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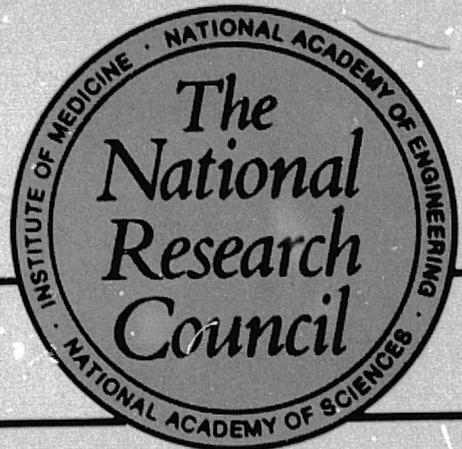
NAS W-3043

# Microwave Remote Sensing from Space for Earth Resource Surveys

(NASA-CR-157891) MICROWAVE REMOTE SENSING  
FROM SPACE FOR EARTH RESOURCE SURVEYS  
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Committee on Remote Sensing Programs for Earth Resource Surveys

Commission on Natural Resources

ERRATA SHEET FOR NATIONAL RESEARCH COUNCIL REPORT:

MICROWAVE REMOTE SENSING  
FROM SPACE FOR  
EARTH RESOURCE SURVEYS

- 1) Pages 62 and 84

Change Note 1 to Read:

Ulaby, F., Director, Remote Sensing Laboratory, University of  
Kansas, Presentation to CORSPERS, April 15, 1977.

- 2) Page 137

Replace Appendix C - Radar Band Designations with the corrected  
version.

# Microwave Remote Sensing from Space for Earth Resource Surveys

A report prepared by the  
Committee on Remote Sensing Programs  
for Earth Resource Surveys

Commission on Natural Resources

National Research Council

NATIONAL ACADEMY OF SCIENCES  
Washington, D.C. 1977

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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COMMITTEE ON REMOTE SENSING PROGRAMS  
FOR EARTH RESOURCE SURVEYS

October 31, 1977

Dr. Gilbert White  
Chairman, Commission on Natural Resources  
National Research Council  
Washington, D.C. 20548

Dear Dr. White:

The Committee on Remote Sensing Programs for Earth Resource Surveys, COMSPERS, has completed a review of a proposed Microwave Remote Sensing Program Five Year Technical Plan, 1977-78, currently under consideration by the Office of Applications in NASA.

The Plan, as presented to the Committee, was still in its early formative stages. This made it somewhat difficult for the Committee to make definitive recommendations. The Committee took a more fundamental approach to the use of microwave sensing by analyzing each of the remote sensing application objectives of the Plan in terms of the basic capabilities of active and passive microwave sensors. The results of these analyses were then used in formulating the Committee's recommendations with respect to the sensing systems in the Five Year Plan.

The Committee concluded that an adequate experimental data base was available to support the initial development of an experimental radiometer sensor system (passive microwave sensor) for soil moisture, sub-surface phenomena, and salinity measurements and a single-frequency single-polarization radar for geological explorations as scuffle experiments. The Committee did not feel that an adequate experimental data base was available to support the initial development of a multi-frequency multi-polarization radar for soil moisture measurements and vegetation or crop classification purposes.

I am pleased to transmit to the Commission on Natural Resources the Committee's report, "Microwave Remote Sensing from Space for Earth Resource Surveys".

Sincerely,



Arthur G. Anderson,  
Chairman

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# Contents

ACTION SUMMARY	1
I. INTRODUCTION	7
II. EARTH RESOURCES SENSING WITH RADAR	11
2.1 Concepts of Radar Remote Sensing	11
2.1.1 Normal Radar Measurements	12
2.1.2 Amplitude Measurements	13
2.1.3 Other Factors	15
2.2 Radar Technology Review and Available Data Base	16
2.2.1 Synthetic Aperture Radar	16
2.2.2 Area and Boundary Mapping	18
2.2.3 Soil Moisture	20
2.2.4 Crop Identification	21
2.2.5 Multi-Frequency Multi-Polarization Data	24
III. EARTH RESOURCES SENSING WITH MICROWAVE RADIOMETRY	29
3.1 Concepts of Microwave Radiometry	29
3.1.1 Brightness Temperature	29
3.1.2 Microwave Radiometer Implementation	31
3.1.3 Antenna Considerations	32
3.1.4 Relative Advantages and Limitations of the Microwave Radiometer	34
3.2 Microwave Radiometer	34
3.2.1 Applications of Microwave Radiometry	34
3.2.2 Space Experience	35
3.2.3 Measurement of Soil Moisture	37
3.2.4 Earth Resource Sensing by Microwave Radiometry	38

IV. APPLICATIONS OF REMOTELY SENSED RESOURCE SURVEY DATA	43
4.0 Introduction	43
4.1 Hydrology	49
4.1.1 Surface Water	49
4.1.2 Drainage Patterns	50
4.1.3 Runoff Coefficient	51
4.1.4 Urban Drainage Features	51
4.1.5 Precipitation Rate Over Land	52
4.1.6 Other Applications	52
4.1.7 Conclusions	52
4.2 Vegetation Resource Analysis	56
4.2.1 Vegetation Classification	57
4.2.2 World Carbon Budget	58
4.2.3 Soil Moisture	58
4.2.4 Conclusions	60
4.3 Geology	64
4.3.1 Mapping of Geologic Structure	65
4.3.2 Rock Type Identification	65
4.3.3 System Parameters	66
4.3.4 Conclusions	67
4.4 Land Use	69
4.4.1 Conclusions	71
4.5 Cartography as a User Discipline	73
4.5.1 Conclusions	75
4.6 Environmental Monitoring	76
4.6.1 Introduction	76
4.6.2 Water Quality	76
4.6.3 Land Quality	77
4.7 Coastal Features and Processes	80
4.7.1 Wetlands Mapping	80
4.7.2 Estuaries and Inland Waters	81
4.7.3 Coastal Storm Impact	82
4.7.4 Conclusions	83
4.8 Ice and Snow	87
V. CONCLUDING DISCUSSION	91

5.0	Introduction	91
5.1	Approved Space Microwave Sensors	91
5.1.1	SEASAT	92
5.1.2	SIR-A	92
5.2	Proposed Microwave Sensors	92
5.2.1	Active Systems	92
5.2.2	Passive Systems	94
5.3	The Use of the Shuttle as a Development Platform	95
5.4	A Suggested Development Logic	95
APPENDIXES		
A.	SEASAT-A	99
B.	SIR-A	107
C.	SIR-B	113
D.	THEMATIC MAPPER and MSS	121
E.	SIMS	123
F.	SMMRE	129
G.	Radar Band Designations	137
H.	Acronyms	139

# Action Summary

In response to a request from the National Aeronautics and Space Administration (NASA) and the collaborating federal agencies, the National Research Council Committee on Remote Sensing Programs for Earth Resource Surveys, CORSPERS, reviewed the proposed Microwave Remote Sensing Program Five Year Technical Plan, 1977-1982, currently under consideration by the Office of Applications in NASA.

Some of the well recognized capabilities of microwave sensors can make useful contributions to earth resource sensing. Their capability to penetrate cloud cover and possibly vegetation cover can be important in land regions that are often obscured by clouds or are covered by vegetation. Their capability to function both during day and night can also be useful in some applications. In the active microwave area, the Committee was made aware of the aircraft radar mapping of Brazil, Project RADAM. In the passive microwave area, the Committee noted extensive experience in the meteorological program to measure brightness temperature differences, which should also have useful applications in earth resource surveys.

## 1. Passive Microwave Sensors

The Committee reviewed the proposed plan to apply passive microwave techniques to earth resource sensing. The Committee agreed that either the proposed JPL Shuttle Imaging Microwave System (SIMS) or the GSFC Shuttle Multi-function Microwave Radiometer Experiment (SMMRE), could serve as a useful research and development tool to extend our present understanding of passive technique obtained from the meteorological program into the field of earth resource applications. The complementary use of airborne passive sensors along with a carefully planned program to collect ground truth data would be, in the Committee's judgment, a reasonable approach to the exploitation of passive microwave technology for earth resource surveys from space.

## 2. Active Microwave Sensors

One of the primary capabilities of an active microwave radar is to measure distance. With synthetic aperture techniques, this capability can be extended to produce imagery that shows the spatial distribution of elements within a scene. With the proper viewing angle and proper spatial resolution, this capability can produce useful data on surface features of interest to geologists, land use planners, and water resource managers. Project RADAM provided an example of this capability from airborne radars for large regional surveys. Recent experiments on combining LANDSAT imagery with aircraft radar imagery of a higher resolution provided indications of the potential of space radar as a companion sensor to LANDSAT sensors. The Committee understands that NASA is proceeding with the SIR-A, an L-band single frequency modified SEASAT radar, for launch in the shuttle around July 1979. The SIR-A should provide data on the potential of radars in space to measure the spatial distribution of features on the surface of the earth. The Committee expects that this radar imagery, when used in conjunction with LANDSAT 1, 2 and 3 imagery, will enhance the usefulness of LANDSAT for geologic and other land use applications, although it will not serve conventional cartography. Even though the potential enhancement of the higher resolution LANDSAT D (THEMATIC MAPPER) data may not be as significant, the Committee expects the complementary use of these two sensors to be a worthwhile experiment.

A major objective of the Five Year Technical Plan is to develop an active microwave dual-frequency, dual-polarization imaging radar for vegetation classification and soil moisture measurement. The expectation is that the variation in signal return from elements in the illuminated scene at different frequencies and different polarizations will provide reliable signatures to classify the individual elements in the scene. In the Committee's view the experimental data base, as presented, is too limited to support this development. The experiments to date have covered only a very narrow range of conditions. The lack of adequate ground truth in some cases has seriously degraded the credibility of these experiments. The Committee is concerned that, while intensity variations were noted in the experimental aircraft imagery collected at different frequencies and different polarizations, the repeatability of these variations was not demonstrated. The signal, as received by the sensor, is a measure of the backscattered energy returned from the target. Individual elements in the illuminated scene act as independent radiators. The backscattered energy is affected by the shape, size, orientation, roughness, moisture content, dielectric constant, etc. of each illuminated element. The random and

variable nature and distribution of these elements from scene to scene and their relative independence from the object to be classified presents an extremely difficult classification problem.

In the Committee's view, the critical consideration lies in understanding the complex interrelationships of the factors that affect the magnitude and intensity of the backscattered signal, and the relationship of this signal to the desired information. The evidence presented to the Committee did not establish that this understanding exists nor that an empirical relationship between the measured data and the desired information can be developed. Therefore it is not possible at this time to speculate on the potential usefulness of active microwave sensors for vegetation classification.

### 3. Soil Moisture Measurements

The Committee recognizes that soil moisture information is an important parameter in crop forecasting. In the Committee's view the proposed approach in the Five Year Technical Plan to measure soil moisture at 30 meters resolution is not realistic for several reasons. No evidence was presented to the Committee that radar cross section per unit area can be measured with the necessary accuracy to provide meaningful soil moisture information.

The Committee wishes to point out that high resolution space sensors normally are associated with high cost, high data rate, narrow swath width, and low revisit time of the same area. For crop forecasting purposes the frequency of coverage (revisit time) for soil moisture conditions is critical during the active growing season. In order to determine this frequency, we must have a reasonably good understanding of the dynamics of the soil moisture model for various soils and soil conditions. The relationship of the surface or near-surface manifestations of moisture down to and below the plant root depth must be understood. Only by understanding the dynamics of this relationship can one determine the required measurement interval. The information on the soil moisture model, as presented to the Committee, was not adequate to make this determination. Intuitively, the Committee feels that the required interval is probably much shorter than the current LANDSAT nine day interval, which is also the proposed coverage frequency for the 30 meter resolution LANDSAT D system. Experimental work should be done to develop a better understanding of the soil moisture model in order to establish the range of acceptable measurement time intervals.

The Committee does not agree that it is necessary to measure soil moisture at the proposed high spatial resolutions for crop forecasting purposes. While there may be small scale variations in soil moisture due to varying soil and drainage conditions or highly localized thunderstorms that can best be measured at a relatively high spatial resolution, the Committee does not consider these variations significant in overall crop forecasting. Natural moisture conditions significant to this purpose are generally related to wide area meteorological phenomena and therefore are of comparable scale. It would seem that the coarse spatial resolution normally associated with passive systems should be adequate to assist in crop forecasting. Therefore, by relaxing the spatial resolution requirement for soil moisture, system trade-offs should be possible that will provide adequate coverage frequency at reasonable data rates. There is experimental evidence that measurements by passive microwave systems can be related to the soil moisture conditions, provided the frequency of measurements is adequate.

#### 4. Recommendations

In conclusion, the Committee:

- Endorses proceeding with the passive imaging microwave program,
- Endorses the development of active microwave space-borne sensors that can measure the spatial distribution of the elements within a scene,
- Urges extensive and repeated experiments with multi-frequency and multi-polarization active microwave sensors under a controlled but expanded range of conditions with adequate ground truth to determine the repeatability of vegetation classification before proceeding with the development of space systems,
- Suggests that for crop forecasting applications, passive rather than active microwave techniques are probably more cost-effective in providing the necessary soil moisture measurements, and
- Suggests that for general earth resource survey purposes, microwave techniques from space should be considered an adjunct to the LANDSAT visible and infrared techniques rather than a primary source for earth resource data.

Development of microwave sensors should not move forward with the same risk factor or uncertainty of success used

when the original ERTS (LANDSAT) program decisions were made. The urgency to expand the current visible and IR space sensing capability by the addition of microwave sensors is not as critical as that for the creation of the initial space sensing capability.

## CHAPTER I

### Introduction

Since 1967, NASA has been developing spacecraft as remote sensing platforms for the collection of useful earth resource data. Historically, this development has included not only the design and flight testing of equipment in space, but also the research and development of remote sensing systems using experimental aircraft platforms and, to a limited extent, basic research into the physics of remote sensing. This work led to the development of the highly successful Multi-Spectral Scanner (MSS) on the LANDSAT 1 and 2 spacecraft and the Earth Resources Experiment Package (EREP) carried on SKYLAB. The THEMATIC MAPPER (See Appendix D), now in the development stage, is being designed as a follow-on sensor for use in LANDSAT-D and should represent a significant improvement over the MSS.

The first active microwave sensing system to be developed for earth sensing from space is SEASAT-A (See Appendix A), scheduled for launch in 1978. As its name implies, this satellite is primarily intended for applications requiring sensing of ocean surfaces. In the past several years, attention has also been focused on the applicability of passive and active microwave remote sensing techniques to earth resource surveys. Although there are currently no approved plans for a satellite system specifically intended for this purpose, the interest in the potential capabilities of microwave technology and the availability of the space shuttle with its large payload volume has led NASA to consider the development of microwave systems for earth resource applications.

As a platform for space system experimentation, the space shuttle represents a departure from previous platforms in that it can accommodate large antenna structures, will provide for onboard data storage, has fewer power limitations, will provide the opportunity to modify the

hardware between experiments and will provide for the possibility of on-board attendance during experiments. Because of the antenna size and the large number of variables involved in optimizing a microwave sensing system, the shuttle provides an attractive opportunity for this development.

In late 1976 NASA requested the Committee on Remote Sensing Programs for Earth Resource Surveys (CORSPERS) of the National Research Council to evaluate the utility of both active and passive microwave remote sensing for earth resource applications as a supplement to or in lieu of sensing systems in the visible and infrared region. CORSPERS had previously completed an extensive review of the LANDSAT 1 investigator results in six principal application areas. The results of this review are reported in the National Academy of Sciences (NAS) report, "Remote Sensing for Resource and Environmental Surveys -- 1974." The Committee followed this study with an evaluation of the THEMATIC MAPPER, proposed as a follow-on sensor to the Multi-Spectral Scanner (MSS) carried in the initial series of LANDSAT spacecraft. In the Committee's judgment this proposed sensor, with a few minor modifications, would provide a major increase in the utility of the data for all earth resource survey applications. This evaluation is reported in the NAS report, "Resource and Environmental Surveys from Space with the THEMATIC MAPPER in the 1980's."

In conducting the present analysis, the Committee first made a general review of the active and passive microwave technologies as they relate to remote sensing. The Committee then analyzed the available experimental data base to determine the readiness of these technologies to proceed with the initial development phase leading to eventual development of operational space systems.

In making this evaluation, the Committee made several assumptions which are implicit in the report:

1. The present LANDSAT program will continue (LANDSAT 1, 2 C, D...) and will eventually become an operational system.

2. The LANDSAT operational system will be equivalent to a two spacecraft LANDSAT D system; i.e., it will have a 30 meter ground IFOV (instantaneous field of view) and a 9 day revisit time. Each spacecraft will carry a THEMATIC MAPPER and possibly, for as long as there are requirements for the data, a Multi-Spectral Scanner equivalent to the LANDSAT C type.

3. The users of microwave sensed earth resource data will generally be found in an expanded LANDSAT user community.

4. Since the development of visible and infrared remote sensing technology has matured to the point where operationally useful systems can now be designed and deployed, there is less justification than with the earlier ERTS (LANDSAT) program to proceed with a high risk development program to develop microwave sensors for the same general application.

The case for active microwave sensors is reported in Chapter II and that for passive microwave sensors is reported in Chapter III. This is followed by an analysis in Chapter IV of the potential utility of spaceborne microwave sensors to provide useful data for specific earth resource applications. Finally, Chapter V provides a concluding discussion of these analyses and the Committee's conclusions and recommendations.

Included in the Appendix of this report are supporting papers and tables to this study report which were provided by the federal agencies and other sources. Appendix A contains a brief description of the sensor complement to be carried on board SEASAT-A. This represents an important early step in the proposed development of microwave sensors for earth resource surveys since the synthetic aperture radar in SIR-A is a modified SEASAT radar. The other microwave sensors in SEASAT-A should also be of general interest to earth resource managers.

Appendixes B and C provide a description of the synthetic aperture radars in the proposed Five Year Plan. Appendix D includes a table listing the characteristics of the LANDSAT 1 and 2 multispectral scanner and the THEMATIC MAPPER scheduled for LANDSAT-D in 1980

Appendixes E and F include papers that describe the two proposed passive microwave radiometers which are under consideration for the Five Year Plan. One of these, or some modification thereof, will be selected for inclusion in the plan.

Appendixes G and H include a listing of the radar band designations and sensor system acronyms used in the text of this report.

## CHAPTER II

# Earth Resources Sensing With Radar

### 2.1 Concepts of Radar Remote Sensing

Much information can be inferred from the active microwave sensor (radar) echo about the nature of a scattering object (target). The basic information available from radar observations is well known, and to a large extent radar capabilities have been amply demonstrated in many applications. Some of the proposed uses of radar for conducting earth resource surveys from a space platform, however, are different from those normally associated with conventional radars or other spaceborne radars. The purpose of this section is to briefly review the basic measurements that can be made by radar. Section 2.2 will attempt to relate them to the spacecraft radar measurements proposed for the Earth Resource Survey Program. This is not meant to be an exhaustive review, but simply to indicate what radar can and cannot do.

It should be kept in mind that a radar is responsive to the reflected energy from sharp discontinuities in the transmission medium or from those features of the target that have sizes comparable to the sensor's wavelength. Thus, the energy of a microwave radar signal interacts with those features of a target that have characteristic sizes on the order of centimeters, while optical and IR sensors are sensitive to scatterer sizes on the order of micrometers. The radar senses different characteristics of a target than an optical or an IR sensor. A radar image should therefore not be expected to look like or contain the identical information as an optical image even if the resolutions are comparable.

### 2.1.1 Normal Radar Measurements

Range Range, or distance to the target, is the major measurement that can be made by radar, for which it has no competitor. An accuracy of a few tens of meters, independent of range, is not uncommon; an accuracy of several centimeters is possible. (This will be the basis for the measurement of the earth's geoid by the SEASAT altimeter in 1978. This is discussed in Appendix A.)

Range Profile Good range accuracy implies the possibility of good resolution in the range coordinate. Scattering centers separated by several centimeters in the range coordinate can be resolved with modern radar technology. High range resolution permits the profile of a scattering object to be determined. This is used in the SEASAT radar altimeter for the measurement of wave height. It is also an important component of imaging radars, such as the synthetic aperture radar (SAR), that provide high resolution in both range and cross-range. (See Section 2.2.1 for a more detailed discussion of SAR.)

Angle Directive (narrow beamwidth) antennas are commonly used in radar to determine the angular location of targets. This is an important measurement in many conventional ground or airborne radar applications. In order to achieve the same linear resolution of target features from space sensors, the angular resolution in beamwidth required in a space system is far more stringent because of the greater distances involved. A beamwidth on the order of a fraction of a degree is probably the best that is practical from space, while the smallest beamwidth achieved with precision ground-based antennas is slightly less than one milliradian. Since beamwidth is critical in determining angular resolution in conventional radars, other techniques, such as the doppler frequency shift discussed below, are of interest in developing equivalent angular resolution from space systems.

Doppler Frequency Shift A target's radial component of movement relative to the radar produces a doppler shift in the frequency of the radar signal return. In conventional radar applications, this doppler shift is a measurement of the rate-of-change of the radial-range component, or relative velocity. This technique is employed in ground or airborne CW (continuous wave), MTI (moving target indication), and pulse doppler radars to separate undesired fixed-target echoes from desired moving-target echoes. This technique of using the doppler frequency shift to obtain relative radial velocity as an end product is not of interest in earth resource survey applications. However, the use of the doppler frequency shift is of significance in spaceborne synthetic aperture radar (SAR) (Section 2.2.1)

since it can provide resolution in the cross-range coordinate. In general, whatever resolution can be obtained in the range coordinate can also be obtained in the cross-range coordinate. When the SAR antenna beam is directed broadside (perpendicular to the platform trajectory), the cross-range coordinate is parallel to the platform motion and perpendicular to the range coordinate.

### 2.1.2 Amplitude Measurements

The range, range profile, angle, and doppler frequency shift measurements discussed above are the normal measurements made by radar and are dependent on antenna design, frequency, bandwidth, and time duration of the signal. The target cross-section, obtained from the amplitude of the echo signal, provides additional information about the target. Echo signal amplitude, however, has not been generally used as an information carrier and its effectiveness for this purpose is less certain. This is briefly discussed below.

Amplitude as a Function of Frequency The variation of the echo amplitude as a function of frequency provides a measurement of the target size in the range coordinate. Such a measurement can sometimes provide information on surface roughness. If the frequency spectrum over which the amplitude observation is made is continuous, the range profile measurement made by a short pulse or a pulse-compression waveform occupying the same frequency band would be equivalent. If the amplitude measurement is made at only a few discrete frequencies within this band, the quality of the measurement or its information content is less certain. The utility of a few discrete measurements, as proposed for some earth resource survey applications, will depend on the particular nature of the scattering object. Discrete or sampled measurements, in principle, result in ambiguities whose significance depends on the nature of the sampling and the type of target. There have been few, if any, successful applications of this principle. The dual-frequency, dual-polarization radar considered for crop identification (discussed in Section 2.2.4), as described to the Committee, is based, in part, on the utilization of amplitude variations of the scattering with frequency.

Amplitude as a Function of Time In principle, this is a measurement of the change of target "shape." It has been used to good advantage in ground-based Space Object Identification (SOI) radar where the target is an isolated object against an empty background. The converse system, with a radar in space sensing objects on the surface of the earth, is not able to make useful measurements because the

rapid motion of the platform masks any differences in target motion within a scene on the earth.

Amplitude as a Function of Viewing Aspect This provides a measurement of the target shape. The SEASAT-A scatterometer (see Appendix A) is based on the principle of measuring amplitude as a function of viewing aspect. The scatterometer measures the microwave backscatter cross section of a surface for various angles of incidence. During flight over an area of interest, radar backscatter as a function of incidence angle is generated from which some physical attributes of the surface can be inferred. The quality of the shape measurement will depend on the number of different viewing aspects examined and the nature of the target.

Amplitude as a Function of Polarization The amplitude of the echo signal as a function of the polarization is, in its simplest form, a measurement of the target symmetry. Two extreme examples of target symmetry are a sphere and a long, thin rod. For a linearly polarized transmitted signal, the echo from a sphere exhibits no change with a change of polarization direction, but the echo from a rod exhibits a wide range of changes. The measurement of target symmetry by means of polarization can be complicated by the variation of echo amplitude with polarization as a consequence of the dielectric properties, surface roughness, incidence angle, and transmitter wavelength. In general, the scattering properties of an object can be described by the polarization matrix, which includes the amplitude and phase response of an object to two orthogonal polarizations as well as the cross-polarized response.

Absolute Amplitude Measurement The above are all basically relative measurements, that is, they measure the rate of change of amplitude as a function of frequency, spatial position, time, or polarization. It may not be as obvious, but the phase measurements of Section 2.1.1 that yield range, angle, and doppler velocity are also relative measurements of phase with respect to frequency, aspect, and time, respectively. An absolute measurement of radar cross-section can, in principle, also yield information regarding the dielectric properties of the scattering object, if the reflection coefficient of the scatterer's surface can be extracted.

Reflection Coefficient If the shape of the scattering object is known so that its cross-section can be inferred, or if the cross-section is known a priori by other means, the reflection coefficient of the object can be obtained from an absolute measurement of the echo signal. Since the reflection coefficient depends on the dielectric constant (permittivity) and the conductivity of the material making up

the scattering object, something can be inferred about the nature of the scattering material. This technique was applied to the radar echoes from the moon in order to estimate the dielectric constant and conductivity of the moon's surface. To separate the effects of the dielectric constant and the conductivity of the surface, measurements of the reflection coefficient have to be made as a function of frequency. (The proposed measurement of soil moisture by measuring the absolute echo amplitude, which is discussed in Section 2.2.3, is based on the measurement of the reflection coefficient.)

