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APPLICATIONS REVIEW FOR A SPACE PROGRAM IMAGING RADAR
(SPIR)

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GEOGRAPHY REMOTE SENSING UNIT

GRSU Technical Report 1

EDITED: D.S. Simonett

July, 1976



National Aeronautics and Space Administration
LYNDON B. JOHNSON SPACE CENTER
Houston, Texas



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APPLICATIONS REVIEW FOR A SPACE PROGRAM IMAGING RADAR
(S P I R)

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Supported by:

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Lyndon B. Johnson Space Center

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A NOTE ON THE PREPARATION OF THIS REPORT

This report is the second of two items prepared under Contract NAS 9-14816 for the Johnson Space Center, Houston, by a Space Program Imaging Radar study group funded through a contract (NAS 9-14816) with the University of California, Santa Barbara.

The first item was a major briefing to NASA Headquarters personnel by the members of the study group. The texts and view graphs prepared for the briefing have been expanded, and modified, fleshed out with recent published and unpublished materials, and documented with appropriate references to constitute this report. All members of the study group have participated in the preparation of one or more of the chapters in the report.

In addition, the following persons have provided illustrative materials, published and unpublished texts and written materials which have been incorporated in the appropriate chapters: F.T. Ulaby, M.L. Bryan, C. Elachi, F. Leberl, E. Hajic, and J. Jensen.

The members of the Space Program Imaging Radar (SPIR) Study Group are given on the following page.

SPACE PROGRAM IMAGING RADAR

—SPIR—→

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CHAPTER 1

SPACE PROGRAM IMAGING RADAR (SPIR)

INTRODUCTION AND EXECUTIVE SUMMARY †

SUMMARY

The advantages of space program imaging radar(s) are:

- * Resolutions compatible with LANDSAT D.
- * All-weather capability to guarantee total or sample coverage, and to bridge cloudy areas with other sensors.
- * 6-octave bandwidth, providing multiple channels to improve discrimination.
- * Clearly differentiated wavelengths for various applications.
- * Only region where some vegetation penetration is feasible.
- * Control of look direction and look angle for improving identification.
- * Providing multiple polarization and texture discrimination capability.
- * Selected applications where radar would be a unique sensor include flood monitoring, soil moisture determination, sea ice mapping, and multi-look geological exploration-mapping.

RECOMMENDATIONS

We have three recommendations:

- * NASA should place an imaging radar on Space Shuttle, which offers an ideal platform with adequate size, and power.
- * The Shuttle radar imager should be multifrequency and multipolarization, with at least one long and one short wavelength. Candidate frequencies appear to be around 4 GHz, and between 14 and 18 GHz.
- * NASA should provide (through a central facility) Shuttle digital radar computer-compatible tapes to users, geometrically rectified to be compatible with LANDSAT D (or then-equivalent satellites). This will ensure maximum user acceptance. In some instances these should be at least partially theme-processed.

† Prepared by D.S. Simonett

INTRODUCTION

The National Aeronautics and Space Administration (NASA) is much concerned with having the case for any space sensor clearly documented as to user needs, and support, and with clear evidence of technical capability which can withstand critical scrutiny within NASA, by the user community, and by the Office of Management and Budget. This report reviews needs, applications, user support, and empirical research and theoretical studies with imaging radar. We believe the case for a Space Shuttle radar imager is now close to strong enough that a commitment to build such a radar could be made within a year or so.

Following this overview, summary of applications and recommendations, eight chapters are given which deal in turn with the applications of radar and supporting research in:

- * Water resources: emphasis on soil moisture, flood area, snow accumulation and melt, and watershed parameters.
- * Mineral and petroleum exploration: emphasizing fracture lineament analyses to improve the sighting of oil and gas wells, mine roof instability, gravity ground water, and prospective mineral locations.
- * Vegetation resources: crops, pastures, and forests.
- * Ocean radar imaging: waves, sea and lake ice, icebergs, oil spills.
- * Cartography: small-scale mapping, mosaicing.
- * State and regional examples: water in California, sea ice/energy in Alaska, saline seeps in the Northern Great Plains, wetlands on the Gulf Coast.
- * Federal agency interests: Example - Department of the Interior
- * Roles for shuttle radar: experiments, concepts, hardware development.

What is the state of documentation of space radar applications today? It is really much akin to the situation with the visible sensors just before the launch of LANDSAT. 1. There is lots of promise, a mixed bag of hard, medium, and soft evidence, much research still remaining, but a good theoretical base. In fact, we think the theoretical base for radar is very strong, principally

because as evidence accumulates our theoretical expectations are generally confirmed. There are three major differences in comparison to the situation before the launch of LANDSAT. It is worth dwelling on these briefly:

- 1) The resources devoted by NASA to radar have been very small, probably less than ten percent of those devoted to the visible and infrared regions,
- 2) There are few users who have in-depth analytical experience with radar, while many are familiar with the optical region,
- 3) Despite this situation, the amount of significant evidence is surprisingly large.

With a wider array of people well experienced with radar and with a more substantial data base to work with, we believe the case for a space radar imager would have already been made.

In the Fall of 1974, the Active Microwave Workshop was held in Houston, and much of the research that is documented in there, of 1973 or earlier vintage, is summarized in this study. We have also leaned heavily on a significant body of research over the last three years, much published since January, 1975, but a good deal still to be published.

RADAR HAS MANY ADVANTAGES

The question could be asked why should NASA and the user community bother with radar? These are some of the advantages radar will bring to the space program. First, resolutions the same as LANDSAT D (30m) will be obtained with radar and the imagery should be capable of merging both optically and particularly digitally. Figure 6.7 shows an optical merge of an area near Tucson, Arizona. Digital merging experiments are underway at NASA's Wallops Island facility, and it is proposed to digitally merge radar imagery obtained during a June, 1976 radar flight, coincident with LANDSAT II passage over the Lacie Super-site near

Garden City, Kansas.

Second, the all-weather capability will enable radar to meet federal agency demands for data in a compressed time frame. Examples of such time demands are the June 15th U. S. Department of Agriculture crop acreage estimate, the July 15th so-called drop dead date of the U. S. Department of Agriculture for crop production estimates, daily soil moisture needed by the National Oceanographic and Atmospheric Administration and the Army Corps of Engineers, for incorporation in soil moisture modeling procedures, and the December 15th plow down date in California for the pink boll worm (California has a mandatory requirement of plowing in cotton by a certain date in order to interrupt the breeding cycle).

Third, the all-weather capability will also enable agency requirements to be met for either a proper sample design and coverage or total coverage, a requirement not capable of being met except under the most unusual of circumstances in the visible region. Examples of agency requirements in this area are the United States Department of Agriculture acreage, yield, and production estimates, and the Soil Conservation Service and National Oceanographic and Atmospheric Administration watershed water yield estimates.

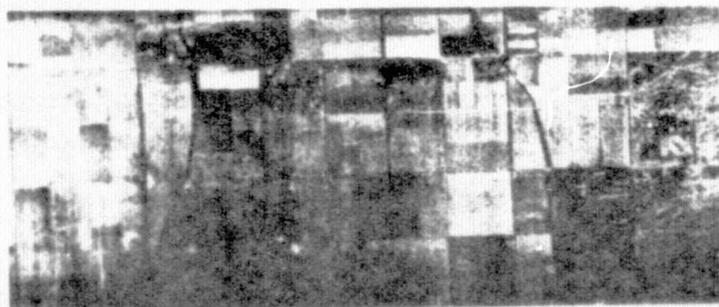
Fourth, space radar covers six octaves, similar in range to the visible plus the near and the thermal infrared which covers five octaves. The radar region which can be used in space covers from about one centimeter to 64 centimeters.

Fifth, there is clear evidence of both spectral and polarization sensitivity of radar. In Figure 1.1 is shown an area east of Gilbert, Arizona, as recorded in X and L-Band parallel (HH) polarization and cross (HV) polarization. A systematic comparison between the X and L-Band parallel polarizations, the two cross polarizations, and between like and cross at a given wavelength, clearly shows differences in each band and each polarization. It would be easy to prepare a color combination of these strikingly different bands if they were at the same

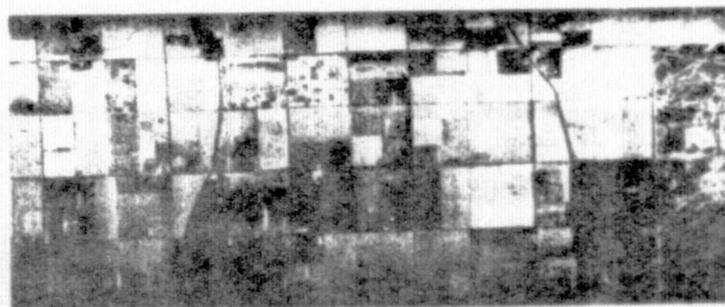
SIMULTANEOUSLY OBTAINED DUAL FREQUENCY RADAR IMAGERY

APRIL 5, 1974

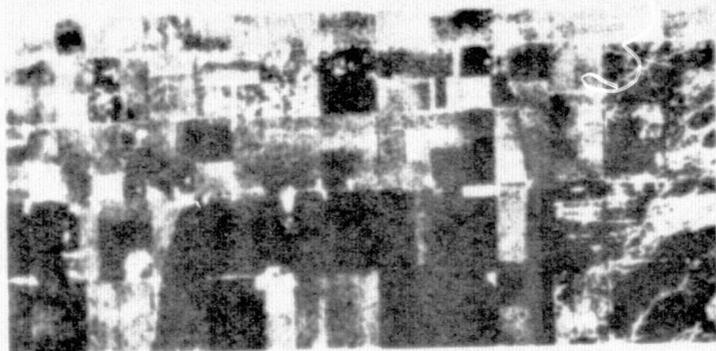
AGRICULTURAL TEST EAST OF GILBERT, ARIZONA



X-BAND PARALLEL POLARIZATION
30' x 30'



X-BAND CROSS POLARIZATION
30' x 30'



L-BAND PARALLEL POLARIZATION
30' x 30'



L-BAND CROSS POLARIZATION
30' x 30'

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ORIGINAL PAGE IS POOR

vertical and horizontal scale. This would make the point most effectively. Unfortunately when one looks closely at the photographs it is seen that the images are not at the same vertical and horizontal scale. The magnitude of the differences is such that it is an unambiguous indication that crops have different responses in different parts of the radar spectrum and of radar polarization. Numerous examples of this X and L-Band system are given in later chapters. These differences are fully as great, or greater, than four wavelength bands in the visible near-infrared and thermal infrared. When added to the latter they would very substantially increase the power of our observations. It would be specifically one of the aims of the space program imaging radar to support the LANDSAT imaging systems, to extend observations with LANDSAT, to reinforce the conclusions of LANDSAT, and for those parts of the world where cloudiness is quite pervasive substitute if necessary for LANDSAT D.

Sixth, just as in the visible region there are clearly differentiated microwave regions for different applications. For example, soil moisture appears to be best determined at about 7.5 cm. (4 GHz) and near-nadir incidence angles, whereas vegetation discrimination seems optimal in the 2 centimeter (14-18 GHz) region. The near-nadir incidence angles (7-15°) for the best results with soil moisture determination is not unexpected because we wish to see mostly soil and very little vegetation. On the other hand, if we look at oblique angles mostly vegetation is seen. We also therefore find that high incidence angles in the 40-50° range seem mostly to be optimal for vegetation. In addition, the sensitivity of the soil moisture response in decibels also increases as a function of declining incidence angles.

Figure 1.2 shows examples of this soil moisture sensitivity. Further examples are to be seen in Chapter 2.

Seventh, the radar region is the only area in the electromagnetic spectrum suitable for some penetration of vegetation and soils, coupled with high

RADAR IS SENSITIVE TO SOIL MOISTURE

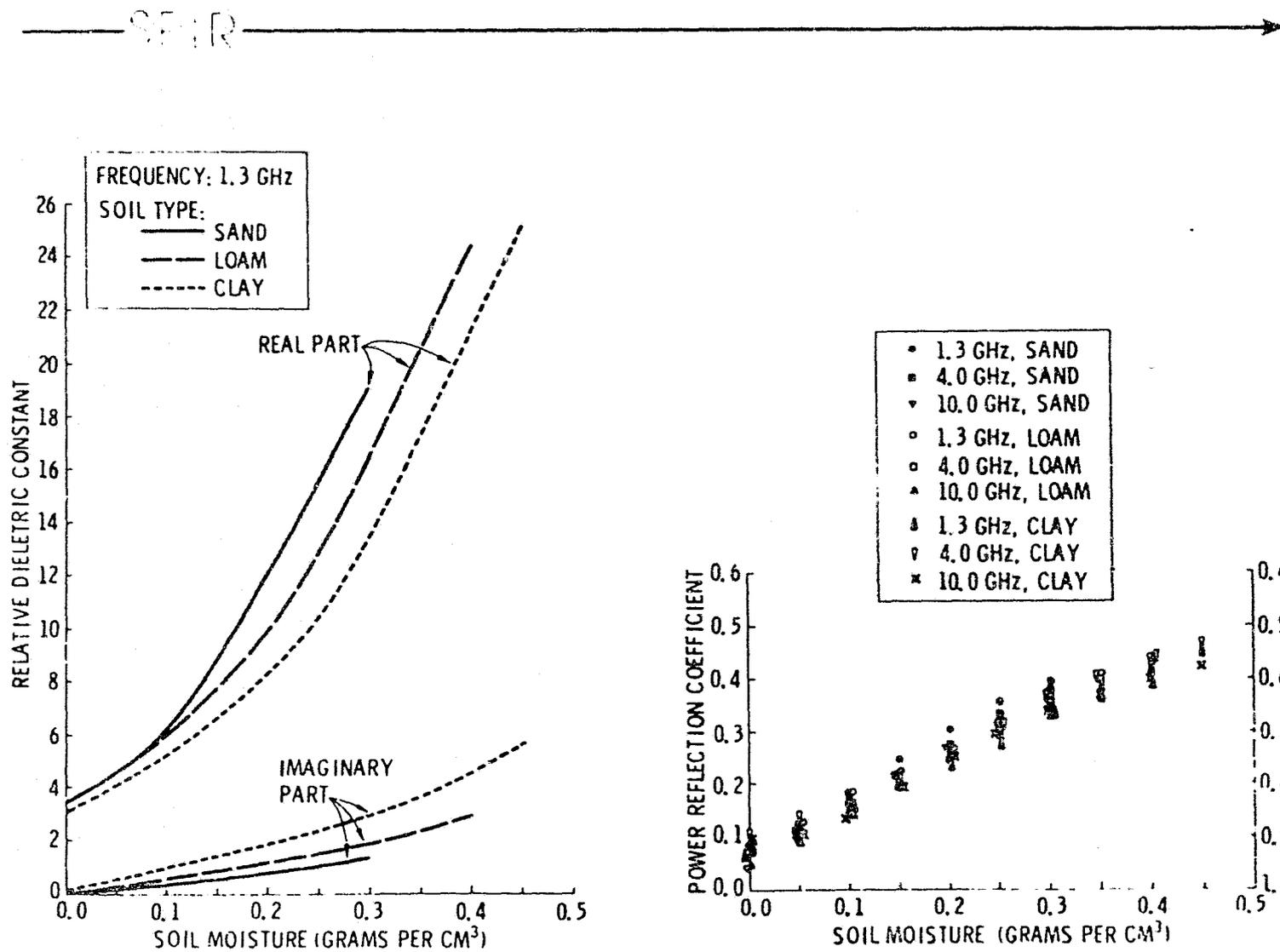


Figure 1.2
1-7

resolution. Thus, at short wavelengths reflections come principally from the upper leaves and the moisture in the upper leaves of trees, pastures and crops. As progressively longer and longer wavelengths are used, penetration into the twigs, stem, trunk and then the ground layer takes place. Clearly then radar will be differentially sensitive as a function of wavelength depending upon the complex scattering geometry arising from differential penetration of the upper layers of vegetation, or of soil in bare or lightly-vegetated regions.

Eighth, radar systems have look direction under their control and look angle under their control to a degree not feasible in the optical, passive region sensors in which the angles for given latitudes and times of day are simply constrained by the solar illumination period. This can be important in seeking to differentially emphasize geologic, vegetation and other features in both high and low latitudes, using if necessary the same angles in widely spread latitudes, something not feasible if the angles are extreme (near-nadir and near-grazing).

Finally, the radar region is the only area of the electromagnetic spectrum where wavelengths are of the order of the sizes of natural and artificial surfaces. Consequently, the physical dimensions of objects become a factor in the radar return which is not the case in the optical region. Also, many natural surfaces appear smooth to only slightly rough at the longer wavelengths and produce different responses from the optical region as a result.

RADAR WILL SUPPORT OTHER SENSORS

Radar will support other sensors in the following ways:

- * Guaranteeing coverage - through its cloud and rain penetrating capability.
- * Bridging cloudy areas - sample designs in agriculture could be built which would use visible and radar sensors for crop identification and a sample area enumeration in regions where there were no clouds and then for the cloudy regions just using the radar alone. The Statistical Reporting Service of the USDA is in fact currently looking at designs of this type to work with LANDSAT data.

- * Providing additional channels for improving digital identification. This point may be emphasized strongly by returning to Figure 1.1 of the agricultural test area east of Gilbert, Arizona. What do these images have that will add information to the visible and thermal channels? First, we know from studies by Simonett, et al. (1967) and more recent studies by Ulaby and associates in Kansas (1974, 1975, 1976) that radar is sensitive to crop geometry. In fact, it is the differences between crops to which radar is most sensitive. Parametric variables such as percent ground cover, height of crop, contained crop moisture, and so on, while important are rather lesser contributors to the return signal than the between-crop geometric differences. This means that the radar region can identify crops, but that the basis for identification is the complex back-scattering geometry which is different to the situation in the visible and near infrared. If digital merging proves experimentally feasible, as there is every reason to believe it will, from initial studies at Wallops Island this would strengthen the reasons as to why it is important to the LANDSAT thematic mapper to have radar images in support. It would guarantee coverage and ensure meeting agency commitments on a time and sample design basis. It should also improve identification accuracies and significantly it should enable systems information transfer between the multispectral scanner and the radar system. In a properly integrated remote sensing system information tends to flow back and forth between the components of the system. Supporting sensors can substitute or even be the prime sensor when the appropriate relationships are established. In Chapter 6 (Figure 6.7) is seen an optical merge of LANDSAT and radar imagery.
- * Providing stereoscopy - from space altitudes radar can obtain stereoscopy imagery of great assistance in identification, just as well as it can from aircraft altitudes. We know already that stereoscopy greatly improves mapping of natural drainage systems, geologic interpretation, and natural vegetation mapping. With sufficiently high resolution it is also of considerable value in agricultural mapping as well. These items have been documented in depth in Project RADAM in the Amazon where in Brazil over eight million square kilometers and other portions of Brazil have been covered with imaging radar, on a one-time basis.
- * Providing multiple/control look angles in tropical and polar areas constrained by sun-synchronous missions. Look directions other than solar illumination can be obtained in both high and low latitudes at times of the year when they could not be obtained using the sun's illumination.
- * Providing a whole new set of energy-matter interactions - the radar wavelengths mean that radar is sensitive to dielectric variations and surface roughnesses of scales that other regions of the EM spectrum are simply not sensitive to.
- * Providing different textural characteristics - recent studies with LANDSAT data has shown improvements in crop and other identification accuracies coming from incorporating texture algorithms with multi-spectral pattern recognition routines. Physical region texture and radar texture are dissimilar, just as they are in other aspects of energy/matter interactions. With digital merge we will have a double barreled effect available to us of multi-spectral and texture accuracy improvement procedures.

IMAGING RADAR WILL BE THE PRIME SENSOR WITH UNIQUE ROLES

Radar imagery will be the prime sensor with unique roles for a number of applications simply because of the cloud cover problem, or because of radar's sensitivity to surface roughness, and the effects of dielectric of contained moisture. These areas where imaging radar will be the prime sensor with unique roles are:

- * Flood area monitoring when needed in the presence of clouds and rain.
- * Surface and sub-surface soil moisture estimation.
- * Snow melt estimation when needed and with high resolution.
- * Sea, lake ice, and iceberg detection, identification and tracking.
- * Oil pollution with high resolution.
- * Crop acreage/production improved estimation in very cloudy environments.
- * Mineral and petroleum exploration in very mountainous and/or cloudy regions.

These unique roles are also summarized along with complementary roles for radar in Table 1.1.

Complementary roles where radar can support other sensors, but would not normally carry the full burden of the application, are also to be found in the following areas:

- * Agriculture/range/forestry - crop identification, range/forest inventory and soils mapping.
- * Water resources - snow accumulation/melt/snow moisture, surface water surveys, glacier monitoring, coastal wetlands mapping and water pollution.
- * Mineral/petroleum and geology - ground water exploration, major construction sites and construction material surveys.
- * Ocean dynamics - oil spill monitoring, ship routing, ocean salinity, coastal processes monitoring, oil pollution.
- * Disaster assessment - wind damage, fire damage, earthquake damage, volcanic activity (see also Table 1.1).

TABLE 1.1— POTENTIAL ROLES OF RADAR WITHIN APPLICATIONS AREAS.

Applications Area	Unique Roles*	Complementary Roles†
Agriculture/Range/ Forestry	Soil moisture, cover condition, saline seep detection and monitoring.	Cover identification, range/forestry inventory, soils mapping.
Water Resources	Flood monitoring, flood forecasting (soil moisture), watershed monitoring.	Snow accumulation/melt/snow moisture ^{††} , surface water surveys, glacier monitoring, coastal wetlands mapping, water pollution.
Mineral/Petroleum and Geology	Multi/look direction, fracture lineament detection, geological mapping ^{**} .	Ground water exploration, major construction sites and construction material surveys.
Ocean Dynamics	Sea waves measurement, storm monitoring and forecasting, sea ice/iceberg surveys.	Oil spill monitoring ^{††} , ship routing ^{††} , ocean salinity, coastal processes monitoring, pollution.
Disaster Assessment	Flooding	Wind damage, fire damage, earthquake damage, volcano activity.

* Cannot be done by other sensors satisfactorily.

† Radar can support other sensors.

**In persistently cloudy area.

††If radar experiments prove successful, these applications may shift to unique roles.

QUALITY OF EVIDENCE FOR RADAR APPLICATIONS

There is very good evidence - and a demonstrated need for space radar - and with high user priority for the following applications areas:

- Soil moisture determination
- Flood area monitoring
- Crop discrimination
- Crop production estimation improvement
- Plant biomass
- Mineral exploration, petroleum exploration
- Sea and lake ice
- Iceberg monitoring
- Ocean ship monitoring/navigation.

By good evidence we mean that while further research will alter the weights and strengthen some of these areas, the general relationships are not likely to change much.

Other applications areas generally of high priority for identified federal and state agencies and the private sector, but for which the evidence is not so strong, containing either ambiguities or just very preliminary studies are, ocean waves, snow accumulation and melt, oil spills, land use, land ice monitoring, and urban study areas. Sometimes in these latter areas the evidence is based more on theoretical justification than on well documented empirical evidence. However, in the right context a good theoretical argument is adequate although it is clear that in the coming years significant empirical data will need to be accumulated on these areas.

SPACE RADAR VERSUS AIRCRAFT RADAR

In bringing this brief introduction to a close we need to address the question of why a space radar, rather than an all-aircraft development of special-purpose images.

There are four principal reasons why space (and in particular a Shuttle) radar is appropriate. The first is that resolution with synthetic aperture antennas is independent of altitude. The second is that we need incidence angles

not obtainable easily with aircraft for many experiments and for many operational monitoring procedures. The third is that we require rapid large-area, widely-separated coverage for certain experiments and for operational usage and this is best met with space radar. Finally, insofar as shuttle is concerned, shuttle is already committed and is an ideal platform with adequate power and weight for experiments, applications, and defining the parameters needed for operational free-flyer radars. We believe Shuttle should carry an imager on it.

RECOMMENDATIONS

We have three recommendations:

- * NASA should take advantage of the unique capability of shuttle to carry an imaging radar.
- * The radar should be multifrequency and multipolarization. The frequencies should be widely separated. At this time the most suitable frequencies seem to be 4 GHz for the long wavelength region, and between 14 and 17 GHz for the short wavelength region.
- * NASA should establish a central facility to process the radar data into highly usable products. This will insure maximum user-agency acceptance, and use of the data. Digital radar computer compatible tapes should be provided geometrically rectified to be compatible with LANDSAT D and later follow on satellites. These preferably should also be at least partially theme-processed.

EXECUTIVE SUMMARY

The Executive Summary has been prepared by taking the first page of each chapter. On these first pages each author has given a brief summary and one or more recommendations. These nine chapter heading pages now follow.

CHAPTER 1

SPACE PROGRAM IMAGING RADAR (SPIR)

INTRODUCTION AND EXECUTIVE SUMMARY †

SUMMARY

The advantages of space program imaging radar(s) are:

- * Resolutions compatible with LANDSAT D.
- * All-weather capability to guarantee total or sample coverage, and to bridge cloudy areas with other sensors.
- * 6-octave bandwidth, providing multiple channels to improve discrimination.
- * Clearly differentiated wavelengths for various applications.
- * Only region where some vegetation penetration is feasible.
- * Control of look direction and look angle for improving identification.
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We have three recommendations:

- * NASA should place an imaging radar on Space Shuttle, which offers an ideal platform with adequate size, and power.
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- * NASA should provide (through a central facility) Shuttle digital radar computer-compatible tapes to users, geometrically rectified to be compatible with LANDSAT D (or then-equivalent satellites). This will ensure maximum user acceptance. In some instances these should be at least partially theme-processed.

† Prepared by D.S. Simonett

CHAPTER 2

MICROWAVE SENSING OF WATER RESOURCES +

SUMMARY

The overall conclusions of this analysis of active microwave remote sensing and water resources are:

- * There is a unique match between the observation capability with space radar and the requirements for better observations of fundamental hydrologic parameters and events.
- * To improve monitoring and management of water supplies we need to develop space radar as rapidly as possible.
- * Optimal parameters for soil moisture determination now seems likely to be in the range of 4 GHz, 7-15 degree incidence angles, and either VV or HH polarization. We need promptly to expand these ground-based studies with aircraft and space systems.
- * Fundamental and applied radar studies are needed in snow depth, condition, liquid water content, and fresh water ice to bring these areas rapidly to maturity for operational space sensing.

RECOMMENDATIONS

The Space Program Imaging Radar Program should:

- * Implement flood monitoring promptly with SEASAT, and Space Shuttle Imaging radar.
- * Significantly strengthen and expand research in active microwave aircraft and ground based monitoring of soil moisture, snow condition, thickness, and liquid water content, and fresh water and land ice monitoring.
- * Define applications science experiments and preliminary operations tests in these areas for Space Shuttle.
- * Examine cost/benefit studies for all areas of water resource monitoring for active microwave in manned and satellite-radar imaging systems.

+ Prepared by V.V. Salomonson and D.S. Simonett, including materials supplied by F.T. Ulaby.

CHAPTER 3

SPACE SHUTTLE IMAGING RADAR ROLES IN MINERAL AND PETROLEUM EXPLORATION[†]

SUMMARY

Significant applications of a Shuttle Program Imaging Radar, in support of mineral and petroleum exploration principally, but not exclusively in the form of one-time benefits (during the lifetime of shuttle) will include:

- * provisions of multiple controlled look angles at any location (This is not possible with sun-synchronous passive sensor missions). These will enable improved geologic structural mapping and interpretation, hence improving the exploration base.
- * provision of multiple look directions, other than those given by solar illumination, to further add to and thereby improve structural interpretation and exploration, over those observed with LANDSAT.
- * multi-season observation with controlled look angles and directions, thereby allowing season to be a pure discriminant.
- * multi-frequency effects leading to some vegetation penetration and wavelength-particle size interaction to infer lithologic information.

RECOMMENDATIONS

The Shuttle Program Imaging Radar Program should:

- * include provision for both day and night observations to obtain the widest array of look directions (including orthogonal).
- * be at least two-frequency, one of long wavelength.
- * be multiple polarization to aid in lithologic and lithology-related discrimination.
- * include an R and D phase before the Shuttle launch to more fully investigate parametric relations between frequency, polarization, and ground conditions and cover, in order to parameterize space observations more completely.

[†] Prepared by H.C. MacDonald.

CHAPTER 4

VEGETATION RESOURCE ANALYSIS WITH RADAR †

SUMMARY

The major conclusions reached on vegetation studies with radar are:

- * High levels of crop identification will be achievable with multi-frequency, multipolarization, multi-date radar imagery.
- * There are strong frequency dependencies in discrimination between crops, pasture and forest lands.
- * Polarization is an important discriminant in crop, pasture and forest identification.
- * The temporal element is a key component of plant community or crop identification.
- * Radar texture is an important discriminant of natural vegetation, and with high resolution, of crop land as well.
- * Stereoscopy aids in natural plant community inventory and monitoring.

RECOMMENDATIONS

The Space Program Imaging Radar Program should:

- * Vigorously pursue development of additional multifrequency/polarization radar spectrometers to extend the work initiated at the University of Kansas to a wide range of environments.
- * Move expeditiously to expansion of aircraft-based multiplex radar studies over natural and cultivated vegetation.
- * Conduct research rapidly in vegetation in order to define suitable specifications for a Shuttle Radar optimized in part at least for vegetation analysis.

† Prepared by David Simonett using materials supplied by F. T. Ulaby and F. P. Weber.

CHAPTER 5

SPACE RADAR APPLICATIONS FOR OCEAN AND SHIP MONITORING[†]

SUMMARY

The dominant areas of oceanographic information needs to which a Space Imaging Radar can contribute are:

- * ship navigation and routing
- * ice surveillance
- * environmental wave forecasting and general circulation patterns
- * hazard detection, pollution monitoring, fishing vessel monitoring
- * ship and coastal structures design
- * coastal structures placement

RECOMMENDATIONS

Space Program Imaging Radar Program should:

- * conduct more research to establish quantitative relations between radar image characteristics and wave and surface parameters including wave height, wind strength and direction, precipitation and others. This knowledge should also lead to relations between the wave spectrum and the image two-dimensional spectrum.
- * include additional research on radar observation of internal waves, extreme sea state, especially in hurricanes, and on wave generation under a wide variety of conditions.
- * continue the extensive experiments on sea ice and iceberg discrimination and dynamics.
- * develop operational information systems incorporating the above research, and real-time data for improving ship-routing, climatological understanding and weather forecasting, structure design and environmental monitoring.
- * define the roles for space shuttle imaging radar experiments in support of the SEASAT program.

[†] Review prepared by Earl J. Hajic and David S. Simonett, incorporating materials provided by Paul Teleki, M. Leonard Bryan, and Charles Elachi.

CHAPTER 6

SPACE SHUTTLE IMAGING RADAR AND ITS APPLICABILITY TO MAPPING, CHARTING, AND GEODESY[†]

SUMMARY

The most significant Mapping, Charting, and Geodesy (MC&G) applications of Space Program Imaging Radar will include:

- * continued small scale planimetric mapping (1:50,000)
- * small scale map revision
- * geoscience applications of radar imagery geometrically merged with other multispectral data (e.g. Landsat D & Space Shuttle Radar)
- * positioning of maritime floating aids, ships, and icebergs
- * mapping of lake and polar sea ice
- * contingency flood mapping

RECOMMENDATIONS

Space Program Imaging Radar Program should:

- * conduct more intensive research on classical mapping tasks such as stereoradargrammetry, block adjustment, and absolute/relative point positioning. Space Shuttle will serve as an excellent testbed to develop these techniques and expand radar's capability beyond reconnaissance type mapping.
- * be geometrically correct (orthoradar), radiometrically correct, and partially theme processed to a mapping projection (e.g. UTM) for maximum user application. Space Shuttle will provide a testbed for the creation of such data prior to a dedicated orbital satellite.

[†] Prepared by J. Jensen and F. Leberl and including materials provided by A.B. Park and D.S. Simonett.

CHAPTER 7

STATE APPLICATIONS OF A SPACE PROGRAM IMAGING RADAR[†]

SUMMARY

This chapter discusses four case studies representative of the use of radar for state and regional level planning and monitoring:

- * California - Managing the water resources for 1/10 of the nation's population.
- * Alaska - Sea ice affects our nation's ability to exploit critical energy resources.
- * Texas - Monitoring coastal environments where 3/4 of our nation's population live.
- * Northern Great Plains Region - Saline seeps create problems for agriculture.

RECOMMENDATIONS

The Shuttle Program Imaging Radar Program should:

- * conduct a specific study on the range of applications of active microwave systems data to state and regional planning and inventory requirements.
- * initiate a program to make state and regional entities aware of the potential of active microwave data to meet their data/information needs.
- * provide information concerning the current availability of active microwave data to states and regions.
- * provide microwave data for application to state and regional level information needs which are geometrically and radiometrically corrected.

[†] Prepared by John E. Estes, Earl Hajic and John Jensen.

CHAPTER 8

FEDERAL AGENCY REQUIREMENTS

EXAMPLE: DEPARTMENT OF THE INTERIOR[†]

SUMMARY

In this chapter is presented a series of tables containing the requirements for spatial resolution, expressed as instantaneous field of view (IFOV), and for observation frequency for tasks of the several Agencies and Bureaux of the Department of the Interior. These tasks were those for which an imaging radar would have some applicability.

The figures given for IFOV suggest that the bulk of these tasks could be met by a space imaging radar with 25 meters presentation resolution, namely, the resolution already proposed for a Space Shuttle imaging radar.

The range of tasks involves principally areas where observations are needed of water, snow, ice, bare soil and rock, moisture in the soil, and various classes of natural and cultivated vegetation. These tasks would require at least a 2 frequency, multiple polarization system for the levels of identification accuracy needed. The frequencies which at this time appear of greatest interest are 4 GHz and the 14 to 18 GHz region. However, there will clearly be particular applications over the range of wavelengths from 64 cm (0.47 GHz) to 1 cm (30 GHz). These remain to be defined by appropriate experiments.

RECOMMENDATIONS

The Space Program Imaging Radar study group should:

- * Examine these IFOV and observation frequency requirements to determine how well the SEASAT and Space Shuttle program radars will be able to meet the requirements under different operating constraints.

[†] Prepared by G. A. Thorley.

CHAPTER 9

SOME ROLES OF SHUTTLE RADAR[†]

SUMMARY

There are three primary roles for a Space Shuttle Imaging Radar:

- * The performance of experiments that can only be performed from a space platform and for which aircraft just will not do the job. These include experiments requiring a narrow range of incidence angles, comparisons between widely separated areas, experiments involving gradations of conditions over large areas, remote area coverage, and problems requiring synoptic coverage.
- * The testing of applications concepts and hardware techniques for future space radars. Applications over large areas such as soil moisture, sea ice, and vegetation stress are included. Hardware concepts would involve antenna studies, processing and display, and spacecraft SAR performance.
- * Support of development of future SAR's for unmanned spacecraft. Shuttle has the great advantages of flexibility, and greater capability of power, swath width, resolution and multiple test frequencies. It also will have the ability to test system parameter variations and hardware concepts, and to concentrate on areas of interest found by small-spacecraft instruments.

RECOMMENDATIONS

We have three recommendations:

- * NASA should place an imaging radar on Space Shuttle.
- * This radar should be multifrequency and multipolarization. The frequencies should be widely separated.
- * NASA should provide Shuttle digital radar computer compatible tapes to users, geometrically rectified to be compatible with LANDSAT D. These should also be at least partially theme-processed.

[†] Prepared by R.K. Moore

CHAPTER 2

MICROWAVE SENSING OF WATER RESOURCES +

SUMMARY

The overall conclusions of this analysis of active microwave remote sensing and water resources are:

- * There is a unique match between the observation capability with space radar and the requirements for better observations of fundamental hydrologic parameters and events.
- * To improve monitoring and management of water supplies we need to develop space radar as rapidly as possible.
- * Optimal parameters for soil moisture determination now seems likely to be in the range of 4 GHz, 7-15 degree incidence angles, and either VV or HH polarization. We need promptly to expand these ground-based studies with aircraft and space systems.
- * Fundamental and applied radar studies are needed in snow depth, condition, liquid water content, and fresh water ice to bring these areas rapidly to maturity for operational space sensing.

RECOMMENDATIONS

The Space Program Imaging Radar Program should:

- * Implement flood monitoring promptly with SEASAT, and Space Shuttle Imaging radar.
- * Significantly strengthen and expand research in active microwave aircraft and ground based monitoring of soil moisture, snow condition, thickness, and liquid water content, and fresh water and land ice monitoring.
- * Define applications science experiments and preliminary operations tests in these areas for Space Shuttle.
- * Examine cost/benefit studies for all areas of water resource monitoring for active microwave in manned and satellite-radar imaging systems.

+ Prepared by V.V. Salomonson and D.S. Simonett, including materials supplied by F.T. Ulaby.

INTRODUCTION AND BACKGROUND

Increasing population, the commensurate need for more food and energy, and a general desire for an improved quality of life by nearly all people creates a demand for more water. Responsible projections of global water demand and use indicates that they will increase by a factor of 3 to 5 by the year 2000. To accommodate this increased demand will require that existing water supplies within a given area be managed more efficiently and that the feasibility of inter-regional transfers of water from regions of plenty to regions of scarcity be carefully evaluated.

To improve the efficiency of water use and monitor water supplies for interregional transfers requires an observing system that can effectively monitor water supplies over large areas. Satellite observing systems are ideal for this task in that they inherently provide the large-area, synoptic view on a repetitive basis. The purpose of this presentation is to detail the contributions spaceborne, radar imaging systems can offer in meeting this need.

A system effectively monitoring and inventoring water supplies is viewed as being an attractive possibility for meeting priority needs by many government agencies at all levels. These agencies have mandated responsibilities for monitoring and managing water supplies. Examples of Federal agencies and relevant offices, are:

- * U.S. Department of Agriculture (Agricultural Research Service, Soil Conservation Service, and U.S. Forest Service)
- * U.S. Department of the Interior (U.S. Geological Survey, U.S. Bureau of Reclamation, Bureau of Sport Fisheries, Bureau of Land Management, etc.)
- * U.S. Army Corp of Engineers

Many state agencies also have mandated responsibilities in water monitoring and management. Typically there are a dozen or so agencies, or offices

in each state and thus Nationwide there are some 500 groups at this level. In addition there are a wide range of regional and local agencies. These range in size from groups of states, in large watersheds, through groups of counties to individual counties. In all there are many thousands of such regional and local agencies with responsibilities in these areas.

A variety of specific needs for water resource information have come to light during the preparation of this report. Typical applications of these data are in assessing flood potential and watershed yield, crop yield prediction, irrigation efficiency improvement, snowpack monitoring, reservoir management and watershed planning and waterworks design. In nearly all cases these data are needed to provide essential input to models that are used by agencies as their major management decision-making mechanism. Many of these watershed models are presently limited by the accuracy and timeliness of their input data. They are, nevertheless, the major mechanisms used for watershed management, engineering design studies and a wide range of decisions on water storage and release, water allocation policy and similar areas. The Agricultural Weather Service of N.O.A.A., for example, needs data on soil moisture levels for formulating agricultural Weather Advisories and for modelling crop-weather relationships. The Office of Hydrology, also of N.O.A.A., needs to observe and model soil moisture and snow cover and equivalent liquid water content for river discharge forecasts as well as mapping flood extent for areas of major flooding.

Examples of other documented Federal agency needs are as follows:

BUREAU OF RECLAMATION/USDI

- * Snowfield mapping for runoff prediction
- * River ice for ice jams and flooding
- * Watershed surface drainage characteristics

- * Soil moisture for irrigation drainage investigation and planning

WATER RESOURCES DIVISION/USGS/USDI

- * Identification of water surfaces to delineate flood hazard area
- * Seasonal snowcover monitoring
- * Glacier monitoring for hazardous behavior

SOIL CONSERVATION SERVICE/USDA

- * Flood delineation during peak flow
- * Snow surveys
- * Soil moisture content on plowed or fallow areas to indicate susceptibility to wind erosion

U.S. FOREST SERVICE/USDA

- * Snowpack monitoring for avalanche prediction and flood forecasting
- * Soil moisture in plant root zone for predicting biomass productivity

ADVANTAGES OF MICROWAVE OBSERVATIONS

Some substantial contributions to improved data gathering for water resources management have already been provided by space-borne remote sensing systems using visible, near infrared and thermal infrared portions of the spectrum. However, there are some fundamental hydrologic parameters and situations that are inadequately observed at these wavelengths. These parameters include soil moisture, snowpack moisture and wetness, timely flood observations, and precipitation distribution. Therefore, the need for examining the applicability of the microwave portion of the spectrum in water resources management is quite clear particularly when considering the fundamental advantages afforded by a developed microwave observational capability such as, for example, the direct sampling of sub-surface soil moisture, nearly all-weather capability affording timely observations, and the ability to penetrate mod-

erate amounts of vegetation. The fundamental advantage of active microwave imaging systems, as opposed to passive systems, is the fine spatial resolution that can be provided. This fine spatial resolution makes it feasible to monitor specific fields for soil moisture content, establish flooded area boundaries with sufficient accuracy for use in post-flood damage surveys, and delineate soil and surface cover properties for assessing water-shed runoff potential. These advantages are summarized in Table 2.1.

STATUS OF IMAGING ACTIVE MICROWAVE OBSERVATIONS OF HYDROLOGIC PARAMETERS

There are some hydrologic parameters where active microwave systems have been conclusively shown to be effective. Extensive studies of many river basins show that drainage patterns and relief features can be delineated even where extreme cloudiness, vegetation or snowcover may be obscuring observations taken in other spectral regions.

Studies by McCoy (1967), and Lewis (1971), have shown that radar image derived measurements of drainage basin variables can be made with the level of detail that would be available on 1:24,000 scale topographic maps. Each radar system requires separate calibration to map values, but is internally consistent once this relationship is established. This correlation exists for each of the stream network variables in drainage basins, but is highest ($>.95$) for basin area, total network length, total number of stream segments and basin perimeter.

The distribution of surface water can be delineated because of the low backscatter from open surface water and can be also used as an index of water supplies over larger regions, lake, river and reservoir status (Roswell, 1969). This capability provides, in particular, timely observations of flooded areas while flooding is in progress and when clouds are normally present -- a situation limiting applications within other spectral regions. Figure 2.1 shows

TABLE 2.1

RADAR HAS INHERENT ADVANTAGES FOR WATER RESOURCES MONITORING

—SPIR—



2.6

GENERAL ADVANTAGES

- DEPTH PENETRATION FACILITATES DETECTION OF NEAR SURFACE SOIL MOISTURE, AND SNOWPACK WETNESS AND MOISTURE EQUIVALENT.
- SENSITIVE TO DIELECTRIC VARIATIONS CAUSED BY PRESENCE OF WATER
- ABILITY TO SEE THROUGH CLOUDS
- ABILITY TO PENETRATE MODERATE AMOUNTS OF VEGETATION
- RADAR WITH DATA FROM OTHER SENSORS CAN FACILITATE DETECTION AND IDENTIFICATION

SPECIFIC ADVANTAGES

- SYNTHETIC APERTURE RADAR PROVIDES HIGH RESOLUTION DATA

flooding along the Missouri river near Kansas City as imaged by a Ka - band radar (3 cm. wavelength). It clearly shows the contrast between open water and other features, of the May 1973 Missouri River flood.

It is also quite well established that frozen versus unfrozen soils can be delineated with microwave observations and this important information can be used to better predict watershed runoff (Mathews, 1975).

One of the most needed observations for a broad range of applications is that of soil moisture. There are a substantial body of results from investigations of passive and active microwave observations that microwave responses are sensitive to soil moisture variations at depths of a few centimeters. In the case of active microwave observations many flights of appropriate sensors show sensitivity to large moisture differences. Figure 2.2 shows a low altitude oblique photograph of a group of fields near St. Charles, Mo. The area marked "A" involves a situation with a strong gradient of soil moisture. This difference can also be seen quite clearly in the synthetic aperture radar L band, cross-polarization results acquired on November 10, 1975 and shown in Figure 2.3.

The ability of active microwave observations to discriminate between several levels of soil moisture ranging from field capacity to wilting point has been most extensively evaluated using ground-based instrumentation at the University of Kansas. Figure 2.4 shows a compilation of some of these observations illustrating a useful relationship between back-scattering coefficient and percent moisture by weight even in the presence of various crops. In this relation it is clear that sensitivity is greater near nadir (10° : 0.30dB/1% moisture) than somewhat off-nadir (30° : 0.14dB/1% soil moisture). The main conclusion that arises from these studies to date, besides clearly demonstrating sensitivity to soil moisture, is that the best single frequency is at 4 GHz

RADAR FLOOD MONITORING

...THROUGH CLOUDS ...AT NIGHT



KANSAS CITY

- SHARP LAND/WATER CONTRASTS
- ACCURATE MAPPING OF FLOOD EXTENT
- FLOOD WATER/ICE DISCRIMINATION IN ALASKA, UPPER MISSISSIPPI
- URBAN LAND USE DELINEATION PRIOR TO AND DURING FLOOD FOR DISASTER ASSESSMENT

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

Figure 2.1

STRONG SOIL MOISTURE GRADIENT NEAR ST. CHARLES, MO.

