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FINAL TECHNICAL REPORT

FREQUENCY REQUIREMENTS FOR ACTIVE EARTH OBSERVATION SENSORS

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1. Introduction

In the areas of earth resources, meteorology, and oceanography, a new research tool involving active microwave sensing is evolving. An active microwave sensor is a radiolocation device; that is, a radar. The device may be an imager (scanning pencil-beam or synthetic aperture), a scatterometer or altimeter. The need for synoptic worldwide measurements dictates use of spaceborne platforms for the active sensor devices; however, there are few specific international agreements regarding spectrum use by spaceborne radars. Hence, there is an immediate need to address future remote sensing spectrum allocation requirements, particularly in light of the 1979 General World Administrative Radio Conference (WARC-79) of the International Telecommunication Union (ITU). The urgency is due to the scope and complexity of the national and international coordination that must be achieved prior to the WARC. The results of the actions taken at WARC-79 will, for all practical purposes, stand until the year 2000.

The ITU has the responsibility for developing internationally agreed upon spectrum sharing criteria. The International Radio Consultative Committee (CCIR) supports the ITU by providing the technical rationale for the sharing criteria. One form of space/terrestrial sharing criteria developed by the CCIR, for communications systems, has been power flux density limitations at the surface of the earth from satellite-borne transmitters. A second is power flux density limitations at geostationary orbit altitude.

The latest set of power flux density requirements for these purposes developed by the CCIR are shown in Table 1. These limits were proposed by the Special Joint Meeting of the CCIR in February, 1971 and adopted by the 1971 World Administrative Radio Conference (Space). The United States Interdepartment Radio Advisory Committee (IRAC) approved these limits with only one modification, the lower limit of the lowest frequency band being reduced to 1.0 GHz. However, these power flux density limits were based primarily upon considerations of the needs and requirements of terrestrial and geostationary communication systems. No power flux density limits or sharing criteria exist for active spaceborne sensors.

A recent report, "Sharing Analysis Between Active Spaceborne Microwave Sensors and Radiolocation Systems" (Nicholas, 1977) has addressed the problem of sharing. This report concluded that sharing between spaceborne radars and terrestrial radars was no more difficult than sharing between terrestrial radars or sharing between terrestrial and airborne radars.

TABLE 1

POWER FLUX DENSITY LIMITS PRODUCED AT THE SURFACE OF THE EARTH BY SATELLITE SYSTEMS

BAND (GHz)	PFD LIMIT ($dBW/m^2/4$ kHz)	ANGLE OF ARRIVAL (ELEVATION)
1.7 to 2.3	-154	$0° < \theta < 5°$
	$-154+(\theta-5)/2$	$5° \leq \theta \leq 25°$
	-144	$25° < \theta \leq 90°$
3.0 to 8.0	-152	$0° < \theta < 5°$
	$-152+(\theta-5)/2$	$5° \leq \theta \leq 25°$
	-142	$25° < \theta \leq 90°$
8.0 to 11.7	-150	$0° < \theta < 5°$
	$-150+(\theta-5)/2$	$5° \leq \theta \leq 25°$
	-140	$25° < \theta \leq 90°$
12.5 to 12.75	-148	$0° < \theta < 5°$
	$-148+(\theta-5)/2$	$5° \leq \theta \leq 25°$
	-138	$25° < \theta \leq 90°$
	($dBW/m^2/1$ MHz)	
15.4 to 23.0	-115	$0° < \theta < 5°$
	$-115+(\theta-5)/2$	$5° \leq \theta \leq 25°$
	-105	$25° < \theta \leq 90°$

POWER FLUX DENSITY LIMITS PRODUCED AT GEOSTATIONARY ORBIT ALTITUDES

8.025-8.400	-174 $dBW/m^2/4$ kHz

Thus, it is the purpose of this report to present the foundation and rationale for the selection of microwave frequencies for active remote sensing usage for subsequent use in determination of sharing criteria and allocation strategies for the WARC-79.

2. Background on Microwave Remote Sensing

The successful missions of the experimental earth resources satellites, LANDSAT 1 and 2, have proven convincingly that earth exploration by satellite-borne remote sensing systems offers significant advantages. The scanning instruments on-board these satellites, operating in the visible and infrared portions of the frequency spectrum, have provided important data from which literally thousands of images of the Earth have been constructed. However, based on the knowledge gained from these LANDSAT missions, it is evident that the visible and infrared remote sensing devices cannot provide all the data needed for globally measuring and monitoring the Earth's atmosphere and surface. A variety of sensors, operating over a wide range of frequencies, will be required to achieve the full potential of spaceborne remote sensing techniques.

In analyzing the results and capabilities afforded by the visible and infrared sensors on LANDSAT, it has been shown that:

- An all weather, day or night remote sensing capability would significantly improve orbital monitoring of terrain and ocean surface.

- The unique and/or supplementary information obtainable in the longer wavelength regions of the electromagnetic spectrum would substantially increase the value of remote sensing measurements for Earth, ocean and atmospheric applications.

Microwave sensors would meet these needs.

Studies have shown that microwave systems offer unique capabilities, in addition to the capabilities which will complement the visible/infrared systems. These unique capabilities include the ability to penetrate vegetation and near-surface material, sensitivity to moisture in vegetation, soil, and snow, and the ability to operate day or night and in near all-weather conditions, including through cloud cover. Studies are also being conducted to explore the effects of surface roughness, soil type, vertical distribution of soil moisture, and vegetation cover on the relationship between microwave observations and soil moisture. Extensive agricultural field measurements have been conducted to measure the response of vegetation to the incident radar signal, as a function of various instrument parameters, and soil and vegetation conditions. Investigations have been conducted into remote sensing of ocean surface winds and waves for prediction of world-wide weather and world ocean monitoring. Similar studies have also been carried on with promising results in the areas of geology and water resources. Aircraft imaging radars and scatterometers, truck based radar spectrometers, and the Skylab scatterometer are examples of instrumentation used in these studies. Data reduction, analysis and display techniques, as well as theoretical models, have been developed to support experiments.

The National Aeronautics and Space Administration, as well as other agencies, universities and private industry, have been pursuing the types of studies mentioned above, and NASA has for the past several years been actively developing a number of microwave instruments which will further expand the technology and application potential of the devices.

In 1974, NASA conducted an Active Microwave Workshop in Houston to focus all elements of the active microwave remote sensing field, and to emphasize and document the applications of this technology. The results of the Workshop are contained in the final report, NASA Document SP-376, 1975. Subsequent activities of NASA and other interested parties are described in the Active Microwave Applications Task Force Report of July 1976 and the Active Microwave Workshop Report dated August 1976.

2.1 NASA's Microwave Program

As a result of microwave measurement studies and the findings of various Active Microwave Working Groups and task forces, NASA initiated a Microwave Program in the Office of Applications, which has overall responsibility for coordinating microwave applications and technology development activities in the Earth resources, oceanography, and weather and climate discipline areas. The fundamental objective of this program is to determine the measurement potential of active and passive microwave sensors for use in future earth exploration missions.

The specific known discipline areas in which microwave techniques can be used for earth exploration are:

- Earth Resources Applications
  - Water Resources
  - Vegetation Resources
  - Geologic Applications
  - Terrain Mapping
- Oceanographic Applications
  - Wave Properties
  - Geoid, Ocean Currents
  - Fisheries
  - Coastal Processes
  - Shipping and Resources Extraction
- Weather and Climate Applications
  - Atmospheric Parameters
  - Ocean Parameters
  - Polar Ice Parameters
- Environmental Quality Applications
  - Atmospheric Pollutants
  - Water Pollutants (oil spills)

The Microwave Program concentrates on development of the capability and use of spaceborne microwave observations for:

- Monitoring and forecasting global crop production and domestic rangeland conditions;
- Improving the techniques for water management;
- Improving the techniques for forest management;
- Providing specialized information on geological structure and geophysical characteristics for mineral and energy resources exploration;
- Providing baseline information and monitor changes in land utilization, and for improving coastal zone management;
- Detecting and monitoring air and water quality;
- Detecting, monitoring and predicting severe storms;
- Monitoring ocean dynamics;
- Developing techniques for acquiring relevant measurement data for climate studies;
- Developing techniques for observing and studying sea ice and ice sheet parameters;
- Improving techniques for terrain mapping.

2.2 Microwave Sensor Development Activities

This section describes the major microwave sensor developments being considered by NASA.*

The capability of microwave sensors to obtain information of direct value to specific applications must be demonstrated as early as possible, if the user community is to obtain the type of data desired in this century. To demonstrate this capability, basic experimentation, model development and flight experiments must be performed, and supportive technology activities and appropriate interpretative techniques studies are needed.

During the course of this study, research was undertaken to identify those activites currently planned by the NASA in its Microwave Program during the next several years. Basically, the approach involves a multi-faceted approach including ground based analyses, aircraft instrument modifications, test flights, applications studies in disciplines using both ground based and aircraft tests, technology development activities and a number of orbital sensor study and development activities.

The significant applications studies currently being considered, in long range plans, utilizing both passive and active sensors, are summarized in Table 2, which lists the application and the planned activity.

*The information herein regarding NASA programs is a result of extensive research into available documentation, some of which is preliminary in nature, and verification, where possible, with NASA and other personnel. However, the report in no way should be construed as official NASA information.

TABLE 2

PLANNED APPLICATIONS STUDIES

Applications	Planned Activities
Water Resources	Develop microwave remote sensing techniques for determining soil wetness and estimating watershed run-off.
Soil Wetness	Demonstrate that microwave data are more effective than conventional data or other remote sensing data in specifying initial conditions and updating values of soil wetness for upper zone storage parameters in river forecasting procedures.
Hydrologic Response/Runoff Coefficient	Demonstrate the use of microwave data to quantify the run-off potential or coefficient for watersheds of varying surface cover and soil characteristics given specific levels of soil wetness and precipitation input.
Snowpack Properties	Demonstrate that microwave data are responsive to temporal and spatial variations in snowpack properties, including moisture equivalent, wetness, depth and areal extent.
Surface Water and Ice	Demonstrate the capability of microwave sensors to obtain timely, accurate measurements of surface water, floods, and fresh water ice characteristics.

TABLE 2 (cont.)

PLANNED APPLICATIONS STUDIES

Applications	Planned Activities
Vegetation Resources	1. Develop microwave remote sensing techniques for determining soil moisture content as input to crop yield prediction models.
	2. Develop microwave remote sensing techniques to provide all-weather, day or night identification of natural and cultivated vegetation species and plant moisture.
	3. Develop microwave remote sensing techniques for forest community identification and inventorying.
	4. Develop microwave remote sensing techniques for early identification and mapping of saline seeps.
Geologic Applications	1. Demonstrate the capability of microwave sensor data to provide improved definition of lineaments and other geologic features not subject to short-term change.
	2. Demonstrate the capability of microwave sensor data to monitor natural and man-induced physical or chemical terrain alterations.
	3. Develop a microwave remote sensing technique to identify surface materials.
Oceanographic Applications	1. Demonstrate the capability of microwave sensors to measure the topography of the oceans, including the geoid, currents, and surges.
	2. Demonstrate the capability of microwave sensors to measure the surface temperature of the oceans; to map salinity distributions; and to identify high sea state conditions.

TABLE 2 (cont.)

PLANNED APPLICATIONS STUDIES

Applications	Planned Activities
Oceanographic Applications (cont.)	3. Demonstrate the capability of microwave sensors to measure surface wind velocity and direction over the oceans.
	4. Demonstrate the capability of microwave sensors to record sea ice dynamics and identify icebergs.
	5. Develop microwave remote sensing techniques to measure ocean wave spectra.
Weather and Climate Applications	1. Develop microwave remote sensing techniques for determining pollution concentrations in the upper atmosphere.
	2. Develop microwave remote sensing techniques for determining precipitation intensity on a global scale.
	3. Develop microwave remote sensing techniques to aid in identifying and tracking severe storms.
	4. Develop microwave remote sensing techniques for measuring surface pressure.
	5. Develop a coordinated effort to incorporate Seasat measurements into the Weather and Climate Program.
Technology Development	1. Maintain, upgrade, and expand the ground-based microwave sensing capability required to support the experiments program.
	2. Maintain and upgrade the airborne radar scatterometer and microwave radiometer capability.
	3. Improve the airborne imaging radar sensor capability to provide calibrated, digital, multiparameter measurements.

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Refer to: 652-CST:sc

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Attention: Acquisitions Branch:

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Enclosed for your systems input and listing in the unlimited unclassified category of STAR, are two copies of the following subcontractor reports:

953984	The Boeing Company - June 1977.
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954328	Battelle - Final Report, February 1, 1977.
954339	Battelle - Seventh Quarterly Report, July 20, 1977.
954344	University of South Carolina - Sixth Quarterly Report, June 27, 1977.
954356	Honeywell Corporation - Sixth Quarterly Report, June 30, 1977.
954373	Crystal Systems Seventh Quarterly Progress Report, July 1, 1977.
954374	Varian Associates - Fifth Quarterly Report, July 7, 1977.
954376	Motorola Incorporated - Fifth Quarterly Technical Report, June 1977.
954393	General Electric - Assessment Report, July 8, 1977.
954405	Texas Instruments - Annual Report, March, 1977.
954458	Rockwell International - Fifth Quarterly Progress Report, July 1, 1977.

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954521	Simulation Physics - Fourth Quarterly Progress Report, May, 1977.
954588	Motorola Incorporated - Final Report, April, 1977.
954600	Spectrolab Incorporated - Tenth Monthly Report, July 15, 1977.
954654	Westinghouse - First Quarterly Report.
954669	Systematic General Corp. - Final Technical Report, May, 1977.

Very truly yours,

George G. Mitchka

for Joseph A. Wynecoop, Manager
Information Support Section
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cc: J. J. Waldo, Acquisitions Branch

- The orbital-sensor activities under consideration are summarized in Table 3. The planning process for orbital microwave sensors is apparently being directed toward the use of the Shuttle/Spacelab in the 1980's, following the SEASAT-A free-flyer flight which will carry the Synthetic Aperture Radar. The Spaceborne Imaging Radar (SIR) listed in Table 3 will likely be the primary component in a comprehensive microwave sensor development program in the next few years. The SIR development will:

- Provide the capability to acquire all-weather orbital image data of sufficient information content to supplement Landsat for agricultural, geologic, and water resources applications.

- Permit acquisition of orbital active microwave images (from the Shuttle) of geologic structures, land use, and similar temporally insensitive terrain features, especially in cloud dense regions of the globe, to augment and improve the success of mineral and petroleum exploration, and terrain mapping projects.

- To employ the Shuttle as a test bed for development of the application and engineering parameters for future free-flyer active microwave all-weather imaging sensors.

TABLE 3

PLANNED ORBITAL SENSOR ACTIVITIES

Sensor System	Planned Activity
Seasat/Nimbus-G	Evaluate the engineering performance of the Seasat-A sensors and Nimbus-G. Compare the actual performance to the expected performance and identify the design concepts subject to reevaluation.
Spacelab Orbital Flight Test (OFT-2) Synthetic Aperture Radar	Construct the OFT-2 SAR, integrate onto the Shuttle, conduct the designated geology mission, and evaluate the engineering performance and data quality.
Orbital SAR Data Acquisition Plan	Formulate a development and implementation plan to acquire multiparameter orbital SAR data supportive of the applications development effort.
Spaceborne SAR Feasibility	Conduct studies to establish the feasibility of an advanced, calibrated, multiparameter SAR system for Shuttle operation. Primary emphasis will be given to the high frequency antenna structure, especially the required dimensional tolerances and thermal stability.
Advanced SAR Systems	Conduct studies of advanced SAR system design concepts suitable for operation on free-flying satellites in the period beyond 1985.

TABLE 3 (cont.)

PLANNED ORBITAL SENSOR ACTIVITIES

Sensor System	Planned Activity
Spaceborne Imaging Radar Development (SIR B&C)	Construct a system to provide orbital multiparameter SAR images from Shuttle. The system shall have as a minimum, dual-wavelengths, dual-polarization, multiple incident angle capability. It shall be calibrated and employ electronic processing. The JSC Spaceborne Imaging Radar concept shall be used as the baseline design. The goal is to acquire the full system capability for operation on the Shuttle. SIR-B will provide 9 cm and 3 cm image data beginning in the first quarter of 1982. SIR-C will provide dual-wavelength, dual-polarization image data in late-1984.
Multifunction Short Pulse Radar	Develop and fly a multifunction short pulse radar on Spacelab for wind, wave spectra, sea state, and altimetry experiment. If successful, design, and develop a free-flyer system for future Seasats.
Meteorlogical Radar	Define and develop a Shuttle-based multibeam radar capability for three dimensional precipitation mapping and two dimensional 2 km ground resolution scatterometer images for soil moisture, ice, sea state, etc., experiments.
Active Pressure Sensor	Design and develop an active surface pressure sensor. For a monostatic system, the Spacelab will be used to demonstrate the capabilities of the sensor while for a bistatic system, the Spacelab may be used to deploy a small, low-cost free-flyer to operate either in conjunction with the Spacelab or possibly with a second free-flyer of opportunity.

The Shuttle/Spacelab is expected to be one of the primary carriers of spaceborne microwave sensors in the 1980's and therefore it offers a new capability in earth exploration. Not only will the Shuttle/Spacelab permit access to space for laboratory-type experimentation and testing, but it offers unique advantages over conventional flights, which are as follows:

- The size of the payload allows flight of large instruments such as radars or multiple instruments.
- The return of the instrument permits retrieval of film and other samples to be examined after the flight.
- Instruments may be modified and flown again.
- Instruments may be flown in an early stage of development before they are ready for extended periods of free flight.
- Astronaut/specialists can control the investigations, identify targets, and apply immediate judgements to alter the operational mode.
- Experimental hardware (antennas, booms, etc.) can be constructed or altered manually. Orbits can be adjusted to view specific ground sights.