### 2.1.3 Other Factors

Coupling of Radar Measurements There is usually little coupling between the classical radar measurements of range, angle, and doppler velocity. In most applications they can be effectively decoupled. Measurements based on amplitude or cross-section, however, are not always easy to separate. For example, the measurement of the reflection coefficient can be confused by unknown surface roughness, size, orientation, and shape. These unknowns can cause the dependences on polarization to be either strong or weak. If variations of amplitude with polarization and frequency are measured, the effects of polarization may be different at the different frequencies. The relative contributions of frequency and polarization to the amplitude measurement must be made clear. The need to make soil moisture measurements over a limited range of incidence angles also seems to be based on the need to decouple the various effects that contribute to the backscattered energy.

All-weather Radar is said to be an all-weather sensor, especially when compared to infrared and optical sensors. However the weather, and in particular rain, can seriously affect some microwave measurements. The higher the radar frequency, the greater the effects. There are two basic effects of the weather on radar measurement. One is due to the backscatter from the rain within the resolution cell containing the target. The rain echo therefore needs to be small relative to the target echo if it is not to mask the desired characteristic to be measured. Rainwater actually collecting on the target can also modify the backscattered signal and mask the true nature of the target. The other effect of the rain is frequency-dependent attenuation. Both the attenuation and the backscatter vary as the fourth power of the signal frequency in the microwave region. Radars that depend on the measurement of the relative responses of the target as a function of frequency, such as proposed for crop identification, can be confused by the frequency-dependent attenuation of rain. Any radar operating at C

band (5250-5925MHz) or higher will probably suffer significant effects from rain.

## 2.2 Radar Technology Review and Available Data Base

The specific radar measurements that have been proposed for the Earth Resource Survey Program are discussed in this section. These are related to the basic measurements discussed in Section 2.1 that can be made with radar. This should provide a basis for evaluating the capability of radar to sense the desired earth resource information. The ability to make such radar measurements and their utility to earth resource surveys must be based on the current theoretical understanding of what a radar actually senses and, where this is deficient, on radar observations that can form an empirical data base. Unfortunately, a firm theoretical foundation exists only in the area of the normal radar measurements discussed in Section 2.1.1. Such an understanding does not exist in interpreting amplitude measurements discussed in Sections 2.1.2 and 2.1.3 nor is there a sufficiently comprehensive empirical data base available to provide an adequate level of confidence that the proposed radars can make effective and useful measurements of amplitude.

This section will concentrate on the three primary radar applications that have been presented to the Committee by the federal agencies. These are: 1) area and boundary mapping, 2) soil moisture measurement, and 3) crop identification. All of these applications require the use of a synthetic aperture radar (SAR).

This section also includes a discussion of the desirability of looking at polarizations other than HH, VV, and HV in the experimental program. It is conceivable that some other combination of transmit-receive polarizations may be optimal for a given application which has not as yet been considered. Such an analysis might indicate that for a given application a single frequency, four-polarization radar may be as useful as a multifrequency, two-polarization radar and, at the same time, may be considerably less expensive.

### 2.2.1 Synthetic Aperture Radar

A synthetic aperture radar (SAR) uses the cross-range motion of its mounting platform to produce an image or map of land and sea surfaces. The range coordinate resolution is obtained by conventional means, using, for example, short pulse or pulse-compression waveform techniques. (Pulse compression utilizes frequency or phase modulations on a

long pulse to provide a "tagging" of the various parts of the pulse so that, on reception, different time delays can be applied to the different parts of the pulse in order to compress it into a shorter pulse with the energy of the long pulse but the resolution of the short pulse.)

An SAR obtains its resolution in the cross-range dimension by synthesizing in space a large (imaginary) antenna aperture. It does this by storing the coherent radar echoes for the time required by the platform to move a distance equal to the length of the aperture needed to achieve the desired angular, or cross-range resolution. The processing of the radar data from a synthetic aperture radar is therefore complex. The number of pulses to be stored and processed will depend on the range. The storage and processing must be done with coherent signals in order to preserve the phase information contained in the echo signal. A focusing correction must be applied to the phase of each echo signal because the object under view is generally within the Fresnel region of the synthetic antenna. This focusing is range dependent. A range-dependent weighting must also be applied to the data to provide a suitable taper to the aperture illumination of the synthetic antenna (apodization).

Optical processing has been used in many previous SAR systems. This is not performed in real time and therefore requires the radar data to be stored on film for subsequent processing. When the amount of data collected by the SAR is not too large, digital processing in real time may be more convenient than optical processing. Digital processing can be performed on board with the processed data relayed to ground, or the radar output can be relayed to ground with the processing done on the ground.

The resolutions in range and cross-range are generally made equal. Unlike optical sensors, the resolution is essentially independent of range as long as the received signals have sufficiently high signal-to-noise ratio. The complexity of the radar increases with resolution. Because of the increasing complexity of the system, the highest resolution obtainable is not always the best for a particular application. The resolution should therefore be tailored to the requirements of the application. The resolution proposed by the federal agencies for the spacecraft SAR is 30 meters, which would make it compatible with the LANDSAT follow-on sensors.

An image produced by an SAR radar does not necessarily resemble an optical image of the same resolution since the radar echo is reflected from those features of the scene comparable in size to the radar wavelength. A radar image has therefore a more speckled, or spotty appearance, than a

photo made in the visible spectrum with ambient incoherent illumination. In this respect, the radar image is more like an image seen with a laser which are both formed by coherent electromagnetic energy.

SAR has been employed by the military, and almost all of its development has been supported in pursuit of military interests. SEASAT A, (See Appendix A) scheduled for launch in 1978, carries the first SAR sensor to be flown in space by NASA. The SEASAT SAR is a single frequency system designed to provide global ocean dynamics monitoring measurements. While the proposed SARs for earth resource sensing are similar to the SEASAT SAR, the proposed target interaction mechanism is quite different. There is good assurance that the type of radars proposed for earth resource surveys can be built and flown. The ability of these radars to make the desired measurements, however, is less certain.

A number of resource management applications have been proposed that are expected to use the data from a spacecraft Earth Resource Survey (ERS) radar. These include soil moisture mapping, water resource management, vegetation classification, geologic surveys, and terrain mapping. It is highly questionable whether a single design optimization can provide useful measurements for this variety of users. The proposed designs have not addressed the compromises required by the conflicting demands placed on the radar. While many ideas were presented to the Committee on what could be done with imaging radar, there was little coherence among the various proponents. It has been difficult to discern a unified approach either to the design or use of a spaceborne radar. As an aid to sorting out the several types of radar measurements being considered, the Committee categorized the systems into three types, based on information to be obtained for the proposed applications. These are: 1) area and boundary mapping, 2) soil moisture measurement, and 3) vegetation classification.

### 2.2.2 Area and Boundary Mapping

Area and boundary mapping and the distribution of elements within a scene is the classical application for an SAR. The SIR-A radar system, scheduled to be flown in Orbital Flight Test-2 (OFT-2) (see Appendix B) in July 1979, is a modified SEASAT radar designed for this purpose. It is a single-frequency radar with a 40 meter resolution and a 50 km swath width. The main purpose of this radar is to gather experimental data for land use mapping, geological surveys, ice dynamics, and for mapping surface water and floods. It represents the first step in the possible development of a spaceborne active microwave sensor for earth resource

surveys. There is a reasonable basis of understanding of what this type of radar measures for these applications. It is expected that a radar of this type can complement and extend LANDSAT's capabilities. Its primary purpose would be to obtain data under conditions of darkness and cloud cover when the visible and IR sensors of LANDSAT are unable to function.

Commercial use has been made of conventional SAR type radar from aircraft for geological and land use applications. Major surveys and exploration mapping of several countries, including all of Brazil, have been completed. The proposed application of an SAR for area and boundary mapping and the distribution of elements within a scene is one of the more straightforward of the several applications proposed for ERS. There is good understanding of the technical factors involved and a system can be designed for this application. Areas and their boundaries are determined by their contrast to bordering areas. SAR images can present land-water boundaries such as rivers, lakes, and flooding, as well as roads and airport runways in an easily recognizable pattern. It is also possible to recognize significant geological features within a scene.

A major criterion used by NASA in the design of a space radar system to perform area and boundary mapping is that the radar resolution be similar to that obtained with LANDSAT visible and IR sensors. Only limited information was presented to the Committee that addressed the important questions of optimum radar frequency, polarizations, resolution, and incidence angles derived from the intended geological, surface water, and flood mapping applications. Only limited reference was made to the anticipated value of this type of radar information for the intended applications relative to data from other sources. The apparent basis for proceeding with this radar experiment for ERS appears to be: 1) that which is desired from the radar is within known technology; 2) it is assumed that radar can be an important sensor in the future and therefore it is important to learn what imaging radar can do from space; and 3) equipment now exists that can serve as the first step in such a development program.

A cursory examination of the SIR-A radar and the intended applications indicates that it will have a rather limited capability. Further study and experience with the data should indicate whether a SIR-A type radar should be considered for "routine" sensing as a "free-flyer" for the continuing acquisition of data, or whether it can only be considered as the first step in the development of a more sophisticated radar with enhanced capabilities.

### 2.2.3 Soil Moisture

Soil moisture measurements for use in crop forecasting were reported to the Committee as being the primary objective of the development of the spaceborne radar. This is described as the medium-term (mid to late 1980s) microwave sensing goal of the Earth Resource Survey Program. The interest in active microwave radar for this application is based on the belief that the radar can penetrate vegetation and measure the moisture in the upper layer of the soil. Even though the passive radiometer has been more successful than active radar in measuring soil moisture, NASA apparently favors active microwave radar as the preferred approach for this application because of its superior resolution and possibly greater soil penetration capability.

Simonett (1976) has suggested that the preferred radar frequency for soil moisture measurements is around 4 GHz (C-band), and that the optimum incidence angles are between 7 and 15 degrees. Rouse<sup>2</sup> reports that the proposed SIR-B system, (See Appendix C) will be X-band plus either L-band or C-band. The incidence angle for the X-band will be 43 to 47 degrees and 10 to 20 degrees for the L or C-band. (Incidence angle is the angle between nadir and the center of the antenna beam pointing to the target.) The swath width will be relatively narrow (50 km) as compared with the LANDSAT swath wide of 185 km. The narrow swath width is not conducive to wide area measurements or frequent revisits. The criterion used for the choice of optimum resolution was not defined nor was sufficient data presented to indicate system performance sensitivity to the selection of a non-optimum frequency for a soil moisture measurement radar.

Experimental measurements made with a truck-mounted radar show an apparent correlation of radar echo strength and soil moisture.<sup>3</sup> Some of the data was obtained over vegetated fields, but some was over bare fields. Examination of the available experimental data leads to the conclusion that the spread in data is too large to provide a meaningful relationship between a radar measurement of the scattering coefficient,  $\sigma^0$ , and the percent moisture content.

The data presented to the Committee were not adequate to demonstrate that a radar can provide a unique measurement of the soil moisture, irrespective of vegetation cover and soil type and condition, with a variance small enough to be useful. It was claimed that both the vegetation above the soil and the roughness of the soil would have only a minor effect on the soil moisture measurement. The evidence presented to support this conclusion was not persuasive. At best, the radar is sensitive to the moisture in only the top

layer, and therefore cannot make meaningful measurements of moisture in the root-zone layers, which are of significance in agricultural crop forecasting. Little or no evidence was presented to support the contention that the soil moisture measurement from a spacecraft or aircraft radar is repeatable. Because of the lack of theoretical understanding and the need to depend on experimental data, more evidence is needed of "blindfold" tests in which an algorithm relating the radar measurements to soil moisture is developed on the basis of data from known fields, and then applied to new, unknown fields to test its validity. This empirical verification should be a critical step in the development process.

An important reservation to the proposed use of radar for soil moisture measurement is that the plan, as presented, relates moisture by an absolute measurement of the radar backscatter cross section. Reported test data indicate that the mean scattering coefficient,  $\sigma^0$ , might vary by 9 dB for a variation of moisture content from 5% to 35% (Simonett 1976:4-21). Since this is a mean, the actual spread of the measurements over the range will be much greater. While the accuracy required for  $\sigma^0$  for meaningful soil moisture measurements was not stated, it would appear that it must be better than can be achieved with the current radar state of the art.

If soil moisture were to be determined as suggested, the measurement would require an absolute measure of the radar cross section to a degree of precision not previously demonstrated. For example, in the laboratory the agreement between experimental measurements and theory is not likely to be better than 2 to 3 dB. The best measurements made under field conditions with good calibration against known targets is likely to be no better than 3 to 5 dB. The accuracy of field measurements with ordinary calibration is likely to range from 5 to 10 dB. Although it is claimed that good calibration can be obtained in the Shuttle environment, there is little reason to believe that routine measurements with an accuracy better than 3 to 5 dB can be made. The available ground-based radar experimental measurements do not indicate that this accuracy, which must be considered a good value, will provide meaningful soil moisture information.

#### 2.2.4 Crop Identification

Measurements for crop identification through clouds were reported to the Committee as the long range (late 1980s to 1990s) goal of active microwave sensors for the Earth Resource Survey Program.\* Many of the available radar images of agricultural scenes show that different crops can give

different responses. The differences noted in experimental observation form the basis for the contention that these differences in radar responses can be used to identify different types of crop. However, there has been little experimental work of a quantitative nature that can be used to confidently assess the potential offered by radar for providing useful classification measurements.

The July 1976 NASA report, "Applications Review for a Space Program Imaging Radar," (Simonett 1976) concludes that multifrequency, multipolarization, multirate (temporal), and possibly stereoscopic radar imagery is desirable for vegetation studies. Although it is agreed that the radar echo from crops depends on the frequency, polarization, and the time during the crop growth cycle at which the observation is made, no specific evidence was presented to the Committee that indicates quantitatively what the parameters of a suitable crop identification radar should be. The Simonett report (1976) also indicates that a single-frequency radar can be used for crop identification. The optimal frequency region indicated is somewhere between 14 and 18 GHz (Ku band) with incidence angles of 40 to 50 degrees. A quantitative (or even a qualitative) comparison of a single-frequency radar to a multiple-frequency, dual-polarization radar called for in the above two reports does not seem to be available.

The Simonett report (Simonett 1976:4-30) suggests that a dual-frequency imaging radar operating at C-band and either Ku or X band should be flown in the shuttle for vegetation classification purposes. The SIR-B imaging radar (see Appendix C), proposed to be flown in the shuttle in 1981 and 1982, is to be a dual-frequency radar with one frequency at X-band and the other at either L or C-band, depending on the needs for soil moisture measurements. The frequencies and other parameters of these radars seem to be governed to a large extent by the desire to use existing radar equipment as an economy measure. The objectives for SIR-B have been given as soil moisture measurements, geologic and water resources surveys, and vegetation classification. It is not expected that the dual-frequencies will produce significant information on crop classification since the L-band radar does not see enough vegetation to be useful.<sup>2</sup> According to the Simonett (1976) report, only the X-band system can be used for crop identification and the dual-frequency radars are intended primarily for uses in geology. That report also indicated the possibility that the dual-frequency measurements will be useful for soil moisture measurement.

Using data acquired by the University of Kansas ground-based active microwave spectrometer operating over a frequency range of 8 to 18 GHz, Bush and Ulaby (1977) conclude "that a dual polarized (HH and VV) radar operating

at about 14 GHz with an off-nadir angle of around 50° is most suitable for crop classification purposes." It was suggested that data be gathered on four dates in the growth cycle of a crop, separated in time by ten days. The basic measurement to be used for discrimination is the time history of the scattering coefficient  $\sigma^0$  at the two polarizations. Bush and Ulaby (1977) also seem to indicate that good classification of crops can be obtained with only single-polarization data obtained at 10-day intervals during a 30-day period in the growth cycle. No information seems to be available concerning the optimum radar resolution and the effect of "texture" on classification measurements.

Although crop height, crop moisture, soil moisture, and percent ground cover affect the radar scattering from crops, the most significant factor in determining the radar return is said to be the crop type (Simonett 1976:4-4). It is not clear, based on the information presented to the Committee, whether it is the geometrical differences or the dielectric differences, or both, that are anticipated to be the dominant factor affecting the radar backscatter signal. In either case, the basic measurement depends on the amplitude of the backscatter signal ( $\sigma^0$ ). This measurement needs to be made with good accuracy, but no accuracy specification was indicated for such a measurement. Since the extraction of the crop identity is based on a series of relative temporal measurements, the requirement of an accurate absolute measurement may not be as great as that required for the measurement of soil moisture. That is, it is the relative measurement of  $\sigma^0$  with time, polarization, and spatial resolution cell (and perhaps frequency) that is important, so that a fixed error in the value of  $\sigma^0$  might not be as critical as in the case of soil moisture. However, it will be necessary for the radar system to remain very stable over the period of repetitive observation, perhaps 30 days, so that equipment instabilities do not mask the important small variations caused by the crop vitality and growth. This may be difficult to achieve with the precision that seems to be required to measure the small incremental changes necessary for crop identification.

Another factor that affects the signal return in crop identification is the effect of the viewing angle or aspect. This may not be significant with the fixed ground-based radar used in the University of Kansas experiments, but from space, different portions of the area covered by the radar will be viewed with different aspect angles. In the shuttle radar, at a nominal altitude of 225 km, the aspect angle difference within a 50 km swath width scene is about 5 degrees. While this may not be significant for the narrow swath width proposed in the SAR-A and B, in future operational SARs with greater swath widths, this can become a problem. Thus similar crops located in different parts of

the scene might have variations in  $\sigma^0$  due to variations in aspect angle that perturb or mask the  $\sigma^0$  variation expected from the crop growth. A particular field might also be viewed from different aspect angles during different 10-day passes of the satellite, thus causing a potential source of undesired variability. Little or no consideration of this problem was indicated in the information presented. If the basic radar discriminant is the shape of the scattering object, as suggested, it would seem that viewing aspect will be important, unless the individual scatterers are oriented more or less randomly.

Another possible factor influencing the nature of the radar image is the geometry of the crop layout, such as spacing between the crop rows and the orientation of the rows relative to the pointing direction of the radar antenna beam. It may be difficult to analyze this factor from ground-based measurements, and may require actual SAR imagery from a space platform. The attenuation due to rain at Ku band and the change in the backscattered energy from wet crops may also reduce the effectiveness of this classification measurement under adverse weather conditions.

The proposed program depends on the scattering coefficient,  $\sigma^0$ , which is due primarily to the characteristic geometry of the crop species, as the basic measurement for crop classification. It is also likely that other variables related to the crop and its environment will affect the radar measurement. To discriminate one crop from another, it has been proposed to measure the relative time history of  $\sigma^0$  during the plant growth cycle. This then sets the requirements for revisit time of the satellite. Because of polarization differences due to either the crop geometry or to different dielectric properties of the crops, dual orthogonal polarizations are expected to improve the ability to identify crops. With variations in crop  $\sigma^0$  as a function of frequency, it is conjectured that these variations can be used in a multiple-frequency radar to either eliminate the need for temporal measurements or to improve the general ability to identify crops.

#### 2.2.5 Multi-Frequency Multi-Polarization Data

There is promise in ultimately using several received radar signals simultaneously for providing improved classifications of terrain type and condition. For example, echoes for different transmitter frequencies and various combinations of transmit-receive polarizations might be used. Measured values of  $\sigma^0$  are now available for a number of frequencies versus incidence angle for HH, VV, and HV polarizations, but data are needed for a wider range of surface types and conditions and for other polarizations.

Radar echo from terrain depends on transmitter frequency, incidence angle, and both the transmit and receive polarization (polarization pair). These parameters influence  $\sigma^0$  in complex ways. Thus it is difficult to describe how  $\sigma^0$  varies, even for one surface type, with changes in these four parameters. Because of the complexity of the problem, little is known about the magnitude of  $\sigma^0$  for the rarely used polarization pairs such as circular polarizations or a combination of linear and circular polarizations.

As already suggested, there are almost no data for polarizations other than HH, VV, and HV. Furthermore, there is at present no methodology that will enable a designer to calculate  $\sigma^0$  for any polarization pair from known data for other polarizations. This type of calculation can probably be made by extending the technique developed by Long (1977) for  $\sigma^0$  for circular polarizations from  $\sigma^0$  data for HH, VV and HV polarizations.

There is a possibility that the polarization pairs most useful for a given radar mission have not yet been considered. For example, the relative echo strengths as a function of terrain type and condition, frequency, and incidence angle for the polarizations given in Table 2.1 are not known.

TABLE 2.1

Some Possible Polarization Choices

Transmit Polarization	Receive Polarizations
H	H, V, R, L
V	H, V, R, L
R	H, V, R, L

where

- H - horizontal polarization
- V - vertical polarization
- L - left circular polarization
- R - right circular polarization

Since the effects on average echo strength of changes in polarization pair, frequency, and incidence angle are not independent, nor are the effects of moisture content, surface roughness and vegetation type on cross section, the problem of optimizing the choice for several radar

parameters to be used simultaneously is complex. Even so, there may be cost benefits to be obtained through system design trade-offs. If the design objective is to select optimum radar parameters for a given mission, it may be more cost effective to use a single frequency, four polarization radar than a two frequency, two polarization radar.

In summary, it is known that polarization, frequency and incidence angle affect target reflectivity. It is also known that improved target recognition has sometimes been obtained by actually using multiparameter radars. General effects of frequency and incidence angle on echo strengths for HH, VV, and HV polarizations for some target types and conditions are known. It seems that an analysis program should be undertaken to select radar parameters to optimize the information from several simultaneously received signals for various polarization pairs and possibly for various frequencies. Although such a program would initially consist of in-depth theoretical analyses, it should be supported by additional experimental measurements. Also, the existing data base should be extended to include wider differences in surface types and conditions in order to be more representative of different terrains.

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TABLE 2.2 Space Radar Systems

	SEASAT	SIR-A	SIR-B	
Frequency	L-Band	L-Band	X-Band	and L-Band or C-Band
Resolution	25 m	40 m	25 m	50 m
Swath width	100 km	50 km	25 km	50 km
polarization	HH	HH	HH	HH
Incidence angle	17° - 23°	48° - 53°	43° - 47°	10° - 20°
Dynamic range	18 dB	18 dB	40 dB	21 dB

SOURCE: Rouse (1977a).

## NOTES

1. For a more general introduction to the subject of radar technology, see M.W. Long (1975) Radar Reflectivity of Land and Sea. Lexington, Mass.: D.C. Heath and Co.; and M. Skolnik (1962) Introduction to Radar Systems. New York: McGraw Hill.
2. Rouse, J., Consultant to National Aeronautics and Space Administration, Presentation to CORSPERS, May 6, 1977.
3. Ulaby, F., Director, Remote Sensing Laboratory, Univ. of Kansas, Presentation to CORSPERS, April 15, 1977.
4. Smith, O.G., Assistant Manager of Earth Resources Program, Johnson Space Center, Presentation to CORSPERS, April 15, 1977.

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- Bush, T.F. and F.T. Ulaby (1977) Cropland Inventories Using an Orbital Imaging Radar. Technical Report No. 330-4. Lawrence, Kan.: University of Kansas Remote Sensing Laboratory.
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## CHAPTER III

# Earth Resources Sensing With Microwave Radiometry

### 3.1 Concepts of Microwave Radiometry

The microwave radiometer measures the electromagnetic energy radiated towards it from some target or area. Being a passive sensor, it is related more to the classical optical and IR sensors than to radar, its companion active microwave sensor. The energy detected by a radiometer at microwave frequencies is the thermal emission from the target itself as well as thermal emission from the sky that arrives at the radiometer after reflection from the target. The thermal emission depends on the product of the target's absolute temperature and its emissivity. At microwave frequencies, it is the change in emissivity rather than the change in temperature that produces most of the significant differences between the various targets. The intervening atmosphere between the target and the radiometer can have an adverse effect on the measurement by attenuating the desired target signal and contributing unwanted thermal radiated energy due to its own temperature and emissivity.

#### 3.1.1 Brightness Temperature

A body at temperature  $T$  emits radiation at all frequencies in accordance with the Planck radiation law. At microwave frequencies, Planck's law states that the flux radiated per unit solid angle, or brightness is

$$\text{Brightness} = \frac{2k\epsilon T}{\lambda^2} \quad \text{watts/m}^2/\text{Hz/steradian} \quad (1)$$

where  $k$  = Boltzmann's constant,  $\epsilon$  = emissivity  $< 1$ ,  $T$  = absolute temperature, and  $\lambda$  = wavelength. Direct radiation from a thermal source is randomly polarized, but a microwave radiometer antenna is sensitive to only a single

polarization. This results in a reduction of the apparent brightness in Eq. (1) by a factor of 2.