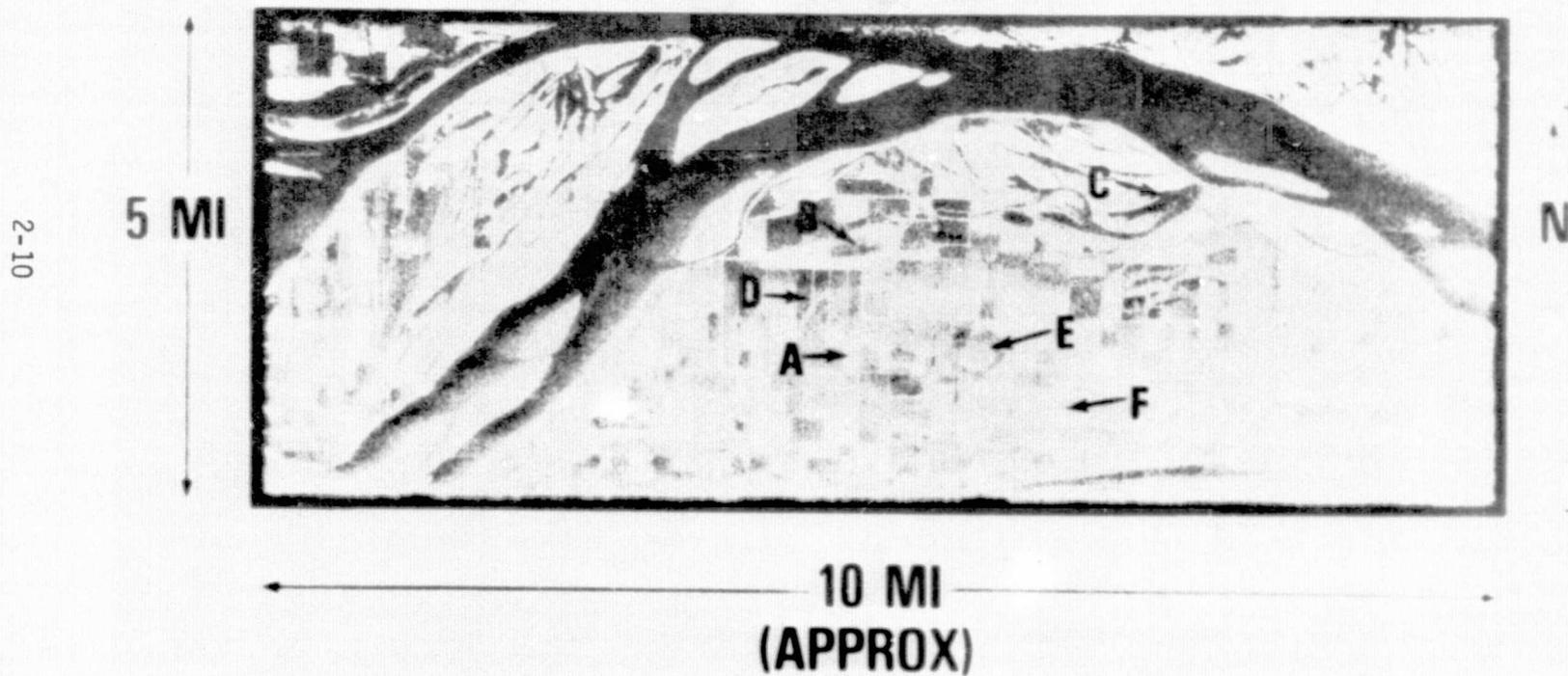
— SPIR —————→



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PRONOUNCED SURFACE SOIL MOISTURE GRADIENT
SEEN ON L-BAND RADAR

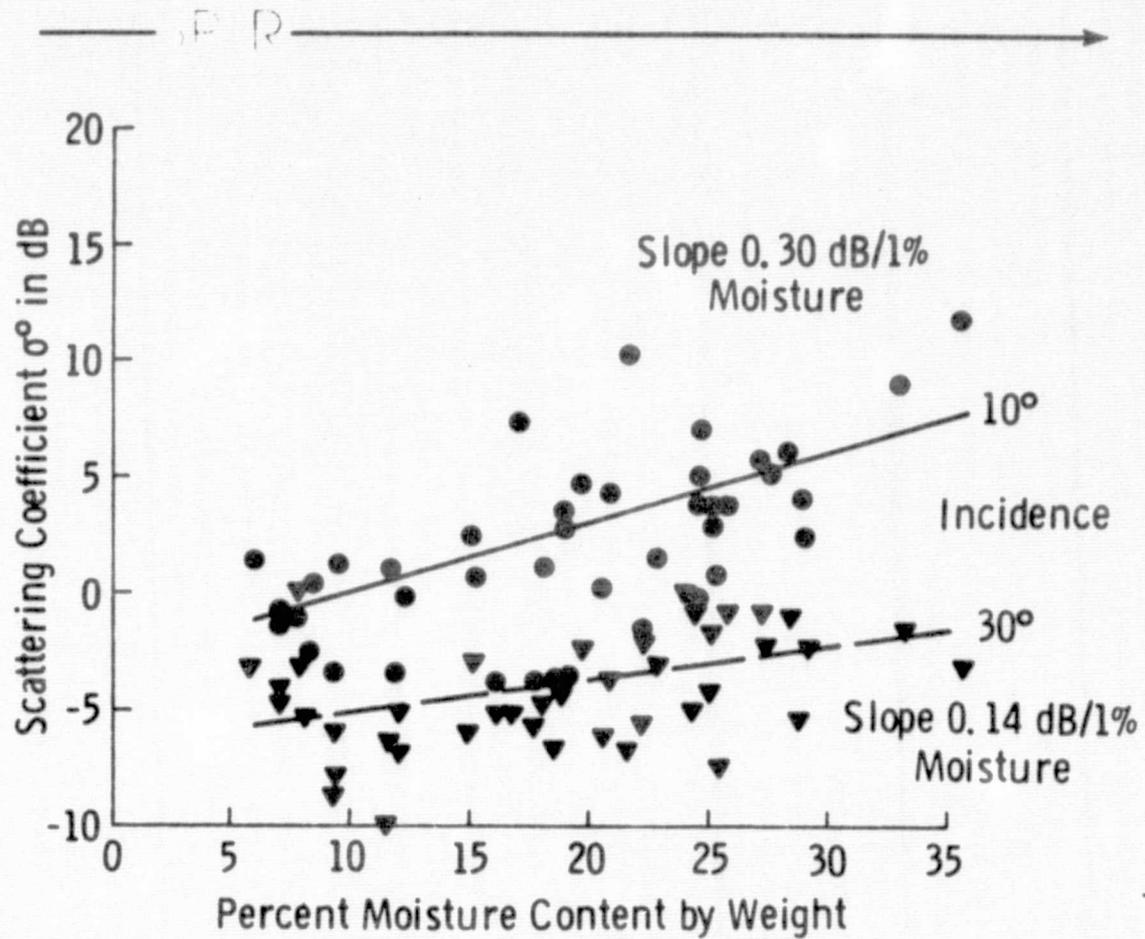
ST. CHARLES COUNTY MO.



ERIM CROSS POLARIZED RADAR IMAGE

Figure 2.3

RADAR BACKSCATTER RESPONSE TO SOIL MOISTURE



Crop Type	Crop Height (m)	Freq. GHz	Pol.
Corn	2.4	4.7	HH
Soybeans	1.0		
Milo	1.0		
Alfalfa	0.5		

Figure 2.4
2-11

and the best range of incidence angles is between 7 and 15°. These studies by Ulaby and associates have been important also in showing that even at these relatively long wavelengths radars are sensitive principally to surficial (top few centimeters) soil moisture in soils free of vegetation.

The optimum radar parameters for mapping soil moisture have been studied by Ulaby and Batlivala (1976). They reported on an extensive series of experiments carried out by them and their colleagues at the University of Kansas over the last 3 years, using a truck-mounted radar spectrometer covering the range 2-8 GHz. These investigations showed that either VV or HH polarization were acceptable and that operation at 4 GHz (7.5cm) was a suitable compromise frequency for soil moisture mapping in unvegetated fields. Fields which were rough to moderately rough had an optimum frequency of 4.75 GHz (6.3cm). Smooth fields (smooth to the impinging wavelength, and relatively rare under normal conditions of cultivation) had an optimum wavelength of 10cm (3 GHz).

The greatest sensitivities tended to occur near nadir ($0.4 \text{ dB}/0.01\text{g}/\text{cm}^3$), but within the acceptable angles of incidence for maximum correlation between radar return and soil moisture - 7° to 15° - , a median sensitivity of $0.25 \text{ dB}/0.01\text{g}/\text{cm}^3$ was obtained. The combination of recommended parameters (4 GHz, 7°-15°) minimizes confusing factors arising from surface roughness effects. Various of these relationships are shown in Figures 2.5, 2.6 and 2.7, all drawn from the Kansas studies.

Figure 2.5 gives a comparison between 4.7 and 7.1 GHz. Radar returns at the lower frequency show the stronger correlation with soil moisture, and greater sensitivity, at all incidence angles. It also shows that angles of incidence between 7 to 15 degrees are most desirable for soil moisture mapping and that there is little to choose between VV & HH polarizations.

RADAR IS MOST SENSITIVE TO SOIL MOISTURE NEAR NADIR INCIDENCE ANGLES

← SPIR →

Designation	Polarization	Frequency
---○---	HH	4.7 GHz
---▲---	HH	7.1 GHz
---●---	VV	4.7 GHz
---△---	VV	7.1 GHz

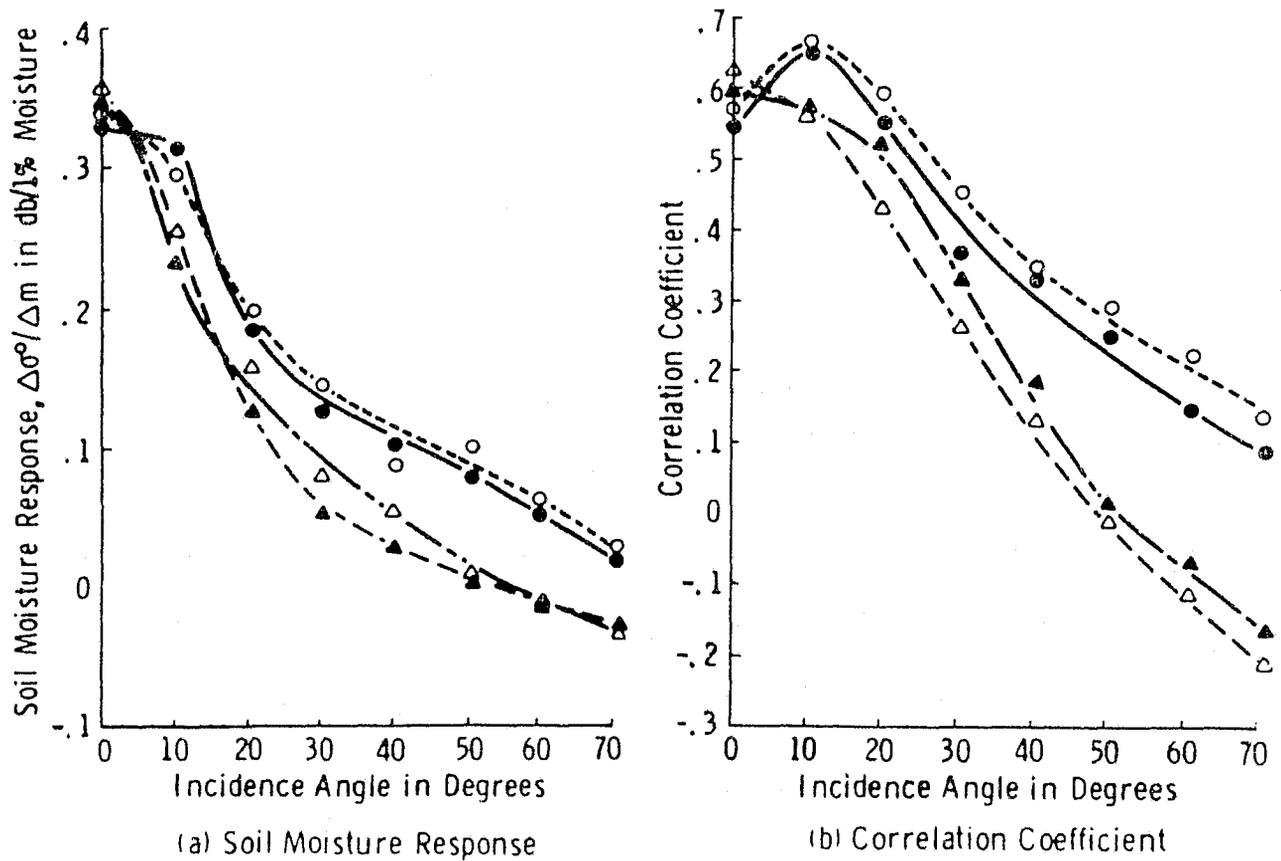


Figure 2.5

Figure 2.6 shows the scatter of data points at a 10 degree incidence angle, for VV polarization, and 4.75 GHz, for combinations of rough, moderate and smooth surface conditions. The correlation coefficient is 0.75 with a sensitivity of 0.25 dB/0.01g/cm³.

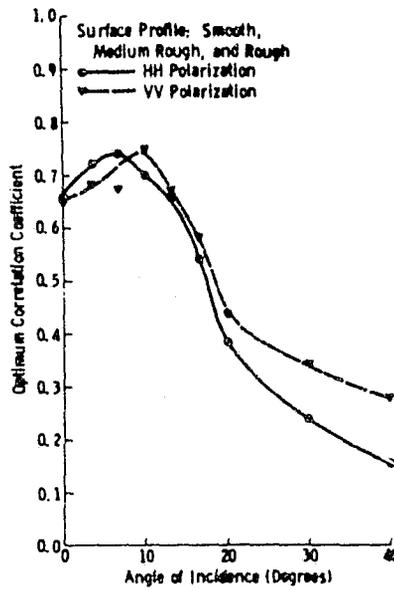
Finally, Figure 2.7 plots the optimum value for each of a) correlation coefficient, b) sensitivity, and c) frequency, as a function of angle of incidence for all smooth, medium, and rough surface conditions, combined:

- * within the optimum angular region for maximum correlation - 7 to 15 degrees - there is little to choose between HH and VV polarizations (at longer wavelengths VV appears somewhat better)
- * as angles of incidence progressively increase there is a shift of the optimum to higher frequencies
- * there is a general decrease in sensitivity of radar returns to soil moisture with increasing incidence angle.

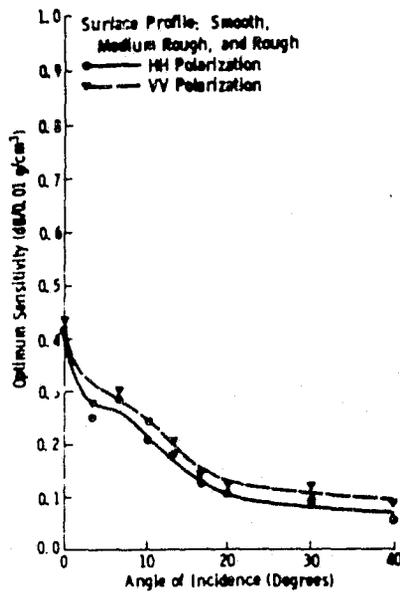
All of these results taken together lead to the compromise recommendation of 4 GHz, 7-15° and VV or HH polarization given earlier.

These results significantly modify the earlier suggestions of L-band as a suitable frequency for soil moisture analysis given in Mathews (1975). The Kansas studies drawn on and extended in Ulaby and Batlivala (1976) are Batlivala and Ulaby, 1975, Cihlar and Ulaby, 1974, 1975; Cihlar, Ulaby and Mueller, 1975; Ulaby, Bush, Batlivala, and Cihlar, 1974; Ulaby, Batlivala, Cihlar and Schmutge, 1975; and Ulaby, Cihlar, and Moore, 1975.

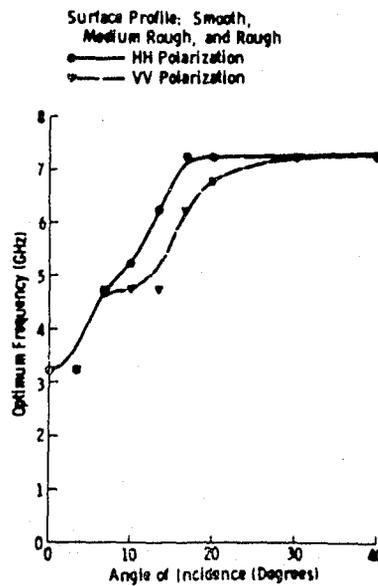
Decision-making in the development and management of water resources is based primarily on mathematical watershed models of varying complexity. Very few of the watersheds in the U.S. smaller than 500 km² have acceptable and reliable input data due to the cost and time required to obtain such data. One of the representative models is that used by the Soil Conservation Service wherein a single number or coefficient represents the combined effects of soil type, land use, and antecedent moisture conditions. To objectively specify this coefficient is difficult but there are results from studies of passive microwave which show



(a)



(b)



(c)

Figure 2.7. Optimum (a) correlation coefficient, (b) sensitivity, and (c) frequency plotted as a function of angle of incidence for the smooth, medium rough, and rough surface profiles combined. (After Ulaby and Batlivala, 1976)

that this coefficient can be specified quite well by passive microwave observations averaged over the total small watershed area. These results are illustrated in Figure 2.8. Because active microwave observations are sensitive to roughness, moisture, and soil properties, they will also be quite useful in this regard. (Preliminary, and still unpublished analyses of radar data in watersheds in Oklahoma give similar indications: personal communication, B. Blanchard). Such analyses should permit the soil conservation service of the USDA, for example, to more accurately and quickly acquire runoff coefficients and perform the approximately 1000 design studies needed each year for the construction of flood control structures on small watersheds.

The melting of snow in a majority of the watersheds in the Western United States provides the most important portion of the total runoff and this runoff occurs over a relatively short period of time in the spring. Analyses and applications of satellite snowcover observations from LANDSAT and NOAA satellites have demonstrated their contribution for improved management of snowpack runoff. However, the more fundamental observation of snowpack moisture equivalent and wetness would obviously contribute to better snowpack runoff forecasts by providing a direct measure of the amount of water stored in the snowpack rather than an index of this quantity. The microwave system would also allow observations to be made through the cloud cover that persists most notably in the Pacific Northwest, where hydroelectric power generation is prevalent, and in Alaska. Radar images have been acquired that show snowcover can be delineated and theoretical studies show the sensitivity of backscatter observations to variations in snowpack wetness. However, much more analysis of active and passive microwave observations needs to be accomplished to establish the potential in this area (Salomonson, 1974; Mathews, 1975). It would appear that the level of utility of successful observations would certainly justify such an effort.

RELATION BETWEEN STORM RUN OFF (CURVE NUMBERS) AND MICROWAVE TEMPERATURE

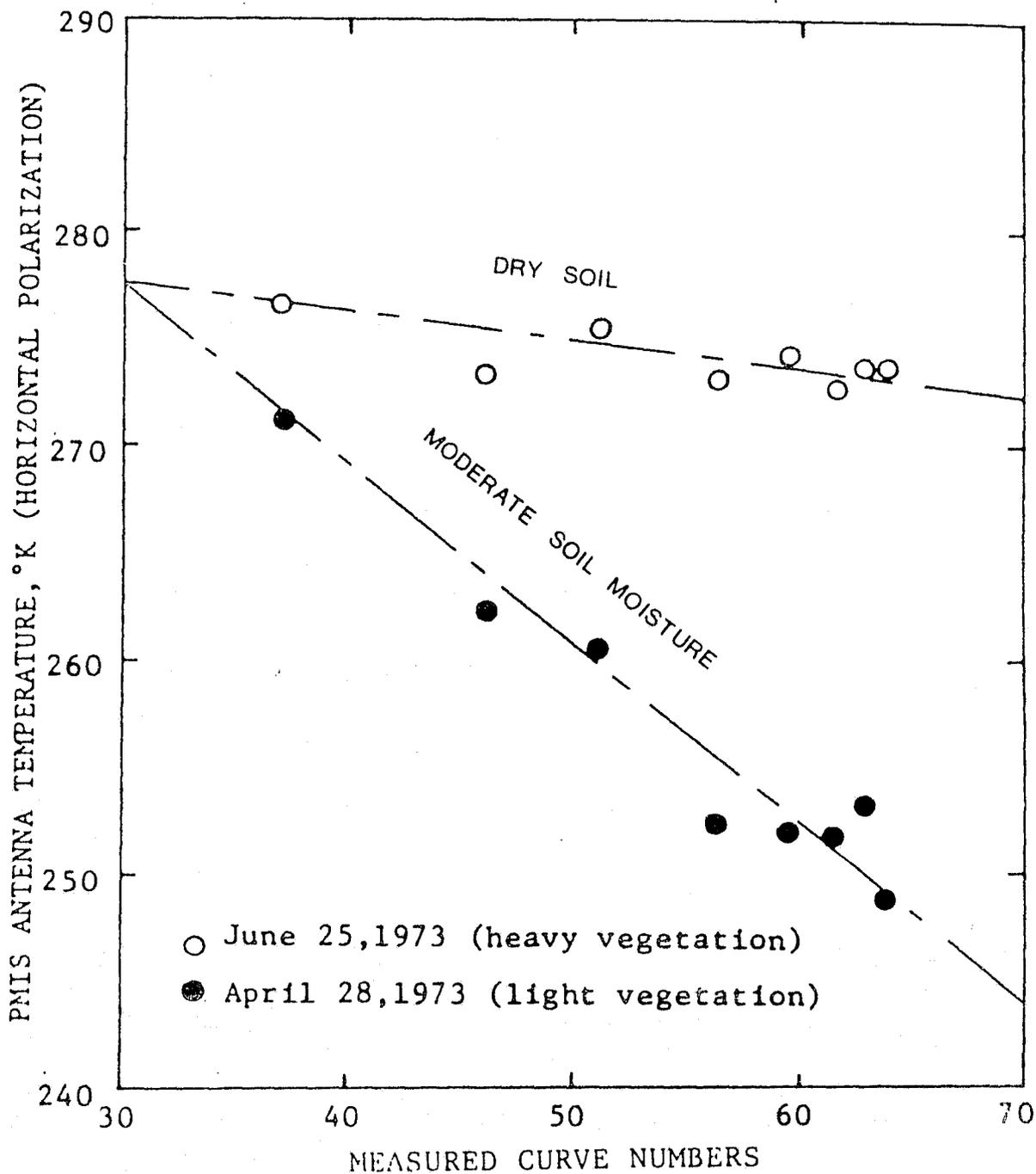


Figure 2.8

The ability of active microwave observations for monitoring lake ice is quite well established by projects such as the airborne SLAR effort on the Great Lakes over the past few years (Bryan and Larson, 1975). It has also been possible, using active microwave observations, to distinguish totally frozen from partially frozen lakes in Alaska offering a means of helping local communities to find winter supplies of potable and fire prevention water supplies. Applying this capability for locating and assessing the extent of ice jamming on rivers and ice cover, ice type, thickness, cracks and leads should be of help in river management (flooding) and river navigation and commerce. For studies of glaciers including the assessing of mass balance, and locating permanent snowlines, high spatial resolution microwave observations again offer substantial potential (Mathews, 1975).

There are other areas where active microwave observations appears capable of providing a contributory and beneficial observational capability. These include the monitoring of soil moisture patterns in such a way as to delineate precipitation patterns. When coupled with meteorological satellite observations (particularly geostationary satellites) and the appropriate water balance-models, such a demonstrated capability would clearly provide improved watershed model input and runoff forecasting (Cihlar and Ulaby, 1975).

CONCLUSIONS: ROLES FOR SPACE SHUTTLE

It is clear that microwave observations have fundamental properties which will enable space remote sensing to make substantial contributions to water resources management at all levels. Particularly will this be so in the better monitoring of hydrologic parameters, management of regional and continental water supplies, and understanding of the global hydrologic cycle.

There is a demonstrated capability to monitor flooding in progress that should be implemented on spaceborne systems as soon as possible. The overall

importance for so many applications would indicate that the significant capability indicated in ground based radar observations of soil moisture should be further explored using aircraft and spacecraft systems as soon as possible. The promise suggested by existing studies employing microwave observations for objectively specifying watershed runoff potential needs to be brought to function at the earliest opportunity. The potential indicated by both theoretical and practical studies for monitoring snowpack moisture and liquid water content indicates that a strong observational effort needs to be launched to fully explore what level of contribution can be made by spaceborne radar systems in this high priority area. (Eagleman and Lin, 1975; Edgerton et al., 1970; Waite and MacDonald, 1970; Kunzi and Staelin, 1975; Linlor et al., 1975; Moore et al., 1975).

Supporting studies defining spatial resolution, temporal and spectral frequency and cost effectiveness and benefits to be expected are also needed to validate the specific observational needs and economic justification for this effort. It seems quite safe to predict, because of the fundamental nature of the hydrologic parameters amenable to microwave remote sensing that with success in this area the number of uses or applications and the overall acceptance of remote sensing by the water resources management agencies will grow by an order of magnitude by the year 2000.

Roles for a multifrequency, multipolarization, multi-look angle and direction radar on Space Shuttle are seen in the following areas:

- 1) Flood observations on either a contingency or a when-available basis. Since flooding takes place almost weekly at some location in the world it would be likely to be used often for this purpose. Since SEASAT would be of value also for this purpose the double coverage should give a high frequency of temporal data.
- 2) Surveillance of fresh water ice conditions, freeze up, and break-up of ice in the Great Lakes, upper St. Lawrence Seaway, and Arctic river

systems and lakes in Alaska, Canada and the Soviet Union and glacier ice coverage. The long and short wavelengths plus multiple polarization would extend the SEASAT capability for this purpose.

- 3) Space confirmation of the appropriate look angle and frequency coverage of a wide range of bare and vegetated soil moisture determination. Monitoring during the cropping season will demand both long and short wavelengths, variable polarization, and different look angles on different passes. Experimental testing over large areas under a variety of circumstances seems well suited to the Shuttle sortie mode over a 4 or 5 month period with some half-dozen flights during that time.
- 4) Snow depth, liquid water content and condition monitoring in relation to varying slopes and vegetation cover, particularly in the Northern Great Plains and Interior Canada and the Rocky Mountains.

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CHAPTER 3

SPACE SHUTTLE IMAGING RADAR ROLES IN MINERAL AND PETROLEUM EXPLORATION[†]

SUMMARY

Significant applications of a Shuttle Program Imaging Radar, in support of mineral and petroleum exploration principally, but not exclusively in the form of one-time benefits (during the lifetime of shuttle) will include:

- * provisions of multiple controlled look angles at any location (This is not possible with sun-synchronous passive sensor missions). These will enable improved geologic structural mapping and interpretation, hence improving the exploration base.
- * provision of multiple look directions, other than those given by solar illumination, to further add to and thereby improve structural interpretation and exploration, over those observed with LANDSAT.
- * multi-season observation with controlled look angles and directions, thereby allowing season to be a pure discriminant.
- * multi-frequency effects leading to some vegetation penetration and wavelength-particle size interaction to infer lithologic information.

RECOMMENDATIONS

The Shuttle Program Imaging Radar Program should:

- * include provision for both day and night observations to obtain the widest array of look directions (including orthogonal).
- * be at least two-frequency, one of long wavelength.
- * be multiple polarization to aid in lithologic and lithology-related discrimination.
- * include an R and D phase before the Shuttle launch to more fully investigate parametric relations between frequency, polarization, and ground conditions and cover, in order to parameterize space observations more completely.

[†] Prepared by H.C. MacDonald.

INTRODUCTION AND BACKGROUND

Our future to a considerable degree depends on the reserves of minerals and fuels that still lie within the earth. Because the U.S. uses nearly 30% of the world's minerals and fuels we are vitally interested in foreign as well as domestic exploration. As the search for additional resources intensifies the difficulty of discovering new deposits also increases. The cost of exploration alone has become so prohibitive for small companies and small or developing nations that the search for mineral and petroleum deposits is not economically feasible without external capital. Many mining companies having adequate risk capital estimate that a minimum of twenty million dollars is required to find one deposit worth development. The cost of oil and gas exploration is also high; one estimate puts the drilling of dry holes in the United States alone at a billion dollars a year. From the geologist's point of view, the search for economic deposits frequently requires him to examine several hundred prospects before he finds one he can recommend for detailed investigation. It may take examination of a thousand prospects before a single discovery is made.

Radar imagery offer the geologist an important technique to assist him in defining exploration prospects and thereby reducing costs. In those regions of the world that are pervasively cloud covered, radar provides the only practical geological reconnaissance exploration method. However, even where other remote sensor data are available, radar contributes unique geologic information, and may be used in conjunction with other sensors. In order to show this unique capability it is appropriate first to briefly look at some comparisons of radar with both photography and LANDSAT data.

RADAR AND SOLAR SHADOWING FOR TERRAIN ENHANCEMENT

When geologic features such as joint systems, faults, or folded strata are enhanced on radar imagery, the enhancement can usually be attributable to radar shadowing. Figure 3.1 provides marked contrasts in terrain extractable information between the radar on the right versus the photograph on the left. The radar signal return and shadowing emphasizes irregularities of the earth's surface so that terrain morphology from which structural or geologic inferences can be made is depicted more starkly than on photography. Radar's shadow enhancement capability was in fact one of the sparks that ignited interest in low sun angle photography in the late 1960's and ultimately influenced the selection of a 9:30 a.m. equatorial crossing of LANDSAT 1 and 2. Analogous examples of shadow enhanced geologic features have also been observed on LANDSAT images which were taken at times of very low sun-angle. From orbital altitudes, particularly with analysis of oblique images, low angles of solar illumination have proven useful for accentuating otherwise subtle relief of geologic and exploration interest which might otherwise have been undetected.

The exploitation of any prescribed earth-sun relationship necessitates a preset flight schedule embracing a limited time period. For example, if low sun-angle photographic coverage is desired for a known terrain configuration which is dominated by north-south linear trends, maximum terrain enhancement on the photography could only be achieved during early morning or late afternoon flights. However, during this same time of flight coverage any east-west trending linear features would be suppressed because of the absence of shadowing. Thus, low sun-angle photographic coverage would only provide maximum enhancement for those terrain features which were in proper alignment to produce shadowing.

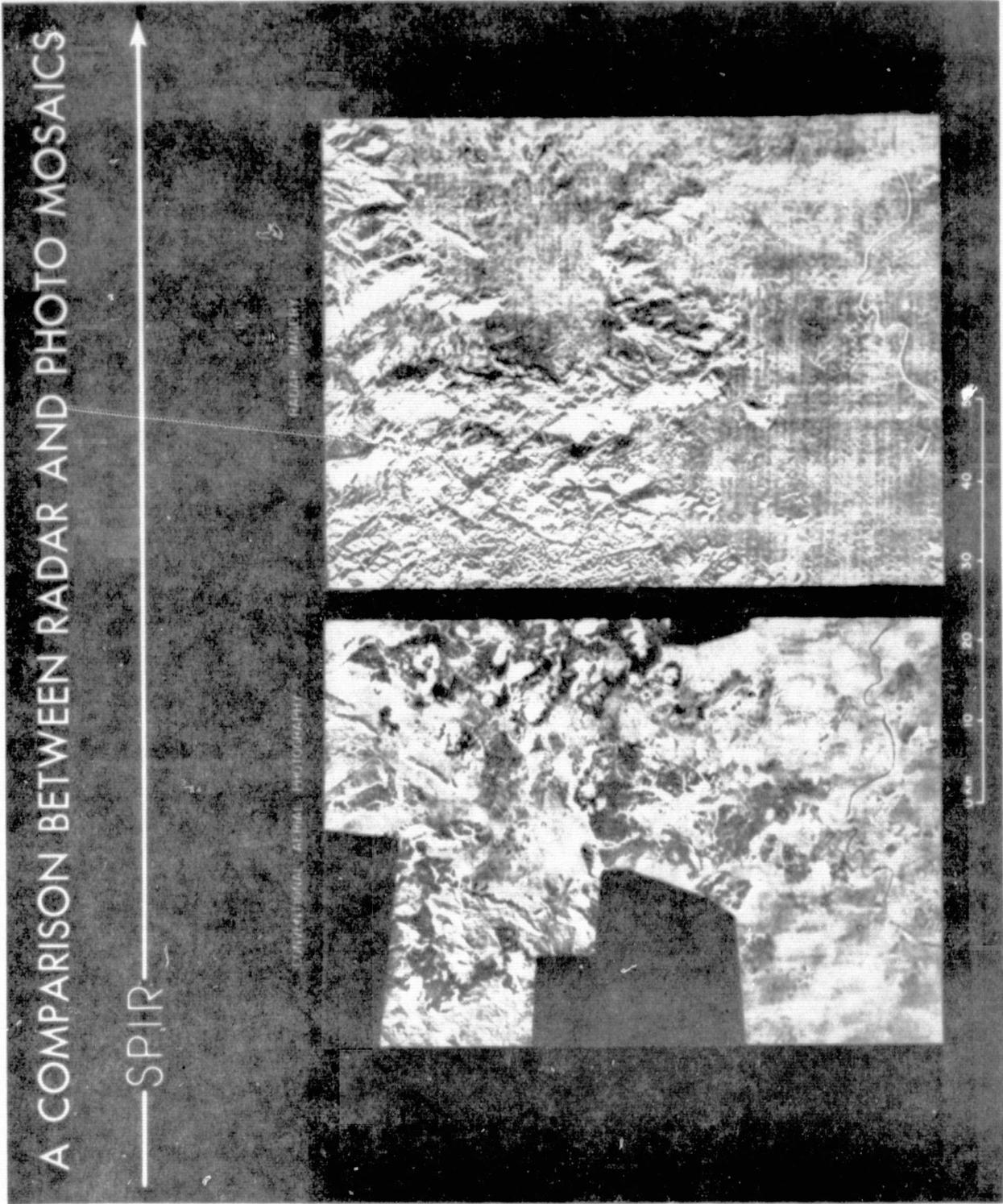


Figure 3.1

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With SLAR imagery systems, terrain features can be imaged from multiple look-directions, and at preselected incidence angles. The capability would be particularly advantageous in an area where only limited reconnaissance data are available. Here, the selection of preferred look-directions and resultant shadowing would result in the enhancement of certain structural trends.

The pseudo-three dimensionality that simplifies the geologist's task when viewing monoscopic radar imagery can be roughly simulated by viewing low sun angle or winter LANDSAT scenes. The differential shadowing provided by seasonal variations in solar elevation can be seen by contrasting the summer--June 12, 1972--LANDSAT image of northern Arkansas (Figure 3.2, 60° solar elevation) with a winter--December 15, 1972--image (Figure 3.3, 25° solar elevation). The winter image shows strong shadow enhancement. In fact, many of the northeast trending, through-going lineaments were first recognized and mapped from this LANDSAT image.

Because the delineation of fracture patterns, faults and lineaments is of importance to all phases of geological exploration, it is important to compare radar imagery and LANDSAT, in an attempt to determine overall value. Figure 3.4 illustrates approximately the same area as imaged by LANDSAT-2 and SLAR. This LANDSAT image was obtained at near optimum times, i.e. at relatively low sun angle (40°) and when the terrain was essentially foliage-free and snow covered. The radar image was taken with a slightly different angle of illumination. The north-south trending fracture patterns are unquestionably better defined on the radar images. In part this is a product of the better radar resolution.

THE GEOLOGIC VALUE OF RADAR SHADOWING

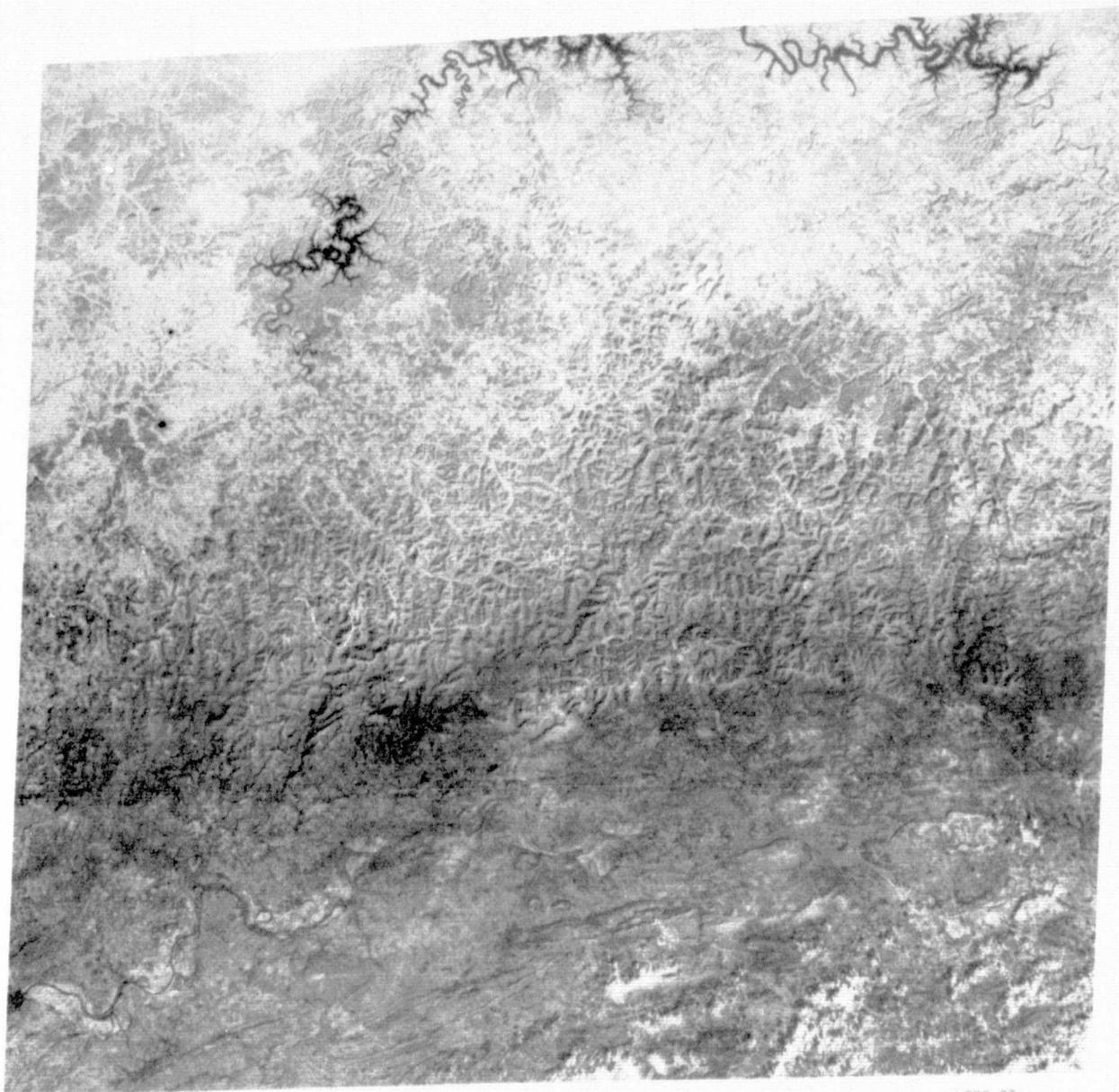
Recent NASA publications have documented the fact that low sun angle



Figure 3.2

3-6

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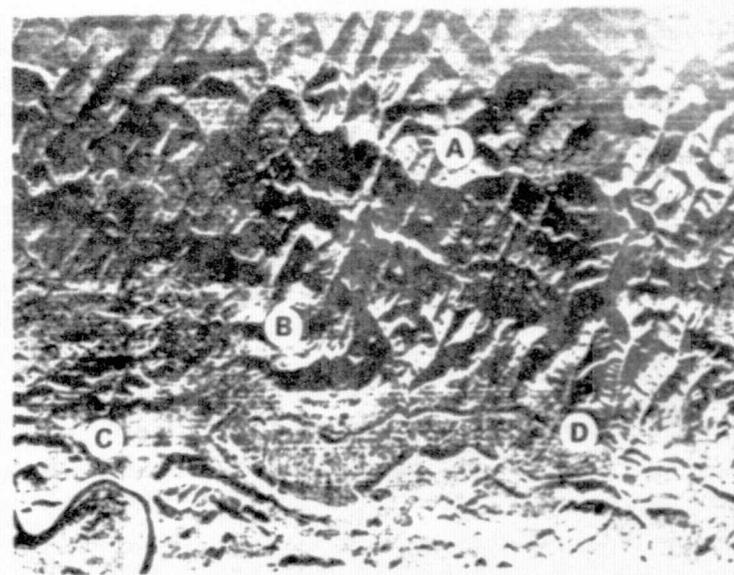
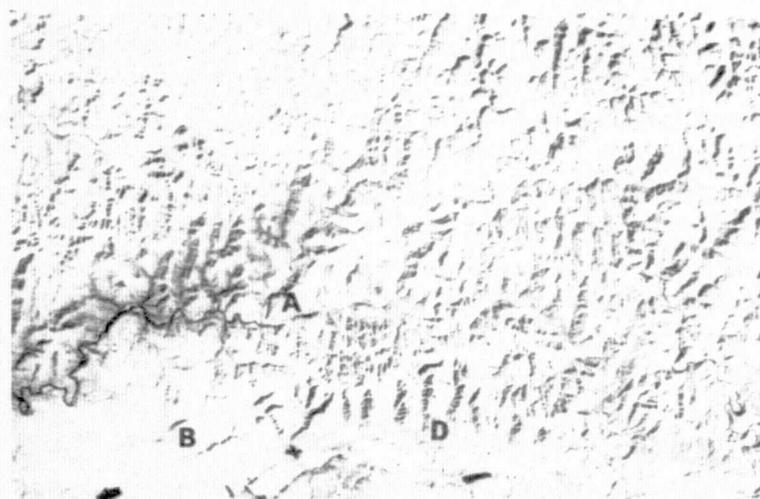


11094-20 11094-201 11093-201 11093-201
15DEC72 C N35-53-4093-36 N N35-51-4093-34 MSS 5 D SUN EL25 AZ152 198-2021-G-1-N-D-2L NASA ERTS E-1145-16235-5 R

Figure 3.3

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BOSTON MOUNTAINS, ARKANSAS



LANDSAT-2 SUN ELEVATION 40°
SNOW ENHANCED - BAND 7

RADAR IMAGERY

Figure 3.4

3-8

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is of definite geological advantage by enhancing subtle terrain features that are normally just below the threshold of recognition. What has not been widely publicized is the fact that during the past 6 years, many exploration companies have conducted radar mapping programs to take advantage of radar's flexibility in the selection of both depression angles and look-direction. The Bureau of Mines in 1971 for example, radar mapped 600 mi² in the coal mining area of Buchanan county, Virginia to test SLAR as a tool for geological structure analysis (Figure 3.5). The purpose of the mapping was to test SLAR as a tool for structural analysis, specifically to see if radar could define surface features that might be indicative of either roof rock instability or zones of abnormally high rates of water and methane emission through permeable fractures. A radar mosaic (Figure 3.6) provided the base for mapping suspected faults and joint systems. Core holes were then drilled on these radar defined patterns as illustrated in the center of Figure 3.6. Core holes drilled along radar mapped linears were more gassy than those drilled off-linears. SLAR surveys were determined to be superior to other sensor systems for alerting engineers to potentially dangerous areas where high gas emission and/or fractured roof strata may be expected (Elder, et al., 1974).

Even in the United States where LANDSAT imagery and aerial photography are available, SLAR fracture mapping programs are being conducted. The San Francisco District, Corps of Engineers recently released a remote sensing study (Gelnett, 1975) using a multiple sensor data package of the sensors used for the engineering geology and civil works investigation. Radar was cited as providing substantially more regional and local structure detail than thermal IR, multiband cameras and LANDSAT 1 and 2 imagery. Most recently in the January 1976 issue of World Oil (Rumsey and Gelnett, 1976), radar was cited as an airborne technique for exploring for deep fracture



Figure 3.6

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controlled oil and gas reservoirs. Many of the world's oil and gas fields have reservoirs in which porosity, and possibly more important, permeability, are fracture controlled. Because many of these fractures are propagated upwards and may be reflected on the surface as subtle linears, SLAR can be a valuable tool for searching for new fields. The radar mapping program reported in World Oil involved 14,000 mi² in the cloud-free four corners area of Utah, Colorado, Arizona, and New Mexico.

GEOLOGIC VALUE OF RADAR SENSITIVITY TO TERRAIN ROUGHNESS

Other unique data inputs that SLAR provides the geologist are terrain texture and roughness parameters. In humid areas where vegetation covers the ground surface, the average radar image tone depends on such variables as spacing of individual trees, spacing of branches, size and density of leaves, and orientation or slope configuration of the plant community. Where vegetation is sparse however, reradiation (or signal return) is influenced mainly by the scattering characteristics of the terrain ... particle size, geometric orientation, and effective incidence angle. Regions having a continuous plant canopy provide the radar interpreter with a relatively difficult situation for inferring types of surficial materials, and consequently, landform association becomes of primary importance. However, in arid and semi-arid areas, imaging radar is very sensitive to terrain surface roughness, and geoscience analyses should become more reliable.

