water pollution problems; thus, actual demonstration of the utility of radar must yet be produced. The best developed radar application appears to be in detecting, monitoring, and possibly assessing the thickness of oil slicks. However, application of radar for this purpose in the inland freshwaters needs to be demonstrated.

Other aspects of water pollution that result in surface roughness alterations, although theoretically detectable, have not been addressed.

Summary

Two major areas of water pollution are considered: oilspills and plant growth. Oilspills are the strongest area of study and application, not necessarily in terms of present operational status, but because of economic and environmental impact and importance. Present radar systems provide usable data, although more work is necessary for determining the optimum sensors for this work. One of the most important needs is in the area of interpretation and analysis.

PART C

AGRICULTURE, FORESTRY, RANGE, AND SOILS

INTRODUCTION AND GENERAL OBJECTIVES

In remote sensing of vegetation and soils, the important factor is the region of the electromagnetic spectrum to be sensed. Green vegetation absorbs strongly in the blue and red wavelengths primarily because of its chlorophyll content. Figure 2–24 shows a typical spectral reflectance pattern of a closed crop canopy and the corresponding spectral bands of the ERTS–1 MSS. The strong reflectance in the near IR is the result of matrices of cells and intercellular spaces, differing refractive indices, and large critical angles formed by cell walls in plant leaves.

The wavelengths used in microwave sensing are considerably longer than those used by ERTS. Therefore, the microwave return from vegetation is primarily influenced by the roughness (crop morphology) and dielectric properties rather than the cellular and molecular structure of plants. Thus, the determination of crop species, crop cover and/or leaf area, and crop vigor by microwave sensing depends on the effects of those factors on the crop structure and/or dielectric properties.

Crop vigor can be affected by many factors; for example, overgrazing, nutrition, drought, flooding, disease, and insects. One of the primary factors affecting agronomic production is plant-water deficit. Slight changes in plant-water content can cause significant decreases in growth and production. Some plant species change leaf orientation and hence basic geometry during periods of water deficit. Such changes in structure may be more readily detected by microwave than by visible or near-IR sensors. Dielectric properties of crops depend primarily on water content. Therefore, if small changes in dielectric properties of the crop can be detected, microwave sensors may prove valuable in detecting water deficits and the beginning of disease and insect damage. Extreme drought, disease, and insect damage would certainly be detectable because of leaf loss and consequent large changes in both crop morphology and dielectric properties.

The most important advantage of microwave sensing in agriculture is the all-weather capability. Timeliness in gathering data at specific growth stages in the ontogeny of the plants cannot be overstated.

Several promising applications for sensing of soil properties are made possible by some of the unique penetration capabilities of mi-

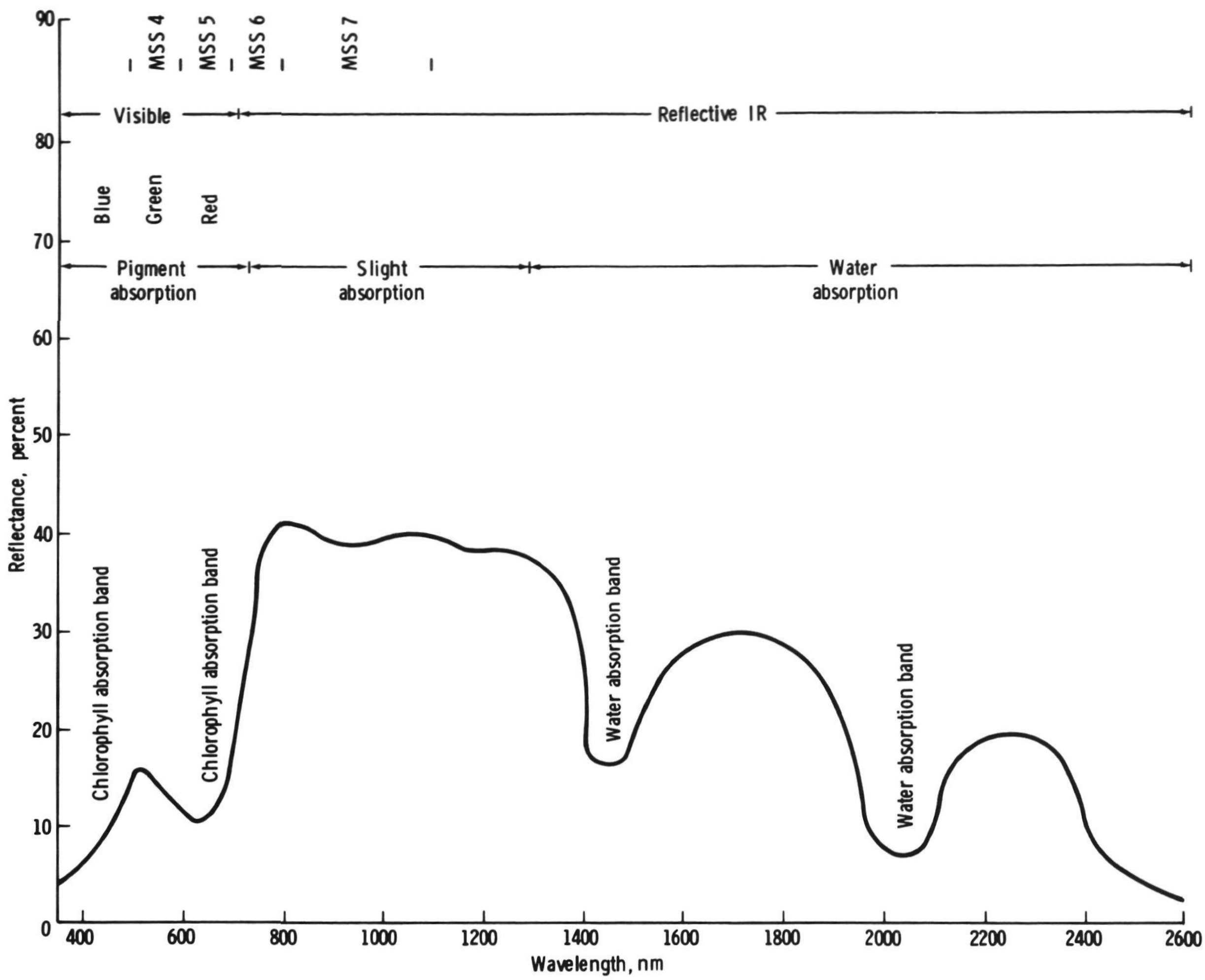


FIGURE 2–24.—Spectral hemispherical reflectance of a typical green crop canopy. The spectral response of ERTS–1 MSS bands and the primary absorption bands of chlorophyll and water are shown.

crowave systems. Measurement of soil water content would allow the development of a soil-moisture index that, in turn, could be used as input to prediction models for watershed runoff, crop yield, and soil strength or trafficability. Microwave measurements also offer possible new techniques in soil-type mapping for agricultural and military use. Other applications of regional value appear to be possible because of the ability of microwave sensors to readily distinguish differences in state (i.e., ice and water).

The primary need for measurement of soil moisture over large areas comes from the desire to develop more precise mathematical models for water-resources and crop-yield predictions. The spatial distribution of soil moisture indicates that such a measurement is feasible with active microwave systems.

Complex continuous watershed models have been developed in the past decade to mathematically represent the movement of water in the Earth-surface portion of the hydrologic cycle. These models are presently the only means of calculating "low flow" or continuous streamflows. Low-flow values for streams and the temporal distribution of flow volumes are extremely important for the study of water supplies and the environmental input of changes in a watershed drainage area. Presently, soil moisture input to the models cannot be measured and is generated by submodels based on parameters developed by fitting the overall model to existing watershed data. The use of complex models is thereby restricted to use on watersheds with existing historical records.

Development of a soil-moisture index for use as input to crop-yield models is also very important. Crop-yield models are vital to improving timely estimates of world food production. However, no adequate system for measurement of moisture available to the plant root zone has been developed. Laboratory experiments on penetration and soil-moisture measurement with microwave systems indicate that reasonable estimates of moisture availability for plant growth are feasible.

Other applications in the areas of soil and soil moisture will require more refined spatial measurement; however, with improved technology in the following decade, most of the applications should become useful.

The general objectives of agricultural remote sensing are—

1. To provide information that is not readily available for decisionmaking in the agricultural extension, marketing, and processing industries.
2. To provide a better method for obtaining data for the Statistical Reporting Service, Agricultural Stabilization and Conservation Service, SCS, and Economic Research Service.
3. To monitor changes in agricultural land use for general research and development.

The specific objectives of microwave remote sensing are—

1. To identify major crops as one of a family of sensors to insure a timely and continuous remote-sensing capability.
2. To perform inventories of major crops, particularly those that either develop during the cloudy season (e.g., tropical rice) or may be identifiable on the basis of internal spatial structures rather than by visible/near-IR response (e.g., rubber).
3. To determine crop condition, disease severity, insect damage, leaf area index, and ontogeny to the extent that these factors affect either the plant-water status, gross crop morphology, or yield.
4. To determine the extent and timing of certain crop management practices such as irrigation, fertilization, and rotation.

CROPS, FOREST, AND RANGE

Demonstrated Remote-Sensing Observations for Crop, Forest, and Range Resources

The ERTS–1 observations.—The feasibility of crop identification from ERTS–1 has been demonstrated for selected crops and test areas: corn, alfalfa, and soybeans in South Dakota; wheat in Kansas; and various field and vegetable crops in California (ref. 2–97). An accuracy of 90 percent can be accomplished for field sizes larger than 10 hm^2. Usually, correct identification can be accomplished by knowing each crop calendar in each crop region.

Identification and mapping of major large-field crops (a prerequisite to yield and production estimates by remote sensing) is considered feasible. Once the crop has been identified, field mensuration is feasible with an accuracy of 70 to 90 percent using ERTS data. Timely and accurate estimates of winter wheat acreage, yield, and production in southwest Kansas were shown to be possible by Morain and Williams (ref. 2–98).

Feasibility for determining water deficit and disease severity from the ERTS data has not yet been determined. One of the primary difficulties has been the collection of data on a timely basis. Diseases spread rapidly, and the possibility that clouds might obscure the ground on a given ERTS pass can completely preclude their timely detection (ref. 2–99). The MSS has been used for determining leaf area and percent cover. The ratio of MSS band 4 to 5 has been found to relate to the amount of leaf area for wheat in Kansas, whereas the ratio of MSS band 5 to 7 is best for estimating the leaf area for cotton and sorghum in Texas. This difference in ratioing techniques is apparently due to the low leaf area of wheat compared to the higher leaf areas of cotton and sorghum.

Forest discrimination into coniferous and deciduous types has been developed to a 90- to 95-percent accuracy level. Using multistage sampling techniques, the timber volume of a national forest district has been estimated to a confidence level and standard deviation acceptable to the U.S. Forest Service at a very favorable cost/benefit time/benefit ratio (ref. 2–100).

Range species/plant community vegetation mapping has been accomplished at various levels of success (70- to 90-percent accuracy). Several investigators have obtained encouraging initial results in range biomass estimation and range readiness predictions. If results continue to indicate good agreement between biomass and ratioed radiance levels, such data can be used not only as planning information for regional purposes but also as range-carrying-capacity decisionmaking information for the area manager at the field level on a near-real-time basis. A principal problem area in implementing this application is the requirement for data turnaround no more than 10 days after satellite acquisition.

A serious limitation documented by the NASA review of the ERTS–1 investigations is the frequent occurrence of cloud cover at critical periods in the growing cycle of crops (ref. 2–101). Persistent cloud cover is especially troublesome over Europe and tropical forest areas.

Active microwave observations.—Several published examples illustrate the capability of radar to differentiate both cultural and natural vegetation classes (refs. 2–102 to 2–104). Annotated examples of the imagery used in these studies are shown in figures 2–25 to 2–27. For agriculture, specifically, the feasibility for identifying crops has been shown for a combination of Ka-, Ku-, and X-band imagery. The values in table 2–V summarize the current capability as derived from film density data extracted from images.

The percent crop segregation in table 2–V was calculated as a percent of all fields comprising the fractional codes, not as a fraction of all fields of a given crop type. For example, grain sorghum on commercial imagery for September 1965 comprised 69 percent of all crops contained in the data space bounded by an upper and lower hyperplane, but approximately 95 percent of all grain sorghum fields plotted on the scattergram occurred within that data space. In other words, although most of the sorghum fields occur

TABLE 2–V.—*Percent Crop Segregation on Scattergrams as a Function of Radar Frequency and Date in the Growing Season*

Crop	Radar, band, and date			
	Westinghouse AN/APQ–97, Ka-band, July 1966	NASA DPD–2, Ku-band, Sept. 4, 1969	Westinghouse AN/APQ–97, Ka-band, Sept. 15, 1965	Michigan, X-band, Oct. 1969
Wheat	Not present	—	—	—
Grain sorghum	—	—	69	77
Corn	82 (cropped)	28	92	—
Alfalfa	—	50	—	—
Sugarbeets	92	—	97	64
Bare ground	91 [a]	90	83	91

[a] Including wheat stubble.