All the sources with various temperatures and emissivities within view of the radiometer antenna radiate energy that can be collected by the antenna. The power at the antenna terminal,  $P$ , is usually described by a temperature  $T_a$ , called the antenna temperature. This is defined as the temperature of a blackbody at the antenna terminals which would have produced the observed power,  $P$ , or

$$P = kT_a B \quad (2)$$

where  $B$  = the bandwidth of the observing instrument. The antenna temperature,  $T_a$  is the measurement made by the radiometer. For the situation where an ideal antenna sees only a distributed radiation source of temperature  $T$  and emissivity  $\epsilon$ , without any intervening attenuating atmosphere or clouds, the temperature measured by the radiometer is  $T_a = \epsilon T$ . The antenna temperature under these ideal conditions is also called the brightness temperature,  $T_B$ . Under more realistic conditions, the antenna temperature is actually an average of the brightness temperature  $T_B(\theta, \phi)$  weighted over  $4\pi$  steradians by the antenna gain  $G(\theta, \phi)$ , so that the antenna temperature is

$$T_a = \frac{1}{4\pi} \int T_B(\theta, \phi) G(\theta, \phi) d\Omega \quad (3)$$

where  $d\Omega$  represents the differential solid angle.

The antenna temperature does not measure the true brightness temperature of the radiating source if the source subtends a smaller angle than the antenna, or the antenna sidelobes view other sources with other brightness temperatures, or the presence of an intervening atmosphere contaminates the radiometer measurement. Nevertheless, the antenna temperature, as measured by the microwave radiometer, is commonly taken as an approximation to the brightness temperature. The radiometer makes a measurement of the antenna temperature by comparing the power received at the antenna terminals with the power from a matched load of known temperature.

The observed brightness temperature seen by an airborne or spaceborne microwave radiometer at altitude  $H$  above the ground with an angle of incidence  $\theta$  may be approximated by (Schugge et al. 1976)

$$T_a = \left[ \epsilon T_{\text{surf}} + (1-\epsilon) T_{\text{sky}} \right] \tau(H, \theta) + T_{\text{atm}}(H, \theta) \quad (4)$$

where  $T_{\text{surf}}$  is the surface temperature,  $\epsilon$  = surface emissivity,  $(1 - \epsilon)$  = surface reflectivity,  $T_{\text{sky}}$  = sky

brightness temperature,  $\tau(H, \theta)$  = atmospheric absorption of the radiation coming from the surface, and  $T_{atm}(H, \theta)$  is the contribution from the atmospheric emissions. The first term represents energy emitted by the surface itself and the second term,  $(1-\epsilon)T_{sky}$  is the energy emitted by the "sky" that finds its way to the radiometer after reflection from the surface. Both terms are reduced by the attenuation of the atmosphere,  $\tau(H, \theta)$ . The third term is the radiation emitted by the intervening atmosphere that arrives at the radiometer. In general, all of these terms are frequency dependent.

The brightness temperature, as measured at microwave frequencies, is not the same as the actual temperature,  $T$ , of the body because of the effect of emissivity,  $\epsilon$ . Seawater, for example, has an emissivity of 0.4 to 0.6, so that its brightness temperatures might be from 120°K to 180°K when its actual temperature is 300°K. Land has emissivities from 0.85 to 1.0, and snow and ice have emissivities from 0.7 to 1.0. Thus water appears cold compared to its surroundings. At microwave frequencies the actual temperature differences encountered are small. It is the differences in emissivities that cause most of the observed difference in brightness temperature. This difference can be large. The emissivity depends on the roughness of the surface, the angle of incidence, as well as the dielectric properties of the surface and the frequency.

### 3.1.2 Microwave Radiometer Implementation

The microwave radiometer is basically a sensitive receiver which makes a measurement of the noise power received at the antenna terminals. From the measurement of noise power, the antenna temperature, or brightness temperature, is obtained according to Eq. (2). The technology of the microwave radiometer is well established. Much of the development of the modern microwave radiometer has been due to the needs and diligence of the radio astronomer who uses such an instrument to measure sky temperature. Since a microwave radiometer must be able to sense small differences in receiver noise, it differs from the conventional receiver in requiring exceptionally good stability. The popular Dicke-type microwave radiometer is a superheterodyne receiver in which the receiver input is alternately switched between the antenna and a matched load at a known temperature. The antenna temperature is then determined by comparison of the received signal with the known temperature. The rapid comparison of the receiver input noise with a known source alleviates the need for long-term stability. The ability to measure the antenna temperature,  $T_a$ , is determined in part by the radiometer receiver noise temperature,  $T_r$ . The sensitivity of a

radiometer is often expressed by the minimum detectable difference in temperature (King, 1970) which is

$$\Delta T_{\min} = a \frac{T_a + T_r}{\sqrt{B\tau}} \quad (5)$$

where  $a$  is the "radiometer constant" that depends on the particular signal processing technique used ( $1 \leq a \leq 2\sqrt{2}$ ),  $T_a$  = antenna temperature,  $T_r$  = radiometer receiver noise temperature,  $B$  = receiver bandwidth, and  $\tau$  = receiver post-detection integration time. It is customary to give  $\Delta T_{\min}$  for  $\tau = 1$ s. Sensitivities of a fraction of a degree are possible at microwave frequencies. For example, assume a radiometer in space viewing the earth sees an antenna temperature  $T_a = 300^\circ\text{K}$ . If the receiver system has an effective noise temperature of  $200^\circ\text{K}$ , bandwidth of 100 MHz,  $a = 2$ , then for an integration time of one second,  $\Delta T = 0.1^\circ\text{K}$ . If a sensitivity of  $1^\circ\text{K}$  were sufficient, the integration time, which is the time available for observation, could be as low as 0.01 second.

In order to differentiate an area of brightness temperature  $T_1$  from an area of brightness temperature  $T_2$ , the difference  $T_2 - T_1$  must be greater than  $\Delta T_{\min}$ . If the area of interest with temperature  $T_1$  is smaller than the resolution area, or footprint, of the radiometer antenna, and if it is surrounded by a scene of temperature  $T_2$ , the temperature difference must be greater to compensate for the dilution caused by the target area not filling the resolution area and by the remaining area being at a different temperature.

In a spaceborne application, the post-detection integration time is generally not a parameter under full control of the radiometer designer, as it is with the radio astronomer. The integration time will be determined by the length of time a particular scene is within view of the radiometer, which depends on the satellite speed (altitude), antenna beamwidth, and coverage. The bandwidth of the radiometer should therefore be as large as possible, although there are practical limits to the bandwidth due to the presence of interfering electromagnetic emanations from radar, communications, and navigation systems that will be readily seen from a high altitude spacecraft viewing the earth.

### 3.1.3 Antenna Considerations

The microwave radiometer, essentially, measures the brightness temperature of those objects within the footprint or resolution of its antenna beam. The angle coordinate of the antenna determines the resolution of the sensor. At the

long ranges characteristic of spacecraft sensors, the attainable angular resolutions are poor. This is one of the disadvantages of the passive microwave (radiometer) sensor compared to the resolutions possible with the active microwave sensor (radar). The radar achieves good resolution in range by means of pulse compression and in cross-range by means of synthetic aperture processing techniques.

The diameter of the resolution area seen on the ground by an antenna of diameter  $D$  and wavelength  $\lambda$ , at a height  $H$  above the ground and looking at nadir, is

$$\Delta = H\lambda/D \quad (6)$$

For  $H = 1000$  km and  $D = 100 \lambda$ , the diameter of the resolution cell is 10 km. As the radiometer antenna scans off of nadir, the resolution cell broadens for several reasons, such as the increased angle of incidence; the earth's curvature; and, if a phased array is used, the obliquity factor of the aperture. The maximum size of a microwave antenna that can be employed in space is determined by the mechanical tolerances with which the antenna can be constructed.

The precise value of the maximum antenna size that can be used is not important, since it is clear that the resolution offered by the microwave radiometer with feasible antennas is from 2 to 3 orders of magnitude worse than from a synthetic aperture radar or from the optical and IR sensors carried on LANDSAT. This poor resolution puts the microwave radiometer at a disadvantage for many ERS applications compared with other sensors. While lower altitude or a higher frequency will give better resolution, it still is not competitive in this parameter with the other spaceborne sensors. In spite of the poor resolution the radiometer has demonstrated characteristics that make it of significant interest as a remote sensor of the environment and other surface features for which high resolution is not critical.

As long as the target area under observation is of greater extent than the antenna resolution area, the sensitivity of the radiometer is independent of the resolution cell size, or beamwidth. A large resolution cell, however, has the disadvantage of producing a brightness temperature measurement averaged over all the various sources within its view. Thus, the measurement of a field with a particular crop might be contaminated by unwanted contributions from the roads, trees, houses, and water that lie within the resolution area, or antenna beam footprint, of the radiometer.

The area of the ground covered by the antenna beam should be small in order to resolve areas of interest. To cover a reasonably large swath, the radiometer beam can be scanned in the direction perpendicular to the ground track by means of a phased array antenna or other rapid-scanning antenna. Alternatively, the area of interest could be covered with a number of contiguous, fixed beams each with its own radiometer receiver. While the multiple beam approach is generally more complex and expensive than the scanning beam approach, it is also more sensitive.

In addition to a narrow antenna beam, the antenna sidelobe level should be low so that the receiver measurement is not degraded by energy from sources not within view of the main beam. Low sidelobes require that the antenna aperture be slightly larger than a conventional antenna and that the mechanical configuration of the antenna be held to at better tolerances.

#### 3.1.4 Relative Advantages and Limitations of the Microwave Radiometer

As mentioned previously, one of the major limitations of a spaceborne radiometer is its relatively crude resolution, which is a consequence of the antenna beamwidth and the long range to the target area. The thermal radiation from a body of temperature  $T$  is not as great in the microwave as in the IR region. The microwave radiometer is also less sensitive. There are, however, significant differences in the brightness temperature measurement at microwave frequencies that make the radiometer of interest as a remote sensor. Measurements at microwave frequencies, both active and passive, are less affected by haze, fog, and clouds than are those of IR and optical sensors. The size, weight, and primary power requirements of a microwave radiometer are much less than a radar. This is an important consideration in spacecraft applications. Being passive, the microwave radiometer does not radiate active signals that interfere with other users of the electromagnetic spectrum.

### 3.2 Microwave Radiometer

#### 3.2.1 Applications of Microwave Radiometry

The microwave radiometer has been used as a sensor of both geophysical and meteorological phenomena, with most of the interest (and success) concentrated in probing the atmosphere. A microwave radiometer can provide measurements of atmospheric water vapor and liquid water over oceans, storms over land, the atmospheric temperature profile, ice and snow coverage, sea-ice boundaries, discrimination of

first year and multiple-year ice, salinity of water, oil slicks on the ocean, sea state, surface temperature, and soil moisture (Staelin 1969). It has the desirable property of being able to make its measurements in the presence of most clouds. A radiometer is able to obtain such diverse information by operating at different frequencies to take advantage of the frequency-selective resonances of the phenomenon under observation. The chief weakness of the radiometer has been the poor resolution with which measurements can be made, as limited by the antenna beamwidth.

### 3.2.2 Space Experience

NIMBUS-5, launched in 1972, was the first U.S. satellite to carry a microwave radiometer which was known as the NIMBUS-E Microwave Spectrometer (NEMS). It viewed nadir with five channels at wavelengths from 1.35 to 0.5 cm to measure the atmospheric temperature profile, and the atmosphere water vapor and liquid water over ocean areas. The antenna beamwidth was 10°. NIMBUS-5 also carried an Electronically Scanned Microwave Radiometer (ESMR) at 1.4 cm wavelength to produce images of the Earth's microwave emission to yield maps of precipitation areas over oceans and sea-ice boundaries in polar regions.

NIMBUS-6, launched in June 1975, carried the Scanning Microwave Spectrometer (SCAMS), similar to the NIMBUS-5 NEMS but with a scanning antenna for producing images. It covered a swath 2500 km wide, divided into 13 resolution cells varying from 150 to 300 km, depending on the viewing angle. It provided atmospheric measurements similar to those of NEMS, but over a wider swath. It was also able to map ice and snow. NIMBUS-6 carried an Electronically Scanned Microwave Radiometer (ESMR) at 0.8 cm wavelength whose beam was scanned in a conical manner to keep the angle of incidence constant.

An L-band radiometer at 21.4 cm wavelength (S194 experiment) was flown on SKYLAB from May 1973 to February 1974 for the purpose of measuring soil moisture. The resolution was 115 km. It has been claimed (McFarland 1976) that the correlation between brightness temperatures and soil moisture was "excellent," although it was cautioned that definite conclusions could not be reached because of the limited number of independent measurements.

TIROS-N is planned to carry a Microwave Sounder Unit (MSU) with multiple frequencies near 0.5 mm wavelength to produce atmospheric temperature profiles for operational use. The Defense Meteorological Satellite Program also carried a scanning microwave radiometer for atmospheric

temperature profiles. A Scanning Multifrequency Microwave Radiometer (SMNR) with five channels between 0.8 and 4.5 cm wavelength is planned for both NIMBUS-G and SEASAT. In addition to atmospheric water and sea ice boundaries, SMNR will measure sea surface temperature and sea state. The resolution of SMNR is about 40 km.

It has been proposed to fly a larger radiometer with more frequencies and with a larger antenna to provide resolution of about 3 km at the shorter wavelengths, on the Space Shuttle. There are two competing proposals. One is the Shuttle Imaging Microwave System (SIMS) proposed by the Jet Propulsion Laboratory (JPL) (See Appendix E). The other is the Shuttle Multiple-function Microwave Radiometer Experiment (SMMRE) proposed by Goddard Space Flight Center which uses existing instruments (See Appendix F). Since both proposals are directed at essentially the same earth resource applications, only the SIMS will be discussed here (Walters et al. 1975, Staelin 1976).

SIMS is intended to operate at 11 wavelengths ranging from 50 cm to 2.6 mm to measure atmospheric water vapor to an accuracy of 0.2 gm/cm<sup>2</sup>, precipitation, sea surface temperature, sea state, sea and lake ice-boundaries to 0.5 km resolution, storms over land, sea surface wind speed to 2 m/s, and soil moisture content over the 10 to 40% range with an estimated accuracy of 5%. SIMS should also measure ocean salinity and subsurface phenomena such as water, permafrost depths, and temperature gradients. The Space Shuttle is also supposed to carry a Microwave Limb Sounder to observe emissions from the atmospheric limb in order to obtain information on the Earth's upper atmosphere.

With the extensive experience in the field of meteorology, the microwave radiometer has demonstrated some interesting capabilities for sensing the Earth's surface and atmosphere from space. There is a better understanding of the cause and effect relationship between what the radiometer measures and the desired geophysical or meteorological information than there is with similar information obtained by radar. The type of measurements that can be made by the radiometer depend on the frequency selected. Operating around various absorption bands or transparent bands provides the differences in measurement that yield the desired environmental information. For this reason, microwave radiometers operate at a number of frequencies over a wide part of the microwave and millimeter-wave spectrum.

Much of the past interest in microwave radiometry has been focused on atmospheric probing, with only minor interest in Earth Resource Surveys. According to NASA the short-term objective for microwave sensor development, both

active and passive, for earth resources applications was stated to be for geological, surface water, and flood mapping. Medium-term objectives were to include measurement of soil moisture and snow moisture content, among others, while the long-range objective was directed towards crop identification through clouds. The radiometer can perform the area and boundary mapping of the short-term objective, but with a relatively crude resolution (about 3 to 10 km) when compared to that of LANDSAT or the proposed synthetic aperture imaging radars. While these measurements are well understood, their utility has not been established. Little information was presented to the Committee regarding the use of the radiometer for crop identification and, therefore, will not be discussed in this report. Serious consideration was given to the potential use of the radiometer for measuring soil moisture which was also identified to the Committee as a major objective for the imaging radar. In the Committee's view, soil moisture measurements should also be considered a major objective for the microwave radiometer in the overall Earth Resource Survey Program.

### 3.2.3 Measurement of Soil Moisture

The measurement of soil moisture is based on the measurement of surface emissivity due to the dielectric constant of liquid water. The real part of the dielectric constant of water at the lower microwave frequencies (L band or below) is about 80, and that of most dry soils is about 3 (Schmugge et al. 1976). Thus the addition of water to dry soils causes significant changes in the dielectric properties, which can be sensed by the microwave radiometer. The measurement is also affected by the type of soil, surface roughness, vegetation cover, surface temperature, and time of day. The emissivity measured by a radiometer is determined by the dielectric properties of the surface soil layer to a depth of about one-tenth of a wavelength. Thus lower frequencies are favored both because they are able to measure moisture to a greater depth and because they are less affected by vegetation cover and surface roughness. For example, measurements with a 21 cm wavelength radiometer show the radiometer to be "highly responsive to the moisture content of the upper 2.5-cm layer of soil," (Eagleman and Lin 1976) and it "can sense soil-moisture variations on grasslands or other areas of moderate vegetative cover" (Schmugge et al. 1976). [A possibility also is suggested that indicators of soil moisture and surface roughness may be separated by making measurements with orthogonal polarizations (Schmugge 1976)]. Unfortunately, the lower the frequency, the larger the antenna must be to achieve a given resolution.

Microwave radiometer measurements of soil moisture have been made by truck-mounted instruments, aircraft, and from space (SKYLAB). There is a significant spread in the data when brightness temperature is plotted against soil moisture "ground-truth" measured at selected points. It is encouraging that this spread is less than that obtained with radar measurements of soil moisture. It appears that the variance in the "ground-truth" measurements is due to the small number of actual measurements made which might contribute to the large variation in the data. Overall, however, it appears that the accuracy of the measurements made by passive microwave is more impressive than that obtained with active microwave. The microwave radiometer may be able to establish the soil moisture measurement in four or five steps over the range from "wilting point" to "field capacity." The microwave radiometer measurements seem to show a higher correlation between the measurements and antecedent precipitation, one of the major factors affecting soil moisture (McFarland 1976).

#### 3.2.4 Earth Resource Sensing by Microwave Radiometry

The microwave radiometer has proven to be a versatile sensor for remote sensing of the environment from space. Its application to atmospheric probing seems to be adequately appreciated and this work will apparently continue. As a sensor for the Earth Resource Survey Program, it does not have the resolution capability of radar for area and boundary mapping. It appears, however, to be able to make more useful measurements of soil moisture than radar. Thus the radiometer should be considered for applications where low resolution can be tolerated, such as large area wetness measurements and surveys of drainage basins.

Although the SIMS radiometer proposed for the Space Shuttle will have a resolution of about 3 km at 1.5 cm wavelength (20 GHz), the measurement of soil moisture is best made at lower frequencies. At L band (21 cm), the frequency at which soil moisture measurements were made on SKYLAB, the resolution of SIMS will be 44 km. The resolutions for the SIMS and the SSMRE carried in the shuttle are given in Table 3.1. For the lower frequencies, the largest antenna that might be considered for deployment in space is probably around of 300 wavelengths, which results in a beamwidth of  $0.2^\circ$ . At a height of 1000 km, which would be a reasonably stable orbit, the nadir resolution at L bands would be 3.3 km. At L-band, a 300 wavelength antenna has a size of 63 meters, which is a formidable space structure. With "reasonably" large antennas, the resolutions that might be expected from a 1000

km orbit would be from 20 to 40 km at L band or, from a 500 km orbit, 10 to 20 km respectively.

TABLE 3.1 Passive Microwave Systems

Frequency (GHz)	(cm)	<u>SMMRE</u> <sup>1</sup>			<u>SIMS</u> <sup>2</sup>	
		Resolution (km)	$\Delta T$ ( $^{\circ}K$ ) I*    II*		Resolution (km)	$\Delta T$ ( $^{\circ}K$ )
.510	50	-	-	-	102	.17
1.4	21	26	0.4	0.4	44	.23
2.6	11	-	-	-	23	.68
6.6	4.6	13	0.17	0.14	9.5	.22
10.7	2.8	8.2	0.21	0.17	5.8	.36
18.0	1.5	5.2	0.45	0.37	3.1	.31
21.0	1.3	3.6	0.58	0.47	2.8	1.1
37	0.9	2.4	1.32	0.76	1.7	1.3
53	.57	-	-	-	1.2	2.4
94	.32	4.5	.45	.45	.66	3.2
118	.26	3.6	.9	.9	.52	6.7
183		2.2	1.22	1.22	-	-
19.35		8.4	1.1	1.1	-	-

\*There are two possible configurations for the proposed SMMRE system (see Appendix F). Configuration I is a single reflector unit, Configuration II is a 3-reflector unit.

SOURCE: 1) King, NASA, Greenbelt, Md., Personal Communication, 1977.  
2) Waters et al. (1975).

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## CHAPTER IV

# Applications of Remotely Sensed Resource Survey Data

### 4.0 Introduction

One of the issues in the field of remote sensing that is not given adequate recognition is the direct relationship between the character of the remotely sensed data and the level of decision making for which the data are appropriate. In a sense, the issue is one of scale--the scale and resolution of the data or the detail of the information and its relationship to the level of decision making, whether global, national, regional, or local. Historically, in order to develop a usable data base appropriate to regional, national or global decision making, data collected at the local level, at a specific site for use in decisions on that level, have been combined, averaged, degraded as necessary, and otherwise manipulated. With the advent of high-altitude remote sensing, it has become possible in some cases to gather data for large global, national, and regional decisions directly without going through the aggregating process. LANDSAT data is an example. While its 80 m resolution makes it inappropriate for many local uses, the 185x185 km scenes with 80 m resolution are quite adequate for decision making processes at the regional or national level.

An apparent manifestation of this difference in requirements is the continuing strong support at the national level for 80 meter LANDSAT 1 and 2 imagery, and the apparent lack of support for the 30 meter THEMATIC MAPPER data. At the local and regional level, the interest in the 80 meter data is low compared to the interest in the 30 meter resolution imagery. The availability of the fine-grained information associated with the 30 meter THEMATIC MAPPER data is of crucial importance to many local resource

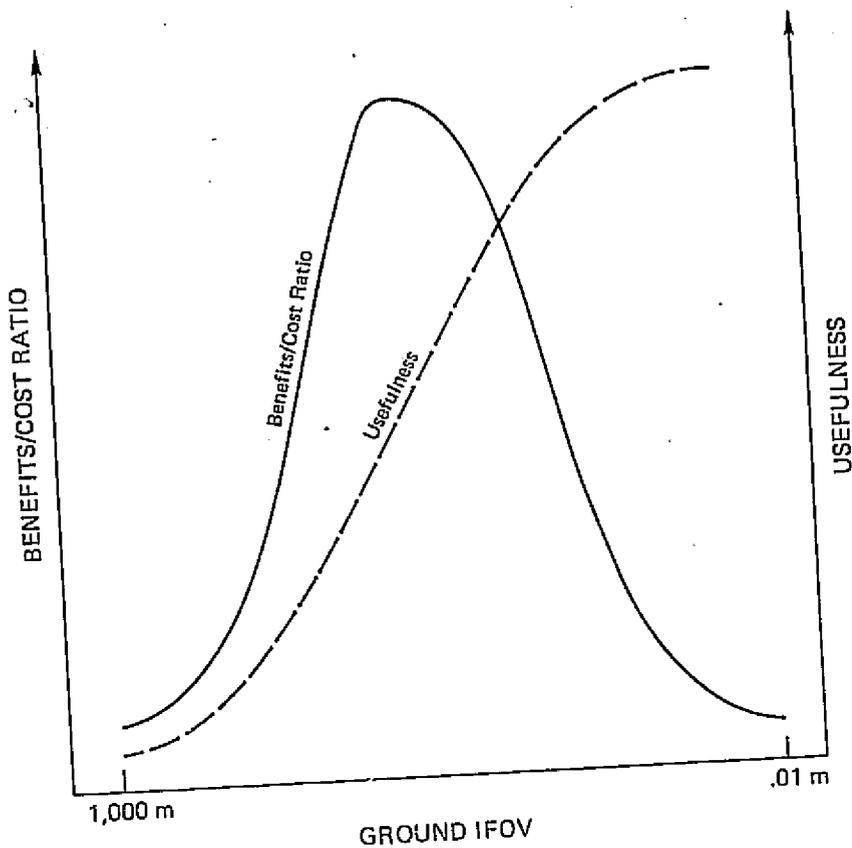
managers, while, at the regional or national decision level, much of this fine-grained information would normally not be used.

There is constant pressure at the national level to apply large area information to local uses. This reverses the historical direction of information transfer. The existing institutional mechanisms for information transfer are designed to take local, site-specific data and, by synthesis and generalization, to extract the information needed for higher level decision making. Reversing the information flow implies restructuring some of these mechanisms. This could have several effects. First, the cost-effectiveness of basing local decisions on large area data bases could be extremely low. Second, such an approach may be questionable on purely practical or scientific grounds. For example, the information that 20% of a large stand of trees is diseased is significant to a general inventory of forest land but may not be of practical value to a forester unless he also knows which 20% is diseased.

Perhaps the most serious danger of reversing the direction of information transfer would be the tendency to make local decisions at a higher level, that is, rather than simply supplying data to local decision makers, there would probably be a temptation to supply the decisions as well. This could have disturbing effects on the local decision making process, such as in land use planning, irrigation, and water allocation.

It is not within the scope of this study to explore the potential implications of reversing the direction of information transfer on the utility of earth resource survey data. It will be assumed here that the existing information transfer mechanisms will remain intact. The data characteristics demanded by users at the two ends of the user spectrum are quite different, usually varying from the fine resolution and frequent coverage required by the local user to the cruder resolution and less frequent coverage for regional, national, and global users.

The CORSPERS report (NRC 1976:17-24) included a discussion of the relationships between ground IFOV (instantaneous field of view), spatial resolution, usefulness of remotely sensed data, and benefits/cost ratio, for the disciplines that use or expect to use remotely sensed data from LANDSAT and the THEMATIC MAPPER. (Figure 4.1 is taken from that report.) Given the similarity between IFOV for the multi-spectral scanner and resolution for the microwave sensors, this discussion is as valid and pertinent to microwave remote sensing systems as it is to the LANDSAT and THEMATIC MAPPER sensor systems.



