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Bibliography of Geologic Studies Using Imaging Radar

M. Leonard Bryan

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National Aeronautics and Space Administration

Jet Propulsion Laboratory
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ABSTRACT

This bibliography has been prepared for use at the NASA/JPL Radar Geology Workshop held in Snowmass, Colorado on 16 - 20 July 1979. A selection of those papers dealing with geologic applications of imaging radars and that have appeared in the open literature are included. Complete abstracts, where available, and additional commentary are included for each of the citations. Three previous bibliographies dealing with radar (Bryan, 1973; Carter, 1969; and Dellwig, et al., 1975) have provided the core of this present bibliography. One hundred and ninety citations are listed alphabetically by the senior author. An index by National Technical Information Service Citation number is included. Several illustrations of L-band radar imagery are also included.

CONTENTS

BIBLIOGRAPHY

(The entries in this bibliography are arranged first alphabetically by the senior author's surname, and second by the year of publication.)

BAIR, G. L. and G. E. CARLSON, 1975

Height Measurement with Stereoradar

Photogrammetric Engineering and Remote Sensing, Vol. 41, No. 2, pp. 167–176.

Authors' Abstract: *The effect of image dissimilarities on terrain height-measurement capabilities of three stereoradar techniques for obtaining stereoimage pairs is compared by using computer-generated simulated radar images Simulated images are used because two of the stereoradar techniques are not presently implemented. The stereoradar techniques are· an improved single-flight technique which has been implemented. Improved stereoviewability is observed for the improved single-flight technique as compared with the pre-single-flight technique, and both single-flight techniques are better than the previously implemented two-flight technique. The improved stereoviewability of the single-flight images results in terrain height-measuring errors which are only 59 percent as large as those for the two-flight technique.*

The "previously proposed single-flight technique" involved beams squinted ahead of and behind the side-looking direction. To achieve stereo, Carlson shows that these beams must be obtained from real-aperture antennas physically oriented perpendicular to the beams and consequently not carried along the side of the aircraft as for SLAR. He shows that the parallax displacement for such beams is along the line of sight, but the parallax displacement for his "conical surface" beam is normal to the flight line even when the beam is pointed well ahead of (or behind) the side-looking direction. The "conical surface" beam is the type obtained by using phase advance in a real aperture antenna to achieve squint, and is the only type possible with the synthetic aperture. The height measuring capability demonstrated here depends on the difference in the size of the parallax displacement for the side-looking and the canted beam, since their displacements are both in the same direction. (From: Dellwig, et al., 1975.)

BARR, D. J., 1968

Use of Side-Looking Airborne Radar Imagery for Engineering Soils Studies

Ph. D. Dissertation, Department of Civil Engineering, Purdue University, 206 pp. (Available from U.S. Army Topographic Laboratories as Technical Report 46-TR, NTIS No. AD 701 902.)

Author's Abstract: *This research report is concerned with the development and evaluation of techniques of utilizing side-looking airborne radar (SLAR) imagery for engineering soils studies. The primary objective was the development of a systematic SLAR image interpretation technique Secondary objectives included an evaluation of methods for quantification of SLAR image textures and radar shadows.*

SLAR images from a variety of physiographic regions within the United States were evaluated. Systems operating at several wavelengths were represented in the study. Although none of the SLAR flights were made during the course of this investigation, field checking was performed for several of the study sites.

The qualitative analysis of SLAR imagery consisted of the evaluation of the pattern elements of image tone and texture followed by the interpretation of land form and engineering soil types from image patterns. A systematic approach to the evaluation of pattern elements and resultant patterns of drainage, topography, and local land surface condition was developed.

Quantitative aspects of the project included the generation of probability density curves from SLAR images by means of a densitometer coupled to a multichannel analyzer. Curve shape was

characterized by a number and correlated with visually defined image textures. In addition, radar shadow measurements were taken from SLAR images and correlated with a terrain roughness parameter.

Major conclusions derived from this study include: (1) the interpretation of regional engineering soil types from SLAR imagery is possible by means of an inference technique based on the recognition and evaluation of repetitive, unique patterns, (2) the extent to which inferences can be made concerning local land surface conditions such as local surface roughness or vegetative cover is governed by the dynamic range of tone values expressed on the imagery; a wider dynamic range permits a more detailed interpretation; (3) no evidence of significant microwave energy penetration was found on the imagery used for this study; (4) the shape of probability density curves generated from SLAR images is a quantitative measure of visual image texture; and (5) radar shadow measurements obtained from linear image scans oriented perpendicular to the flight line can be empirically related to a terrain macroroughness expressed by Fischer's dispersion factor "K." (Abstract from· Dissertation Abstracts Section B. Sciences and Engineering Vol. 29, No. 8, February 1969. pp. 2864B-2865B)

BATEMAN, P. C., 1966

Geologic Evaluation of Radar Imagery

U.S. Geological Survey Technical Letter – NASA-27, May, 9 pp. (NTIS No. N70-38899).

Abstract: *Geologic features, especially those related to volcanism and faulting, have topographic expressions that can be readily distinguished on radar imagery. Certain rock types that have distinctive weathering characteristics and drainage patterns can also be delineated. Radar imagery shows greatest utility in determining moisture distribution in alluvium It seems also to have very great value locally in forest covered areas, because of an apparent ability to "see" below the cover. (From. Carter, W. D., 1969.)*

BEATTY, F. D., et al., 1965

Geoscience Potentials of Side-Looking Radar

Raytheon Autometric Corporation, Alexandria, 10 September, Vol. I, x + 99 pp., Vol. II 114 pp. (Prepared for NASA by U.S. Army Corps of Engineers under Contract No. DA-44-009-AMC-1040 (X).)

From Author's Proloque: *The report represents the combined efforts of a panel of radar interpreters having geoscience backgrounds. The authors of this report have assumed that the readers will have only a rudimentary background in radar theory and the process of radar interpretation.. It is the authors' aim to present to the geoscientist the basic principles and theories necessary to "set the stage" for an appreciation of radar imagery and extraction of geoscientific data from these reports. . . . The authors feel that a word of caution is in order. Publications dealing with image interpretation and containing many illustrations, as does this one, soon become interpretation keys . . . either in thought or in actual practice. This report is not intended to be used as an interpretation key. Each image was selected to illustrate a type and kind of data contained in the image and extractable by an interpreter. The reader, perhaps having a different background, is urged to examine the images in the light of his own experiences to determine for himself the extractability of additional information suitable for his own pursuits. . . . The reader is advised that the imagery displayed in this report is from prototype equipment and largely resulted from flights while the systems were undergoing experimental evaluation tests. The potential user can expect higher quality imagery in the future.*

This report is probably one of the best overall reports thus far presented in the unclassified literature. Unfortunately, it is out of print and copies are extremely difficult to locate. In two volumes of large format (12 x 14 in.), it presents both text and numerous images obtained from a wide assortment of imaging radar systems. Following an introduction which includes resumés of remote sensing, radar theory and operation, radargrammetry, image interpretation and mosaicking, approximately 50 pages of explanations and interpretations of the images complete the first volume. Volume II consists of images and interpretation (acetate) overlays. Although this work was done in 1965 and presents many images from instruments not entirely operational, it is a valuable paper and highly recommended.

BECCASIO, A. D. and J. H. SIMONS, 1965

Regional Geologic Interpretation from Side-Looking Airborne Radar (SLAR)

Presented at the 31st Annual Meeting, American Society of Photogrammetry, Washington, 28 March to 3 April.

Photogrammetric Engineering, Vol. 31, No. 3, July, pp. 507.

Authors' Abstract: *One of the most important aspects of geologic and geomorphic mapping with side-looking airborne radar (SLAR) is the interpretation of the continuity of regional lithologic, structural and geomorphic units.*

Representative areas studies in parts of the Folded Ouachitas and in the Rocky Mountain Front indicate that SLAR provides an unusual opportunity for rapid regional geologic reconnaissance and analysis The relatively small-scale-large-area coverage afforded by SLAR records permits continuous observation of trends not obtainable in conventional aerial photography without extensive mosaicking. (Copyrighted by the American Society of Photogrammetry.)

BERLIN, G. L., 1971

Radar Mosaics

The Professional Geographer, Vol. XXIII, No. 1, January, p. 66.

From the Paper. The applicability of radar sensing in geographic research has been amply demonstrated during the past decade. Although many geographers are keeping abreast of these developments, few are aware that three experimental radar mosaics have been compiled at a 1 500,000 scale by the U.S Geological Survey and are available for a nominal fee. The mosaics display Yellowstone National Park and the entire state of Massachusetts from east and west range directions.

Radar data for the Yellowstone project were collected by a Westinghouse K_a-band system, and only 10 image strips were needed to provide coverage for the 21 million acre park Microwave reflections from a complex landscape have produced significant image shadows. Consequently, features such as fissures, faults, joints, lava flows, moraines, and stream terraces are easily identified. The northwest-trending faults near the Lamar River, joints south of the Obsidian Cliffs, and lava flows southeast of Bechler Canyon are much more conspicuous on the mosaic than on panchromatic photographs.

The two mosaics depicting Massachusetts were prepared to accommodate look-direction experiments. A Motorola X-band unit was flown 8,000 feet above sea level, and backscatter was intercepted from a 15.5 mile swath on both sides of the aircraft. Coverage for a land and water area approaching 13,000 square miles was accomplished by splicing 19 flight strips.

In addition to recording physical occurrences, the Massachusetts mosaics display considerable cultural detail. Concerning the former, coastal features, glacial lakes, drainage systems, drumlins, fault blocks, and trap ridges are especially prominent. A preliminary examination reveals many topographic and structural relationships. Favorable dielectric and geometric parameters make it possible to delineate urban areas and certain transportation systems because these phenomena are responsible for bright energy returns. At the 1 500,000 scale, metallic objects such as ships in Boston Harbor and even bridges crossing the Connecticut River are visible

Since radar mosaics display large areas in a small format, they represent a complementary tool for analyzing various regional distributions and relationships. Therefore, by using mosaics a geographer can gain a rapid and comprehensive overview of a region. All that remains to satisfy this requirement is to have more mosaics made available to the geographic community, and if current trends are a barometer of the future, radar mosaics will be continually released by the U.S. Geological Survey. (Copyrighted by Association of American Geographers.) (See also Berlin and Schaber, 1971.)

BERLIN, G. L. and G. C. SCHABER, 1971

Geology and Radar Mosaics

Journal Geological Education, Vol. 19, No. 5, November, pp. 212–217.

Authors' Abstract. *Radar mosaics represent one of the latest remote sensing innovations, and unlike photo mosaics, the data are unaffected by solar illuminative variations or weather. Such complications are especially applicable to reconnaissance surveys where broad overviews of the terrain are needed. The image detail is sufficient for interpreting and mapping various regional morphologic distributions and structural relationships. Radar mosaics can also be used as instructional aids for a variety of geologic discussions. Four mosaics are currently available, three may be purchased from the U.S. Geological Survey and one from the Raytheon Company. (Abstract copyrighted by National Association of Geological Teachers.)*

A brief discussion of the operation of a SLAR system is followed by a presentation of three radar mosaics (Massachusetts, Yellowstone Park, and Darien Province, Panama) together with ordering information for securing copies of each mosaic. Some interpretation for the images is offered. (Also see. Berlin, G. L., 1971.)

BORDEN, R. C. and E. C. WILLIAMS, 1950

Radar Mapping of the Chicago–New York Airway

Technical Development Report No. 66, Technical Development and Evaluation Center, Civil Aeronautics Administration, U.S. Dept. of Commerce, Indianapolis, April, 9 pp.

Authors' Summary. *This report describes a radar flight from Chicago to New York during which time several hundred pictures of the radar indicator were taken with a Fairchild Type 05-A radar camera. A number of representative radar prints are included together with explanatory remarks and a discussion of the possibilities and limitations of navigation by radar. The equipment used was an AN/APS-10 3-cm airborne search radar installed in NX-300, a B-25J airplane*

From Authors' Conclusions: *Radar navigation is considered impractical in areas where more easily interpreted navigational facilities are available . . . . The possibility of making a mistake over . . . areas of similar geography cannot be overlooked. In order to accurately determine a location, several different targets must be cross-checked. Attempts to navigate by radar over uncertain territory should not be attempted without the aid of previously prepared radar maps, preferably from actual radar photographs. Any discrepancies between characteristics or operating conditions (frequency band, sensitivity, antenna pattern, range scale, etc.), will complicate the problem considerably. Radar photography should be carried out with the sensitivity of the radar turned well down. Adoption of radar solely as a navigational aid on the basis of its search function alone appears unfeasible for scheduled flying.*

Several good PPI photos together with map locations and basic interpretations of terrain features are included in the paper.

BRENNAN, P. A., 1968

The Geology of the N.A.S.A. Arizona Sedimentary Test Site, Mohave Co., Arizona

M.S. Thesis, Geology, University of Nevada, Reno, June ix + 93, pp. + maps.

From Author's Abstract: *The NASA Fundamental Sedimentary Test Site in northern Mohave County, Arizona, contains exposures of limestone, sandstone, conglomerate, and thin layers of basalt. Structurally, the area consists of southeasterly dipping rock units transversed by a series of minor high-angle faults, and a major low-angle normal fault . . . The topography is moderate, much of the site being in a broad flat valley Because of the arid weathering conditions, large detrital fans have been developed in the valleys These fans support typical high desert vegetation. . . . Remote sensing aircraft flights have yielded photographs, imagery, and sensor data which, with detailed ground information, provide an almost unique area in which to study the possible contributions of remote sensing to geology. Radar, ultraviolet, photographic infrared, thermal infrared, microwave radiometry, and scatterometry are available for the site . . . . Two systems, the radar and the thermal infrared, have been completely evaluated and are included.*

This paper presents a geologic description of the NASA test site (one of many selected in the mid-1960s), and contains some data obtained during NASA missions 44 and 59. The radar used was the AN/APQ 97 (K-band). Although several images are presented (HH, HV) little is noted about the actual utility of the sensor data. The strength of this thesis is the description of the test site for which many data are presently in the NASA archives.

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.G.S. Technical Letter – NASA-45, August, 15 pp. (NTIS No. N70-38893.)

Abstract *Radar imagery along the San Andreas Fault Zone seems to enhance the photographic contrast between unconsolidated geologic units and bedrock; thus, alluvium, lacustrine deposits, landslide debris, and similar units appear dark in tone, and contrast sharply with more consolidated bedrock units. Different kinds of bedrock units, however, are indistinguishable on the radar imagery except where such units engender a characteristic form of topographic expression. The side-looking angle accentuates topographic features, particularly linear features that are parallel or oblique to the line of flight. (From: Carter, W.O., 1969.)*

BRYAN, M. L., 1973

Radar Remote Sensing for Geosciences: an Annotated and Tutorial Bibliography

Ann Arbor, MI.: Environmental Research Institute of Michigan, Ann Arbor, Michigan, 298 pp., illus., Paper.

No Author's Abstract

This bibliography consists of 383 references, with annotations and complete author's abstracts of the papers that have appeared in the open literature, and that deal specifically with radar remote sensing. Imaging radars, PPI radar, and, on occasions, navigation radars are considered. The chapters are arranged by earth resources subject: (1) Origin, History and Development of Radar; (2) Applications in Agriculture and Vegetation; (3) Applications in Geology, Geomorphology, Topography, and Soils; (4) Applications in Hydrology and Water Resources, including Oceanography; (5) Cultural Applications; (6) Cartography and Map Compilation; (7) Other Applications and General References, and (8) Bibliographic Resources.

CAMERON, H. L., 1965a

Radar as a Surveying Instrument in Hydrology and Geology

Proceedings, Third Symposium on Remote Sensing of the Environment, Report No. 4864-9-X, Willow Run Laboratories of the Institute of Science and Technology, The University of Michigan, Ann Arbor, November, pp. 441–452. (NTIS No. AD 614 032.)

Author's Abstract *High-definition radar scope photography is investigated as a new means for studying the earth's surface. The radar is installed in an R.A.F. V-bomber and operated at approximately 41,000 feet; photographs of the scope are obtained at 5-minute intervals, providing adequate "stereo" overlap The radar photos resulting from flights over Gaspé and Scotland are presented and discussed.*

Aerial photography interpretation assumes "that all topography is a reflection of the underlying bedrock geology moulded by the forces which have acted on it." The author points out that when elevations are less than 3000 ft, shadows caused by this relief are small and of little consequence. However, when the relief of the terrain exceeds approximately 10% of the aircraft altitude, these shadows can be of great importance. Photography (35 mm) of a PPI scope illustrates the article. (See other articles by this author.)

CAMERON, H. L., 1965b

Radar and Geology

Report 65-202, Air Force Cambridge Research Laboratories, Office of Aerospace Research USAF, Bedford, Mass., July, 11 pp. plus figs. (NTIS No. AD 624 887.)

Author's Abstract. *The topographic mapping possibilities of radar have been investigated almost since radar was developed. The geological interpretation of P.P I. scope photography is discussed with possible explanations for the geological expression of certain features*

The example of radar ice mapping is given and the radar geology of part of Eastern Canada described.

The radar geology of Scotland is briefly described.

The application of radar photography to the study of geological structures is recommended as a new and possibly unique method.

Study of 35 mm photography of a PPI scope (using both center and sector scan) has yielded information on several previously unknown faults in the Gaspé area of Canada. Some rock groups are easily identified, but this is thought to be due to differential erosion rather than some unique component of the rocks. Studies of scattered geology were also made using the PPI photographs, and have yielded similar information. The scales of the data were quite small, in the neighborhood of 1:1,000,000 to 1:1,300,000, and the use of several look directions is recommended. This is a fairly early and innovative work.

CAMPBELL, A. B., 1968

Current U.S. Geological Survey Research in Yellowstone National Park

Annual Meeting, Rocky Mountain Section, Geological Society of America, Bozeman, Mt., 7–12 May.

Geological Society of America, Special Paper 121, Abstracts for 1968, Boulder, Colo., p. 590 (abstract only).

Author's Abstract: *Limited U.S. Geological Survey studies have been pursued intermittently for many years in Yellowstone National Park During the summer of 1965, a greatly expanded program was begun, made possible through the cooperation of the National Aeronautics and Space Administration and the National Park Service Current work under this cooperative program includes bedrock and surficial geologic mapping of the entire Park with attendant stratigraphic and paleontological studies, geophysical studies involving gravity, resistivity, magnetic and seismic surveys, including operation of a seismic network; isotopic studies, and a detailed study of thermal features.*

U S Geological Survey personnel are using these newly acquired data in the empirical evaluation of aerial imagery obtained over the Park to appraise possible geologic applications of various remote sensing devices. Photographs, particularly color, have proved useful in geologic interpretation. Side-looking radar enhances certain geologic features generally observable to some degree on aerial photographs, and has the advantages of synoptic coverage and an all-weather capability. Thermal infrared imagery has very limited geologic application except in areas of thermal activity Further experimentation with these and other remote sensors is planned. (Copyrighted by GSA.)

CANNON, P. J., 1972

The Application of Radar and Infrared Imagery to Quantitative Geomorphological Problems

Proceedings, Third Annual Congress on Remote Sensing in Arid Lands. Office of Arid Land Studies, College of Earth Sciences, The University of Arizona, Tucson, Ariz., November, 379 pp., pp. 104–122.

From Author's Introduction and Summary· *The purpose of this study was to determine how a detailed quantitative geomorphic investigation of an area could be supported by radar and infrared imagery. The usefulness of radar imagery as a quantitative geomorphic tool depends on the size of the area to be investigated, the relief, and the distribution of*

vegetation. Although unclassified radar imagery provides no quantitative information on relief in areas like Mill Creek, Oklahoma (the study area and an area of low relief), it does provide useable areal information for drainage basins greater than approximately 30 square miles in area. Radar and infrared imagery can be used in conjunction to counteract their shortcomings, providing a new and valuable tool to the quantitative geomorphic investigations of drainage basins

The study deals with real aperture (Westinghouse ?) data obtained under the USGS—NASA remote sensing studies programs. Cross-polarized data provided the best geologic information if obtained between 10,000 to 20,000 feet altitude, above actual ground level. The evaluation was conducted by sketching drainage maps from the imagery and comparing them to the topographic maps available. No information concerning the statistical comparison of this quantitative information is printed, although it is referred to in the text. No comments concerning, resolution depression angles, look direction with respect to relief, and other important radar parameters are included in the paper.

CANNON, P. J., 1973

The Application of Radar and Infrared Imagery to Quantitative Geomorphic Investigations

Proceedings, Second Annual Remote Sensing of Earth Resources Conference, University of Tennessee Space Institute, Tullahoma, Tenn , March.

Author's Abstract *Quantitative geomorphic data were derived from airborne radar and thermal infrared imagery of an area in south-central Oklahoma. These data were carefully compared and contrasted with quantitative data taken from a detailed topographic and photographic study of the area. The usefulness of radar imagery as a quantitative geomorphic tool depends on the size of the area to be investigated, the relief, and the distribution of vegetation. Radar imagery provides useable areal information for basins greater than 30 square miles in area. From the areal parameters, meaningful elongation ratios, bifurcation ratios, drainage densities, and crenation ratios can be calculated. Infrared imagery can provide excellent geomorphic information for small basins. The detail of the information is dependent upon the altitude of acquisition Predrawn imagery can provide details of channel-ways in areas of dense vegetation that cannot be seen on aerial photographs. It can also provide a means to make an extremely accurate inventory of surface water distribution.*

CANNON, P. J., 1974

Rock Type Discrimination Using Radar Imagery

Remote Sensing of Earth Resources, Vol. III, Edited by F. Shahrokhi. The University of Tennessee Space Institute, Tullahoma, Tenn., xiii, 813 pp., pp. 339—352.

Author's Abstract. *Geologic mapping from radar imagery of the Wichita and Arbuckle Mountains of southern Oklahoma indicates that in areas of sparce to moderate vegetation, certain rock types can be readily discriminated on the radar imagery. They can be distinguished because the returns of radar energy from rock outcrops are strongly influenced by the geometry of the rock surfaces. The angular configuration exibited by the outcrop is the most important factor in returning the propagated radar energy to an airborne receiver The outcrop geometry can vary greatly between rock types due to the differences in grain size, rates of weathering, and structure. The scale of the outcrop geometry in relation to the wavelength of the propagated radar energy is also an influencing factor of importance.*

The radar used in this study was the Westinghouse, AN/APQ-97 (Ka-band) and the data were collected in 1965 and 1969 by NASA under the USGS Remote Sensing Application's Program. The author notes that ". . . rock type discrimination using radar imagery is possible by understanding the unique surface characteristics of various rock types." It is also noted that the subangular pebbles of the Cretaceous marls in the study area are considered to ". . . provide the optimum geometry to return the K-band radar energy." Interestingly, the author notes that the blocky limestones of the Arbuckle Mountains apparently, due to the geometry of the outcrop, reflect radar energy in a manner similar to the granites of the Wichita Mountains. The separation of rock types in the areas studied is accounted for by the geometry of the rock surfaces. No comments concerning the microrelief relative to the wavelength, or incidence angle and other radar parameters are made.

CANNON, P. J., 1976

Critical Landform Mapping of Alaska Using Radar Imagery

Proceedings, 2nd Annual W. T. Pecora Memorial Symposium. Sioux Falls, S. D., 25-29OCT76, American Society of Photogrammetry, pp. 144—160.

Author's Abstract: *A critical landform is a physiographic feature, pattern of physiographic features, or assemblage of such features, which is used to interpret geologic processes and geologic features that have current economic importance. Natural resources and the natural environment are of current economic importance in Alaska. Radar imagery has been acquired of portions of Alaska in order to supplement an information shortage about environmentally important geomorphic features and associated natural processes The unique ability of radar imagery to enhance subtle geomorphic features provides information on a perceptual level that has, only recently, become available to scientists in Alaska. This type of information is forcing a major change in the interpretation of the geomorphic history of Alaska. The geomorphic history is based on the construction of a chronology of geomorphic events. Current spatial information and sequential observations of much of the coastal areas of Alaska are necessary to investigators, charged with making environmental evaluations of these areas. Radar imagery is the only remote sensing technique which can satisfy this necessity because of the weather conditions and the winter darkness of the Arctic. As a result, significant scientific information about coasts, sea ice, and glaciers has been recently obtained from radar imagery, which cannot be obtained by any other remote sensing technique. This information is being mapped, creating a reference by which possible developmental impacts can be evaluated*

This paper presents a series of radar images (obtained from an unidentified real aperture X-band system) of several areas of Alaska. Little detail of the actual mapping is presented, with the exception of some landform maps and lineament maps of SE Alaska. The author may be guilty of somewhat inflated enthusiasm with such statements as "The detection and location of the lineaments across the Mapaspina ice mass is unique and can be done only by using the radar imagery," and "The radar imagery provides more information about ice conditions than any other remote sensing techniques." The strength of the article is the numerous radar images, and it is this vehicle that is used to suggest the potentials for geomorphic mapping based on radar data.

CARROLL, D. M. and R. EVANS, 1971

The Application of Remote Sensing Methods to Soil Mapping in England and Wales

Proceedings, 7th International Symposium of Remote Sensing of Environment, Report No. 10259-1-X, Willow Run Laboratories of the Institute of Science and Technology, The University of Michigan, Ann Arbor, May, pp. 1443—1446.

Authors' Abstract· *Problems encountered while using air photos for soil mapping in England and Wales and the current programme of photo-interpretation research in lowland arable and upland areas are described. Initial experience of colour aerial photography suggests that the additional benefits gained are small. Plans for a trial of multispectral and thermal imagery are outlined.*

Following a brief discussion of aerial photography and thermal imagery, the authors state the following concerning radar imagery for soil mapping:

"Some sideways looking airborne radar imagery has been inspected and compared with conventional aerial photography. The radar imagery has poor resolution, a diffuse and distorted nature and is marred by much shadow. All the features seen were also clearly recognizable on panchromatic prints. The sole advantage seemed to be the greater emphasis given to some minor geomorphological features, and this type of imagery seems at present of little use in detailed soil mapping."

CARTER, W. D., 1969

Annotated Bibliography of USGS Technical Letters — NASA Papers on Remote Sensing Investigations Through June 1967

U.S. Geological Survey Open File Report, Technical Letter — NASA-86, ii plus 46 pp.

Author's Preface· *This annotated bibliography includes reports written as a result of feasibility studies in remote sensing by the U.S. Geological Survey working in cooperation with and funded by the National Aeronautics and Space Administration (NASA) under its Earth Resources Survey Program. These reports cover a span of three years, from inception of the program in late 1964 through June 1967. It is intended that the bibliography will be periodically updated.*

Comments on the usefulness and content of this bibliography or suggestions for future revised and updated editions or supplements are invited

The work, citing 19 radar references, is organized into several major sections defined by the wavelengths of the EM spectrum used: (a) Photography, (b) Radar, (c) Infrared, (d) Ultraviolet. Two additional sections are applications of remote sensing and a list of all NASA Tech letters prepared by the USGS. Although the papers are considered as preliminary, and therefore not to be freely quoted, they are of interest to the scholar who wishes to observe the stages of progress of remote sensing studies. Many of the papers are available through NTIS and are also included here.

CHRISTIANSEN, R. L., et al., 1966

Preliminary Evaluation of Radar Imagery of Yellowstone Park

U.S. Geological Survey Technical Letter — NASA-30, July (NTIS No. N70 38847).

Abstract: *Preliminary studies of radar imagery in the Yellowstone Park area show that it has certain valuable uses in regional geological reconnaissance. Foremost among these are its all-weather capability and wide areal coverage. Geologic features are best expressed by topographic irregularities that include lineaments (faults and fractures), contrasting stream drainage patterns, and glacial deposits. Distinctive flow structures in the surface of rhyolite flows enable one to distinguish them from ash flows and basaltic lava flows, whereas distinctive stream dissection patterns enable differentiation between lava flows and ash flows. Imprecision and variability of scale are considered to be major disadvantages. Furthermore, there is no apparent expression of grain size, color or composition of rock types.*

CLARK, M. M., 1971

Comparison of SLAR Images and Small-Scale Low-Sun Aerial Photographs

Geological Society of America Bulletin, Vol. 82, No. 6, July, pp. 1735–1742.

Author's Abstract. *A comparison of side-looking airborne radar (SLAR) images and black and white aerial photos of similar scale and illumination of an area in the Mojave Desert of California shows that aerial photos yield far more information about geology than do SLAR images because of greater resolution, tonal range, and geometric fidelity, and easier use in stereo Nevertheless, radar can differentiate some materials or surfaces that aerial photos cannot, thus, they should be considered as complementary, rather than competing tools in geologic investigations*

The most significant advantage of SLAR, however, is its freedom from the stringent conditions of weather, date, and time that are required by small-scale aerial photos taken with a specified direction and angle of illumination. Indeed, in low latitudes, SLAR is the only way to obtain small-scale images with low illumination from certain directions, moreover, in areas of nearly continuous cloudiness, radar may be the only practical source of small-scale images (Copyright by GSA)

The author also states, "The relative advantage of aerial photos will probably diminish as resolution, planimetric fidelity, and tonal range improve in future SLAR instruments. Moreover, in this comparison of terrain nearly devoid of vegetation, aerial photos may show to their best advantage. Radar might be far more sensitive to surface form and material than aerial photos in regions of heavy vegetation. However, this has yet to be reported in a comparison using photos of comparable scale and illumination.

"Some studies also indicate that the low resolution and, possibly, high contrast of small-scale radar images suppress distracting detail and thereby reveal subtle regional features such as lineaments. However, this benefit of radar has . . . not yet been demonstrated . . . " (See also: Lyon, R. J., P. J. Mercado, and R. Campbell, Jr., 1970.)

CLARK, M. M., 1973

Comparison of SLAR Images and Small-Scale Low-Sun Aerial Photographs: Reply

Geological Society of America Bulletin, Vol. 84, No. 1, January, pp. 359–362.

No Author's Abstract

This paper completes the discussion of an earlier paper by Clark (1971) and a discussion by Dellwig and McCauley (1973). The author contends that his original conclusions are not altered by the discussion. His approach, quite valid, is that SLAR is useful for much geological work, but the usefulness has not been as adequately demonstrated as some researchers would claim. SLAR and aerial photo illustrations are included in support of the arguments. (See also: Dellwig and McCauley, 1973.)

COINER, J. C. and L. F. DELLWIG, 1972

Similarities and Differences in the Interpretation of Air Photos and SLAR Imagery

Proceedings, Technical Program, Electro-Optical Systems Design Conference, New York, 12-14 September, pp. 89–94.

Author's Summary. *Of the object recognition elements originally defined for photo interpretation, only shape, pattern, and size have direct parallels in the interpretation of SLAR imagery. This must be qualified by the systems limitation (resolution) of the SLAR. Tone, shadow and texture, critical in any type of interpretation, are highly dependent upon the remote sensing system being employed, and no direct parallel exists for these terms between air photo and SLAR image analysis. In aerial photographs, these terms are descriptive of the amount and angle of reflected solar energy, while in SLAR images, the terms are descriptive of backscatter (influenced by frequency, resolution and depression angle of the system) from the scene being sensed Therefore, terminology originally developed for one system (aerial photography) should be employed with extreme caution to interpretation of imagery acquired by other systems, specifically SLAR. (Reprinted from Proceedings of the 1972 Electro-Optical Systems Design Conference. Copyright © 1972 by Industrial and Scientific Conference Management Inc)*

The crux of the argument presented in this paper is that the terms developed for use in aerial photograph interpretation can be used only with caution when applied to SLAR imagery interpretation. This reviewer has some difficulty understanding this admonition by the authors because the terms in both applications are defined in precisely the same manner. What is being changed is the wavelength of the energy which is being studied. This is pointed out by the authors when they state ". . . the data that tone expresses are highly related to the realm of the em spectrum where the sensor operates." In this one sentence, much of the basis for their argument is destroyed. Nonetheless, the paper reemphasizes some subtle points which are often missed by fledgling SLAR interpreters when attempting to transfer their aerial photographic knowledge to this new image type. Therefore, it is well worth the reading by new SLAR interpretation students.

COOPER, J. R., 1966

Radar Imagery of Twin Buttes Area, Arizona Test Site 15

U.S. Geological Survey Technical Letter – NASA-28, May, 15 pp. (NTIS No. N70 40311.)

Abstract: *Outcrops of glass-rich igneous rock appear as conspicuous dark spots on the depolarized radar image but are obscure on the polarized image and on aerial photographs Both types of radar imagery clearly outlined an ancient, previously unrecognized flood plain.*

DAILY, M., et al., 1978a

Application of Multispectral Radar and LANDSAT Imagery to Geologic Mapping in Death Valley

Publication 78-19, Jet Propulsion Laboratory, Pasadena, Calif., March 30, ix, 47 pp. plus figs., tables, refs. (NTIS N78-30635.)

Authors' Abstract: *The purpose of this study was to apply the techniques of computer image processing to data sets from sensors operating in visible and microwave wavelengths as an aid to discriminating surficial geologic units*

Side-Looking Airborne Radar (SLAR) images acquired by JPL and Strategic Air Command systems and visible and near-infrared LANDSAT imagery were applied to studies of the Quaternary alluvial and evaporite deposits in Death Valley, California. Unprocessed radar imagery revealed considerable variation in microwave backscatter, generally correlated with surface roughness.

Individual images were registered to a common geographic base by first manually selecting an array of tiepoints and then geometrically distorting the images in a computer The registered images were ratioed, picture element by picture element, then contrast-stretched to enhance the spectral differences.

For Death Valley, LANDSAT imagery is of limited value in discriminating the Quaternary units except for alluvial units distinguishable by presence or absence of desert varnish or evaporite units whose extremely rough surfaces are strongly shadowed.

In contrast, radar returns are most strongly dependent on surface roughness, a property more strongly correlated with surficial geology than is surface chemistry. While no single radar band is capable of separating all the surface units, use of two frequencies. (1) X-band, $\lambda = 3$ cm and (2) L-band, $\lambda = 25$ cm, and two polarizations (1) vertical-transmit, vertical-receive (VV) and (2) vertical-transmit, horizontal-receive (VH) permits complete separation of all units except the two younger gravel units (Qg_3 and Qg_4 and the enfant terrible of the study, the floodplain (Qf). By including any one LANDSAT band, Qg_3 and Qg_4 become distinguishable, while Qf remains intractable

Microwave scattering mechanisms in the Valley include specular reflection, diffuse (depolarizing), multiple scattering, and the effects of penetration.

This paper consists of seven major sections, of which Section 4 (Radar Imagery) and Section 6 (Digital Image Processing) are possibly the most interesting. The text is quite detailed with the descriptions of the various surfaces encountered in Death Valley. Although the data were digitized, and therefore it was possible to present the images in an (uncalibrated) quantitative way, the authors chose to discuss the radar image brightness as "estimated by eye." This seems to have reduced the purpose of digital imagery to registration only. The bulk of the paper deals with presentation of the geologic scene and discussion of the registration techniques used. In this respect, especially for the latter, it is an exceptionally tutorial paper.

DAILY, M., et al., 1978b

Discrimination of Geologic Units in Death Valley Using Dual Frequency and Polarization Imaging Radar Data

Geophysical Research Letters, Vol. 5, No. 10, October, pp. 889–892.

From Authors' Abstract: *Simultaneous analysis of dual frequency and dual polarization radar imagery of a portion of Death Valley, California, has yielded a nearly complete discrimination of surficial geologic units. Radar imagery in the like polarized L-band and crosspolarized L-band and like polarized X-band were digitally combined and ratioed to enhance the variation in the backscatter cross-section of the different geologic units. In the case of Death Valley, the variation between the different geologic units is clearly reflected in the surface roughness or particle size These, in turn, have a strong affect on the radar backscatter cross-section.*

This short paper notes that the cross-polarized backscatter cross-section is proportional to the overall roughness spectrum of the surface. In addition, for surfaces covered by discrete scatterers, the like-polarized return is related mainly to the size of the scatterers, whereas the cross-polarized return is apparently related primarily to the density of the scatterers. The authors also make the case for distinguishing between the surface roughness and the dielectric roughness. This distinction is especially important in areas where there may be water immediately under the surface, which is quite dry. Such a situation is observed in Death Valley, Calif. Unfortunately, the system of citation used in the text is not continued in the references and the reader cannot pursue points made by the authors.

DALKE, G. E. and R. M. McCOY, 1969

Regional Slopes with Non-Stereo Radar

Photogrammetric Engineering, Vol. 35, No. 5, May, pp. 446–452.

Authors' Abstract: *Two monoscopic radar images of the same area of terrain can be used for measurement of regional slopes. By measuring the lengths of individual slopes on each of the images, and knowing the look angle at each point across the images, the angle of each slope can be computed. The two pieces of imagery may be taken from opposite sides of an area or both from the same side. Accuracy for individual slopes is fair, but for regional mean slope the accuracy is high 'Compensation can be made for apparent slope, and ground range or slant range display systems. (Copyrighted by the American Society of Photogrammetry.)*

DELLWIG, L. F., J. N. KIRK, and R. L. WALTERS, 1966

The Potential of Low-Resolution Radar Imagery in Regional Geologic Studies

Journal of Geophysical Research, Vol. 71, No. 20, October, pp. 4995–4998.

No Authors' Abstract.