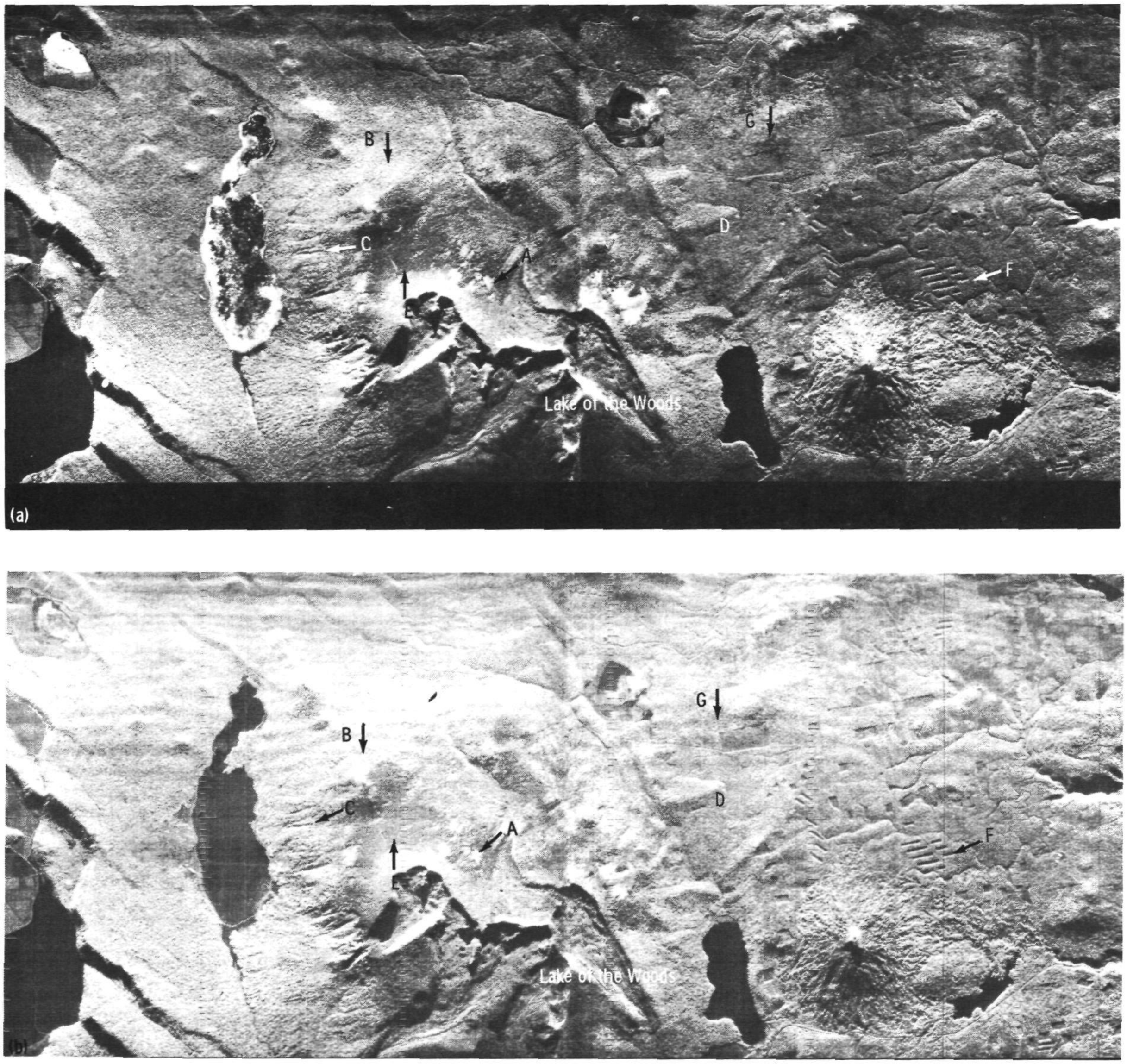
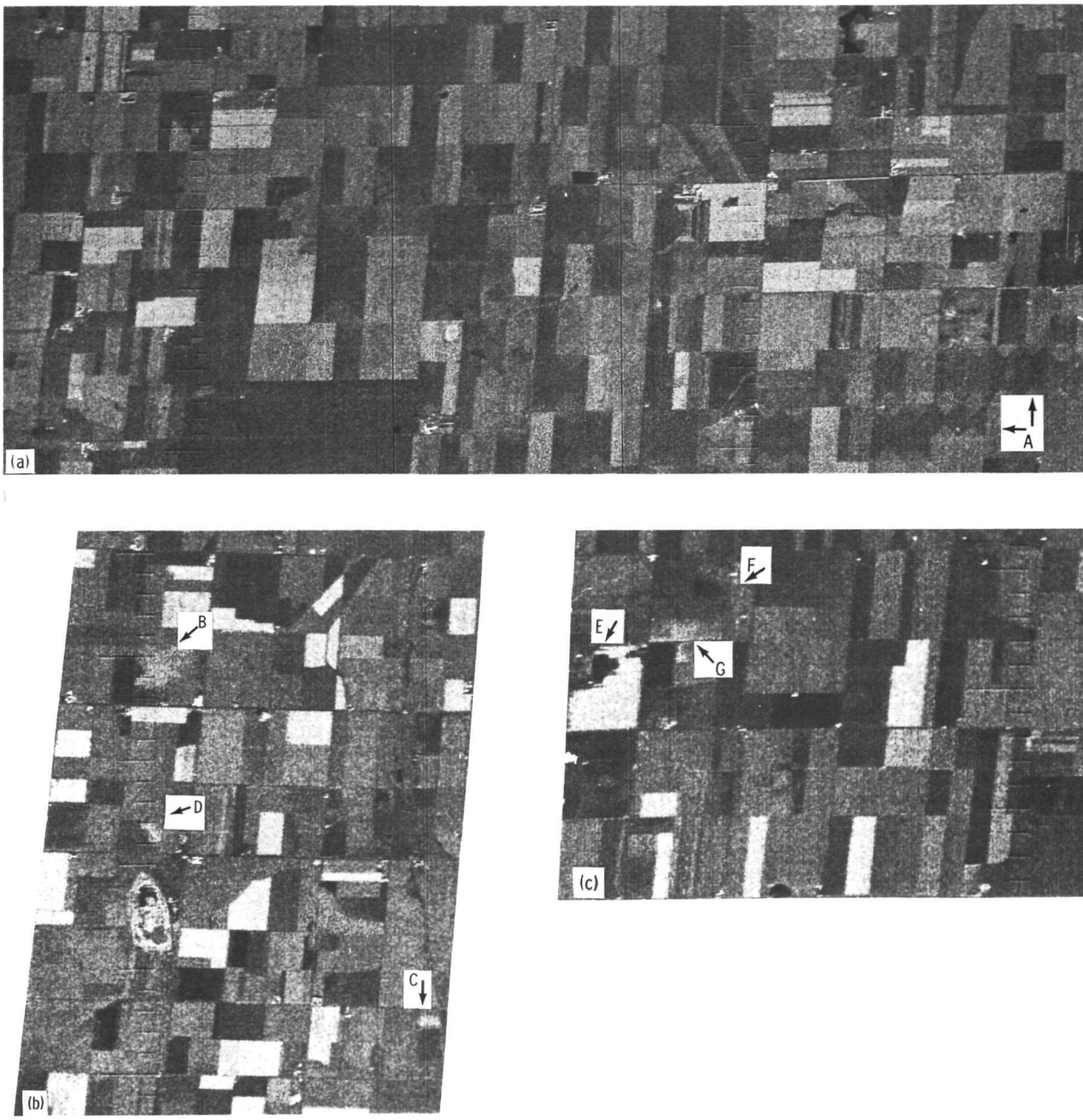


FIGURE 2–25.—Dual-polarization Ka-band images of a forested area east of Klamath Falls in southern Oregon. Forest tones and textures on different polarizations are findings of dominant species. Irregular breaks in the forest canopy are burn scars that can be categorized by age according to successional stages (compare the clarity of boundaries at *A*, *B*, and *C*). Most of the area is dominated by ponderosa pine (*D*) with sizable areas of white fir (*E*). Clear-cut logging operations are evident (*F*), which can be categorized by age according to regrowth. Both the logged-over and burned areas are dominated in early successional stages by chaparral, a favored habitat for deer; later stages are characterized by the encroachment of trees and, at this time, begin to acquire a textured appearance on radar (*G*). For further examples see reference 2–104. (*a*) An HH polarization. (*b*) An HV polarization.


(a)
A
B
D
C
(b)
F
E
G
(c)

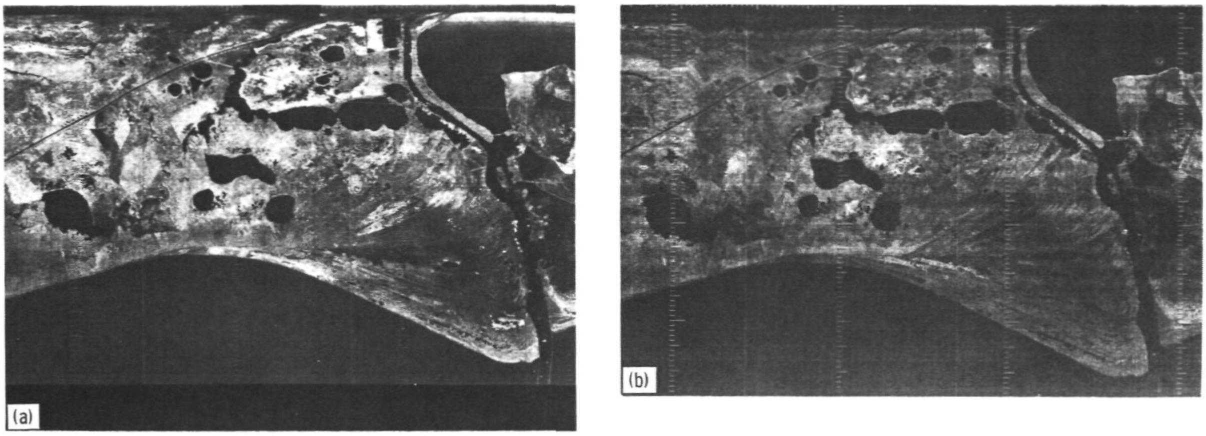


FIGURE 2–27.—Dual-polarization imagery of a grassland and marshland area along the gulf coast of Texas. Of striking interest is the difference in the pattern of bright areas on the two views. On the HH image, the brightness caused by moisture is added to the brightness contributed by surface scattering. The HV imagery is less sensitive to moisture and surface scattering but more sensitive to volume scattering; the area of high signal return is therefore much reduced on the HV imagery. Because of evidence such as this, it is believed that radar may have a unique role in grassland (rangeland) moisture monitoring, rice surveys, aquatic-plant density surveys in recreational areas, and plant phenological studies. For more information on the role of radar in phenology see reference 2–105. (*a*) An HH polarization. (*b*) An HV polarization.

within a fairly well defined data space, they cannot be unambiguously discriminated from many other crops.

From these efforts has come the basic justification for current ground-based microwave research in agriculture experiments by DeLoor and Jurrieens (ref. 2–106), Ulaby (ref. 2–107), and others. These experiments are extending the knowledge of signal interactions with crops and soils under differing cover, moisture, and plant morphology conditions. Generally, increase in plant cover is associated with increasing scene moisture; hence, the microwave response also increases. As crops decline in leaf area, dry out, or are harvested, signal strength drops. These cy-

FIGURE 2–26.—Examples of Ka-band HH images of agricultural patterns near Garden City, Kansas. (*a*) A general scene showing field pattern and ability to discriminate crop types. In this September scene, the lighter gray fields are corn, the medium gray fields are dominantly mature corn and sorghum with some newly planted (sparse cover) wheat. The darkest fields are bare or newly planted wheat. The fact that plow patterns are detectable (*A*) suggests that look direction and soil roughness are important considerations in SLAR interpretation. Crop moisture throughout the scene is generally low because the crops are maturing and drying out. New wheat has higher moisture but covers little of the ground. Therefore, the overall appearance of the image shows reduced gray scale contrast. (*b*) An area showing increased gray scale contrast resulting from higher moisture differential between crop types. The brightest fields are sugar beets with large turgid leaves. Moisture patterns within fields can be observed as irregularly shaped areas (*B*, *C*, and *D*), which suggest that information about crop condition may be obtained from radar. (*c*) An image similar to that in figure 2–26(*b*) but indicating an additional potential for radar to distinguish areas of flooding and faulty irrigation practices (*E*). Gradual tone transitions at points *F* and *G* also relate to crop or field condition.

clical trends can be useful for crop identification; also, when viewed under anomalous circumstances, they might aid as stress indicators.

However, to monitor and interpret seasonal trends, it is abundantly clear that sequential data must be obtained at several frequencies, polarizations, and viewing angles. Among the most fundamental issues to be resolved are tradeoffs in signal response from initially bare soils to partly covered fields to fully covered fields and their continuously varying moisture regions. Related tradeoffs, also to be quantified, include depth of signal penetration under variable moisture conditions.

