Science Requirements for Free-Flying Imaging Radar (FIREX) Experiment

For Sea Ice, Renewable Resources, Nonrenewable Resources, and Oceanography

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ABSTRACT

The Seasat Synthetic Aperture Radar (SAR) data set has clearly proven the research and operational potential of such observational systems. As a consequence, the U.S. National Aeronautics and Space Administration and the Canadian Department of Energy, Mines and Resources have undertaken bilateral studies to define a future bilateral SAR satellite program. These studies have been given the names Free-Flying Imaging Radar Experiment (FIREX) in the U.S. and RADARSAT in Canada. The studies include addressing the requirements supporting a SAR mission posed by four disciplines: science and operations in sea-ice-covered waters, oceanography, renewable resources, and nonrenewable resources. In each discipline, workshops were held to bring together experts to examine the ways in which an augmented SAR satellite could enable progress on the significant research problems within the discipline, and to define the instrument, mission, and program parameters imposed by the approaches to those problems. Documents describing these mission requirements are being published elsewhere; here, summaries from the various workshops are collected together to show the total research investigations supporting a SAR flight and the subsequent overall mission requirements and tradeoffs.

FOREWORD

This document is one of a series describing the Free-Flying Imaging Radar Experiment (FIREX) mission requirements:

Science Requirements for Free-Flying Imaging Radar Experiment for Sea Ice, Renewable Resources, Nonrenewable Resources, and Oceanography

Sea Ice Mission Requirements for the U.S. FIREX and Canada RADARSAT Programs

Nonrenewable Resources Mission Requirements for the Free-Flying Imaging Radar Experiment (FIREX)

Renewable Resources Mission Requirements for the Free-Flying Imaging Radar Experiment (FIREX)

RADARSAT-FIREX MISSION STUDY

Introduction

In response to a Canadian initiative, the U.S. National Aeronautics and Space Administration (NASA) and the Canadian Division of Energy, Mines and Resources (DEMR) agreed on November 26, 1980, to conduct a bilateral study of the mission requirements for a future satellite which would have as its primary sensor a Synthetic Aperture Radar. The agreement was signed by Anthony J. Calio for NASA and John D. Keyes for DEMR. At that time, Dr. Calio was Associate Administrator for Space and Terrestrial Applications at NASA and Dr. Keyes, Assistant Deputy Minister for DEMR. The American effort was given the name FIREX (Free-Flying Imaging Radar Experiment), and the Canadian program, RADARSAT.

Apart from the bilateral sharing and discussion of future plans, the major activity undertaken in response to this agreement has been to determine the scientific and, to some extent, operational requirements for the proposed satellite. To do this, each country empanelled a science working group in each of four areas--ice, oceans, renewable resources, and nonrenewable resources. From the start, the Ice Panels from the two countries have functioned together and their findings are being presented as a single report. The executive summary of their findings is included as Chapter 1. Although the other groups have shared information and, in some cases met together, they will each produce separate reports. Chapter 2 consists of the findings of the U.S. Oceans Study Team. The executive summaries of the findings of the U.S. Renewable and Nonrenewable Groups comprise Chapters 3 and 4. The names of the members of the various science working groups that produced Chapters 1-4 are listed in Appendix A. Chapter 5 is an executive summary of all of the Canadian findings provided by Dr. Edryd Shaw, manager of the Canadian efforts, and Appendix B contains the Canadian study teams' membership.

During the process which has led to this report, some facts have become clearer about the status of SAR technology and its uses. At the same time, the budgets and future plans for investments in space by both countries have undergone considerable change. It now appears that our best current understanding of SAR usefulness is in the ice area. Here, a SAR of sufficient swath width offers the unique possibility of enabling studies of the dynamics of the ice pack. SAR also can be used to guide ships and others operating in polar waters by revealing those areas with leads or thin ice. The land resource teams have determined that SAR data will be of considerable use in mapping, geology, and crop studies. Currently, the details of how the observations will be used are not as well specified as they are for ice observations, but there is a considerable desire in this area for multiple look angles, frequencies, and polarizations on a SAR instrument. These capabilities would represent a significant advance in technology over those SARs flown to date. Our understanding of how to use SAR data in the oceans area is the least mature at present. The range of oceanographic problems which may be addressed is quite broad and the future promise of the technique is felt to be considerable.

Future plans for the eventual deployment of a SAR satellite are still being developed and remain uncertain.

As the manager of the NASA study, I would like to take this opportunity to thank the members of the several study teams for their efforts. I hope that this activity has been of some benefit to each of you and that the working relationships between the two communities of researchers will continue and prosper.

I also wish to thank Dr. Frank Carsey (JPL) for assembling this document, Sandi Thomas (JPL) for her secretarial support, and Paulette Cali (JPL) for her editorial assistance on the FIREX document.

Dixon M. Butler
Environmental Observations Division
NASA

February 1982

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I. SEA ICE MISSION REQUIREMENTS SUMMARY

Report Based on Bilateral Ice Study Team Workshop
Cornwall, Ontario
February 11-13, 1981

The Seasat data set established the potential of Synthetic Aperture Radar (SAR) data for application to research problems in sea-ice science and operations. The basic utility of SAR is in locating, identifying, and tracking ice features of importance in a wide variety of scientific and engineering problems. Subsequent analysis has shown that an even more powerful sea-ice surveillance tool would result from supplementing SAR with an areal-integral measurement technique such as scatterometry, microwave radiometry, or both, and combining these data with meteorological and oceanographic data collected by satellite-monitored buoys. Clearly, a highly productive sea-ice science research mission can be defined for a satellite so instrumented, provided that a suitably designed research program commences prior to launch. In order to design such a mission, Canadian RADARSAT and NASA FIREX (Free-Flying Imaging Radar Experiment) study teams were set up to examine the research problems such a bilaterally supported mission could address, and to determine the mission requirements indicated to assure good progress on those problems. This document discusses some significant research problems associated with ice-covered seas, the consequent mission requirements, and the recommended satellite instrumentation.

Research questions requiring SAR information are divided into two broad classifications: science problems and operational problems, with much overlap and interrelationship. Science problems can be divided into (1) circulation of ocean and atmosphere, (2) climatology, and (3) the response of sea ice as a material. Operational problems can be divided into (1) fixed-installation design, (2) navigation, and (3) offshore activities. Simulation of operational application of SAR is recommended as a necessary step in the transition of SAR from a finely focused research tool to an operational tool; here the similarities to the Landsat program are obvious. Progress on the operational and science research problems requires SAR and ancillary satellite data, buoy data, improved knowledge of microwave properties of sea ice, and prelaunch pilot studies using Seasat, aircraft, or Shuttle data. An efficient means of production and an effective means of communicating the results to remote sites are also needed. All research and simulation activities call for an image-format presentation of a variety of ice types and features; however, some differences exist among activities as to required resolution and repetition or coverage. All activities either require or would profit by buoy data products, including measurements of the geostrophic wind vector and air temperature. Table 1 summarizes the operational and science information requirements.

The program required consists of (1) the instrumented satellite with attendant ground and data-processing systems, (2) an information dissemination system capable of relays to remote points, (3) a data buoy monitoring system, (4) data supplementation and verification by aircraft, ship, and fixed

Table 1. Summary Information Requirements (Operational/Science)

Feature	Resolution	Coverage	Registration	Timeliness	SAR	Other
Pack ice edge	0.5/10 km	Daily/3 daily	0.5/10 km	Day/month	Yes	Scatterometer or radiometer
First-year ice	10%	Weekly	5/10 km	Day/month	Yes	Scatterometer or radiometer
Multiyear area	10%	Weekly	5/10 km	Day/month	Yes	Scatterometer or radiometer
Multiyear flow	$20\ m^2$/NA	Weekly/NA	0.5 km/NA	3 days/NA	Yes/NA	None/NA
Large ridge height	50 m	Weekly	0.5 km	3 days	Doubtful	None
Ice islands	$20\ m^2$/NA	Weekly/NA	2 km/NA	3 days/NA	Yes	None
Icebergs	$20\ m^2$/NA	Weekly/NA	5 km/NA	3 days/NA	Probable	None
Leads, thin ice	$30\ m^2$	Daily/3 daily	0.5/10 km	3 days/month	Yes	Scatterometer or radiometer
Surface temperature	$100\ km^2$	3 daily	50 km	Day/month	No	Buoy
Geostrophic wind speed	1 m/s	Daily	100 km	Day/month	No	Buoy
Direction	20°	Daily	100 km	Day/month	No	Buoy

NA = not applicable.

a/b = a, operations; b, science requirement.

platforms, (5) more information on sea-ice microwave properties, (6) advances in image-processing technology to speed the quantitative analysis of the data, (7) simulation of operational use of SAR, and (8) sea-ice scientific research.

The satellite called for has, in addition to a buoy monitoring system and the required flight and data-link electronics, instrumentation in the form of the SAR complemented by a scatterometer and/or a radiometer. In general, SAR is an identification and location tool for a number of ice features such as ridges, floes, and leads resulting in a data set from which ice motion and deformation data can be extracted. The low-resolution scatterometer/radiometer systems, on the other hand, measure distributed phenomena such as ice-type fraction or amount of open water. The scatterometer/radiometer data will therefore constitute a global ice extent and type data set. It will also have time and space scales suitable to weather and climate research and to operational forecasting applications in which local SAR data are used with a variety of other types of basin-wide low-resolution data. Also, the combination of a feature-identification tool (such as SAR) with a well-calibrated, areally integrating tool (such as the scatterometer) will permit more quantitative estimates of feature variables. All of these instruments have flown in space aboard Seasat, and considerations are now underway by several nations for future flights of similar instruments.

If a SAR system were deployed in the absence of these complementary instruments, the optimum radar frequency for discriminating between first-year ice, multiyear ice, and water on radar backscatter alone would be between 11 and 15 GHz for incidence angles between 20° and 50°. At frequencies in the range between 1 and 10 GHz, the differences in radar backscatter between different ice types are less significant. However, if the SAR system used for feature tracking is supplemented by a 19- or 37-GHz radiometer or a 11- to 15-GHz scatterometer used for ice-type determination, the recommended SAR wavelength would be at L-band (1-2 GHz) with like polarization. At the L-band frequency, first-year ice which has not undergone much deformation can easily be distinguished from multiyear ice, and highly deformed first-year ice and multiyear ice can usually be distinguished by shape and, possibly, by geographical location. While the trend for improved ice feature recognition in SAR data at higher frequencies is reasonably well established, the greatest changes for program success call for the use of systems which are proven in space, of known calibration, and produce familiar data. These systems are the L-band SAR and the higher frequency scatterometer or radiometer.