This paper, published in the "letters" section of the journal, presents the argument that although resolution cell size of operating radars is being constantly decreased, a fairly large resolution cell size for the study of regional geologic structure definitely has advantages. Using X-band (3.2-cm) brute force radar with a range resolution of approximately 15 m and an azimuth resolution of 208 m at 90 km, the authors were able to detect lineaments which were not detected on either low altitude (1:20,000) aerial photography or from low-flying aircraft or ground observations. After citing some data which is interpreted as showing the lack of influence of varing precipitation rates in the study area, they state that both the wavelength and the variations in evaporation may be excluded as major factors affecting the radar backscatter. Scale is considered as one of the major significant factors in bringing out the lineaments, together with the low resolution (which suppresses vegetation, minor streams, etc.) and the broad coverage (the mapping range of the X-band system was 2.8 to 90 km on each side of the aircraft). For comparisons, they present a Ka-band image, having improved resolution, of the same area that has been imaged with X-band. Although the radars viewed in opposite look-directions, linear patterns are more easily detected on the low-resolution X-band system.

DELLWIG, L. F. and R. K. MOORE, 1966

The Geological Value of Simultaneously Produced Like- and Cross-Polarized Radar Imagery

Journal of Geophysical Research, Vol. 71, No. 14, 15 July, pp. 3597–3601.

Authors' Abstract: *Westinghouse radar (AN/APQ-97) was used in the vicinity of Pisgah Crater, California Four polarization combinations were available The combination of terrain slope, polarization and look angle of the radar both obscured and enhanced the contacts of various rock and sediment units The suggestion is made that surface roughness rather than contrasting lithologies may be the controlling factor in the depolarization of the radar. This is a fairly early paper in this area of research. (Abstract copyrighted by American Geophysical Union)*

DELLWIG, L. F., 1968

Pluses and Minuses of Radar in Geological Exploration

Earth Resources Aircraft Program Status Review, Vol. 1. Geology, Geography and Sensor Studies, NASA, MSC, Houston, September, pp. 14–1 to 14–25. (NTIS No. N71 16126.)

No Author's Abstract.

"The purpose of this presentation is to . . . outline the unique contributions of radar in geological investigations, to point out weaknesses, and suggest needs for further investigations."

The author considers that the major usefulness of radar will come in areas which are difficult to map, for regional work, and in areas which presently lack proper mapping. In small-scale studies, radar value may not be lost, but it will probably be decreased. It is here with the detailed geologic studies that radar polarization and wavelength variations will have their greatest significance. Several examples are given: Darien Province, Panama; Cane Springs, Arizona; Pisgah Crater, Calif.; together with some additional work in the Wasatch Range, Utah and the Boston Mts. of Arkansas. Generally, linears not visible on aerial photomosaics were detected on the radar images. With longer wavelengths (P-band) there was some penetration of windblown silts at the California site. Also, the longer wavelengths "smoothed" several surfaces and the author states that "the real value of long-wavelength radar . . . is not its penetrative capability or any other single factor per se, but its unique total response to terrain characteristics, as compared to a shorter wavelength radar system."

Radar shortcomings included: (1) look-direction dependency, (2) impracticality of making mosaics from slant-range imagery, (3) radar shadowing in areas of high relief, (4) distortion caused by slant-range presentation, and (5) displacement of elevated features caused by layover.

One set of examples shows how one terrain element, the drainage net, changes with look direction.

Some suggested areas of research for geoscience radar are the effects of look direction on radar signals; a greater effort needs to be directed toward the evaluation of the remote sensing system as a whole.

A 25-page appendix documents the paper with illustrations of the discussed imagery and statements of the outlines and summaries of the work conducted at the several sites.

DELLWIG, L. F., J. N. KIRK, and L. H. JEFFERIS, 1968

The Importance of Radar Look-Direction in Lineament Pattern Detection

Presented at the Annual Meeting, Geological Society of America, Mexico City, 11–13 November.

Special Paper 121, Abstracts for 1968, Boulder, p. 72 (abstract only).

Authors' Abstract *The value of radar for lineament detection has been demonstrated in a number of studies and in a variety of terrains Although lineaments are generally better defined on radar imagery than on conventional aerial photographs, questions have arisen as to the degree of dependency of radar-lineament detection on look-direction.*

An experiment was conducted in the Boston Mountains of Arkansas utilizing eight different imaging passes over the same geographic area by a K-band side-looking radar with all terrain and operational parameters, except look-direction, held nearly constant during the over flights. Results of this study must be considered applicable only for terrain similar to that of the Boston Mountains.

This study indicates that, to some degree, look-direction of the radar system does influence the radar recording of radar lineaments. However, the influence of look-direction is not sufficient to invalidate the use of radar imagery for lineament studies, or to require multiple-imaging passes over a terrain in order to record major lineament trends. (copyrighted by GSA.)

DELLWIG, L. F., H. C. MacDONALD, and J. N. KIRK, 1968

The Potential of Radar in Geological Exploration

Proceedings, Fifth Symposium on Remote Sensing of the Environment, Report No. 4864-18-X, Willow Run Laboratories of the Institute of Science and Technology, The University of Michigan, Ann Arbor, April, pp. 747-763 (NTIS No. AD 676 327).

Reprinted in: Tulsa Geological Society Digest, Vol. 36, 1968, pp. 26-42.

Authors' Abstract: *At the present time, side-looking airborne radars (SLAR) are most useful to the geologist for regional studies of remote, previously unmapped areas. Imaging radar systems may ultimately be most valuable for conducting regional investigations, but areas requiring detailed investigation can benefit from SLAR's unique ability to present certain types of data. Regardless of the nature of the study, dual-polarization imagery has proven the most effective in geologic investigation.*

In regional studies, radar should be the primary, and in some instances may be the sole sensor. The value is best demonstrated in areas where photographic coverage is not possible (or feasible) and where ground investigations are difficult or impossible. Gross structural patterns are well-displayed on SLAR imagery because of the radar's capability to continuously image wide swaths of terrain. Such a use takes maximum advantage of the relatively low resolution, which suppresses distracting and redundant detail. SLAR is especially valuable in the detection of regional-scale lineaments, and has demonstrated itself superior in most instances to aerial photography for such studies

In detailed studies, the significant contribution of radar lies primarily in the detection of subtle changes of lithology In some instances lithologic changes appear to be directly responsible for isolating anomalous areas. In other cases, the delineation of rock type may be achieved indirectly from radar imagery through examination of fracture textures, patterns of weathering, topography and vegetation. The full geologic significance of SLAR systems has not yet been demonstrated, however, it is anticipated that the value of radar to the geologist will be greatly enhanced when improved multi-band and dual-polarization systems can be utilized to obtain geologic data. The value of long-wavelength imagery will be realized only when it is produced simultaneously with X- or K-band imagery

The emphasis in this paper is the use of radars for regional geological exploration. No quantitative data are included, but several good images are given to illustrate the discussion. The authors warn against the "variety of baseless or unqualified claims regarding the value of radar" for use in geological (and other) work.

DELLWIG, L. F., 1969

An Evaluation of Multifrequency Radar Imagery of the Pisgah Crater Area, California

Modern Geology, Vol. 1, No. 1, November, pp. 65-73.

(Also: CRES Technical Report No. 118-6, September, 1968.)

Author's Abstract: *The Pisgah Crater test site has been imaged by several different radar systems Although simultaneous imaging by K-, C-, and P-band radars has not been realized, cautious comparison (recognizing the influence of variations in system and surface parameters) of available, nonsimultaneously recorded imagery point to the value of simultaneous imaging by long and short wavelength systems. The imagery evaluated has well documented the wavelength dependence of the return signal from some cultural and natural phenomena Variations in return were primarily a function of surface roughness although some penetration by long wavelength radar was also demonstrated.*

A detailed account of the interpretation of radar imagery from three bands of one area includes an identification of eleven different natural and cultural items. A table facilitates the comparison of features indicated on accompanying imagery with the different radar bands. It appears that there was P-band penetration of up to 1.8 m in areas of windblown silts. An appendix gives a geologic description of the area. (See also: Ellermeier, R. D., D. S. Simonett, and L. F. Dellwig, 1967.)

DELLWIG, L. F., and C. H. BURCHELL, 1971

Side-Look Radar: Its Uses and Limitations as a Reconnaissance Tool

Presented at the 51st Annual Meeting, Highway Research Board, Washington, 17-21 January 1972.

Highway Research Abstracts, Vol. 41, No. 12, December, pp. 71-72 (abstract only).

Authors' Abstract: *The short-time imaging of Darien Province, Panama, and the subsequent analysis of the imagery by geoscientists indicated a great potential for side-look radar as a reconnaissance tool in many areas of earth study, particularly where climatic conditions are adverse to aerial photography Evaluation of additional radar imagery from other environments has demonstrated the reality of this potential Rapid, all-weather imaging and the resulting synoptic, ground-range presentation point to radar as a valuable first-look tool. From acquisition-scale imagery or from an easily assembled mosaic, relief and slope data can be obtained, drainage patterns and basins can be accurately defined, and bedrock geology, surface material, and vegetation studies can be conducted. Structural configuration of bedrock and fracture patterns can also be determined with a high degree of accuracy. Utilizing the dual-polarization capability of radar permits, in addition, the qualitative determination of soil moisture content and may provide added vegetation data. The characteristics of the radar system as well as the factors that influence radar return should be known by the user not only for interpretation but also for mission planning. The ability of side-look radar to rapidly acquire data under all-weather conditions offset the limitations of the relatively high cost for small-area surveys and a resolution capability less than that of the aerial photograph. The prime value of radar is realized from its synoptic presentation in the early stages of a survey.*

DELLWIG, L. F. and J. McCAULEY, 1973

Comparison of SLAR Images and Small-Scale Low-Sun Aerial Photographs: Discussion

Geological Society of America, Bulletin, Vol. 84, No. 1, January, pp. 357–358.

No Authors' Abstract.

This paper is a discussion of the article by Clark, M. M., 1973, in this bibliography. It is pointed out that the data used by Clark were rather old and did not reflect the most recent changes in the radar systems available at the time of publication. This may be of minor import with respect to Clark's argument because he was treating his data honestly and making an evaluation of the best available to him. The authors of this article did not point out that they had been, for numerous years, in an advantageous position for obtaining recent radar data. Comments by these authors, with respect to Clark's paper tend to be rather self-serving and picayune. (See also: Clark, M. M., 1971 and 1973.)

DELLWIG, L. F., et al., 1975

Use of Radar Images in Terrain Analysis: an Annotated Bibliography

ETL Report 0024, U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia.

RSL Technical Report 288-2, University of Kansas Center for Research, Inc., Lawrence, Kansas, September, 318 pp. (NTIS N76-29693.)

Author's Abstract: *An annotated bibliography of articles, papers, and reports dealing with the application of imaging radar systems to the geosciences has been prepared to meet the needs of both the potential user of radar imagery and the researcher in the field of tactical terrain analysis. To aid the uninitiated, the principles of imaging radars are described in an introductory section. Following are bibliographic entries that have been prepared for those pertinent publications produced since the earliest days of imaging radars up to the present time (May 1975) When available, the author's own abstract has been reproduced; in other cases, summaries have been prepared by the reviewer of the entry. In many cases, comments of the reviewers are included to point out publications of major importance, to underscore significant conclusions, and to expose those conclusions that are unfounded based on the research described. When actual radar imagery has been used in a publication, the location and date of the imagery as well as the system that acquired it are noted in the bibliographic entry. Author affilitiations at the time of publication are also included in a separate section. An exhaustive cross-reference index has been prepared to aid in identifying those papers that are even in a small part pertinent to any geoscience disipline, system parameter evaluation, or imaging radar system.*

DELLWIG, L. F. and J. E. BARÉ, 1978

A Radar Investigation of North Louisiana Salt Domes

Photogrammetric Engineering and Remote Sensing, Vol. 44, No. 11, November, pp. 1411–1419.

Authors' Abstract: *An imaging radar mission over the North Louisiana Salt Dome area was designed to explore the possibility of providing terrain data concerning faulting associated with solution collapse and/or upward movement of the salt as well as doming* *over the salt mass itself. To maximize the possibilities of data acquisition, the mission was flown to provide orthogonal looks at minimum depression angles in order to accentuate the minimal terrain relief in this area. However, terrain slopes (generally less than depression angle), vegetative cover, and lack of expression of structure provided a surface environment from which structural data could not be extracted in spite of the high quality of the imagery*

An X-band (12-meter resolution) system was used to obtain the imagery. Depression angles of 5 deg to 15 deg were used for the data collection. Although no structural information was forthcoming from these data, it is noted that vegetation can be discriminated (pines vs broadleaf) in that the broadleaf has a stronger backscatter. Several domes and 'anomalies' (suspected salt domes) were seen on the imagery, primarily through the vegetation patterns. The authors concluded that "radar is basically a reconnaissance tool." Also, they conclude that the fact that radar was not suitable for identifying structure associated with the salt domes does not argue that radar cannot be effective in other investigations. Additional analysis of the vegetation patterns and overall organization would have greatly improved this publication.

DRAKE, B., 1972

Applications of Side-looking Radar to Geologic Investigations

Wagner, T. et al, Tunnel-Site selection by Remote Sensing Techniques, Report No. 10018-13-F, Willow Run Laboratories of the Institute of Science and Technology, The University of Michigan, Ann Arbor, September, x + 91 pp., pp. 68–79.

Report Abstract: *A study of the role of remote sensing for geologic reconnaissance for tunnel-site selection was commenced For this study, remote sensing was defined as ultraviolet to thermal infrared multispectral scanning, X- and L-band synthetic aperture radar, and aerial photography. Data from these sensors were processed and evaluated in terms of their complementary use. In addition to general geologic interpretation and evaluation of remote sensing, specific work was performed to improve the state of the art and thereby contribute to better geologic interpretation. Our areas of study included (1) image ratioing to indicate SiO_2 and iron oxide content, representing the final step toward compositional (or lithologic) remote sensing in geology; (2) the analysis and processing of remote sensing data from a glacial drift region for which level slicing, ratioing, and multichannel statistical pattern recognition of multispectral data were employed, also, the correlation of thermal variation studies, aerial photographs, and radar imagery to obtain information on soils, geology, and hydrology; and (3) the analysis of two-frequency multipolarized radar imagery in terms of its capability to delineate geologic features This report can be used tutorially on the data processing and basic instrumentation of conventional remote sensing. Future research directions are suggested, and the extension of remote sensing to include airborne passive microwave sensor systems, magnetometry, gamma-ray sensors, gravimetry, and airborne electromagnetic sounding systems is discussed*

This portion of the larger paper is essentially a short review of the use of SLAR in geologic interpretation of the terrain. The various aspects of the terrain as they affect backscatter are mentioned. Two features of radar interpretation seldom discussed in the literature are included:

(1) The use of the wide dynamic range of radar and the possibilities of recording this on a film with a much smaller dynamic range (15–20 dB for film, 50 dB or greater for radar).

(2) A brief discussion (by R. Mitchell) concerning the enhancement of geologic features by various types of optical processing.

The development of an analog-to-digital converter with its applications to radar interpretation techniques is mentioned.

ELDER, C. H., P. W. JERAN, and D. A. KECK, 1974

Geologic Structure Analysis Using Radar Imagery of the Coal Mining Area of Buchanan County, VA

Report of Investigations 7869, U.S. Dept. Interior, Bureau of Mines, Washington, D.C., ii, 29 pp. (Report prepared by Pittsburgh Mining and Safety Research Center, Pittsburgh, PA.).

Authors' Abstract. *An analysis of the geologic structure of an area of Buchanan County, Va., was made by the Bureau of Mines using imagery from an airborne AN/APQ-97 side-looking radar system to evaluate the mapping technique for delineating structural features that may cause mining problems. Side-looking airborne radar (SLAR) was found to be a useful remote sensing tool for geologic structural analysis. Fault and joint systems identified by lineaments and linear patterns in the imagery were verified by surface and in-mine observations. Little Paw Paw fault was extended 10 miles by SLAR lineament analysis A 22-mile fault, here named the Bishop-Bradshaw Creek fault, was mapped by lineament analysis and verified by observations of the fault on the Bishop Coal Co. mine map and on offset patterns of commercial gas production along the fault, and surface observations of lineament along the fault. Three major superimposed joint sets and several fault or fracture zones were identified by SLAR lineament analysis, showing more complex structure than earlier mapping indicated. SLAR imagery accurately delineated structural features that are known to affect gas migration and accumulation and that weaken the rock forming the immediate room to mine workings, causing mining problems and potentially hazardous environment in the mines.*

Two sets of radar flights, forming two mosaics at two different look directions, were prepared for the study. These mosaics were interpreted using conventional (air photo) techniques, and also through Ronchi gratings. The latter made the lineament direction somewhat more conspicuous. A brief description of the geology of the study area in the KY/VA/WV area is presented. With respect to the SLAR analysis, numerous faults, joints, and other lineaments are detected and related to the previously known geology. There was excellent agreement between the two data sets ("ground truth" and SLAR), and several faults were extended beyond their previously mapped boundaries following more thorough investigations based on SLAR analysis. It is stated that SLAR analysis provided a better representation of the regional geologic structure than did air photo analysis, defined many more faults and tectonic details than had been previously mapped, and can be used as a guide for the best locations for drilling holes to drain gas for both production and mine drainage. Several excellent mosaics are included in the paper.

ELLERMEIER, R. D., A. K. FUNG, and D. S. SIMONETT, 1966

Some Empirical and Theoretical Interpretations of Multiple Polarization Radar Data

Proceedings, Fourth Symposium on Remote Sensing of the Environment, Report No. 4864-11-X, Willow Run Laboratories of the Institute of Science and Technology, The University of Michigan, Ann Arbor, April, pp. 657-670 (NTIS No. AD 638 919).

Authors' Abstract. *Interpretation of radar backscatter return is rapidly gaining prominence as a valuable adjunct to the earth-scientist's interpretive tools. Experiments using aircraft-borne polypolarization radars have shown that terrain phenomena are identifiable and that inferences, at least, may be drawn as to the compositional nature of these phenomena. Such interpretation has been largely subjective to date due to the lack of analytical techniques for the prediction of the effect of terrain depolarization on the radar return Recent theoretical work at the University of Kansas (CRES Report 48-5, 1965) has shown, however, that to a first order approximation.*

(1) *the direct polarized backscattered radar signal is proportional to the product of the appropriate Fresnel reflection coefficient and the sum of the cosine of the angle of incidence and a slope term measured along the terrain profile in the plane of incidence,*

(2) *the cross polarized backscattered radar signal is proportional to the product of the sum of the two Fresnel reflection coefficients and the slope measured along the profile perpendicular to the incident plane.*

Thus, a measure of the surface roughness may be obtained by proper instrumentation of the direct and cross polarized components of the signal return. This development is unique in that the cross polarized as well as the direct polarized return components are explicit in the formulation.

Empirical evidence supporting the theoretical study has been obtained from analysis of multiple polarization imagery using single frequency direct and cross polarized radar data.

Basically, the paper provides qualitative data to support earlier theoretical determinations by one of the authors (Fung) concerning the radar backscatter from the terrain. The area used for the study was Pisgah Crater. Briefly stated, the authors noted that the cross-polarized term is greatest in areas where the terrain slope is normal to the incident plane and the like-polarized term is relatively greater where the terrain slope is greatest in the plane of incidence. The assumption of reciprocity made by Fung's formulations is supported; that is, HV and VH returns are the same, assuming also that all other things are equal. Hence, either one of these returns can be discarded during interpretation without loss of information from the radar imagery. Several sets of imagery support the authors' arguments. The paper warrants careful study of both text and imagery.

ELLERMEIR, R. D., D. S. SIMONETT, and L. F. DELLWIG, 1967

The Use of Multi-Parameter Radar Imagery for the Discrimination of Terrain Characteristics

IEEE, International Convention Record, Part 2, New York, March, pp. 127-135.

Authors' Abstract: *This paper illustrates the use of radar image combination and enhancement techniques for the discrimination of terrain characteristics using multiple polarization radar images. Examples of these techniques used both for agricultural and natural vegetation discrimination are described and discussed Also shown are examples of the effects of variation of radar wavelength for the discrimination of geologic phenomena*

Parameters considered are (1) frequency, (2) transmitted polarization, and (3) received polarization. A brief description covers the image discrimination and enhancement equipment as well as the color display equipment used. With respect to discriminating crops and natural vegetation, the following is stated: "Radar has demonstrated that it can detect changes in crops through a growing season, but the demonstration has only been in a limited set of experiments with radars operating between one and four centimeters." This work was done in Kansas, and, in general, concerns sugar beets, alfalfa, grain sorghum and bare ground. Discrimination for these several categories has been quite good and tremendously aided by the color enhancement. For natural vegetation an Oregon test site was selected and the discrimination (successful) confined to differences between pine, sagebrush, and grassland. The investigation was at that time in the elementary stages, but said to be very promising.

A second portion of the paper deals with geologic studies in the Pisgah Crater area, California. Data presented show some radar penetration into the dry sand, and reflections from lava surfaces below. High reflections also from the areas of phreatophytes were attributed to a combination of mounds of sediment around the bushes and penetration and reflection from the more moist areas around the bush root-structure. The playa surface patterns resulting from dessication cracks are better differentiated on radar imagery than on aerial photographs. (The scale of the comparison photographs is not given.) This is a fairly important paper, and one packing a maximum amount of information into the space allocated to its publication. It is unfortunate that the color pictures referred to could not be reproduced.

ELLISON, J. H. and L. O. WILLIAMS, 1969

Measurement on Radar Images of Number of Valleys Per Unit Area as a Discriminant of Sedimentary Rock Types in the Physiographic Regions of Tennessee

Remote Sensing Institute Technical Report No. 7, East Tennessee State University, Johnson City, 34 pp. (Contract: Office of Naval Research: N00014-67-A-0102-0001.)

Authors' Introduction: *The purpose of this paper is to evaluate the feasibility of using a parameter of topographic expression that can be measured on a radar image, as an indicator of differing sedimentary rock types. To do this, the authors studied the radar images of 8 areas of southern Tennessee and compared the valleys, per unit area, as measured thereon to the existing topographic and geologic maps . . .*

Authors' Conclusions: *(1) Discrimination of sedimentary lithologies in a humid climate by isoplething average number of valleys intercepted by the six radii of hexagonal cells on grid overlays of a radar image is not possible with any degree of certainty. (2) The average number of valleys per unit area as measured on radar images of eight areas in the physiographic provinces of Tennessee does suggest underlying sedimentary lithologies because there are more valleys per unit area on relatively impermeable clays and shales than on more permeable sandstones, limestones, dolomites, and alluvium. It follows, where adjacent sedimentary rock units are sufficiently different in lithology, that this method can be used only as an aid to discriminate rock units*

See also: Williams, L. O., 1968, 1969.

EPPES, T. A. and J. W. Rouse, Jr., 1974

Viewing-Angle Effects in Radar Images

Photogrammetric Engineering, Vol. 40, No. 2, pp. 169–173.

Author's Abstract: *A quantitative determination of the effect of viewing angle on the detectability of topographic linears in radar imagery is presented. Variations of azimuth and aspect angles of an imaging radar antenna relative to a topographic linear were simulated using low-angle illumination of controlled linear features on polystyrene sheets. The several model surfaces represented idealized versions of surface types that may be expected in areas of geologic interest. Fourier transform spectra of the radar image simulations were obtained using a coherent-optics system. These spectra were found to correlate with a detectability factor obtained directly from the radar image simulations. Fourier transform spectra of a linear feature observed from multiple viewing angles by a K-band imaging radar were also obtained and a detectability factor was estimated which agreed closely with theoretical predictions.*

The detectability factor of features off-normal can be improved by spatial filtering in the Fourier plane of a single look direction.

The practical effect of the viewing-angle dependence of radar images is to reduce the accuracy of lineament maps obtained from these data. (From: Dellwig, et al., 1975.)

EVANS, D. L., 1978

Radar Observations of a Volcanic Terrain: Askja Caldera, Iceland

Publication 78-81, Jet Propulsion Laboratory, Pasadena, Calif., October 1, vii, 39 pp. (NTIS N78-33645.)

Author's Abstract: *Surface roughness spectra of nine radar backscatter units in the Askja Caldera region of Iceland were predicted from computer-enhanced like- and cross-polarized radar images. A field survey of the caldera was then undertaken to check the accuracy of the preliminary analysis. There was good agreement between predicted surface roughness of backscatter units and surface roughness observed in the field. In some cases, variations in surface roughness could be correlated with previously mapped geologic units.*

This paper, consisting of four major sections (geologic setting, radar images, computer image processing, and radar response to surface materials) is primarily a description of the basic processing of radar images (LHH, LHV) of a volcanic terrain. Nine backscatter units of the volcanic terrain were identified on the radar imagery. These were then scanned and the DN values of the data were identified for each of the backscatter units. No mention is made of the fact that the radar was not calibrated, and therefore the project may not be repeatable. Numerous scan lines are given, and inference relating the roughness to the DN values is made. Within the limited amount of data available, it is noted that the curve relating relative power of the radar backscatter (in dB) to the roughness of the surface has a decided knick-point. This is a result similar to that described for Death Valley in Schaber, et al., 1976, upon which this paper is heavily dependent. Numerous excellent ground photographs that comprised the majority of the field survey, are included. No conclusions or discussion of the presented material are included in the paper.

FEDER, A. M., 1959

Radar as a Terrain-Analyzing Device

Geological Society of America, Bulletin, Vol. 70, No. 12, December, pp. 1804–1805 (abstract only).

Author's Abstract: *Conventional radars can gather terrain information often denied other sensors while automatically performing a concurrent analysis of the data collected. Additional values are the nearly all-weather capability of radar, the relatively large-area coverage possible, and the trend toward geodetic accuracy of PPI-type displays.*

K_u-band terrain reradiation curves demonstrate how in World Warr II the subject use of radar could have precluded an unnecessary loss of lives. The casualties resulted from the inability of aerial photograph to penetrate dense vegetation. Some X- through K_a-band reradiation data show radar's ability to interpret surface textures, moisture content, and snow cover for trafficability purposes and texture and composition for civil engineering and geologic purposes.

In all these applications, radar is stressed not as a panacea for terrain analyses but as a heretofore somewhat neglected valuable adjunct to other means of information collection.

FEDER, A. M., 1960a

Radar Geology

M.A. Thesis, Department of Geology, University of Buffalo, Buffalo, N.Y., February, xiv plus 80 plus Appendix.

Author's Summary

(1) *The purpose of this research was to establish that terrain components can generate consistent, characteristic electromagnetic reradiations (Section I)*

(2) *Most of this research was to be done by means of a field work phase, the purpose of which was to make a controlled study of some natural rock outcrops that are ideally situated for qualitative terrain return analysis (Section IV A and B)*

(3) *In order to have value for application, the reradiations had to be proved a function of factors such as material chemistry, for example, as well as surface texture (Section I).*

(4) *The application of such reradiation data in all of its ramifications is herein entitled Radar Geology. Practical aspects of a successful radar geologic science are given (Section II B-D).*

(5) *Radar Geology is not a new concept. It has, in effect, been unknowingly performed for many years (Section III A and B)*

(6) *Results of the field work, though it was a restricted program (Section IV D) indicate that consistent, characteristic returns can be obtained from a controlled radar source (Section IV C).*

(7) *A particularly interesting conclusion is that a rock's chemistry can be of greater influence in controlling reradiation amplitudes than the rock's surface texture (Section IV, D, 1).*

(8) *The findings of other investigators indicate that the results of this thesis' field work are not unique (Section V). For example, the requirement that in practical applications the reradiation amplitude from a substance need remain constant over a wide range of aspect angles (Section V, B, 1), is demonstrated as capable of being satisfied by the field work (Section IV, A, 4) and findings from at least two other programs (Sections V, B, 2 and B, 4).*

(9) *Conclusion is made that radar geology is a practical science (Section V, C, 5) and that the purpose of this program was satisfied (Section IV, D, 3).*

FEDER, A. M., 1960b

Interpreting Natural Terrain from Radar Displays

Photogrammetric Engineering, Vol. 26, No. 4, September, pp. 618–630.

Author's Abstract· *Radar is demonstrated to be an effective means for acquiring terrain data A significant capability in such application stems from radar providing its own illumination. With control of the energy propagation factor, terrain information is to some effect automatically interpreted by the electronic process leading to display.*

The display content is strongly controlled by radar energy's ability to penetrate terrain as well as to discriminate among surface conditions The penetration data given and the related reradiation amplitudes evidence how subsurface composition and conditions, such as moisture and metallic contents and temperature, can be determined by radar. Re-radiation graphs are also used to demonstrate the derivation of information concerning the veneer on the terrain, such as gravel sizes, and the water content of snow.

Some simple interpretations of PPI scope graphics are possible AN/APQ-13 displays are interpreted geomorphologically. An AN/APQ-23 frame is interpreted for veneer textures and a sidelooking radar display reveals stratigraphic data, land-use detail and offshore information.

An advantage of the former two radar types is shown in the area coverages possible per display photograph (e.g , 2700 square miles) while automatically retaining some element of geographic-control The development of high-resolution, sidelooking radar is tending toward geodetic-control accuracy but sacrifices the extensive area coverage capability. Therefore trade-offs such as these, and dependence of display interpretation on data from other sources indicate radar is a valuable complement to other sensors, not a substitute for them. (Copyrighted by the American Society of Photogrammetry – Reprinted by permission)

In this early paper, based primarily upon information received from K-band radars (Ka, Ku), the author has identified seven capabilities of radar. These are:

(1) To read compositions and conditions below the visual rocks and soil surface of the terrain.

(2) To penetrate vegetation to read subsurface information.

(3) To determine the textures of terrain surface materials.

(4) To determine moisture content of terrain.

(5) To determine temperature of terrain material, given the moisture content.

(6) To read the metallic content of terrain surface and near surface materials.

(7) To read properties of snow cover or the terrain beneath the snow.

In each of the cases, the author cites some cases where radar, with its capabilities, would have been useful. The data were collected primarily from radars of WWII vintage; several PPI type displays and one side-looking image are presented. This paper seems a rather optimistic statement about the capabilities of radar and should be taken with this in mind. The author is also aware of his overstatements when he writes: "It should be remembered that all this is done, however, at the expense of the resolution provided by most types of aerial photography and with a dependence on data from other sources before positive analysis can be made."

FEDER, A. M., 1962

Radar Geology Can Aid Regional Oil Exploration

World Oil, Vol. 155, No. 1, July, pp. 130-138.

No Author's Abstract.

"Radar geology will never be a panacea for all geologic reconnaissance, but holds considerable promise for complementing other reconnaissance techniques." There is a brief discussion of the nature of rock porosity and its effect on radar return (i.e., the dehydrated rock could be expected to attenuate radar energy more than would its denser counterpart with the same surface texture, slope, etc). In the future, the sensitivity of radar to certain chemical (especially iron compounds) aspects of rocks and soils may be very significant, says the author. The need is noted for further research in the absolute measurement of radar signal-terrain material interactions. (See also Feder, A. M., 1960b.)

GELNETT, R. H., 1975

Airborne Remote Sensors Applied to Engineering Geology and Civil Works Design Investigations

Technical Report TR-17621, Motorola Aerial Remote Sensing, Inc., Phoenix, Arizona, December, iv plus 22 pp. plus figs.

From Author's Conclusions: *The purpose of this study is to assist engineering geologists and engineers in determining the applicability of airborne remote sensing systems in the detection and identification of geological features that may affect the design of the Butler Valley Dam and Blue Lake Project. Primary objectives are*

(1) To refine the location of known regional faults and possibly detect previously unknown faults;

(2) To determine the presence or absence of a regional fault and fracture pattern that may be related to that found locally in the vicinity of the project;

(3) To assist in defining landslides existing along the proposed relocated road; and

(4) To evaluate the applicability of individual sensors for future use by other engineers and geologists

Airborne remote sensor coverage in this study is unusually complete, they include (1) multiple scale metric, multiband and infrared photography, (2) thermal infrared imagery, (3) side-looking airborne radar imagery, and (4) LandSat-1 imagery. The application, interpretive results, and concluding remarks herein on the utility of the various kinds of imagery pertain almost exclusively to the detection of geologic structures featured in a tree-covered environment.

Relative to the stated objectives, Radar revealed substantially more regional and local geologic structural detail than any of the other systems. Radar's ability to perceive minute topographic and geologic features lies primarily in its unique format which tends to supress vegetative detail, and its low oblique-illumination angle which accentuates these features Additionally, the small scale synoptic view of Radar imagery allows the investigator to recognize discontinuous or intermittent fault traces for what they really are. On large-scale imagery, these features are often misinterpreted or overlooked entirely.

Radar-air photo combination was found to provide the most accurate and complete information Although most of the subject geologic structural features could not be recognized directly from air photos in this study, they were used extensively to field check the existance and location of features identified on Radar.

The radar imagery was acquired by the 184th Military Intelligence Company (Aerial Surveillance, Ft. Lewis, Wash.) using an X-band APS/94D real aperture system mounted in a OV-1D Mohawk aircraft. The work was sponsored by NASA and U.S. Army Corps of Engineers (San Francisco District). Some excellent imagery of the northern California study area is presented.

GELNETT, R. H., L. F. DELLWIG, and J. E. BARÉ, 1978

Increased Visibility from the Invisible: A Comparison of Radar and Landsat in Tropical Environments

Proceedings of the 12th International Symposium on Remote Sensing of the Environment, Manilla, Philippines. Environmental Research Institute of Michigan, Ann Arbor, Mich., April, Vol. III, pp. 2205–2216.

Authors' Abstract: *The unique capability of side looking airborne radar in recording terrain data essentially regardless of daylight or weather conditions has been sufficient justification for its utilization in cloud shrouded areas throughout the world, particularly when there is a critical time factor or a need for specific seasonal coverage. In geologic exploration, RADAR imagery has often been considered for utilization only if LANDSAT imagery or aerial photographs are not available. However, imaging in a segment of the electromagnetic spectrum other than the visible and near infrared portions should be expected to provide information supplemental to other kinds of imagery.*

A comparison of LANDSAT and RADAR images in several areas substantiates this expectation Specifically

1. *Because RADAR senses microrelief or surface configuration and dielectric properties of vegetation rather than degree of vigor as in near infrared imagery, any initial classification is supplemented and a level of discrimination not otherwise obtainable is realized.*

2. *Linear and curvilinear geologic elements identifiable on both LANDSAT and RADAR imagery can be more precisely defined on RADAR imagery. Furthermore, even some major linear features may be well defined on RADAR imagery although not identifiable on LANDSAT imagery. Definition is largely a function of finer resolution and to some lesser degree shadowing.*

3. *Drainage networks may be more accurately located on RADAR imagery and networks may be expanded to include lower order streams than those identifiable on the LANDSAT image. Such improvement is primarily due to contrasts in the canopy configuration or microrelief of the vegetation.*

A series of examples of radar imagery (obtained by the Motorola X-band real aperture system in 1977) of Nigeria and Togo are presented together with Landsat imagery of the same localities. Often, because of adverse weather, simultaneous, or nearly simultaneous, Landsat data are not available. The paper emphasizes that the Landsat and Radar data are complementary and should be used together for optimum results. Examples are primarily from vegetation, drainage patterns, and geologic (relief) features.

GILLERMAN, E., 1967

Investigation of Cross-Polarized Radar on Volcanic Rocks

Technical Report No. 61-25, CRES, Inc , University of Kansas, Lawrence, February, 11 pp. (NTIS No. N67-36566).

Author's Abstract *A number of areas of volcanic rocks, mostly in the southwestern United States, exhibit differences in radar return on simultaneously produced like-polarized and cross-polarized K-band radar imagery. Preliminary investigations have failed to afford conclusive proof that this is due to the glass content of the rock. Roughness, degree and type of vegetation cover, and perhaps age of the rocks may be contributing factors. Additional investigations, including microscopic studies, now underway, will be necessary to determine more accurately the subtle effects of mineral composition, texture, and glass content on radar return.*

For areas of volcanics in Arizona, California, Oregon and Yellowstone National Park, the author notes that despite suggestions that the glass content of volcanics is responsible for the low return on cross-polarized signals, roughness, topography and rock composition (in addition to glass content) are possibly equally important. For the numerous sites and images available, look direction and depression angle of the radar were often of little or no importance. (See: MacDONALD, et al., 1969, for an alternate view concerning other geologic problems). Suggestions are made that extensive radar coverage and ground truth are needed for the proper evaluation of these radar return parameters. The entire study is qualitative.

GILLERMAN, E., 1968

Major Lineament and Possible Calderas Defined by Side-Looking Airborne Radar Imagery, St. Francois Mountains, Missouri

Technical Report 118-12, CRES, Inc., University of Kansas, Lawrence, October, 29 pp. (NTIS No. N69-32469).

Author's Abstract· *Side-looking radar imagery in the St Francois Mountains of southeast Missouri has revealed many structural features which are obscure or only poorly depicted on aerial photos. This superiority of radar imagery over aerial photography is discussed.*

Linear structural features depicted on the radar imagery represent faults or fractures. Most prominent among these is the previously unrecognized Roselle lineament, which is excellently portrayed. When correlated with structural and topographic features north and south of the limits of radar coverage, the Roselle lineament can be traced for over 135 miles Its relationships of mineral localization in the Bonne Terre-Fredericktown area may be of importance

Circular patterns were also observed on the radar imagery Their origin is obscure but ancient astroblemes or calderas are suggested as working hypotheses.

The advantages of radar imagery over aerial photographs for this type of geologic work are stated to be the broad coverage, the continuous strip of imagery, and the suppression of minor details by SLAR. However, in some areas cultural changes of the natural terrain obscured part of some traces of lineaments and made tracing of these features difficult if not impossible. As in similar studies, the lineaments need surface expression in order to be visible in the imagery — either topographic expression, the drainage pattern, or possibly vegetation patterns. (See Gillerman, E., 1970.)

GILLERMAN, E., 1970

Roselle Lineament of Southeast Missouri

Bulletin of the Geological Association of America, Vol. 81, No. 3, March, pp. 975-982.

