavelength ratio. If this criterion is used and limiting frequencies of 1 and 35 GHz are assumed, the choice for a single intermediate frequency would be approximately 6 GHz, which is very dependent on the low-frequency limit. For example, using limits of 0.5 and 35 GHz would give a middle frequency centered on 4 GHz. The literature available in the area of soil moisture prediction with microwaves indicates a need for using the lowest practical frequency. This consensus tends to favor 4 GHz as a more reasonable choice of intermediate frequency.

Even a simplified argument such as that presented here shows the need for additional investigations in the frequency dependence of the scattered return before selection of frequency parameters. If possible, this investigation should be conducted not by funding one or two investigations of frequency dependence, but by making available to a wide variety of investigators imagery taken at frequencies other than the traditional X- and Ka-bands. This procedure would serve to possibly uncover new applications and to insure that the data are evaluated for several different applications in widely different disciplines.

Resolution

Because of the coherent nature of the illumination with active microwave sensors, no determination of resolution can intelligently be made without simultaneously considering scintillation and scale. For example, a 10-m resolution in a radar imaging system is not equivalent to a 10-m resolution in a photographic imaging system. If the radar sensor is assumed to be a fully focused synthetic aperture system, a single 10-m resolution cell from a homogeneous population represents only a single sample from a randomly varying distribution, which, in the case of Rayleigh fading, has a 5- to 95-percent range of approximately 18 dB. Thus, obtaining a reasonable estimate of signal intensity (or gray tone) requires the averaging of numerous independent samples. This averaging, in turn, decreases the effective resolution of the system for the sensing of area-extensive targets. However, for a photographic system with a listed 10-m resolution using panchromatic illumination, the signal intensity of a single cell is the sum of the contributions from many independent samples spaced in frequency. The gray tone of a homogeneous region is thus even, and the effective resolution is essentially the same as the listed system resolution.

The image scale is a consideration because it is the most frequently used means of performing the required averaging for fading in the radar image. In a small-scale format in which the image resolution cell is not resolvable by the eye, the eye will perform the necessary averaging. However, on magnification, the image will start to break up and exhibit graininess as the visual resolution approaches that of the image. Assuming a 10-m, fully focused, synthetic aperture system and taking 16 cells as the necessary number of independent samples, the effective resolution is actually 40 m. Thus, scale may be adjusted only to match this figure with the visual resolution of the interpreter. Any magnification beyond this point is useless in the interpretation of area-extensive targets.

An example of the confusion caused by this effect may be cited from the two major systems currently flying commercial radar imagery. Both have system resolution listed as 10 m; however, one is a synthetic aperture system, and the other a real aperture system. The real aperture operation provides some averaging; thus, the effective resolution is somewhat better. This result may best be seen by magnifying imagery from both systems to larger scales where the breakup occurs at a slightly larger scale, or increased magnification, for the real aperture system.

In summary, the specification of resolution should be in terms of the effective resolution with consideration given to the statistics of the fading return. It would also be helpful to the individual investigator to transform this need into a specification of largest usable scale. The "user" evaluation of variable-resolution radar systems has not received adequate research support.

Dellwig has provided some information by attempting to define the geologic utility of variable-resolution radar (refs. 2–34 and 2–35). The amount of topographic detail recorded on relatively high-resolution radars provides increased detectability of specific terrain features; however, specific geologic utility has not been demonstrated. Certainly an increase in the number of lithic or structural units inferred from a radar format would improve the geologist's interpretation; however, Dellwig and McCauley (ref. 2–35) concluded that, in regional or large-scale studies, coarser resolution appears to be more desirable.

General

Spectral resolution can have two widely different interpretations. First, it can refer to the specification of multiple discrete frequencies to adequately describe the variations over the spectral region of interest. Second, as exemplified in the panchromatic visual imaging system, additional independent samples may be obtained in the frequency domain and averaged before image formation. In this case, the spectral resolution (or system bandwidth) could be significantly greater than that associated with the equivalent pulse length for the 10-m-range resolution.

The first specification is, of course, intimately related to the specification of the operating frequencies. In fact, the specification of three discrete frequencies implies sufficient knowledge of the target spectral response and frequency correlation function to determine that three independent frequency samples are all that are contained in the spectral region of interest. The discussion in the section entitled "Frequencies" should demonstrate that this knowledge is not available and that the selection of the number and value of discrete frequencies is little more than an educated guess.