Comparison between radar imagery and photography of the same area (Figure 3.7) shows the potential for using SLAR for determining terrain texture. Especially for those terrain conditions where overlapping tonal contrasts recorded on aerial photography may provide ambiguous data, extrapolation of radar-derived, terrain texture data would appear to provide important corroborative information (MacDonald and Waite, 1973). This additional data

DIFFERENTIAL ENHANCEMENT OF TERRAIN TEXTURE
SHOWN ON RADAR AND PHOTOGRAPHS

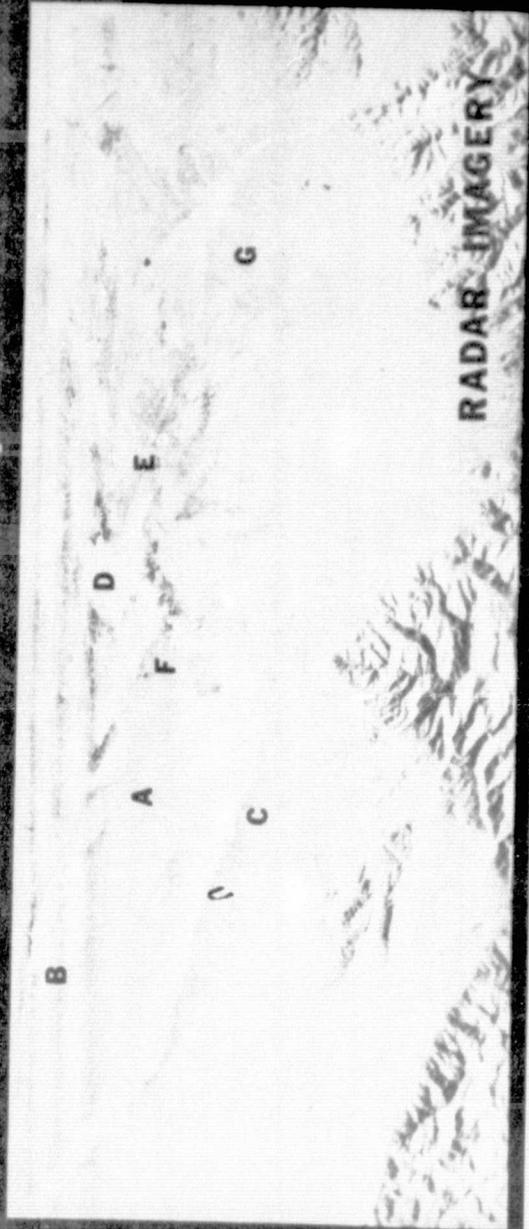


Figure 3.7

source will allow an increase in interpreter proficiency.

GEOLOGIC VALUE OF MULTI-SEASON RADAR IMAGES

Recently numerous studies have shown the seasonal variation in data content of LANDSAT images. Aerial cameras and scanners in the visible and near IR regions depend on color and texture contrasts for detection of terrain characteristics. Radars depend on surface configuration and dielectric properties. Thus, seasonal changes in vegetation are effected by changes in leaf or crop geometry and moisture content, and in bare soil or rock areas by the same factors.

SLAR being an active system provides its own source of illumination and does not measure diurnal changes in the radiation emitted or reflected from the earth's surface. This relative independency from time of day and weather is a particularly important advantage for monitoring features which are constantly changing or when data are required at regular or specific times. Although the surface geology does not change rapidly (except in the case of some mass wasting processes such as landslides, or faulting associated with earthquakes) interpretation can be improved by imaging the surface when it is vegetated, nonvegetated, dry, wet, and in some cases snow-covered.

Two flights of AN/APQ-102 imagery (Figure 3.8, courtesy L.F. Dellwig, University of Kansas) covering the Denver-Colorado Springs Corridor demonstrate the influence of seasonal terrain variations on radar return signals. One image was generated on February 23, 1972 and the other on May 25, 1972. Each image has characteristics which facilitate certain types of interpretation. The winter image shows a suppression of return from low surface vegetation. Thus, different types of low natural vegetation, crops, field conditions and soil textures which produce different tones on the spring imagery, give uniformly dark tones on winter imagery and are difficult to separate.

ENHANCEMENT OF GEOLOGIC FEATURES ON
MULTI-DATE RADAR IMAGES
(NEAR DENVER, COLO.)

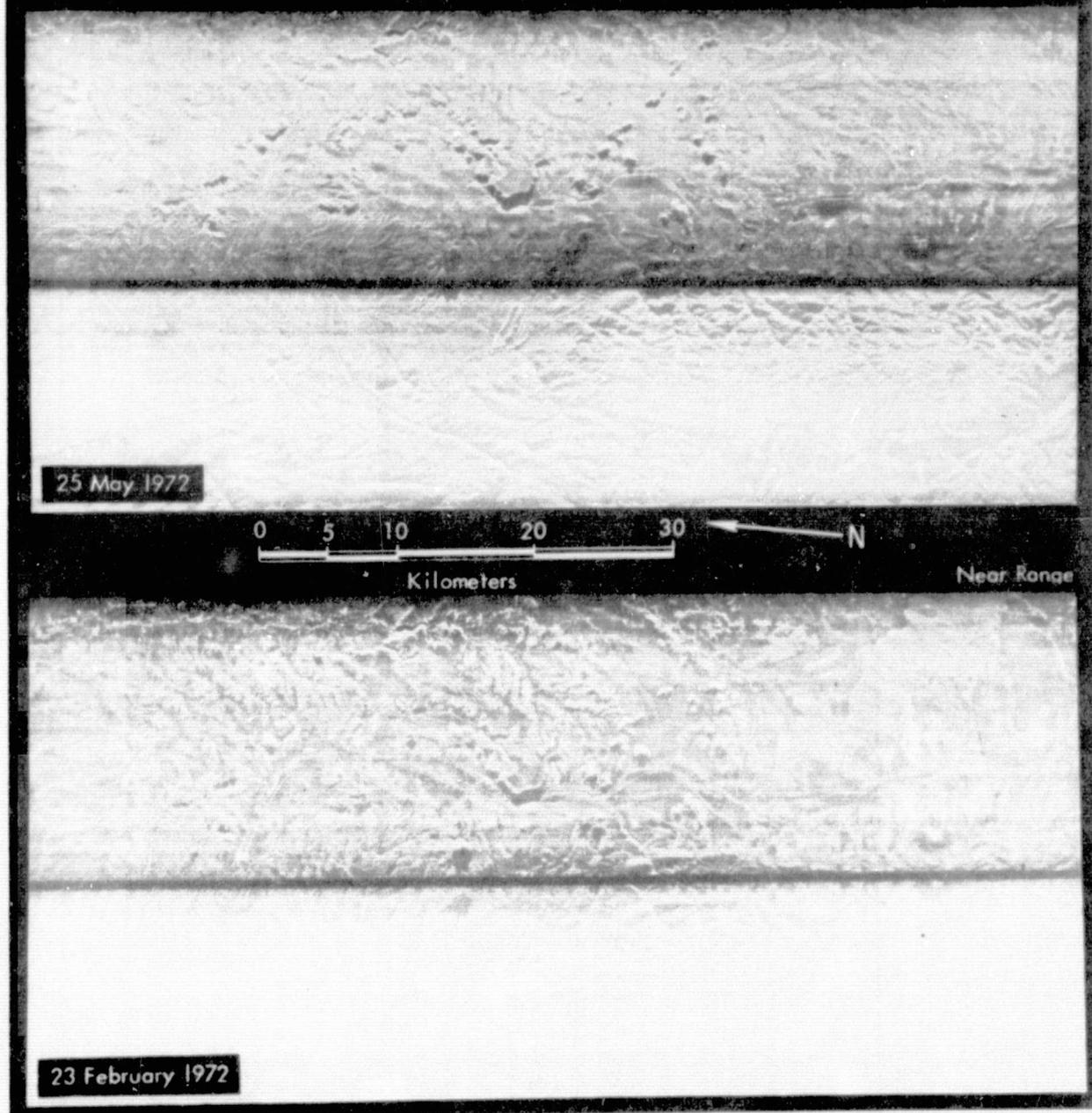


Figure 3.8

Consequently, high relief features such as buildings, fences, powerlines, tall shrubs and trees are enhanced.

While at first sight most applications in geology will not strongly justify repetitive coverage ... in fact, repetitive coverage does assist significantly in geologic interpretation. Differential variations in surface vegetation and terrain moisture are associated with different rock types and/or structural controls. Thus, while the geology doesn't change its appearance does. Geologists can indeed make effective use of temporal data.

RADAR OPERATIONAL CAPABILITIES

Thus far we have examined those situations where radar complements geologic data obtained from other sensors. Now it is appropriate to examine radar capability in areas where other remote sensing information is limited because of clouds or lighting conditions.

Eastern Panama Radar Mosaic

Radar imagery obtained from a high resolution SLAR system in less than 20 hours of recording time was successfully used for geological reconnaissance mapping of more than 30,000 KM² in eastern Panama and northwestern Columbia (Figure 3.9). The area is typical of many cloud-covered tropical areas with dense vegetation in which adequate surveys cannot be made with aerial photography or other visible spectrum sensors. The radar imagery covering all of Darien Province, Panama, part of northwestern Colombia, and much of east-central Panama was obtained in 1967 and 1969 for the U.S. Army Engineer Topographic Laboratory to determine the operational feasibility of radar mapping, and to obtain terrain data for a potential interoceanic canal route.

With the exception of data provided by field investigation, geologic reconnaissance information interpreted from radar imagery of eastern Panama

RADAR MOSAIC OF EASTERN PANAMA

SPiR

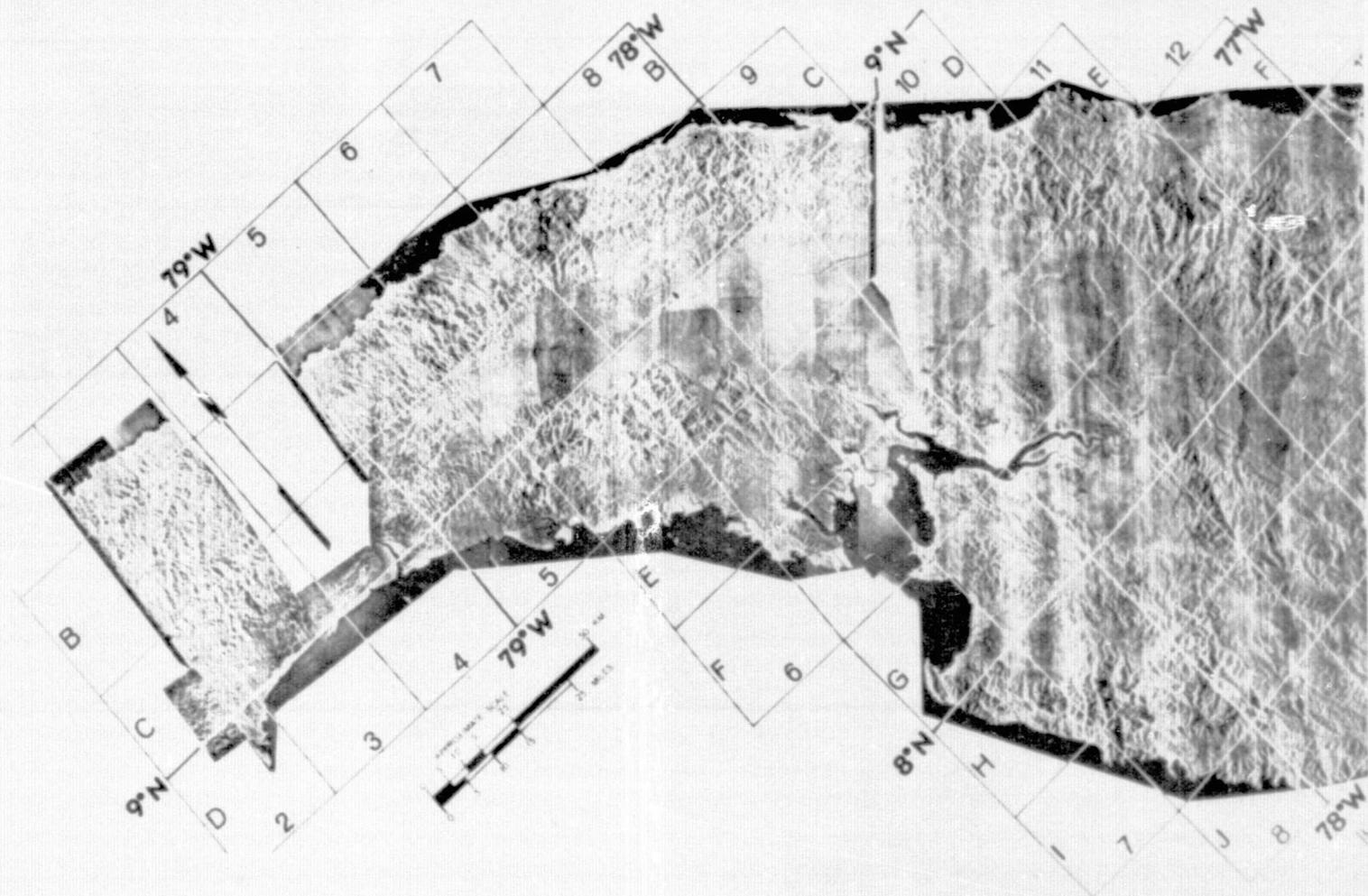


Figure 3.9

3-17

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(Figure 3.10) far exceeded that previously available. Reconnaissance is the term applied to incomplete or generalized mapping, normally preceding more detailed or localized studies. Reconnaissance mapping can also enlarge local studies, providing a general geologic picture of a region. Such mapping may be the only feasible geological exploration method because of limitations in time, funds, adequate base maps, and accessibility.

Large scale structures can be synoptically studied, and the single strip format used in conjunction with a radar mosaic helps familiarize geologists with features of structural provinces. The distribution, continuity and structural grain of key strata derived from the imagery provided a geologic data base for mineral and petroleum resource evaluation. Prospective sites for future mineral exploration were delineated, and petroleum provinces were designated according to favorable rock type and structure (MacDonald, 1969; and Wing, 1971).

Mineral Discovery in Panama

In 1970 and 1971, using SLAR imagery as a data base, field investigations of the second phase mineral exploration project carried out by the government of Panama with United Nations assistance, led to a mineral discovery. The radar imagery (Figure 3.10) illustrates part of the new mineral belt in the Cordillera along the San Blas coast, adjacent to the Colombian border. This discovery area contains mainly copper mineralization with indications of molybdenum, zinc, and gold. The most promising mineralization occurs in highly fractured and sheared zones generally associated with extensive silicification (U.N. Development Programme, 1972).

SLAR Mapping in Venezuela

Radar mapping of more than 100,000 miles in Venezuela has proven the utility of SLAR. Figure 3.11 (courtesy Goodyear/Aeroservice Corporation

RADAR DERIVED GEOLOGIC STRUCTURES OF EASTERN PANAMA

SPiR →

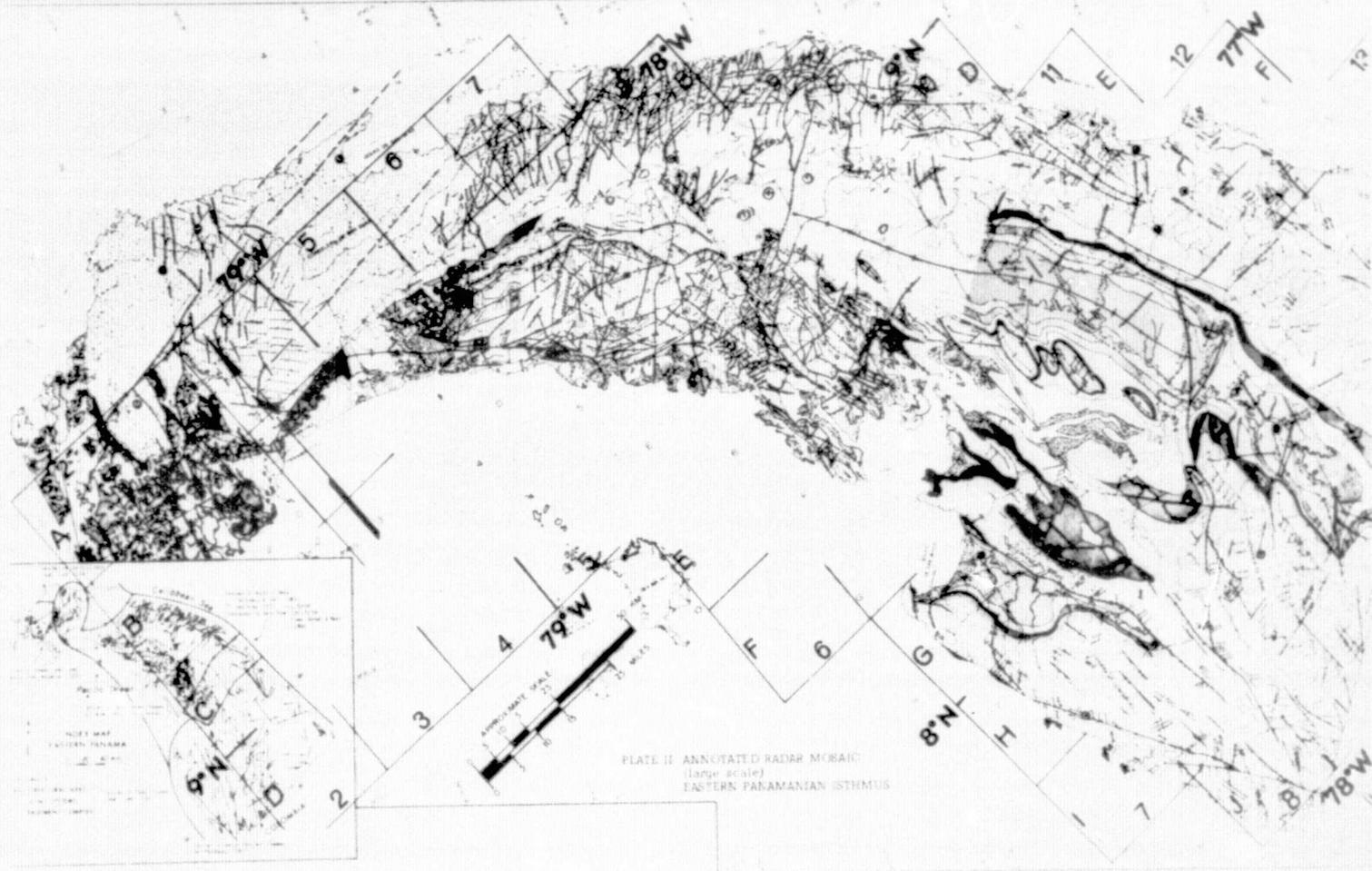


Figure 3.10

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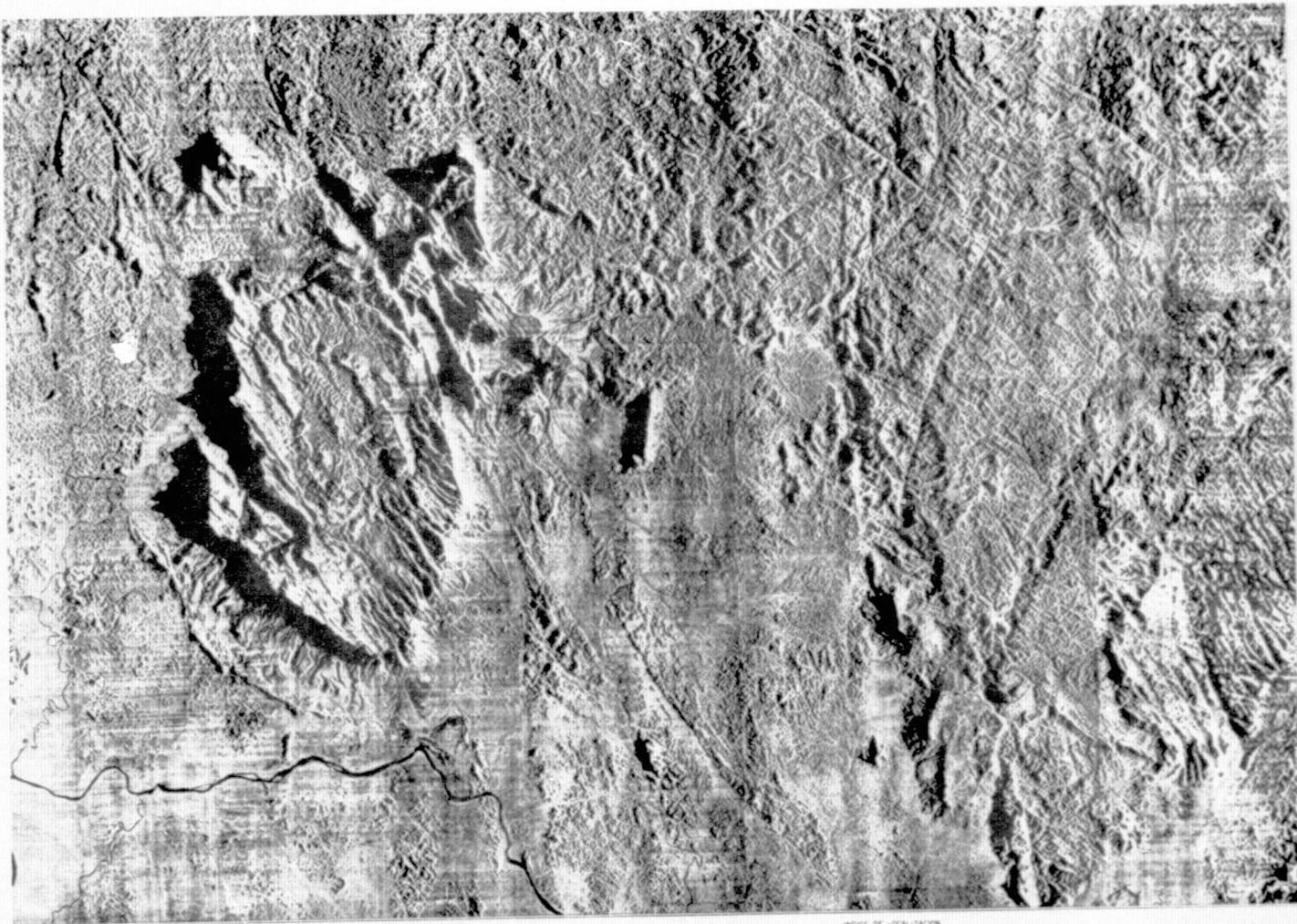


Figure 3.11

3-20

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0 5 10 20 30 40 50

INDICE DE LOCALIZACION



MINISTERIO DE ENERGIA Y PETROLIO	
COMISION PARA EL DESARROLLO DEL SUR DE VENEZUELA	
LABORATORIO DE FISICA	
DEL TERRITORIO FEDERAL AUTONOMO	
MUNICIPIO DE PARAGUAY	
NO. 22	COLECCION 118
INTERNACIONAL ALIADO SERVICIO CONTINENTAL	



illustrates one of the many radar mosaics produced for this project. The geologic interpretations not only gave the first true picture of the general distribution of rocks in the Amazonas province but also pinpointed a highly anomalous location, later discovered to contain significant reserves of both iron and rare earth elements.

During the fall of 1972 President Rafael Caldera of Venezuela announced a new mineral find "of great importance", including iron and possibly uranium, as a result of the radar mapping of the vast, virgin Venezuelan south. The imagery itself did not show mineral deposits but indicated to geologists where "ground truth" surveys should be made. Dr. Caldera said the find, named Cerro Impacto, contains a complex combination of minerals of great commercial and strategic value including a high content of iron, manganese, thorium, niobium, and radioactive materials.

ROLE OF SHUTTLE IMAGING RADAR--CONCLUSIONS

Space imaging radar systems will provide the longest wavelengths of the family of instruments used for sensing the reflected or emitted electromagnetic radiation from the Earth's surface. Radar is likewise unique in being the only active sensor in this family. This combination of active operation and relatively long wavelength give to radar a very distinct operational advantage aside from any unique information content in this spectral region. This is of course, the well known and well publicized ability of radar to image at night, through clouds, and even through substantial amounts of precipitation.

Many of the demonstrated geologic applications of radar imagery have utilized this operational advantage rather than any unique information contained in the microwave spectrum. Where solar illumination is impossible such as the arctic regions during winter or where cloud cover is nearly perpetual

such as in portions of the equatorial region, radar becomes not merely a unique sensor but often the only imaging sensor that can be employed. In regions where lack of illumination or cloud cover is not a continuing problem, radar often retains its operational advantage where the timeliness of data acquisition is critical. This is often the case in monitoring such targets as agricultural crops, or fleeting snow enhancement for geology.

In addition to the advantages inherent in active operation and cloud penetration, SPIR would also possess the ability to control to some extent the look direction and incidence angle of the illumination. This is probably the next best known feature of radar, namely the ability to enhance topographic relief through radar shadowing. The geologic applications and contributions of a space imaging radar may be divided into two categories, unique and supportive:

1. Unique Contributions

- a. Unique capability where cloud cover and lack of sunlight provide operational disadvantages. Improvement in world resource inventory.
- b. Selection of wavelength and angle of incidence permits some degree of vegetation penetration and suppression of vegetation detail, thus enhancing underlying surface structure.
- c. Control of aspect angle and look-direction improves delineation of surface features expressed in the terrain configuration. Linears not recognizable on LANDSAT or photography may be revealed.
- d. Return is sensitive to structure or texture in a wavelength (size) range compatible with determining surface grain size and inferring lithologic information.

2. Supporting and/or Systems Contributions

The roughness of texture sensitivity of the return adds another dimension to discriminate wherever another sensor can provide information

regarding homogeneity of material. For instance, particle size in arid or semi-arid regions is easily inferred if the influence of vegetation can be eliminated. Vegetation component can be obtained from LANDSAT imagery.

Needed Research

1. Extension of ground-based measurements for controlled materials and configurations.
2. Production of high quality multifrequency, multipolarization imagery for a variety of terrain conditions.
3. Determination of vegetation penetration capability.

COST-BENEFIT OF SPIR

In the DOI (Department of Interior) sponsored Cost-Benefit Study of LANDSAT I, carried out by Earth Satellite Corporation/Booz Allen Applied Research, the benefits accruing to geologic mapping and mineral and petroleum exploration were treated as one-time benefits, at the early insistence of O.M.B. (Office of Management and Budget). Though by the end of the study it was apparent that this position could not be fully sustained (i.e. there appeared to be a residual modest stream of benefits accruing through multi-time observations over long periods beyond the lifetime of LANDSATs 1, 2, and C), the principal benefits to geologic mapping and exploration with any new remote sensing system are likely to be one-time in the above sense and could be set against the sunk costs on that basis only.

The significance of these remarks is that the value of the Shuttle Program Imaging Radar likely will accrue primarily if not solely through the Shuttle program itself and not through any geologic advantages from a long-term operational system.

Thus in seeking justification for the Shuttle Program Imaging Radar, the

mineral/petroleum exploration case should bulk large in the analysis, for Shuttle will reap the major share of the benefits if a significant volume of radar imagery is obtained under shuttle auspices. This will be true even with the constraint of operating in the Shuttle Sortie mode which appears to be neutral in influencing the value of Shuttle geologic mapping. In making this point it is also stressed that an operational satellite could obtain the lion's share of the benefits if only a modest radar geology data base is obtained in the shuttle program. Thus the volume, diversity and geographical location of shuttle coverage for petroleum and mineral exploration will require close examination.

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CHAPTER 4

VEGETATION RESOURCE ANALYSIS WITH RADAR †

SUMMARY

The major conclusions reached on vegetation studies with radar are:

- * High levels of crop identification will be achievable with multi-frequency, multipolarization, multi-date radar imagery.
- * There are strong frequency dependencies in discrimination between crops, pasture and forest lands.
- * Polarization is an important discriminant in crop, pasture and forest identification.
- * The temporal element is a key component of plant community or crop identification.
- * Radar texture is an important discriminant of natural vegetation, and with high resolution, of crop land as well.
- * Stereoscopy aids in natural plant community inventory and monitoring.

RECOMMENDATIONS

The Space Program Imaging Radar Program should:

- * Vigorously pursue development of additional multifrequency/polarization radar spectrometers to extend the work initiated at the University of Kansas to a wide range of environments.
- * Move expeditiously to expansion of aircraft-based multiplex radar studies over natural and cultivated vegetation.
- * Conduct research rapidly in vegetation in order to define suitable specifications for a Shuttle Radar optimized in part at least for vegetation analysis.

† Prepared by David Simonett using materials supplied by F. T. Ulaby and F. P. Weber.

INTRODUCTION AND BACKGROUND

The monitoring of vegetation type, condition, and production is not only of central concern to nations, federal government agencies and state agencies, it is also a central concern of remote sensing. The bulk of the remote sensing work with vegetation has been carried out in the visible and near infrared with rather less in the thermal IR region and distinctly less in the radar region. However, both the quantity and quality of ground observations with radar during the last three years, through experiments at the University of Kansas using a truck mounted radar spectrometer, have begun sharply to modify this situation.

The earliest radar studies on vegetation were carried out with a Ka-band (Westinghouse AN/APO-97) aircraft imaging radar. The imagery obtained from this system in the mid 1960's indicated the possible potentials that existed in multipolarization Ka band imagery and suggested the need to experiment with multifrequency systems and particularly to obtain ground based spectrometric measurements.

During the time when at the University of Kansas the radar spectrometers were being built multispectral observations in the visible and near infrared region continued both on the ground and with aircraft data leading in due course to the multispectral LANDSAT satellite system. Because of this concentration on the visible and near- IR regions the work with radar has been on the periphery of vision of the natural resource-community dealing with vegetation. Since some extraordinarily interesting and distinctly encouraging results are now coming out of a well designed series of experiments at the University of Kansas it is now appropriate to examine the potential of radar sensing, bearing in mind its central advantage of penetration through cloud and (with long enough wavelengths) even through moderate falling rain.

The areas of interest in radar sensing are:

- * crop identification
- * crop and pasture condition, including moisture stress, disease, and temporal variability of condition
- * variability of crop and pasture identifications through time and as a function of radar wavelength and polarization
- * soil moisture determination
- * natural vegetation and shrubland mapping and condition
- * forest community and condition identification.

In this analysis we emphasize agricultural crop assessment (a mandated responsibility of several federal agencies and of which the large area crop inventory experiment (LACIE) is a part) and renewable resources evaluation for wildland and forests (again legislatively mandated). Many federal agencies are concerned with monitoring vegetation and its condition, including in the U.S. Dept. of Agriculture, the Agricultural Research Service, the Foreign Agricultural Stabilization and Commodity Service.

In the Dept. of the Interior there are included the Bureau of Indian Affairs and the Bureau of Land Management and the Fish and Wildlife Service. There are of course many state agencies ranging from land planning commissions to depts. of water resources, forestry and agriculture, all of whom have considerable interest in vegetation and its health.

AGRICULTURAL CROP ASSESSMENT OBJECTIVES

The U.S. Dept. of Agriculture needs to obtain timely, accurate global crop production information. This information is needed on a worldwide basis, not just domestic production. The U.S. must know where surpluses and deficits are worldwide because of their implications both for pricing policy, A.I.D.

programs, and foreign policy.

The U.S.D.A. concern is with the identification of major field crops and this requires identifying the crop and accurately measuring its acreage.

Crop Identification Studies

Crop identification studies using multispectral scanners are very numerous primarily because there is a substantial data base available. Until quite recently the absence of a good data base has seriously retarded radar crop classification studies.

The first major study of radar crop identification was by Simonett, et al. (1967). This study used Ka band imagery obtained by the Westinghouse AN/APQ-97 radar near Garden City, Kansas. Imagery was obtained in October and November of 1964, and in August and September of 1965. (Figures 4.1 and 4.2). At the time of flight a substantial body of ground truth data was taken. This included data on crop type, crop height, percent ground cover, crop contained moisture, and soil moisture. In each case for each field at least three, and sometimes five samples were obtained and aggregated in order to reduce somewhat the within-field variance. This data base was of sufficient volume and contained enough measurements of parametric variables that it was possible to subject it to covariance, multiple covariance, correlation and regression analyses. For each field the radar return was averaged from the imagery after applying correction for density variations due to side-lobing, scratches, and other imperfections on the imagery. These density measurements were then used as an independent variable in the statistical analyses.

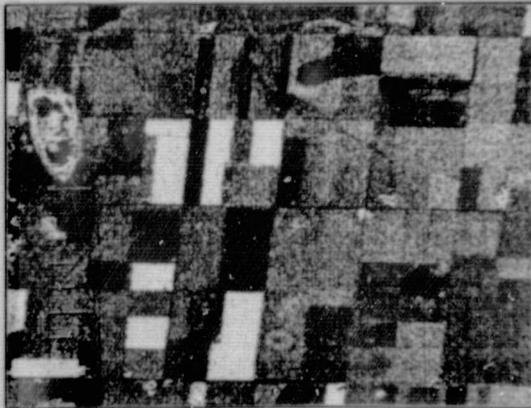
The principal conclusion of this study was that crop type was the most significant factor in determining radar return. (In other words while the parametric variables such as height, crop moisture, soil moisture, etc., were important, they were overshadowed by the basic between-crop geometric differences).

RADAR CROP IDENTIFICATION

GARDEN CITY, KANSAS



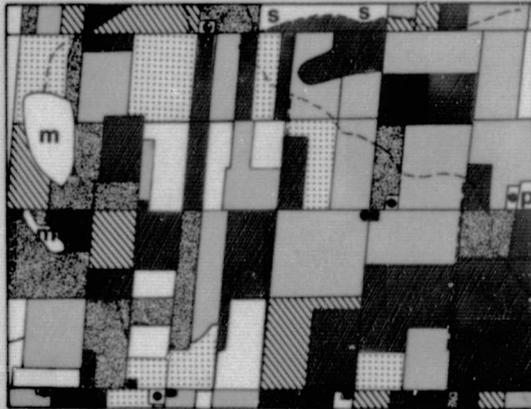
K-BAND
RADAR IMAGE



COLOR-COMBINED
HH-HV POLARIZATION
IMAGE



LAND USE



- ALFALFA
- BARE
- CROP RESIDUE
- FARMSTEAD
- MARSH
- PASTURE
- SORGHUM
- SUDAN
- SUGAR BEETS
- WHEAT
- IRRIGATION DITCH



Within each crop the various parameters contributed significantly to explaining the variance in return. Plant height was the most significant. Until maximum ground cover was reached, the percent ground cover was also very significant as would be expected since both cover and height are quite strongly correlated. Plant moisture was also significant but critical only when the plants were maturing and drying.

This data was all single frequency and single polarization. Since several dates were available it was possible to use the time variable as a discriminant. Simonett, et al. (1967) found that sugar beets were easily confused with other crops in August but in September, October or November they were correctly identified 100%. This capability appeared to be the result of the sugar beets increasing height, groundcover, and moistness at times of the year when other crops were maturing (corn, sorghum) or were of low groundcover (wheat). Other major major conclusions were:

- 1) that acquisition of imagery on a monthly basis throughout the growing season would significantly add the time discriminant for radar crop identification, and,
- 2) multi-frequency and multi-polarization should also aid in crop discrimination.

Further studies by Haralick, Caspall and Simonett (1969) and Schwarz and Caspall (1968) used Ka-band imagery with dual polarization. These images were obtained in August of 1965 (HH polarization), September of 1965 (HH and HV polarization) and July of 1966 (HH, HV, VH, and VV polarization). The main aim of the two studies was to see if radar crop identification was better with time sequential imagery with one or a few polarizations or with single date multipolarization images. The images were digitized for use in various classification methods. Haralick, Caspall and Simonett (1969) used a

Baysian classification rule, which showed that if only the July data were used 78% were classified correctly but if August and September were used the percentage of groups correctly classified rose to 90%. A Euclidian distance clustering technique was also used (for the first time in crop identification studies) and was found to discriminate crop types nearly as well as the other methods of categorization using training sets. The principal conclusions were that:

- * Multiple polarization was helpful in discriminating among croptypes.
- * Temporal multi-date imagery added significant information.
- * Since both time and polarization proved useful, that multi-wavelength data in the radar domain should be just as useful as multi-spectral data in the visible and near-infrared region.
- * A satellite platform would be helpful in providing the repetitive coverage found so useful for improving classification accuracies. An example of this imagery and the color combinations produced with HH and HV polarization Ka-Band images is shown in Figure 4.1. A scatter diagram of the HH and HV polarization data is shown in Figure 4.2.

In a similar study Steiner (1970) analyzed the time dimension for crop surveys from space using panchromatic aerial photography and coverage on 13 dates, from April 10 to August 8. Using linear discriminant analysis and the F-Statistic (the ratio of between-group variance to the within-group variance) Steiner derived the dates which gave the best discrimination. With a single day he was able to correctly classify 55% of his samples. With 3 dates he obtained 90% correct. Steiner usefully makes a point which those working with radar are concerned, "We are aware of the difficulties produced by the presence of frequent cloud cover over certain areas, of course. However, data gathering at more irregular intervals might produce satisfactory results, or else the use of another spectral band less or not affected by clouds (emphasis provided by us) might be the solution."

The results obtained in these studies were sufficiently encouraging that a proposal was made by R. K. Moore, D. S. Simonett, F. T. Ulaby, R. M. Haralick and colleagues at the University of Kansas for expanded and deepened radar

parametric studies and in particular for funding to build radar spectrometers. This proposal submitted and funded in 1970 began the work that led to the development of the spectrometers over the next 2-3 years. The radar spectrometers were in use in an effective manner in 1972-73. Their effectiveness has significantly increased as they have been improved and as the wavelength range has been expanded from 2-8 and 8-18 GHz. Before discussing in some detail the work with this truck mounted pair of spectrometers, further analyses of several imaging radars are worth reporting on.

The first of these is by Schuchman and Drake (1974) who reported on the feasibility of using multiplex slar imagery for both water resource management and mapping vegetation communities. The multiplex slar was an X and L-Band multiple polarization system developed by the Environmental Research Institute of Michigan (ERIM). The results of that and later studies clearly show striking differences in the two frequency multi-polarization imagery:

- * The striking radar imagery of Gilbert, Arizona illustrated in Chapter 1 is from this system. The same system obtained the imagery along the Gulf Coast of Florida used in Chapter 7.
- * The magnitude of the differences displayed in these images is such that the reality of the value of multispectral multipolarization data in the radar region is graphically displayed.

Batlivala and Ulaby (1975) analyzed data from the ERIM synthetic aperture system obtained on September 13, 1973 of a Huntington County, Indiana test site. Both HH and HV imagery were obtained in L-Band. No X-Band data was obtained. The major vegetation types in the area were corn, soybeans, pasture land and wooded areas. They used a linear discriminant analysis and found the highest probability of correct classification with both HH and HV polarization data (71% correct classification). When only using HH data the correct classification was 64%. It was also noted that the cross-polarized data provided better information for separating fields of corn from woods.

Truck Mounted Radar Spectrometer Studies

The principal ground studies of crops through the growing season have been carried out by Ohio State University in the late 1950's using X, Ku and Ka-Band (Cosgriff, Peake, and Taylor, 1960) in the Netherlands by de Loor and associates (de Loor and Jurriens, 1971; de Loor, 1974a, Attema and Van Kuilenburg, 1974; de Loor, 1974b; de Loor and Jurriens, 1972; and de Loor and Jurriens, 1974) and at the University of Kansas using the truck mounted spectrometer (Bush and Ulaby, 1975, 1976a, 1976b; Ulaby and Batlivala, 1975a, 1975b, 1976, Batlivala and Ulaby, 1975a, 1975b, 1976; Ulaby, Bush and Batlivala, 1975; Ulaby, 1975; Ulaby and Moore, 1973; Ulaby, Moore, Moe and Holtzman, 1972; Ulaby and Bush, 1976; Bush, Ulaby and Metzler, 1975). Considerations of space make it infeasible to discuss the work by Cosgriff, Peake and Taylor and by de Loor and associates. In addition, the sheer volume of work which is now coming to fruition at Kansas is such that only selected areas can be emphasized. These will be presented mainly as a series of illustrations derived from the work by Ulaby and associates and given in Figures 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 4.9, 4.10 and 4.11.

The evidence obtained in these spectrometer studies is very substantial and convincing with respect to the value of multi-frequency, multi-polarization and multi-temporal radar systems in crop discrimination and in stress detection. We have solid evidence from Finney County that this multi-frequency radar spectral data can give high accuracy with a range of crops including wheat stubble, tall alfalfa, short alfalfa, short and tall milo, tall soybeans, and green wheat. The first figure (Figure 4.3; after Ulaby, 1976) shows that both multi-frequency and multi-polarization improves crop classification accuracy. The classification procedure used is unsupervised clustering. Several polarizations are used (VV, and HH separately, and in combination. In addition a range of wavelengths between 8 and 18 GHz are used. The percent correct classification given from unsupervised clustering is shown for both single frequencies and multiple frequencies.

BOTH MULTIFREQUENCY AND MULTIPOLARIZATION IMPROVE CROP CLASSIFICATION ACCURACY

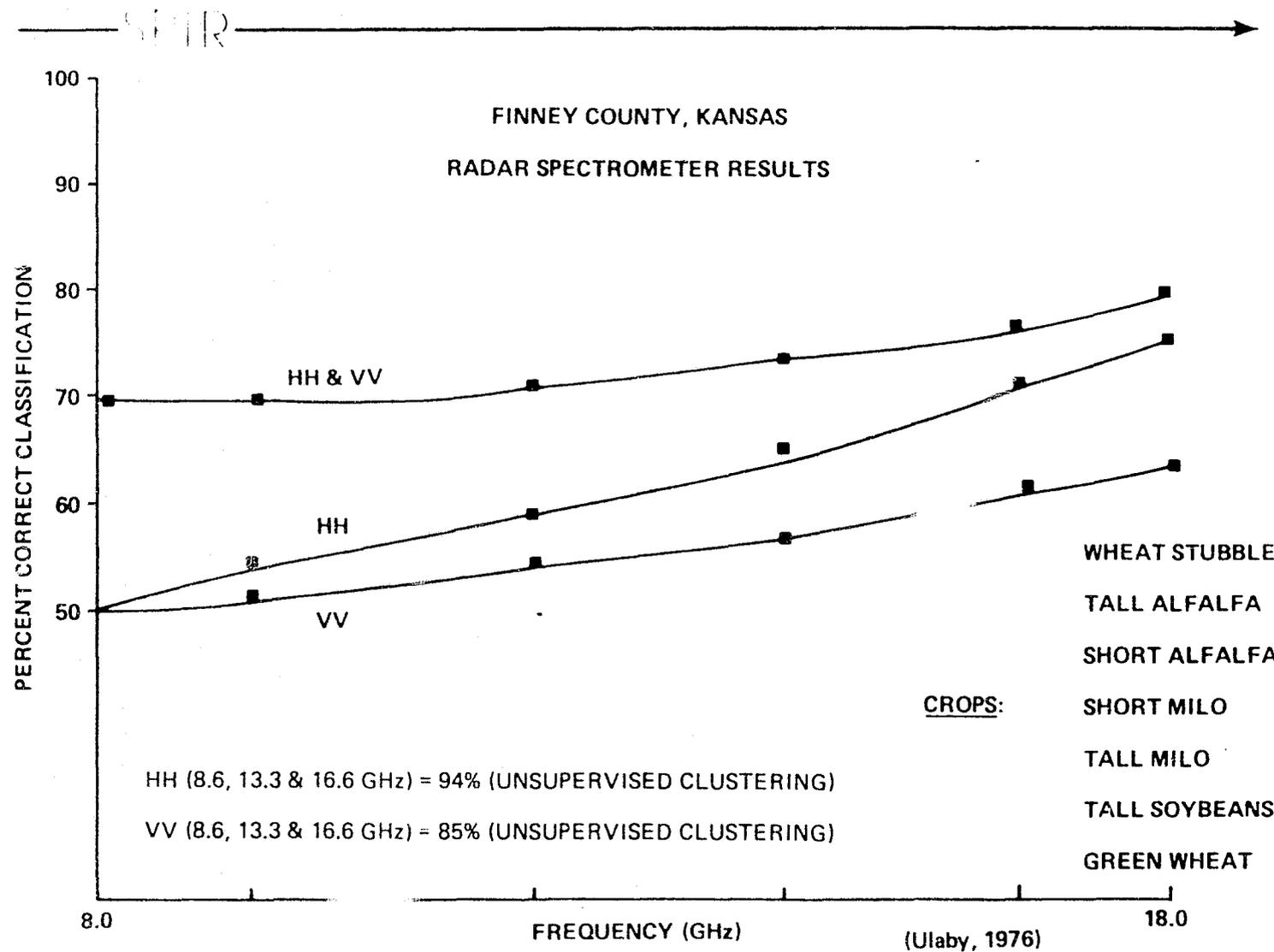


Figure 4.3

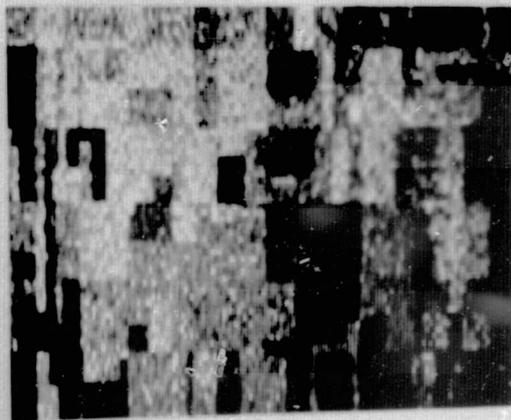
The graph shows the rise in percent correct classification as one moves from 8 to 18 GHz (3.7 to 1.67 cm). This shows both VV and HH and the combined HH and VV at each frequency step. Thus the shorter wavelengths are more suitable for crop identification studies. Generally, it now seems that wavelengths somewhere between 14 and 18 are optimal when just a single frequency is used. Note also that multiple polarization is valuable in increasing classification accuracy. HH polarization (in the shorter wavelengths especially) appears to be more satisfactory.

The identification accuracies for combinations of wavelengths (8.6, 13.3, and 16.6 GHz) are given for HH (94%) and VV (85%) polarization: accuracy depends on both frequency and polarization. Only a relatively small sample of fields (about 40) was used in this study, but that is of course one of the problems of working with a truck based spectrometer. We will obtain substantial wide area statistics when we move to multi-frequency imaging systems. Nevertheless, we can predict from these spectrometer results with some confidence, at least to the degree we were able to do with ERTS before it was launched.