Author's Abstract: *Examination of side-looking radar imagery of the St. Francois Mountains of southeast Missouri has revealed many structural features which are obscure or only poorly depicted on conventional aerial photographs Most prominent is a distinct linear element extending southward across the imagery from east of Flat River to southeast of Ironton, Missouri, through the southeast Missouri Lead Belt. Field examination has confirmed a fault zone, named the Roselle fault by the author. This structure has not previously been recognized, no mention of it was found in literature, nor is it shown on any geologic map of the area. The structure traverses Precambrian and Paleozoic rocks.*

Analysis of geologic and topographic maps north and south of the area covered by radar imagery reveals a series of topographic and structural features remarkably well aligned with the Roselle fault. To the south, these include drainage alignments and a buried Precambrian scarp, and to the north, the Plattin anticline and the course of the Mississippi River north of Crystal City. These features form an almost continuous alignment extending for over 155 mi from southwest of Poplar Bluff, Missouri, north-northeast to the vicinity of the junction of the Mississippi and Missouri Rivers This alignment of features is termed the Roselle lineament. I suggest this lineament has been in existence since the Precambrian as a major lineament of this portion of the crust and that it may have been important in localization of mineral deposition in southeast Missouri. (Copyrighted by GSA.)

The use of synoptic and broad coverage of radar is emphasized as a strong tool for identification of a previously unsuspected (and possibly major) structural feature.

GOODYEAR AEROSPACE CORPORATION, 1971a

Simplified Description of the Principles and Applications of Synthetic Aperture Terrain Imaging Radar

Report No. GIB-9202, Arizona Division, Litchfield Park, May 26, viii plus 48 pp.

Author's Abstract: *This document serves as a nonmathematical, technically complete description of synthetic aperture terrain imaging radar. It should be useful for individuals in the general intelligence community — including photo-interpreters, photogrammetrists, and analysts.*

The publication is divided into four major sections: (a) introduction; (b) imaging sensors (wave motion and optical sensor characteristics); (c) terrain imaging radar (general, image formation, image geometry and resolution) and (d) synthetic aperture radar (general, synthetic aperture formation, synthetic aperture geometry and synthetic aperture resolution).

Nonmathematical in the main, but does require some very basic understanding of optics, especially in the discussion of image formation. A very good basic statement.

GOODYEAR AEROSPACE CORPORATION, 1971b

Uses of Terrain Imaging Radar

Report No. GIB-9210, Code 99696, Arizona Division, Goodyear Aerospace Corp., Litchfield Park, 2 pp. plus images.

No Author's Abstract.

Following several general statements mentioning the possible uses of SLAR, two glossy images (produced by the Goodyear Electromagnetic Mapping System) of the Tuscon, Arizona area are presented. These images are of high quality and clearly depict drainage and field patterns, housing conglomerations and topography, among other features.

GRANT, T. A., and L. S. CLUFF, 1974

Radar Imagery in Defining Regional Tectonic Structure

Annual Review of Earth and Planetary Sciences, Edited by F. A. Donath, Annual Reviews Inc., Palo Alto, Calif., Vol. 4, pp. 123-145.

No Authors' Abstract.

This paper briefly reviews the two types of imaging radar (real and synthetic aperture), compares the imagery produced with photographic systems, and gives some excellent examples of regional tectonic interpretations based on radar imagery. Most of the interpretations are based on previously published papers, but several examples of the NW coast of the U.S. have been based on unpublished reports. A good review article.

GUSEV, N. A., 1972

Use of Information of Radar Aerial Survey During Study of Geological Structure of Kamchatkin, [Isopol 'zovanie Materialov Radiolokatsionni Aeros 'emki Pri Izuchenii Geologicheskogo Stroeniia Kamchatki]

New Methods of Obtaining Information by Various Remote Sensors and its Adaptation for Solving Geological Problems. [Novye Metody Polucheniia Informatsii Razlichnymi Distantsionnymi Priemnikami i ee Obrabotki Dlia Resheniia Geologicheskikh Zadach] VIEMS, Moscow, (Russian).

Reviewer's Summary: *A variety of structural, geomorphic and volcanic features are exposed on the Kamchatka peninsula, in some areas concealed by a thick blanket of Quaternary deposits. In the areas covered by thick alluvial deposits, the vegetative flora assemblages (forest, swamp, etc.) most directly influence return but where the alluvial cover is thin, the underlying structure is much more significant in determining radar return.*

Part of the area is mountainous with local relief up to 1,000 m, which results in excessive shadowing. In some cases orientation of slopes toward the antenna causes such strong back-scattering that virtually no data can be derived. Generally, shadowing enhances detection of faults, even in cases where fault systems of two ages are superimposed.

Radar imagery contributes significant amounts of geologic data not available from aerial photographs including data on the regional geologic structure. (From Dellwig, et al, 1975.)

HACKMAN, R. J., 1967

Geologic Evaluation of Radar Imagery in Southern Utah

U.S. Geological Survey Research Professional Paper 575, Chap. D., pp. D135-D142. (NTIS No. N70 41147). (Also: U.S.G.S. Technical Letter – NASA-58, 1966.)

Author's Abstract: *A comparison of radar imagery with conventional aerial photography shows that radar imagery has some distinct advantages It has all-weather, day or night capability of imaging large areas of terrain Side-looking radar produces a "shadow" enhancement effect that shows greater topographic detail, important to observation of many geologic features. One structural fault that could be only poorly discerned on conventional photography was clearly visible on radar imagery. Calcareous and gypsiferous sedimentary rocks were shown as very light tones of gray in contrast to darker sandstones and shales. These contrasts were reversed and less conspicuous on the conventional aerial photography. However, many of the rock units, readily distinguishable on the photography, could not be positively differentiated on the radar imagery.*

K-band, dual-polarized radar was used. Distinction between unconsolidated sand and sandstone was not possible. Some of the darker toned areas may have had greater moisture content in the alluvium.

HARRIS, G., Jr., and L. C. Graham, 1976

Landsat-Radar Synergism

Paper presented at the XIII Congress of the International Society for Photogrammetry, Helsinki, Commission VII, 26 pp. (Copy obtained from Goodyear Aerospace Corp., Litchfield Park, Ariz.)

Authors' Abstract: *U.S. Geological Survey EROS Data Center and Goodyear Aerospace Corporation engineers, working independently at first and then in cooperation, have synergistically combined Landsat multispectral scanner data and airborne synthetic aperture radar imagery.*

This paper presents the techniques and procedures used in the experiments. Examples of Landsat and radar images of the same terrain, separate and combined, are presented to show that providing the two types of data in a single image retains all the information available from each sensor system and additional detailed data resulting from the simultaneous viewing of the two in superposition.

From Authors' Conclusions: *Several methods of photographically combining Landsat and GEMS radar data have been investigated and presented in this paper. It would appear from the test results that the method is repeatable and can be produced at very small cost once the radar and Landsat data are available.*

The problems of geometric alignment can be lessened if a radar flightpath is chosen that simulates the ground track of the Landsat.

Of the four methods considered, it would appear that the results of Method 3 (see Figure 12) give the best data presentation It is recognized that some of the Landsat radiance is attenuated, but this is offset by the radar detail. The Landsat detail can be recognized through the areas of radar shadowing.

Although Method 4 was not considered as a prime candidate for the photographic experiments, it will be the subject of continued investigation. The next series of experiments will be to digitally merge Landsat and radar data using algorithms to compensate for radiance and radar intensity variations.

The methods used for combining Landsat and radar were:

(1) Radar combined with each of the Landsat channels in the process of forming the Landsat composite.

(2) Standard Landsat composite prepared and radar added as the last step.

(3) A set of six exposures — the first three using Landsat bands 4, 5, 7 individually, the next three using Landsat bands 4, 5, 7 with radar, then all six are combined.

(4) Substitution of radar for one of the Landsat channels.

The paper includes examples of each of the methods, together with a brief description of Landsat and radar and their geometries.

HARWOOD, D. S., 1967

Radar Imagery: Parmachenee Lake Area, West-Central Maine

U.S. Geological Survey Earth Resources Survey Program Technical Letter NASA-81, Washington, D.C., June, 6 pp. plus figs.

Author's Conclusions: *Radar imagery of the Parmachenee Lake area shows the influence of resistant bedrock units on topography far better than the existing aerial photographs. There is no indication in this area, however, that the radar beam can distinguish rock types in any way other than by their topographic expression. Because the radar enhances topographic features that parallel the line of flight, it might be prudent to cover an area of complex geology on orthogonal flight lines and thus reduce any possible bias in the interpretation.*

There is little indication that the radar beam effectively penetrates the dense foliage in the area. On the contrary, the radar appears to be very effective in distinguishing evergreen from deciduous trees. Radar imagery of this area taken when the leaves are off the trees might prove more valuable than that taken during the summer.

Radar imagery is a valuable adjunct to aerial photographs in this area of Maine Its chief advantages are enhanced topographic expression of resistant bedrock units, continuous strip coverage, and its all-weather capabilities. Aerial photographs show the logging roads, which are invaluable to woods navigation, much more clearly than the radar imagery.

The radar system used was not identified, although it is assumed to be the Westinghouse Ka-band system.

HILPERT, L. S., 1966

Geological Evaluation of Radar Imagery, Southwestern and Central Utah

U.S. Geological Survey Technical Newsletter - NASA-38, August, 9 pp. (NTIS No. N70 41126)

Author's Abstract: *Radar imagery was obtained with a high frequency side-looking radar in southwestern and central Utah along three flight lines having an aggregate length of about 650 miles. A selective evaluation indicates the radar imagery might be useful to broadly classify some rock units on the basis of their surficial textures or other characteristics. Tonal contrasts, however, in the areas that have been evaluated, probably represent differences in the degree of soil development, moisture content of the soils, and the vegetative cover If so, these features may indirectly be useful for classifying the bedrock*

Geologic structures are readily visible in the imagery where they are expressed physiographically and show with about the same clarity as in conventional photography Subsurface structures without physiographic expression were not observed in the imagery.

Radar imagery might be useful in terrain and trafficability analyses, especially when used in conjunction with other types of imagery, such as ordinary photography Railroads clearly show in the radar imagery, but only some roads can be seen. Blacktop roads show as dark lines if they are more than 30 ft wide Graded and unimproved dirt roads and blacktop roads less than 30 ft wide can also be detected as light lines where they are flanked by road cuts or earth fills. The imagery of concrete surfaced roads could not be evaluated, as there are none in the areas flown.

A K-band radar transmitted H polarization and received H and V. The finished product had an average scale of 1:160,000. In one area, a rectangular pattern is thought to be the result of moisture variations in tilled fields. Several radar images are included in this paper.

HODLER, T. W., 1977

Remote Sensing Applications in Hydro-Geothermal Exploration of the Northern Basin and Range Province

Ph.D. Thesis, Oregon State University, June, 235 pp. Dissertation Abstracts International, B Sciences and Engineering, January 1978, Vol. 38, No. 7, pp. 3104-B (abstract only).

Author's Abstract: *A program of remote sensing overflights with ground truth teams was initiated in order to evaluate the effectiveness of remote sensing applications to geothermal resource reconnaissance in the northern section of the Basin and Range physiographic province. This area included parts of south central Oregon and northeastern California. It is composed of land both privately owned and publically administered by many branches of government. The government's involvement in this area, specifically the Fremont National Forest, was the impetus for seeking such the evaluation of the existing geothermal potential Such an evaluation was conducted utilizing side-looking-airborne-radar (SLAR) and thermal infrared (TIR) detectors in a complementary fashion flown by the Oregon Army National Guard.*

The program consisted of preliminary overflights of SLAR for the detection of fault lineaments along which surface expressions of hydro-geothermal activity are localized Interpretation of the SLAR imagery was used to generate TIR flightlines corresponding to the major lineaments. Subsequent flights incorporated TIR line scanners utilizing the mercury-cadmium-telluride (HgCdTe, 8-14 µm), indium antimonide (InSb, 1-6 µm), and indium arsenide (InAs, 1-3.4 µm) detectors A map was produced depicting the interpreted data. The map graphically portrays the structural relationship between the interpreted surface hydro-geothermal sites and the fracture traces, at a scale of 1 500,000

From the SLAR imagery two classes of lineaments were distinguished, those greater than 500 meters vertical displacement and those smaller scarplets of lesser relief. The two fault trends, of NW-SE and NE-SW are easily seen on the map The lineaments of greater displacement have a tendency to run NE-SW and are relatively few in number. The lesser displacement lineaments are quite numerous and trend NW-SE.

Analysis of the TIR imagery located one new potential hydro-geothermal site and determined a more accurate designation of geographic coordinates for five other sites than were provided in previous studies Location was more easily accomplished through the use of a dual channel system. The HgCdTe detector provided detailed terrain imagery and is best suited for actual geographic location, while the InAs detector senses only the hotter targets (greater than 50° C.). The InSb detector exhibits partial traits of both the HgCdTe and the InAs sensors, resulting from their wavelength characteristics. As a result of several technical difficulties, this research was not conclusive in determining which sensor or sensor combination was best suited for locating hydro-geothermal sources

During overflight the following temperatures were measured by ground teams: air, soil, water, and radiometer. These parameters were used as site-specific indicators of the physical attributes depicted on the imagery.

The map product graphically depicts the relationship of the hydro-geothermal sites to the geologic structure. The hydro-geothermal sites located were found to exist along the major lineaments. A clustering of hot springs was found to exist at three locations in the study area. Lineaments and hydro-geothermal locations were interpreted from the imagery while all surface temperatures were derived by on-site measurements.

Utilizing a temperature decay function (0.27° C/km), isothermal rings were established utilizing each of the hot spring clusters, plus one singly occurring hot spring as the centroids. The area within each isotherm can theoretically be supplied with the equivalent temperature water from the relative centroid. The majority of the study area can be supplied with 70° C temperature water or hotter. This research suggests the principle use of the hydro-geothermal resource in the study area is for space heating of homes and other structures.

Although the remote sensing survey of surface hydro-geothermal sites failed to show heat potential for near surface direct electrical production, the thermo-structural relationship mapped may serve along with other geophysical techniques to direct subsurface exploration of the resource. Structural lineaments and hydro-geothermal source locations can be determined through the complementary use of SLAR and TIR. Once potential locations are determined, limited ground truthing would be required to verify the remotely sensed data. Such a reconnaissance tool may be of greatest value in a less developed area with similar geologic structure and geothermal promise. (Order No. 77-29, 413, 235 pages.)

With respect to radar: The SLAR used was an X-band (9245-MHz) AN/APS-94C unit. Although used for the structural analysis of the study site, and it was useful in defining 26 percent more structural lineaments than the Landsat analysis and 12 percent more than appeared on existing geologic maps, the exact usefulness of SLAR in this type of study is not adequately demonstrated. The analysis was highly dependent on ground-truth data; remote sensors, including SLAR, apparently provided little insight into the location of potential hydrothermal sites.

HOLMES, R. F., 1967

Engineering Materials and Side-Looking Radar

Photogrammetric Engineering, Vol. 33, No. 7, July, pp. 767–770.

Author's Abstract: *Recent interpretation studies of Side-Looking Airborne Radar Imagery have demonstrated the potential value of SLAR in the classification of surficial materials prior to field tests. Through processes familiar to the interpreter of conventional photography, an interpretation of conventional and radar imagery, taken simultaneously, has shown that the recognition of diagnostic patterns of vegetation, geology, drainage, land use and landforms will enable an experienced soil scientist to make a reasonable assessment of regional engineering surficial material conditions. Recently developed SLAR imagery includes potential advantages and inherent disadvantages (Copyrighted by the American Society of Photogrammetry.)*

Using K-band AN/APQ-56 radar, the author has prepared an engineering materials map of an area of Colorado and Wyoming. Engineering materials are defined as "unconsolidated residual, alluvial, or glacial deposits covering the bedrock of a region." Several suggestions are given for interpretation of SLAR imagery, and because of the small scale of the imagery used (1:200,000 to 1:400,000), this type of interpretation is best confined to reconnaissance work.

IRWIN, W. P., 1966

Geologic Appraisal of Radar Imagery of Southwestern Oregon

U.S. Geological Survey Technical Letter – NASA-23, June, 5 pp. (NTIS No. 70 38892).

Abstract: *The most obvious geologic feature shown on radar images is straight-line lineaments of the Klamath Mountains and the Coast Range province which parallel major known lithic and structural trends. A large granitic pluton near Grants Pass was outlined chiefly by its distinctive topographic pattern of fine dissections.*

JEFFERIS, L. H., 1969a

Lineaments in the Grand Canyon Area, Northern Arizona – A Radar Analysis

Report No. 118-9, CRES, Inc., The University of Kansas, Lawrence, February, ii + 16 pp. (NTIS No. N69 32799).

Author's Abstract: *A comparison of structural data obtained from side-looking radar (SLAR) imagery of the Grand Canyon area, northern Arizona, with previously published reports demonstrates the potential of radar imagery as a tool for geologic reconnaissance studies. The study, designed to determine the geologic causes for a pronounced lineament pattern on the radar image, also provided a measure of reliability for the radar image interpretation, particularly the size of structure which may be interpreted with confidence.*

The radar lineaments of the Grand Canyon area indicate the location of faults in the deformed Precambrian and relatively undeformed Paleozoic strata. The strong correspondence of radar lineaments with known faults is indisputable and to a lesser but still significant degree the joint pattern and the radar lineament pattern showed a close correlation. A number of lineaments on SLAR imagery in areas where no faults have been mapped substantiates the previous suggestion of SLAR as a geologic reconnaissance tool.

The length of a fault is an important factor in a radar image identification. In the study area, a fault of less than one mile in length is difficult to identify as a geologic structure, while the increasing length of a lineament lends creditability to a structural interpretation.

The paper states:

(1) There is a strong positive correlation between major radar lineament patterns and the major normal faults in the study area.

(2) Look direction is of major importance in determining the quality of the images.

(3) The longer lineaments can be more easily and accurately interpreted on the SLAR imagery.

(4) SLAR is a most useful regional geological reconnaissance tool, aiding the field team to identify areas of best potential returns for their efforts.

JEFFERIS, L. H., 1969b

An Evaluation of Radar Imagery for Structural Analysis in Gently Deformed Strata: A Study in Northeast Kansas

Technical Report 118-16, CRES, Inc., University of Kansas, Lawrence, July, 31 pp.

Author's Abstract: *A study comparing a structural interpretation of side-looking radar (SLAR) imagery with known geologic data from an area in northeast Kansas demonstrates the potential of radar imagery as a geologic reconnaissance tool for areas of gently deformed strata with low topographic relief. The study provided structural geologic data for comparison with initial interpretation of pronounced lineament patterns observed on the imagery.*

The initial imagery interpretation yielded evidence suggesting a large plunging anticline, a series of normal faults crossing the anticline at right angles, and other zones of fracturing adjacent to the anticline. Field examination of the study area provided data confirming many of the initial interpretations and indicating where modifications were needed

Faults of the study area are directly related to radar linear patterns whereas joints do not correlate well enough with radar lineaments to suggest a casual relationship.

The study also indicated the type and amount of data obtained from aerial photos in comparison with radar imagery from the area. Whereas radar imagery displayed evidence for the interpretation of large regional structures which did not appear on aerial photos, the photos show data on linear features too short to be displayed on the radar image The primary reasons for the additional lineament data on radar imagery are the low angle of illumination of the radar energy and the synoptic view which allows the visual integration of features over a large area.

The scale of the radar and photographic imagery used in this study was variable: 1:125,000 for radar and 1:21,000 for photography. This is stated by the author to be a possible reason for the different analyses of the two data source products.

JOHNSON, R. B., 1966

Geologic Evaluation of Radar Imagery of the Near Spanish Peaks Region, Colorado

U.S. Geological Survey Technical Letter - NASA-47, October, 6 pp. (NTIS No. N70 38938).

Abstract: *Conspicuous northwest-southwest striking lineaments in tertiary sedimentary rocks of continental origin were noted in radar images of the Spanish Peaks Region, Colorado The lineaments are not visible in aerial photographs of the region and had not been observed on the ground by field mapping. Close inspection in the field failed to find geologic features responsible for the lineaments on the radar image.*

Other features such as dikes radiating from the Spanish Peaks and the "stonewall" formed by upturned beds of Dakota sandstone were well displayed on the radar image A major fault along the front of the Sangre de Cristo Mountains, mapped on the ground, can be traced on the radar image for several miles (From: Carter, W. D., 1969.)

KEDAR, E. Y. and SHIN-YI HSU, 1972

Side-Looking Radar Imagery Applied in Seismic-Risk Mapping

Proceedings, Eighth International Symposium on Remote Sensing of Environment, Report No. 195600-1-X, Willow Run Laboratories, Institute of Science and Technology, The University of Michigan, Ann Arbor, 2-6 October, pp. 1195-1198.

From Authors' Abstract: *Earthquake-risk mapping is a synoptic analysis of the likelihood of the occurrence of earthquakes in different locales It can be achieved by combining seismic history regarding earthquake magnitude of intensity, geological data concerning structural lineaments, and geophysical data dealing with the strain released and gravity anomaly. The role of remote sensing in this topic is to provide additional geological structural data, from space photos and imagery of other sensors, that conventional geological field-work is either not feasible or failing to provide. The purpose of this paper is to demonstrate that side-looking radar imagery, like space photos, is applicable to infer structural lineament information for earthquake-risk mapping. The test area is the greater San Francisco Bay Area.*

Seismologists, to date, are not able to predict earthquakes - their location and magnitude. Because earthquakes are the result of earth's crustal movements and adjustments, geological and geophysical evidences on land surface should indicate their relative likelihood of seismic activities. It has also been recognized that air and space photos are superior to field work in detecting large (regional) structural units for seismic-potential investigations. Furthermore, side-looking radar imagery can be better than regular air photos because of its all-weather capability.

The seismic-risk maps were based on the following data (for 3 x 3 mi areas):

(1) Relative density of structural lines on imagery.

(2) Relative density of faults on geological maps.

(3) Cumulative seismic scenes, from earthquake records.

(4) Cumulative scores obtained from geophysical data.

The resulting maps, which the authors state should be studied in a manner similar to synoptic weather maps, show that in the study area, the western portion has a higher earthquake risk than the eastern portion. It is suggested that by combining ERTS and SLAR imagery (the latter for cloudy areas) a world-wide seismic map could be prepared. Its accuracy, however, may be questionable because the method requires some historical records (No. 3 above) which may be lacking in many areas.

KEEFER, W. R., 1968

Evaluation of Radar and Infrared Imagery of Sedimentary Rock Terrane, South-Central Yellowstone National Park, Wyoming

U.S. Geological Survey Open File Report, NASA Interagency Report - NASA-106, March, 12 pp. (NTIS No. N68 23210).

Author's Abstract: *Side-looking radar imagery (K-band) and night-time infrared imagery (3-5μ) were compared over the same sedimentary terrane of south-central Yellowstone National Park to determine if either type of imagery could be used in (1) differentiating rock types and (2) delineating structural features.*

Although sedimentary rocks of greatly contrasting composition occur in the area, none had detectable tonal characteristics on either type of imagery. This is believed to be due, in part, to masking by vegetation Flat lying volcanic rocks having smooth topographic profile were readily detectable on both radar and IR imagery. Quaternary surficial deposits were easily detected in IR imagery.

Numerous faults of large displacement were not detected by either form of imagery except where the faults were expressed by topography.

The original paper has three very good images (one radar, two IR) which are annotated for geology and topographic features. Hot springs, shallow and deeper lakes, wet meadows are all apparent in the IR imagery. Glacial features and topography are clearly visible, especially on the radar imagery. Many faults, shown on geologic annotations, are not visible on either type of imagery. The entire analysis is visual.

KEPPIE, J. D., 1976

Interpretation of P.P.I. Radar Imagery of Nova Scotia

Paper 76-3, Department of Mines, Halifax, Nova Scotia, ii, 31 pp. + figs., maps.

Author's Abstract: *Sector scan and central position Plan Position Indicator (P P.I) radar scope photographs taken between 1961 and 1965 were used. Advantages of radar photographs over regular air photographs include the large area visible on one image and the prominence of gross features uncluttered by smaller features. Three factors, elevation angle, topographic relief, and the relative orientations of linear topographic features and the sweep direction, impose limitations which collectively mean that each image provides only partial information on the area covered. The use of different images of one area overcomes such limitations Geometrical errors in the images arise from variations in the slant range, the forward motion of the aircraft, and some technical characteristics of radar. The small scale of the photographs reduces these errors to a minimum.*

The accompanying map (Figure 1) represents a compilation of the lineaments observed on the radar photographs. The amount of information reflects the number of images available for any area. Interpretation of the major lineaments suggests that most represent faults and some coincide with lithological boundaries Cape Breton Island is dominated by a group of north-easterly trending lineaments which control the main topographic features of the Island. The Aspy and Coolavee Faults form part of this group. Transverse lineaments, often with irregular traces are also present. The Margaree-St. Ann and Ingonish-Cheticamp River Lineament Systems are examples of these latter lineaments and are interpreted as faults. Mainland Nova Scotia is dominated by the E-W Cobequid-Chedabucto Fault system. A secondary north-easterly trending fault system is exemplified by the Hollow and Valley Faults NW-SE faults are prominent in the Meguma Group Lineaments with other trends are also present.

Following a short description of the radar and its operation and the interpretation of the P.P.I. imagery (actually 35-mm photography of the P.P.I. scope), the author presents imagery and descriptions of 62 different lineaments identified on the imagery. Many of the lineaments correlate with known geological features, some extend further than the mapped features, and some of the lineaments identified are entirely new features, not previously mapped (see also: Cameron, H.L., 1965a, b).

KIRK, J. N. and R. L. WALTERS, 1966

Radar Imagery, a New Tool for the Geologist

The Compass of Sigma Gamma Epsilon, Vol. 43, No. 2, January, pp. 85-93.

Authors' Abstract: *Studies sponsored by the National Aeronautics and Space Administration (NASA) at the University of Kansas with several other universities and government research organizations are exploring the applicability of remote sensing through radar imagery in many fields of the earth sciences. Studies to date indicate that radar imagery may become an excellent tool in regional geologic and lineament studies.*

In this qualitative analysis of X-band radar imagery of an area near Little Rock, Arkansas, the terrain is easily divided into three structural (geological) provinces composed of 15 rock units. This differentiation was based primarily upon the topographic expression and relative positions in the sequence of these rock units. Because the area under investigation has a heavy vegetation cover, the importance of lithologies as a determining factor of magnitude of radar return is diminished. Two images, three maps and five references are included.

KIRK, J. N., 1969

A Regional Study of Radar Lineament Patterns in the Ouachita Mountains, McAlester Basin – Arkansas Valley, and Ozark Regions of Oklahoma and Arkansas

M.S. Thesis, Department of Geology, University of Kansas, Lawrence, 1969 (?), vi + 44 pp. + app.

Author's Abstract. *Imagery produced by airborne, side-looking radar systems was used to examine radar lineaments and their patterns in a structurally diverse region exhibiting a range of deformational intensity.*

Radar lineaments appear on the image as linear boundaries between adjacent areas of differing power return and represent narrow, continuous or discontinuous features of a terrain. In the area of this study, radar lineaments almost exclusively represent surface drainage channels that exhibit patterns characteristic of fracture system control.

Properties of radar systems and terrain features that affect the recording of radar lineaments include surface roughness, incidence angle, radar shadowing, foreshortening, slant-range distortions, and look-direction.

In examining the relationship between radar lineament trends and fracture patterns, a comparison of rosette diagrams representing the patterns of joint and lineament trends indicates that, in general, radar lineament patterns exhibit directional trends similar to joint patterns and fault trends.

A comparison of the variations of lineament trends with variations of fold trends suggests that the fracture patterns represented by the radar lineaments in the Ouachita Mountains and Arkansas Valley Provinces are products of the same stresses that produced the folded structures, and that in the Boston Mountains area, the fracture system was produced by stresses whose orientations were not everywhere the same as those responsible for the development of the folds.

Chapter 2 (properties of Radar Systems and of Terrain that Influence Radar Lineament Definition) presents a brief review of the interaction of radar energy and terrain. Several good diagrams, generally from other sources reviewed in this bibliography, are given to illustrate radar range, backscatter and shadowing. However, no examples of these concepts are explicitly shown on the images of the study area used in this thesis.

KNEPPER, D. H. and R. W. MARRS, 1972

Remote Sensing Aids Geologic Mapping

Proceedings, Eighth International Symposium on Remote Sensing of Environment, Report No. No. 196500-1-X, Willow Run Laboratories, Institute of Science and Technology, The University of Michigan, Ann Arbor, 2-6 October, pp. 1127-1136.

Authors' Abstract: *Remote sensing techniques have been applied to general geologic mapping along the Rio Grande rift zone in central Colorado. A geologic map of about 1,100 square miles was prepared utilizing (1) prior published and unpublished maps, (2) detailed and reconnaissance field maps made for this study, and (3) remote sensor data interpretations The map is to be used for interpretation of the complex Cenozoic tectonic and geomorphic histories of the area.*

Regional and local geologic mapping can be aided by the proper application of remote sensing techniques. Conventional color infrared photos contain a large amount of easily-extractable general geologic information and are easily used by geologists untrained in the field of remote sensing. Other kinds of sensor data used in this study, with the exception of SLAR imagery, were generally found to be impractical or unappropriate for broad-scale general geologic mapping; these data can, however, be effectively applied to specific problems in relatively small areas, but some knowledge of the principles of remote sensing is necessary for the acquisition of the proper data and for subsequent interpretation.

The study, conducted in an environment much more complex than the normal experimental "test site," utilized several remote sensors and machine analysis and enhancement techniques. Both brute-force and synthetic aperture radars were used. Polarizations employed are not specified. The authors state:

> *SLAR imagery has thus far been sparingly used. The imagery is generally poor quality (low resolution, flat contrast, frequent image disruption) and does not justly represent the potential of SLAR imagery for regional structural analysis. Analysis of a few fair-quality images suggests that good quality, high-resolution SLAR imagery of the entire area would have aided in delineating and mapping major topographically-expressed structural features at an early stage of the study. This would, of course, have allowed areas for detailed field and photo study to have been more judiciously chosen.*

The authors rate sensors as to their relative usefulness for geological mapping in the following order:

(1) Low-altitude color photos
(2) Low-altitude color IR photos
(3) High-altitude color IR photos
(4) High-altitude color photos
(5) Low sun-angle photos
(6) SLAR
(7) Multiband photos
(8) Thermal IR imagery

However, as emphasized in the abstract, this listing is subject to change depending on the problem to be solved. Radar, for example, shows high utility "for broad-scale geologic mapping programs, particularly in the early stages."

KOMAROV, V. B. and B. P. NIAVRO, 1972

Methodology of Radar Aerial Survey With the Side Scanner TOROS in Geological Research. [Metodika Radiolokatsionnoi Aeros'emki Sistemoi Bokovogo Obzora TOROS Dlia Geologicheskikh Issledovanii]

New Methods of Obtaining Information by Various Remote Sensors and its Adaptation for Solving Geological Problems [Novye Metody Polucheniia Informatsii Razlichnymi Distantsionnymi Priemnikami i ee Obrabotki Dlia Resheniia Geologicheskikh Zadach], VIEMS, Moscow, (Russian).

Reviewer's Summary: *The Toros side scanning radar system was developed for use in evaluation of ice conditions. Since that time geological applications have also been defined.*

A parabolic antenna generates a signal of constant intensity in a centimeter wavelength range. The reflected signal is returned from the terrain to the antenna, processed through a cathode ray tube and recorded on moving photographic film which is synchronized with the aircraft speed. Return signals from directly below the aircraft are eliminated because of the poor quality of the image. Usually antennae are mounted on both sides of the aircraft so that two swaths of terrain can be imaged on each pass.

Flight lines are planned to include 50% overlap to facilitate the construction of a mosaic. Flat-lying terrain is generally imaged from 3–4 kilometers, while mountainous terrain is imaged from 6 or more kilometers elevation. (From Dellwig, et al, 1975.)

KOMAROV, V. B., V. A. STAROSTIN and B. P. NIAVRO (date Unknown)

Radar Aerial Survey and Its Significance in the Complement of Aerial and Space Geological Research Techniques

IKI Institute of the U.S.S.R., Academy of Sciences, Moscow, 23 pp.

Authors' Abstract: *This paper contains a discussion of the possibilities of using the aerial radar technique for geological research. The radar aerial survey data make it possible to obtain valuable information about the structural-tectonic composition, the material composition of rocks, and the nature of the relief. Radar aerial photographs are of great interest when studying enclosed territories. In solving geological problems, the joint application of data from high altitude and space radar surveys is most effective. (From Dellwig, et al., 1975.)*

"Toros" radar imagery has been used successfully to identify a variety of volcanic, geomorphic, and structural features in relatively unknown regions of the U.S.S.R.

KOOPMANS, B. N., 1973

Drainage Analysis on Radar Imagery

ITC Journal, pp. 464–479.

Author's Abstract: *A comparison is made between the value of monoscopic side-looking radar images, stereoscopic side-looking radar images, and aerial photographs for drainage analysis in an area near Baudó, Dept. of Choco, Colombia. Restriction of material limited the conclusions to one specific area of low relief. Ka band images of the Westinghouse*

AN/APQ 96 system were used. As a basis for comparison, the existing topographic maps, scale 1:25,000 were used. Drainage interpretation on stereo radar was roughly identical to the drainage network on the topographic maps, with the exception of the flat valley areas where the dense vegetation entirely covered the drainage channels. The larger scale of the aerial photographs and the better resolution gave more detail in these areas. Drainage density in the area with relief was the same as or higher on the stereo radar interpretation than on the topographic map. For the monoscopic radar interpretation, drainage density was on average 24% lower than for the map. Moreover, the drainage network and outline of the river basins differed greatly from the map and from other interpretations For the average river segment length a shift of about one order occurred from the monoscopic radar interpretation towards the stereoscopic radar interpretation. It can be concluded that for base map construction of the test area, stereo radar images can be used to obtain a reliable drainage network. This is not true for monoscopic radar interpretation. Deformation errors within the images have not been taken into account in this study.

This study considered one large drainage basin (45.7 km^2) which was divided into five subbasins of area 0.6 km^2 to 3.7 km^2. The schemes of drainage basin geometry and stream ordering of Strahler and Horton were used for calculations. It is concluded that the stereo radar is the better of the several methods for determining the drainage density and drainage net, giving a density approximately 1.5 times larger than that derived from monoscopic radars. In turn, monoscopic radar was considered to be poorer than aerial photography for drainage density. Several problems with this particular study are, however, emphasized (e.g., poor aerial photographs, and variations in radar look directions).

Studies such as this one and those by McCoy should be continued to allow definitive statements to be made concerning radar measurement of drainage densities. To date, such studies have been in diverse environments and the results are often not applicable to new sites and situations – as pointed out by Koopmans in his paper.

KOOPMANS, B. N., 1979

Should Stereo SLAR Imagery be Preferred to Single Strip Imagery for Thematic Mapping?

Proceedings, Symposium on Remote Sensing and Photo Interpretation. International Society for Photogrammetry. Commission VII, 07-11OCT7, Banff, Alberta, Canada, pp. 841-861.

Available from the Canadian Institute of Surveying.

Author's Abstract: *To date, images of the "side-looking radar" have been interpreted mainly in a monoscopic way. The radar shadows on the imagery give the interpreter a relief impression, which makes recognition of surface characteristics possible. With the present geometric fidelity of consecutive radar-strips and constant scan-direction, stereo viewing is possible to obtain a three-dimensional picture. The principles of height and slope measurements are treated for single strip imagery and stereo images.*

Drainage interpretation of stereo radar imagery and single strip imagery are compared for different terrain types Stereo viewing of overlapping radar strips offer considerable advantages over monoscopic viewing for interpretation purposes. Details, from far range and near range, are observed simultaneously. Moreover, the three dimensional picture allows relative altitude correlations (often not possible in single strip imagery) and increases the interpretability of the radar strips.

This paper consists of two major parts: 1) A discussion of the measurements from single strip and stereo SLAR imagery, together with the techniques and formulae used in such studies and 2) examples of drainage analysis using both single and stereo SLAR. For areas of high relief, only single strip data were available and it was determined that the relationship to the topographic maps was very poor. This study area was in Columbia. Moderate relief areas (using data from Arizona) indicated that drainage interpretation using both radar configurations was about the same. For the low relief areas (tropical wet and tropical semi-dry areas of Columbia) the stereo was, in general, far superior to the monoscopic imagery. For flat areas, stereo was essentially of no use. The author concludes that stereo radar, by adding the third dimension, increases the confidence in the interpretation obtained from the data. In low relief areas, the depression angle may be such as to generate few shadows (in the near range) and for high relief areas, in the far range, shadows may dominate the image.

KOVER, A. N., 1967

Radar Imagery as an Aid in Geologic Mapping

Presented at the 33rd Annual Meeting, American Society of Photogrammetry, Washington, 5-10 March.

Photogrammetric Engineering, Vol. 33, No. 6, June, p. 679 (abstract only).

Author's Abstract: *The United States Geological Survey, in cooperation with the NASA Earth Resources Survey Program, is evaluating sidelooking radar imagery in many areas of varying terrain, surface conditions, and rock types to determine its utility as an aid in geological mapping. Initially, the radar imagery is being used by geologists of considerable experience in the study areas much as they would use conventional aerial photography. Preliminary results are summarized and the radar imagery presented for 17 test areas. (Copyrighted by the American Society of Photogrammetry.)*

LaPRADE, G. L. and E. S. LEONARDO, 1969

Elevations from Radar Imagery

Photogrammetric Engineering, Vol. 35, No. 4, April, pp. 366—371.

