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 (interception, surface storage, and infiltration). Measurement of one or all of the characteristics can improve current manual techniques for estimation of coefficients for storm runoff equations. In the commonly used Soil Conservation Service (SCS) runoff reference (eq. (2–1)), the coefficient CN is based on the soil-cover complex over a watershed surface.

$$Q=\frac{(P-0.2S)^2}{P+0.8S} \qquad (2\text{–}1)$$

where Q is inches of runoff; P is rainfall (storm); S is water storage factor equal to $(1000/CN)-10$; and CN is function of soil type, cover, roughness, and soil moisture.

Active microwave systems of appropriate wavelengths are sensitive to soil particle size, vegetation, roughness, and scene moisture; thus, a good possibility exists that the integrated influence of these characteristics can be quantitatively measured by microwave systems. Present technology favors active rather than passive microwave systems for imaging with longer wavelengths. The application is an area of primary research concern because it has not been tested with an active microwave system.

Application: The application for active microwave sensing would be to obtain data on the watershed runoff of medium-sized watersheds.

Acquisition: The data would be acquired by use of the following techniques:

1. Multifrequency wavelengths (X- and L-bands or longer).
2. Minimum of 20 data points per km^2 using seven-bit digital data.
3. Vertical and horizontal polarization.
4. Steepest possible depression angle and onboard tape recording.
5. Processing with data reduced to digital interface (registered) computer-compatible tape (CCT).
6. Gridded film output for location of data in irregularly shaped areas.
7. Display and distribution (as minimum user requirements) of CCT and film output or average value of each polarization of each wavelength used for requested surface area.

Justification: This system would provide all-weather capability and improve evaluations of hydrologic classification of soil by imaging in longer wavelengths than now available in passive images. The system could be used for space platforms and could improve ERTS saving by $2.5 million a year.

Anticipated results using active microwave sensing: Improved prediction of storm runoff used in the design of flood-control structures is anticipated (accuracy: 5 yr, 80 percent; 10 yr, 95 percent). The resulting information would be of use to the U.S. Department of Agriculture SCS, the U.S. Department of the Interior, and underdeveloped countries.

The ERTS studies by Blanchard (ref. 2–48) indicate that the SCS parameter CN can be related to the difference between MSS bands 4 and 5 in the southern Great Plains, especially during dry, dormant conditions. The ERTS scenes for such conditions are not always available when they are most needed for these measurements; however, benefits from this application have been estimated at $2.5 to $5.0 million if applied nationwide. This ratioing technique has not yet been tested using Skylab data. The Passive Microwave Imaging System (PMIS) measurements at X-band over eight small watersheds indicate the feasibility of microwave measurements of the coefficient CN. Figure 2–6 illustrates the apparent relationship of horizontally polarized PMIS temperature to the SCS runoff coefficient CN from these watersheds in central Oklahoma.

Cost/benefit.—The 1973 Dynatrend report (ref. 2–1) lists annual benefits in excess of $200 million at 1972 values. A modest saving is recognized for improvements in monitoring impounded water forecasts of irrigation water availability.

Recommendations.—The first requirement is to define and measure CN for the SCS equation. The second requirement is to attempt measurements of individual parameters for use in existing complex runoff equations (soil moisture, soil porosity or infiltration capacity, interception storage, etc.).

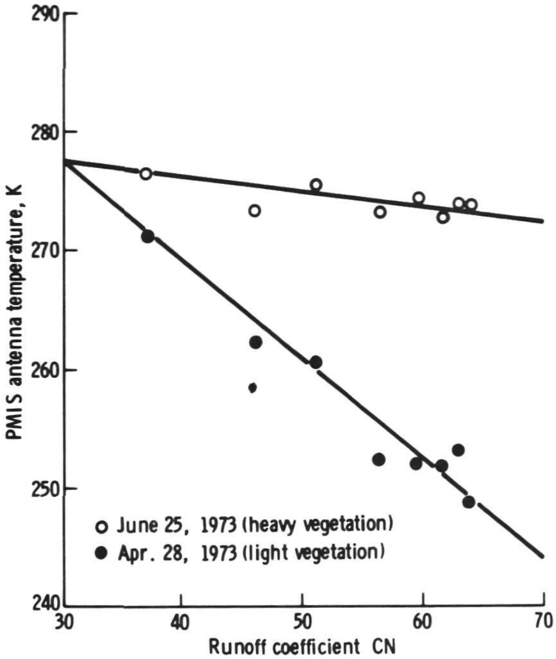


FIGURE 2–6.—Apparent relationship of the horizontally polarized PMIS temperature to the SCS runoff coefficient *CN* from watersheds in central Oklahoma.

During the first phase, aircraft platforms should be used over intensely instrumented watersheds to develop the relationship between microwave response and runoff coefficient. A second set of watersheds should then be used to test these prediction coefficients. Such a program could have results in 2 to 5 yr.

The second phase should be concurrent with the first and should involve use of a truck-mounted system over controlled plots. The experimental design might closely follow the design already initiated at the University of Kansas. After establishing basic relationships for each hydrologic variable, the knowledge must be repackaged for aircraft application.

Estimates of streamflow based on network analysis.—The objective of this application is to measure a different parameter of storm runoff; namely, Strahler numbers. This analysis is independent of the drainage-basin size and could therefore be more universally applicable than the previously discussed SCS runoff equation.

In the evaluations of ERTS–1 imagery, several investigators have shown the capability of satellite imagery for defining basin shapes, sizes, and drainage patterns. The extent and direction of streamflow were defined by imagery, and high-quality correlative streamflow data have been acquired by the data collection system (DCS) and used by State and Federal agencies. Historical streamflow data, which were routinely collected at gaging stations, have been extrapolated to ungaged sites by relating stream discharge to geometric and surface characteristics of the drainage basin. Some of the basin variables most easily extracted from ERTS–1 imagery are amount of open water, area of vegetative cover, area of snow cover, network geometry, drainage area, and major basin modifications by man; that is, urban development or cultivation.

The application of airborne radar to the identification and measurement of drainage-basin variables has been investigated by McCoy (ref. 2–49) and Lewis (ref. 2–18) (fig. 2–7). Investigation has shown that each different radar system yields different amounts of detail; however, the consistency of information content in any given radar system allows extrapolation of data to the level of detail that would be available on a 1:24 000 topographic map. This potential exists for each of the stream network variables in drainage basins, but it is strongest for basin area, total network length, total number of stream segments, and basin perimeter. High levels of correlation were found to exist between data derived from topographic maps and radar imagery. Figure 2–8 illustrates this general conformity. Because radar imagery can be the base for a reasonably accurate map of drainage-basin networks, it has proved to be very useful in compiling and updating drainage maps of inaccessible, cloudy environments such as the Amazon Basin.

Drainage area and stream network length are readily measured from radar images, and

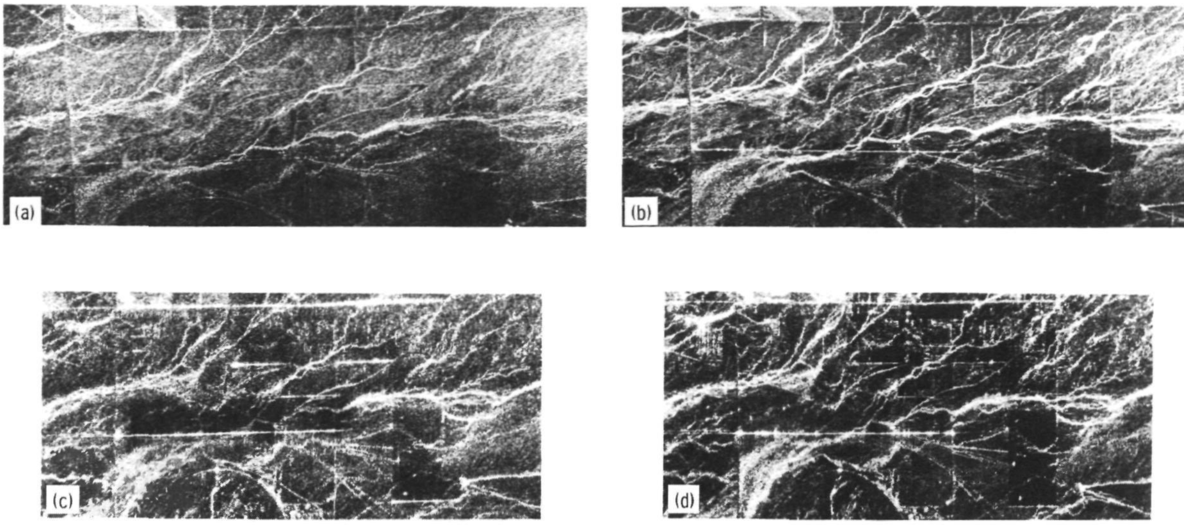


FIGURE 2–7.—Simultaneously obtained dual-frequency radar imagery of creek drainage patterns east of Gilbert, Ariz. (April 5, 1974); resolution is 10 by 10 m. (*a*) An X-band parallel polarization. (*b*) An X-band cross polarization. (*c*) An L-band parallel polarization. (*d*) An L-band cross polarization.

each is a significant variable related to streamflow. Assuming that terrain texture (expressed as network length) and drainage area are valid expressions of the surface characteristics affecting runoff, radar imagery can provide useful hydrologic information. To illustrate the potential of radar imagery in streamflow estimates, length measurements from radar imagery were compared to their rendition on existing maps and later correlated with streamflow. Figure 2–9 shows the relationship of network lengths obtained by edge enhancement of radar imagery and by manual measurement on topographic maps. Figures 2–10 and 2–11 show relationships of streamflow to terrain variables taken from topographic maps but that are available from radar images.

Functional requirements.—The functional requirements of the system are as follows:

1. Frequency: K- and X-band imaging has been successfully used; no information is available for other frequencies.
2. Resolution: A 15- to 100-m resolution has been tested satisfactorily. Better resolution appears not to be required.
3. Coverage: Large areas of coverage (as much as 100 km^2) within a zone of shallow depression angles (20° to 50°) would be most useful for low-distortion mapping of large basins.
4. Repetition: Regular repetition is important only when a DCS is being used. For basin geometric measurements, repetition is not necessary.

Justification: Drainage mapping and measurement of drainage geometry obtained from active microwave sensor data give results comparable to topographic maps (1:24 000). The added advantage of large areal coverage in a single frame is important.

Anticipated results: Water management agencies at the State and national levels would be able to establish streamflow or unit area runoff models for ungaged drainage basins that would be of great benefit in surveys of potential water yield. Water-supply estimates would become available for regions where no data are now available.

Recommendation.—Two key research areas

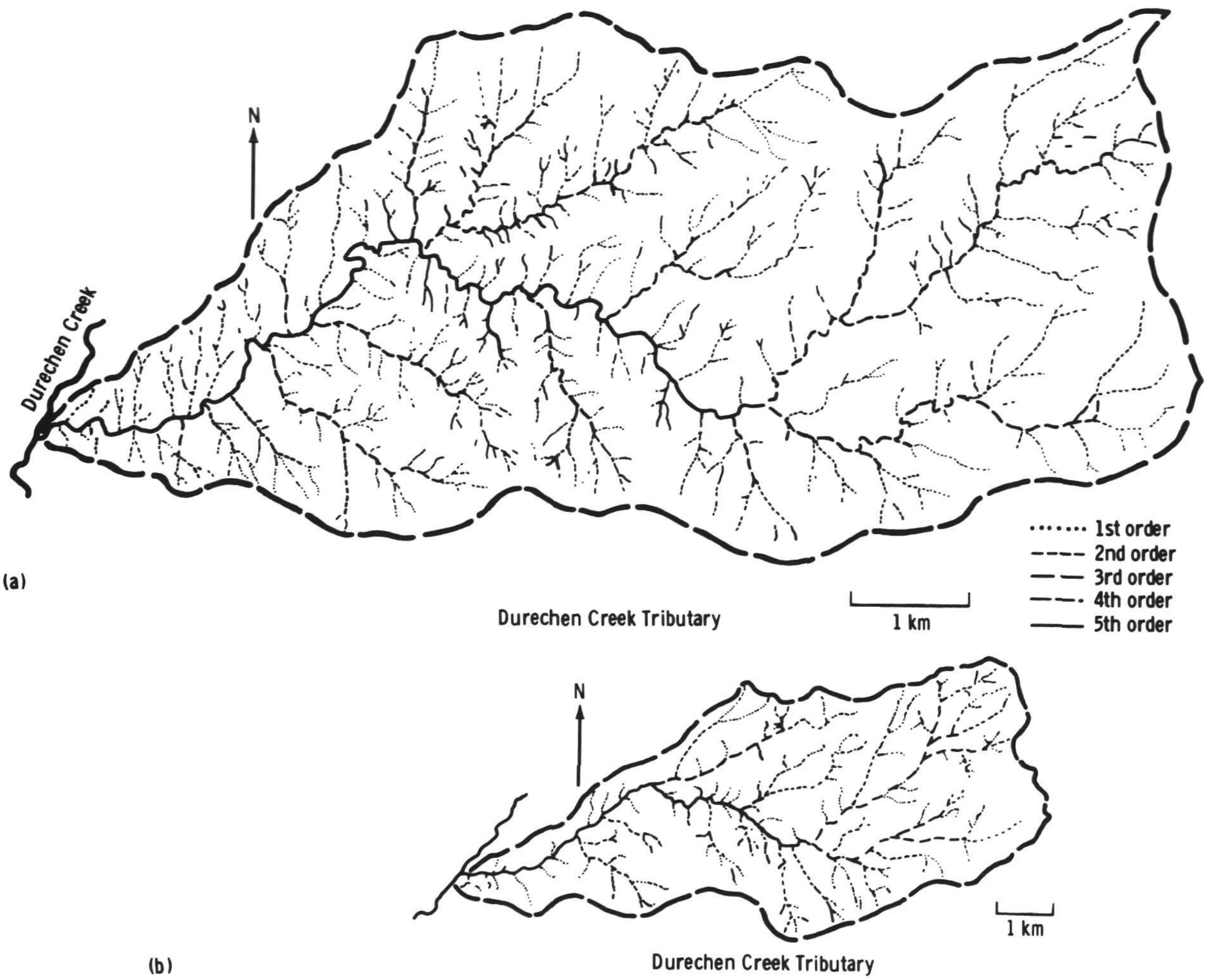


FIGURE 2–8.—*Correlation between drainage basin data derived from topographic map and from radar imagery of the Durechen Creek tributary.* (*a*) Topographic map; scale of 1:24 000. (*b*) K-band radar.