SOURCE: CORSPERS (1976)

FIGURE 4.1 Schematic Graph of Relationship Between Data Usefulness, Benefit/Cost Ratio and Sensor Ground IFOV

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If microwave remote sensing, active or passive or both, was the only spaceborne sensing method available or feasible, then its usefulness, benefits, and benefits/cost ratio would probably be more favorable for most applications. However, the technology and experience in the use of visible and IR imagery do provide an available capability. Alternatively, if microwave sensors can provide unique data which is critical to some applications, the value of the microwave sensor for these applications would be high. In the Committee's judgment, spaceborne microwave sensing, at this stage of development, should only be considered as a supplementary data source to sensors in the visible and IR portion of the spectrum because of the extensive experience, proven capability, and investment in LANDSAT and the THEMATIC MAPPER. The benefits of spaceborne microwave sensing should therefore be evaluated on the basis of incremental additions to visible and IR sensing.

The curves in Figure 4.1 of usefulness and benefits/cost ratio, as functions of ground IFOV, will change if microwave sensing is introduced as an adjunct to the LANDSAT and/or THEMATIC MAPPER systems. The direction and magnitude of these changes will generally be different for each discipline. The addition of microwave sensing may increase usefulness in some disciplines because of the microwave system's ability to penetrate cloud cover. However, because of the potential quality of the THEMATIC MAPPER data, the increase in the aggregate usefulness (due to the addition of microwave capability) in most disciplines is likely to be small, while the increase in cost may be relatively high. This will adversely affect the benefits/cost ratio curve.

It was not possible in this study to quantify usefulness, benefits, and benefits/cost ratios for each discipline. The shapes of the curves as functions of ground IFOV in Figure 4.1 are qualitative representations only. Even if an extensive analysis were conducted at this time, the quantification of these factors probably would not aid in making the decisions now pending in the proposed microwave sensor development program.

The analysis of microwave sensing in the following sections was conducted from the perspective of specific application areas. Within each application area the logic of the evaluation proceeded in the following steps:

1. reviewed the data requirements that might be satisfied from space platforms,
2. reviewed the deficiencies of the visible and infrared data that might be compensated for by the addition of microwave data,

3. assessed the adequacy of the available microwave experimental data base to support the initial development phase of active and passive microwave sensing systems for earth resource surveys.

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## 4.1 Hydrology

To the extent that hydrologic manifestations are related to topography and surface features, remote sensing is an important tool for hydrology surveys. Until rather recently, nearly all of the useful remote sensing data has come from visible and IR sensors, the most prominent of which are the multi-spectral scanners on LANDSAT-1 and 2. Microwave sensors are now being considered as an interesting supplement to the visible and IR sensors and, in some cases, as a potentially valuable extension for gathering new kinds of data.

### 4.1.1 Surface Water

One of the most significant water-related measurements possible with LANDSAT imagery is that of the areal extent of surface water: lakes, rivers, streams, standing water after rainfall, post-flooding inundation, etc. Near-infrared imagery is particularly useful for delineating the land/water boundary. The accuracy of the areal measurements and the precision of boundary locations will improve with the use of the THEMATIC MAPPER and its higher resolution, but problems will remain in detecting standing water in vegetated areas and under cloud cover. These problems are primarily related to flood mapping. Flooded areas are often overcast for long periods of time after flooding, and even when the skies clear, the inability to detect water underlying vegetation can lead to serious underestimation of the total areal extent of the flooding.

One of the major advantages of microwave sensors is their ability to penetrate cloud cover and, to some extent, vegetation cover. The all-weather capability implies that flood mapping can take place when the area is still overcast. Sensors operating at L-bands can be used both during a storm and afterward. To the extent that microwaves are able to penetrate the vegetation cover, flood mapping with microwaves could be more accurate than with visible or IR sensors of comparable resolution. Microwave penetration of vegetation cover is frequency-sensitive, and therefore not all frequencies can be used for this purpose. Some vegetation is also highly resistant to penetration at any frequency; for example, significant penetration through a forest canopy is not likely. There could, however, be a significant advantage to using microwaves for flood mapping on grassy plains (Roswell 1969).

A fundamental capability of active microwave systems is the accurate measurement of distance. This capability will be tested using the SEASAT-A short pulse radar altimeter (see Appendix A) for measurement of sea slope and geoid

shape. Extending the over-ocean capability of SEASAT to a capability overland, and specifically addressing the problem of measuring the relative elevation of points on river surfaces could be an important area for research (Cameron 1964, McGoogan 1975). The difference in dielectric constant of the water and the adjoining land areas may make it possible to extract the river surface elevation information from the signal return. The difference in elevation enters into the calculation of hydraulic slope, which is a factor in calculating the rate of flow of a river. The accuracy required in the measurement of height difference,  $\Delta h$ , depends on the square root of the magnitude of  $\Delta h$  and the length of the section of river for which a rate of flow calculation can reasonably be made. If  $\Delta h$  can be derived from imaging radar or radar altimeter data, it will be of great value to a large range of problems in hydrology even though the rate of flow is less sensitive to  $\Delta h$  than it is to other factors (cross-sectional area, wetted perimeter, roughness). Imagery from satellite altitudes, which gives a synoptic view of entire watersheds, could, over a period of time, give important insights into the hydraulics of the watershed system.

#### 4.1.2 Drainage Patterns

Remote sensing provides a practical advantage over other methods of delineating drainage patterns because it can cover an entire watershed at one time. The drainage patterns are directly related to the geomorphology of an area. Delineating the drainage patterns is a function of the accuracy of relief mapping which can be aided by remote sensing. LANDSAT has already proven quite useful in this area even though the 80 m IFOV is rather crude and the high sun angles are not really ideal for topography measurements. The THEMATIC MAPPER (Appendix D) data (30 m IFOV), available by 1980, should contribute to improvements in the relief mapping information. Visible and IR imagery, however, can be ambiguous. In some cases the vegetation may outline streams that would otherwise not be apparent. In other cases vegetation may contribute to the variability of gray scale values, which can camouflage the terrain features (Long 1975).

Radar sensors are generally less affected by vegetation cover than visible or IR sensors and are more sensitive to terrain characteristics. Radar sensors should therefore be more effective for mapping drainage patterns. Based on aircraft experience, McCoy (1969) found that a radar system can yield surface feature detail comparable to that available on a 1:24,000 topographic map. MacDonald et al. (1967) discuss data for the Cane Springs, Arizona, region for which airborne K-Band radar revealed terrestrial

features not readily apparent in aerial photographs, even though the radar resolution was somewhat less than that of the photographs. However, there are also problems with the radar imagery. If, for instance, the general orientation of a drainage basin is perpendicular to the flight line (assuming SAR is being used), it was noted (MacDonald et al. 1969) that much of the detail that would be apparent if the flight line were shifted by 90° was missing. Some detail is also lost due to shadowing, especially in mountainous terrain (Feder and Bark 1972). This problem may be overcome by imaging an area from two directions approximately 90° apart. This may not be very practical from a space radar system, however.

Radar data is probably best viewed as a supplement to optical imagery, as far as delineation of drainage basins is concerned. The one exception to this rule is in areas usually overcast, in which case radar imagery would have to be considered as a primary data source.

#### 4.1.3 Runoff Coefficient

An important method for estimating water runoff is the Soil Conservation Service method [Reference Hydrology, Supplement A to Section 4, "Engineering Handbook" Washington, D.C., USDA, SCS, 1968] which uses a Curve Number (CN) that describes runoff potential for various hydrologic soil-cover complexes. The CN is an extremely important factor needed to estimate water runoff. Blanchard (1974) reports that CN can be related to the difference between MSS bands 4 and 5 in the southern Great Plains, especially during dry dormant periods.

Microwave systems are apparently capable of making measurements related to CN. The Passive Microwave Imaging System (PMIS), an X-Band aircraft mounted scanning radiometer, has been used to test the feasibility of making microwave measurements of the coefficient CN (Matthews 1975:67-70). Little, if any, work has yet been done to explore the applicability of active microwave systems to the measurement of CN. But since CN is a function of soil type, vegetation cover, roughness, and soil moisture -- parameters to which a radar system is sensitive -- there is a possibility that a radar system may be capable of measuring CN.

#### 4.1.4 Urban Drainage Features

The natural drainage patterns in urban areas are more related to the extent and placement of paved area relative to unpaved area than to the topography. The ratio of paved

to unpaved area, a level I land use classification (Anderson et al. 1972), can be measured by remote sensing methods. Ragan and Jackson (1975) have used visible and IR imagery to classify urban areas, and have used this classification to calculate the percent imperviousness of the urban region. Microwave remote sensing would probably be as effective as optical remote sensing for this purpose. As yet, however, there have been no studies based on the use of microwaves that are equivalent to Ragan and Jackson's study.

#### 4.1.5 Precipitation Rate over Land

One measurement that is particularly important for hydrology is the precipitation rate over land. Optical remote sensing is entirely inadequate for this purpose. The NIMBUS 5 Electronically Scanned Microwave Radiometer (ESMR) has already been used to measure some categories of precipitation over open water. It may be possible to make reasonable estimates of the precipitation rate using microwave systems. Hydrologic models are now in existence that need this information at all scales. Measurements of precipitation over land could yield great benefits. Theoretical and experimental work is needed to explore the potential capabilities and limitations of microwave radiometer techniques in detecting precipitation over land.

#### 4.1.6 Other Applications

There are a few other applications important to hydrology, which are covered in other sections of this report. The most important of these is the soil moisture measurement discussed in Section 4.2.2; ice and snow cover discussed in Section 4.8; wetlands mapping, a subtopic of land use mapping in Section 4.4; and water pollution monitoring, included under environmental monitoring, Section 4.6.1.

#### 4.1.7 Conclusions

Three applications of microwave remote sensing to hydrology stand out as particularly important: the use of imaging radar as an altimeter to measure the relative elevation of points on rivers, the use of an imaging radiometer to detect precipitation over land, and the use of passive, and later, active systems to measure soil moisture. All require considerable research, as outlined briefly above, but all are potentially high-yield applications of microwave systems.

Beyond these three areas, space microwave systems will serve primarily as a supplement to LANDSAT for hydrologic users. The primary advantage of microwave systems in these cases is their all-weather capability.

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## 4.2 Vegetation Resource Analysis

Vegetation inventory and assessment is one of the successful applications of remote sensor technology. Whether for farm, forestry, range, wetland, or wildlife management purposes, the requirements are similar: to identify vegetation by species or species group, determine density (or biomass) and vigor, and determine growth rates. All of this must be done under a wide variety of conditions, because age of vegetation, soil type, season of year, and attacks by insect and disease all alter responses of vegetation recorded in remote sensor data.

Many of the applications of vegetation resource analysis in land management decision making need information that is site-specific and timely. This requires remote sensing data with high geometric resolution and frequent repeat coverage.

In many cases, aircraft at nominal altitudes are the most effective remote sensing platforms. Poorer geometric resolution makes high altitude aircraft and satellite data most important at regional, national, or global levels of decision making, where, normally, site-specific actions are not the immediate result of the decision making process. While data from LANDSAT-1 and -2 have provided maps of standing crops over large areas, the higher geometric resolution (30 meters) expected from the THEMATIC MAPPER on LANDSAT-D will significantly improve the utility of satellite data for vegetation analysis. The increased number of spectral bands with better spectral resolution planned for the THEMATIC MAPPER will also increase vegetation resource analysis capabilities, as compared with LANDSAT-1 and -2 (NRC 1976).

Inability to provide data through clouds is a major shortcoming of LANDSAT, especially in geographic areas with persistent cloud cover such as the Pacific Northwest of the United States and Canada, the Gulf Coast of the United States and Mexico, and many tropical areas. This problem is particularly troublesome for agricultural applications in which repetitive measurements at short time intervals are required during critical periods of the growing season. Both the critical period and frequency of coverage vary with crop type, planting time, geographic location, and weather. An active microwave system capable of penetrating most cloud cover would fill part of the gap in data coverage obtainable from LANDSAT. It is not clear, however, that any of the presently proposed space radars can provide the large area coverage (wide swath width), frequent repeat coverage, continuous data flow, and resolution needed to meet vegetation analysis needs. It is also not clear that the vegetation classification can be done satisfactorily using microwave imagery.

In some vegetation resource analysis applications, notably those requiring determination of stress and/or growth rate, repeat coverage is needed at intervals of less than nine days. LANDSAT cannot fill this need, and cost considerations make it unlikely that any satellite platform will provide the high frequency, high resolution coverage needed at different seasons of the year in different geographic locations. Satellite data supplemented by aircraft data, or aircraft data alone, appear more promising.

#### 4.2.1 Vegetation Classification

It is not clear that vegetation can be effectively classified from radar data. Early results with single frequency radars were promising but largely qualitative, and it appears that acceptable classification accuracy from single frequency systems requires either perpendicular flight lines (Hardy et al. 1971) or multiple polarization (Morain 1976). The former is almost impossible to implement from space in a meaningful way. The latter is easier to implement from space platforms, and would seem to be more effective because it can make greater use of subtle textural differences in the radar return.

Dual-frequency, dual-polarization systems are a promising recent development (Schuchman et al. 1975, Simonett 1976).<sup>1</sup> Thus far studies with these systems have been restricted to such a limited number of species, soil backgrounds, and moisture conditions that data are insufficient to provide confidence in extrapolated projections of utility in vegetation analysis. Too little is known about the interacting effects of variations in the dielectric constant, or differences in plant shape, size, and orientation, on backscatter of microwave radiation at different frequencies.

Geometric resolution requirements for vegetation analysis cannot be met by existing or planned passive microwave systems. Of the active microwave systems proposed for space use, the 30 meter resolution of the SIR-A and SIR-B radars is quite useable, although the 25 meter resolution of the SEASAT synthetic aperture radar (SAR) would be preferred by most users. Because of the uncertainties concerning the utility of space radar data for vegetation analysis, every effort should be made to utilize SEASAT SAR data in exploring the areas of uncertainty (see Section 2.2 of this report). The frequency and incidence angle (Table 2.2) are considered appropriate for vegetation mapping (Simonett 1976). Although SEASAT will not provide extensive land coverage, coastal areas such as the Delmarva peninsula should provide excellent test areas for evaluating

vegetation mapping capabilities of the SEASAT SAR. Extensive ground and aircraft work will be needed to support such an investigation and corroborate the SEASAT measurements. Since none of the proposed space radars (SEASAT, SIR-A, SIR-B) include dual- or cross-polarization capabilities, a ground-based and aircraft-based research program will be needed in any case. Coupling with SEASAT, where possible, this can increase the impact of the ground and aircraft experimental work.

#### 4.2.2 World Carbon Budget

Growing concern over the inability to account for some 20 to 30 percent of the carbon released to the atmosphere by the combustion of fossil fuels (Lerman et al. 1977) has stimulated increasing interest in better definition of the world carbon budget (Kerr 1977). Estimates of carbon storage in standing forests and of total world forest area are major sources of uncertainty in previous efforts to define the world carbon budget.

Data requirements for estimating world forest area and monitoring changes due to land clearing and desertification are enormous. Approximately 1200 LANDSAT scenes are required to cover the tropical forests alone. Even with an effective sampling scheme, cloud cover limits the utility of LANDSAT data. Of the approximately 1200 scenes needed to cover the tropical forests, nearly 200 were never imaged with less than 10 percent cloud cover during the first 34 months (54 passes) of LANDSAT-1. Of these 200 scenes, almost half were never imaged with less than 50 percent cloud cover (World Bank 1976). In such areas, LANDSAT cannot provide all needed data even if the required observation frequency is only once a year.

An active microwave system with nearly all-weather capability could help fill this data gap, but it is not clear that satellite radar systems would be more effective than aircraft radar systems. The primary need is to distinguish between forest and cleared (non-forested) land, a classification task that appears to be within the capability of existing radar technology. Canopy penetration is not required, and a relatively short wavelength, possibly X-band, system with 25 meter resolution should be adequate. Polarization does not appear to be critical.

#### 4.2.3 Soil Moisture

Crop yield is highly dependent on the availability of proper amounts of water at the proper time. Any attempt to estimate yield of agricultural or forest crops must make

assumptions about, predict, or measure soil moisture. Some experimental data provide a basis for believing that microwave measurements are sufficiently related to soil moisture levels to permit estimation of soil moisture content from the microwave measurements (Simonett 1976).<sup>2</sup> Unfortunately, it is not clear that signal effects due to soil moisture content can be separated from effects due to other causes, such as the vegetative cover, surface roughness of the soil, or soil type and chemical composition. It is generally agreed that energy at longer wavelengths is less affected by surface roughness or vegetative cover than energy at shorter wavelengths (Schmugge et al. 1976), but the relationships are not clearly understood for any wavelength.

The lack of understanding of the variation in microwave signals with changes in moisture content within the soil profile is a fundamental problem limiting use of microwave measurements for estimating soil moisture content. A low moisture content near the surface may result in the same signal amplitude as much higher moisture content slightly lower in the profile; or, high moisture content at the surface may mask very dry soil conditions just below the surface. Plants respond to moisture availability throughout their root zone. While roots are more numerous near the soil surface, water uptake from deeper roots is important to plant growth and survival. In areas where sub-surface flow permits soil moisture recharge without new rainfall on the specific site, and in areas with a high groundwater table, soil moisture conditions below the surface layer may be more important in regulating plant growth than moisture conditions at the surface. Extensive drainage to promote agriculture in many areas, especially in the Great Plains and in the Atlantic and Gulf Coastal Plains, indicates that this latter problem is not trivial.

It should be remembered that precipitation falling on a soil surface has no appreciable effect on soil moisture content in any layer below the surface until the moisture content of all of the layers above the one in question has been raised to field capacity. Water in the upper 3 to 5 cm evaporates quickly, and its effects on plant growth are short-lived. It is for this reason that far better information on the interactions of microwave energy with soil moisture is needed before reliable and meaningful estimates of soil moisture content can be extracted from microwave measurements. Even after these relationships have been determined, models will be needed that are capable of extrapolating from surface and near-surface soil moisture measurements to the moisture content of the soil profile in the entire plant root zone. Separate models, or modifiers, will probably be needed for different soil types, plant types, and plant ages.

Knowledge of the moisture content in the upper 5 cm of soil may well be adequate for estimating germination success and early growth of crops. For purposes of crop yield forecasting, however, moisture content of the upper 30 to 90 cm may be needed. Although many plant species have root zones that extend to depths of more than 90 cm, most have their greatest concentration of roots in the upper 30 cm of the soil profile. Considering the present state-of-the-art in crop yield forecasting, accurate estimates of the water available for plant growth within the upper 30 cm of the soil profile would be a significant step forward. Estimates of soil moisture for shallower depths would be of decreasing value as the depth of the estimate became shallower. The phrase "water available for plant growth," used above, is most important. All water in soil is not available for plant growth because some is held so tightly in, or on the surface of the soil particles that it cannot be extracted by plants. In addition, water in excess of field capacity cannot be held in a soil layer against gravitational forces. Thus, only that part of the soil moisture content between field capacity and some lower level, usually referred to as the wilting point for that soil, is actually available for plant growth. It is this amount of water that is important in estimating crop yield, and it is this amount of water that needs to be measured. No information was presented to the Committee that indicated that such measurements could be extracted from microwave data.

#### 4.2.4 Conclusions

Active microwave systems show a great deal of promise in large area vegetation mapping, particularly in areas which are often obscured by clouds. There is not sufficient evidence, however, to conclude that active microwaves can be used to differentiate consistently among various important species. The available experimental data cannot be considered adequate to support the development of an active microwave sensor system for vegetation classification at this time. A principal weakness of the data base is the lack of repeatable data supported by adequate ground truth verification. Research should be continued to develop a better understanding of the target interaction with active electromagnetic radiation at microwave frequencies.

A short-wavelength, high resolution radar system could probably be immediately useful in making an estimate of the total areal extent of forests, an estimate of great importance in defining the total carbon budget of the earth. The system requirements in this case are well within the capabilities of microwave technology.

The use of active microwave remote sensors for soil moisture measurement is still very much in the research stage. While the research results to date are promising, further aircraft and field studies are necessary to refine the relationship between the microwave signal and soil moisture, and to quantify the effect of vegetation and surface roughness on the signal. Soil moisture dynamics must also be modeled more completely for a wide range of soil types. There is inadequate experimental evidence to support selection of the design parameters of a sensor system that could make unique soil moisture measurements. In the judgment of the Committee, it is premature to make major program commitments to developing a space microwave system primarily for making soil moisture measurements.

## NOTE

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### 4.3 Geology

Remote sensing from both aircraft and spacecraft platforms has been a valuable supplement to field and exploration geology, as illustrated by the favorable response of the geological community to the use of LANDSAT imagery. LANDSAT images have been particularly useful in identifying geologic faults, folds, and lineaments. The fact that the mineral and petroleum exploration community is the largest single group of LANDSAT data buyers indicates their interest in these data.

There are two principal deficiencies with the LANDSAT data. The first is that there are several regions on earth where cloud cover has prevented adequate viewing by LANDSAT sensors. The second has to do with the fact that in terrain with low relief, which is typical of many petroleum-bearing regions, low sun angles are required to enhance the subtle features of relief in these images. Because of its dependence on solar illumination, LANDSAT acquires images with low sun angle illumination only at higher latitudes.

A radar system would not normally be subject to these limitations. (A passive microwave system is not considered because the poor spatial resolution would not be adequate for most geological purposes). Radar systems in the L and C-band regions have essentially all-weather capability, and are not hampered by clouds, although rain does interfere to a degree with C-band systems. For this reason, petroleum and mineral exploration groups have used aircraft radar coverage of areas generally obscured by clouds and difficult to photograph. The capability to penetrate cloud cover was also one of the driving forces behind project RADAM, which made a complete radar survey of Brazil. The interior of Venezuela has also been surveyed with radar imagery.

Radar imagery, since it does not depend on the sun as an energy source, can theoretically be acquired at the optimum incidence angle to enhance subtle geological features. The 50° and 45° incidence angles of the proposed SIR-A and SIR-B systems, respectively, are not ideal. (See Appendix B and C.) A larger incidence angle would be preferable.

A space radar system is potentially useful for geological purposes. The primary use of microwave sensors in geological applications will be in studies of regional geology, and in particular, geologic structure studies. The available experimental data do not support the possibility of directly interpreting signatures of ore deposits or rock type from microwave imagery.

#### 4.3.1 Mapping of Geologic Structure

Topographic features in forested terrain may be more apparent on aircraft radar images than on single aerial photographs (non-stereoscopic), photomosaics, or on LANDSAT images. Fault scarps, lineaments, and patterns of joints, fractures, and foliation are usually strongly enhanced on radar images. This enhancement has been mistakenly attributed to radar energy penetrating the forest canopy. Radar theory, however, states that the commonly used radar wavelength (X-band) interacts with structures that are the size of leaves, twigs, and branches and therefore cannot penetrate heavily forested canopies. A practical demonstration of the interaction between radar energy and foliage is the fact that, on aircraft radar images of agricultural areas, bare fields are readily distinguished from those covered with crops. Differences between crop types can also be noted on the images. If radar energy were penetrating the foliage, these distinctions would not be apparent (Myers 1975, p. 1730-1735; Reeves et al. 1975, p. 1273; Sabins, in press). It has been suggested (Sabins, in press) that the relatively coarse spatial resolution of airborne radar images ( $\approx 10\text{m}$ ) eliminates the return from individual trees, thereby enhancing the expression of geologic structures which typically have dimensions of hundreds of meters. The target interaction process resulting in the enhancement of geologic structures on radar images of forested terrain is not clearly understood. This, however, in no way hampers geologists in their utilization of radar imagery, even though a better understanding of the process might enhance the usefulness of the data. It is possible that radar of longer wavelengths, such as L-band, may penetrate vegetation cover, but no examples of this imagery are available for evaluation.

#### 4.3.2 Rock Type Identification

In addition to large-scale topographic relief, radar measurements are influenced by two properties of surface materials: complex dielectric constant and surface roughness. In typical dry rocks and soils there is a small range of variation in dielectric constants which influence the amplitude of the reflected signal. The presence of moisture, however, has a much stronger influence on the actual dielectric constant than does variation in the composition of rock types.

Surface roughness may be related to rock type only in the case of unconsolidated sediments (gravel, sand, clay), which are defined on the basis of grain size. For consolidated rocks, the surface roughness is largely determined by weathering properties rather than by rock

type. For these reasons, rock types have not been reliably identified from aircraft radar images and there is no reason to anticipate an improvement with spacecraft images. Rock types with different surface roughness properties can be distinguished and mapped (not identified) in some aircraft radar images and presumably this should also be possible in some spacecraft images. It is anticipated that geologists will use spacecraft radar images predominantly for structural mapping, that is, the geometry of features in the image will be of greater use to geologists than the reflection characteristics which depend on surface roughness and dielectric constants.

#### 4.3.3 System Parameters

A large radar incidence angle is preferable for most geological observations. The optimum incidence angle depends on the particular application and the character of the terrain. In flat terrain, an incidence angle of greater than  $70^\circ$  is desirable to enhance subtle topographic features. In areas of high relief, however, a somewhat shallower incidence angle of less than  $70^\circ$  would be preferable. (The maximum incidence angle available in the SIR-A is  $53^\circ$  and  $47^\circ$  in SIR-B) (See Appendix B and C). The choice of frequency does not seem critical at this time. A longer wavelength, such as L-band, might be preferable since it would theoretically penetrate vegetation more readily than a shorter wavelength. There is not enough experimental data to verify this.