Other radar parameters can be approximately determined from summary mission requirements. The depression angle should be in the range 20° to 50°. A resolution of 25 m appears adequate although some measurements would tolerate a reduction to 100 m. The swath width required to obtain adequate coverage needs should be 200 km to satisfy operational requirements and somewhat less for many scientific programs. The orbit geometry should provide maximum areal coverage for the supplemental sensors as well as maximum orbit tracks over coastal waters in order for the radar imager to support the operational research objectives. Thus, an orbit providing SAR ground coverage poleward to 76° N in the form of long, nearly east-to-west transects across the Arctic, and scatterometer/radiometer coverage to approximately 85° N for science and for forecasting, is called for. If other satellites are deployed which take the complementary data, the orbit could be lowered a bit. Should a more polar orbit be chosen to accommodate other measurements, the 200-km swath would become a minimum.

The data-processing requirement for operational research problems calls for daily processing of 30 minutes of data within 2 hours of acquisition. The scientific program would require processed data at that speed only rarely--1 or 2 minutes on 10 to 20 days per year--to support field efforts in areas where rapid changes in ice conditions are common (for example, the open ocean margin and the shear zone). For the remainder of the science program, data turnaround time is not appreciably a problem. Geographically, science data demand over a year will call for an uneven mix of zones of long-term surveillance and zones of brief, intense observation to document specific seasonal changes or to support field programs. Under most circumstances, data products would not be in demand sooner than a month after acquisition. However, the data required would need to be of optimum dynamic range and calibration. Thus, the operational research need would call for some 3×10^6 km^2 images per day with a 4-bit range and ± 2-dB absolute calibration, while the science program would require about half as much data processed on a relaxed schedule, possibly involving use of processor time in the summer, but calling for a 5-bit range and ± 1-dB absolute calibration.

As mentioned, the sea-ice science problems which would materially benefit from an augmented SAR deployment are divided into three categories: oceanic and atmospheric circulation, climatology, and materials response. The circulation of the ocean and atmosphere are affected by sea ice because ice changes the surface albedo, alters the fluxes of heat, mass, and momentum between the water and the air, advects latent heat equatorward, changes the stability of the upper ocean, and influences the surface stress on the water column. Specific science questions on which significant progress could be made using data from this program include: How do surface fluxes modify the oceanic circulation of ice-covered seas? How do horizontal and vertical fluxes near the ice edge affect the edge location? What is the net heat loss of the Southern Ocean? What processes control the response of the ice pack to forcing at the coastal boundary? The key measurements of sea ice required for answering these questions are concentration, thickness, velocity, and pressure ridge density. Of these, SAR does an excellent job with velocity, a good job with concentration and ridge density, and provides some information on ice thickness via the determination of ice type. Summary information requirements for science are presented in Table 1.

The research problems associated with future operations in sea-ice-laden waters are divided into three categories: design of fixed installation, navigation, and offshore activities. Ice is of operational interest because it can damage both fixed or floating structures, it strongly influences surface transport even by icebreaker, and it can impede or occasionally enhance a wide variety of offshore support activities. Ice velocity, type, concentration, and ridge density are key measurements for operational problems just as they are for science problems. Specific research questions from anticipated polar operations include: What is required to forecast the location of navigational hazards and of areas of ice not under compression? How can ridge parameters such as height be accurately determined? What kinds of ice features can be expected in a given season at a given location? What is the impact of ice cover information on global weather forecasting? Also, as precise forecasting of ice conditions is important in polar operations, there is a particular need to improve the accuracy of short-term, 1-5 day, ice response forecasts. Summary information requirements for research in operations and engineering are presented in Table 1.

In general, researchers involved with operational problems need accuracy in different areas than do researchers involved with science. For example, the computation of fluxes between the ocean and the atmosphere requires rather detailed knowledge of the ice thickness distribution with an emphasis on the accurate measurement of the areal fractions of thinner ice and open water. The operations problem, on the other hand, is primarily concerned with the exact location of thin ice, open water, and heavy ridging. Thus, the calibration needs are different; clearly more of the total operational problem can be more fully accomplished by a simpler, longer wavelength, Seasat-type radar. Such a system, complemented by a wide-swath coarse footprint instrument, such as a scatterometer or radiometer, constitutes the basic requirement for research on sea-ice operational problems. In the context of a spacecraft SAR development program spanning several decades, a simple SAR similar to the Seasat instrument would satisfy short-term operational needs and would also contribute significantly to progress in long-term science goals. However, it appears that these goals would be better met, of course, by shorter wavelength, higher-resolution systems of the future.

The proposed sea-ice imaging radar program can be summarized as follows. At the soonest possible time, a satellite carrying a Seasat-type Synthetic Aperture Radar (SAR) should be deployed. The SAR system should be augmented by a system or systems that provide areal measurements of ice characteristics, such as a scatterometer or radiometer. Also a data-buoy interrogation system should be deployed. Such a combined system would largely satisfy the research community involved with operational problems and would also enable considerable progress to be made in those areas of sea-ice science concerned with ice dynamics. By the time improvements in SAR technology permit higher frequencies and higher resolutions, the science community should be prepared to exploit these new systems. At the same time, the research community concerned with sea-ice operations problems should be prepared to justify an operational level SAR free-flyer. Thus, part of the recommended program for current consideration is concerned with the implementation of operational-simulation projects involving engineers, scientists, and managers from a variety of agencies and private organizations. These projects would be concerned with actual application exercises such as navigation of an ice-breaking tanker or deployment of a drill ship. This program, centered on the flight of a Seasat-type SAR with supplementary instruments, would provide a valuable scientific data set plus operational experience that could be followed by more sophisticated flight systems with improved capabilities for both science and operations. Such developments would presumably be entirely supported by operational agencies and/or the private sector that is concerned with sea-ice operations. This overall program provides a logical exploitation of techniques for observing sea ice from space for the immediate and longer range future.

II. RENEWABLE RESOURCES MISSION REQUIREMENTS SUMMARY

Report Based on NASA Renewable Resources
Study Team Workshop
Greenbelt, MD
May 20-21, 1981

This mission requirements summary, prepared by the U.S. Renewable Resources Study Team, covers (1) the major potential renewable resources applications of L-band (1.275) and/or C-band (5.3 GHz) Synthetic Aperture Radar (SAR) imagery acquired from an orbital free-flying satellite, (2) key radar parameter, specific research issues (e.g., recommended angles, frequencies, or polarizations) which must be addressed in order to specify the SAR satellite mission requirements, and (3) a preliminary specification of the mission requirements for SAR to be used in a future satellite-based research program. Although this document focuses on SAR mission requirements, the philosophy adopted is that SAR imagery is complementary to visible and infrared imagery in the context of potential applications and that both types of imagery must be considered in an eventual mission definition.

A. POTENTIAL RENEWABLE RESOURCES APPLICATIONS

The Renewable Resources Study Team has identified four major potential applications of space-borne L-band and/or C-band SAR imagery, which are identified in priority order in Table 2. It should be noted that priority category 4 is a combination of three diverse hydrological applications and that a further subdivision of priorities among these three was not possible.

The top two potential applications are viewed as of primary importance, and the bottom two are still high priority but of secondary ranking. The highest priority potential applications is the identification, area estimation, and condition assessment for major agricultural crops such as corn, wheat, soybeans, barley, sorghum, rice, cotton, and sunflowers using SAR imagery either alone or in combination with visible/infrared imagery [e.g., Landsat Multispectral Scanner (MSS) or Thematic Mapper (TM)]. The second-ranked potential application is in mapping and monitoring of soil moisture over a wide range of field roughness and vegetative covers, for use in crop growth, yield models, and hydrological models.

B. KEY RADAR PARAMETER RESEARCH ISSUES

A mission requirements specification for a SAR satellite must include the desirable frequency(ies), angle(s) of incidence, polarization(s), resolution(s), and revisit interval(s). Radar parameters of less crucial importance include swath width, dynamic range, registration, etc. The optimum radar parameters must be specified in the context of both SAR and visible/infrared coregistered images; considerations of SAR alone will not allow a meaningful specification of optimum remote sensor system parameters.

Table 2. Renewable Resources Potential Applications for Spacecraft L- and/or C-band Applications

Priority Category	Potential Applications
	Primary Applications
1	Agricultural crop identification, area estimation, and canopy condition assessment.
2	Soil moisture condition assessment for agricultural and hydrological applications.
	Secondary Applications
3	Forest species identification, area estimation, and canopy condition assessment.
4	Wetlands and coastal land over identification and area estimation, snow wetness and water equivalent, flood extent mapping.

A great deal of radar signature research has been conducted in the past decade and has revealed that C-band or higher frequency radar backscattered signals obtained at high incidence angles are sensitive principally to the water content in a vegetative canopy. Indeed, these higher-frequency radars may be used to distinguish among crop types when measurements are made at periodic intervals through the growing season. These experimental studies have also revealed that a C-band radar operating in the 10^{o}-20^{o} incidence angle range shows a strong sensitivity to soil moisture in the top few centimeters of fields with a wide range of surface roughness and vegetative covers. Significant effects of row structure and row direction have been observed at all frequencies, especially near L-band and near 20^{o} incidence. Most of these experimental studies have been conducted using truck-based boom-mounted radar spectrometers or airborne scatterometers in the 1-18 GHz frequency range.

The specific radar parameter research issues of interest in the present study are more narrowly focused on the question of the utility of L- and/or C-band SAR imagery for the potential applications listed in Table 2. Key research questions are:

When considering data from both radar and visible and infrared sensors, what are the best choices for wavelength, incidence angle, and polarization?

What should the revisit time be?

What is the best combination of resolution and number of looks?

What improvement would be realized by using both L- and C-band?

What improvement would be realized by using two polarizations, e.g., like and cross?

