EVALUATION OF RADAR IMAGERY FOR GEOLOGIC AND CARTOGRAPHIC APPLICATIONS

SUMMARY REPORT OF INVESTIGATIONS

Compiled By

Gerald K. Moore and Cynthia A. Sheehan

1981

U.S. Geological Survey Open-File Report 81-1358

CONTENTS

TABLES

ILLUSTRATIONS

EVALUATION OF RADAR IMAGERY FOR GEOLOGIC AND CARTOGRAPHIC APPLICATIONS

By Gerald K. Moore and Cynthia Sheehan

SUMMARY AND CONCLUSIONS

The House/Senate conference report on H.R. 4930 (96th Congress), the Department of the Interior and Related Agencies Appropriations bill, 1980, stated that the U.S. Geological Survey should "begin the use of side-looking airborne radar imagery for topographic and geological mapping, and geological resource surveys in promising areas, particularly Alaska." In response to this mandate, the Survey acquired radar data and began scientific studies to analyze and interpret these data. About 70 percent of the project funding was used to acquire radar imagery and to evaluate Alaskan applications. Results of these studies indicate that radar images have a unique incremental value for certain geologic and cartographic applications but that the images are best suited for use as supplemental information sources or as primary data sources in areas of persistent cloud cover.

The value of radar data is greatest for geologic mapping and resource surveys, particularly for mineral and petroleum exploration, where the objective is to locate any single feature or group of features that may control the occurrences of these resources. Radar images are considered by oil and gas companies to be worth the cost of data acquisition within a limited area of active exploration.

Radar images also have incremental value for geologic site studies and hazard mapping. The need in these cases is to inventory all geologic hazards to human life, property, resources, and the environment. For other geologic applications, radar images have a relatively small incremental value over a combination of Landsat images and aerial photographs.

The value of radar images for cartographic applications is minimal, except when they are used as a substitute for aerial photographs and topographic maps in persistently cloud-covered areas. If conventional data sources are not available, radar images provide useful information on terrain relief, landforms, drainage patterns, and land cover. Screenless lithography is a low-cost method of reproducing the images.

The images from modern, commercially available radar systems have good visual quality; they also have better geometric accuracy and higher information content than images from older systems. Images from modern systems, however, also have some of the same disadvantages as those from older systems. The most serious problem is that considerable information is lost in the process of recording the radar return on film. Another problem is that the oblique radar view of the landscape results in interpretations that are biased by look direction. A compromise antenna depression angle also commonly results in inadequate or excessive shadowing in parts of the image. There is a need for high-resolution digital data, not currently available from the private sector, to significantly improve the utility of radar data for geologic and cartographic applications.

INTRODUCTION

The Geological Survey has completed a project to acquire and evaluate modern side-looking airborne radar (SLAR) images. The Geologic, National Mapping, and Water Resources Divisions worked with the Office of Earth Sciences Applications in this effort. The USGS Radar Project began in November 1979 as a result of the House/Senate conference report on H.R. 4930 (96th Congress), the Department of the Interior and Related Agencies Appropriations bill, 1980, that stated: "$2,000,000 from within available funds should be used to begin the use of side-looking airborne radar imagery for topographic and geological mapping, and geological resource surveys in promising areas, particularly Alaska." In response to this mandate, funds were reprogrammed and used to acquire modern, commercially available radar data and to begin scientific studies to analyze and evaluate these data. About 70 percent of the total funding was used to acquire data and to evaluate the applications of radar imagery in Alaska.

The goals of the Radar Project were to evaluate:

- the applicability of radar technology to the U.S. Geological Survey's mission and to the geologic and cartographic communities, and

- the incremental value or the ability to extract from radar images information that is not available from existing data bases.

Project objectives designed to meet these goals were to:

- evaluate geologic, hydrologic, and mineral resources information discernible in radar images, particularly for geologic mapping in Alaska,

- evaluate the applicability of radar images to the improvement of base map preparation, and

- compare results obtained by real and synthetic aperture radar systems with those of other remote sensing systems.

A seminar on results of the Survey's Radar Project was held in Sioux Falls, South Dakota, on August 12-14, 1981. Results and conclusions of the scientific studies conducted by the U.S. Geological Survey, and by Autometric, Inc., and Dr. P. Jan Cannon under contract to the Survey, were presented and are summarized in this report. A panel discussion on the value of radar imagery was held on August 14. Representatives of Congress, universities, industry, and the Geological Survey participated in the discussion and expressed their viewpoints. The range of these opinions is also summarized in this report.

This summary of investigations is not intended to be a final report on the detailed results of the Survey's scientific studies; such documents will be prepared by the individual investigators. A list of radar project studies and principal investigators is provided in Appendix I. Moreover, this report does not address the issue of whether an operational program for the acquisition and dissemination of SLAR imagery should be considered by the Congress; all recommendations are included in a separate document.

RADAR SYSTEM AND DATA CHARACTERISTICS

Radar is an active remote sensing system in which an antenna on the side of an aircraft transmits pulses of microwave energy and receives the corresponding reflections from the ground. Each returning train of reflections is used to record a line of the radar image. As the aircraft moves along a flight line, a continuous strip image is obtained providing a synoptic view with an oblique look direction. The angle between the horizontal plane and a line connecting the target and the antenna is called the depression angle. Radar systems and data are classified according to wavelength (frequency) of microwave energy, polarization of the transmitted and received signals, method of data acquisition and processing (real or synthetic aperture systems), and data type (film or digital).

Wavelengths

The wavelengths used in radar remote sensing are shown in table 1.

Table 1.--Radar bands used for acquisition of remotely sensed data

Band	Wavelength, cm[1/]	Frequency, GHz[2/]
Ka	0.8 - 1.2	40-27
K	1.2 - 1.7	27-18
Ku	1.7 - 2.4	18-12
X	2.4 - 3.8	12-8
C	3.8 - 7.5	8-4
S	7.5 - 15.0	4-2
L	15.0 - 30.0	2-1
P	30.0 - 100.0	1-0.3

1/ centimeters
2/ gigahertz or billion cycles per second

The wavelength selected for the sensing system, the transmission path, and the characteristics of the Earth's surface interact to affect the amount of energy returned to the sensor, and thus, the tonal brightness of the image. In transmission of shorter wavelengths (K- to X-band), considerable microwave energy may be absorbed and backscattered in the atmosphere by water droplets such as moderate rain, sleet, or snow. Longer wavelengths are less affected by atmospheric absorption and backscatter.

Polarization

Transmitted microwave energy may be polarized either horizontally or vertically, and some systems receive both like-polarized (HH or VV) and cross-polarized (HV or VH) returns. Because the horizontal dimension is dominant in most landscape features, antenna systems which transmit and receive horizontally polarized energy (HH) recover the largest amounts of reflected energy. Antenna systems which transmit and receive vertically polarized energy (VV) enhance detection of reflectance from vertical features. The returns on a cross-polarized image (HV or VH) are believed to result from multiple reflections, particularly in rough terrain where landscape features have diverse orientations. Radar polarizations, in order of common use, are HH, HV, VV, and VH.

Image Resolution

The resolution of real aperture radar systems varies with distance from the aircraft because the radar beam width increases away from the aircraft. Synthetic aperture systems achieve a nominal 3- to 20-m resolution independent of distance from the aircraft. Synthetic aperture images thus are able to show more surface detail on enlarged images.

Method of Data Storage and Analysis

Real aperture radar systems record film images aboard the aircraft. Synthetic aperture systems record the radar equivalent of a hologram, and the final radar image is produced by optical or digital processing.

Radar returns have about a 50- to 60-dB (décibel) range, whereas photographic films are able to record only a 20-dB range (Mathews, 1975, p. 62). Thus, small tonal differences between landscape features are shown on the images relative to the larger actual differences in radar reflectance. Tonal differences are particularly difficult to interpret in bright and dark areas of the image. This difficulty is compounded by printing in black and white. The result is a loss of interpretable resolution and information on all film radar images.

Digital data from multiband radar systems can be classified by the same software algorithms that are used for data from multispectral scanners. Microwave spectral classes thus can be mathematically derived, and these classes may be meaningful in areas of uniform slope and consistently rough surface. Digital processing also can be used for geometric corrections, so that radar images can be registered with each other and with maps.

Examples of effects of characteristics on interpretation

Two well-known principles of nonstereoscopic photograph interpretation are that (1) nearly all landforms are easier to detect and identify in an oblique view than in a vertical view, and (2) large landforms and patterns are easier to recognize on images and mosaics that provide a synoptic view. Because radar strip images and mosaics cover a relatively large area and represent an oblique view of the landscape, they are especially useful for detection and mapping of large-scale structural features. However, results are more or less biased by antenna look direction and depression angle. This bias is most apparent in the mapping of linear topographic features. Linear features that trend in the look direction are obscured. Topographic depressions are maximally enhanced by a narrow shadow; they are less visible if there is not a shadow, and they commonly are obscured by the shadows or layover from other terrain features. The directional bias means that the images are best suited for mapping individual fractures, folds, and other geologic features and hazards. Directional bias may be reduced by interpretation of stereoscopic radar images and by obtaining other look directions.

Because small changes in surface roughness and slope can produce large differences in image tone, differences in reflectance from various land cover classes may be obscure. Lithologies, for example, are rarely apparent on radar images, but may be detected and mapped because of unique image textures including distinct fracture patterns, differential erosion and drainage patterns, and distinctive topographic expressions.

RADAR DATA ACQUISITION

Most radar systems produce only single-band black-and-white images, but flight line altitudes, spacing, and azimuths can be selected to acquire stereoscopic coverage and a variety of look directions and depression angles. Also, radar images can be obtained day or night and through clouds, fog, and light rain. This capability can be important in persistently cloud-covered areas such as southern Alaska.

Several types of radar data were purchased for the USGS Radar Project. The two principal vendors were:

1. Aero Service Division
   Western Geophysical Company
   8100 Westpark Drive
   Houston, TX 77063

2. MARS, Incorporated
   3644 East McDowell Road, Suite 207
   Phoenix, AZ 85008

Both vendors supply X-band, HH polarized, radar strip images and mosaics. Aero Service uses a synthetic aperture radar system whereas MARS uses a real aperture system. A comparison of characteristics affecting acquisition cost, photographic reproduction, and image interpretation is provided in table 2.

The imagery from both the Aero Service GEMS 101 radar system and the MARS APS 94 radar system offers a synoptic view of the terrain, especially when it is compiled into mosaics. The geometric accuracy of the mosaics produced by both vendors was similar; average root-mean-square errors were about 200 m. The USGS costs for data acquisition from the vendors were also similar ($4.25-$6.56/km^2), considering the contract differences in number of look directions and stereoscopic coverage. However, the radar data costs are more than twice as expensive as those for high-altitude, stereoscopic aerial photographs ($1.50-$1.90/km^2 in 1981).

Neither vendor currently provides digital radar data. The Aero Service signal (holographic) film is archived, and theoretically it could be optically recorrelated and the radar image digitized. Some digital Seasat radar data have been produced in this manner. The Aero Service signal film also can be reprocessed for other ranges in radar return magnitude, but this capability was not evaluated in the USGS studies.

The principal acquisitions of radar images from Aero Service and MARS were in Alaska (figs. 1 and 2). Synthetic aperture strip images and mosaics were purchased under a contract with Aero Service for 13 quadrangles on the Alaska Peninsula (fig. 1). Stereoscopic strip images in both northwest and southeast look directions and the corresponding mosaics were obtained for three of these quadrangles: Bristol Bay, Ugashik, and Karluk. The data acquisition contract with MARS included coverage of these same three quadrangles with real aperture stereoscopic strip images and corresponding mosaics in north and south look directions. Similar strip images and mosaics in two look directions also were acquired by MARS for eight quadrangles in northern Alaska (fig. 2). The northern Alaska area includes parts of the Brooks Range and the North Slope.

Table 2.--Comparison of real and synthetic aperture radar systems and products.

A. Synthetic aperture (Aero Service)

1. 10- x 12-m resolution at all range distances.
2. Cost of $\$4.25/km^2$ for single.look direction coverage with 20-percent overlap.
3. Swath width of 37 km; original image scale of 1:400,000, as two image strips on a single film strip.
4. Ground range presentation; selected depression angles of 10^o to 60^o.
5. Image produced by later processing; signal film can be reprocessed for other return magnitude ranges.
6. Image strips can be enlarged to 1:50,000 scale.
7. Image strip negatives have medium contrast and are easily reproduced with conventional photographic equipment.
8. Geometric accuracy is similar for image strips and mosaics.
9. Depression angle is not shown on strip images or mosaic. Date of acquisition on mosaic is not specific.
10. Stereoscopic strip images are reported to have fair to very good parallax; vertical exaggeration is good but variable along the strips.
11. Some existing proprietary strip images and mosaics have less than optimum depression angles for enhancement of average terrain relief by shadowing.
12. Obtains images from one side of aircraft.

B. Real aperture (MARS)

1. 30- x 70-m resolution at near range to 30-x 157-m resolution at far range.
2. Cost of $\$6.56/km^2$ for dual look direction, stereo coverage with 60-percent overlap.
3. Swath of 25 km; original scale of 1:250,000 as single image strip.
4. Slant range presentation; selected depression angles of 8^o to 35^o.
5. Real-time image production; image cannot be changed by later processing.
6. Image strips can be enlarged to 1:125,000 scale.
7. Image strip negatives have high contrast and are difficult to reproduce with conventional photographic equipment.
8. Geometric accuracy is better in mosaics than in strip images.
9. Depression angle is not shown on strip images or mosaic. Date of acquisition on mosaic is not specific.
10. Stereoscopic strip images are reported to have variable parallax along the strips; vertical exaggeration is poor to good and variable along the strips.
11. All image examples show a near optimum depression angle for enhancement of the average terrain relief by shadowing.
12. Obtains images simultaneously from both sides of aircraft.

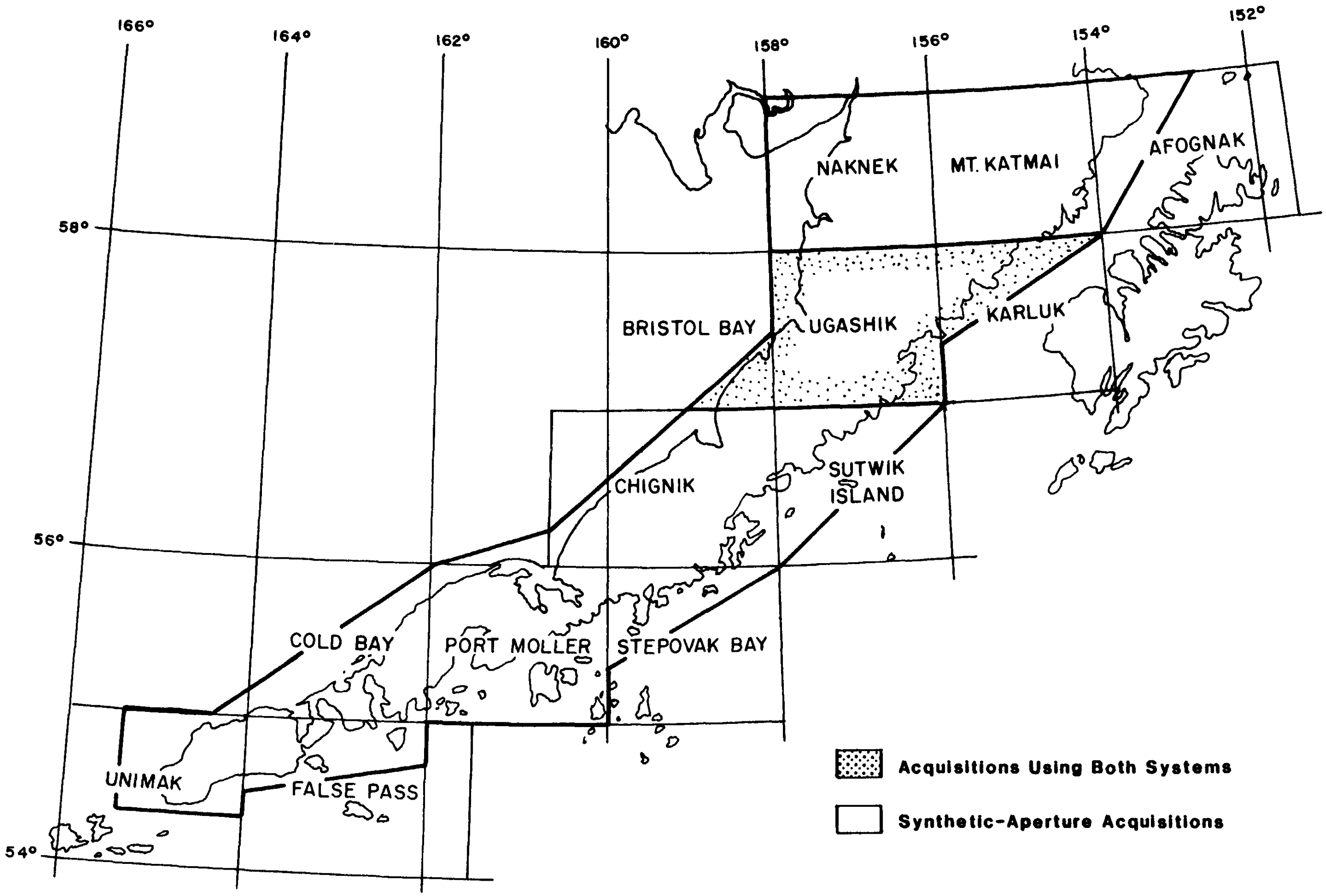


Figure 1.--Map of Alaska Peninsula Project area showing locations for which real and synthetic aperture strip images and mosaics are available.