For a large-area inventory of a single crop for which identification can be achieved on the basis of its unique phenology (e.g., winter wheat) or environmental conditions (e.g., flooded rice), active microwave sensing may not require the level of research effort alluded to previously. For example, a survey of winter wheat acreage was performed for Finney County, Kans., using Ku-band imagery. The results (table 2–VI) indicate the feasibility of accurately tabulating acreage for this particular crop. Once the acreage is determined, the application of an appropriate yield model enables the calculation of total production for a given area.

TABLE 2–VI.—*Quadruplicated Automatic Data Processing Acreage Estimate for Wheat in Finney County* [a]

[Ku-band NASA imagery for June 1971]

Trial number	Estimated acreage	Comparison to SRS,[b] percent difference
1	181 081	5.7 low
2	177 559	8 low
3	171 776	11 low
4	204 687	6 high

[a] Unpublished research conducted at Kansas University Center for Research.

[b] The acreage reported by the Statistical Reporting Service (SRS) was 192 000 acres.

In conducting an inventory of natural vegetation, Morain and Simonett (ref. 2–108) investigated methods for the interpretation of vegetation from radar imagery by using an image discrimination, enhancement, combination, and sampling system developed at the University of Kansas. The study concerned various color combinations possible with HH- and HV-polarization K-band imagery on which various forms of level slicing and data-space sampling were performed. In this study, probability density functions confirmed that data-space sampling on a single image, or in two-space on two images, together with color combinations, is a valid discriminatory tool in studying natural plant communities.

Viksne, Liston, and Sapp (ref. 2–109) reported on the use of SLAR for forestry purposes in tropical zones. A great advantage of radar was that operations could be started and finished on schedule regardless of the weather. The authors briefly described the mapping of vegetation over an area of 17 000 km^2 in Panama. Coverage with overlap was obtained in approximately 4 hr with a YEA–3A aircraft having a groundspeed of 180 m/sec. The APQ–97 SLAR, which operates at K-band, was chosen for this area because near-perennial cloud cover limits the application of aerial photography. Because K-band signals do not penetrate vegetative cover at low depression angles, the technique enabled the evaluation of various vegetation types based on their radar return characteristics. Only very broad regions can be delineated in Colombia from radar imagery (scale approximately 1:220 000) of the area between Tumaco, Barbacoas, and Guapi. These regions are based on physiographic differences obtained from the interpretation of the radar imagery bands:

1. Region 1: Coastal zone influenced by the sea.
2. Region 2: Alluvial plains and low terraces subject to inundation.
3. Region 3: Terraces intersected by low hills.
4. Region 4: High hills and high plains.

Only subsequent interpretation of small-scale aerial photographs (in Colombia approximately 1:40 000), visual aerial reconnaissance, and knowledge of the vegetation enabled further subdivision of these regions into two to five vegetation types on smaller areas.

Nicaragua information on 1:250 000-scale radar imagery flown in 1971 by Hunting is given by Francis.[1] A commercial radar, operating in the Ka-band, reveals similar units to those previously described but also shows *Pinus caribeae* stands to be darker than the other units. It was possible to distinguish three density classes in the pine stands. For areas larger than 15 000 km^2, radar was cheaper than black-and-white photography. A disadvantage is that a relatively large aircraft is required.

Perhaps the most ambitious use of radar in tropical forest land inventory has been in Brazil. Project Radar of the Amazon has acquired radar imagery of more than 5 million km^2 of the Amazon Basin. Radar mosaics at a scale of 1:200 000 are being produced from commercial synthetic aperture SLAR images. Brazilian scientists interpret the imagery and conduct ground-truth operations to produce maps of the geology, geomorphology, hydrology, vegetation cover, soil types, and land-use potential of this vast area. These maps will be used to select priority areas for more detailed remote sensing and ground survey.

An additional paper of interest, which emphasizes the potential aspects of radar for vegetation studies, is by Daus and Lauer (ref. 2–110). The principal conclusions of Daus and Lauer are summarized as follows:

1. Two primary characteristics of the SLAR imagery were found useful in analyzing wild-land vegetation resources: image tone and texture.
2. In this wild-land area, vegetation was the major factor affecting the texture, whereas slope and aspect were the main factors affecting tone.
3. A skilled interpreter can delineate differences in major vegetation cover types, especially in areas of nearly flat terrain.
4. In areas that were nearly flat and level, timber stands were consistently distinguished from everything else because of their relatively coarse texture.
5. Slight differences in topographic relief or change in slant range often caused two nearly identical timber stands to appear quite different on the SLAR imagery.

[1] Personal communication, 1972.

Functional Requirement for Active Microwave Sensing in Agricultural, Forestry, and Range Applications

With the possible exception of crop inventory and identification, fundamental ground and aircraft research must still be performed to determine the microwave response of important crops at various stages of growth and moisture status. Only then can these crop parameters be incorporated into useful models for predicting yield, biomass, and erodibility or incorporated as input into many managerial decisions. Research for all agricultural applications requires repetitive and/or multifrequency data collection over a range of viewing angles.

In general, the functional requirement for an operational active microwave program in agriculture depends on timely and repetitive coverage. It is impossible to be more specific concerning the number of required "looks" because this number varies as a function of crop species and geographic location. Inventories require relatively few looks (perhaps six per growing season) with a tolerable envelope of as much as 2 weeks. However, crop cover and vigor measurement leading to yield predictions or managerial decisions require near-real-time data with a tolerable envelope of not more than 3 days.

Available evidence shows the need for either a sweep frequency or multifrequency system operating in the 1- to 12-cm-wavelength region (and perhaps longer) over a variety of viewing angles from 30° to 70° off vertical. A spatial resolution of 15 m is desirable (particularly for small-field agricultural systems), but 30 m would suffice for many useful applications. Gray scale resolution will need to be from 1 to 2 dB. Polarization and swath width are less easily predicted on the basis of current evidence. Probably, HH and cross-polarizations would be most generally useful, and swath width could vary without serious effect as a function of other design parameters.

Anticipated Microwave Results

It is anticipated that crop identification (and subsequent use in crop inventory) using a microwave system will be as accurate as those reported using the ERTS MSS (i.e., 90 to 95 percent for large fields of wheat, sorghum, corn, soybean, and alfalfa). There are many geographical locations where cloud cover has precluded any attempts to use MSS data. This would not be the case if a microwave system were the primary sensor.

Predictions of crop production rely heavily on soil-moisture conditions and crop vigor (e.g., disease and insect damage). Therefore, there is potential for a major contribution in this area for microwave sensors. Another area in which microwave sensing can make a unique contribution is in the assessment of areas of potential erosion in which crop cover and surface moisture are important parameters. Other areas of potential contribution are rangeland surveys and crop water deficits.

It has been postulated that long-wavelength microwave sensors capable of penetrating the vegetative cover of forests will provide returns from tree trunks and stems, thus allowing accurate estimates to be made of their volume. This theory must be tested; however, classification of major vegetation types in areas of moderate relief will be possible, perhaps for the first time in areas with persistent inclement weather.

Anticipated users.—Crop identification represents the first step in agricultural remote sensing. Thus, success in this task is potentially useful to the entire agricultural community. Government agencies such as the Statistical Reporting Service, Foreign Agricultural Service, and Economic Research Service are perhaps the primary users together with particular commodity groups such as the National Association of Wheat Growers. State and local tax-assessing boards have a vested interest in accurate crop identification for tax purposes. Other groups are interested in projecting water use and allocation.

Assessment of crop condition is immediately useful at local levels of agriculture and all the supporting agricultural businesses (fig. 2–28); consequently, farm and farm-support communities probably comprise most of the users. When crop condition impinges on yield and productivity, the users previously cited should also be included. For crop cover assessment, the Wind Erosion Laboratory of the U.S. Department of Agriculture Agricultural Research Service, the Soil Conservation Service, and similar organizations might be included.

Use and management of national rangeland by the individual owners and operators involve management decisions on a day-to-day basis. These decisions involve determination of optimum grazing density, regional animal movement, grain-feed demand, spraying to prevent encroachment, and decisions resulting from the effects of regional drought. Estimates of quality and quantity of rangeland on a regional basis affect decisions involving relocation of animals, natural grazing as compared to feedlot operations, and marketing practices. In the six Great Plains States extending from Texas to North Dakota, there are approximately 400 000 independent ranchers and farmers concerned with rangeland conditions. These six States produce 40 percent of the Nation's beef. The beef industry in this region exceeds $10 billion annually, but it is inadequately provided with regional rangeland condition information. The *Weekly Weather and Crop Bulletin* provides a gross rangeland condition map derived from county agents; however, these data are inadequate to support effective management practices on a regional basis.

The current lack of synoptic, regional

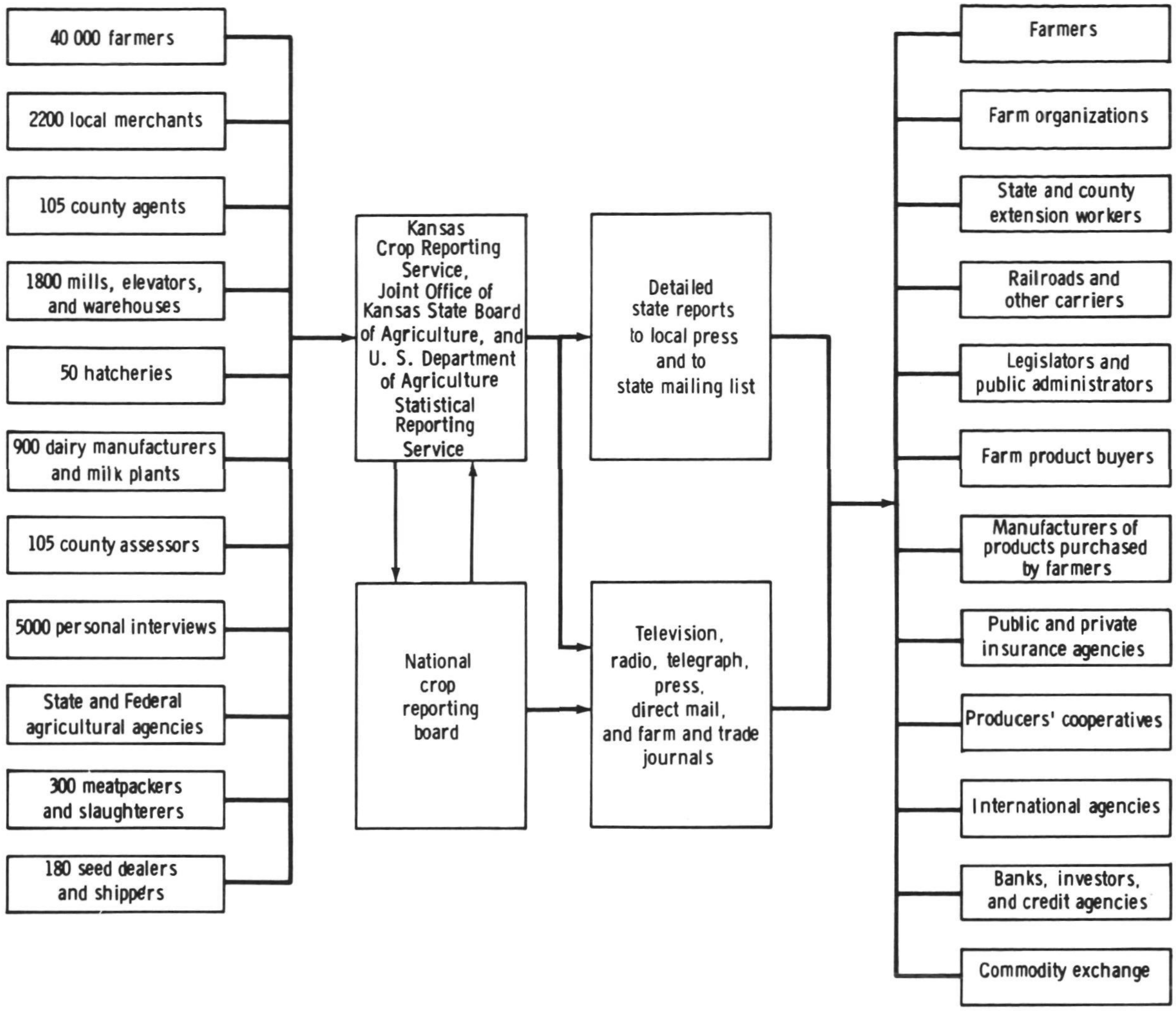


FIGURE 2–28.—Sources and uses of Kansas crop and livestock reporting information.

rangeland condition information has hampered effective use of this natural resource. The availability of regional ERTS data is expected to improve the coordination of rangeland management practices over large segments of the country. Assuming the acceptance of this new information source by managers, the need for more reliable rangeland condition information will become evident. Forest-land managers in the United States normally require more detailed information than can be provided by spaceborne radar systems. However, large areas of the globe are characterized by sparse population and/or persistent inclement weather, including parts of northern Europe, Asia, and North America; the equatorial rain forests of Africa, Asia, and South America; and parts of the tropics and subtropics. The land managers in these areas need the type data provided by SLAR to make forest classification maps and to document land-use change.