Authors' Abstract: *Radar is a ranging device while the camera is an angle-measuring device. This difference means that entirely different relationships are used for elevation measurements As radar provides its own source of illumination, it also has capabilities not available with conventional cameras For example, under certain circumstances, the height of vertical features can be determined solely from the image itself with no knowledge of the radar system or aircraft position. Radar can additionally have either slant or ground range images. Each type of image requires the use of different geometrical relationships. This paper develops the mathematical expressions for measuring the heights of vertical and non-vertical features with both slant- and ground-range images. Significant applications are discussed and the experimental accuracies obtained in actual practice are given. (Copyrighted by the American Society of Photogrammetry.)*

This short tutorial paper presents the basic mathematical arguments for determining height from both slant and ground range radar imagery for both vertical and non-vertical objects. This clearly written paper is highly recommended.

LATTMAN, L. H., 1973

Evaluation of Remote Sensors for Exploration Geomorphology

Presented at the 54th AAPG – 47th SEPM National Meetings, Anaheim, California, 14-16 May.

American Association of Petroleum Geologists Bulletin, Vol. 57, No. 4, April, pp. 790 (abstract only).

Author's Abstract: *Remote-sensor imagery embraces black and white aerial photography (including black and white infrared photography and various film-filter combinations), color aerial photography, color infrared aerial photography, thermal infrared, and radar. For the three general types of geomorphic exploration techniques – drainage analysis, tonal analysis, and fracture analysis – no single remote sensor is best. Terrain, vegetative cover, and extent of human activity influence the selection of imagery for analysis.*

Black and white and color photography seem best for routine surface-drainage analysis, especially of low-order streams. Thermal infrared and color infrared give considerable information on groundwater-discharge locations and soil-drainage characteristics Radar imagery allows excellent mapping of higher-order drainage patterns of large areas, and is least affected by vegetative cover.

Tonal anomalies are best seen on black and white infrared and black and white panchromatic photography. Color photography is less useful for this technique, and color infrared is poor to unusable, especially in grass-covered regions Thermal infrared is very poor, and radar cannot be used for tonal studies in exploration geomorphology.

Fracture-trace analysis is done best on stereo-aerial photography of all types, and least well on thermal-infrared and radar imagery. Lineament analysis is done best on aerial photographic mosaics, and particularly well on radar.

Radar and aerial photographic mosaics are well-suited for regional studies, as are images from satellites; aerial photographs and thermal infrared imagery are best for local, detailed studies. (Abstract copyrighted by AAPG.)

LEIGHTY, R. D., 1966

Terrain Information from High Altitude Side-Looking Radar Imagery of an Arctic Area

Proceedings, Fourth Symposium on Remote Sensing of the Environment, Report No. 4864-11-X, Willow Run Laboratories of the Institute of Science and Technology, The University of Michigan, Ann Arbor, April, pp. 575–597 (NTIS No AD 638 919).

Author's Abstract: *Radar imagery was obtained at altitudes of 30,000 to 60,000 feet over arctic terrain with the AN/APQ56 (XAA) side-looking radar (high altitude) set during two flight programs (November–December 1960 and March 1962) Generalities of terrain information retrieval from radar imagery are presented with background information on the regional terrain characteristics in northwest Greenland and discussion of representative project imagery*

This paper accompanied by 12 radar and aerial photo illustrations, presents a series of interpretations and explanations of the radar images. An excellent paper for such illustrations. In the final section, the author reached these general conclusions.

(1) SLAR equipment can provide imagery from which terrain information can be obtained.

(2) Information obtained is mainly dependent on the experience of the interpreter.

(3) Organization of image tones is more difficult with SLAR than with aerial photos.

(4) Less terrain detail is available from SLAR than aerial photos because of low SLAR resolution.

(5) Some versatility in selecting the radar mode is useful for changing from reconnaissance to specific imagery.

(6) The relative return from terrain materials, in decreasing order is: snow, glacial ice, soils and rocks, lake ice, sea ice and open water. (Note: This is the general progression; there are variations within it.)

LEIGHTY, R. D., 1968

Remote Sensing for Engineering Investigation of Terrain — Radar Systems

Proceedings, Fifth Symposium on Remote Sensing of Environment, Report No. 4864-18-X, Willow Run Laboratories of the Institute of Science and Technology, The University of Michigan, Ann Arbor, 16-18 April, pp. 669–685 (NTIS No. AD 676 327).

Author's Abstract: *This paper discusses the present and future potential of radar for engineering investigation of terrain. The purpose is to acquaint the engineer with the applicable radar literature pertaining to radar uses, radar systems, radar theory and empirical measurements, qualitative analysis of radar imagery, and miscellaneous radar techniques.*

Extensive quoted material essentially describes the present state-of-the-art of radar remote sensing for engineering applications. Three illustrations and 28 references are included (all unclassified, but not readily available). The final paragraph of one section emphasizes that before the engineers can utilize such remote sensing instruments, it must be demonstrated that valid measurements can be made for a wide variety of terrain types and situations beyond the unique and often highly controlled laboratory situations from which much data originates.

LEWIS, A. J., 1971

Geomorphic Evaluation of Radar Imagery of Southeastern Panama and Northwestern Colombia

Ph. D. Dissertation, Department of Geography, University of Kansas, Lawrence, 178 pp (NTIS No. 724 118).

CRES Technical Report 133-18, and U.S. Army Topographic Command, Engineering Topographic Laboratories, Report No. ETL-CR-71-2.

Author's Abstract: *Airborne imaging radar systems have not received the attention they warrant from geomorphologists largely due to the lower resolution capabilities of radar imagery compared to aerial photography. However, the near all-weather, 24-hour, imaging ability of radar can act as a trade-off for resolution when lighting conditions or cloud cover prohibit the collection of aerial photography. Imaging radar systems also have the advantage of large scale coverage presented on a continuous strip of film closely resembling a shaded relief map.*

Although the general applications of radar imagery to geoscience are dealt with by several authors, most studies have not progressed beyond the stage of speculation or theoretical consideration. The acquisition of radar imagery covering over 17,000 square kilometers in southeastern Panama and northwestern Colombia afforded the opportunity to test the operational practicality, reliability, and consistency of techniques for deriving morphometric data from radar imagery, as well as the identification of individual geomorphic features and the delineation of geomorphic regions. Included in the imaged area was Route 17, a proposed sea-level canal route for which topographic and regional geomorphic data were available.

Route 17 provided the data base against which were tested (1) the qualitative delineation of landform regions on radar imagery and (2) the quantitative determination of relative relief from radar shadows and terrain slope from radar foreshortening. Cumulative frequency curves of terrain slope derived from radar shadow frequency across the range of the imagery were compared to similar map-extracted curves of slope distribution for six areas throughout the United States.

The comparison of map- and radar-derived geomorphic regions of Route 17 was favorable. The method was then extended into the Darien Province where topographic maps are essentially non-existent. The final product is a map (Plate I) of the regional geomorphology of the study area at a scale of 1:250,000. Four geomorphic regions were delineated: plains, low hills, high hills, and mountains.

The radar shadow frequency method also proved successful and was extended into the Darien Province where cumulative frequency curves of slope were derived from two strips of radar imagery across the Darien Province. This provided a quantitative statement of slope values for qualitatively described landform regions The results appear in Plates II and III. Distinct cumulative frequency slope curves, one for each general landform region previously discriminated qualitatively, resulted from the use of this method.

Statistical analyses of terrain slope and relative relief measurements from radar foreshortening indicate that the method as tested is not operational for determining individual slope or relative relief values, however, the accurate calculation of the mean regional slope and relative relief and the range of slope and relative relief values is feasible using radar foreshortening.

The correlation between radar power return and terrain slope was lower than anticipated, however, the relationship needs further testing The correlation between map-derived and radar-shadow-derived relative relief data indicated that relative relief can be determined accurately and reliably from radar shadows

Some of the individual geomorphic features identifiable on radar imagery are tidal flats. mangrove, beach ridges, wave refraction and surf, barrier reefs, shell reefs, estuarine meanders, shoreline configuration, deltas and associated features, and drainage patterns Although the detection and mapping of geomorphic features in unknown areas is important, the real importance is the use of geomorphic features as surrogates for obtaining genetic and environmental information.

Radar geometry as it relates to the collection of morphometric data is also thoroughly discussed. (Abstract from. Dissertation Abstracts, Sec. B., Sciences and Engineering, Vol. 32, No. 4, October 1971, pp. 2224–2225B.)

LEWIS, A. J. and H. C. MacDONALD, 1971

Radar Geomorphology of Garachine Bay, Panama, and the Attrato Delta, Colombia

Presented at the Annual Meeting, Association of American Geographers, Kansas City, March.

Authors' Abstract: *The recent acquisition of radar imagery of Eastern Panama and Northwestern Colombia has provided the geomorphologist with a new source of geomorphic data that is presented at a regional scale but with a spatial resolution enabling the identification of individual landform features.*

Two geographic regions, Garachine Bay, Panama, and the Attrato Delta, Colombia, were selected to demonstrate some of the geomorphic information interpretable from radar imagery. Because of the high contrast ratio in radar return between land and water, a large proportion of the features identified and illustrated are coastal or alluvial, such as shell bars, estuarine meanders, tidal flats, surf zone, wave refraction, off-shore river mouth bars, cut-off meanders, scrolls, levees, crevasses, and others. In both regions the identifications of individual geomorphic features were used as surrogates for inferring geomorphic process and development:

LEWIS, A. J. and W. P. WAITE, 1971a

Cumulative Frequency Curves of Terrain Slopes from Radar Shadow Frequency

37th Annual Meeting, American Society of Photogrammetry, 7—12 March, pp. 228—244.

Photogrammetric Engineering, Vol. 37, No. 5, May, p. 488 (abstract only).

Authors' Abstract: *To date, the geoscientist has made only limited use of radar shadows for collecting quantitative geomorphic data. Although Levine (1960) and McAherney (1966) described methods for calculating relative relief from the length of a radar shadow, the relationship between the occurrence of radar shadows and terrain slope angle has not been previously utilized. Because a terrain feature will shadow only where the back slope of the feature is greater than the depression angle at which it is imaged, slope information is available from the frequency of radar shadowing. By sampling across the range of the radar image, a cumulative frequency curve of slope distribution can be constructed.*

The radar shadow frequency method for determining terrain slope information was tested in six regions in the United States where both radar imagery and topographic maps were available. Results indicate that the radar-derived slope curves are comparable to topographic-map-derived slope distribution curves, and seem to be more realistic in mountainous regions.

This paper describes the radar shadow-frequency method for determining the distribution of terrain slopes and the basis for its use, presents and evaluates the results of the comparison of map-derived and radar-derived slope; and discusses the advantages and disadvantages of such a method as a primary data source for the geomorphologist. (Copyrighted by the American Society of Photogrammetry.)

Both local and regional slopes are determinable, with results for the former being more accurate. In regional slope work, both near- and far-range areas must be homogeneous. If only one look-direction is used and it is near the grazing angle, a saw-tooth model for the topography is assumed in the determination of regional slope. It is also assumed that the slope angles are randomly distributed. Although the method has some severe limitations (e.g., dependence upon look angle), it readily lends itself to automatic pattern recognition methods. The results show a high correlation with map data. All work was done in areas of high slopes and may have limited usefulness in more level terrains. The method is considered rapid and accurate for high mountain areas; its limitations are (1) some of the basic assumptions, and (2) the need for multiple-look directions. The lower boundary of detectable slopes was 15 degrees (see also: Lewis and Waite, 1972).

LEWIS, A. J. and W. P. WAITE, 1971b

Cumulative Frequency Curves of the Darien Province, Panama

Propagation Limitations in Remote Sensing, Edited by J. B. Lomax
Proceedings, 17th Symposium of the Electromagnetic Wave Propagation Panel of AGARD, 21—25 June, No. 90. Colorado Springs, CO., pp. 10-1 to 10-10 (NTIS No. AD 736 309).

Authors' Summary: *Histograms and cumulative frequency curves of terrain slope are important in the quantitative description of geomorphic regions and aid in the study of land utilization and terrain mobility. Recently a method for obtaining such terrain slope information from radar imagery was developed utilizing (1) the necessary relationship between terrain slope, α, and the depression angle, β, for the occurrence of radar shadows i.e., $\alpha > \beta$; and (2) the variation in depression angle from near to far range across the radar image.*

Six different geographic regions were selected in the United States, where both topographic coverage and radar imagery were available for testing the method. The results were very encouraging, especially in rugged mountainous terrain where topographic coverage is generally the least accurate. Subsequently, the method was applied to two strips of radar imagery of the Darien Province, Panama. Each strip of imagery was approximately

1,000 square miles in area and oriented transverse to the structural grain of the landform regions. A cumulative frequency slope curve was determined for each geomorphic region qualitatively delineated on the radar imagery of the Darien Province.

The characteristic shape of the cumulative frequency curves for each of the four general geomorphic regions — plains, low hills, high hills, and mountains — proved diagnostic. This helps to substantiate both the qualitative geomorphic boundaries and the quantitative slope data determined from radar imagery. The curves also represent the only quantitative regional slope information available for the poorly mapped Darien area.

This is essentially the same paper presented by these authors in two other publications. (See comments for LEWIS and WAITE, 1971a and 1972.)

LEWIS, A. J. and W. P. WAITE, 1972

Relative Relief Measurements from Radar Shadows: Methods and Evaluation

Proceedings, 68th Annual Meeting of Association of American Geographers, Kansas City, MO., 23–26 April, V. 4, pp. 65–70.

Authors' Abstract: *Two of the principal criteria used in describing and delimiting landform regions — terrain slope and relative relief — exhibit simple geometric relationships with radar shadows. Since radar shadows are ubiquitous features on radar imagery of rugged mountainous topography, they loom as an important potential source of topographic data, especially in the world's inadequately mapped, inaccessible mountainous regions where photographic coverage is practically nonexistent. This paper focuses on the determination of relative (local) relief from radar shadows. The scope of the paper is as follows: (1) discussion of the conditions necessary for radar shadowing, (2) discussion of the length of radar shadows as a function of depression angle, β , and the height of the terrain feature, h, (3) consideration of the three types of elevated terrain features as related to imaging radar systems and the restrictions imposed on relative relief measurements by each terrain type, (4) presentation of the equations of Levine (1960), McAnerney (1966), and Lewis (1971) for calculating of relative relief from radar shadow length, (5) evaluation of the operational accuracy of these three equations based on the correlation of the radar-derived and map-derived topographic data, and (6) selection of the most parsimonious equation. The statistical results strongly indicate that the measurement of relative relief can be effectively accomplished using radar shadows Although the statistics for all three equations are very similar ($r \approx 0.86$; SEE $\approx$ 108 feet and $P > .001$), Lewis' equation was deemed most practical because fewer measurements are required for the calculation of relative relief from radar shadows. (Reprinted by permission of AAG.)*

The authors' note that the Lewis equation requires fewer measurements and also note that one assumption, that of a level datum plane on both sides of the object casting the shadow, is necessary. This may be quite erroneous in the high terrain areas where they did this work (a portion of Panama). Levine's equation does not make this assumption and therefore requires the simultaneous solving of equations for two unknowns. Several suggestions are made for further radar applications to geomorphology (see also: Lewis and Waite, 1971).

LEWIS, A. J., and H. C. MacDONALD, 1973

Radar Geomorphology of Coastal and Wetland Environments

Proceedings, American Society of Photogrammetry. Fall Meeting, October, Part II, pp. 992–1003.

Authors' Abstract: *Side Looking Airborne Radar (SLAR) imaging systems are of special interest to the coastal and wetland geomorphologist. Continuous strip presentation of the land-water interface of at least 16 kilometers wide and hundreds of miles long is advantageous for the study of the relatively narrow coastal zone. In addition, the near all-weather, 24-hour imaging capability is a particular asset in coastal and wetland environs commonly obscured by cloud cover.*

A variety of coastal environments have been imaged with commercial radar mapping systems during the past 10 years. Some of these coastal areas include the Arctic Coast of Alaska, the Gulf Coast of Louisiana and Texas, the California and Oregon Coasts, Chesapeake Bay, and the Atlantic and Pacific Coasts of Central and South America. The wetland environment of the Atchafalaya Basin and the coastal swamp and marsh region in Louisiana have also been imaged.

This study summarizes the past work in radar coastal morphology by the authors and their co-workers but primarily focuses on recently completed research in the wetland environment of Louisiana and the coastal environment of Oregon.

The work reported in this paper is essentially a summary of previously published works based on K-band imagery. A comparison of the work of Roswell and that prepared by these authors with respect to lake size and detectability for various environments are quite comparable. The point is often made that some of the items detected on the radar imagery were known to exist prior to the interpretation, and that one should keep this in mind to avoid making "...wild and grandiose evaluations of the ability of radar imagery." An interesting summary article.

LEWIS, A. J. and W. P. WAITE, 1973

Radar Shadow Frequency

Photogrammetric Engineering, Vol. 38, No. 2, February, pp. 189–196.

Authors' Abstract: *To date, the geoscientist has only made limited use of radar shadows for collecting quantitative geomorphic data. Although methods for calculating relative relief from the length of a radar shadow have been described, the relationship between the occurrence of radar shadows and terrain slope angle has not been previously utilized. As a terrain feature will shadow only if the backslope of the feature is greater than the depression angle at which it is imaged, slope information is available from the frequency of radar shadowing. By sampling across the range of the radar image, a cumulative frequency curve of slope distribution can be constructed The radar shadow frequency method for determining terrain slope information was tested in six regions in the United States where both radar imagery and topographic maps were available. The results indicate that the radar-derived slope curves are comparable to topographic map-derived slope distribution curves and apparently are more realistic in mountainous regions. (Copyrighted by the American Society of Photogrammetry.)*

This paper is essentially the same as three other papers: LEWIS and WAITE, 1971a, 1971b, and 1972.

LIU, C. C., 1973a

Geology of the Area "Senhor do Bonfim" Based on SLAR Mosaic Interpretation

Instituto de Pesquisas Espaciais, São José dos Campos, Brasil, 14 pp.

Author's Abstract: *From the criteria of tonal contrast, drainage pattern, all the landforms and the characteristic distribution and contact relationships of the rocks in the SLAR mosaic, the writer distinguished the different rock units as the Basement Complex, the Plutonic Unit, the Metamorphic Unit, the Intrusive Plutonic Unit, the Clastic Sedimentary Unit, the Calcareous Sedimentary Unit 1 and 2, and the Alluvium. They are listed above in ascending order. From the topographic expressions and their microfeatures, distribution of the aerogeologic rock units, and the lineaments, many folds, faults and features are recognized from the SLAR mosaic. Tombador Mountain Range divides this area of study into two parts. The sedimentary terrain, which is in the west of Tombador Mountain, yields the greatest amount of information from the radar imagery. The basement complex terrain, which is in the east of the mountain, yields the least information. In the Tombador Mountain Range there are several large intrusive granite bodies containing prominent dikes, and around the intrusive bodies there are features which suggest contact metamorphosis. Therefore, this region of Tombador Mountain is hopeful for valuable economic mineral researches. (From: Dellwig, et al., 1975.)*

A radar mosaic was used for geologic mapping in a remote region. The importance of look direction is recognized.

LIU, C. C., 1973b

Radar Geological Observations on the Low Hilly Terrain Amidst Piauí, Pernambuco and Bahia State, Brazil

Instituto de Pesquisas Espaciais, São José dos Campos, Brasil, 10 pp.

Author's Abstract: *This study was based only in the use of SLAR mosaics as a geological tool in mapping low hilly terrain, comprising monotonous Precambrian rocks with similar erosional resistance, lack of topographically characteristic appearance and poor outcrops due to thick soil cover.*

From the careful study of drainage patterns, tonal contrast, topographic features and contact relationship on the SLAR mosaic of the studied area, fifteen radargeologic rock units are distinguished.

From the careful analysis of the topographic depressions, lineaments and contact relationship between different rock units, many faults and fractures are recognized. From the different directions of dipslopes, many anticlinal and synclinal foldings are also recognized.

Radar imagery is proving to be an effective remote sensor tool for geological reconnaissance studies. Thus radargeology enables us to obtain geological information through the study and analysis of radar imagery. (From: Dellwig, et al., 1975.)

Radar imagery provided data for geologic mapping in an unexplored region.

LINTZ, J., Jr., 1972

Remote Sensing for Petroleum

American Association of Petroleum Geologists Bulletin, Vol. 56, No. 3, March 1972, pp. 542–553.

Author's Abstract: *Remote sensing techniques in the exploration for petroleum have not moved from the small-scale, limited study-area, experimental state to full-scale, large-area, operational status. Remote sensing techniques will have come to maturity when total basin survey for known and potential hydrocarbon anomalies are commonplace. As with much of petroleum exploration, remote sensing is primarily an indirect approach limited to the development of drillable petroleum prospects. The techniques include spectroscopic analysis, which offers the potential for airborne compositional analysis. Research toward the latter objective is still in early phases.*

The most commonly used wavelengths are the visible part of the spectrum (0.3—0.7µ), infrared film emulsions (0.3—0.9µ), and thermal infrared (8—14µ). Equipment and materials covering these spectral bands are the best developed and the most widely available.

Exploration in areas of consistently poor illumination because of meteorologic conditions will bring about increased use of the longer wavelength (microwave) equipment. Cloud penetration is a function of wavelength; passive microwave radiometers, side-looking radar, and scatterometers possess this capability. Currently, airborne microwave instrumentation is not widely available, but indications are that it will come into wider use.

Service companies prepared to perform multisensor data collecting on a global scale are now operational. They offer, on a contract basis, sophisticated equipment in advanced aircraft, with or without interpretation packages. In addition to petroleum companies, their clientele includes mining companies, widely diversified agricultural interests, and domestic and foreign government agencies. (Abstract copyrighted by AAPC.)

The basic operation and capabilities of several sensors are presented. The author comments that often low-angle visible photography is as good as SLAR; he also comments that often SLAR can obtain data where all other sensors are inoperative (i.e., during periods of poor light and/or weather). Several good images from the various sensors are included.

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 Open File Report – NASA-168, February, 11 pp. + figs. (NTIS No. N72 18356)

From Author's Introduction: *This study is a generalized geologic evaluation of lines, localities, and features of various types that are visible on a series of radar image strips covering the Teton Range and Jackson Hole in northwestern Wyoming. No attempt was made to collate a complete geologic map with the radar image at each locality.*

Formation names, problems of geologic interpretation, and details of stratigraphy and structure that are not directly pertinent to the study of the imagery are omitted . . .

The paper opens with four general comments, summarized below:

(1) The like-polarized image is much clearer than the cross-polarized image in the areas of high relief.

(2) Vegetation and soil mantle in the Jackson Hole area have a considerable effect on the tone of the images. These differences should be useful in interpreting the surficial geology.

(3) The direction in which the beam is pointed is of paramount importance in evaluating the quality and content of the image. This is sufficiently important to influence judgments on whether or not radar imagery is worthwhile in a given area and for a given rock type.

(4) A serious criticism to straight-line traverses is that they may not show the geology in a manner suitable for accurate interpretation. For future planning, the first step should be to devise a plan for the most effective and economical geologically oriented radar flight lines.

The author has compared radar images with oblique photographs of plastic raised relief maps. This was partially in an attempt to reply to (4), above. The technique was useful. He noted that radar imagery accentuated relief and geologic features may often be inferred through the vegetation, which is often clearly visible in the images. Several faults, with strikingly different images on opposite sides, are noted. These differences are interpreted as arising from topographic differences which in turn result from differential weathering of the unlike bedrock. In general, no rule can apparently be voiced concerning the identification of various rock types. Vegetation and spatially contiguous rock types play an important role in the ease of identification, as also do the beam angle (i.e., look direction) of the radar signal. Several hot springs were not identifiable on the images. However, in several images, "many middle and late Pleistocene features and deposits are strikingly displayed on the radar image and their succession of development of interrelation can be interpreted." One set of images, with opposite look directions, is used to clearly illustrate the advantage of this duplication. In several areas, landslides can be easily recognized by their "concentrically lumpy surface configuration." The author gave no indication of the radar system parameters. Eleven images, with annotations, and seven references are included.

LUNDIEN, J. R., 1966

Terrain Analysis by Electromagnetic Means

Report 2, Radar Responses to Laboratory Prepared Soil Samples, Technical Report No. 3-693, U.S. Army Corps of Engineers, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, September, ix + 55 pp. + app. (NTIS No. N67 11854, AD 802 104).

Author's Summary: *Laboratory tests were conducted with radar sensors to detect the presence of and measure the depth to subsurface interfaces when the surface was bare, and to determine the influence on radar responses of vegetation at various stages of growth. A secondary purpose was to continue earlier studies to relate radar returns and the electrical constants they provide, to moisture content and density of samples.*

Large laboratory samples were prepared at various moisture contents and densities and with various depths to a subsurface metal plate. Standard pulsed radar sensors operating with frequencies of 297, 5870, 9375, and 34,543 megacycle/sec were employed and directed at various angles of incidence to the surface

The results of this laboratory study indicate that the standard pulsed radar sensors can provide information that will permit an estimate of the moisture content of deep, homogeneous soil samples and the detection of surface vegetation of various heights. Radar signatures of vegetation-covered soil were more significantly altered at Ka-, X-, and C-band frequencies than at P-band frequencies. However, standard pulsed radar sensors used monochromatically cannot provide information for predicting depth to a subsurface interface or for directly indicating the presence of subsurface interfaces.

The systematic manner in which soil depths were varied in this study permitted an analytical solution to the problem of measuring depths of layers and led to the conclusion that properly designed radar systems could measure depths to subsurface interfaces. Three such systems are proposed.

The first three sections of this report deal with an introductory statement defining purposes of the study: (a) to detect the presence of sample layers of various moisture contents, densities, and soil types, and measure depth of these layers, (b) to measure the electrical properties of soils of various moisture contents, and (c) to measure the effect on a soil radar signature of a stand of wheat at various stages of growth and describe both the experimental technique and the apparatus used.

Part four, titled "Data Analysis," presents a short statement on the basis of the analysis; this is followed by a mathematical treatment of the method of analysis for both signature and depth-of-penetration tests. Arguments are given for the calculation of electrical properties from interference patterns, and the computation of electrical constants of samples by the wavelength method and by surface reflections. All soil test surfaces were smooth at all radar wavelengths used – only the vegetation surface (wheat) was not specular at incidence angles other than vertical. Only with P-band (the longest wavelength used) was sufficient data available to determine the depth of penetration actually achieved. This varied from 24 to 8 inches with increasing moisture content, to a maximum of 35 percent for silt loam and 51 percent for clay. The lack of adequate data for study of depth-of-penetration at shorter wavelengths occurred because the number of oscillations produced for each depth is roughly proportional to the frequency. Consequently, at higher frequency, there are a greater number of oscillations, and a need for more data points to define the pattern of the oscillations. Similar discussions are presented concerning the study of layered soils and dry perlite.

The apparent relative dielectric constant and conductivity were determined for the several samples at each of the radar wavelengths – these are not the same for all frequencies. The data indicate that the dielectric constant of the soil depends primarily on the quantity of water in the soil; the effect of soil type is minor. "This dielectric constant-moisture content correlation may provide an important relation for remote terrain investigations." With respect to the study on the one vegetation type, the normalized echo for the long-wavelength radar did not fluctuate as much as with the three shorter wavelengths: Hence, it is suggested that the shorter wavelengths could be used to measure vegetation parameters (height, thickness, moisture content) and the long wavelengths be used for soil studies. Three types of radars (monopulse, FM, and variable frequency systems) are discussed as to their potential uses for such studies.

The radar used in this study was not an imaging system, nor is the data directly related to the interpretation of radar images. However, studies such as this are needed for aid and guidance in radar image interpretation.

LYON, R. J. P. and K. LEE, 1970

Remote Sensing in Exploration for Mineral Deposits

Economic Geology, Vol. 63, No. 7, November, pp. 785–800.
Originally presented at Alaska Remote Sensing Conference, Anchorage, Alaska, 9 December 1969.

Authors' Abstract: *Remote sensing, a new term for an old practice of airborne exploration, has become a "cure-all" for the search for new mineral deposits. This paper seeks to evaluate those aspects of the technology which can be of use to the exploration geologist, and to place the various sensors in a priority-listing for several types of geological targets A point of significance to be clearly understood is that the "skin" (or penetration) depth of most sensors is shallow. Remote sensing really offers a chance to rapidly survey large areas, in seeking the diagnostic surface phenomena from more deeply hidden ore deposits (Copyrighted by Economic Geology Publishing Co.)*

The authors comment on the engineering (rather than the applicational) approach to the development of remote sensors for geology and environment problems. That is, there is an emphasis on the given wavelength (and the state-of-the-art of sensor development) and not on the problem to be solved. One might thus be tempted to force a sensor into a problem to which it is not best suited. As an indication of the best sensor/problem fit, the authors offer a "Definition of Target Phenomena and Remote Sensor Selection." Interestingly, radar makes a rather poor showing, being noted as Class A (highest) for surface texture (rock type) and gravel and placer deposit detection; Class B for structure (i.e., surface relief), lineaments, structural traps (for hydrocarbons), topography and drainage; Class D for several permafrost studies (patterned rocks, thermokarst features and pingos; and Class E for polygonal ground. No class (even the lowest) is assigned to radar for the study of vegetation differences, rock chemistry and mineralogy, or soil moisture. This last is somewhat at variance with some of the "proven" applications included in the present bibliography.

The paper includes several good sets of radar images, one of which (Fig. 4) affords comparison of a standard low sun angle, black and white airphoto mosaic and a radar (K-band) image. A striking resemblance between the latter two is clearly evident. A SLAR image of Mono Craters, California (U. Kansas, K-band, like-polarization) is presented with geologic annotations identifying 14 different features. The authors suggest that "remote sensing should be a small-scale personal effort, strongly involving the geologist . . . He must direct the program, define its objectives, and personally be present during data-gathering."

LYON, R. J. P., J. MERCADO, and R. CAMPBELL, Jr., 1970

Pseudo Radar

Photogrammetric Engineering, Vol. 36, No. 12, December, pp. 1257–1261.

Authors' Abstract: *An analysis of side-looking, K-band radar imagery indicated that most of its geological usefulness came from (a) its small-scale presentation (around 1·200,000), and (b) its strong, jet-black shadows, which markedly emphasized the topographic relief. Several published papers have emphasized the effect of low sun-angle on the appearance of vertical aerial photography, so we developed from this a technique for simulating side-looking radar (SLAR) by conventional aerial photography, but with the sun around 20–30 degrees above the horizon. It is proposed that this unconventional type of aerial photography be termed Low Sun–Angle Photography (LSAP). (Copyrighted by the American Society of Photogrammetry.)*

Similarities of the two methods:

(1) Both use strong illumination and measure reflected energy.

(2) Both emphasize third dimension by heavy shadowing.

Differences of the two methods:

(1) Radar beam fans out, thus shadow lengths increase (for a given height of an object) with increasing range.

(2) Aerial photography does not require extensive electronic equipment.

(3) Photogrammetry is well known; radargrammetry is in its infancy.

(4) Aerial photos retain full stereo properties.

(5) Radar shadowing can enhance any portion of the terrain, with aerial photography one is limited by sun position.

(6) Sun angle and azimuth are continually changing; change of radar shadow length is constant, over about 50 degrees spread.

Aerial photos show some features that the radar does not, and one example is included as a frontispiece. However, the angle and azimuth of illumination of the two techniques, over this terrain, were not the same, and therefore the two images (radar vs. aerial photograph) should probably not be compared (see No. 5 above).

The paper fails to note some of the other advantages of radar over aerial photography (i.e., differences as to the all-weather capability). An example from flat terrain would have been useful.

The aerial-photography pseudo radar technique could be helpful for simulating radar topographic enhancement images prior to implementing a full scale project. (See also: CLARK. M.M., 1971.)

MacDONALD, H. C., P. A. BRENNAN, and L. F. DELLWIG, 1967

Geologic Evaluation by Radar of NASA Sedimentary Test Site

IEEE Transactions, Geoscience Electronics, Vol. GE. 5, No. 3, December, pp. 72–78.

Authors' Abstract: *Interdisciplinary research on the geoscience value of radar systems is being conducted by geoscientists and electrical engineers at the Center for Research in Engineering Science (CRES), University of Kansas, Lawrence. This paper presents a segment of the research in which the investigators studied similarities and contrasts between panchromatic aerial photography and radar imagery from the Cane Springs area in Arizona, for which precise surface geologic data are available. Lithologic and structural information is available on the radar imagery which is not as apparent on the air photography; however, the converse is also true. Interpretations also reveal the fundamental advantage of multisensor reconnaissance, in which several discrete parts of the electromagnetic spectrum are utilized. The resulting extrapolation of data can provide a valuable supplement to geological reconnaissance. (Abstract copyrighted by IEEE.)*

Surface roughness, expressed in wavelength units, can generally be measured on radar imagery to within an accuracy of wavelength/2 or wavelength/4 as the lower boundary. In this article accuracy is considered wavelength/10.

Use of VH radar polarization seems best for the definition of the lithologic boundaries. Vegetation in the study area was quite dry, thus having a low dielectric which, when combined with its scattered nature, gave essentially no radar return. The importance of the angle of incidence of the signal in relation to the nature of the back-scattering was noted, emphasizing that, should radar be the only data source available, this parameter could lead to grossly erroneous interpretations.

MacDONALD, H. C., 1969a

Remote Sensing Techniques in Petroleum Exploration

Presented at the 18th Annual Meeting, Rocky Mountain Section, American Association of Petroleum Geologists, Albuquerque, 23–26 February.

American Association of Petroleum Geologists, Bulletin, Vol. 53, No. 1, January, p. 216 (abstract only).

Author's Abstract: *In recent years, geological reconnaissance has been augmented by sophisticated terrain data-gathering techniques which have been categorized as remote sensors. Remote sensing, which can be defined simply as reconnaissance at a distance, is hardly a new concept. Remote sensing techniques utilizing the aerial camera or magnetometer are well known to the petroleum geologist. Several airborne devices are now available to supplement the aerial camera for the detection of natural resources, and a multisensor approach to terrane reconnaissance should allow exploitation of the entire electromagnetic spectrum. Ranging from the very short wavelengths at which gamma rays are emitted, to the comparatively long wavelengths at which radar operates, multisensor terrane data from the same area allow extrapolation of geologic information not available with a single sensor.*

Those remote sensing techniques that appear to have immediate potential for petroleum exploration include: (1) scanning infrared systems which detect thermal variations between adjacent features, (2) spectrophotography which permits simultaneous recording of narrow-band regions ranging from the visible to near-infrared, and (3) side-scanning radar systems which will operate in the microwave region of the spectrum. Imaging radar perhaps will be the sensor that captures the imagination of the exploration geologist because of the synoptic presentation of regional geologic structures and the penetration capability which has been forecast for long-wavelength systems. Although investigation of the geologic potential of this new family of remote sensors is in its infancy, it is apparent that no single sensor will provide a panacea for *petroleum exploration; however, these new data sources will certainly both complement and supplement existing geological reconnaissance methods. (Abstract copyrighted by AAPG.)*

MacDONALD. H. C., 1969b

Geologic Evaluation of Radar Imagery from Darien Province, Panama

Ph. D. Dissertation, Department of Geology, The University of Kansas, Lawrence, 141 pp. (NTIS No. AD 698 346).
(Also in: Modern Geology, Vol. 1, No. 1, November, pp. 1–63.)

Abstract: *The availability of extensive radar imagery covering approximately 17,000 square km in eastern Panama and northwestern Colombia has provided geologic data for an area where previous geological investigations have been extremely limited because of inaccessibility and perpetual cloud cover.* In previous radar-related geologic studies, most of the radar imagery was collected from areas within the continental United States where temperate climatic conditions prevail and where detailed geologic information was available. The radar imagery of eastern Panama, however, represents not only unique terrain information from the tropical environment but the first practical mapping application of side-looking radar systems.*

The primary objectives of this study were to (1) determine the utility of radar in the compilation of geological reconnaissance maps, (2) define and analyze radar-linears (joint systems and faults) and infer the nature of the tectonic forces responsible for certain types of local structures, (3) examine the effect of radar look-direction (direction orthogonal to ground track of the aircraft) and determine if there is a factor of directional dependency with radar systems, and (4) evaluate the potential of radar as a single geological reconnaissance tool in the tropical environment and what application these imaging systems may possess for future geological reconnaissance surveys in similar geographic areas.

As in aerial photographic interpretation, the analysis of tone, texture, shape, and pattern are recognition elements on radar imagery which contribute to the interpretation of geologic data. These recognition elements as well as the distortions inherent to radar imagery are evaluated in this study.

Analysis of single-strip radar imagery in combination with the radar mosaic have, for the first time, provided an accurate representation of the regional geologic relationships of eastern Panama and northwestern Colombia. A ready subdivision can generally be made between igneous and sedimentary rocks, and large scale structures can be synoptically studied enabling the geologist to become quickly familiar with the essential features of structural provinces. On a more detailed scale, a relative stratigraphic sequence can be determined if the lithic units are topographically expressed. Where collateral field data have been used in conjunction with radar imagery interpretation, the geologic information interpretable from the radar imagery of eastern Panama far exceeds those data previously available.