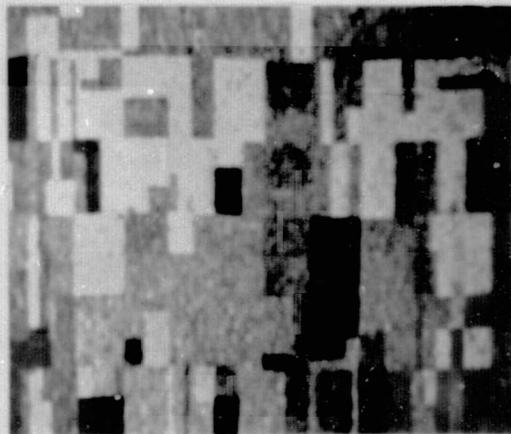
This same data has been used to develop color simulated images shown in Figure 4.4. In this illustration both HH and VV color simulations are given for the same approximate wavelengths used in Figure 4.3. It is particularly to be observed that there are decided differences between the VV color simulation and the HH color simulation indicating the value of both polarizations. The data has the typical fading statistics of radar added in the simulation. The average data on a perfield basis was obtained with the spectrometer and then expanded over the entire field. The image therefore lacks the natural internal variability arising from differences in crop response, variations in soil moisture and differences in soil types. Nonetheless, it is quite consistent with the appearance of radar images actually obtained of the same area in Garden City. Note for example the absence of internal variability in the Ka-Band radar image

THREE-FREQUENCY RADAR CROP SIMULATION FINNEY COUNTY, KANSAS

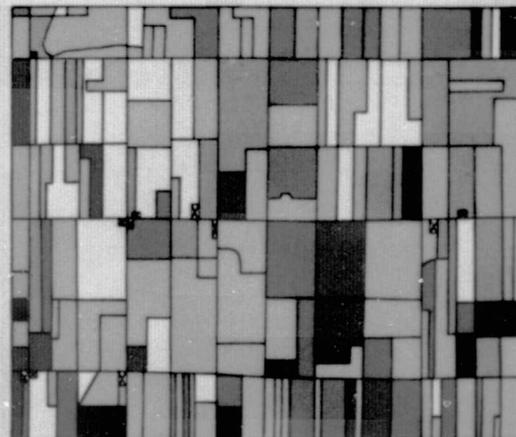
← SPIR →



*VV COLOR SIMULATION



*HH COLOR SIMULATION



GROUND INVESTIGATION

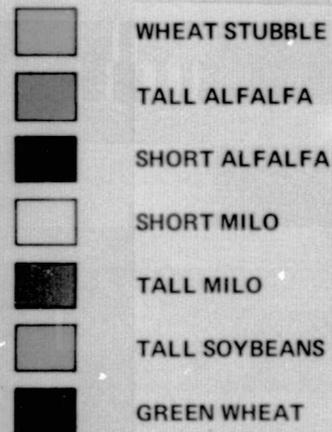
*COLOR SIMULATION OF AN AGRICULTURAL
SCENE AS IT WOULD BE IMAGED BY A
MULTIFREQUENCY RADAR:

8.6 GHz is red

13.8 GHz is green

16.2 GHz is blue

(Radar Spectrometer Information From R. K. Moore And F. Ulaby)



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shown in Figure 4.1 in the same general area.

The value of a series of wavelengths and of the time dimension are shown in Figures 4.5 through 4.9. Figure 4.5, taken from Ulaby and Bush (1976) shows the variation in scattering coefficient at 14.2 GHz, VV polarization, 50° angle of incidence, for each of alfalfa, corn, soybeans, milo and wheat over the time period May 19th through September 26th at 5-day intervals. It is clear from this figure that the scattering coefficient from corn is much higher than any other crop between June 8 and July 18. Thereafter, it tends to overlap the average values for other crops. The values for unharvested and harvested wheat are much lower than other crops (once milo is emergent) except that wheat suddenly rises to a peak just at harvest. Similarly, late in the growing season, as the milo comes to maturity it rises to values higher than other crops and rises above corn which in August is beginning to decline. In short, the illustration shows that temporal variability is one of the principal discriminants along with the intrinsic differences between crops at that wavelength.

Figure 4.6 also from Ulaby and Bush (1976) shows the percent correct classification using unsupervised classification at 14.2 GHz, for two polarizations. The peak time for obtaining maximum discrimination of crops is in mid-June; two polarizations, vertical and horizontal, one better than one. The poorest time for discrimination is mid-August.

In Figure 4.7 from Ulaby and Bush (1976) the improvement in accuracy obtained by adding another wavelength (9.0 GHz) is seen. The upper solid line shows that in mid-June accuracies of virtually one hundred percent are obtained using 14.2 H and V and 9.0 GHz, H and V. However, even at other times of the year (May, September) the accuracies are above 85%. They fall to a minimum of 75% in mid-August.

Finally, in this sequence we see in Figure 4.8 the addition of yet another frequency (17.0 GHz). The three frequency system uses one polarization in each

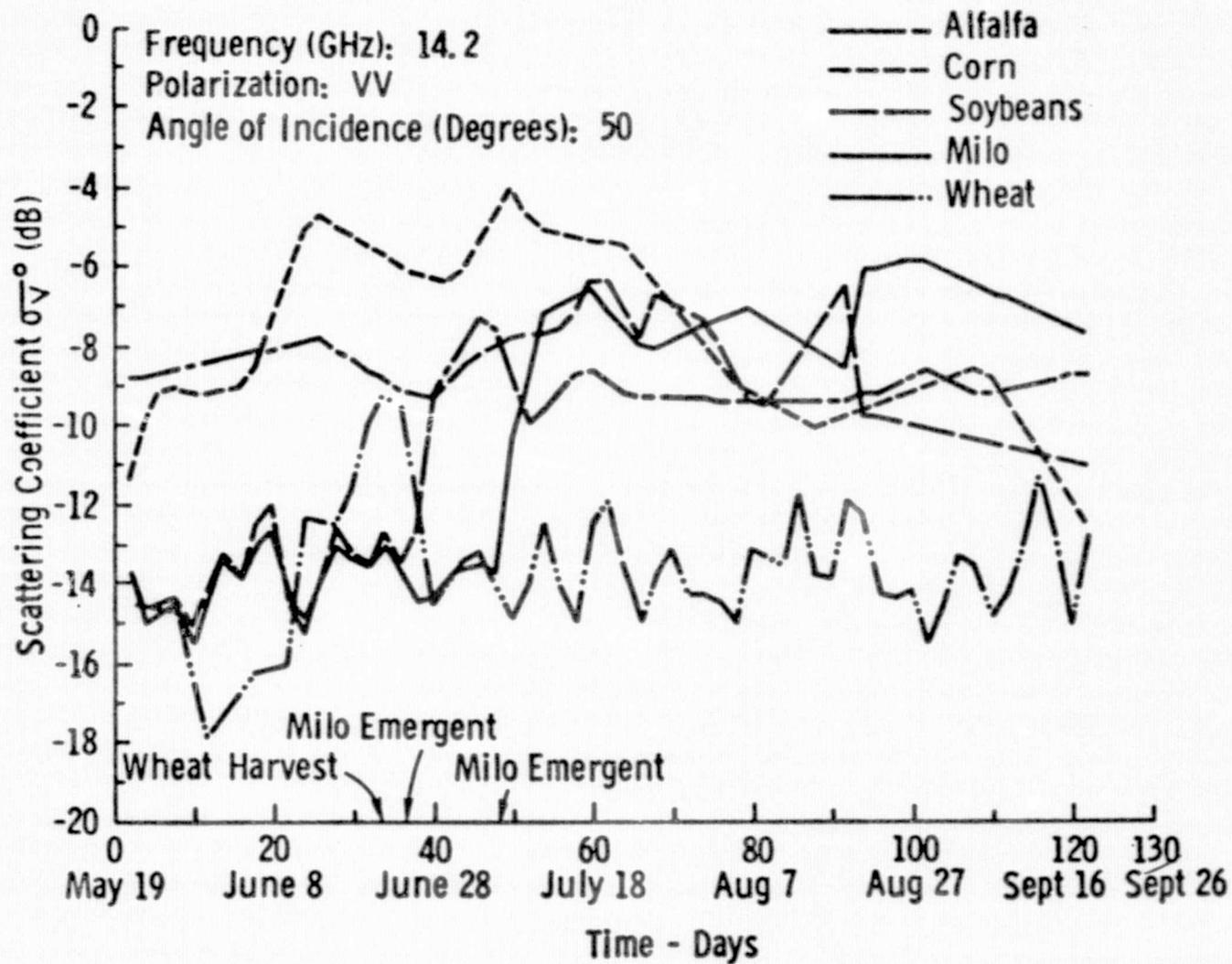


Figure 4.5

4-16

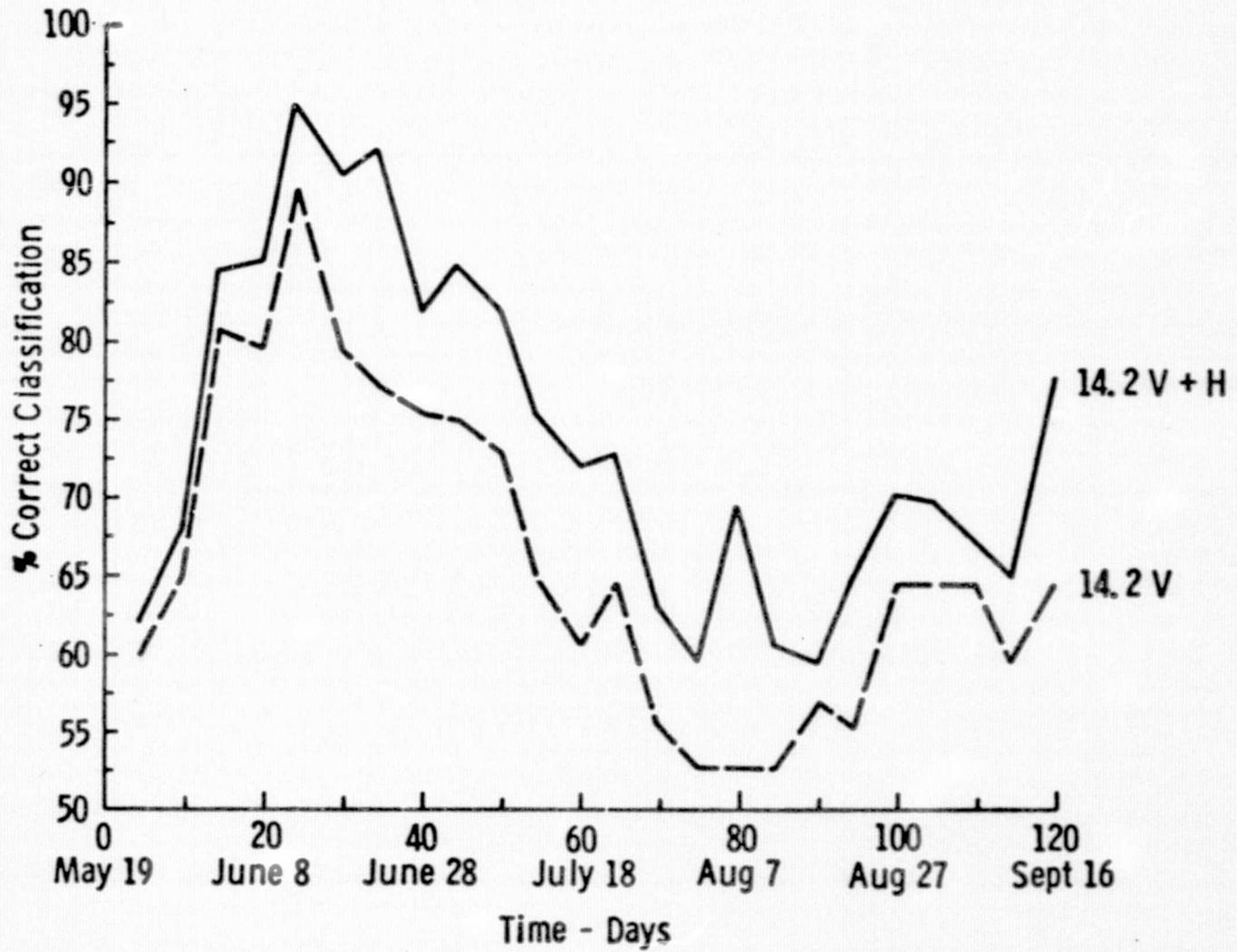


Figure 4.6

4-17

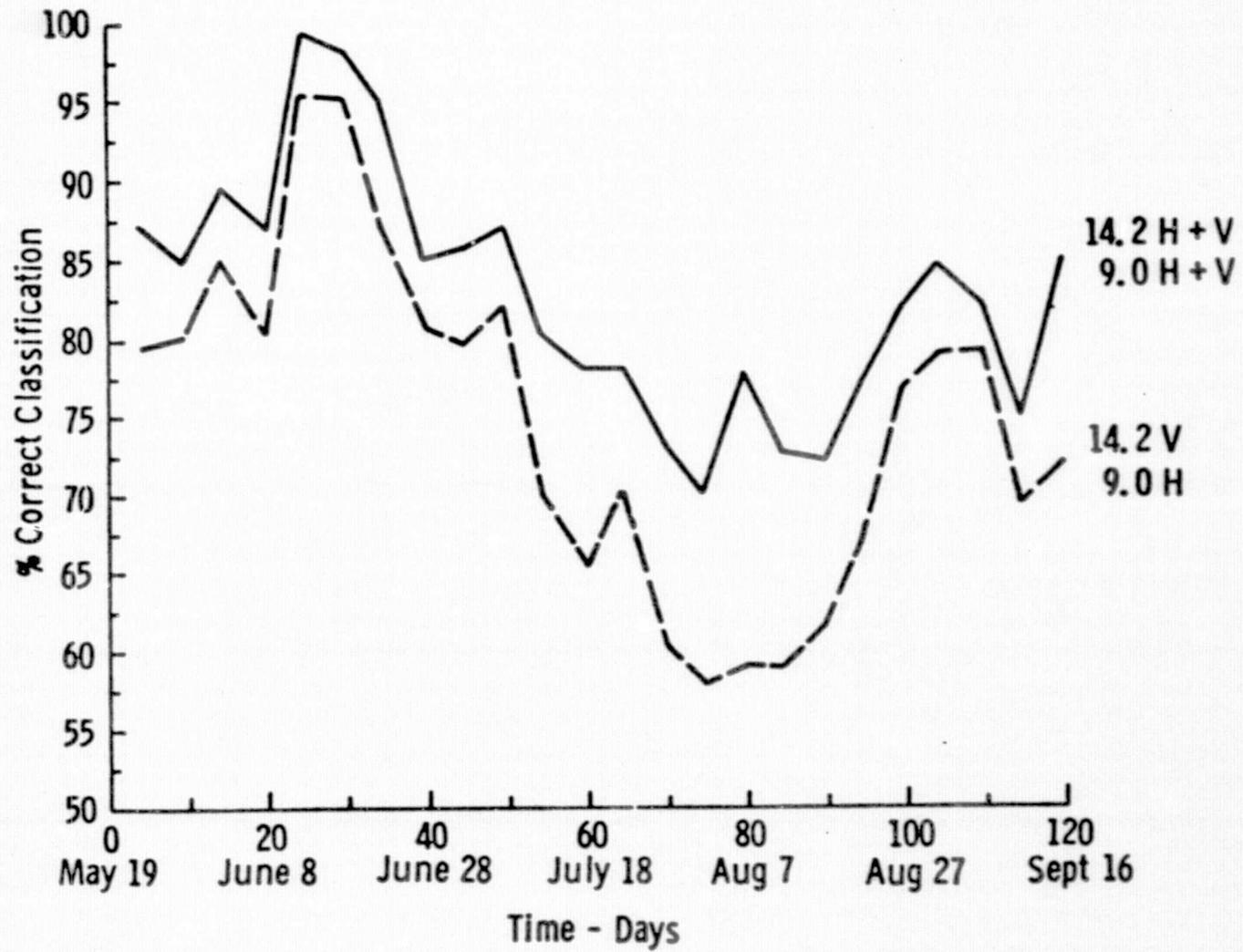


Figure 4.7

4-18

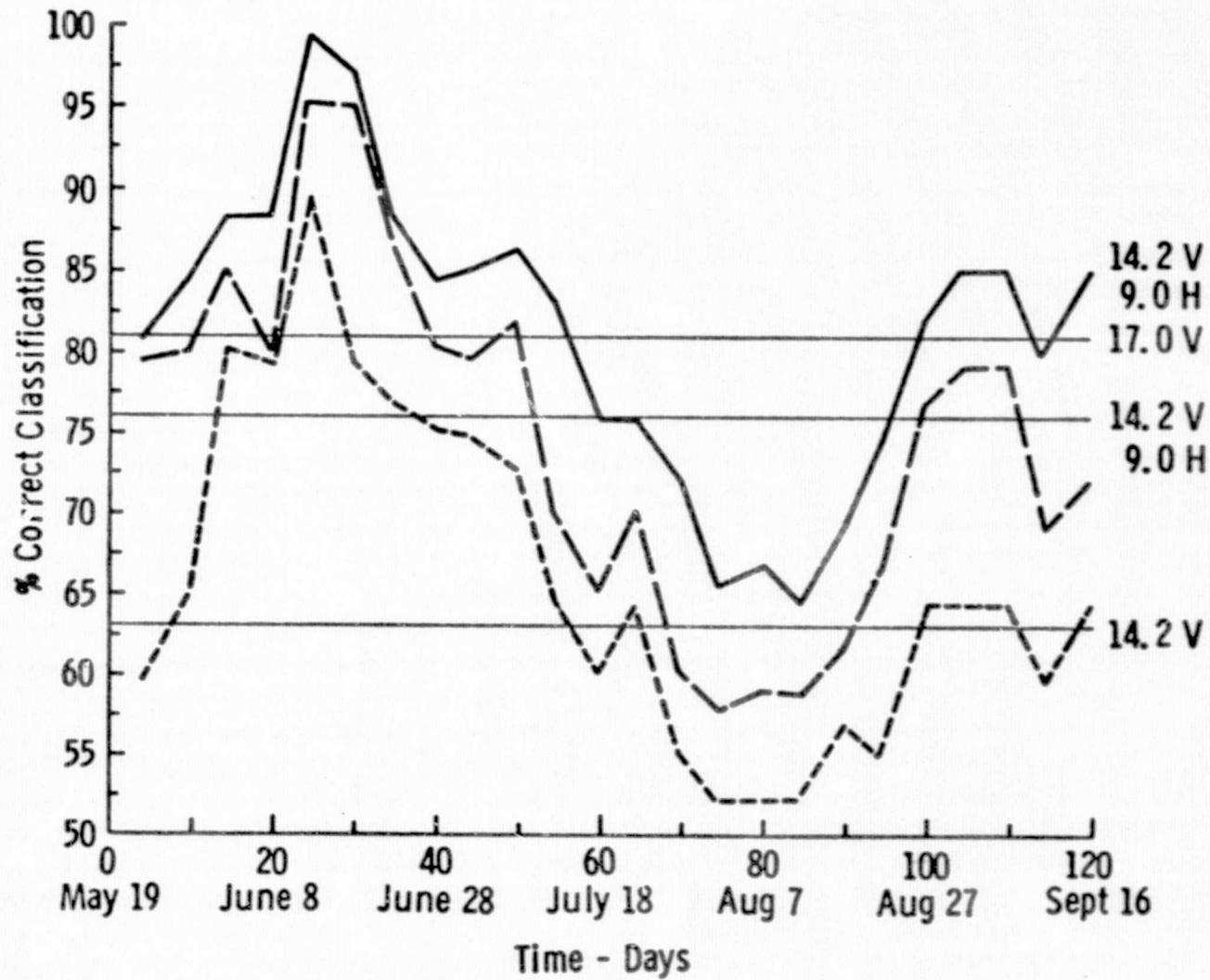


Figure 4.8

case and is quite close to the two-frequency two polarization case given in Figure 4.7, indicating that both polarization and frequency are partially tradeable in crop identification. An interesting conclusion is that it may be less costly to implement a new polarization than a new wavelength, or vice versa.

Finally, in Figure 4.9 is shown the percent classification using sequential 14.2 GHz and vertical polarization data. The time over which this analysis was carried out was 35 days. During that period if just three dates were available at day 10, day 20 and day 30 respectively each additional date gave an improvement in accuracy of identification: initially from 65% to 85% and then to 94%. When four dates were available, the respective jumps in accuracy from day 4 to days 14, 24, and 35 were respectively from 60%, 87%, 94% and finally 97%. It is also seen that when seven days were available that the accuracies were no better than four days. This indicates that data obtained more frequently than at 8-day intervals during that time period were not of great value because of strong correlations between close days. The same general results are shown with sequential 14.2 GHz horizontal and vertical polarization data combined. In this case also the 3-day data was distinctly inferior to four dates and the latter in turn was roughly comparable to 7-day data. When the full cropping season is taken, other studies by Ulaby and Bush show that the proper sampling time is approximately between 10 to 15 days in order to avoid unnecessary correlation between days too close to one another. This tells us something very important about the frequency of return of a radar imager in either aircraft or space in order to obtain the maximum information with the minimum redundancy. It turns out that the proposed 9-day interval for LANDSAT-D is very nearly optimal if the experience presented by Ulaby and Bush is of general applicability. It also indicates that with a radar satellite a frequency of recurrence interval of perhaps 10 days may prove most satisfactory. More work is needed with more crops to establish whether this relationship holds generally. On general principles it

4-20

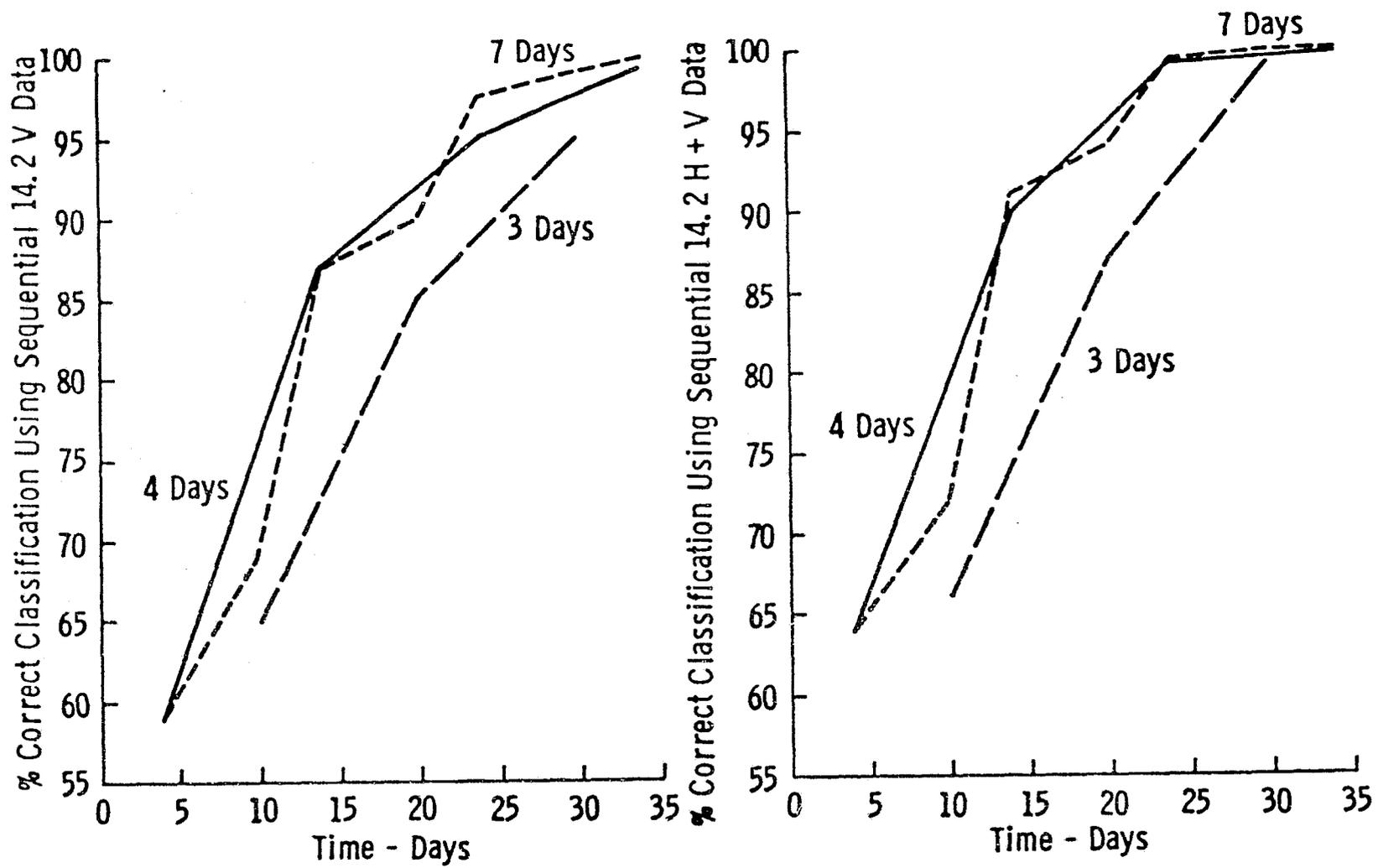


Figure 4.9

is reasonable to anticipate - knowing the rate at which changes occur in crops - that approximately 10 days to two weeks will in fact prove out to be very nearly optimal for almost all cropping circumstances.

Important conclusions from other studies at Kansas are the following:

- * The percent of moisture in the soil under crops has a very pronounced effect on σ_0 , particularly at the lower frequencies and angles of incidence. An example of this effect is shown in Figure 2.3 in Chapter 2 which shows the effect of differing incidence angles at a frequency of 4.7 GHz. (Ulaby, Bush and Batlivala, 1974).
- * A pronounced diurnal variation in σ_0 has repeatedly been observed. This cyclical variation measured at 2.75 GHz is at a maximum around dawn. The total excursion may be as much as 8-9 dB for horizontal polarized σ_0 at 10° incidence angles. However, even at 50° it can vary by as much as 6 dB. With increase in frequency variations are markedly reduced. If radar is to be used for both day and night sensing of vegetation, frequencies greater than about 8 GHz should be used. On the other hand the diurnal variability may be related to crop turgor and could be a useful tool in stress studies. For this purpose wavelengths perhaps of 2-3 GHz may be nearly optimal. (Ulaby and Batlivala, 1976). The rate of change of σ_0 as a function of time showed that while it was relatively constant during the earlier portion, it rapidly increased just before harvest and then rapidly decreased after harvest. Ulaby and Bush suggest that such an indicator may be used as a measure of plants' nearness to harvest or that harvest had taken place.
- * Multidate data was obtained from fields of alfalfa, milo, and soybeans. For these crops there was little relation between σ_0 and crop characteristics. (Bush and Ulaby, 1976a; Bush, Ulaby and Metzler, 1975).

Along with the crop identification accuracy we need accurately to measure fields. The three frequency crop simulation shown in Figure 4.4 shows that there is both a frequency and polarization dependence with respect to field identification. In other words, it will be necessary to have multiple frequency and polarizations to achieve the maximum identification of acreages. This of course is true also in the visible and near infrared regions. (See also Figures 1.1, 4.1, and 4.2).

AGRICULTURAL CROP ASSESSMENT OBJECTIVES.

This second agricultural objective is to monitor plant vigor, growth stage and yield. Plant moisture gives an indication of plant stress, hence vigor and

yield potential.

We have substantial evidence in this area. Crop geometry changes in relation to leaf turgor, are in turn related to stress and moisture in the plant. As seen earlier there are also day/night differences which are substantial and require further research.

Radar Monitoring of Plant Moisture

With wheat there is a correlation of .9 between radar backscatter and normalized plant water content. The most sensitive wavelength is at 9.4 GHz and the best viewing angles are close to nadir. As noted also the rapid variation in backscatter shortly before and after harvest can give unique harvesting information.

With corn, the correlation is .96. The most sensitive wavelength is at 17 GHz and the best viewing angle at 50°. The correlation shown in Figure 4.10 is for a 50° incidence angle, VV polarization, and 17 GHz.

The unit of measurement of water contained in the plants is the "normalized plant water content, w_{pn} ."

$$w_{pn} = \frac{m_w - m_d}{h}$$

where m_w = wet plant mass (gm)
 m_d = dry plant mass (gm)
 h = plant height (m)

The maximum correlation of .962 between normalized plant water content and with vertical polarization was noted at 50°. However, quite acceptable correlations were obtained in the full range from 30° to 70°. This relationship would be important for monitoring corn maturation, because as the corn dries backscattering should be responsive to the drying. This also would be a good signal of early maturation in drought years (Ulaby and Bush, 1975).

2

SIGNIFICANT RELATION BETWEEN RADAR BACKSCATTER FROM CORN AND CROP WATER MASS PER UNIT VOLUME

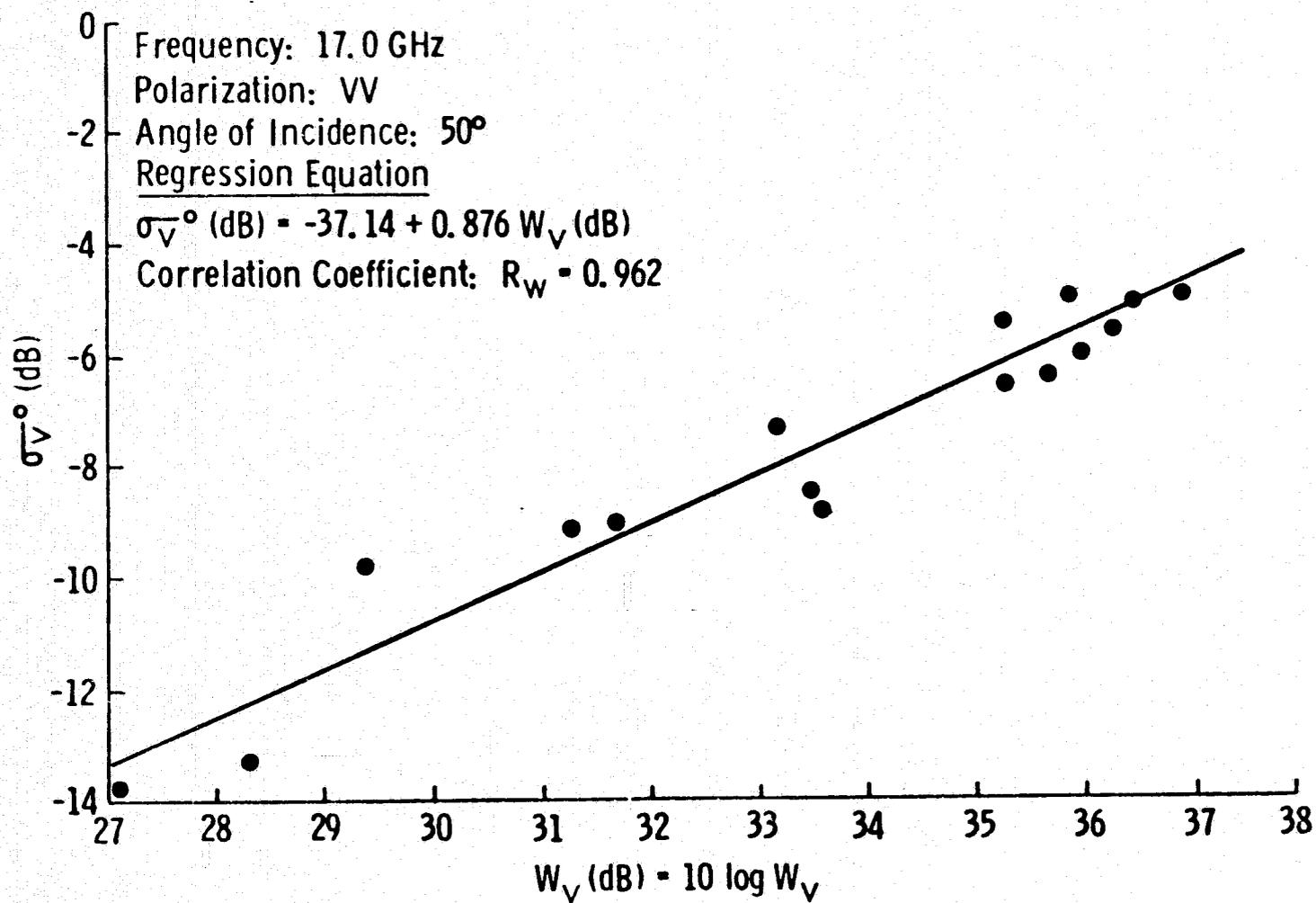


Figure 4.10

The temporal variability of corn crop backscatter in relation to normalized plant water content through the growing season from May 20th to September 17th, at different growth stages is shown in Figure 4.11. These relationships could be used for predictive purposes (Ulaby and Bush, 1975).

As seen in Chapter 2 there is a correlation between backscatter and soil moisture in bare soil. This correlation is most pronounced at long wavelengths (4 GHz), while the sensitivity to crop moisture tends to peak in the 14 to 17 GHz region (with a crop cover there is a loss of sensitivity to soil moisture through attenuation of shorter wavelengths in dense canopies). Also when radar looks near vertical it sees more soil than crop per unit area. This combination of factors means that a near-nadir long wavelength radar is optimal for monitoring soil moisture, while a distinctly off-nadir (say 40° - 50° incidence angle) and short wavelength (14-17 GHz) nadir appears optimal both for crop identification and for detection of crop moisture. This latter effect is consistent with the earlier results with Ka-Band imagery obtained by Simonett, et al. in 1967. Since one of the major concerns with ground based radar spectrometry is the degree to which it is extrapolatable to aircraft, it is important to note cases where aircraft and the ground spectrometer produce essentially similar results.

FOREST AND WILDLAND EVALUATION

Forest and wildland evaluation is legislatively mandated through a great variety of federal and state programs. Recently, these programs have been strengthened through the passage of the Renewable Resources Evaluation Program (R-RPA, 1974).

Under this renewable resources program numerous studies are underway in testing various remote sensing capabilities. Radar evaluation of forest and wildland mapping, and monitoring of condition is not as well documented as are

TEMPORAL VARIABILITY OF CORN CROP BACKSCATTER IN RELATION TO CROP MOISTURE

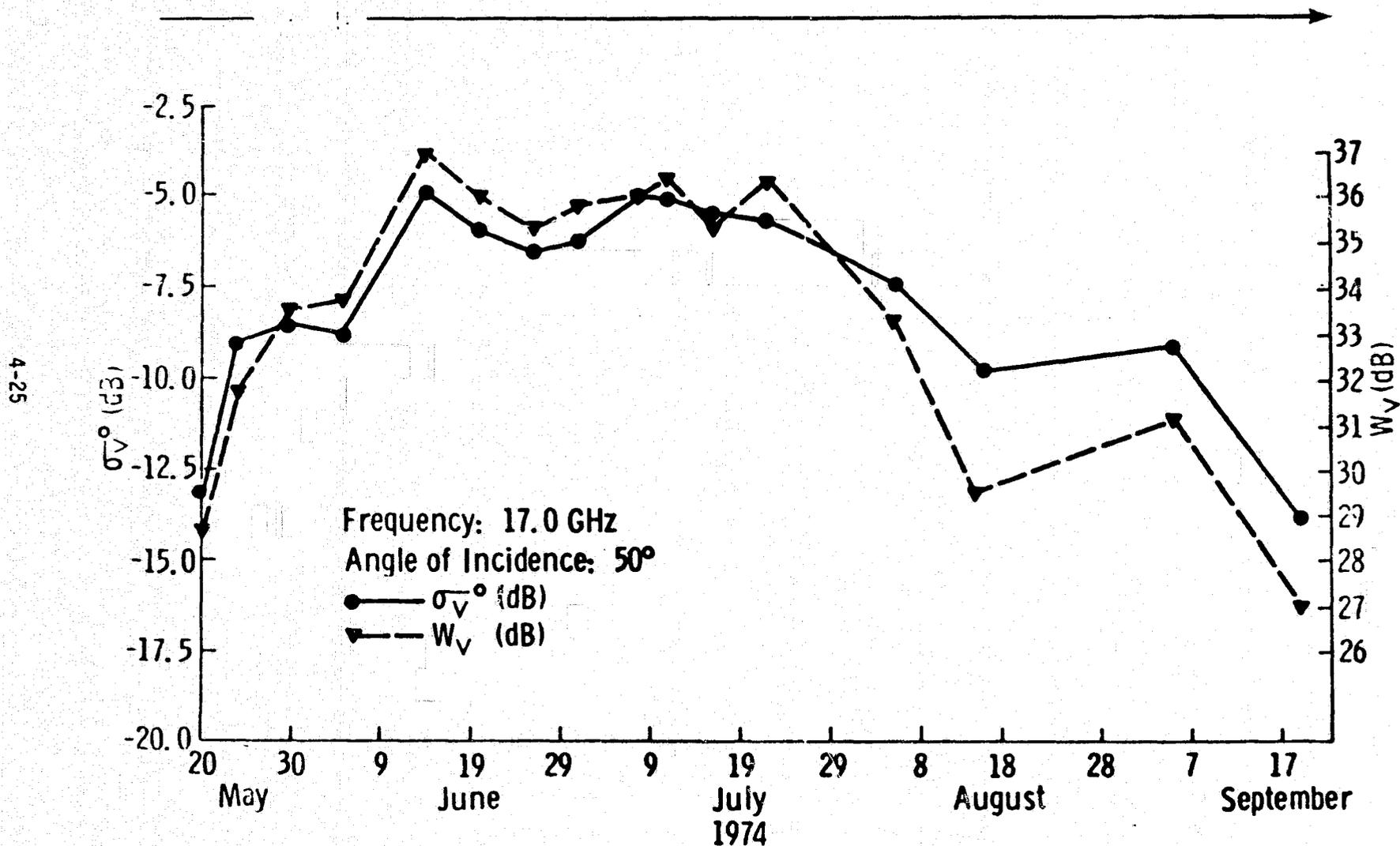


Figure 4.11

crops. We emphasize three areas. First is assessment of timber death, second is forest and rangeland fuel status, and third is forest and range biomass.

The Forest Service needs to assess timber death in order to locate and map standing dead merchantable timber. This is currently the single most important data requirement in the Forest Service for which data collection and sampling methods are lacking. It has a very high priority within the Service, which needs this information to get to this otherwise wasted dead timber to lumber it out and also remove a source of potential fungal infection and insect attack. There appears to be good evidence in classified imagery that this can be done but it requires verification. Multi-frequency, multi-polarization radar will surely be needed to identify stands of an acre or so of dead timber. A recent study by Bush, Ulaby, Metzler and Stiles (1976) - some data of which is shown in Figure 4.12 - is relevant.

In Figure 4.12 is shown the differential backscattering for vertical and horizontal polarization for Kansas deciduous trees near Lawrence, Kansas at a 40° angle of incidence in both Spring and Fall. During Spring leafout backscattering increases as leaves appear and as the water volume per unit area increases. During autumn when the leaves are senescent backscatter is distinctly less. There is also a strong frequency dependence: the most effective separation would be at 17 GHz between trees that are in vigorous growth and those that are dead or senescent.

The second major problem which concerns the Forest Service and the Bureau of Land Management is that of forest and rangeland fuel moisture status. This data is very important as an input to fire models, to predict the rate of fire spread. This is a very high priority with both agencies and is not currently satisfied. The evidence of radar contribution at the moment is soft in the sense that not much has been done on the moisture status of litter on the ground or in the standing timber, shrubland and grassland as they go into senescence.

4-27

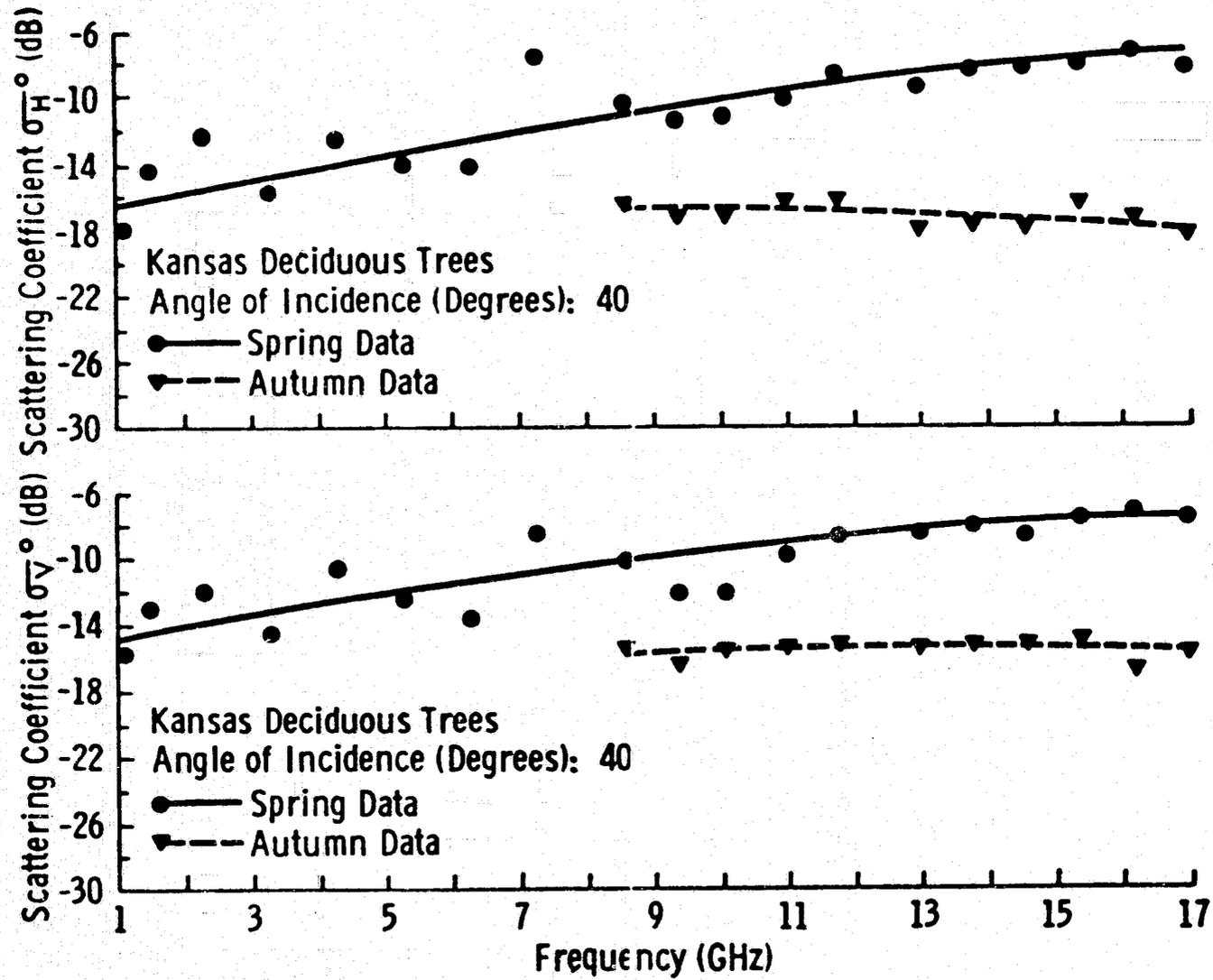


Figure 4-12

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On the other hand, it is possible to reason from the crop research and the deciduous tree results (Figure 4.12) reported on by Ulaby and associates, that there should be a relationship between the return and plant moisture. It should be possible to calibrate an area over time and make predictions from the appearance of the imagery. This may be easier in range than in forest, because both grassland and shrublands more nearly resemble croplands than do the forests. Major research will be needed.

Another major concern of the Forest Service is that of forest and range biomass. The Service must estimate biomass for use in fire fuel prediction. In other words, in addition to the moisture content of the fuel the sheer volume of biomass is also important in providing the base for the fire. These same biomass estimates can be used in rangeland management to monitor carrying capacity for livestock and wildlife. Evidence for the radar contribution is moderate for range: Hardy, et al (1971), Morain and Simonett (1967), Morain (1967), Simonett, et al (1967), Morain (1970), and Morain and Coiner (1970) are relevant once an area is typed. Also it is possible to extend by inference Ulaby's work with his associates which shows that as crops mature there is a relationship between backscatter and total biomass. This area has not yet been studied even inferentially for forests. It may be feasible but clearly major research is needed.

Related to these questions of biomass and the contained water content in the biomass is a further problem of soil moisture in the plant root zone needed for rangeland just as for croplands. The largest payoff for this application would be for predicting biomass productivity based on site potential and the measurement of soil moisture. The Forest Service and the Bureau of Land Management both rank biomass productivity as high in their priorities. The evidence of the radar contribution in this area is again inferential from the work by Ulaby and colleagues.

CONCLUSIONS: ROLES FOR SPACE SHUTTLE

In reviewing the current status of work in radar remote sensing the following conclusions emerge:

- 1) Regional classification of natural vegetation is possible with single frequency radar. The principal studies are those by Hardy, Coiner, and Lockman (1971), Waite and MacDonald (1971), Morain (1967), Morain (1970), Peterson, et al (1969), and Morain and Simonett (1967), Bush, Ulaby and Metzler and Stiles (1976), Dellwig (1972), and unpublished observation by Simonett in New Guinea and Brazil. However, single frequency, single polarization radar is not as good as having multiple polarizations and frequencies: Dellwig, 1972; Bush, et al, 1976; Schuchman and Drake, 1974; Battivala and Ulaby, 1975a. Multi-temporal data will also be useful in forest and wildland studies just as with agricultural lands (Bush, et al, 1976).
- 2) Significant changes in timber stand geometry can be delimited. Unpublished analyses by Weber using classified imagery have shown the ability to detect (through changes in timber stand geometry) areas of dead but merchantable timber. This is also seen in Morain (1967), and Morain and Simonett (1967) in delimiting areas of different growth stages in Ponderosa pine forests at Horsefly Mountain, Oregon. By extension, Bush, et al (1976), reach the same conclusion for Kansas deciduous trees.
- 3) Polarization is an important discriminant in vegetation analysis. This has already been demonstrated repeatedly with respect to crop lands and it has been shown enough times in pasturelands and in forest lands that the case no longer needs to be made. All that is required is further documentation of the effects and unpacking for different environments what the quantitative relationships are. Since this cannot be done with a truck based spectrometer except over crop and pasturelands, it will await the use of aircraft over forest lands, for further documentation.
- 4) Radar return with vegetation varies with frequency. Enough images involving comparisons between X and L-Band have already been obtained with the ERIM system to indicate that wildland and forestland as well as crops show discrimination with frequency. In a study in Florida, Dellwig (1972) demonstrated the same with multiple wavelengths in the K, X, and P-Band region.
- 5) The type of crop is the most important variable in influencing single frequency radar return in agricultural areas. This is also true with multi-frequency radar. There is a residual influence within a single crop of much significance relating to parametric variables such as the height of the crop, the density of the ground cover, contained vegetation moisture and so on.
- 6) Radar texture is an important discriminant of natural vegetation. This is a very important discriminant and has been a major factor in assisting plant community identification in the project RADAM studies in the Amazon (Simonett, unpublished memoranda). While we have very little

imagery in a range of frequencies there is every reason to believe not only will there be frequency and polarization dependence there will also be differential texture dependence as a function of frequency and polarization. While this is a theoretical proposition arguing from general principles we assert with considerable confidence that it will hold and that it will add substantially to our discriminatory power in natural plant community mapping. Morain and Coiner (1970) also show that high resolution radar enables crops to be separated through, inter alia, differential texture effects.