Value to the users.—The Dynatrend report (ref. 2–1) estimates that the annual benefit to U.S. users from accurate location and identification of major crops might approach $2 million (1972 dollar value). The bulk of this benefit is expected to result from improvements in remote sensing, especially if identification accuracies can be improved for irregularly shaped fields smaller than 50 hm^2.

Furthermore, the report indicates that half the annual benefit derived from more timely and accurate crop inventories could be contributed by remote sensing; that is, an expected total of $5.6 billion (1972 dollar value). According to estimates, the annual value of improved inventories for wheat approached $100 million; an additional $100 million accrues for other major wheat-growing countries (Argentina, Australia, Canada, France, West Germany, and Italy). Improved rice inventories are expected to benefit U.S. decisionmakers in excess of $45 million and to benefit the rest of the rice-growing world considerably more.

Based on incomplete evidence concerning crop condition, the Dynatrend assessment suggests that remote sensing may contribute approximately 20 percent of the annual benefits from this activity (approximately $113 million at 1972 values). It is too early to assess the value of monitoring crop diseases from space or by microwave systems, because current sensors show limited capacity to satisfy these tasks on a timely basis.

Finally, the Dynatrend report lists several beneficial applications relating to management practices. Knowledge of diurnal and season transpiration rates, evaporation mapping, detection of faulty irrigation practices, soil-moisture mapping, improved range management, and other factors is crudely estimated to have annual world benefits of $500 million (1972 value). This number is projected into the tens of billions during the next several years. Because of electromagnetic limitations and resolution, present sensors are incapable of contributing to much of this annual benefit. Given the necessary research and development support for active microwave sensing, there is good reason to believe that some, and perhaps a large part, of this benefit could be achieved through decisions based on microwave sensing.

In forest resources, improvement in location of marketable resources and their identification by type should have an annual national benefit of $1.5 to $3 million and a worldwide benefit of perhaps $50 million. Accurate estimates of timber yield could benefit forest industries by $30 million annually ($1.6 billion worldwide). Finally, if forest-fire detection and damage assessment become operational applications, the Dynatrend report states that benefits in the range of an additional $1.5 to $3 million would accrue. To the extent that active microwave sensing can contribute, it can be assumed that developmental costs for sensing this flow resource would be worthwhile.

Cost/Benefit

There are complex economic considerations concerning the benefit portion of any cost/benefit analysis. Typical estimated benefits have already been presented. However, considerations of cost can be quite accurately determined and vary only according to the completeness of the line items included. For active microwave sensing in the next 5 to 10 yr, most costs are anticipated to be in sensor design and testing and in development of interpretation skills, including model building and data-processing techniques.

Principal Application Areas

The major advantage of including active microwave sensors among the systems for agricultural use is that it provides a continuous temporal capability. The unique contribution of microwave sensing is the potential for detecting crop-water phenomena that are major factors in limiting yield and production and that are important input in current yield-prediction models.

Large area crop inventory.—To accurately determine the acreage of a specific crop for inventory, the identity and area of the cropped field must be determined. This determination is equally true for range surveys. To identify the field and determine its area, knowledge of the crop calendar and the crop signature is required. Therefore, measurements of microwave return must be made at specific times corresponding to various growth stages. Because the signal strength will depend primarily on structure and the dielectric properties of the viewed surface, there is an urgent need for information on the influence of crop morphology on microwave scattering and for separation of the scattering contribution of the underlying soil surface from that of plants.

Crop production estimates and erosion assessments.—The success of estimating crop production and rangeland biomass depends on the ability to identify the crop species. Although the range surveys are lower priority than crop inventories, they are an important application, especially in the Great Plains States. The current lack of synoptic regional range-condition information has hampered effective use of this natural resource.

Crop production estimates require inputs such as soil moisture and crop vigor. Surveillance of crop vigor will require data acquisition on a timely basis. Subtle changes in plant-water content must be detectable to be useful in assessing crop vigor. Soil-water potential in the root zone must be determined. Crop-cover and surface-moisture content will also be required for erosion assessment.

Depending on the success of measuring crop condition, active microwave data could provide solutions to many problems affecting managerial decisions, among which are—

1. Erodibility.
2. Irrigation scheduling.
3. Overgrazing.
4. Encroachment of undesirable range species.
5. Infestation by insects.
6. Epidemiology of disease.
7. Assessment of flooding or other storm damage.

Forest-land classification.—Classification of forest lands is the first step in the inventory and monitoring of this important resource. In many areas of the world, information of the type and extent of forest resources is lacking due to adverse ground conditions and persistent inclement weather, which hampers acquisition of aerial photography. The SLAR can provide the basic data necessary for production of reconnaissance maps and monitoring of shifting cultivation.

Principal Research Areas

Signal/terrain interactions.—Three simultaneous programs need to be established, each with a critical path and decision points to insure that research in the next decade is productive: (1) the development of theories and models, (2) the testing of these models using ground-based microwave systems, and (3) the integration of ground-based measurements with aircraft and eventually spacecraft sensors and with data from other sensor systems. Among theories and models, the most urgent needs are for data on crop morphology (leaf sizes, stalk lengths, leaf area index, fruit size, shape, arrangement, etc.) and the influence of crop morphology on scattering. Laboratory and field studies should be continued and expanded to determine the quantitative or, at least, the relative contribution of geometry and moisture content to signal backscatter over a range of frequencies and polarizations. In this regard, microwave sensing is at the developmental stage experienced in visible and IR multispectral scanning during the early to middle 1960's.

In addition to studies on signal/plant interactions, research should be supported on the spatial relationships of crops in fields (i.e., the areal dimensions of crops are as important as the shape of the individual plants that comprise the field). Subresolution phenomena (such as row spacings) and other spatial attributes (such as row direction) need to be studied to determine their contribution to crop identification. Signal returns from different canopy covers, soil-moisture contents, surface plow treatments, surface-moisture films, and so forth, need to be compared as functions of viewing angle, frequency, and polarization. The purpose of all the studies recommended here should be to develop broadband microwave systems as prime sensors for crop condition and vigor assessment.

Major research areas in forestry include the development of procedures to compensate for changes in signal strength resulting from topography and the testing of multispectral radar (including long wavelengths) to aid volume inventory and classification of multistoried forest communities.

While the basic signal/plant and signal/crop relationships on the ground are being studied, efforts should be directed at simultaneously imaging the phenomena from aircraft. The purpose is to keep the interpretive and data-processing arts abreast of developments in signal/terrain understanding. In the past, there has been a tendency to interpret radar imagery as though it were panchromatic photography. A specific program should be initiated to stimulate the proper interpretation of imagery based on microwave principles.

Supporting research.—Effective use of active microwave sensors will require a thorough understanding of the sensor environment. Research should be initiated at different but appropriate levels of intensity to (1) document system transfer functions; (2) evaluate atmospheric effects (e.g., the comparative reflectance from dry terrain compared to terrain that was recently wet, scatter affected by nighttime moisture films compared to scatter under dry but windy conditions, etc.); (3) establish sampling strategies for plant and crop morphometry and for plant and soil moisture (areally and vertically); (4) determine depth of signal penetration in different angular, frequency, and moisture domains; and (5) develop calibrated spectral data for integrating active microwave and MSS data in processing schemes.

Recommendations

The following are recommendations for the development of remote sensing of crops, forests, and ranges:

1. Continue and expand the program for ground-based microwave studies.
2. Relate threshold detectable moisture conditions to critical soil and plant water limits.
3. Design models for relating detectable moisture phenomena and ground cover to crop vigor and yield.
4. Support efforts to establish levels of acceptable accuracies required by the user community, which should be done for specific applications at several levels in the user hierarchy.
5. Continue and expand the program in active microwave sensor data processing to insure its compatibility with other sensor data and to promote its interpretability at the user levels.
6. Continue and expand programs of testing multispectral active microwave systems over cultural and natural vegetation communities.

SOIL MAPPING WITH ACTIVE MICROWAVE SENSORS

Introduction

Although aerial photographs have been used extensively in national soil surveys, little use has been made of radar imagery in soil surveys. This situation is the result of several factors, but a major restriction on the use of radar imagery is the present inability to interpret the radar image. The success of aerial photography for soil surveys has been built on an ability to relate soil patterns, usually not actually visible on the imagery, with the distribution of other landscape features visible on the imagery. Radar studies have lacked the dual understanding of image pattern and soil distribution that has been essential in the use of aerial photography. This limitation is largely the result of a tendency to regard the radar image simply as a photograph and to ignore its special characteristics.

Previous research on radar reflectance from soils has used one of two approaches. The first approach is laboratory research such as that conducted by Lundien (refs. 2–111 and 2–112), who measured radar reflectance from artificially structured soils at several texture and moisture conditions. A second approach, used by Sheridan (ref. 2–113), Simonett (ref. 2–114), and Barr and Miles (ref. 2–115), applied airphotographic interpretation procedures to radar imagery to demonstrate that natural soil distributions in the field correspond, in some areas and under certain conditions, to patterns observed on radar imagery. However, their interpretations largely ignore the differences between radar and photography and present strictly empirical interpretations, without an explanation of the soil properties recorded on the imagery. The objective of this section is to outline an approach combining both these techniques to produce image interpretations based on analysis of microwave behavior and reflectance properties of Earth materials. The result will be a preliminary outline of (1) the kinds of soil properties that can be expected to appear on radar images, and (2) the necessary conditions for such imaging.

Functional Requirements for Active Microwave Sensing

Review of theory.—The SLAR operates by transmitting a known signal and receiving that portion reflected back toward the receiver from objects on the ground. The power returned to the receiver from any reflecting element is a function of the transmitted power, the gain of the antenna, the wavelength of the transmitted energy, the scattering cross section for the element, some function of the incident angle and beamwidth, and the distance to the target. Each sensor parameter can be controlled so that the only variable is the scattering cross section of the specific ground object.

Black-and-white line-scan imagery is produced by converting the backscattered energy into a spot of light, which is regulated in intensity according to the strength of the received signal. A strong reflection will produce relatively bright tones, whereas a weak signal will result in relatively dark tones. These tones are described as relative because they presently cannot be converted into absolute values of scattering cross section. Nevertheless, relative values can be useful if factors determining reflection strength can be applied to image interpretations and if these factors can be related to landscape patterns. These factors can be divided into ground variables and system variables. The most important ground variables for soil mapping are (1) dielectric properties, determined mostly by moisture content, and (2) surface roughness, determined mostly by the textural composition of the soil, microrelief, and vegetative cover. In addition, image interpretation must also consider the microwave variables of frequency, incident angle, and resolution. Interaction between ground and system variables produces the tone observed on the image. Because these interactions operate in a predictable fashion, they can be used as clues in image interpretation.

Effects of microwave variables on soil mapping.—Dielectric properties of soil are directly related to water content (ref. 2–112). The nature of the relationship has been empirically derived by Lundien (ref. 2–111) for Richfield silt loam at four radar frequencies (fig. 2–29). For all frequencies

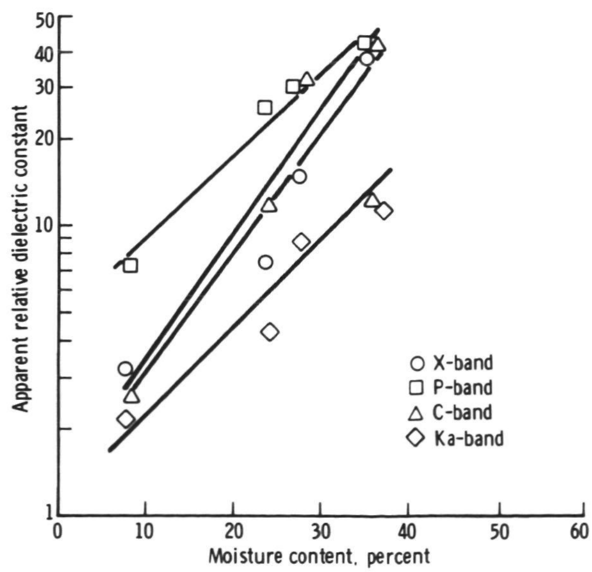


FIGURE 2–29.—Apparent relative dielectric constant of Richfield silt loam as a function of moisture content.

measured, the dielectric constant increased with increasing moisture. In a similar manner, for any two soils having nearly the same characteristics of particle size, shape, and arrangement (together with pore size, shape, and arrangement), the soil with the higher water content should have the higher dielectric constant and appear in relatively light tones on imagery. The relationship is such that one would expect a small increase in soil moisture near wilting capacity to result in a significant increase in radar reflectivity and, hence, image tone. However, the addition of moisture to an already moist soil should not significantly alter its already high reflection.

These general observations have led interpreters to regard radar as a potentially useful sensor for mapping regional soil moistures and for monitoring the relative moisture status of fallow fields. The usefulness of tonal changes, however, will depend on the position of these changes on the wetting and drying curves. Therefore, the case for radar as a monitor of available moisture depends upon future research demonstrating that radar is sensitive to changes between field capacity and wilting point. For the present, only gross differences in image tone between saturated and nonsaturated soils have been reported (ref. 2–38).