should be pursued: (1) Models relating hydrologic variables to terrain variables obtained from radar imagery should be developed and tested, and (2) techniques for automatic measurement of terrain variables from radar imagery should be developed further.

Flood Mapping

General objectives.—The general objectives are to study the extent, duration, and seasonality of flooding in both rural and urban settings. Data concerning the extent and duration are needed in real time, whereas seasonality requires long-term repetitive coverage for several years. Ground-cover analysis is viewed by many as an approach to determine infrequent or singular flooding (e.g., 100-yr floods). A program of flood mapping would provide additional remote-sensing data for delineating flood plains and thus be a primary benefit to land use planning authorities.

Demonstrated remote-sensing performance compared to objectives.—Evaluation of available satellite and aicraft imagery of floods has indicated that feasible methods exist for mapping the extent of inundation several

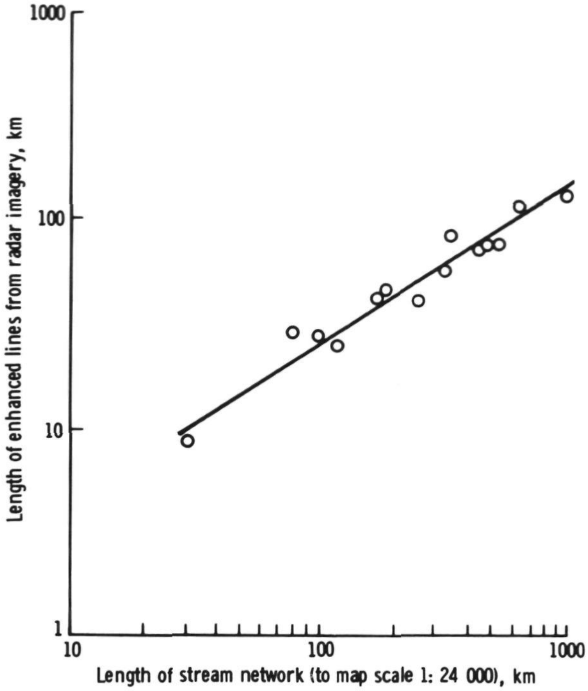


FIGURE 2–9.—Stream length measurements based on radar imagery compared with manual measurements on topographic map.

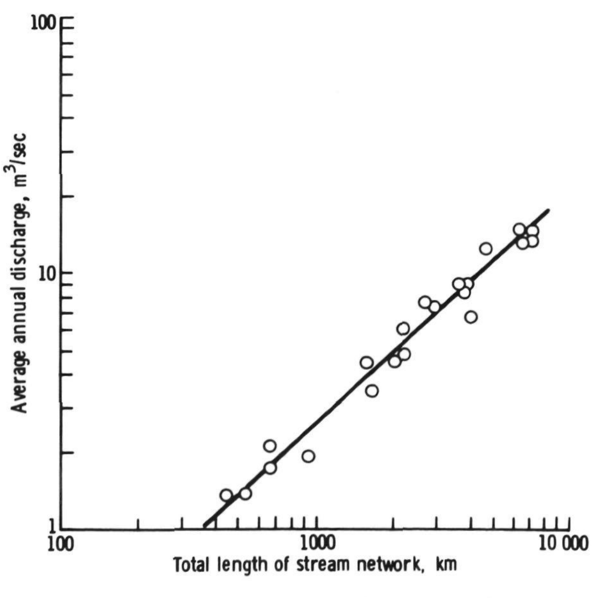


FIGURE 2–10.—Average annual discharge of stream as a function of the total length of stream network.

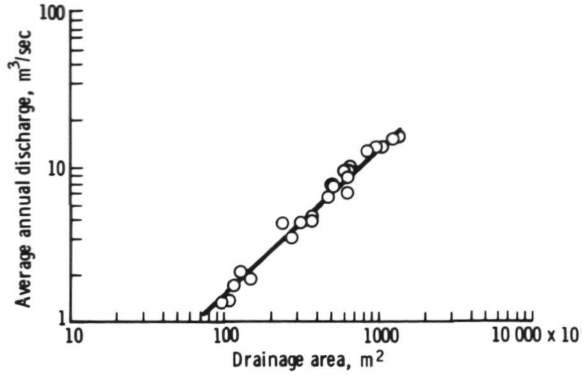


FIGURE 2–11.—Average annual discharge of stream as a function of the stream drainage area.

days after floodwaters have receded. The main phenomena mapped are the latent effects of high soil moisture on soil reflectivity and plant reflectivity. Characteristics of IR radiation (including the absorption of near-visible IR wavelengths by water, the reduced IR reflectance of wet soil and stressed plants, and the different reflective properties of snow and ice at IR wavelengths) have shown that IR photographic techniques are satisfactory for flood mapping (ref. 2–50). In addition, it has been demonstrated that Kodak IR Aero film 2424 with an 89B Wratten filter produces imagery that permits detection of floodwater levels following the recession of those waters. For example, such a study dealt with the floods in southeastern Michigan following a northeasterly storm on Lake Erie in the spring of 1973 (ref. 2–51). The items detected were the flotsam line remaining at the high-water mark.

Major flooding originates in a drainage basin, generating a pulse of water that eventually reaches a major tributary moving downstream. Flood crest at a given point may occur during nondaylight hours or at times when photographic sensing is not possible. Real-time knowledge of the extent of local inundation is vital for improving civil defense procedure. In a less real-time context, data could be used for flood-plain management.

Active microwave sensors could significantly enhance real-time data acquisition. In

addition, active microwave sensors should provide excellent flood inundation mapping because of the high moisture dependence of the electrical properties (e.g., dielectric constant) of the soils. Figure 2–12 shows APQ–97 imagery of the 1973 Missouri River flood. Some wavelength radar systems capable of reasonable penetration into the soil (2 to 5 cm) have been used to map changes in near-surface soil moisture for bare soils. Operation of wavelengths in the 20- to 30-cm range appear to enable soil moisture monitoring even under vegetative canopies (ref. 2–52).

Functional requirements for active microwave measurements.—The functional requirements are as follows:

1. Frequency: L-band (30 cm).
2. Resolution: 30 m.
3. Coverage: 20-km swath width.
4. Polarization: Dual polarization (like and cross).
5. Stereographic: Highly desired.

Processing.—The data will be processed as follows:

1. Onboard processing required for aircraft and Space Shuttle.
2. Display and distribution to consist of real-time capability, permanent record on print developed onboard aircraft, and digital tapes to be recorded for later processing and enhancement.
3. Real-time ground truth required and documentation with conventional aerial photographic techniques where possible.
4. Satellite data to be telemetered and processed in real time at data collection centers; data to be rapidly transmitted to users by telecom links.

Unique justification for active microwave sensing.—Nighttime and all-weather observations are required.

FIGURE 2–12.—Radar imagery of the May 1973 Missouri River flood. Water appears as black, which indicates areas of no signal return, because its surface is smooth to a wavelength of approximately 3 cm.

Anticipated active microwave results in 5 to 10 yr.—After 5 yr, 95 percent accuracy is anticipated in the use of active microwave sensing for flood-disaster monitoring and 100 percent accuracy is expected after 10-yr use. After 5 yr, 70 percent accuracy is anticipated for flood-plain mapping; after 10 yr, 95 percent accuracy is expected.

Users.—Two primary uses will be made of the data by the agencies shown in the following list.

1. Extent and duration of flooding: U.S. Geological Survey, State geological surveys, U.S. Army Corps of Engineers, U.S. Office of Emergency Preparedness, and State civil defense offices.
2. Seasonality of flooding: U.S. Department of the Interior, U.S. Environmental Protection Agency, State offices of planning and programing, and State land-use planning agencies.

Value.—Conventional flood-mapping investigations cost thousands of dollars and require months and even years to complete. Remotely sensed data of floods offer timeliness and synoptic coverage at low costs. (When active microwave sensors are used, timeliness is improved as a result of all-weather observations.) By improving runoff predictions, an annual saving of approximately $150 million in flood damage has been estimated (ref. 2–1).

Recommendations.—Active microwave research investigations of flooding and flood plains should be conducted to define the optimum sensor configuration for aircraft and satellite systems.

Mapping of Lakes

General mapping.—The general objectives of this water resource activity are to (1) map surface water bodies, (2) measure their surface areas, (3) calculate their changing levels for predicting floods or estimating hydroelectric potential, and (4) interpret and map the resource base of wetland environments.

Demonstrated performance.—The near-IR bands (6 and 7) of the ERTS MSS produce large tonal contrasts between land and water, which clearly define the land/water interface. Lakes less than 0.5 hm^2 and streams only 65 m across have been identified on ERTS imagery. Turbidity and plume patterns are also discernible on the visible and near-visible bands.

Reports on the utility of ERTS imagery for wetland studies have indicated that mapping the land/water interface, upper wetland boundary, plant community boundaries, spoil banks, and dredge and fill operations are all feasible on 1:250 000 ERTS imagery (refs. 2–53 and 2–54). At larger scales (1:125 000), information on transition zones, plant communities (such as *Spartina patens* and *Juncus roemerianas*), and drainage on mosquito ditches can be identified (ref. 2–54).

The application of side-looking radar to the detection of water bodies has received little attention. The one study that discusses this topic in depth is by Roswell (ref. 2–55). Roswell determined that the detection of lakes on radar imagery is based on (1) the large contrast between radar return from the land and water, (2) the frequency occurrence of bright return from the far range of the water body, and (3) the drainage elements around the water body.

Environmental parameters (relief, slope, and drainage) were found to influence microwave detectability. The relationship is such that lake detectability decreases with increasing relief and slope and decreasing drainage (i.e., poorly drained environs). As expected, the highest percentage of lake detection is in well-drained lowlands. In these areas, 60 percent of the lakes between 1 and 3 hm^2 and 93 percent of the lakes larger than 15 hm^2 were detected on imagery having a 15-m resolution. Simpson (ref. 2–56) reported a 100-percent detection of all lakes larger than 4 hm^2 on imagery from the same system. Radar imaging systems might therefore be valuable for updating maps ranging in scale from 1:250 000 to 1:24 000.

Roswell states that, although detectability increases with lake size, the extent of radar shadowing and layover is more important than the resolution of the radar system. Roswell's data indicate that lake detection is consistently lower in the near range than in the middle or far range. No single look direction proved better for lake detection, but, in high-relief and slope areas, multiple looks increase detection.

Functional requirements.—Based on Roswell's data, it appears that an X-band system would be adequate for lake detection, although the optimum frequency is unknown. Resolution of approximately 5 to 10 m would also be adequate. With respect to depression angles, detectability is poorest in the near range. Therefore, angles of 15° to 45° are suggested. Repetition, including multiple looks, is important for both increasing detection and monitoring lake-level changes.

Processing may also be important. By processing the data to favor the variation of return from the lake rather than land surface, radar imagery may provide more than a medium for lake detection. Added information, such as windspeed and direction based on water-surface roughness or the detection of oil slicks, might possibly be obtained.