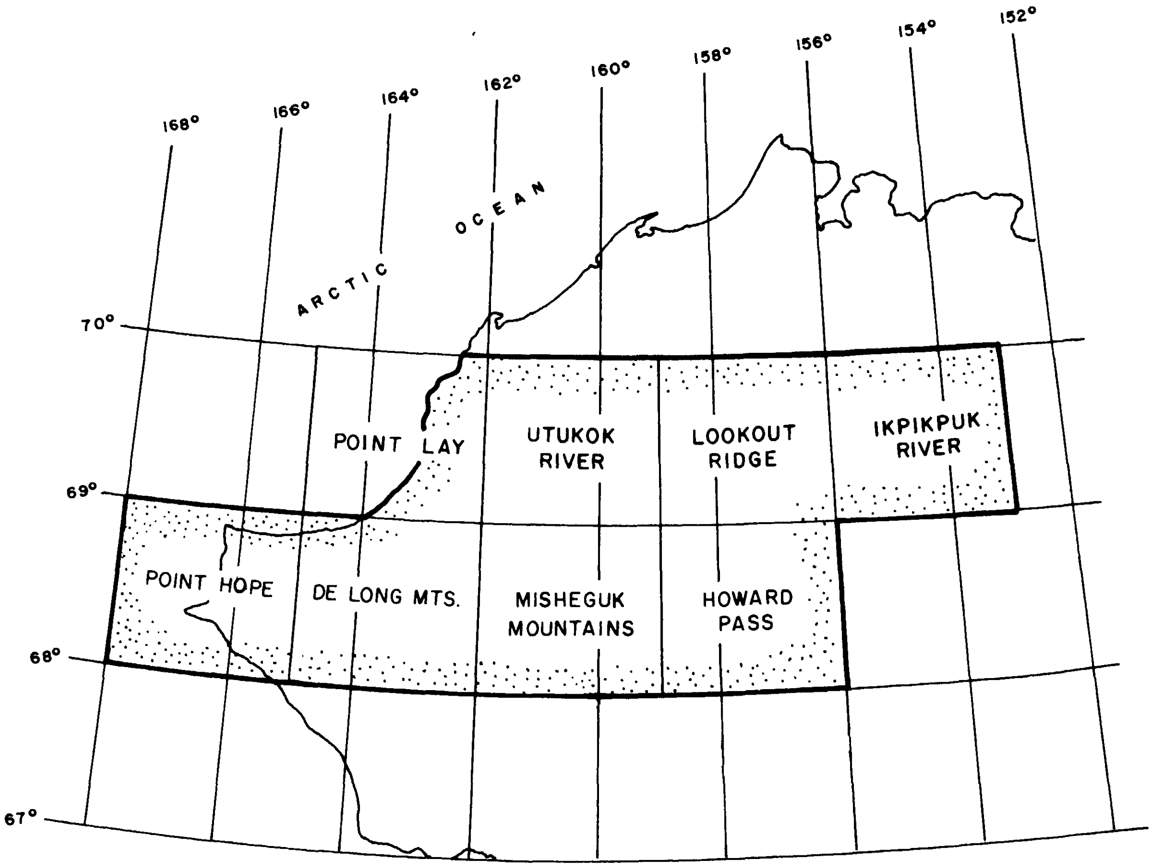


Figure 2.--Map of northern Alaska Project area showing locations for which real aperture strip images and mosaics are available in two look directions.

All of the radar images of Alaska were purchased outright by the Survey and are available at the cost of reproduction from the Earth Resources Observation Systems (EROS) Data Center. Inquiries and orders should be directed to:

User Services
EROS Data Center
Sioux Falls, SD 57198
(605) 594-6159; FTS: 784-7159

Other radar data also were acquired and evaluated. Synthetic aperture strip images and mosaics were acquired on a proprietary basis from Aero Service for five 1:250,000-scale quadrangles in the Western Overthrust Belt of Idaho, Montana, and Utah: Wallace, Choteau, Butte, Dillon, and Richfield. Prints of three other radar quadrangle mosaics in Alaska also were obtained from Aero Service: Utukok River, Lookout Ridge, and Circle. Similar proprietary, real aperture radar strip images and mosaics were obtained from MARS for eight quadrangles in western Washington: Cape Flattery, Victoria, Concrete, Copalis Beach, Seattle, Wenatchee, Hoquiam, and Yakima. These proprietary data are not available for public distribution or sale from the Geological Survey.

Dual wavelength (X-band and L-band), dual polarization (HH and HV) radar strip images were obtained from the Environmental Research Institute of Michigan (ERIM) for two 15-minute quadrangle areas north of Flagstaff, Arizona. Other radar images (Ka-band to L-band wavelengths) were acquired with various look directions, incidence angles, and polarizations from eight aircraft missions in the Flagstaff area.

Repetitive X-band, real aperture images and dual wavelength (X-band and L-band), dual polarization images of Mount St. Helens were acquired from the National Aeronautics and Space Administration (NASA). Digital radar data at X-band, with two polarizations and depression angles, also were acquired from NASA for an area between Fredericksburg and Richmond, Virginia. Finally, several Survey investigators obtained and evaluated Seasat radar digital data or images. These other radar data generally are not available from the U.S. Geological Survey but may be available from vendors and other Government agencies.

Data acquisition costs for the USGS Radar Project were approximately $1.5 million. These costs were distributed as follows:

Purchased Alaskan images. . . .	$1,338,000
Proprietary radar images	$ 144,000
Other radar data.	$ 49,000
Total	$1,531,000

SUMMARY OF RESEARCH ON GEOLOGIC APPLICATIONS

The Congressional mandate specified that the Geological Survey evaluate the use of radar imagery for "geological mapping and geological resource surveys in promising areas, particularly Alaska." This directive has been addressed by studies of (1) mineral resource applications in the Western Overthrust Belt, (2) lithologic mapping by vegetation cover type in Virginia, (3) geologic mapping in northern Arizona, (4) evaluation of radar images of Mount St. Helens, (5) engineering geology studies in the Appalachian Mountains, (6) geologic mapping in Alaska, and (7) hydrologic mapping in Alaska and in the conterminous United States. The studies are not complete, but most results have been obtained. Final reports on the detailed results of these studies will be prepared and published by the individual investigators.

Mineral Resource Applications in the Western Overthrust Belt

The use of radar interpretations for the Survey's CUSMAP (Conterminous United States Mineral Appraisal Program) was investigated by Lawrence C. Rowan, using proprietary synthetic aperture radar mosaics of parts of Idaho and Montana. In CUSMAP, multiple data sets are compiled and used to indicate areas of potential mineral occurrence. The significant geological information generally consists of structure and the lithologic units and variations associated with this structure. Lithologies generally are mapped on the ground, although remote sensing can be of significant help for this mapping in arid regions. In vegetated regions, such as are found in the Wallace, Butte, and Dillon quadrangles, Montana, the main use of remote sensing is for mapping linear features that may represent fracture patterns.

The results of lineament mapping on Landsat multispectral scanner (MSS) images and on radar mosaics were evaluated and compared. The major faults in the Wallace quadrangle area trend northwestward. Because this trend parallels the solar azimuth on the Landsat images, faults are not obvious. However, an east-trending lineament on the Landsat images corresponds with gravity and audio magnetotelluric anomalies; the cause probably is a buried igneous intrusion. The gravity and aeromagnetic maps of this and adjacent areas have several prominent east-trending anomalies, which may indicate that deep-seated structures with similar trends controlled the emplacement of this body. Thus, the other east-trending lineaments on the Landsat image may represent tension fractures and may have a diagenetic relationship with the intrusive process. Other Landsat lineaments trend northeastward, and there is no obvious explanation for these features on the geologic map. The northeast trends are confirmed by gravity data, so that these lineaments may represent basement block faulting. Landsat image interpretations thus resulted in information that is useful for CUSMAP data compilations.

Diagrams (fig. 3) were prepared to show the frequency of lineament trends on both Landsat and radar images of the Wallace quadrangle. The radar data proved to be difficult to interpret. A northeast-trending maximum corresponds with that on the Landsat diagram, but there are lineament minima in an easterly direction and in a northerly direction. The radar look direction was westward, and little enhancement of lineaments was expected in this direction. However, the north-trending minimum was not expected; apparently it is caused by widespread shadowing that obscures much of the terrain in the mountains.

Similar interpretation problems were encountered on the radar mosaic of the Butte quadrangle. Extensive shadowing in the mountains obscured 40 percent of the image in one area and 34 percent in another area. There is less terrain relief in part of the Butte quadrangle; lineaments on Landsat and radar images correspond fairly

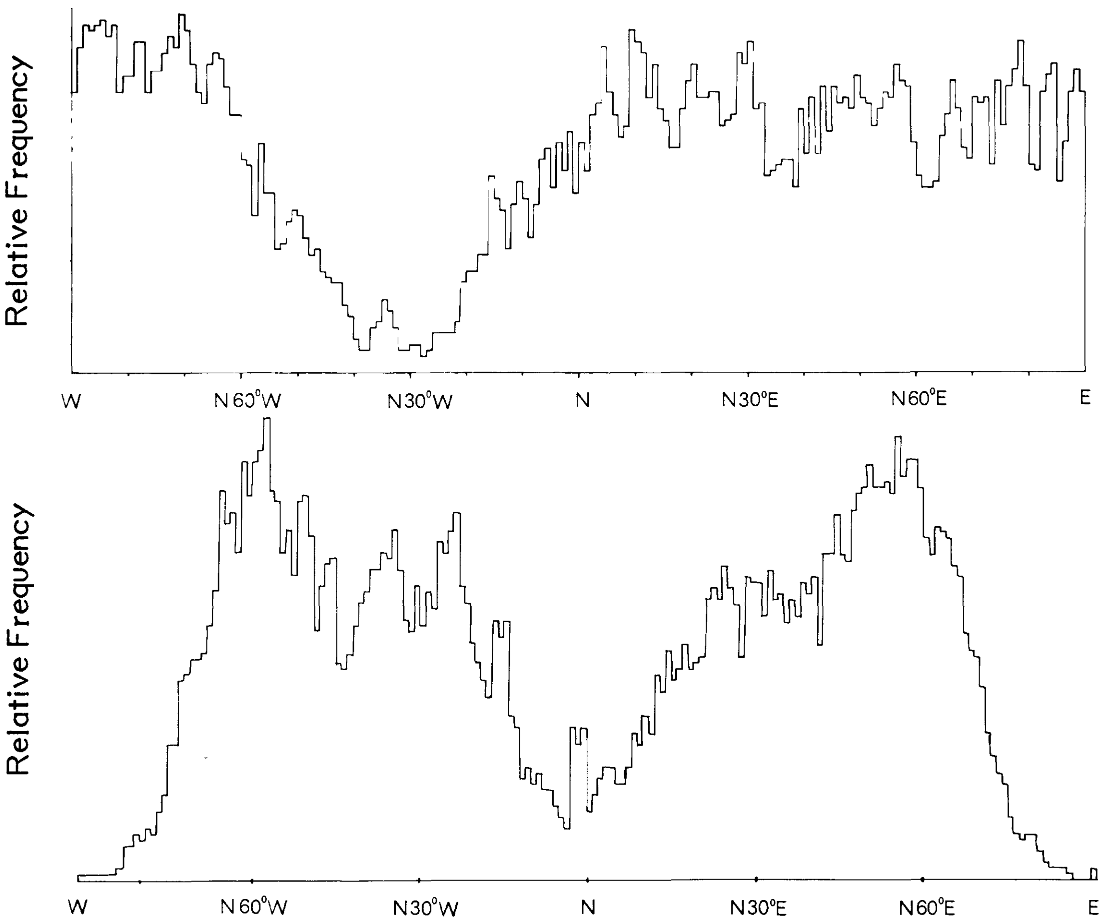


Figure 3.--Histograms showing a dominant northeast trend of lineaments from a synthetic aperture radar mosaic (bottom) and a MSS color-infrared composite Landsat image (top) of the Wallace quadrangle, Montana.

well in these areas. Also, the radar mosaics showed some trends that were not visible on the Landsat image in the southwestern corner of the Butte quadrangle and in the northwestern corner of the Dillon quadrangle. Nevertheless, a lineament frequency diagram for the Butte radar mosaic shows the same northeast-trending maximum and the same minima in northerly and easterly directions as does the diagram for Wallace. Apparently extensive shadows disrupt the continuity of north- and east-trending structures, so that these features are not detectable.

Two other characteristics of the radar mosaics in Montana and Idaho were noted. First, the mosaic images did not correspond well with overlays from existing maps: small parts of an overlay can be matched to an image, but shifts are necessary to match other parts of the same overlay. Second, very little information on lithologies can be obtained from the radar images in bedrock areas. In basin areas, on the other hand, a more appropriate shadowing enhances landforms and drainage patterns. It was concluded that the radar images are less useful than was expected for structure mapping in this area and that the radar interpretation made only a marginal contribution to these CUSMAP studies.

A radar mosaic of the Richfield, Utah, quadrangle was compared with Landsat return beam vidicon (RBV) images and other data sets by Melvin H. Podwysocki as a part of the CUSMAP study of this area. The objectives of the remote sensing study are structural mapping and lithologic mapping of hydrothermally altered areas. The existing geologic maps show dominant northeast-trending faults, whereas the aeromagnetic map has an east-trending grain.

The lineaments mapped on both the RBV and radar images have a northeast-trending maximum. This trend is confirmed by the geologic map. East-trending lineaments are less evident on the radar mosaic than on the RBV images, probably because of the westerly radar look direction. North trends are much less obvious on either image than the northeast trends. The north-south trends are important because many mineral districts in this area are located at the intersections of north-trending and east-trending fractures. These intersections are much more apparent on the RBV images than on the radar mosaic. There are more lineaments in the mountains than in the basins on both types of images.

The radar mosaics proved more useful for mapping of structural features in this area than in Montana and Idaho, probably because the terrain has a lower relief and shadowing is less extensive. Nevertheless, the radar images do not show as many lineaments related to mineralization in the Richfield quadrangle as do the RBV images.