The Shuttle/Spacelab will be a new tool for spaceborne experimentation with active microwave systems. It is an ideal platform with adequate power, volume, and weight for active microwave systems and it is expected that in the future the Shuttle/Spacelab will be used extensively for spaceborne active microwave applications studies.

3. Discussion of Study Findings

The purpose of this study was to identify the foundation, rationale and scientific justification for the selection of microwave frequencies for active remote sensing. In order to gather this information, an intensive literative search was accomplished. Over 150 scientific documents were identified which have contributed significantly to the formulation of active sensor frequency needs. In addition to the literative search, appropriate members of the scientific and engineering community were contacted regarding technological and scientific considerations.

The findings disclosed that an important advantage of microwave devices is their capability to observe Earth phenomena in the presence of clouds and darkness. This advantage enables the acquisition of data in specified or compressed time frames. Furthermore, certain applications are critically dependent on the availability of imagery within a limited time frame. In frequency bands below 5 GHz, atmospheric absorption and scattering cause minimum errors, and light and moderate rainfalls can be penetrated. Therefore, microwave sensors provide nearly all-weather remote sensing capability at such frequencies.

The findings also disclosed that active microwave sensors have two other primary advantages over passive microwave sensors, namely: 1) high spacial resolution capability (Synthetic Aperture Radar), and 2) altitude resolution capability. In addition, in certain measurement areas, active devices have unique contributions to make to the measurement, although active microwave devices, unlike passive microwave sensors, have not demonstrated the ability to measure atmospheric constituents.

In future operational systems where measurements could be accomplished by either active or passive microwave sensor, the choice between utilizing passive or active techniques will be determined by operational requirements such as resolution and associated system costs. Active sensor systems, particularly synthetic aperture radars, are currently more costly than passive radiometers. Only when active sensors provide unique advantages would their cost likely justify operational implementation. This cost/performance balance would change if bandwidth restrictions on passive allocations force the use of costly multi-beam, multi-receiver radiometers. The overall trend, though, is far from clear, since both active and microwave sensing programs and technology are still evolving.

The following paragraphs describe each measurement phenomenon identified in the literative search, as well as the associated frequency requirements. Also, any unique advantages of active sensing, other than increased resolution, are presented. Although specific frequency bands will be cited as optimal, based on the measurement alone, it must be recognized that the response range is rather broad. Due to the broad frequency response range of all phenomena, there is a great need for simultaneous measurements at various frequencies so that each phenomenon may be separated from the others. For example, the generally optimal region for soil moisture measurements is the 4 GHz region, yet vegetation effects must be considered when producing soil moisture maps. Therefore, measurement of vegetation must be simultaneously made at 14-18 GHz which has been shown to be the generally optimal region for vegetation measurements.

The overall frequency requirement findings, as elaborated on in the following discussions, indicate that 5 to 6 frequency bands octavely related, are required over the 1-18 GHz region. Also, a band in both the 35-40 and 50-55 GHz regions could possibly be utilized by spaceborne active sensors.

The following measurements are those that have been identified during the study. Those measurements for which a reasonable amount of research has been conducted are given further elaboration in Appendices A-F.

- Soil Moisture (Appendix A) - The study of the distribution and amount of soil moisture is primarily important for agriculture and hydrology applications. For agriculture, soil moisture measurements can help determine yield and optimal times for irrigation. For the hydrologist, soil moisture measurements are an integral part in determining watershed run-off.

Run-off predictions are used in reservoir management of water for hydroelectric power, flood control, irrigation, recreation and consumption.

The general optimum frequency region was found to be around 4.7 GHz, operating at a 5-17° incidence angle (off spacecraft nadir). However, a lower frequency, such as ~1 GHz, could possibly be used for measurements through vegetation and at deeper soil depths.

- Vegetation Measurements (Appendix B) - The monitoring of vegetation type and conditions are important primarily for agriculture and forestry. Also, vegetation information can be utilized in ecological and land use planning. The knowledge of vegetation types and conditions, along with other environmental variables, could be utilized for improving crop forecasting on a worldwide scale. Such information has enormous impact on domestic pricing, A.I.D. programs, foreign policy, and balance of trade. Of less dramatic impact, but still important to domestic planning, is the potential for improved forest and grazing land usage.

  Vegetation measurements, based on crop discrimination, were found to be best conducted at moderate-to-high incidence angles, using a multi-frequency, multi-polarization and multi-temporal radar system. If only a single frequency were available, then the 14-18 GHz region appears to be optimal.

- Snow Measurements - The study of the distribution, depth and water content of snow is primarily important for hydrology. Snow-melt affects reservoir management which in turn effects flood control, hydro-electric power generation, irrigation, and recreation. For many drainage basins in the temperate zones of the world, melt waters represent a major part of the annual yield of the basin. To properly use this water resource and to control flood drainage from high-stream discharges during the melt period, hydrologists must have timely information to perform their long- and short-term forecasts.

  Few quantitive investigations on active measurements of snow parameters have been conducted. Waite and MacDonald (1970) have flown a 35 GHz radar for snow mapping purposes, while Lindor and Jiravek (1975) have developed a multi-layer snow scattering model.

- Geology Measurements - The acquisition of geological information is important for producing geological maps. Geological maps have been produced by airborne radars. These maps contain delineation of fracture patterns, faults, lineaments and other surface features that are important to all phases of geological exploration.

Two of the most important geological areas are the exploration for minerals and energy supplies (gas, coal, oil, uranium and geothermal sources). Also, the location of faults and delineation of drainage basins are also important.

Geological mapping has been conducted over a range of frequencies from 1 to 35 GHz. Attempts at direct measurement of surface composition has met with little success - and only in highly limited circumstances (MacDonald and Waite, 1973). Recently, Lythe and Lager (1975) have developed a theoretical model for multi-layered media. Previously, Lundien (1974) proposed a swept frequency radar (0.25-8 GHz) to measure such multi-layered media.

- <u>Land Use Mapping</u> - The study of land use pattern is extremely important to the proper development and utilization of the nation's resources.

  Little research has occurred in the area of radar land use mapping. However, in a recent study, Bryan (1975) found that utilizing 1 and 9 GHz radars, several types of urban land use were accurately identified. The 9 GHz radar was generally more useful since it was more sensitive to roughness. Many other investigators when investigating soil moisture, vegetation and geology have found that rural land use differences are apparent in radar images.

- Ice Measurements (Appendix C) - The study of ice dynamics, and properties such as ice boundries, depth, and type are particularly important primarily due to the polar ice effects on weather and climate. The distribution of ice thickness in the Arctic ocean is needed to correctly model the mechanics of ice interaction so that the drift, and the dynamics of the Arctic ice pack, can be predicted for oceanographic, meteorological and economical purposes. Ice thickness information is needed to accurately calculate the mass budgets of ice packs for input to climatic models. Thickness information is useful for a wide variety of applications such as those involving ice-breaking by ships and the transport of heavy equipment over ice. The knowledge of the surface roughness characteristics is important for determining the momentum the wind imparts to the ice cover.

  Imaging radars can map ice extent and, in various degrees, determine surface topography as the radar frequency is increased. Ice thickness measurements have not been able to be made directly, but must be inferred from ice type and age determinations.

Based on data available, a frequency between 9 and 17 GHz appears to be best at determining sea ice types. A lower frequency, such as 1 GHz, would be useful in resolving thin ice ambiguities, and in lake ice measurements, if utilized in conjunction with the higher frequency radar. Frequencies above 17 GHz also apparently hold some promise.

- Wave Structure (Appendix D) - The measurement of wave structure, which includes wave heights, patterns and wave length, is important for accurate determination of atmospheric/ocean dynamics involving heat and momentum transfer. Not only are such dynamics important to meteorological forecasting, but they are needed for better planning of shipping routes, designing of ships and designing of off-shore structures.

  Most research efforts have concentrated on scatterometer measurements to determine significant wave heights. However, synthetic aperture radars appear to have a greater long-term potential for overall ocean structure determination. Spaceborne imaging radars have the capability of detecting long gravity waves and directions primarily because capillary waves vary in intensity along the profile of long waves. For large ocean waves, active microwave measurements are expected to produce routine estimates of significant wave height and of the directional wave spectrum. Apparently, a broad range of frequencies could be utilized. The SEASAT Synthetic Aperture Radar will operate at 1.275 GHz.

In the 1 to 5 GHz region, synthetic aperture radars can produce higher resolutions than passive microwave sensors utilizing the same size antenna and, hence, ocean structure can actually be "seen" in the images.

- Wind Measurements (Appendix E) - The measurement of surface wind and directivity is important for weather forecasting and climatology studies. Also, wind measurements over the ocean are particularly important since the ocean serves as a vital transportation link, and supplies food and mineral resources. Surface wind information, if used in conjunction with a variational analysis scheme, can significantly improve weather forecasting. Wind also affects the economics surrounding ocean transportation, fishing and mining. Since little wind information can be gathered directly at sea, there has been much interest in large scale synoptic measurements of wind magnitude and direction.

It is generally accepted that the small roughness elements convey the transfer of momentum from wind to sea and that these roughness elements are in equilibrium or near equilibrium with the wind. The fact that scatterometers and radiometers are good roughness sensors has led many to believe that the surface winds can be inferred from remote microwave observations. For spaceborne applications, a frequency in the 10-15 GHz range is a desirable compromise based on spacial resolution, sensitivity to wind, and atmospheric degradation considerations.

A scatterometer is possibly more advantageous than a passive radiometer since it may be possible to determine not only wind speed, but direction also.

- Geoid Measurements - The water surface of the ocean has the unique property of seeking an equilibrium with the equipotential gravity forces, and the satellite altimeter provides a direct measurement of the shape of this ocean surface. Therefore, the altimeter measurements of the ocean surfaces are almost direct geoid measurements, increasing the number of terms in the knowledge of the gravity field. Other significant results of satellite altimetry are in the detection of features such as trenches, seamounts, ridges and caps. In areas where the topography is not well known, the altimeter would contribute to the improved mapping of these features.

McGoogan has addressed the application of satellite altimetry to oceanographic studies. The basic idea behind altimetry is to utilize the highly stable platform provided by a satellite as a moving reference system from which vertical measurements to the ocean surface are made. The choice of frequency is primarily determined by the achievable antenna size versus the desired spacial resolution. Previous NASA altimeters have operated in the 13 GHz region.

Passive microwave devices are not capable of making geoid measurements, since they cannot measure altitude.

- Rain Measurements (Appendix F) - The measurement of rainfall intensity, measurements of storm maximum echo heights, and measurements of the height of the melting layer in clouds are important to improved weather prediction and climatology studies.

  Terrestrial meteorological radars have been in use for many years and their adaptation to space-use is expected. Although a multi-frequency radar is generally preferred, a one frequency radar seems adequate for measuring precipitation rates. The 9-10 GHz region appears optional with 15 GHz being the upperbound for reasonable dynamic range in rain-rate.

The primary advantage of radars over passive microwave radiometers for rain measurements is that radars provide attitude information on precipitation distributions over land masses as well as oceans.

- Surface Pressure Measurements - The measurement of surface pressure is needed for input into numerical weather forecasting models. Measurement of the surface pressure field, along with the temperature field, will allow for reconstruction of the entire 3-dimensional pressure field.

  Two methods for measuring surface pressure have been proposed. Peckham (1973) has proposed a two-frequency absorption comparison radar. One frequency would be on an absorption line and the other frequency would be close by. The O_2 - 5mm band (50-60 GHz) was considered the most promising region. Another method proposed by Eckerman involves a two-satellite bistatic radar approach using a single frequency. A broad frequency range could be utilized, but 10-15 GHz appears most useful when considering trade-offs involving equipment and atmospherics. Both techniques are applicable only over ocean surfaces.

  Passive microwave devices are incapable of making surface pressure measurements.

In conclusion, the study has found that active microwave remote sensing requires the simultaneous measurements of various phenomena at multiple frequencies in order to separate each phenomenon of interest. The required frequencies primarily span the 1-18 GHz region, with possible requirements in the 35-40 and 50-55 GHz range.

4. Conclusions and Observations

Active microwave sensors can, in some ways, perform the same measurements as a passive microwave device, yet it is the measurement unique capabilities, and the high spacial and altitude resolution abilities that make active devices highly desirable. However, the cost of active sensor systems are significantly more than passive systems. Thus, only when active sensor advantages off-set their higher costs would operational implementation be likely. This cost/performance balance would change if bandwidth restrictions on passive allocations force the use of costly multi-beam, multi-receiver radiometers. The overall trend, though, is far from being clear since both active microwave sensing programs and technology are still evolving.

Although active microwave research is still in its infancy, and new findings will likely occur, it seems apparent that the range of useful frequencies for space applications will span the 1-18 GHz range with possible usage of frequencies around 35-40 and 50-55 GHz. The bandwidth requirements for spaceborne radars could range between 1-1000 MHz depending primarily on the range resolution desired. Imaging radars would likely require bandwidths between 10-100 MHz, while altimeters would likely require between 300-1000 MHz of bandwidth. Scatterometers on the other hand, require very little bandwidth, on the order of a MHz or so.

Recently, a NASA-supported Active Microwave Study Group (Simonett, 1976), recommended that a need existed for a 6-octave, multi-polarization radar. Those recommendations are generally supported by the independent work entailed in this report. Since a previous study (Nicholas, 1977) has indicated the ability of spaceborne radars to share with other radio-location devices, the following radiolocation bands would meet the active sensor requirements for the earth resources, meteorological and oceanographic disciplines:

- 1.215-1.3 GHz
- 3.1-3.3 GHz
- 5.25-5.35 GHz
- 9.5-9.8 GHz
- 13.4-14.0 GHz
- 15.7-17.7 GHz
- 33.4-36.0 GHz

No radiolocation allocation currently exists in the 50-55 GHz region - though use of the bistatic approach would negate the need for such an allocation.

In the final analysis, all of the above allocations will be required if active sensors are to achieve their potential for improving man's understanding and control of his environment.

APPENDICES A - F

APPENDIX A

SOIL MOISTURE

1. Introduction

The study of the distribution and amount of soil moisture is primarily important for agriculture and hydrology applications. For agriculture, soil moisture measurements can help determine yield and optimal times for irrigation. For the hydrologist, soil moisture measurements are an integral part in determining water shed run-off. Run-off predictions are used in reservoir management of water for hydroelectric power, flood control, irrigation, recreation and consumption.

Significant work on passive microwave measurement of soil moisture has been accomplished (e.g. Edgerton et. al. 1968, 1971; Poe et. al. 1971; Jean et. al. 1972; Schmugge et. al. 1972, 1974; and Peck et. al. 1975). Passive sensors, however, have limited spacial resolution at frequencies of interest. Consequently, attention has been given to high resolution, synthetic aperture radar techniques. One of the earliest studies of land backscatter was by Grant and Yaplee (1957). Their work indicated that there were gross differences between returns from dry and moist soil. More detailed research on the nature of the radar returns from moist soil have been conducted by Lundien (1966) and later supported by Leightly (1968). The most important finding was that variations in the dielectric properties of the soil were a function of moisture content. However, these experiments were conducted on smooth soil under laboratory conditions.

MacDonald and Waite (1971) stepped outside of the laboratory and utilized an imaging radar on actual terrain. It was found that gross soil moisture content could be determined if vegetation cover were dry or leafless.

Further actual target measurements have been made by Dickey (1972), King (1973), and Cihlar (1974 and 1975), Ulaby (1974 and 1975). Most of the work over this period utilized airborne and truck-mounted radars; however, use was also made of data from the Skylab S-193 Radiometer/Scatterometer. Further recent work by Ulaby and Batlivala (1976) has indicated a general optimum region for radar soil moisture measurements.

2. Frequency Requirements

The amount of reflected power from the soil depends on the roughness of the soil, the vegetation cover, dielectric constant of soil, and angle of incidence.

The amount of moisture in the soil is known to change the dielectric constant. Lundien (1966) conducted a carefully controlled experiment at the U. S. Army Engineer Waterways Experimental Station to determine the radar response to laboratory prepared soil samples. The soil samples were placed in a cart and the top surface smoothed over. A multi-frequency radar (P, C, X, and Ka band) was utilized to gather the radar response of the soil under test for different viewing angles. The most important finding in Lundien's effort is that the dielectric properties of the soil samples vary as a function of the moisture content (Figures A-1a, A-1b). Lundien also found that the dielectric constant of soil depends only on the quantity of water, and the effect of soil type was minor at P-band. Also, as indicated in Figures A-1a, A-1b, on bare, flat soils, radar reflectivity for various frequencies increased with increasing soil moisture. These results were later supported by Leighty (1968).

However, bare, flat soil structure is rarely encountered. MacDonald and Waite (1971) found that in actual scene usage, it is extremely difficult to separate soil moisture from the terrain parameters such as surface roughness and vegetation cover. An airborne Ka-band (35 GHz) side-looking radar was used in these experiments and, hence, a high degree of diffuse scattering could be expected on rough or vegetated surface. Indeed, theoretical studies had indicated that the return signal variations due to changes in dielectric constant will be swamped by surface roughness effects for frequencies between 10 and 40 GHz. However, MacDonald and Waite were able to determine gross soil moisture content, but only when vegetation cover was dry and essentially leafless. They also supported earlier work by Grant and Yaplee (1957) which indicated that angles of incidence must be less than 45° to separate soil moisture from other roughness effects.