1. Incidence Angles for Vegetation (Especially Crop) Applications

Preliminary results suggest that the preferred incidence angles for vegetation canopy identification and condition assessment by SAR are in the 45^{o}-60^{o} range due to the fact that this configuration minimizes surface scatter from the soil under the canopy and maximizes volume scattering from water contained in the canopy. However, additional research is needed to establish firmly these results for L- and C-band SARs. Multidate data over several crops, forest types, and wetlands types at L- and C-band for angles from 45^{o}-60^{o} are needed to allow researchers to address this issue.

2. Dual-Frequency Utility

The team recommends both C- and L-band based on the approximately 4 to 1 wavelength ratio and the importance of wavelength to volume and surface backscattering. The performance of a dual-frequency L- and C-band system needs to be quantified as compared to a C-band system alone for crops, forest types, and soil moisture. This issue should be addressed now. Multidate like-polarization data are needed for both L- and C-band to address this issue.

3. Dual-Polarization Utility

The added performance of a dual-polarization (like and cross) system needs to be determined as compared to a like-polarized system alone for crops and snow cover. Multidate dual-polarization C- and L-band data are needed for this issue.

4. Spatial Resolution, Revisit Interval, and Swath Width for Soil Moisture

According to one computer simulation study, sensing soil moisture can be done at relatively low resolution (~100 m) for the 15^o C-band HH configuration. The simulation work is being continued with more realistic model assumptions concerning the spatial distributions of plant and soil characteristics. Also, the interleaved constraints of viewing angle range, spatial resolution, swath width, and revisit interval need to be considered to determine if a practical and useful SAR mission configuration can be designed for soil moisture surveying. To support the research for this issue, the team recommends a nominal 30 m (4 looks) spatial resolution since one may degrade that resolution if desired.

C. SUMMARY OF PRELIMINARY MISSION REQUIREMENTS

The renewable resources SAR mission requirements summarized in Table 3 are preliminary and based on our present understanding of the available literature of radar backscatter research. Some of these findings may be modified as a result of the proposed experimental program discussed earlier. These SAR minimum requirements may be viewed as a least common denominator to the crop classification and soil moisture potential applications. They would allow a system with enough flexibility to permit the test and evaluation from space of the preliminary information extraction procedures based on truck radar spectrometer and airborne radar scatterometer measurements and analyses coupled with theoretical models.

Thus, the minimum system is a VV-polarized, C- and L-band SAR which operates simultaneously in both a low-angle and high-angle mode. The low-angle mode is principally for soil moisture mapping and the high-angle mode for crop type and forest species condition and identification. In addition, the synergism of a combination of visible/infrared data and SAR data (1-4 channels) may enhance system performance as compared to any one data source alone. Although the optimum revisit interval for soil moisture mapping may be as short as 1-2 days, in an operational mode, it is felt that the 10-day revisit interval required for crop classification would allow an adequate test of the soil moisture mapping concept in a research mode. Since no operational uses are envisioned for the research spacecraft SAR addressed here, it is not

Table 3. Preliminary SAR Mission Requirements for Renewable Resources

SAR Parameter	Recommended Minimum Configuration
Frequency	C-band and L-band
Polarization	VV
Low-Angle Mode	
Angle of incidence	15°
Resolution	30 m
Number of azimuth looks	4
Swath width	130 km
Revisit interval	<10 days
High-Angle Mode	
Angle of incidence	45°-60°
Resolution	30 m
Number of azimuth looks	4
Swath width	130 km
Revisit interval	<10 days

necessary that a 1-2 day revisit interval be specified. It would be most cost effective to investigate the question of needed revisit intervals through simulations of spacecraft SAR data and truck-based experiments instead of through use of actual spacecraft SAR data acquired every day. The same is true for snow applications as well, where the optimum revisit interval is probably less than the 10-day revisit interval recommended here for the research satellite.

III. NONRENEWABLE RESOURCES MISSION REQUIREMENTS SUMMARY

Report Based on NASA FIREX Nonrenewable Resources
Study Team Workshop
Washington, D.C.
December 1981

This mission requirements summary, prepared by the U.S. Nonrenewable Resources Study Team covers (1) the major potential nonrenewable resources applications objectives for orbital free-flying Synthetic Aperture Radar (SAR) imagery acquired at either L-band (1.275 GHz) and/or C-band (5.3 GHz), (2) key radar parameters and specific research issues (e.g., recommended angles, frequencies, or polarizations) which must be addressed in order to adequately specify the SAR satellite mission requirements, (3) an experimental program using aircraft SAR data which could address those key research issues, and (4) a preliminary specification of the mission requirements for SAR to be used in a future satellite-based research program. This satellite program is referred to in this document as FIREX (Free-Flying Imaging Radar Experiment).

A. POTENTIAL NONRENEWABLE RESOURCES APPLICATIONS OBJECTIVES

The Nonrenewable Resources Study Team proposes three objectives for FIREX: (1) to complete the investigation of satellite radar's sensitivity to topography, (2) to develop the use of backscatter radiance as a discriminator among geologic features, and (3) to conduct radar stereo imaging research. The Study Team emphasizes that these objectives require the highest possible geometric and radiometric control of the radar data.

The primary recognized advantage of radar in remote sensing geology is radar's sensitivity to topography. This sensitivity is greatest at incidence angles less than 25° and greater than 60°. Seasat provided high quality radar data at a 22° incidence angle. FIREX should first provide calibrated registered imagery at a high-look angle of 60°-65° for use in structural mapping. Space-borne SAR sensitivity to topography should be further explored by additionally imaging at an intermediate-look angle of 30°-35°; the combination of intermediate- and high-look angle data permits 30° convergence stereo which has been shown to be a powerful tool in geomorphology. Finally, a low-look angle mode of 15°-20° should be included to permit studies of subtle topographic expression.

At a single wavelength, single-look angle, and single polarization, a given geologic unit may not have a unique signature since its radiometric brightness on an image depends on local slopes, surface moisture, vegetation cover, etc. Geologic interpretation of radar imagery is based on the analysis of image recognition elements which include tone, texture, shape, pattern, and context. However, when it is possible to vary the wavelength, or incidence angle, or polarization, a much more powerful imaging capability is made available because independent looks are acquired which can be used to discriminate among different geologic structures.

Radar backscatter radiance has considerable potential for discrimination among soil and rock types, and geobotanical features. Topographical effects are a confusion factor for this application so that intermediate-look angles (30^{o}-35^{o}) are preferred. Theory and field studies highlight the importance for discrimination based upon backscatter radiance of acquiring both like- and cross-polarized data. Radar backscatter radiance varies with surface geometry and moisture content, while infrared reflectance varies primarily with surface chemistry. The essential independence of these two processes suggests that radar and infrared reflectances should be combined for multicomponent analyses. The experiment would be further enhanced by a second radar wavelength to permit microwave as well as infrared spectral discrimination.

B. KEY RADAR PARAMETER RESEARCH ISSUES

A mission requirements specification for a SAR satellite must include the desirable frequency(ies), angle(s) of incidence, polarization(s), resolution(s), number of looks, and revisit interval(s). Other radar parameters of particular importance to the geologist include swath width, calibration, dynamic range, registration, and multiple looks.

In order to specify these parameters for a meaningful satellite radar geology experiment, the following research issues must be addressed:

1. <u>Sensitivity to topography</u>, vs. frequency, polarization, resolution, and angle of incidence.

2. <u>Sensitivity to surface roughness and vegetation cover</u>, vs. frequency, polarization, resolution, and angle of incidence.

3. <u>Sensitivity to soil moisture</u>, vs. frequency, resolution, and angle of incidence.

It is stressed that these issues can only be addressed with high quality (calibrated and registered) multiparameter SAR imagery over wide swaths. From a practical viewpoint, some of this work can be done using airborne multiparameter SARs and, indeed, specific experiments can be proposed to utilize airborne SAR data. But even the best airborne SAR data suffers from a wide variation in incidence angle over the swath width so that suturing 10-20-km wide images to form a 100-km mosaic presents formidable problems when large-swath regional context images are needed. This serious angle-dependence of airborne SAR data means that only space-borne SAR data over 75-150-km swath widths, with a relatively constant angle of incidence, are adequate to address the utility of SAR for regional geologic mapping applications.

C. SUMMARY OF MISSION REQUIREMENTS

The recommendations of the Study Team for a FIREX configuration are based upon (1) a tentative understanding of the roles played by wavelength, incidence angle, and polarization in radar imagery, (2) valuable experience gained through both Seasat L-band SAR imagery as well as aircraft L-band, and K-band SAR imagery over various geologic test sites, and (3) the collective judgments of both the Study Team and a much larger radar geology community as discussed for example in the recent Snowmass Report [Snowmass Report, 1979]. The Study Team began with the baseline FIREX mission (C-band, 35^{o}-45^{o}, HH) and developed four increasingly ambitious radar system configurations that were consistent with the radar parameter research issues and applications objectives discussed above.

The preliminary mission requirements are summarized in Table 4.

The low-angle mode gives an enhanced sensitivity to topography, where subtle slope changes are depicted with expanded contrast. This region is best for low-lying rough terrain, since layover and compression will severely distort mountainous terrain.

The intermediate-angle mode, using both like- and cross-polarized data, is at an intermediate angle where sensitivity to topography is minimized and where slope effects can be minimized in studies of rock types and geobotanical anomalies. Furthermore, when taken in combination with the high-angle data mode, 30^{o} convergence stereo pairs would be obtained as a powerful tool in geomorphological studies.

The high-angle mode is useful for topographic mapping, with no layover and reduced slope distortion and minimal shadowing.

Table 4. Preliminary SAR Mission Requirements for Nonrenewable Resources

SAR Parameter	Recommended Configuration
Frequency	C-band
Resolution	30 m
Noise equivalent	-35 dB
Polarization mode isolation	25 dB
Swath width	150 km (1 channel) 75 km (2 channels) 50 km (3 channels)
Low-Angle Mode	
Look angle	$15^{\circ}-20^{\circ}$
Number of azimuth looks	TBD
Polarization	HH
Revisit interval	Seasonal
Intermediate-Angle Mode	
Look angle	$30^{\circ}-35^{\circ}$
Number of azimuth looks	TBD
Polarization	HH + HV
Revisit interval	Seasonal
High-Angle Mode	
Look angle	$60^{\circ}-65^{\circ}$
Number of azimuth looks	TBD
Polarization	HH
Revisit interval	TBD

IV. OCEANS MISSION REQUIREMENTS SUMMARY

Report Based on NASA Oceanography
Study Team Workshop
Washington, D.C.
April 27-28, 1981

Over the ocean, a Synthetic Aperture Radar (SAR) is sensitive to short gravity waves or to capillary-gravity waves and the oceanographic phenomena measurable in this way are those that influence the structure or distribution of these short waves.