There is a potential problem in choosing an optimum flight path. Geologists have been impressed by the identification of lineaments on radar images. Because of the highlighting and shadowing effect, lineaments oriented parallel to the flight path are enhanced considerably more than those perpendicular to the flight path. Ideally, each geographic area would have a flight path with a preferred azimuth, depending on the orientation of linear features to be measured. This is not a problem for aircraft radar systems because these flight paths can be oriented for the particular mission. Satellite coverage is another matter. To acquire optimum imagery of every area, a satellite would need to cover each area twice on perpendicular or nearly perpendicular flight lines. A low inclination orbit, such as that used by Skylab, provides a better orientation at the lower latitudes than the essentially north-south orbital path of the LANDSAT. A low inclination orbit, however, would have other disadvantages, including failure to cover the higher latitudes where ice mapping is very important.

Some attempts have been made to identify rock types on dual-polarized (HH and HV) Ka band aircraft images (Dellwig

and Moore 1966). Field checking indicates, however, that the difference in radar return intensity are probably related to differences in vegetation rather than differences in rock type. With the present limited knowledge about the mechanism of depolarization, there is no strong geologic requirement for multiple polarized images.

#### 4.3.4 Conclusions

Radar data should be immediately useful in mapping large geological structures particularly in forested areas and in areas which are perennially overcast. A radar system using a large incidence angle would be particularly useful in highlighting relief in relatively flat terrain. This is important since many geological features significant to petroleum exploration occur in areas of flat relief. The combined use of visible and IR data with radar data may aid in differentiating rock units by analyzing seasonal variations in vegetation cover.

A great deal of research and experimentation needs to be done to define the interaction of microwaves with the ground targets. The amplitude of the radar return signal is determined by several factors including soil moisture, vegetation, and surface roughness. At present, however, it is not possible to separate the contributions of each of these factors. The effect of vegetation cover on the return signal is uncertain; this is particularly important for interpreting imagery of forested terrain. Ground or aircraft radar systems can be used for primary research experiments, which should include careful ground truth data. Every opportunity should also be taken to utilize the SEASAT space radar to gather experimental data even though the SEASAT parameters are not optimized for geological applications. This should be possible with a minimum of effort since members of the geologic community are experienced in interpreting and utilizing radar information for exploration and should therefore be able to utilize SEASAT imagery with a minimum of training.

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## 4.4 Land Use

Land use planning and management activities are related to three functions: (1) land use inventory or monitoring, (2) assessment of land suitability or capacity, and (3) actual land use decision making, operation, and enforcement. Land use ultimately encompasses most of the other applications covered in this report, since they are related to the use of land and adjacent water. Land use planning focuses on man's social and economic activities as reflected in patterns of urban and regional development. It is this point of view which defines the data requirements for a remote sensing system for land use applications.

There is a political problem that must be addressed in considering the use of radar imagery for land use management. Decisions affecting the use of land are of direct concern to the local residents. The majority of the land use management decisions are made at the local level and require using a map of a scale commensurate with the land area involved. Thus, unlike many of the other applications, the users of land use data are typically a politically motivated group responsible for local decisions and require high resolution information. Such groups are normally unaccustomed to using data of the complexity of radar imagery. Furthermore, they tend to resist any input into the decision-making process from the regional or national level, fearing outside interference in local affairs. This is particularly true in developed countries such as the United States.

Remote sensing has demonstrated its capability to provide accurate, frequently updated classification maps that can be enormously useful in all aspects of land use management. Considerable use has already been made of remote sensing data in solving land use problems. The most useful data have been in the form of aerial large scale photographs, which are primarily used at the local level. Satellite imagery, as represented by the LANDSAT 1 and 2, on the other hand, has been of only limited usefulness thus far, because of the small scale of the maps which can be produced from this imagery. These data are only adequate for level I classification (Anderson et al. 1972), and are primarily useful on the regional or national planning level.

The advantage of satellite imagery is that it provides reasonably uniform and repetitive information for many areas of the world. The space systems proposed for the 1980's, using visible, IR, and active microwave sensors, will all have comparable resolutions of approximately 30 to 40 meters. Radar, however, has a distinct advantage in that it functions essentially independently of weather (at wavelengths greater than 3 cm). This is particularly

important considering that many areas of the world that lack accurate and current land use data are perpetually cloud covered (i.e., tropical developing nations). Unfortunately, the classification techniques available for visible and IR imagery have not been extended to microwave imagery. The work that has been done using radar for land use mapping suggests that space radar systems can become an effective survey tool (Nunnally 1969, Henderson 1975, Lewis et al. 1969). Experience with interpretation of microwave imagery is, however, only in its early stages of development. There has been substantial work, such as in Project RADAM, which demonstrated that airborne radar images can effectively show the distribution of elements in a scene.

It is quite likely that the characteristics that will be used for radar land use classification will have to differ from those used in the visible and IR. Henderson (1976) listed five key characteristics relevant to the creation of radar land use categories:

1. Surface configuration -- the topography and drainage network of an area; specifically, the relative relief, slope, and general geomorphic-physical setting of an area visible on radar imagery.
2. Natural vegetation -- the indigenous plant communities found on the land (i.e., riparian) as opposed to mesic vegetation such as hay fields or cropped fields.
3. Field patterns and size -- the location and shape of fields in relation to the overall scene.
4. Settlement pattern -- the relative density, arrangement, and location of farms and towns.
5. Transportation/communication network -- the location, relative density, and direction of roads and railroads. Since portions of high tension power lines are sometimes detectable on radar, they are included as a second component of this characteristic.

Another consideration that affects the use of radar is the difficulty of quantifying the information. Current aircraft radar systems are uncalibrated, that is the grey scale values may change along the flightline. This increases the difficulty and affects the confidence in data interpretation. The processing of radar data is more complex and time consuming, and therefore more expensive than optical data processing. This raises the question of the cost-effectiveness of radar as a tool for land use mapping. Radar imagery provides a perspective of the land use environment different from that to which land use managers are accustomed. While radar imagery may be useful,

it is not clear that this new perspective will provide a significant addition to existing information sources.

#### 4.4.1 Conclusions

The development of space radar sensors with resolutions comparable to visible and IR sensors does not appear justified based on incremental value added to land use applications. There is not an adequate experimental data base available at this time to relate signal classification to ground truth. This is not to say, however, that microwave systems should never be developed. Their potential all-weather capability (at wavelengths greater than 3 cm) would be of considerable importance in many areas of the world that are perpetually obscured. Land use planning and management programs would also benefit from any sensor system with adequate resolution that can make quantitative measurements of soil moisture and identify vegetative or ground cover classes.

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## 4.5 Cartography as a User Discipline

In the previous CORSPERS report (NRC 1976), a distinction was made between the application of cartography by the user disciplines and cartography as a user of remote sensing data. This distinction is continued in the present report. The application of cartography by the user disciplines is discussed in section 4.0 of the present report, and cartography as a user of remote sensing data is discussed below.

Spaceborne imaging radar (SIR) and passive radiometers, as presently planned, will have little use as an adjunct to LANDSAT or the THEMATIC MAPPER in conventional cartography (mapping and charting), for the following reasons:

1. The resolution of the imaging microwave sensors will not provide an improvement over the instantaneous field of view (IFOV) of THEMATIC MAPPER sensors in the visible and IR portions of the spectrum.

2. The imaging microwave sensors will not provide topographic relief information of the quality required for cartographic purposes. Cartography will have to continue to rely on stereo imagery from aircraft altitudes for accurate topography. SIR-A or B will be of only minor assistance in topographic interpretation. The Committee has not been shown how data from the proposed spaceborne imaging microwave sensors can provide horizontal and vertical position accuracies necessary to satisfy the United States National Map Accuracy Standards or be comparable to the standards of the United States Geological Survey.

3. The positional accuracy of cartographic data from SIR-A or B will not be as good as the positional accuracy of data from LANDSAT in the visible and IR regions.

4. The difficulties of recognizing and identifying SIR-A or B imagery and the difficulties of correlating SIR images with images in the visible and IR, for example due to layover, will add to, rather than alleviate the problems of cartographic interpretation. Layover, which is the displacement of an object or feature due to relief in a radar image, is in the opposite direction to that of relief displacement in an image derived from visible or IR sensors. Furthermore, the magnitude of layover is not the same as the magnitude of relief displacement in a visible or IR image, except by unusual coincidence. At small incidence angles, layover is large and visible/IR relief displacement is small. At large incidence angles, layover is small and visible/IR relief displacement is large.

5. Worldwide all-weather microwave sensor coverage would be convenient but not necessary for conventional cartography. Long time period repetitive coverage is sufficient for cartography. The few areas of the world that are covered by clouds most of the time could be mapped by radar from aircraft. Cartography of these areas alone does not justify worldwide all-weather radar coverage.

The spectacular radar survey of Brazil through extensive cloud cover is often given as proof of the importance of microwave remote sensing. The importance of this Brazilian radar survey lies principally in the fact that the country was poorly mapped before, so that the radar data, which was not of cartographic quality, could make a major contribution. Information about all the maps that resulted from the project have not been released by Brazilian authorities, but the accuracy and degree of detail of the topographic maps derived from this survey are not expected to satisfy conventional cartographic standards.

One of the stated goals of the Microwave Remote Sensing Program Five Year Technical Plan, 1977-1982, as presented to the Committee, <sup>1</sup> is "...to develop the sensor systems, and data processing techniques to produce highly accurate terrain profile maps for use in aircraft hazard avoidance, producing USGS quality topographic maps, measuring subsidence, monitoring dilatency...". As stated earlier, no evidence was presented to the Committee on how the necessary horizontal and vertical positional accuracies required for these applications can be achieved by the microwave remote sensor systems proposed in the Technical Plan for the 1977-1982 time period.

Positional accuracy on maps and charts, i.e. geometric fidelity, is a major objective of cartography. Radar can measure distances accurately between two points, as is done in ground surveying, but it has not yet been demonstrated that spaceborne synthetic aperture radar can produce an area display in which all image points are located with respect to each other with accuracies that meet cartographic standards.

The National Academy of Sciences/National Research Council has repeatedly recommended that accurate photogrammetric-type cameras be deployed in space vehicles to produce hard-copy imagery that can be recovered, that is, photographic plates exposed in satellite-borne photogrammetric cameras that can be returned to ground to provide geometrically accurate cartographic data. The space shuttle will make this hard-copy recovery possible and practical. For example, a 9 in x 18 in format photogrammetric orbiter camera was proposed (NASA 1977) to be launched by OFT-5. An orbiter camera such as this, or a

photogrammetric camera that stays with the space shuttle, would be far more useful for cartographic purposes than either the SIR-A or B.

#### 4.5.1 Conclusion

The requirements of cartography as a user discipline do not justify or support the deployment of SIR-A or B or passive microwave sensors in the space shuttle or in other spacecraft, as supplements to LANDSAT/THEMATIC MAPPER systems.

#### NOTE

1. Rouse, J.W. (1977) Microwave Remote Sensing Five-Year Technical Plan, Page 7, Paragraph 2.2.4. National Aeronautics and Space Administration, Office of Applications. Unpublished preliminary draft.

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## 4.6 Environmental Monitoring

### 4.6.1 Introduction

The objective of environmental monitoring is to provide data to assist in the effective management of earth resources. One part of the monitoring task is to compile resource inventory data, as collected for other applications discussed in this report. Environmental monitoring also has its own specialized data requirements, derived primarily from the need to observe the environmental dynamics of the resource utilization processes: pollution dispersion and impact, and degradation of land, air, and water resources. These are also the data requirements of a specialized user community concerned with the operational enforcement of environmental protection programs. These programs often dictate stringent requirements as to the accuracy, timeliness, and reliability of the data.

Environmental monitoring has only recently turned to remote sensing as an observational tool. Experience with remote sensing techniques is therefore limited. This is particularly true of microwave sensors. What experience there is suggests that microwave sensors, primarily imaging radar, may be valuable for several applications. But data are limited and results are preliminary. Considerable research, accompanied by detailed ground truth measurements, is needed before an accurate assessment can be made of the utility of radar imagery for environmental monitoring.

### 4.6.2 Water Quality

Water quality studies are normally concerned with the detection of substances in the water. Since microwaves do not penetrate the water, many substances of particular interest to environmental monitoring--suspended sediment, algal concentration--are beyond the range of microwave remote sensing. To be detectable, a substance must affect the dielectric constant of the surface.

Mauer and Edgerton (1976) have demonstrated the capability of radar sensors to detect oil spills. It would be helpful if radar imagery could distinguish oil types for a variety of water surface (sea state) conditions. There is some preliminary evidence that microwave sensors can be used to detect the type and thickness of the oil but a considerable amount of research, supported by adequate ground truth measurements, is needed to verify and extend these results. Microwave sensors have the added day and night, and, for certain frequencies, all weather advantage of detecting oil spills. This application, however, places particularly severe coverage requirements on a space system.

Oil spill monitoring typically requires frequent coverage, high resolution, and real time data. These requirements are more readily met with aircraft systems such as those being used by the U.S. Coast Guard in their airborne oil spill detection system (Rouse 1975).

The only other water quality parameter that has been studied using microwave sensors is salinity. This is discussed in Section 4.7.1.

#### 4.6.3 Land Quality

The assessment of land degradation often involves evaluation of the type and condition of vegetation and soil. Microwave applications in these areas are discussed under vegetation mapping and geology (Section 4.2 and 4.3).

The most promising use of microwaves for environmental monitoring of land is the observation of strip mining operations. High resolution radar is required for this purpose. Ten meter resolution would be quite useful (Shuchman et al. 1975) although higher resolution would be preferable. (The resolution of the proposed SIR-A and B is 40 and 25 meters, respectively. See Table 2.2.)

There are several advantages to using microwave rather than optical sensors for strip mine monitoring. The capability to penetrate cloud cover is of critical importance in several areas (Eastern Kentucky) where cloud cover is a perennial problem. In addition, the sensitivity of radar to surface roughness, subtle height variations, and orientations makes detection of significant features possible. These features include the presence of high walls, slumping of the outcrops, water impoundment, tailing piles, roads and erosion patterns. Shuchman et al. (1975) have been able to classify strip mines in three categories based on observation of these features using an airborne dual-frequency, multiple-polarization radar.

Although radar appears very promising as a tool for strip mine monitoring, several problems do exist. Shuchman et al. indicate that dual-frequency and multiple polarization were necessary for accurate classification. Shuchman et al. (1975) also recommend two orthogonal look directions (see Geology Section 4.3.3) to improve the information content of the imagery. This creates a problem for space radar systems which are confined to relatively fixed orbits. The limited orbital change capability of the shuttle does not provide a satisfactory solution. Aircraft radar systems do not have this flight path limitation.

Microwave remote sensing could prove useful in the observation of soil erosion and sedimentation patterns, monitoring of sanitary landfills and other waste disposal projects, and observation of changes induced by man (road construction, shoreline use, cleared land).

However diverse the specific data needs may be, environmental monitoring projects are all typically concerned with localized problems. The data needs usually require a very high resolution. In several cases this is combined with a requirement for a fast response time and frequent return coverage, requirements not easily satisfied by space systems.

One of the few areas of environmental monitoring that does not require high resolution is air quality monitoring. This is one area in which microwave sensors may be particularly promising. The variability in atmospheric absorption of microwaves at different frequencies opens some interesting possibilities. This should be stressed with respect to the passive systems planned for the space shuttle (SIMS and SMMRE).

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## 4.7 Coastal Features and Processes

Remote sensing has played a fairly important role in the study of coastal areas. Since these areas are often highly variable and involve dynamic processes, the frequent coverage and large area synoptic view provided by remote sensors can be most valuable in coastal studies.

### 4.7.1 Wetlands Mapping

The desired capabilities of remote sensing systems for coastal zone management include vegetation mapping, detection of surface water, and observation of geologic features. LANDSAT and SKYLAB imagery has been used with a fair degree of success in mapping wetlands vegetation (Klemas et al. 1975, Anderson et al. 1975). Classification accuracy should improve considerably in the 1980's with the THEMATIC MAPPER because of its improved spatial resolution and the more suitable spectral response characteristics (NRC 1976).

Vegetation mapping with microwave sensors has received relatively little attention, and its potential is difficult to assess at this time (see Section 4.2). This is particularly true for wetlands mapping. What work has been done is primarily concerned with a limited number of species of agricultural crops and forests, under a limited range of conditions (Hardy et al. 1971, Moraine and Coiner 1970, Ulaby 1977). Recently Shuchman and Lowry (in press) had considerable success in classifying coastal wetlands using dual-frequency, dual-polarization SAR imagery. The success of the classification seemed to depend far more on geometry--differences in the size, shape, and structure of the vegetation--than on changes in the dielectric constant. Judging from the work of Ulaby (1977) and Shuchman and Lowry (in press), successful vegetation classification will probably depend on the use of multiple-frequency and multiple-polarization radar systems. At present, however, very little experimental data are available in this area. For the near future, the potential use of radar will probably be limited to measuring topographic features, as an all-weather supplement to the visible and IR sensors in LANDSAT, including the THEMATIC MAPPER. This can be a significant supplement for areas normally obscured by cloud cover, as in Panama or Columbia (MacDonald et al. 1971, Lewis and MacDonald 1972). Optical and IR systems are expected to continue to dominate classification of vegetation in wetlands.

Microwave systems are competitive with optical and IR systems in their ability to detect surface water. In fact, microwaves may have an advantage since it should be

possible, particularly at the longer wavelengths, to detect water under the vegetation (Shuchman and Lowry, in press). Microwave remote sensing can also be used to observe the extent of tidal inundation and as a measure of the mean high water level.

The ability of passive microwave remote sensors to observe variations in salinity has been demonstrated (Paris 1972, Blume et al. 1977). Since the microwave radiometer measures apparent temperature, it is necessary to have either an independent measure of the actual surface temperature from a thermal infrared radiometer, or a dual-frequency microwave radiometer system to separate temperature variations from salinity variations. Even though the resulting salinity measurement is very coarse, with an accuracy of no more than 1%, it would still be useful in mapping coastal wetlands, where both the temporal and spatial variations in salinity often exceed 10%.

Tidal zone features and coastal geology may also be attractive targets of microwave remote sensing, primarily radar, because of its sensitivity to topographic features and surface roughness. System requirements and capabilities are covered in detail in the discussion of geology (Section 4.3) in this report. The one peculiarity associated with coastal areas is that the best-look direction appears to be with the flight path parallel to the shoreline and with the imaging system over the water, looking toward the land (Matthews 1975). Spaceborne radar sensors obviously cannot consistently respond to this requirement on a local basis.

#### 4.7.2 Estuaries and Inland Waters

Microwave remote sensing of water is limited entirely to surface effects. There is practically no penetration of the water. This is in contrast to optical remote sensing of water, which depends to a large extent on the volume characteristics of the water. Thus microwaves are ineffective for the detection of most coastal zone pollutants, which are usually identified by color or tonal differences. The one clear exception is in the detection and identification of surface slicks caused by oil and other substances.

The mechanism for detecting of oil slicks by microwave radiometry (Catoe & McClean 1972) or radar (van Kuilenberg 1973) is the measurement of the local change in sea state due to the damping effect of the oil. It is also possible to estimate the thickness of the oil by microwave radiometry because of the change in emissivity of the water surface due to the presence of oil.

The available evidence seems to indicate that microwave sensors are not as effective as visible or IR sensors in either detection, classification, or quantification of oil spills. The real advantage of using microwave sensors in oil spill monitoring is their essentially all-weather capability. Microwave sensors should therefore be viewed primarily as an all-weather supplement to other remote sensing systems.

A real strength of radar systems is the ability to accurately measure distances. Theoretically, a radar altimeter could give the surface slope for an entire estuary. This could provide extremely important data for hydrodynamic models. The development of a high-resolution, 30 meters, imaging radar system capable of accurate measurement of relative heights to  $\pm 3$  cm merits serious consideration.

The SEASAT altimeter (nadir view only) will be capable of an absolute accuracy of  $\pm 25$  cm with a relative accuracy of  $\pm 10$  cm. This is only marginally useful for most estuarine or coastal applications. SEASAT altimetry, however, would be adequate for large-scale estuarine hydrodynamic modeling, particularly if combined with surface salinity measurements using microwave radiometry.

#### 4.7.3 Coastal Storm Impact

Remote sensing has been invaluable in observing short- and long-term shoreline changes (Herbich and Hales 1971). Aerial photography using a mapping camera, with its high resolution and cartographic accuracy, is ideal for observing local changes (Stafford and Langfelder 1971). Larger area (smaller scale) changes can be quite effectively monitored with LANDSAT imagery and the effectiveness is likely to increase when the higher resolution THEMATIC MAPPER imagery becomes available. A radar system could, of course, be useful for monitoring long-term shoreline changes in cloud covered environments (MacDonald et al. 1971). Radical, rapid changes in shoreline features often occur during storms, that is, under cloud cover. The only feasible way of monitoring such changes is with frequent (hourly), repetitive coverage with a high resolution, airborne imaging radar system.

Imaging radar data can also be used to determine the slope (directional) spectra of the storm waves as well as to estimate the wave heights and thus to make a detailed assessment of the impact of storm waves on the shoreline (Panicker 1974, Longuet-Higgins 1956). Such an assessment would require a system with very high resolution (10 meters or less). Shuchman et al. (1977) concluded that the SEASAT

resolution of 25 meters was only sufficient for determining the speed of high velocity waves and that the 180° ambiguity in direction can only be marginally resolved.

All things considered, it appears that observations of storm wave spectra and the associated shoreline changes would be more efficiently handled by an aircraft imaging radar than by a satellite or shuttle system for several reasons: the need for high frequency of coverage; the sporadic nature of storm occurrence; and the need for high resolution, which is presently available only in aircraft systems. A space radar system would be more appropriate for observation of the development of deep-water, storm-generated waves and their transformation to shallow water waves. The SEASAT imaging radar should be effective for this purpose. Unfortunately, SEASAT will be covering only limited areas of the deep-ocean. Its coverage is limited by the placement of the four data receiving stations since it will not have the capability of on-board recording of radar (SAR) data. Furthermore, for the first year of SEASAT SAR operation, only 400 passes will be processed for all targets observed from all four stations. Problems such as the momentum transfer in the generation of waves during storms are of considerable importance and cannot be studied adequately with this limited readout coverage.

#### 4.7.4 Conclusions

Imaging radar and radar altimetry have several unique applications in the observation of coastal processes. Radar altimetry can provide important surface slope data for hydrodynamic models of large coastal water bodies. The impact of storm waves on the shoreline can be observed with imaging radar, which provides directional (slope) wave spectra and maps shoreline changes independent of cloud cover.

In many cases, the high temporal and spatial variability of the coastal processes would be more efficiently observed from an aircraft system with high spatial resolution and frequent coverage.

The proposed shuttle radar systems should not be restricted entirely to terrestrial applications. Important oceanographic phenomena, beyond the reach of SEASAT, should also be included.

## NOTE

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## 4.8 Ice and Snow

Ice and snow mapping is important primarily because it provides essential information for water resources management. The monitoring of sea ice movement is important for marine transportation. In many parts of the world, snow melt waters provide a major part of the annual water supply and accurate early estimates of the total snow cover can become critically important. This is illustrated by the experience with the predicted 1977 drought in the Pacific Northwest. The severity of the drought was drastically overestimated because of an underestimate of the snowfall. This was costly to many local farmers who either did not plant their crops or invested in expensive, often unnecessary irrigation systems because of the forecasted water shortage.

Under ideal conditions, LANDSAT imagery can give a good estimate of the total areal extent of the snow. Furthermore, Barnes (1973) indicates that LANDSAT band 7 (near infrared) may be useful for distinguishing wet snow from dry snow. But there are a number of serious problems associated with optical imaging systems such as LANDSAT. Snow is often indistinguishable from bare rock or from clouds, under a partially cloudy sky. Snow is difficult to detect in shadows, and cloud cover often makes any observation impossible in important areas. The most serious problem, however, is that an optical system can only be used to give an estimate of the extent of snow, which may not be indicative of the water content of the snow cover. Microwave systems may offer at least a partial solution. Except for the higher frequency range, microwaves are largely unaffected by haze and cloud cover. There should be little difficulty in observing the extent of snow cover under overcast or partially cloudy skies, nor would shadowing be a problem at small incidence angles. But most important is the theoretical possibility that microwave sensors will be useful for distinguishing between old and new snow, compacted and non-compacted snow, and wet and dry snow. Dry cold snow has a permittivity close to unity and has low loss. Compacted cold snow has a higher permittivity but has low loss. Snow containing water in unfrozen form has much higher permittivity and loss (Evans 1965, Matthews 1975). There is the potential then of determining the equivalent water content of the snow and the pattern and rate of snow melt with sufficient lead time to make an adequate forecast of the runoff water (Seifert et al. 1975).

There are observations which tend to confirm this theoretical potential. Edgerton et al. (1971) have observed that wet snow has a very much higher microwave brightness temperature than dry snow of equal depth. Chang et al. (1976) have used a theoretical scattering model to relate

the observed brightness temperature to the snow grain-size, physical temperature, and variation in loss tangent for snow on glacier ice. They concluded that it might be possible to determine snow accumulation rates by using the model in conjunction with multi-frequency microwave radiometry.

This model, or one like it, should be expanded to include snow on land with variable grain-size distribution, and should be verified by extensive observations. Observations should also be made to test the feasibility of using a multi-frequency microwave radiometer system as a tool for measuring the moisture content, depth, and extent of snow.