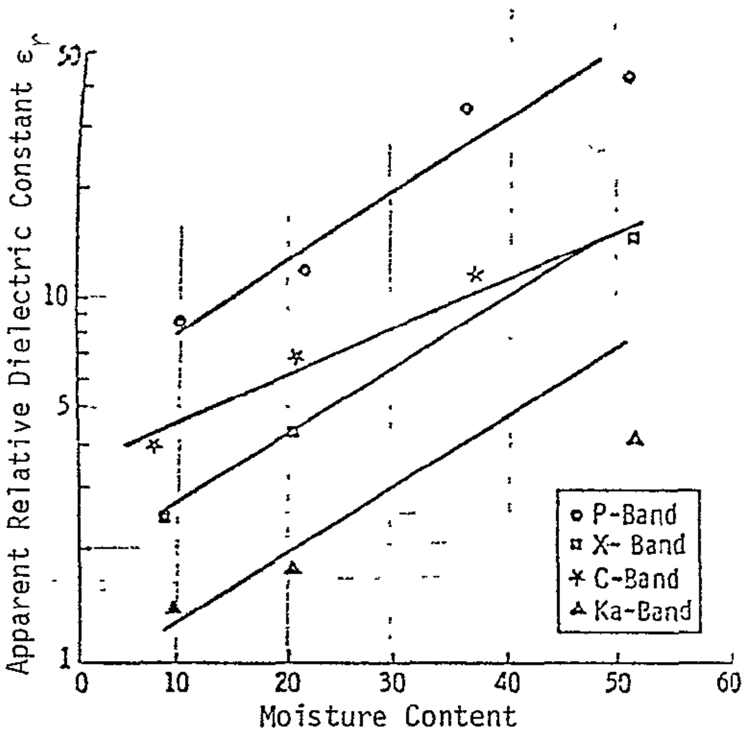


Figure A-1a. APPARENT RELATIVE DIELECTRIC CONSTANT VS. MOISTURE CONTENT. (SHARKEY CLAY), (AFTER LUNDIEN)

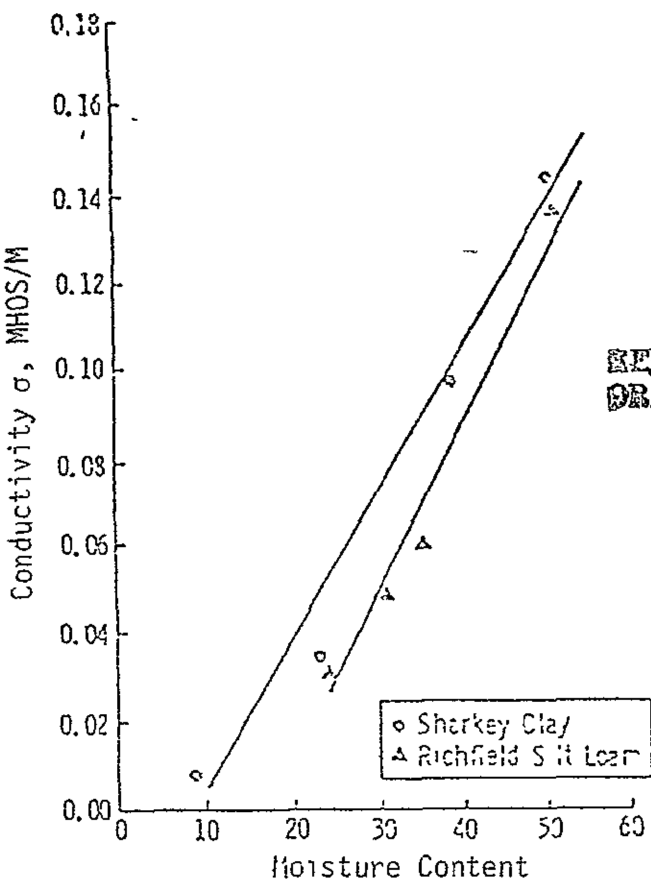


Figure A-1b. CONDUCTIVITY VS. MOISTURE CONTENT AT P-BAND. (AFTER LUNDIEN)

King (1973) also made soil moisture measurements under field conditions utilizing scatterometers in order to accurately determine scattering behavior. Frequencies of 400 MHz and 13.3 GHz were utilized at various incidence angles and for various types of crop cover. The figures in Figure A-2 illustrates backscatter variation at 13.3 GHz for different incidence angles and crops. Figure A-3 presents the same type of information for 400 MHz. The conclusion drawn from King's work was that significant sensitivity to soil moisture at 13.3 GHz was observable, while a weaker dependence was noticed at 400 MHz. Additionally, incidence angles of the radar emission should be below 40° for proper discrimination.

Ulaby and associates (1974, 1975, and 1976) have extensively studied radar backscatter from soil moisture at 4.7, 5.9, and 7.1 GHz. Figure A-4 illustrates the overall results from this research. This figure indicates that there is little difference between like polarizations for 4.7 and 7.1 GHz, and that sensitivity decreases with increasing incidence angle. Figure A-5 presents an optimum frequency comparison versus angle of incidence as given by Ulaby (1976). Ulaby felt that 4.7 GHz was a suitable compromise for mapping soil/moisture in vegetated fields, particularly when considering roughness effects on the return. However, others (JSC 1976) have indicated that L-band is likely to be required for soil moisture

Mission 133 Site Garden City, Kansas
Frequency 13.3 GHz Date June 26, 1970
Polarization VV Field 222

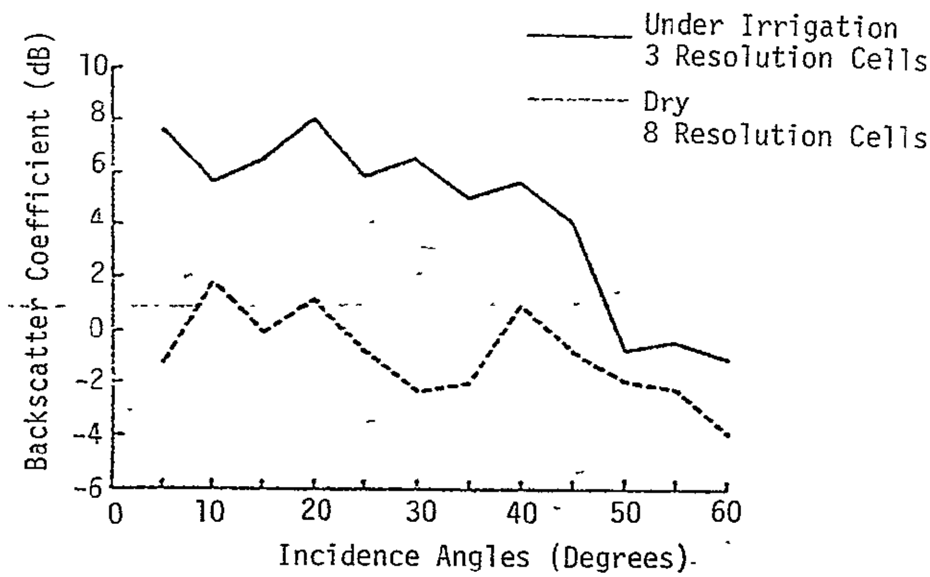


Figure A-2a. Corn, 19 inches, Ku-Band

Mission 133 Site Garden City, Kansas
Frequency 13.3 GHz Date June 26, 1970
Polarization VV

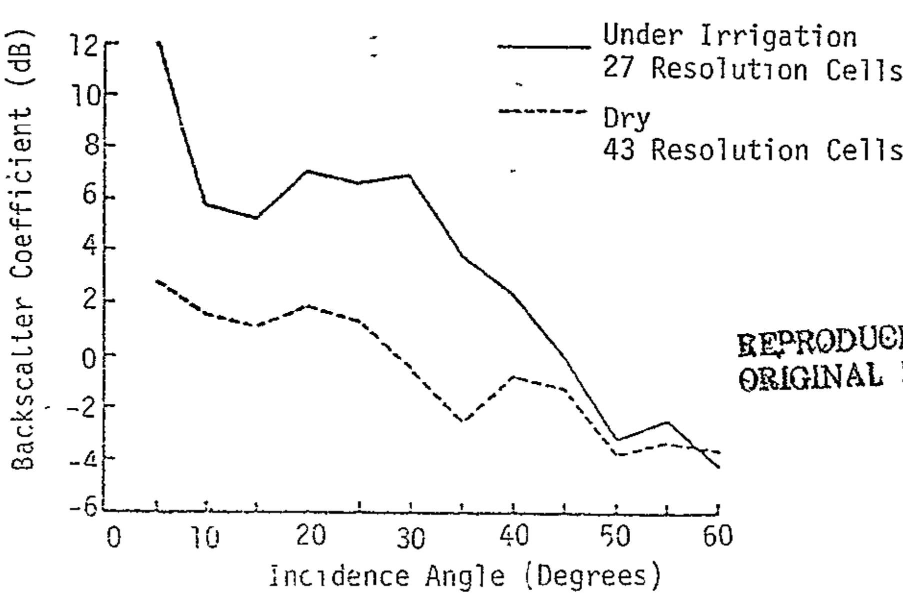


Figure A-2b. Average of the Partially Wet and Dry Fields of the Entire Test Site, Ku-Band

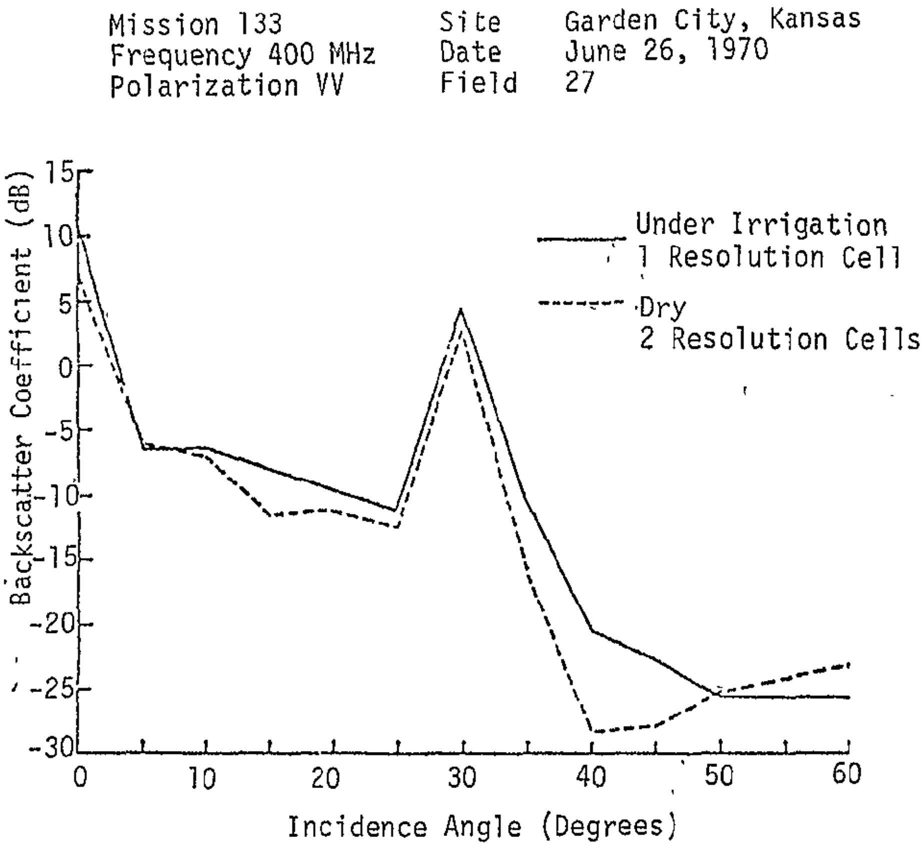


Figure A-3a. Corn, 36 inches, P-Bank, VV Polarization

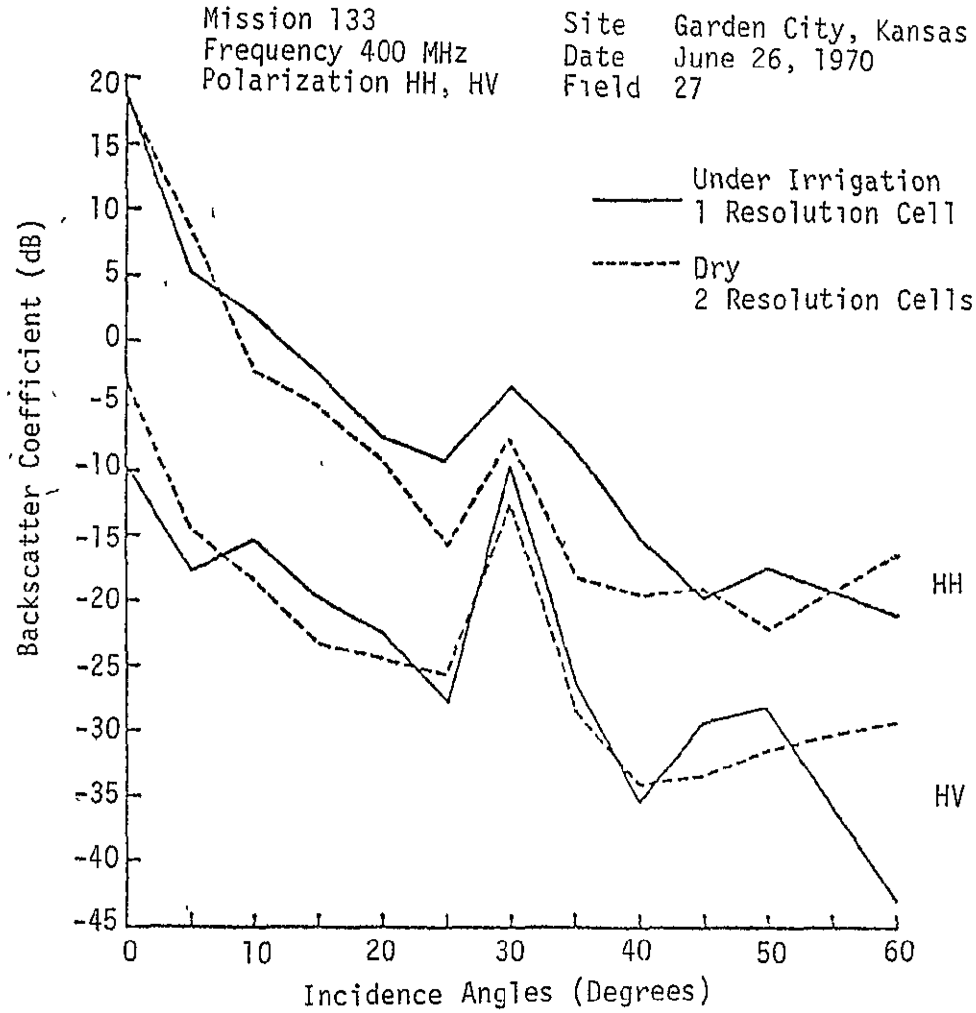
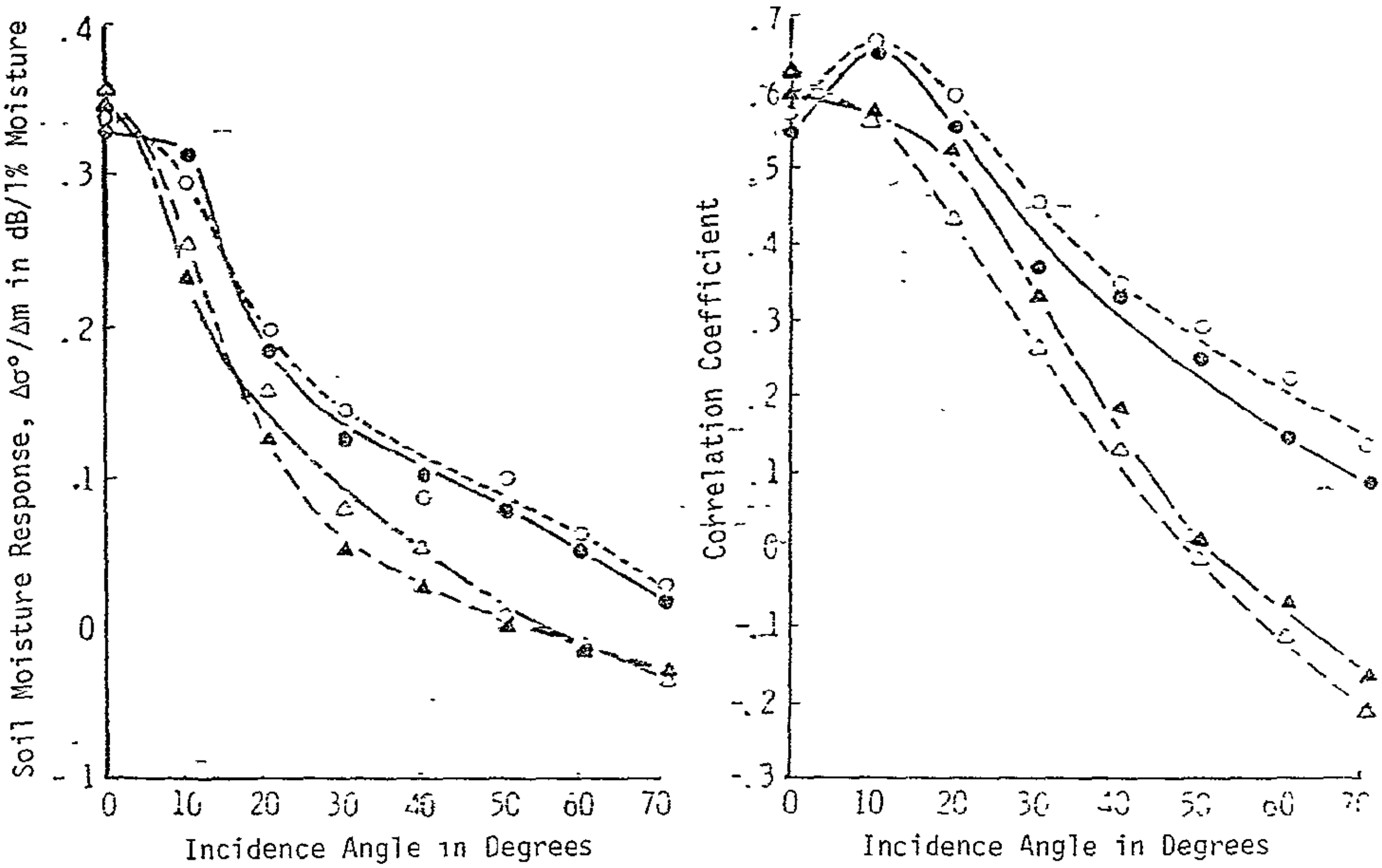