Unique applications.—Three applications unique to active microwave sensing are (1) monitoring lake-level changes, (2) monitoring spring thaw of ice-covered lakes, and (3) studying wind patterns over water.

Anticipated results.—The surface-water hydrology of many parts of the world is relatively unknown. Radar imagery could provide accurate information at very low cost. Mapping ephemeral lakes in arid and semiarid regions would also improve regional climatic data to permit the introduction of new land-use practices.

Recommendations.—Future work should document the conditions under which lakes can be detected on radar images. The practicality of active microwave systems for supplying flood prediction and regional climatic data by lake monitoring should be emphasized.

Specific applications: lake levels, lake flooding, and eutrophication.—Active microwave sensors can contribute data on at least two limnological characteristics: seasonal change in lake levels and eutrophication. Areas flooded by high lake levels could be identified with radar and could provide guidance regarding potential shoreline uses to Federal, State, and local planners and resource managers. Seasonal lake-level data would also be useful for assessing water supply. Eutrophication is an important clue to the ecological balance around a lake and to man's impact on the local environment. Eutrophication affects wildlife and drastically alters the local recreational resource and water supply.

Remote sensing of lake levels.—Lake-level changes can be approached by studying temporal changes in shoreline positions. Conventional aerial photography has been used to document lake-level changes and shoreline positions in Lake Rudolf. Lind (ref. 2–57) has applied ERTS data to assess seasonal changes in lake levels in Lake Champlain. Satellite observations have also been conducted on saline lakes in the United States.

For large lakes, synoptic and systematic coverage of the type that can be obtained from aircraft or satellites is desirable and can yield useful information on the effects of lake-level change. Active microwave sensors offer special advantages because they can be applied on demand when, for example, maximum or minimum stages have been reached. For many of the tropical regions, where cloud cover usually obscures the high-lake stage of the annual cycle, active microwave sensor data offer the only reliable means for assessing those lake levels.

The application of active microwave sensors should include not only large freshwater bodies (e.g., Great Lakes), but also farm ponds, beaver ponds, prairie potholes, and sinkholes. Microwave remote sensing can also apply to the brackish and saline water bodies along desert margins. Such information may facilitate the use of lake waters for irrigation purposes and for water supply (through possible desalinization). Fresh, brackish, and saline lakes are scattered throughout the developing countries of the world, and data on water quality and fluctuation patterns could provide the basis for use of the waters and shores in a manner consistent with the individual environmental settings.

Resolutions of 3 to 10 m could conceivably provide the necessary data for lake-level studies. Other functional requirements that apply are those associated with existing conventional SLAR systems.

Seasonal coverage is a critical temporal requirement due to the fluctuation pattern of lakes. For mid- and high-latitude lakes, a minimum of two annual synoptic coverages would be needed to encompass the extreme periods of fluctuation. For tropical lakes, a somewhat greater frequency seems desirable because there are often interseasonal fluctuations. Thus, four annual synoptic coverages spaced to include the extremes and the transition periods leading to maximum and minimum levels would provide minimum data. On a worldwide scale, weekly observations would be needed to cover the time range of fluctuations for the diverse lake-level regimes.

Processing.—Processing the image data can be accomplished through standard photointerpretation procedures or through semiautomated or automated optical processing. An overlay procedure used in the mapping of lake levels for Lake Champlain is just as applicable for radar image data.

Display and distribution.—A map format involving the transfer of shoreline position to suitable base maps would provide users with a readily usable product; however, basic processed radar images could also provide data for resource management decisions. The scale of presentation is somewhat dependent on the resolution of the data involved. A scale of 1:62 500 is satisfactory for larger areas. Larger scales (e.g., 1:10 000) could be possible with finer resolution data.

Supplementary data.—When available, lake gage data should be related to the remotely acquired data to establish a relationship between specific gage values and shoreline changes. Thus, it would be possible to establish certain critical gage levels relating to specific shoreline positions. However, because most of the lakes of the world are ungaged, the remote-sensing data would need to be sufficient. For areas where reliable topographic maps exist, some relatively crude relationships might be established. Though useful, gage data are not critical to successful remote sensing.

Justification.—Because they can be applied at the appropriate times regardless of cloudiness and time of day, active microwave sensors would provide an especially valuable source of data on lake-level changes and effects. Reliability on a temporal scale is critical to assessing lake levels; thus, because many lakes are in the cloudiest portions of the globe, radar could make an important national and worldwide contribution. Although especially important limnologically, this contribution has considerable practical resource significance.

Anticipated active microwave results.—If properly researched and developed, the application of radar could pave the way toward—

1. Providing basic data for mapping seasonal lake-level changes on a systematic basis regardless of cloud-cover problems, which severely limit visible sensors.
2. Establishing lake fluctuation models based on water budgets (relationship to key climatic factors).
3. Providing maps and/or processed images of seasonal or multiseasonal fluctuations in lake level.

Because the technology for the study of lake levels is already available, implementation of a program of such surveys using active microwave sensors could be easily established within a 5-yr period. Improvements in resolution to provide the best possible data for this task will probably result in a 90-percent mapping accuracy. This level of accuracy may already be attainable, but no detailed studies exist to confirm it.

Cost/benefit considerations.—No cost/benefit studies seem to exist that address this application area even at a local level. Increases in data-gathering efficiencies attributable to radar and the multiple use of radar data for other applications would seem to provide at least a moderate-level benefit. This benefit, combined with the fact that lake-level data for most lakes of the world are nonexistent and could be supplied through radar applications, seems to tip the balance toward a favorable cost/benefit ratio.

Recommendations.—The mapping of lake levels with active microwave sensors can be implemented without much further research. Research relative to mapping accuracies seems to be needed; however, the overall application should not be hindered by this need.

Although aircraft could be used for highly detailed studies, the base data for large-scale investigations involving lakes in different climatic regions could be obtained from satellite vantage points and Space Shuttle vehicles. Because data processing can be done with known techniques, the results could be made available within a short time and without major expense for data processing. In summary, radar surveys of seasonal lake-level changes should provide immediate and useful results.

Eutrophication and plant growth in lakes.—The application of active microwave sensors for lake eutrophication is limited to detection of various floating and surface-protruding plantlife forms that often accompany the advanced stages of eutrophication. Color and color IR aerial photography have generally been used for investigations of lake plant growth; for example, Scherz (ref. 2–58) and Kiefer and Scherz (ref. 2–59). Only one investigator (ref. 2–60) has indicated the potential that radar may have for these studies. Many plant forms come to the water surface and therefore would be susceptible to radar detections. Algal mats, extensive water-lily and water-hyacinth infestations, and various water weeds are examples. These plant growths may attain such large proportions that they affect the qualities of lakes. In parts of the tropics and subtropics, for example, water-hyacinth infestations have ruined entire lakes. Some assessment of the degree of plant growth in lakes is of considerable importance. Microwave remote sensing provides a means for systematically monitoring detrimental plant growth in lakes, which is illustrated in figure 2–13.

Observations with like- and cross-polarized radar show that a clear distinction can be made between vegetation-covered water bodies (ricefields in Texas) and adjoining land or vegetation-free lakes. On like-polarized imagery alone, the vegetated water surface might be mistaken for land; on cross-polarized imagery the presence of vegetation might be missed.

Functional requirements.—Research is needed to establish accuracy levels for both detection and mapping. The following functional requirements are estimates:

1. Spatial resolution: 3 to 10 m.
2. Gray scale resolution: 5 to 10 dB.
3. Wavelength: 1 to 30 cm.
4. Polarization: horizontal transmit/horizontal receive (HH) and horizontal transmit/vertical receive (HV).
5. Wavelength bands: 2 to 3.
6. Swath width: 20 km.
7. Ground truth: to establish accuracies in detection and mapping.
8. Collateral sensors: visible and IR, which may not be required.
9. Underflight sensors: visible.
10. Timing: seasonal (three to four times a year minimum).
11. Format to user: maps and processed images.

Justification.—Water resources and management agencies are especially concerned with the problem of plant growth in lakes. Active microwave sensor data would provide the agencies with information on the extent of infestation. Although this phenomenon can be assessed with conventional visible sensors, radar offers a supplemental coverage in those regions where cloudiness would prevent the timely use of conventional sensors and in

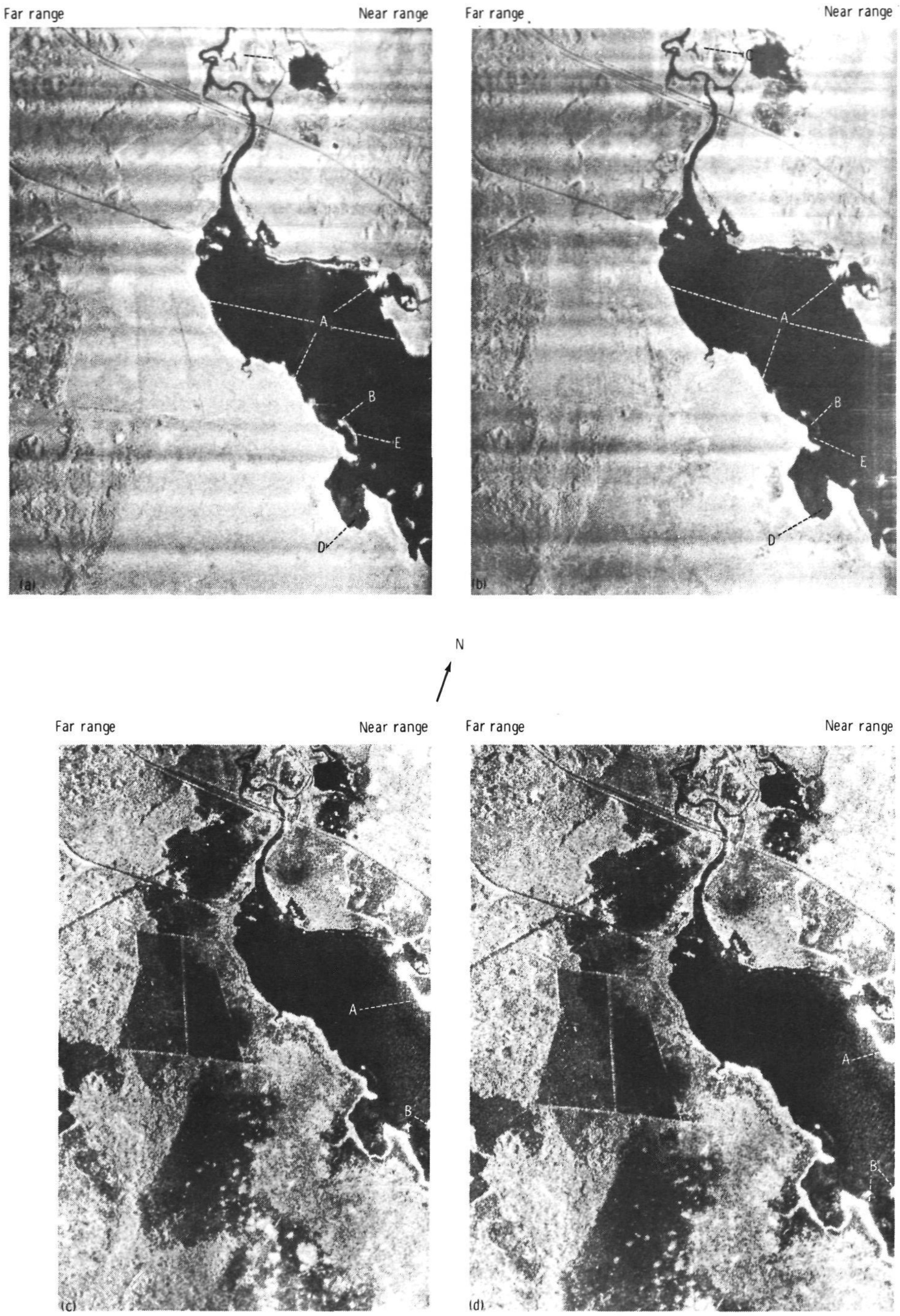


FIGURE 2–13.—Simultaneously obtained dual-wavelength radar imagery of Lake Poinsett region, St. Johns River, Brevard County, Florida; resolution of 10 by 10 m. (A—stationary water hyacinths, B—floating (migrating) water hyacinths, C—region of river channels choked with water hyacinths, D—water lilies, E—reeds growing and anchored in river.) (*a*) An X-band parallel polarization. (*b*) An X-band cross polarization. (*c*) An L-band parallel polarization. (*d*) An L-band cross polarization.

other regions where persistent cloudiness is found.

Recommendations.—Because radar has not been previously used for this application, a research effort is required to establish accuracy levels for detection and mapping and to establish radar system parameters. Such research could be completed within 5 yr. After the necessary experimentation, the operational use of radar could be implemented, which could occur within 5 to 10 yr.