While a radar system would have the important advantage of much higher spatial resolution, considerably less is known about radar return from snow. Research by Waite and MacDonald (1970) indicates a significant difference in signal return between old and new snow, and the feasibility of using a K-band imaging radar for mapping old snow cover. There is, however, no model of the interaction of a radar signal with snow and there has been very little experimentation with radar systems for snow cover observations.

For both active and passive systems, the needed research should rely heavily on extensive ground truth measurements. The research should focus on areas that can be monitored frequently (bi-weekly). But even when space microwave data become available, it is unlikely that the need for aircraft data will diminish. Aircraft systems will be particularly important during periods of rapid melt, when frequent coverage is essential.

Some of the most impressive recent work in microwave observation of snow and ice has been in the area of ice dynamics and morphology. Ice dynamics and morphology are crucial to climatological modeling and there is every indication that microwave systems are capable of determining age, type, structure, and dynamics of ice. Both active and passive systems are needed; the passive for determinations of ice type and age, and the active for determination of structure and dynamics.

To some extent, the success of microwaves in ice dynamics studies is due simply to the capability of microwave sensors to penetrate cloud cover and operate during hours of darkness. Polar regions are in darkness or at least in low illumination for half the year. Even during the summer, an inversion causes cloud cover at both poles for almost 70% of the time. Optical sensors cannot adequately cover the area under these conditions.

There are also several unique characteristics of microwave systems that can be of particular value. Passive microwave systems have proven capability to determine ice age and type for both sea and lake ice. In sea ice the dielectric constant is a function of salinity and the salinity is a function of the age of the ice. The change in the dielectric constant is sufficient to distinguish between first-year and multi-year ice (Campbell et al. 1975, Gloersen et al. 1973). In the case of snow and freshwater ice, when there is no melting, the ice and snow act as volume scatterers of microwave radiation. Air bubbles entrapped in the ice will also affect the signal. It is the internal properties of the ice structure rather than the salinity which affects the microwave radiation. Most of the change in brightness temperature is associated with the period of early growth from thin ice to several centimeters, although Tiuri et al (1975) found significant changes for thicknesses of up to 120 cm in low salinity (1%) ice with long wavelength (50 cm radar).

For measurement of ice dynamics and structure, an active microwave sensor system is required primarily because of the need for much higher resolution. A radar system can be used to distinguish between ice, even thin ice, and clear water. Land permafrost can clearly be distinguished from shorefast ice, water, and pack ice. Furthermore, the ice-type distinction is good enough to permit distinctions between water, thin ice, thicker first-year ice, and the thicker multi-year ice (Matthews 1975).

A radar system is also useful for understanding glacier and other land-ice dynamics. This is not only a matter of mapping the areal extent of ice and monitoring its growth and diminution, but of observing the flow patterns of the ice. Longer wavelengths (L band) are capable of penetrating the ice sheet to a depth of meters or tens of meters, revealing wave structure in the ice (essentially gravity waves), which delineates the glacial flow patterns in the ice.

Studies of ice dynamics and morphology have progressed to the point that they are ready for an experimental data collection program with both passive and active space microwave systems. A space system would require strong aircraft and ground support. The current experience with microwave systems for snow and ice monitoring is sufficient to warrant expansion to an experimental system in space.

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## CHAPTER V

# Concluding Discussion

### 5.0 Introduction

There is obviously a great deal of information potentially available from microwave data. Several authors have noted significant changes in the magnitude of the return signal that are correlated with changes in the frequency, polarization, or the incidence angle. But in many cases there is only a hint as to the cause of this variability. The full potential of microwave remote sensing can be realized only if these clues are followed up with research, both theoretical and experimental. The experimental work requires extensive ground truth measurements closely coordinated with the microwave sensor system. The level of control needed and the importance of repeatability imply greater emphasis on the use of aircraft than satellite platforms.

### 5.1 Approved Space Microwave Sensors

Both SEASAT and SIR-A have been approved. SEASAT is scheduled for launch in 1978 and SIR-A is scheduled for use on the space shuttle OFT-2 in 1979. The earth resource applications mentioned in Chapter IV can benefit, to varying degrees, from experimentation with the microwave data as they become available from these space systems. All of these applications should use these data sources where possible. In all cases requiring signal amplitude analysis, the emphasis should be on research to develop an understanding of the interaction of microwaves with the ground targets. This experimentation requires careful ground truth measurements made in parallel with the radar and radiometer measurements from ground or aircraft installations, and from the space platform installations mentioned before. Because of the complex nature of the

C-2

target interaction, the careful correlation of ground truth and sensor measurements is critical to these experiments.

### 5.1.1 SEASAT

SEASAT, as its name implies, is primarily designed for use in studies of ocean dynamics. Nonetheless, the microwave systems on board should also be useful for limited experimentation with applications to earth resource sensing. The SEASAT SAR data should be useful for experimenting with geologic measurements, broad area soil moisture measurements, vegetation mapping in coastal areas, observation of major coastline changes during storms, ice mapping, and monitoring ship traffic in selected areas. Because of the extremely crude spatial resolution, the passive microwave sensors on SEASAT will probably not be of much help for most earth resource sensing. Other limitations for earth resource sensing, such as limited read-out areas, are evident in the description in Appendix A.

### 5.1.2 SIR-A

The SIR-A system scheduled for the shuttle OFT-2 is intended primarily for exploratory geological applications. In the Committee's view, even though the SIR-A incidence angle of  $50^\circ$  is not ideal, active microwave sensors can probably make their most significant contribution at the present time in this application area. SIR-A data should make it possible to expand on the information derived from the visible and IR sensor data. The SAR system should be able to map large geological structures, including those in forested areas and in areas which are perennially overcast. The incidence angle ( $50^\circ$ ) unfortunately will not highlight the relief in relatively flat terrain to the degree desired by the geological community. SIR-A should also be useful in measuring the areal extent of tropical forests and in making ice observations.

## 5.2 Proposed Microwave Sensors

### 5.2.1 Active Systems

Most radar area and boundary mapping applications are reasonably well established. Imaging radar is very good at detecting land-water boundaries of rivers, lakes, and flooded areas, as well as delineating roads and airport runways. It can also be used to recognize significant geological features and to detect ice-water and ice-land boundaries. The requirements for these applications are

within known technology and in many cases the equipment already exists.

Yet, the details of the interaction between the radar signal and the ground targets are poorly understood. Since some of the more important potential applications of active microwave sensors depend on understanding the relationship between signal amplitude and surface shape and roughness, dielectric constant, radar frequency, incidence angle and polarization, there is a need for additional basic experiments and analyses. The following are particularly important:

1. The interrelationships of soil moisture, soil type, roughness, and vegetation cover.
2. The effective depth of the soil moisture radar measurement and its relationship to the soil moisture profile.
3. The extent to which microwave radiation penetrates vegetation. This is important not only for soil moisture measurements, but also for mapping topographic features, flood mapping, snow mapping, and vegetation classification.
4. The effect of the complex liquid and crystalline structure of ice and snow on the return radar signal and its penetration depth.

In all applications, the usefulness of the data will depend, to a varying degree, on the choice of the frequency or frequencies and the polarization(s) used in the sensor systems. At present there are inadequate experimental data and systems analyses to support the optimum choice for parameters of experimental systems. In selecting the system parameters, the Committee suggests that the following considerations be kept in mind:

1. Although space microwave sensor systems are proposed because of their presumed all-weather capability, the atmosphere does have effects that vary with the frequency used.
2. Since improved target recognition has sometimes been obtained using multi-frequency and multi-polarization data, an extensive analysis should be undertaken to selecting radar parameters to optimize information content for several simultaneously received signals. Although such a program should initially consist of in-depth analytical studies, it should also be supported by additional experimental measurements so that the available data base is representative of a wide range of geographical conditions.

3. In exploring the possible uses of multiple polarizations, combinations of linear and circular polarizations as well as HH, VV, and HV polarizations should be investigated.

#### 5.2.2 Passive Systems

Because of the extensive experience with meteorological sensing, there is less uncertainty with passive microwave remote sensing than with active microwave sensing from space platforms. For the major areas of application there is a more comprehensive data base than for similar applications using radar, and the data are also less ambiguous. In the Committee's view, in several applications, including broad area soil moisture measurements, oil spill detection, and mapping the areal extent of snow cover, a spaceborne imaging microwave radiometer could probably provide some qualitative information of immediate utility. Of these applications, the soil moisture measurements may be the most significant. As with radar, the full potential of microwave radiometry cannot be realized until a better understanding of the relationship between the desired information and the measured antenna temperature is developed. Suggested areas of effort include:

1. Conduct controlled laboratory and field experiments to quantify the relationship between brightness temperature and soil moisture content, under a variety of conditions,
2. Explore the relationship between multiple frequency observations and the soil moisture profile,
3. Conduct appropriate experiments to determine the feasibility of measuring precipitation rates over land,
4. Conduct necessary experiments to determine the utility of microwave radiometry for measuring the thickness and compactness of snow, and for determining snow accumulation rates,
5. Conduct necessary experiments to determine the limits of accuracy of microwave salinity measurements, and
6. Continue work in the investigation of ice morphology.

Since the Committee did not study the proposed SIMS and SMNRE passive shuttle systems in detail, it does not wish to express a preference between the two proposed designs.

### 5.3 The Use of the Shuttle as a Development Platform

A major limitation to using the space shuttle as an experimental platform is that it will only be able to provide limited and aperiodic coverage. Under the best of circumstances, with only one flight scheduled every six weeks, not all scheduled flights dedicated to earth resource sensing, and a maximum of six hours of data per dedicated flight, only a limited number of sites can be visited. This is an important consideration, particularly for experiments that require repeat coverage (ice dynamics), or for which the timing is critical (flood mapping), or both (coastal storm impact). The need to design and deploy, on a coordinated basis, a compatible and parallel ground truth effort raises complex operational problems. The need for coverage of different experimental areas by the different applications also creates serious priority problems and further decreases the coverage available to an experimenter.

The space shuttle does, however, provide an opportunity to make experimental measurements of earth resources under a sensor/target geometric relationship similar to that anticipated in an operational system. This may be a significant factor in removing as many uncontrolled variables in the experiment as is possible. In addition, experimental systems are expected to be reparable during a flight, and can be modified or changed between flights in response to new understanding acquired during the course of the experiment. Within the limitations of compatibility imposed by the different experiments, the multiple flights of the shuttle may provide an opportunity to tailor individual flights to emphasize the data requirements of specific applications.

### 5.4 A Suggested Development Logic

The development of a remote sensing instrument should follow a series of logical steps. For example:

1. Measurements of the phenomenon are made with sensors of different characteristics under varying conditions and parameters. Theoretical arguments might provide some basis on which to make the initial measurements. However, in dealing with complex natural phenomena in the absence of adequate scientific understanding, careful experiments to gather empirical data over the full range of anticipated variations are necessary.

2. A study of the data is made to determine if the measurements can be correlated with the desired information, and if so, how, and to what extent.

3. After a correlation is established, a quantitative relationship (or an algorithm) is derived in order to express the desired information in terms of the data. This relationship might be established on the basis of a theoretical model or on the basis of a significant quantity of reproducible data from which such empirical relationships can be derived.

4. The utility of the relationship derived between the data and the desired information is then verified by testing with new data not previously used to establish the basic relationship or algorithm. This testing should be done on a "blindfold" basis under realistic conditions.

5. The remote sensing technique should then be verified in space under conditions similar to those expected operationally.

The microwave remote sensing program seems to be attentive to all but the third and fourth steps, that is, the establishment of a firm and reliable relationship between the sensor measurements and the desired information, as well as the unambiguous demonstration of its validity. The plans presented to the Committee indicate a beginning, and plans for a demonstration from space. The necessary intermediate steps, however, are deficient and need bolstering before the final verification phase is conducted.

The Committee recognizes that because of the extensive lead time required for the development of a new sensor system, NASA's program decisions must often be based on the system potential as extrapolated from existing data or understanding, rather than from hard experimental evidence. Before proceeding on this basis, however, the potential applications must be significant and urgent, and the possibility of success reasonably strong, particularly if experimentation with space systems, which are inherently expensive, are involved.

Development of microwave sensors should not move forward with the same risk factor or uncertainty of success used when the original ERTS (LANDSAT) program decisions were made. The urgency to expand the current visible and IR space sensing capability by the addition of microwave sensors is not as critical as that for the creation of the initial space sensing capability.

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## Appendixes A - H

## Appendix A SEASAT-A

Excerpted from: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Solicitation for a Letter of Interest for SEASAT-A Experimenters, Enclosure II, dated June 23, 1970.

The SEASAT-A project was initiated in 1974 by NASA's Office of Applications, after several years of study by NASA, other U.S. Agencies, academic and industrial scientists and research managers. Microwave instruments suitable for ocean remote sensing had been in development in both aircraft and satellite programs for a number of years, and their potential applicability to global ocean monitoring tasks demonstrated. The complement of instruments selected for SEASAT-A was drawn from this background. The objective of the project is to verify certain remote sensing concepts regarding ocean monitoring from space, including precision altimetry for marine geoid and sea surface topography studies, accurate determination of wave directional spectra using microwave imaging, measurement of global wind speeds and directions by means of radar scatterometry, and all-weather sea surface temperature determination by microwave emission measurements. SEASAT-A will be launched during the second quarter of calendar year 1978.

### THE SATELLITE SYSTEM

#### The Instrument Complement

Synthetic Aperture Radar (SAR) The Synthetic Aperture Radar (SAR) is an active imaging device designed to provide data on ocean waves, coastal regions, and sea ice. The

derivation of ocean wave directional spectra from SAR images should provide a capability of importance to wave climate and propagation studies, and to studies of wave diffraction and refraction in shelf and island regions. The studies of coastal processes and ice, sea ice, and large glacial provinces, are expected to benefit from SAR data, particularly in light of its all-weather capability. The instrument's resolution will be 25 meters, with a swath width of approximately 100 km. Because of thermal control, power, and ground processing limitations, the SAR will be operated selectively, with an overall duty cycle of some four percent. SAR data are returned via a separate data link, at very high data rates. Table A-1 lists the principal characteristics of the SEASAT-A SAR.

Radar Altimeter Precision altimetry from space offers the potential for remote monitoring of ocean current systems, storm surges, wind set-ups, and tides. Sea surface topographic studies will require combined range measurement precision and orbit determination accuracy in the order of 0.1 meter. At least initially, the process will be iterative, as a more precise marine geoid than currently available must first be determined. Smaller scale phenomena characterized by departures from the stable geoid of 20-30 cm should, however, be readily detectable.

The altimeter footprint, centered at satellite nadir, will vary from 1.2 to 12 km, depending on sea state. By suitably processing the return pulse, an estimate of sea state can be obtained to an anticipated precision of  $\pm 10$  percent wave height in the range of 2 to 20 meters. The characteristics of the SEASAT-A radar altimeter are summarized in Table A-1.

Scatterometer The use of radar backscatter at K-band frequencies to measure surface winds has been demonstrated both by aircraft tests and the Skylab S-193 experiment. The backscatter dependence on wind speed is derived from the effect of wind on the ocean surface capillary wave spectrum, and is therefore affected by small scale surface disturbances such as those induced by falling rain. The geometry selected for the SEASAT-A wind field scatterometer is such that for each sampled area (roughly a parallelogram 50 km in diagonal dimension), two orthogonal observations are made, the comparison of which yields an estimate of surface wind direction and magnitude. The nature of the directional dependence is such that ambiguities in wind direction will appear in the first calculated set of individual wind vectors. These ambiguities must be removed by a combination of internal consistency arguments developed in the course of generating a smoothed vector wind field and rms fitting to a hindcast wind field. The range in wind speed over which the scatterometer is expected to yield

vector wind measurements is between four and better than twenty meters per second. Precision is expected to be  $\pm 25\%$  or  $\pm 2\text{m sec}^{-1}$  in wind speed and  $\pm 20^\circ$  in direction. A summary of the characteristics for the SEASAT-A wind field scatterometer is given in Table A-1.

#### Scanning Multifrequency Microwave Radiometers (SMMR)

The measurement of sea surface temperature on a global scale through clouds and light rain was early recognized as a potentially powerful tool for climatological and ocean dynamics studies. The five-channel Scanning Multi-frequency Microwave Radiometer (SMMR) instrument designed for the NIMBUS-G satellite was added to the SEASAT-A payload to provide this capability. The instantaneous fields of view vary from 21 km at 37 GHz to 121 km at 6.6 GHz.

Measurements of the several microwave frequencies will yield, in addition to sea surface temperature, information on liquid water and water vapor column densities, sea surface winds, and potentially useful sea ice signatures. The SMMR swath is offset to the right of the satellite ground trace in order to provide good overlap with the wind field scatterometer and Synthetic Aperture Radar (SAR) swaths. For SEASAT-A, the overlap with the scatterometer allows the evaluation of SMMR tropospheric sounding as a path attenuation correction data type. SMMR-SAR overlap will strengthen sea ice interpretation of both active and passive measurements. A summary of SMMR characteristics is given in Table A-2.

Very High Resolution Radiometer (VHRR) A modest visual and infrared imaging instrument, intended primarily to provide feature recognition, clear air sea surface temperature calibration data and, perhaps, precipitating cloud identification in support of the microwave instruments, completes the SEASAT-A payload. The instrument is identical to the ITOS series of very high resolution radiometer (VHRR), with the addition of on-board conversion to a digital data stream. The surface resolution of the instrument will be approximately 9 km, and its expected temperature resolution about  $1.0^\circ\text{C}$ .

#### Data Readout

The satellite will transmit data at three rates on two separate carriers. All data except those produced by the synthetic aperture radar can be transmitted both in real time at a 25 kbps rate or played back from two on-board ( $4 \times 10^8$  bits capacity) tape recorders at a rate of 800 kbps. The playback mode is used to provide global coverage from limited telemetry coverage planned for the mission. Only the readout station at Fairbanks, Alaska (ULA) (see Figure A-1) will acquire data for near real-time use (up to 6 hours

after initial acquisition by the sensor). The only data loss for near real-time use is from the central part of Europe and a small segment of the Pacific Ocean of South America. The non-real-time, low data rate will be received at Alaska (ULA), Goldstone (GDS), Rosman (ROS), Madrid (MAD), and Orroval (ORR). Data from SAR will not be recorded on board but will be read out at ULA, GDS, ROS, and St. John. All the coastline of the United States will be covered by SAR with the exception of Hawaii.

#### ORBIT DESIGN

The SEASAT-A orbit has been selected to provide a ground trace network suitable for precise geodetic studies. An equatorial spacing of some 18 km will be accomplished in 152 days of operation, yielding two "geodetic cycles" in the one year of the standard mission. The orbit inclination of  $108^{\circ}$  yields near-optimal mid-latitude ascending-descending orbit intersection angles for geodetic purposes, and the altitude of 800 km provides a period consistent with the required geodetic closure time (approximately six months), while at the same time permitting an acceptable range for the active microwave sensors. The orbit eccentricity will be driven as close to zero as possible (0.002) in order to minimize altitude fluctuations, which tend to complicate instrument design (range gates and doppler filters, for example). Orbit trim capability is required to offset the perturbing effects of atmospheric drag, but the frequency of orbit adjust must be kept to a nominal level (no more than once per month) in the interest of precision orbit determination.

#### DATA PROCESSING AND DISTRIBUTION

There are two time scales for data processing and analysis in the SEASAT-A data system. First, a near-real time data link, via commercial communication satellite, links the tracking station at Fairbanks, Alaska with the Navy's Fleet Numerical Weather Central (FNWC) in Monterey, California. This link has been established for evaluating the effectiveness of global sea-surface temperatures, wind fields, and sea state data provided by SEASAT in conjunction with the FNWC's numerical weather forecasting abilities.

A second path is followed by the data intended for experiment team evaluation and general research purposes. This path is slower, with throughput times measured in days rather than hours or minutes. Its output is, however, a fully annotated, geophysically processed global data set with all the ancillary data required for research purposes. Following an initial period of evaluation, geophysically processed data will be provided to the National Oceanic and

Atmospheric Administration's (NOAA) Environmental Data Service. Some researchers may be both willing and able to utilize "raw" spacecraft data, that is, data which have undergone a minimum of processing (conversion to engineering units, earth located). These data, which are used as the input to geophysical processing, will be made available to experimenters as soon as the proper operation of the sensors has been verified within a few weeks after orbit insertion.

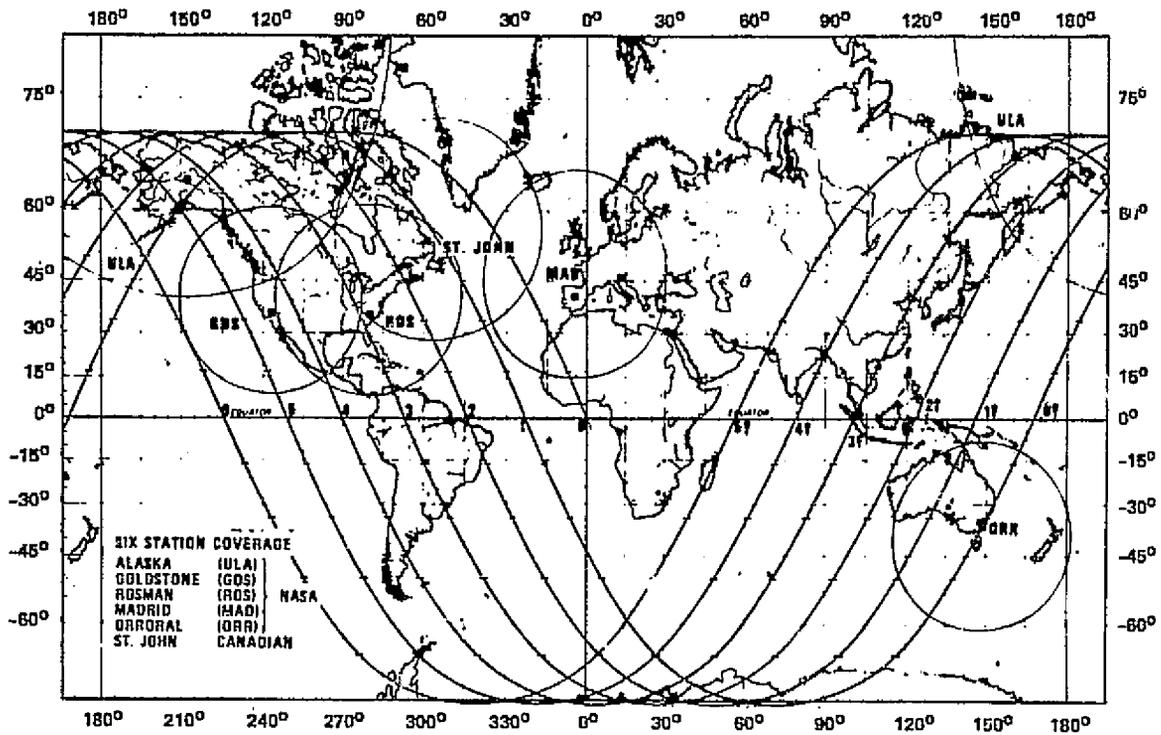


FIGURE A-1. SEASAT-A trajectory and ground station coverage.

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TABLE A-1. Radar Altimeter (ALT), Wind Field Scatterometer (SCAT) and Synthetic Aperture Radar (SAR) Instrument Characteristics

	ALT	SCAT	SAR
Frequency	13.5 GHz	14.6 GHz	1.3 GHz
Bandwidth	320 MHz	$\pm$ 500 kHz	19 MHz
Transmit time/ total time	$3.3 \times 10^{-3}$	0.2	0.35
Pulse width	3.2 $\mu$ sec	4.8 msec	33.8 $\mu$ sec
Chirp rate	100 MHz/sec	-	0.562 MHz/sec
Pulse compression ratio	1000	-	642
Effective pulse width	3.2 nsec	4.8 msec	53 nsec
Peak transmitted power	2.0 kW	110 W	800 W nom, 1125 W max
PRF (pulses/sec)	1030	34	1464, 1540, 1647
System noise temp	3364°K	1250°K	$\leq$ 550°K
Gain control	Automatic, digital	Automatic	Automatic- commandable
Antenna peak gain	40 dB	32.5 dB	35 dB
Antenna polarization	Linear	Horizontal/ vertical	Horizontal
Data rate	8.5 kbps	540 bps	110 Mbps
Swath width	1.2 - 12 km	750 km (2)	100 km
Resolution cell size	1.2 - 12 km	50 km x 50 km	25 m x 25 m
Antenna dimensions	1 m dia	3 m x 15 cm	11 m x 2 m
Nadir angle	0 deg	25 - 65 deg	17 - 23 deg
Integration time	1 sec	1.89 sec	2 sec (4 looks)

TABLE A- 2 . Scanning Multifrequency Microwave Radiometer Instrument Characteristics

Frequency, GHz	6.6	10.69	18	21	37
RF bandwidth, MHz	←-----250-----→				
System noise temperature, K	490	490	693	703	715
Polarization	←-----Dual linear-----→				
Data rate	←-----2 kbps total-----→				
Swath arc width, km	←-----679-----→				
Full swath angle, deg	←-----50-----→				
Footprint dimensions (Major axis) (Minor axis), km	121 79	74 49	44 29	38 25	21 14
Antenna diameter, m	←-----0.79-----→				
Antenna beamwidth, half-power, deg	4.02	2.48	1.47	1.26	0.72
Incidence angle of beam center at surface, deg	←-----48.8-----→				
Integration time constant, milliseconds	126	62	62	62	30
Temperature resolution, K (1σ) (77K target)	0.34	0.48	0.67	0.72	1.09
Absolute temperature accuracy, K (1σ)	←-----2-----→				
Dynamic temperature range, K	←-----10-330-----→				

## Appendix B SIR-A

Excerpted and Modified from: National Aeronautic and Space Administration (Sept. 1977) Spaceborne Imaging Radar - B (SIF-B) Preliminary Project Plan, A Joint Project of Lyndon B. Johnson Space Center and Jet Propulsion Laboratory.