Figure A-3b. Corn, 36 inches, P-Band, HH and HV Polarization

RADAR IS MOST SENSITIVE TO SOIL MOISTURE NEAR NADIR INCIDENCE ANGLES

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



(a) Soil Moisture Response

(b) Correlation Coefficient

Figure A-4

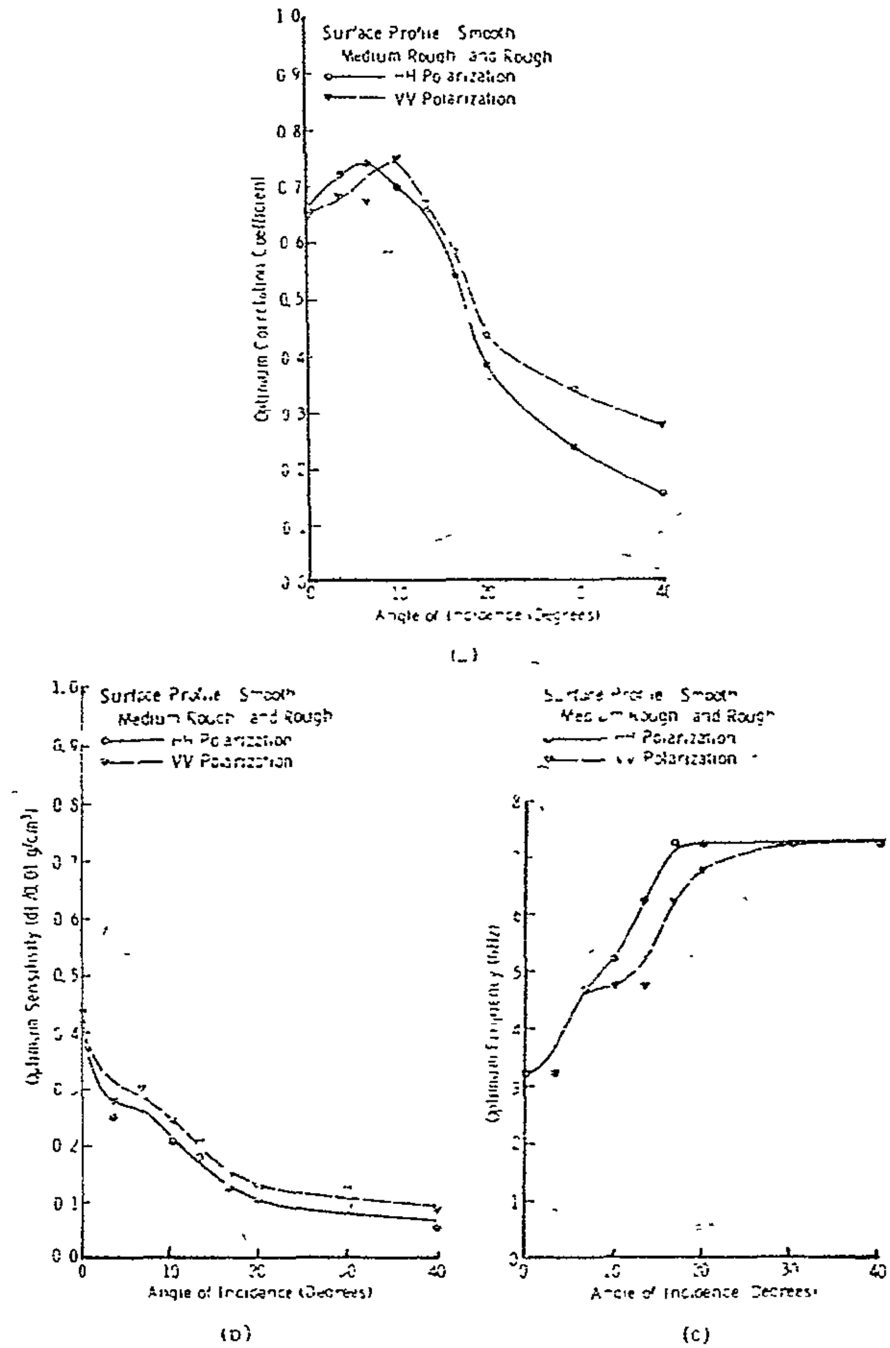


Figure A-5. Optimum (a) correlation coefficient, (b) sensitivity, and (c) frequency plotted as a function of angle of incidence for the smooth, medium rough, and rough surface profiles combined. (After Ulaby and Batlivala, 1976) measurements through general classes of vegetation. L-band also has the potential to measure more deeply into the sub-soil.

In conclusion, C-band (4.7 GHz) at a 5-17° incidence angle appears an overall desirable compromise. However, L-band could possibly provide measurements through vegetation and at deeper soil depths. In addition, a higher supplemental frequency such as Ku-band would be useful in measuring vegetation cover and helping to provide correction for this obscuring factor.

APPENDIX B

VEGETATION MEASUREMENTS

1. Introduction

The monitoring of vegetation type and conditions are important primarily for agriculture and forestry. Also vegetation information can be utilized in ecological and land use planning.

The knowledge of vegetation types and conditions, along with other environmental variables, could be utilized for improving crop forecasting on a worldwide scale. Such information has enormous impact on domestic pricing, A.I.D. programs, foreign policy, and balance of trade. Of less dramatic impact, but still important to domestic planning, is the potential for improved forest and grazing land usage.

Little passive microwave research has been conducted on vegetation identification. One of the first active microwave terrain studies was conducted by Grant and Yaplee (1957), while the first crop study reported was by Ohio State University researchers Cosgriff, Peake and Taylor (1960). These works indicated the potentials for radar remote sensing usages.

The first major study of crop identification was by Morain and Simonett (1967). They found that crop type was the most significant parameter affecting radar returns. Further studies by Haralick, Caspall and Simonett (1970) and Schwarz and Caspall (1968) utilized various polarizations, along with time sequential imagery - both approaches yielded increased vegetation discrimination. Hardy, Coiner and Lochman (1971) were later able to demonstrate that an airborne radar imager could provide vegetation maps utilizing ground truth. Shuchman and Drake (1974) further reported on the feasibility of using multiplexed side-looking airborne radars for both water resources management and mapping of vegetation communities.

International support for vegetation determination by active means has come from deLoor and associates in the Netherlands. (deLoor and Jurriens (1971), deLoor and Jurriens (1972), deLoor and Jurriens (1974), and Attena and Kuilenburg (1974)).

By far, the most intensive research, which has been reported, is that by Ulaby and associates from 1972 to present. Utilizing a truck-mounted scatterometer, these experiments have indicated that increased discrimination of vegetation occurs for multi-frequency, multipolarization and multi-temporal radar systems.

2. Frequency Requirements

The amount of reflected power from vegetation depends on the roughness of the vegetation, vegetation and soil moisture, vegetation dielectric constant and angle of incidence.

The first major vegetation study by Morain and Simonett (1967) was of crop identification at Ka band (35 GHz). Figure B-1 presents a cluster analysis by Simonett that indicates bulk difference between some crops, while other crops are not so discernable. The principle conclusion of this research was that crop morphology was more significant than plant or soil moisture in determining the amount of reflected return. Also, a time history was found to be useful in crop identification. For example, in August sugar beets were easily confused with other crops, yet in the fall the beets were identified 100%. This increased discrimination appeared to be the result of growth and plant moisture, at a time when corn and sorghum were matured and dry.

Further studies by Haralick, Caspall and Simonett (1969) and Caspall and Schwarz (1968) also used a Ka band radar, but with a dual polarization capability (HH, HV, VH, and VV transmit/receive configurations). The purpose of these studies was to determine if multi-polarization combinations could improve time-sequence measurements. Using a baysian classification scheme, July data produced a 78% crop classification accuracy, while 90% were correctly identified using August and September data. Consequently, it was concluded that multi-polarization and multi-temporal data improved vegetation discrimination.

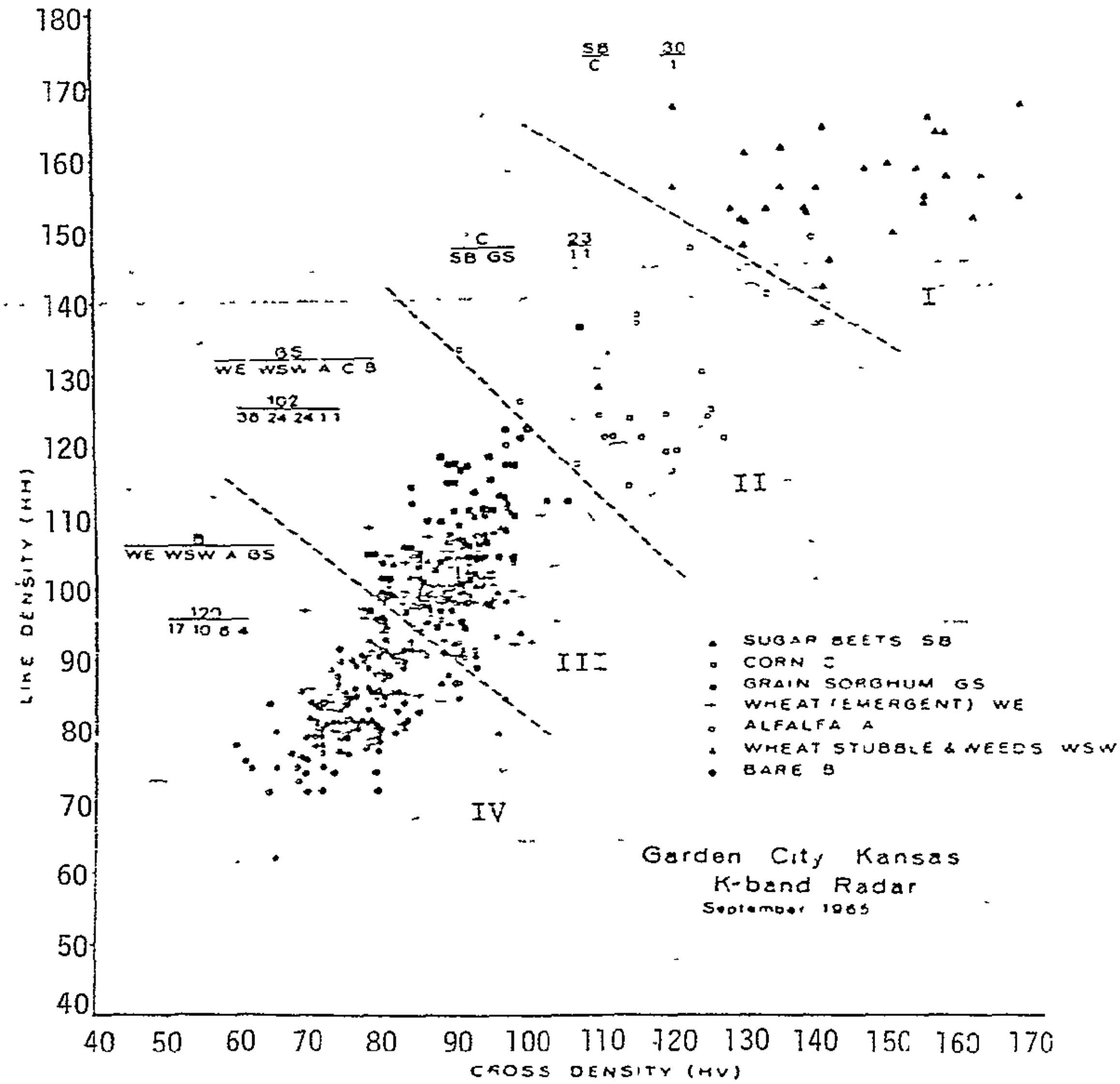


Figure B-1. Crop Cluster Analysis

In an area other than crops, Hardy, Coiner, and Lochman (1971) have produced vegetation maps over a large region of Yellowstone National Park utilizing a Ka band radar and ground truth.

Schuman and Drake (1974) further reported on the feasibility of using multiplexed side-looking airborne radars for both water resource management and mapping of vegetation communities. Horizontal/vertical L-band (1.3 GHz) and X-band (9.4 GHz) radars were utilized to study test areas in Brevard County, Florida and crops in southeastern Michigan. In the Florida tests improved cattle pastures, citrus groves, different types of rangeland, forest and water areas were distinguishable when utilizing supplemental ground truth. In the crop study, standing corn and soybeans could generally be distinguished, though corn and soybean stubble were difficult to separate. Growing winter wheat could be distinguished from standing or cut corn and soybeans, though not from alfalfa pasture. Deciduous trees could also be differentiated from conifers during the fall. In general, X and L band were preferable to utilization of only one frequency.

International support of vegetation determination by active means has come from deLoor and associates in the Netherlands. (1971, 1972, and 1974). Utilizing mostly an X-band (9GHz) radar, deLoor has concluded that the radar backscatter coefficient as a function of frequency and polarization seems to be the only possible classifier for vegetation species. However, deLoor found that wind could strongly affect the scattering coefficient for crops.

By far, the most intensive reported research has been by Ulaby and associates from 1972 to present. Measurements of vegetation, primarily crops, have been made by a truck mounted radar, first operating over the 4-8 GHz range and later expanded to 18 GHz. Ulaby (1973) showed that at large incidence angles, soil moisture was not a significant factor in the radar return - this is illustrated in Figure B-2. Also, an interesting finding regarding blighted corn was reported. Blighted corn, due to a lower water content, exhibited a return of 1-2 dB less than healthy corn at a 40° incidence angle. In addition, the VV polarization was found to exhibit greater sensitivity to crop type than HH polarization.

Radar spectrometer results from Ulaby's recent work (1976) are presented in Figure B-3. The figure indicates that vegetation classification improves with increasing frequency and with combination HH and VV polarizations. Thus, the shorter wavelengths are apparently more suitable for crop identification studies. Ulaby concluded that wavelengths somewhere between 14 and 18 are optimal when just a single frequency is used.

Also presented in Figure B-3 are the results of multi-polarization, multi-frequency, unsupervised cluster analysis.