Coastal Wetlands

General statement of problem.—The coastal zone is a unique environment in which three spheres interact: lithosphere (land), hydrosphere (ocean), and atmosphere (air). The coastal zone is therefore a highly variable, dynamic, and complex region. The high utility of the coastal zone is affirmed by high land values and population densities. Pressures are being exerted on the land, water, and air by those who wish to use the region for recreational, industrial, and commercial development. Not enough is known of the coastal zone to properly evaluate these uses.

Coastal geomorphologists interested in the frequently cloud-obscured coastal zone are increasingly using active microwave systems. Imaging radar provides a continuous image strip exhibiting a high-contrast coastline. Because coastal change is often greatest during the height of a storm (ref. 2–61), the near-all-weather ability of microwave systems should provide data that would aid in better understanding the process of coastal erosion.

Demonstrated remote-sensing observations.—Coastal maps have been updated by using radar (ref. 2–62). In addition, a variety of coastal zone features has been mapped in Panama and Colombia (refs. 2–18, and 2–62 to 2–64). An example is shown in figure 2–14. Most of these features were mapped for the first time and, as a consequence, pro-

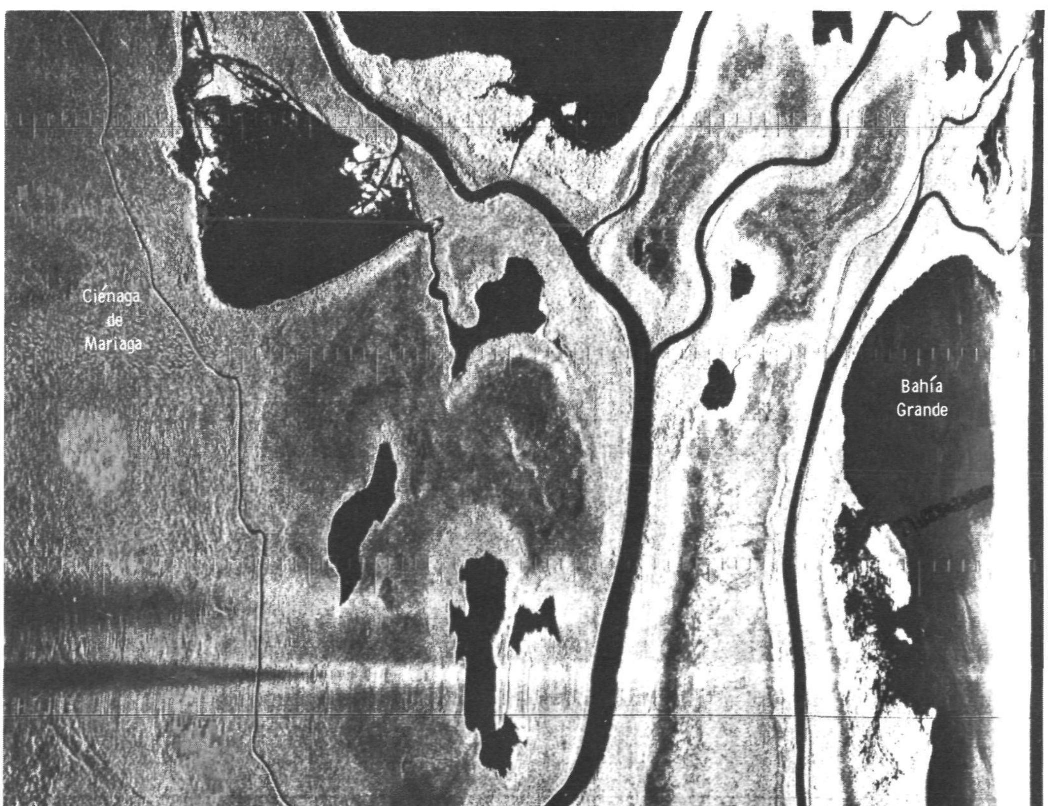
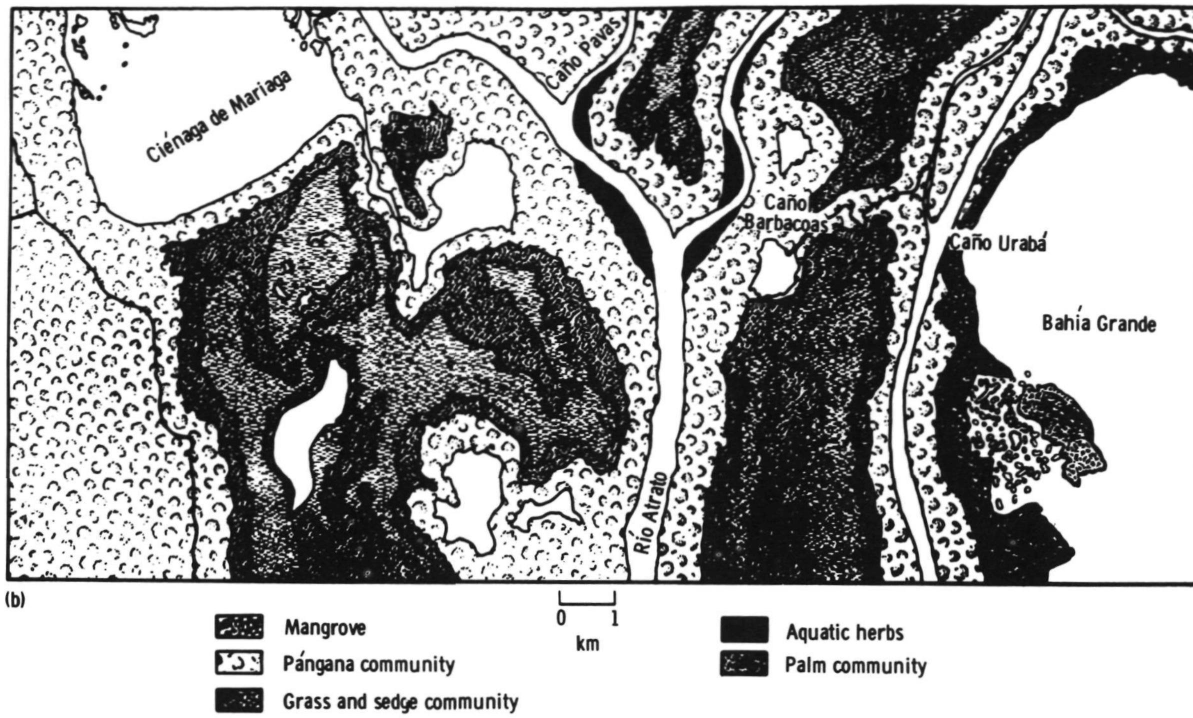


FIGURE 2–14.—Coastal map and radar image of an area of Panama. (*a*) Radar image.



(*b*) Radar-derived map showing various coastal zone features.

vided information on the tidal influence, wave energy, and climate not previously known (ref. 2–18).

The detection of tidal zone features, such as mud flats and shell reefs, and the surf zone has subsequently been found to be strongly affected by position in the range (fig. 2–15). Like the detection of lakes, these features are better detected in the near range (ref. 2–65).

Cultural features unique to coastal/wetland environments are also evident on radar imagery. These features include marsh buggy tracks, access canals and pipelines, offshore oil platforms, ships and accompanying wakes, jetties, groins, piers, and buoys. The effect of groins can be monitored by noting the deposition on the upcurrent side of the groin.

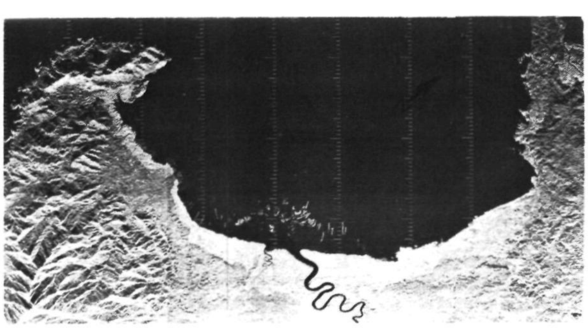


FIGURE 2–15.—Example of radar imagery showing coastal features.

For strictly freshwater coasts, a study conducted under the ERTS program is pursuing the comparison of several near-simultaneous imagery sets for identification of the extent of coastal flooding. This study used aerial IR photography, ERTS–1 MSS imagery, and dual-frequency, dual-polarization SLAR imagery. The analysis has not been completed, but the correlation between the preliminary interpretation of the imagery from the three sensors is quite high. Figures 2–16 to 2–18 are maps derived from these data.

Functional requirements.—Most data requirements could be satisfied by an aircraft-mounted sensor. Periodically gathered satellite data would serve best for change

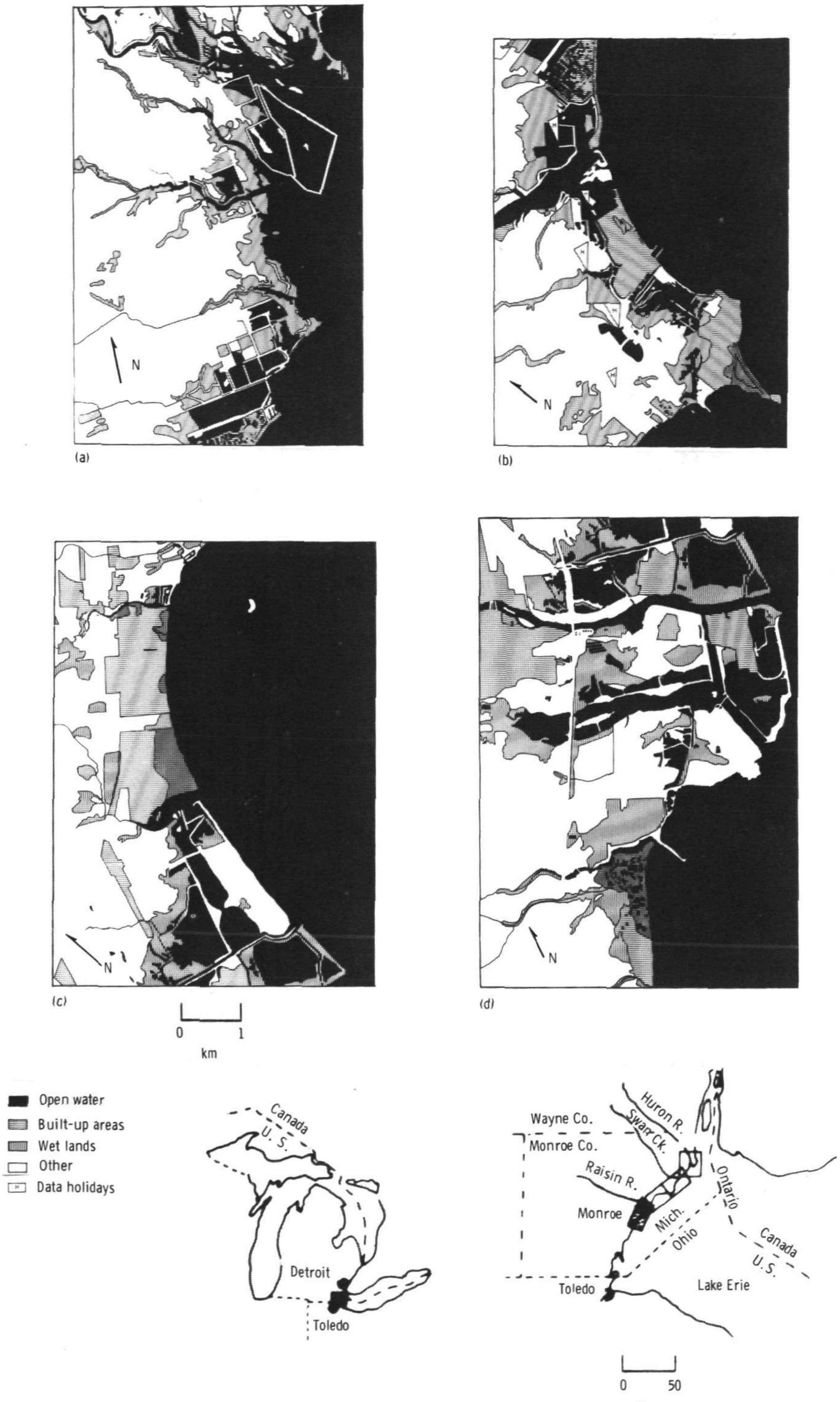


FIGURE 2-16.—Interpretation of aerial IR imagery of coastal flooding in the Great Lakes region. (*a*) View 1. (*b*) View 2. (*c*) View 3. (*d*) View 4.