Relationships between wavelength and soil texture are shown in figure 2–30. In this diagram, the radar wavelength for "rough" (2λ) and "smooth" ($\lambda/10$) surfaces for midpoints in the bandwidths of V-, K-, X-, and L-bands are matched with U.S. Department of Agriculture soil texture classes. Several assumptions are inherent: (1) that the re-

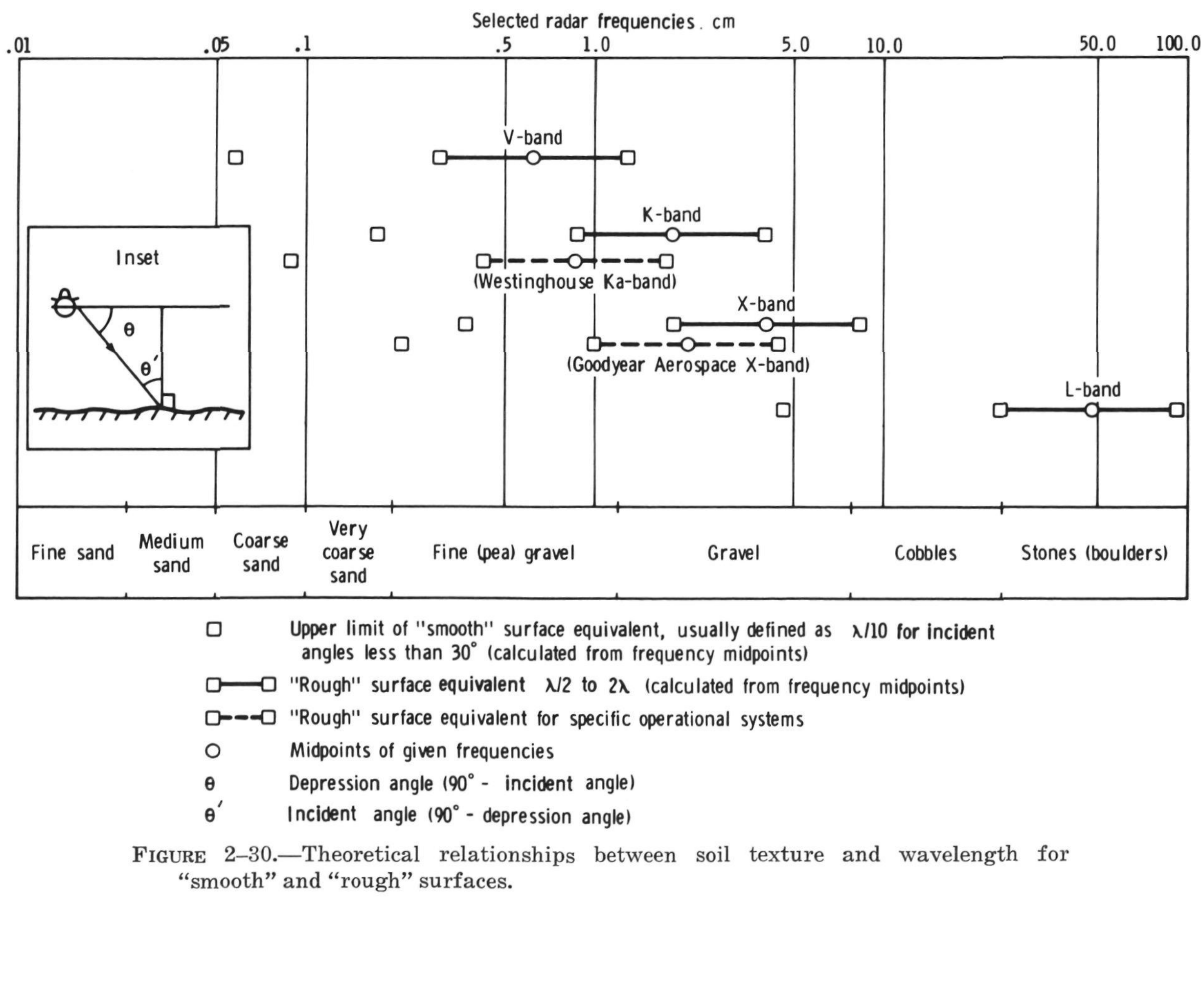


FIGURE 2–30.—Theoretical relationships between soil texture and wavelength for "smooth" and "rough" surfaces.

flecting terrain is sufficiently flat that reflection differences related to slope are negligible, (2) that the surface elements are uniform in size and distribution, and are sufficiently free of vegetation so that complications from composite reflection do not arise, (3) that signal returns are from surface rather than subsurface phenomena, and (4) that increases in return as a result of moisture are negligible. Based on the knowledge that rough surfaces have stronger reflection than smooth surfaces, the diagram suggests that at V-band, for example, returns should be highest for surfaces covered by small (pea-sized) to medium gravel and least for all textures finer than medium sand. At progressively lower frequencies (e.g., K-, X-, and L-bands), all other factors being equal, radar reflection from bare ground should be dominated by progressively coarser textured materials. Thus for L-band at incident angles less than 30°, boulder surfaces should give relatively brighter returns than their finer textured surroundings. Simultaneously produced imagery from both X- and L-bands should show gravel surfaces to be light gray or white at X-band and dark gray or black at L-band.

These relationships are expectations based on theory. In practice, identification of surface materials is much less precise because of the variable importance of moisture content and vegetal cover. Nevertheless, Sheridan (ref. 2–113) has verified from field examinations near Bishop, Calif., that on Ka-band imagery, gravelly soils image in comparatively light-gray tones, whereas silty and clayey soils appear in darker tones. His observations were made over an incident-angle range from 30° to 65°. Morain and Campbell (ref. 2–104) believe that arid lands offer the best opportunity for surface material identification because there is little surface moisture or dense vegetation to complicate the situation.

Kellogg and Orvedal (ref. 2–116) state that, at a scale of 1:50 000, the minimum mappable soil area is approximately 10 hm^2. At 1:1 000 000, the minimum area is approximately 4000 hm^2. At a scale of 1:50 000, a radar imaging system having 10-m resolution would have 1000 independent cells from which to generate an average gray level for every 10-hm^2 area. This number is more than that necessary for statistical significance. The resolution of images contained in figures 2–31(*a*) and 2–31(*b*) ranges from 12 to 15 m. For cartographic purposes, such resolution is satisfactory for generalized soil mapping.

However, for actual image interpretation, the adequacy of resolution depends on vegetation density and incident angle. Three idealized surfaces are as follows: (1) exposed soil of uniform moisture and texture having microrelief less than $\lambda/2$; (2) a similar, densely vegetated surface; and (3) a similar but partially vegetated surface. For exposed smooth surfaces, the major factors affecting reflection are soil texture, structure, cloddiness (microrelief), and moisture. These factors contribute so much to tone that, for practical purposes, average returns would be the same, whether the resolution cell was 3 or 15 m. Similarly, in densely vegetated scenes, soil studies by direct interpretation are precluded, whether radar or photography is used. Uncertainties surrounding the depth of signal penetration and the effects of moisture in vegetation make soil interpretations highly suspect. In densely vegetated areas, finer resolution alone will not improve the utility of radar for generalized soil mapping.

However, in the case of partially vegetated surfaces, resolution is an important consideration for image interpretation because, in each resolution cell, the process of signal averaging sums the reflectivities of different objects. Thus, signal returns from elements of varying sizes, shapes, and arrangements are averaged in different proportions depending on system resolution. The proportion of soil surface to vegetation is maximum at vertical incidence and declines as the incident angle increases to grazing. For radar systems having a wide angular range, there should be more soil information contained in the near-range portion of the image.

These considerations indicate that resolu-

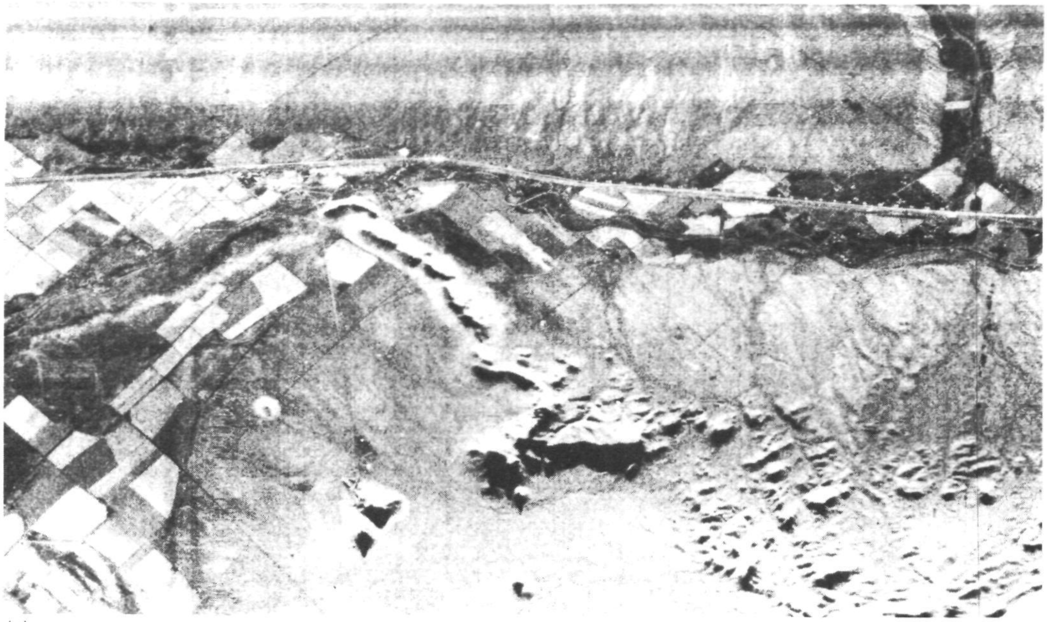


FIGURE 2–31.—Radar images in the vicinity of Tucson Mountains, Arizona. (*a*) Ka-band (0.86 cm) real aperture image; 15-m resolution; scale, 1:136 000 (October 1965). (*b*) X-band (3 cm) synthetic aperture image; 12-m resolution; scale, 1:195 000 (April 1971).

tion requirements for radar soil studies depend on radar incident angle and vegetation patterns. For practical reasons, it seems unlikely that resolution better than a few meters would greatly improve the production of soil maps from radar.

For a fixed resolution cell size, the scattering cross section has angular dependencies that are a function of the roughness, volume scattering, and resonances determined by object geometry. "Smooth" surfaces, those with reflecting facets (surface height deviations from a mean plane) less than $\lambda/10$, are characterized by specularlike reflection. At incident angles between 10° and 30°, these objects reflect signals away from the receiver and appear very dark gray or black on the image. "Rougher" surfaces (usually defined as those with reflecting facets between $\lambda/2$ and 2λ) function more nearly as isotropic reflectors. In extreme cases, these surfaces tend to have more or less equal reflecting potential, regardless of incident angle. In a natural scene with two or more materials contributing to the radar return, the situation is more complex.

To investigate the application of this principle in a real landscape (near Tucson, Ariz.), Morain and Campbell (ref. 2–104) estimated the amounts of soil and vegetation visible at several incident angles. Quadrats similar in size to a resolution cell in figure 2–31 were laid out, and, within each, the size and location of each shrub were recorded. The only two terrain elements present were soil and creosote bush (*Larrea divaricata*). In the laboratory, these data were used to reconstruct models of the quadrats, which were then photographed at several angles. The resulting negatives were scanned by an area integrator, and the percentages of shrub and soil were calculated. The results from a typical quadrat clearly indicated that, for these rather simple landscapes, soil is the dominant visual element, even at incident angles as high as 75°. Since soil studies are equally concerned with mapping and determinations of soil-moisture status, active microwave systems should be designed for steep depression angles (from 60° to perhaps 75° off horizontal).

Anticipated Microwave Results

Soil surveys for generalized maps are less intensive and narrower in objectives than detailed surveys. Their purpose is usually to determine the range of variability likely to be found in a region to provide an outline for initial development and to select areas requiring more detailed mapping. Observations are made at wider intervals than in detailed surveys, and the mapping units are usually soil associations or broad soil patterns (ref. 2–117).

The main contribution of SLAR imagery (or any imagery) for generalized mapping is to provide knowledge of geographic distributions and estimates of relative areas of soil units. Most of the actual pedologic information cannot come from the imagery but must come from collateral information, field surveys, and the knowledge of the soil scientists. The imagery can only provide information about soil distributions. To interpret this information, the soil scientist must have a general knowledge of local climate, vegetation, and topography; identical requirements apply for producing a map by conventional methods. In addition, a knowledge of radar theory enables the interpreter to separate soil patterns from other patterns on radar images.

Morain and Campbell (ref. 2–104) illustrate this principle by applying radar theory to analysis of two SLAR images. An image of an area near Tucson, Ariz., shows a pattern related to variable vegetation densities, which are, in turn, closely related to soil and topographic patterns.