At the present time, radar remote sensing offers the only practical technique for geological reconnaissance mapping in the tropical environment, however, to obtain the maximum benefit from such studies in poorly mapped areas, it will be necessary to image a specific region from four orthogonal look-directions. Regardless of the inherent limitations of radar geological reconnaissance, the capability of obtaining topographic mapping data simultaneously with geologic information provides the geologist with an important exploration tool. (Abstract from. Dissertation Abstracts International Section B: Sciences and Engineering Vol. 30, No. 6, 1969, p. 2762-1B)

**Supported by Contract No DAAK 02-68-C-0089.*

MacDONALD, H. C. and L. F. DELLWIG, 1969

Geologic Interpretation of Radar Imagery from Eastern Panama and Northwest Colombia

Presented at the 82nd Annual Meeting, Geological Society of America, Atlantic City, 10–12 November.

Abstracts with Programs for 1969, Geological Society of America, Part 7, pp. 140–141 (abstract only).

Authors' Abstract: *The availability of extensive radar imagery covering approximately 17,000 square km, primarily in Darien Province, Panama, has provided geologic data for an area where previous geological investigations have been extremely meager because of limited accessibility and perpetual cloud cover. The radar imagery represents unique terrain information from this geographic area, and the first practical mapping application of a side-looking radar system.*

In the tropical environment, the interpretation of radar imagery provides a ready subdivision between igneous and sedimentary rocks, and large-scale structures can be synoptically studied enabling the geologist to become quickly familiar with the essential features of structural provinces. On a more detailed scale, a relative stratigraphic sequence can be determined using radar imagery, but only if the lithic units are expressed in the terrain configuration. Lithologic interpretation from radar imagery is largely provisional, unless corroborative data are available. However, the actual structural configuration, as well as the pattern of regional faults and joint systems, have never been revealed in such detail as those interpreted from the radar imagery. Analysis of single-strip imagery in combination with the radar mosaic have, for the first time, provided an accurate representation of the regional geologic relationships from this part of Central America.

In the tropical environment where conventional reconnaissance techniques cannot be utilized, radar remote sensing offers the only practical techniques for geological reconnaissance. (Copyrighted by GSA.)

MacDONALD, H. C., et al., 1969

The Influence of Radar Look-Direction on the Detection of Selected Geological Features

Proceedings, Sixth International Symposium on Remote Sensing of the Environment, Report No. 31069-2-X, Willow Run Laboratories of the Institute of Science and Technology, The University of Michigan, Ann Arbor, October, pp. 637–650.

Author's Abstract: *The synoptic presentation of side-looking radar systems in combination with an oblique angle of incident "illumination" has provided enhancement of certain topographically expressed geologic features (such as faults and lineaments) which were neither obvious nor interpretable on conventional aerial photography. Multiple imagery passes were not available for most areas previously studied, therefore, the capability for repeatedly recognizing these anomalous geologic features on multiple imaging passes and the influence of a preferred look-direction (direction orthogonal to the ground track of the aircraft) could not be investigated. The recent availability of multiple flight coverage from eastern Panama and northwestern Colombia, however, has provided sufficient data for a semi-quantitative look-direction analysis in which the detection of certain geologic features under a variety of terrain conditions has been examined. The geologic features selected for this study are faults, joint systems, and dip slopes.*

Specific examples from those few areas of the United States with multiple pass coverage are compared with the data obtained from the Panama imagery, and it is apparent that look-direction does influence the detectability of certain geologic features. Depending on the relative topographic relief, effective incidence angle, and look-direction, geologic features

can be advantageously enhanced or can be completely suppressed. Maximum data retrieval from radar geological reconnaissance in poorly mapped areas necessitates imaging the specific region from four orthogonal look-directions; nevertheless, single strip imagery can contribute significant information for geologic analysis.

MacDONALD, H. C. and A. J. LEWIS, 1969

Applications of Radar Imagery in Geologic and Geomorphic Reconnaissance of Tropical Environments

Presented at the Third Annual Meeting, South-Central Section, Geological Society of America, Lawrence, 27–29 March.

Geological Society of America, Abstracts with Programs for 1969, Part 2, pp. 18–19 (abstract only).

Authors' Abstract: *Unlike many remote sensing techniques, especially conventional optical sensors, radar can record terrain data irrespective of most weather conditions and totally independent of solar illumination. Radar imagery of eastern Panama and northwestern Colombia represents neoteric terrain information from a relatively unmapped region where conventional reconnaissance methods have been particularly unproductive due to perpetual cloud cover and limited accessibility. Interpretation of this terrain information for geologic and geomorphic analyses has allowed the definition of certain advantages and limitations when utilizing radar-derived data for geoscience investigations.*

Through the analysis of radar imagery the areal distribution of rock type and geometric orientation of structures can be inferred for the determination of structural provinces. Where contrasting lithologies are topographically expressed, stratigraphic sequences can also be inferred Radar imagery resembling a shaded-relief map provides an excellent tool for delimiting geomorphic regions. The added geologic and hydrologic information available from radar increases reliability of landform analysis; however, in certain tropical terrain environments, multiple imagery passes utilizing four different orthogonal look directions will be required to accurately define certain geologic and geomorphic parameters.

The geoscience data available on the radar imagery for eastern Panama and northwestern Colombia far exceed the terrain information previously available, and when supplemented by corroborative field reconnaissance data, radar remote sensing offers the only practical reconnaissance in cloud-shrouded inaccessible environments. (Copyrighted by GSA.)

MacDONALD, H. C. and W. P. WAITE, 1970

Optimum Radar Depression Angles for Geological Analysis

Technical Report No. 177-9, CRES, The University of Kansas, Lawrence, August, vi + 30 pp.

Authors' Abstract: *Side-looking imaging radars have proven to be a major sensor for geological reconnaissance studies in cloudy environments. Results have been sufficiently encouraging to support investigation of high-resolution radars as a spacecraft sensor for mapping and resource evaluation. For geological practicality, it is assumed that radar's most significant contribution would be in those geographic regions containing relatively inaccessible, poorly mapped, mountainous terrain where photography cannot be obtained. However, data analysis from this study reveals that for certain terrain configurations, the amount of retrievable geologic information will be of marginal utility unless careful consideration is given to the geometry of both the imaging system and the terrain itself.*

In low-relief areas, the oblique illumination and resultant shadowing by imaging radars can generally provide enhancement of topographically expressed geological features, but in mountainous terrain, radar shadowing can deter geological interpretation. Especially in rugged terrain, two inherent disadvantages of a radar imagery format which can hinder geologic interpretation are extensive shadowing and layover. Radar depression angle and terrain slope define the range over which shadow and layover will occur, but the extent of either parameter is defined by relative relief. For most operational side-looking radar systems, the interpretive data loss increases as terrain slopes exceed 35 degrees and local relief surpasses 1000 meters. Trade-offs between loss of geologic data due to radar shadow and layover, versus swath-coverage, have been evaluated. Similarly, the advantage of slight radar shadowing in low relief areas is considered Near- and far-range depression angles have been recommended according to five global terrain categories, and imaging altitudes are considered for both airborne and spaceborne platforms.

The authors give a very substantial discussion of the problems of radar layover and shadowing, complete with idealized diagrams and real examples of radar imagery. Several calculations relate incidence angle to percent of radar foreshortening for determining the operational parameters (relating swath width, depression angle and aircraft operating altitude). Two maps illustrating gross topography of the world are included, and suggested optimum depression angles for the five slope categories. Study of these maps indicates that depression angles in the range of 10 to 55^{o} will be suitable for covering the various slopes of the world's terrain with an optimum look angle from airborne radars.

MacDONALD, H. C. and W. P. WAITE, 1972

Remote Sensing Practicality: Radar Geology

Proceedings, Technical Papers, Electro-Optical Systems Design Conference, New York, 12-14 September, pp. 68-78.

Authors' Summary: *The geologist in the field was not replaced with the advent of the aerial photograph, but his job was made easier and his data became more understandable and meaningful. Similarly, it is not the intent of this paper to claim that radar is a panacea for geological reconnaissance, but simply to point out that the interpretation of radar imagery may contribute significant geologic data for reconnaissance surveys*

Unquestionably, radar will add information not obtained by other remote sensors, even when the weather is suitable for them. However, radar will prove to be the primary sensor for any survey that must be performed in a specified time, regardless of operational constraints.

In general, the unique contribution of radar is most likely to be at a maximum (1) in remote and poorly-mapped areas of the world, (2) where a regional rather than detailed picture is desirable and (3) where climatic conditions are adverse to ground and aerial photographic investigation. Certainly radar remote sensing offers the only practical technique for reconnaissance mapping in the wet tropics; however, where aerial photography can be obtained, radar imagery should be visualized as a supplement providing its own unique data contribution.

Realistically appraising the inherent limitations of radar geological reconnaissance, the capability of obtaining topographic mapping data simultaneously with geologic information provides the geologist with an important exploration tool.

Evidence accumulated to date suggests that multi-frequency, polypolarization radar systems mounted on orbiting spacecraft will usefully complement ground-based studies in tackling gross scale mapping problems. The full geological significance of side-looking radars has not yet been demonstrated; however, it seems certain that when new systems with longer *wavelengths and improved resolutions are developed, the geologist will find the value of radar greatly enhanced (Reprinted from Proceedings of the 1972 Electro-Optical Systems Design Conference. Copyright ©1972 by Industrial and Scientific Conference Management, Inc.)*

This paper is essentially a repeat of numerous other papers presented by the same authors. There is no attempt to quantify any of the statements and the entire paper is primarily a qualitative review of the authors' previous work. Some statements concerning vegetation penetration and ability of radar to detect soil moisture, are still speculative, as pointed out in the paper; but it appears to this reviewer that there is now the pressing need to go beyond the broad-brush picture and proceed with data quantification. The paper is introductory – of possible use for a first reading in radar geology.

MacDONALD, H. C. and R. S. WING, 1972

Petroleum Exploration with Radar – Eastern Panama and Northwestern Colombia

Presented at the 57th Annual Meeting, American Association of Petroleum Geologists 17–19 April, Denver (abstract only).

Authors' Abstract: *Petroleum exploration in eastern Panama and northwestern Colombia has gained impetus from recent sidelooking radar mapping. Radar-derived geologic information is now available for approximately 40,000 sq km where previous reconnaissance investigations have been extremely limited because of inaccessibility and perpetual cloud cover.*

With radar imagery as the sole source of remote sensing data, the distribution, continuity, and structural grain of key strata provide evidence that the eastern Panamanian Isthmus can be divided into 3 main physiographic-structural parts. Two composite coastal mountain ranges are separated by the Medial Basin which trends southeastward from the mouth of the Bayano River to the Atrato River valley of northwestern Colombia. Within the Medial Basin, the most obvious site for petroleum exploration, the majority of clearly exposed surface structures are not particularly attractive prospects because prime reservoir strata have been stripped from their crests. However, several large geomorphic anomalies which have been mapped in the Medial Basin may be reflections of subsurface structures having a complete stratigraphic section. The possibilities of gravity-type entrapment in fractured organic shales, siltstones, and carbonates have been suggested along the southern synclinal trends of the Medial Basin. The southwestward extension of the Medial Basin trend, coincident with unique beach ridges from a possible granite source, provides an attractive petroleum prospect in the western part of the Gulf of Panama. The occurrence of active shell bars in the Bay of San Miguel and present reef trends on the northern Caribbean coast suggest possible offshore sites for geophysical surveying. (Abstract copyrighted by AAPG.)

MacDONALD, H. C., 1973

Imaging Radar – Tool for Petroleum and Mineral Exploration

Presented at the 54th AAPG – 47th SEPM National Meetings, Anaheim, Calif., 14–16 May.

American Association of Petroleum Geologists, Bulletin, Vol. 57, No. 4, April, pp. 792 (abstract only).

Author's Abstract: *Remote sensing methods have great potential application in geologic exploration for fuel and mineral resources. Unfortunately, many of the more exotic*

remote-sensing techniques are still in research and development stages, and most surveys must be conducted in the framework of experimentation rather than routine operation. Sidelooking radar (SLAR) is one of the exceptions to this overall categorization SLAR systems, originally developed as all-weather military reconnaissance sensors, are providing extremely encouraging results in geologic exploration. Although the success of SLAR surveys has not been widely publicized, more than 6 million sq km of radar mapping has been completed during the past 3 years. Three commercial radar-mapping contractors have conducted geologic-reconnaissance surveys in some of the world's most inaccessible and remote terrain. Radar imagery is providing a first look at many cloud-shrouded regions in Brazil, Venezuela, Colombia, Panama, Nicaragua, Indonesia, and Australia.

The fine resolution of aerial photography is not presently available with imaging radars; however, they do offer the distinct advantages of a large swath of ground coverage (typically at least 20 km). This synoptic presentation allows the interpreter to become quickly familiar with the essential features of structural provinces Minimal scale distortion allows stereoscopic interpretation on imagery strips that can be enlarged to at least 10 times the acquisition scale. Radar-mosaic construction has provided sufficient base-map information to anticipate and evaluate logistic problems to be encountered during seismic operations or when reconnoitering a territory for favorable drilling sites Side-looking radar, like any tool, has limitations as well as capabilities for petroleum and mineral exploration. (Abstract copyrighted by AAPG.)

MacDONALD, H. C. and W. P. WAITE, 1973

Imaging Radars Provide Terrain Texture and Roughness Parameters in Semi-Arid Environments

Modern Geology, 1973. Vol. 4. pp. 145-158.

Also published in essentially the same form as: Terrain Roughness and Surface Materials Discrimination with SLAR in Arid Environments, Report 177-25, Center for Research in Engineering Sciences, Space Technology Laboratories, University of Kansas, Lawrence, Kansas, January, 37 pp.

Authors' Abstract: *Regions having a continuous vegetal canopy provide the radar interpreter with a relatively difficult terrain configuration for inferring surface roughness and surface materials. Where vegetation covers the ground surface, the radar return signal may be influenced by the combination of the vegetation and the terrain surface beneath the vegetation. Where vegetation is sparse or absent, however, an imaging radar becomes extremely sensitive to the actual surface roughness and surface particle size and texture dominate the microwave return signal*

The physical characteristics of desert valleys and playas are of concern to the geoscientist. Desert valleys are being exploited for their potential hydrologic-land use significance, while desert playas may provide potential aircraft or spacecraft landing sites. In this unique and environment the dual-sensor combination of an imaging radar and aerial photography provides a practical method of monitoring gross changes in surface textures of alluvial fans and playa surface conditions. In addition, it appears feasible that surface materials and relative surface roughness may be inferred with an improved degree of interpretive reliability.

This paper is divided into two major parts. Part I deals with the basic radar equations with respect to wavelength, incidence, angle, surface roughness and dielectric constant of the surface material. Part II is concerned with the interpretation of aerial photography and Ka-band radar imagery of desert environments, specifically alluvial fans and playa lakes. The study area was Winnemucca, Nevada, and the AN/APQ-97 radar provided the imagery. The authors note that, by using the radar data, it is possible to differentiate the younger (lighter toned) alluvial fans from the smoother and older fans. For areas of playa lakes, the aerial photo/radar combination provided especially good discrimination of the surface conditions. It is suggested that a controlled experiment be conducted to verify the results.

MacDONALD, H. C. and W. P. WAITE, 1977

Preliminary Geologic Evaluation of L-Band Radar Imagery – Arkansas Test Site. Final Report

University of Arkansas, Fayetteville, Arkansas, November, 28 pp. (NTIS N78-33644)

Authors' Abstract: *Radar imagery at 25-cm wavelength (L-band) was obtained over the Arkansas test site on November 4, 1976 and May 29, 1977. Preliminary geologic evaluation of the Jet Propulsion Laboratory L-band data included comparison with Landsat, Skylab, and other shorter wavelength radar imagery previously obtained over the test site.*

The relatively small angles of incidence (steep depression angles) of the L-band system provide minimal shadowing on terrain back-slopes and considerable foreshortening on terrain fore-slopes which sacrifice much of the topographic enhancement afforded by a more oblique angle of illumination. In addition, the dynamic range of the return from the vegetated surfaces is substantially less for the L-band system and many surface features defined primarily by subtle changes in vegetation are lost. In areas having terrain conditions similar to those of northern Arkansas, and where Landsat and shorter wavelength aircraft radar data are available, the value of the JPL L-band imagery (especially in the normal mode configuration as mounted on the NASA Convair CV 990) as either a complementary or supplementary geologic data source is not obvious If the L-band imagery provided for this preliminary evaluation is an example of what might be expected from space (SIR-A), then we anticipate a considerable degree of reluctance by the geologic community to accept radar as an improved geologic remote sensing technique

The Arkansas test site is in the Arkoma basin, an east-west trending synclinorium. A large portion of this paper deals with the general problems of radar interpretation, specifically imagery format, radar foreshortening, radar layover, and radar shadow.

The authors note, with respect to the L-band data, the following:

". . . lack of shadowing and consequent suppression of landform definitions is evident on the L-band imagery."

"Detection of drainage pattern other than major tributaries is especially difficult on the L-band imagery."

"If we assume that a similar product (to the L-band data) would be obtained from space and if Landsat, photographic and aircraft radar data are not available, then some geologic information can be extracted; however, the complementary or supplementary value in relation to other data sources is not obvious at this time."

With respect to polarization differences, only comments concerning vegetation are offered, that is, that the differences in forested terrain are not obvious and the polarization differences seem to be most sensitive to bare fields rather than cultivated fields. It is only in the summary that resolution is mentioned with respect to the several radar systems used for comparison. The paper is apparently incorrectly titled, for although the authors give a recitation of the geologic setting, they do not relate these geologic features to the radar data, and vice versa. Only a few general topographic features are actually described, and then in quite general and qualitative terms.

MALIN, M. C., D. EVANS, and C. ELACHI, 1978

Imaging Radar Observations of Askja Caldera, Iceland

Geophysical Research Letters, Vol. 5, No. 11, November, pp. 931–934

Authors' Abstract. *Surface roughness of nine radar backscatter units in the Askja Caldera region of Iceland was examined in computer-enhanced like- and cross-polarized radar images*

A field survey of the caldera was then used to check the accuracy of the preliminary analysis. There was good agreement between predicted surface roughness of backscatter units and surface roughness observed in the field. In some cases, variations could be correlated with previously mapped geologic units.

Using the L-band (25-cm) radar operated by the Jet Propulsion Laboratory, and the HH, HV data from that system, the authors determined the brightness (i.e., reflectivity) from image film and then ratioed the values (HH/HV) for nine units identified on the radar imagery. A short conceptual discussion of the scattering of radar energy from these units (Bragg and Rayleigh scattering) and general radar interpretation problems are included in the paper. A brief field visit confirmed that radar imagery, used in the way described, will be especially useful in distinguishing surface roughness of the several units. Some contribution to the radar energy reflectivity is attributed to two sources: moisture and wet lichens on the surface. The authors make two observations that have general application to radar interpretation. (a) smooth surfaces, regardless of their origin, can be identified, but the material causing that smooth surface (e.g., ash, sands, loess, gravels, etc.) cannot be distinguished, and (b) "That as long as radar interpreters do not attempt to draw from their radar images information beyond the capacity of radar systems and interpretative techniques to provide, radar appears to hold significant promise in certain remote sensing applications."

MARTIN–KAYE, P. H. A., 1973

Geology of Eastern and Central Nicaragua – Interpretation of Side-Looking Radar Imagery

Presented at the 54th AAPG–47th SEPM National Meetings, Anaheim, CA., 14–16 May.

American Association of Petroleum Geologists, Bulletin, Vol. 57, No. 4, April, pp. 792 (abstract only).

Author's Abstract: *In late 1971, the entire country of Nicaragua was surveyed by side-looking radar for the production of a 47-sheet sequence of 1 100,000-scale mosaics Interpretation of the imagery of the central highlands and eastward toward the Atlantic Coast has contributed substantially to the elucidation of the geology of this previously little-known region. Although little that is new has been added to the stratigraphic column. the distribution of the main stratigraphic units has been clarified, and the principal structural elements established. The work in Nicaragua is an additional example of the quality of side-looking radar for rapid regional geologic interpretation and consequent guidance of ground programs. (Abstract copyrighted by AAPG)*

MARTIN–KAYE, P. H. A., and A. K. WILLIAMS, 1973

Radargeologic Map of Eastern Nicaragua

Memorina de la IX Conferencia Inter-Guayanas, Boletin de Geologia, Publicacion Especial No. 6, Caracas, Venezuela, pp. 600–605.

Authors' Abstract: *The speed of side-look radar survey, independence from daylight and most weather conditions, together with the strength of imagery for interpretation, render the system particularly valuable for rapid regional studies of areas with persistent cloud overcast.*

In 1971 the Westinghouse Electric Corporation undertook a radar survey of the entire country of Nicaragua, the interpretation of approximately 2/3rds of the resulting 1 250,000 scale imagery in geologic and other terms was subsequently carried out by Hunting Geology and Geophysics. Ltd The study, covering about 80,000 square kilometers, forms part of Phase II of the two-phase country-wide survey programme of Catastro e Inventario de Recursos Naturales for the assessment of Nicaragua's land development and mineral potential. The Phase II project *area encompasses East, North and Central Nicaragua much of which is poorly accessible and has been geologically little known.*

The geological interpretation of the imagery, presented in a map sheet series at 1:100,000 scale to overlay radar mosaic sheets, was executed without ground check work and relied upon interpretational skill and the generally sparse existing data. There are limitations to detail and confidence in surveys of this nature but a very much improved geological map of the region has resulted. Of particular importance is the regional guidance that map can now provide to mineral exploration. A simplified compilation at 1:500,000 scale of this map is presented.

Nicaragua belongs partly to Nuclear Central America and partly to the South Central American Orogen. The country is made up of eight major structural units. (1) A Paleozoic Nucleus in the northwest consisting of schists, greywackes, conglomerates and limestones. (2) A Mesozoic platform in the north and centre consisting of limestones, shales, conglomerates and volcanics, overlain in part by relics of a Tertiary volcanic archipelago. The Paleozoic and Mesozoic are cut by a number of Laramide Granitic plutons. (3) A southern Volcanic Province, apparently largely of submarine volcanics and some Lower Tertiary sediments. (4) A Central Highland Transition zone between (2) and (3) above, of confused structure and overlapped partly by (5). (5) An Ignimbrite Province east of the Nicaragua Depression in the central parts of the country characterized by ignimbritic effusions. (6) The Atlantic Coastal Basins occupied by Tertiary sedimentary sequences. (7) The Nicaraguan Graben, marked by the Nicaraguan Depression. (8) The Pacific Coastlands and Sierras. All except (8) are represented in the Phase II Project Area. (1) and (2) belong to Nuclear Central America, the remainder to the South Central American Orogen or transition zones.

Faulting is on a large scale. Two main directions are recognized NW-SE to NNW-SSE, the Amerisque trend, and NE-SW to NNE-SSW, the Isabella trend, the latter being in part younger. A very large Amerisque fracture zone, the Matiguas Fault zone, traverses the country from Punta Mona on the Atlantic Coast to the Honduran border, continuing northwards for a total of about 500 km. Mineralisation appears mainly associated with faults of the Isabella trend.

A brief description of the geology and stratigraphy of Eastern Nicaragua is presented in this paper, but it is difficult to determine the exact role that was played by radar in the definition of these two items. The authors do note, however, that.

(1) Paleozoic metasediments "... are clearly recognisable on the radar imagery "

(2) "On the imagery these (Mesozoic) rocks can be easily identified by the parallel linear features exhibited by the bedded sequences; individual members are sometimes traceable over many kilometers."

(3) "Correlation (of Tertiary volcanics) with radar units is not practicable without ground check. On the radar map some sub-division of sediments considered as Tertiary is possible."

(4) "Young (Late Tertiary and Quaternary) sediments are widespread in the coastal and plain-land areas. Several units are readily separable on the imagery."

In their introduction, they note that "resolution improves with increase of wavelength." Also, it is noted that "The good resolution of the K-band brings greater susceptibility to interference by rainfall..." Both of these comments indicate some confusion between resolution and wavelength.

MATTHEWS, R. E., editor, 1975

Active Microwave Workshop Report

NASA SP—376, U.S. Government Printing Office, Washington, D.C., xii, 501 pp. (NTIS N76—11811).

No author's abstract.

Data from a conference on active microwave systems are summarized. Summaries cover remote sensing of earth/land features, ocean/atmosphere interaction and equipment and instrument technology. This volume is somewhat difficult to read due to the lack of any comprehensive index and because it was written by a number of individuals. Hence, when the various portions were blended together, some variance will be noted in notation, style, etc. Nonetheless, this report is one of the most up-to-date comprehensive statements on the state-of-the-art vis-a-vis imaging radar remote sensing as applied to earth resources.

McANERNEY, J. M., 1966

Terrain Interpretation from Radar Imagery

Proceedings, Fourth Symposium on Remote Sensing of Environment, Report No. 4864—11—X, Willow Run Laboratories of the Institute of Science and Technology, The University of Michigan, Ann Arbor, pp. 731—750 (NTIS No. AD 638 919).

Author's Abstract: *The interpretation of physiographic and cultural terrain features from imagery obtained with high resolution, side-looking radar alone is demonstrated. Two areas in the central United States are used as examples. Through a deductive process similar to that used in interpretation of visual aerial photography, it is shown that a trained interpreter can describe the physiography, geology and soil of a land surface and provide a reasonable assessment of the geography of a populated region. The discussion includes an example of measuring terrain relief from radar shadows.*

Two sets of images, sketch maps, and aerial photos are shown to illustrate some basic concepts and procedures for radar image interpretation. Although the ground truth was done several years after the images were taken, the interpretations, dealing with major cultural and physiographic features, remain valid. In one of the study cases, 2 in. of snow covered the ground, but is not readily apparent in the images. The radar used was an AN/APQ-56 operating in the Ku-band.

McCAULEY, J. R., 1972a

Surface Configuration as an Explanation for Lithology-Related Cross Polarized Radar Image Anomalies

4th Annual Earth Resources Program Review, Vol. 2, University Programs, NASA, MSC, Houston, January, pp. 36—1 to 36—9 (NTIS No. N72-29327).

From Author's Introduction *With the development of multipolarized side-looking radar systems, it became possible to record two orthogonal components of the backscattered radiation in the form of two congruent and simultaneously produced radar images, a like-polarized image, either HH or VV, and a corresponding cross-polarized image, HV or VH. Study of Westinghouse AN/APQ-97 Ka-band multipolarized imagery acquired in 1965 and 1966 as part of the Earth Resources Program has uncovered various targets that appear differently on the like- and cross-polarized images One group of polarization anomalies has concerned geologists for some time, namely the significantly lower cross-polarized returns produced by certain volcanic rocks*

The author's conclusions state that three rock types produce radar images characterized by bright like-polarized returns and dark cross-polarized returns: (1) geologically recent blocky lavas, (2) some Tertiary volcanics, and (3) certain massive sandstones. Outcrops of these three share certain features:

(1) Large planar rock surfaces in comparison with the wavelength of the incident radar are abundant, and detrital material and vegetation are of secondary importance.

(2) The planar surfaces appear to contribute significantly to the returning radar energy with this energy maintaining a constant polarization.

(3) The outcrop areas are of sufficient size and sufficiently uniform character to be delineated on small scale K-band imagery.

Cross-polarization may become more important in the design and utilization of future radar systems.

McCAULEY, J. R., 1972b

An Evaluation of Radar Imagery in Areas of Alpine Glaciation

Presented at the Sixth Annual Meeting of the South-Central Section of the Geological Society of America, Manhattan, Kansas, 6–8 April.

Abstracts with Programs, Geological Society of America, Vol. 4, No. 4, February, p. 285 (abstract only).

Author's Abstract: *Side-looking radar's oblique illumination affords a terrain display that enhances many of the landforms resulting from alpine glaciation. Imagery of the San Juan Mountains of Colorado, the Sierra Nevada of California, and the Yellowstone-Jackson Hole region of Wyoming was used in the evaluation. Cirques, aretes, glacial troughs, hanging valleys, roche moutonnees and other erosive effects of alpine glaciation are all displayed on the imagery, as are depositional landforms including lateral and terminal moraines, outwash plains, and knob and kettle topography. Although shadowing in the far range is found to be excessive in some areas of high relief, this same shadowing feature of side-looking radar is shown to be beneficial in delineating features of subtle topographic expression such as low morainal ridges. Long linear grooves of up to three miles in length resulting from differential glacial erosion are also vividly displayed in one area of study. Although the large scale of the imagery discourages detailed studies, it aids those of a regional nature. Differential glacial erosion due to variations in local climate is expressed in imagery spanning the crest of the Sierras, and large scale imagery of the Jackson Hole area allows the inference of glacial history. In addition, radar imagery shows potential for inter-regional studies (Copyrighted by GSA.)*

MOORE, R. K. and L. F. DELLWIG, 1966

Terrain Discrimination by Radar Image Polarization Comparison

IEEE, Proceedings, Vol. 54, No. 9, September, pp. 1213–1214.

No Authors' Abstract.

An AN/APQ-97 radar (U.S. Army Electronics Command/Westinghouse) was used to obtain like- and cross-polarized (HV, HH) imagery of the Pisgah Crater NASA test site. Alluvial fans and lava flows are easily defined on HV imagery, demonstrating the importance of simultaneous like- and cross-polarized imagery for geologic interpretation.

MOTOROLA AERIAL REMOTE SENSING, INC., 1976

An Application of Side-Looking Airborne Radar for Surveying Geology and Natural Resources Potential

Motorola, Inc., Phoenix, Arizona, August, 26 pp.

Introduction: *This brochure specifically outlines the application of side-looking airborne radar in resources inventory, land utilization and geologic studies. The equipment and techniques explained have recently become available commercially for resource surveys and related work through Motorola Aerial Remote Sensing, Inc.*

The survey involves three basic operational phases as follows:

1) *Data Gathering — A side-looking airborne radar survey of the total geographic area of interest;*
2) *Data Processing — Preparation of radar imagery strips and radar mosaics covering standard 1:250,000 topographic map sheets; and*
3) *Data Interpretation — Maps providing an initial geological interpretation of the survey data to the extent needed to provide basic geologic and resource classification.*

These phases are more thoroughly discussed and illustrated in following sections of this brochure.

NATIONAL RESEARCH COUNCIL, 1977

Microwave Remote Sensing from Space for Earth Resource Surveys

Committee on Remote Sensing Programs for Earth Resources Surveys, National Academy of Sciences, Washington, D.C., October, ix, 139 pp. + figs., tables, refs.

No Author's Abstract.

This report is a review, by the Committee on Remote Sensing Programs for Earth Resources Surveys, of a NASA sponsored Microwave Remote Sensing Program Five Year Technical Plan, 1977—1982. It is an especially interesting document because it presents a rather candid and possibly controversial review of the NASA proposals. Basically, the Committee supports passive microwave for soil moisture and salinity studies and single polarization radars for geological studies. The arguments and data used by the Committee are included in the report. Thus, this report provides quite interesting reading with respect to the decisions that are being made concerning microwave remote sensing from satellites.

NORMAN, J. W., 1972

Geological Applications of Side-Looking Radar

Side-looking Radar Systems and Their Potential Applications to Earth Resource Surveys, Vol. 3, Potential Applications of SLR to Remote Sensing of Earth Resources. Elliot Automation Space and Advanced Military Systems, Comberley, England. Ref. No. 5795, July, vi + 135 pp. + app., pp. 64–84 (NTIS No. N73–12401, N73–12406).

No Author's Abstract.

As with the other papers in this series (EASAMS, 1972c), the introductory section consists of a brief review of the background of the discipline of geology. The nature of various rock types and surface structures (desert pavements, soil properties, faults, fractures, etc.) of interest to geologists is treated. The present status of SLR for securing geological information is presented, with examples of the type of information devices. (These are not repeated here because the references supplied by the author have been amply expanded elsewhere in this bibliography.) Some potential applications of SLR for geologic work are mentioned, including general geologic mapping (1:100,000 or smaller), fracture trace analysis, possible damage assessment following earthquake and volcano disasters, soil moisture, and snow monitoring. It is suggested that more study is needed on the ability of radar to penetrate tree canopies and soil, and also in microrelief studies.

Recommendations for an experimental program emphasize that the decision to continue support should depend on: (a) instrument performance, (b) testing of instrument under field conditions, (c) training a cadre of interpreters and (d) development of data processing techniques. A program for each of these topics is briefly outlined in the paper. It is also suggested that spectral signatures are likely to yield more reliable results than do pattern recognition techniques. Ground parameters to be studied are presented, with a list of six proposed large test sites. The author concludes with several statements comparing SLR to other sensor data (e.g., aerial photographs) and presents the balanced view, that (a) although SLR instrumentation will be perfected, so will other sensors; (b) SLR has a wider dynamic range and, if the data are placed directly on magnetic tape, it will be of great use; and (c) an interpretation bottleneck may develop, both in terms of human and machine interpretation. A 16-item bibliography is included.

ORR, D. G. and J. R. QUICK, 1971

Construction Materials in Delta Areas

Photogrammetric Engineering, Vol. 37, No. 4, April, pp. 337–351.

Authors' Abstract. *Procedures for identifying likely sources of materials for engineering construction with multi-spectral remote sensor are applied to a part of the Mississippi Delta. Sensors included panchromaticolor and color-infrared photographs, thermal-infrared imagery, radar, nine-channel multispectral scan imagery, and small-scale photo-index mosaics Ground truth was acquired concurrently with the remote sensor overflights, it included soil moisture, soil temperature, wind velocity, ground photographs and soil samples A two-phase procedure involved a regional analysis followed by a detailed analysis. The APQ-97 was the most versatile radar system for regional analysis Color infrared photographs were preferred in most instances for detailed analysis in the delta environment Thermal-infrared imagery provided useful information where it was applied in conjunction with photographs. The highest potential sources of construction materials in this area were within the cheniers, point bars, river bars and active beaches (Copyrighted by the American Society of Photogrammetry.)*

Three radar systems (APQ-102, APQ-97, and APS-94) were used; the second gives excellent results for both the location of terraces and abandoned channels.

PAGE, R. M., 1962

The Early History of Radar

Proceedings, IRE, Vol. 50, No. 5, May, pp. 1232–1236.

Author's Summary: *Five basic ideas are identified, the combination of which constitutes radar. A clear distinction is then made between this combination of ideas, the contemporary technology from which it grew, and the contemporary scientific knowledge on which it was based. The mainstream of the development of radar is traced in a sequence of related events from 1922 to 1941. The technological problems encountered and the solutions employed in the first radar development are outlined in some detail. Two sidestreams of radar development are identified. Relationships among the three streams are discussed*

The five basic ideas constituting radar are:

(1) Detection and location of remote reflecting objects by means of electro-magnetic radiation at high radio frequencies.

(2) Radiation in pulses separated by 'silent' intervals.

(3) Detection and display of returned pulses.

(4) Measurement of pulse travel distance (transmission and return) by means of an independent time standard.

(5) Direction determination with a highly directive radio antenna.

PAGE, L. R., 1969

Geologic Analysis of the X-Band Radar Mosaic of Massachusetts

Second Annual Earth Resources Aircraft Program Status Review, Vol. 1, pp. 4–1 to 4–19.

Author's Abstract: *The X-band radar mosaic of Massachusetts, at a scale of 1 500,000 made by the Grumman Aircraft Engineering Corporation under contract for the U S. Geological Survey in cooperation with the U.S. Army and National Aeronautics and Space Administration, presents an overall view of the geologic and geographic features of the state.*

Lineament patterns allow recognition of major structural features that can be related by geologists familiar with local areas to faults, joints, folds, and stratigraphy of the bedrock and drumlins, fans, and channels of Pleistocene deposits.

More refinement of the method is needed to obtain uniform quality of imagery, correctness of scale, and appropriate orientation of flight lines for maximum use in unknown terrain (From. Dellwig, et al., 1975.)

The synoptic coverage afforded by the Massachusetts radar mosaic would have enabled the mapping program to focus on the best areas to begin mapping if a mosaic had been available at the outset. Problems confronting interpreters included (1) imagery scale variations, (2) a lack of understanding of variations in reflectivity and (3) identification of linear features normal to flight lines.

PARRY, J. T., 1973

The Role of AN/APS-94D X-Band SLAR In Terrain Analysis

Defense Research Board of Canada, Ottawa, Ontario, Canada (Contract SP2-7090163, Serial 2SP3-0024), November, 128 pp., figs., refs., tables.

From the Author's Conclusions: *Radar may be considered as a unique sensor with the following specific advantages and shortcomings with regard to terrain analysis:*

a) *rapid data acquisition and a synoptic view of the terrain;*

b) *synoptic capability extended through the production of mosaics, but this is more difficult with slant range than ground range format data;*

c) *constant illumination angle for the entire swath of radar data;*

d) *accentuation of topographic detail due to oblique look angle;*

e) *radar shadowing emphasizes directional trends of the topography;*

f) *radar shadow data show high correlation with local relief if the random azimuth method is used;*

g) *more textural detail is available from radar than from other types of imagery at equivalent scales;*

h) *radar most effective in definition of water bodies for a summer scene;*
radar is less effective at definition of drainage patterns especially for first and second order streams;

i) *soil and rock types are identified by inference only;*

j) *typically strong returns are received from man-made features.*

The radar used in this study was the AN/APS-94D (X-band) real aperture system. The study area was the Rouge River area northwest of Montreal, Quebec, Canada. Data were collected on 08FEB72 and on 04JUL72. Two rather lengthy tutorial statements concerning SLAR principles and the general principles of radargram interpretation are included and these are followed by specific examples of the study area with respect to urban and terrain features. Specifically, it is noted that as the range of the radar increases, the density of the film recordings increases to a point where the depression angle is approximately 10 degrees. At that point, the density curve reverses. This is true for water bodies in the study area. A small study was conducted to determine if water bodies could be differentiated from shadow on a basis of film density, and it was determined that this can indeed be done. A morphology study (i.e., terrain relief) was conducted — see conclusion "f" above. There may be a slight overstatement in that the conclusions should be regarded as applicable to the particular radar set used. This is especially true with respect to resolution — i.e., the comments would not be applicable to a synthetic aperture radar (falling off of resolution with range).