The radar images show very few differences and changes in lithology in the bedrock areas, primarily because image tones in these areas are determined mostly by terrain, slope, and aspect. Some lithologic information can be obtained, however, in the basin areas. The tone of an alluvial fan may indicate material roughness and grain size. Further, image textures in one area indicate vegetation types and an ancient shoreline of Lake Bonneville. Greasewood (Sarcobatus vermiculatus) grows along this old shoreline and nowhere else and other areas have a sparse cover of sagebrush (Artemisia sp.) and grass. These vegetation differences are also apparent on aerial photographs. The radar mosaic provided some unique and useful lithologic information in the basin areas. This information is obtained from image texture, which is produced by the surface roughness of vegetation.

Lithologic Mapping by Vegetation Cover Type in Virginia

The discrimination of vegetation types on digital-format remotely sensed data of the Piedmont province was investigated by M. Dennis Krohn and N. M. Milton. Vegetation communities often indicate the underlying rock and soil types. Digital Landsat MSS, Seasat radar, and X-band, dual-polarized, dual depression angle aircraft radar data are being used for this study, but the aircraft data have not yet been analyzed. The test site is located between Fredericksburg and Richmond, Virginia. This area is heavily vegetated, and the bedrock is covered by a thick layer of saprolite (weathered rock); lithologic mapping is difficult on the ground.

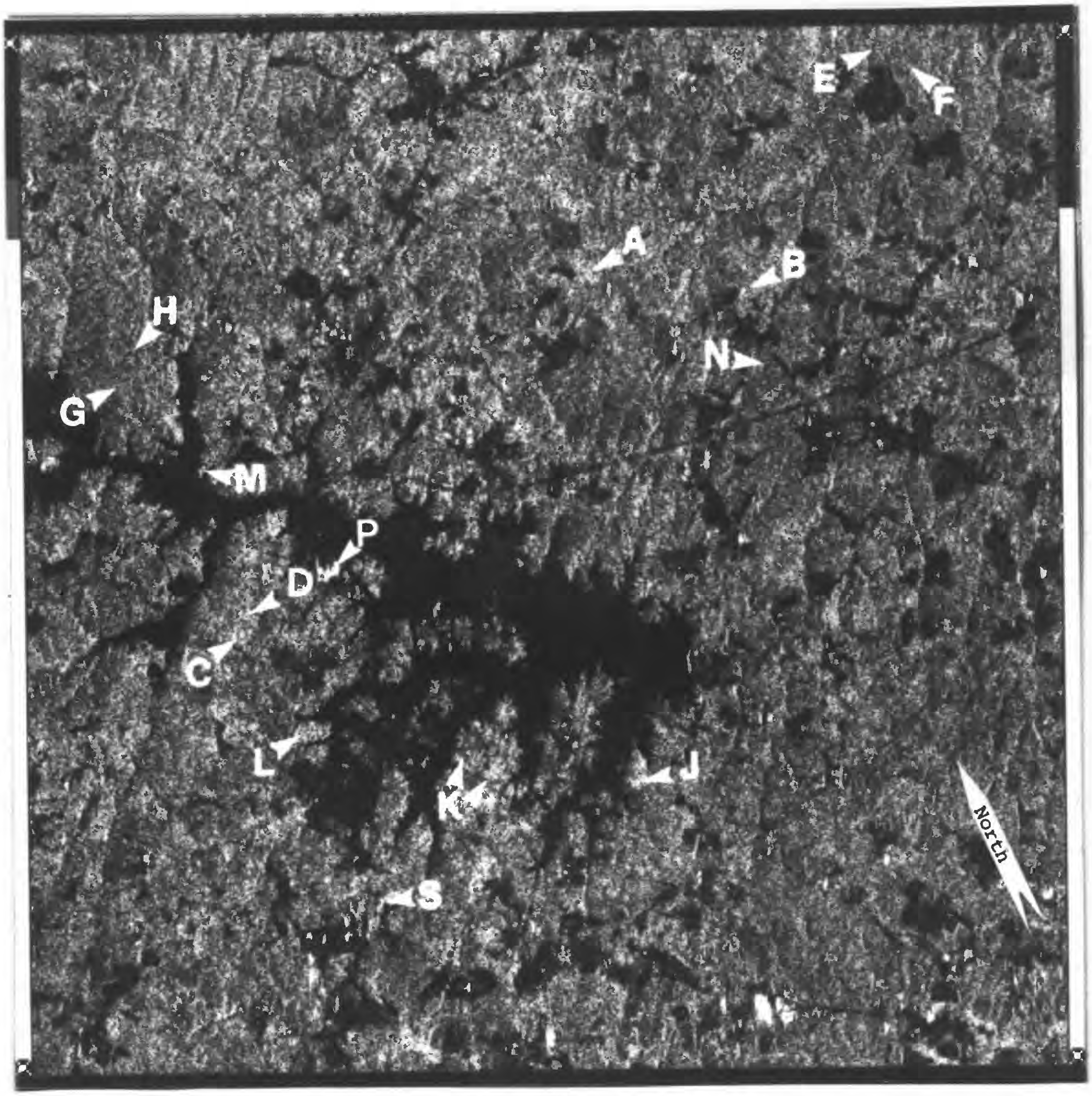
Forest vegetation types are not distinctive on the Landsat images, but areas covered by chestnut oak (*Quercus prinus*) can be detected after a principal components transformation of the digital MSS data for a winter scene (Krohn and others, 1981). Chestnut oak forest areas are important because (1) they overlie a quartz-rich metavolcanic unit in the mining district of Mineral, Virginia, (2) they mark a linear zone that may be associated with deep-seated fracturing in the overthust belt, and (3) along the James River they grow upon and commonly indicate coarse terrace gravels.

Digitally correlated Seasat radar data were obtained from the Jet Propulsion Laboratory for a 100- x 100-km area around Fredericksburg. Visually the Seasat data appear to have a poorer resolution than Landsat images because of radar image speckle. Marsh vegetation over standing water has a light tone, but other vegetation has a consistent tone of medium gray.

One study area for the Seasat radar image is a wetland near Richmond. The darkest radar image tones in this area prove to be water tupelo (*Nyssa aquatica*) above standing water. An intermediate gray tone is a mixture of sweet gum (*Liquidambar styraciflua*), red maple (*Acer rubrum*), and other trees in a multitiered vegetation canopy. The brightest image area consists of *Sagittaria* and various marsh grasses over standing water. Vegetation types in wetlands generally reflect soil type and period and frequency of inundation. Long-wavelength radar systems penetrate some vegetation cover, and high-resolution images may prove to be a useful supplement to color-infrared photographs for wetland mapping.

Digital enhancement of a small subscene (fig. 4) of the Seasat radar image near Lake Anna showed that upland forests dominated by Virginia pine (*Pinus virginiana*) have slightly brighter returns than other forest types. However, the difference is very small and easily obscured by changes in terrain slope and image speckle.

Statistical tests showed that there was not a significant difference in the mean digital values of tested areas which represented various forest types. Also, there was not a consistent pattern in measures of skewness and kurtosis, nor in the spatial patterns of spectral values. A plot of means versus standard deviations, however, showed a very high correlation (r=0.99) for the regression line and thus indicates a Raleigh distribution with a slope of 3.6 for the radar speckle. Further, results indicate that (1) areas of Virginia pine probably can be separated from areas of loblolly pine (*Pinus echinata*) and deciduous trees by measures of variance, (2) areas of loblolly pine cannot be separated from deciduous trees, (3) the variance within Virginia pine forest may be larger than the differences in variance between other forest types, (4) areas that have an unusually large variance probably represent a nonhomogenous population, and (5) some information on forest type is contained in the radar speckle, which produces image texture.



Approximate Scale 1:168,000

Figure 4.--A digitally enhanced Seasat radar image of Lake Anna, Virginia, shows small differences in gray tone between wetlands, Virginia pine, and other forest types. Sites A, B, C, and D are Virginia pine forest; sites E and F are loblolly pine forest; sites G and H are deciduous chestnut oak forests; sites, J, K, and L are Virginia pine forests; site P is a power plant at Lake Anna; and site S is a swamp with standing water.

The separability of Virginia pine areas was confirmed by a series of averaging algorithms, which convert the effects of speckle to an average gray tone for an area. A 9- x 9-pixel (picture element) average seemed to produce best results with the Seasat digital data.

The separation of areas dominated by Virginia pine is not geologically significant, and the precise reason for a backscatter difference between Virginia pine and loblolly pine is not known. This backscatter difference may occur because of needle length (1-2 inches for Virginia pine and 6 inches for loblolly), growth habit and branch structure, or moisture content of the trees or the ground. A separation of conifer types can be geologically important in other parts of the country. Also, the data processing techniques developed in this study may be useful in other radar research on forests and lithologic mapping.

Geologic Mapping in Northern Arizona

Over 200 radar images of north-central Arizona near Flagstaff were compared and evaluated by Gerald G. Schaber. These images represent various radar systems, wavelengths, polarizations, incidence angles, and look directions. The primary objectives of this study were first to determine the potential for using uncalibrated radar images in geologic investigations and then to develop empirical models of radar backscatter. Work on the first objective is nearly complete, and an initial study has been finished on backscattering from SP Mountain and SP lava flow (Schaber and others, 1980).

The Arizona test site is arid and nearly free of vegetation; it consists of a sedimentary rock plateau that is partly covered by multiple volcanic lava flows and cinder cones. The terrain thus represents a wide range of lithologies, surface roughnesses, slopes, and dielectric constants.

The 3-m resolution of some radar images is excellent for mapping fine detail and small fractures, but a 15-m resolution is adequate for most geologic purposes. The synoptic view of mosaics facilitates most types of structure mapping, especially the extrapolation of structural trends.

Most parts of the terrain appear rough or light toned on the shorter wavelength Ka-band and X-band images, but a combination of this high reflectance and a high incidence angle produces excellent landform detail. Soil moisture variations are shown best on HH-polarized images, but the HV-polarized images are useful in vegetation and terrain discrimination. Longer wavelength L-band images are best for mapping differences in roughness of the lava flows as well as for detecting small scarps, surface texture differences, and small outcrops of rock in flat areas. The blocky basalt of the SP lava flow has two different surface roughnesses, which can only be differentiated on the L-band images.

It was concluded that there is geologic value in the radar images of north-central Arizona, but the amount of information and the value of this information depends on study objectives and radar-system parameters. For most geologic studies, multiple wavelengths, polarizations, and look directions are necessary for best results.

Evaluation of Radar Images of Mount St. Helens

Radar images of Mount St. Helens were analyzed by Hugh Kieffer. Some of these images (fig. 5) were acquired on May 18, 1980, the day of the largest eruption, but inclement weather and hazardous access prevented acquisition of vertical photography until June 19. A radar system, designed to detect moving targets, was used to record the movement of ash flows and debris-laden streams; these flows appear bright on the moving target image. Images from the other radar channel detected topographic changes, crater debris flows, and log-covered lakes.

Later radar images also have been interpreted. The presence and growth of a lava dome in the crater of Mount St. Helens was detected by radar 1 day before it could be confirmed by visual observation. Cross-polarized X-band images proved to best show areas of tree blow-down and other evidence of devastation. A composite image was made by optically subtracting like-polarized from cross-polarized images (fig. 6). The composite image showed subdued topographic effects and proved useful for mapping the extent of ash and debris flows and the area of tree blow-down on a single image. Where ash and pyroclastic flows cover older material of a different type, they are apparent on radar images. Recurrent flows cannot be discriminated where they cover similar material.

It was concluded that radar imagery is very useful for monitoring volcanic processes and hazards during eruptions. It is important that the images be produced as rapidly as possible so that they can be used for planning and warnings.

Engineering Geology Studies in the Appalachian Mountains

Proprietary radar mosaics of West Virginia and parts of adjacent States have been used by William E. Davies for engineering geology studies. These uses have included the mapping of folds, fractures (especially faults), landslides, rock streams, frost-riven areas, circular and arcuate patterns, alluvial fans, and surface mines. The maps are providing information on the origin and significance of these features. The study area includes parts of the Appalachian Plateau, Valley and Ridge, Blue Ridge, and Piedmont provinces.

The radar mosaics of the Appalachian area have a near ideal resolution, look direction, and depression angle for environmental and engineering geology studies. Nearly all of the significant landforms have a topographic expression and are enhanced by shadowing on the radar images. Numerous previously unknown faults and fracture zones have been mapped by using the images, as have areas of debris avalanche and soil creep. The patterns formed by occurrences and clusters of these features apparently are a reflection of deep-seated structural processes. Resulting maps thus are being studied for evidence of recent movement and of possible hazards to life, structures, and property.

Davies decided that the main advantages of radar imagery in the Appalachian areas are (1) a resolution that is better than Landsat MSS images and more appropriate for engineering geology mapping in this area, (2) a synoptic view that is not obtained from aerial photographs, (3) an oblique view and shadow enhancement of landforms and other topographic features, (4) a clear view of the landscape despite persistent haze and clouds over the mountains, and (5) suppression of cultural features and patterns, which distract the interpreter and obscure some structures.

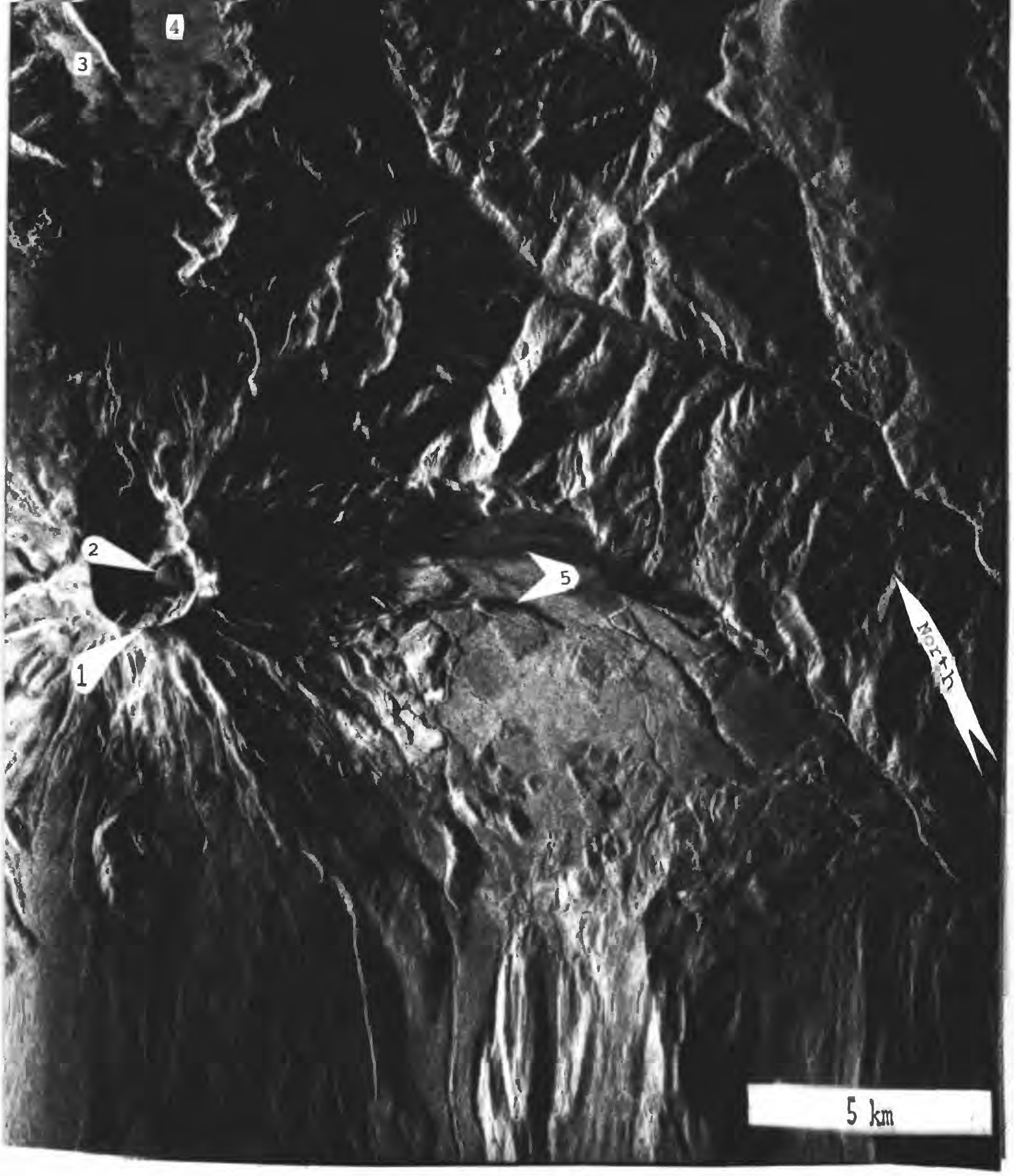


Figure 5.--An X-band radar image of Mount St. Helens during the May 18, 1980 eruption shows (1) the crater rim, (2) a new lava dome, (3) and (4) the eastern and western arms of Spirit Lake, (5) new ash flows at Muddy and Pine creeks, and (6) a typical clear cut forest area.