- 7) Temporal imagery is important in discrimination. This has now been abundantly documented in croplands. By inference the same will apply in pasture and forest lands where there are significant changes in state throughout the year.
- 8) Stereoscopy greatly aids plant community mapping. In natural vegetation community mapping stereoscopy significantly assists in that mapping as shown in both Brazil and New Guinea (Simonett, unpublished memoranda). We can obtain stereoscopy from space probably better than from aircraft.

Roles for Space Shuttle Imaging Radar

Significant roles for a Space Shuttle Imaging Radar will arise from:

- * The flexibility of Shuttle in allowing multi-frequency long and short wavelength radar (probably C and either Ku or X-Band, preferably Ku), Multi-polarization imagery to be tested repeatedly are very large areas, with a variety of look angles and directions.
- * The support a shuttle radar will give to providing multi-date information for planning in the very cloudy underdeveloped areas of the tropics.
- * Integration of shuttle imaging with a LACIE program using LANDSAT D and later satellites.
- * Firming up the final specifications for an agricultural monitoring radar satellite to be used in parallel with an optical-region satellite.
- * Detailing vegetation/flooding area relationships over millions of square miles in developable tropical land.
- * Provision of a world-wide natural plant community image file to merge with LANDSAT Data for improved inventory.

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CHAPTER 5

SPACE RADAR APPLICATIONS FOR OCEAN AND SHIP MONITORING[†]

SUMMARY

The dominant areas of oceanographic information needs to which a Space Imaging Radar can contribute are:

- * ship navigation and routing
- * ice surveillance
- * environmental wave forecasting and general circulation patterns
- * hazard detection, pollution monitoring, fishing vessel monitoring
- * ship and coastal structures design
- * coastal structures placement

RECOMMENDATIONS

Space Program Imaging Radar Program should:

- * conduct more research to establish quantitative relations between radar image characteristics and wave and surface parameters including wave height, wind strength and direction, precipitation and others. This knowledge should also lead to relations between the wave spectrum and the image two-dimensional spectrum.
- * include additional research on radar observation of internal waves, extreme sea state, especially in hurricanes, and on wave generation under a wide variety of conditions.
- * continue the extensive experiments on sea ice and iceberg discrimination and dynamics.
- * develop operational information systems incorporating the above research, and real-time data for improving ship-routing, climatological understanding and weather forecasting, structure design and environmental monitoring.
- * define the roles for space shuttle imaging radar experiments in support of the SEASAT program.

[†] Review prepared by Earl J. Hajic and David S. Simonett, incorporating materials provided by Paul Teleki, M. Leonard Bryan, and Charles Elachi.

INTRODUCTION AND BACKGROUND

Imaging radars in future operational ocean surveillance systems will provide information having a significant impact on the effectiveness and safety with which we will use the ocean. They will aid ocean fishing, mineral extraction and farming and provide for the improved design of ocean structures. Finally, they will provide us a sensitive means of monitoring the environmental effects of various uses and warn of impending natural hazards. These capabilities will mature slowly. Thus the SEASAT A mission of 1978-79 will provide valuable program inputs to the shuttle radar ship navigation and ocean measurement experiments. This in turn can lead to more advanced operational satellites incorporating imaging radars and other sensors, and linked to ocean and aircraft observations in a full system. Eventually, we look towards polar orbiting satellites and multiple orbits, all weather day/night capability, real time coverage every 90 minutes and user orientation/low cost missions and data.

Tables 5.1 and 5.2 summarize user needs and requirements and Table 5.3 identifies the operational capabilities that are needed (Tables prepared by Paul Teleki).

As seen in these tables the main areas in which there is a pressing user need are:

- * wave forecasting
- * operational meteorological forecasting
- * general circulation
- * hazard warnings
- * ship routing
- * detection and monitoring of near-shore pollution
- * harbor and coastal power plant location
- * detection, monitoring, and routing of fishing and other vessels

TABLE 5.1

OCEAN DYNAMICS NEEDS AND REQUIREMENTS

PIR →

- OPERATIONAL METEOROLOGICAL AND MARITIME FORECASTS
 - IMPROVE N. PACIFIC AND N. ATLANTIC NUMERICAL SEA STATE/WIND FORECASTS NAVY
 - GENERATE DATA FOR S. ATLANTIC, S. PACIFIC AND INDIAN OCEAN MODELS NAVY, UNIV.
 - TRACK MAJOR STORMS DOD, NOAA

- NAVIGATION HAZARDS
 - IMPROVE AND/OR EXTEND ICEBERG PATROLS CG
 - SHIP ROUTING AROUND STORMS DOD, NOAA, AIMS
 - IMPROVED SHIP DESIGN FROM GLOBAL OCEAN DATA NAVY, MARAD, AIMS
 - SHIP ROUTING IN SEA ICE AND LAKE ICE CG

- ECONOMICAL NAVIGATION
 - REDUCE MERCHANT MARINE TRANSIT TIMES AIMS
 - ROUTE FISHING FLEETS AIMS, NOAA

TABLE 5.2

OCEAN DYNAMICS NEEDS AND REQUIREMENTS

— SPIR —————→

- OCEAN ENGINEERING HAZARDS
 - ACCURATE 3-DAY, 3-HOUR FORECASTS FOR THE CONTINENTAL SHELF EXPLORATION USGS, INDUSTRY
 - DETECTION AND MONITORING POLLUTANTS EPA, CG, USGS
 - BETTER ESTIMATES OF SEA FLOOR EROSION USGS, INDUSTRY
 - IMPROVED WAVE FORCE CALCULATIONS FOR STRUCTURES INDUSTRY, USGS, USACE, NOAA

- COASTAL PROTECTION AND LAND USE
 - REDUCE AND PREDICT COASTAL EROSION USACE, USGS
 - FORECAST EXTREME EVENTS (STORM SURGES, TSUNAMIS) NOAA, USGS, USACE
 - PREDICT POLLUTANT TRANSFER EPA, USGS
 - IMPROVED WARNING/EVACUATION PROCEDURES IN LOW LYING AREAS NOAA, FDIA
 - LAND USE INVENTORIES, MONITORING, PLANNING AND MANAGEMENT NOAA, BLM, STATES
 - RAIN PREDICTION AND NUMERICAL ESTIMATES OF PRECIPITATION USDA, NOAA
 - ENVIRONMENTAL ASSESSMENTS AND MONITORING FED., STATE, LOCAL

- MILITARY STRATEGY
 - SEA SURFACE TOPOGRAPHY AND SEA STATE KNOWLEDGE NAVY, NOAA
 - IMPROVED SURFACE VESSEL DESIGN NAVY
 - LOGISTICS OF FLEET DEPLOYMENT AND ROUTING NAVY,
 - WEAPON SYSTEM DESIGN NAVY, USAF

TABLE 5.3

NEEDED OPERATIONAL CAPABILITIES

— SPIR —————→

- POLAR ORBITING SATELLITES IN MULTIPLE ORBITS
- ALL-WEATHER, DAY-NIGHT CAPABILITY
- REAL TIME COVERAGE OF SEA STATE, WIND, HAZARDS
- GLOBAL COVERAGE EVERY 90 MINUTES
- USER-ORIENTATION LOW COST MISSIONS AND DATA
- ROUTINE DATA ANALYSIS FOR OPERATIONAL USES
- COORDINATION OF SPACECRAFT CAPABILITIES FOR GIVEN OPERATIONAL USE

Rouse (1975) summarizes these needs in the following manner:

"The shipping industry requires timely information on the condition of shipping lanes to insure rapid, safe transport. The conditions of concern include surface ice, icebergs, surface winds, wave conditions (especially storm buildup), storms, and ship activity in the vicinity. These data are required on a continuous, day/night, rapid-response basis.

Surface ice type, distribution, and movement must be charted to determine (1) optimum paths through ice sheets, or (2) earliest opportunity (spring season) and latest opportunity (winter season) for clear water passage through ice covered areas. Primary factors of interest are areas of thin or thinning ice, areas of hazardous ice, ice ridges, and shore-fast ice.

Presence, size, velocity (speed and direction) of icebergs must be charted.

Wave conditions, especially large waves and storm buildup, must be known over large areas of the open ocean, and their change conditions, i.e. growing or decaying, must be predicted. Similar information on surface winds is required."

Thus the status of navigation hazards, economical navigation and sea forecasts are prime shipping information needs. These are further elaborated in Tables 5.4 and 5.5 (prepared by Paul Teleki) with the imaging radar contributions identified.

The imaging radar applications given in Tables 5.4 and 5.5 are presented in the broad context of microwave instruments generally. This is done in order to emphasize that the radar imager--be it SEASAT, or Shuttle, or both--is part of a system of ocean surveillance, and is valuable to the degree that it provides not only unique information, but also shores up the system as a whole.

These two tables show the array of microwave instruments needed to answer the various components of ocean surface features and the parts which appear most amenable to space radar imaging systems. In Table 5.4 we see that the operational forecasts are broken into parameters to be measured, the method of analysis, applicable microwave instruments, and present status of knowledge. A space imaging radar has applications in wavelength and direction and in height, although a radar altimeter may be more appropriate for the latter.

A mix of sensors is needed to resolve the data required for improved

TABLE 5.4

OCEAN DYNAMICS APPLICATIONS REQUIRING MICROWAVE INSTRUMENTS

← SPUR →

NEEDS	PARAMETERS TO BE MEASURED	ANALYTICAL SCHEME	APPLICABLE MICROWAVE INSTR.	STATUS OF KNOWLEDGE
NAVIGATION HAZARDS	ICEBERG-LOCAT'N	ICEBERG TRACK CHARTS	SYNTH. APERT. RADAR	CG OPER'L
	-DENSITY	ICEBERG STATISTICS	REAL APERT. RADAR	
	-SIZE			
	-MOTION			
	CURRENTS-SPEED	SHIP CROSSINGS		
	-DIRECTION			
	WAVES-EXTREMES	WAVE CLIMATE ANAL	SYNTH. APERT. RADAR	SEASAT SURF. TRUTH '76-77
	SEA/LAKE ICE	ICE LEAD CHARTS, THICK'S	SYNTH/REAL APERT. RADAR	ERIM. JPL, WESTINGHOUSE ETC.
ECONOMICAL NAVIGATION	WAVES-EXTREMES	WAVE PREDICTION	SYNTH. APERT. RADAR	SEASAT SURF. TRUTH '76-77
		WAVE CLIMATE INFO	RADAR ALTIMETER	DO.
		SHIP DESIGN PARAM		
	CURRENTS	AS BEFORE	AS BEFORE	
	TARGET DETECT'N	SHIP COUNT/TRAFFIC STRUCTURE IDENTIF'N	REAL APERT. RADAR SYNTH. APERT. RADAR	PPI'S, MARINELAND '75 MARINELAND '75

TABLE 5.5

OCEAN DYNAMICS APPLICATIONS REQUIRING MICROWAVE INSTRUMENTS

← FIR →

NEEDS	PARAMETERS TO BE MEASURED	ANALYTICAL SCHEME	APPLICABLE MICROWAVE INSTR.	STATUS OF KNOWLEDGE
OPERATIONAL FORECASTS	WAVE LENGTH	DIRECT, WAVE SPECTRA	SYNTH. APERT. RADAR	MARINELAND, 1975 GATE '74
	PERIOD	SIGNIF. WAVE PERIOD	REAL APERT. RADAR	NAVY '75
	DIRECT'N	WAVE STATISTICS	NANOSECOND RADAR	NRL
	HEIGHT	SIGNIF. HEIGHT	RADAR ALTIMETER	GEOS-3
	WIND SPEED	WIND FIELD CHARTS	SCATTEROMETER	SKYLAB, JONSWAP '75
	DIRECT'N	WIND/WAVE INTERACT'N	MIRCROWAVE RADIOMETER	NIMBUS-G, SEASAT-A
	CURRENTS-SPEED	OCEAN CURRENTS CHART		
	DIRECT'N	WAVE-CURRENT INTERACT		
	GRADIENT	SURFACE TOPOGRAPHY	RADAR ALTIMETER	GEOS-3
	EXTENT		MICROWAVE RADIOMETER	(NOAA-3, SMS)
	SEA TEMPERATURE	SURFACE TEMP. DISTRIB.	MICROWAVE RADIOMETER	(DMSP, NOAA)
	CLOUD COVER			(ITOS, TIROS)

operational forecasts, but as indicated by the recommendation of the SEASAT Committee an imaging radar is an important component of the system. A further factor to bear in mind is that it will be possible to transfer back and forward between sensors various parts of the identification or parametric evaluation process and thus imaging radar in the long run may have other applications than those listed here.

Each of these areas of application may now be reviewed in turn, giving details of the problem and evidence from analysis of radar images.

Ice Hazard Monitoring

Sea and lake ice and icebergs are navigation hazards which can be detected and thence analyzed using imaging radar data. The following excerpts on ice hazards are from the Microwave Workshop (Matthews, 1975):

Ice includes three distinct forms that have widely divergent properties:

1. Sea ice, which covers large parts of polar oceans and some subpolar seas, contains brine, averages one to several meters in thickness, and ranges in age from hours to several years.
2. Lake ice and estuary ice, which is fresh and brackish water ice of a wide variety of thicknesses and ranges in age from hours to several months.
3. Icecaps and glaciers, which are composed of freshwater ice that averages several kilometers in thickness for Antarctica and Greenland and is tens of thousands of years old.

Of all the forms of frozen water that exist on Earth, the one about which least is known is the sea ice that covers vast areas of the oceans.

Individual ice floes have been observed to move 50 km in a day, and speeds of 10 to 20 km/day are common. Leads (cracks) and polynyas (large irregular openings) open and close at all times. The seasonal variations in areal extent of the ice canopies are large; approximately 15 percent for the Arctic and 80 percent for the Antarctic. In short, sea ice is the most rapidly varying solid on the Earth surface. As such it also has a significant impact on global climate (which will be briefly treated later).

Several of the world's major shipping routes are covered by lake or brackish ice for several months a year (i.e., Gulf of St. Lawrence and Baltic Sea), and great efforts are being made to extend the navigable season in these areas. To do this, two uses of sequential radar imagery are necessary: (1) as input into numerical models of ice dynamics and thermodynamics, and (2) as routing maps to direct ship traffic through the thinnest ice in an area.

The measurement of sea ice type, distribution and measurement has become an increasingly important activity in recent years due to the rapidly expanding use of the Arctic regions to provide petroleum and mineral resources. Further, these measurements are now being used in intensive international studies of the influence of the Arctic on global climatology.

There is and has been high interest in improving ship navigation through ice fields (e.g. by the definition of optimum paths) both in open ocean and Great Lakes and along shore leads, especially along the north coast of Alaska (Beaufort Sea). The interested parties include shippers, USCG lake ice center, the U.S. Navy, and barge operators on the North Coast. Shipping in the Great Lakes is a major factor in the economy of the highly industrialized lake shore states. Ice on the Great Lakes severely limits the total annual tonnage shipped. Efforts to extend the shipping season by improving ice forecasts and by using ice breakers are of considerable economic importance. The Corps of Engineers, working with NASA Lewis Research Center, have developed an improved lake ice monitoring and information system built around the use of airborne imaging radar sensors. This activity has clearly demonstrated the unique capability of radar sensors to provide the relevant information for this application. ERIM has obtained L-band and X-band SAR imagery of lake ice. Their images have been analyzed by Bryan and Larson (1975) who found that ice types and open water leads can be clearly identified and that ice thickness can be inferred from the data. Analyses of sea ice as well as lake ice have shown (Rouse, 1975; Bryan and Larson, 1975; Leberl et al., 1976; Bryan et al., 1976) that it is feasible to:

- * monitor ice sheets on a quasi-operational basis (Lewis Center at Cleveland and the lake ice work)
- * differentiate between rough (old) and smooth (new) ice, and a variety of ice types
- * identify open water areas (especially for large polynyas and if a slight wind blowing) by using dual polarization radar

- * determine sea ice drift and to measure the amount of drift
- * observe shear motion of packed ice and formation of ridges and leads

These studies have shown in a preliminary way that qualitative, quantitative, and operational measurements of ice can be made with multi-frequency, multipolarization radar. (See Figure 5.1) Although much research is underway in the AIDJEX (Arctic Ice Dynamics Joint Experiment) Project, there is a need for extensive analysis of the presently available sea ice data to substantiate the ability to identify ice types, open water vs. new ice, ice movement on an operational basis.

During the Skylab 4 overflights, SLAR imagery was obtained of the covers in Lake Ontario and the Gulf of St. Lawrence. These data additionally show that radar remote sensing of lake and brackish ice can distinguish:

1. leads and polynyas from all forms of ice including ridges
2. rafted from undisturbed, and shorefast from moving ice
3. ice floe size and shape
4. the approximate age of ice in terms of gray, gray-white, and white ice

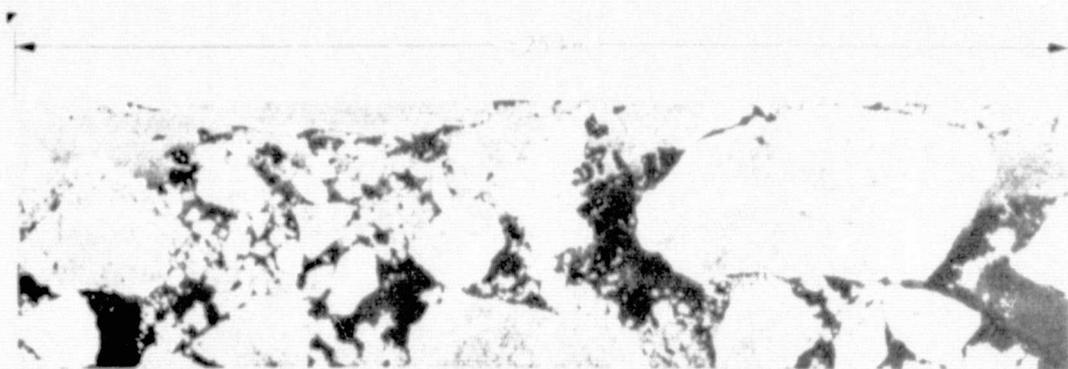
While further work is needed to make these capabilities operational, it now seems clear that the case is substantially made for radar sea ice monitoring.

Icebergs, Icecaps, and Glaciers

About 85% of the earth's freshwater exists on ice in Antarctica and Greenland. A complex of interactions between icecaps, glaciers and climate exists. Icebergs accumulation and ablation rates and calving are vital information needs.

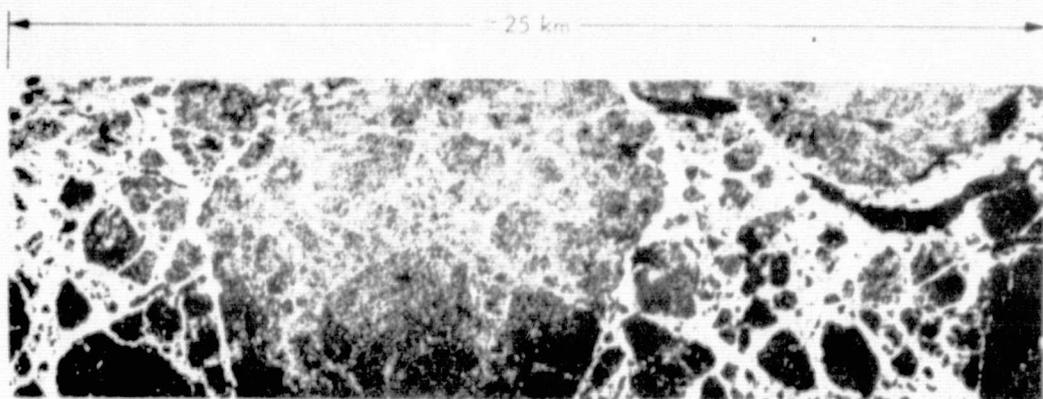
Two-dimensional SLAR images of glaciers and icecaps have been obtained by V.V. Bogorodsky and V.S. Loshchilov of the Arctic and Antarctic Research Institute of Leningrad. These data are exciting because one of the most difficult things to measure in glaciers is the rate and pattern of accumulation and ablation. As a glacier flows, the deposited layers of snow metamorphose into ice, which slowly flows downslope. Therefore, the pattern of foliation planes observed is due to two processes: accumulation/ablation and flow.

Bogorodsky and Loshchilov believe that SLAR measurements of glaciers can be used for accumulation studies. They have also obtained images of Arctic ice islands (pieces of icecaps that have calved off an ice shelf and drifted about within the matrix of sea ice floes). These images all showed the ice to have parallel



18 AUG 75 (74° 52'N, 138° 08'W)

(a)



10 OCT 75 (72° 35'N, 149° 25'W)

(b)



Figure 5.1 Radar Imagery of Sea Ice

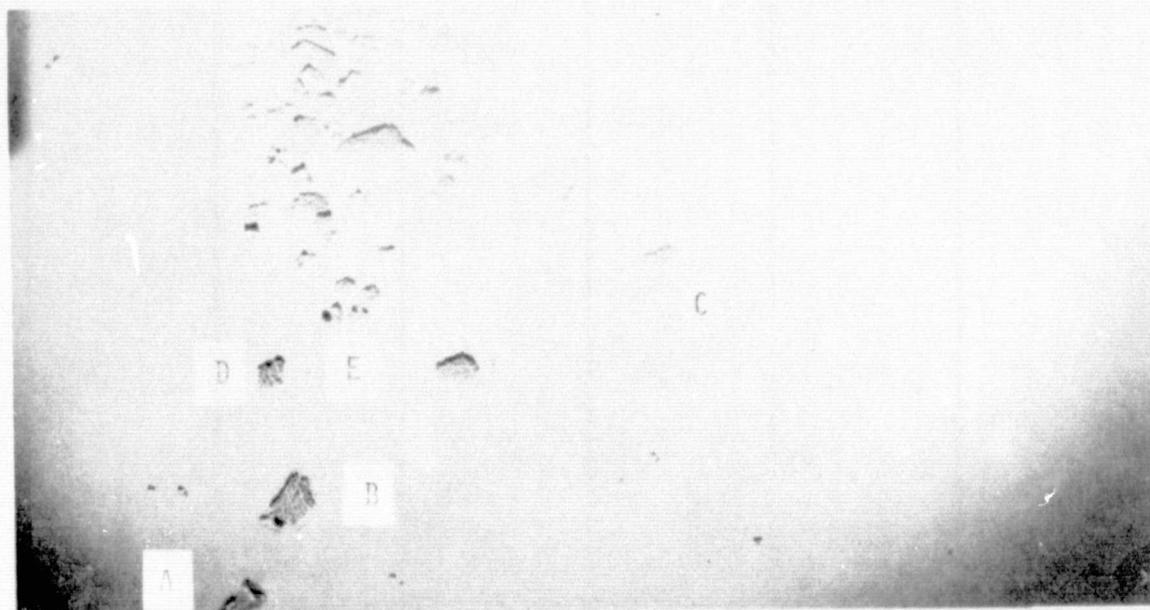
banded structure, with the bands having a spacing on the order of several hundred meters. They do not know what the bands are, but surmise that they were formed by the accumulation process existing on the icecap where the island was formed. The structural differences between ice island and sea were so great that distinguishing between the two was always possible. (Matthews, 1975)

Monitoring of the origin, dispersal and movement of icebergs is needed, especially in the northwest North Atlantic Ocean. The U.S. Coast Guard International Ice Patrol has this task. Areas of particular interest are calving glaciers of Greenland and in North Canada. Iceberg monitoring is of special interest to COMINTECEPAT New York in the 40 to 50 north and 42 degrees to 60 degrees longitude west region. They presently require data every six hours on iceberg positions and movements in the shipping lane areas. This charting activity, now conducted using visual reconnaissance from ship and aircraft platforms, is an important one for improving ship safety. Although the present charting is based upon a sampling procedure, it has been very successful in minimizing the potential hazard caused by icebergs in the shipping lanes.

The capability of radar to distinguish icebergs in open water and sea ice has been convincingly demonstrated in several studies (Anderson, 1966; Rouse, 1969; Parashar, 1975; Leberl et. al., 1976). There is no question that the full measurement information content required in this application can be acquired with imaging radar sensors.

Figure 5.2 shows the ability to monitor icebergs. Additionally there is a proven ability to detect calving glaciers and icebergs formed late in the previous season (and still frozen in the sea ice) which would provide icebergs in the early portion of the season. These can give an indication of the expected activity during the ensuing season.

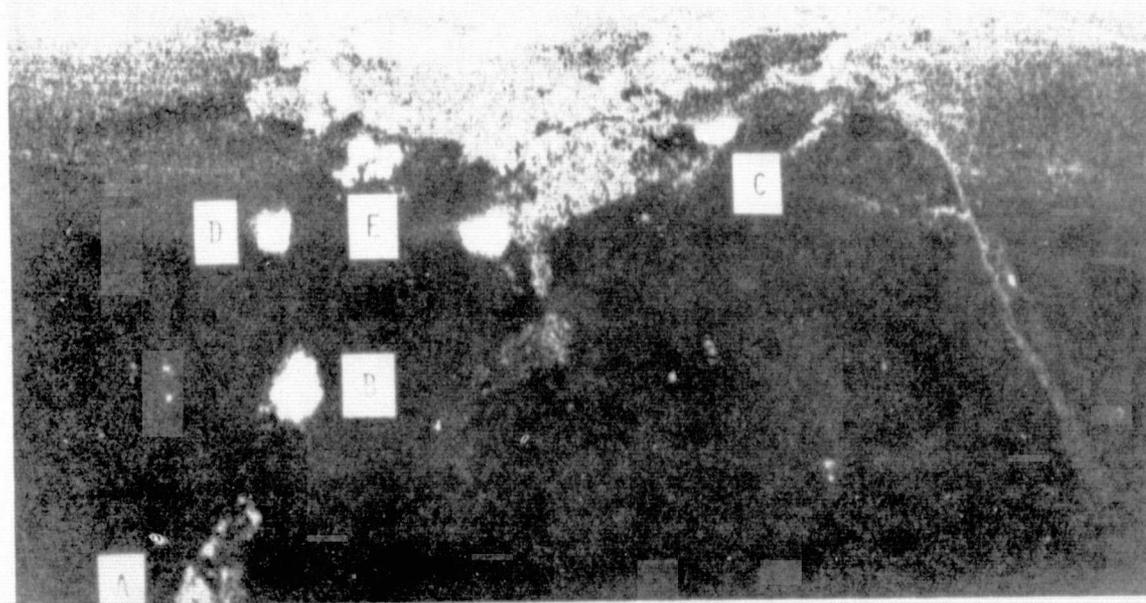
It is considered that a high resolution, multifrequency, and multipolarization imaging radar is essential for the quality of data needed. Further data are required to determine minimum size of icebergs visible in an open ocean of given wave height and swell.



AIR PHOTO

SLAR L-BAND (25 CM)

jpl →



GREENLAND

Figure 5.2 Photo and Radar Images of Sea Ice and Icebergs

Wave Hazards, Dynamics and Climatology

There is a significant need in economical, safe shipping for timely alerting of present areas of extreme waves, advance warning of such buildup and longer term wave forecasting. There is also a need for a vast increase in the quantitative measurement and understanding of wave dynamics and processes for the forecasting models.

The dynamics of surface waves in both capillary and gravity ranges indicate that microwave technology provides a superior means of measuring simultaneously the spatial and temporal properties of ocean waves. Ocean waves receive most of their energy from wind. The state of the art in wind measurement by conventional methods shows a gross inadequacy of present surface-sampling techniques for global weather and wave forecasting; imaging radar along with microwave radiometers, scatterometers and altimeters offers the potential to alleviate many of the problems.

Ocean waves may be defined as undulations of the surface with time scales in the range from 0.025 to 24 sec, corresponding to wavelengths in the range from 0.02 to 1000 m, respectively. These are subclassified as (1) gravity waves, with time scales in the range from 0.1 to 25 sec, length scales from 2 cm to 500 m, and heights to 30 m, or (2) capillary waves, with time scales in the range from 10^{-1} to 10^{-2} sec, length scales from 0.5 to 2.0 cm, and heights of less than 1.0 cm. Ocean waves are random, and a time record of the ocean-surface displacement in a storm region may contain wave periods in the entire range indicated earlier. Far from a storm center, waves become more organized as the longer waves propagate more rapidly out of the region. Long waves occurring away from storm centers are referred to as swells. Long waves approaching a coastline are influenced by the drag of the bottom and become shallow-water waves. Wave energy is eventually dissipated through breaking in an active near-shore area called the surface zone. Wave energy is also dissipated offshore through viscous effects and by breaking, which is evidenced by the presence of whitecaps. The processes of wave generation by wind; the transfer of energy between the various wave spectral components by wave-to-wave interaction; and the dissipation of energy by viscosity, breaking, and bottom effects are extremely complex and constitute a research area under intensive investigation by theoreticians and experimentalists. (Matthews, 1975)

There is ample evidence that microwave sensing of ocean surface characteristics is feasible, and that it is the most advantageous approach. Experiments with microwave radiometers, scatterometers and altimeters have shown that ocean surface roughness characteristics can be effectively measured. Several theoretical models

have been developed and tested which describe reasonably well the interaction mechanisms involved in this sensing technique. The imaging radar, especially synthetic aperture array radar, shows significant potential for estimates of wave heights and slopes. SEASAT-A is scheduled to carry an L-band side-looking synthetic aperture radar (SAR) capable of 25 m resolution over a 100 km wide swath. The rationale for this instrument comes mainly from the analysis of ocean wave data imaged by JPL using an L-band airborne SAR, and from examination of theoretical models (Rouse, 1975).

Figure 5.3 is an example of JPL imagery of enhanced wave structure on the ocean surface. The digital 2-D fourier spectra are of synthetic aperture constructed waves rather than actual waves. The relationship of the radar image to actual ocean waves is still not clear; also in question is whether or not such data can be used to generate an accurate estimate of ocean wave spectra. Further at issue is the question as to whether these aircraft data are representative of the anticipated orbital SAR data. SEASAT will answer these issues (Rouse, 1975). Figures 5.4 and 5.5 show L-band detection of oceanic and coastal waves. Figure 5.4 shows the relationship between the $\frac{H}{V}$ ratios at 57 seconds and 37 seconds indicating the differential emphasis of wave structures. Figure 5.5 shows coastal waves in Huntington Beach and Mission Bay area, very strikingly detected. Internal waves have also been detected with the JPL L-band imager (Figure 5.6).

The radar imagery does provide relevant information for ship navigation purposes, in terms of surface conditions, i.e. high or low wave areas. Determination of storm buildup, as well as the magnitude and propagation characteristics, appear feasible using orbital imaging radar based upon aircraft studies conducted by JPL and modeling studies conducted at the Naval Research Laboratories. Determination of the full capacity to acquire this information can be determined only by conducting an orbital experiment. The SEASAT and Shuttle experiments are necessary steps in the evolution of this operational capability (Rouse, 1975).

JPL IMAGING RADAR, OCEAN SWELLS
DIGITAL 2-D INTENSITY SPECTRA AND ENHANCEMENT

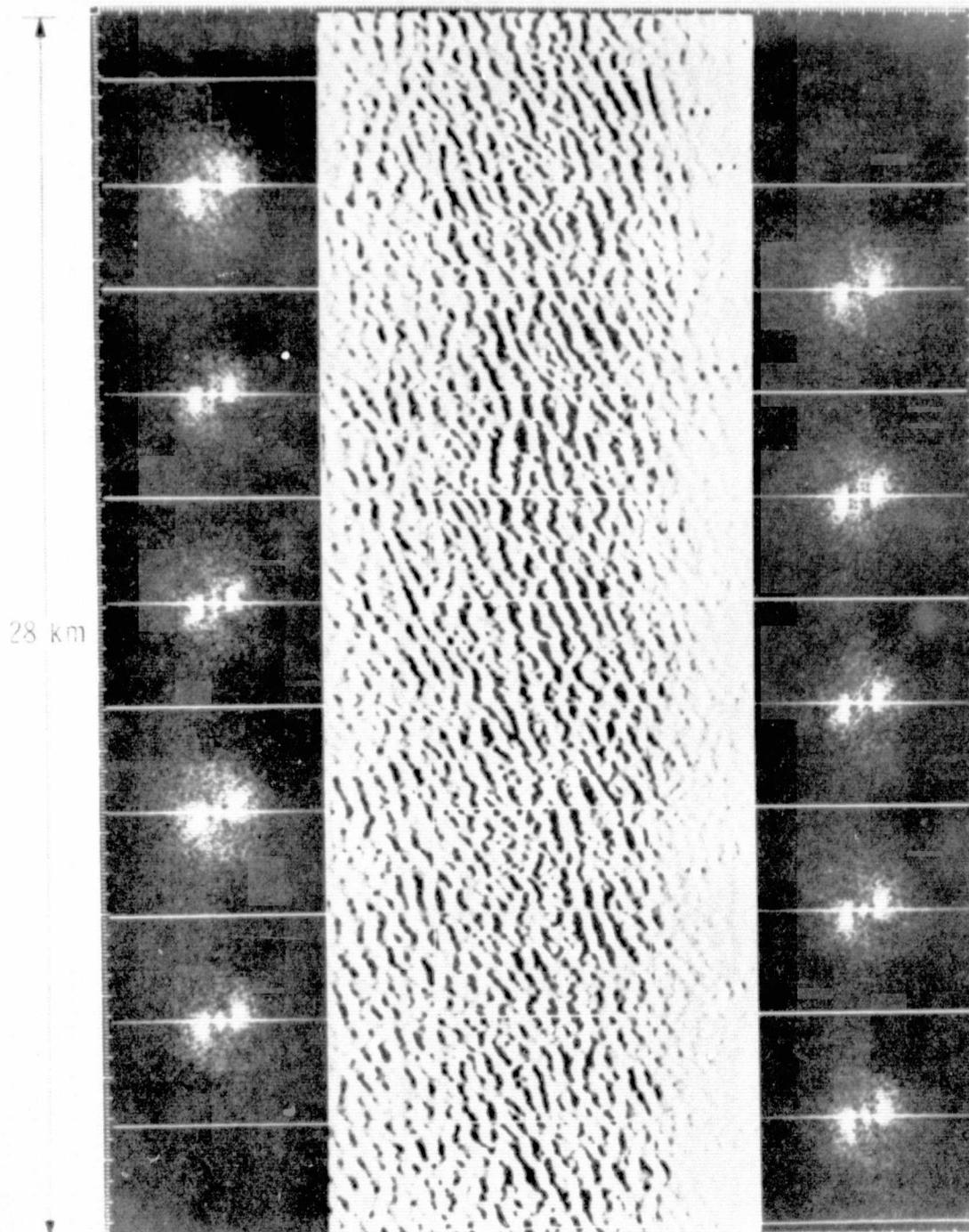


Figure 5.3 L-band radar image of the Gulf of Alaska showing ocean swells wave structure (Jet Propulsion Laboratory)
(Fourier analysis of radar wave image)

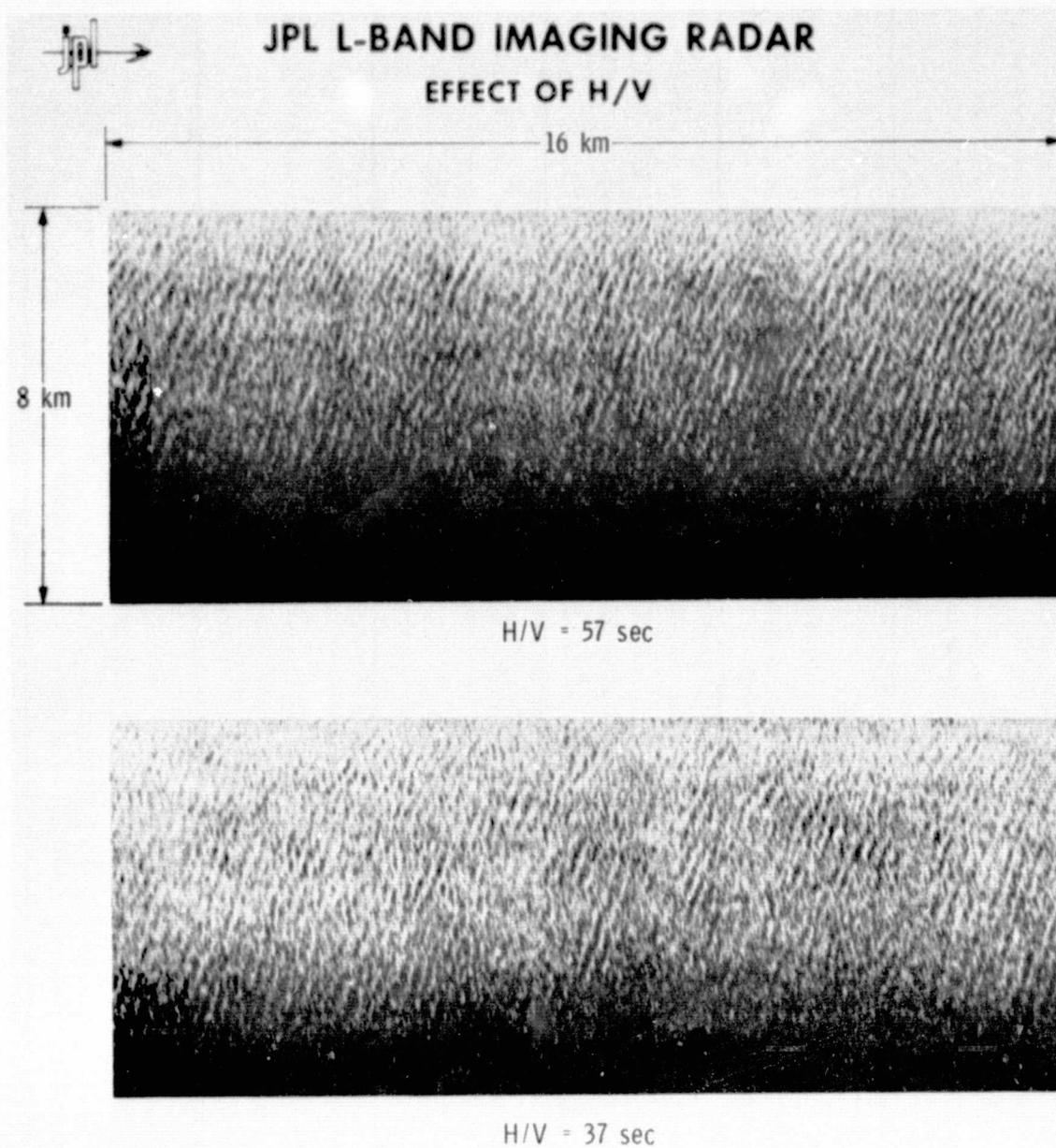


Figure 5.4 L-band synthetic aperture radar images showing the effect of differing H/V on image formation of waves.

JPL L-BAND IMAGING RADAR
COSTAL WAVES (HUNTINGTON BEACH AND MISSION BAY)

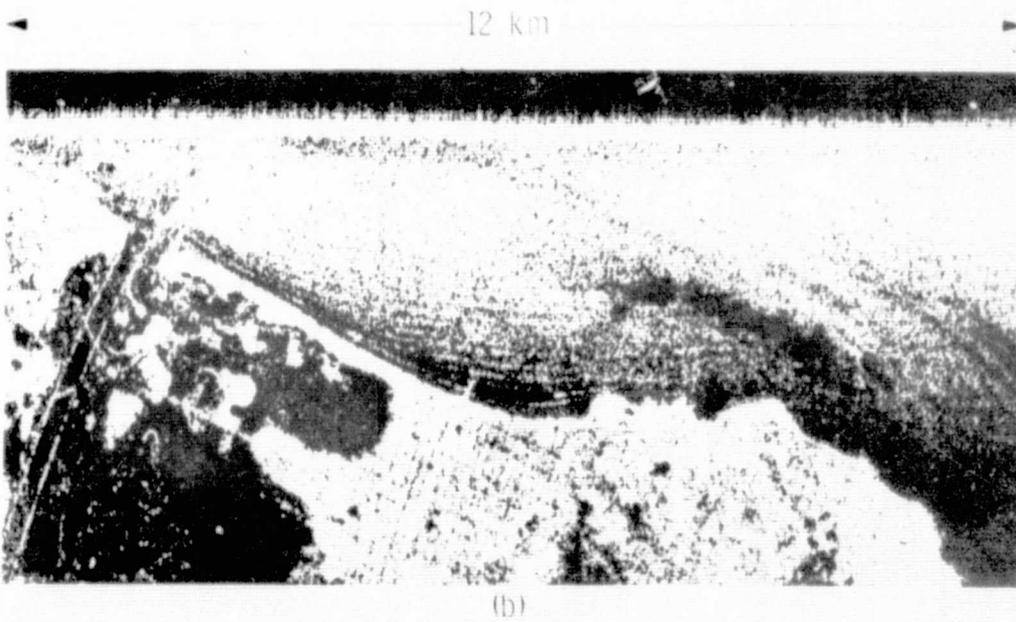
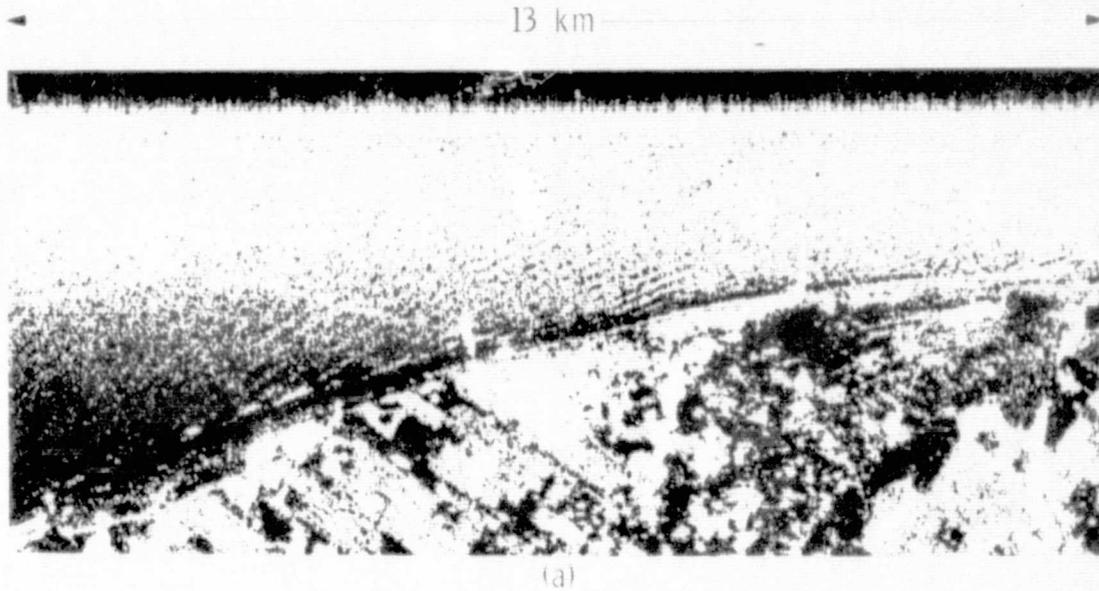


Figure 5.5

JPL L-BAND IMAGING RADAR-INTERNAL WAVES



Figure 5.6

5-20

Economic Navigation and Operation

The culmination of forecasting wave dynamics and tracking oceanic hazards--be they icebergs, sea or lake ice, or storm surges, is (from the viewpoint of shipping) an economical, safe crossing.