The study of microwave techniques and their applications has been a significant element of the program since its initiation. Beginning with a relatively small group of knowledgeable personnel in limited testing facilities, these techniques have been developed to a point where it is reasonable to consider the implementation of a space system for further research and development leading to the definition of specific operational systems. Active microwave sensors have had limited application; however, the active microwave field has the advantage of a far more extensive background in theoretical and analytical modeling studies than did the visible and infrared field at the same stage of development.

Microwave systems offer unique capabilities in addition to capabilities which will complement the visible and infrared systems, such as 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 cloud cover.

Studies are 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, soil, and vegetation conditions. Results have indicated that optimum instrument parameters of frequency, polarization, and incidence angle can distinguish crop type, maturity, and stress. Radar back-scattering cross-section shows a strong correlation 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 experiments. Data reduction, analysis and display techniques, and theoretical models have been developed to support these experiments.

The SIR-A represents the first phase of the Spaceborne Imaging Radar Program for earth resource sensing. It will consist of refllying the SEASAT-A L-band SAR with minor modifications on the second Shuttle orbital flight test (OPT-2) in July 1979.

The prime objective of the SIR-A experiment is to evaluate the potential and demonstrate the applicability of spaceborne imaging radars as tools for geologic exploration in general, and mineral exploration, petroleum exploration, and fault mapping in particular.

The identification of potential sites for mineral and petroleum exploration is of major national and international importance. The overall problem of energy is one of the most critical at this time. Airborne imaging radars are being used, in conjunction with other sensors, by petroleum companies to identify exploration sites. The SIR-A experiment would vastly extend the benefit of this technique by mapping large areas from orbit.

A second major objective is to develop and test techniques to evaluate extending the spectral coverage of remote sensors of land resources. The SIR-A experiment will provide imagery in the L-band (23-cm wavelength) region of the spectrum, which is compatible with the Landsat imagery. It will also demonstrate the potential of merging these images and will use the SIR-A data as one more band in the LANDSAT images. The radar image brightness is proportional to backscatter cross-section of the surface; this, in turn, is related to the surface topography, roughness, dielectric constant, and vegetation coverage. Thus, the radar data would add new information to the LANDSAT imagery. It is expected that the resulting product would significantly improve the usefulness of both the LANDSAT and the radar imagery taken separately.

A third objective is to demonstrate and verify the research capabilities of the Space Shuttle for applications, science, and technology. The area which would be mapped

during the 5-day OFT-2 mission would be approximately 8.4 million square kilometers (i.e., the equivalent of 90 percent of the area of the continental United States), and the sensor could still be used for future Shuttle missions. This experiment would also provide important information for the development of future operational multispectral imaging radars for the Shuttle and for free-flying systems. In conjunction with the information from the SEASAT imaging radar, the requirements for look angles, resolution, dynamic range, relative calibration, absolute calibration, and other engineering parameters will be defined. The SIR-A experiment will also allow the comparison of optically and digitally recorded data.

The SIR-A experiment will use modified SEASAT-A residual SAR hardware and an APOLLO (from the APOLLO lunar sounder experiment) optical data recorder. Table B-I summarizes the instrument characteristics. Two methods of data collection are planned, denoted "baseline path" and "additional path."

The salient features of the "baseline path" system are as follows:

1. The existing SEASAT-A radar engineering model instrument will receive a modular addition to convert its current 1275-MHz center frequency output to 2.5 MHz, along with a reduction in output signal bandwidth from 20 MHz to 5 MHz. This modification will make the SEASAT radar instrument compatible with the existing 5-MHz APOLLO optical recorder. No internal modifications to the existing SEASAT hardware are anticipated.

2. The data are recorded on film with an existing optical recorder used and qualified for the APOLLO program. This recorder must be modified to store a maximum of 6 hours of data (from its present 2 hours) and to accommodate the change in spacecraft velocity.

3. As much as 6 hours of data are returned to the ground for subsequent optical correlation in the JPL correlator, in which the image is electronically digitized by an image dissector, and then formatted into high-density digital tapes (HDDT's), compatible with Earth Resources Observation Systems (EROS), and recorded. One HDDT has sufficient capacity to store the data collected on a single roll of film.

This baseline path has the advantage of allowing maximum ground coverage of arbitrary predetermined areas of interest, limited only by the 6-hour capacity of the optical film recorder. It appears to be the simplest and lowest risk method of obtaining substantial amounts of data over large portions of the globe.

The other method of data collection proposed, the "additional path," is identical to the SEASAT configuration, including the 20-MHz real-time data link used in SEASAT. The "additional path" has the advantage of requiring no functional modification of existing equipment in the spaceborne portion, and possibly none on the ground. In addition, because of its inherent 20-MHz bandwidth capacity, it is potentially capable of producing higher resolution imagery compared to the baseline option. Its disadvantages are as follows:

1. It may have to be time-shared with SEASAT reception.

2. It provides only limited coverage, through the two southernmost SEASAT-A ground stations (presently Merritt Island and Goldstone).

TABLE B-1. - SUMMARY OF SAR DESIGN PARAMETERS FOR SIR-A

Parameter	Baseline path 5-MHz onboard optical recorder	Additional path with a 20-MHz data link
Frequency, MHz . . . . .	1275	1275
PRF, Hz . . . . .	1550 ± 7 percent	1550 ± 7 percent
Altitude, km (nominal) . . . . .	200	200
RF bandwidth, MHz . . . . .	19	19
System bandwidth, MHz . . . . .	5	19
Peak radiated power, W . . . . .	800	800
Antenna length, m . . . . .	9.38	9.38
Antenna width, m . . . . .	2.16	2.16
Off-nadir angle, deg . . . . .	50	50
Ground resolution, m . . . . .	40 or 100	40 or 100
Single-look resolution, m . . . . .	6 by 40	6 by 10
Swath width, km . . . . .	50	50
Noise equivalent $\sigma^0$ (receiver output), dB . . . . .	-37	-37
Number of looks . . . . .	7 or 40	25 or 150
Least detectable $\sigma^0$ difference (90 percent confidence), dB . . . . .	4 or 2	2 or 1
Coverage . . . . .	6 hr max.	Real time only
Processing . . . . .	Optical	Digital
EROS-compatible high-density digital tape (HDDT) output . . . . .	Yes	Yes

## Appendix C SIR-B

Excerpted and Modified from: National Aeronautics and Space Administration (Sept. 1977) Spaceborne Imaging Radar - B (SIR-B) Preliminary Project Plan, A Joint Project of Lyndon B. Johnson Space Center and Jet Propulsion Laboratory. Unpublished draft.

The objective of the Spaceborne Imaging Radar-B (SIR-B) experiment is to develop the technical base and evaluate the application potential of spaceborne radar imagers for Earth resources observation. Present imagers (on LANDSAT) cover a very small range of the electromagnetic spectrum (visible and near-infrared). The extension of the spectral coverage to the microwave region would provide additional information on the properties of the Earth's surface. This information would help in the monitoring, managing, and evaluating of Earth resources. The SIR-B experiment is an applications proof-of-concept experiment for the imaging radar, which is a natural candidate for the payload of the Global Resources Monitoring System (GRMS).

Though the main objective of the SIR-B experiment is general, there will be three main themes covering the most critical applications and technical problems.

1. Understand the radar signature of geologic surfaces and determine the extent to which radar imagers complement the THEMATIC MAPPER for geologic mapping, mineral and petroleum exploration, ground-water exploration, and civil works planning.

2. Evaluate and demonstrate the capability of radar imagers to measure soil moisture and identify crops on a global basis.

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3. Test advanced sophisticated hardware systems that are necessary for future operational spaceborne radars.

Because of the wide variety of potential radar applications, the SIR-B experiment also has a number of secondary objectives. Specifically, the following experiments will be conducted.

1. Observation and study of precipitation.
2. Mapping of ocean-wave patterns under different observation conditions and different sensor operating frequencies from those of SEASAT-A.
3. Mapping of watersheds and flooded regions.
4. Measurement of snow water content.
5. Mapping of a number of urban regions for land use monitoring.

Some of these secondary objectives would become primary objectives for later Shuttle flights (SIR-C, -D, etc.) using the same sensor system as SIR-B, with appropriate modification.

The proposed approach consists of two key Shuttle experiments. The first is the SIR-A, which is an L-band imager with a direct polarization (HH) and fixed look angle ( $50^\circ$  from vertical). It will fly on the second orbital flight test (OFT-2). The second is the SIR-B, which is the subject of this plan. These two experiments are complementary.

A summary of the characteristics of the SIR-A and the SIR-B is given in Table C-1. The SIR-B is a flexible sensor that allows changes in the observation parameters. It consists of a dual frequency (C- and X-band) synthetic-aperture radar. The X-band will have direct and cross-polarized channels. The incidence angle is selectable anywhere between  $15^\circ$  (from straight down) and about  $65^\circ$ . The combination of the SIR-A and SIR-B experiment would provide sufficient information to define the parameters of the required operational spaceborne radar sensor.

#### Radar System

The SIR-B radar system, its capabilities, and constraints are generally summarized in Figure C-1.

Figure C-1 illustrates the approximate experiment geometry as seen in the plane normal to the spacecraft

velocity vector. For purposes of detailed characterization, three distinct regions, each with a characteristic angle of incidence, area defined. These three regions are bounded by both the assumed antenna beamwidth and by potential interference with subsequent transmitted pulses and appear to be quite adequate to meet the objectives of the SIR-B experiment.

Central control of the experiment is contained within the Spacelab habitable module in the form of a control and display subsystem. All necessary controls and operator interfaces, as well as tape recorders and displays, are located in the same general area. It is anticipated that, with the exception of the tape recorder, the system will be fully automatic with a preprogrammed mission sequence. Occasionally, however, the capability for override by the mission specialist may be exercised.

The data from a typical 7-day mission are returned to the ground and played back, through a tape recorder similar to that in the spacecraft, into a ground digital processor. The processor provides both range and azimuth correlation and also performs a first-order geometric correction. Outputs from the correlator are produced in film and in high-density digital tape (HDDT). The film is probably most useful as an indicator of data regions deserving more quantitative analysis. The HDDT's, on the other hand, contain the full complement of radiometric and geometric correction information for use with subsequent user algorithms.

The final step in data usage and application rests with the users. The special processing, including specific algorithm development, is best performed as a set of more or less independent developments. It is anticipated, for example, that the requirements of geological users regarding radiometric and geometric accuracy might differ significantly from those of agricultural users. The "standard" product supplied to the users is, therefore, as application-independent as possible.

### Antenna System

The deployable antenna system will be developed to be integrated and used functionally with radar systems. The antenna will provide (1) dual-polarized transmission and reception at X-band and single polarized transmission and reception at C-band, (2) look angles of 15°, 47°, and 60°, and (3) a nominal 50-km swath width. The antenna panel sections will be connected in such a way that the antenna panels and support structure can be folded twice and stowed on top of the Spacelab pallet to which the antenna system

will be attached. Jettison devices will be installed for use if a failure in the mechanism prevents Shuttle cargo door closure.

The antenna will be constructed of eight antenna panels, each designed and fabricated to provide the same characteristics. These sections will be connected with a corporate feed network to provide radiofrequency continuity of the total antenna. The panels will be mechanically connected in a holding structure, which will be in three sections to be compatible with the folding requirements defined by the mount. The holding structure will be designed to provide the strength to hold the antenna panel sections in place and to provide the thermal stability to hold the panel flatness to the required tolerance. The three structures will be connected to the mount structure, which will provide the folding capabilities and the mechanical isolation from the Shuttle bending and thermal characteristic inputs.

Control The antenna control panel will be installed in the Spacelab pressurized module racks with the radar system control from which the prime power will be obtained. The antenna control panel will be used to prepare the antenna for operation, monitor antenna performance, and provide required operational parameters during data gathering. The operations to be performed in the Spacelab by the payload specialist using the control panel will be (1) deployment of the antenna system and verification of alignment, (2) selection of the proper look-angle coverage by antenna tilt, (3) monitoring of antenna performance parameters, and (4) folding for storage. Polarization selection will be a function of the radar system panel, and pointing of the antenna will be with Shuttle inertial systems within the standard tolerance ranges.

Antenna Mount The mount structure will attach the antenna panel and holding structure to the Spacelab pallet and deploy and fold the antenna. The total area required for mounting both X-band antennas and one C-band antenna is approximately 3 m by 8 m. A critical factor, overall antenna flatness tolerance, is determined by the highest frequency (X-band) and requires that less than 0.5-cm variation be experienced across the total surface of the deployed antenna under all thermal conditions and vehicle fluctuations. This flatness is required to maintain minimum phase error between the radiating elements of the antenna. Minimum errors are required to maintain antenna pattern purity and to control sidelobe level.

Antenna The proposed baseline antenna is a planar array with basic dimensions to provide ground illuminations with azimuth beamwidths of  $0.37^\circ$  (C-band) or  $0.20^\circ$  (X-band)

and elevation beamwidths at both frequencies of 10° and 2.5° (approximately). These two elevation beamwidths will be selectable using the same antenna by switching radiated and received power to/from either part of the array width or the full array. The antenna will be composed of eight panels; each will contain a C-band horizontally polarized array with switches for selecting aperture size, plus horizontal and vertically polarized X-band antennas, also with aperture switches. These panels will be connected in holding structures and joined electrically by a corporate feed network.

The choice of a planar radiating configuration as opposed to another configuration, such as a curved reflector with line source feeds, is predicated in part on the fact that the radiating surface is exposed to space or solar radiation at varying angles and that the use of a planar surface minimizes shadowing. Uneven heating or cooling and associated thermal distortions are avoided. Induced distortions are more significant with reflector antennas because a given displacement from the desired surface changes the distance traveled by a wave from the aperture to the reflector surface and from the surface to the feed, essentially doubling the effect. For the same reason, tolerances on reflector surfaces are tighter than those on the flatness of planar arrays.

#### SR&T Activities

The SIR-B project will serve as a significant step in the overall applications program, which is aimed at demonstrating both unique and supplementary potentials of microwave sensors for the earth and ocean observations discipline. Before SIR-B, experiments (with existing and new sensors) will be conducted to define system specifications, data-processing algorithms, and analysis techniques/models for each application. Analysis of SIR-B data will be considered as part of a continued SR&T effort in ultimately specifying and developing an operational free-flying system. The following are the elements of the SR&T activities:

1. Development of data-processing algorithms and systems.
2. Development of new or modified aircraft and ground radars.
3. Applications research for the demonstration and use of the potential of microwave remote sensing.

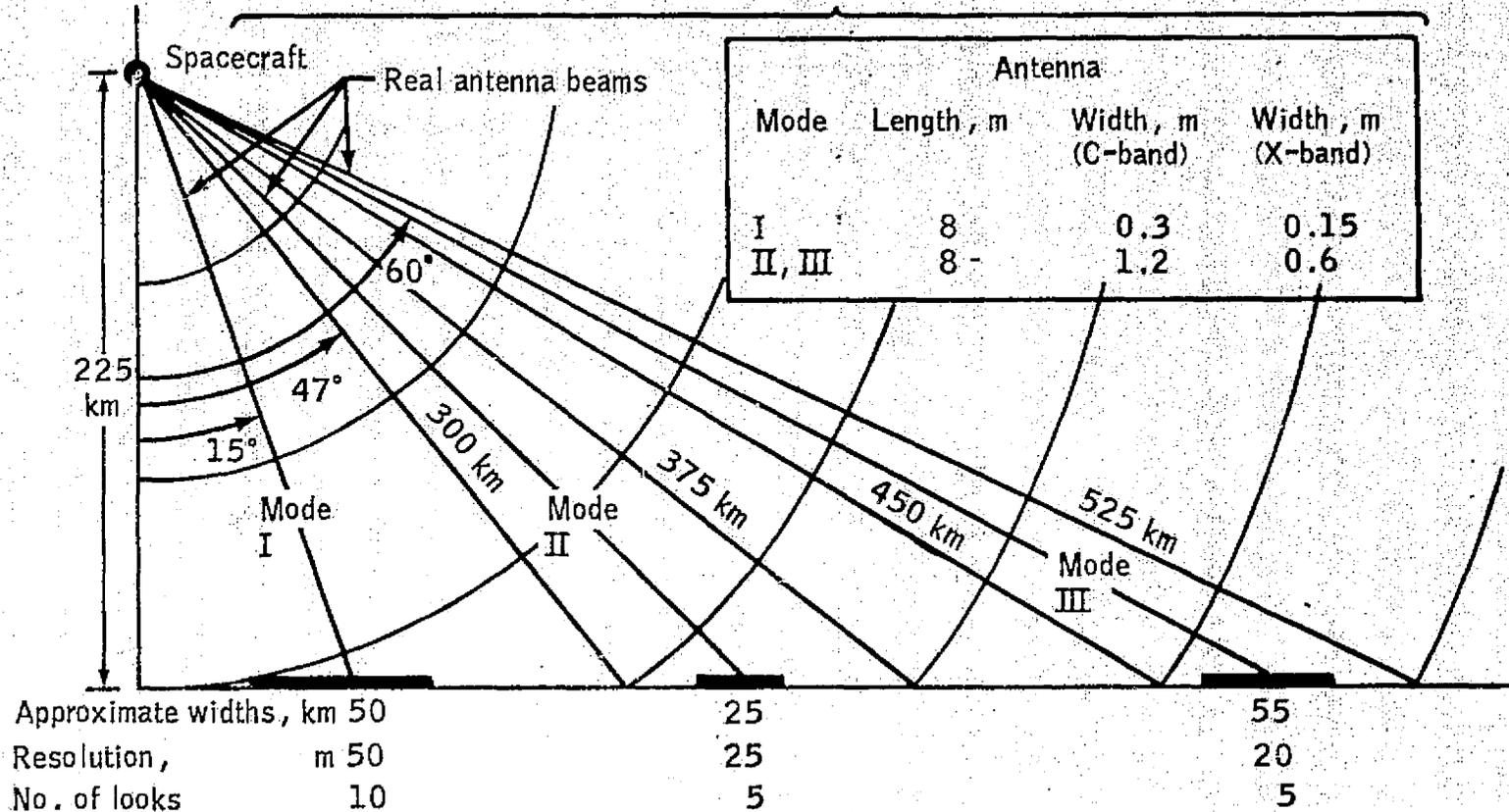
4. Development of predictive mathematical models for each application. (These models are based on microwave alone, microwave combined with LANDSAT, and multisatellite data; this will allow selection of an appropriate model for each application.)

5. Development of orbit and mission requirements with appropriate rationale needed to address various applications.

Data-Processing Algorithm The development of processing algorithms should parallel ground and onboard SAR data-processor-hardware development. Electronic processing of SAR data into images appears superior to the optical processing used to date. The state of the art for ground-based electronic processing is well advanced. Hence, development of a system for SIR-B can be started at an appropriate time to make it available for use with the Shuttle tape-recorded data for that system.

Radar systems with modest resolution can use on-board processing of signals into images. The telemetry bandwidth for the processed image will be significantly less than that required for the signal itself. However, for systems that achieve the finest possible resolution and have multiple channels, on-board data processing is complicated and needs development. Consequently, the testing of these systems on the Shuttle and use of them on early free-flying spacecraft should be an integral part of the microwave remote sensing for earth observation.

First through sixth half-wave fronts  
at PRF = 2000 Hz



Note. There are two swath widths defined in this proposal: The 3-dB antenna width and the actual sampled swath; widths given here are approximate and depend on the final configuration.

FIGURE C-1. - Geometric constraints of SIR-B.

TABLE C-1. - COMPARATIVE SUMMARY OF SAR PARAMETERS FOR SIR-A AND SIR-B

Parameter	Microwave band		
	SIR-A	SIR-B	
	L-band	X-band	C-band
Frequency, MHz . . . . .	1275	9600	5280
Postrepetition frequency (PRF), Hz . . . . .	1550 ± 7 percent	2000 ± 16 percent	2000 ± 16 percent
Altitude, km (nominal) . . . . .	200	225	225
Radiofrequency (RF) bandwidth, MHz . . . . .	19	10	10
System bandwidth, MHz . . . . .	5	10	10
Peak radiated power, kW . . . . .	0.8	50	1.5
Antenna length, m . . . . .	9.38	8	8
Antenna width, m . . . . .	2.16	0.66	1.32
Off-nadir angle, deg . . . . .	50	Selectable	Selectable
Polarization . . . . .	HH	HH, HV, VV	HH
Single-look resolution, m . . . . .	6 by 40	4.5 by 25	4.5 by 25
Swath width, km . . . . .	50	25 to 50	25 to 50
Noise equivalent $\sigma^0$ (receiver output), dB . . . . .	-37	-38 at 70°	-41 at 47°
Number of looks . . . . .	7 or 40	5	5
Coverage/flight, hr . . . . .	6	10	10
Processing . . . . .	Optical	Digital	Digital
EROS-compatible high-density digital tape (HDDT) output . . . . .	Yes	Yes	Yes

120

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Appendix D  
Main Characteristics of the Thematic Mapper and the  
LANDSAT 1 and 2 Multi-Spectral Scanner

APPENDIX D

Main Characteristics of the Thematic Mapper and the LANDSAT 1 and 2 Multi-Spectral Scanner

	THEMATIC MAPPER		LANDSAT 1 and 2 (MSS)	
	MICROMETERS	RADIOMETRIC SENSITIVITY (NEΔρ)	MICROMETERS	RADIOMETRIC SENSITIVITY (NEΔρ)
SPECTRAL BANDS				
1	.45 - .52	.80%	0.5 - 0.6	.57%
2	.52 - .60	.5%	0.6 - 0.7	.57%
3	.63 - .69	.5%	0.7 - 0.8	.65%
4	.76 - .90	.5%	0.8 - 1.1	.70%
5	1.55 - 1.75	1.0%		
6	10.40 - 12.50	0.5°K (NEΔT) at 300°K	10.40 - 12.60	1.4°K (NEΔT)
GROUND IFOV	30 m (BANDS 1-5) 120 m (BAND 6)		78 m (BANDS 1-4) 234 m (BAND 5)	
DATA RATE	110 MB/S		15 MB/S	
QUANTIZATION LEVELS	256		64	
INTERBAND REGISTRATION	0.1 IFOV		0.25 IFOV	
LONG TERM SCAN STABILITY	0.5 IFOV		1.5 IFOV	
EQUATORIAL CROSSING TIME	0930 hrs. local		0930 hrs. local	
ALTITUDE	~700 km		~900 km	
WEIGHT	270 kg		54 kg	
SIZE	0.9 x 0.9 x 1.8 m		0.35 x 0.4 x 0.9 m	
POWER	250 WATTS		42 WATTS	

Appendix E  
The Shuttle Imaging Microwave System Experiment  
(SIMS)

Modified from: Waters, J.W., F.T. Barath, E.Y. Chow, A.F.H. Goetz, E.J. Johnston, J.M. Stacey, J.J. Gustincic, D.H. Staelin, J.A. Kong, E.G. Njoku, K.F. Kunzi, D.O. Muhleman, and T.T. Wilheit (1975) The Shuttle Imaging Microwave System Experiment. Proceedings of the IEEE National Telecommunications Conference, December 1-3, 1975, New Orleans, Louisiana. New York: Institute of Electrical and Electronics Engineers.

The Shuttle Imaging Microwave System (SIMS) is an earth observations experiment, now in late definition phase, which is being planned to utilize the capabilities of the Space Shuttle for performing measurements of thermal emission from the Earth's atmosphere and surface in several microwave spectral bands. Simultaneous, coincident observations in infrared and visible bands are also planned to supplement the microwave observations. These measurements will be useful for atmospheric, oceanographic, and earth resources disciplines. An offset parabolic torus reflector with rotating feeds and radiometers can be used to obtain rapid, wide-angle scanning of the antenna beams over the full spectral range.

The wavelengths and observables which have been tentatively determined for the SIMS channels are given in Table E-1. More details of the channel specifications are given below in the discussion of the SIMS instrument.

In addition to the wavelengths shown in Table E-1, simultaneous and coincident observations are planned with two channels in the visible and infrared spectral regions, respectively, to supplement the microwave measurements. Consideration is also being given to including a channel on SIMS for observing microwave beacons from selected sources.

The primary observable listed beside each wavelength in Table E-1 does not indicate that only that wavelength is used in obtaining the observable; simultaneous observations at several of the wavelengths shown are needed to obtain certain of the observable quantities.