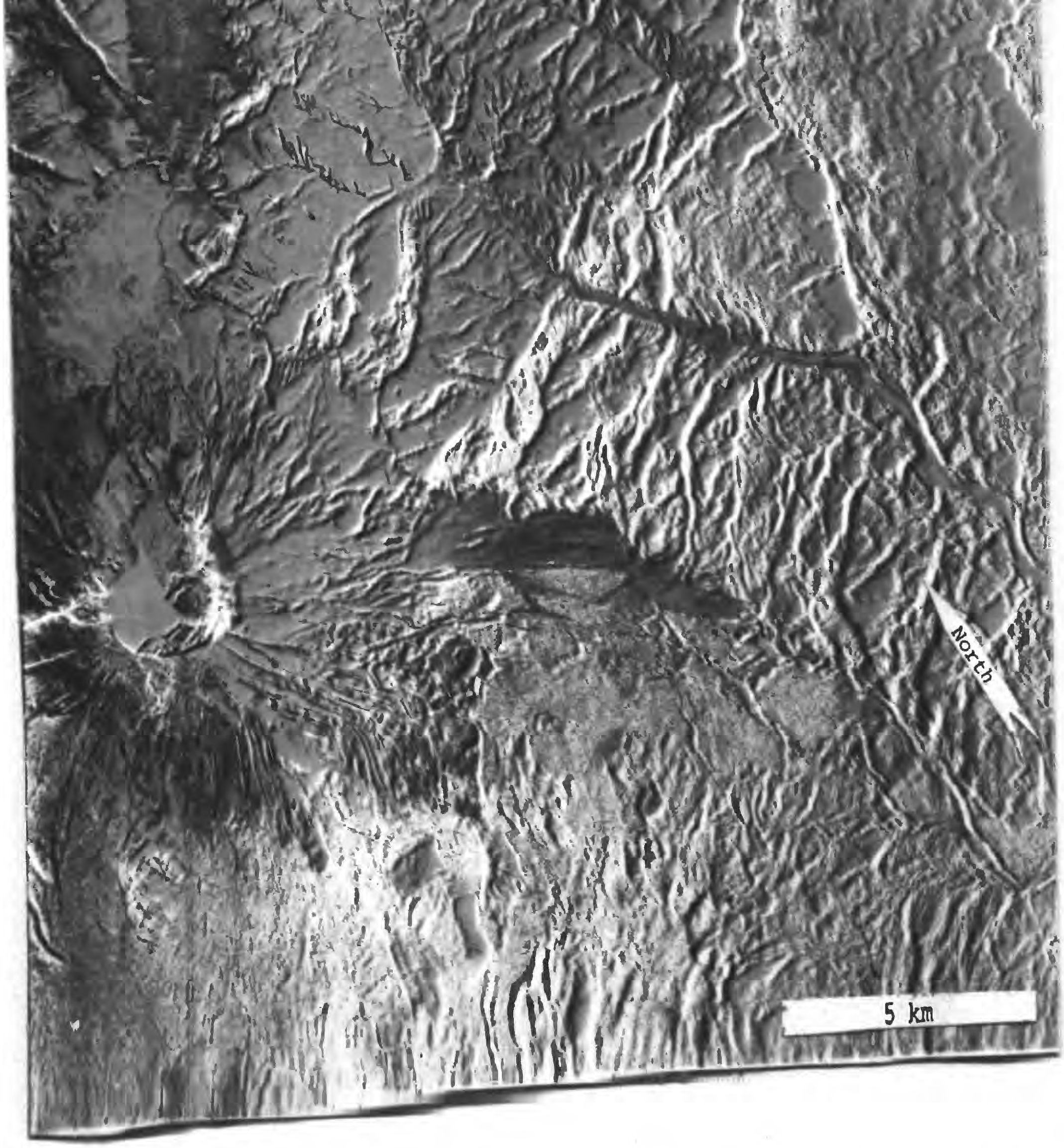


Figure 6.--The areas of devastation and new ash flows near Mount St. Helens are enhanced on an optical composite of like-polarized and cross polarized radar images.

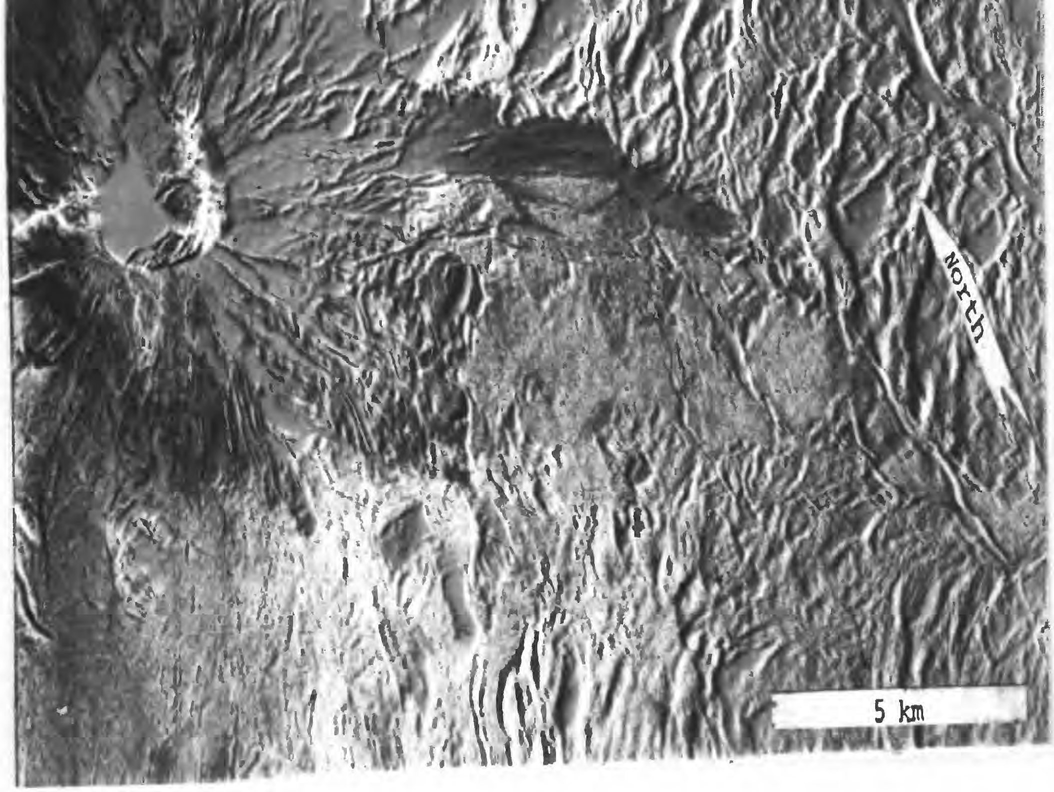


Figure 6.--The areas of devastation and new ash flows near Mount St. Helens are enhanced on an optical composite of like-polarized and cross polarized radar images.

Geologic Mapping in Alaska

Some of the geological studies in Alaska were made by a team of scientists under the leadership of John W. Cady. This group included Daniel H. Knepper, Jr., Terry W. Offield, Don L. Sawatzky, Ellen N. Penner, Julie K. Brigham, and Shirley L. Houser. Most of these studies were made in the northwestern Alaska area (fig. 2), for which real aperture radar images are available. This area includes parts of the Brooks Range and the North Slope. The North Slope is a sedimentary basin that is actively being explored for petroleum. One study in this group used radar images of the Ugashik quadrangle (fig. 1) on the Alaska Peninsula.

A linear feature analysis of four North Slope quadrangles was made by Don L. Sawatzky. Initial interpretations of the radar imagery were made on the mosaics in order to obtain the best synoptic view. The placements and trends of the linear features then were confirmed on the strip images. Overlays obtained from the north-look and south-look images were combined (fig. 7) and digitized for a directional analysis. Results of the radar analysis then were compared with those obtained from Landsat MSS band 7 and RBV images.

A dominant N. 30° W. trend on the radar mosaics of the Point Lay quadrangle extends eastward but dies out in the Ikpikpuk River quadrangle. This same trend can be seen but is less obvious on the RBV images. This trend is obscure on the MSS image. All images show a prominent trend between N. 30° E. and N. 90° E.

The study concluded that radar images can be used effectively for regional fracture analysis of the North Slope area. Landsat images are preferred as a primary data set, however, because they provide multispectral information on vegetation, soil, and lithology characteristics.

A number of beach ridges were detected by Julie K. Brigham at various altitudes on the coastal plain sediments of the North Slope. On radar mosaics of the Point Lay quadrangle, beach ridges were delineated at elevations of 8 m, 16 m, 30 m, 60 m, and about 120 m. The origin of these features is poorly understood, but they apparently reflect Pleistocene to recent changes in sea level or epeirogenic uplift. Beach ridges at elevations of 60 m and at 95-120 m also can be identified and traced for some distances on the Utukok River, Lookout Ridge, and Ikpikpuk River quadrangles. The conclusions were that these beach ridges can be seen on aerial photographs but that radar images are better for showing continuity and thus are useful for delineation and mapping.

Folds on the radar mosaics were examined by Shirley L. Houser. Most of her work was on the Utukok River quadrangle. Folds are easily seen on both Landsat images and radar mosaics in the southern part of the quadrangle. Somewhat farther north, most bedding is outlined or indicated by vegetation patterns, and folds are more easily detected on a color composite Landsat image.

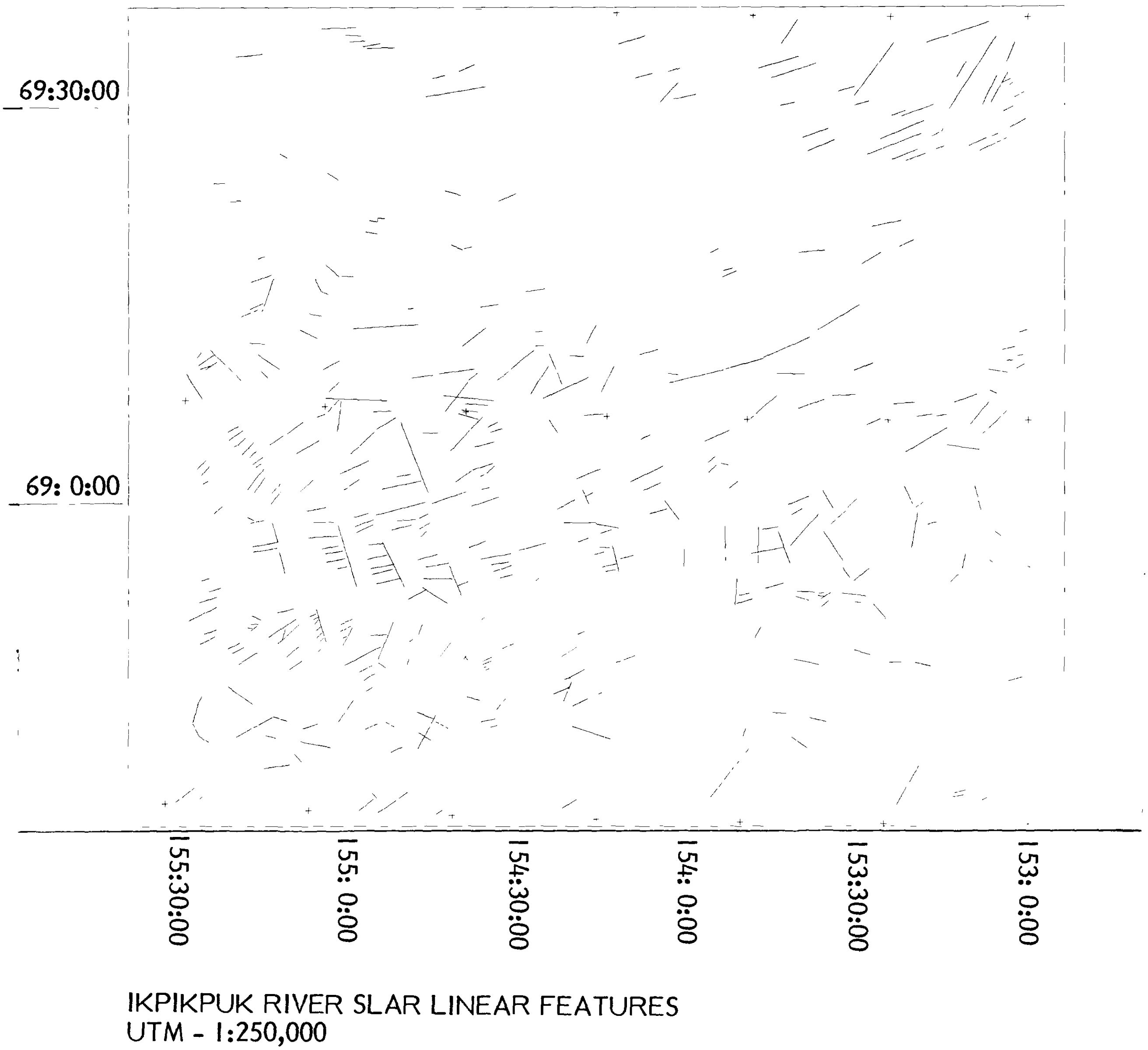


Figure 7.--Linear features detected on a radar mosaic of the Ikpikpuk River quadrangle probably reflect faults and other fractures.

A study of regional geomorphic characteristics was made by Daniel H. Knepper, Jr., for the Lookout Ridge quadrangle. The purpose was to compare the utility of SLAR images, as a tool for regional terrain analysis, with Landsat images. Most radar interpretations were made on the quadrangle mosaics because of the importance of synoptic view in a study of this type. The separate image strips also were examined to confirm results and to eliminate the effects of join lines and other mosaic artifacts. Three approaches were used: delineation of regional geomorphic units, definition of local geomorphic anomalies, and analysis of stream frequencies in selected areas.

Three geomorphic subdivisions can be distinguished in the Lookout Ridge quadrangle on the basis of landform, drainage, and vegetation characteristics. The landform factors are relative elevation, relief, erosional maturity, and structural control of landscape features. Drainage factors are texture, pattern, channel slope, floodplain width, and meander wavelength. Vegetation factors are type, distribution, pattern, and density.

The most important factors in recognition of the geomorphic subdivisions are drainage texture and vegetation density. Vegetation characteristics are seen best on color composite Landsat images; the subdivisions thus are first and best seen on these images. They are less apparent but can be distinguished on the radar images by areal comparisons of the other factors. Prominent folds can be seen on both the radar and Landsat images, but somewhat obscure folds can be seen and traced more easily on the radar mosaics.

Three local geomorphic anomalies were delineated: a lakeless area, a major lineament, and an area lacking obvious fold axes. All three anomalies were initially apparent because of differences in vegetation density and were recognized first on the Landsat image. These areas are indicated on the radar images because of other factors.

On an average, 2.5 times more stream segments can be seen on radar images than on the Landsat MSS images, probably because of the difference in resolution. A measure of stream density is made by counting all segments between stream intersections. An average 0.28 segments/km^2 were measured on the Landsat image of the Lookout Ridge quadrangle and 0.48 segments/km^2 on the Utukok River quadrangle. The average on all radar images is 0.68 segments/km^2.