The presently demonstrated capabilities of SAR are predominately in the area of mapping of oceanographic (and atmospheric) features that produce contrasts in short surface wave structures over relatively small horizontal scales. Many familiar phenomena have been detected, including swell, internal waves, warm core rings and oceanic fronts, and a number of new (and sometimes unexpected) properties have been discerned, including apparent filamentation of large-scale current systems, apparent small-scale "eddies" of 10-50 km, and surface indications of bottom topography produced by tidal flow in relatively shallow water.

Within the next five years, we hope that much of the pattern information presently available will be enhanced by the ability to interpret quantitatively the modulations or variations in return intensity, in terms of the characteristics of the ocean structures that produce them--wave height, current shear, wind speed, and perhaps temperature contrast across features. These developments will considerably increase the utility of SAR for oceanographic purposes.

Over a longer time span, it may be possible to use Doppler information to measure the speed of propagation of the surface structures producing the SAR return and thus infer surface current speeds. We do not underestimate the technical difficulty of measuring small velocities from a rapidly moving platform, and to date there has not been a careful study to assess such feasibility. To achieve this will require thorough analytical evaluation of existing data and a substantial development program. Nor do we underestimate the difficulty of interpretation of the velocity so measured--the speed of short surface waves is influenced by the orbital velocities of longer waves if they are freely travelling, and harmonic constituents of longer waves will also be detected which travel at a phase speed appropriate to the basic wave, not to the harmonic detected. The speed of propagation of short surface waves is also influenced by surface wind drift so that, to infer the velocity of the underlying current, corrections would be necessary to subtract out the influence of both longer waves and wind and these corrections may well be larger than the signal sought. Our expectation of the success of such an endeavour is therefore low; nevertheless, if it were successful, the oceanographic returns would be extremely high. Consequently, the expected return, the product of the two, is highly uncertain.

In the following sections, we attempt to respond to the charges listed in the introduction, and consider the operational and research needs in various oceanographic subject areas in which the use of Synthetic Aperture Radar might have a significant impact.

A. SURFACE WAVES

There is an operational need for 2-dimensional wave spectra in deep water both for purposes of wave forecasting and for the verification and refinement of wave models used in wave forecasting. The accumulation of observations of this kind is necessary for a better definition of the climatology of waves. For deep-water wave spectra, a 15^{o}-angular resolution is desirable together with a 0.5-m accuracy in significant wave height over the range 1-20 m. A 20 percent accuracy in spectral density is desired over about 15 frequency bands between 0.05 to 0.3 Hz with a resolution better than 0.01 Hz near the spectral peak. Information should be at grid scales of 100 km in major ocean basins with the capability of going to 10 km over small regions; an ideal coverage would be every three hours.

In shallow water (depth less than 100), there is again a need for 2-dimensional wave spectra for the verification and refinement of wave models for coastal wave forecasting and to establish the climatology of waves, the influence of wave-current interactions, and the spatial variability of wave and currents. The requirements for shallow water spectra are rather tighter-- an angular resolution of 5^{o}, a 0.25-m significant wave height accuracy in the 1-20-m range and a grid scale that could be as small as 1 km. Other specifications are the same as for deep water.

There are also significant research needs for wave data. There is presently considerable interest in the spatial distribution of wave "groupiness," and well-defined spectra are needed for spatial evolution studies. Observational information is needed on wave-current interactions and on the characteristics and distribution of breaking waves. In shallow water, data are needed on wave-bottom interactions, including refraction, attenuation, and breaking, as well as on wave-current interactions in shallow water. For research purposes, the data are needed with the maximum possible accuracy attainable.

In this area, the present capabilities of SAR include the measurement of wave length and direction, particularly of swell, and the characteristics of swell propagation from storms and refraction in shallow water. SAR can resolve wave lengths and directions in complex wave fields as in hurricanes. Potential capabilities include the measurement of significant wave height, the directional wave distribution, the spectra in shallow water, and the determination of wind speed and direction. SAR also has useful potential in the measurement of wave fields in severe storms.

B. INTERNAL WAVES

Internal wave activity in the ocean is of considerable research interest, and groups of internal waves have been detected by SAR, particularly in coastal regions. However, the detection of internal waves from their surface manifestations is certainly very selective, limited probably to the low-mode, large-amplitude waves, usually tidally generated near the shelf break, and constitute only a small subset of all internal wave motions. Nevertheless, there is interest in the measurement of group and phase velocities of these waves since this gives information on the density structure below the water surface. There is interest in determining the source of these particular waves and their mechanisms of attenuation and the processes of their interaction with current shear. There is also interest in the dissipation of these waves which may produce local mixing and thus affect the primary energy production and diffusion in coastal waters.

C. MARINE METEOROLOGY

Operational and research needs in this area include determination of wind speed and direction over both water and ice, measurement of atmospheric stability, particularly in the lower atmosphere, the 2-dimensional structure of weather patterns and their movements, the location and characteristics of intense storms, and mesoscale atmospheric variability. SAR imagery appears to provide information on mesoscale variability (scales 1-10 km) that is not readily obtainable in other ways, but the range of conditions over which useful information can be extracted may be limited to low wind speeds. SAR is capable of providing the precise location of atmospheric fronts and this ability may be useful in conditions in which a general cloud cover is present. Capabilities in this area are still somewhat unexplored and there may be useful information in existing SAR data that has not as yet been extracted.

D. CURRENTS

Oceanic current systems exist over a wide range of scales, spatially and temporally, and the usefulness of SAR varies widely in different context.

(a) At the largest scale are the general circulation synoptic scale disturbances at 50-200 km with temporal scales greater than 5 days. These represent large-scale currents and major oceanic fronts along the boundaries of different water masses and associated eddies. Dynamically, they are quasi-geostrophic below the surface frictional layer and have associated currents of 10-200 cm; they are delineated by variations in sea surface temperature, and the currents are associated with a variation of sea surface level relative to the geoid. In decreasing order of success, they are measurable and mappable by means of altimetry, infrared radiometry and the Doppler SAR (SARD) if ever it becomes operational. In addition, there is the wind driven component of the current (the surface Ekman layer), 30-50 m in depth, which can be associated with regional winds over past time, and also equatorial currents which do not have geostrophic surface slopes. These cannot be measured by altimetry or IR but could be measured by SARD.

Imaging SAR is of limited utility at these scales except for the identification and location of oceanic fronts at water mass boundaries. There is not a great deal of experience concerning the detection threshold contrast in properties across such a boundary, though some indication of this might be extractable from existing SAR imagery.

(b) Often embedded in or adjacent to these large features are medium-scale, low-frequency structures with horizontal scales of 5-100 km and temporal scales of 1-5 days. These are less well-known than the larger scale motions but are only semi-geostrophic, are subject to horizontal advection by larger scales, and could be rapidly evolving and difficult to measure with passes repeated at time intervals larger than 5 days. These features have been observed in SAR imagery in the coastal zone and as smaller scale, filamented structures embedded in larger scale currents, and their geometrical features could be mapped by repeated observation. They can also be detected by IR. They could be measured with SARD or by altimetry, though the water velocities involved (5-50 cm) and their relatively small scales put them near the limits of resolution.

(c) Medium-scale tidal motions form the dominant current signal in coastal areas. Horizontal scales depend on topography and are characteristically 5-50 km. Such motions are predominantly barotropic (unrelated to the density field) and extend throughout the water column, with vertical surface displacements of 1-10 m and horizontal currents of 10-200 cm. They produce streaming and rifts related to bottom topography and give notable SAR imagery, in particular, locations such as the Nantucket Shoals and the Southern North Sea. For the measurement of these motions by remote sensing, altimetry would be preferred as an operational tool, or SARD if it becomes available.

(d) Small-scale motions (50 m-5 km) include internal waves already described, as well as, possibly, wind-wave generated Langmuir cells. The latter are close to the limit of resolution of SAR and may be best detected optically (as they have been in the past).

(e) Estuarine flows are of considerable significance in fields from coastal engineering to marine biology. Questions of sediment transports, storm surges, river discharges, and tidal exchanges (both patterns and velocities) are of both research and operational interest. Interesting patterns can be discerned in SAR imagery and altimetry may be useful, although it may not offer the clear advantages over traditional methods that remote sensing does offer offshore. SARD would be extraordinarily useful in delineating the often complex current patterns; IR has demonstrated the existence of biologically important estuary fronts.

If SARD becomes operational, there would be great oceanographic interest in applications to all of these areas except possibly (d), and the need would be continuing. Unique SARD capabilities include the ability to measure wind driven and geostrophic motions and the capability of medium-scale mapping. In addition to general coverage, it would also be of utility to special-purpose, local oceanographic studies.

An imaging SAR is capable of providing support information in the areas of (b), (c) and possibly (e) and is of utility in special-purpose oceanographic and bathymetric studies. It is difficult, however, to discern a strong need for long-term monitoring in these areas.

E. DEEP CONVECTION

Deep convection events occur in Arctic and Antarctic waters and in the Mediterranean Sea as intermediate ocean water by transfer downwards of surface water. The convection leads to a sink-type converging flow near the surface, and is of small to medium scale (tens of kilometers), localized and organized within larger scale phenomena. The associated vertical velocities are in the range of 10-100 m per day; the horizontal velocities are unknown. These events are of great oceanographic interest, but as yet, they have not been detected by remote sensing (or, at least, not identified), but SARD may provide a characteristic signature that would allow detection.

F. ICE LEADS

The heat transfer through leads in pack ice is crucially important in the heat budgets of models of polar regions as discussed in Chapter 1. They have horizontal scales from 0.01-5 km, though are sometimes larger and subject to change as a result of local and nonlocal wind. SARD provides the best measurement tool.

The wind field over ice is an important determinant of the ice motion and its measurement provides an interesting challenge. One possible method is to use the length and direction of we ′shadows′ in the lee of ice flows in SAR imagery, though it remains to be seen if this technique is useful. One would anticipate that its usefulness may be limited to the summer season when the leads do not contain sheet or much ice.