To intelligently select the number and value of operating frequencies requires definition of the spectral response for the range of targets of interest. This task would best be accomplished by performing continuous frequency measurements over the frequency range of approximately 0.5 to 40 GHz and over all classes of targets. Alternatively, this task requirement could be better defined with wide dissemination to several different disciplines of multiple-frequency imagery acquired over target areas of interest. As noted earlier, the only widely disseminated imagery at this time is at the X- and Ka-bands. Little of this imagery is available over the same areas, and it is not acquired at the same time.

Obviously, the acquisition of calibration curves of continuous spectral response over all possible targets is impossible; however, it appears essential that this type acquisition be performed for at least a limited number of target classifications. These data may then be extrapolated to additional targets when simultaneous multiple-frequency imagery is available to investigators from a variety of disciplines.

Analysis of the ERIM simultaneous X- and L-band data will undoubtedly help clarify this problem. However, care should be taken not to be unduly influenced by a limited analysis of these discrete frequency data for a single restrictive objective such as moisture detection. If the results obtained from this system are to be one of the principal criteria for the determination of operating frequencies, these data should be made available to a much wider community of potential investigators.

Temporal

Seasonal variations provide contrasts in the geological information available on ERTS imagery. In addition, snow-enhanced ERTS imagery has proven to be of value for geologic mapping. Although snow enhancement provides a mechanism to increase the geologic utility of visible- or near-IR imagery acquired by terrestrially oriented satellite systems, this effect may not be true for microwave systems. Waite and MacDonald (ref. 2–36) have noted that subtle landform features may be completely obliterated on radar imagery if specific kinds of snow cover are present. However, seasonal variations do enhance the information in radar images (e.g., the imagery of woodland swamps with defoliated tree cover as compared to trees with full foliage) has been noted (ref. 2–3). In general, the temporal aspect of gathering microwave terrain data has not been well documented.

Dynamic Range

As discussed previously, the tradeoff with resolution involves the variance of the return (or the effective resolution of area-extensive targets). Any tradeoff of spatial resolution to compress the dynamic range of the already-averaged signal intensity would be a serious mistake.

Unquestionably, the dynamic range of the return far exceeds that of the image film; thus, compression of the dynamic range is a necessity in most instances. The dynamic range of the return signal, even without considering fading effects, is from 50 to 60 dB, whereas the image film can accommodate only approximately 20 dB. Obviously, if the full dynamic range of the signal is compressed to that of the film, it will only be at the expense of intensity (amplitude) resolution.

Current imaging systems do not attempt to display the full dynamic range of the signal return; data loss occurs at both the high and low extremes. The center range is controlled by some form of slow-response automatic gain control (AGC), which centers the mean signal intensity of the scene in the center of the film range. In most instances, this technique works acceptably; however, there are important exceptions. The return from old snow (or firn) has been shown to saturate the film of the APQ–97 system in virtually all cases. However, the returns from relatively smooth surfaces, such as playas, sand bars, and so forth, have been shown to be below the film sensitivity threshold. To include these extremes in the image dynamic range would seriously affect the intensity resolution and thus many other applications using midrange variations in intensity. For instance, applications such as soil-moisture detection or crop identification require the distinction of subtle tonal changes caused by signal variations of approximately 1 to 2 dB. Decreasing the intensity resolution of the image would completely obliterate many of the boundary distinctions that can be made with the currently available imagery.

The best solution to this problem appears to be either control of the dynamic range compression or, preferably, control of the portion of the signal dynamic range presented on the image film; that is, in essence, control of the AGC so that midrange signals could be permitted to saturate when it is desirable to view extremely low amplitude variations with good intensity resolution. The same technique in reverse could obviously be used to view high-amplitude variations in the return from firn while permitting the midrange variations to go below the film threshold.

Because orbital active microwave imaging systems will almost certainly use a synthetic aperture, implementation of this type control may be done with multiple processing of the image film. However, this does imply that preprocessing of the received signal will not sacrifice the dynamic range of the signal. Thus, any techniques for onboard preprocessing before downlink transmission to conserve information bandwidth should be weighed against the possible degradation of the inherently large dynamic range present in the Doppler return compared to that used in the formation of a single image.

Polarization

The potential value of simultaneously recorded like- and cross-polarized radar return was demonstrated by Dellwig and Moore (ref. 2–21), who made a preliminary evaluation of anomalously depolarized return signals in the Pisgah Crater area. About the same time, Morain (ref. 2–37) noted that the relatively uniformly textured and even-toned return from the vegetation on the like-polarized return was separable into areas of variable tones on the cross-polarized return. The degree of depolarization was directly related to vegetation type, the area boundaries paralleling those defined by the U.S. Forest Service map.