Drainage maps were compiled by Ellen N. Penner from the north-look and south-look radar mosaics of Ikpikpuk River quadrangle. The two drainage overlays then were compared. Despite the fact that shadowing is nearly ideal on these mosaics, about 15 percent of the smaller stream channels in each mosaic cannot be seen from the other look direction. The missing streams on the north-look mosaic are on south-facing slopes; obscured streams on the south-look mosaic are on north slopes. Bright returns and very light image tones apparently obscure detail in many near-slope areas. This problem is not serious when images from opposite look directions are available, but biased results are obtained when images from only a single look direction are used for interpretation.

Another problem was noted in the compilation of drainage overlays from radar strip images and mosaics. Portions of a drainage overlay traced from one image cannot be exactly matched to another image because of geometric distortions. These displacements vary from 0.5 to 1 km on image strips and up to 2 km at the join lines on the mosaics, thus, geologic interpretations of drainage trends and patterns from radar images must be made cautiously. Apparent drainage anomalies may be produced by drafting adjustments for geometric distortions.

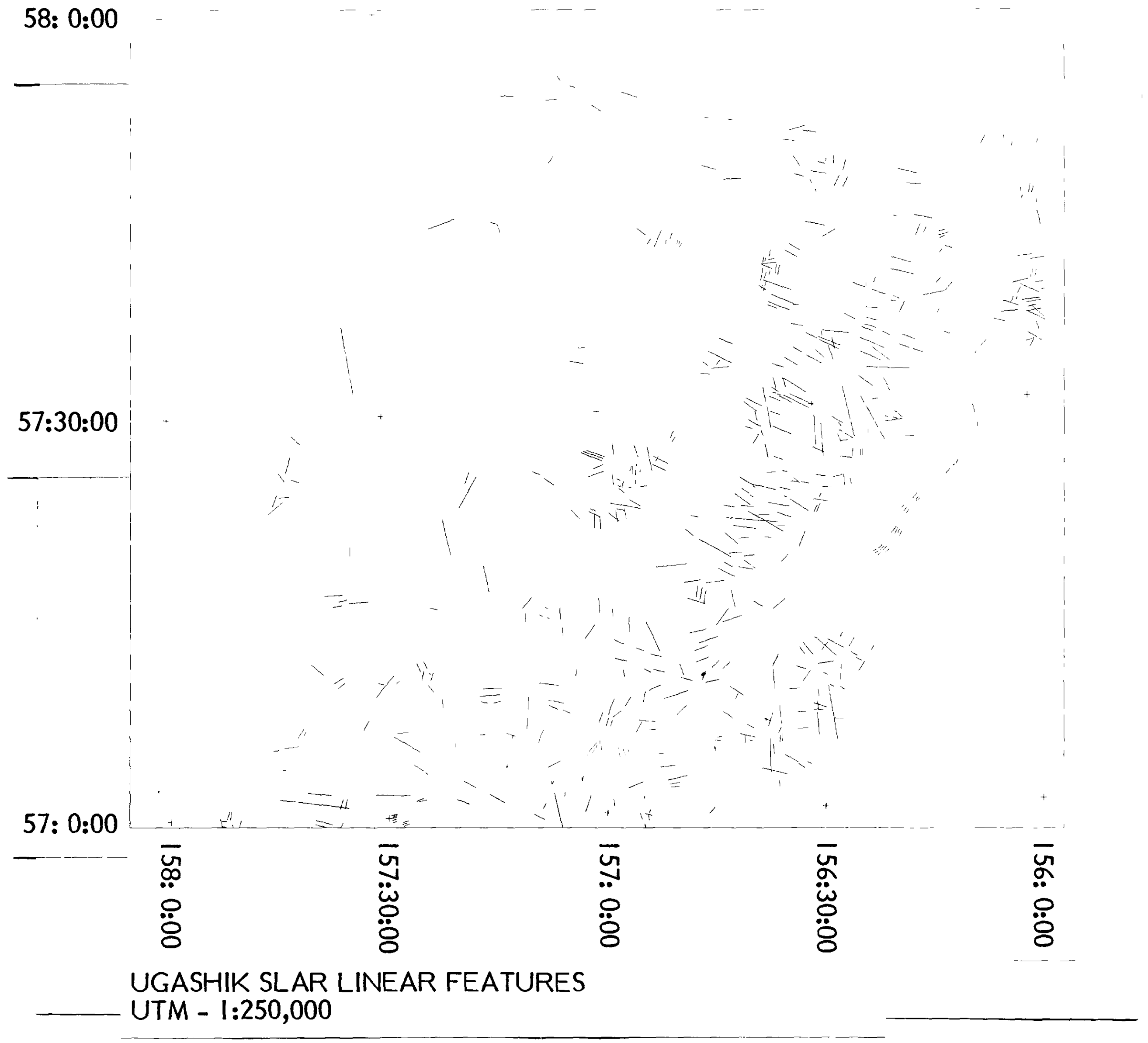


Figure 8.--Map of linear features interpreted from synthetic aperture radar mosaic of Ugashik quadrangle.

An unusual circular feature on the Ikpikpuk River quadrangle was studied by John W. Cady. Geologic work in this area during the 1950's produced only fairly detailed results, and some structures cannot be seen very well on aerial photographs. The real aperture radar depression angle is near optimum in this area. Thus, a dip slope to the north can be identified as can a curving back slope and part of a strike ridge. A stereoscopic plotter then was used to measure dips, which range from 0.4° to 4.8°, on the aerial photographs of this area. The circular feature is interpreted to be a doubly plunging syncline, which is open to the northeast.

Other bedding inclinations can be identified from the radar mosaics of the Ikpikpuk River quadrangle; in many places, however, bedding can be seen on aerial photographs but not on the radar images. The conclusions are that radar images of this area can be used for a first-look reconnaissance study of regional structure and geomorphology. However, a combination of Landsat images and aerial photographs are better than radar images as a primary data set. The best use of radar images is as a supplementary data set that can be used to confirm and refine geologic interpretations or conceptual geologic models.

An analysis and comparison of linear trends and frequencies was made by Terry W. Offield and Don L. Sawatzky on real and synthetic aperture radar mosaics and Landsat images in the Ugashik quadrangle of the Alaska Peninsula. Dominant northeast and northwest trends can be seen on the Landsat image of this area. The northwest trend also is visible on both real and synthetic aperture radar mosaics. The northeast trend is apparent but not dominant on the real aperture images. The synthetic aperture images show a dominant trend in a north-northeast direction.

More linear features were detected on the Landsat image than on any of the separate radar mosaics of the Ugashik area, but the combined result from the two radar look directions is better than that from Landsat. The higher resolution and steeper depression angle of the synthetic aperture images produces best results in the mountainous area within the quadrangle (fig. 8); there is some excessive shadowing on the real aperture images of this area. The real aperture images, however, show more linear features in the lowlands northwest of the mountains (fig. 9).

Other geological studies in Alaska were made by a team of geologists headed by Nairn R. D. Albert. Other members included L. David Carter, Warren E. Yeend, Edwin L. Cruz, James R. LeCompte, James R. Riehle, and Frederic H. Wilson.

Coastal plain studies of Quaternary geology are being conducted by L. David Carter, who concluded that real aperture radar images of the North Slope area facilitate the recognition of low-relief landforms. For example, on radar images areas with thick surficial silt deposits are readily differentiated from other areas having a thin layer of silt over bedrock; real aperture radar images are better for this purpose than either conventional aerial photographs or Landsat images. Similarly, the southern boundary of a large stabilized sand sea is more readily seen on radar images than on either aerial photographs or summer or winter Landsat images. Aerial photographs are preferred for use as the primary data set in this area because their resolution is better than that of radar images. Nevertheless, radar images are useful as a supplementary source of information.

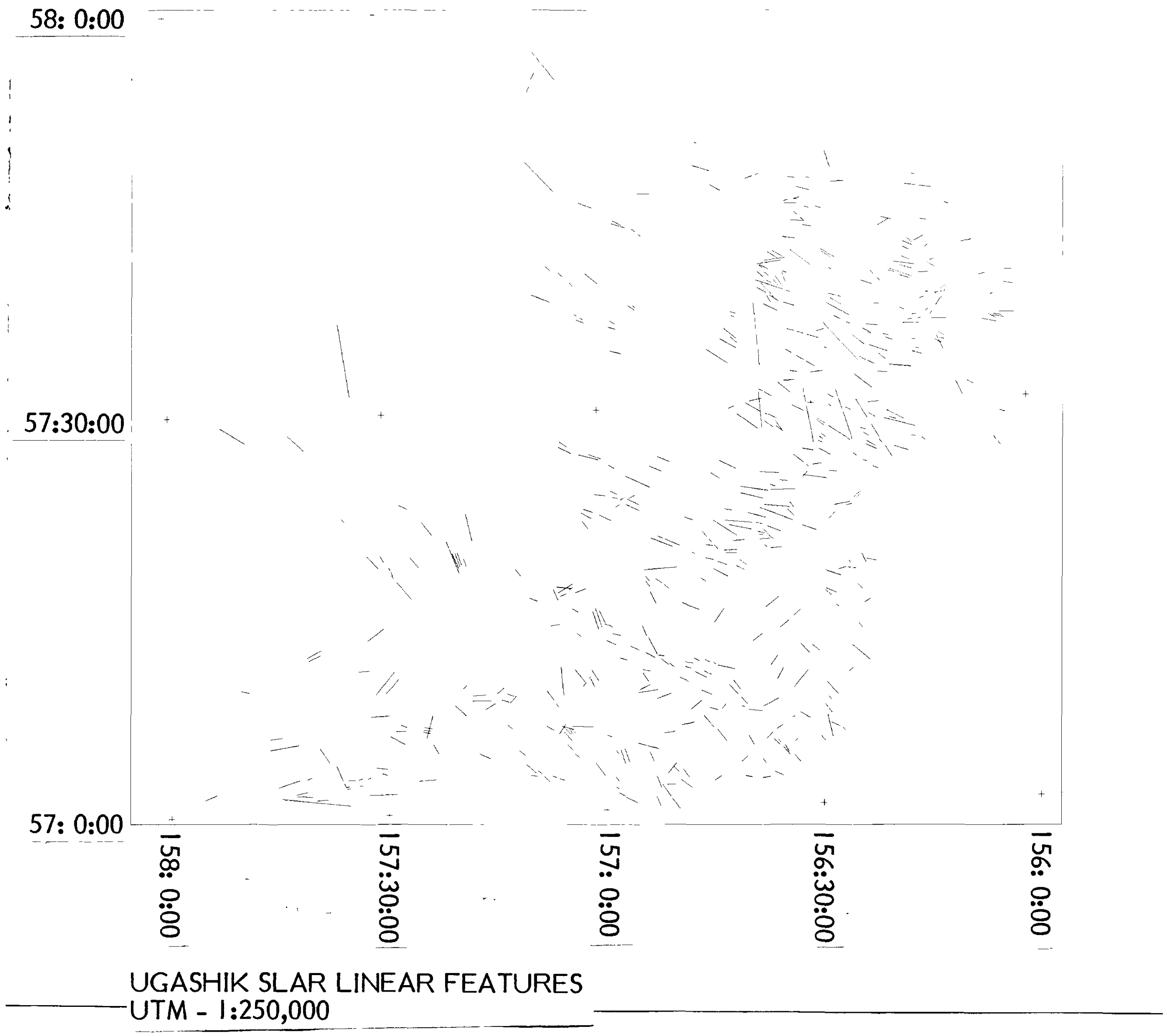


Figure 9.--Map of linear features interpreted from the real aperture radar mosaic of Ugashik quadrangle.

Warren E. Yeend analyzed the geomorphology in the Utukok River quadrangle of northwestern Alaska, using real aperture radar images. He concluded that aerial photographs better serve the needs for landform and lithologic mapping in this quadrangle because adequate resolution and detail are not available from the radar imagery. Furthermore, the stereoscopic strip images of this area do not produce adequate vertical exaggeration.

The geomorphology shown on synthetic aperture radar mosaics of the southernmost five quadrangles on the Alaska Peninsula (fig. 1) was evaluated by Edwin L. Cruz. Individual lava flows, cinder cones, drumlins, and other glacial deposits can be seen on the mosaic of the Unimak quadrangle. Similarly, in the Cold Bay area, lava flows and cinder cones are apparent. Relatively young volcanoes can also be distinguished from older, Tertiary-age craters, and glaciated mountains can be distinguished from unglaciated areas. Areas covered by glacial deposits can be delineated.

The Port Moller area of the southern Peninsula was also evaluated. Areas underlain by Mesozoic-age and Tertiary-age sediments can be delineated, but lithologies cannot be determined. Craters, cinder cones, lava flows, and ash deposits can be seen. Terminal moraines, representing three periods of glaciation, can be partially mapped, and glaciated mountains are easily identified. A fault was discovered on the radar mosaic, and some, but not all, other mapped faults can be seen.

A different result was obtained in the other two quadrangles, False Pass and Stepovak Bay. The Tertiary sediments and volcanic flows in these areas cannot be readily distinguished on the radar images.

A structural study of the Chingnik and Sutwik Island quadrangles (fig. 1) was completed by James R. LeCompte. In these areas, circular features and lineaments previously were mapped on Landsat images (LeCompte and Steele, 1981). A good correlation was obtained between the circular features and geochemical samples having anomalously large concentrations of copper, zinc, and other metals. The circular features could not be detected, however, on synthetic aperture radar mosaics. Furthermore, only a few lineaments were detected on these mosaics, and they did not correspond with lineaments identified on the Landsat images.

As part of volcanic hazard studies in Alaska, James R. Riehle analyzed real and synthetic aperture radar images of Ugashik quadrangle on the Alaska Peninsula. This study concluded that aerial photographs are better for hazard studies than are radar images. The aerial photographs have a higher resolution than radar images, and landscape features are not obscured by shadowing or distorted by foreshortening in the photographs. The lineaments mapped on radar images do not always correspond with those mapped on aerial photographs and Landsat images. In combination, however, the latter two data sets better enhance lineaments and other geologic features.

Riehle also compared results obtained from the real and synthetic aperture radar images. Numerous lineaments, detected on both types of images, tentatively are interpreted to be conjugate shear joints that may have undergone minor differential movement. Lithologic contacts and bedding attitudes can be detected and mapped more accurately on the synthetic aperture images, but both sets of images show a similar amount of detail on the surface morphology of volcanic deposits.

In the same Ugashik quadrangle area, a similar study was completed by Frederic H. Wilson, who concluded that neither type of radar image offers any significant advantages over high-quality aerial photographs, except when used as a reconnaissance tool. Thus, the synoptic view of radar images is recognized as somewhat advantageous for reconnaissance mapping of structural features. He also concluded that the real aperture images show more surficial detail in lowland areas. This effect may have been caused entirely, however, by the season of data acquisition (November for the real aperture images and August for the synthetic aperture images).

A geologic map compiled from interpretations of real and synthetic aperture radar images of the Bristol Bay, Ugashik, and Karluk quadrangles was drawn by Nairn R. D. Albert. This map basically shows a flat glacier-covered area, a series of large lakes, and a group of mountains that contain sedimentary, volcanic, and intrusive rocks. In the glacier-covered area, considerably more detail can be seen than is shown on published geologic maps. Extensive terminal moraines, representing at least three periods of glaciation, can be delineated. A linear feature near the base of the northwest side of the mountains, was initially interpreted as a possible fault but is now believed to represent an alinement of terminal moraines. Several lateral moraines, probable dune fields, and a drumlin field also can be identified on the images. The real aperture images show more detail in the lowland areas than do the synthetic aperture images.

A number of volcanic craters and lineaments also were mapped from the radar images. Several of the lineaments apparently are faults because some evidence of uplift or downdrop can be seen on the images. A right lateral fault also can be identified.

Gross sedimentary rock units can be mapped in the mountains and the direction and relative slope of the dip on these beds can be estimated on the synthetic aperture images. Four anticlines and synclines (including directions of plunge) can be recognized and mapped on the radar images. Published geologic maps, based on aerial photograph interpretations and field work, show other folds, however.