G. SAR SPECIFICATIONS FOR OCEANOGRAPHIC PURPOSES

(1) Frequency: The choice of frequency involves somewhat of a compromise. High frequencies are attractive for the best imagery of short surface waves (C-band or above). High frequencies also yield the maximum wind-speed sensitivity but data on possible cross-section saturation at high winds are not yet available. On the other hand, lower frequencies (L-band) are known to produce increasing cross sections at high wind speeds, and low frequencies may possibly be preferable in terms of interpretation since the wave dynamics of short gravity waves are simpler than gravity-capillary waves or small-scale wave breaking.

(2) Resolution: 25 x 25 m.

(3) Swath width: 100 km or greater.

(4) Incidence angle: Preferably variable from 12^o to 50^o; also nadir.

(5) Orbit: Again a choice must be made. For estaurine and surface wave studies, and investigations of small-scale current features, the orbit should provide maximum coverage in coastal regions. Preferably, coverage of any area should be every 6 hours, but every 12 is acceptable. The temporal coverage should be on the order of 10 minutes. On the other hand, for wind structure, fronts and internal wave studies, the orbit should provide global coverage--not sun-synchronous--so that the same spot is not always observed at the same time.

H. COMPLEMENTARY SENSORS

The utility of SAR will be greatly enhanced if certain complementary sensors are available. Most useful will be an altimeter (ALT) on board the same satellite. There appears to be no need to mount a separate altimeter--a separate downward looking antenna is required with the same power supply and using certain electronic components common to SAR. A hybrid SAR/ALT system could be designed to incorporate the requirements for both altimetry and ocean surface imagery. A cost-benefit evaluation of such a system appears desirable.

A scatterometer on board the same satellite will enhance and extend the capability of measuring wind speeds over the ocean. It should operate at a different frequency from SAR and have a larger swath. Note also that a calibrated SAR can be operated in a real aperture mode precisely as a scatterometer.

Of lower priority are visible and infrared sensors. Information of this kind can be obtained from other satellites--a resolution of 1 km is acceptable but finer resolution is desirable.

I. UNRESOLVED QUESTIONS

(1) Can the hydrodynamic and electromagnetic effects of current gradients be adequately understood to allow quantitative measurement of these gradients by SAR?

(2) Can the SAR Doppler be used to detect ocean currents with a spatial resolution greater than 5 km, a temporal resolution greater than one day, with current velocities of 5-10 cm?

(3) Can SAR be unambiguously related to currents--can wind and wave signals be "removed"?

(4) Is a line-of-flight Doppler sufficient or is a new design at a variable beam direction required?

V. CANADIAN SCIENCE AND OPERATIONS REQUIREMENTS SUMMARY

A. INTRODUCTION

As a first step in the implementation of a major operational program plan to meet a known requirement, it is necessary to conduct a program of investigative studies. Results of these studies should ensure the procurement or design of the most effective hardware and the institution of the most efficient operational processes and procedures throughout the initial operational phase of the program.

RADARSAT, which envisages the design, construction and launch in the late 1980s or early 1990s of a polar orbiting satellite carrying as its primary sensor a Synthetic Aperture Radar (SAR), is just such a program. Although numerous discussions of possibilities on a national and international scale have been carried on for a number of years, the program officially commenced in April 1981 with the Phase A studies and R&D program initiated by the Department of Energy, Mines and Resources.

Information essential to the R&D program is a statement of firm mission requirements for the various disciplines that will be served by the satellite. These mission requirements are obtained by comparing the information requirements of the disciplines to be served; these disciplines are represented by study teams. The composition of the four applications study teams (Renewable Land Resources, Nonrenewable Land Resources, Sea Ice, and Oceanography) formed to review the requirements within applicable disciplines, and the study teams′ findings, conclusions, recommendations, including the description of a series of proposed airborne SAR experiments, are described in reports to be published by those committees. The experiments were designed to increase team members′ knowledge of the acquistion, processing, analysis, and particularly, the application of SAR data.

The purpose of this document is to report the activities and progress of the study teams in determining mission requirements in their applicable areas of interest and to make recommendations that will assist other study teams engaged in the design of satellite and sensor hardware, processing and analysis equipment, orbits, operational procedures, etc. In the original Phase A study schedule, the publication of a Final Mission Requirements Document was envisaged as it seemed that by this phase of the program, sufficient Seasat and new Convair 580/SAR data would have been analyzed to provide team members with conclusive data on which to base firm recommendations. Unfortunately, contract delays and equipment unserviceabilities prevented the acquisition, processing, and analysis of much new data, and recommendations presented are based primarily on available literature, workshop discussions, analysis and/or reanalysis of existing Seasat and airborne SAR data acquired during the SURSAT experiment. Although a number of recommendations may be considered "final," the continuance of the program ensures that team members will be provided with new data which, through further study, may present evidence that will cause them to revise their present concepts. Continued revision of the mission requirements as presented, and further dialogue with members of mission concept and SAR design teams, will therefore be mandatory as the program proceeds.

B. It is a relatively simple task for each user, within his area of interest, to define his requirements as he perceives SAR application to his problems. Unfortunately, in a program such as RADARSAT, a user's ideal requirements may be difficult or impossible to meet due to technical or operational constraints. Through discussions with engineering and other design authorities, applications study teams have been made aware of foreseeable constraints and anticipated possible tradeoffs. The study teams' reports reflect their attempts to stay within technical and operational guidelines established. Flexibility has been maintained whenever possible by categorizing requirements as optimal, acceptable, or marginal. Teams have attempted in all cases to specify requirements in known and acceptable engineering terms, e.g., the SAR signal response should be consistent to within ±0.25 dB in a given scene.

C. MISSION REQUIREMENTS CORRELATION

It is obvious that a fixed set of satellite and radar parameters will not satisfy the requirements of all applications teams, or even all of the various applications within any one team's area of responsibility. Within imposed technical and operational limits, teams have reached a consensus on the most acceptable requirement compromise which retains essential usefulness of SAR within their area. Value judgments on which their choices are based are detailed in each report. No attempt has been made in this section to justify parameters presented; they are listed in Tables 5 to 9 inclusive, under specific headings, to highlight commonalities in applications requirements. This permitted the selection, categorization, and presentation in Table 9 of the sets of parameters most likely to meet the greatest number of requirements.

D. RATIONALIZATION

This section outlines the rationale on which parameter selection was based.

1. Frequency and Incidence Angles

In accordance with established Canadian baseline restraints, only two frequencies, C-band at 5.3 GHz, 6-cm wavelength, and L-band at 1 GHz, 23-cm wavelength have been considered. In all cases, incidence angle is measured from nadir to the center ray of the radar transmit beam. Frequency and incidence angle are so closely interrelated that they are discussed jointly.

Requirements for frequency and incidence angle stated by applications teams are summarized as follows:

Table 5. Renewable Land Resources

Parameter[a]	Requirements		
	Optimal	Acceptable	Marginal
Frequency	C- + L-band	C-band	L-band
Incidence angle	20° and 50° in each band	$40^{\circ}-45^{\circ}$	$25^{\circ}-35^{\circ}$
Polarization	VV	HH	HH
Swath width	200 km	150 km	<150 km
Area cover	All of Canadian landmass	All of Canadian landmass	Same
Revisit interval	<10 days in priority areas	15 days	>17 days
Spatial resolution	30 x 30m 16 looks (7.5 x 7.5 m, 1 look)	30 x 30 m, 4 looks (30 x 7.5 m, 1 look)	Less
Geometric positioning	≤15 m	25 m	>25 m
Type of data	Radiometrically and geometrically corrected digital tape or image	Same	Same
Process time	6-12 hours	24 hours	>24 hours
Calibration	Relative ±0.5 dB	Relative ±0.75 dB	Relative ±1 dB
Radiometric resolution	0.25 dB, 256 grey levels at 90 percent confidence level	0.4 dB not specified	>0.6 dB not specified
S/N ratio	Not specified	Not specified	Not specified
Dynamic range	60 dB	60 dB	60 dB
Secondary sensors	Visible and infrared optical scanner	Visible and infrared optical scanner	Microwave radiometer

[a]Parameters listed in this table apply to the following:

(1) Agriculture:

location and acreage of cereals, oil seeds, fallow and forage; soil moisture distribution; crop growth and development; range woody vegetation; rangeland condition; soil salinity; land use change; soil classification; soil erosion.

(2) Forestry:

timber volume; regrowth; surficial materials; fire monitoring; clearcut monitoring; burned areas mapping; tree defoliation.

(3) Hydrology:

snow distribution; snowmelt; river and lake ice for winter transport; state of ground and permafrost; flood mapping; terrain roughness; wetland classification; glacier melting; crop irrigation.

Table 6. Nonrenewable Land Resources

Parameter[a]	Requirements		
	Optimal	Acceptable	Marginal
Frequency	C-band	C- or L-band	L-band
Incidence angle	50^o and 30^o	50^o	30^o
Polarization	HH 50^o and 30^o HV 30^o only	HH	HH
Swath width	150 km	150 km	100 km
Area cover	Entire Canadian landmass	Same	Same
Revisit interval	Biannual at each incidence angle and 2 look directions	Same	Same
Spatial resolution	20 x 20 m, 4 looks	25 x 25 m, 4 looks	30 x 30 m, 4 looks
Geometric positioning	40 m	150 m	150 m
Type of data	Radiometrically and geometrically corrected digital tape or image	Same	Same
Process time	2 weeks	1 month	1 month
Calibration	Relative <1.5 dB across swath <3.0 dB swath to swath	Not specified	Not specified
Radiometric resolution	<3 dB with 4 looks, 10 grey levels at 90 percent confidence level	Not specified	Not specified
S/N ratio	15 dB	10 dB	10 dB
Dynamic range	30 dB linear response	Not specified	Not specified
Secondary sensors	Visible and infrared optical scanner	Visible and infrared optical scanner	Nil

[a]Parameters listed in this table apply to the following: lithology; structure; and surficial geology.