A better defined capability of dual-polarized radar is in the revelation of a qualitative estimate of soil moisture content by MacDonald and Waite (ref. 2–38). These two authors, utilizing like- and cross-polarized returns, discriminated between wet and dry areas in the near range in portions of the Gulf Coast with sufficient accuracy to warrant further investigation of this capability. Realizing the high degree of correlation between the electrical properties of soil and soil-moisture content, indications are that areas of permafrost in the Arctic regions could be easily delineated in a similar manner. Definition of soil-moisture content having been achieved with Ka-band imagery suggests an even greater potential for determination of soil moisture content for the as-yet-untested long-wavelength microwave systems.

Depression Angle

For geologic practicality, it is assumed that the most significant and immediate contribution of active microwave imaging sensors will be in those geographic regions containing relatively inaccessible, poorly mapped, mountainous terrain where photography cannot be obtained. However, data presented in a recent study by MacDonald and Waite (ref. 2–38) reveal that, for certain terrain configurations, the amount of retrievable geologic information will be of marginal utility unless the geometry of both the imaging system and the terrain is carefully considered.

In low-relief areas, the oblique illumination and resultant shadowing by imaging radar can generally provide enhancement of topographically expressed geological features; however, in mountainous terrain, radar shadowing can deter geologic interpretation. Especially in rugged terrain, two inherent disadvantages of a radar imagery format that can hinder geologic interpretation are extensive shadowing and layover. Radar depression angle and terrain slope define the range over which shadow and layover will occur, but the extent of either parameter is defined by relative relief. From most operational side-looking radar systems, the interpretive data loss increases as terrain slopes exceed 35° and local relief surpasses 1000 m. Tradeoffs between loss of geologic data caused by radar shadow and layover as compared to swath coverage should be evaluated. Similarly, the advantage of slight radar shadowing in low-relief areas should be considered.

The selection of the depression angle ranges in high-relief areas should be biased slightly toward the higher values, which will increase the occurrence of layover but decrease the occurrence of shadowing. The justification for this approach is that in such high-relief areas the near-range slope is severely foreshortened, whereas the far-range slope is presented near its true length. The slight intentional bias toward layover is introduced to sacrifice the least usable portion of the imagery.

The tradeoff decisions for selection of optimum depression angles is considerably easier for the categories with lower slope and relief. The probability of obtaining both layover and shadowing near the same angular range is less, and the decisions involve more the extent of shadowing desirable. In the lowest relief areas, shadowing is deliberately introduced to provide topographic enhancement.

It is apparent from the preceding discussion that an aircraft imaging system designed to maximize geologic data gathering should be capable of high-altitude operation and coverage of a range of depression angles from 10° to 55°, with a minimum elevation beamwidth of 20° to 25°. The adjustment of depression angle may be made by using an antenna with a broad elevation beamwidth that spans the entire range with the area imaged varied by adjustment of time delay and sweep rate. A higher gain antenna with a minimum elevation beamwidth of 20° to 25° could also be used with a mechanical drive system capable of varying the antenna pointing angle by approximately 25°. A spacecraft imaging radar system, although having the advantage of increased coverage for a small range of depression angles, should also be capable of a similar range of adjustments.

Look Direction

Because of the large areal coverage, SLAR imaging systems enable the eye to integrate subtle topographic differences over long distances. This synoptic presentation in conjunction with an oblique angle of incident illumination provides enhancement of topographic features that are not evident on conventional aerial photography, even when viewed stereoscopically. Thus, the geologist is able to see the terrain portrayed in a configuration that is normally not available to him. Many examples have been cited in the literature in which radar has actually defined structural features such as lineaments and faults, which had not been previously detected by using normal geological reconnaissance methods (refs. 2–14, 2–22, 2–34, and 2–39 to 2–42). Multiple-imagery passes were not available for most areas previously studied; therefore, the capability for repeatedly recognizing these anomalous geologic features on multiple-imaging passes and the influence of a preferred look direction (direction orthogonal to the groundtrack of the aircraft) could not be investigated. However, the availability of multiple flight coverage from eastern Panama and northwestern Colombia provided sufficient data for a semiquantitative look-direction analysis in which the detection of certain geologic features under a variety of terrain conditions could be examined.

Depending on the relative topographic relief, effective incident angle, and look direction, geologic features can be advantageously enhanced or can be completely suppressed. Maximum data retrieval from radar geological reconnaissance in poorly mapped areas necessitates imaging the specific region from two orthogonal look directions (ref. 2–43).