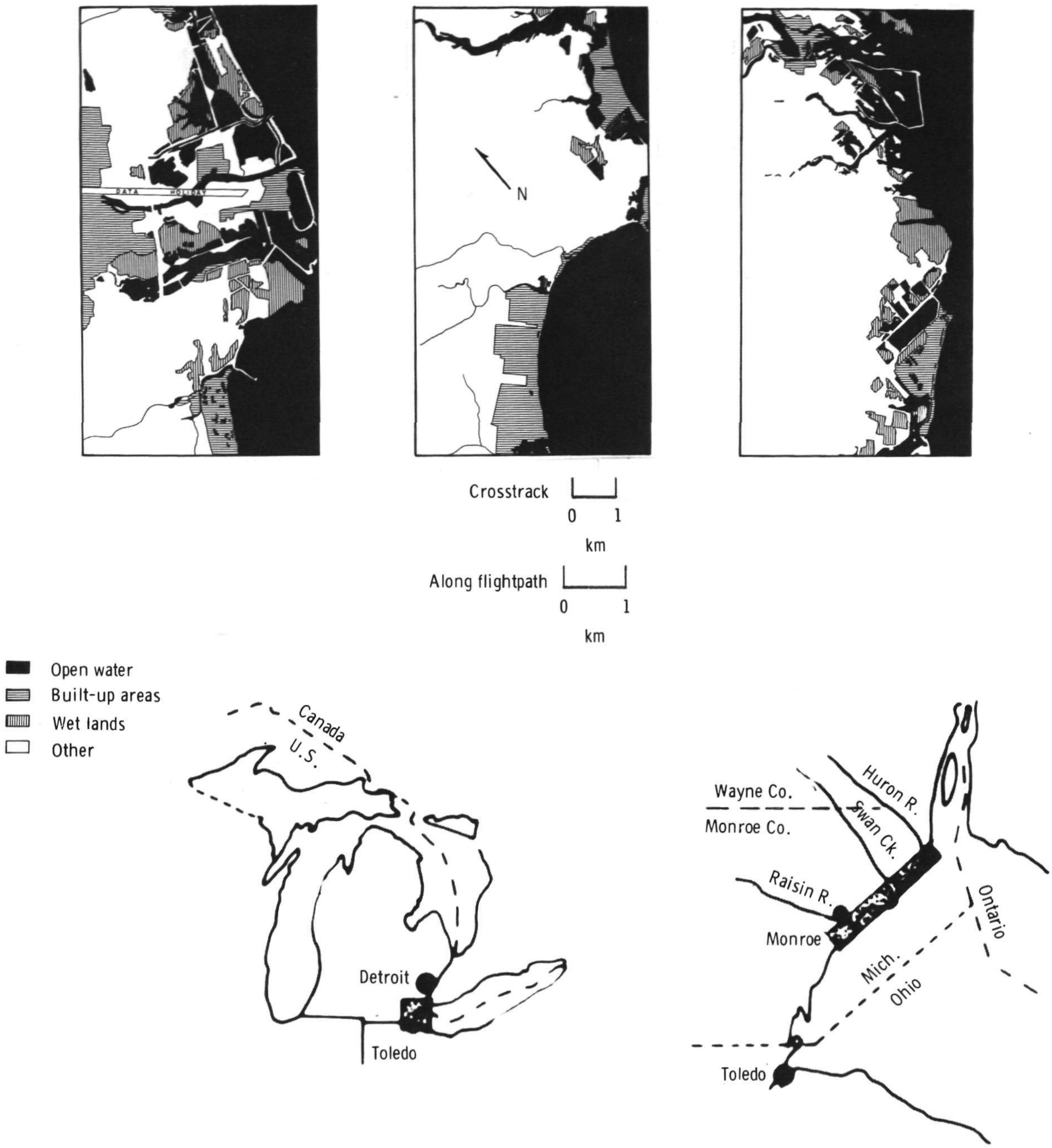


FIGURE 2–17.—Interpretation of SLAR imagery of the Great Lakes area.

detection, whereas data on random or ephemerous phenomena would require more flexible aircraft systems.

Resolution requirements and other system specifications would vary, depending on the scale of the study and the features or processes involved. For example, the 15-m resolution of most of the imagery previously used is generally suitable for coastal mapping of scales of 1:125 000. Occasionally, detailed

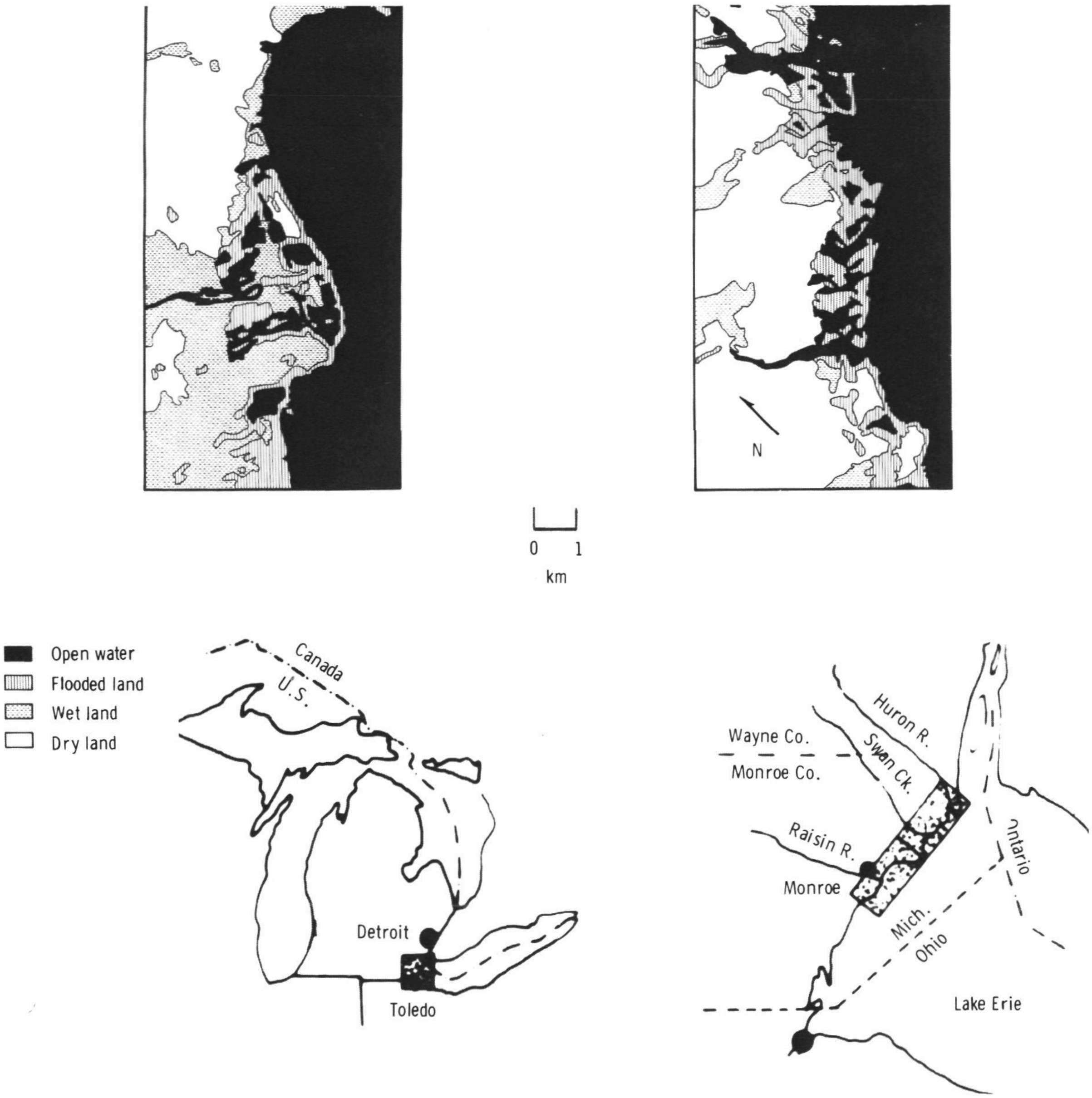


FIGURE 2–18.—Interpretation of ERTS–1 MSS imagery of the Great Lakes area.

mapping at 1:62 500 can be accomplished. An increase in resolution to 3 m would disclose new uses for active microwave systems not mentioned previously.

The optimum depression angles vary with both the type of region (coastal mountain as compared to coastal plain) and the features to be identified. In flat coastal plains, shallow depression angles between 3° and 17° would provide maximum topographic information. The use of low depression angles results in the enhancement of topography and suppression of vegetation or surface material information. Radar shadowing is increased and would be undesirable in other than flat terrain with subtle topographic relief or slope angle.

The use of high depression angles (between 45° and 76°) is valuable in mapping mangroves (ref. 2–62), lakes (ref. 2–55), tidal flats, shell reefs, and surf zones (ref. 2–65). These features are much easier to define in the near range of present operating systems.

Alteration of the gain setting to record the subtle tonal changes in the low-return areas of open sand, some marsh vegetation, and water would provide information not available with the radar imagery taken with AGC setting for the normally high-return land targets. The use of magnetic tape to record the signal and special processing techniques would be one approach to solving the problem and providing the user with a sliding, expanding, or contracting dynamic range.

In low coastal plain environments, look direction is not especially important. However, the best look direction appears to be with the aircraft flightpath parallel to the shoreline and with the imaging system over the water looking toward land. This look direction is especially important for high-cliffed or mountainous coasts; otherwise, the shoreline would be obscured by radar shadow.

STUDY OF HYDROLOGY OF SOLID WATER

This section briefly explores the literature concerning remote sensing of ice and snow surfaces. Four areas of interest are considered: (1) permafrost, seasonally frozen ground; (2) glacial ice (both cold and temperate), including the concept of sounding polar icecaps with a nonimaging radar; (3) snow, with special reference to the study of the free water content and water equivalent and the use of these data for hydrologic applications; and (4) freshwater lake ice, including a description of a presently operational system oriented to problems of navigation through the ice in the upper Great Lakes of the United States and Canada.

The problems of remote sensing of the Earth surface materials are highly complex and have been the subject of numerous articles. With snow and ice, there are constraints not associated with many other materials. The most obvious constraint is temperature, because the maximum attainable temperature is 273 K. A second constraint is that, at this maximum temperature, water can exist in two states: liquid and/or solid. To a degree, this dual state can also occur at slightly lower temperatures if the liquid phase is transitory or newly introduced from without. Also, snow generally has a fairly high albedo in the visible portion of the electromagnetic spectrum, which makes it readily seen against darker, natural backgrounds.

Aerial photography and satellite photography are excellent sensors for identification of snow-covered areas (refs. 2–66 to 2–69). In addition to conventional photography, radar has been useful in identifying snowfields (ref. 2–36) and could be used for delineating aerial distribution of these features. Active microwave sensors have an output that is computer compatible, have essentially all-weather capabilities, and could provide near-real-time information.

Permafrost

Introduction.—Permafrost is defined as a temperature condition of the ground, and permafrost is said to exist when the temperature is permanently below 273 K. Often, but not always, this condition coincides with the presence of frozen ground; that is, ground in which ice is present.

Permafrost poses severe problems in geotechnology, construction of pipelines, roads, airfields, dams, and oil and mineral exploration and recovery. These problems are often associated with volume percentages of ice in excess of the pore volume of the soil and rock matrix; thus, melting of the ground can result in collapse and soil failure. The large-scale activities planned in Alaska—transportation corridors, the Alaskan oil and gas pipeline, and the military pipeline from the Naval Petroleum Reserve—might benefit from more reliable remote sensor data. The need for or location of heat pipes along the Alaskan pipeline is an example of the possible integration of two technologies.

Basic objectives of remote sensors for *permafrost*.—The information sought from sensors for geotechnical endeavors are—

1. Delineating permafrost bodies in the discontinuous zone.
2. Locating permafrost "windows" in the continuous zone.
3. Determining ice content of permafrost.
4. Determining the thickness of permafrost.
5. Determining the depth of thaw of the active layer.
6. Monitoring degradation of permafrost caused by natural (e.g., forest fires) and manmade activities.

Sensor capabilities.—To adequately discuss sensor capabilities, some basic facts about permafrost must be outlined.

1. Permafrost occurs in almost every known soil and rock type; thus, the variations in geological and dielectric properties of permafrost are as large as those observed in unfrozen ground. Only by comparing similar material types in the frozen and thawed state are certain differences discerned. For example, permafrost with resistivities less than 50 ohm-m were observed in marine sediments at Barrow, Alaska, whereas permafrost at Galbraith Lake had a resistivity of 10^6 ohm-m (greater than frozen limestone).
2. The top 0.5 to 1 m of permafrost thaws in the summer and is frozen in the winter. This "active layer" often consists of a saturated, organic material. The large seasonal variation in surface properties greatly influences sensor capabilities.
3. The depth of permafrost varies from 1 km in the most northern regions of the U.S.S.R. to less than 1 m at the southern boundary of permafrost (e.g., Copper River Basin in Alaska).