Table 7. Sea Ice

Parameter[a]	Requirements		
	Optimal	Acceptable	Marginal
Frequency	C-band	C- or L-band	Same
Incidence angle	40°-50° value attached to steerable antenna in lower latitudes	25°-50°	$<25^{\circ}$
Polarization	HH	HH or VV	Same
Swath width	200 km or more (100 km if steerable antenna)	200 km	<180 km
Area cover	For operations, all Canadian ice covered and ice infested water, global for scientific	All Canadian ice covered waters north of 60°	Same
Revisit interval	Operations, daily or more often scientific, 1-5 days	Operations, daily scientific, 1-5 days	Same
Spatial resolution	25 m	Low ≤100 m, high 25 m	>100 m
Geometric positioning	±250 m	Same	Same
Type of data	Radiometrically corrected digital tape	Same	Optical
Process time	3 hours or less operationally several weeks for science	Same	Same
Calibration	Relative ±2 dB	Same	Same
Radiometric resolution	Not specified	Not specified	Not specified
S/N ratio	Not specified	Not specified	Not specified
Dynamic range	Not specified	Not specified	Not specified
Secondary sensors	Passive microwave radiometer and scatterometer	Passive microwave radiometer	SAR only

[a]Parameters listed in this table apply to the following: sea ice distribution and surface characteristics; ice types; ice movement; convergence and divergence; and ice/water boundaries as a step in determining concentration.

Table 8. Oceans

Parameter[a]	Requirements		
	Optimal	Acceptable	Marginal
Frequency	C-band	L-band	Same
Incidence angle	25^{o}-35^{o}	Same	Same
Polarization	HH	HH	HH
Swath width	Not specified	Not specified	Not specified
Area cover	Operational 200 nm swath on both coasts, global for scientific	Same	Same
Revisit interval	Not specified	Not specified	Not specified
Spatial resolution	Single look 25 x 25 m	Same	Same
Geometric positioning	Not specified	Not specified	Not specified
Type of data	Geometrically corrected digital tapes and images	Same	Same
Process time	Operational, 1.5 hours scientific, several days	Same	Same
Calibration	Absolute <2 dB	Same	Same
Radiometric resolution	Not specified	Same	Same
S/N ratio	Not specified	Same	Same
Dynamic range	Not specified	Same	Same
Secondary sensors	Scatterometer and passive microwave radiometer	Scatterometer	Radiometer

[a]Parameters listed in this table apply to the following: surface winds; wave direction and peak wavelength; wave height, larger scale features; surface currents; bathymetry; and water temperature.

Table 9. Multidiscipline Compromise Parameters

Compromise Parameters All Applications				Baseline Parameters References	
Parameter	Optimal	Acceptable	Marginal	SPAR Baseline	Seasat Design
Frequency	C- + L-band[b]	C-band	L-band	L- or C-band	L-band
Incidence angle	Center, 25° and 45° fixed ±5° shift	40°-45° fixed ±5° shift	25°-35°	≥35°	22°
Polarization	HH	HH	HH	HH	HH
Swath width	200 km	>150 km	<150 km	L - 200 km C - 150 km	100 km
Area cover	All Canadian ice covered/ infested waters and landmass plus oceans	Same	Same Nonglobal	Variable with latitude and swath width	Variable
Revisit interval	Multiple daily to biannual	Daily	Same	Variable with latitude and swath width	
Spatial resolution	20 x 20 m, 4 looks	25 x 25 m, 4 looks	3 x 50 m 4 looks	25 x 25 m 3 looks	25 x 25 m, 4 looks
Geometric positioning	15 m	50 m	100 m	Not specified	100-700 m
Type of data	Geometrically and radiometrically corrected digital tapes and images	Same	Same	Digital	Digital tape and optical
Process time	3 hours to several days	3 hours for 50 percent and up to 2 weeks for remainder[a]	Same	Not specified	1 day
Calibration	Relative ±0.5 dB	Same	Same	Not specified	2.3 dB across swath
Radiometric resolution	TBD	TBD	TBD	Not specified	2-3 gray levels at 90 percent confidence level
S/N ratio	TBD	TBD	TBD	Noise equivalent backscatter σ_0 C - 25.2 dB/m^2 L - 26.6 dB/m^2	Not specified
Dynamic range	TBD	TBD	TBD	Not specified	50 dB
Secondary sensors	Visible and infrared optical scanner, passive microwave radiometer, scatterometer	TBD	SAR only	Not specified	Microwave radiometer, scatterometer, altimeter

[a]The 3-hour processing requirement equals approximately 70 scenes per day.

[b]Priority in tradeoffs given to optimal specification for incidence angle e.g., sacrifice L-band and swath width first.

a. Renewable Land Resources

A 2-frequency (C + L) and 2-incidence angle ($20^o + 50^o$) system will meet most of the wide variety of applications required for agriculture, forestry, and hydrology. Operation as a 4-band system, i.e., C-band at $20^o + 50^o$, and L-band at $20^o + 50^o$, providing simultaneous data acquisition, is desirable but not mandatory. The second most desirable is a C- + L-band system at 45^o or higher incidence angle; a C-band system having two incidence angles of $20^o + 50^o$ is the third choice. It should be noted that the above are preferred systems; carefully selected single-frequency/single-incidence angle system would still provide much useful data.

b. Nonrenewable Resources

The probability of C-band providing better textural and soil moisture discrimination makes it a first choice for geological applications, although at this time, L-band appears to be acceptable. The extraction of geological information from radar images is greatly facilitated by viewing the Earth's surface in stereo. Although a stereo image can be created by imaging the terrain from opposite directions, the most effective stereo models have been achieved with images that have the same look direction, but a difference in incidence angle of between 15^o and 30^o. There is a requirement therefore, for continuous recording of the same terrain at two different incidence angles during adjacent, parallel orbits. A C-band system having two incidence angles of $30^o + 50^o$ is optimum.

c. Ice

A large number of different ice parameters must be monitored. Only a few sets of simultaneously recorded C- and L-band images of ice have been made available to the Ice Team for study. However, based on analysis of image interpretability, a C-band system is preferred; L-band is acceptable. Incidence angle does not appear to be critical and could range from 40^o to 50^o for optimum performance. Should a tradeoff for increased swath width be possible, incidence angles as low as 35^o are acceptable.

d. Oceans

A C-band frequency is preferred at an incidence angle of between 25^o and 35^o; L-band is marginally acceptable at the same (25^o to 35^o) incidence angle.

e. Discussion

A preference for C-band has been established by all study teams. No team considered L-band to be totally unacceptable and Renewable Land Resources has expressed a requirement for an additional L-band channel with a steep (20^{o}) incidence angle. The dual-freuqency, 4-channel system deemed necessary by Renewable Land Resources will also meet the stereo requirements of Nonrenewable Land Resources and is obviously acceptable to other teams; thus, it must be considered optimal. The recently proposed concept of a fixed $\pm 5^{o}$ steerable antenna increases the effective swath width over specific areas (to be discussed later), and could provide the desired incidence angle range, albeit without simultaneous cover. A single-channel system with C-band at 40^{o} to 45^{o} incidence angle will meet most requirements of all but the oceans group.

2. Polarization

The polarization requirements by applications teams is summarized as follows:

a. Renewable Land Resources

There is a very weak preference for VV polarization. HH is acceptable for all applications.

b. Nonrenewable Land Resources

HH polarization is preferred at both 50^{o} and 30^{o} incidence angles. An optional channel at HV polarization, 30^{o}-incidence angle, may provide additional information on moisture in soils and rocks and assist in the identification of vegetation types.

c. Ice

HH polarization is desirable. VV polarization and/or cross-polarization are marginally acceptable and unacceptable respectively.

d. Oceans

HH is the only polarization considered.

e. Discussion

The preference for VV polarization by Renewable Land Resources is weak and HH polarization is fully acceptable. The advantages to be gained with the HV, 30° channel discussed by Nonrenewable Land Resources are not significant enough to alter the overall preference for HH polarization.

3. Swath Width, Area Cover, and Revisit Interval

Swath width, area cover, and the revisit interval are interdependent; i.e., as swath width increases, so does the area covered within a specified time period, and the revisit time interval decreases. These parameters will therefore be discussed together. Requirements stated by applications teams are summarized as follows:

a. Renewable Land Resources

Renewable Land Resources has a wide variety of area cover requirements and shows revisit cycles ranging from 1 to 180 days. Hydrological requirements are the most demanding. Prime areas of interest require, in most cases, revisit cycles of 10 days or less with 15 days acceptable.

b. Nonrenewable Land Resources

A swath width of 150 km will meet Nonrenewable Land Resources requirements. The twice yearly coverage at each of two look directions (from ascending and descending orbits), of the entire Canadian landmass is easily accomplished.

c. Ice

The operational requirement for the Ice Team is to cover all ice infested/covered waters as frequently as possible, with particular emphasis on at least daily coverage of the proposed northern tanker routes. Tanker routes down the east coast, at latitudes lower than 72° N, are difficult to cover on a daily basis regardless of the type of orbit planned. Scientific and certain types of operational requirements need global coverage, with a revisit period of from 1 to 5 days in specific areas.

d. Oceans

Oceans requirements are similar in nature to those of the Ice Team. Operationally, at least daily coverage is necessary over a 370-km swatch extending outwards from all coasts. Global coverage is required on a 1 to 5 day revisit cycle to assist in forecasting weather and ocean conditions.

e. Discussion

The large northern area coverage and short revisit cycle specified by the Ice Team will be the dominant factors in determining the swath width, revisit cycles, and area cover for the satellite. A satellite SAR having a 200-km swath width and fixed antenna can very nearly meet northern requirements, but east coast shipping routes below 72^{o} latitude cannot be adequately monitored by a single satellite. In this mode, coverage of Renewable Land Resources priority areas will also vary from 7 to 14 days and the operational requirements of the oceans group cannot be met. A $\pm 5^{o}$ steerable antenna will ensure that all northern areas of interest are covered within the desirable revisit interval. With judicious programming of the antenna incidence angle, most northern, east coast shipping routes will receive adequate coverage even if the swath width is reduced to 150 km. Renewable Land Resources requirements for specific area cover during dynamic growth cycles, infestations, or disasters could also be largely met by the steerable antenna. The system could be used to advantage in monitoring specific operational areas at lower latitudes to meet the oceans requirement. Global coverage with a minimum 5-day revisit cycle (for ice or oceans scientific studies) cannot be met with a single satellite regardless of antenna configuration. However, the steerable antenna will, in many instances, permit coverage of storm centres or other phenomena that would not normally be accessible with a fixed antenna system. A $\pm 5^{o}$ steerable antenna at a swath width of 150 km is therefore considered to be the optimal configuration. A minimum fixed antenna swath width of 200 km will be only just acceptable to meet major requirements; 180 km is considered as marginally acceptable.