The effect of look direction on the detectability of linears in radar image data using a spatial frequency analysis technique, which uses a coherent-optics system, has been presented in a quantitative fashion by Eppes and Rouse (ref. 2–44). The authors concluded that the detectability factor of off-normal features can be improved by spatial filtering in the Fourier plane of a single look-direction image. A much less complicated and certainly more practical technique (image presentation or format still retained) for detecting linears can be achieved by using the widely accepted and inexpensive Ronchi grating (ref. 2–45). The Ronchi grating has been used as an effective method for determining geologic structure from radar imagery in coal-mining areas of Virginia (ref. 2–46). Radar imagery viewed through a Ronchi grating reveals lineaments enhanced by diffraction image overlap only when the grating lines are perpendicular to the lineament direction. The frequency and spacing of linear features determine the degree of enhancement. Because the linear trend is always added to the spurious images produced by objects with no actual alinement, the lineament direction is always more conspicuous. In those terrain environments in which manmade linear features (such as fence lines, field boundaries, etc.) occur with natural linears, the task of the geoscientist becomes complex if the imagery itself is not viewed.

The conclusion that might be apparent to a nongeoscientist from the previous discussion is that spatial filtering might negate the necessity of obtaining multiple-look-direction imagery over the terrain to be examined for geological studies. Unfortunately, geologic interpretation from any remote sensor image entails considerably more than just the mapping of linears or lineaments. For example, dip slopes are an integral component of any structural analysis and were one of the geologic parameters examined in the original look-direction study by MacDonald et al. (ref. 2–43). These authors concluded that the influence of radar foreshortening, as dictated by look direction, is inherently related to the nondetectability of dip slopes. The state-of-the-art data processing (including the two techniques previously described) does not provide detection improvement for dip slopes; however, orthogonal look directions would provide a realistic alternative for optimum data retrieval.

Radar Stereoscopy

Radar relief displacement is an inherent characteristic of SLAR systems. This displacement is toward the nadir if the object is above the datum (topographic high), and it is away from the nadir if the object is below the datum (topographic low). Therefore, the relief displacement is in the opposite direction from the displacement direction in optical systems.

Because the appearance of high-resolution radar imagery is similar to a photograph, a visual stereographic image can be formed with appropriate radar stereographic coverage. However, adverse shadowing conditions are more predominant in radar imagery because of the oblique angle of illumination. In addition, radar foreshortening and layover make radar stereoscopy exceedingly difficult to obtain where terrain relief is relatively great. When one object is imaged twice at two different look directions at the same altitude (i.e., opposite-side configuration) or at two different altitudes (i.e., same-side configuration), then radar stereoscopy can be obtained. Especially in rugged terrain with the opposite-side configuration, shadowing may be sufficient to negate the utility of stereoscopy. However, in those areas where terrain slopes are minimal, radar stereoscopy will aid geologic interpretation.

SUMMARY

Major application areas for active microwave remote sensing include (1) exploration of petroleum, mineral, and ground water resources; (2) mapping surface and structural features; (3) terrain analysis, both morphometric and genetic; (4) application in civil works; and (5) application in the areas of earthquake prediction and crustal movements.

Although the success of radar surveys has not been widely publicized, they have been used as a prime reconnaissance data base for mineral exploration and land-use evaluation in areas where photography cannot be obtained. Radar imagery is providing a "first look" at some 6 million km^2 throughout the world.

Microwave remote sensing, especially from aircraft or satellites, has several important attributes that establish its desirability for mineral resources and geologic applications:

1. Expediency: Conventional field measurement can be time consuming, inconvenient, and costly.

2. Efficiency: Large areas can be covered in a short time.

3. Vantage: Some measurements are practicable only from air.

4. Coverage of areas is possible when not directly accessible because of local conditions.

5. Unique and corroborative data contribution is available only in the microwave portion of the electromagnetic spectrum.

Several unique characteristics of microwave sensors make them valuable for geologically oriented investigations. The proven application of an all-weather day/night sensor is an obvious advantage in many poorly mapped regions (especially tropical) of the world, and the low angles of oblique illumination have been demonstrated to emphasize subtle terrain features, which normally would have been overlooked when using standard photographic techniques. Where vegetation cover masks the ground surface, the radar signal may be influenced by the combination of the vegetation and the terrain surface beneath the vegetation; consequently, the extent to which terrain parameters can be mapped from microwave terrain data varies considerably depending on (1) the geologic and geomorphic characteristics of a region, (2) the climate, (3) the density of vegetation, and (4) the amount of surficial debris. However, the feasibility of using multifrequency microwave data over heavily vegetated areas may increase the accuracy of measuring many terrain parameters. Where vegetation is sparse or absent, an imaging radar becomes extremely sensitive to the actual surface roughness; thus, surface particle size and texture dominate the microwave return signal. The feasibility of obtaining multifrequency-multipolarization terrain data and an insight into dielectric properties will provide terrain information that is not available with existing airborne systems.