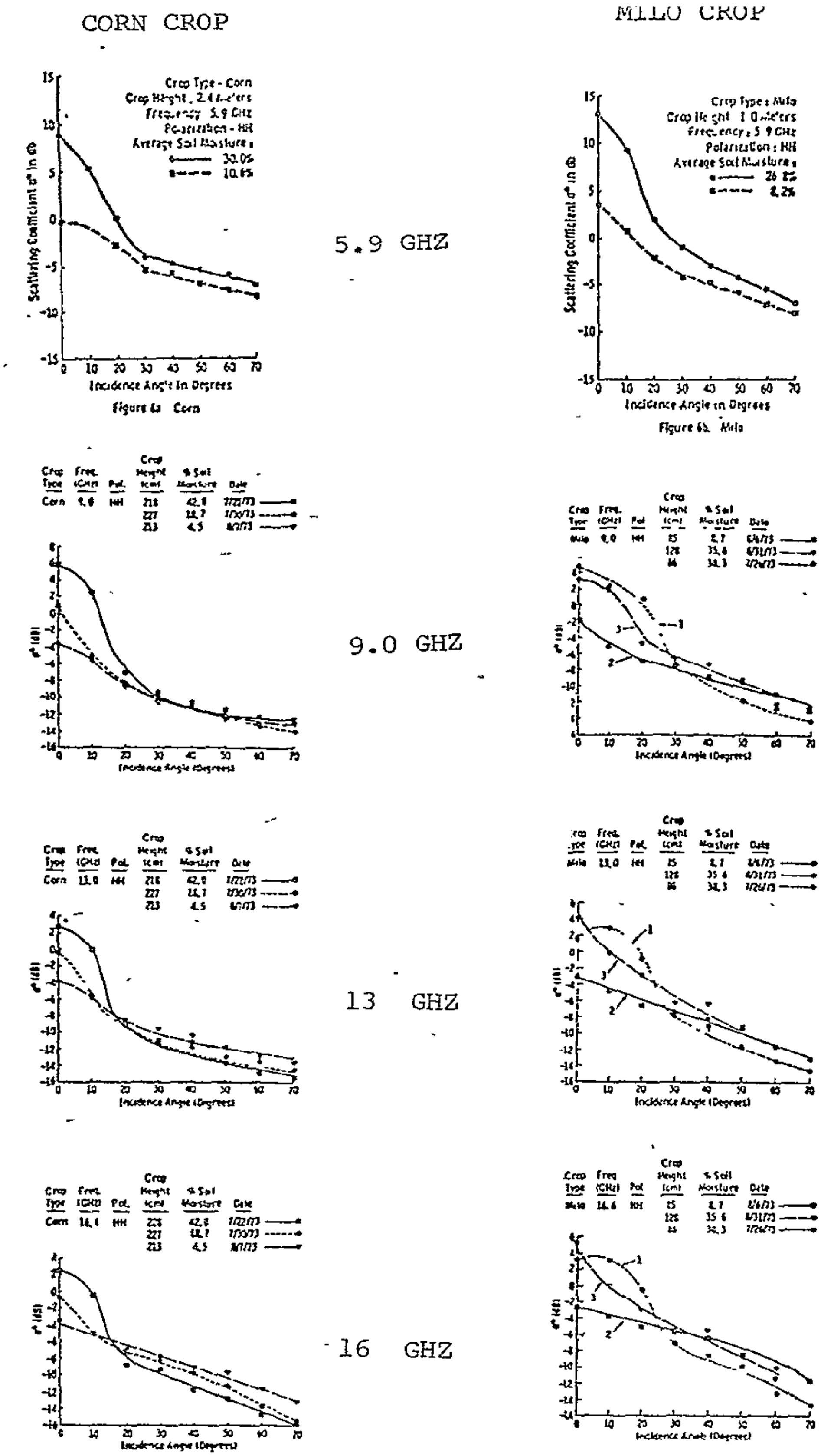


Figure B-2 Backscatter as a Function of Incidence Angle From Vertical, Showing Dependence on Soil Moisture, Frequency, and Crop Type (Ulaby)

BOTH MULTIFREQUENCY AND MULTIPOLARIZATION IMPROVE CROP CLASSIFICATION ACCURACY

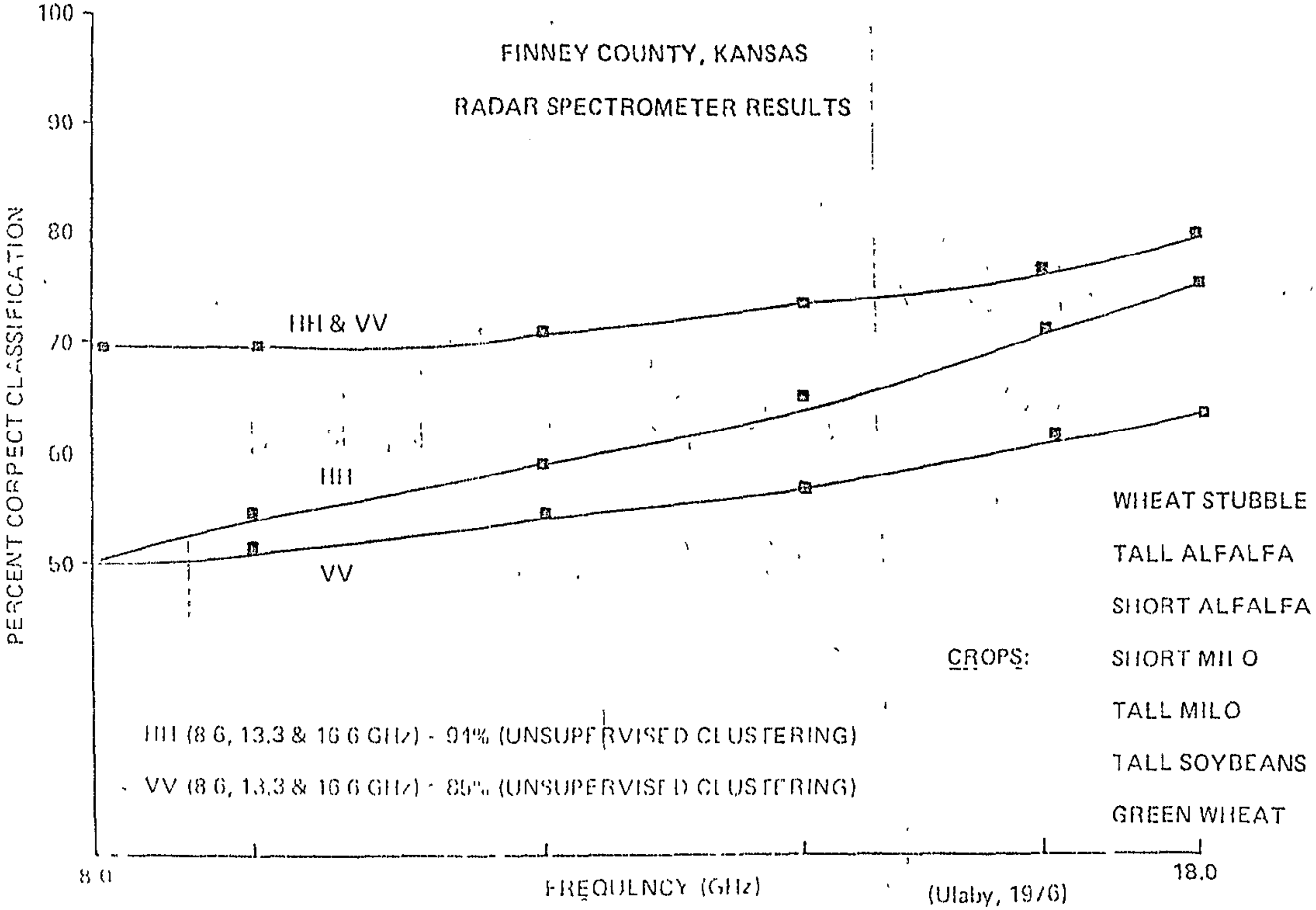


Figure B-3. Crop Classification Accuracy vs. Frequency and Polarization

The identification accuracies for combinations of wavelengths (8.6, 13.3, and 16.6 GHz) are given for HH (94%) and VV (85%) polarizations. Thus accuracy depends on both frequency and polarization combinations.

Figure B-4, from Ulaby and Bush (1976), presents the variation in scattering coefficient at 14.2 GHz, VV polarization and a 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. The scattering coefficient from corn was much higher than any other crop between June 8 and July 18, and thereafter, it tended to overlap the average values for other crops. The values for unharvested and harvested wheat were much lower than other crops (once milo was emergent) except that the wheat value suddently rose to a peak at harvest. Similarly, late in the growing season, as the milo matures, the coefficient rose to values higher than other crops and even above corn, which in August was beginning to decline. The figure basically illustrates that temporal variability is one of the principal discriminants along with the intrinsic differences between crops.

Figure B-5, also from Ulaby and Bush (1976), illustrates the improvements in classification accuracy as more polarization and frequency combinations are used. Maximum discrimination occured during the month of June, while August was the worst. Figure B-6, illustrates the improvements in classification

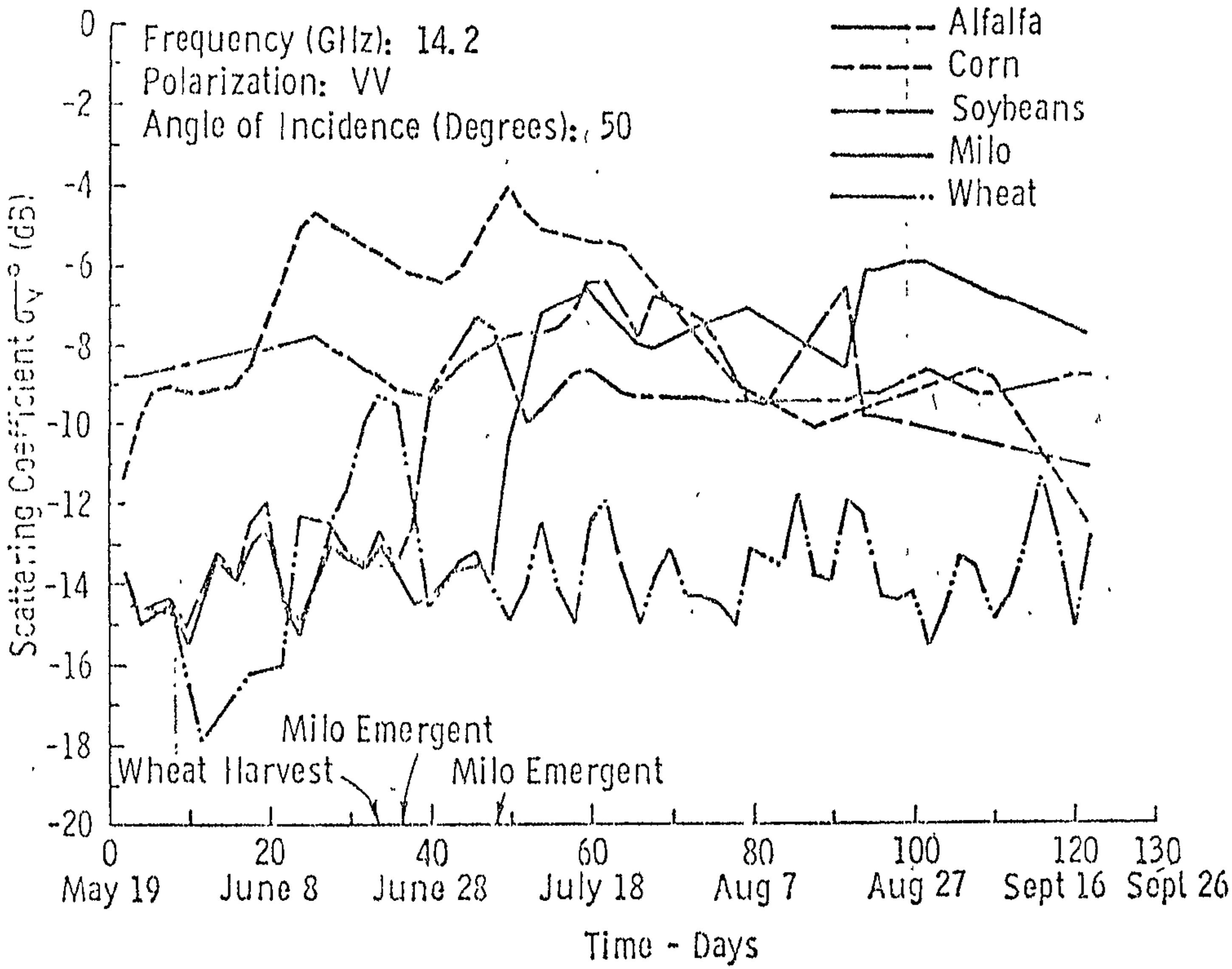


Figure B-4. Time Variation of Scattering Coefficient for Different Crops at 14.2 GHz

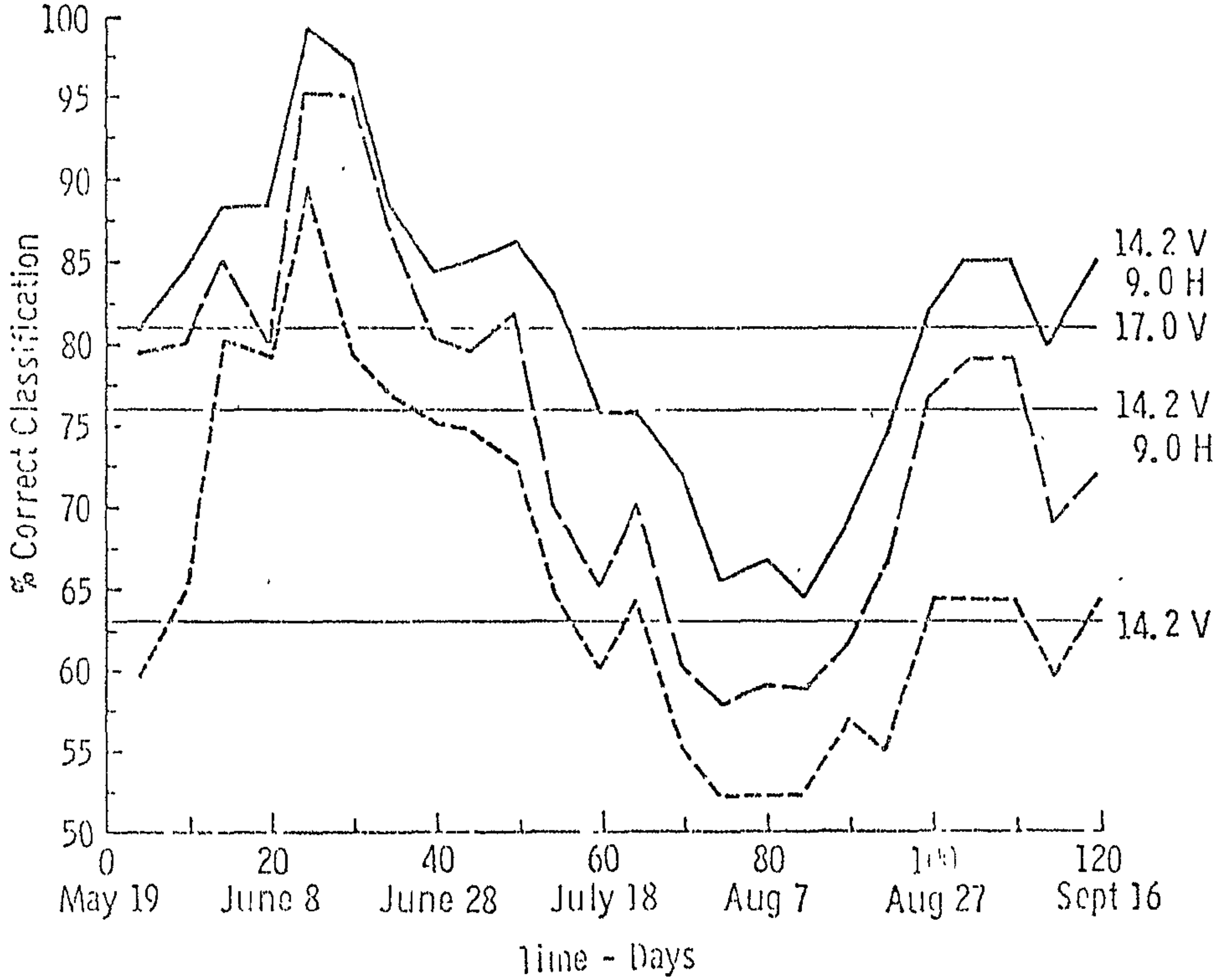


Figure B-5. Classification Accuracy Improvement with Multifrequency Data

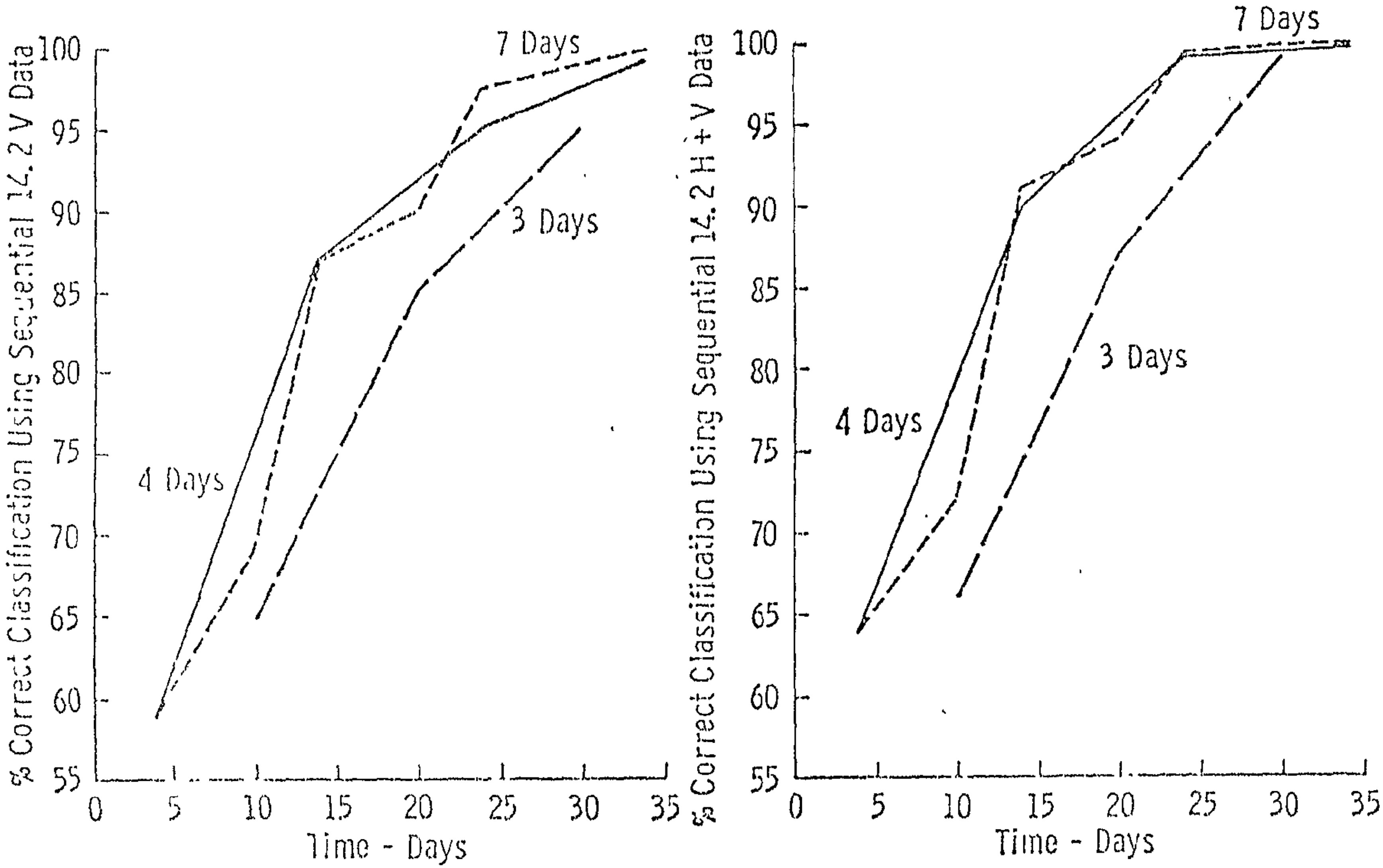


Figure B-6. Classification Improvement for Multipolarization and Time Sequencing from time sequenced data, as well as V and H polarization at 14.2 GHz.