Albert concluded that the geology mapped from radar images in the mountains is simplified but otherwise corresponds fairly well with the geology shown on published maps. The synthetic aperture images show more detail than the real aperture images and, thus, allow a more accurate structural interpretation in the mountains.

An analysis of the radar mosaic of the Circle 1:250,000-scale quadrangle in east central Alaska was made by William E. Davies, who used a proprietary radar image from Aero Service. This analysis is incomplete, but a number of geologic features have been examined on the mosaic, and some tentative conclusions have been made.

Upland areas on the Circle quadrangle generally are bare, but the fine-scale topography is disrupted by frost riving, which has produced frost boils, pingoes, tors, and boulder fields. These features obscure small scarps, other evidence of faulting, and other linear trends on the radar images. Similar problems occur in areas covered by black spruce, which produces a rough surface and a high reflectance of X-band wavelength. Excellent fine-scale topography can be seen in loess-covered areas and in the lowlands. Thus, terrace deposits, loess, alluvial fans, drainage patterns, and abandoned stream channels can be identified and delineated. Areas of metamorphic rock and areas of frost riving can also be mapped.

The final geologic study in Alaska was made by Autometric, Inc., under contract to the Geological Survey. The principal objectives of this study were to (1) quantitatively determine the unique incremental value of SLAR to the mapping of structural geology, (2) quantitatively compare the structural information content of real and synthetic aperture radar images, (3) evaluate the contribution of two opposite-look directions and stereoscopic viewing to the amount of geologic information that can be obtained from radar images, (4) determine the structural information in enlarged strip images, and (5) measure the cartographic accuracy of radar quadrangle mosaics. Only the results of the first four study objectives are summarized in this report.

Six kinds of imagery were interpreted: synthetic aperture radar images, real aperture radar images, standard Landsat MSS image products, digitally enhanced Landsat MSS images, aerial photographs, and Seasat radar images. The Seasat images are of poor quality, and the results of that interpretation were not used.

The structural features which were mapped consist of probable faults, possible faults (other lineaments), and anticlinal and synclinal axes. Each image was interpreted by two geologists working independently. When the interpretations were complete, they were overlaid, compared, and discussed. A composite interpretation then was drawn to show only the linear features that both investigators agreed were present and detectable. These features then were digitized, so that interpretive results could be compared by computer processing. Comparisons were made of the number of features, length of features, features detected by two or more sensors, and features detected by only one sensor.

If Landsat images or a combination of Landsat images and aerial photographs are used as a primary data set, additional structural information is contributed by linear features that are detected only on radar images. This additional information is the unique incremental value of the radar images. The actual value of the information, however, is determined by study objectives and by the amount of structural information that would be added by using a different data set as an alternative to radar images. These findings are based on data from the combined Ugashik quadrangle, Alaska Peninsula, and the Utukok and Lookout Ridge quadrangles, northwestern Alaska, an area of approximately 38,850 km^2. Those findings with references to aerial photographs are based on data from the area of the Utukok and Lookout Ridge quadrangles that is covered by SLAR images, Landsat images, and aerial photographs. This area is approximately 8,300 km^2. The comparisons show:

1. Aerial photographs add 100 percent (by length) of additional information to a standard Landsat image product interpretation and 51 percent to the interpretation of a digitally enhanced Landsat image.

2. Real aperture radar images add 121 percent of additional information to the interpretation of standard Landsat image products and 61 percent of additional information to the interpretation of digitally enhanced Landsat images. Real aperture radar images add 35 percent of additional information to a standard Landsat product/aerial photograph interpretation and 29 percent additional information to an enhanced Landsat image/aerial photograph interpretation.

3. Synthetic aperture radar images add 86 percent of additional information to a standard Landsat image product interpretation and 35 percent of additional information to the interpretation of digitally enhanced Landsat images. Synthetic

aperture radar images add 19 percent additional information to a standard Landsat product/aerial photograph interpretation and 11 percent additional information to an enhanced Landsat image/aerial photograph interpretation.

4. Real aperture radar images add an average 80 percent of additional information to an interpretation of synthetic aperture images. Synthetic aperture images add an average 35 percent of additional information to an interpretation of real aperture images.

These results show that radar images have considerable incremental value when added to a Landsat image data base. However, this value is much less if digitally enhanced Landsat images are used instead of the standard film products. The added value of radar images is also much less when the primary data set consists of a combination of a Landsat image and aerial photographs. The comparisons also show that aerial photographs have nearly the same incremental value as radar images when added to a Landsat image data base.

The structural information content of synthetic and real aperture radar images was compared. In the combined Ugashik/Utukok/Lookout area, a total 8,029 km of linear features were detected on real aperture images versus 6,019 km of linear features on synthetic aperture images. Thus, the synthetic aperture images produced only 77 percent (by length) as much information as did the real aperture images. In the separate test sites, the synthetic aperture images produced 88 percent as much information as the real aperture images in the Ugashik quadrangle, Alaska Peninsula and 71 percent as much information in the combined Utukok River and Lookout Ridge quadrangles, northwestern Alaska. These results represent differences in depression angle in the northwestern Alaska area and differences in both look direction and depression angle in the Peninsula area. Results also may have been affected by differences in ground conditions at the times of data acquisition.

The additions to structural information provided by two opposed radar look directions and by stereoscopic viewing were evaluated. It was estimated that opposed look directions contributed virtually nothing in flat and rolling terrain and contributed a visually (not quantitatively) estimated 15 percent in mountainous areas.

The narrow zones of overlap on all strip images cause inconvenience in stereoscopic viewing and prevent a synoptic view. The strips must be frequently shifted and adjusted to look at new areas. It was concluded that stereoscopic viewing is useful principally as an adjunct to monoscopic viewing except in anomalous and complex areas--that is, areas for which an interpretation is benefited by a three-dimensional view. Stereoscopic viewing also proved useful for determining dip directions and for mapping fold axes on synthetic aperture images of the Utukok River and Lookout Ridge quadrangles. The synthetic aperture images represent a steeper antenna depression angle than the real aperture images of this area, and folds are not as well enhanced by shadowing. Thus, more information was obtained by stereoscopic viewing of the synthetic aperture strip images than of the real aperture images.

Synthetic aperture radar images have a higher resolution than real aperture images and, thus, retain more detail on enlarged images. The effects of enlargement on structural information content was tested in four small areas within the Ugashik quadrangle; the resulting measurements then were combined to show the structural information (length of lineaments) that is detectable at various image scales:

	Scale		
	1:250,000	1:100,000	1:50,000
Synthetic aperture	249 km	362 km	462 km
Real aperture	359 km	291 km	330 km

These results show that the synthetic aperture radar images are more useful at enlarged scales.

Hydrologic Mapping in Alaska and in the Conterminous United States

Two investigations of hydrologic applications were made for the USGS Radar Project. One study mapped landforms, structure, and drainage characteristics in several quadrangles on the Alaska Peninsula. The other investigation was made on five quadrangles in the Western Overthrust Belt.

A comparison of the utility of radar and Landsat images for hydrogeologic mapping on the Alaska Peninsula was made by P. Jan Cannon, under contract to the U.S. Geological Survey. The first study objective was the mapping of landform and lithologic boundaries in the Bristol Bay, Ugashik, and Karluk quadrangles on the basis of image tones, textures, shapes, and patterns. The lithologies of these areas then were interpreted. Resolution of the images proved to be less important than topographic enhancement and image contrast in obtaining detailed maps. Thus, winter Landsat MSS scenes were more useful for geomorphic mapping than scenes acquired in other seasons. Real aperture radar images proved best for geomorphic mapping in this area. A total 263 landform units in 39 classes were mapped from these images. The synthetic aperture radar images resulted in 210 map units in 30 landform classes, and the Landsat images produced 169 map units in 31 landform classes.

Maps of structural features in the Ugashik area were compiled to show an interpretation of faults and other lineaments. Topographic enhancement proved to be the most important factor in the mapping of structural features; the other factors were illumination direction, tonal contrast, and image resolution. The importance of illumination direction is shown by frequency diagrams of lineament trends. The north-look and south-look directions of the real aperture radar system resulted in lineament peaks at N. 50° E. and N. 50° W. The northwest and southeast look directions of the synthetic aperture system produced lineament peaks at N. 20° E. and N. 70° W. The southeast-trending solar azimuth of the Landsat images resulted in major lineament orientations of N. 10° E., N. 60° E., and N. 60° W. A total of 782 lineaments were mapped from the real aperture radar images, 626 from the synthetic aperture radar images, and 389 from the Landsat images. Standard Landsat image products were used for this analysis.

Two small streams, Andrew Creek and Deer Creek in the Ugashik quadrangle, were selected for an analysis of drainage characteristics. The basin of Andrew Creek has relatively low relief and low drainage density, whereas the basin of Deer Creek has relatively high relief and high drainage density. Interpretations of the radar images were compared with those from Landsat RBV images and with topographic maps. Image resolution proved to be the most important factor in the detection and mapping of the drainage nets. Landsat RBV images, which have about a 30-m resolution, were used for this analysis because drainage nets could not be delineated from Landsat MSS images.

Real and synthetic aperture radar images and Landsat RBV images produced similar results in Deer Creek basin. However, fewer stream segments were detected on these images than are shown on published topographic maps (compiled from aerial photographs). In the flatter Andrew Creek basin, more stream segments can be seen on synthetic aperture radar images than on real aperture radar images. A drainage net could not be constructed from the Landsat RBV images of this area. More stream segments also are visible on the synthetic aperture radar images of Andrew Creek than are shown on a 1:250,000-scale topographic map.

Cannon concluded that geomorphic maps interpreted from radar images have adequate detail for most reconnaissance purposes and that radar imagery is an excellent tool for mapping regional structural features. He also concluded that radar images can provide a useful data base for the quantitative analysis of drainage basins.

An evaluation of proprietary radar images from Aero Service was made by Maurice E. Cooley and Robert E. Davis. Only synthetic aperture radar mosaics with a westerly look direction were available for this study in the Western Overthrust Belt. The Richfield quadrangle is in west central Utah and the Wallace, Choteau, Butte, and Dillon quadrangles are in western Montana. The study objectives were (1) to evaluate the information content and determine the applicability of radar imagery to hydrologic data acquisitions and investigations, and (2) to determine the relative value of radar images in comparison with Landsat images and ground data.

Bedrock areas can be separated from valley fills on the radar mosaics, and various unconsolidated lithologies can be mapped. In the Richfield quadrangle, these lithologies consist of alluvial fans, gravel deposits, sand channels, sand and dust dunes, and landslide deposits. In the Montana quadrangles, valley fill deposits can be mapped, but the boundaries between alluvial and glacial deposits generally are obscure. Floodplain deposits can be separated from other types of valley fill on the radar mosaics. The edges of some terraces also can be seen. Two deposits of gravelly glacial outwash can be mapped on the Montana quadrangles, and glacial moraines commonly can be recognized as areas of irregular topography and dense conifer cover.

Most large lakes and reservoirs are conspicuous on the radar mosaics. In the Richfield quadrangle, however, only 21 of 39 small lakes in valleys could be detected on the radar images, and nearly all lakes in the mountains were obscured by shadows. Other small lakes are visible on Landsat images. Similarly, the 5-km long Gibson reservoir in Montana is hidden in shadow and cannot be seen on the mosaic. Other large lakes in Montana were frozen at the time of data acquisition (December) and have medium-gray to dark-gray tones on the radar images; some of these lakes are difficult to locate and identify. Small lakes cannot be seen in the Montana study area.

Only a few stream reaches can be seen on the Utah radar mosaic. Braided gravel and sand channels on alluvial fans or in canyons are more easily seen than other types and locations of channels. Some other reaches can be inferred by a narrow floodplain, by a dark band indicating vegetation or a moist area near a channel, or by the locations and irregular boundaries of cultivated fields. Many stream channels are difficult to locate, however, even with the aid of Landsat images and topographic maps.

Large streams with widths of 23 m to more than 120 m are visible on the radar mosaics of Montana, except where they are obscured by shadows. About 80 percent of these channels can be delineated. Riparian vegetation obscures most reaches of other perennial streams in this area, and ephemeral channels generally cannot be seen on the radar images.

Streamflow diversion for irrigation occurs in all quadrangles. A few segments of canals and irrigation ditches can be seen, but these comprise a small percentage of the networks shown on large-scale topographic maps. Pishkin Canal, which is 15-18 m in width, is apparent on the radar images only near Pishkin Reservoir in Montana. The locations of some canal segments are apparent only because of the bright radar returns from spoil banks or adjacent roads.

The general directions of ground-water movement in the study areas can be determined equally well by analysis of the radar mosaics, Landsat images, or aerial photographs. The principal aquifers are in the intermontaine valleys. These aquifers receive most recharge along the lower mountain slopes and discharge water to streams and lakes. Playa lakes and phreatophytes also represent areas of ground-water discharge, as do crops irrigated by pumpage of ground-water.

The other landscape features that have a significance for ground-water occurrence are bottomlands, springs, perennial streams, coarse-grained soils, alluvial fans, moraines, glacial outwash, fractures, folds, and riparian vegetation. Some features indicate coarse-grained or fine-grained materials, and other features indicate a shallow or a relatively deep water table. Examples of all these features can be seen on the radar images, but other known examples are undetectable.

The main contributions of radar imagery to ground-water studies in the Utah and Montana areas may be to show thin belts of riparian vegetation, small areas of woody phreatophytes, and lineaments that may be fractures. Riparian vegetation and phreatophytes indicate a shallow water table, and such small or thin areas of vegetation are not apparent on Landsat images. Fractures can form dams and conduits for the storage and movement of ground water. Some lineaments can be seen on Landsat images and aerial photographs, but others are apparent only on the radar mosaics.

The study concluded that the main use of radar imagery in the Montana and Utah quadrangles is for hydrologic interpretations in plains and intermontaine valley areas. The synoptic view of the mosaics permits a quick overview of landforms, lakes, drainage characteristics, and land cover. Radar imagery is more suitable, however, as a supplementary rather than as a primary data set for detailed hydrologic studies.

SUMMARY OF RESEARCH IN CARTOGRAPHIC APPLICATIONS

The Congressional mandate which initiated the USGS Radar Project also specified that the use of radar imagery for topographic mapping be investigated. Because topographic maps portray hypsographic (elevation), hydrologic, and cultural (manmade) features at their precise horizontal and vertical positions within certain tolerances known as the National Map Accuracy Standards, a data source of high geometric accuracy and resolution is required for their compilation. The lack of control over the geometric accuracy and the low spatial resolution of radar imagery relative to conventional aerial photographs are strong deterrents to their use for the compilation of topographic maps. The unique geometry of radar imagery would further require the research, development, and testing of specialized computer programs for use with equipment such as analytical stereoplotters and the development of other custom computer programs to plot elevations. Additional problems are engendered by the oblique view of radar systems which causes shadowing or overlapping of topographic features, resulting in loss of information and discontinuity of hydrologic and cultural features.

Given these considerations, research in cartographic applications was directed toward: (1) experimentally producing low cost planimetric radar image maps, (2) evaluating the geometric accuracy of radar images and mosaics, (3) diminishing radar terrain shadows, and (4) evaluating the delineation of base map categories.

Experimental Production of Planimetric Radar Image Maps

High-quality screenless lithographic prints of selected radar images were produced by Lawrence E. Anderson and Lee U. Bender. Tools, quality control materials, and a negative image density range were selected to retain as much of the original tonal and textural detail as possible. However, about a 10- to 20-percent loss in resolution resulted. Lithographic image maps could be produced at a cost of about $2.50 each as compared with a cost of $25.00 each for photographic prints of the same image mosaic.

Future plans call for screenless lithographic printing of about 10 radar image products of the Ugashik quadrangle. These products include strip images and quadrangle mosaics from both real and synthetic aperture systems. A base map showing cultural features will also be fitted to the radar mosaics, and the combinations will be printed as shaded relief maps.