Geotechnical endeavors often require that the information listed previously (in the section regarding basic objectives) be obtained to a depth of 15 m. For example, the thaw bulb under the buried section of the proposed Alaskan pipeline will reach a depth of approximately 10 to 15 m after 2 yr of operation.

Table 2–II lists the geophysical, electrical, and electromagnetic sensors used in the past and planned for the future to probe permafrost to depths of 15 m or more. The application of these methods relies on the fact that frozen and unfrozen ground differ in electrical resistivity (fig. 2–19) and that the ice content of the ground is related to resistivity (fig. 2–20).

The dielectric properties of frozen ground at ultrahigh frequency (uhf) and microwave frequencies are mainly determined by the amount of liquid water in frozen soil. The dielectric loss of a frozen soil as a function of temperature is shown in figure 2–21. Based on these data and on the fact that in the summer the top 0.5 m of permafrost is thawed and water saturated, active microwave sensors will lack the penetration required to satisfy the geotechnical objectives previously listed.

However, this limitation does not mean that active microwave sensors have no use

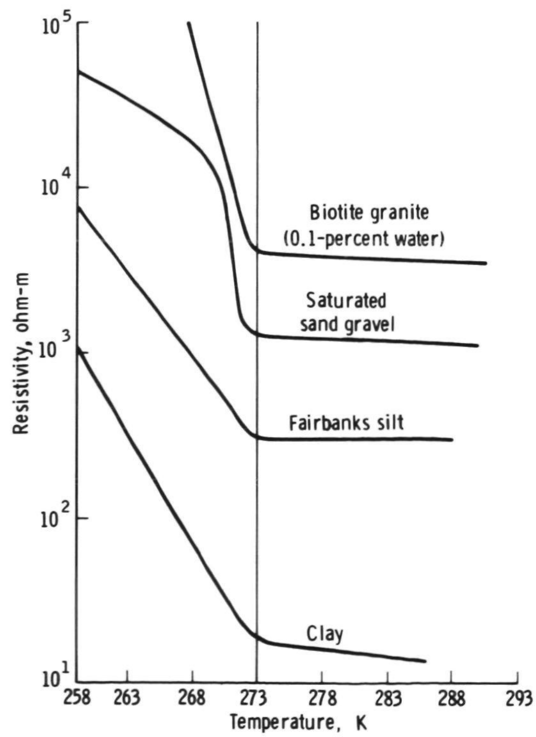


FIGURE 2–19.—Resistivity of soil types and a rock type as a function of temperature.

c, 2

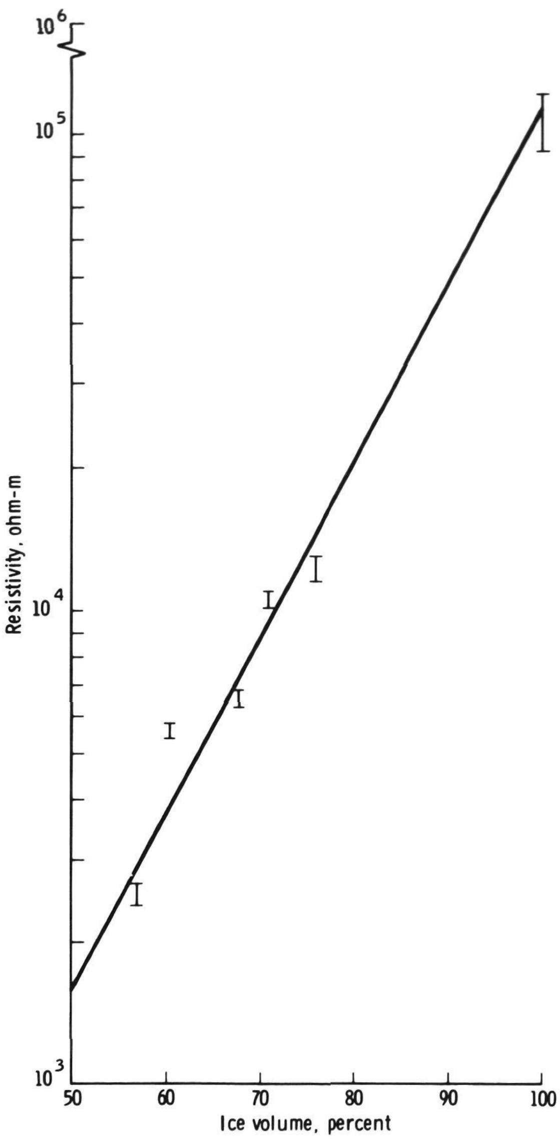


FIGURE 2–20.—The resistivity of frozen Fairbanks silt as a function of ice content by volume.

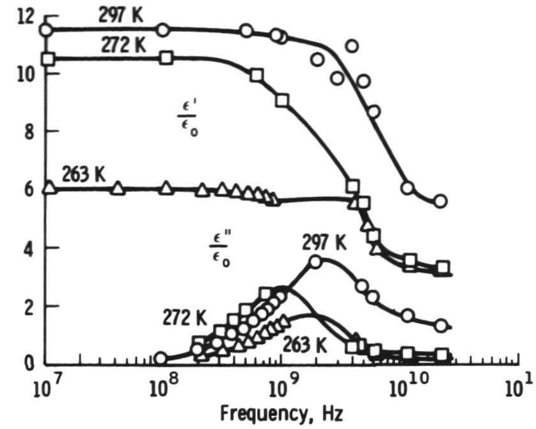


FIGURE 2–21.—The dielectric constant ϵ'/ϵ_0 and the dielectric loss ϵ''/ϵ_0 for a clay soil at several temperatures as a function of frequency.

in permafrost regions. The starting point of any exploration program is a good base map of the area on, for example, a 1:2500 scale. Because of the all-weather and day/night operation, SLAR may significantly reduce the cost of photocoverage.

Finally, the previous statements apply to geotechnical exploration. Permafrost differs from other regions of the world only in the presence of permanently frozen ground. All objectives pertaining to geology, surface water, and oil and mineral exploration apply equally to polar regions, perhaps even more so, because of the general inaccessibility of Arctic regions.

Demonstrated remote sensor observations.—Next to surficial geological mapping from aerial photographs, the most promising sensors for reducing the cost and improving the quality of subsurface exploration in the Arctic are those used in airborne resistivity mapping techniques. Several airborne surveys have been conducted in Canada and Alaska, and more are planned.

The ERTS imagery of Alaska has provided some high-quality photographs of all areas of Alaska. These images are used for—

1. General landform mapping.
2. Determining areas covered by lakes and some estimates on the depth of the lakes.
3. Maps of snow cover extent.

The U.S. Geological Survey Mohawk aircraft with SLAR imaging equipment were flown over the coastal plains near Barrow, Alaska. The images distinguished between lakes frozen to the bottom and lakes with a certain amount of water under the ice. Conventional photographic coverage has been used to monitor the environmental effect of recent construction.

Functional requirements.—Functional re-

TABLE 2–II.—*Summary of Geophysical, Electrical, and Electromagnetic Sensors Used and Planned for Permafrost Mapping*

Sensor type	Frequency	Comments	Present users
Galvanic resistivity measurements.	dc	Deep penetration possible; area coverage expensive.	Sensor is frequently used in U.S.S.R., Canada, and United States for onsite exploration.
Ground and airborne radiowave methods.	15 kHz to 1 MHz	Penetration as much as 91 m; cost approximately $30 per line mile.	First surveys were flown by Geological Survey of Canada, U.S. Geological Survey, and Cold Regions Research and Engineering Laboratory (CRREL) in 1973; system is going into routine operation.
Ground and airborne dipole-dipole methods.	100 Hz to 10 kHz	Ground method in use; airborne methods under development.	Several geophysical companies offer equipment and service for ground measurements; airborne equipment is available for mining technology only.
Magnetotelluric measurements.	0.001 Hz to 10 kHz	Under development and testing.	Sensor is used by the U.S. Geological Survey, Geological Survey of Canada, and CRREL.

quirements are identical to those listed under geology, cartography, oil and mineral exploration, and surface waters.

Permafrost summary.—The greatest need for remote sensing of permafrost areas of Alaska, Canada, and the U.S.S.R. is in geotechnology, route selection, and site selection. Sensors need to be developed that reduce the amount of exploratory drilling and provide better extrapolation between drill holes. Improved subsurface information will reduce environmental damage to permafrost terrain.

Because of the depth required in geotechnology, the most successful sensors should operate in the frequency range from 100 Hz to 1 MHz. High-altitude aircraft and satellite sensors may have a supporting role in geotechnical exploration.

Except for the study of geotechnology, the sensor requirements for permafrost regions do not differ from the sensor requirements for other areas of the world. Hence, the objectives pertaining to geology, land use, and surface waters apply equally to permafrost terrain.

Glacial Sounding

A unique application of active microwave systems exists in the cold glaciers of the world (glaciers in which the temperature is permanently below 273 K). Two major examples are the Greenland and Antarctic ice sheets. Because of the low signal attenuation in snow and ice, microwave radiation penetrates to great depths. A pulse that is transmitted from an antenna mounted under an aircraft is partially reflected from the air-ice interface and partially transmitted into the ice where it is subsequently reflected from the ice-bedrock surface and from other layers in the ice.

Attempts have been made to use similar systems on temperate glaciers, sea ice, and lake ice. In general, signal attenuation, limited thickness, and inhomogeneities have caused problems. Some of these problems may be alleviated in future systems.

Snow Cover

For many drainage basins in the temperate zones of the world, melt waters represent a major part of the annual yield of the basin. To properly use this water resource and to control flood drainage from high-stream discharges during the melt period, hydrologists must have timely information to perform their long- and short-term forecasts. Long-term forecasts are important for irrigation, navigation, hydroelectric power, and water supply. These forecasts are usually made on an annual basis. The initial prediction is made at the beginning of winter, based on moisture conditions existing in the drainage basin at that time, and the basin response (annual runoff) is projected to various levels of snow accumulation (normal, above normal, and below normal) during winter months. The initial forecasts are revised as additional data on the areal extent of snow cover, depth of cover, and water equivalent become available. This forecasting process continues through the snowmelt period when additional data become important in determining the volume of melt-water runoff.

Therefore, the basic objective of the long-term forecast is to provide as accurate a prediction of annual runoff from snowmelt as possible and with sufficient leadtime to provide maximum use of the runoff. Attaining this objective requires accurate monitoring of snow cover. Specific uses and user agencies would include

1. Irrigation: Irrigation districts, U.S. Department of Agriculture, U.S. Bureau of Reclamation, and State regulatory agencies.
2. Hydroelectric power: U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, Bonneville Power Administration, public power utilities, and private power companies.
3. Water supply: U.S. Bureau of Reclamation, State regulating agencies, water supply districts, and municipalities.
4. Navigation: U.S. Army Corps of Engineers.

Short-term forecasts are primarily involved in flood prediction and assessment of flood-hazard potential. Severe snowmelt floods have occurred in the upper Missouri River and Mississippi River basins in 1965 and 1969. Although flood damage was extensive in both instances, good forecasts of the flood potential and advanced planning by Federal, State, and local authorities served to mitigate the amount of damage. Improved techniques for forecasting could result in even less damage. For flood-forecasting purposes, accurate definition of the areal distribution of the snow cover, snow depth, and water equivalent of the snow are important, as well as the rate of production of snowmelt runoff. The principal Federal agencies involved in flood forecasting are the National Weather Service (NWS) and the U.S. Army Corps of Engineers. Numerous agencies are involved at the State and local level.

Demonstrated remote sensing observations.—Barnes (ref. 2–70) reports results indicating that ERTS imagery from MSS bands 4 and 5 have substantial practical application for snow mapping. The author states that snow cover can be mapped in more detail than is depicted on aerial survey snow charts. Barnes also indicates that ERTS MSS band 7 may be used to distinguish between wet snow and dry snow. Meier (ref. 2–71) reports that, for cloud-free and nonforested terrain, ERTS imagery enables rapid measurement of snow cover for specific drainage basins, but he reports that cloud cover causes problems in identification. Weisnet (ref. 2–72) performed a comparison of ERTS NOAA–2 data for snow-cover mapping and obtained good results.

Haefner et al. (ref. 2–73) have used imagery from ERTS for mapping snow cover in the Swiss Alps. The authors believe the imagery has potential, although many problems remain to be solved.

Active microwave results.—Knowledge of radar return from snow is limited. It is known that old snow gives strong isotropic returns at 35 GHz, at least in summer. It is also known that snow returns at 35 GHz (in the spring at Quebec) are strong enough to obscure the underlying terrain features. Dielectric properties of snow are known. Dry-cold snow has a permittivity close to unity and has low loss. Compacted cold snow has a higher permittivity but has low loss. Snow containing water in unfrozen form has much higher permittivity and loss. Research by Waite and MacDonald (ref. 2–36) indicates a feasibility for mapping the extent of old snow cover by using K-band imagery, regardless of most weather conditions. Their work also indicates a significant difference in signal return between old and new snow.