In conclusion, vegetation measurements are best conducted at moderate to high incidence angles, using a multi-frequency, multi-polarization, and multi-temporal radar system. If a single frequency were only available, then 14-18 GHz appears optimal.

APPENDIX C

Ice Measurements

1. Introduction

The study of ice dynamics, and properties such as ice boundries, depth, and type are particularly important primarily due to the polar ice effects on weather and climate.

The variations of ice thickness and roughness, or topographic relief of ice cover, are extremely important. The distribution of ice thickness in the Artic ocean is needed to correctly model the mechanics of ice interaction so that the drift, and the dynamics of the Artic ice pack, can be predicted for oceanographic, meteorological and economical purposes. Ice thickness information is needed to accurately calculate the mass budgets of ice packs for input to climatic models. Thickness information is useful for a wide variety of applications such as those involving ice-breaking by ships and the transport of heavy equipment over ice. The knowledge of the surface roughness characteristics is important for determining the momentum the wind imparts to the ice cover.

Significant passive microwave sensing research in ice type and depth has been accomplished [e.g. Addinson 1969, Edgerton and Stogryn 1971, Wilbert 1972, Gloerson and Nordberg 1973, and Hollikanen 1974]. In fact research is worth being conducted in space on Nimbus 5 and 6. Active microwave sensing was first attempted in the early 1960's by the U. S. Army Cold Regions Research and Engineering Laboratory (CRREL) utilizing a side-looking airborne radar [Anderson 1966]. Most of the work since the early 60's concentrated on understanding the basic ice-electromagnetic interactions of scattering. Scattering is primarily affected by surface roughness, electrical properties (complex dialectric constant) and material microstructure.

In the area of microstructure, Weeks and Assur [1969] studied the dynamics and evolution of ice crystal structure in lake and sea ice. They also studied typical salinity profiles for different ice thicknesses. MacNeil and Hoekstra [1973] experimentally measured temperature and salinity profiles for different ice types and depths. While Weeks and Cox [1973] pointed out that salinity distribution in multi-year ice is dependent on ice topography.

In the area of surface roughness, there is a general lack of quantative data. Some information on roughness parameters can be found in Kazo and Diachok [1973], Ling and Untersteiner [1974] and Weeks, et al [1974]. The electrical properties of pure ice and freshwater ice have been well established by many previous efforts, notably Auty and Cole (1952), Cummings (1952), Dorsey (1940) and Murphy (1934). However, the electrical properties of sea ice are different than pure ice due to impurities such as brine and trapped air bubbles. Most of the sea ice electrical properties research has been conducted below 100 MHz by such researchers as Ragle [1964], Wentworth and Cohn [1964], Fujina [1966], Addison and Pounder [1966] and Addison [1970]. It was only in 1971 that an attempt was made by Hoekstra and Capillino to determine the complex dielectric constant of sea ice in the frequency range from 100 MHz to 23 GHz. Byrd, et al [1972] have reported the variation of loss tangent with salinity in natural sea ice, at the frequency of 34 GHz.

The electrical properties of sea ice as reported in the literature have one feature in common: the complex dielectric constant of sea ice is dependent on both temperature and brine volumes. The brine volume in turn depends on salinity and temperature. Salinity and temperature change with thickness and depth of sea ice, so the electrical properties of sea ice are a function of ice thickness and depth [Parashar 1975].

2. Frequency Requirements

The amount of reflected radar return from a surface is determined by the radar frequency, surface roughness, surface dielectric properties, angle of incidence and aspect, and subsurface microstructure.

A 34.9 GHz side-looking airborne imaging radar (SLAR) was first used to map sea ice in the early 1960's by CRREL. Anderson [1966] in analyzing CRREL images, determined that major sea ice types could be distinguished. Older ice would be differentiated from new ice primarily due to surface roughness differences - older ice is smoother due to weathering. Also, smooth refrozen leads, polynyas, younger thin ice and open water were distinguishable.

In 1967, a joint Arctic sea ice mission was conducted by the National Aeronautics and Space Administration (NASA), Navy Oceanographic Office, U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), the Arctic Institute of North America, and the University of Kansas. The purpose of this mission was to quantify the ability of a 13.3 GHz, vertically polarized radar to identify sea ice types. A calibrated radar scatterometer was used to provide quantifiable data on backscattering coefficient as a function of illumination angle. Rouse [1968], in analyzing the scatterometer data, was able to show that different ice-types were indeed identifiable. In particular, it was found that multi-year (old) ice produced higher reflected returns, over all illumination angles, than first-year ice.

During September 1969, the U. S. Coast Guard, conducted ice-mapping experiments in the Northwest Passage utilizing a Ku-band (16.5 GHz) radar. Later Johnson and Farmer (1971) found in analyzing experiment results that the radar could readily detect ice concentration, floe size and number, and water openings. It was also possible to identify, through careful image interpretation, ice age, ice drift, surface topography, fractures, and pressure characteristics. The most difficult characteristic of the ice to determine from radar imagery, other than its actual thickness, was found to be categorical age. An important feature that could be interpreted was whether or not ice had been under pressure. It was also possible to identify topographic features such as pressure ridges, hummocks, and cracks.

The Coast Guard experimental data was also used to determine the drift of sea ice. Johnson and Farmer, in another paper (1971), found that single ice floes, as well as general ice masses, could be tracked to an accuracy of nearly one nautical mile. In another study conducted at Biache by Bracie (1971) utilizing the same experimental imagery, major ice types, cracks and leads could be identified.

In April 1970, another experiment was conducted jointly by NASA, Naval Oceanographic Office, and the University of Kansas in the vicinity of Pt. Barrow, Alaska. Parashar (1974) later analyzed the backscatter measurements at 400 MHz (HH, VV, VH and HV polarizations) and 13.3 GHz (VV polarization). The scatterometer data was separated into seven categories of sea ice according to age and thickness as interpreted from low-altitude stereo aerial photographs. Multi-year ice (sea ice greater than 180 cm thick) gave the strongest return at 13.3 GHz. First-year ice (30 to 90 cm thick) and open water gave the strongest return at 400 MHz. Open water could be differentiated at both frequencies. Although 400 MHz was not found to be as satisfactory for ice identification as 13.3 GHz, combining a 13.3 GHz and a 400 MHz system eliminated the ambiguity regarding very thin ice. An attempt was also made by Parashar to formulate a theory for polarized radar backscatter cross-section for sea ice by taking into account the amount of brine entrapped, temperature, and surface roughness. The computed results from the theory were in general agreement with the experimental results.

In studies conducted by Raytheon company [1970, 1972] and Photographic Interpretation Corporation [1972], it was shown that a radar could map the changing nature of sea ice. Major ice types such as new ice, young ice, first-year ice and multi-year ice could be identified on the imagery. It was not possible to make a finer delineation of categories.

In 1972, the Canadian Department of National Defense, and the Atmospheric Environment Service of Canada, conducted tests of a 9.4 GHz radar for ice measurements. The results indicated that it was generally possible to identify open water by low radar returns. It was difficult to distinguish new ice from open water since both surfaces are generally smooth. It was possible to determine floe size and concentration, and to distinguish first year ice, fast ice and multi-year ice.

In one of the few multifrequency radar experiment analyses, Ketchum and Tooma (1973), using data from a 1968 U. S. Naval Oceanographic Office experiment, showed that the shorter-wavelength X-band radar appeared to have the greatest potential for sea ice measurements when more definitive information such as mapping, distributions of stages of ice development, and fracture pattern analysis is required. The X-band radar imagery can be used to discriminate old and young ice, since the old ice produced a higher return. Young ice, which is smooth, could not be discriminated from open water in this experiment. There were no notable differences between horizontally and vertically polarized X-band imagery. The potential value of the L-band radar was primarily useful for determining the more topographic features such as ridges and hummocks. Only the most prominent features, such as large floes and fractures could be identified on the P-band (400 MHz) radar imagery. The authors noted that for motion studies in which reidentification of specific features is necessary, the X-band or preferably K-band radars, would be the best choice.

In international research, the Russians have been conducting SLAR experiments on its TOROS satellites since 1968. Glushkov and Komarov (1971) and Loshchilov (1972) demonstrated the use of SLAR imagery, obtained from the TOROS, for determining the ice conditions and ice drift. By 1973, it was believed that the TOROS system was operational for mapping ice to permit optimal ship routing for convoys along the USSR's northern sea routes.

In one of the few studies of radar reflections from lake ice, Elachi, Brayon and Weeks (1976) utilized L (1.2 GHz) and X (10 GHz) band radars. The patterns of the returns suggested that a low-return indicated that the lake was frozen completely to the bottom, while a high-return indicated the presence of fresh-water between the ice cover and the lake bed. The effects were more striking in the L-band imagery. This effect could be explained by the fact that volume inhomogeneities, such as air bubbles, will cause more scattering and conductivity losses, and thus more attenuation, at the shorter wavelengths.

In conclusion, imaging radars can map ice extent and, in various degrees, determine surface topography as the radar frequency is increased. Ice thickness measurements have not been able to be made directly, but must be inferred from ice type and age determinations. Based on data available, a frequency between X and Ku appears to be best at determining sea ice types. An L-band radar would be useful in resolving thin ice ambiguities, and in lake ice measurements, if utilized in conjunction with an X or Ku band radar. Higher frequencies also apparently hold promise.

APPENDIX D

WAVE STRUCTURE

1. Introduction

The measurement of wave structure, which includes wave heights, patterns and wave frequency, is important for accurate determination of atmospheric/ocean dynamics involving heat and momentum transfer. Not only are such dynamics important to meteorological forecasting, but they are needed for better planning of shipping routes, designing of ships and designing of offshore structures.

Goldstein (1946) was one of the first to study quantitatively the effects of surface roughness on radar returns and support for his work was later presented by MacDonald (1956) and Wiltse el at (1957). Grant and Yaplee (1957), and Ament et al (1959) took data measurements of a wide range of incidence angles.

In the late 1950's more attention was given to the nature of sea echo and scatter mechanisms. Crombie (1955) showed, through measurements of microwave sea return that definite regions and trends in the echo were functions of frequency, sea state (wind-speed), polarization, and incident angle. Theoretical efforts by Wright (1968) and Barrick (1972) on the subject of rough surface scattering have also contributed significantly to the interpretation of the physical mechanisms responsible for sea scatter.

The surface roughness effects on radar returns have been shown to be dominated by small "capillary" waves riding on long "gravity" waves. Shemdin et al (1972), and Wright and Keller (1974) have conducted laboratory experiments which have shown a strong interaction between these capillary and gravity waves. Further research by Long (1974) has explained the relationship between the radar cross section for sea echo and polarization showing a support for the two-scatterer concept.

Due to the statistical nature of wave motion, Weissman and Johnson (1977) have developed a radar technique for measuring the statistical height properties of a random rough surface. Elachi and Brown (1977) have recently analyzed several models which would explain ocean wave imagery taken with a synthetic aperture imaging radar and showed that each model gives a modulation which has a different dependence on the angle Ø between the line of flight and the wave direction.

Imaging radars appear to have great potential for measuring ocean structure. The modulation of capillary waves by long gravity waves over a wide range of windspeeds, can be more easily investigated by active microwave instruments.

2. Frequency Requirements

The amount of reflected radar return from ocean surfaces is primarily determined by the radar frequency, surface topology and angle of incidence and aspect. The surface topology consist of large ocean waves (that is, gravity waves) which act like a group of specular reflectors so that the strength of the scatterer is proportional to the slope of the gravity waves. Ocean waves comparable to the wavelengths of the microwave systems used, show resonant (Bragg) scattering effects for angles of incidence larger than 20°. This Bragg scattering is controlled by the capillary waves, which in turn depend on the local short-term surface wind field and the ocean water surface tension. The latter changes, for instance, when an oil film covers the water surface, resulting in a modification of the character of the capillary waves. The waves actually become smoother becaus of the greater surface tension of oil.

One of the early scientists who examined methods of sea state determination was Goldstein (1946). Goldstein studied the frequency dependence of sea return over various grazing angles. He introduced the dimensionless quantity σ°, average radar cross-section per unit area, or scattering coefficient, which has become the standard unit of measurement for radar backscatter from the sea surface. Goldstein presented the following observations on the radar cross-section from sea returns:

- There is a definite polarization dependence of σ°, which depends on the roughness of the sea. For example, in calm seas horizontal polarization gives less return than vertical polarization. The difference between the two decreases is rougher seas.

- There is a "critical incidence angle" above which $\sigma°$ decreases rapidly with increasing angle and below which it rises much more slowly or remains constant. Also, the critical angle increases with increasing frequency.

- The frequency dependence of $\sigma°$ varies between approximately λ^{-4} in calm seas to about $\lambda°$ in rough seas, where λ is the free space wavelength of the incident radiation.

Measurements at various polarizations made by MacDonald (1956) and Wiltse et al, (1957) tend to agree with Goldstein's observations. MacDonald found that radar backscatter for vertical polarization decreases with wind direction, while Wiltse's measurements indicated that at an incidence angle of 60°, $\sigma°$ is almost independent of wave aspect for the frequencies used in his experiments (9.5, 24 and 35 GHz).

Grant and Yaplee (1957) made measurements of $\sigma°$ over a wide range of incidence angles, whereas, Goldstein had made measurements only at grazing angles. Their measurements indicated that $\sigma°$ increases with wind velocity for angles of normal incidence at 24 and 35 GHz. Measurements at 9.5 GHz increased with wind velocity up to 10-15 knots, then decreased for higher wind velocities.

Crombie (1955) deduced from measured sea echo that the dominant scatter mechanism at hf frequencies (10 MHz) is resonant (or Bragg) scatter. This type of scatter originates from ocean wavetrains that have a spatial period of one-half the radar wavelength (for backscatter near grazing), and are travelling toward and away from the radar. Measurements by others (Kerr, 1951; Ruck, 1970; and Skolnik, 1970) at approximately 10 GHz showed definite regions and trends in the echo that were functions of frequency, sea state (windspeed), polarization, and incident angle.

Wright (1968) and Barrick (1972) completed theoretical studies on the subject of rough surface scattering in an attempt to better explain the physical mechanisms responsible for sea scatter. Theoretical results indicate that for returns near normal incidence (that is, less than approximately 20°), large gravity waves are the dominant contributors to sea return. For returns away from normal (that is, incident angles larger than 20°), the dominant contributor to sea return in the microwave region is the capillary wave. Thus, the two-scale scattering theory indicates that the interactions between the gravity and the capillary waves must be considered.

Sea waves are generated by the wind, and gravity is the force that controls their characteristics. Capillary waves (small wind ripples) are also generated by the wind, but surface tension is the controlling characteristic. Capillary waves are quite sensitive to the wind, are very small, and have wavelengths of about one inch or less. If the breeze that generates capillary waves dies out, they soon flatten and disappear. This is in contrast to gravity waves which continue to run and become swells after the wind stops. In the two-scatterer concept for sea echo, the scatters are a wind-dependent fine structure of the sea (ripples) and smooth areas (facets) of the wave structure.

The detection of sea-surface roughness by active microwave instruments offers the potential of remote determination of windspeed. The roughness of the sea is interpreted by the density and structure of capillary waves. To understand the dynamics of capillary waves, one must understand radar return at higher angles of incidence.

Capillary waves are sensitive to wind forcing, local currents, orbital velocities of long gravity waves, and changes in surface tension due to slicks induced by oil spills or biological activity. Shemdin et al (1972) showed through laboratory experiments that there was a linear relationship between capillary wave slope energy, Øs, and windspeed, W, for each frequency. This relationship is shown in Figure D-1. A saturation level is achieved at a certain windspeed beyond which the slope energy remains constant. Higher frequencies achieve saturation at higher windspeeds. Figure D-2 indicates the influence of long waves on capillary waves at various windspeeds.

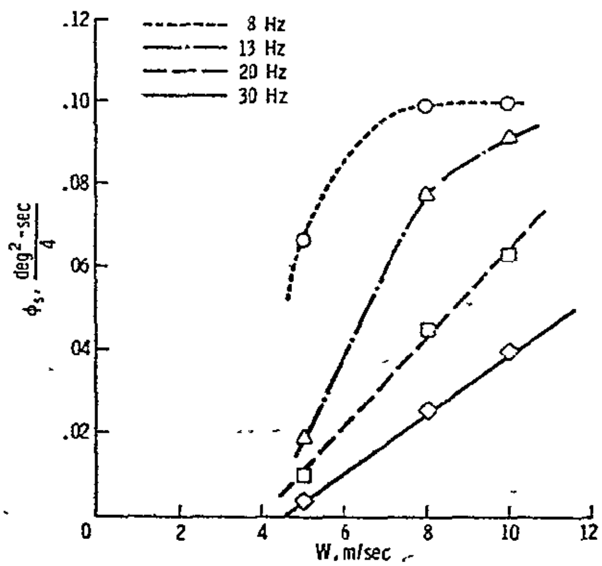


FIGURE D-1 Wind dependence of slope spectral values at different frequencies.