A site from Arizona was selected because an area with relatively low and uniform ground moisture was needed so that the effects of roughness could be studied independently of moisture. Furthermore, arid-zone vegetation is relatively sparse and soil-vegetation relationships are strongly expressed. The authors were fortunate in locating a region northwest of Tucson imaged by two different SLAR systems having slightly different system variables (fig. 2–31). Attention was focused on the nonagricultural lands because they were subject to relatively few changes during the interval between data collection and field observations. There were no available soil surveys for this particular environment, but the work of Gile and Hawley (ref. 2–118) with a similar environment near Las Cruces, N. Mex., assisted the interpretation. The authors identified Entisols and two orders of Aridisols on the alluvial fans. The approach was to examine a range of soil-vegetation types and to compare ground conditions with patterns on the radar images. These comparisons produced generalizations regarding the interpretation of soils from SLAR imagery.

A summary of observations for one particular landscape is given in figure 2–32, which shows a portion of the 3-cm (X-band) image together with landscape photographs and respective closeup photographs of the terrain types. Three terrain types are defined: (1) the riparian vegetation (*d*) and (*e*), which appears in light-gray tones; (2) transitional (*c*), the gentle shrub-mantled slopes (3°) that appear in medium-gray tones; and (3) interfluves (*b*) characterized by angular gravel pavement. These last two appear as dark filaments on the image. Two other land-surface entities are included in figure 2–32. The first is an abandoned airstrip (*a*), which does not appear in the SLAR image; the second is a streambed that does not appear on the SLAR image because, in that particular area, no drainage line was wide enough to be visible through the ri-

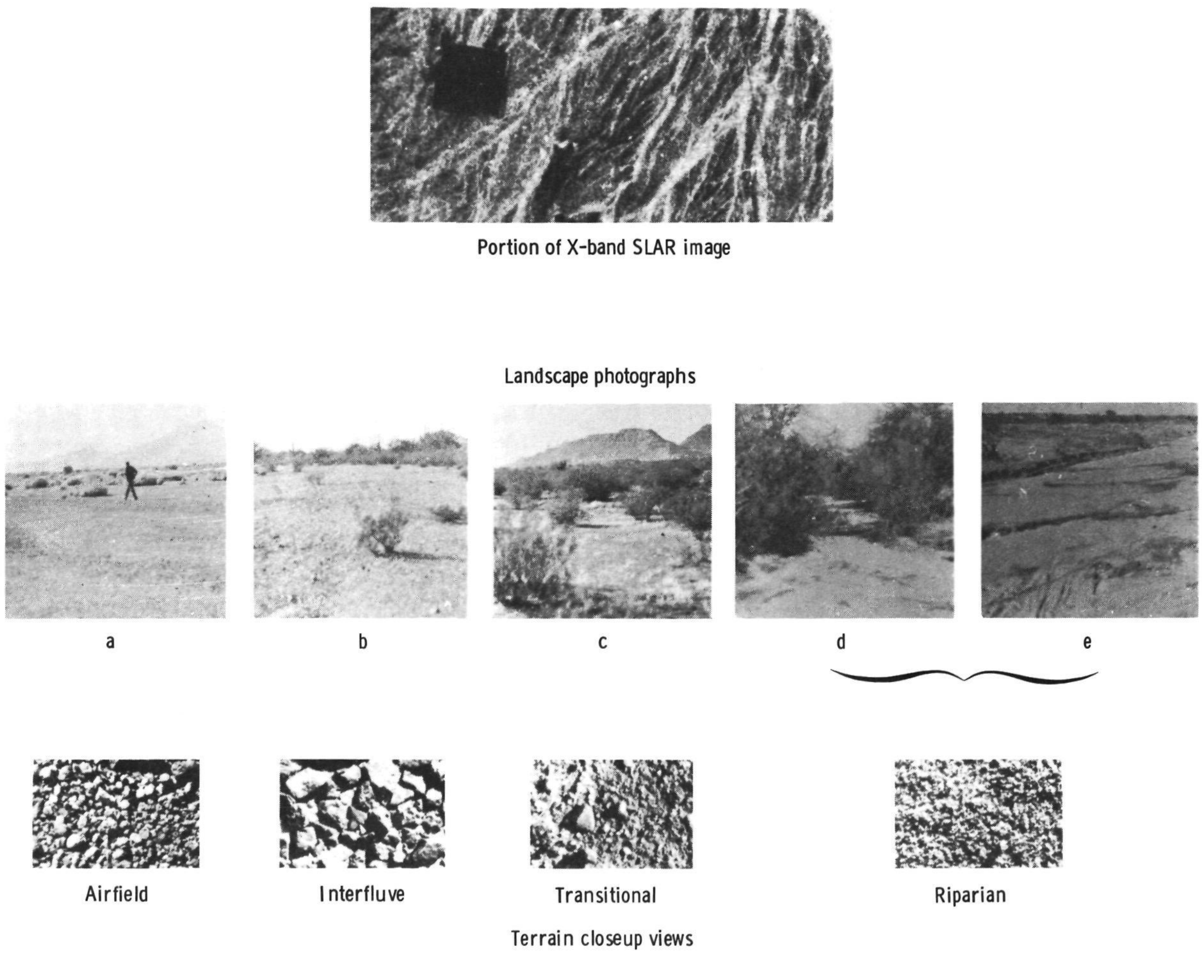


FIGURE 2–32.—Summary of observations for a designated landscape. Top: X-band SLAR image; center: landscape photographs (*a*) to (*e*) of the same area; bottom: closeup views of respective terrain types.

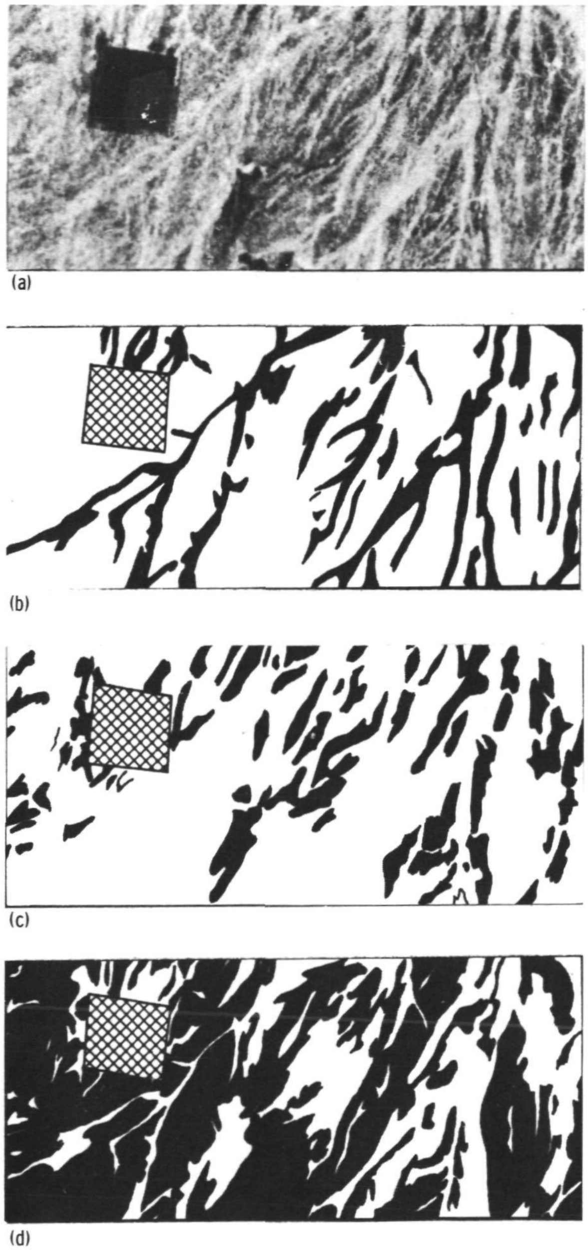


FIGURE 2–33.—Soil categories identified on the SLAR image of alluvial fan. (*a*) Major pattern of SLAR image. (*b*) Distribution of brighter tones corresponding to riparian vegetation. (*c*) Distribution of darkest tones, which are the interfluves and are characterized by desert pavements of stones and cobbles. (*d*) Soil categories positioned between those in figures 2–33(*b*) and 2–33(*c*).

parian vegetation. When the look direction is oblique (as in this case) or orthogonal to the drainage, streambeds will not image unless they are sufficiently wide that vegetation along the banks does not obscure the bed from radar observation. Such a streambed appears as a thin black line on figure 2–31(*b*) (arrow *A*).

"Rough" surfaces are defined as having reflecting facets in the range from $\lambda/2$ to 2λ (where $\lambda=3$ cm) or, in this case, in the gravel range from 1.5 to 6 cm. Such gravel surfaces should image in dark gray tones at K- and X-bands. In the insets of figure 2–32, it appears that both the airstrip and streambed have narrow particle-size ranges centering on 0.5 and 0.2 cm, respectively (the detailed insets have a 1-cm scale). The interfluve and transition categories appear to have wider particle-size ranges including infrequent cobbles up to several centimeters. Most surface materials appear to have particle sizes of approximately 1.0 and 0.05 cm. Photographs of the surfaces of all five terrain types indicate that no surface has a particle size exceeding 1.5 cm. Theoretically, when exposed and dry, these surfaces should all appear in similar dark tones. The fact that they do not appear this way on the image is explained by variations in vegetation density.

As the proportion of soil to vegetation increases, the strength of signal return decreases. For example, the areas marked *B* and *B′* on figure 2–31(*b*) are almost identical creosote bush landscapes. No apparent surface textural differences were observed between them. The only significant difference is that, in area *B′*, the shrubs are shorter and farther apart. From this evidence, it is concluded that *B′* appears darker than *B* on the image because there is less radar reflection from vegetation.

This knowledge, combined with topographic information, provides a basis for matching image patterns with the soil categories that Gile and Hawley found in similar environments in New Mexico. The major pattern found on the alluvial fan is shown in the SLAR image in figure 2–33(*a*). The distribution of brighter tones corresponding to riparian vegetation is shown in figure 2–33(*b*). These tones correspond to areas of riverwash and are probably bordered by small areas of Torrifluvents. In figure 2–33(*c*), the darkest tones are shown, which are the interfluves characterized by desert pavements of stones and cobbles. The interfluves represent the oldest and most stable surfaces, and the soils are probably Haplargids. Figure 2–33(*d*) shows the types positioned between those in figures 2–33(*b*) and 2–33(*c*), which are likely to be Camborthids.

In dry environments, the attributes most influencing radar returns are size, shape, and arrangement of the reflecting material rather than moisture content. Microphyll species have leaves comparable in size to gravelly and cobbly veneers. The tendency for desert plants to minimize evaporative loss through pubescence, thorniness, and schlerophylly suggests that little plant moisture would be visible to radar signals. It is suspected that the effect of shrubs on radar reflectance from desert terrain is confined to surface roughness and that this influence adds to reflectance from soil surfaces.

Microrelief contributes more to radar reflectivity than soil texture. However, because image tone is determined basically by roughness at the wavelength scale, it would seem that only those forms of microrelief having a commensurate scale should be important; for example, ripple marks in sand. Some plow patterns on bare soil are reported to increase radar reflection from cultivated fields (ref. 2–119), but no examples from natural landscapes have been reported. Field investigations at Tucson confirmed, in all cases, that exposed soil surfaces imaged in very dark gray or black tones at X- and Ka-bands. This type imaging occurred despite the variable microrelief, which in some cases exceeded 2λ by a factor of 3.

MacDonald and Waite (ref. 2–38) demonstrated that imaging radars are, under certain conditions, sensitive to gross soil-moisture variations. Morain and Campbell (ref. 2–104) have also observed moisture patterns of an area west of Hutchinson, Minn. (fig. 2–34). The numerous white and light-gray spots observable on the image are one of

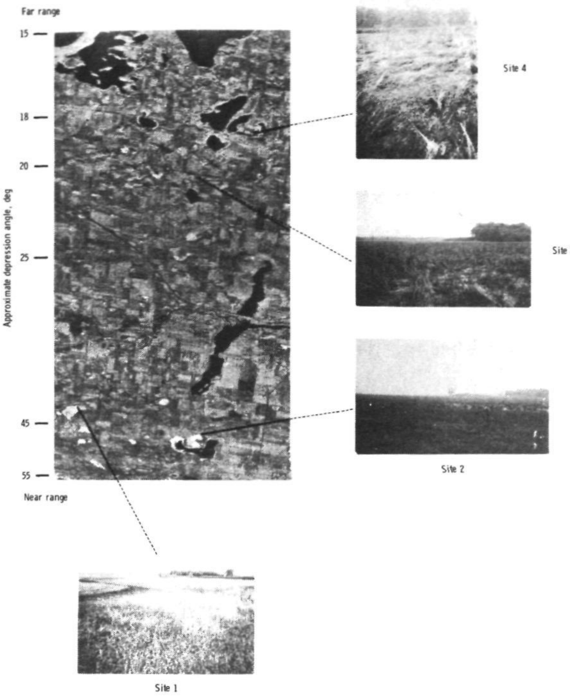


FIGURE 2–34.—Radar image and related landscape photographs showing moisture patterns of an area west of Hutchinson, Minn. Sites 1 and 2, imaged at a depression angle of approximately 45°, have bright tones of similar intensity. Sites 3 and 4, positioned at 20° and 18° depression angles, respectively, appear brighter than surrounding agricultural and wooded areas, although not as bright as sites 1 and 2.

the expressions of that moisture. Topographic maps, soil maps, and field observations reveal that these spots correspond in size, shape, and position to poorly drained depressions usually mapped as peat or muck soil.