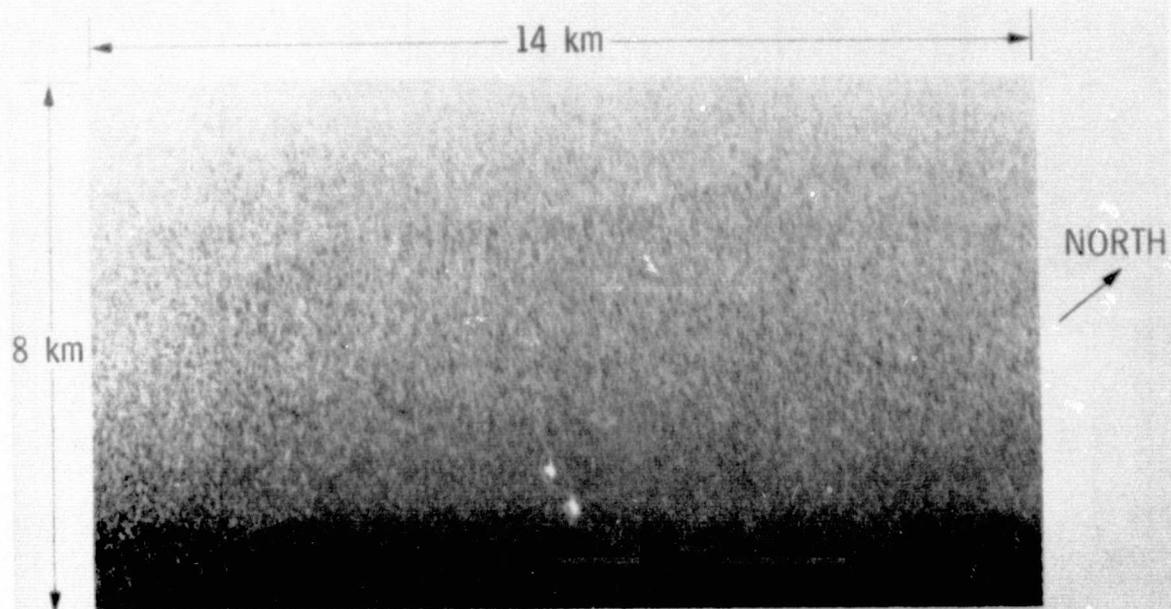
Apart from the significance of ship positions in relation to hazards, it is also vital to monitor territorial waters for fishing and other vessels, and pollution. Economical navigation in the commercial sector is also of interest to reduce Merchant Marine and fishing fleet transit times.

The capability of imaging radar sensors to record the presence of ships in low to moderate seas is well established and has been used operationally by the military for many years. The capability to identify ships by type is a function of spatial resolution of the system, but detection is possible even with resolutions which are large relative to the size of the ship (see Figure 5.7).

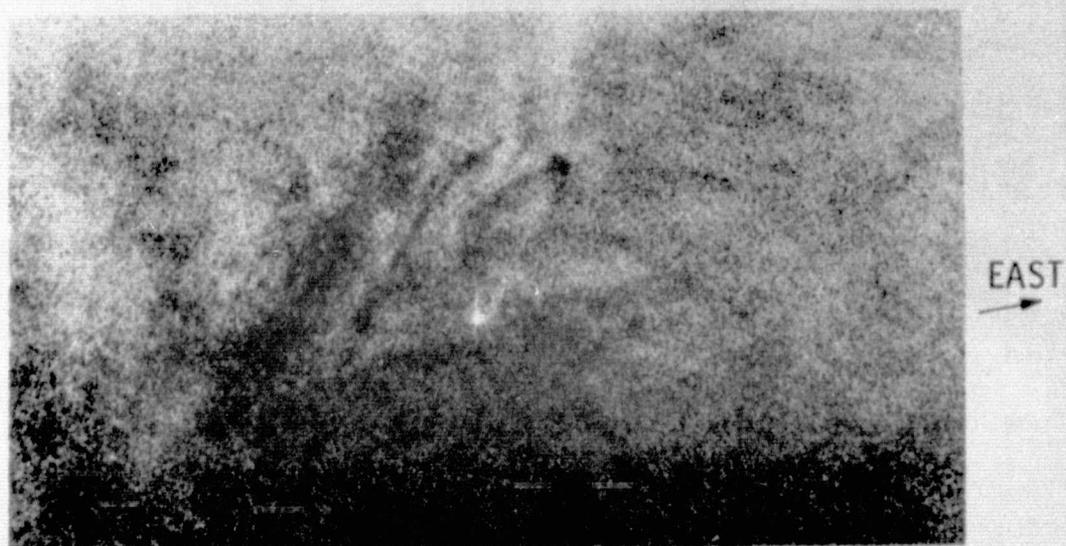
The increasing pressure on fish resources has caused many nations to review their policies on coastal waters. Several attempts have been made to extend territorial limits from 12 miles to 200 miles from shore in an effort to restrict access to marine resources in these coastal waters. These actions, along with the expansion of shipping on the open oceans, especially the increase in super tanker traffic, are placing new demands on governments to accurately monitor ship activities. Further, the added concern about pollution and its effects requires new and better information on accidental and intentional oil spills associated with ship activities.

The capability of radar sensors to record oil spill pollution has been demonstrated in several studies (Estes and Senger, 1972; Guinard and Purves, 1970). These studies do not adequately confirm oil spill detection for a sufficiently wide range of oil types and ocean surface conditions to support an unqualified endorsement of radar for this application. However, the available evidence is

JPL L-BAND IMAGING RADAR
POSITION OF SHIPS



22:11 GMT, 10/08/75
59° 36' N, 143° 15' W



22:15 GMT, 10/08/75
59° 39' N, 142° 40' W

Figure 5.7

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

sufficiently good to suggest that of the remote sensing techniques available radar is the most advantageous approach to the problem. The U.S. Coast Guard is employing microwave sensors, including SLAR, in their airborne oil spill detection system (Rouse, 1975).

Operational Forecasts, Coastal Protection and Structural Design

Improved knowledge of wave climatology extends beyond forecasting major storm surges. It also encompasses understanding the complex interactions between sea and land.

For coastal protection and land use there is a large array of user needs ranging from improved warning for evacuation procedures for low lying areas, to the forecasting of extreme events, major waves, rain prediction and environmental assessments. There is, further, the whole interplay of forces on structures, both oceangoing and fixed, and forces on the coast itself--making it in many instances a prime subject for updating by imaging radar.

Both meteorological and maritime forecasts require numerical seastate and wind forecasts. Ocean models are needed by the Navy and universities. Diverging ice input data is needed for open water mapping and heat balance determinations. The formation of leads gives rise to rapid ice production. This is especially significant to heat balance modelling since the heat loss from open waters is about 2 orders of magnitude greater than from old ice.

A mix of sensors will be needed to resolve the data inputs on ocean wave spectra and sea ice type and distribution required for an improved operational forecast model. An imaging radar is an important component of the SEASAT system which currently plans the use of scatterometers, passive microwave and imaging radar for this purpose. (Nagler and McCandless, 1975)

The Shuttle radar imager should have some roles in this area, but its exact

contributions remain to be defined and suitable experiments to be designed.

POTENTIAL CONTRIBUTIONS OF A SHUTTLE RADAR

In the preceding sections of this chapter, the emphasis has been on imaging space radar in general. We need now to examine the feasible roles a Shuttle imaging radar may have for oceanography.

Because the Shuttle radar will have multiple frequencies, polarizations and look angles it has the potential to explore areas not available to the SEASAT imager, which is single frequency (1.275 GHz), single polarization (HH), and fixed look angle (roughly 20°), covering from about 16 to 24 degrees off-nadir. In this sense it would be broadly supportive of the SEASAT program. In practice, however, the degree to which the Shuttle imager would in fact support the SEASAT mission is still in some question.

Among the questions which need to be resolved are the following:

1. The irregular schedule and long gaps with the Shuttle imager in the Sortie mode do not lend themselves well to providing the block of continuous data desired by N.O.A.A., D.O.D. and others concerned with atmospheric, ocean and sea ice problems. It is true that stringing such missions together will be of some experimental value, but the N.O.A.A. community is habituated to lengthy and uninterrupted data streams from the meteorological satellite program, and it would require a re-thinking of their procedures to accommodate sporadic data accumulation and analysis.
2. Since it is uncertain whether the 1.275 GHz frequency in SEASAT will be optimal for ocean wave detection, Shuttle could usefully support the SEASAT program by experiments using the flexibility of the Shuttle system. It remains to be seen to what degree the Shuttle imager will constitute an improvement in measuring ocean wave spectra.
3. The Shuttle SAR may well be more suitable than the SEASAT radar for investigating snow and ice because multiple wavelengths and polarizations are required for reliable ice type identification. However, in present plans it will not be until the mid-1980's when higher inclination orbits over sea and (significant) land ice areas will be achieved. Early Shuttle missions will, of course, cover Great Lakes and St. Lawrence Seaway ice.
4. There is strong practical evidence that imaging radar is differentially sensitive to the presence of oil on water--as a function of frequency,

and sea state--and thus on the face of it Shuttle could explore for the more suitable frequencies. In addition there are major programs beginning--such as N.O.A.A.'s oil spill concentration and trajectory forecast program--for which coastal and deep ocean oil spill data is desired for large areas. The problem is, however, complicated by other, non-technical issues. First the problem of bilge pumping at sea will not occur as often because at prices above \$8.00 per barrel it is more economical to recover than to deliberately spill oil. Second, the U.S. Coast Guard is planning a very large fleet of radar equipped aircraft to monitor U.S. coastal areas and may thereby skim off much of the benefits attributable to accidental oil spill monitoring by satellite. Third, not all Federal Agencies are yet convinced of the value of satellite monitoring of spills on a world-wide basis.

5. The proposed swath widths for Shuttle at shallow depression angles (60 km) are somewhat less than the 100 km proposed for SEASAT. (The steeper depression angles for Shuttle do envisage 100 km swaths.) This is a disadvantage for Shuttle in that the combination of infrequent flights and sometimes narrower swaths will constrain research vessel routing.
6. The detection of ships in a background of sea clutter (of high seas) has not proven universally successful and basic work is needed to define the circumstances under which--as a function of resolution, frequency, polarization, sea state, and ship size and type--detection and monitoring may be achieved reliably. In the teeth of these present uncertainties, the nature of the contribution of a Shuttle radar over an uncertain SEASAT capability is speculative.
7. Ocean climatology data acquisition (for improved design of structures on the continental shelf amongst other needs) will involve competitive evaluation of in-situ sensors vs. satellite plus in-situ sensors. It is moot at this time whether the contributions from Shuttle (or indeed from SEASAT) will be sufficient to make the case for satellite monitoring for this application.

It is clear from these comments that the practical issues of employing Shuttle radar intelligently for oceanographic experiments, and the parallel issues for the SEASAT program, as well as the experimental and practical relations between the two programs, will require close scrutiny.

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CHAPTER 6

SPACE SHUTTLE IMAGING RADAR AND ITS APPLICABILITY TO MAPPING, CHARTING, AND GEODESY[†]

SUMMARY

The most significant Mapping, Charting, and Geodesy (MC&G) applications of Space Program Imaging Radar will include:

- * continued small scale planimetric mapping (1:50,000)
- * small scale map revision
- * geoscience applications of radar imagery geometrically merged with other multispectral data (e.g. Landsat D & Space Shuttle Radar)
- * positioning of maritime floating aids, ships, and icebergs
- * mapping of lake and polar sea ice
- * contingency flood mapping

RECOMMENDATIONS

Space Program Imaging Radar Program should:

- * conduct more intensive research on classical mapping tasks such as stereoradargrammetry, block adjustment, and absolute/relative point positioning. Space Shuttle will serve as an excellent testbed to develop these techniques and expand radar's capability beyond reconnaissance type mapping.
- * be geometrically correct (orthoradar), radiometrically correct, and partially theme processed to a mapping projection (e.g. UTM) for maximum user application. Space Shuttle will provide a testbed for the creation of such data prior to a dedicated orbital satellite.

[†] Prepared by J. Jensen and F. Leberl and including materials provided by A.B. Park and D.S. Simonett.

INTRODUCTION AND BACKGROUND

The Federal Mapping Task Force (Donelson, 1973) identifies Mapping, Charting, and Geodesy tasks as being:

- * Land Surveys (point positioning for geodesy, cadaster, engineering)
- * Land Mapping (planimetric, topographic, thematic)
- * Marine Mapping (nautical chart, bathymetry, floating aid, hazard)

This can serve as a general cartographic requirements list for most countries of the world. Such tasks are carried out within the United States' national mapping programs primarily by the U.S. Geological Survey and the National Oceanic and Atmospheric Administration. These and other agencies are further involved in a number of additional MC&G tasks. However, this federal MC&G task force cannot presently meet the requirement for maps, charts, and geodetic information; for example, the U.S. Geological Survey can satisfy only about 16% of the first priority needs for new mapping and 39% for revision of outdated maps (Donelson, 1973). In addition to these domestic mapping constraints, the United States cannot get by just inventorying and mapping its own natural resources. It is in the national interest to know exactly the world situation with respect to renewable and non-renewable resources because the U.S. uses so much of them and is heavily involved in international trade and aid.

It is against such a background that the United States and foreign MC&G communities are investigating alternatives to effectively meet the expanding cartographic challenge. In this context, space imaging radar will be evaluated to determine its potential applicability to MC&G tasks.

LAND SURVEYS

Radar block adjustments is a field of study that has not attracted the attention of many research workers. The comparatively weak geometry of

all dynamic (kinematic) or line-perspective imaging systems does not present great promise for control network densification based on image blocks. From airborne radar, accuracy of relative point positioning cannot be expected to be better than about 10 meters (see Table 6.1). The only figure thus far available for orbital radar concerns the Apollo Lunar Sounder Experiment (ALSE) which resulted in a low accuracy of relative positioning of 100 to 200 meters due primarily to the steep look angles (Leberl, 1975). It is possible that the accuracy of point positioning from orbital radar could be dramatically better than the results obtained from the Apollo Sounder data. Space Shuttle Imaging Radar could play a key role in the research to establish accuracy models for orbital radar.

However, the accuracy of point positioning to be expected from radar images is not competitive with modern ground based methods employing observation of navigation satellites, nor with aerial or spaceborne photogrammetry based on metric photography. Therefore, radar could only be of marginal use for the densification of terrestrial nets of geodetic points.

LAND MAPPING

Planimetric

The most significant operational imaging radar application has been the planimetric reconnaissance-type mapping of pervasively cloudy, remote areas at scales of 1:100,000 and smaller. Vast areas of the world have been mapped in this way with the majority of these efforts taking place since 1972. For example, although Brazil began its extensive Radar Mapping of the Amazon--RADAM--in 1971 (Azevedo, 1971; Moreira, 1973), it only recently (in spite of available LANDSAT-MSS coverage) completed the acquisition of radar imagery of its entire territory of 9 million km². All Latin American countries sharing the Amazon Basin have now obtained radar coverage of this area (see Figure 6.1).

TABLE 61: MAPPING ACCURACIES ACHIEVED IN SINGLE IMAGE RADARGRAMMETRY
(after Leberl, 1976)

Source	Year	Mapping Acc. (m) in Check-points:		Topogr. Relief (m)	# Control Pts. per 100 km ²	Radar Ground Resolu. (m)	Antenna Stabilized	Type of Radar	Image Scale	Remarks
		Along	Across							
Gracie et al	1970	20	14	217 to 302	10	17	yes	Synth. Ap. An-APQ 102		Atlanta, Georgia
Leberl	1971	50	23	flat	10	30	no	Real Ap. EM1	1:200,000	N.E. Netherlands
Bosman et al	1972	47	60	flat	10	30	no	Real Ap. EM1	1:250,000	Netherlands
Konecny	1972	152	255	mount.		16	yes	Real Ap. Westinghouse	1:250,000	New Guinea Conformal Transf.
Greve et al	1974	35					yes	Synthetic Ap. Topo II	1:100,000	Digital mono plotting
Goodyear	1974	38	30	flat	3	12	yes	Synth. Ap. GEMS 1000	1:400,000	Phoenix, Arizona
Derenyi	1974	89	111	0 to 150	1.1	16	yes	Real Ap. Westinghouse	1:250,000	Washington, D.C.
DBA Systems	1974	51	26		0.5	3	yes	Synth. Ap. An-ASQ142	1:100,000	Radar interferometer
Konecny	1975	80	79	flat		12	yes	Synth. Ap. GEMS 1000	1:400,000	Phoenix, Arizona
Derenyi	1975	30	28	flat		12	yes	Synth Ap. GEMS 1000	1:400,000	Phoenix, Arizona
Tierman et al	1976	209	257	flat	0.7	30 to 150	no	ALSE orbit radar	1:1,000,000	Apollo 17 mission to moon steep look angles
Leberl	1976	147	233	flat	0.27	20 to 150	no	ALSE orbit radar	1:1,000,000	Apollo 17 mission to moon, steep look angle
Hirsch et al	1976	120		flat	3	30	no	Real Ap. EM1	1:100,000	Netherlands
Leberl et al	1976	140	170	flat	0.27	25 to 150	no	Synth. Ap. JPL-L-Band	1: 500,000	Alaskan tundra Steep look angles

RADAR LAND MAPPING APPLICATION PLANIMETRIC LINE - AND IMAGE MAPS

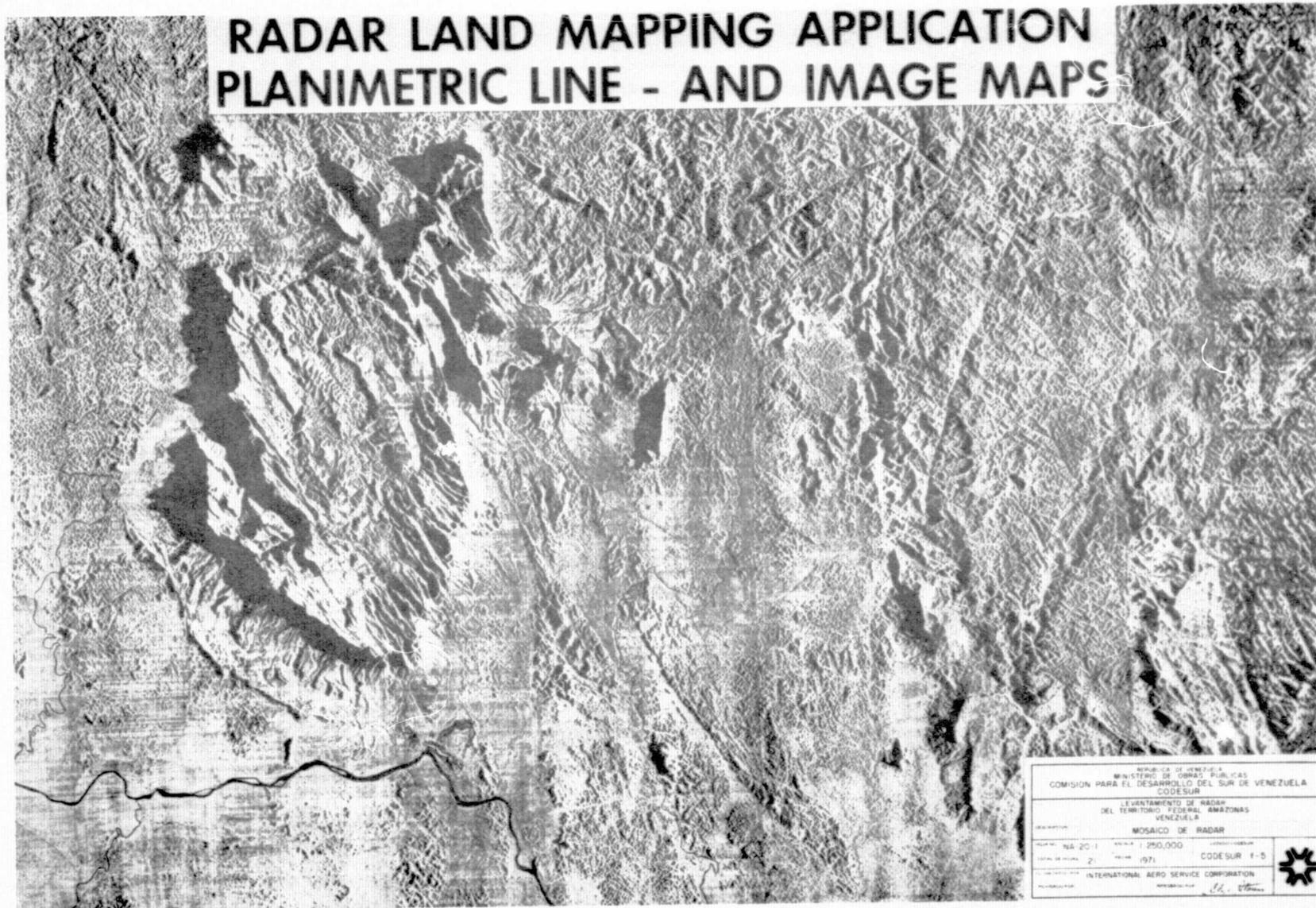


Figure 6.1. This is a semi-controlled radar mosaic of a portion of Venezuela compiled and published at a reconnaissance scale of 1:250,000. It is one of a series of sheets that provide the first overview of much of this perennially cloud-covered country.

In addition, Peru mapped a large portion of the Andes by radar, Colombia its Pacific coast, and Nicaragua its entire territory. Other mapping projects include portions of the Philippines, Indonesia, New Guinea and Australia.

The small scale (i.e. $\leq 1:100,000$) is basically the result of the geometric ground resolution of radar images. Because radar ground resolution in range depends only on angle and on pulse length rather than upon distance from the antenna to the ground (Doyle, 1975), orbital radar and photography approach each other in range resolution as illustrated by Figure 6.2. Similarly, for a synthetic aperture system azimuth resolution is range independent. By comparing the ground resolution in Figure 6.2 with the percent of potential users satisfied in Figure 6.3 (after Donelson, 1973), it is clear that radar can play a role in future small scale planimetric mapping particularly with resolution of ≤ 30 meters and geometric rectification. This can further be confirmed in the context of National Map Accuracy Standards. According to these, 90% of check points measured on the final map must lie within 0.02" of their correct position for class A, within 0.04" for class B, and within 0.08" for class C-1 maps. This converts to the following meter-values on the ground, specifying 90% limits and standard deviations (1σ) of coordinate errors, σ_x , σ_y , as opposed to point-errors $\sigma_p = (\sigma_x^2 + \sigma_y^2)^{1/2}$:

Scale	90% of coord. errors(m)			Stand. deviation of coord. errors (m)		
	Class			Class		
	A	B	C-1	A	B	C-1
1:250,000	90	180	359	54	110	218
1:100,000	36	72	143	22	44	87
1:50,000	18	36	72	11	22	44

Comparison of these requirements with the mapping accuracies shown in Table 6.1

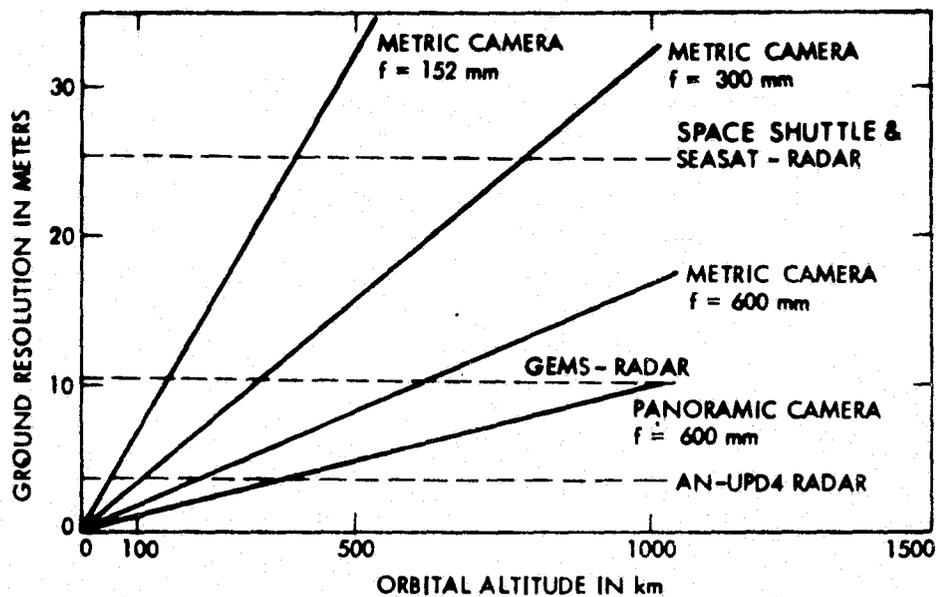


Figure 6.2 Comparison of orbital radar and photographic system resolution. Note how the radar resolution remains constant for a given synthetic aperture system.

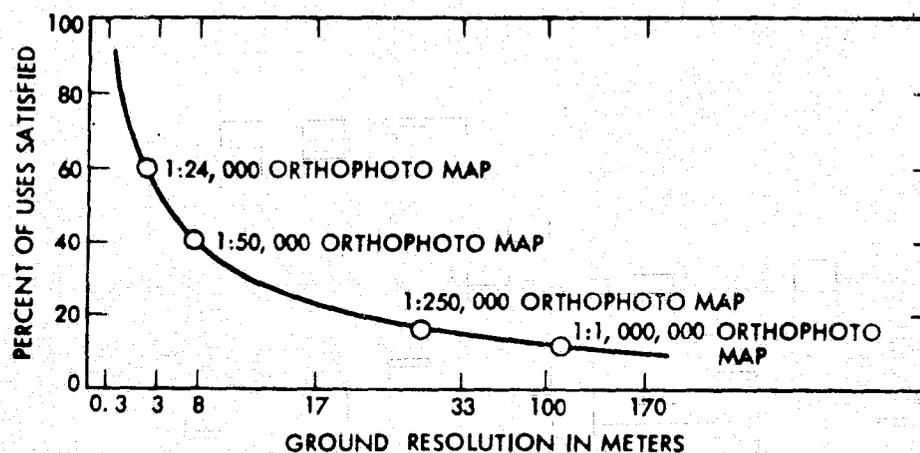


Figure 6.3 Relationship between resolution, mapping scale, and percent of users satisfied for orthophoto map products (adapted from Donelson et al., 1973).

indicates that airborne radar can satisfy class A mapping standards at scales up to 1:100,000, *depending on the amount of ground control used for rectification (or gridding)*; scales of 1:50,000 can be met at class B levels. This leads one to hope that satellite radar will be useful at similar mapping scales.

Rectification

The along track and across track coordinates of radar images are generated independently of each other. There is, therefore, the possibility of inconsistencies in along and across-track scales. In the case of synthetic aperture radar images these can, if known, be removed in the process of converting the raw sensor output (the signal-histories) into the "map" film. The method employs a variable scale setting in the optical correlator (Jensen, 1975; Petersen, 1976). However, there are many more image deformations possible than just those due to a differential scale. Possible sources of such deformation were described by Van Roessel (1971), Leberl (1972a), Van Roessel and de Godoy (1974). Methods of rectification are numerical-graphical (Hockeborn, 1971); electro-optical (diCarlo et al., 1968, 1971; Yoritomo, 1972; Masry et al., 1976); or purely digital (Van Roessel, 1971; Thompson et al., 1972; Leberl et al., 1976).

For the numerical-graphical method, an ordered set of image-points ("tick-marks") is first transformed into a map system. Square shaped image patches are then rectified graphically using the four surrounding tick-marks and an anamorphic viewer as described by Ambrose (1967).

The electro-optical method uses a set of ground control points to compute the empirical relationship between the raw and rectified image. The settings of an electro-optical differential rectifier (Gestalt Radar Restitutor) are then calculated and the radar image is rectified. In the purely digital approach, the radar image is rectified in a digital image processing routine,

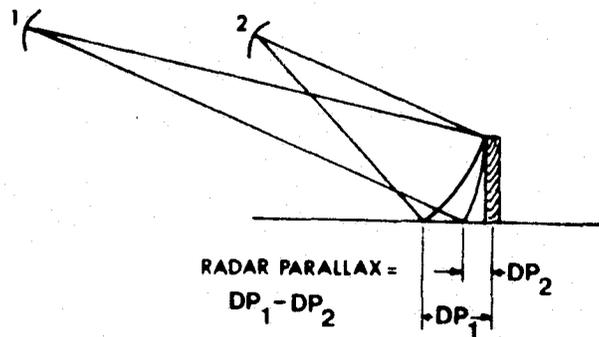
using knowledge about systematic corrections and a set of ground control points to determine the coefficients of a "rubbersheet" stretch of the radar image. The use of rubber sheeting will enable Space Shuttle Imaging Radar to overcome spatial distortions in gentle relief without stereoscopy. Space Shuttle will provide a valuable testbed for this research.

The most satisfactory rectification program would not only employ a minimum of geodetic ground control points, but also R.B.V. images from LANDSAT-D and future LANDSATS, and a few satellite fixes for an adjustment of whole blocks of radar images.

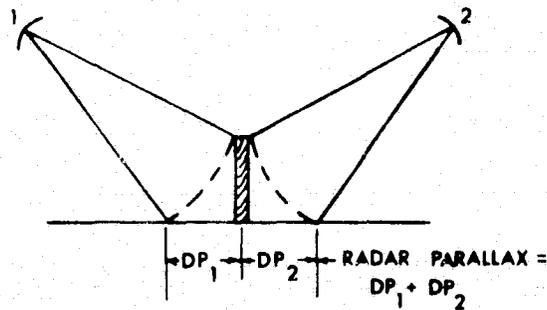
Stereo Configuration

For areas of significant relief, the unique stereo capability of Space Program Imaging Radar will be important for generating differentially rectified orthoradar products. The normal case of stereo radargrammetry consists of two parallel flight lines on the same side of the imaged area (same-side stereo; see Figure 6.4A). Other configurations, e.g. parallel flight lines on opposite sides of the imaged area (opposite-side; see Figure 6.4B), or at right angles (cross-wise; see Graham, 1975) can create difficulties in visually perceiving a stereoscopic model, to the point that such configurations cannot be employed. This exhausts the possibilities for synthetic aperture radar. For real aperture radar, there are still a number of possible stereo configurations, which can be generated along a single flight-line, for example imaging with convergent scanning planes (Leberl, 1972a; Bair and Carlsson, 1975), and with both radar and infrared scanner (Moore, 1969).

Experimental stereo analyses have been performed by a number of authors. An overview of the results is given in Table 6.2. In some cases the accuracies quoted are optimistic, particularly if they concern opposite-side stereo configurations. Opposite-side stereoscopic viewing may be mainly possible



A: SAME SIDE-SAME ALTITUDE RADAR CONFIGURATION



B: OPPOSITE SIDE-SAME ALTITUDE RADAR CONFIGURATION

Figure 6.4 AB. Radar relief displacement is an inherent characteristic of side-looking imaging systems and is towards the nadir if the object is above the datum and away from nadir if the object is below the datum. The relief displacement, therefore, is in the opposite direction from the displacement in optical camera systems. When one object is imaged twice at two different look-directions, i.e., either same side (A) or opposite side (B) configuration at the same altitude, then radar parallax can be measured and radar stereoscopy attained.

TABLE 62. MAPPING ACCURACIES ACHIEVED IN STEREO-RADARGRAMMETRY
(after Leberl, 1976)

Source	Year	Mapping Acc. (m) In Checkpoints			Control Pts. per 100 km ²	Radar Ground Resolution (m)	Antenna Stabilized	Type of Radar	Remarks
		Along	Across	Height					
Gracie	1970	12.1	7.7	13.2	35	17	yes	Synth. Ap. AN-APQ 102	Atlanta, Georgia
Konecny	1972	68	138	240		16	yes	Real Ap. Westinghouse	New Guinea, opposite side stereo
		130	428	1548					New Guinea, same side stereo
DBA-System	1974	26.8	21.9	16.7	1.2	3	yes	Synth. Ap. AN-ASQ 142	Opposite side
		29.5	25.6	19.7	1.2				Same side
Goodyear	1974			93	3	12	yes	Synth. Ap. GEMS 1000	Phoenix, Arizona, Op- posite side stereo
Derenyl	1975			33		12	yes	Synth Ap. GEMS 1000	Phoenix, Arizona, Op- posite side stereo
				177					Phoenix, Arizona, same side stereo
Leberl	1975	173	510	109	0.27	30-150	no	Synth. Ap. ALSE-UHF	Apollo 17 orbital radar stereo intersection angles 2°

in the case of fairly flat terrain or only isolated mountains surrounded by flat terrain. In other cases, lay-over, shadowing, and general differences in the contents of overlapping image pairs may not permit opposite-side stereo measurements to be taken, although geometrically, the opposite-side stereo arrangement is superior, because of greater parallax differences.

Based on a general evaluation of Table 6.2, height mapping from orbital stereo radar is only possible with an accuracy in the range of 100 meters. From orbital altitudes of about 1000 km, radar heights would be competitive with heights derived from metric photography but hardly useful in terrestrial mapping except in the last unmapped mountain regions of the Earth (Cordilleras, Himalaya). This indicates that orbital stereo mapping may not for some time come to be the way to derive terrestrial topographic height, whether it be from photography or other types of images. However, in all fairness to the capability of stereo radar it has only been investigated in the context of reconnaissance type mapping rather than classical mapping approaches (Leberl, 1976). For example, contouring from radar stereo models has been reported on only two occasions; Norvelle (1972) demonstrated the use of the analytical plotter AS-11-A to directly plot contour lines from a deformed radar model. Leberl (1975) produced a radar contour plot of a lunar feature, however not by directly tracing the contour lines, but by first acquiring a digital height model, from which the contours were interpolated numerically.

Considerable research is required before a definitive statement can be made about orbital radar's contribution to topographic mapping. Space Shuttle will certainly further this research. However, it should be stressed that there is no doubt about the value of stereo-radar for purposes other than terrestrial topographic height mapping. For example, Koopmans (1973) demonstrated clearly the dramatic improvement in the mapping of drainage if stereo radar rather than

monoscopic radar is employed. The first significant use of stereo-radar for drainage mapping was in 1970 in studies for Kennecott Copper Corporation in West Irian (Simonett and McCoy, Earth Satellite Corporation, unpublished memorandum, 1970).

Merging Radar with other Multispectral Data

A major radargrammetric application is the merging of radar image data with imagery from other sensors. Attempts to merge data from different sensors are presently being undertaken (Harris and Graham, 1976). No specific conclusions have been reached as to a geoscience application of such techniques. However, there seems to be a growing awareness among remote sensing specialists that ultimately remote sensor data from many sources have to be combined for optimum interpretability. Stereo capability may be required for all areas except extensive plains, in order to merge both the radar and M.S.S. images. Because of the improved resolution of LANDSAT D MSS, strictly speaking, the MSS should also have stereo capability to achieve a satisfactory orthophoto/projection-based merge. Rubber sheet adjustments can of course be made for both images in the absence of stereoscopy, but the latter is preferred.

Figures 6.5, 6.6, and 6.7 give a good indication of the potential of geometrically merging multispectral sensor products. When the LANDSAT color composite (Blue, Band 4; Green, Band 5; Red, Band 7) is combined with the X-band radar image, a definite improvement in overall image information and interpretability is produced. Extrapolate the capability of this technique to combining LANDSAT-D (≤ 30 meters) and Space Program Imaging Radar (≤ 30 meters) and we will potentially have a powerful resource analysis product. Such data will be of great importance to the next topic which considers SPIR's role in thematic mapping.

Figure 6.5 LANDSAT color composite of an area near Tucson, Arizona. Bands 4, 5, and 7 were filtered (blue, green, red respectively) and optically combined to produce the 1:1,000,000 (original scale) image. Note the lack of spatial and spectral detail present in the open pit mine areas shown by the absence of small color contrasts. (Courtesy of Goodyear Aerospace Corporation)

Figure 6.6 X-band synthetic aperture radar image of the area near Tucson, Arizona produced by the Goodyear Gems APS-102 system. (Courtesy of Goodyear Aerospace Corporation)

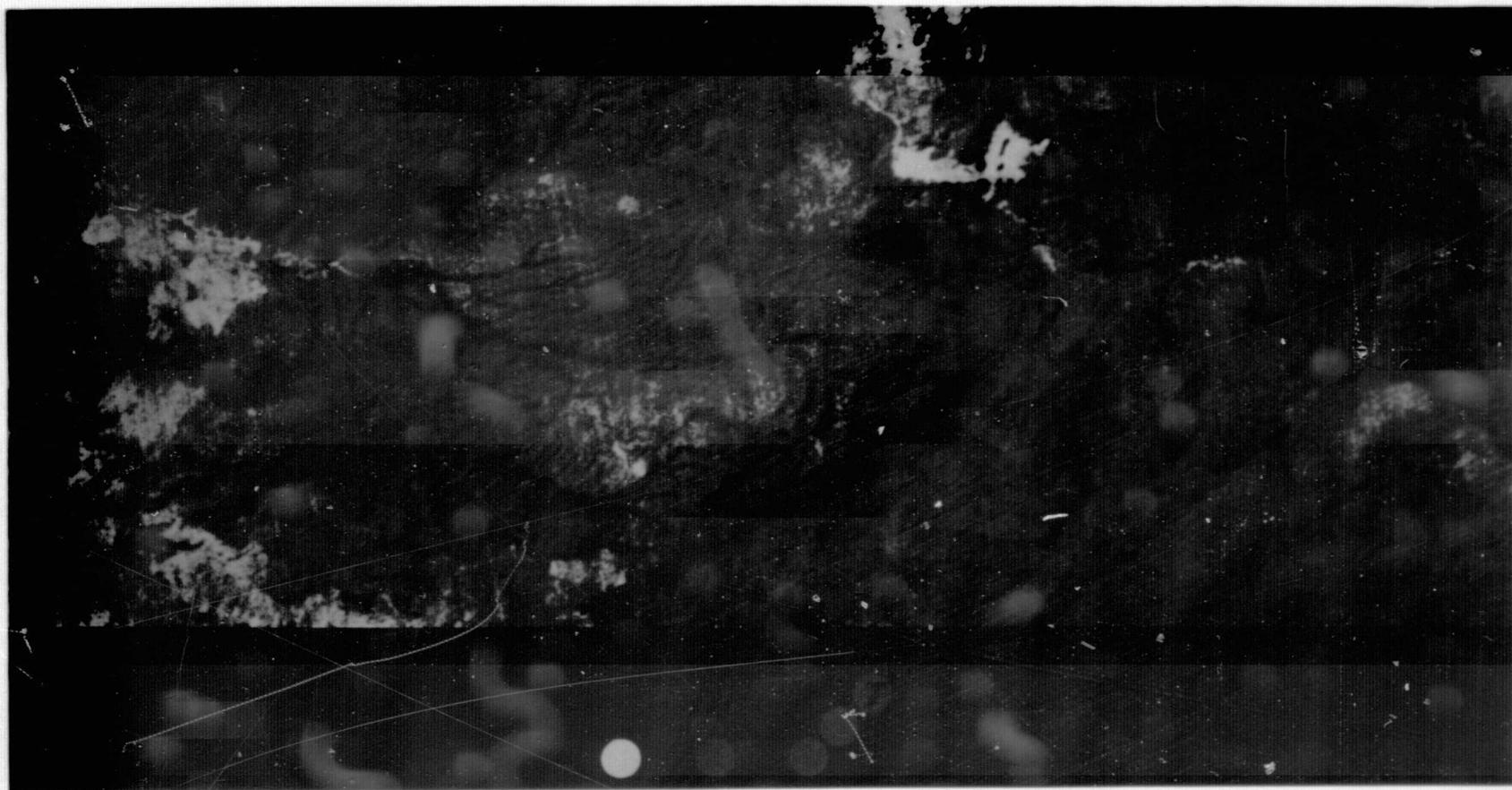
Figure 6.7 Optically combined X-band radar/LANDSAT image (see Figures 6.5 and 6.6) of the area near Tucson, Arizona. Note the increase in detail produced when the high resolution synthetic aperture radar image is merged with the low resolution (i.e. 80m pixels) LANDSAT image. More importantly, note also that this spatial detail is accompanied by parallel changes in color indicating that the radar image is providing additional spectral as well as spatial information.

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LANDSAT COLOR IMAGE NEAR TUCSON, ARIZONA
(AUGUST, 1975)

—SPIR—

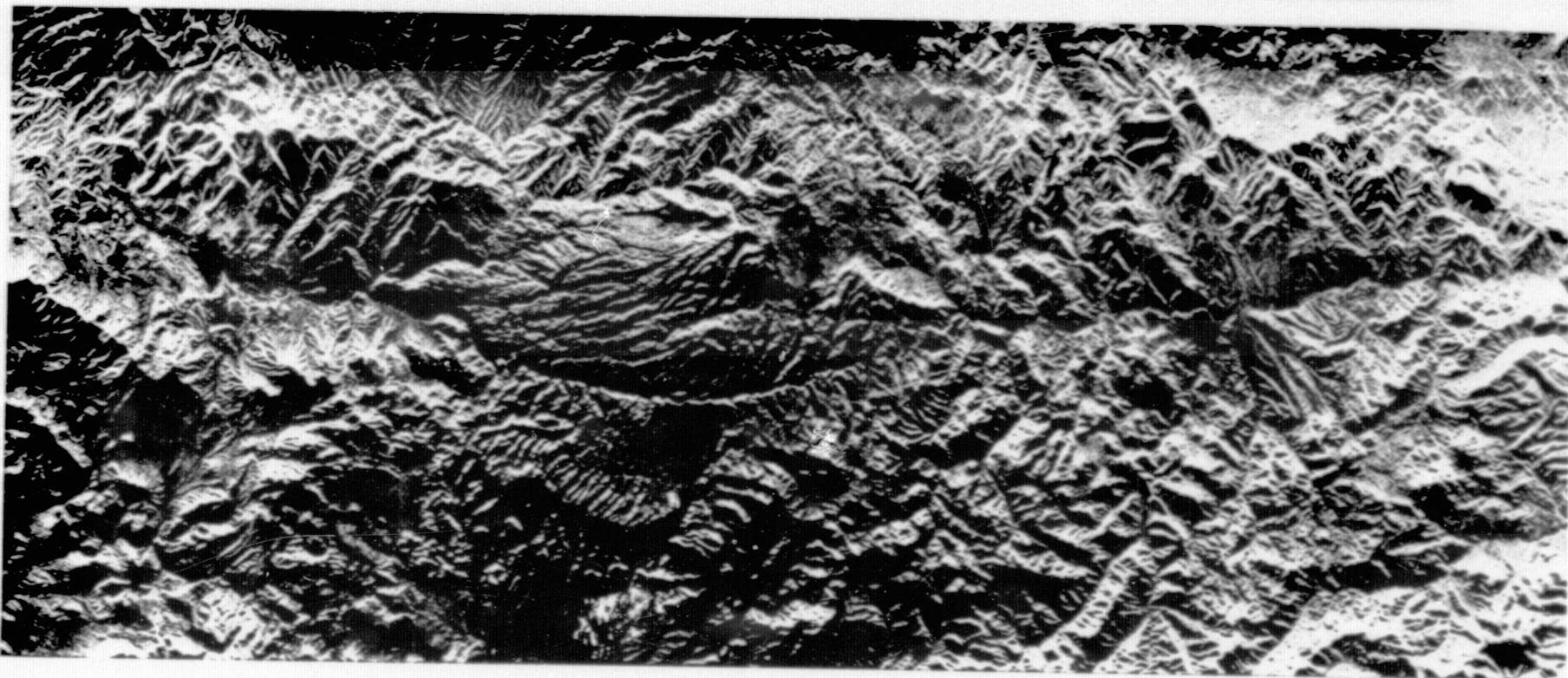


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X-BAND RADAR IMAGE NEAR TUCSON, ARIZONA (AUGUST, 1975)

—SPIR—→

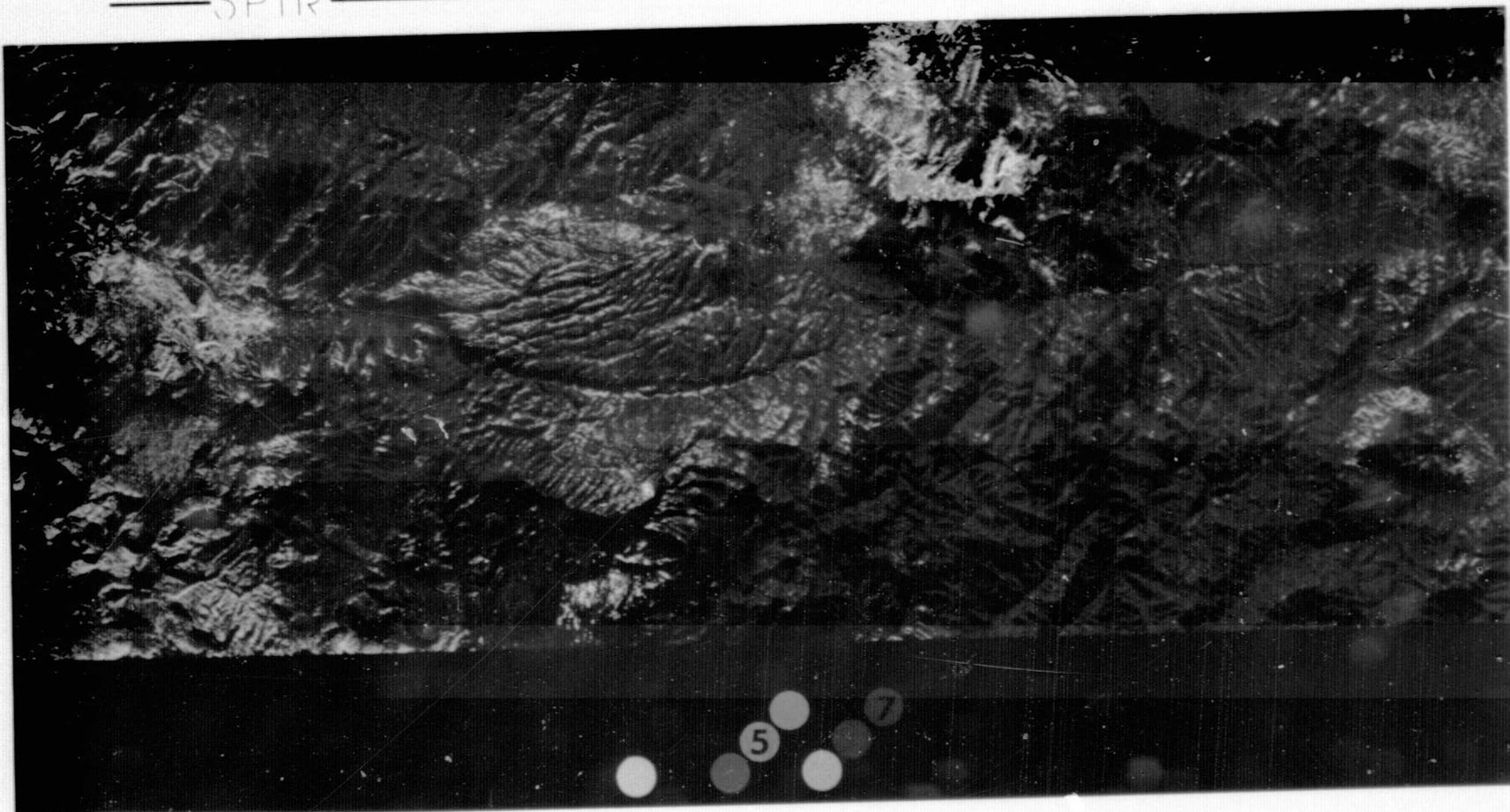


NASA
S- 76- 27031

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OPTICALLY COMBINED RADAR/LANDSAT IMAGE
NEAR TUCSON, ARIZONA (AUGUST, 1975)

—SPIR—



Thematic Mapping

Thematic maps emphasize themes symbolized on a basemap which contains reference information. One of the primary strengths of Space Program Imaging Radar will be its unique capability to generate thematic data which may be unobtainable from any other sensor configuration. For example, Table 6.3 summarizes some of the radar capabilities and their general significance to thematic mapping.