A shaded relief map was generated from the digitized topographic contours on three 15-minute quadrangles near Butte, Montana, by the USGS Astrogeology Center in Flagstaff, Arizona. A variety of image maps can be generated, representing solar azimuths of any of the eight principal compass headings and any selected elevation angle. The shaded relief map was compared with color-infrared photographs and a radar mosaic of the same area by Lawrence C. Rowan. Fewer lineaments were detectable on the shaded relief map than on the aerial photographs, and the trends of the lineaments were different on all three data sets. This effect may be due in part to the enhancement of fracture patterns by vegetation visible only on the color-infrared photographs.

A latitude and longitude grid was fitted to a radar mosaic of the Seattle quadrangle, Washington, by Lawrence E. Anderson and Lee U. Bender. Tests showed that the method of grid fitting that had been developed for Landsat images worked well for radar images except in areas of high relief. The positions of selected control points at approximately the same elevation were measured on the radar images and on large scale maps. A computer program then calculated and delineated the latitude and longitude grid lines or ticks for the radar image.

Evaluation of Geometric Accuracy

The geometric accuracy of radar image mosaics was determined by Paul H. Salamonowicz. After the application of a fitted grid to the real aperture mosaic of the Seattle quadrangle, the planimetric root-mean-square geometric error (RMSE) was calculated to be 265 m. This error is about the same as that on uncorrected Landsat images. Measurements of geometric accuracy on the image mosaics of Ugashik quadrangle showed an RMSE of 160 m for the real aperture image and 190 m for the synthetic aperture image. These RMSE values are based on a similarity transformation. When a fitted grid was applied to the real aperture mosaic, the RMSE was reduced to 133 m. When a fitted grid was applied to the synthetic aperture mosaic, the RMSE was 74 m. The RMSE values apply only to terrain near to the elevation of the control points. In areas of high relief, the planimetric error can be much higher because of layover.

A different procedure was used to measure the geometric errors of the radar strip images of Ugashik quadrangle. The image positions of a selected group of identified ground positions were measured, and the geometric relationships between these points were used to predict the ground positions of other image points. The ground positions of all points were actually measured on topographic maps. Other assumptions were a straight flight line and a constant altitude. The horizontal RMSE for predicted points proved to be about 102 m for the real aperture imagery. Even more accurate results may be possible by allowing a variation in flight altitude and by including image positions from the opposite look direction.

The accuracy of synthetic aperture strip images proved to be about 90 m. For both real and synthetic aperture strips, the elevations of points could not be reliably predicted. Initial results are promising for the use of digital radar data to prepare geometrically accurate image maps. Digital data, however, are not currently available from commercial sources.

Reduction of Terrain Shadow

Lawrence E. Anderson and Lee U. Bender merged east-look and west-look radar images of the westernmost quarter of the Hoquiam quadrangle, Washington, to reduce terrain shadowing. Although some of the shadowing could be removed by this method, the images could not be accurately registered because mountain crests on the separate images were displaced toward the aircraft flight line, image layover occurred on the steepest slopes, and the times of signal return from near slopes varied.

Evaluation of Base Map Categories

Sheila E. Martin and Neil L. Falcone conducted a study to evaluate and compare delineation of drainage and transportation networks, nonvegetative features, and surface cover on Landsat 3 MSS band 5 and RBV (return beam vidicon) images, a Seasat L-band radar image, and ERIM dual wavelength (X-band and L-band), dual polarized (HH and HV) SLAR images. All images were enlarged to 1:125,000-scale paper prints for comparative purposes. The study area covers two 15-minute quadrangle areas north of Flagstaff, Arizona.

Although quality and time of acquisition varied greatly for the different image types, the following general conclusions could be drawn. Some of the finest drainage lines could be seen only on the SLAR images; L-band HV images and X-band HH images were the best for this purpose. Somewhat longer drainage lines were easiest to detect and more continuous on the Landsat RBV image. On the Seasat image, major drainage lines were distinct only where they were orthogonal to the look direction. Only the longest drainage lines were visible on the Landsat MSS image. Results from the comparison of transportation networks were similar for the different image types.

Nonvegetative features in the SP Mountain area consist mainly of volcanic craters, cinder cones, lava flows, and outcrop areas of the Kaibab Limestone. All volcanic landforms were relatively well defined on the SLAR images, and image tones generally indicated differences in surface roughness: the L-band HV image is better than the other SLAR images for this purpose. However, the best separation of all nonvegetative features was made on the Landsat RBV image. The Kaibab Limestone can be distinguished on both the MSS and RBV images, but in volcanic areas fewer details are visible.

The L-band SLAR images proved best for interpreting forested and non-forested areas; image tones were distinctive, and forest boundaries could be easily delineated. However, the X-band SLAR images were inferior to the Landsat MSS band 5 and Seasat images for this purpose.

Following the detailed comparisons of images in the Flagstaff area, the study was expanded to include similar landscape features on real and synthetic aperture radar mosaics in Washington and Montana. Only landforms and drainage lines could be easily identified on these mosaics without making reference to a topographic map. Roads and other transportation lines were discontinuous on the radar mosaics. Urban areas had a distinctive pattern, but individual features such as buildings and airports did not have a distinctive shape on the images. The study concluded that radar images are not as useful as aerial photographs and Landsat RBV images for detection of base map categories.

Experience has shown that certain land cover categories are more difficult to detect and delineate than others. On most aerial photographs, for example, forested wetlands have the same appearance as well-drained forests. Similarly, some areas of perennial snow and ice cannot be detected because they are covered by a thin layer of soil material or because they occur in areas that are persistently cloud covered. John L. Place investigated the potential use of radar images to identify these three land cover classes.

A Seasat L-band radar image of the DelMarVa Peninsula on the eastern seaboard was used to investigate wetlands. Forested wetland on the floodplain of the Pocomoke River has a nearly white tone on the image, and grassy marsh is nearly black; surrounding dry forest areas have an intermediate gray tone on the image. The very light tones closely correspond with the forested wetland area on an existing map of land cover. This result is especially interesting because the Seasat image was acquired on September 25, 1978, during a very dry period.

The potential for use of Seasat radar images to delineate wetlands was confirmed by another recent study (MacDonald and others, 1980) in the lower Mississippi Valley. These studies indicate that best results are obtained (1) in relatively flat terrains, (2) with a long-wavelength (L-band) radar system, and (3) with a steep depression angle (about 70^{o} for Seasat images).

For examination of perennial snow and ice, real aperture radar mosaics of the Olympic Mountains in western Washington and synthetic aperture radar mosaics of the Bitterroot Mountains in Montana and Idaho were obtained. Although the images of the Olympic Mountains were acquired in August when perennial ice and snow occur on the higher peaks, ice and snow were not apparent on the mosaics. The images of the Bitterroot Mountains were acquired in December and March when the area was extensively snow covered; however, the snow could not be identified with any certainty. One problem in both areas is that the bright returns from steep near slopes obscured the reflectance differences between snow and non-snow areas.

A shorter wavelength (such as K-band) radar system is needed for delineation of snow cover, but best results generally cannot be obtained in mountainous areas because of slope changes and shadowing. The results of this study confirm those of previous studies.

REFERENCES CITED

Krohn, M. D., Milton, N. M., Segal, Donald, and England, Anthony, 1981, Discrimination of a chestnut-oak forest unit for geologic mapping by means of a principal component enhancement of Landsat multispectral scanner data: Geophysical Research Letters, v. 8, no. 2, p. 151-154.

LeCompte, J. R., and Steele, W. C., 1981, Maps showing interpretation of Landsat imagery of the Ugashik and Sutwik Island quadrangles, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-1053-0, scale 1:250,000, 2 sheets.

MacDonald, H. C., Waite, W. P., and Demarcke, J. S., [1980], Use of Seasat radar imagery for the detection of standing water beneath forest vegetation, in American Society of Photogrammetry Fall Technical Meeting, New York, 1980, Technical Papers: Falls Church, Virginia, American Society of Photogrammetry, p. RS-3-B-1 to B-12.

Mathews, R. E., ed., 1975, Active microwave workshop report: National Aeronautics and Space Administration Report, NASA SP-376 (NTIS N76-11811), 501 p.

Schaber, G. G., Elachi, Charles, and Farr, T. G., 1980, Remote sensing of SP Mountain and SP lava flow in north-central Arizona: Remote Sensing of Environment, v. 9, no. 2, p. 149-170.

APPENDIX I

RADAR PROJECT STUDIES AND PRINCIPAL INVESTIGATORS

FY 1980

1. Title: Utility of SLAR for delimiting wetland and perennial snow

   Objectives: Determine the possibly unique value of SLAR imagery for delineating boundaries of forested wetlands and perennial ice or snow. Evaluate use of SLAR images to improve accuracy of land cover maps.

   Principal Investigator: John L. Place, National Mapping Division, U.S. Geological Survey, Reston, Virginia.

2. Title: Analysis of different types of radar for base mapping categories determination

   Objectives: Evaluate the use of radar images to obtain information for compilation of base maps: land surface shape, vegetation boundaries, and cultural features.

   Principal Investigator: James W. Schoonmaker, Jr., National Mapping Division, U.S. Geological Survey, Reston, Virginia

3. Title: Rectification of radar imagery

   Objectives: Modify existing mathematical models and software and develop a USGS capability for geometric rectification of radar imagery. Evaluate root-mean-square errors of selected radar sets.

   Principal Investigator: Lee U. Bender, National Mapping Division, U.S. Geological Survey, Reston, Virginia

4. Title: SLAR and Landsat image comparison study

   Objectives: Compare side-looking airborne radar and Landsat images of the Flagstaff, Arizona, area. Evaluate the use of these images for compilation of base maps: land surface shape, vegetation boundaries, and cultural features.

   Principal Investigator: Sheila E. Martin, National Mapping Division, U.S. Geological Survey, Reston, Virginia

5. Title: Lithographic printing of 1:250,000-scale SLAR imagery

   Objectives: Determine feasibility of using screenless printing to overlay cultural map features and SLAR images and to preserve the tonal fidelity of the images. Evaluate procedures, costs, and results.

   Principal Investigator: Larry Anderson, National Mapping Division, U.S. Geological Survey, Reston, Virginia

6. Title: Photographic process composition of dual-look SLAR images

Objectives: Evaluate feasibility of using dual-look SLAR images to produce a composite image in which shadows are deleted and all terrain reflectance information is retained.

Principal Investigator: Larry Anderson, National Mapping Division, U.S. Geological Survey, Reston, Virginia

7. Title: Comparison of 1:62,500-scale image base maps prepared from SLAR and shaded relief imagery

Objectives: Generate shaded relief map from digitized 1:24,000-scale topographic maps, and compare land surface configuration with a SLAR image of the same area.

Principal Investigators: Sheila E. Martin/Paul H. Salamonowicz, National Mapping Division, U.S. Geological Survey, Reston, Virginia

8. Title: Microwave studies in a vegetated terrain

Objectives: Evaluate SLAR imagery as a supplement to Landsat data for geological studies in forested regions. Model forest backscatter differences from various forest types.

Principal Investigator: M. Dennis Krohn, Geologic Division, U.S. Geological Survey, Reston, Virginia

9. Title: Analysis of SLAR images of the Western Overthrust Belt

Objectives: Compile, analyze, and interpret linear trends and textural information on SLAR and Landsat images for comparison with geological, geophysical, and geochemical data. Assess importance of system parameters. Evaluate geologic significance of results.

Principal Investigator: Lawrence C. Rowan, Geologic Division, U.S. Geological Survey, Reston, Virginia

10. Title: Evaluation of SLAR images of part of the Western Overthrust Belt, Richfield, Utah

Objectives: Analyze and interpret lineament patterns; relate these patterns to anomalies in geologic, geophysical, and geochemical data; and define and test models for faulting and mineralization in the Richfield, Utah, quadrangle.

Principal Investigator: Melvin H. Podwysocki, Geologic Division, U.S. Geological Survey, Reston, Virginia

11. Title: Geological and remote sensing evaluation of SLAR imagery of Alaska

Objectives: Evaluate SLAR imagery for geologic and mineral resources mapping in Alaska. Compare information content of real and synthetic aperture images.

Principal Investigators: Nairne R. D. Albert, Geologic Division, U.S. Geological Survey, Menlo Park, California, and John W. Cady, Geologic Division, U.S. Geological Survey, Denver, Colorado

12. Title: Comparative analysis of two types of SLAR imagery for topographic mapping of Alaska

Objectives: Determine accuracy of horizontal and vertical positions on the land surface from real and synthetic aperture stereoscopic SLAR imagery of the Ugashik 1:250,000-scale quadrange in Alaska.

Principal Investigator: Lee U. Bender, National Mapping Division, U.S. Geological Survey, Reston, Virginia

13. Title: Evaluation of radar systems: northern Arizona test site

Objectives: Evaluate geologic information content of various radar-image types in northern Arizona (images from eight missions with various resolution, wavelengths, incidence angle, look azimuth, and polarization parameters).

Principal Investigator: Gerald Schaber, Geologic Division, U.S. Geological Survey, Flagstaff, Arizona

14. Title: Analysis and evaluation of SLAR for possible use in hydrologic investigations in five $1^{\circ} \times 2^{\circ}$ quandrangles in Montana, Idaho, and Utah

Objectives: Evaluate SLAR imagery for hydrologic information in the western overthrust area; determine applicability of SLAR imagery to ground-water and surface-water investigations.

Principal Investigator: Maurice E. Cooley, Water Resources Division, U.S. Geological Survey, Cheyenne, Wyoming

15. Title: Correlation of thermal and SLAR data for Mount St. Helens

Objectives: Correlation of SLAR and thermal-infrared data to identify surface cover and material types near Mount St. Helens, Washington. Characterize volcanic lithologies under cloudy or hazy conditions. Correct and calibrate SLAR return for terrain slope.

Principal Investigator: Hugh Kieffer, Geologic Division, U.S. Geological Survey, Flagstaff, Arizona

16. Title: Determination of the unique incremental contribution of SLAR to geologic mapping and resources survey

Objectives: Interpret SLAR images acquired over key areas in Alaska; also interpret Seasat radar images, Landsat images, and aerial photographs of the same areas. Merge data sets to isolate and measure the unique incremental contribution of each image set and various combinations of image sets. Compare utility of real and synthetic aperture radar image products.

Principal Investigator: Richard F. Pascucci, Autometric, Inc., Falls Church, Virginia

17. Title: SLAR image maps of Alaska

Objectives: Print 2,000 copies by the screenless lithographic process of real and synthetic aperture radar strip images and mosaics for subareas on the Alaskan Peninsula. Evaluate procedures, costs, and results.

Principal Investigator: Lee U. Bender, National Mapping Division, U.S. Geological Survey, Reston, Virginia

18. Title: Evaluate the utility of SLAR for distinguishing between frozen wetland, frozen marshland, and dry forest

Objective: Perform analysis to separate frozen swamp from frozen marsh using the synthetic aperture data of the northern Rocky Mountains. These two wetland types resemble each other in the SLAR images, but both are discernably different from dry forest or rangeland.

Principal Investigator: John L. Place, National Mapping Division, U.S. Geological Survey, Reston, Virginia

19. Title. Evaluation of the incremental value of SLAR imagery for certain geologic applications as contrasted with other remotely sensed data

Objectives: Evaluate the applicability of SLAR to geomorphology; determine the incremental value of SLAR as an information source when compared to the existing data sets; and evaluate the two data sources, real and synthetic aperture.

Principal Investigator: Dr. P. Jan Cannon, University of Alaska, Fairbanks, Alaska

20. Title: Summary evaluations and conclusions of the SLAR project

Objectives: Provide a technical staff role for administration of the USGS radar evaluation project. This effort includes coordination of the project, presenting a seminar on results of the separate studies, and preparation of a summary USGS open-file report of the study results.

Principal Investigator: Gerald K. Moore, Office of Earth Sciences Applications, EROS Data Center, Sioux Falls, South Dakota

APPENDIX 2

BIBLIOGRAPHY OF USGS RADAR INVESTIGATIONS

Bateman, P. C., 1966, Geologic evaluation of radar imagery: U.S. Geological Survey Technical Letter NASA-27 to National Aeronautics and Space Administration (NTIS N70-38899), 9 p.