The importance of incident angle on the magnitude of the received signal from a moist surface is illustrated in figure 2–34. At more nearly vertical angles, signal strength declines and gray tones are observed on the image. All sites have approximately the same vegetation and moisture characteristics. Sites 1 and 2, imaged at approximately the same depression angle (approximately 45°), have bright tones of similar intensity. Sites 3 and 4, positioned at 20° to 18° depression, respectively, appear brighter than surrounding agricultural and wooded areas, although not as bright as sites 1 and 2. Moore (ref. 2–120) states that at shallow depression angles the height of vegetation may have a significant effect on reflection, particularly if the plants have a high moisture content. Therefore, it is possible that the bright spots at steep depression angles result from the cumulative effects of plant and soil moisture. At shallow angles, the topographic depressions are still somewhat brighter than their surroundings because they are relatively wetter, but the contrast is reduced by stronger returns from vegetation.

High moisture content and rough texture (relative to wavelength) tend to increase reflection. Thus, it is easy to envision situations in which an interpreter could not distinguish between reflection from a fine-textured moist soil and that from a coarse-textured dry soil. Theoretically, both types should appear as bright tones on an image and should not be easily distinguishable with a single radar frequency. In practice, however, an interpreter should resolve such confusion with multiple coverage using different radar characteristics, much the same as different film and filter combinations are used in photography.

Cost/Benefit

Much work should be done to document the economic factors associated with improved soil type and association mapping. The Dynatrend report (ref. 2–1) notes several studies of benefits in this area of remote-sensing applications, but these are considered questionable.

For cataloging soil environmental characteristics, the world might benefit to the extent of $30 million annually. Use of satellite data for locating and surveying potentially cultivable soils might save developing countries an additional $75 million. These values may be an order-of-magnitude low or high (probably not the latter), but in either case they suggest that there is valid economic reason to improve soil-mapping capabilities.

Conclusions

Radar sensors will not completely replace photography as a mapping aid for either detailed or generalized soil surveys. Nevertheless, the unique contributions of active microwave sensing for resource inventories in arid and semiarid environments or the perennially cloudy tropic and arctic zones should be pursued. These contributions are especially important when the penetration capabilities of longer wavelength systems are considered. Only a small portion of the electromagnetic spectrum has presently been used (mostly the visible portion) in remote sensor studies of the soil. Unique and valuable information on texture and texture-related phenomena, moisture, and possibly even subsurface texture contrasts could probably be partially provided by radar imagery.

Observations from aerial photographs have shown that local experience and knowledge are important factors in soil interpretation. These same factors will probably be important for interpretations from SLAR. Knowledge of the sensor principles and operation is of greater importance in SLAR studies because of the unfamiliarity of most people with this sensor. As a result, soil interpretations from SLAR are unlikely to progress without individuals having combined knowledge of local soils, soil science, and SLAR theory. Because such imagery is available only for certain areas and because the combination of interpretation skills is possessed by only a few interpreters, advances in radar mapping have been slow.

Additional research is needed to ascertain the relationships of radar reflection to system frequency, polarization, dielectric constant, and incident angle. Investigations confirm that near-vertical incident angles are best for detecting differences in soil moisture and, possibly, for discriminating soil types on the basis of their surface texture. In reviewing the theory and observations, the relative reflection strengths caused by moisture and texture are believed to intersect in both the frequency and angular domains; thus, interpreters cannot readily distinguish between a moist fine-textured soil and a dry coarse-textured soil if all other parameters are equal. These tradeoffs should be reconcilable by comparing the reflection characteristics of soils over a broad range of microwave frequencies, angles, and moisture conditions. In the same way that various film-filter combinations aid in the interpretation of objects that otherwise look the same on panchromatic photography, it should be possible to distinguish between soil-moisture and texture differences by judicious selection of radar parameters.

SOIL MOISTURE MEASUREMENT

Introduction

Civilization and the existence of water in soil are inseparable; thus, when prolonged droughts occur, civilizations vanish. As presently demonstrated in Africa, even the lack of water in soils for periods of weeks can seriously alter the precarious balance between food supply and demand. The ability to monitor and predict moisture in soils on a global scale has been a longstanding objective that has thus far eluded man. Active microwave sensors offer a promising approach based on scientific reasoning and preliminary results. Additional research and development is required to arrive at a functional capability.

Two promising applications for sensing of soil properties are made possible by some of the unique penetration capabilities of microwave systems. Measurement of soil water content would allow the development of a soil moisture index that could be used as input to watershed runoff and crop-yield models. Soil moisture monitoring for irrigation requirements has local value and may be accomplished after more precise techniques are developed.

The primary need for soil-moisture measurements over large areas stems from a desire to improve prediction models for water resources and crop yield. The spatial distribution of soil moisture indicates that such measurements are feasible with active microwave systems.

Complex, continuous watershed models have been developed in past decades to mathematically represent the movement of water in the Earth-surface portion of the hydrologic cycle. Presently, these models are the only means of calculating "low flow" or continuous streamflows. Low-flow values for streams and the temporal distribution of flow volumes are extremely important for the study of water supplies and the environmental input of changes in a watershed drainage area. Presently, soil-moisture input to the models cannot be measured, and the input is generated by submodels based on parameters developed by fitting the overall model to existing watershed data. The use of complex models is thereby restricted to use on watersheds with existing historical records.

Development of a soil-moisture index for use as input to crop-yield models is also very important. Crop-yield models are vital to improvement in timely estimates of world food production. Identification and mapping of some major crops are considered feasible. However, no adequate system has been developed for measuring the moisture available for the plant root zone. Laboratory experiments on penetration and soil-moisture measurements with microwave systems (refs. 2–121 and 2–122) indicate that reasonable estimates of moisture availability for plant growth are feasible.

Demonstrated Remote-Sensing Observations

ERTS–1 and aircraft photography.—Preliminary results from ERTS suggest that relative soil-moisture variations can be detected in desert playas and areas of alkaline soils (refs. 2–123 and 2–124). Quantitative measurements cannot be made based on spectral appearance in the visible region. The MSS's and cameras on aircraft platforms show similar feasibility for moisture detection. In general, soils that are moist have somewhat darker tones in comparison to their dry state. However, no known mathematical relationship exists between soil color and moisture content.

Skylab S193 and aircraft radar observations.—Several research programs have centered on laboratory studies regarding the measurement of electrical properties of the soil-water mix (refs. 2–112, 2–125, and 2–126). These studies have shown that the water content has a major effect on the electrical properties of soil media. Differences in soil type do not have an important effect on the relative dielectric constant.

Other research programs have demonstrated the use of radar measurements from elevated platforms to detect changes in soil properties (refs. 2–107, 2–111, 2–112, and 2–121). These efforts have indicated that near-vertical measurements are more desirable than low-depression-angle measurements because the predominance of the surface-roughness comparison of the total radar backscatter is reduced, and the significance of the reflection from vegetation is reduced. Field studies by Morain and Campbell (ref. 2–104) confirm these observations. When measurements are made on smooth surfaces at these near-vertical angles, the reflectance can be correlated with soil moisture. In addition, when skin depths are significantly large, subsurface composition can be inferred.

The S193 scatterometer on Skylab made numerous measurements over test sites from which soil-moisture data are available or for which soil moisture can be inferred from nearby rainfall measurements. Because these data are being analyzed at this time, no conclusive results can be reported. However, the general indications are that soil moisture may correlate with measurements made with the truck-mounted radar and airborne scatterometers. In cursory examination of Skylab data, vegetation appeared to have a disturbing influence on the K-band measurements.

Wavelengths from 0.8 to 21 cm and incident angles from vertical to 50° have been used in passive microwave measurements on soils (ref. 2–122). Because these microwave devices measure the natural emission from the target, they are sensitive to the target temperature and emissivity. The natural emission from a soil target is very dependent on surface roughness and on bulk electrical properties. Thus, a change in the water content in a soil would show up in an apparent change in temperature. The depth at which the bulk of the energy originates is determined by the wavelength and the water-content profiles.

A truck-mounted passive microwave system has been used recently to determine antenna temperature changes as a result of changes in soil moisture, roughness, and vegetation. Preliminary measurements indicate that an L-band (1.41 GHz) radiometer wil be necessary to overcome some of the influence of roughness and vegetation on soil-moisture measurement (ref. 2–127). However, limitations on antenna size may prevent design of radiometers in a scanning mode at L-band. Another study using an L-band radiometer (S194) on Skylab has shown good correlation between antenna temperatures and a 30-day decayed antecedent precipitation index. An index of this nature would be adequate for prediction of moisture for wheat production if repeated coverage could be provided over the Great Plains at 2-week intervals. At best, the passive systems are hampered by antenna size requirements that do not restrict the active microwave systems.

Functional Requirements

The response of microwave energy in soil media is determined by the electrical properties of soil and their spatial distribution. The use of microwave sensors is advancing because of known relationships between electrical properties of soils and water content. The electrical conductivity of soils at low frequency is almost exclusively ionic and occurs as a result of the motion of free or exchangeable ions in the soil solution. Because exchangeable ions often dominate over free ions in solutions, clays have a higher conductivity than coarser grained soils. Typically, the conductivity of soils varies from 10^{-1} mho/m for clay soils to 10^{-3} mho/m for sands and gravel. Because of these high conductivities, conduction currents dominate over displacement currents for frequencies above approximately 10^6 Hz.

Water content influences the conductivity of soils, but other factors such as soil and clay type are as important as water content in determining the conductivity of soils. At frequencies above 10^7 Hz, the influence of conductivity of soils on the propagation constant begins to diminish and the relaxation of water in soils becomes important. Figure 2–35 shows the relative dielectric constant of typical soils as a function of volumetric water content at a frequency of 1.074 GHz (parallel and perpendicular polarization). The 12 soils included sands, silts, and clays. Increasing the frequency to 10^{10} Hz causes the relative dielectric constant to decrease significantly from its low-frequency value (ref. 2–125), as will subjecting the soil to low temperatures.

A transverse electromagnetic wave normally incident on a smooth surface, which has a finite conductivity, will be partly reflected at the surface, and the remainder will penetrate into the soil. The electric and magnetic fields in the ground will decay exponentially with depth. The skin depth in soil media can have values as much as several meters in the 10^8- to 10^9-Hz frequency range. In the 10^9- to 10^{10}-Hz range, the skin depth can shrink to only a few centimeters. Thus, by selecting a number of frequencies for operation, it may be possible to define soil media as a function of depth.

Images produced from SLAR systems can be divided into areas of relatively consistent tonal and texture patterns. A relatively few samples from these areas of consistent patterns will serve to identify the physical properties of these areas. Thus, information from a few bench-mark stations can be extrapolated to large surface areas. These bench-mark stations can be entirely composed of ground-truth measurements or a limited amount of ground truth supplemented by direct measurements with airborne or truck-mounted radars.

The functional requirements for active microwave systems to measure soil moisture vary considerably with the required ultimate operational system. Three areas of application for soil moisture data are (1) modeling of watersheds, (2) crop-yield predictions, and (3) scheduling of irrigation. Table 2–VII outlines some of the characteristics required in active microwave systems desired

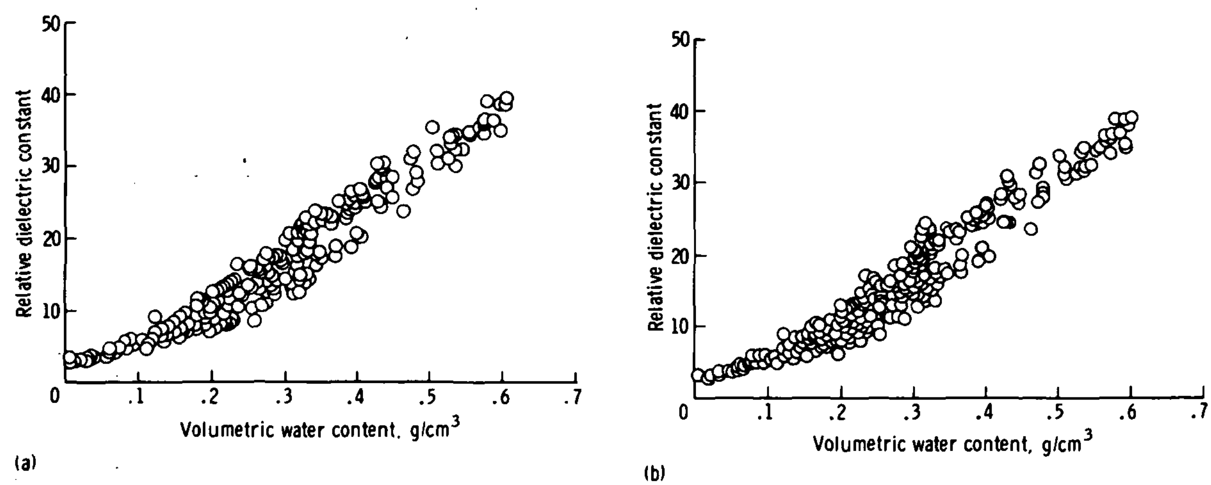


FIGURE 2–35.—Effect of water content on the relative dielectric constant of soils (sands, silts, and clays) at a frequency of 1.074 GHz. (*a*) Parallel polarization. (*b*) Perpendicular polarization.

for these applications in the soil-moisture area.