4. Spatial Resolution

Requirements for spatial resolution stated by applications teams are summarized as follows:

a. Renewable Land Resources

The Renewable Land Resources Team suggested that a minimum target size required in forestry applications will be a cutover of 0.4 ha. However, forest roads may be only 10 m wide and some agricultural crops may occupy fields no more than 50 m wide. Optimum spatial resolution has been established as 7.5 x 7.5 m, 1 look, or 30 x 30 m, 16 looks. Acceptable resolution can be as low as 30 x 7.5 m, 1 look, or 30 x 30 m, 4 looks.

b. Nonrenewable Resources

Geologists are primarily concerned with the detection and identification of surface features that, by inference, will establish subsurface geology. Surface features may vary greatly in size and shape, and it is therefore difficult to establish a minimum target size. However, as resolution of the system improves more features can be identified. A spatial resolution of 20 x 20 m at 4 looks was selected primarily to match the projected resolution of other satellite sensors that are proposed for launch in the 1990s. A 25 x 25 m at 4 looks is acceptable with 30 x 30 m at 4 looks considered marginal.

c. Ice

Identifiable and measurable target size and shape varies widely for ice applications. It may be necessary to establish the width variation, on a day to day basis, of a long, very narrow open water lead, estimate the size and extent of ice ridges or merely plot the position and subsequent movement of ice floes that cover an area of several square kilometers. A 25 x 25 m resolution is deemed to be optimal, a low resolution of $\pm$100 m is acceptable for rapid access data, and less than 100 m is considered marginal.

d. Oceans

A 25 x 25 m, 1-look resolution has been established as optimal, but this figure is based on theory only. The Oceans Team has had insufficient experience in the analysis of SAR data to establish a firm spatial resolution that will meet their major requirements.

e. Discussion

Spatial resolution is difficult to define, as so many factors other than the target size must be taken into consideration, e.g., the geometry of the target, its orientation to the radar transmission, its contrast (to the radar), etc. In addition, requirements vary greatly from application to application. A 20 x 20 m, 4-looks spatial resolution was established as optimal in that this is probably the maximum resolution that can be expected of satellite SAR systems by 1990. A spatial resolution of 25 x 25 m, 4 looks, identical to Seasat performance, is acceptable; 30 x 50 m, 4 looks is marginal.

5. Geometric Positioning

Requirements for positioning or registration in latitude and longitude stated by applications teams are summarized as follows:

a. Renewable Land Resources

A value of 25 m was established by personal communication with team members. All figures apply to position accuracy in an image which has been geometrically corrected to ground control points.

b. Nonrenewable Land Resources

The Nonrenewable Land Resources Team is concerned that geometric positioning be sufficiently accurate to permit coregistration with other digital data sets. Although they recognize that in SAR imagery accuracies will vary considerably as the distance from ground control points increases, they feel that a considerable effort should be made to achieve absolute accuracies of 40 m. Accuracies of up to 150 m will still permit extraction of useful imagery and are acceptable.

c. Ice

A great deal of the ice information will be acquired over water or ice precluding the use of ground control points to facilitate geometric correction. A figure of 100 m is sufficiently accurate to meet most rapid turnaround requirements.

d. Oceans

The Oceans Team has not discussed a need for specific geometric position accuracy. It is assumed that the 100 m suggested by the Ice Team will meet their requirement.

e. Discussion

Geometric position accuracy is obviously of much greater concern to the land resources teams than to ice and oceans groups. Greater accuracies are also possible over land due to the ability of ground control points. The compromise figures shown in Table 5, are based on the most stringent requirements stated by Renewable Land Resources and will, therefore, satisfy the requirements of the other teams. It is realized that the optimal figure (15 m) cannot be achieved at even relatively short distances from ground control points. However, in view of the importance of this parameter, the 15-m figure has been inserted as a firm goal to be achieved whenever advances in technology will so permit.

6. Type of Data

Requirements for data type stated by applications teams are summarized as follows:

a. Renewable Land Resources

The large number of different application requirements to be met will necessitate the provision of a variety of data types with delivery times ranging from a few days to several weeks. Both image and CCT data will be required. It is envisaged that much of the analysis will be performed by computers and therefore, digital data which is radiometrically corrected or in geocoded form will be necessary.

b. Nonrenewable Land Resources

The prime concern is provision of data which is geometrically corrected to permit coregistration with other data. Radiometric correction for variations in image intensity across the swath is also necessary. It is assumed that some image analysis will be performed by computers, but a large number of images will be required for visual analysis. As rapid delivery of products will in most cases not be a restrictive factor, production of precise geometrically and radiometrically corrected digital data should be possible.

c. Ice

For operational sea ice applications, rapid turnaround is the predominant factor affecting the type of product that can be provided. As backscatter values from various ice features and/or open water is essential to analysis, radiometric correction is the primary consideration in the provision of both digital CCTs and images. Geometric correction is also important in determining the geographic location and configuration of features such as ice floes, open leads, etc. Science for sea ice applications, full geometric and radiometric correction, will be required for both digital tapes and images; longer turnaround times will permit the accomplishment of precision processing.

d. Oceans

Requirements are similar to those of the Ice Team in that the end use (operational or scientific) of the data will influence the degree of processing and the delivery time required. Geometrically and radiometrically corrected digital tapes and images will be essential in all cases.

e. Discussion

All teams emphasize the use of computers for analysis, with images playing an important role in some applications. Radiometric correction will maximize the amount of information that can be extracted from the data; geometric corrections will facilitate the registration of obtained information to base maps or with other available data. It is generally agreed that geometrically and radiometrically corrected digital tapes and images must be available on demand.

7. Process Time

Requirements for process time or timeliness stated by applications teams are summarized as follows:

a. Renewable Land Resources

Time from data acquistion to the delivery of a usable product varies widely with the type of product required and its specific application.

b. Nonrenewable Land Resources

Image quality rather than rapid delivery is stressed. The optimal 2-week, and acceptable 1-month, delivery time is acceptable for delivery of a specific scene since it is doubtful that the entire Canadian landmass will be covered within a 15-day time period.

c. Ice

Delivery of certain types of products must be accomplished within 3 hours of data acquisition over certain operational areas in northern ice infested/covered waters. For scientific purposes, depending on the product and its application, delivery time may vary from several days to several weeks.

d. Oceans

Requirements are similar to those of the Ice Team. Ideally, delivery of tapes or images produced from data acquired over operational areas should be accomplished within 1.5 hours. A compromise on the quantity and type of products provided can be made if it will ensure the delivery of operational data within the required time frame.

e. Discussion

Data delivery requirements vary widely from application to application. Extremely short delivery times for products are essential to the operational use of SAR data for certain ice and oceans applications. The 3-hour turnaround time specified by the ice team applies to only 50 percent of their required area cover and represents approximately 70 scenes per day. The quantity of data delivered will obviously be limited if the stated oceans requirement is to be met. It should be possible to meet most of the product delivery requirements specified by the Renewable Land Resources and Nonrenewable Land Resources Teams.

8. Calibration

Requirements for calibration stated by applications teams are summarized as follows:

a. Renewable Land Resources

It is estimated that for agricultural crops, 90 percent of the backscatter will be within 6 dB at the C-band frequency. Crop identification is of prime importance, and if this is to be accomplished using SAR data, response should be consistent to within 1/2 dB in a given scene and be stable over a season for a given target within 1 dB.

b. Nonrenewable Land Resources

Maintenance of relative brightness levels across the swath is important for mapping and correlating tonal features. Radiometric control is extremely important to the effective manipulation (ratioing, slicing, etc.) of SAR data and in stereo mapping or mosaic production. A relative calibration value of 1.5 dB within the swath and ±3 dB between swaths is considered to be essential.

c. Ice

Insufficient C-band imagery of sea ice is available to assess the difference in radar backscatter coefficients between various ice types. A relative calibration of 2 dB is considered, at this time, to be adequate for most purposes.

d. Oceans

An absolute calibration of the radar to 2 dB is required for the quantitative analysis of SAR ocean data.

e. Discussion

The Renewable Land Resources Team has justified the need for a radar system that will maintain a relative calibration of 0.5 dB within a given scene. This is more than adequate to meet the requirements stated by the Nonrenewable Land and Ice Teams and therefore is shown as a desirable characteristic to be considered in the design of a satellite SAR system. The absolute calibration figure of 2 dB, required by the Oceans Team, may be impossible to achieve due to the wide variation in incidence angles possible with a steerable antenna and unpredictable attenuation of the signal due to constantly changing atmospheric conditions.

9. Radiometric Resolution, Signal-to-Noise Ratio, and Dynamic Range

a. Discussion

A number of team members have attempted to define specific limits within which radiometric resolution, signal-to-noise ratio, and dynamic range parameters should be established to meet their requirements. However, after discussion of specifications presented in their reports, it was agreed that team members require additional information before they can make firm recommendations regarding these parameters. Action to be taken is detailed in recommendation number 3 in this report.

10. Secondary Sensors

Requirements for secondary sensors stated by applications teams are as follows:

a. Renewable Land Resources

The inclusion of a visible and infrared (VIR) sensor is a priority item. The combination of data acquired by the SAR and VIR sensors will increase the accuracy and reliability of both types of data obtained.

b. Nonrenewable Land Resources

Experience with data acquired from existing satellite sensor systems shows that much useful geological information can be obtained from visible and infrared sensing devices. It is envisaged that a pushbroom, visible and solar infrared scanner, having switchable/tunable channels will be available by 1990, and that such a system is recommended as a secondary sensor.

c. Ice

The inclusion of a low resolution passive microwave radiometer (PMR) and/or scatterometer is mandatory if hemispheric and global coverage requirements are to be met.

d. Oceans

Within the present knowledge and experience of team members, a low resolution PMR and/or scatterometer are more effective than a SAR in meeting major requirements of the Oceans Team. Their choice of a secondary sensor is therefore obvious.

e. Discussion

Although none of the teams have ruled out the possible value of data obtained from alternate sensors, their choice of a secondary sensor is firm and indicates an even split between Land Resources and the Ice/Oceans Teams. It is suggested therefore that, based on technical feasibility, consideration be given to the inclusion of all secondary sensors requested. This does not imply that there is a requirement to utilize all sensors simultaneously; various combinations of instruments could be activated on an as required basis.