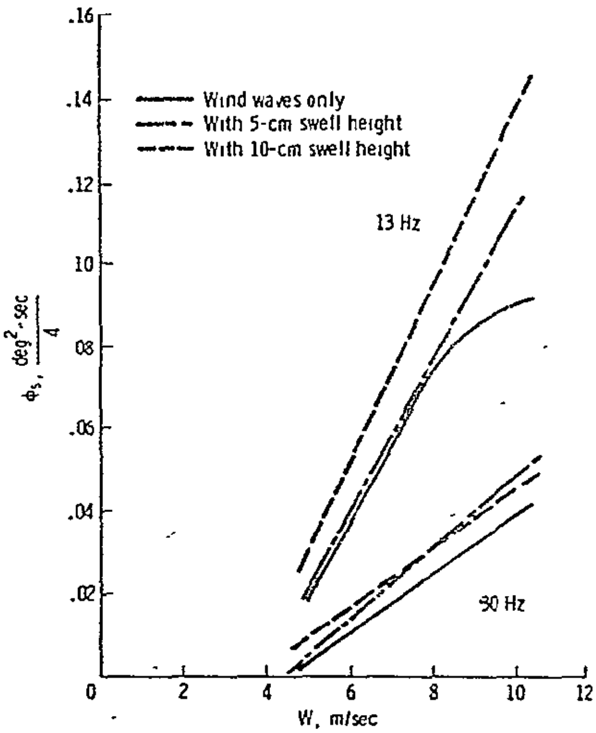


FIGURE D-2 Dependence of slope spectral values at 13 and 30 Hz on mechanically generated waves.

The modulation of capillary waves by long gravity waves can be more easily investigated by active microwave instruments in a wide range of windspeeds. Wright and Keller (1974) verified this by placing an X-band Doppler radar over Shemdin's laboratory facility. They found that the return from the water surface is strongly modulated by the long gravity waves. Sufficient evidence exists that suggests that radar return is governed not only by wind but also by all physical and dynamical factors that control the generation and decay of capillary waves.

Long (1974) attempted to refine the relationship between the radar cross section for sea echo and polarization. Theories developed recently in the U. S. and Russia predict that average radar cross section of sea echo for transmitting and receiving horizontal polarization never exceed that for vertical polarization. However, at small incidence (grazing) angles, sea echo is affected by reflection from facets, such that the horizontal polarization can exceed the vertical.

Recently, Weissman and Johnson (1977) have applied a radar technique used for measuring the statistical height properties of a random rough surface, to the problem of measuring the significant wave height and probability density function of ocean waves from an aircraft or spacecraft. The method relies on the assumption that a rough ocean surface will backscatter normally incident microwave energy as the sum of contributions from numerous independent specular points. The characteristic property of this technique is that it measures the spread in range of the incoherent specular points. Progress has been made in understanding the underlying theory of this technique and applying this measurement to the ocean surface using an airborne instrument. Results to date have demonstrated the accuracy and simplicity of the measurement and data reduction procedures.

Although, most research efforts have concentrated on scatterometer type measurements of the sea to determine structure, the use of synthetic aperture radars seem to hold additonal promise. Elachi and Brown (1977) have analyzed a number of models which would explain ocean wave imagery taken with a synthetic aperture imaging radar. Experimental observations have demonstrated that ocean surface waves and patterns can be imaged using a synthetic aperture radar. Wave scattering effects on synthetic aperture radar processing of returns from the ocean surface have been studied both theoretically and experimentally for many years. The imaging radar appears to have a great long-term potential for ocean structure determination. Spaceborne imaging radars have the capability of detecting long gravity waves and directions primarily because capillary waves vary in intensity along the profile of long waves. The variation is caused directly or indirectly by the orbital velocities of the long waves.

In conclusion, wavelength and direction of ocean waves can presently be obtained from an imaging radar. However, determining exact wave height has not been fully explored. Research into the dynamics of capillary wave modulation by long waves and the effect on surface backscatter may be useful in relating heights of long gravity waves to the modulation of the capillary wave backscatter over the wave profile. For large ocean waves, active microwave measurements are expected to produce routine estimates of significant wave height and of the directional wave spectrum. Apparently, a broad range of frequencies could be utilized. The SEASAT synthetic aperture radar will operate at 1.275 GHz.

APPENDIX E

WIND MEASUREMENTS

1. Introduction

The measurement of surface wind and directivity is important for weather forecasting and climatology studies. Also, wind measurements over the ocean are particularly important since the ocean serves as a vital transportation link, and supplies food and mineral resources.

Surface wind information, if used in conjunction with a variational analysis scheme, can significantly improve weather forecasting. Wind also affects the economics surrounding ocean transportation, fishing and mining. Since little wind information can be gathered directly at sea, there has been much interest in large scale synoptic measurements of wind magnitude and direction.

Significant passive microwave sensing research on wind magnitude measurements has been accomplished (e.g. Nordberg 1968 and 1971, William 1969, Droppleman 1970, Hollinger 1970 and 1971, and Ross 1970 and 1974). In fact, research is currently being conducted in space on Nimbus-5 and -6. However, passive sensors cannot measure wind direction.

Radar observations of the scattering cross sections from the ocean surfaces have been conducted for nearly 30 years.

Kerr (1951) was one of the first to experiment with radar-observed sea echo and led the way for future radar studies. In almost all cases, only the backscattering cross sections have been measured.

The NRL has conducted the most comprehensive measurements of the backscattering cross sections from ocean surfaces as reported by MacDonald (1956), Grant (1957) and Daley (1968). A summary of the significant NRL measurements is given in Table E-1 under Frequency Requirements. NRL has used both airborne and ground sensors, utilizing several frequencies and polarization combinations.

Krishen (1971), Moore (1971), and Newton and Rouse (1972) have described NASA missions utilizing spaceborne and airborne sensors over ocean surfaces. A summary of these measurements is also given in Table E-1.

An investigation of the possibilities of more complete observations by a composite radiometer-scatterometer instrument for remotely sensing sea winds has been conducted by Claassen et al (1973). It was found that the composite system was an improvement over either instrument separately.

Recently, Price (1976) described the wind measurement technique to be utilized by SEASAT. It was felt that the scatterometer technique to be employed will yield an estimation of surface wind speed and direction.

2. Frequency Requirements

The wind stress acting at the air-sea interface locally accounts for the wind-wave interaction. The interaction of the ocean surface winds and waves is a complex phenomenon. A complete mathematical model of ocean surface roughness as a function of surface wind velocity, has not been developed. The large volume of the radar-backscattering cross-section data gathered over rough oceans, however, has aided in the understanding of the interaction of waves and winds on the ocean surface.

It is generally accepted that the small roughness elements convey the transfer of momentum from wind to sea and that these roughness elements are in equilibrium or near equilibrium with the wind. The fact that scatterometers and radiometers are good roughness sensors has led many to believe that the surface winds can be inferred from remote microwave observations. Since this initial recognition, the value of each of these microwave devices as a sea wind sensor has been substantially demonstrated by a number of investigators.

Roughness effects, in which a scene or object scatters incident microwave energy, can be assessed by measuring the radar-scattering cross sections at various frequencies, polarizations, and incidence angles. A microwave scatterometer is a special purpose radar device which is used to quantitatively measure only the target reflectance or scattering cross section. In general, microwave scatterometers are simpler than conventional radar mechanisms because range and velocity measurement capability, and the high spacial resolution (short-pulse) requirements, are eliminated. Long-pulse and continuous wave scatterometers have been used to measure the scattering signatures of rough surfaces such as terrain or the ocean. The backscattering radar cross section σ_0, which is the backscattered power-per-unit area normalized for antenna gain, range loss, and transmitted power, is of greatest interest.

Kerr (1951) was one of the first researchers of radar-observed sea echo. He made experimental studies at 3.2, 9.3 and 24 GHz. These studies demonstrated the feasibility of measuring ocean surface conditions using microwave systems, as well as helped in the improvement of radar design and performance.

Measurements of both the ocean-surface contour and the backscattering cross sections were conducted by MacDonald (1956). These measurements were conducted at 1.25 GHz with an airborne radar, and the data corresponding to VV and HH polarization combinations were gathered. The details of ocean-surface wind, significant wave height, and mean-square slopes were presented by MacDonald. At higher angles of incidence (40° to 82°), the radar cross section decreased from -30 to -60 dB. The data showed a strong windspeed dependence with horizontal polarization returns relative to vertical returns. The range of wind velocities for these measurements extended from 0 to 15 m/sec.

The widely quoted experiments by Grant and Yaplee (1957) of NRL were performed at 9.3, 24 and 35 GHz. These data were taken with a bridge-mounted radar system using VV polarizations and with the surface wind velocities ranging from 0 to 12.9 m/sec. The measurements showed a rapid decrease in the backscattering cross section as a function of angle of incidence for surface windspeeds below 1 m/sec. At normal incidence for scattering, cross section decreased with an increase in surface wind velocity. For 24 and 35 GHz, the scattering cross section increased with wind velocity for incident angles higher than 20°.

In recent years, spaceborne microwave sensors have been used by the Naval Research Laboratory (NRL), the National Aeronautics and Space Administration (NASA), and the National Oceanic and Atmospheric Administration (NOAA) to gather both active and passive microwave data over oceans. Table E-1 gives a summary of the active measurements.

Table E-1

Available Radar Backscattering Cross Sections Over Water/Ocean Surfaces

Type of measurement and organization	Wavelength or frequency	Polarization combinations *	Approximate range of angles of incidence, deg	Range of winds or waves
Spaceborne experiments:				
JSC	13.9 GHz	VV, VH, HV, and HH	0 to 53	2.1 m/sec to more than 28.3 m/sec
Airborne experiments:				
NRL	0.428, 1.228, 1.25, 4.425, and 8.91 GHz	VV, VH, HV, and HH	0 to 89	2.1 m/sec to 24.7 m/sec
JSC	13.3 GHz	VV	0 to 60	3.1 m/sec to more than 28.3 m/sec
	0.4 GHz	VV, VH, HV, and HH	0 to 60	
	13.9 GHz	VV, VH, HV, and HH	0 to 50	
LaRC	13.9 GHz	VV, VH, HV, and HH	0 to 50	3.1 m/sec to 20.6 m/sec
From platform/bridges				
NRL	8.6 mm, 1.25, and 3.2 cm	VV	0 to 80	0 to 12.9 m/sec
Wave tank measurements:				
NRL	9.375 GHz	VV and HH	10 to 86	Millimeter waves of wavelengths from 1.6 to 6 cm.

* VV=vertical transmit/vertical receive, VH=vertical transmit/horizontal receive; HH=horizontal transmit/horizontal receive; and HV=horizontal transmit/vertical receive

The NRL measurements were made over the 1964 to 1971 period using a single, four-frequency airborne radar. Four major measurement programs were conducted by NRL with surface truth measurements established by ground-based observations.

A summary of NRL measurements and ground data measurements was given by Daley (1973). The NRL measurements were presented as the median normalized radar cross section (MNRCS). The scattering cross section per unit area was defined as normalized radar cross section (NRCS).

To establish the average value of the backscattering cross section σ^0, the probability distribution of the NRCS must be known. For a Rayleigh-distributed NRCS, σ^0 can be computed by adding 1.6 dB to MNRCS. Both theory and experiment have shown that the sea return may have a probability density distribution other than Rayleigh. Hence, the average-to-median ratio may differ from 1.6 dB and depend on the sea-surface roughness.

The NRL measurements have been used to develop models for the frequency dependence of radar-backscattering cross section from the ocean surface. A more recent analysis of NRL data shows correlations between surface wind velocity and the normalized radar cross section.

During a period of several years, many aircraft missions have been flown by NASA/JSC to study the dependence of radar return on such parameters as local windspeed, wind direction, and the spectrum of the sea. Data have been collected using scatterometers at frequencies of 0.4, 13.3, and 13.9 GHz.

Extensive surface truth has been compiled, including wind and wave measurements. Krishen (1971) described the 0.4 and 13.3 GHz scatterometers whose data are collected simultaneously over incident angles between 60° and -60° by using coherent Doppler techniques. The typical backscattering cross sections from a NASA mission are presented in Figure E-1 for 13.36 GHz. A strong dependence of the backscattering cross section on surface-wind velocity was evident.

The NASA Skylab S-193 Radiometer/Scatterometer/Altimeter experiment (1972) was the first attempt to gather data using earth-oriented, spaceborne, active, microwave systems. This experiment acquired nearly simultaneous radiometric brightness temperature and radar backscatter data over land and ocean surfaces, using spaceborne microwave sensors. Definitions of sensor specifications, mission requirements, data handling, and ground truth coordination for the GEOS-C and SEASAT-A programs were influenced directly by the performance of the S-193 sensor.

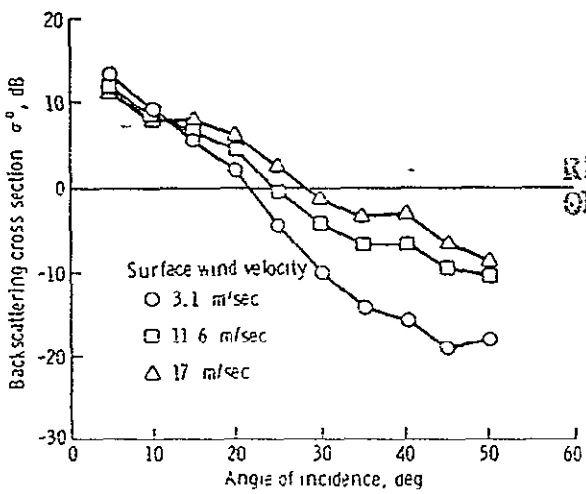


Figure E-1. Backscattering cross section as a function of angle of incidence for 13.3 GHz scatterometer (vertical transmit/vertical receive polarization).

The result of measurements taken to date reveals the following information about the dependence of the backscattering cross section from the ocean on windspeed:

- A range of radar wavelengths exists for which backscatter is primarily dependent on surface windspeed, relatively insensitive to large-scale roughness.
- Backscatter at and near the vertical (0° incident angle) monotonically decreases with increasing windspeed.
- Backscatter from incident angles greater than 20° from the vertical monotonically increases with increasing windspeed.

A representation of these three features of ocean backscatter as a function of windspeed and incident angle for a 10 to 15 GHz radar is shown in Figure E-2. The continuation of the curves beyond 30 m/sec would indicate that the monotonic changes in backscatter cross section initiated at low windspeeds probably do not stop abruptly, but become very slight at higher windspeeds. The local slope of the curves at high windspeeds indicates that extremely accurate measurements of the backscatter must be made to sense small percentage changes in windspeeds, but this accuracy is required over only a small range of backscatter values. Alternatively, the local slopes at low windspeeds indicate that less accurate measurements are required to sense small percentage windspeed changes.

The set of curves for backscatter is compared to windspeed at all angles of incidence between 0° and 55° lies between the curves shown in Figure E-2, being far apart at low windspeeds and close together at high windspeeds. The dashed line in Figure E-2 indicates that a "hypothetical incident angle of constant backscatter" lies at approximately the average level of the backscatter as compared to windspeed for incident angles between 5° and 20°.

Other aspects of backscatter measurements which present both opportunities and problems are: 1) the upwind, downwind, and crosswind viewing directions give different values for backscatter cross sections; 2) the sensitivity of backscatter to upwind, downwind, and crosswind viewing directions is different at each angle; 3) the sensitivity of backscatter at each angle to upwind, downwind, and crosswind viewing also depends on windspeed. Figure E-3 illustrates this upwind-downwinds dependency.

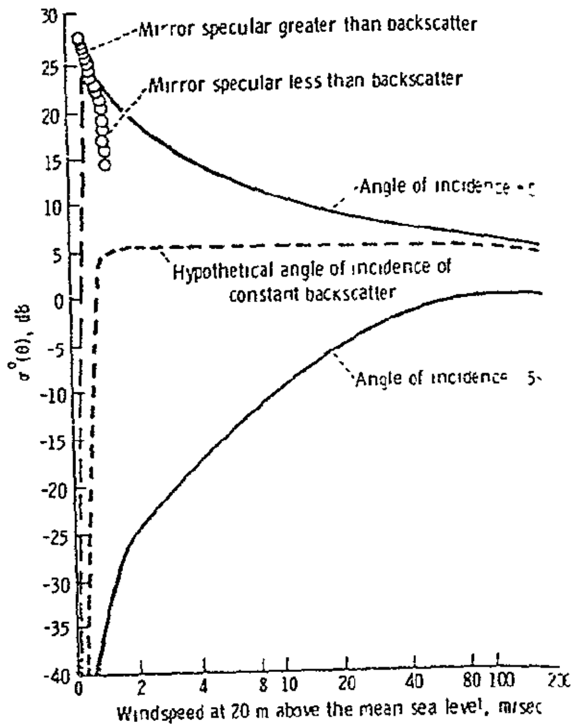


Figure E-2. Representation of approximate magnitude of backscatter cross section from the ocean at 10 to 15 GHz radar.

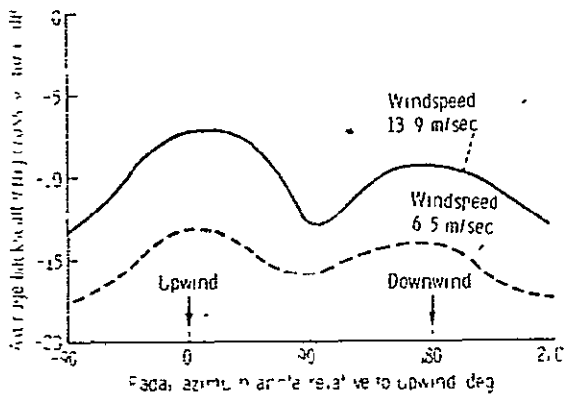


Figure E-3. Langley Res... Center values of σ^0 compared to wind heading (vertical transmit/vertical receive polarization; incident angle of 40°).