Processing of radar image data for the preparation of thematic maps involves the rectification of images, compilation of semi-controlled or other image mosaics, and registration of images from different sources, followed by the compilation of the thematic content on the rectified and mosaicked base.

Along with the significant federal and state requirements for thematic products already presented in this report, the U.S. business community has definite thematic radar requirements (Archibald Park, General Electric Corporation (personal communication)). In particular, private industry finds that almost all client requirements are cartographic. Dr. Park recommends that NASA establish a specialized processing facility and carry the processing a long way to widen the user base. Three options are proposed (see Table 6.4). The first is raw data and CCT. This has a high cost to the user and substantially cuts the number of users down and means that there is an immense amount of redundant work in the user community. The second is to take the raw data, radiometrically and geometrically correct it, and then give it to the user as a CCT. This still has a moderate cost to the user and much redundancy which in the long run is not cost-effective. The third and recommended option is that NASA radiometrically correct, geometrically correct (i.e. to orthoradar), theme pre-process, and then place the image into a cartographic format such as a UTM projection. This has the lowest cost and most benefit to the user community. All image

Table 6.3: Radar Capabilities and their Significance in Thematic Mapping Applications

CAPABILITY	COMMENTS
Provides its own illumination	Timeliness enables thematic data to be obtained at all times and in inhospitable regions.
Penetrates clouds and rain	
Penetrates vegetation	Potentially important geologically; improves land/water delineation.
Permits control of illumination angle	Enhances topography.
Permits control of illumination direction	For emphasizing geologic structures. In space will occur as orbits precess, and between ascending and descending orbits.
Resolution independent of distance	Can make satellite radar complementary to satellite photography.
Multifrequency capability	Combined image may reveal greater content of information than single frequency.
Multi-Polarization capability	Significant differences exist between like images (HH vs VV) and between them and cross images (HV).
Employs EM spectrum different from visible	Records dielectric properties of targets.
Sensitivity to surface roughness	Significant for geological and engineering studies.
Sensitivity to surface soil moisture	Valuable for watershed runoff, agricultural yield.
Stereoscopy	Provides 3-dimensional terrain model for thematic data extraction.

and derived thematic data of all dates could then be laid on top of one another to create geobase information systems with congruent geometry.

Marine Mapping

Increased point positioning and planimetric mapping capability developed through Space Shuttle Radar experiments could be potentially useful for acquiring planimetric data (original or updated for four of the five basic types of NOAA/NOS nautical chart programs including:

<u>Type</u>	<u>Scale Range</u>
Sailing	1:600,000 and smaller
General	1:100,000 to 1:600,000
Coastal	1:50,000 to 1:100,000
Harbor	1:50,000 and larger

While general charts are designed for coastal navigation well offshore they still require planimetric reference to coastal landmarks, lights, and bouys. Area coverage of this chart series is about 95 percent complete, with an updating interval governed by the rate of change in a particular area which ranges from 6 months to 4 years. However, there are major inadequacies such as the incomplete coverage of Alaskan waters (Donelson et al., 1973). Because radar creates its own illumination it is not perturbed by the low level of illumination of the polar regions nor the frequent, dense cloud cover which has hampered photographic data collection. Therefore, for many inhospitable regions radar could provide data to complete or update nautical map series.

Probably the most significant marine impact of Space Program Imaging Radar will be the mapping of point man-made features (such as ships, floating aids), natural features (such as icebergs) and area extensive features such as ice. The timely monitoring of point features becomes increasingly important in view of a growing density of ship movement and the extension of national fishing zones. In addition to its all-weather capability previously mentioned, microwave sensing is especially capable of resolving many marine features

because of the relative ease with which it is possible to signalize features on a specularly reflecting water surface. In fact, the application of radar to tracking icebergs is now considered near-operational (Schertler et al., 1975).

The application of radar to mapping area extensive lake ice is also considered to be near-operational (Super and Osmer, 1975). This application to polar sea ice, however, seems only to have been developed to this status in the U.S.S.R. (Glushkov et al., 1972). A major future task, particularly well suited to Space Program Imaging Radar will be the capability to map the polar sea ice and its associated ice motion (Ice dynamics). Although Shuttle Radar will only be on 7-day sorties, certain experiments could capitalize on the system's multipolarization, frequency, and look angle capability to suggest improvements in point feature identification and ice monitoring from future orbital microwave systems.

CONCLUSIONS: ROLE OF SHUTTLE IMAGING RADAR IN MC&G

The 7-day missions of the space shuttle are well suited to provide radar data that permit an evaluation of their applicability to MC&G tasks under near-operational conditions. The data acquired during a specific sortie could be evaluated to recommend parameter changes for dedicated microwave orbital systems.

Application of radar to classical mapping tasks has been limited to reconnaissance mapping of remote areas. The radar images have not been used to their full potential in these projects. It is recommended that the Space Shuttle Imaging Radar be applied to specific radargrammetric mapping projects to determine the true capability of orbital planimetric mapping, map revision, stereo radargrammetry, block adjustment, and the relative/absolute point positioning. In the realm of thematic mapping, Space Shuttle

can only satisfy the requirements for monitoring slowly changing phenomena, perhaps providing only a few complete coverages per year. Nevertheless, the geometric merging of radar with other multispectral data and the techniques of theme pre-processing could be significantly advanced via the shuttle sortie concept.

Timeliness and costs of Mapping, Charting and Geodesy (MC&G) products are such an overriding concern that a significant number of MC&G tasks have evolved in the past for airborne side looking radar. However, when arguing the case for orbital radar it is appropriate to consider the relative merits of airborne versus orbital systems. Apart from the requirements for repetitive imaging of dynamic features such as those associated with marine mapping, where the low variable cost of orbital mapping soon results in an advantage over airborne mapping, there is even an argument for orbital radar imaging in the case of single coverage. This is demonstrated in Figure 6.8, which relates the fixed and variable cost of airborne and orbital radar imaging. In this context, Space Shuttle Imaging Radar will allow a rigorous analysis to be made concerning the cost effectiveness of orbital radar mapping applications. We recommend that this be examined specifically in later shuttle studies.

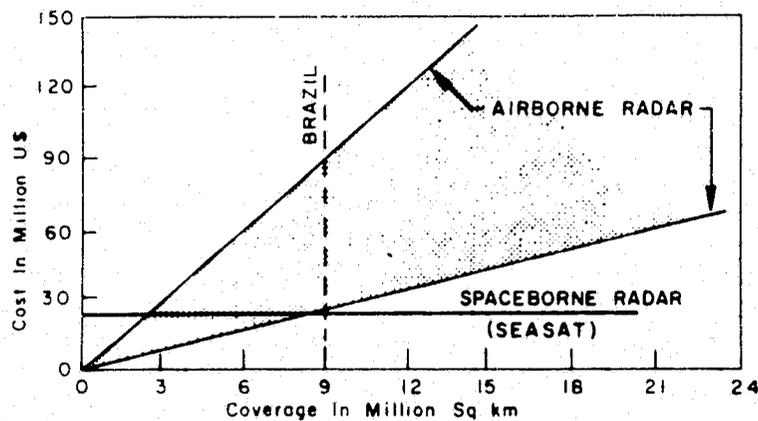


Figure 6.8 Estimate of costs versus coverage with airborne and orbital imaging radar. For airborne radar, prices per square kilometer can be about \$3-10. The SEASAT synthetic aperture radar will cost approximately \$14 million with mission and ground support being approximately \$6 million. Radar data processing costs are rather small if the development costs of processing technology are not considered. (Jet Propulsion Laboratory).

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CHAPTER 7

STATE APPLICATIONS OF A SPACE PROGRAM IMAGING RADAR[†]

SUMMARY

This chapter discusses four case studies representative of the use of radar for state and regional level planning and monitoring:

- * California - Managing the water resources for 1/10 of the nation's population.
- * Alaska - Sea ice affects our nation's ability to exploit critical energy resources.
- * Texas - Monitoring coastal environments where 3/4 of our nation's population live.
- * Northern Great Plains Region - Saline seeps create problems for agriculture.

RECOMMENDATIONS

The Shuttle Program Imaging Radar Program should:

- * conduct a specific study on the range of applications of active microwave systems data to state and regional planning and inventory requirements.
- * initiate a program to make state and regional entities aware of the potential of active microwave data to meet their data/information needs.
- * provide information concerning the current availability of active microwave data to states and regions.
- * provide microwave data for application to state and regional level information needs which are geometrically and radiometrically corrected.

[†] Prepared by John E. Estes, Earl Hajic and John Jensen.

INTRODUCTION AND BACKGROUND

Application of remote sensing can be made to problems of national, regional, state and local scale. This chapter emphasizes state and regional examples.

In 1975, NASA contracted Ambionics Incorporated to survey state government activities and determine the extent to which LANDSAT data were assisting in planning and monitoring functions. This report (Bailey and DeGraff, 1975) identifies by state and agency, applications in which remote sensing (particularly LANDSAT) is employed. The report also comments on the effectiveness of state activity and future plans for continued use of remotely sensed data. State government activities listed suggest that:

- * States have a wide range of requirements for which remote sensing data are useful; and that
- * Availability of inexpensive LANDSAT data (and NASA's encouragement) has influenced states to initiate activities to employ the data.

The emphasis in states' use of remote sensing is still almost exclusively in areas where visible or photographic region measurements are most valuable. Surveys of state remote sensing activities, such as the Ambionics report, naturally therefore do not identify needs for which radar is uniquely appropriate. They do, however, identify needs where radar can contribute significantly.

Table 7.1 contains material from the Ambionics report. It shows areas where microwave data could be of value in most state programs. A wide variety of state agencies can make use of radar data in their inventory and monitoring activities. Tables 7.2 and 7.3 focus specifically on potential applications of a space program imaging radar for state agencies within California and for State and Federal agencies with mandated inventory and monitoring responsibilities in Alaska. Tables 7.2 and 7.3 clearly illustrate the variety of agencies and the range of potential active microwave applications in these two states.

TABLE 7.1

POTENTIAL APPLICATIONS OF MICROWAVE REMOTE SENSING
TO STATE AGENCY INVENTORY AND MONITORING REQUIREMENTS

<u>Applications</u>	<u>State Agency</u>
Strip Mine Monitoring	Alabama Geological Survey
	Indiana Department of Natural Resources
	Kentucky Department of Natural Resources and Environmental Protection
	Maryland Bureau of Mines
	Ohio Department of Economic and Community Development
	Oklahoma Geological Survey
Surface Water Mapping	Florida Fish and Wildlife Office
	Georgia Department of Natural Resources
	Kentucky Department of Natural Resources and Environmental Protection
	Missouri Department of Natural Resources
	Alabama Geological Survey
Coastlines, Coastal Processes, and Wetlands	California Office of Science and Technology
	Delaware Department of Natural Resources
	Georgia Office of the Governor
	Louisiana Center for Wetlands Resources
	Maryland Department of Natural Resources
	Indiana Geological Survey
Minerals and Construction Materials	Iowa Geological Survey
	New Mexico Office of Planning

TABLE 7.1 (cont.)

<u>Applications</u>	<u>State Agency</u>
<p>Geologic Structures (landslide prone areas, "griddle structures," landforms, and drainage systems)</p>	<p>Alaska Geophysical Institute Arkansas State Highway Department Georgia Department of Natural Resources New York Geological Survey</p>
<p>Soil Moisture (fire hazard, irrigation lands and watershed runoff)</p>	<p>California Office of Science and Technology Florida Fish and Wildlife Office Maine Department of Transportation</p>
<p>Flood Damage</p>	<p>Louisiana Technology Transfer Office</p>
<p>Lake Ice Monitoring</p>	<p>Ohio Department of Economic and Community Development</p>

TABLE 7.2

CALIFORNIA STATE AGENCY INFORMATION REQUIREMENTS - SPACE PROGRAM IMAGING RADAR APPLICATIONS

	Dept. Water Resources	State Water Control Board	Dept. of Fish and Game	Dept. of Navigation & Ocean Development	Dept. Conservation-Div. of Forestry	State Energy Commission	Dept. of Food & Agriculture	Dept. of Parks and Recreation	Dept. of Transportation-Div. of Highways	State Land Commission-State Lands Div.	Dept. of Public Health	Office of Emergency Services	Office of Science and Technology
RADAR APPLICATIONS PROVEN FEASIBLE:													
Lake ice monitoring	•	•											
Flood mapping	•	•	•									•	
Oil spill detection	•	•										•	•
Landform/terrain analysis	•			•	•	•	•	•	•	•			
Grain crop identification	•					•							
Broad class landuse	•	•		•	•	•	•	•	•	•			•
RADAR APPLICATIONS BELIEVED MEASURABLE:													
Soil moisture determination	•												•
Soil type mapping	•			•									
Petroleum exploration				•					•				•
Rangeland inventories	•				•								
Crop condition/biomass	•			•	•								
Mineral deposit mapping					•								•
Coastal wetlands mapping			•	•						•	•	•	
Snowfield mapping	•									•			
OTHER RADAR APPLICATIONS:													
Map rain intensity	•												
Atmospheric water content	•												
Flood forecasting	•												
Lake level, extent	•	•											
Water pollution	•	•										•	
Frozen water hydrology	•												
Assess disasters	•	•										•	•
Watershed management	•	•	•	•	•								
Monitor coastal processes				•									
Monitor storm water buildup				•									
Groundwater	•					•							
Construction materials				•					•				
Wildland vegetation mapping				•				•					

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TABLE 7.3

ALASKA STATE AGENCY INFORMATION REQUIREMENTS - SPACE PROGRAM IMAGING RADAR APPLICATIONS

	Native Corporations	Division Water Programs-Dept. Environmental Conservation	Water Resources Board-Dept. Natural Resources	Water Resources Div.-Alaska Power Admin.	Outer Continental Shelf Energy Program (BLM-NOAA)	Coastal Zone Management Plans (1976)	Div. Commercial Fisheries-Dept. Fish & Game	Joint Fed. State Land Use Planning Commission	Civil Defense Office	Div. Geologic & Geophysical Surveys-DNR	Div. of Lands-DNR	Div. of Terrestrial Programs-DEC	Materials Div.-Dept. of Highways	Fed. Energy Administration	U.S. Geological Survey	
RADAR APPLICATIONS PROVEN FEASIBLE:																
Lake ice monitoring	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Flood mapping	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Oil spill detection	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Landform/terrain analysis	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Grain crop identification	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Broad class landuse	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
RADAR APPLICATIONS BELIEVED MEASURABLE:																
Soil moisture	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Soil type	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Petroleum exploration	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Rangeland inventories	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Crop condition	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Mineral deposits	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Coastal wetlands	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Snowfield mapping	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
OTHER RADAR APPLICATIONS:																
Map rain intensity	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Atmospheric water content	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Flood forecasting	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Lake level, extent	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Water pollution	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Frozen water hydrology	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Watershed management	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Monitor coastal processes	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Monitor wave building	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Groundwater	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Construction materials	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Assess disasters	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•

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There are many states and many problems. The following discussion concentrates on four examples where critical information requirements exist which may be met in part with a space program imaging radar:

- * California - Water Resources
- * Alaska - Sea Ice
- * Texas - Coastal Zone Management
- * Northern Great Plains Region - Saline Seeps.

CALIFORNIA

Management of Interregional Water Transport - A Key Issue

Four California state agencies have key roles in water management.

They are:

- * The Department of Water Resources - mandated total water systems responsibilities.
- * The State Water Resources Control Board concerned with land use, pollution surveillance and climatologic data.
- * The Energy Conservation and Development Commission concerned with optimal use of hydropower.
- * The Department of Food and Agriculture concerned with all types of agricultural water demand information.

The livelihood of California is tied to interregional water transport management. The information requirements of California's water supply, demand and transport network already receive important data from remote sensing activities (California State Water Resources Control Board, 1975; Sawyer, 1975). Space radar, however, can offer important information improvements for key management concerns.

Supply

The estimated mean seasonal runoff of all California streams is about 71,000,000 acre feet (Durrenberger, 1967). The streams of the northern coastal area of California provide about 41% of this total, the streams of the Sacramento

River basin another 32%. Almost all the rest is accounted for by streams in the San Joaquin Valley. Conversely, the population has a substantial south coast element in the driest portion of the state. Water transport management is therefore a key issue in the state because northern waters are aqueducted and pumped to the southlands. Timely, accurate water supply and demand data is mandatory as well as water network monitoring.

Let us briefly examine how radar can be used to provide information on some aspects of water supply modeling. We have already seen how water supply information is vital to effective water resources management (Chapter 2).

Key input variables to watershed modeling includes:

- * landcover,
- * snowpack characteristics,
- * soil moisture, and
- * areas of active precipitation.

Landcover: Numerous studies document the ability of radar to provide a variety of land cover information (Lewis, 1968; Nunnally, 1969; Simonett, 1971; Morain, 1974; Matthews, 1975; and Reeves, 1975 among others). Therefore the topic will not be dealt with at length here. It is important to note, however, that an active microwave system can provide landcover data at a scale and of a resolution well suited to the demands of many hydrologic models.

Snowpack: Some 80% to 90% of California's irrigation water originates in snow pack. Timely snow pack measurements are vital. California's snowpack measurement program has grown from the ground measurement surveys coordinated since 1929 to a current one using aerial surveys of snow courses and automatic snow sensors. From these inputs, forecasts are issued five times a year. Recent studies have attempted to assess the incremental improvement in forecasts which can be achieved through the high altitude photography and LANDSAT imagery--

the latter under the cooperative Combined Snow Survey for selected southwest U.S. regions (Colwell et al., 1976). Radar has demonstrated mapping capabilities through cloud cover. Radar shows promise in determining the water equivalent of snow; though the few studies conducted to date have produced somewhat ambiguous results (Linlor & Jiracek, 1975). In some cases seasonal snow is detected--in others it may be quite indistinct. At present it appears that multifrequency radar systems may enable determination of snow thickness and density, but clearly much research is needed.

Soil Moisture: Soil moisture is vitally related not only to watershed runoff but to optimization of harvest as well. Participants in the recent Active Microwave Workshop (Matthews, 1975) noted that: "Moisture content at the surface of bare soil can be inferred from visible and IR sensor data. However, if the soil is covered with dense vegetation, monitoring changes in moisture content is impossible without using the penetrating capability of microwave signals. Furthermore, even with bare soil, the capability of the microwave signal to obtain responses from some distances (centimeters to meters) within the soil means that moist subsurface layers can be observed even if the top centimeter has dried. The effect of a recent small rainfall or heavy dew in barely wetting the surface can be discounted when microwave sensors observe the integrated effect of the surface and near-surface. The wavelength of the microwave sensors is particularly important for this application because longer wavelengths can penetrate more vegetation and soil."

Recent experiments with radar have noted significant changes in selected crop back-scattering coefficients as the crops have matured (see Chapter 4). Crop health and biomass measurements which center on the determination of the amount of water in the plant have been effectively sensed. Good sensitivities to soil moisture variations have also been observed (Ulaby, 1975; Battivala and Ulaby).

Demand

California's population (1/10 of the nation's) is concentrated in the south central and coastal regions and along the Central Valley. In contrast, water supply areas are located in Northern California, and the Colorado River Basin. Residential commercial and industrial water use in California's semiarid southern regions is high. Southern California's urban expansion could not have occurred without water from the Owens Valley, and Colorado River and Feather River drainage basins. In California's Great Central Valley the Friant-Kern and Delta-Mendocino Canals provided water to farmers in the southern part of the Valley long before the Feather River Project. California agriculture provides an annual crop income of over three billion dollars which is about 12% of the U.S. total annual crop income. Major agricultural regions include the north, central and south coasts, the Sacramento and San Joaquin Valleys and the desert. Peak harvest periods occur somewhere in these regions every month of the year. Many of these peak harvest periods are particularly critical. They consist of relatively short time windows which can be optimized with timely knowledge of soil moisture conditions and crop maturity in preceding, predictive periods.

The degree to which this information may be available from remotely sensed data for a given region is, in part, a function of cloud cover. For example, north coast agricultural regions have peak harvest periods ranging from June through October; the latter month is important for wine grapes and walnuts. However, by October the north coast region is experiencing probabilities of some cloud cover of 50 to 60%. October and November are key periods for the Sacramento Valley crops of olives, walnuts, potatoes, rice, sugar beets, and prunes. During this time the probability of some cloud cover is also around 50%.

It is important then to realize that management information describing

the characteristics of water supply and demand can experience gaps caused by cloud cover and fog. In water supply, the areal extent and water content of snow pack are frequently "beclouded" by the very cover that can produce significant increases or decreases in the pack! As just seen, water demand information is especially critical in anticipating peak harvest periods. At this time, north coast and central valley agricultural regions are experiencing 50% probability of cloud cover.

Supply/Demand Forecasting

As seen from this discussion active microwave might be used to upgrade the quality of a variety of important watershed model inputs, particularly for a more timely and accurate determination of runoff. Quantitative assessments of the value of this information to the long and short-term management of hydropower, flood water management and release, and irrigation water allocation and use are all required. Similarly the fact that the imaging radar supplies information during periods of cloud cover should not be dismissed or underrated because it is a case of common knowledge. Again, a quantitative assessment of the value of increased, timely information on snowpack and watershed runoff characteristics unencumbered by missed data at critical survey times should be made.

Water demand forecasting will also benefit from imaging radar measurements. The extent and location of irrigated agriculture has been discussed. Crop type determination, soil moisture boundary conditions, and the delineation of water-logged and salt affected soils may also be improved via radar data (Matthews, 1975; California Institute of Technology, 1975).

In summary on both the supply and demand sides, as well as with water transportation, there appear to be areas where active microwave could have a role in state water management.

ALASKA

Sea Ice Affects Energy Resource Development

Alaska has some 34,000 miles of coastline, over half of which is affected by ice most of the year. Surrounding this lengthy coastline are some 350 million acres of continental shelf potentially exploitable through construction of offshore facilities. Climatically Alaska is a prima facie case for radar monitoring with severe weather and low angles of solar illumination limiting the practicability of most remote sensor systems. Field work is typically difficult and hazardous. The discoveries of oil on Alaska's north slope have increased our nation's potential for greater energy independence. However, with heightened environmental awareness these discoveries have generated controversy about the potential environmental disruption associated with exploiting these resources. Timely, accurate information is required to inventory critical resources and monitor this development to minimize or eliminate potential adverse environmental impacts. This analysis will focus on only one critical parameter, i.e., the monitoring of Alaskan sea ice.

Sea Ice: The ability to monitor sea ice is important in the development of Alaska's resources. A number of Federal and State agencies are studying sea ice and its impact on the development of transport of resources, goods, and supplies.

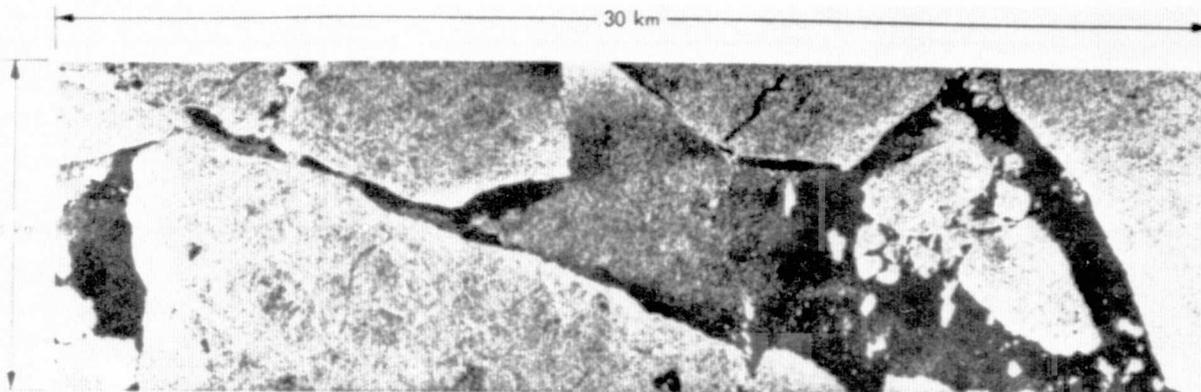
Sea ice affects both the Bering and Arctic coastlines. The arctic coast of Alaska is bordered by sea ice every year during the winter; ice may be offshore all summer. Marine plants grow in the lower layers of sea ice during early spring. These support abundant marine life. Productivity is unknown but is assumed to be high. The Bering Sea coast is bordered by sea ice during winters of most years. Plant production in the northern Bering Sea is probably the highest in the world. These plants support abundant marine life

which rivals that of the best fishing anywhere else in the world.

Because this environmentally productive and unique ecosystem is about to be subjected to what one Alaskan researcher calls "a horrendous offshore oil development proposed by the Federal Government" (Hall, 1975), the Outer Continental Shelf Energy Program was initiated. This program is studying the potential impact of offshore oil development in the Gulf of Alaska, Bering Sea, Beaufort Sea, and Chukchi Sea. The Bureau of Land Management, which is responsible for these studies, has contracted the task of environmental assessment to NOAA. A substantial part of this evaluation is the assessment of sea ice parameters as they will influence or be influenced by the offshore development.

Although the electronically scanning microwave radiometer (ESMR) on Nimbus 5 has provided a daily synoptic view of polar sea ice distribution, it does not provide the kind of high-resolution data needed for a wide variety of scientific and commercial purposes. To test the existing and developing numerical models for sea ice dynamics and thermodynamics, high-resolution sequential imagery of select areas is badly needed. The optimum sensors for this program would appear to be active microwave sensors. Figure 7.1, acquired in the Canadian arctic, shows the ability of radar to monitor ice movement through time. Data inputs such as these can lead to more efficient ice breaking operations by providing data on the distribution and changing patterns of leads, thicknesses and ridges.

The first American active microwave experiment on sea ice in which sequential images of ice were obtained took place north of Point Barrow during April and May 1973 when a joint U.S. Geological Survey/Cold Regions Research and Engineering Laboratory (CRREL) team used an X-band SLAR mounted in a Mohawk aircraft (Matthews, 1975). Based on this and other studies (Campbell et al., 1973; Leberl et al., 1976) it has been concluded that SLAR remote

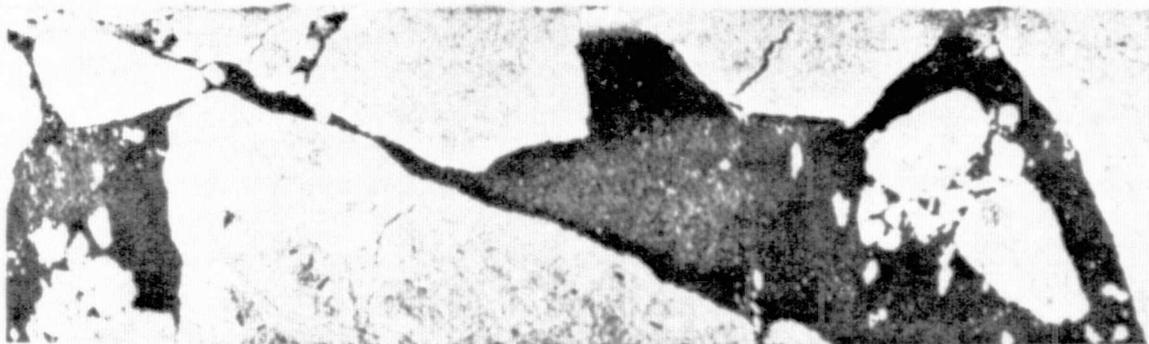


(a) L-BAND

HH

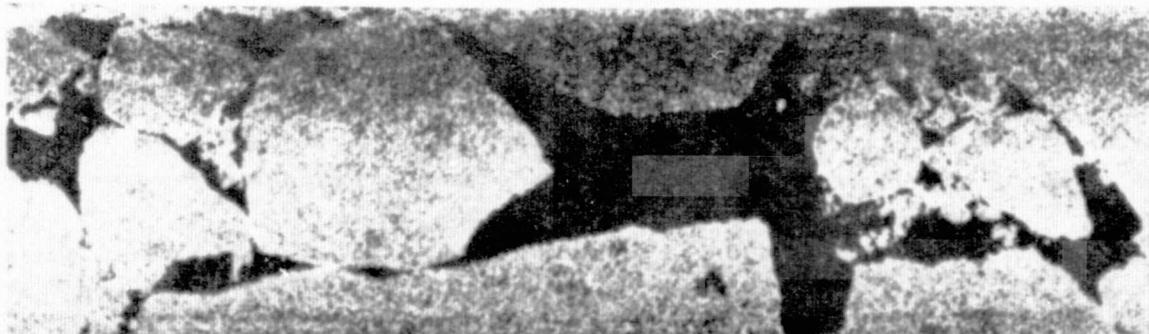
18 AUG 75

74° 42' N
139° 23' W



(b)

HV



(c) L-BAND HH

22 AUG 75

74° 40' N
140° 43' W

7-14

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

Figure 7.1 These L-band images acquired in August of 1975 in the Canadian Arctic demonstrate the ability of an active microwave sensor to monitor ice movements through time (Imagery Courtesy Jet Propulsion Laboratory)

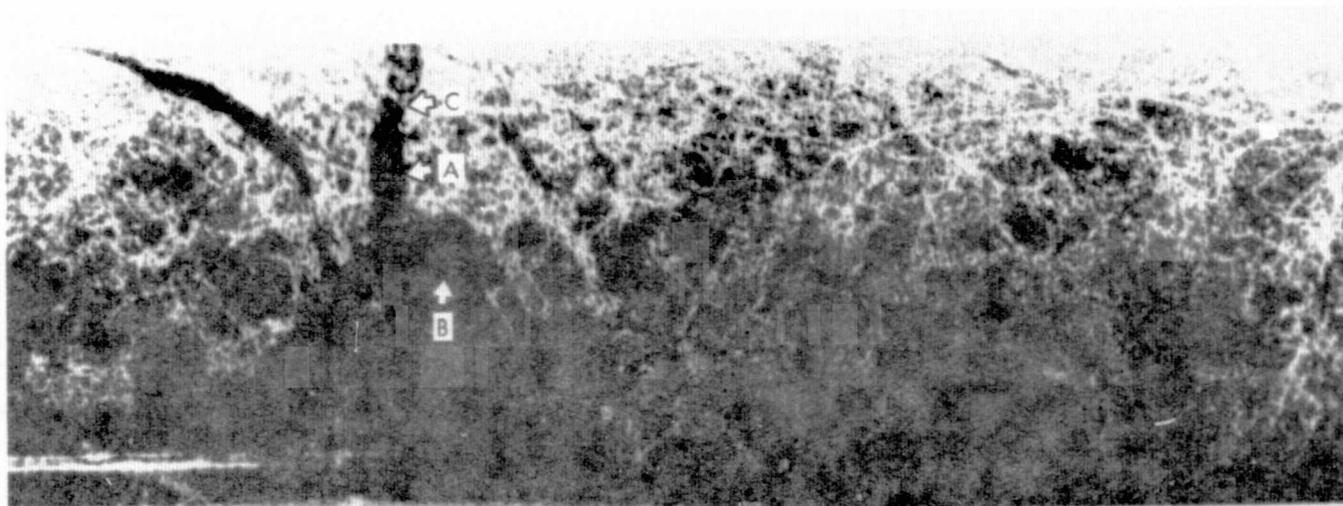
sensing of sea ice provides discernment of the following features:

- * leads and polynyas can be distinguished from ice (see Figure 7.2)
- * thin ice can be distinguished from open water in leads and polynyas
- * ridges can be distinguished from leads
- * land (Permafrost) can be distinguished from shorefast ice, water, and pack ice
- * ice-type distinction is good enough to permit distinctions between water, thin ice, thicker first-year ice, and the thicker multi-year ice

The shorefast ice alluded to above has special implications for the petroleum industry in Alaska, the Outer Continental Shelf Program, and the Coastal Zone Management Plan of Alaska which will probably be passed by the state legislature in 1976 (personal communication, A.E. Belon, University of Alaska, 1976).

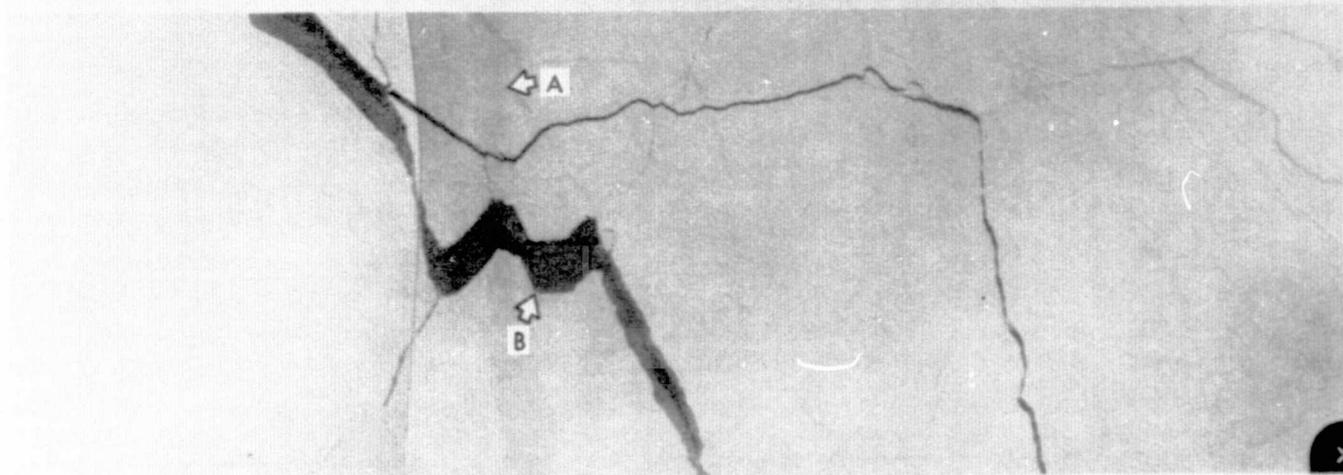
There is considerable interest in the possibility of locating petroleum industry structures in the waters off Arctic and Chukchi coasts. The existence of large masses of grounded, shorefast ice indicate that underwater cables, pipes, and other structures must be buried sufficiently deep in the ocean floor that they are not subject to disruption when the bottom scouring of sea and shorefast ice occurs. In order to develop a morphological model of bottom plowing and shorefast ice, more information is required (Stringer, 1974). This type of data is uniquely suited to sensing in the microwave region, coupled with ice depth and type observations at the time of imaging.

The use of morphological and ice dynamics models can lead to more efficient routing of resources, goods and supplies. Indeed, airborne radar is currently being used on the great lakes to provide real time, all weather information to ship navigators on ice conditions.



L-BAND SIDE-LOOKING AIRBORNE RADAR IMAGE

(a)



AERIAL PHOTOGRAPH

19 APR 75

(83° 03'N; 165° 00'W)

(b)

Figure 7.2 This radar image taken over the Beaufort Sea illustrates the potential of radar to provide information on leads. Although the small new lead is not differentiated on the radar the older larger lead not apparent on the aerial photo can easily be detected.

TEXAS

Monitoring the Coastal Environment

Typical of a class of problems faced by states is the need for monitoring coastal environments (see Table 7.1). It is estimated that over 3/4 of the nation's population lives in the coastal zone. Studies indicate that existing baseline information for coastal areas is sketchy, outdated or non-existent. The key problem is that the most basic mapping data for almost all states is sadly out of date. The two federal agencies responsible for land and water mapping in the coastal zone are the United States Geological Survey (USGS) of the Department of Interior and the National Ocean Survey (NOS) from the Department of Commerce. These agencies simply do not have the resources to resurvey all coastal areas of the United States on a reasonable schedule; say every ten years on the average. In Texas, for instance, many 7½ minute coastal quadrangle maps are decades old. Similarly, basic data for many NOS charts of Texas coastal waters go back in some cases to before the turn of the century. This means that currently published maps and charts which are typically used as information sources by planners show shoreline locations, coastal cultural and topographical and coastal water depths which are substantially in error (Benton Jr., 1975). Radar has been used to update coastal maps (MacDonald, Lewis and Wing, 1971). Many are now suggesting that states should develop for themselves the necessary methods and systems for gathering up-to-date information on the coastal areas they are required to manage (Benton Jr., 1975).

Cloud cover: The Texas coast is some 354 miles in length. Cloud cover can hamper sensors operating in the visible and thermal infrared portion of the spectrum during critical periods. Dr. Bruce Blanchard of Texas A&M University has been attempting to obtain cloud free LANDSAT data of specific coastal

watersheds in winter when vegetation in the area is dormant. After reviewing all LANDSAT data of his area none was deemed satisfactory (Blanchard, 1976). His studies designed to give an objective measure of the runoff potential of these watersheds is desired by the Texas Water Development Board who are interested in freshwater inflows in the estuarine environment. These data, among other things, provide information on salt and freshwater mixing important for fisheries maintenance and development.

Figure 7.3, a multi-frequency multipolarization image shows the increased information achieved through its use. In this area of low marshy vegetation, soil moisture patterns show better on L-band images irrespective of vegetation ... X-band is more sensitive to vegetation. Imagery such as this flown on a timely repetitive basis would provide researchers such as Dr. Blanchard with much of the information they require.

Development: Again, as with many areas, Texas is interested in monitoring the impact of coastal zone development. Much oil exploitation occurs in offshore areas where the potential for spills during periods of low visibility is a consideration. Selecting the best location for a new super tanker port is also important to the state. A number of preliminary studies have been accomplished (Stogsdill and Willingham, 1971). The economic impact of increased refinery output is considerable. Using multipliers from the Texas input-output model this impact has been estimated to be 24.7 billion dollars per year in 1980 and 33.8 billion dollars per year in 1985 (Bragg and Bradley, 1972). New jobs anticipated in Texas range from approximately 194,000 in 1980 to 337,000 in 1985. Bragg and Bradley, 1972, go on to state that without a deep water terminal, the State will lose future jobs with a reduction in tax monies and reduced levels of activity throughout the State's economy.

MULTIPOLARIZATION/FREQUENCY RADAR IMAGERY ENABLES
DIFFERENTIATION OF COASTAL MARSHLAND FEATURES



X-BAND (HH)
3 x 5 RESOLUTION



X-BAND (HV)
3 x 5 RESOLUTION

DECEMBER 15, 1975
MARINELAND TEST SITE



L-BAND (HH)
3 x 5 RESOLUTION



L-BAND (HV)
3 x 5 RESOLUTION

Figure 7.3

Wetlands mapping: Finally, as seen in Table 7.1, many states are interested in wetlands mapping and management. The Active Microwave Workshop report shows that radar can provide important supplemental information concerning these areas (Matthews, 1975). Figure 7.4 is a multiple-polarized color combined Ka-band radar image of an area in Jefferson Parish, Louisiana west of Sabine Pass. The coastal location and low lying terrain make soil and vegetation sensitive to small variations in moisture. The brown and orange colors are areas of grassland and coastal marshland. The mottled appearance of the brown is caused by the pattern of surface vegetation and wet areas. Rectangular field patterns in mixed orange and green are rice fields at various stages of development. Images such as these, in addition to providing important information on agriculture in the Coastal Zone, can aid planners not only on the Gulf Coast but in other areas where clouds or fog may be a problem to more efficiently inventory, monitor and manage this critical resource.

NORTHERN GREAT PLAINS REGION (Minnesota, Montana, North Dakota, South Dakota)

Impact of Saline Seeps on Agriculture

As can be seen from Figure 7.5, the problem of saline seeps has been recognized as important at the gubernatorial level.[†] The governors of Minnesota, North Dakota, South Dakota, and Montana met in 1975 and agreed on the need for information concerning the location and degree of development of saline seeps.

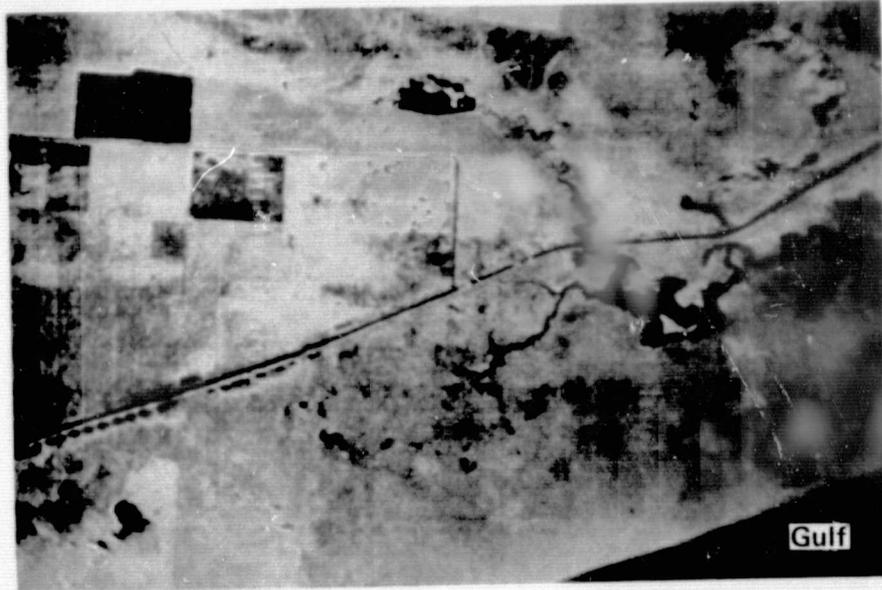
Figure 7.6 shows the areas most affected by saline seeps. In Montana some 200,000 to 500,000 acres of seeps have been estimated. Two percent of the total area of North Dakota and South Dakota is affected as are areas in Wyoming, Nebraska, Alberta, Saskatchewan, Manitoba, and Minnesota.

[†] This recognition of the ability of remote sensing to provide data on a regional basis has also been recognized at the Governors' level in Oregon, Washington, and Idaho. The joint NASA, Department of Interior, and Pacific Northwest Program is an excellent example of the commitment states can make to remote sensing given proper aid and guidance.

MULTIPOLARIZATION RADAR IS SENSITIVE TO VARIATIONS IN VEGETATION COVER AND GROUND MOISTURE

— SPIR —————→

JEFFERSON COUNTY, TEXAS



Intracoastal
Waterway

PRECEDING PAGE BLANK NOT FOR

IMAGES: HH AND HV, KA BAND



STATE OF SOUTH DAKOTA

RICHARD F. KNEIP
GOVERNOR

EXECUTIVE OFFICE

PIERRE
57501

February 26, 1976

Office of the Director
National Aeronautics and Space Administration
Johnson Space Flight Center
Houston, Texas 77058

Dear Sir:

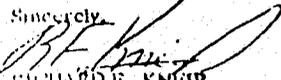
Personnel at South Dakota State University are involved in a regional project with North Dakota State and Montana State Universities in an important investigation using remote sensing technology for possible early detection of saline seeps.

The conditions favoring formation of saline seeps are present over vast areas of Montana, North Dakota, South Dakota and Canada, including about 228,000 square miles in the three states. Early detection of these saline areas using remote sensing technology may permit implementing corrective measures before many of these areas become seriously affected.

It has been called to my attention that the National Aeronautics and Space Administration may be interested in supporting a feasibility investigation of early detection of saline seeps using microwave instrumentation. I strongly encourage participation of NASA in this effort since your help can be of great benefit. This is a problem that represents great agricultural loss to the Northern Plains and one that is progressively deteriorating. We believe this to be a problem for which there are already solutions, if we can develop early detection procedures.

I respectfully request your support and assistance for this project and I will be awaiting your favorable reply.