PARRY, J. T., 1974

X-Band Radar in Terrain Analysis Under Summer and Winter Conditions

Proceedings, Second Canadian Symposium on Remote Sensing. Guelph, Ontario. Apr. 1974, pp. 471–485.

Author's Abstract: *When considered as a remote sensing system for terrain reconnaissance, radar has many advantages. The outstanding features of SLAR systems are their wide angle coverage, the capability of imaging in darkness and poor visibility, the enhancement of topographic features as a result of oblique illumination, and the provision of information regarding terrain roughness and local relief in the texture and shadow of the radar image. Motorola AN/APS-94D, X-band radar was used in this study with imagery obtained along a 65 km transect in the Laurentians between the Ottawa valley and Mt. Trembland Park in both summer and winter conditions. All aspects of terrain were examined including surface composition vegetation and snow cover, and surface morphology. Densitometric techniques were used to examine the differences in radar backscattering between the various surface and cover types, to assess the effects of depression angle on the image tones, and to discriminate between water bodies and radar shadows Radar tone and texture were shown to be related to differences in vegetation structure. The role of radar imagery in providing a basis for terrain type mapping was demonstrated and a technique elaborated for using radar shadows in the analysis of local relief.*

The author of this paper has addressed himself to several of the features that are commonly studied by geomorphologists. Although the study was based upon two sets of imagery collected from the same location at two seasons, and therefore possibly not representative of other terrain situations, it is a well organized and presented study and provides guidance for others working in the discipline. It is noted that geologic structure (but not lithology), 3rd order streams and larger, and general vegetation types are detectable. A very interesting discussion concerning the distinction between water bodies and shadows (generally the former are slightly brighter) is presented and deserves close study. Although little that is genuinely new to the general study of radar imagery (termed radargrams in this paper), it is one of the few published papers (to this date) that presents explorations of quantitative geomorphology and terrain analysis from radar image data.

PASCUCCI, R. F., 1971

Comparative Contribution of Three Sensors to the Remote Sensing of Geologic Environment

Paper presented at 37th Annual Meeting of the American Society of Photogrammetry, 7–12 March.

Photogrammetric Engineering, Vol. 37, No. 5, May, p. 491 (abstract only).

Author's Abstract: *In order to determine the relative and unique contributions to the mapping of geologic environment that could be made by three of the most promising non-photographic, remote, airborne sensors, two test areas in California were overflown, one in the western foothills of the Sierra Nevadas and the other on the eastern flank of the Coastal Range. The sensors used were an APQ-97 side-looking radar, an AAS-10 thermal infrared line-scanning system, and two passive microwave radiometers operating at 30.2 and 10.0 GHz. Interpretation of the sensor data thus acquired, and comparison of these data with the available "ground truth" maps of the area, revealed that the side-looking radar was superior to the others both in geologic content and interpretational accuracy. The thermal infrared was found to contain less useful geologic data, of which some was redundant and much was liable to spurious interpretation. However, it was also found that the infrared, by sensing in a different parametric regime, detected features that the radar did not, suggesting that the infrared can be a valuable adjunct to side-looking radar in a multiple sensor geologic survey.*

It could not be satisfactorily demonstrated that the passive microwave radiometers provided any useful geologic data at all. (Copyrighted by the American Society of Photogrammetry.)

PETERSON, R.M., 1969

Observations on the Geomorphology and Land Use of Part of the Wasatch Range, Utah

The Utility of Radar and Other Remote Sensors in Thematic Land Use Mapping from Spacecraft: Annual Report, Edited by D. S. Simonett, U.S. Geological Survey Interagency Report - NASA-140, iv + 113 pp., pp. 75–113 (NTIS No. N69-16255).

From Author's Introduction: *This paper is an analysis of radar imagery of a region near Salt Lake City, Utah. K-band radar of an area 12 miles wide and 30 miles long was examined to document its potential for obtaining information on physiography, surface material, geomorphic history, mineralized areas, drainage, land use, and transportation*

Both HH and HV polarizations of the AN/APQ-97 radar were examined with the naked eye and with a 5-power microscope. 2X prints of the radar imagery were also used in the study.

Thorough study of the radar imagery resulted in a wealth of information, much of which is new and not in reports or maps of the area. Examples are some ancestral stream patterns with resultant information on the origin of the Wasatch Range, fracture zones, and possibly undiscovered mineralized areas

After a study of the radar, information obtained from the imagery was compared with data on topographic maps, geologic maps, and 1:63,360-scale aerial photomosaics It is significant that even though the scale of the radar imagery is only approximately 1:160,000, it was necessary to consult maps of 1:24,000 scale to observe some of the same features. In some cases comparison of first-round radar data with published data gave clues to more features to search for on radar imagery and resulted in new discoveries. Examples are two previously unreported major fracture zones and a joint set that appear to control location of mineral deposits in the Park City area.

The following items are noted as being identified on the radar imagery: stream canyons cutting the Wasatch front, nucleated farm settlements, the relationship between well drained land and villages and farm locations, clusters of cottages and mine buildings, stream terraces, Lake Bonneville terraces, drainage patterns (both modern and ancestral), moraines and other features of alpine glaciation, geologic structure, mine dumps (especially when HH and HV imagery are compared). The author states that "radar imagery appears to have value as a tool in studying genetic landscape evolution and for quantitative geomorphic classification" and presents a physiographic map of the area derived from the available radar imagery. Eight separate thematic maps were prepared from the imagery, including transportation, surface materials, landform classification, present drainage, ancestral drainage and physiography [p. 102]. Of these, seven are included in the paper. The paper is, in general, an excellent and concise presentation of the potentials of radar for geomorphology and land use data gathering. It should be more widely circulated to serious researchers.

POWERS, R. E., 1972

Side-Look Radar Provides a New Tool for Topographic and Geological Surveys

Westinghouse Engineer, Vol. 32, No. 6, November, pp. 176–181.

No Author's Abstract.

This introductory paper presents the basic concepts of using SLR for earth resource studies. Following a brief discussion of the geometry of radar imaging – including the aircraft flight line, ground track, antenna orientation and CRT trace modulation and adjustment – the author discusses some successes of SLR mapping programs. Specifically mentioned are mapping efforts in Brazil, Indonesia, Nicaragua, and Ecuador. Although short wavelength radar is not considered to be able to penetrate vegetation, the vegetation in the dense jungle closely follows terrain and is further enhanced by geologic, soil, and moisture diversities. Thus, by analogy, the surface relief can be determined and inferences can be made as to the mineral and petroleum potential of the study area. This method of exploration, using the Westinghouse APQ-97 radar, has had some large successes. Agricultural use of radar for crop identification is briefly mentioned. Future suggested tasks for SLR include a study of rectification of imagery to meet standards for topographic mapping accuracy, and signature studies to facilitate automated data processing. The author concludes: "Of all the relatively new remote sensors in use (IR scanners, radiometers, scatterometers, etc.) side-look radar has been the most useful and most successfully applied tool for earth resource development."

PROSTKA, H. J., 1970

Geologic Interpretation of a Radar Mosaic of Yellowstone National Park

Inter-Agency Report NASA-179, U.S. Geological Survey, Washington, D.C. (NASA-CR-121425; NTIS: N71-33185), 16 pp.

Author's Abstract: *A radar mosaic of the Yellowstone National Park area depicts the topographic and surface textural features of five major rock units and structural features well enough that a fairly accurate generalized geologic map could be drawn. Correct rock units are shown in 70 percent of the area of this interpretive map. Interpretive errors result in the areas where diagnostic features are masked by surficial deposits or have been modified by glacial scour or young faults. (From: Dellwig, et al., 1975.)*

Radar imagery is primarily useful for detection of geologic elements with distinctive topographic expression or unique surface texture which are not masked by surficial deposits.

RATHEON COMPANY, 1973

Advanced Radar Topographic Application

Raytheon Co., Equipment Division, Autometric Operation, Arlington, Virginia, (FR-72-1478) for: U.S. Army Engineer Topographic Laboratories, Ft. Belvoir, Virginia, (ETL-CR-73-2), February, v, 52 pp. + app. (Contract No. DACA-76-72-C-0003) (NTIS AD-908-394).

Authors' Summary: *The technical objective of this study was to determine the capability of a Reconnaissance Radar System and Topo II Radar System for application to point positioning, map revision, and gap filling.*

The investigation was essentially a test to determine how accurately target images, appearing on a reconnaissance radar record, can be transferred to a data base. No a priori knowledge of either the radar equipment or the flight parameters was assumed. The work included a study to determine the behavior of error propagation across the radar format based on a preassumed radar transformation, errors in radar imagery measurements, and errors in control point coordinates. Photo, radar, and map data bases were employed in the investigation.

A small part of the study was the examining of radar records for ground detail normally shown on maps. A 21-parameter transformation program, fully documented, is a deliverable item.

It was concluded that the Reconnaissance radar geometry is sufficiently stable and has adequate resolution for 1.50,000 scale map revision, both for positioning and map detail. A photo base provides the best graphic for transferring points from radar records The "calibration" of a radar record, by determining transformation parameters over a control area, appears feasible.

It was recommended that actual tests be conducted to determine the map content and accuracy of placement that can be realized, using the Reconnaissance or Topo II radar imagery, for map revision and gap filling.

Authors' Conclusions:

1. Most of the total error in transforming points comes from misidentification of conjugate points;
2. Photo base is superior to map base for use with SLAR;
3. Only a limited number of points are needed (about 6);
4. Local transformations are preferred to extended area transformations;
5. B&L Zoom Transfer Scope is only of limited usefulness;
6. Geometrical accuracy and ground resolution of reconnaissance radar are adequate for use at scales of 1:50,000 or smaller;
7. Stated ground resolution of reconnaissance radar is misleading for the type of detail of interest to mapping or for ground control points;
8. The "calibration" of a radar record by determining transformation parameters over a control area appears feasible.

The term "calibration" as used in this report refers to the use of the same parameters for an entire mission, with the minimum of additional ground control. Two appendices (Radar-Ground Transformation and Operation Manual for Radar-Ground Transformation Program) are included. Several comments with respect to the identification of cultural and terrain features on the radar imagery are given. The radar systems used in this project were the Reconnaissance Radar System and a slightly modified AN/APQ-102 (XA-2) radar system designated as the AN/APQ-152.

REEVES, R. G. and A. N. KOVER, 1966

Radar From Orbit for Geologic Studies

Presented at the 32nd Annual Meeting of the American Society of Photogrammetry, Washington, D.C., 6–11 March.

Photogrammetric Engineering, Vol. 32, No. 5, September, pp. 889 (abstract only).

Authors' Abstract: *Radar systems for orbital missions, earth and lunar, are being developed. The system for the initial earth-and-lunar missions consists of a two-frequency (0.4 and 8 gigacycle) altimeter-scatterometer and 8 gc polypolarization imager. A more advanced multifrequency (0 5, 2, and 8 gc) polypolarization imager, with color display and other image enhancement techniques, is proposed.*

To establish the feasibility of radar as a tool for geologic studies, and to develop techniques for its use, radar scatterometer data and imagery have been obtained from aircraft flights. Preliminary results suggest that radar data are useful for structural geological analysis, for distinguishing among gross lithologic units, and for distinguishing between various rock surfaces such as those of aa and pahoehoe lava flows. Faults, poorly recognizable on conventional aerial photographs, are often seen clearly on radar images. As the amount of soil moisture greatly influences signal return, radar should be a useful tool for hydrologic studies. Geomorphic features are accentuated by low angle illumination in side-looking radar. (Copyrighted by the American Society of Photogrammetry.)

REEVES, R. G., 1968a

Use of Radar Imagery for Structural Geologic Studies

Presented at the Annual Meeting, Northeastern Section, Geological Society of America, Washington, 15–17 February.

Geological Society of America, Special Paper 121, Abstracts for 1968, Boulder, p. 369 (abstract only).

Author's Abstract: *Certain structural geologic features may be more readily recognized on side-looking (airborne) radar (SLAR) imagery than on conventional aerial photography or other remote sensor imagery, or by ground observations. SLAR systems look obliquely to one or both sides. The image resembles oblique aerial photography taken at low sun angle, with the sun directly behind the camera, but differs from it in geometry, resolution, and information content. Radar operates at much lower frequencies than the human eye, camera, or infrared sensors, and thus "sees" differently. The lower frequency enables it to penetrate most clouds and some precipitation, and limited surficial cover. Radar provides its own illumination which can be closely controlled in intensity and frequency. It is narrow band, or essentially monochromatic.*

Low relief and subdued features are accentuated when viewed from the proper direction. Two different runs over the same area in the vicinity of Meteor Crater, Arizona, at 90 degrees from each other, show that images taken in one direction emphasize features that are not emphasized on those taken in the other direction; optimum direction is determined by the features desired to be emphasized for the purpose of the study.

Folded sedimentary rocks cut by faults can be clearly seen on radar imagery of northern Alabama and central Pennsylvania. Lineaments interpreted as faults stand out on radar imagery of central and western Nevada. In these areas, certain structural and stratigraphic features are more pronounced on the radar imagery than on conventional photography, and the radar imagery materially aids structural interpretation. (Copyrighted by GSA.)

REEVES, R. G., 1968b

Structural Geologic Interpretation from Radar Imagery

U.S. Geological Survey Open File Report – NASA-102, Washington, D.C., 14 pp. + figs. (NTIS No. N69 13927).

Author's Abstract: *Certain structural geologic features may be more readily recognized on side-looking airborne radar (SLAR) imagery than on conventional aerial photography or other remote sensor imagery or by ground observations. SLAR systems look obliquely to one or both sides. SLAR images resemble aerial photographs taken at low sun angle, with the sun directly behind the camera, but differ from them in geometry, resolution, and* *information content. Radar operates at much lower frequencies than the human eye and camera or infrared sensors, and thus "sees" differently. The lower frequency enables it to penetrate most clouds and some precipitation, haze and dust, and some vegetation. Radar provides its own illumination which can be closely controlled in intensity and frequency. It is narrow band, or essentially monochromatic.*

Low relief and subdued features are accentuated when viewed from the proper direction. Runs over the same area, at significantly different directions (more than 45 degrees) from each other, show that images taken in one direction may emphasize features that are not emphasized on those taken in the other direction; optimum direction is determined by the features desired to be emphasized for the purpose of the study.

Lineaments interpreted as faults stand out on radar imagery of central and western Nevada. Folded sedimentary rocks cut by faults can be clearly seen on radar imagery of northern Alabama. In these areas, certain structural and stratigraphic features are more pronounced on the radar imagery than on conventional photography, and the radar imagery materially aids structural interpretation.

Several radar images together with geologic interpretation illustrate this paper. Major interpretations appear for linear features (e.g., faults, axis of folds), and some consideration is given to the identification of alluvial fans and fine-grained valley fill materials.

Radar wavelength is not identified. Both like- and cross-polarized images are included in the illustrations.

REEVES, R. G., 1968c

Radar Geology

McGraw-Hill Yearbook of Science and Technology, McGraw-Hill, Inc., N.Y., pp. 322–328.

No Author's Abstract.

This general, but comprehensive, article describes the operation and usefulness of radar systems. Both PPI and SLAR systems are discussed. Several images, with annotations, are included in this paper. Recommended for introductory readings.

REEVES, R. G., 1969

Structural Geologic Interpretations from Radar Imagery

Geological Society of America Bulletin, Vol. 80, No. 11, November, pp. 2159–2164 (see also: Reeves, R. G., 1968b).

No Author's Abstract.

A good general discussion of radar and target parameters and their influence on the resulting image. Several plates are included but suffer excessive layover and distortion (approximately 10 percent loss) because aircraft flight lines were non-linear. "Chief value of radar imagery . . . is that it calls attention to anomalous features which merit further investigations and identification," according to the authors.

REEVES, R. G., 1972

Geologic Analysis of Remote Sensor Data, Bonanza Project

57th Annual Meeting, American Association of Petroleum Geologists, Denver, 17–19 April.

American Association of Petroleum Geologists, Vol. 56, No. 3, March, p. 647 (abstract only)

Author's Abstract: *The NASA-supported Bonanza Project of the Colorado School of Mines and Martin Marietta Corporation has as its principal objectives (1) education in the geologic applications of remote sensing, (2) development of techniques for the geologic interpretation of remote sensor data, and (3) specification of the most useful parts of the electromagnetic spectrum for geologic remote sensing. The ultimate goal is to provide a test site over which to calibrate spaceborne remote sensors and from which to extrapolate interpretations of remote sensor data into surrounding areas. Research to accomplish these objectives is carried out in the field in the Bonanza test site (an area of approximately 10,000 sq mi in west-central Colorado) and in laboratories at CSM and MMC. Airborne remote sensor data, including aerial photography, infrared imagery and radiometric data, microwave radiometric data, and radar imagery and scatterometric data are acquired (by NASA) and interpreted. Detailed ground measurements are made during overflights, and extensive ground investigations to assist in the interpretation of the airborne data have been carried out. Measurements include surface and subsurface temperatures, soil moisture, atmospheric characteristics, and incoming solar radiation. Ground investigations include detailed geologic mapping, studies of physical properties of rocks and soils, spectral reflectances of natural materials, and relation of vegetation of geology. To date, the research has added to structural and stratigraphic knowledge of the Sangre de Cristo and Sawatch Ranges and San Luis and upper Arkansas valleys, and to knowledge of structure, rocks, and geologic history of the Bonanza volcanic field. (Abstract copyrighted by AAPG.)*

RIB, H. T., 1967

An Optimum Multisensor Approach for Detailed Engineering Soils Mapping

Ph. D., Dissertation, Department of Civil Engineering, Purdue University, West Lafayette, 449 pp.

Author's Abstract: *This research study investigated the potential of available types of remote sensing systems for the evaluation of soils and soil conditions for the purpose of developing an optimum multisensor approach for detailed engineering soils mapping. Other objectives of the study were: (1) to investigate the value of quantitative measurements on aerial photography and imagery for assistance in interpretation; and (2) to perform a limited study to determine which parameters would be of value to measure at the time of flights.*

Three test sites were selected which contained a variety of land forms and soil units. A total of nine flight programs were obtained over the test sites during the period from May 1965 to June 1966. Coverage was obtained with various types of aerial films (color, color-infrared, color negative, black-and-white panchromatic and black-and-white infrared), a multiband camera, a radar sensor (K-band), infrared sensors (far infrared), and a multichannel sensor (ultraviolet through far infrared). All of these types were not obtained in any one flight program, but generally several combinations were obtained at one time. Daytime and nighttime imagery were also obtained during one flight.

The field investigations included field radiometer readings (taken during last two flight programs), soil moisture content measurements, and resistivity surveys. Ground photographs were taken during aerial flights to record the conditions existing at flight time. Meteorological data were also collected during flights. The resistivity surveys were performed to add to the existing information known about the test areas. The remainder of the data were used to help evaluate the influence of various parameters on the data collected.

Quantitative aspects of the project included performing continuous scans with reflection and transmission densitometers, to determine if typical density patterns existed for various land forms. Attempts were also made to prepare isotonal maps. Densitometers were used to prepare normalized response curves from multichannel data. A system was also developed which determines the Munsell color notation on aerial photographs based on densitometer readings with four filters. Based on this color measuring system, a method was developed to prepare isochromal maps (maps showing areas of uniform colors).

Major conclusions obtained in this study include· (1) the optimum multisensor system for detailed engineering soils mapping is a multichannel sensor (minimum of seven bands in ultraviolet through far infrared) obtained simultaneously with medium scale color aerial photography; (2) alternate systems depending on availability of equipment and security restrictions are color and color-infrared photography and infrared imagery obtained simultaneously, or color and color-infrared photography obtained simultaneously; (3) spectral response curves obtained by normalizing multichannel data has great potential for differentiating between various soils and soil conditions automatically; (4) typical patterns for various land forms are not obtained by densitometric scans. Influence of various parameters results in more variations within land forms than between them; (5) the technique of determining Munsell notations by means of densitometer readings is a simple, rapid method whose accuracy (for the intended purpose) is commensurate with other color measuring systems; and (6) field measurements found to be of greatest value in evaluating the photography and imagery include field radiometer readings, ground photographs taken at the time of flight, and meteorological data. (Abstract from. Dissertation Abstracts, Section B: Science and Engineering, Vol. 28, No. 2, August, pp. 670B–671B.)

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, Washington, 35 pp. (NTIS No. N71 33374).

No Author's Abstract.

Using Westinghouse radar data from 1965, the author attempts to identify the usefulness of like- and cross-polarized returns for geologic interpretation. The study initially divides the park into 14 areas of 'general geologic and geographic uniformity.' The general types of vegetation (the imaged area is completely forested) are then related to the 14 divisions previously made.

Some of the generalizations about the imagery include:

(1) recognition of radar shadow areas on the 'lee' side of mountains

(2) the possibility of over-return from slopes roughly normal to the radar beam

(3) increase of geologic information from the image interpretation when the intermediate return of the radar is recorded

(4) optimum conditions for geologic interpretation in areas of moderate slopes – although the actual relief may be great, the abrupt changes in slope are absent

The differences between HH and HV polarization were most abundant in areas of cliffed mountainous regions, especially along the margins of the 'whiteout' regions. These differences include (in terms of surface geology):

(1) angular-to subrounded, blocky to slabby talus rubble

(2) combinations of cliffs and talus rubble

(3) wet meadows underlain by silt, cobble-gravel and sand, diatomaceous deposits, and those in association with hot-springs

(4) gravel beach bars along lakes and waves on large lakes

(5) thin stony glacial debris overlying rolling bedrock uplands

For most of these features, there was no anomaly seen between HH and HV imagery. It is therefore suggested that some other factor (slope, look-direction, rather than variety of rock type or rock material) may be the cause of these observed anomalies. Also, vegetation may be the cause of these observations. However, the use of various electronic interpretation aids is precluded because the surface situation is so complex (i.e., so many variables), and there is a "virtual lack of fundamental controlled experimental data. Such data are needed to guide in the evaluation of these many variables, some one or combination of which may be the explanation of any given anomaly."

The paper has 15 radar images with extensive annotations for each.

ROBERTS, R. J., 1966

Geological Evaluation of Radar Imagery, North-Central Nevada

U.S. Geological Survey Technical Letter –NASA-49, Washington, August, 15 pp. (NTIS No. N70 38894).

Abstract: *Faults, unrecognized during earlier geologic mapping, were discovered near the Carlin Mine, Eureka County, Nevada, as a result of radar image analysis. Because the major faults show clearly, and many minor faults can be recognized, radar imagery is considered to be very useful in structural analysis in this area.*

Radar is also helpful in distinguishing major rock units by tonal contrasts, but its small scale offers little help to the geologist in differentiating small geologic units. (From Carter, W. D., 1969.)

ROUSE, J. W., Jr., H. C. MacDONALD, and W. P. WAITE, 1969

Geoscience Applications of Radar Sensors

IEEE Transactions, Geoscience Electronics, Vol. GE-7, No. 1, January, pp. 1–19.

Authors' Abstract: *Studies sponsored by NASA at the Center for Research, Inc., University of Kansas, in cooperation with several other universities and government research agencies have substantiated the applicability of remote sensing to many fields within the earth sciences, agriculture, and oceanography [1]. The purpose of this paper is to show how the properties of radar are used to provide geoscience information. (Abstract copyrighted by IEEE.)*

The paper is divided into two major parts:

Radar Return – A review of radar return parameters, especially as applied to scatterometer data for sea state, terrain type, and ice type

Imagery Interpretation –

(1) Interpretation of radar imagery in hydrologic studies – with special emphasis on drainage basins and terrain slope analysis.

(2) Interpretation of radar imagery in agriculture and natural vegetation studies.

(3) Interpretation of radar imagery in geologic studies – with examples from Pisgah Crater, California; Boston Mts., Arkansas; and applications for Pliestocene geomorphology.

This paper is one of the better papers available for a brief overview of some of the applications of radar in several major areas of geography and geology. It contains an excellent bibliography of 25 items together with 12 large radar images of the areas discussed. Highly recommended.

ROWAN, L. C., and P. J. CANNON, 1970

Remote-Sensing Investigations Near Mill Creek, Oklahoma

Oklahoma Geology Notes, Vol. 30, No. 6, December, pp. 127–135.

Authors' Summary: *Remote-sensing investigations by the U.S. Geological Survey at Mill Creek, Oklahoma, have demonstrated the usefulness in the test site of side-looking radar images for delineating fractures and faults and of infrared (8–14 μm) images for discriminating limestone, dolomite, and granite. The thermal contrast of the limestone and dolomite in the predawn image can be explained in terms of the thermal and reflectivity properties of the two rock types.*

"Radar images have been especially useful for delineating regional and local structural features, particularly faults and fractures" (p. 128). "The enhancement of subtle topography and vegetation on the radar image . . . reveals many small tectonic anomalies or lineaments that transect the test site" (p. 130).

RUMSEY, I. A. P., 1972

Application of Thermal Infrared, Colour Infrared and Side Looking Radar to Mineral Exploration

Canadian Mining Journal, Vol. 93, No. 8, April, pp. 56–60.

No Author's Abstract

The fact that remote sensing has often been oversold and/or conducted by inexperienced operators and interpreters has led to a certain amount of justified criticism by persons seeking to use remote sensing data. The author emphasizes that reasonable, rational and valid planning, coupled with experienced interpretation will lead to better utility of remote sensing data.

Some examples of remote sensing in mineral exploration are in determining positive thermal anomalies over salt domes, over ore bodies, and along fault zones. With SLAR, " . . . topography causes the strongest return (but) is least important from an interpretative point of view . . ." One might question this comment, even within the context of the title, for even minor topographic expression often leads to major insights concerning the underlying geology. SLAR is stated to be useful in (a) mapping gross lithologic differences, (b) mapping faults, (c) mapping discrete rock bodies, and (d) for "stripping off" the vegetation. Finally, using false color IR film to denote trace elements in trees (due to changes in tree reflectance) can lead to discovery of underlying mineral bodies.

The author comments that any company specializing in remote sensing data or interpretation should be careful not to be "financially associated with the manufacturers of remote sensing equipment," thus allowing greater latitude in selection of instrumentation for any particular job. He also re-emphasizes the need for combining good imagery with good interpretation. Both are needed for success in remote sensing.

RUMSEY, I. A. P., and R. H. GELNETT, 1976

Airborne Radar Finds Deep Fracture Controlled Pools

World Oil, January.

No Authors' Abstract.

This article explains the basic principles of SLAR and presents several examples of applications around known producing areas in the Rocky Mountains of the United States. A radar mosaic, obtained by the Motorola real aperture systems and covering a 100 x 150 mile area centered on the Four Corners area of Utah, Colorado, New Mexico and Arizona is presented and discussed. The discussion centers on the analysis of fracture and fracture traces as seen on the SLAR image. A bibliography of 22 articles, dealing primarily with fractures, is included.

RYDSTROM, H. O., 1966

Interpreting Local Geology from Radar Imagery

Proceedings, Fourth Symposium on Remote Sensing of the Environment, Report No. 4864-11-X, Willow Run Laboratories of the Institute of Science and Technology, The University of Michigan, Ann Arbor, pp. 193–201.

Geological Society of America, Bulletin, Vol. 78, No. 3, March, 1967, pp. 429–436 (NTIS No. AD 638 919).

Author's Abstract: *The intensity of radar return energy, as modified by the factors of radar illumination, surface roughness, and the geometry of objects, is discussed as applicable to local geologic interpretation. The principles involved are described and applied to analyses of local geology in the southwestern United States. Consideration is given to the use of return intensity in conjunction with geomorphic features to obtain a maximum of information. Local geologic interpretations of radar imagery are applicable to military terrain intelligence, natural resources exploration, and planetary exploration.*

This paper is essentially a state-of-the-art report in which radar is discovered to be more discerning of surface texture and geometric structure than of surface material. Low level, very low angle flights located some fine deviations in contour and slope beyond the capacity of detailed field maps. The accompanying diagrams are excellent.

RYDSTROM, H. O., 1970

Geologic Exploration with High Resolution Radar

GIB-9193A, Goodyear Aerospace Corporation, Arizona Division, Litchfield Park, July, vi + 48 pp.

Author's Abstract: *A number of natural features are annotated on high-resolution, side-looking radar imagery and briefly analyzed. Another group of images is analyzed in greater detail and the results applied to specific geologic problems in such fields as petroleum, ground water, and metallic minerals. The introduction briefly discusses and illustrates some of the radar imaging principles applicable to the earth sciences.*

The introduction portion of this book is similar to the author's earlier publications. The major feature of this booklet is the extensive use of imagery and the explanations and annotations included on 19 images.

SABINS, F. R., Jr., 1973

Geologic Interpretation of Radar and Space Imagery of California

Presented at the 54th AAPG — 47th SEPM National Meetings, Anaheim, California, 14—16 May.

American Association of Petroleum Geologists, Bulletin, Vol. 57, No. 4, April, p. 802 (abstract only).

Author's Abstract: *Side-looking airborne radar (SLAR) imagery in California is interpreted in terms of geologic structure and rock type. Field checks and comparison with published geologic maps indicate some revisions of existing maps. In particular, linears on the radar imagery point to previously unmapped faults. In outcrops where surface texture is related to bedrock lithology, the radar signature may indicate rock type.*

The unmanned Earth Resources Technology Satellite (ERTS) telemeters multispectral-scanner imagery that is reconstituted into reflected-infrared-color imagery. With respect to radar imagery, the ERTS imagery has poorer spatial resolution and smaller scale; nevertheless, useful regional patterns may be interpreted. Repetition of ERTS imagery on an 18-day cycle should enable us to determine the season for obtaining maximum geologic information. (Copyright by AAPG.)

SCHABER, G. G., 1966

Radar Imagery-Meteor Crater, Arizona

U.S. Geological Survey Technical Letter — NASA-62, Washington, November, 18 pp.

Abstract: *Side-looking radar systems enhance both large and small topographic features in a manner far superior to conventional aerial photography. Linear geologic features such as fractures and faults are especially well recorded on radar imagery. Moisture retention of various ground surface materials is well displayed and is of significant value in geologic and geomorphic interpretation.*

Compositional and textural variations, on the other hand, are poorly differentiated in the images of this area. Stratigraphic units within the crater walls could not be distinguished. (From· Carter, W. D., 1969.)

SCHABER, G. G., 1968

Radar and Infrared in Geological Studies of Northern Arizona

Earth Resources Aircraft Program Status Review, Vol. 1, Geology, Geography and Sensor Studies, NASA, MSC, Houston, September, pp. 13–1 to 13–29 (NTIS No. N71 16126).

Author's Conclusions and Suggestions: *Both the IR and radar data of the northern Arizona sites were found to contribute at least something of unique geologic value. The radar imagery contributed mainly because of its synoptic scale, moisture delineation, and topographic enhancement capabilities. All of these furnish data useful in interpretation of tectonics, surface moisture, and overlapping sequences of lava flows Evaluation of the IR scanner data in this study provides several new suggested uses for the system. (1) location of prehistorical Indian agricultural sites, and (2) means of discriminating between recent (unweathered) volcanic ash and lighter, older (weathered) ash-fall deposits as a function of radiant temperature and possible moisture content.*

Both the radar and IR scanner imagery provided rather disappointing distinction between rock types in the study area. Part of this problem, however, lies in the fact that the relationships between surface conditions and atmospheric attenuation with signal response are still not well defined or understood for radar IR scanners, as well as the other sensors currently being investigated. Basic spectral research in the laboratory and under simple field conditions is the most urgent direction to proceed at the present time.

Although the gathering, interpreting, and field checking of images from these devices is of great importance and should be continued, the users are becoming more and more aware of the complexities which arise from diverse surface textures, moisture content, and changing atmospheric conditions. As long as such parameters as these are misunderstood, scientifically useful evaluations of image data will be almost impossible.

It has become obvious that the laboratory spectral research and image evaluation programs must become more balanced and that the results from each study more easily disseminated to the users. Hopefully then, in the next few years, these programs will enjoy a fruitful union that will be to the advantage of the earth resources remote-sensing technology

Using K-band multi-polarized radar, images were taken of the following sites: San Francisco Volcanic Field, Meteor Crater, Hopi Buttes and the Grand Canyon. Well reproduced imagery complete with annotations keyed to the discussion is included. The author suggests a triangular array of flight lines over an area, look direction toward the center of the triangle, offers enhancement of linears and topographic scarps in all azimuth directions, as well as [furnishing] maximum and more uniform signal-strength returns from areas of interest.

In the Meteor Crater site, the cross-polarized return was better than the like-polarized image for delineation of moisture concentration areas and rock types. Many washes whose topographic relief measured in inches, were clearly evidenced on the radar images because of their moisture retention qualities. However, "ground detail, emphasized by moisture content, was found to decrease appreciably with lateral distance from the aircraft . . ."

"The negative features of the radar data are the usual poor resolution of stratigraphic units and the innate image and scale distortion which preclude the use of standard photogrammetric techniques."

On the imagery of the Grand Canyon the author was able to accurately define nearly all lineaments as plotted on the latest U.S. Geological Survey map of the area.

In the Hopi Buttes study area, moisture retention qualities identified by radar aided in the delineation of many complex Quarternary soil units.

SCHABER, G. G. and W. E. BROWN, Jr., 1972

Long-Wavelength Radar Images of Northern Arizona – A Geologic Evaluation

U.S. Geological Survey Professional Paper No. 800-B, Washington, pp. B175–B181.

Authors' Abstract: *Radar images at 25-cm wavelength (λ) were obtained in 1969 in an area near Flagstaff, in northern Arizona, as part of a feasibility program to evaluate the geologic potential of long-wavelength radar systems for terrestrial applications, as well as for lunar and planetary orbital research. The instrument, operating in a side-looking mode (0 degrees – 45 degrees look angle), provided image data which sharply delineated regions of fine-grained alluvium as areas of very low radar backscatter. The 25-cm data enhance such alluvial materials far more than both 0.86-cm-λ data and low-altitude aerial photography of the site. Similar radar sensors with varying wavelengths in the decimeter range may enable discrimination of unconsolidated materials of a significantly greater range in grain size.*

Resolution for this 25 cm radar was 60 to 100 m in range (at a 45 degree look angle) and 20 m in azimuth. Topographically expressed features are only moderately to poorly distinct. Orientation of the features relative to the flight path of the aircraft plays a very important role in the utility of the images for identification of features. Generally, shadowing effects from this radar are less than from the K-band (approximately 1 cm) radar. The finer and deeper (at least 4 to 5 inch) alluvial deposits yielded a darker (i.e., lower backscatter) image. For a larger range of sediment particle sizes, change in backscatter with variations in wavelengths decreased. Therefore, it is argued, use of multifrequency and simultaneous radar allows a probability frequency distribution of the surface sediment particles to be made if the material is unconsolidated. For determining the texture of surface materials, 25-cm radar is very good but is virtually useless for structural and morphological studies.

SCHABER, G. G., L. BERLIN, and W. E. BROWN, Jr., 1976

Variations in Surface Roughness Within Death Valley, California: Geologic Evaluation of 25-cm Wavelength Radar Images

Interagency Report: Astrogeology 65, U.S. Geological Survey, Flagstaff, Arizona, February, 35 pp.

Also, Geological Society of America Bulletin, Vol. 87, No. 1, January, pp. 29–41.

Authors' Abstract: *Side-looking long-wavelength (25 cm) radar images of the salt flats and gravel fans on the floor of Death Valley, California, show distinctive varitions in radar backscatter (image gray tones) that can be correlated with systematic changes in surface roughness of differing geologic units. Well-developed desert pavements on the oldest of the late Pleistocene boulder gravels are clearly delineated as weak backscatterers on the images. A size grading of gravels near the base of the giant gravel fans was found to be associated with a sharp transition from strongly diffuse to weakly diffuse backscatter observed on the images. The transition takes place at gravel radii between 0.08 λ and 0.14 λ (2.0 cm and 3.5 cm) in agreement with a scattering model presented in the paper. The model predicts a breakpoint in the Rayleigh scattering region of the total radar cross-section that is virtually independent of depression angle as long as the surface resolution element does not fall in the first pulse width of the echo (the 90 degree depression angle). Antenna depression angles of 45 degrees to 90 degrees appear to be well suited for investigations of surface roughness with the longer wavelength radar systems because of the suppression of radar shadows and the increased radar return from the near field.*

SCHEPS, B. B., 1962

The History of Radar Geology

Proceedings, First Symposium on Remote Sensing of the Environment, Report No. 4864-1-X, Willow Run Laboratories of the Institute of Science and Technology, The University of Michigan, Ann Arbor, March, pp. 79–81 (NTIS No. AD 274 155).

No Author's Abstract.

A colloquially written article describing the method through which radar has been introduced as an additional tool for geologists. Original work was done in Greenland and Antarctica, and almost by accident, mapping techniques were worked out using data from photographs of WW II-vintage radar PPI scopes. Various individuals were introduced to the possibilities of collecting geological data, and eventually the USGS became involved. The author believes that most geological information will come from the results of differential weathering rather than variations in chemical constituents in the rocks.

SCHWARZ, D. E., and R. D. MOWER, 1969

The Potential for Deriving Landform Regions from Radar Imagery: A Puerto Rican Example

The Utility of Radar and Other Remote Sensors in Thematic Land Use Mapping from Spacecraft: Annual Report, U.S. Geological Survey, Interagency Report – NASA-140, Edited by D. S. Simonett, January, vi + 113 pp., pp. 22–27. (NTIS No. N69 16255.)