Studies of NASA scatterometer data at 13.3 GHz have shown a wind speed dependence w for observations in the upwind direction given by:

$$\sigma^0{}_{35}/\sigma^0{}_{10} = Kw^{1.49}$$

where $\sigma^0{}_{35}$ and $\sigma^0{}_{10}$ are scattering coefficients at 35° and 10° incident angles, respectively. The wind dependence has been interpreted in terms of a ratio of scattering coefficients to assure a measure of wind dependence largely independent of the accuracy and calibration of the scatterometer. Also, Claassen (1973), in a rather extensive analysis of NRL upwind scatterometer data from two missions, identified a power law wind dependence in each of the missions.

Although the active microwave measurement of windspeed has been accomplished, the measurement of its directivity has only been theoretically explored. Two methods to determine directionality were thought to be viable: 1) directivity determined by wave directions in images from synthetic aperture radars; and 2) directivity determined by two orthonormal scatterometer measurements. Since measurement by the former method is intuitive, the latter method is further explained below.

A general description of the SEASAT scatterometer has been given by Price (1976). From a height of approximately 800 kilometers the instrument will measure radar backscatter at 13.9 GHz (λ = 2.2 cm). Measurements will be taken in a cross-track pattern, with radar footprints at angles (in azimuth) 45° to right and left, fore and aft of the subsatellite track. Due to satellite motion the backscatter from a spot on the ocean surface will be measured twice, at nearly coincident times, but with a separation of 90° in the direction of measurement (Figure E-4). These two measurements of radar cross section σ, permit estimation of two quantities, surface wind speed V, and direction χ. This geometry appears to be optimum for observation from a satellite, given the level of instrumentation which is currently feasible. Observations at a number of azimuth angles would be desirable, but this would cause greater complexity in the radar scanning mechanism and electronics. The dependence of radar cross section on surface roughness has been estimated theoretically, but experimental results are not completely understood. For present purposes the dependence of cross section on surface wind is assumed, and the problem is that of inverting $\sigma(\chi,V)$ σ_2 $(\chi + 90°, V)$ to infer σ and V.

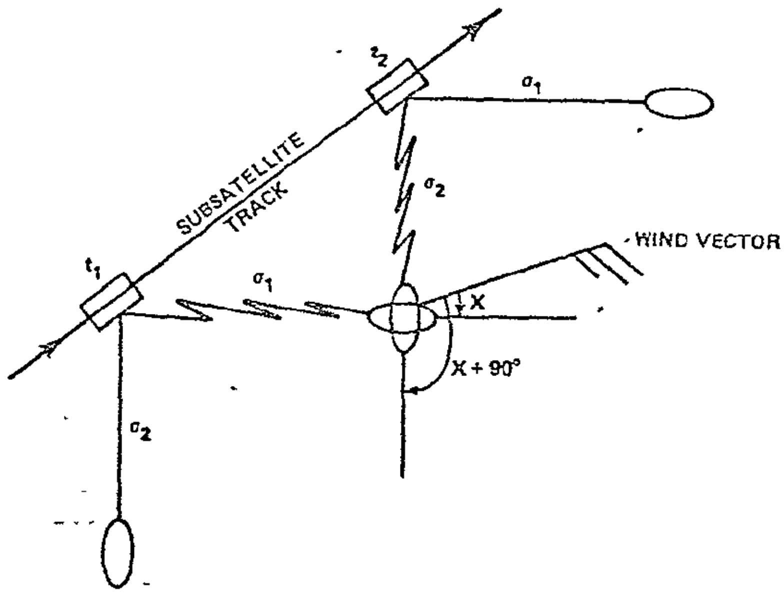


Figure E-4. View from above of scatterometer measurement geometry. The instrument is planned to view left as well as right (shown), and to scan in nadir angle from 25° to 45°, providing parallel swaths along the subsatellite track.

By scanning in nadir angle the SEASAT scatterometer will provide wind field estimates in swaths on both sides of the subsatellite track. An additional backscatter measurement along the subsatellite track, scanned from 0-65° nadir angle, will provide information to aid in joining the wind fields generated from the left and right backscatter measurement patterns (at near nadir viewing the pairs of measurements are not independent and no information is available on wind direction.

In conclusion, the performance of NASA 13.3-13.9 GHz scatterometers has been fully demonstrated by aircraft and Skylab missions. These systems were basically experimental and other frequencies up to 35 GHz bave been utilized. Recent discussions with experimenters indicate that for scatterometer wind measurements 10-15 GHz is a useful region since the windspeed dynamic range is high and atmospheric effects are small.

APPENDIX F

RAIN MEASUREMENTS

1. Introduction

The measurement of rainfall intensity, measurements of storm maximum echo heights, and measurements of the height of the melting layer in clouds are important to improved weather prediction and climatology studies.

Ground meteorological radars have been in use for over 25 years Ground radars have been shown to be able to detect the presence of precipitation, map its physical size and shape, and determine its intensity. Thus, it was natural that during the late 1950's several papers were published on the potential of spaceborne radars. Moot and Johnson were probably the first to describe a downward looking spaceborne radar (1959). Some of the problems with radar meteorological satellites were discussed by Keigler and Krawitz (1960). The primary problems discussed were the effect of ground return on the measurement of precipitation and the limitation imposed by the antenna beamwidth on the vertical discrimination.

Also in 1960, Katzenstein and Sullivan suggested that the echo from rain could be distinguished from the ground echo on the basis of different doppler frequency shifts. Interferometry methods were suggested as possible means for improving discrimination.

Dennis (1963) presented a contrasting viewpoint to Katzenstein and Sullivan. Dennis stressed the difficulty of separating of the ground echo from the precipitation echo. He was pessimistic as to the feasibility of radar meteorological satellites, noting that radar observations of precipitation cannot be extrapolated very far in either time or space.

In the years following the Dennis report, radar technology has seen various improvements. In addition, numerical models for weather prediction have been developed for use, along with models of cloud and precipitation processes. Therefore, more meaningful results have been obtained in subsequent radar studies.

V. D. Stepanenko's work (1973) indicated that with a downward looking, scanning pencil beam antenna, the effect of the earth echo is not important. However, earth echo was shown to be important when a fixed, planar radiation pattern was employed.

Mitchell (1966) was one of the first to present detailed considerations for the choice of radar precipitation frequencies. Atlas and Ulbrich (1973) supported Mitchell's findings. The concept of multifrequency radar, for possible improvements in observing and measuring precipitation, was also addressed by Eccles (1970), Atlas (1973), and Goldhirsh (1974). The desirability of multifrequency usage is based on the fact that rainfall rate and reflectivity are not uniquely determinable.

Skolnik (1974) further explored the possibility of using satellite radars for the observation of precipitation. Skolnik primarily addressed the detection of the minimum amount of rainfall, and the coarse measurement of its physical extent in space. Spaceborne radars, he felt, could indeed obtain useful measurements of precipitation; however, the economics were considered the primary limitation to practical applications.

Richter (1975) recently described a very sensitive, very high range resolution radar which was specifically designed for remote sensing of refractivity fluctuations in the clear atmosphere. McCormick and Hendry (1975) have investigated methods for determing certain parameters of precipitation particles by means of a radar with two-channel orthogonal polarization capability.

Also in 1975, Eckerman (NASA-Goddard) proposed a meteorological radar capable of 3-dimensional mapping of rain intensity, as well as wind movement within storms. His proposed system would utilize multiple, narrow beams in a "push broom" mode.

Satellites could provide for a significant increase of the meteorological radar coverage by extending observations to the oceans and other areas that are not presently covered by weather radar systems. Most importantly, active sensors have a vertical resolution capability which is useful in three-dimensional mapping. Passive sensors have only a two-dimensional rain mapping capability.

2. Frequency Requirements

The amount of reflected radar return from precipitation is primarily determined by the drop-size and vertical distribution of the rain. Vertical distribution of rain drops, in turn, is dependent on the rain rate.

Since ground meteorological radars had been utilized for many years, it was natural that in the 1950's consideration was given to employing meteorological radars in space.

A review of the early considerations involving radar meteorological satellites was made by Dennis (1963). Dennis pointed out two main problems in the use of meteorological satellite-borne radar systems:

- Observations are limited to a narrow subsatellite swath due to the need for separating the contribution of the precipitation, and of the ground or sea surface underneath (Keigler and Krawitz, 1960).

- Observations of precipitation cannot be extrapolated very far in either time or space. Therefore, an orbiting satellite providing observations on a 12- or 24-hour return cycle would not be of much value to the usual operational application of weather radar data.

Stepanenko (1973) discussed in detail the use of radar and microwave radiometry in satellites for obtaining meteorological and hydrological information. Stepanenko studied the effects of utilizing a scanning pencil beam or a fixed planar beam on a space-borne meteorological satellite. It was found that a scanning pencil beam antenna minimized clutter returns form the Earth's surface. Earth echo, however, was found to be extremely important for fixed planar beams.

Stepanenko chose an X-band (10 GHz) for his scanning pencil beam system since, at this wavelength, detailed scattering coefficient data, as a function of view in angle, were available for various surfaces of the Earth. It was expected that a 1.5 mm/hr rainfall rate could be detected. Stepanenko further indicated that in the future, it should be possible to measure rainfall intensity in addition to simple detection.

To improve the sensitivity in clutter conditions, Skolnik (1974) suggested a dual-band radar similar to that proposed by Keigler and Krawitz (1960). In order to increase the radar system effectiveness for precipitation measurement it is necessary to try to reduce the effect of the ground reflection. To a large degree, this problem can be solved by utilizing a dual-band radar, rather than a planar beam radar. Table F-1a and F-1b present Skolnik's calculated minimum detectable rain intensity for a planar-beam radar and a dual-band radar. For the dual band radar, frequencies of 10 and 37.5 GHz were utilized since detailed values were available for the diffuse earth reflection coefficient as a function of viewing angle.

Skolnik stressed the importance of insuring a sufficient signal-to-clutter (S/C) ratio, as well as a sufficient signal-to-noise (S/N) ratio. The signal-to-clutter ratio can be increased by increasing the frequency since the volume reflectivity of rain increases almost as f^4 (f = frequency), but the clutter cross section increases only slowly with frequency.

TABLE F-1a

MINIMUM DETECTABLE INTENSITY OF
RAIN (mm/hr) WITH RADAR WITH PLANAR BEAMS

	Orbital Altitude (R_m), km			
Clutter	300	400	500	600
from land	9.1	8.0	7.0	7.3
without clutter	1.5	2.0	2.8	3.4
from water surface	2.0	3.1	2.8	3.7

TABLE F-1b

MINIMUM DETECTABLE INTENSITY OF
RAIN (mm/hr) WITH TWO-BAND RADAR

		B^o - depression angle of near-edge of coverage			
Surface	R_m, km	10	30	50	70
Land	300	0.5	1.8	3.6	4.0
Sea		0.42	0.42	0.42	0.42
Land	400	0.76	0.76	3.16	3.5
Sea		0.7	0.7	0.7	0.7
Land	500	0.95	1.73	2.9	3.1
Sea	0.93	0.93	0.93	0.93	0.93
Land	600	1.2	1.79	2.8	3.0
Sea	1.16	1.16	1.16	1.16	1.16

Table F-2 lists the characteristics of four single-frequency radar systems, as presented by Skolnik. The antenna beamwidths were fixed, but the transmitter power was decreased with increasing frequency due to greater reflectivity and hence S/C and S/N. The system noise temperature however increases with frequency. Skolnik pointed out that the values presented in table F-2 were calculated on the basis of Rayleigh scatter so that $\eta \sim f^4$ (where η = radar cross section of rain per unit volume reflectivity). In the millimeter wave region, Rayleigh scatter is not applicable and η will probably be less than is given by the Rayleigh law. Thus, the minimum detectable rainfall rate calculated for the millimeter wave radar is probably optimistic, and hence, a rain measuring spaceborne radar should operate below 94 GHz.

Skolnik felt that if a 9 m antenna could be implemented on a satellite, a good choice of frequency is X band. If antenna size is a problem, then the Ka band (35 GHz) radar would be a more suitable frequency. A more thorough analysis was felt to be needed before optimum frequencies could be selected. However, Skolnik preferred the Ka band radar, with an attempt to improve the signal-to-noise ratio by an increase of transmitter power to 180 W average.

Although, in the sidelooking radar, the echo signal from rain competes with the echo from ground clutter, the system parameters in table F-2 were chosen so that the S/C and S/N ratios would be adequate. However, a scanning pencil beam antenna might be more beneficial.

TABLE F-2

SIDELOOKING RADAR CHARACTERISTICS

Frequency	10 GHz	16 GHz	35 GHz	94 GHz
Transmitter average power	500 w	200 w	100 w	50 w
Antenna:				
elevation beam	28°	28°	28°	28°
azimuth beam	0.2°	0.2°	0.2°	0.2°
size	9m by 12cm	5.6m by 8cm	2.6m by 3.5cm	0.96m by 1.3cm
Pulse width, μsec	40	40	40	40
Pulse repetition rate, Hz	80	80	80	80
Maximum range, nmi	1000	1000	1000	1000
System noise temp. °K	1000	2000	3000	5000
System losses, dB	10	10	10	10
Peak power, kw	160	65	32	16
Rainfall rate, mm/hr*	4.36	6.7	4.93	3.04
S/N at max. range	13 dB	13 dB	13 dB	13 dB
S/N at min. range	26 dB	26 dB	26 dB	26 dB
S/C at max. range (r=4mm/hr)	27 dB	27 dB	27 dB	27 dB
S/C at min. range (r=4mm/hr)	14 dB	14 dB	14 dB	14 dB

Satellite altitude = 220 nmi.

Swath coverage = 200 to 950 nmi off ground track, 750 nmi total

*Noise limited

For low orbit and synchronous orbit applications, Skolnik made the following observations.

- Low Orbit - the downward-looking scanning pencil beam could detect a lighter rainfall than the fixed sidelooking system; it has a lower power, but requires a more complex antenna and has a smaller swath coverage. It is the only radar considered that has the ability to measure the height of the precipitation, especially the height of the cloud top and the freezing layer. It can also provide a quantitative measure of the precipitation intensity. No other passive or active sensor seems to have the capability provided by the downward-looking scanning pencil beam radar.

- Synchronous Satellite - a synchronous satellite has the advantage of being able to observe a storm continuously anywhere within a large area on the earth's surface. Both a downward looking scanning pencil beam system and a horizon scanning pencil beam system could be utilized. They both have the capability of rainfall detection, but the latter is probably capable of greater coverage. They should be able to detect 4 mm/hr. rainfall. Radars in synchronous orbit would be large and heavier than those in low orbit, but the chief concern is their extremely poor spacial resolution and high required powers. The size of the resolution cell in the cross-range dimensions will likely be larger than most storms.

Skolnik primarily addressed the problem of detection of precipitation. However, measuring the rate of precipitation is of

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paramount concern. A simple ranging radar, capable of detecting precipitation, could estimate rain rates by measuring the maximum echo height and melting layer in clouds.

Maximum echo height is a good indicator of the intensity of a storm and the rate of rain production in convective storms. Maximum echo heights from 5 to 8 km are associated with rains caused by middle-latitude cyclonic storms. Other typical maximum echo heights are Thunderstorms - (>10 km) Hailstorms - (>13 km) and Severe storms with tornadoes - (20 km).

The height of the melting layer is detected by radar as a "bright band", which is characterized by a significant increase of radar reflectivity at this level due to the partial melting of frozen hydrometers. The height of the melting layer can also be used as a measure of the intensity and state of development of tropical storms.

However, direct measurement of precipitation rates at various levels within precipitation systems is most desirable. The concept of multi-frequency radar has been advanced by Eccles (1970), Atlas (1973), and Goldhirsh (1974) as a method for measuring precipitation rates. It has been found that there is no specific relationship between precipitation rate and radar reflectivity, due to variations in rain-drop size and distributions. However, a comparison of radar reflectivity at attenuating and non-attenuating frequencies was believed to have potential for accurate measurements. In general, these authors discuss various frequency combinations around 2, 5, 10, 30 and 60 GHz.

A spaceborne meteorological radar has been proposed for the space shuttle (Echerman, 1975). This radar would use narrow, multiple beams in a "push broom" mode in order to both minimize ground clutter and achieve higher measurement accuracy through integration of multiple returns over the 3-dB beamwidth. Eckerman also proposed the addition of a doppler capability to the radar in order to monitor mean wind fields inside precipitation systems using the precipitation particles as tracers for wind motion. Eckerman noted that due to trade-offs between spacial resolution/antenna size, sensitivity and dynamic range, the use of multi-frequencies is highly desirable. However, recent discussions with the author indicate that a single frequency with an assumed drop-size spectrum is as good as a two frequency system. Based on the author's recent work, the highest useful frequency, with large rain-rate dynamic range, is 15 GHz. Based on dynamic range requirements of 1-200 mm/hr, high resolution requirements and limitations on practical spaceborne antenna sizes, a one frequency radar in the 9-10 GHz region would appear optional.

In conclusion, terrestrial meteorological radars have been in use for many years and their adaptation to space-use is expected. Although a multifrequency radar is generally preferred, a one frequency radar seems adequate for measuring precipitation rates. The 9-10 GHz region appears optional with 15 GHz being the upperbound with reasonable dynamic range. The primary advantage of radars over passive microwave radiometers is that radars provide vertical profiles of precipitation distributions over land masses as well as oceans.

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