E. CONCLUSIONS

It is concluded that:

(1) Within technical and operational parameters presently set, it is possible to design a SAR system for operational use on a satellite that will meet the major applications requirements for Renewable and Nonrenewable Resources and Sea Ice Teams; marginally for the Oceans Team.

(2) All study teams stress the high quality processing and efficient distribution of acquired data as an essential part of the SAR-equipped satellite operational program.

(3) Study teams emphasize the need for a secondary sensor on the satellite. Requirements are evenly split between the four teams --Land Resources Team favour a VIR scanner; Ice/Oceans Teams consider a passive microwave radiometer and/or a scatterometer to be essential.

The choice of sensor type may depend on a further cost-benefit study or on technical feasibility.

F. RECOMMENDATIONS

It is recommended that:

(1) SAR parameters identified as "optimal" in Table 9 to this document be considered as firm basic requirements at this phase of the program.

(2) Within the Mission Requirements Program, data acquisition, image processing, and analysis continue as planned. Commencing in March 1982, monthly meetings will convene and team leaders will present in writing to satellite/SAR design authorities the findings and conclusions that support or modify existing parameter values.

(3) There should commence immediately the production and examination of a set of images having their technical specifications, i.e., signal-to-noise ratio, dynamic range, etc., altered by known amounts. Study and comparison of such images will assist team members and users in general to understand factors affecting image quality and enable them to quantify their stated requirements.

APPENDIX A: NASA STUDY TEAMS´ MEMBERSHIP

SEA ICE

Dr. W. Weeks (Chairman)
CRREL
Hanover, NH

Dr. W. Campbell
USGS
Tacoma, WA

Dr. F. Carsey
JPL
Pasadena, CA

Dr. R. Chase
WHOI
Woods Hole, MA

Dr. F. Deily
EXXON
Houston, TX

Mr. D. Echert
Oceanographic Services, Inc.
Goleta, CA

Captain R. Kollmeyer
U.S. Coast Guard
New London, CN

Dr. J. Kreider
Shell Development Co.
Houston, TX

Dr. B. Lettau
National Science Foundation
Washington, D.C.

Mr. C. Luther
Office of Naval Research
Alexandria, VA

Dr. R. Onstott
University of Kansas
Lawrence, KA

Mr. R. Shuchman
ERIM
Ann Arbor, MI

Dr. W. Spring
Mobil Oil
Dallas, TX

Dr. C. Swift
University of Massachusetts
Amherst, MA

Dr. D. Thompson
JPL
Pasadena, CA

Dr. A. Thorndike
Polar Science Center
Seattle, WA

Dr. N. Untersteiner
University of Washington
Seattle, WA

OCEANOGRAPHY

Dr. O. M. Phillips (Chairman)
Johns Hopkins University
Baltimore, MD

Dr. O. Shemdin
JPL
Pasadena, CA

Dr. V. Cardone
Oceanweather, Inc.
White Plains, NY

Dr. T. Dillon
Oregon State University
Covallis, OR

Dr. L. Fu
JPL
Pasadena, CA

Dr. F. Jackson
NASA Goddard Space Flight Center
Greenbelt, MD

Dr. R. Johnson
Oceanroutes Inc.
Palo Alto, CA

Dr. T. M. Joyce
WHOI
Woods Hole, MA

Dr. R. Pinkel
Scripps Institution of Oceanography
La Jolla, CA

Dr. W. Plant
Naval Research Laboratory
Washington, D.C.

Dr. C. Rufenach
NOAA/ERL/Wave Propagation Laboratory
Boulder, CO

Mr. R. Shuchman
ERIM
Ann Arbor, MI

Additional contributors:

Dr. R. Keeley
MEDS
Ottawa, Ontario

Dr. E. Langham
National Hydrology Research Institute
Hull, Quebec

Dr. C. S. Mason
Bedford Institute of Oceanography
Dartmouth, Nova Scotia

Dr. S. Peteherych (ARMA)
Atmospheric Environmental Services
Toronto, Ontario

RENEWABLE RESOURCES

Dr. K. R. Carver (Chairman)
NASA
Washington, D.C.

Mr. M. A. Calabrese
NASA
Washington, D.C.

Dr. J. F. Paris (Co-Chairman)
JSC
Houston, TX

Dr. D. K. Hall
NASA GSFC
Greenbelt, MD

Dr. S. Wu
NASA NSTL
NSTL, MS

Dr. F. T. Ulaby
University of Kansas
Lawrence, KA

NONRENEWABLE RESOURCES

Dr. K. R. Carver (Chairman)
NASA
Washington, D.C.

Dr. A. W. England (Co-Chairman)
NASA JSC
Houston, TX

Dr. C. Elachi
JPL
Pasadena, CA

Dr. D. Krohn
USGS
Reston, VA

Dr. J. V. Taranik
NASA
Washington, D.C.

Dr. H. C. MacDonald
University of Arkansas
Fayetteville, AK

Dr. A. Correa
Conoco Inc.
Golden, CO

Dr. A. Blanchard
Texas A&M University
College Station, TX

APPENDIX B: RADARSAT STUDY TEAMS´ MEMBERSHIP

SEA ICE

Dr. A. Allan
C-CORE
St. John´s, Newfoundland

Dr. F. G. Bercha
F. G. Bercha and Associates
Calgary, Alberta

Dr. W. Denner
Memorial University
St. John´s, Newfoundland

Dr. D. Dixit
Melville Shipping
Calgary, Alberta

Mr. M. Dunne
Leigh Instruments
Ottawa, Ontario

Mr. D. Lapp
Atmospheric Environment Service
Ottawa, Ontario

Dr. C. E. Livingstone
Canada Centre for Remote Sensing
Ottawa, Ontario

Dr. R. Lowry
INTERA
Ottawa, Ontario

Dr. B. Mercer
Dome Petroleum Ltd.
Calgary, Alberta

Mr. J. Miller
Petro Canada
Calgary, Alberta

Mr. T. Mullane
Ice Forecasting Central
Ottawa, Ontario

Dr. V. Neralla
Atmospheric Evironment Service
Downsview, Ontario

Dr. R. O. Ramseier
AES
Ottawa, Ontario

Dr. J. Rossiter
HUNTEC LTd.
Scarborough, Ontario

Mr. E. Sadler
DND DREP FMO
Victoria, B.C.

Mr. L. G. Spedding
Esso Resources
Calgary, Alberta

Dr. S. Waterman
MDA
Richmond, British Columbia

Captain P. Whitehead
Canadian Coast Guard
Dartmouth, N.S.

RENEWABLE LAND RESOURCES

M. H. Audeť
Ministere de L´Energie et des Resources

Dr. J. Cihlar (Chairman)
Canada Centre for Remote Sensing

Dr. B. E. Goodison
Atmospheric Environment Service

Dr. N. E. Hardy
Eridale College

Dr. P. Kourtz
Environment Canada

Mr. A. R. Mack
Agriculture Canada

Dr. A. K. McQuillan
Canada Centre for Remote Sensing

Miss N. Prout
Intera Environmental Consultants Ltd.

Mr. A. Jano
Ontario Ministry of Natural Resources

Dr. J. Parry
Mcgill University

Dr. S. Parashar
Remotec Applications Inc.

Dr. P. M. Teillet
Canada Centre for Remote Sensing

Dr. K. P. B. Thompson (Secretary)
Canada Centre for Remote Sensing

Mr. J. Whiting
Saskatchewan Research Council

NONRENEWABLE RESOURCES

T. Alfoldi
Intera Environmental Consultants
Ottawa, Ontario

E. Derenyi
University of New Brunswick
Fredericton, New Brunswick

T. Feuchtwanger
Gulf Canada Resources Inc.
Calgary, Alberta

D. Forsyth
Department of Energy, Mines and Resources
Ottawa, Ontario

B. Guindon
Canada Centre for Remote Sensing
Ottawa, Ontario

M. Gwyn
University of Sherbrooke
Sherbrooke, P.Q.

N. Haimila
N. H. Consulting Ltd.
Cochrane, Alberta

S. Pala
Ministry of Natural Resources
Toronto, Ontario

R. Slaney (Chairman)
Geological Survey of Canada
Ottawa, Ontario

M. Tanguay
Ecole Polytechnique
Montreal, P.Q.

R. B. Taylor
Bedford Institute of Oceanography
Dartmouth, Nova Scotia

J. Wightman
Nova Scotia Land Survey Institute
Lawrencetown, Annapolis County

J. Harris
F. G. Bercha and Associates Ltd.
Ottawa, Ontario

OCEANS

J. Buckley
Petro-Canada
Calgary, Alberta

B. Dawe
Remotec Applications Lt.
St. John´s, Newfoundland

F. W. Dobson
Department of Fisheries and Oceans
Dartmouth, Nova Scotia

W. Emery
University of British Columbia
Vancouver, B.C.

R. Goodman
Esso Resources Canada Ltd.
Calgary, Alberta

J. F. R. Gower
Institute of Ocean Sciences
Sidney, British Columbia

D. Hodgins
Seaconsult Marine Research Ltd.
Vancouver, B.C.

B. Hughes
Defence Research Establishment Pacific
Victoria, B.C.

D. Huntley
Dalhousie University
Halifax, Nova Scotia

S. Jain
Moniteq Limited
Concord, Ontario

R. Keeley
Ocean Science and Surveys
Ottawa, Ontario

B. Kerman
Atmospheric Environment Service
Downsview, Ontario

P. LeBlond
University of British Columbia
Vancouver, B.C.

R. T. Lowry
INTERA
Ottawa, Ontario

C. S. Mason
Department of Fisheries and Oceans
Dartmouth, Nova Scotia

D. North
Mobil Oil Canada Ltd.
Calgary, Alberta

S. Peteherych
Atmospheric Environment Service
Downsview, Ontario

O. M. Phillips
Johns Hopkins University
Baltimore, MD

J. Ploeg
National Research Council
Ottawa, Ontario

R. K. Raney
Canada Centre for Remote Sensing
Ottawa, Ontario

S. Skey
MacLaren Plansearch Inc.
Dartmouth, Nova Scotia

P. E. Vandall, Jr.
Department Energy, Mines and Resources
Ottawa, Ontario

NASA—JPL—Coml., L.A., Calif

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