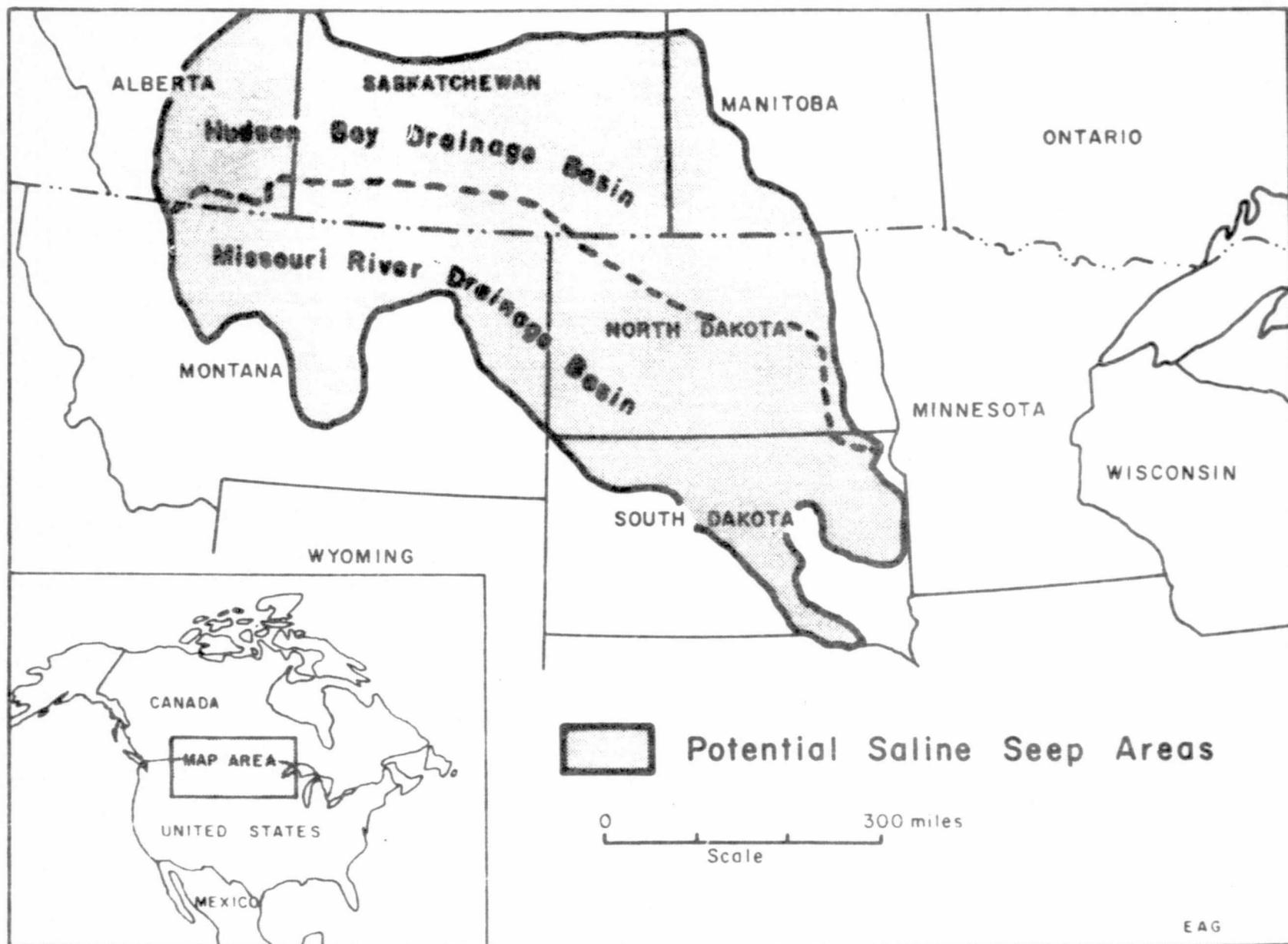
Sincerely,


RICHARD F. KNEIP
GOVERNOR

cc: Victor I. Myers, Remote Sensing Institute, SDSU
Don R. Bucks, Commissioner, State Planning Bureau

Figure 7.5

RECEIVED: [illegible]



EAG

The total area affected by saline seeps is growing. For example, areas affected by seeps increased by 300% in Montana between 1969 and 1974. This figure is considered typical of other areas. In addition, significant seep areas can appear in a single year.

Causes

What are the causes? Basically, the causes are thought to be associated with fallowing practices which cause ponding of saline water zones with thin permeable soil layers over impermeable salt releasing shales. The severity of these seeps depends to a large extent on local topography. Figure 7.7 shows a seep area. When an area reaches this level of severity little can be done to save it. Saline seeps can be cured, however, if early detection can be accomplished. Rehabilitation is accomplished by planting alfalfa. This initiates "pumping" which increases evapotranspiration which decreases ponding and salt concentrations.

Radar role

Studies by Dr. Keith Carver at the University of New Mexico indicate that radar can play a role in early seep detection (Carver, 1976). At present it appears that 300' - 500' spatial resolutions would be adequate and that multiple polarization C or L-band systems would provide the best possible frequencies for picking up the subtle changes which occur in the complex dielectric of the soils in incipient seep areas. More work, however, on scattering cross-sections and modeling of surface roughness is required. However, overall preliminary results are encouraging, and the impact of these seeps on the economy is great. In Montana alone there is an estimated loss in wheat production of \$48,000,000 per year (Carver, 1976).

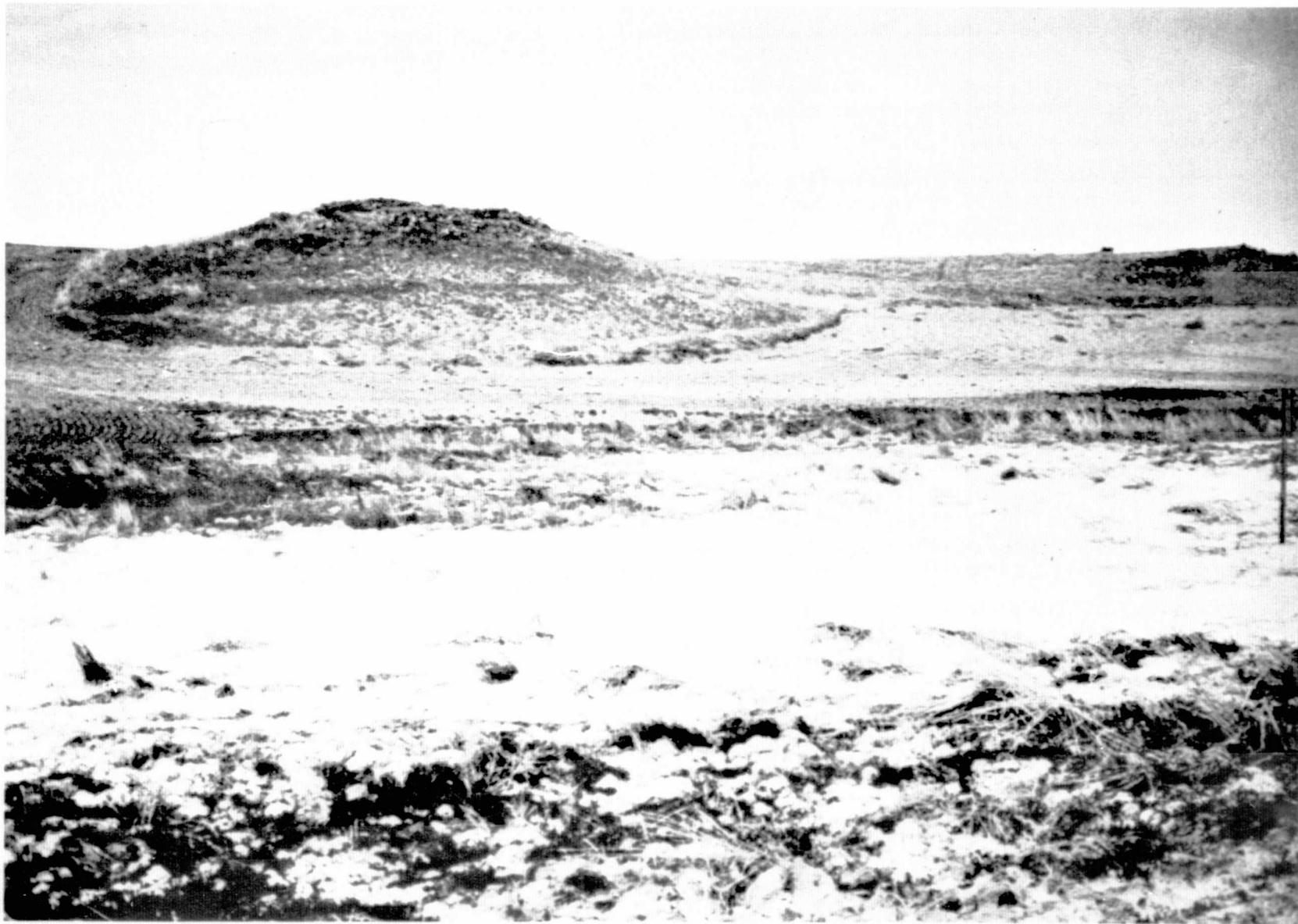


Figure 7.7 Close-up of area affected by Saline Seep. Areas in white are salt crusted. When seeps reach this level of development little can be done to reclaim the area.

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CHAPTER 8

FEDERAL AGENCY REQUIREMENTS

EXAMPLE: DEPARTMENT OF THE INTERIOR[†]

SUMMARY

In this chapter is presented a series of tables containing the requirements for spatial resolution, expressed as instantaneous field of view (IFOV), and for observation frequency for tasks of the several Agencies and Bureaux of the Department of the Interior. These tasks were those for which an imaging radar would have some applicability.

The figures given for IFOV suggest that the bulk of these tasks could be met by a space imaging radar with 25 meters presentation resolution, namely, the resolution already proposed for a Space Shuttle imaging radar.

The range of tasks involves principally areas where observations are needed of water, snow, ice, bare soil and rock, moisture in the soil, and various classes of natural and cultivated vegetation. These tasks would require at least a 2 frequency, multiple polarization system for the levels of identification accuracy needed. The frequencies which at this time appear of greatest interest are 4 GHz and the 14 to 18 GHz region. However, there will clearly be particular applications over the range of wavelengths from 64 cm (0.47 GHz) to 1 cm (30 GHz). These remain to be defined by appropriate experiments.

RECOMMENDATIONS

The Space Program Imaging Radar study group should:

- * Examine these IFOV and observation frequency requirements to determine how well the SEASAT and Space Shuttle program radars will be able to meet the requirements under different operating constraints.

[†] Prepared by G. A. Thorley.

INTRODUCTION AND BACKGROUND

In this chapter is presented a series of tables containing the requirements for spatial resolution and other requirements for various tasks of several Bureaux of the United States Department of the Interior. The tables were prepared by remote sensing experts of the respective Bureaux. These experts were asked to develop these requirements with reference to agency mandated tasks, for which imaging radar would have some applicability. The figures given for desirable observation frequency, instantaneous field of view (IFOV), and priority are averages. Lesser resolution or less frequent data would not necessarily render such material valueless. Rather the tables indicate the likely values which would be used when mission definition studies get underway for a spacecraft radar imaging system.

The tables of instantaneous field of view range in size from 100 hectares down to one meter square. The most commonly requested IFOV values are 0.4 hectares (ha), 0.2 ha, 0.06 ha. The smaller of these values (0.06 ha) is the image presentation IFOV of the proposed Shuttle imaging radar. Thus the great majority of the expected uses could be met with the anticipated resolution. This is the principal concern in bringing these tabulations forward at this time.

The data on observation frequency shows that there are a wide range of desired radar return frequencies. Since many of the problems occur in situations of extensive cloud cover (e.g. flood monitoring and snow melting) the all-weather capability of radar may prove essential for obtaining the needed data. These data will be valuable as mission definition studies get underway.

To introduce each Agency and Bureau of the Department of Interior used in this example, a brief quotation is given, describing the mission of the respective Agency or Bureau. These quotations are from a recent study by General Electric Corporation entitled Total Earth Resources System for the Shuttle Era (TERSSE).

Following each agency brief comes the respective table.

The range of tasks involve principally areas where observations are needed of water, snow, ice, bare soil and rock, moisture in the soil and various classes of natural and cultivated vegetation. These tasks demand at least a two-frequency, multi-polarization imaging system to meet the identification accuracies desired.

The frequencies of greatest interest currently seem to be around 3 to 5 GHz, and 14 to 18 GHz. Particular applications however, may require frequencies anywhere between 0.5 GHz and 30 GHz. These remain to be defined by appropriate experiments.

U.S. DEPARTMENT OF THE INTERIOR

The Department of the Interior is the principal agency of the Federal Government responsible for the management of the Nation's natural resources. In addition, USDI is also the manager and trustee for the public and Indian lands territories and outer continental shelf areas. The mission of the USDI is to encourage the efficient use of natural resources; improve the quality of the environment; ensure adequate resource development in order to meet the Nation's current and future needs; promote an equitable distribution of the benefits from nationally-owned resources; encourage the maximum use of recreational areas; and ensure the orderly incorporation of Indian and Alaska Native people into the mainstream of national life by creating conditions which will advance their social and economic adjustment. (TER SSE)

Bureaux with resource management information needs which are amenable to use of spaceborne imaging RADAR as a primary or supplementary data source include:

- * Geological Survey
- * Bureau of Reclamation
- * Fish and Wildlife Service
- * Bureau of Land Management
- * Bureau of Indian Affairs

GEOLOGICAL SURVEY

The mission of the Geological Survey is to provide basic scientific data concerning water, land, and mineral resources, and to supervise the prospecting, development, and production of minerals and mineral fuels on leased Federal, Indian, and Outer Continental Shelf land. Geological Survey functions include the conduct of surveys, investigations, and research pertaining to the topography, geology, and the mineral and water resources of the United States; the classification of land as to mineral character and water and power resources; the enforcement of USDI regulations applicable to oil, gas, and other mining leases, permits, licenses, development contracts, and gas storage contracts; and the publishing and dissemination of data relative to the foregoing areas. (TERSE)

See Table 8-1 for the required IFOV and observation frequency.

TABLE 1
GEOLOGICAL SURVEY

<u>APPLICATION AREA</u>	<u>OBSERVATION FREQUENCY</u>	<u>IFOV</u>	<u>PRIORITY</u>
GEOLOGIC			
- MINERAL EXPLORATION	SEASONAL	0.06 HA	MODERATE
- FUEL EXPLORATION	SEASONAL	0.06 HA	MODERATE
- OFFSHORE GEOLOGIC SURVEYS (COASTAL OIL SEEPS/COASTAL FAULTS)	MONTHLY	0.06 HA	HIGH
- GEOLOGIC MAPPING	SEASONAL	0.06 HA	MODERATE
- COASTAL PROCESSES	ANNUALLY AND AFTER SEVERE STORMS	0.06 HA	MODERATE
- HAZARD SURVEYS	SEASONAL AND AFTER CATASTROPHIC EVENTS	0.06 HA	HIGH

TABLE 1 (Contd)
GEOLOGICAL SURVEY

<u>APPLICATION AREA</u>	<u>OBSERVATION FREQUENCY</u>	<u>IFOV</u>	<u>PRIORITY</u>
WATER			
- SURFACE WATER IDENTIFICATION			
FLOODS	AS NEEDED	0.01 - 0.25 HA	MODERATE TO HIGH
ESTUARIES			
LAKES			
RIVERS			
- SEA/LAKE ICE SURVEY	AS NEEDED	0.06 HA	HIGH
- SNOW AND GLACIER SURVEY			
SNOW COVER MONITORING	EVERY 5 DAYS DURING MELT SEASON	1 - 25 HA	HIGH
GLACIER MONITORING	10 - 20 DAYS	0.25 HA	MODERATE
THICKNESS OF GREAT ICE SHEETS	AS NEEDED	4 - 100 HA	MODERATE

TABLE 1 (Contd)
GEOLOGICAL SURVEY

<u>APPLICATION AREA</u>	<u>OBSERVATION FREQUENCY</u>	<u>IFOV</u>	<u>PRIORITY</u>
WATER (CONT'D)			
- SOIL MOISTURE CONTENT (RELATION TO HYDROLOGIC SYSTEM)	AS NEEDED	0.01 - 1 HA	MODERATE TO HIGH
WETLAND HYDROLOGY AND DELINEATION	5 - 30 DAYS	0.01 - 1 HA	MODERATE
DRAINAGE BASIN ROUGHNESS AND HYDROLOGIC SYSTEM CLASSIFICATION	30 - 60 DAYS	0.4 HA	LOW
DETECTION OF GEOLOGIC FRACTURES AND ZONES (AS AN AID TO GROUND WATER ANALYSIS)	30 - 120 DAYS	0.01 HA	MODERATE

BUREAU OF RECLAMATION

The Bureau of Reclamation has as its mission the promotion of economic growth in the 17 contiguous western states through the optimum development of water and related land resources. The Bureau performs functions relating to the investigation and development of plans for the regulation, conservation, and utilization of water and related land resources including basin-wide water studies: the conduct of research programs to develop maximum use of water resources including weather modification: the design, construction, operation, and maintenance of projects: the review of operations and maintenance of Bureau-built projects and facilities which are operated and maintained by water users: the settlement of public or acquired lands on Bureau projects: the administration of the Small Reclamation Projects Act of 1956 and the granting of loans for the construction or rehabilitation of irrigation systems: and the negotiation, execution, and administration of repayment contracts, water-user operation and maintenance contracts and contracts required by statutes relating to the irrigation of excess lands. (TERSSE)

TABLE 2
BUREAU OF RECLAMATION

<u>APPLICATION AREA</u>	<u>OBSERVATION FREQUENCY</u>	<u>IFOV</u>	<u>PRIORITY</u>
GEOLOGIC			
- LAND FORM IDENTIFICATION AND TERRAIN ANALYSIS	1/SITE	0.4 HA	MODERATE
- MINERAL DEPOSIT LOCATIONS (EFFECT ON WATER QUALITY)	1/SITE	0.4 HA	LOW
- GROUND WATER EXPLORATION	2-4/SITE/YEAR	0.4 HA	MODERATE
- GEOTHERMAL SITE LOCATION AND SELECTION	1/SITE	0.4 HA	MODERATE
- CIVIL WORKS			
PROJECT SITE SELECTION	1/SITE	0.4 HA	LOW
CONSTRUCTION MATERIAL LOCATION	1/SITE	0.4 HA	LOW
WATER			
- WATERSHED SURFACE DRAINAGE CHARACTERISTICS	1/SITE	0.4 HA	MODERATE

TABLE 2 (Contd)
BUREAU OF RECLAMATION

<u>APPLICATION AREA</u>	<u>OBSERVATION FREQUENCY</u>	<u>IFOV</u>	<u>PRIORITY</u>
<u>WATER (CONT'D.)</u>			
- FLOOD FORECASTING AND MONITORING (IN COOPERATION WITH NOAA AND SCS)	DAILY DURING FLOOD	0.4 HA	MODERATE
- WETLANDS MAPPING (RIVER FLOOD PLAIN AND WILDLIFE HABITATS)	2-4/SITE/YEAR	0.4 HA	LOW
- FROZEN WATER HYDROLOGIC APPLICATIONS			
SNOWFIELD MAPPING FOR RUNOFF PREDICTION)	WEEKLY DURING	4 HA	MODERATE
RIVER ICE FOR ICE JAM AND FLOODING	MELT SEASON	0.2 HA	LOW
<u>AGRICULTURE/FOREST/RANGE</u>			
- CROP IDENTIFICATION AND INVENTORY	MONTHLY	0.4 HA	LOW
- SOIL TYPES AND PROPERTIES MAPPING	1/SITE	0.4 HA	LOW
- SOIL MOISTURE DETERMINATION			
WATERSHED MONITORING	2/SITE/MONTH	0.4 HA	LOW
CROP YIELD PREDICTION	WEEKLY	0.4 HA	LOW
IRRIGATION DRAINAGE INVESTIGATION AND PLANNING	4-6/SITE/YEAR	0.4 HA	MODERATE

TABLE 2 (Contd)
BUREAU OF RECLAMATION

<u>APPLICATION AREA</u>	<u>OBSERVATION FREQUENCY</u>	<u>IFOV</u>	<u>PRIORITY</u>
LAND USE AND ENVIRONMENTAL MONITORING			
- EXISTING LAND USE	1/SITE/2 YEARS	0.4 HA	LOW
- TRANSPORTATION NETWORKS	1/SITE/2 YEARS	0.4 HA	LOW
- LOCATION OF ENGINEERING MATERIALS	1/SITE	0.4 HA	MODERATE
- PROJECT PLANNING AND SITE SELECTION	1/SITE	0.4 HA	HIGH
- ENVIRONMENTAL IMPACT MONITORING AND PREDICTION	1/SITE/2 YEARS	0.4 HA	LOW
DISASTER MONITORING AND PREDICTION			
- FLOODS	DAILY DURING FLOOD	0.4 HA	LOW
- FAULT LOCATION	1/SITE	0.4 HA	HIGH
- LANDSLIDES	1/SITE/ON OCCURANCE	0.4 HA	LOW

8-12

FISH AND WILDLIFE SERVICE

The mission of F&WS is to ensure the perpetuation, use, understanding, and enjoyment by the people, of the sportfish and wildlife resources of the Nation. F&WS performs functions relating to the production and distribution of hatchery fish; the operation of a nationwide system of wildlife refuges; the regulation of migratory bird hunting; the management of fish and wildlife population by scientific research and methods, and the improvement and protection of a quality environment for fish and wildlife resources. All of these functions are conducted in cooperation with the States and private organizations. (TERSE)

TABLE 3
FISH AND WILDLIFE SERVICE

<u>APPLICATION AREA</u>	<u>OBSERVATION FREQUENCY</u>	<u>IFOV</u>	<u>PRIORITY</u>
HABITAT INVENTORY			
- VEGETATIVE COMMUNITIES	1/SITE/YEAR	VARIABLE 1m ² - 10 HA	MODERATE
- VIGOR (CARRYING CAPACITY)	SEASONAL (DAILY WHERE HABITAT STRESSED)	1 HA	HIGH
- INUNDATED AREA (MARSHES, MUDFLATS)	DAILY - MONTHLY	1 m ²	MODERATE
- SNOW/ICE COVER (MELT INTERFACE)	DAILY DURING CRITICAL TIME PERIODS	0.01 HA	HIGH

BUREAU OF LAND MANAGEMENT

The Bureau of Land Management serves as the caretaker of the Nation's public lands. BLM's mission is to classify, manage, and dispose of the public lands and their related resources according to the principles of multiple-use management. In addition, BLM is also responsible for administering the mineral resources connected with acquired lands and the submerged lands of the Outer Continental Shelf. BLM performs functions relating to the disposal of public land under the various public land resources; the leasing of rights to extract minerals, including leasing on the Outer Continental Shelf; the administration of provisions of the General Mining Law for gold, silver, and other minerals mined on public land; the leasing of grazing rights to western ranchers; the protection and enhancement of wildlife habitat; the development of areas having opportunities for outdoor recreation; and the management of watersheds on public land. (TERSSE)

TABLE 4

BUREAU OF LAND MANAGEMENT

<u>APPLICATION AREA</u>	<u>OBSERVATION FREQUENCY</u>	<u>IFOV</u>	<u>PRIORITY</u>
<u>GEOLOGIC</u>			
- GEOLOGIC MAPPING	1/SITE	0.4 HA	MODERATE
- HAZARD SURVEY	AS NEEDED	0.4 HA	LOW
- SURFACE MINING MONITORING	MONTHLY	0.4 HA	VERY HIGH
- OIL/GAS DEVELOPMENT MONITORING	SEASONAL	0.4 HA	VERY HIGH
<u>AGRICULTURE/FOREST/RANGE</u>			
- VEGETATION INVENTORY	} SEASONAL (3-5 YEAR TIME SPAN)	0.4 HA	VERY HIGH
- TREND		0.4 HA	HIGH
- VIGOR/CONDITION		MONTHLY (WEEKLY DURING GROWING SEASON)	0.4 HA
- CRITICAL AREA MONITORING	AS NEEDED	0.4 HA	MODERATE
- SOILS INVENTORY			
CHARACTERISTICS	1/SITE/5-10 YEARS	0.4 HA	HIGH
MOISTURE	WEEKLY DURING GROWING SEASON	0.4 HA	MODERATE

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BUREAU OF INDIAN AFFAIRS

The Bureau of Indian Affairs is the legal trustee for the land and water rights of Indians and Alaska Natives. BIA's mission consists of promoting the economic self sufficiency of Indians and Alaskan Natives and protecting the land and water resources of these people. BIA performs functions in areas relating to economic development, natural resource management, education, community development, and social welfare. (TER SSE)

TABLE 5

BUREAU OF INDIAN AFFAIRS.

<u>APPLICATION AREA</u>	<u>OBSERVATION FREQUENCY</u>	<u>IFOV</u>	<u>PRIORITY</u>
GEOLOGIC			
- MINERAL/PETROLEUM EXPLORATION	1/SITE	0.4 HA	HIGH
- GROUNDWATER EXPLORATION	2-4/SITE/YEAR	0.4 HA	HIGH
WATER			
- WATER VOLUME	AS NEEDED	0.4 HA	VERY HIGH
- WATER POLLUTION/WATER QUALITY		0.4 HA	HIGH
(TARGETING AREAS FOR HIGHER RESOLUTION COVERAGE)			
AGRICULTURE/FOREST/RANGE			
- VEGETATIVE FOREST AND RANGE COVER AND CONDITION	SEASONAL	0.4 HA	HIGH
- SOIL TYPES AND PROPERTIES	1/SITE/5-10 YEARS	0.4 HA	HIGH
- CROP ID, COVER AND CONDITION	2 WEEKS-ONE MONTH IN GROWING SEASON	0.4 HA	HIGH
LAND USE			
- RESOURCE MANAGEMENT	SEASONAL	0.4 HA	HIGH
- LAND USE	ANNUAL	0.4 HA	HIGH
- DISASTER MONITORING	AS NEEDED	0.4 HA	MODERATE

CHAPTER 9

SOME ROLES OF SHUTTLE RADAR[†]

SUMMARY

There are three primary roles for a Space Shuttle Imaging Radar:

- * The performance of experiments that can only be performed from a space platform and for which aircraft just will not do the job. These include experiments requiring a narrow range of incidence angles, comparisons between widely separated areas, experiments involving gradations of conditions over large areas, remote area coverage, and problems requiring synoptic coverage.
- * The testing of applications concepts and hardware techniques for future space radars. Applications over large areas such as soil moisture, sea ice, and vegetation stress are included. Hardware concepts would involve antenna studies, processing and display, and spacecraft SAR performance.
- * Support of development of future SAR's for unmanned spacecraft. Shuttle has the great advantages of flexibility, and greater capability of power, swath width, resolution and multiple test frequencies. It also will have the ability to test system parameter variations and hardware concepts, and to concentrate on areas of interest found by small-spacecraft instruments.

RECOMMENDATIONS

We have three recommendations:

- * NASA should place an imaging radar on Space Shuttle.
- * This radar should be multifrequency and multipolarization. The frequencies should be widely separated.
- * NASA should provide Shuttle digital radar computer compatible tapes to users, geometrically rectified to be compatible with LANDSAT D. These should also be at least partially theme-processed.

[†] Prepared by R.K. Moore

INTRODUCTION AND BACKGROUND

In 1964, just three months after a radar-team 3-year study was started to develop specifications for a multifrequency spacecraft imaging radar system and its associated applications and data handling system, we were asked to put together a detailed proposal for such a system for NASA. That system looked surprisingly like those now being proposed for Shuttle.

Today we have far more justification for our choice of system parameters; we know about applications and parameters we could only guess about then.

With this background you can see why the Earth Resources and Radar communities are excited that Shuttle finally seems to provide a large enough and capable enough vehicle to test and confirm radar roles of value to the user community.

Some of the roles discussed in the earlier chapters require more or less continuous coverage. Others can be accomplished in short missions. If the Shuttle radar were useable only for the short-mission applications, it might not be justified. However, its role is much more than that. Shuttle can be used to test concepts and hardware ideas that will impact all future space imagers. At the same time it can do so much more conveniently than would be possible if a completely new system had to be built for each trial or experiment.

Three primary topics are addressed in this chapter:

1. important experiments that can only be performed from a space platform,
2. tests of hardware and applications concepts for which the shuttle radar can serve as a test bed, and
3. supportive roles of the shuttle with regard to potential future space radars.

EXPERIMENTS THAT CAN ONLY BE PERFORMED FROM A SPACE PLATFORM

There are experiments that can only be performed from space platforms. They are important to various applications, but for these applications aircraft measurements are not adequate.

One of the most important characteristics of a spaceborne radar is that wide areas can be viewed with almost the same angle of incidence. Examples for which we have good evidence that such a view is important include monitoring soil moisture, where angles near vertical are needed, geologic mapping in mountainous areas where shadowing is too great near grazing and overlay occurs near vertical, and monitoring the maturation of wheat, where angles between 50° and 70° from vertical are required. These examples are shown in Figure 9.1, and Table 9.1.

In monitoring soil moisture from aircraft even at 20 km altitude one can only obtain a 5.6 km swath. This may be adequate for experiments, but it is certainly inadequate even to test the wide-area applicability of the concept, much less to monitor soil moisture operationally. In some geologic applications, particularly in mountainous regions, only a 5° range of angles of incidence is really satisfactory: commercial aircraft radars have to use numerous passes for adequate coverage, yet a 200 km spacecraft can cover over 65 km swath in this range of angles, and a 1000 km spacecraft can cover about 250 km. The aircraft does somewhat better for the wheat-maturation problem, but for coverage of the vast areas of the wheat belts in this country and the Soviet Union the much wider swaths possible from spacecraft are the key to both the monitoring and the testing of the ability to monitor. In principle, one could cover almost 800 km swath to one side of a spacecraft in this angular range, but ambiguity considerations in synthetic-aperture design will probably limit the coverage somewhat.

Another application where the spacecraft can provide much better tests and operation than aircraft is performing comparisons between widely separated areas. The aircraft would have to do this on multiple days. It would be difficult to maintain calibration from flight to flight of a quality sufficient to determine small differences. Since the space radar can obtain its coverage

USE OF SHUTTLE RADAR WILL ALLOW APPLICATIONS EXPERIMENTS REQUIRING NARROW ANGULAR RANGES NOT FEASIBLE FROM AIRCRAFT ALTITUDES

← S F R →

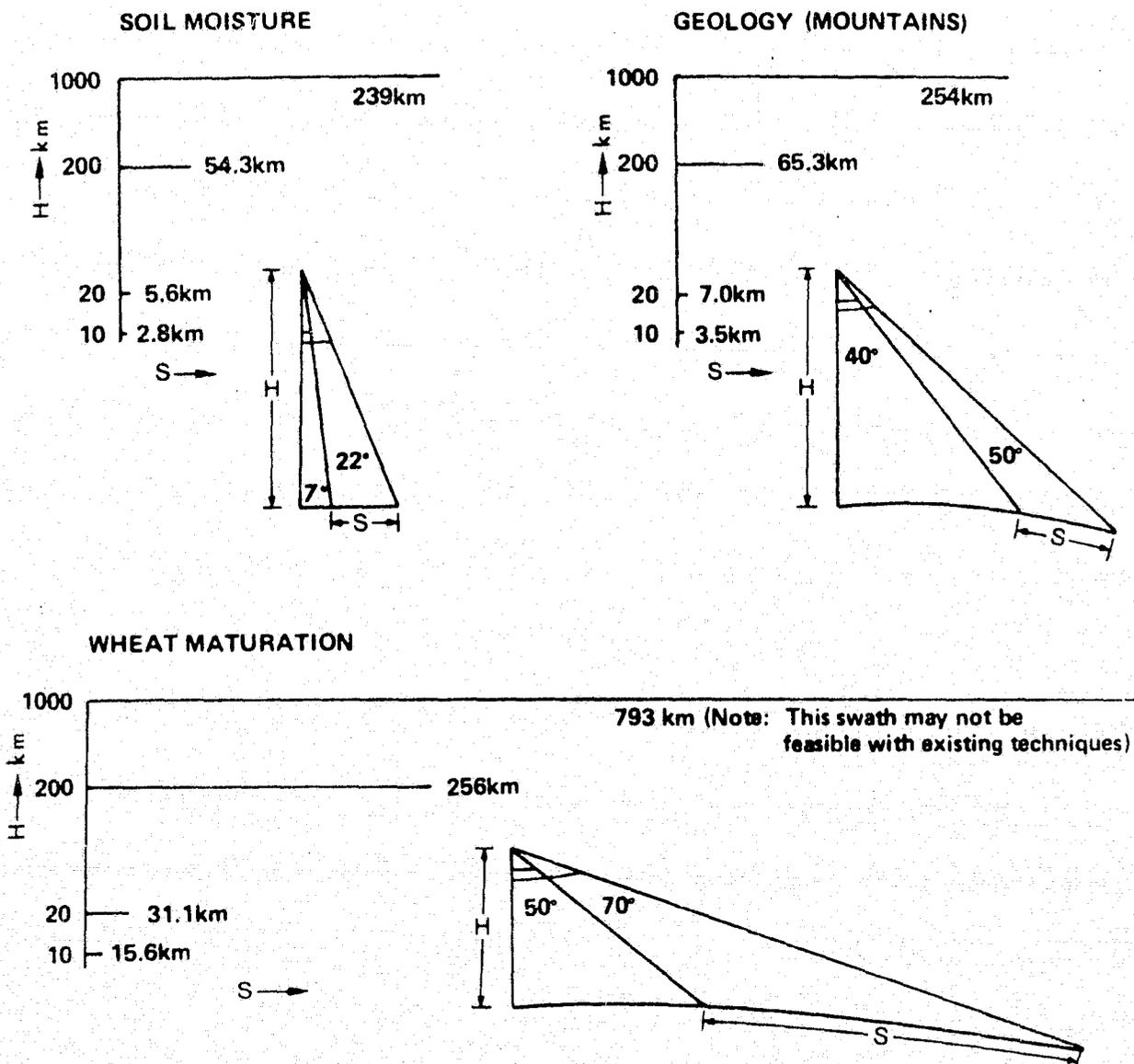


Figure 9.1

TABLE 9.1

APPLICATIONS EXPERIMENTS WITH SHUTTLE RADAR FOR WHICH AIRCRAFT RADARS DO NOT SUFFICE

— SPIR —————→

- **NARROW RANGES OF INCIDENCE ANGLE**
 - EXAMPLES:
 - + SOIL MOISTURE
 - + GEOLOGY IN MOUNTAINOUS AREAS
 - + WHEAT MATURATION MONITORING
- **COMPARISONS BETWEEN DIFFERENT AREAS —**
 - STABILITY OF CALIBRATION OF SPACE RADAR FOR SHORT FLIGHT TIME MUCH BETTER THAN MULTIPLE AIRCRAFT FLIGHTS
- **GRADATIONS OF CONDITIONS OVER LARGE AREAS**
 - + SOIL MOISTURE
 - + PLANT STRESS
 - + VEGETATION DENSITY
 - + SNOW AND ICE
 - + OCEAN WINDS AND WAVES
- **REMOTE AREA COVERAGE**
 - + TROPICS
 - + OCEANS
 - + POLAR REGIONS
 - + OVERSEAS DISASTER AREAS
- **SYNOPTIC COVERAGE**
 - + SOIL MOISTURE
 - + AREA OF STANDING WATER (PONDS, LAKES, RIVERS)
 - + OCEANS
 - + SNOW
 - + ICE (SEA AND LAKE)

in a matter of minutes or hours and in many cases this is much less of a problem with space than with aircraft radars. Also, since the space radar remains in a constant environment it is less susceptible to calibration changes in any case.

Many quantities which are important to monitor change gradually over a large area, yet these gradual changes are important. The spacecraft is a natural vehicle for such measurements. Of course, local variations would be easy to monitor from aircraft but the gradation in moisture content across, for example, an area of the size of the Great Plains, calls for the rapid coverage and constant calibration of a space system.

The use of a spacecraft is especially important in remote areas where aircraft missions are difficult to mount: tropical areas, the oceans, and polar regions. Even localized disasters in many overseas areas would be hard to reach with an aircraft radar in time for meaningful monitoring.

The spacecraft radar, then, because of its great speed and wide-area coverage, is important for any application where synoptic coverage is essential. There are many applications described in the earlier chapters for which it is not enough to know the conditions in one place one week and in another a week or so hence! Examples may be found in crop and plant stress monitoring, surface snow cover, soil moisture and related areas.

TESTS OF APPLICATIONS CONCEPTS AND HARDWARE TECHNIQUES FOR FUTURE SPACE RADAR

A Shuttle synthetic-aperture radar can be extremely valuable as a test bed, both in its original configuration, and with modifications that can be made for future flights. The latter would use most of the equipment with only parts replaced by new experimental equipment. Of course one of the most important applications is to test applications concepts. These tests will be important in determining appropriate parameters for the design of simpler systems to be carried on future manned or unmanned long-duration missions.

Desirable studies with the Shuttle radar would include analyses of:

- * resolution requirements
- * effect of the multiple frequencies available
- * effect of the multiple polarizations available
- * synoptic study of regional variations
- * small-angular-range studies
- * remote-area studies
- * value of stereo techniques from multiple depression angles

Each of these areas is briefly considered below.

The Shuttle system should have better resolution than that needed for many specific-mission radars. Use of modest-resolution systems on smaller spacecraft will represent significant savings in size and power. Recent studies at the University of Kansas have related interpretability to effective resolution via regressions for different targets. The methodology used can be applied to determine the critical resolution needed for any application if the Shuttle system has a better resolution than that required for the other mission.

Another advantage of a Shuttle multi-frequency system is that multiple frequencies are easier to put on a big spacecraft. They can be used for each application to determine whether one of the Shuttle radar frequencies is adequate for a particular application or whether multiple frequencies will be needed.

Although multiple polarizations are easier to put in small radars than multiple frequencies, the Shuttle radar can demonstrate whether the additional expense will be justified.

The synopticity of the Shuttle space radar can be used to verify the many applications where we expect it will be needed, and also to show if it really is as important as anticipated in each case.

The Shuttle radar will permit performing the small-angular range experiments discussed earlier. If, as expected, these concepts prove valuable, the results will go into design of specialized or flexible future systems.

The studies in remote areas are self-explanatory and are indeed one of the central advantages of any space system.

Finally, the value of stereoscopy, obtained with a range of depression angles for a variety of situations, could be explored more fully with a Shuttle imager than with aircraft radar.

Some examples of applications where Shuttle could provide a useful test but for which longer missions would be needed for operations are as follows:

- * soil moisture--broad swath at correct angles
- * sea and lake ice--better frequency and incidence angle than SEASAT
- * icebergs and ships--better incidence angle than SEASAT
- * small-angular-range images for geology
- * crop inventory
- * vegetation stress over large areas
- * forest monitoring/mapping over small angular range

The soil moisture experiment described earlier is clearly an application where the combination of narrow range of acceptable viewing angles and synoptic coverage needed make a space platform essential for an effective experiment. At the same time it is clear that Shuttle would not constitute a satisfactory base for long-term operations.

We also anticipate that while SEASAT will be able to test snow and ice monitoring to some degree, both its frequency and angle of incidence--which were chosen primarily for ocean wave monitoring--may not be optimal for these applications. Shuttle would be able, over a wide range of conditions, to explore this area and define the appropriate specifications for a snow and ice monitoring system. The same applies to monitoring both icebergs and shipping or fishing

fleets.

Flexibility of pointing angle would be important for geologic imaging in mountainous areas. This flexibility will not be present in SEASAT, and the swaths obtainable from aircraft are inadequate--as seen earlier--for large area coverage. While longer-term missions will be desirable for some geologic applications Shuttle may well, by itself, provide a substantial body of geologic data, thus siphoning off some of the benefits of an operational system for geology.

The other applications--on crop inventory, vegetation stress over large areas and forest monitoring over a small angular range--are clearly areas where operational satellites will ultimately be desired. Shuttle experiments can play a significant role in establishing the parameters for these satellites.

A most important test-bed use of the Shuttle imaging radar is in evaluating new hardware concepts. Some of these (shown in Table 9.2) involve antennas, both the means of erecting them and some different ideas requiring different antennas. Other concepts involve new and more effective ways to process synthetic-aperture signals into pictures and telemeter them to the ground. We really need to know what kinds of constraints to place on spacecraft that must carry synthetic-aperture radars, and Shuttle will give us a chance to test them. Certain special ideas can be tried. All of these tests can be made without major changes to the system. Another class, that should be reserved for missions far down the road, involves major changes to the system itself--but not total replacement.

Examples of techniques involving antenna erection and modification are:

- * test capability for men to erect large SAR antennas in space
- * test techniques for automatic erection of large SAR antennas in space
- * test ability to achieve antenna elevation pointing mechanically
- * test electronic antenna elevation pointing and scanning
- * test use of squinted antennas to achieve single-pass orthogonal looks

TABLE 9.2

THE VALUE OF A SHUTTLE SAR AS A TEST BED

—SPIR—→

- APPLICATIONS USING FIRST-GENERATION SHUTTLE SAR
 - TESTING APPLICATIONS CONCEPTS FOR FUTURE SPACE SAR ON MANNED OR UNMANNED PLATFORMS
 - HARDWARE CONCEPT EVALUATION
 - + TECHNIQUES INVOLVING ANTENNA ERECTION AND MODIFICATION
 - + TECHNIQUES FOR PROCESSING AND DISPLAY
 - + EVALUATION OF SPACECRAFT SAR REQUIREMENTS
 - + SPECIAL TECHNIQUES
- APPLICATIONS REQUIRING SIGNIFICANT MODIFICATIONS TO FIRST-GENERATION SYSTEM

The first four of these are self-explanatory. The fifth may be very important, for many applications requiring viewing for orthogonal directions.

Numerous techniques have been developed for processing synthetic-aperture signals digitally to make images. Performance can be simulated, but the real test can only come by trying them on the Shuttle on different (or even the same) missions.

Shuttle testing of techniques to reduce telemetry requirements for future manned or unmanned space radars could include evaluation of 1) different digital on-board correlation methods, 2) different electronic analog on-board correlation methods, 3) on-board optical correlation (some advantages may accrue from this traditional technique), 4) different techniques for radar telemetry band-width compression without loss of significant image information techniques for future manned operational missions (a major problem with such a high data rate system is telemetry band-width), 5) various methods and use of on-board display, and, finally 6) zoom techniques for achieving different spatial resolutions.

Although we have calculated the stability requirements for the spacecraft carrying a synthetic aperture radar, experiments to find whether these calculations are too conservative would be most helpful. Some applications call for great geometric precision, and the ability to achieve it and its impact on the vehicle can be evaluated. The Shuttle will provide a unique test bed to examine not only spacecraft stability, but also the electronic stability needs of synthetic aperture imagers, their dynamic range and sensitivity requirements, and various calibration techniques.

Various special techniques could also be evaluated including:

- 1) superimposition of radar and visible/infrared imaging
- 2) joint scanner/radar stereo
- 3) determining the potential uses of real aperture spacecraft radar

All of the previous tests can be performed without significant changes in the first-generation Shuttle radar system. There are also applications requiring significant modifications to the first-generation system, but which promise real payoff. One of these is the use of more frequencies to identify the best frequency or frequencies for specific uses, which could get its real test on Shuttle, though ground measurements could point the way. A second is testing of the distributed radar concept to improve efficiency, reliability, and performance and to provide redundancy, and permit lower-power transmitter components. A third would be to use very wide bandwidths in a "panchromatic" radar to achieve both finer resolution and improved image quality. Clearly, these modifications are a long way down the turnpike! A first-generation imager has yet to be approved for Shuttle!

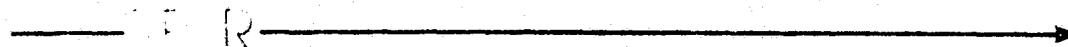
ROLES FOR SHUTTLE SAR IN SUPPORT OF SARS FOR UNMANNED SPACECRAFT

In addition to these applications and hardware tests there are further roles for Shuttle in support of SAR's for unmanned spacecraft. Many of these have already been mentioned in earlier chapters. They are summarized here and in Table 9.3.

The greatest advantage for a radar on a Shuttle is its flexibility and its capability to use large amounts of power, achieve wide swath and fine resolution, and to use a variety of frequencies. Because of these advantages, it can be used to test our ability to take a wide variety of needed measurements, whereas a special mission radar such as that for SEASAT cannot do this nearly as well because its design is aimed at one application. The Shuttle's size and reusability will allow many more variations of system parameters than would be feasible on small spacecraft without having many different craft. The various hardware concepts suggested can be tested easily on the reusable system because only one subsystem need be changed at a time, and this is important

TABLE 9.3

THE ROLE OF A SHUTTLE SAR IN SUPPORT OF SARS FOR UNMANNED SPACECRAFT



- **GREAT ADVANTAGES OF SHUTTLE**
 - + **FLEXIBILITY**
 - + **GREATER POTENTIAL CAPABILITY**
 - **POWER**
 - **SWATH**
 - **RESOLUTION**
 - **MULTIPLE FREQUENCIES**

- **SHUTTLE SAR CAN TEST**
 - + **ABILITY TO MAKE MEASUREMENTS OF DIFFERENT TYPES OF AREA - NOT COMMITTED TO SPECIFIC APPLICATION**
 - + **SYSTEM PARAMETER VARIATIONS (FREQUENCY, INCIDENCE ANGLE, RESOLUTION, POLARIZATION) - DESIGN NOT AS CONSTRAINED AS ON SMALL SPACECRAFT**
 - + **HARDWARE CONCEPTS IN ANTENNAS, PROCESSING, STEREO, TELEMETRY - SINCE ONLY COMPONENT TESTED NEED CHANGE FROM FLIGHT TO FLIGHT**

- **SHUTTLE SAR CAN CONCENTRATE BETTER CAPABILITY ON AREAS OF INTEREST FOUND BY SMALL SPACECRAFT INSTRUMENTS**

for antenna-related items, processing techniques, stereo, telemetry, and so on.

Another application of Shuttle, a long-term one, is that it can concentrate its more capable systems on areas of interest found by smaller, more-specialized system. At the moment we don't know what these applications are, but we can be sure they will turn up.

In conclusion, I believe that the material presented in this and the earlier chapters has shown that many needs of numerous governmental and non-governmental agencies can be met with a spacecraft imaging radar--many of them only with such a system. Placing a radar on Shuttle will permit some of these needs to be met directly, but the Shuttle radar's primary role would be to provide tests for other applications that ultimately will require their own continuously-orbiting spacecraft with specialized radars. In addition, the flexible Shuttle system will permit us to try many innovations that would take much longer to develop if each had to be tested on a special spacecraft.

We are pleased that our proposals of 1964 still seem, with minor modifications, feasible and desirable in 1976. Those of us who have worked over the years to learn the value of the many applications, and the choice of parameters we guessed at in 1964, are delighted at the possibility that Shuttle will allow us to make this 12-year dream come true.