From Authors' Introduction: *This report is an evaluation of classified radar imagery obtained during a February, 1964, flight over the island of Puerto Rico. Though allusions will be made to such thematic potentials as agricultural land use mapping or detailed landform study, the major purpose is to compare a landform regionalization scheme derived from the radar imagery with the systematic descriptive classifications of Puerto Rican landforms (as previously developed).*

To date, much analysis of remotely sensed imagery, regardless of the particular system, has been directed at studying single, particular phenomena such as natural vegetation, agriculture, geology, transportation, or the like. Those characteristics of remotely sensed data which are normally deemed least desirable for just such studies – the generally small scale and relatively poor resolution – become to a degree desirable for more broad scale analysis. Geographers especially should be cognizant of such potential.

The authors were able to make some valid comparisons of landform regions observed on imagery of limited coverage and marginal quality with a landform classification scheme designed especially for Puerto Rico. The landform classification was essentially by a single element of topography, that of slope. Three major classes are delimited: (1) lowlands – in which both the "earliest" and the radar classifications have a high correspondence, (2) hill-lands – for which correspondence is good, but most difficult to reconcile in the two schemes and (c) mountain lands – of which the last two of the three divisions could not be delimited on radar imagery. The authors conclude that for this type of study, i.e., the regionalization of relief by slope, radar is probably the single best sensor; however, they hasten to point out that no one sensor is totally adequate for such work.

SCHWARZ, D. E. and A. J. LEWIS, 1971

Landform Regionalization Using Radar Imagery

Proceedings, 67th Annual Meeting, Association of American Geographers, Boston, April, Vol. 3, pp. 194–195 (abstract only).

Authors' Abstract: *Radar imagery is peculiarly well adapted to the study and regionalization of landforms. Its response is primarily to the gross geometry of the earth's surface, and it can be obtained without solar illumination and through cloud cover Comparison of landform regions drawn from short wavelength radar imagery of portions of Panama and Puerto Rico indicate that radar-derived regions are equally as valid as those drawn using traditional techniques. In some cases boundaries are even more accurately drawn due to freedom from unit-area averaging of such characteristics as slope, which is necessary when doing traditional regionalization from topographic sheets. The ease of radar acquisition, its broad coverage and ready interpretation make its use for landform regionalization especially attractive in unmapped areas to expedite planning allocations such as those based on the delimitation of land-suitability classes. (Copyrighted by AAG.)*

SHEPARD, J. R., 1966

Radar Geology Test Area, Willcox Playa, Arizona

U.S. Army Corps of Engineers, Ft. Belvoir, Virginia, January, 6 pp.

No Author's Abstract.

This report is basically a letter describing the radar test range located approximately 75 miles east of Tucson, Arizona. Several reflectors, both above and below ground, and various areas of different rock types (crushed rocks sorted to different sizes) are available for radar test flights. A diagram of the test area and maps showing its location are included. Investigators are invited to avail themselves of the facility by contacting the U.S. Army Electronics Proving Ground, Ft. Huachuca, Arizona.

SHERIDAN, M. F., 1966

Preliminary Studies of Soil Patterns Observed in Radar Images, Bishop Area, California

U.S. Geological Survey Technical Letter – NASA-63, Washington, November, 8 pp. (NTIS No. N70 38885).

Author's Abstract: *Contrasting soil patterns reflecting light and dark tones noted by BATEMAN (U.S.G.S. Tech. Letter NASA-27, 1966) on radar imagery of the Bishop area were studied in the field to determine if soil moisture or grain size of the materials was the cause of such response. Preliminary qualitative investigations indicate that at nine locations examined, no samples contained soil moisture and there was a good correlation (between) grain size and radar response. Light patterns on radar imagery corresponded to areas where soils were composed of gravel-sized and larger materials, dark areas, on the other hand, were fine-grained materials composed largely of silt and clay particles.*

SHUCHMAN, R. A., C. F. DAVIS, and P. L. JACKSON, 1975

Contour Strip-Mine Detection and Identification with Imaging Radar

Bulletin of the Association of Engineering Geologists, Vol. 12, No. 2, pp. 99–118.

Record, IEEE, 1975 International Radar Conference, April 21–23, 1975, Arlington, Virginia, pp. 516–521.

Authors' Summary: *Using four channel imaging radar, the recognition of three basic types of contour strip mining has been shown. Active, reclaimed, and unreclaimed "orphan" mines were detected and identified. Highwalls, benches, relative bench vegetation and texture, outslope, spoils, sediment ponds, and mining machinery were recognized on the imagery. In some cases all four radar channels are needed for recognition of these features.*

Radar is especially sensitive to surface roughness, subtle height variations, and orientation of surfaces. In addition, its all-weather capability and its resolution (essentially independent of distance), both of which are unique in imaging devices, make imaging radar particularly useful for strip mine monitoring.

Small contour mines and unreclaimed "orphan" areas were resolved by radar under cloudy conditions. Other remote sensors are hampered by often persistent cloud cover, and other types of satellite imaging systems do not resolve these small mines.

Imaging radar is most useful for the following:

1) *Mapping unreclaimed "orphan" areas.*
2) *Monitoring wildcat (illegal) mining operations.*
3) *Highwall detection.*
4) *Reclamation evaluation for enforcement purposes.*

This qualitative paper, based on imagery obtained at two frequencies and two polarizations for each frequency, presents a listing of the tone and texture for each of the four radar images with respect to the various mine features detected. The "Discussion" deals primarily with the radar system and not with its utility for strip mine detection and analysis. The importance of depression angle and look direction of the radar is emphasized, and it is recommended that two flight tracks, perpendicular to one another, should be used for optimum data collection for strip mine detection.

SIEGAL, B. S., F. G. SNIDER, and N. R. TILFORD, 1978

Remote Sensing for Nuclear Power Plant Siting, Batan Peninsula, Republic of the Philippines

Proceedings, 12 International Symposium on Remote Sensing of Environment, Manila, Philippines, April.

Authors' Abstract: *The siting of the first nuclear power plant in the Republic of the Philippines entailed an extensive remote sensing study to help evaluate tectonics, volcanism, and the structural setting of potential site regions. Over 10,000 square km of Side-Looking Airborne Radar was obtained, covering Mt. Pinatubo south to the Taal-Banahao volcanic area and from the west coast of Luzon east to Laguna de Bay; these data were analyzed concurrently with Landsat imagery, thermal IR imagery, and black-and-white and color aerial photography. Analysis included photographic processing, color additive viewing, Ronchi rulings and stereoscopic viewing, where applicable. Results of the remote sensing study, in conjunction with seismological and field and laboratory analyses, provided an effective method of identifying and evaluating potential sites. Initial phases of the remote sensing study revealed that*

several of the proposed site regions were unsuitable because of fracturing, gravity movements, or volcanic hazards. SLAR imagery proved invaluable throughout the study in guiding field activities, unraveling structural settings and volcanic stratigraphy. As a result of the siting investigation, Napot Point was selected for the site of the first nuclear power plant in the Republic of the Philippines.

Motorola APS/AN-94D (X-band) real aperture radar system was used. Ground resolution was approximately 20 m.

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, July, 19 pp. (NTIS No. N69 28154).

Author's Summary: *In reconnaissance mapping of vegetation, soils, and geomorphic surfaces in remote, difficult-of-access and under-developed areas in tropical and arctic latitudes, aerial photographs have extensively been used to aid ground studies. Over recent years, studies using nonphotographic remote sensors, particularly infra-red and radar have shown that these systems, used in concert with photography, may add materially to the information available and thereby improve the efficiency of ground reconnaissance. This report focuses attention on side-looking radar as a tool for such reconnaissance. Since radar imagery may be obtained in swaths up to 40 miles wide, largely independent of the weather, its usefulness for reconnaissance-mapping needs careful evaluation.*

A review is given of recent studies with radar on: (1) the mapping of lineaments and lithologic units and its use as a surrogate for 1:24,000 scale maps in hydrologic analysis; (2) the mapping of vegetation types, especially in relation to structure, and (3) its successes and shortcomings as an adjunct to photography in soil reconnaissance surveys.

Two short introductory sections of the paper present reviews of work, primarily by scientists from the University of Kansas, concerning geomorphic and vegetation reconnaissance mapping using a K-band radar. The third section, concerned with soil studies and supplemented by overlay maps of radar imagery, notes that several types of soil and soil/vegetation combinations were distinguished on the imagery. These include: vegetated dunes, vegetated sand sheets, active dunes, badlands, salt plains and flood plains. River terraces are seldom identified from radar imagery, and the first three mentioned above are usually, but not always, distinguishable. The identification of soil associations, using only radar imagery, is very difficult – partially because the vegetation on these soils is primarily cultivated crops. Hence, the author concludes that soil information from radar imagery is "uneven in both distribution and quality . . where extreme differences occur in adjoining plant structures, in soil or plant moisture content, in soil texture, in topography, and within areas of scanty vegetation, in small-scale surface roughness, then discrimination on the radar image of soil units closely tied to these differences will usually be possible."

SIMONS, J. H., 1965

Some Applications of Side-Looking Airborne Radar.

Proceedings, Third Symposium on Remote Sensing of the Environment, Report No. 4864-9-X, Willow Run Laboratories of the Institute of Science and Technology, The University of Michigan, Ann Arbor, November, pp. 563–571.

Selected Papers on Remote Sensing of Environment, American Society of Photogrammetry and Willow Run Laboratories, Washington, July 1966, pp. 205–213.

Author's Abstract: *The applicability of the AN/APQ-56 system to observation of geological structure, geomorphological features, and cultural patterns of land uses is investigated.*

The paper suggests some areas in which SLAR can easily be used, especially in reconnaissance surveys for planimetric mapping, geology and geomorphology and the determination of broad cultural land uses, terrain trafficability and watershed management. Although trained photo-interpreters had difficulty in orienting themselves to working without stereographic viewing, they were able to cover approximately 100 mile^2/hour when interpreting for reconnaissance mapping. Eleven radar images and short titles for each are included.

SNAVELEY, P. D., Jr., and H. C. WAGNER, 1966

Geologic Evaluation of Radar Imagery, Oregon Coast

U.S. Geological Survey Technical Letter – NASA-16

Abstract: *Radar imagery of a coastal strip extending from the Columbia River to near the California border was obtained with a high frequency side-looking radar. Qualitative evaluation indicates that radar imagery is a potentially useful tool for geologic mapping in regions where bedrock is masked by dense vegetation. The radar sensor effectively "defoliated" coastal Oregon, thus greatly enhancing the topographic and tonal expressions of certain Tertiary rock units. Faults and lineaments not identifiable on conventional black and white photography can be recognized.*

Preliminary interpretations indicate that radar returns in this area are dependent principally upon density and water content of the rock units The tonal conditions of certain Tertiary units are distinctive. Miocene basalt flows show the highest returns (lightest tones), sandstones give intermediate tones, and marine mudstones have the lowest radar returns of any of the Tertiary rocks. The juxtaposition of these contrasting tones and differences in topographic expression define the positions of depositional and fault contacts.

SNAVELY, P. D., Jr., and N. S. MacLEOD, 1968

Preliminary Evaluation of Infrared and Radar Imagery, Washington and Oregon Coast

U.S. Geological Survey Interagency Report – NASA-124, September, 23 pp. (NTIS No. N69 25024)

From Authors' Introduction: *This report summarizes the preliminary interpretation of infrared and radar imagery of parts of the Washington and Oregon coast. This coastal area is an ideal testing site for remote sensing techniques inasmuch as, in contrast to other imagery testing sites, it has a dense cover of vegetation, and bedrock is poorly exposed. Thus it serves to define limitations of imagery in areas not ideally suited for geological interpretation of conventional aerial photographs.*

The bulk of the report deals with the infrared imagery (8 μm to 14 μm) taken during the early evening of 16 August 1967, and most of the interpretation of this imagery deals with the tidal cycles and fresh-water plumes entering the ocean. As concerns the radar data (no radar imagery is shown), the reader is referred to SNAVELY and WAGNER, 1966, for the basic interpretations. The authors state that additional data has been collected but analysis has not been completed; they reiterate conclusions presented in the 1966 paper. A comprehensive report on interpretation and evaluation of radar imagery is promised, but as yet this paper does not seem available.

SOUTHWICK, D. L., 1966

Geologic Evaluation of Radar Imagery, Appalachian Piedmont, Harford, and York Counties, Maryland and Pennsylvania

U.S. Geological Survey Technical Letter – NASA-48, Washington.

Abstract: *Radar images reveal very little of the geologic "grain" of the Appalachian Piedmont because of the lack of distinctive topographic expression. Soil and bedrock variations are obscured by the geometric pattern of farmlands and woodlots. Penetration of forest cover is poor in the relatively flat Piedmont but very effective in the more rugged ridge and valley terrain of eastern Pennsylvania.*

STAROSTIN, V. A., N. N. SEMENOVA, and V. G. MOZHAEVA, 1971

Experiment of the Use of Information from Radar Aerial Survey During Geological Interpretation in Central Kazkhstan [Opyt Ispol'zovaniÎa Materialov Radiolokafsionnoi Aeros'emki Pri Geologicheskom Deshifrirovanii v TŝentraInom Kazkhstane]

New Methods of Obtaining Information by Various Remote Sensors and its Adaption for Solving Geological Problems [Novye Metody Polucheniia Informafsii razlichnymi Distantsionnymi Priemnikami i ee Obrabotki DlÎa ResheniÎa Geologicheskikh Zadach] VIEMS, Moscow.

Reviewer's Summary: *In 1970 a large part of the northern Pribalkash area was covered by an airborne radar survey. Through field investigation, geological, geomorphic, geophysical, soil and geobotanical data were simultaneously acquired.*

Areas having distinct topographic forms which result from geologic or geomorphic processes are more easily interpreted than lowland areas of low relief which lack characteristic topographic expression.

Structure and lithology which jointly control landform development of an area permit interpretations of the buried structure and, indirectly, the rock type. In this respect radar imagery is more effectively used than aerial photography because of the regional perspective, especially in determining regional structural relationships.

Areas of varying soil moisture and soil salinity have been detected, and sources of springs have been located.

Some distinctions between quaternary deposits have been made on the basis of surface texture. (From: Dellwig, et al., 1975.)

STRELNIKOV, S. I., 1972

Peculiarities of Geological Interpretation of Radar Aerial Surveys [Osobennosti Geologicheskogo Deshifrirovanie Radiolokatsionnykh Aerosnimkov]

New Methods of Obtaining Information by Various Remote Sensors and its Adaptation for Solving Geological Problems [Novye Metody Polucheniia Informatsii Razlichnymi Distantsionnymi Priemnikami i ee Obrabotki Dlia Resheniia Geologicheskikh Zadach] VIEMS, Moscow, (Russian).

Reviewer's Summary: *The landform method (relief, drainage network, etc.) of image analysis can be applied to both radar and photo interpretation. Two major differences between radar images and aerial photographs must be considered, however; the geometry of the radar image and the response of terrain elements to two different portions of the electromagnetic spectrum.*

Orientation and surface roughness of the terrain surfaces are both determinative factors in radar backscattering. Factors which influence image tone are differential sizes of reflecting surface materials, nature of the vegetal cover, and moisture content of surface material or vegetation.

A true stereo effect is not as easily achieved with radar as with aerial photographs but the sculptured appearance of the terrain caused by shadowing facilitates interpretations. (From: Dellwig, et al., 1975.)

STRELNIKOV, S. I., 1972b

Geological Interpretation of Radar Aerial Photos from Certain Regions of the Polar and Northern Urals, [Geologicheskoe Deshifrirovanie Radiolokatsionnych Aerosnimokov Nekotorykh Raionov Poliarnogo i Severnogo Urala]

New Methods of Obtaining Information by Various Remote Sensors and its Adaptation for Resolving Geological Problems [Novye Metody Polucheniia Infromatsii Razlichnymi Distantsionnymi Priemnikami i ee Obrabotki Dlia Resheniia Geologicheskikh Zadach] VIEMS, Moscow, (Russian).

Reviewer's Summary: *In the northern Ural Mountains, lithologic and stratigraphic influence on local relief was used as a criterion to identify rock formations having unique topographic expression. Diverse rock types (volcanic, igneous intrusives, and sedimentary) were identified in this manner.*

The orientation of geologic structures with respect to the antenna influences the detectability of these features. Surface expression of faults was seen in the development of a trellis drainage network.

Tundra has no identifiable signature. (From: Dellwig, et al., 1975.)

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, May, 11 pp. (NTIS No. N73-89403).

From Author's Evaluation: *In comparison to the geologic map based on photogeology and ground work, radar imagery shows very clearly many geologic features with characteristic topographic expression, but fails to bring out certain subtle distinctions, as between topographically and compositionally similar andesite and basalt lava flows. It [radar] clearly shows the volcanic nature of much of the terrain especially the volcanoes and viscous lava flows and domes, but gives no indication of the nature of the flat lava plain. The imagery shows linear scarps which most probably are faults, an interpretation confirmed by geologic mapping The imagery is hindered by storms, although the cross-polarized strip cuts through some of the cover. Imagery flown during better weather conditions would undoubtedly supply many more details. The radar shows topographic features in forested terrain less clearly than in barren areas, but in timbered areas it is better than aerial photography. The radar permits better interpretation in forested areas of some geologic features, such as linear structures with topographic expression, than does black and white aerial photography.*

TABOR, R., 1966

Application of Radar Imagery to a Geologic Problem at Glacier Peak Volcano, Washington

U.S. Geological Survey Technical Letter – NASA-26, May, 4 pp. (NTIS No. N70 38896).

Abstract: *Radar imagery was found to be more effective than aerial photography in defining the constructional surface and contacts of a large fan of stratified volcanic gravel and sand that extends down the east flank of the Glacier Peak volcano into the Suiattle River Valley.*

van ZUIDAM, R. A., 1978

Terrain Classification Using SLAR Imagery: A Geomorphological Approach

ITC Journal, pp. 705–716

Author's Abstract: *Terrain analysis and classification on the basis of geomorphological principles is becoming more and more accepted for multidisciplinary, semidetailed, and reconnaissance surveys. This concept is also issued for the PRORADAM project, in which SLAR images of the Columbian Amazon region are analysed using the geomorphologic/ecologic landscape approach*

The author notes the general geology and geomorphology of the area and presents several sets of SLAR and Landsat imagery. Although these images are not registered, they are clear enough to show the additional terrain information presented by the SLAR – due primarily to the shadowing of the terrain. With respect to SLAR, it is noted that:

(1) Scales of 1:50,000 to 1:100,000 – difficult to interpret due to speckle and limited stereo imagery; suitable for transfer of information.

(2) Scales of 1:200,000 – most suitable, good stereo.

(3) Scales of 1:400,000 – frequently too small to interpret various terrain units due primarily to the limited size of the units.

(4) Scales of 1:200,000 (mosaic made of far range strips) – reasonable stereoscopic vision, and good possibility to identify terrain units; semicontrolled mosaic used as a base map.

(5) Scale of 1:1,000,000 (mosaic) – useful only for reconnaissance.

The Goodyear APS-102/X radar was used for this project. Terrain consisted primarily of horsts, grabens, four planation levels, three river terrace levels and the floodplain of a river. Imagery from four study areas are presented.

VERSTAPPEN, H. T., 1977

Remote Sensing In Geomorphology

Elsevier Publishing Co., Amsterdam, The Netherlands, ix, 214 pp. + figs., tables, maps.

No Author's Abstract.

This publication, although dealing primarily with aerial photography and visible portions of the EM spectrum, does have a small amount of space devoted to radar and thermal systems. The interesting aspect of this book is that it presents a perspective of remotely sensed data and their application to geomorphological problems that is rather unique in this relatively new aspect (remote sensing) of the geosciences. Individuals having some background in both remote sensing and geomorphology will receive the best benefits from this publication.

VISKNE, A., T. C. LISTON, and C. D. SAPP, 1969

SLR Reconnaissance of Panama

Geophysics, Vol. 34, No. 1, February, pp. 54–64.

Photogrammetric Engineering, Vol. 36, No. 3, March 1970, pp. 253–269.

Authors' Abstract: *SLR (Side-Looking Radar) was successfully used in lieu of optical photography for reconnaissance of the Darien Province of Panama and parts of Northwest Colombia, and for the construction of geoscience products thereof. An AN/APQ-97 side-looking radar was used to produce high-resolution imagery of an area containing approximately 6,600 square miles in 4 hours of flying time — an area, furthermore, that is almost perpetually cloud covered. The SLR imagery was used to prepare an uncontrolled mosaic and a series of geoscience overlays, including. Surface Drainage, Surface Configuration, Vegetation, Engineering Geology. The results of this study are believed to be unique in that they provide the first complete overview of Darien Province, thereby demonstrating the capability of SLR to gather geoscience data in an area that is notorious for the difficulties that its persistent cloud cover poses for the acquisition of usable conventional optical aerial photography. (Abstract copyrighted by Society of Exploration Geophysicists.)*

The authors insist that SLR imagery is best used as a supplement to conventional air photography. Indeed, several of the "geoscience" map overlays were constructed using surrogate data.

WAITE, W. P. and H. C. MacDONALD, 1972

Fracture Analysis with Imaging Radars

Annual Meeting of the American Geophysical Union, San Francisco, December 4–7.

Transactions, American Geophysical Union, EOS, Vol. 53, No. 11, November, p. 981 (abstract only).

Authors' Abstract: *Fracture trends are surface manifestations of subsurface discontinuities which usually delineate zones of increased porosity and permeability. Subsurface feature networks can channel, store, and transport large quantities of groundwater. Fracture* *analysis methods for location of high yield water wells are substantially more effective than a random approach. Although aerial photographs have proven to be an extremely valuable tool for such fracture analysis, radar imagery is now cited as a remote sensing technique which may provide extremely valuable supplemental terrain data. Radar imagery provides an oblique illumination of the terrain which tends to enhance subtle topographic discontinuities which are not usually detected on standard aerial photographs. In addition to satisfying the requirement for a rapid and synoptic terrain data gathering technique, broad spectrum microwave measurements of soil reflectivity provide evidence that variations in soil moisture may also be available with imaging radars. This microwave measurement is sensitive to the moisture content of the soil surface, and the potential for aiding in the detection of fracture trends is particularly appealing for extensive reconnaissance studies.*

Only the abstract, preprinted in its entirety above, is available for this entry.

WALKER, A. S., 1972

Geological Evaluation of Remote Sensing Imagery of the Mesabi Range, Minnesota

Proceedings of the Eighth International Symposium on Remote Sensing of Environment, Report No. 195600-1-X, Willow Run Laboratories of the Institute of Science and Technology, The University of Michigan, Ann Arbor, 2–6 October, pp. 1137–1196.

Author's Abstract: *Remote sensing imagery of Precambrian sedimentary, metasedimentary and intrusive rocks of the Mesabi Range, Minnesota area was analyzed to determine how much geologic information was inherent in each type of imagery. High altitude panchromatic photography, radar, ultraviolet, and day and night thermal infrared imagery were examined. Geologic sketch maps were produced for each type of imagery.*

Radar appears to be the best imagery for mapping rock units and for locating regional faults. Few rock units could be found on the infrared imagery or on the panchromatic photography. Several previously unmapped faults were located, and the surface traces of some faults were extended based on information on the imagery.

A Westinghouse AN/APQ-97 (K-band, 1.86 mm) SLAR over NASA Test Site 41 in October 1965 gave HH and HV radar data which were studied at the scale of 1:147,000. Because HH imagery has a larger tonal contrast than does HV, the latter was of less use in geologic interpretation. However, it appears as if both together yielded more data than either one alone. Iron mines and tailings have high returns and are easily identified because of (a) mineral content, (b) uniformity of surface materials, (c) slope angle relative to the radar image and/or (d) absence of vegetation. Swamps and lakes are easily differentiated from higher and drier lands. Contacts located on the imagery are not in close agreement with those on geologic maps. Of 26 known faults, 19 were found on HH imagery and 15 on HV imagery prior to comparison with the maps. Three could not be found on the imagery, even after consulting the maps. In addition, three faults had longer traces on the imagery than on the maps.

The author also discusses the use of IR panchromatic photography and ultraviolet sensors for geologic studies.

WALKER, G. W., 1966

Evaluation of Radar Imagery of Highly Faulted Volcanic Terrain in Southeast Oregon

U.S. Geological Survey Technical Letter – NASA-25, May, 15 pp. (NTIS No. N70 41122).

Abstract: *Radar images of physiographic and some geologic features in southeast Oregon were found to be well defined, as in conventional aerial photography. Geologic features having topographic expression were best displayed and include large- and small-scale faults marked by linear scarps and valleys. Fine grained, poorly indurated, tuffaceous sedimentary rocks, in places water saturated, fill the basins between faults and stand out as dark areas in contrast to adjacent rocks of greater density having little or no saturated water.*

Valley fill, landslide areas, layered rocks and non-layered rocks can be distinguished. Rock types, distinguished by tonal contrasts on aerial photographs, cannot be differentiated in radar images.

WILLIAMS, L. O., 1968

Radar: An Aid to Geologic Mapping of Crystalline Rocks at Test Site 46, North Carolina

Technical Report No. 5, East Tennessee State University Remote Sensing Institute, Johnson City, 20 pp. (Contract: Office of Naval Research N00014-67-A-0102-0001).

From Author's Introduction: *Obvious differences in topographic expression on the radar image of the Hot Springs-Asheville-Hendersonville area of North Carolina . . . suggest the possibility that certain parameters of topographic expression might correlate with the underlying rock type. The characteristic oblique illumination angle of side-looking radar maps slopes which are orthogonal to the radar beam with a light tone proportional to the length of the intercepting slope interface . . . . Therefore, a map of the average width of the light tone intercept taken from a sampling grid placed on the radar image should be indicative of the distribution of topographic relief.*

This study will evaluate the hypothesis that underlying rock type in the crystalline rocks of western North Carolina is sufficiently different to control differences in topographic relief of the overlying earth's surface, and hence, that a map of topographic expression can materially aid certain geologic mapping projects.

Should such a relationship exist, then automatic terrain analysis with a microdensitometer and a high capacity computer seems feasible because a negative of the radar image can be used with a microdensitometer to map differences in gray tone density.

This study is based on a radar image of the northwest-southeast 50 mile long by 10 mile wide area stretching from the North Carolina-Tennessee state line near Hot Springs, over Asheville, to the vicinity of the North Carolina-South Carolina state line near Hendersonville. The imagery was flown in September 1965.

To illustrate, quantitatively, the "fair to good" correlation between bedrock type and topographic expression (slope), the author overlayed a hexagonal grid on the radar image. The width of the light gray (i.e., high return) area along three of the intersecting six lines in the grid pattern was measured. The values were averaged and considered as the value for the entire cell. These mean values were then used for the construction of an isopleth map. Visual comparison was made between the isopleth map and a recent geological map of the imaged area. Frequency histograms of these values and descriptions of same for several rock types are included.

WILLIAMS, L. O., 1969

Interpretation of Linear Elements on the Radar Image of the Hot Springs-Asheville-Hendersonville Area, North Carolina

Technical Report No. 6, East Tennessee State University-Remote Sensing Institute, Johnson City, 26 pp. (Contract: Office of Naval Reserve N00014-67-A-0102-0001).

Author's Abstract: *A radar image of the Hot Springs-Asheville-Hendersonville area of North Carolina clearly displays regional variations in topographic expression and drainage character and accentuates linear elements in the terrain Field and laboratory work strongly suggests control by differences in rock type and fractures on development of topographic expression. Stereographic projections of poles to 430 foliation surfaces and 450 joint surfaces, which were measured at scattered locations in the map area, and a stereographic projection of 375 poles to linear elements derived from the radar image demonstrate a sufficient correspondence in position of maxima to justify inferring control on linear elements of topography by joint and foliation surfaces in crystalline rocks Radar imagery from an airborne platform has provided an image on a regional scale which is a valuable tool for aiding in fracture analysis in the crystalline rocks of western North Carolina. It is anticipated that such analysis of a radar image will aid groundwater geologists in locating relatively high-yield fracture-controlled water wells in other parts of the Blue Ridge Province.*

Relief as indicated on radar imagery was designated high, moderate or low, depending on the length of the bright (high-return) areas on the radar image between valley bottom and adjacent ridge crests. The relief, as measured, showed a high correlation with a recent USGS geologic map of the same area. There is strong evidence that linear features seen on radar images were caused by joints, shear zones, or foliation surfaces. Because radar images can be taken with a lower illumination angle than is possible with aerial photography, radar should be better for detecting and analyzing structural features in this area than conventional aerial photographs.

WILLIAMS, P. L., 1966

Preliminary Report on Radar Imagery of Cedar City-Iron Springs Area, Utah

U.S. Geological Survey Technical Letter — NASA-44, Washington, September, 18 pp. (NTIS No. N70-38887).

Abstract: *Topographic features of the area are well expressed by shadow enhancement effect caused by the side-looking mode of the radar system Geologic features such as faults marked by linear scarps and resistant beds cropping out as hogbacks having topographic expression are similarly well displayed. Little, if any, tonal contrast was noted between rock types which include Paleozoic, Mesozoic, and Tertiary sedimentary rocks, Tertiary volcanics and hypabyssal intrusions. Quaternary alluvium was readily distinguished from bedrock, and Quaternary basalt flows appeared somewhat darker than older basalts of the area.*

The reflectivity of iron mine dumps was especially high and much greater than would be expected from such minor topographic features. Possibly their high reflectivity is related to their high magnitite content. If so, it is possible that magnetite deposits outcropping at the surface in remote parts of the world could be similarly detected.

WING, R. S., 1970a

Structural Analysis from Radar Imagery, Eastern Panamanian Isthmus

U.S. Army Topographic Command, Corps of Engineers, Engineer Topographic Laboratories, Fort Belvoir, 156 pp..

Technical Report No. 133-15, CRES, The University of Kansas, Lawrence (NTIS No. AD 715 322).

Ph. D. Dissertation, Dept. of Geology, The University of Kansas, Lawrence, 1970, 192 pp.

A portion of this paper was published under: Structural Analysis from Radar Imagery of the Eastern Panamanian Isthmus: Part I, Modern Geology, Vol. 2, No. 1, February 1971, pp. 1–21.

Author's Abstract: *The Panamanian Isthmus, where two continents are tenuously joined and where three major crustal plates have apparently long interacted, must record a strain pattern that can be used to help advance knowledge of global tectonics. Recent radar coverage has provided this previously unobtainable surface geologic data for Eastern Panama. Reconnaissance mapping permits tentative interpretations. A belt of (individually) north-trending left-lateral en echelon anticlines nearly bisects Darien Province, extends northwestward across the Pacific Hills, and culminates in compound large-scale faulted folds adjacent to the east end of the Maje Range. Observed distortion within this belt is compatible with postulated left-lateral movement at depth between longitudinal blocks which constitute the Isthmus and parallel its trend. A similar strain pattern is in evidence in the Maje Range as reflected by longitudinal faults, left-lateral offsets, and related internal folds.*

The Panamanian Isthmus is situated in the southwest corner of the Caribbean plate which, it is postulated, has been subject to compression from active translation of the South American plate. Eastern Panama has apparently been subject to left-lateral simple shear deformation because of the oblique orientation of the principal compressive stress relative to the non-homogeneous make-up of the Isthmus.

In addition, the Caribbean plate has been moving slightly eastward, relative to South America, and the drag between them may account for observed right-lateral transisthmian distortion, notably from San Miguel Bay northward to the Caribbean. However, no transisthmian tear faults are in evidence affecting the Isthmus from coast to coast

The longitudinal wrench faults so characteristic of the Maje Range have been used last for vertical tectonic adjustments, there being an axial horst which is topographically high in the eastern and central portions. The Bayano structural sub-basin, extending westward from the Canazas platform, is cut off from the sea by a nearly peneplaned west-plunging element of the Maje Range across which the Bayano River now flows to the sea. Raised beach ridges near the mouth of this river manifest recent activity along the same fault, which bounds the north side of the axial Maje horst.

The horizontal bending of the San Blas Range seems to have been accomplished by means of an intricate system of left-lateral shears and interspersed tears. (Abstract only· Dissertation Abstracts International, Section B· Sciences and Engineering, Vol. 31, No. 11, May 1971, pp. 6699B–6700B.)

This is one of the more complete articles in a comprehensive study showing the usefulness of radar as an additional data source. Of particular interest for the radar interpreter are four pages giving a brief outline of radar imagery and relating the comments to the several excellent images and maps. The bibliography contains 38 articles.

WING, R. S., 1970b

Cholame Area-San Andreas Fault Zone – California: A Study in SLAR

Modern Geology, Vol. 1, No. 3, June, pp. 173–186.

Author's Abstract: *The Cholame locale, midway between San Francisco and Los Angeles, California, includes a particularly significant "San Andreas Fault zone" segment, characterized by a gradational change in mode of tectonic adjustment, from transient creep (NW) to periodic violent movement (SE). Subordinate fold and fracture patterns on the southwest side of the fault zone have been analyzed with respect to side-looking airborne radar imagery (AN/APQ-97 K-band), part of coverage obtained on mission flight 101 (1965) from San Francisco to San Bernardino, flown by Westinghouse for NASA.*

The primary objective of this study was to investigate and document the use of SLAR imagery for geologic mapping of lineaments and to determine the level of significance of the display. Preferred imagery-lineament orientations were found to favor N30–40^{o}E, N50-60^{o}E, and N40-60^{o}W, as expressed in extensive Paso Robles Formation (Plio-Pleistocene) outcrops The NE-SW lineaments reflect resequent drainage on the *southwesterly dipping Paso Robles strata (continental clastics) along the southwest side of the San Andreas Fault zone here, and probably also reflect incipient left lateral shear and tension sets compatible with this dip bearing. Certain prominent imagery lineaments, trending N60°W ± (20° ± counter-clockwise from the San Andreas bearing) reflect the grain of sharply folded Paso Robles strata in proximity to the San Andreas Fault. An arcuate "flow" of lineations around the northeast flank of the Red Hills - Sand Canyon Anticlines, probably reflects the outcrop pattern of the Paso Robles strata, i.e., slumps and slides, etc., related to exhumation of this older structural high which remains partially covered by Paso Robles debris. Still other lineaments on trend with, north of, and subparallel to, the Red Hills - Sand Canyon Anticlines, may manifest fractures over a still buried northward projection of this same positive linear feature. The various lineaments are generally enhanced to a greater degree on the SLAR imagery than on low altitude conventional aerial photographs.*

"The primary objective of the study has been to further investigate and document the use of . . . SLAR . . . imagery for geologic mapping of lineaments and to determine the level of significance of the display . . . SLAR . . . is not ideal for detection of folds which are so youthful as to lack definitive valleys, etc. . . . It is also less effective in detection of very small folds (e.g., 1 km ± in length). These same limitations, however, also apply more or less to conventional aerial photographs. . . . Radar lineaments, noted in this study, primarily reflect drainage which in turn is strongly controlled by regional dip, folds, and fractures - including faults." Several good diagrams of radar imagery geometry and distortion are included.

WING, R. S. and L. F. DELLWIG, 1970a

Radar Expression of Virginia Dale Precambrian Ring-Dike Complex, Wyoming - Colorado

Bulletin of the Geological Society of America, Vol. 81, No. 1, January, pp. 293-298.

Authors' Abstract: *The Virginia Dale Precambrian ring-dike complex, at the extreme south end of the Laramie Range, was first recognized by W. A Braddock in 1962 from high-altitude air photos. This roughly circular feature is well expressed on 1957 early side-looking airborne radar (SLAR) imagery, from which in 1965 it was independently noted as a striking geomorphic (domal) anomaly. This particular imagery example illustrates the notable potential of radar imagery in general for delineation of larger scale elements, especially lineament patterns*

The Virginia Dale complex is believed by the current authors to be of particular significance, not only for its relevance to precambrian history, but also for possible influence on Phanerozoic events here, and in particular for its possible bearing on location of the Ferris-Aultman and other associated Paleozoic diatremes (copyrighted by GSA).

Radar was extremely useful in identifying a previously unknown geological feature.

WING, R. S. and L. F. DELLWIG, 1970b

Tectonic Development of the Eastern Panamanian Isthmus as Revealed Through Analysis of Radar Imagery

Presented at the Annual Meeting, Geological Society of America, Milwaukee 11-13 November.

Authors' Abstract: *A medial basin, extending the length of the eastern Panamanian Isthmus, separates the Pacific coastal ranges (composed mostly of andesite flows with some basalt) from the Caribbean coastal ranges (generally of andesite flows in Darien Province, but including also granite, granodiorite and some syenite in the western Darien and San Blas*

ranges). A belt of north-trending en echelon anticlines bisects Darien Province, extends northwestward across the Pacific Hills, and culminates in large-scale faulted folds adjacent to the east end of the Maje Range. A similar strain pattern in the Maje Range is reflected by longitudinal faults, left-lateral offsets, and related internal folds. (1) The radical difference between basement lithologies of the Pacific coastal ranges of eastern Panama and of the western Darien and San Blas ranges, and (2) the great alignment of left-lateral adjustments, define a major basement block boundary along this great alignment, with left-lateral movement between the two longitudinal blocks it separates.

The Panamanian Isthmus is situated in the southwest corner of the Carribbean plate which, it is postulated, has been subject to compression through active translation of the South American plate. Eastern Panama has apparently been subject to left-lateral simple shear deformation because of the oblique orientation of the principal compressive stress relative to the nonhomogeneous make-up of the Isthmus. In addition, the Caribbean plate has been moving slightly eastward, relative to South America, thus accounting for observed right-lateral trans-isthmian distortion, notably from San Miguel Bay to the Caribbean. (Copyrighted by GSA).