Berlin, G. L., 1971, Radar mosaics: Professional Geographer, v. 23, no. 1, p. 66.

Berlin, G. L., and Schaber, G. C., 1971, Geology and radar mosaics: Journal of Geological Education, v. 19, no. 5, p. 212-217.

Berlin, G. L., Schaber, G. C., and Horstman, K. C., 1980, Possible fault detection in Cottonball Basin, California: an application of radar remote sensing: Remote Sensing of Environment, v. 9, no. 1, p. 33-42.

Brown, R. D., Jr., 1966, Geologic evaluation of radar imagery: San Andreas Fault zone from Stevens Creek, Santa Clara County, to Musael Rock, San Mateo County, California: U.S. Geological Survey Technical Letter NASA-45 to National Aeronautics and Space Administration (NTIS N70-38893), 15 p.

Campbell, A. B., 1968, Current U.S. Geological Survey research in Yellowstone National Park (abs.): Geological Society of America Special Paper 121, p. 590.

Campbell, W. J., Ramseier, R. O., Weeks, W. F., and Gloersen, Per, 1975, Integrated approach to the remote sensing floating of ice, <u>in</u> Canadian Symposium on Remote Sensing, Alberta, 3d, 1975, Proceedings: Ottawa, Ontario, Canadian Aeronautics and Space Institute, p. 39-72.

Christiansen, R. L., Pierce, K. L., Prostka, H. J., and Ruppel, E. T., 1966, Preliminary evaluation of radar imagery of Yellowstone National Park: U.S. Geological Survey Technical Letter NASA-30 to National Aeronautics and Space Administration (NTIS N70-38847), 30 p.

Clark, M. M., 1971, Comparison of SLAR images and small-scale low-Sun aerial photographs: Geological Society of America Bulletin, v. 82, no. 6, p. 1735-1742.

Cooper, J. R., 1966, Radar imagery of the Twin Buttes area, Arizona test site 15: U.S. Geological Survey Technical Letter NASA-28 to National Aeronautics and Space Administration (NTIS N70-40311), 15 p.

Doyle, F. J., 1975, Cartographic presentation of remote sensor data, <u>in</u> Manual of Remote Sensing: Falls Church, Virginia, American Society of Photogrammetry, v. 2, p. 1077-1106.

Fischer, W. A., 1962, An application of radar to geological interpretation, <u>in</u> Symposium on Remote Sensing of Environment, Michigan, 1st, 1962, Proceedings: Ann Arbor, Michigan, Michigan University, p. 91-93.

Hackman, R. J., 1967, Geologic evaluation of radar imagery in southern Utah: U.S. Geological Survey Professional Paper 575D, p. D135-D142.

Harris, George, and Graham, L. C., 1976, Landsat-radar synergism, in Congress of the International Society for Photogrammetry, Finland, 13th, 1976, Proceedings: Helsinki, Finland, Committee of the 13th International Congress for Photogrammetry, Commission 7, Paper 17, 26 p.

Harwood, D. S., 1967, Radar imagery: Parmachenee Lake area, west-central Maine: U.S. Geological Survey Technical Letter NASA-81 to National Aeronautics and Space Administration, 6 p.

Hilpert, L. S., 1966, Geological evaluation of radar imagery, southwestern and central Utah: U.S. Geological Survey Technical Letter NASA-38 to National Aeronautics and Space Administration (NTIS N70-41126), 9 p.

Irwin, W. P., 1966, Geologic appraisal of radar imagery of southwestern Oregon: U.S. Geological Survey Technical Letter NASA-23 to National Aeronautics and Space Administration (NTIS N70-38892), 5 p.

Johnson, R. B., 1966, Geologic evaluation of radar imagery of the Near Spanish Peaks region, Colorado: U.S. Geological Survey Technical Letter NASA-47 to National Aeronautics and Space Administration (NTIS N70-38938), 6 p.

Keefer, W. R., 1968, Evaluation of radar and infrared imagery of sedimentary rock terrane, south-central Yellowstone National Park, Wyoming: U.S. Geological Survey in Interagency Report NASA-106 to National Aeronautics and Space Administration (NTIS N68-23210), 12 p.

Kover, A. N., 1967, Radar imagery as an aid in geologic mapping (abs.): Photogrammetric Engineering, v. 33, no. 6, p. 679.

Lewis, A. J., 1969, Evaluation of multiple polarized radar imagery for the detection of selected cultural features: U.S. Geological Survey Inter-agency Report NASA-130 to National Aeronautics and Space Administration, 53 p.

Love, J. D., 1970, Generalized geologic evaluation of side-looking radar imagery of the Teton Range and Jackson Hole, northwestern Wyoming: U.S. Geological Survey Interagency Report NASA-168 to National Aeronautics and Space Administration (NTIS N72-18356), 11 p.

Masursky, Harold, Kaula, W. M., McGill, G. E., Pettengill, G. H., Phillips, R. J., Russell, C. T., Schubert, Gerald, and Shapiro, I. I., 1977, The surface and interior of Venus: Space Science Review, v. 20, p. 431-449.

Masursky, Harold, Dial, A. L., Jr., and Strobell, M. E., 1978, Geologic map of the Phoenicus Lacus quadrangle of Mars: U.S. Geological Survey Miscellaneous Investigations Map Map I-896, scale 1:5,000,000.

Masursky, Harold, Eliason, Eric, Ford, P. G., Schaber, G. G., Pettengill, G. H., McGill, George, and Schubert, Gerald, 1980, Pioneer Venus radar results: geology from images and altimetry: Journal of Geophysical Research, v. 85, no. A13, p. 8232-8260.

Nunnally, N. R., 1966, Radar as a tool for regional investigations: U.S. Geological Survey Technical Letter NASA-67 to National Aeronautics and Space Administration, 27 p.

O'Leary, D. W., 1977, Remote sensor applications to tectonism and seismicity in the northern part of the Mississippi embayment: Geophysics, v. 42, no. 3, p. 542-548.

Page, L. R., 1969, Geologic analysis of the X-band radar mosaic of Massachusetts, in Earth Resources Aircraft Program Status Review, 2d: National Aeronautics and Space Administration, Manned Spacecraft Center, Houston, Texas, v. 1, p. 4-1 to 4-19.

Peterson, R. M., 1969, Observations on the geomorphology and land use of a part of the Wasatch Range, Utah: U.S. Geological Survey Interagency Report NASA-140 to National Aeronautics and Space Administration (NTIS N69-16255), p. 75-113.

Pettengill, G. H., Ford, P. G., Brown, W. E., Kaula, W. M., Keller, C. H., Masursky, Harold, and McGill, George, 1979, Pioneer Venus radar mapper experiment: Science, v. 203, p. 806-808.

Pettengill, G. H., Ford, P. G., Brown, W. E., Kaula, W. M., Masursky, Harold, Eliason, Eric, and McGill, G. E., 1979, Venus: preliminary topographic and surface imaging results from the Pioneer orbiter: Science, v. 205, p. 91-93.

Pettengill, G. H., Eliason, Eric, Ford, P. G., Loriot, G. G., Masursky, Harold, and McGill, George, 1980, Pioneer Venus radar results: altimetry and surface properties: Journal of Geophysical Research, v. 85, no. A13, p. 8261-8270.

Prostka, H. J., Jr., 1970, Geologic interpretation of a radar mosaic of Yellowstone National Park: U.S. Geological Survey Interagency Report NASA-179 to National Aeronautics and Space Administration (NTIS N71-33185), 16 p.

Reeves, R. G., 1968a, Radar geology, in Yearbook of Science and Technology: New York, N.Y., McGraw-Hill, p. 322-328.

__________ 1968b, Structural geologic interpretation from radar imagery: U.S. Geological Survey Interagency Report NASA-102 to National Aeronautics and Space Administration (NTIS N69-13927), 14 p.

__________ 1968c, Use of radar imagery for structural geologic studies (abs.): Geological Society of America Special Paper 121, p. 369.

__________ 1969, Structural geologic interpretations from radar imagery: Geological Society of America Bulletin, v. 80, no. 11, p. 2159-2164.

__________ 1972, Geologic analysis of remote sensor data, Bonanza project (abs.): American Association of Petroleum Geology, v. 56, no. 3, p. 647.

Reeves, R. G. and Kover, A. N., 1966, Radar from orbit for geologic studies (abs.): Photogrammetric Engineering, v. 32, no. 5, p. 889.

Reeves, R. G., Kover, A. N., Lyon, R. J. P., and Smith, H. T. U., 1975, Terrain and minerals: Assessment and evaluation, in Manual of Remote Sensing: Falls Church, Virginia, American Society of Photogrammetry, v. 2, p. 1107-1351.

Richmond, G. M., 1971, Geologic evaluation of anomalies between like-polarized and cross-polarized K-band side-looking radar imagery of Yellowstone National Park: U.S. Geological Survey Interagency Report NASA-165 to National Aeronautics and Space Administration (NTIS N71-33374), 35 p.

Roberts, R. J., 1966, Geologic evaluation of radar imagery, north-central Nevada: U.S. Geological Survey Technical Letter NASA-49 to National Aeronautics and Space Administration (NTIS N70-38894), 15 p.

Rowan, L. C., and Cannon, P. J., 1970, Remote sensing investigations near Mill Creek, Oklahoma: Oklahoma Geology Notes, v. 30, no. 6, p. 127-135.

Schaber, G. G., 1966, Radar imagery—Meteor Crater, Arizona: U.S. Geological Survey Technical Letter NASA-62 to National Aeronautics and Space Administration, 18 p.

_____________ 1967, Radar images--San Francisco volcanic field, Arizona--a preliminary evaluation: U.S. Geological Survey Open-File Report, 10 p.

_____________ 1968, Radar and infrared in geological studies of northern Arizona, in Earth Resources Aircraft Program Status Review, 1st: National Aeronautics and Space Administration, Manned Spacecraft Center, Houston, Texas (NTIS N71-16126), p. 13-1 to 13-29.

_____________ 1980, Radar visual and thermal characteristics of Mars: rough plains surfaces: Icarus, v. 42, p. 159-184.

Schaber, G. G., and Brown, W. E., Jr., 1972, Long-wavelength radar images of northern Arizona--a geologic evaluation: U.S. Geological Survey Professional Paper 800-B, p. B175-B181.

Schaber, G. G., Thompson, T. W., and Zisk, S. H., 1975, Lava flows in Mare Imbrium: an evaluation of anomalously low Earth-based radar reflectivity: Moon, v. 13, p. 395-423.

Schaber, G. G., Berlin, G. L., and Brown, W. E., Jr., 1976, Variations in surface roughness within Death Valley, California: geologic evaluation of 25 cm wavelength radar images: Geological Society of America Bulletin, v. 87, no. 1, p. 29-41.

Schaber, G. G., Berlin, G. L., and Pitrone, D. J., 1976, Selection of remote sensing techniques: surface roughness information from 3 cm wavelength SLAR images, in American Society of Photogrammetry, Washington, D.C., 42d Annual Meeting, 1976, Proceedings: Falls Church, Virginia, American Society of Photogrammetry, p. 103-117.

Schaber, G. G., and Boyce, J. M., 1977, Probable distribution of large impact basins on Venus: comparison with Mercury and the Moon, in Impact and Explosion Cratering: New York, N.Y., Pergamon, p. 603-612.

Schaber, G. G., Elachi, Charles, and Farr, T. G., 1980, Remote sensing of SP Mountain and SP lava flow in north-central Arizona: Remote Sensing of Environment, v. 9, no. 2, p. 149-170.

Schwarz, D. E., and Mower, R. D., 1969, The potential for deriving landform regions from radar imagery: a Puerto Rican example: U.S. Geological Survey Interagency Report NASA-140 to National Aeronautics and Space Administration (NTIS N69-16255), p. 22-27.

Sheridan, M. F., 1966, Preliminary studies of soil patterns observed in radar images, Bishop area, California: U.S. Geological Survey Technical Letter NASA-63 to National Aeronautics and Space Administration (NTIS N70-38885), 8 p.

Simonett, D. S., 1968, Potential of radar remote sensing as tools in reconnaissance geomorphic, vegetation, and soils mapping: U.S. Geological Survey Interagency Report NASA-125 to National Aeronautics and Space Administration (NTIS N69-28154), 19 p.

Simonett, D. S., 1969, Utility of radar and other remote sensors in thematic land use mapping from spacecraft: U.S. Geological Survey Interagency Report NASA-140 to National Aeronautics and Space Administration, 113 p.

Snaveley, P. D., Jr., and Wagner, H. C., 1966, Geologic evaluation of radar imagery, Oregon coast: U.S. Geological Survey Technical Letter NASA-16 to National Aeronautics and Space Administration, 13 p.

Snaveley, P. D., Jr., and MacLeod, N. S., 1968, Preliminary evaluation of infrared and radar imagery, Washington and Oregon coast: U.S. Geological Survey Interagency Report NASA-124 to National Aeronautics and Space Administration (NTIS N69-25024), 23 p.

Southwick, D. L., 1966, Geologic evaluation of radar imagery, Appalachian Piedmont, Harford and York Counties, Maryland: U.S. Geological Survey Technical Letter NASA-48 to National Aeronautics and Space Administra-tion, 6 p.

Swanson, D. A., 1966, Geologic evaluation of radar imagery of the central part of the Oregon High Cascade Range: U.S. Geological Survey Technical Letter NASA-19 to National Aeronautics and Space Administration (NTIS N73-89403), 11 p.

Tabor, Rowland, 1966, Application of radar imagery to a geologic problem at Glacier Peak volcano, Washington: U.S. Geological Survey Technical Letter NASA-26 to National Aeronautics and Space Administration (NTIS N70-38896), 4 p.

Teleki, P. G., Schuchman, R. A., Brown, W. E., McLeish, R. A., Ross, Duncan, Mattie, Michael, 1978, Ocean wave detection and direction measurements with microwave radars, in Oceans '78': Washington, D.C., Marine Technology Society, p. 639-648.

Teleki, P. G., Campbell, W. J., Ramseier, R. O., and Ross, Duncan, 1979, The offshore environment: a perspective from Seasat SAR data, in Offshore Technology Conference, Texas, 11th, 1979, Proceedings: Houston, Texas, Offshore Technology Conference, paper 3382, p. 215-224.

Teleki, P. G., and Ramseier, R. O., 1979, The Seasat-A synthetic operature radar experiment, in International Symposium on Remote Sensing for Observation and Inventory of Earth Resources and the Endangered Environment, Federal Republic of Germany, 1978, Proceedings: Freiburg, Germany, International Society for Photogrammetry and International Union of Forest Research Organization, v. 1, p. 93-114.

Walker, G. W., 1966, Evaluation of radar imagery of highly faulted volcanic terrane in southeast Oregon: U.S. Geological Survey Technical Letter NASA-25 to National Aeronautics and Space Administration (NTIS N70-41122), 8 p.

Williams, P. L., 1966, Preliminary report on radar imagery of Cedar City—Iron Springs area, Utah: U.S. Geological Survey Technical Letter NASA-44 to National Aeronautics and Space Administration (NTIS N70-38887), 18 p.

Withington, C. F., and Jacobeen, F. H., 1973, Possible implications of lineaments in the Atlantic Coastal Plain as seen by satellite imagery, in Remote Sensing of Earth Resources Symposium, Tennessee, 2d, 1973, Proceed-ings: Tullahoma, Tenn., University of Tennessee Space Institute, p. 981-996.

Wolfe, E. W., 1966, Radar imagery: Salton Sea area, California: U.S. Geological Survey Technical Letter NASA-29 to National Aeronautics and Space Administration (NTIS N70-38937), 16 p.

Wolfe, E. W., 1969, Geologic evaluation of radar imagery, Caliente and Temblor Ranges, southern California: U.S. Geological Survey interagency report NASA-133 to National Aeronautics and Space Administration (NTIS N69-16988), 29 p.