For certain observables in Table E-1, reliable knowledge exists of the accuracy with which they can be measured. For example, results from NEMS have demonstrated that atmospheric water vapor can be measured to  $\sim 0.2$  gm/cm<sup>2</sup> and that atmospheric liquid water can be measured to  $\sim 0.01$  gm/cm<sup>2</sup> rms accuracies with microwave techniques from earth orbit.<sup>9</sup> Results from ESMR have demonstrated that precipitation areas and sea ice boundaries are readily observable.<sup>11-14</sup> Measurements of atmospheric precipitation and water vapor will be obtained, principally, from SIMS observations at 1.5, 1.3, and 0.9 cm wavelengths. At these wavelengths the spatial resolution of the SIMS observations with the antenna system described below will be 3 km. The SIMS resolution will make possible detailed measurements of the dynamics of water vapor in hurricane systems, which should lead to a better understanding and prediction of the formation and evolution of such systems. Atmospheric water can also be mapped over lake areas, which has not been feasible on prior experiments with coarser resolution. The SIMS channel at 0.32 cm wavelength will be able to map sea and lake ice boundaries to 0.5 km resolution and will be valuable for ship routing in partially frozen waters and for studying ice circulation in the Arctic Ocean. It has been demonstrated that multi-year sea ice can be distinguished from new sea ice with microwave measurements.<sup>23,24</sup> Simultaneous observations at 0.57 and 0.26 cm wavelengths, which are similarly affected by the atmospheric temperature profile but quite differently affected by atmospheric water, should provide maps of storm systems over land areas.

Aircraft measurements have indicated the sensitivity of microwave emission from the sea surface to the sea state.<sup>25, 26</sup> The accuracy with which sea state (as measured by wind speed or percentage foam coverage, for example) and sea surface temperature can be determined from earth orbiting microwave measurements should be determined by results from the SMMR experiment, which will be available before the launch of SIMS. Preliminary estimates of rms accuracies are  $\sim 1-2^\circ$  K for sea surface temperature and  $\sim 2$  m/s for surface wind speed.

The longer wavelength SIMS channels will explore the extent to which microwave techniques can measure soil moisture, ocean salinity, and subsurface phenomena such as water, permafrost depths, temperature gradients, etc. Aircraft measurements have indicated that the percentage by weight of moisture in the top 15 cm of bare fields can be

estimated to ~5% rms accuracy over the 10-40% range.<sup>27</sup> In very dry regions, radiation originates from depths of approximately ten wavelengths and the longest wavelength SIMS channels will be sensitive to subsurface phenomena at depths of a few to several meters in these regions. With the SIMS experiment as presently conceived, useful measurements will be obtained from the longest wavelength channels in large desert areas such as the Southwestern United States, Northern Africa and Central Australia.

It will be noted that SIMS does not contain channels for sounding the atmospheric temperature profile. This is because atmospheric temperature profiles are not required with the fine spatial resolution of SIMS. The channels at 0.57 and 0.26 cm wavelengths will provide an average atmospheric temperature which will aid in interpreting the atmospheric water measurements.

Table E-2 gives parameters for a baseline complement of SIMS radiometers, and the resulting rms measurement noise for both the nadir spatial resolution of the antenna beam and for 10 km spatial resolution. An orbital altitude of 340 km was used for Table E-2. The resulting noise levels with the radiometer parameters of Table E-2 are sufficiently low for meaningful measurements with SIMS. The present plans are for data to be recorded both on digital tape and optical film to be returned to ground. The SIMS data rate of ~3 Mb/s can easily be accommodated by state of the art recorders. Selected SIMS data may be telemetered directly to ground stations via the standard Shuttle telemetry, or to relay satellites which could supply maps of the parameters measured by SIMS in real time to users on the ground. Examples of the use of SIMS data in real time include monitoring the location of hurricanes and routing ships through rough or partially frozen seas or lakes.

TABLE E-1. Wavelengths and Primary Observables of the SIMS Channels

WAVELENGTH (cm)	PRIMARY OBSERVABLE
50 21 11	Soil Moisture, Subsurface Phenomena, Salinity
4.6	Sea Surface Temperature
2.8	Sea State, Heavy Precipitation
1.5 } 1.5 } 0.9 }	{ Atmospheric Water Vapor Moderate and Light Precipitation Drop Size Parameter
0.57	Storms Over Land
0.32	Water-Ice Boundaries
0.26	Storms Over Land

TABLE E-2 A Baseline Complement of Radiometers for SIMS

Polarization	Center Frequency (GHz)	Beam Width (deg)	Nadir Resolution (km)	RMS Noise for Nadir Resolution (K)
HV	0.610	17.2	102	0.17
HV	1.413	7.4	44	0.23
HV	2.695	3.9	23	0.68
HV	6.6	1.6	9.5	0.22
HV	10.69	0.98	5.8	0.62
HV	20.0	0.53	3.1	1.0
HV	22.2	0.47	2.8	1.1
HV	37.0	0.28	1.7	1.3
HV	53.0	0.20	1.2	2.4
HV	94.0	0.11	0.66	3.2
HV	118.7	0.09	0.52	6.7

## FOOTNOTES

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## Appendix F

### Shuttle Multifunction Microwave Radiometer Experiment (SMMRE)

Source: King, L. NASA, Greenbelt, Md., Personal  
Communication, 1977.

The objective of this experiment is to test and evaluate several new microwave radiometers and their applications on board Shuttle Sortie flights. The final goal is to develop advanced microwave radiometer systems for future free-flyer satellites.

The Spacelab experimental system is conveniently divided into three separate modules, roughly along the natural division lines of long, medium, and short wavelengths of the microwave spectrum. The rationale behind this is that from an engineering point of view, it is difficult to fit all frequencies, say 1 to 22 GHz, into a single unit without either compromising the performance of some channels or making the unit excessively costly, or both. The modular approach has more flexibility, both as a facility for testing radiometry application concepts and because it is easily adapted to future missions. Each unit can have vastly different spatial resolutions, methods and speed of beam scanning, and possibly beam pointing direction. After the Shuttle Sortie Experiment, each module can be transferred to free-flyers directly or with some simple size scaling. Depending on the particular mission need, one can select a single module or any combination of them. Finally, the modular approach allows one to capitalize on a number of components and techniques in spaceborne microwave radiometry that have been developed in the last decade, e.g., in previous experiments such as SCAMS and SMMR.

SMMRE consists of the following three modules: an L-band phased array, a mechanically scanning multifrequency system, and a millimeter wave unit. The key features lie in

the implementation of the multifrequency unit, which will be based on a mechanically scanning reflector concept. This approach has the advantage of nearly perfect optics, free from blockage, and relatively compact size and large swath.

1. L-BAND ELECTRONICALLY SCANNING MICROWAVE RADIOMETER (LESMR)

This unit is a three meter aperture electronically scanning phased array operating at 1.4 GHz, principally for the purpose of measuring soil moisture. A survey shows that most practical applications for soil moisture measurement require high spatial resolution and large swath width. Hence, a large electronically scanned phased array is the best type of antenna to meet the requirement. A three meter aperture will be tested in this experiment. However, should future missions demand an antenna aperture larger than three meters, it can be easily scaled up in size. The array will perform cross-track scan, which provides a good nadir resolution. Conical scan is not a must for soil moisture measurement, as constant incidence angle is not an important feature in viewing a diffused terrain surface. More parameters of LESMR are listed in Table F-1. A sketch of LESMR mounted on-board the Shuttle is shown in Figures F-1 and F-2.

2. ADVANCED SCANNING MICROWAVE RADIOMETER (ASMR)

This unit will cover the midfrequency range of C to V-band. It is an advanced version of the Scanning Multichannel Microwave Radiometer (SMMR) to be flown on-board NIMBUS-G and SEASAT-A. ASMR will have better overall performance than SMMR; for example, it will have higher spatial resolution and wider swath width, by virtue of a larger antenna and larger scan angle, than SMMR (from a similar orbit height).

ASMR will have a mechanically scanning (360° continuous rotation) reflector antenna system. There are several alternatives in implementing the scanning system for ASMR. Two concepts will be discussed here. They are: configuration I, single-reflector, rotating reflector, stationary feed, and configuration II, multiple reflector, rotating the whole assembly (reflectors + feeds).

Configuration I will be cheaper, lighter, smaller. It will have slightly poorer temperature sensitivities; and the two linearly polarized brightness temperatures are coupled. Configuration II will be larger, heavier, more costly. It will have a larger angular momentum but better temperature

sensitivities. The two linear polarizations are decoupled. A brief description of each configuration is presented next.

#### Configuration I.

The antenna is a two meter aperture offset paraboloidal reflector fed by a multifrequency horn. The reflector is boresighted at  $45^\circ$ . Depending on the availability of the unobstructed earth viewing angle on each mission and form factor, the antenna may view only the forward  $120^\circ$  of the cone, or it may view both the forward and backward  $120^\circ$  of the cone. Figure F-1 is a sketch of configuration I as a part of the package. The exact frequency range and number of channels of this unit can be varied from experiment to experiment and from mission to mission. To illustrate, assume that it will contain five frequencies identical to those of SMMR, namely, 6.6, 10.7, 18, 21, and 37 GHz and both vertical and horizontal polarizations at each frequency. There will then be ten radiometers, one each for the ten separate channels. It is estimated that a two meter reflector will weigh about 30 pounds, and may have a yaw-axis moment of inertia of about 4 slug-ft<sup>2</sup>. If the reflector scans at a speed such that the antenna rotates exactly one revolution while the subsatellite track advances one in-track footprint at 37 GHz, then the yaw-axis angular momentum will be about 37 ft-lb-sec (for a Shuttle orbit of 400 km). For an 800 km orbit the corresponding angular momentum will be about 17 ft-lb-sec.

#### Configuration II.

In this configuration, there are three 2 meter offset parabolic reflector antennas. They are mounted on a common rotating platform, which also contains three feeds and their associated radiometers. The antennas are pointed  $45^\circ$  from nadir and are  $120^\circ$  apart azimuthally. The whole assembly rotates continuously about a common nadir axis so that a conical surface is generated by each of the 3 antennas. However, each antenna will view the earth scene and take data only in the forward  $160^\circ$  azimuth angle of the cone. If a particular mission demands and the payload form factor allows, then each antenna may view both the forward and backward  $120^\circ$  of the cone. Calibration of the radiometers will be carried out during the period when their antenna is looking outside the  $120^\circ$  zones. Figure F-2 is a sketch of configuration II.

The two configurations resemble those of SMMR in many respects, thus much of the SMMR experience and component development, such as multifrequency feed, off-set parabolic reflector, etc., can be applied to ASMR. One major

difference is that the oscillatory scan motion of SMMR is replaced here by a continuous rotation, which is much easier to handle dynamically, particularly for large reflectors.

### 3. MILLIMETER WAVE IMAGING AND SOUNDING UNIT (MISU)

This module will cover the frequency range of 90 GHz to 183 GHz. Initially it will consist of a 94 GHz window channel for surface and precipitation mapping, a number of channels (approximately eight to ten) centered at the 118 GHz oxygen line for temperature sounding, a window channel at 130 GHz and a set of channels (approximately four to six) centered at 183 GHz for water vapor profiling and precipitation mapping. There may also be a set of channels to test advanced temperature sounding near the 2.5 mm oxygen band, and perhaps to test cloud height detection concepts (together with 118 GHz channels). Since the antenna size needed for these millimeter wavelengths (at Shuttle orbit) is rather modest, MISU will probably have two sets of antennas scanning separately, one for 183, 130, and 118 GHz, and one for 94 and 60 GHz. The antennas will probably resemble those of SCAMS and TIROS-N MSU designs, (i.e., cross-track planar scan), since for atmospheric sounding and precipitation mapping conical scan is not needed. However, in order to increase the flexibility for "following" some small targets of interest, such as the center of a hurricane or a local storm, the MISU antenna should be of a "pointable" type, i.e., the antenna scan plane instead of passing through nadir all the time, as does SCAMS, should be able to move either forward or backward at any step and rate upon command. Similarly, the cross-track scan rate and angle limits must also be controlled to "zoom" in on a small target area of special interest in order to increase the available viewing time from a low Shuttle orbit. Here again, many SCAMS and TIROS-N MSU developed components can be incorporated into the new MISU. The new components needed are in the higher frequency range (90 to 183 GHz).

Details of the design of the three modular units have yet to be worked out in a study. System parameters are summarized in Table F-1.

# SHUTTLE MULTI-FUNCTION MICROWAVE RADIOMETER EXPERIMENT

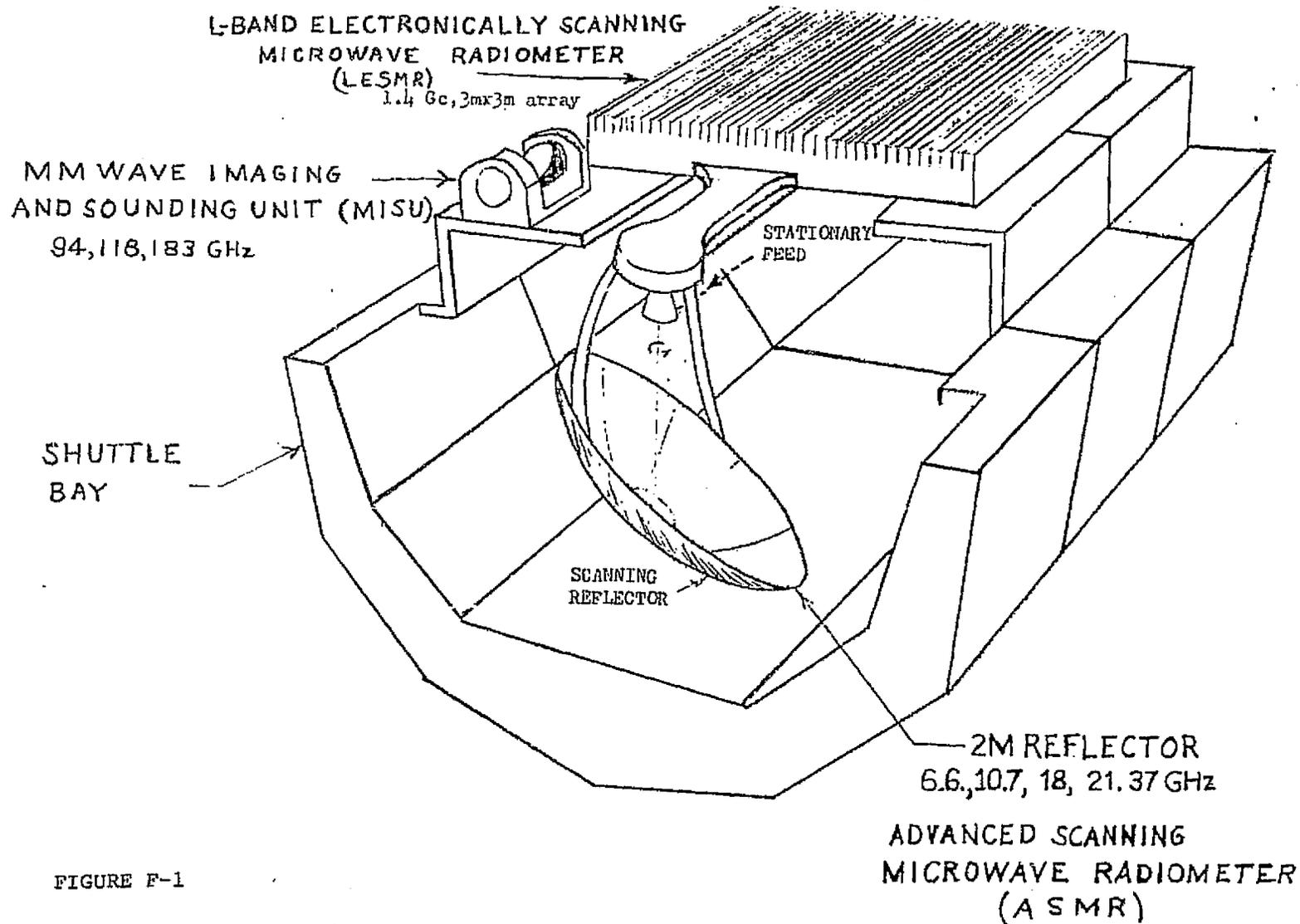
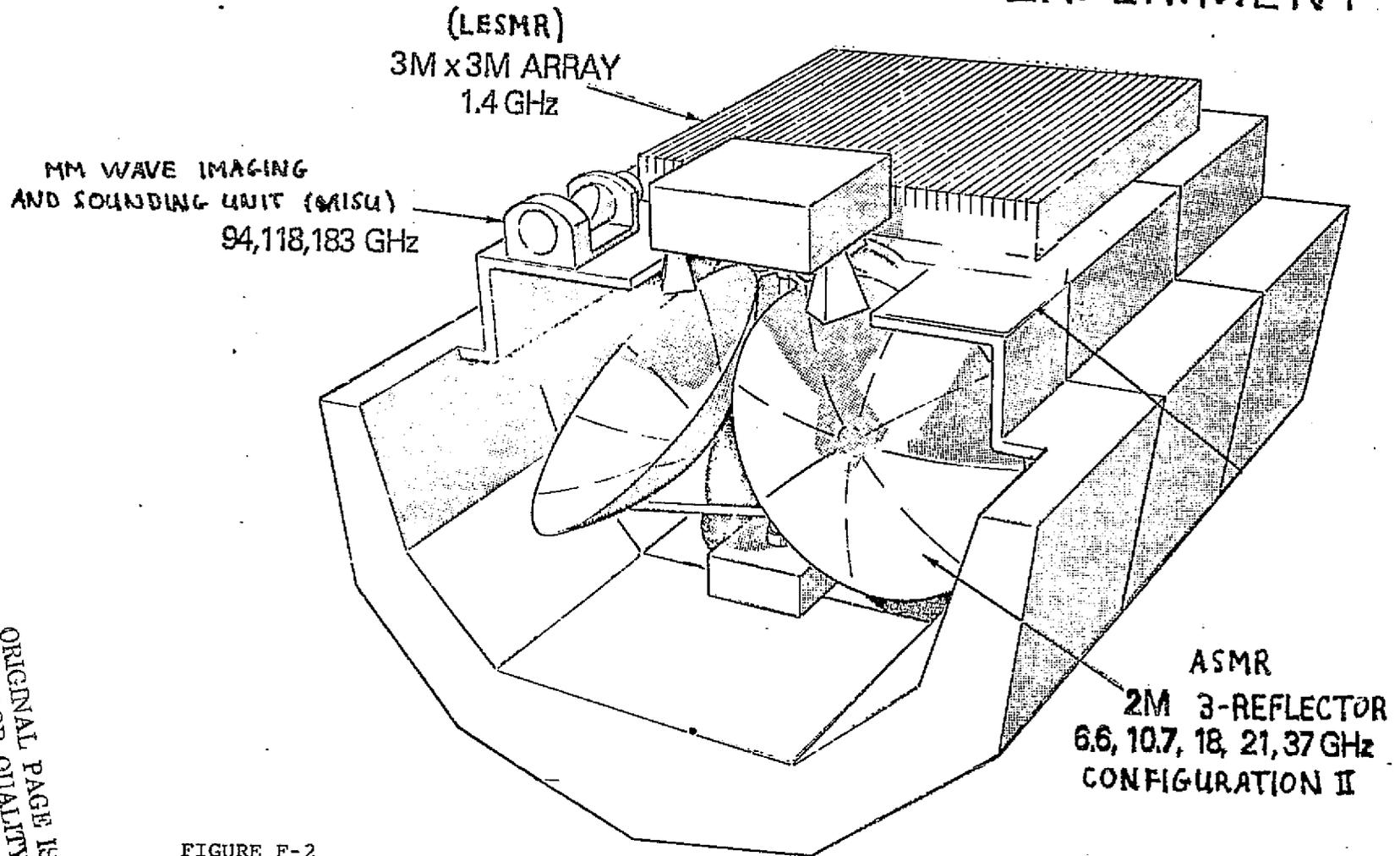


FIGURE F-1

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# SHUTTLE MULTI-FUNCTION MICROWAVE RADIOMETER EXPERIMENT



134

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FIGURE F-2

TABLE F-1 System Parameters of ASMR and LESMR

Module	LESMR	ASMR				
Ant.	3mx3m	I: 1 @, 2m, II: 3 @, 2m				
Pol.	H	H,V	H,V	H,V	H,V	H,V
Freq. (GHz)	1.41	6.6	10.7	18	21	37
$\theta_b$ (o)	5.28	1.65	1.02	0.61	0.52	0.30
I FOV I-T(km)	37	26	16	10	8	5
I FOV C-T(km)	37	17	11	6	5	3
B (MHz)	27	200	1000	1000	1000	1000
N	13	51	83	139	163	285
$t_s$ (s), I	5.1	0.65				
$t_s$ (s), II	5.1	1.95				
$t_i'$ (ms), I	389	395	93	20	12	2.3
$t_i'$ (ms), II	389	593	140	30	18	6.9
$t_i$ (ms), I	389	13	8	5	4	2.3
$t_i$ (ms), II	389	38	23	14	12	7
$\Delta T$ (K), I	0.4	0.17	0.21	0.45	0.58	1.32
$\Delta T$ (K), II	0.4	0.14	0.17	0.37	0.47	0.76

See Notes for Legends

NOTES FOR TABLE F-1

- LESMR - L-Band Electronically Scanning Microwave Radiometer (Phased Array)
- ASMR - Advanced Scanning Microwave Radiometer (mechanically scanning reflectors)
- $t_s$  - scanning period
- Pol. - Polarization
- H - Horizontal
- V - Vertical
- Scan Mode: for LESMR C-T (cross the track) planar step scan  $\pm 40^\circ$  from nadir; for ASMR, conical scan half cone angle =  $45^\circ$ , nadir axis, azimuth angle =  $\pm 60^\circ$
- $\theta_B$  - Half power beamwidth, for LESMR value shown is at nadir
- IFOV - Instantaneous Field of View (footprint size), C-T, I-T: cross-track and in-track, respectively. (for LESMR, values = nadir)
- $t_i$  - Integration time per cell resolution based on IFOV without overlap
- $t_i'$  - Effective integration time when overlapping (lower frequency) IFOV's are accounted for.
- $\Delta T$  - Temperature sensitivity (RMS) when  $t_i'$  is used,  $\Delta T = \frac{2 T_s}{\sqrt{B t_i'}}$
- $T_s$  - System noise temperature
- B - Predetection bandwidth
- N - Number of IFOV's per scan line
- Orbit Height - 400 KM is assumed above; the LESMR has a swath width of 687 km (measured along the arc of a great circle on beam centers). ASMR has a swath width of 716 km.
- For ASMR, system temperature of 1000K (6.5 dB, DSB) is assumed except 6.6 GHz (5.5dB).
- For LESMR, 5.1 dB system noise (or 650 K) is assumed.
- DSB - Double side band

Subscripts I, and II refer to configurations I and II of ASMR

In configuration II, one radiometer per frequency is assumed, i.e. the vertical and horizontal channels will time-share a radiometer. (except 37 GHz where there will be two receivers.

Appendix G  
Radar Band Designations\*

<u>Band</u>	<u>Frequency (GHz)</u>	<u>Wavelength (cm)</u>
UHF**	0.3 - 1.0	30.0 - 100.0
L	1.0 - 2.0	15.0 - 30.0
S	2.0 - 4.0	7.5 - 15.0
C	4.0 - 8.0	3.75 - 7.5
X	8.0 - 12.0	2.5 - 3.75
Ku	12.0 - 18.0	1.67 - 2.5
K	18.0 - 27.0	1.11 - 1.67
Ka	27.0 - 40.0	0.75 - 1.11
mm***	40.0 - 300.0	0.10 - 0.75

\* Based on IEEE Standard Letter Designations for Radar-Frequency Bands, Std. 521-1976, Nov. 30, 1976.

\*\* The band from 420-450 MHz is sometimes called P band, but use is rare.

\*\*\* The region from 46 to 56 GHz (0.652 to 0.536 cm wavelength) has sometimes been called V band. This is the terminology used in this document when referring to passive microwave (radiometry) at these frequencies.

Appendix G  
Radar Band Designations

<u>Band</u>	<u>Frequency (GHz)</u>	<u>Wavelength (cm)</u>
P	0.3 - 1.0	30.0 - 100
L	1.0 - 2.0	15.0 - 30.0
S	2.0 - 4.0	7.5 - 15.0
C	4.0 - 8.0	3.75 - 7.5
X	8.0 - 12.5	2.4 - 3.75
Ku	12.5 - 18.0	1.67 - 2.4
K	18.0 - 26.5	1.10 - 1.67
Ka	26.5 - 40.0	0.75 - 1.10
V (mid freq.)	50.0	0.58

## Appendix H Acronyms

ASMR	- Advanced Scanning Microwave Radiometer (mechanical scan)
CN	- Curve Number (Runoff Coefficient)
CW	- Continuous Wave
ERS	- Earth Resources Survey
ESMR	- Electronically-Scanned Microwave Radiometer
LESMR	- L-Band Electronically Scanning Microwave Radiometer
MMR	- Multichannel Microwave Radiometer
MSU	- Microwave Sounder Unit
MTI	- Moving Target Indication
NEMS	- Nimbus-E Microwave Spectrometer
MISU	- Millimeter Wave Imaging and Sounding Unit
OFT	- Orbital Flight Test
PMIS	- Passive Microwave Imaging System
SAR	- Synthetic Aperture Radar
SCAMS	- Scanning Microwave Spectrometer
SCAT	- Scatterometer
SIMS	- Shuttle Imaging Microwave System (JPL)
SIR	- Spaceborne Imaging Radar
SLAR	- Side-Looking Airborne Radar
SMMR	- Scanning Multi-frequency Microwave Radiometer
SMMRE	- Shuttle Multi-function Microwave Radiometer Experiment
SOI	- Space Object Identification
SSMR	- Shuttle Scanning Microwave Radiometer
V & IR	- Visible and Infrared

138 blank