WING, R. S., W. K. OVERBEY, Jr., and L. F. DELLWIG, 1970

Radar Lineament Analysis, Burning Springs Area, West Virginia - An Aid in the Definition of Appalachian Plateau Thrusts

Bulletin of the Geological Society of America, Vol. 81, No. 11, November, pp. 3437-3444.

Authors' Abstract: *Geomorphic analysis of radar imagery covering an east-west 18-km-wide swath, from Sandyville to Camden, West Virginia, has revealed a striking polygonal topographic pattern. This pattern is apparently an erosional response to varying combinations of at least six fracture sets (strike, dip, and two conjugate shear pairs), related to one-time movement of a great thrust sheet, extending westward from the Appalachian Front to the Burning Springs anticline. The preferred fracture sets were apparently rotated up to 10 degrees counter-clockwise in the Burning Springs area in accordance with "pileup" of the leading edge of the thrust sheet The decollement movement permitted a maximum of the possible fracture sets to advance beyond the incipient stage of development. Immediately west of the Burning Springs anticline, there is notably less expression of the polygonal pattern and only two fracture sets are strongly expressed.*

There was good correspondence between air photo lineament patterns, radar imagery lineament patterns, and surface joint strikes measured in the Burning Springs area. However, air photos generally revealed short lineament segments, whereas the synoptic radar presentation revealed lineups of segments, hence, long integral fracture zones.

The fracture pattern inferred through radar imagery interpretation and confirmed by surface measurement is reflected in the outlines of some oil fields in the area (Copyrighted by GSA).

AN/APQ-97, K-band, HH polarization radar was used. The cross-polarized image was not used in the analysis because the cross-polarization apparently added little unique data to this study. Some problems of blurring and image distortion were encountered. There is a short discussion of metric measurements. Synoptic aspects of radar make it superior, but supplemental, to aerial photographs.

WING, R. S., H. C. MacDONALD, and L. F. DELLWIG, 1970

Tectonic Analysis from Radar - Central and Eastern Panama

Meeting of the South-Central Section of the Geological Society of America, held at College Station, Texas, 2–4 April 1970.

Geological Society of America, Abstracts with Programs, Vol. 2, No. 4, February, pp. 305–306.

WING, R. S. and H. C. MacDONALD, 1973a

Radar Imagery Identifies Hidden Jungle Structures

World Oil, Vol. 176, No 5, April, pp. 67–70.

Authors' Summary: *An aircraft radar survey in eastern Panama gave surface imagery of nearly inaccessible terrain that could not be photographed due to heavy cloud cover. Examples show how typical jungle terrain reflects data on potential hydrocarbon formations*

Following a brief review of the history of radar geology and of geological mapping in the Panamanian area, the authors present an image showing one area of Panama. On this image, detailed analysis showing karst topography, fault blocks, synclinal trends, the Canazas anticline, and several faults is presented. Some suggestions concerning the importance of this imagery for reconnaissance petroleum exploration are given. The broad synoptic coverage and the allweather capabilities of radar are of special importance in this type of work.

WING, R. S. and H. C. MacDONALD, 1973b

Radar Geology-Petroleum Exploration Technique, Eastern Panama and Northwestern Colombia

American Association of Petroleum Geologists Bulletin, Vol. 57, No. 5, May, pp. 825–840.

Authors' Abstract *Petroleum exploration in eastern Panama and northwestern Colombia has gained impetus by recent side-looking radar, geologic reconnaissance mapping. Radar derived geologic information is now available for approximately 40,000 sq km where previous reconnaissance investigations have been extremely limited because of inaccessibility and almost perpetual cloud cover*

With radar imagery as the sole source of remote sensing data, the distribution, continuity, and structural grain of key strata provide evidence that the eastern Panamanian Isthmus can be divided into three main physiographic-structural parts Two composite coastal mountain ranges separated by the taphrogenic Medial basin, which trends southeastward from the mouth of the Bayano River to the Atrato River valley of northwestern Colombia. Within the Medial basin, most of the clearly exposed surface structures are not particularly attractive petroleum prospects because prime reservoir strata have been stripped from their crests. However, several large geomorphic anomalies which have been mapped in the Medial basin may be reflections of subsurface structures having a complete stratigraphic section. Possibilities for gravity-type hydrocarbon accumulations in fractured organic shales, siltstones, and carbonate rocks are suggested within several synclinal elements along the axis of the Medial basin. The southwestward extension of the Medial basin trend, coincident with the western Gulf of Panama may have potential as a future petroleum-producing province. A relatively thick marine stratigraphic section should be present here, with associated paralic and deltaic

clastic rocks derived from acidic San Blas terrace since mid-Miocene time. The occurrence of active shell bars in the Bay of San Miguel and present reef trends on the northern Caribbean coast suggest possible offshore sites for geophysical surveying. (Copyrighted by AAPG).

This paper is an addition to the numerous papers concerning the radar imagery interpretation and applications of the Panamanian and Colombian border zones. Consequently, the reader should consult the other publications in order to obtain a complete picture. It contains numerous excellent radar images and discusses the operation of an imaging radar and the geology of the study area. Again emphasized is the point that the geologic data derived from the imagery was determined by surrogates - and there is a need for topographic or vegetal differentiation, related to the geology, in order to properly use the radar for even reconnaissance geologic mapping. (Of course, the K-band radar has essentially no penetrating ability in the jungle environment.)

WING, R. S. and J. C. MUELLER, 1976

SLAR Reconnaissance, Mimika-Eilander Basin, Southern Trough of Irian Jaya

Proceedings of the NASA Earth Resources Survey Symposium: First Comprehensive Symposium on the Practical Application of Earth Resources Survey Data, Vol. I-B, pp. 599-604, Technical Session Presentations. Geology - Information Systems and Services.

TM X-58168, National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, Texas (NTIS N76-17502).

From the Authors' Abstract: *The SLAR was obtained in early April 1973 by Westinghouse for Conoco by means of an AN/APQ-97 K-band brute-force system. The flight strips are all north-look, with ground range display, and 60% overlap. The interpretation was compiled on a 1/100,000-scale mosaic, but the actual mapping of contacts, dips, lineaments, and the like, was done on 1/100,000-scale stereo-strips. Initial regional mapping was intended as an aid in determining that part of the Southern Trough most likely to be underlain by relatively unmetamorphosed paralic Kembelangan sandstones ideally interdigitated with marine source and cap shales. SLAR reconnaissance mapping met a subsequent need to rapidly and inexpensively narrow the search to that part of the "Fairway" coincident with a favorable structure. The SLAR mosaic clearly displays the Irian mountains, strongly and gently folded foothills belts, and the Southern front of the fold belt south of which is a large complex of alluvial fans. The mosaic also shows various drainage anomalies in the alluvial covered area south of the gently-folded belt. Some of these are coincident with hilly areas and are considered as possibly indicative of reef draping or deeper structures.*

In this study area, which received approximately 5 m of precipitation per year, occasional data holidays were seen due to the heavy precipitation. The southern edge of the alluvial fan-complex was marked by ponds, whereas the northern apex was clearly shown by braided stream patterns. Other large drainage anomalies suggest underlying structure and may reflect a hingeline. The SLAR provided excellent display of fault and fracture lineaments. Use of the stereo-pairs of SLAR aided in the selection of possible seismic lines. The SLAR data, coupled with previous seismic data, has permitted the mapping of many anticlines and the alignments between anticlines. Registry of the SLAR stereo was difficult; vertical exaggeration was similar to what would be seen from 20,000 feet by the naked eye. The authors note that SLAR is a relatively inexpensive reconnaissance tool, and, although they do not claim it is superior to aerial photography, it was the best remote sensing data available and served its purpose well.

WISE, D. U., 1967

Radar Geology and Pseudo-Geology on an Appalachian Piedmont Cross Section

Photogrammetric Engineering, Vol. 33, No. 7, July, pp. 752–761.

Author's Abstract: *Vegetative and cultural patterns are the most prominent fabric elements on side looking, K-band radar imagery of the Appalachian Piedmont along the Susquehanna River of Pennsylvania and Maryland. Geologic contacts appear as more subtle changes in topographic grain, relief, or in changes in forest cover, field shape and orientation. Some dikes and small fracture zones stand out clearly as reflections from steep slopes, small gulleys, elongate meanderpatterns, and linear forest patterns. Other similar-appearing, prominent linears are pseudo-geologic features caused by tree lines having bare trunks exposed to the view of the aircraft and orientations of 10 to 30 degrees to the line of flight. Flight orientation also causes anomalous radar signature of the city of Lancaster, Pennsylvania, with sections of town with streets at 40 to 50 degrees to the flight line yielding almost no radar return. (Copyrighted by the American Society of Photogrammetry.)*

A listing and identification on radar imagery and an accompanying map of 44 separate features (geological, cultural, etc.) emphasizes that radar imagery does not show all features equally well and is best used in conjunction with other data sources.

WISE, D. U., 1969

Pseudo-Radar Topographic Shadowing for Detection of Sub-Continental Sized Fracture Systems

Proceedings, Sixth International Symposium on Remote Sensing of the Environment, Report No. 31069-2-X, Willow Run Laboratories of the Institute of Science and Technology, The University of Michigan, Ann Arbor, October, pp. 603–615.

Author's Abstract: *Radar imagery of real topography or photos of side illuminated raised plastic relief maps enhance many elements of linear topography, particularly those valleys with strikes at acute angles to the light source so that illumination grazes one of the walls. Dozens to hundreds of topographic linears appear on all relief maps examined with scales from 1:62,500 to 1:1,000,000. They are commonly arranged in six to eight strike sets with individual linears persisting for a hundred miles or more, the sets themselves continuing for many hundreds of miles. Complex fracture networks occur with constant orientations over vast areas of North America, Europe, and Iceland, some elements of the networks being correlatable with known fault or fracture systems. The systems extend without change to the edges of continents, they extend unchanged across portions of the Mediterranean; they are strongly developed on the youthful crust of Iceland; they are independent of local curvatures and geometry of the mountain systems in which they occur, they continue unchanged from the Appalachian region into the youthful Coastal Plain The relations suggest tectonic heredity of older systems being propagated upward through youthful covering sediments and/or manifestations of near-modern stress trajectories of constant orientation over areas of at least sub-continental dimensions.*

The shadow enhancement technique applied to plastic relief permits rapid mapping of the linears over vast areas; the requirement of the same linear appearing under a variety of lighting directions provides some control on operator generated pseudo-linears. The method may be a much cheaper and easier technique than traditional photo linear analysis or radar linear analysis The problems with illumination azimuth and selective enhancement of certain linears suggest the need for caution in radar linear analysis and in lunar photo linear analysis. On the other hand, radar flight lines could be designed to bring out pre-selected linear features in a region by using the charts presented.

Comparison is made between radar images and side lighting of raised relief maps, with emphasis on geologic analysis.

WITHINGTON, C. F. and F. H. JACOBEEN, Jr., 1973

Possible Implication of Lineaments in the Atlantic Coastal Plain as Seen by Satellite Imagery

Remote Sensing of Earth Resources, Vol. II, Edited by F. Shahrokhi, Tullahoma, Tenn., xv + 1306 pp., pp. 981–996.

Authors' Abstract: *For almost a century there has been speculation concerning the presence of geologic structures in the unconsolidated sediments of the Atlantic Coastal Plain, but because of the nature of these sediments, little evidence of any structural features can be seen on surface examination. Some faults have been reported from surface exposure but their extent could heretofore only be determined by extensive subsurface exploration.*

With the advent of remote sensing techniques of data gathering there is a definite possibility of identifying hitherto unsuspected structural features. Numerous lineaments, at least some of which representing fault traces, have been recognized in coastal plain sediments on Side Looking Airborne Radar imagery (SLAR) and satellite photography. To date, only one of these lineaments has definitely been identified as the trace of a fault, but further examination will probably show that most of the other lineaments are also related to faulting. The large number of lineaments found by remote sensing suggests that faulting of the Coastal Plain is more prevalent than has previously been suspected. The one lineament proven as a fault trace shows up on a SLAR image of parts of southern Maryland. This lineament represents the trace of a northeast-trending reverse fault that extends from southern Charles County through Prince Georges County. Other lineaments that have been identified so far, appear on SLAR imagery of the eastern shore of Maryland and Delaware, and on Apollo 9 photography of Virginia and North and South Carolina. ERTS-1 imagery will prove invaluable in locating further lineaments.

If the lineaments discovered by remote sensing do, indeed, represent traces of faults, movement of the Coastal Plain sediments is more recent and of a different character than has generally been recognized. The environmental effect that these movements could have on the future development of the Coastal Plain should be emphasized. A whole new concept of the structural and seismic history of the Coastal Plain will result from these studies.

Although one SLAR image from 1972 is included in the paper, there is no discussion of this image other than that included in the paper's abstract.

WOLFE, E. W., 1966

Radar Imagery: Salton Séa Area, California

U.S. Geological Survey Technical Letter – NASA-29, Washington. May, 16 pp. (NTIS No. N70 38937).

Abstract: *The San Andreas fault is marked by low hills near Durmid and linear tone changes along the northeast shore of the Salton Sea. Presumably, the tone change reflects juxtaposition of contrasting lithologies along the fault. The contact between alluvium (dark) and Tertiary bedrock (light) is sharply defined along the edge of the Mecca Hills. (From Carter, W. D., 1969.)*

WOLFE, E. W., 1969

Geologic Evaluation of Radar Imagery, Caliente and Temblor Ranges, Southern California

U. S. Geological Survey, Interagency Report - NASA-133, Open File Report, January, Washington, iv + 29 pp. (NTIS No. N69-16988).

From Author's Conclusions: *The prime factor controlling brightness in the Carrizo Plain radar images is slope orientation. Surfaces that face the scanner at high angles are bright; those that face the scanner at low angles are represented by intermediate tones, those that face away from the scanner are black in the radar image. Differences in radar reflection related to slope orientation are most distinct in the like-polarized (HH) images.*

Microtopography exerts a subordinate effect that is most distinct in the cross-polarized (HV) images. In the Temblor Range, the Santa Margarita conglomerate (relatively rough surface) is bright in the image, and the shale units (relatively smooth surface) are dark in the image.

The radar used was K-band (approximately 1 cm). The paper includes two geology maps and 10 radar images.

NTIS INDEX

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AD 624 887	Cameron, H. L., 1965
AD 638 919	Rydstrom, H. O., 1966
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AD 701 902	Barr, D. J., 1968
AD 715 322	Wing, R. S., 1970
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AD 802 104	Lundien, J. R., 1966
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N 76 29693	Dellwig, L. F., B. C. Hanson, N. E. Hardy, P. L. Hulen, J. R. McCauley, and R. K. Moore
N 78 30635	Daily, M., C. Elachi, T. Farr, W. Stromberg, S. Williams, and G. Schaber, 1978
N 78 33644	MacDonald, H. C., and W. P. Waite, 1977
N 78 33645	Evans, D. L., 1978
N 79 12268	MacDonald, M. C., and W. P. Waite, 1978

L-BAND IMAGERY

Fig. 1. Cumberland Plateau, Kentucky, and Tennessee – Seasat data. This Seasat SAR L-band image of the Appalachian Valley and Ridge Province was taken in July 1978 (orbit 407). Cover is mostly dense mixed deciduous and coniferous forest. Image is optically correlated and digitally mosaicked. Knoxville, Tennessee, and Tennessee River at lower left. Middlesboro, Kentucky, and Cumberland Gap at upper middle right. Abundant natural lineaments mostly reflect topographic slope change. Strong radar layover, especially at left center, occurs at slopes of 30° or greater.

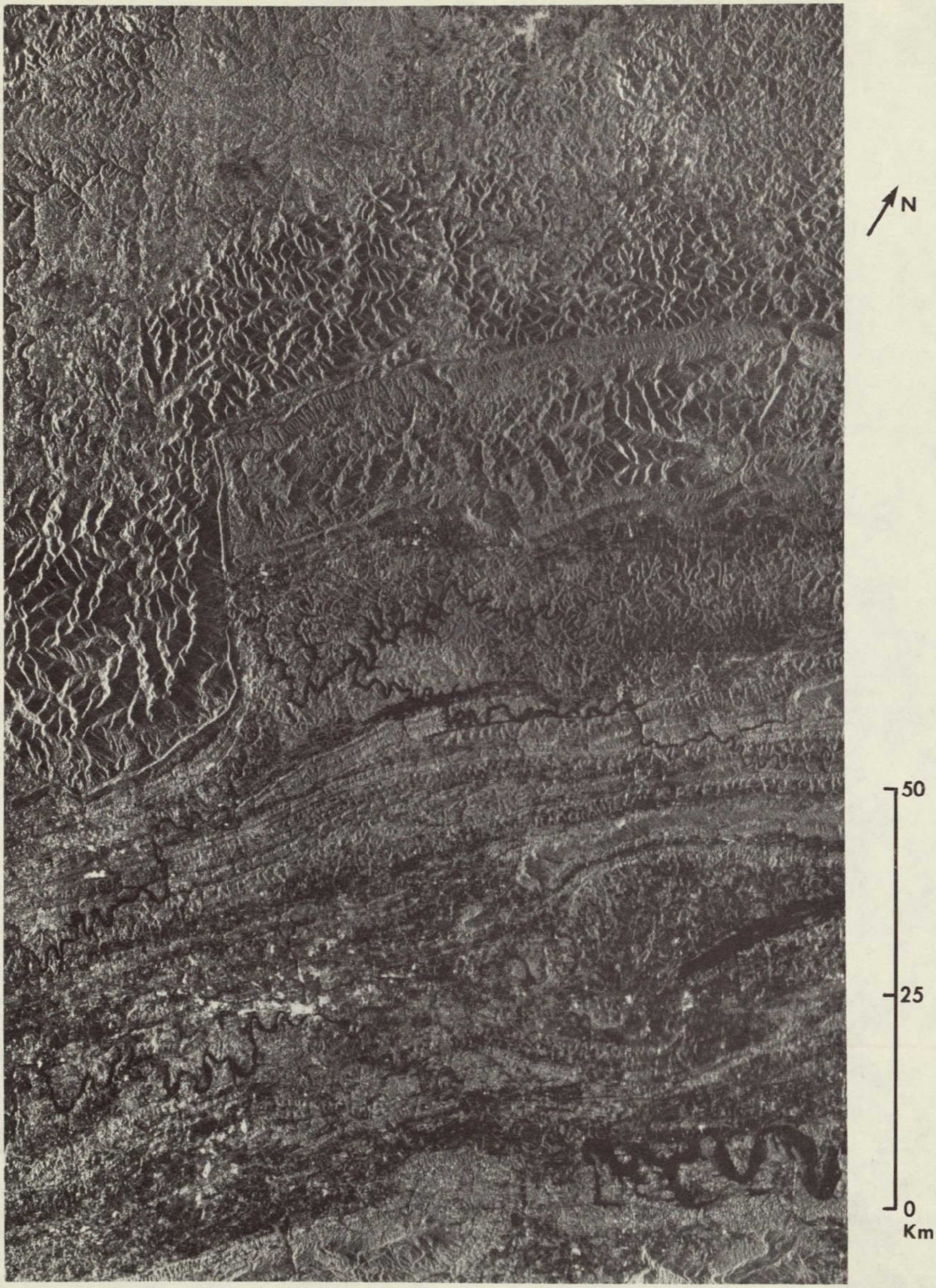

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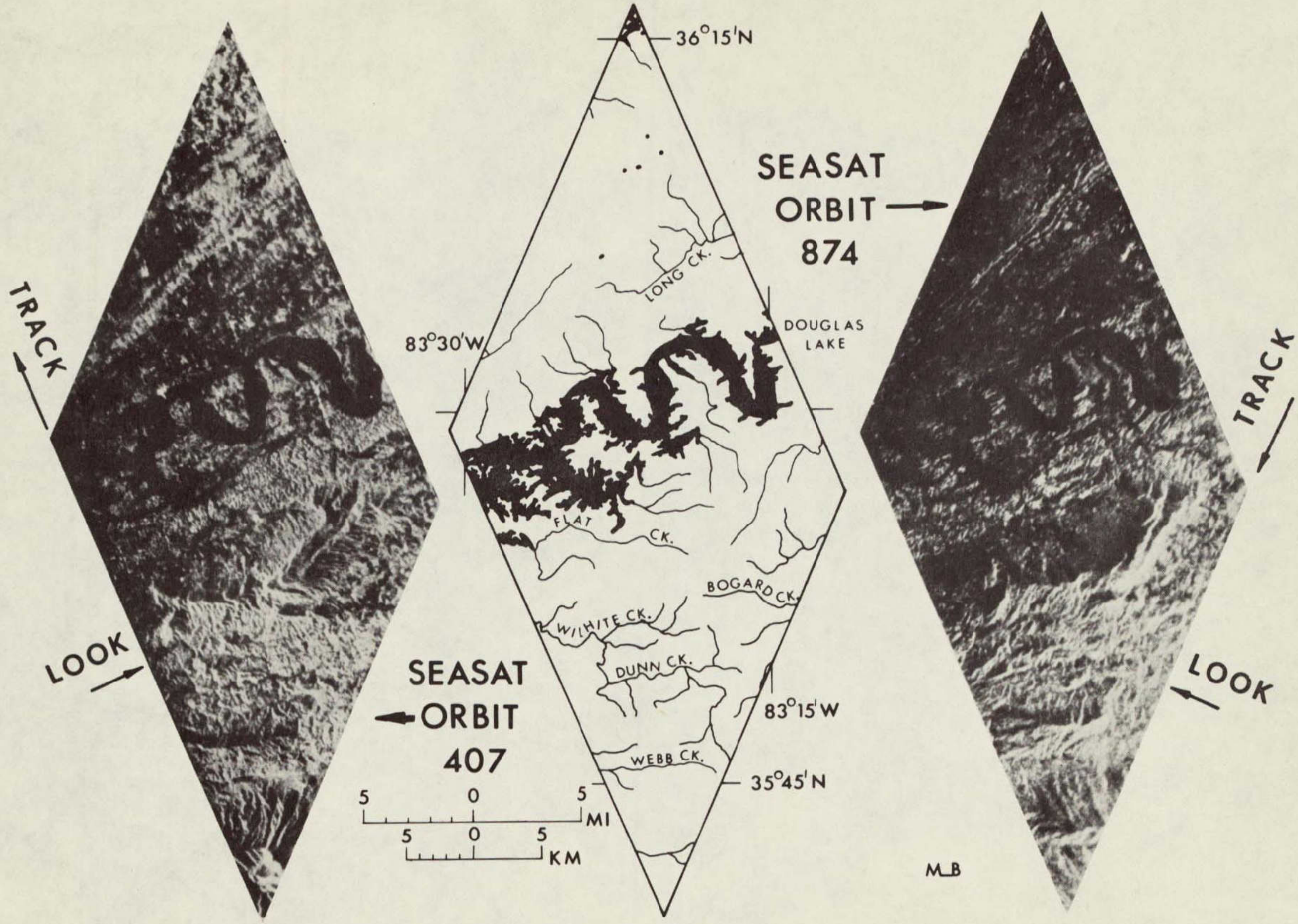
Fig. 2. Cumberland Plateau, Kentucky, and Tennessee - detail of Seasat data shown in Fig. 1. Two Seasat-A orbits (407, 874) illustrate the effect of different look directions on the resulting optically correlated imagery. Especially in the area to the southeast of Norris Lake, this effect is noted where the ridges are strongly enhanced on Orbit 874 (looking across the ridges) and considerably subdued on Orbit 407, which looks along the ridges.


TRACK
LOOK
SEASAT
ORBIT
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36°15'N
LONG CK.
DOUGLAS
LAKE
83°30'W
FLAT CK.
BOGARD CK.
WILHITE CK.
DUNN CK.
83°15'W
WEBB CK.
35°45'N
5 0 5 MI
5 0 5 KM
SEASAT
ORBIT
874
TRACK
LOOK
M_B

Fig. 3. Aircraft radar imagery of the Los Angeles Basin. The Jet Propulsion Laboratory L-band (HH) synthetic aperture imaging radar was used to collect this image of the Los Angeles basin on May 25, 1977. A set of eleven flight lines, with a radar look direction of east or west (flight lines were oriented north and south) were corrected for geometry and intensity, and digitized and mosaicked using computer assistance. Many of the large dark gray areas are the result of the look direction of the radar and the street patterns. A discussion of this mosaic will appear in: Bryan, M. L., "The Effect of Radar Azimuth Angle on Cultural Data", Photogrammetric Engineering and Remote Sensing (to be published, Fall 1979).


Uncontrolled
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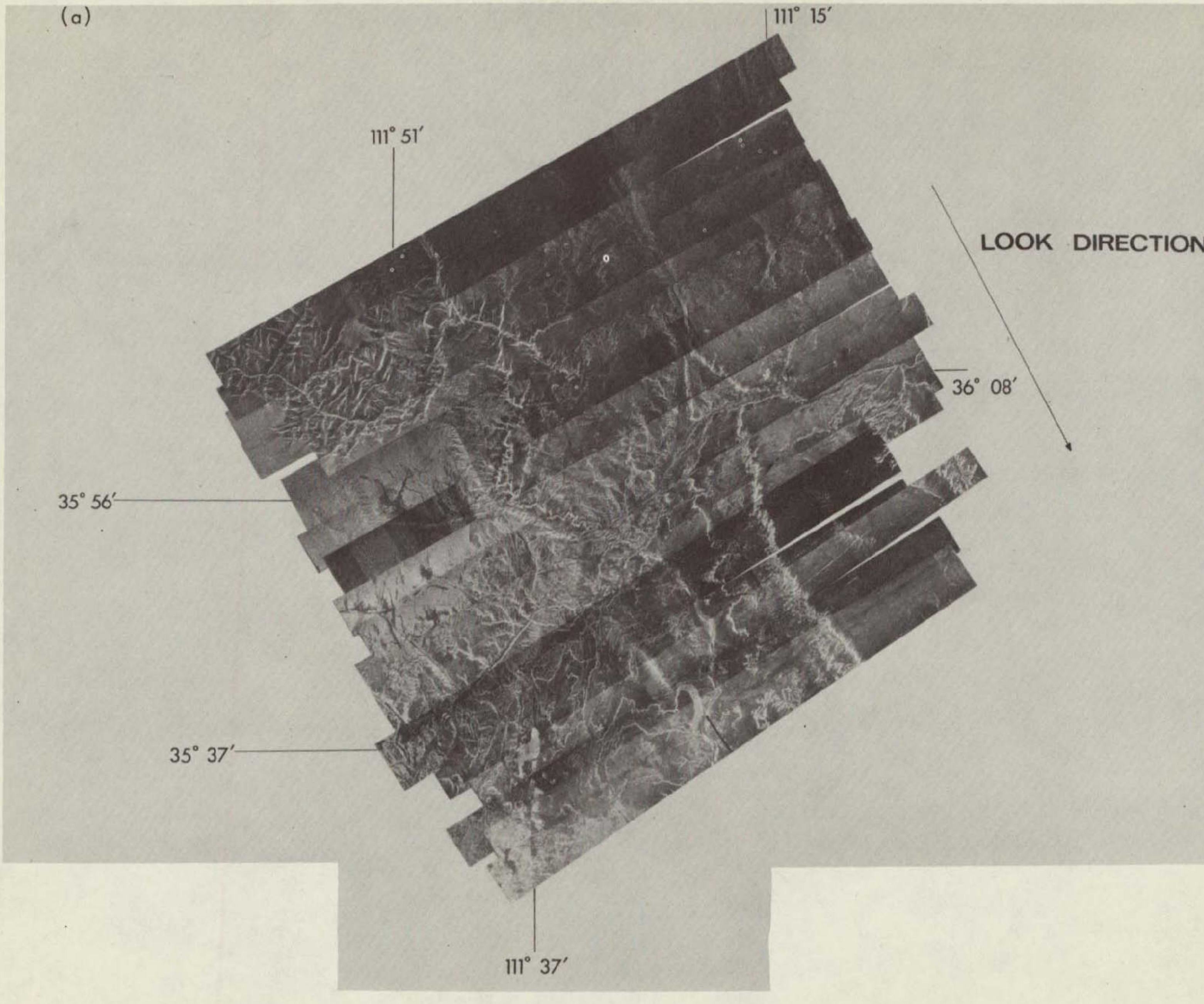
N
0 2 4 6 Mi
0 2 4 6 8 KM

Fig. 4. VOIR radar simulations of the Flagstaff-Grand Canyon area, Arizona. This set of three images of optically correlated and manually mosaicked aircraft L-band radar data were obtained over the Grand Canyon, Arizona, during April and May of 1978. Two parameters of the radar output illustrate the effect of look direction and resolution changes. Resolutions of 25 and 50 meters and look directions of northwest and southeast are illustrated. The data were collected using the Jet Propulsion Laboratory's synthetic aperture imaging radar. (a) Resolution, 25 meters; number of looks, 4; look angle, $45^{o} \pm 5^{o}$; look direction, southeast. (b) Resolution, 50 meters; number of looks, 8; look angle $45^{o} \pm 5^{o}$; look direction, northwest. (c) Resolution, 50 meters; number of looks, 8; look angle $45^{o} \pm 5^{o}$; look direction, southeast.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35° 37′
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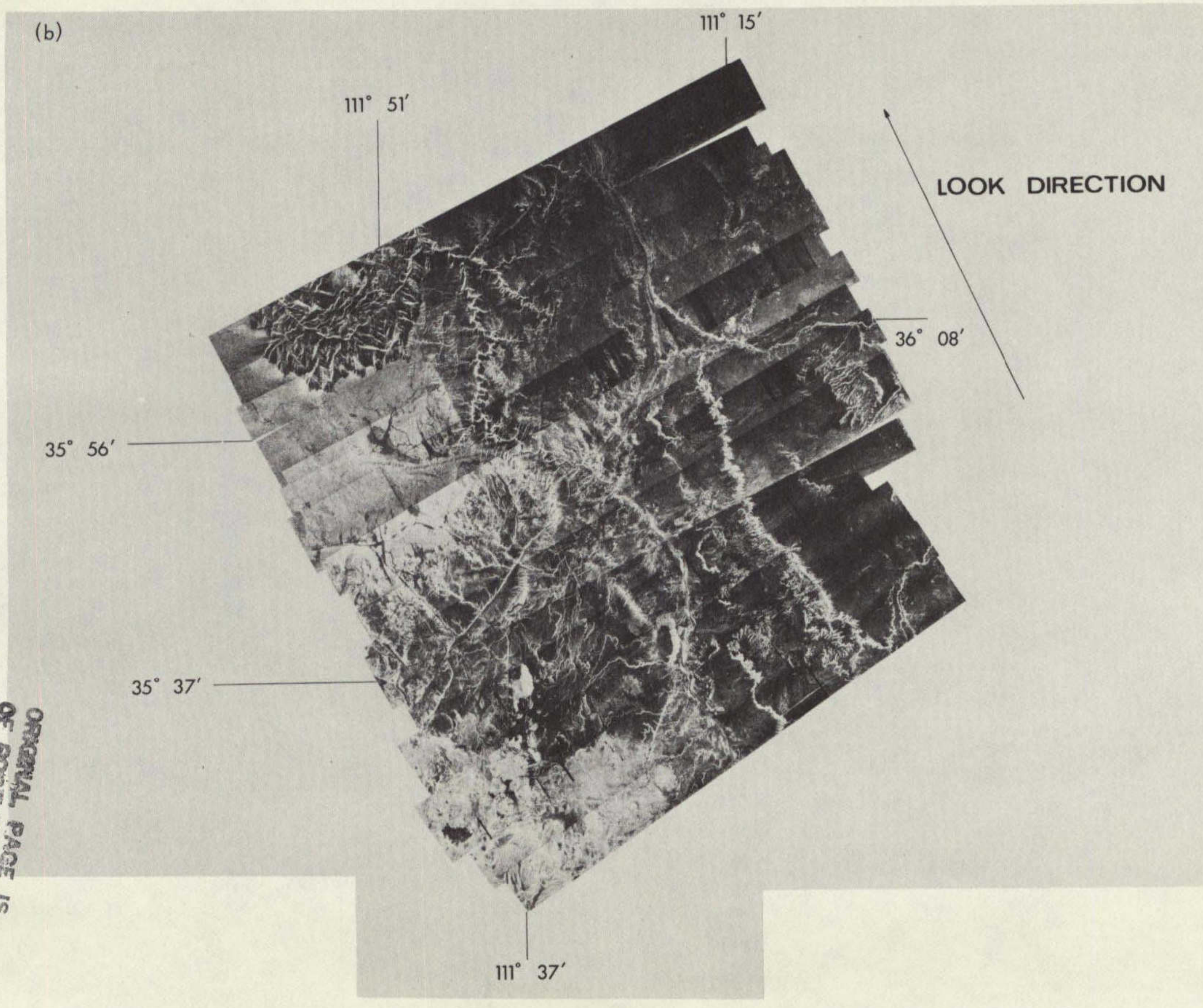
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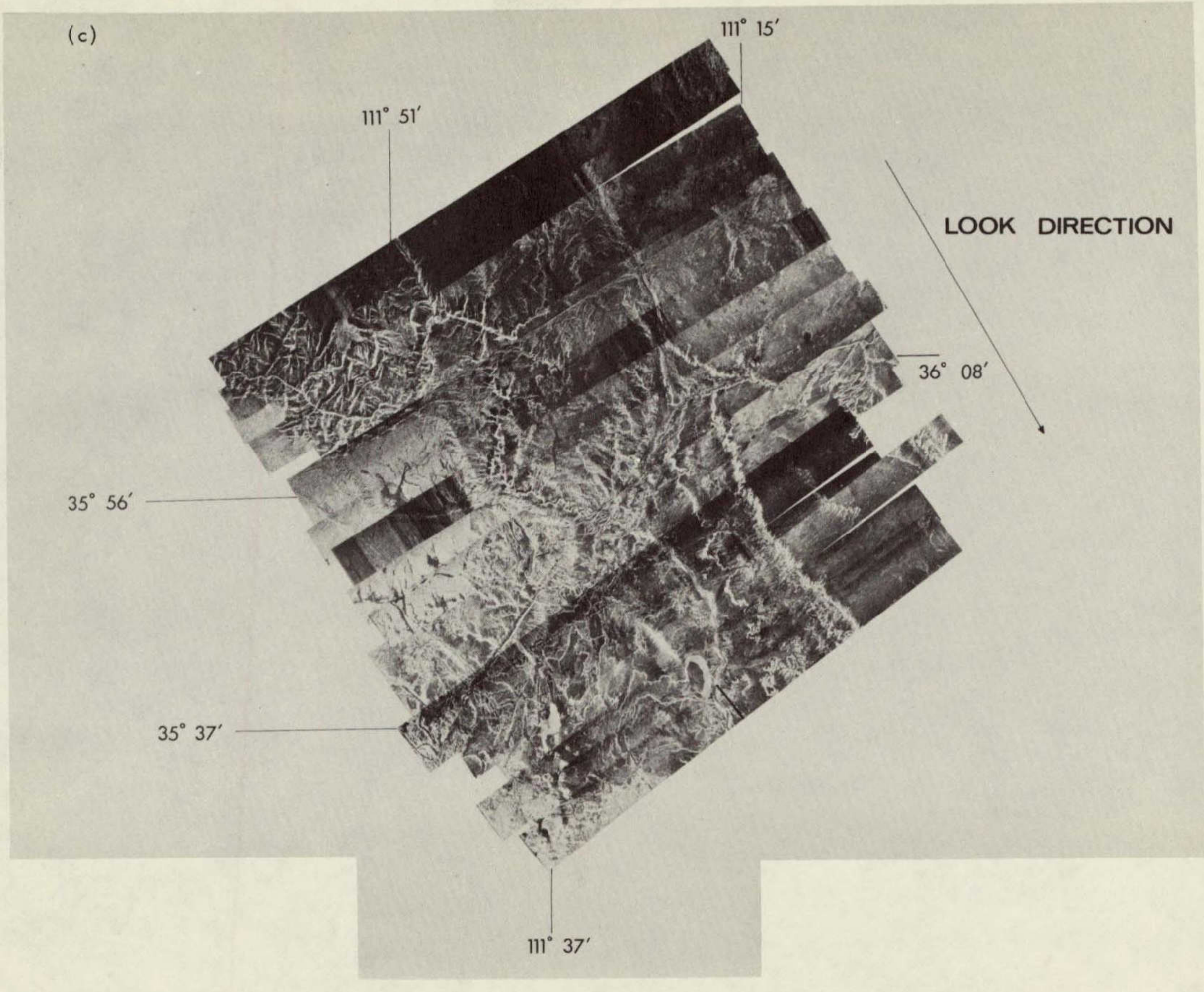
(c)
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35° 56′
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111° 37′

Fig. 5. Radar image of the Riverside region (Southern California). Lake Perris is visible in the center right of the image, and the city of Riverside is in the center left. San Bernardino is in the top left center. City blocks and highways are seen. Highway 10 is in the upper left. The San Jacinto fault zone is across the upper right at the edge of the Badland Hills. Cultivation fields in the Perris Valley and San Jacinto Valley are visible on the right side.

This image was acquired by the Synthetic Aperture Radar (SAR) aboard the Seasat-A satellite (orbit 1291), and was processed digitally at the Jet Propulsion Laboratory using the Interim Digital Processor (IDP). Current throughput capability of the IDP is approximately one Seasat-A 100 km x 100 km frame per fourteen hours of processing time. Radar illumination is from right to left. The image covers an area of 32 km along track (left to right) by 36 km cross-track, and has a 25-meter resolution and 4 looks.

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