A few of the more important terrain parameters of prime concern to the interpreter, which may be inferred with operational microwave systems, include—

1. Geologic structure and lithology, especially faults, folds, fractures, rock stratification, and thickness.

2. Vegetation cover, type, and extent.

3. Surficial materials (nonvegetated) such as texture and microrelief.

4. Landform parameters such as size, shape, slope, relative relief, and elevation.

Systems data generally available to users during the past 10 yr are from high-frequency systems (K- and X-bands), with which no significant penetration should be expected. Limited studies show that with the long-wavelength radars (P- and C-bands), some penetration will be obtained even though the effect is somewhat clouded by the smoothing of surfaces (resulting in low return) that appear rough to short-wavelength radars. However, an important future potential is indicated. Certainly, the aspect of some vegetative penetration might provide insight into the true surface morphology of areas masked by a tree canopy.

At present, resolution is limited in nonclassified systems at approximately 10 m. Whether or not improvement in resolution would be desirable depends on the nature of the survey; for example, a reconnaissance or "first-look" survey (for which radar is best suited) requires no better resolution than that provided by existing commercial systems.

Priority areas of future research include understanding system-terrain interaction. For example, it has been found that the depolarizing of incident energy varies somewhat over the classes of terrains that backscatter microwave energy; thus, if energy of a given polarization is transmitted, the relative amounts of energy returned with like polarization and cross-polarization are different from different terrain classes. There are also differences in the variation of backscattering with wavelength and incident angle. Understanding the many parameters that influence the radar return signal is expected to provide a measure of detailed terrain analysis (ref. 2–47). The potential applications for multipolarization-multifrequency microwave systems, as outlined in

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this section, provide exciting possibilities for retrieving terrain information. For future microwave systems, any terrain parameter that can be measured as additional data or with improved accuracy will probably be valuable. Even if not useful itself, it may provide surrogate data about another vital parameter.

SPECIFIC RESEARCH AREAS

The cover and subsurface penetration in a multifrequency radar system would aid in the following areas:

1. Determining true surface morphology.
2. Determining soil thickness.
3. Determining depth to bedrock.
4. Detecting offshore oil seep.

The following research observations are noteworthy:

1. Contrasts in coastal wetlands vegetation on dual-polarized radar imagery appear to provide an additional data source.
2. Dielectric properties of terrain surficial materials would aid considerably in determining rock or soil composition, the physical properties of Earth materials, and variation due to saturated and unsaturated conditions.
3. Interferometry may provide a means of determining regional or local slope parameters, including the aspect of automatic slope mapping.
4. Quantitative data extraction relative to depression angle dependency for specific slope or terrain configurations has not been thoroughly investigated.
5. The specific needs for calibrated microwave data are not known; however, slope determination from power return seems feasible.
6. Data processing, including spectral ratioing and image enhancements, is needed. Spectral signatures of different rocks, metallic minerals, and alteration zones, together with pattern recognition emphasizing texture and tone are necessary. Need for temporal data has not been fully documented, especially in foliated as compared to nonfoliated terrains. Snow cover is of special concern.

PART B

WATER RESOURCES

This section concerns the various applications and projected applications of active microwave instruments for studying water resources. Most applications involve use of an imaging system operating primarily at wavelengths of less than 30 cm (i.e., K-, X-, and L-bands). Discussion is also included concerning longer wavelength nonimaging systems for use in sounding polar glaciers and icecaps (e.g., Greenland and the Antarctic).

The section is divided into six topics: (1) stream runoff, drainage basin analysis, and floods; (2) lake detection and fluctuating levels; (3) coastal processes and wetlands; (4) seasonally and permanently frozen (permafrost) ground; (5) solid water resources (snow, ice, and glaciers); and (6) water pollution.

SURFACE WATER

Runoff Prediction, Models, and Stream Networks

Runoff potential and modeling.—The general objective is the prediction of runoff potential of ungaged medium-size watersheds that lack prior records. In this context, medium size is defined as a 2- to 500-km^2 drainage area.

Storm runoff is related to the amount of storage available in or on the surface (inter-