Functional requirements.—Active microwave sensor requirements for snow mapping are dictated by the need to measure moisture content of snow, depth and extent of snow, and moisture content or freeze/thaw status of soil. A dual-wavelength microwave system is desired to give short-wavelength response from snow cover and long-wavelength penetration data. A spatial resolution of 15 m is desired, but a resolution of 100 m would be useful. Systematic, reliable coverage on a weekly basis is needed.

If a proper model of the dielectric and geometric properties of natural snow in its various states were available, a theory could be developed to show optimum frequencies and polarizations for the different measurements. Enough is known about the physics of snow and backscatter to permit starting such research immediately.

Although theory can guide system development and data interpretation when properly validated, experiments are needed both to validate the theory and to obtain information for conditions not included by the theory. Furthermore, airborne experiments will be required to develop techniques for use in operational systems.

Ground-based measurements should include the following: (1) controlled and artificially simple snow conditions, (2) natural snow conditions at a site that can be monitored continuously throughout a winter season in which snow remains on the ground for several months, and (3) natural snow conditions in a variety of locations. Because of numerous sites, only occasional measurements can be made of each site. Measurements should be made with a swept or stepped frequency system covering a range of approximately 4 to 40 GHz. Because frequencies above 20 GHz may not soon be usable in space, the measurement might stop at 18 to 20 GHz, but comparison with existing 35-GHz images would certainly be desirable. Multiple polarizations are necessary initially, although early data should be scanned to determine the utility of multipolarized data.

Aircraft measurements will require radar systems at appropriate frequencies; thus, an early attempt should be made to verify the applicability of the X-band. Although synthetic aperture radar will be needed in space, a real aperture system can be used on an aircraft, which will simplify the task of scheduling and locating suitable radars. This system should make flights over test sites having a variety of conditions. For most purposes, operational considerations can determine whether multiple flights over a few sites or a few flights over widely differing sites should be made. However, repeated flights over at least one site should be made to enable testing of change detection.

Repeated aircraft missions are required in the research phase. As the system becomes operational, aircraft mission needs will change, but they may not diminish. Spacecraft can provide regular surveys that will suffice for mapping large-scale phenomena. For short-range forecasting, aircraft missions flown between spacecraft missions will be desirable in areas where meteorological conditions favor rapid melting. The magnitude of this need can be determined only after more information is known on the radar response of snow cover of different kinds.

Spacecraft missions will need to cover critical areas in the mountains biweekly from first snow until near the end of spring melt. Whether weekly coverage by spacecraft is desirable during the melt or whether this need can be satisfied by aircraft should be the subject of a tradeoff study.

Freshwater Ice

Several questions are asked concerning the relationship of remote sensing to lake ice: (1) What do sensors really measure? (2) What can be inferred from these measurements? and (3) What information about lake ice is really needed?

Interpretation of remotely sensed data on lake ice is available (e.g., refs. 2–36, 2–74, and 2–75), but generally these data have been qualitative rather than quantitative. Larrowe interpreted images by comparing airborne photographs taken simultaneously with the radar imagery (X-band, HH polarization). In all the studies, the lack of ground truth seriously limited any real study of the radar imagery concerning ice structure and thickness, crystal orientation, pressure and thrust features, cracking, and similar features.

In the study of seasonal lake ice, the day-to-day changes in the structure and distribution of snow on the surface of the ice sheet will possibly affect the structure of that ice sheet. Newly fallen snow and the drifting of this snow around and in the lee of obstacles on the ice sheet is, if sufficiently thick, capable of producing a significant insulative cover on the ice and thus retarding ice growth (ref. 2–76). In addition, when snowfall is small, ice growth is greater assuming that other climatological and limnological parameters are constant. The possibility also exists that, on a sheet of thin lake ice, the snowfall may be sufficiently great to exceed the bearing strength of the ice, causing it to crack. Cracks may also be caused by thermal expansion and contraction (ref. 2–77). Water, infiltrating through such a crack, may mix with and saturate the overlying snow, forming a slush layer that, when frozen, forms a highly granular ice layer (referred to as "snow ice" or "white ice"). This type of ice is uniquely identifiable on SLAR imagery (ref. 2–78).

Another commonly identifiable feature is called an ice foot. An ice foot is described as being "composed of any combination of frozen spray or lake water, snow accumulations, brash, stranded ice floes, and sand that is either thrown on the ice by wave action or is blown out from the exposed beaches" (ref. 2–79). Although an ice foot is a localized feature, because it occurs only on shorelines of relatively large lakes, it is an important indicator of geomorphic activity along the shoreline. Ice foots often persist into the spring after much of the lake ice has been melted or blown into the lake; thus they act as breakwaters, protecting the shoreline from erosion and deposition. If not removed from the shoreline, ice foots can present a hazard to navigation in a manner similar to icebergs in the North Atlantic. Several recent papers have described these ice foots (refs. 2–78, and 2–80 to 2–82), which are clearly visible on SLAR imagery (fig. 2–22).

Some attributes of lake ice that may be measurable by microwave remote sensing are—

1. Ice thickness, temperature profiles, rates of growth, and structures.
2. Snow accumulation, moisture content and density, and metamorphic stage.
3. Spatial and temporal distribution and thickness of both ice and snow cover, together with the spatial and temporal distributions of open water.

Lake-ice monitoring is an area in which the prototype for an operational system is most advanced. During the winter of 1973 to 1974, the initial steps for an ice information system were taken by a joint agency effort involving the U.S. Coast Guard, NWS, NASA, and the U.S. Army. The system used X-band SLAR imagery from two U.S. Army aircraft and one aircraft operated by NASA Lewis Research Center. Images were interpreted by the research team at Lewis Research Center, following the return of the SLAR-equipped plane to its base; and the image, together with an interpretive chart, was relayed for approval to the Ice Information Center at Cleveland, Ohio. After inclusion of data obtained from visual flights and inclusion of thickness data acquired by NWS, the approved ice chart, together with the radar image, was transmitted to those ships and shore installations having telefacsimile equipment. Approximately 200 such ice-chart radar image products were produced and distributed during the ice season (fig. 2–23).

Midway through the ice season, data from a short-pulse-radar ice thickness profiler, being developed by Lewis Research Center, were incorporated into the ice information system. This special radar was mounted on a C–47 aircraft operated by Lewis Research

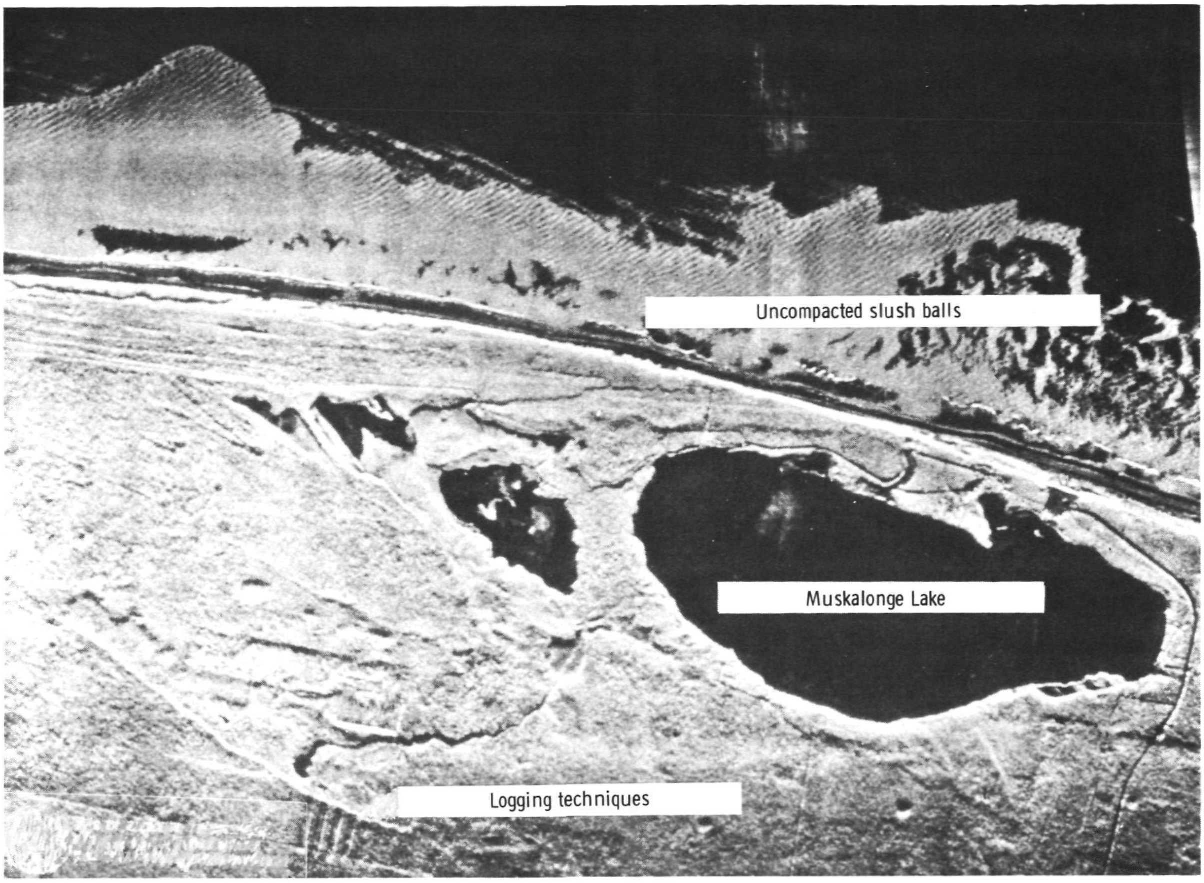


FIGURE 2–22.—X-band radar imagery of northern Michigan shoreline. Bright ridge along the shoreline is an ice foot; note the disconnected ice foots along shore between the slush balls and Muskalonge Lake.

Center and was capable of measuring ice thickness with an accuracy of approximately 5 cm from altitudes up to 1500 m.

Although further studies will be required, preliminary results from this study indicate that the dynamic range of reflected power from the entire range of natural ice/water targets spans only 20 dB. If this fact is true, it is especially important because considerable simplifications in data recording, telemetry, and processing systems could be affected. However, some data from the real aperture system operated by Lewis Research Center seem to indicate a larger dynamic range.

The functional requirements for lake-ice monitoring may be summarized as follows:

1. Frequency: X-band, cross-polarized seems to be adequate.
2. Resolution: 40-m spatial resolution and 2-dB intensity resolution are adequate. Intensity should be recorded over a 20-dB range.
3. Coverage: A swath width of 100 km is adequate, if properly centered.
4. Repetition: Daily coverage would be desirable; however, several passes each day, as would be possible for an equatorial satellite system, are preferred.
5. Recording medium: Digital tape recording onboard is preferred.
6. Timeliness: Update is desired daily; old data are of no use in navigation. However, ice forecasters can use data, together