Anticipated Microwave Results

The applications and unique capabilities of active microwave systems are summarized in table 2–VII. Other applications in the area of soil moisture will require more refined spatial and spectral measurement. However, with improved technology in the following decade, most applications should become feasible.

Several researchers have reported results from airborne microwave measurements (refs. 2–38 and 2–128). Most results can only be reported in rather broad categories of soil-moisture content (e.g., dry or wet). The fact that soil-moisture conditions can be observed in these measurements indicates that such data may be adequate for large-area prediction models. Conventional measurement of soil-moisture distribution over large areas is not presently feasible. Part of the problem concerns the available ground truth at the time the flights were made. Although most laboratory experiments are conducted with highly controlled targets of rather small dimensions, field programs must sample large areas of highly variable properties. Ground truth has been adequate in very few field measurements.

Cost/Benefit

Accurate measurement of soil moisture affects so many vital areas of modern civilization that cost/benefit statements are difficult to formulate or document. The importance of soil moisture for agriculture, runoff prediction, flood-hazard prediction, locust infestation prediction, erodibility, and numerous other uses cannot be overstated. As a fundamental attribute of the terrestrial environment, soil-moisture data become a basic input to all models. By the most conservative estimates, the benefits exceed any costs involved in the data collection.

TABLE 2–VII.—*Soil Properties Capabilities Chart*

Environmental parameter	Application	Unique key capability of active microwave systems	Competing sensors or systems
Water content of soil	Input to crop-yield models and monitoring crop vigor.	Penetration of soil, penetration of clouds, and vegetative cover.	Visual and IR.
	Input to complex watershed models.	Penetration of soils and all-weather capability.	
	Soil strength and trafficability.	...	Geophysical techniques.
State of water in soil surface (frozen or liquid).	Detection of danger from sheet runoff. Infiltration restriction. Restriction of soil moisture evaporation.	...	IR
Soil type	Soil type mapping Input to trafficability models.	Penetration of soil, all-weather capability and penetration of vegetative cover, vegetation mapping and soil reflectivity.	Geophysical techniques.

Conclusions

Research is recommended along two parallel lines: (1) attempts to empirically correlate scattering coefficients and images from present systems with field measurements of soil moisture, and (2) research to build a store of knowledge from which system behavior can be predicted. For some applications, the empirical approach is the only feasible approach (e.g., runoff prediction of watersheds) because the areal extent of the entity to be sensed does not allow control. For irrigation scheduling, the second approach is the most economical way to proceed, because the relationship between the quantity to be measured and its microwave signature varies from one setting to another (e.g., the relationship between microwave signature and water content in Arizona may be unique to that location). To predict the extent to which a certain observed correlation persists in other settings of soil type, vegetation, water, and temperature regime, the interactions between microwave radiation and the Earth need to be fully understood.

Figure 2–36 is a flowchart for required research. Level I research should be a low-level continuous effort conducted simultaneously with research at level II. At level II, the empirical approach and the controlled ex-

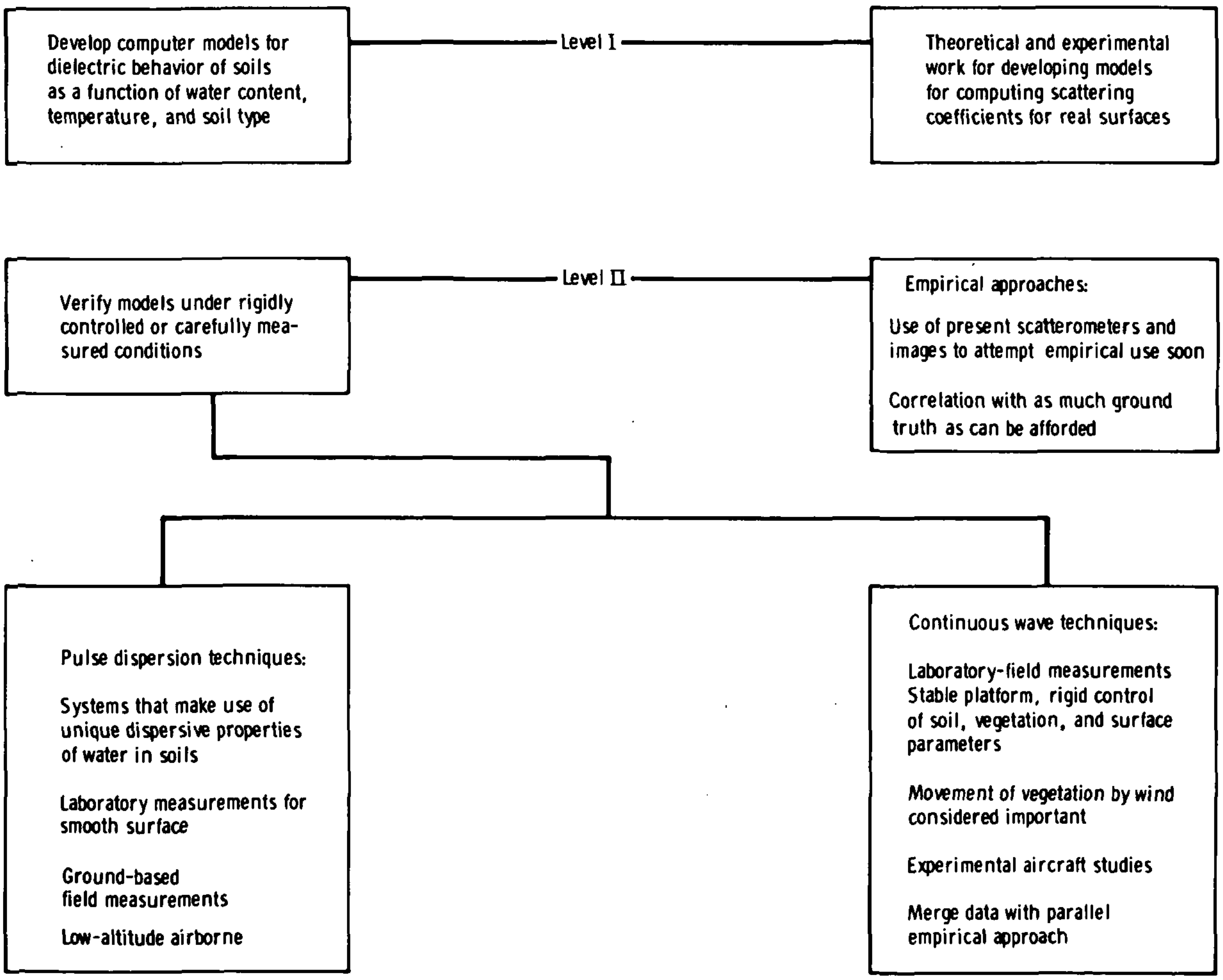


FIGURE 2–36.—Flowchart showing required research for simultaneously measuring moisture content and soil type with microwave sensing.

periments are also recommended to be conducted simultaneously.

SUMMARY

The objectives for active microwave sensing in agriculture, forestry, range, and soils extend those indicated for other sensors. The most unique contribution is expected to be in measurements of soil moisture as input to models of crop and rangeland production, watershed runoff, and trafficability. Theory and preliminary results show the feasibility of measuring moisture status, although research is needed to quantify many complex tradeoffs in signal return as a function of moisture content, vegetational cover, signal penetration, soil structure, root densities, and so forth. Further work will be needed to develop quantitative image interpretation techniques. The functional requirements for such a system will include a multifrequency design with a 1-dB intensity resolution and 50-m spatial resolution. Most important is the need for timely coverage.

For vegetational resources, crop identification for inventory and for yield and production estimates is most feasible. Active microwave sensors are unique in providing continuous temporal monitoring; thus, they are regarded as prime sensors for agricultural survey. The most significant contribution for both agricultural and rangeland surveys is in the potential ability of active microwave sensors to detect crop-water phenomena and total leaf area. Both these parameters are important as input to yield-prediction and crop-vigor models. For tropical agricultural systems, active microwave sensors may have a singular role in monitoring the rate and direction of riceland flooding during the cloudy monsoon season. These flood data can be translated into valuable information on basic rice type and production.

Apart from moisture- and water-related phenomena, active microwave systems are viewed as prime sensors for recording structural and spatial data related to crops and forests. These data are important attributes in determining leaf area indices and, ultimately, crop or timber yield. Tropical tree crops (e.g., rubber, oil, and palm) are expected to be more discernible from their forest surroundings because of the regular spacing and orientation of trees comprising individual plantations. Canopy penetration is essential for obtaining returns from tree trunks to discern the regularity, and only microwave sensors have this ability.

Functional requirements for an operational active microwave system in agriculture include multifrequency (wavelengths of 1 to 12 cm for crops and 1 to 50 cm for forests) and multipolarization (HH, VV, and cross) capabilities. Spatial resolutions of 15 to 30 m and spectral resolutions of 1 to 2 dB are desired over a viewing-angle range from 30° to 70° off vertical. As with all biological sensing, timeliness of data collection is absolutely essential.

The most important application for rangeland sensing is to measure available biomass as input to decisions on animal grazing capacity and improvement of range conditions. Plant cover, moisture status, and soil moisture are key parameters in assessing biomass. Essentially, the same system considerations that pertain to agricultural crops apply to rangelands.

Applications for active microwave sensors in forestry focus on typing community structures with the objective of producing physiognomic maps and, ultimately, to estimate timber volumes in economically important areas. Forest-clearing sites (as in clear-cut logging operations in the Pacific Northwest or tropical slash and burn agriculture) are readily visible on radar images in regions of low relief. Equally interpretable are successive stages of forest regrowth after a clearing or fire. Difficulties occur in mountainous terrain. Functional requirements include a multifrequency, multipolarization system and stereographic coverage having almost complete (90 percent) overlap to satisfactorily image mountainous environments.

Research programs are suggested for advancing knowledge of signal/plant and signal/crop interactions and for learning to

interpret images and digital data obtained from aircraft and spacecraft sensors. Even very conservative estimates of dollar benefits suggest that these efforts could have enormous economic benefit for agricultural businesses and society.

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PART D

LAND USE, URBAN, ENVIRONMENTAL, AND CARTOGRAPHIC APPLICATIONS

LAND USE, DISASTER, AND ENVIRONMENTAL MONITORING

Effective State, regional, and national land-use planning requires the compilation of a wide range of areal data. These include data on static components of the environment (including soils, slope, geology, and hydrologic systems) and on dynamic cultural land use and related components (including transportation routes, urban and rural land use, and public infrastructure). In the interplay of these natural and cultural features, with natural features relatively static and cultural features to a greater or lesser degree dynamic, planning is accomplished. Monitoring the changes in land use is of value not only in itself but also for determining the interaction with other land uses and with the background environment. This section focuses on radar applications and land-use analysis in the monitoring of land-use change, especially the more dynamic components, and the interaction between land use and dynamic features of the environment (floods, hurricanes, etc.). Because public awareness of land planning is relatively new, a more detailed discussion of land planning in relationship to remote sensing is included in this section.

Although the relationships between land use and environmental quality are not well defined and are not conducive to orderly simple analysis (ref. 2–129), general public awareness has increased and has helped focus attention on land-use planning and management as one means of achieving a reasonable balance between economic well-being and environmental quality.

Growth in economic productivity has caused a greater demand for leisure and recreational services, which are highly dependent on environmental quality. Environmental quality is becoming more highly valued in relationship to potential increases in economic standards of living. Growth in productivity depends on increasingly powerful technologies and therefore has greatly increased the geographic and temporal extent of each person's effect on the environment. The results of these trends have been recognized, and new laws have been passed; new institutions have been created for protecting the environment. As new policies have been developed and implemented for controlling specific types of environmental effects, there has been increasing recognition that land-use patterns have a strong influence on the relationship between future economic production and environmental quality. These overall land-use patterns influence such key factors as (1) the location of environmental disruptions that arise from the extraction of resources; (2) the magnitude of wastes generated, especially from transportation activities; and (3) the costs of treatment to lessen the impact of residuals discharged into the environment.

More fundamentally, the experience of the last 5 yr has furthered the recognition that land-use patterns determine who shares which environments and with whom. As this sharing and the resulting external effects include more people over larger areas and for longer times, the potential economic, environmental, and social benefits from more centralized, comprehensive land-use planning