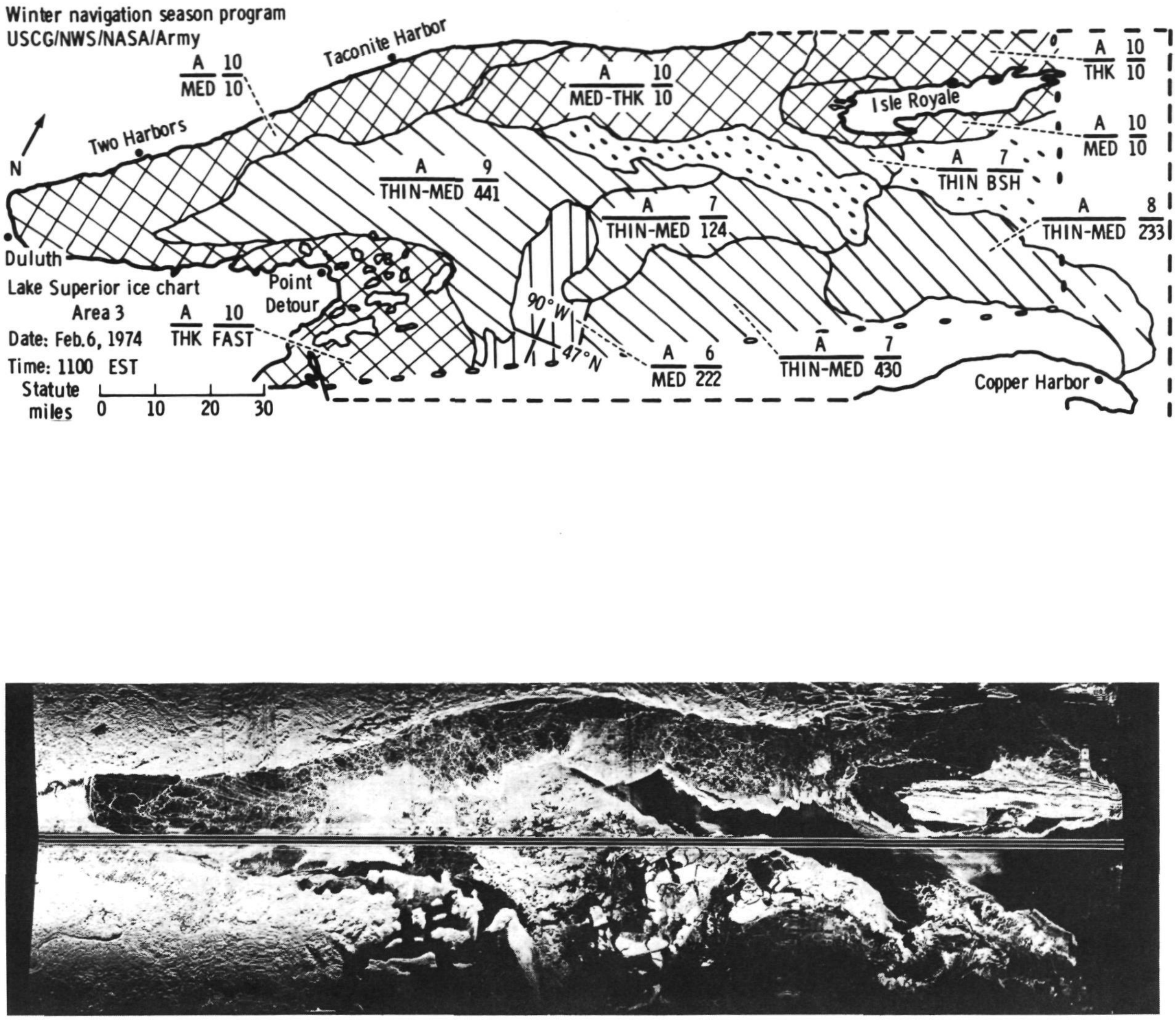


FIGURE 2–23.—Example of an ice chart and the related X-band radar image for the Lake Superior area.

with meteorological data, to predict freezeup and thaw.

7. Scale and projection: Generally, a scale of 1:1 000 000 is used, but for some areas the scale is 1:500 000. The type of projection is irrelevant.

Summary for Hydrology of Solid Water

This section is divided into three topics: (1) permafrost, (2) snow cover, and (3) lake ice. Glaciology, per se, is not directly addressed. However, valid inferences can be drawn from information presented here.

The major objectives of permafrost sensing are location and depth measurement. For many problems involving signal penetration, active microwave systems will be of minimal use. However, the primary contribution of active microwave systems will be the collection of data for base maps to be used in geophysical exploration. Functional requirements are essentially the same as those pertaining to geology, mineralogy, and civil works (table 2–I).

Snow-cover sensing demands a high priority because of the need for better data in runoff prediction, water management, and flood prediction. Much research is needed to determine the feasibility of acquiring data for both water content of snow and the determination of the snow-water equivalent.

With respect to lake ice, a relatively low-resolution (50 m) system would be adequate for operational navigational problems in the upper Great Lakes. A prototype operational system using existing radars has already been initiated. Ice thickness is still a major problem because there are, at present, no known surrogates to aid interpretation. Several short pulse radars that could provide this much-needed data are operational, but their utility in space is marginal.

For lake-ice hydrology, the major needs are more intense ground truth and development of interpretation techniques. Existing radars will probably fulfill the vast majority of the data needs.

WATER POLLUTION

General Objectives

Many governmental agencies are interested in water pollution data. Although the Environmental Protection Agency is the major Federal agency empowered to investigate pollution problems, the U.S. Army Corps of Engineers, the U.S. Geological Survey, and the U.S. Coast Guard also have jurisdictional responsibilities. Amendments to the Federal Water Pollution Control Act, passed October 18, 1972, began a two-phase program to eliminate the discharge of pollutants into navigable waterways. In response, the U.S. Coast Guard began a program of pollution monitoring using remote-sensing techniques, including microwave remote sensing.

Because local, Federal, and international environmental/water resource agencies have the chief responsibilities of identifying, monitoring, and inventorying water pollution, they become data users and must either establish their data collection systems or depend on systems provided by other agencies. Remote sensors have both complementary and supplementary capabilities to provide data not otherwise available. A general objective in remote sensing is to provide rapid assessment of pollution accidents and to provide both supplementary and complementary data relating to pollution monitoring from continuous and semicontinuous sources. For active microwave sensing, the following objectives can be outlined.

1. Determine the nature and extent of inadvertent or intentional oilspills and monitor their dispersion either as they occur or shortly afterward. Possibly assess oil-slick thicknesses.
2. Determine the nature and extent of debris spills and monitor their dispersion.
3. As a complementary sensor, monitor pollution outfalls for surface effects and extent (i.e., scums, flotsam, foam, and water turbulence).
4. As a supplementary sensor, monitor pollution sources during nighttime and during weather conditions that prohibit the use of other remote sensors.
5. As a complementary and supplementary sensor, assess the effects of pollution (i.e., development of excessive algal growth and degradation of shore vegetation).

Demonstrated Remote-Sensing Observations

Aircraft platforms.—Aerial photographic systems have been extensively used in water pollution. Color and color IR imagery have been evaluated by several investigators as summarized in table 2–III by Welch (ref. 2–83). Qualitative studies have predominated, but there have been attempts to measure spectral properties of pollutants and their backgrounds. Examples of such studies include Neumaier and Silvestro (ref. 2–84), Villemonte et al. (ref. 2–85), Lillesand et al. (ref. 2–86), and Piech (ref. 2–87). To date, there has been limited success in quantifying heavy concentrations of industrial wastes.

TABLE 2–III.—*Photographic Specifications for Water Pollution Studies*

Problem	Best film-filter combination [a]	Best black-and-white film-filter combination [a]	Smallest scale used successfully	Notes
Water movement	Color, 1A	Pan, 25A Pan, 58 Pan, 90	1:60 000	Some water impurities caused confusion.
Detection of pollutants	Color, 1A	Pan, 25A Pan, 90	1:60 000	Color is significantly better than black and white.
Oil pollution	Pan, 47B Ortho, 18A	Pan, 47B Ortho, 18A	1:8000	Overcast day appeared to be best.
Inventory of kelp	Color IR, 12	IR, 89B	1:24 000	Sun glare caused problems.
Selecting underwater park sites.	Color IR, 12	None used	1:10 000	Stereoscopic vertical and oblique views were very useful.

[a] Numbers designate Wratten filters. A partial list of suitable film includes the following:
Color: Kodak Aero Negative (MS), Ektachrome Aero, Ektachrome X, and Kodachrome II, Anscochrome.
Color IR: Kodak Ektachrome IR Aero.
Pan (Panchromatic): Kodak Plus-X Aerographic, Double-X Aerographic, and Tri-X Aerocon.
Ortho: Kodak Royal Ortho, commercial.
IR: Kodak IR Aerographic.

A few attempts have been made to interpret other forms of pollution such as algae and aquatic plant concentrations. For example, plant growth on lakes can be outlined with color IR photography (ref. 2–59). Oil slicks have also received attention. Sensors ranging from ultraviolet (ref. 2–88) to thermal IR (ref. 2–89) to radar (ref. 2–90) have been studied. Many other studies have been undertaken for surveillance of thermal discharges using IR scanning (refs. 2–91 and 2–92).

Satellite platforms.—Sensing from orbital altitudes has taken various forms, ranging from assessment of large water bodies to study of individual point sources. The synoptic view provides a basis for documenting such aspects of water quality as general turbidity and eutrophication. Industrial pollution has been detected and mapped in a qualitative way (ref. 2–57). A variety of seasonal data relevant to the dispersal and distribution of pollutants is provided by satellite coverage (e.g., current, turbidity patterns, and flooding), whereas the applications to specific, local water-quality problems seem to concern mainly aircraft remote sensing. This situation could change with the development of new techniques.

Of all water pollution problems listed, radar has contributed most to the detection and mapping of oil slicks. Estes and Senger (ref. 2–93) and Guinard (refs. 2–90, 2–94, and 2–95) have reported on this application. Guinard concluded that a strong functional relationship exists between radar wavelength, sea state, and oil-film thickness. Evidence suggests the use of low frequencies, combined with low sea states, for detecting thin oil films. Thicknesses as small as 0.5 μm have been detected. Also 30- to 100-m resolution cells were sufficient with radar incident angles in the range from 2° to 20°.

The application of radar to other aspects of water pollution has been limited by the basic characteristics of radar signal interactions with water. Radar does provide information on surface features that either float on the water or change its surface geometry. Oil slicks and kelp beds are examples. Oil slicks smooth the water surface and thus reduce the radar cross section of the water compared to its surroundings. Kelp beds have an opposite effect.

With the prospect of using high-resolution radar, some of the surface effects resulting from local pollution, such as surface scums and foam, should be detectable. No significant research has developed in recent years regarding the application of radar for pollution monitoring of these types of surface phenomena, probably because relatively high resolutions are required, and these data have not been generally available.

Functional Requirements for Active Microwave Measurements

Table 2–IV provides an estimation of certain important functional requirements, based on what little has been done and on some theoretical considerations of radar capabilities.

Data processing.—Image data are required for most analyses. Imagery may be derived directly, as with current operational radar, or may be obtained from CCT. The CCT may be processed in much the same way that conventional scanner data are manipulated to produce a spatial pattern.

Image rectification is an important consideration because correlations with output from other sensors are sometimes required, and these correlations will have to be transferred to a data base. In the case of water pollution data, a map base is needed; and, in many cases, absolute locations must be determined. As noted by Moore (ref. 2–96), all images should be converted to the radar equivalent of orthophotographs when correlation is needed with other remote-sensing images for data analysis. However, because of the state of the art with respect to radar, it is clear that further research is required.

Supplementary data.—Substantial ground-truth data are required to properly evaluate water pollution. Mensuration of the complex nature of certain types of effluents is not yet feasible by remote sensing, and possibly may never be feasible. However, the distinct vantage point provided by aerial and space remote-sensing platforms does provide at least qualitative data that may prove valuable. The significant factor is that a rapid assessment of the spatial dimensions of a problem is usually possible. Assessing the specific attributes of any water pollution problem, whether oil spills or industrial effluents, requires more than can be provided by aerial or space remote-sensing platforms and systems. Thus, surface sampling stations are usually needed. In addition, radar missions would need the support of other proven conventional remote-sensing systems to provide maximum information for most water pollution problems.

Accuracy of calibration.—Because most remote-sensing information is rendered in spatial formats, some type of mapping accuracy must usually be considered. The degree of accuracy required becomes a function of the purpose of the available data. Further research on data accuracy problems within the water-pollution/remote-sensing framework is needed.

Cost/Benefit Considerations

As indicated, remote sensing of water pollution has its principal value in presenting a synoptic view of the areal extent of the problem. It has been estimated that with ERTS, mapping can be reduced to costs as low as $0.03 per square kilometer. Assessment of the distributional patterns of water pollutants often requires numerous simultaneous observations, which are costly in both equipment and manpower. Although it would seem that the cost/benefit ratio could have favorable results, actual evaluations have not yet been performed. The U.S. Coast Guard experience with X-band radar could provide an important test case.

Recommendations

It must be recognized that radar may have limited application in the surveillance of

TABLE 2–IV.—*Estimated Radar Functional Requirements for Monitoring Water Pollution*

Objective	Frequency radar band [a]	Spatial resolution, m	Gray resolution	Temporal aspects	Polarization	Look direction	Angle, deg	Complementary remote sensors required	Platform
Oil slick detection and monitoring.	X	10 to 30	Conventional	Spill report and monthly in hazard areas.	Vertical	Side.	>20	No, but desirable	Aircraft
Debris spill detection and monitoring.	P, X, L, C	0.5	Fine under some conditions	Spill report and monthly in problem areas.	Vertical and horizontal.	Side and down.	Unknown	Yes	Aircraft
Surface effects of effluent discharge detection and monitoring.	P, X, L, C	0.5	Fine under some conditions	Intervals specified by control agencies.	Vertical and horizontal.	Side and down.	Unknown	Yes	Aircraft
Monitoring pollution effects, algal mats, and so forth.	P, X, L, C	1 to 10	Fine under some conditions	Seasonal or semiannually.	Vertical and horizontal.	Side and down.	Unknown	Yes	Aircraft and possibly spacecraft

[a] Synthetic aperture.

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-